The quark and the jaguar: Adventures in the simple and the complex

Murray Gell-Mann

Quark JAGUAR

Jk & UARK JAGUAR ADVENTURES IN THE SIMPLE AND THE COMPLEX Murray Gell-Mann □B W. H. Rreeman and Company New York

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FORMARCIA It's good for u»— chaos and color, I mean. Marcta Soudiwick Why me Rivet Disappears

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PREFACE The Quark and the Jaguar is not an autobiography, although it does contain some reminiscences about my childhood and a number of anecdotes about colleagues in science. Nor is it primarily concerned with my work on the quark, although a sizable chunk of the book is devoted to some observations on the fundamental laws of physics, including the behavior of quarks. I may some day write a scientific autobiography, but my aim in this volume is to set forth my views on an emerging synthesis at the cutting edge of inquiry into the character of the world around us—the study of the simple and the complex. That study has started to bring together in a new way material from a great number of different fields in the physical, biological, and behavioral sciences and even in the arts and humanities. It carries with it a point of view that facilitates the making of connections, sometimes between facts or ideas that seem at first glance very remote from each other. Moreover, it begins to answer some gnawing questions that many of us, whether working in the sciences or not, continue to ask ourselves about what simplicity and complexity really mean. The book is divided into four parts. At the beginning of the first part, I describe some personal experiences that led me to write it Taking long walks in tropical forests, studying birds, and planning na- *

 ture conservation activities, I became excited by the idea of sharing with readers my growing awareness of the links between the fundamental laws of physics and the world we see around us. All my life I have loved exploring the realm of living things, but my professional life has been devoted mostly to research on the fundamental laws. These laws underlie all of science (in a sense that is discussed in this book) but often seem far removed from most experience, including a great deal of experience in the other sciences. Reflecting on questions of simplicity and complexity, we perceive connections that help to link together all the phenomena of nature, from the simplest to the most complex. When my wife read me Arthur Sze's poem in which he mentions the quark and the jaguar, I was immediately struck by how well the two images fitted my subject. The quarks are basic building blocks of all matter. Every object that we see is composed, more or less, of quarks and electrons. Even the jaguar, that ancient symbol of power and ferocity, is a bundle of quarks and electrons, but what a bundle! It exhibits an enormous amount of complexity, the result of billions of years of biological evolution. What exactly does complexity mean, though, in this context and how did it arise? Such questions are typical of the ones this book tries to answer. The remainder of the first part is devoted to the relationships among various concepts of simplicity and complexity, as well as to complex adaptive systems—those that learn or evolve in the way that living systems da A child learning a language, bacteria developing resistance to antibiotics, and the human scientific enterprise are all discussed as examples of complex adaptive systems. The role of theory in science is discussed, as well as the issue of which sciences are more fundamental than others, along with the related question of what is meant by reductionism. The second part deals with the fundamental laws of physics, those governing the cosmos and the elementary particles out of which all matter in the universe is composed. Here the quark comes into its own, as do superstrings, which for the first time in history offer the serious possibility of a unified theory of all the particles and forces of nature. The theory of the elementary particles is so abstract that many people find it difficult to follow even when explained, as it is here, without mathematics. Some readers may find it advisable to skim through

 portions of die second part, especially Chapters 11 (on die modern interpretation of quantum mechanics) and 13 (on die standard model of die elementary particles, including quarks). Skimming those chapters, or even die whole part, does not seriously interfere with following the remaining parts. It is ironic that a portion of die book intended to explain why fundamental physical theory is simple should nevertheless be difficult for many readers. Mea culpa! The second part concludes with a chapter on the arrow or arrows of time, culminating in a commentary on why more and more complex structures keep appearing, whedier in complex adaptive systems like biological evolution or in nonadaptive systems like galaxies. The diird part takes up selection pressures operating in complex adaptive systems, especially in biological evolution, human creative thinking, critical and superstitious thinking, and some aspects (including economic ones) of the behavior of human societies. The approximate but convenient notions of fitness and fitness landscapes are introduced. In Chapter 20,1 describe briefly the use of computers as complex adaptive systems, for instance to evolve strategies for playing games or to provide simplified simulations of natural complex adaptive systems. The final part is radier different from die odiers, in mat it is concerned mainly with policy matters radier than science and widi advocacy as much as scholarship. Chapter 21 follows up die discussion in die eadier parts of die book about how die diversity of life on Eardi represents information distilled over nearly four billion yean of biological evolution, and how human cultural diversity has a similar relation to tens of thousands of years of cultural evolution of Homo sapiens sapiens. In Chapter 21,1 argue that it is worth a great effort to preserve both biological and cultural diversity, and I take up some of die problems, paradoxes, and challenges involved. But it is not really possible to consider diose issues in isolation. Today die network of relationships linking die human race to itself and to die rest of die biosphere is so complex that all aspects affect all odiers to an extraordinary degree. Someone should be studying die whole system, however crudely that has to be done, because no gluing togedier of partial studies of a complex nonlinear system can give a good idea of die behavior of die whole. Chapter 22 describes some efforts just getting under way to carry out such a crude study of world problems, including all die

 relevant aspects, not only environmental, demographic, and economic, but also social, political, military, diplomatic, and ideological. The object of die study is not just to speculate about die future, but to try to identify among die multiple possible future padis for die human race and die rest of die biosphere any reasonably probable ones diat could lead to greater sustainability. Here die word sustainability is used in a broad sense, including not only the avoidance of environmental catastrophe, but of catastrophic war, widespread long-lasting tyranny, and other major evils as well. In this volume die reader will find a great many references to die Santa Fe Institute (SFI), which I helped to found and where I now work, having taken early retirement from die California Institute of Technology, where I have become a professor emeritus after being a professor there for more dian diirty-eight years. A good deal of die research done today on simplicity, complexity, and complex adaptive systems is carried out by members of die Institute or, more accurately, of the Institute family. The word family is appropriate because SFI is a radier loose organization. The president, Edward Knapp, is assisted by two vice presidents and an office staff of about a dozen remarkably dedicated workers. There are only diree professors, of whom I am one, all widi five-year appointments. Everyone else is a visitor, staying for periods ranging from a day to a year. The visitors come from all over die world, and a number of diem pay frequent visits. The Institute holds numerous workshops, lasting a few days or sometimes a week or two. In addition, several research networks have been organized on a variety of interdisciplinary topics. The far-flung members of each network communicate widi one anodier by telephone, electronic mail, fax, and die occasional letter, and diey meet from time to time in Santa Fe or sometimes elsewhere. They are experts in dozens of specialties, and diey are all interested in collaborating across disciplinary boundaries. Each one has a home institution, where research can be carried out in a satisfactory manner, but each one also prizes die Santa Fe affiliation, which permits malting connections that are somehow not so easy to make at home. Those home institutions may be great industrial research laboratories, universities, or national laboratories (especially die nearby one at Los Alamos, which has supplied so many brilliant and hard-working mem- ben of die Institute).

 Those who study complex adaptive systems are beginning to find some general principles that underlie all such systems, and seeking out those principles requires intensive discussions and collaborations among specialists in a great many fields. Of course the careful and inspired study of each specialty remains as vital as ever. But integration of those specialties is urgendy needed as well. Important contributions are made by die handful of scholars and scientists who are transforming themselves from specialists into students of simplicity and complexity or of complex adaptive systems in general. Success in making that transition is often associated with a certain style of thought. The philosopher F. W.J. von Schelling introduced die distinction (made famous by Nietzsche) between "Apollonians," who favor logic, die analytical approach, and a dispassionate weighing of evidence, and "Dionysians," who lean more toward intuition, syndiesis, and passion. These traits are sometimes described as correlating very roughly widi emphasis on die use of the left and right brain respectively. But some of us seem to belong to anodier category: die "Odysseans," who combine die two predilections in dieir quest for connections among ideas. Such people often feel lonely in conventional institutions, but they find at SFI a particularly congenial environment. The specialties represented at the Institute include madiematics, computer science, physics, chemistry, population biology, ecology, evolutionary biology, developmental biology, immunology, archaeology, linguistics, political science, economics, and history. SFI holds seminars and issues research reports on topics diat include die spread of die AIDS epidemic, the waves of large-scale abandonment of prehistoric pueblos in die soudiwestern United States, die foraging strategies of ant colonies, whether money can be made by using die nonrandom aspects of price fluctuations in financial markets, what happens to ecological communities when an important species is removed, how to program computers to imitate biological evolution, and how quantum mechanics leads to die familiar world we see around us. SFI is even cooperating widi odier organizations in the attempt, described in Chapter 22, to model ways in which human society on our planet might evolve toward more sustainable patterns of interaction with itself and widi die rest of die biosphere. Here especially we need to overcome die idea, so prevalent in both academic and bureaucratic circles, diat the only work worth taking seriously is highly detailed

 research in a specialty. We need to celebrate the equally vital contribution of those who dare to take what I call "a crude look at the whole." Although SFI is one of very few research centers in the world devoted exclusively to die study of simplicity and complexity across a wide variety of fields, it is by no means die only place—or even die principal place—where important research is being carried out on die various topics involved. Many of the individual projects of die Institute have parallels elsewhere in die world, and in many cases die relevant research was begun earlier in odier institutions, often even before SFI was founded in 1984. In some cases, diose institutions are the home bases of key members of die SFI family. I should like to apologize for what must seem like advertising for SFI, especially since the nature of the relationship between the Institute and odier research and teaching organizations has been somewhat distorted in certain books published by science writers during the last few yean. What amounts to a glorification of Santa Fe at the expense of other places has angered many of our colleagues at those places, especially in Europe. I am sorry if my book gives a similarly misleading impression. The reason for my emphasis on Santa Fe is merely that I am familiar with some of die work carried on here, or by scholan and scientists who visit here, and much less familiar with research, even prior research, carried out elsewhere. In any case, I shall mention at diis point (in no particular order) a few of die leading institutions where significant research on subjects related to simplicity, complexity, and complex adaptive systems is going on and, in most instances, has been going on for many years. Of course, in doing so I risk exacerbating the wrath of the scientists and scholars at those places diat I fail to include in this partial list: The Ecole Normale Superieure in Paris; die Max Planck Institute for Biophysical Chemistry in Gottingen, of which Manfred Eigen is the director; the Institute for Theoretical Chemistry in Vienna, where Peter Schuster has been die director (he is now engaged in starting a new institute in Jena); the University of Michigan, where Arthur Burks, Robert

Axelrod, Michael Cohen, and John Holland form the "BACH group," an interdisciplinary junta that has been conversing about problems of complex systems for a long time—all of them are connected to some extent widi SFI, especially John Holland, who is cochair, along with me, of the Science Board; the University of Stuttgart, where

 Hermann Haken and his associates have long studied complex systems in the physical sciences under the rubric of "synergetics"; die Free University of Brussels, where some interesting work has been carried out for many years; the University of Utrecht; the Department of Pure and Applied Sciences at the University of Tokyo; ATR near Kyoto, where Thomas Ray has moved from the University of Delaware; the centers for nonlinear studies at several campuses of the University of California, including those at Santa Cruz, Berkeley, and Davis; the University of Arizona; the Center for Complex Systems Research at the Beckman Institute of the University of Illinois in Urbana; the program in Computation and Neural Systems at the Beckman Institute of the California Institute of Technology; Chalmers University in Goteborg; NORDITA in Copenhagen; the International Institute for Applied Systems Analyses in Vienna; and the Institute for Scientific Interchange in Turin. Several friends and colleagues whose work I gready respect have been gracious enough to look over the entire manuscript at various stages of completion. I am very grateful for their help, which has been immensely valuable, even though, because of die pressure of time, I have been able to use only a fraction of their excellent suggestions. They include Charles Bennett, John Casti, George Johnson, Rick Lipkin, Seth Lloyd, Cormac McCarthy, Harold Morowitz, and Carl Sagan. In addition, a number of distinguished experts in various fields have been generous with their time in checking on particular passages in the manuscript, including Brian Arthur, James Brown, James Crutchfield, Marcus Feldman, John Fitzpatrick, Walter Gilbert, James Harde, Joseph Kirschvink, Christopher Langton, Benoit Mandelbrot, Charles A. Munn III, Thomas Ray, J. William Schopf, John Schwarz, and Roger Shepard. Of course, the errors that no doubt remain are my sole responsibility and not that of any of these kind and learned people. Anyone who knows me is aware of my intolerance of mistakes, as manifested for example in my ceaseless editing of French, Italian, and Spanish words on American restaurant menus. When I come across an inaccuracy in a book written by somebody else, I become discouraged, wondering whether I can really learn something from an author who has already been proved wrong on at least one point. When the errors concern me or my been proved wrong on at least one point. When the errors concern me or my work, I become furious. The reader of this volume can therefore readily imagine the agonies of embarrassment I am

XVi • PREFACE already enduring just through imagining dozens of serious mistakes being found by my friends and colleagues after publication and pointed out, whether gleefully or sorrowfully, to the perfectionist author. In addition, I keep thinking of the legendary figure described to me by Robert Fox (who writes about the human population problem)—a Norwegian lighthouse keeper who has nodiing to do on long nights throughout the winter but read our books, searching for mistakes. I should like to express my special thanks to my skilled and devoted assistant, Diane Lams, for all the help she has given in the process of completing and editing the book, for managing my affairs so competently that I could devote sufficient time and energy to the project, and especially for putting up with the bad temper that I frequently exhibit in the face of deadlines. The publishers, W. H. Freeman and Company, have been very understanding of my difficulty in dealing with schedules, and they supplied me with a wonderful editorjerry Lyons (now at Springer-Verlag), with whom it has been a delight to work. I should like to thank him not only for his efforts but also for his humor and affability and for the many good times Marcia and I have had with him and his wonderful wife, Lucky. My gratitude is extended also to Sara Yoo, who labored tirelessly in distributing coundess copies and revisions to anxious editors around the world. Liesl Gibson deserves my thanks for her gracious and very efficient assistance with last-minute demands of manuscript preparation. It is a pleasure to acknowledge the hospitality extended by the four institutions with which I have been associated during the writing of diis book: Caltech, SFI, the Aspen Center for Physics, and die Los Alamos National Laboratory. I should also like to thank Alfred P. Sloan Foundation and the U.S. government agencies that have supported my research during recent years: the Department of Energy and the Air Force Office of Scientific Research. (It may surprise a few readers to know that both of these agencies finance research, such as mine, that is neither classified nor connected with weapons. The help given to pure science by such organizations is a tribute to their farsightedness.) Support of my work through donations to SFI by Jeffrey Epstein and by Gideon and Ruth Gartner is also gratefully acknowledged. At Los Alamos, I have been especially well treated by die director of the laboratory, Sig Hecker, by the director of the theoretical division,

PREFACE • xvii Richard Slansky, and by die secretary of the division, Stevie

 Richard Slansky, and by die secretary of the division, Stevie Wilds. At the Santa Fe Institute, every single member of the administration and the staff has been most helpful. At Caltech, die president, the provost, and the outgoing and incoming chairs of the division of physics, mathematics, and astronomy have all been very kind, as has John Schwarz, as well as that wonderful lady who has been secretary to the elementary particle theory group for more than twenty years—Helen Tuck. At die Aspen Center for Physics, since its foundation more than thirty years ago, everything has always revolved around Sally Mencimer, and I should like to thank her too for her many kindnesses. Writing has never come easily to me, probably because my father criticized so vigorously anydiing I wrote as a child. That I was able to complete this project at all is a tribute to my beloved wife, Marcia, who somehow inspired and goaded me into keeping up the work. Her contribution was indispensable in several other ways as well. As a poet an'd an English professor, she was able to cure me of some of my worst habits as a writer, although very many infelicities of style unfortunately remain and should of course not be blamed on her. She persuaded me to work on a computer, to which I have become addicted; it now seems odd diat I could ever have diought of doing without one. In addition, as someone widi little training in science or madiematics who nevertheless has a profound interest in both, she has been an ideal practice target for the book. As a teacher and lecturer, I have often been advised to pick some particular person in the audience and direct the talk to diat individual, even trying to establish repeated eye contact with him or her. In a certain sense, that is what I have done with this volume. It is intended for Marcia, who has tirelessly pointed out places where the explanations are insufficient or the discussions too abstract. I have changed parts of it over and over until she understood and approved. As in so many other respects, more time would have helped. There are, alas, still a number of passages where she would have preferred more clarity. As I write the finishing touches diat deadlines permit, I realize that I have never worked so hard on anything in my life. Research on theoretical physics is entirely different. Of course, a theorist does a great deal of thinking and worrying at odd times, inside or outside of conscious awareness. But a few hours' thought or calculation every day or every few days, plus a good deal of arguing with colleagues and stu-

 dents, have usually sufficed in the way of explicit work—time put in at the desk or the blackboard. Writing, on the contrary, means spending a huge number of hours at the keyboard nearly every day. For a fundamentally lazy person like me, it has come as quite a shock. The most exciting part of writing diis book is being constantly reminded that the project itself is a complex adaptive system. At every stage of composition I have a mental model (or schema) for die book, a concise summary of what it is going to be. That summary needs to be fleshed out with a huge number of details in order to yield a chapter or a part. Then, after my editor, my friends and colleagues, and Marcia and I have had a chance to look over a chapter, the resulting comments and criticisms on the text affect not only die text of diat chapter but the mental model itself, often allowing some variant model to take over. When diat new one is equipped with details in order to produce more text, the same process is repeated. In that way die concept of the entire work keeps evolving. The result of that evolutionary development is the book you are about to read. I hope it succeeds in conveying some of the thrill that all of us experience who think about die chain of relationships linking the quark to the jaguar and to human beings as well.

^ KR T / THE SIMPLE AND THE COMPLEX

1 PROLOGUE: AN ENCOUNTER IN THE JUNGLE I have never really seen a jaguar in the wild. In the course of many long walks through the forests of tropical America and many boat trips on Central and South American rivers, I never experienced that heart- stopping moment when the powerful spotted cat comes into full view. Several friends have told me, though, that meeting a jaguar can change one's! way of looking at the world. The closest I came was in the lowland rain forest of Eastern Ecuador, near the Napo River, a tributary of the Amazon, in 1985. Here a number of Indians from the highlands have settled, clearing small patches of forest for agriculture. They are speakers of Quechua (called Quicjiua in Ecuador), which was the official language of the Inca Empire, and they have given their own names to some of the features of the Amazonian landscape. Flying over that landscape, which stretches for thousands of miles from north to south and east to west, one sees the rivers below as sinuoUs ribbons snaking through the forest. Often the bends in the rivers become oxbows, like the ones on the Mississippi, and the oxbows pinch; off to become lakes, each one connected to the main river by a trickling stream. Local Spanish speakers call such a lake a cocha, using a Quechua word that applies also to highland lakes and to the sea. The aerial observer can see these cochas in all the different stages through 3

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ordinary river bend, then the oxbow, then the newly pinched-off cocha, and then the "ecological succession" as the lake slowly dries up and is gradually reclaimed for the forest by a sequence of plant species. Eventually, it appears from the air only as a light green spot against the darker green of the surrounding forest, and finally, after a century or more, that spot becomes indistinguishable from the rest of the rain forest. When I came near to viewing a jaguar, I was on a forest trail near Pana Cocha, which means "piranha lake." There my companions and I had caught and cooked three different species of piranha, all of which were delicious. Those fish are not quite so dangerous as one might think. True, they sometimes attack people, and it is advisable for a bather who has been bitten to leave the water so the blood will not attract more of them. Still, piranhas are more likely to be the eaten than the eaters in their contacts with humanity. About an hour's walk from the lake, we flushed a group of peccaries, and immediately afterward we sensed the presence of another large mammal just ahead. We smelled a strong pungent odor, very different from that of the wild pigs, and heard the crackling sounds of a heavy creature moving through the underbrush. I caught sight of die tip of its tail, and men it was gone. The master of animals, the emblem of the power of priests and rulers,, had passed by. It was not a jaguar, but another and smaller jungle cat that was to make a difference in my life, by making me aware mat so many of my seemingly disparate interests had come together. Four years after the incident in Ecuador, I was getting acquainted with the flora and fauna of another forested area in tropical America, far from where the Incas had ruled. This was the region where a different Pre-Columbian civilization had flourished, that of the Maya. I was in northwestern Belize, near the Guatemalan and Mexican borders, in a place called Chan Chich, which means "little bird" in the local Mayan language. Many speakers of Mayan languages live in the area today, and traces of me Classic Maya civilization can be found everywhere in that part of Mesoamerica, most dramatically in the physical remains of the abandoned cities. One of the grandest of those cities is Tikal, with its gigantic pyramids and temples, in the northeastern corner of Guatemala, less than a hundred miles from Chan Chich. Speculation abounds on the collapse of the Classic Maya way of life more than a thousand years ago, but the causes remain a mystery and a

 source of controversy to this day. Did the common people tire of laboring at the behest of the rulers and the nobility? Did they lose faith in the elaborate religious system that maintained the power of the elite and held the fabric of society together? Did the wars among the numerous city states lead to general exhaustion? Did the remarkable agricultural practices that supported such large populations in the rain forest finally fail? Archaeologists continue to search for clues to answering these and other questions. At the same time they have to consider the relation between the definitive Classic collapse in the rain forest and what happened in the more arid region of the Yucatan, where in some places the Classic civilization was succeeded by the Postclassic, under Toltec influence. Visiting a gigantic excavated site like Tikal is, of course, unforgettable, but for those willing to go off the beaten track, the jungle affords other pleasures as well, such as coming suddenly upon an unexcavated ruin that isn't indicated on ordinary maps. A ruin reveals itself first as a hillock in the forest, covered, like the flat ground, with trees and shrubs. Approaching, one catches the odd glimpse of old masonry covered with moss and ferns and creepers. Peering through the foliage, one can get a general idea of the size and shape of the site, especially by climbing to a high spot. There, in an instant, one's imagination clears away the jungle and excavates and restores a small Classic Maya site in all its splendor. The forest around Chan Chich is as rich in wildlife as in ruins. Here one can see adult tapirs wrinkling their long noses as they watch over their tiny variegated offspring. One can admire the brilliant plumage of ocellated turkeys, especially the males with their bright blue heads covered with small red knobs. At night a flashlight illuminating the top of a tree may pick out wide-eyed kinkajous clinging to the branches by their prehensile tails. As a lifelong birdwatcher I take particular delight in recording the voices of skulking forest birds, playing back their songs or calls to attract them, and then seeing them (and recording their sounds better) when they come near. In search of birds, I found myself, one day in late December, walking alone on a trail near Chan Chich. The first part of my walk had been uneventful. I had had no luck in recording or sighting any of the bird species I was seeking. Now, after more than an hour, I was no longer concentrating on bird calls or paying close attention to movements in the foliage. My thoughts had

 drifted to a subject that has occupied a good part of my professional life, quantum mechanics. For most of my career as a theoretical physicist, my research has dealt with elementary particles, the basic building blocks of all matter in the universe. Unlike the experimental particle physicist, I don't have to stay close to a giant accelerator or a laboratory deep underground in order to conduct my work. I don't make direct use of elaborate detectors and I don't need a large professional staff*. At most I require only a detectors and I don't need a large professional staff. At most I require only a pencil, some paper, and a wastebasket. Often, even those are not essential. Give me a good night's sleep, freedom from distractions, and time unburdened by worries and obligations, and I can work. Whether I'm standing in the shower, hovering between wakefulness and sleep on a late-night flight, or walking along a wilderness trail, my work can accompany me wherever I go. Quantum mechanics is not itself a theory; rather, it is the framework into which all contemporary physical theory must fit. That framework, as is well known, requires the abandonment of the determinism that characterized the earlier "classical" physics, since quantum mechanics permits, even in principle, only the calculation of probabilities. Physicists know how to use it for predicting the probabilities of the various possible outcomes of an experiment. Since its discovery in 1924, the predictions of quantum mechanics have always worked perfectly, up to the accuracy of the particular experiment and the particular theory concerned. But, in spite of this uniform success, we do not yet fully understand, at the deepest level, what quantum mechanics really means, especially for the universe as a whole. For more than thirty years some of us have been taking steps to construct what I call the "modern interpretation" of quantum mechanics, which permits it to apply to the universe and also to deal with particular events involving individual objects instead of just repeatable experiments on easily reproducible bits of matter. Walking through the forest near Chan Chich, I was pondering how quantum mechanics can be used in principle to treat individuality, to describe which pieces of fruit will be eaten by parrots or the various ways in which a growing tree can shatter a piece of masonry from a ruined temple. My train of thought was broken when a dark figure appeared on the trail about a hundred yards in front of me. I stopped short and carefully raised my binoculars to get a closer look. It was a medium-sized wild

cat, a jaguarundi. It stood across the trail, its head turned toward me, allo^ving me to see its characteristic flattened skull, long body, and short forejegs (features that have prompted some to call it an otter cat). The creature's length—about three feet—and uniform grayish-black coat indicated that it was an adult and of the dark rather than the reddish type. For all I knew, the jaguarundi had been standing there for some time, its brownish eyes trained on me as, bewitched by the mysteries of quantum mechanics, I drew nearer. Though obviously alert, the animal seemed utterly at ease. We stared at each other, both motionless in our tracks, for what seemed like several minutes. It even remained still as I moved closer, to within thirty yards or so. Then, having seen all it cared to see of this particular human being, it faced forward, put its head down, and slowly dissolved into the trees. Such sightings are not very common. The jaguarundi is a shy anintal. Because of the destruction of its native habitat in Mexico and in Central and South America, its numbers have decreased over the years, and it is now included in the Red List of Threatened Animals. Adding to the threat is the creature's apparent inability to reproduce in captivity. My experience with this particular jaguarundi resonated with my thinking about the whole notion of individuality. My memory was jogged back to an earlier encounter with individuality in nature. One day in 1956, when I was a very young professor at Caltech, my first wife Margaret and I were returning to Pasadena from the University of California at Berkeley, where I had given some lectures on theoretical physics. We were in our Hillman Minx convertible with the top down. In those days, academics dressed a little more formally man we do todays —I was wearing a gray flannel suit and Margaret had on a skirt land sweater, with stockings and high heels. We were traveling on Rouje 99 (not yet converted into a freeway) near Tejon Pass, between Bakcrsfield and Los Angeles. When passing through that area, I often scanned the sky, hoping for a glimpse of a California condor. This time, I caught sight of a large form flying low overhead and then rapidly disappearing behind the hill on our right. F was not sure what it was, but I wa$ determined to find out. I pulled the car over to the side of the road,;grabbed my field glasses, jumped out, and ran up the hill. I was deep (in thick red mud most of the way. Part way up, I looked back and there) was Margaret, not far behind, her elegant clothes covered wim mud just like mine. We reached the ridge together and looked down on

 a field where a dead calf was lying. Feasting on it were eleven California condors. They constituted a large fraction of the total population of the species at mat time. We watched them for a long while as they fed, flew off for short distances, landed, walked around, and fed again. I was prepared for their gigantic size (their wing spread is around ten feet), their brighdy colored bare heads, and their black and white plumage. What surprised me was how easily we could tell one of diem from anodier by their lost feadiers. One had a couple of flight feadiers missing from die left wing. Another had a wedge-shaped gap in its tail. None was completely intact. The effect was dramatic. Each bird was an easily identifiable individual, and die observable individuality was a direct result of historical accidents. I wondered whedier these losses of plumage were permanent consequences of die condors' long and eventful lives, or simply die temporary effect of a yearly molt. (I learned later that condors change all their feathers every year.) We are all accustomed to dunking of human beings (and pets) as individuals. But the sight of those distinguishable condors strengthened powerfully my appreciation of how much of the world we perceive as composed of individual objects, animate or inanimate, with dieir own particular histories. Standing, a third of a century later, in the Central American forest, staring at the place where the jaguarundi had disappeared, remembering the ragged condors, and recalling that I had just been thinking about history and individuality in quantum mechanics, it struck me that my two worlds, mat of fundamental physics and diat of condors, jagua- rundis, and Maya ruins, had finally come together. For decades I have lived with diese two intellectual passions, one for my professional work in which I try to understand die universal laws governing the ultimate constituents of all matter and die odier for my avocation of amateur student of the evolution of terrestrial life and of human culture. I always felt that in some way the two were deeply connected, but for a long time I didn't really know how (except for the common theme of the beauty of nature). There would seem to be an enormous gap between fundamental physics and these odier pursuits. In elementary particle dieory we dea\ with objects like die electron and the photon, each of which behaves exacdy the same wherever it occurs in the universe. In fact, all electrons are rigorously interchangeable widi one another, and so are all photons. Elementary particles have no individuality.

 The laws of elementary particle physics are thought to be exact, universal, and immutable (apart from possible cosmological considerations), even though we scientists may approach them by successive approximations. By contrast, subjects like archaeology, linguistics, and natural history are concerned with individual empires, languages, and species, and at a more detailed level with individual artifacts, words, and organisms, including human beings like ourselves. In these subjects the laws are approximate; moreover, they deal with history and with the kind of evolution undergone by biological species or human languages or cultures. But the fundamental quantum-mechanical laws of physics really do give rise to individuality. The physical evolution of the universe, operating in accordance with those laws, has produced, scattered through the (cosmos, particular objects such as our planet Earth. Then, through processes like biological evolution on Earth, the same laws have yielded particular objects such as the jaguarundi and

Earth, the same laws have yielded particular objects such as the jaguarundi and the condors, capable of adaptation and learning, and eventually other particular objects such as human beings, capable of language and civilization and of discovering thoie fundamental physical laws. For some years, my work had been concerned as much with this chain of relationships as with the laws themselves. I had been thinking, for example, about what distinguishes complex adaptive systems, which undergo processes like learning and biological evolution, from evolving systems (such as galaxies and stars) that are nonadaptive. Complex adaptive systems include a human child learning his or her native language, a strain of bacteria becoming resistant to an antibiotic, the scientific corrimunity testing out new theories, an artist getting a creative idea, a society developing new customs or adopting a new set of superstitions, a computer programmed to evolve new strategies for winning at chess, and the human race evolving ways of living in greater harmony with itself and with the other organisms that share the planet Earth. Research on complex adaptive systems and their common properties, as well as work on the modern interpretation of quantum mechanics and on the meaning of simplicity and complexity, had been making steady progress! To further the interdisciplinary study of such issues, I had helped to found the Santa Fe Institute in Santa Fe, New Mexico. Meeting the jaguarundi in Belize somehow strengthened my awareness of the progress my colleagues and I had made in understand-

 ing better die rebdon between die simple and die complex, between die universal and die individual, between die basic laws of nature and die particular, earthly subjects I had always loved. The more I learned about die character of diat rebdon, die more I wanted to communicate it to others. For die first time in my life, I felt me urge to write a book.

2 EARLY LIGHT The tide of diis book comes from a line in a poem by my friend Arthur Sze, a splendid Chinese-American poet who lives in Santa Fe and whom I met through his wife, the talented Hopi weaver Ramona Sakiestewa. The line reads, "The world of the quark has everything to do with a jaguar circling in the night." Quarks are elementary particles, building blocks of the atomic nucleus. I am one of the two theorists who predicted their existence and it was I who gave them their name. In the tide, the quark symbolizes the simple basic physical laws that govern the universe and all the matter in it. It may seem to many people that the word "simple" doesn't apply to contemporary physics;

indeed, explaining how it does apply is one of the aims of this book. The jaguar stands for the complexity of the world around us, especially as manifested in complex adaptive systems. Together, Arthur's images of the quark and the jaguar seem to me to convey perfectly the two aspects of nature that I call the simple and the complex: on the one hand, the underlying physical laws of matter and the universe and, on the other, the rich fabric of the world that we perceive direcdy and of which we are a part. Moreover, just as the quark is a symbol of die physical laws that, once discovered, come into full view before die mind's analytical eye, so the jaguar is, for me at least, a possible metaphor for the elusive complex adaptive system, which continues to avoid a W

 dear analytical gaze, though its pungent scent can be smelled in the bush. But how did I come to be fascinated by subjects like natural history when I was a child? And how and why did I then become a physicist? A Curious I owe most of my early education to my brother Ben, who is nine years older. It was he who taught me to read when I was three (from a Sunshine cracker box) and who introduced me to bird and mammal watching, botanizing, and insect collecting. We lived in New York City, principally in Manhattan, but nature study was possible even there. I thought of New York as a hemlock forest that had been logged too heavily, and we spent much of our time in the small portion that still remained, just north of the Bronx Zoo. Fragments of other habitats survived in places such as Van Cortlandt Park, with its freshwater marsh; die New Dorp area of Staten Island, with its beach and salt marsh; and even, right in our neighborhood, Central Park, which possessed some interesting bird life, especially during die spring and fall migrations. I became aware of the diversity of nature and die striking way in which diat diversity is organized. If you walk along the edge of a swamp and see a northern yellow-throat or hear one singing "Wichita, Wichita, Wichita," you know uiat you are likely to find anodier one former on. If you dig up a fossil, you are likely to run across anodier fossil of die same type near by. After becoming a physicist, I puzzled for some time over how die fundamental laws of physics lay the groundwork for such phenomena. It turns out diat the answer is connected widi die way history is treated in quantum mechanics, and diat die ultimate explanation lies in die condition of die early universe. But apart from such deep physical questions, the less abstruse issue of speciation as a phenomenon in biology is well worth pondering. It is not at all a trivial matter diat mere are such dungs as species; and diey are not just artifacts of die biologist's mind, as has sometimes been claimed. Ernst Mayr, die great ornidiologist and biogeographer, likes to recount how, as a young researcher in New Guinea, he counted a hundred and twenty-seven species of birds nesting in die valley where he was working. The members of die local tribe counted a hundred and

twenty-six; the only difference between their list and his was that they lumped together two very similar species of gerygone that Ernst, with his scientific training, was able to distinguish from each other. Even more important than the agreement among different sorts of people is the fact diat the birds themselves can tell whether or not they belong to the same species. Animals of different species are not usually in the habit of mating with one another, and in the rare cases where they do, the hybrids they produce are likely to be sterile. In fact, one of the most successful definitions of what constitutes a species is the statement that there is no effective exchange of .genes by ordinary means between members of different species. On my early nature walks, I was impressed by the fact that the butterflies, birds, and mammals we saw really did fall neady into species. If you go for a stroll, you may see song sparrows, swamp sparrows, field sparrows, and white-throated sparrows, but you are not likely to see any sparrows that fall in between those categories. Disputes about whether or not two populations belong to the same species arise mosdy when the populations are found in different places or else when they belong to different time periods, with at least one being in the fossil record. Ben and I loved to talk about how species are all related by evolution, like the leaves on an evolutionary "tree," with groupings such as genera, families, and orders representing attempts to specify further the structure of that tree. How distant the relationship is between two different species depends on how far down the tree it is necessary to go in order to find a common ancestor. Ben and I did not spend all our time together in the out-of-doors. We also visited art museums, including those rich in archaeological material (such as the Metropolitan Museum of Art) and those containing objects from medieval Europe (like the Cloisters). We read history books. We learned to read some inscriptions in Egyptian hieroglyphics. We studied Latin and French and Spanish grammars, just for fun, and we noticed how French and Spanish words (and many "ban" words in English) were derived from Latin. We read about the Indo-European language family and learned how many Latin, Greek, and native English words had a common origin, with fairly regular transformation laws. For instance, English "salt" corresponds to Latin "sal" and ancient Greek "hals," while English "six" corresponds to Latin "sex" and ancient Greek "hex"; die initial s in English and Latin goes with rough and ancient Greek "hex", the initial s in English and Latin goes with rough

breathing in ancient Greek, which we indicate by "h." Here was another evolutionary tree, this one for languages. Historical processes, evolutionary trees, organized diversity, and individual variation were all around. In addition to exploring diversity, I also learned that in many cases it was in danger. Ben and I were early conservationists. We saw how the few areas around New York that were more or less natural were becoming still fewer as swamps, for example, were drained and paved over. Back in the 1930s, we were already acutely aware of the finiteness of the Earth, of the encroachment of human activities on plant and animal communities, and of the importance of population limitation, as well as soil conservation, forest protection, and the like. Naturally, I didn't yet connect the need for all these reforms in attitude and practice with the evolution of human society on a planetary scale toward greater sustainability, although that is the way I look at it today. But even then I did have some thoughts about the future of the human race, especially in connection with the textbooks and the scientific romances of H. G. Wells. I loved to read his novels as well. I also devoured books of short stories, and Ben and I read English poetry from anthologies. We went to concerts occasionally, and even the Metropolitan Opera, but we were very poor and had to be content most of the time with activities that were free of charge. We made crude attempts to play the piano and to sing operatic arias as well as songs from Gilbert and Sullivan. We listened to the radio and tried to hear distant stations, both long- and shortwave, and when we succeeded we wrote to them for "verification cards." I remember vividly the ones we received from Australia, with pictures of the kookaburra bird. Ben and I wanted to understand the world and enjoy it, not to sKce it up in some arbitrary way. We didn't differentiate sharply among such categories as the natural sciences, the social and behavioral sciences, the humanities, and the arts. In fact, I have never believed in the primacy of such distinctions. What has always impressed me is the unity of human culture, with science being an important part. Even the distinction between nature and human culture is not a sharp one; we human beings need to remember that we are a part of nature. Specialization, although a necessary feature of our civilization, needs to be supplemented by integration of thinking across disciplines.

One obstacle to integration that keeps obtruding itself is the line separating those who are comfortable with die use of madiematics from those who are not. I was fortunate enough to be exposed to quantitative thinking those who are not. I was fortunate enough to be exposed to quantitative thinking from an early age. Although Ben was interested in physical science and madiematics, it was principally my father who encouraged me to study those subjects. An immigrant from Austria-Hungary in die early yean of die century, he had interrupted his studies at die University of Vienna to come to the United States and help out his parents. They had immigrated a few yean earlier and were living in New York but having trouble making ends meet. My father's first job was at an orphanage in Philadelphia, where he picked up English and baseball from die orphans. Though already a young adult when he started to learn English, his grammar and pronunciation became perfect. When I knew him, die only way one might have guessed he was foreign-born was by noticing that he never made any mistakes. After exploring a number of career opportunities, he finally set- ded, in the 1920s, on die Arthur Gell-Mann School of Languages, where he attempted to teach other immigrants to speak flawless English. He also taught German and hired teachen for French, Spanish, Italian, and Portuguese. The school was a modest success, but things changed in 1929, the year I was born. Not only did die stock market crash, but also a law went into effect severely limiting immigration to the United States. From then on, potential pupils for my father's school were reduced in number by die new quotas and impoverished by die Depression. By the time I was diree yean old, die school had failed and my father had to find a low-paying routine job in a bank to keep us alive. I was brought up to diink of die days before I was born as die good old days. Fadier was intrigued by madiematics, physics, and astronomy, and he would spend houn each day locked in his study poring over books on special and general relativity and on die expanding universe. He encouraged my interest in madiematics, which I came to love, studying it on my own and admiring its coherence and rigor. During my senior year in high school, filling out die application form for admission to Yale, I had to name my probable major subject. When I discussed die choice of field widi my father, he scorned my plans to study archaeology or linguistics, saying I would starve. Instead,

 he suggested engineering. I replied that I would rather starve, and also that whatever I designed would probably rail apart. (Later on, I was told, after an aptitude test, "Anything but engineering!") My father then proposed that we compromise on physics. I explained that I had taken a course in physics in high school, that it was die dullest course in die curriculum, and that it was die only subject in which I had done badly. We had had to memorize such things as die seven kinds of simple machine: die lever, die screw, die inclined plane, and so on. Also, we had studied mechanics, heat, sound, light, electricity, and magnetism, but with no hint of any connections among those topics. My father now switched from economic arguments to promoting physics on die basis of its intellectual and aesthetic appeal. He promised me that advanced physics would be more exciting and satisfying than my high school course, and that I would love special and general relativity and quantum mechanics. I decided to humor die old man, knowing that I could always change my major subject if and when I arrived in New Haven. Once I got there, however, I was too lazy to do so right away. Then, before very long, I was hooked. I began to enjoy theoretical physics. My father had been right about relativity and quantum mechanics. I began to understand, as I studied diem, that die beauty of nature is manifested just as much in die elegance of these fundamental principles as in die cry of a loon or in trails of biolumines- cence made by porpoises at night. Complex Adaptive Systems A wonderful example of die simple underlying principles of nature is die law of gravity, specifically Einstein's general-relativistic theory of gravitation (even though most people regard that theory as anything but simple). The phenomenon of gravitation gave rise, in the course of the physical evolution of the universe, to the clumping of matter into galaxies and then into stars and planets, including our Earth. From die time of their formation, such bodies were already manifesting complexity, diversity, and individuality. But those properties took on new meanings with die emergence of complex adaptive systems. Here on Earth that development was associated with die origin of terrestrial life

 and with the process of biological evolution, which has produced such a striking diversity of species. Our own species, in at least some respects the most complex that has so far evolved on this planet, has succeeded in discovering a great deal of die underlying simplicity, including die theory of gravitation itself. Research on the sciences of simplicity and complexity; as carried out at die Santa Fe Institute and elsewhere around die world, naturally includes teasing out die meaning of die simple and die complex, but also die similarities and differences among complex adaptive systems, functioning in such diverse processes as the origin of life on Earth, biological evolution, the behavior of organisms in ecological systems, the operation of the mammalian immune system, learning and thinking in animals (including human beings), the evolution of human societies, the behavior of investors in financial markets, and the use of computer software and/or hardware designed to evolve strategies or to make predictions based on past observations. The common feature of all these processes is that in each one a complex adaptive system acquires information about its environment and its own interaction with that environment, identifying regularities in that information, condensing those regularities into a kind of "schema" or model, and acting in the real world on the basis of that schema. In each case, there are various competing schemata, and the results of the action in the real world feed back to influence the competition among those schemata. Each of us humans functions in many different ways as a complex adaptive system. (In fact the term "schema" has long been used in psychology to mean a conceptual framework such as a human being always uses to grasp data, to give them meaning.) Imagine you are in a strange city during the evening rush hour, trying to flag down a taxi on a busy avenue leading outward from the center. Taxis rush by you, but they don't stop. Most of them already have passengers, and you notice that those cabs have their roof lights turned off. Aha! You must look for taxis with roof lights on. Then you discover some in that condition and indeed they lack passengers, but they don't stop either. You need a modified schema. Soon you realize that the roof lights have an inner and an outer part, with the the latter marked "Out of Service." What you need is a taxi that has only the inner part of die roof light illuminated. Your new idea receives confirmation when two

 taxis discharge their passengers a block ahead and then their drivers turn on just the inner roof lights. Unfortunately, those taxis are immediately grabbed by other pedestrians. A few more cabs finish their trips nearby, but they too are snapped up. You are impelled to cast your net wider in your search for a successful schema. Finally, you observe, on the other side of the avenue, going in the opposite direction, many taxis cruising with just their inner roof lights on. You cross the avenue, hail one, and climb in. As a further illustration, imagine that you are a subject in a psychology experiment in which you are shown a long sequence of pictures of familiar objects. The pictures represent various things, and each one may be shown many times. You are asked from time to time to predict what the next few images will be, and you keep trying to construct mental schemata for the sequence, inventing theories about how the sequence is structured, based on what you have seen. Any such schema, supplemented by the memory of the last few pictures shown, permits you to make a prediction about the next ones. Typically, those predictions will be wrong the first few times, but if the sequence has an easily grasped structure, the discrepancy between prediction and observation will cause you to reject unsuccessful schemata in favor of ones that observation will cause you to reject unsuccessful schemata in favor of ones that make good predictions. Soon you may be foreseeing accurately what will be shown next. Now imagine a similar experiment run by a sadistic psychologist who exhibits a sequence with no real structure at all. You are likely to go on making up schemata, but this time they keep failing to make good predictions, except occasionally by chance. In this case the results in the real world afford no guidance in choosing a schema, other than the one that says, "This sequence seems to have no rhyme or reason." But human subjects find it hard to accept such a conclusion. Whether putting together a business plan for a new venture, refining a recipe, or learning a language, you are behaving as a complex adaptive system. If you are training a dog, you are watching a complex adaptive system in Operation and you are functioning as one as well (if it is mainly the latter that is happening, then the dog may be training you, as is often the case). When you are investing in a financial market, you and all the other investors are individual complex adaptive systems participating in a collective entity that is evolving through the efforts of all the component parts to improve their positions or at least survive

 economically. Such collective entities can be complex adaptive systems themselves. So can organized collective entities such as business firms or tribes. Humanity as a whole is not yet very well organized, but it already functions to a considerable extent as a complex adaptive system. It is not only learning in die usual sense diat provides examples of the operation of complex adaptive systems. Biological evolution provides many odiers. While human beings acquire knowledge mainly by individual or collective use of dieir brains, die odier animals have acquired a much larger fraction of die information they need to survive by direct genetic inheritance; diat information, evolved over millions of years, underlies what is sometimes radier vaguely called "instinct." Monarch butterflies hatched in parts of die United States "know" how to migrate, in enormous numbers, to die pine-clad slopes of a particular mountain in Mexico to spend die winter. Isaac Asimov, die late biochemist, popularizer of science, and science fiction audior, told me diat he once had an argument widi a dieoretical physicist who denied diat a dog could know Newton's laws of motion. Isaac asked indignandy, "You say diat, even after watching a dog catch a Frisbee with its moudi?" Obviously, die physicist and he were using "knowing" to mean different things: in die case of die physicist, mosdy die result of learning in the cultural context of die human scientific enterprise; in Isaac's case, information stored in die genes, supplemented by some learning from die experience of die individual. That capacity to learn from experience, whedier in paramecia or dogs or people, is itself a product of biological evolution. Furthermore, evolution has given rise not only to learning but to odier new types of complex adaptive systems as well, such as die immune system in mammals. The immune system undergoes a process very similar to biological evolution itself, but on a time scale of hours or days instead of millions of years, enabling die body to identify in a timely fashion an invading organism or an alien protein and produce an immune response. Complex adaptive systems, it turns out, have a general tendency to generate odier such systems. For example, biological evolution may lead to an "instinctive" solution to a problem faced by an organism, but it may also produce enough intelligence for an organism to solve a similar problem by learning. The diagram on die following page illustrates how various complex adaptive systems on Eardi are related to one anodier. Certain chemical reactions involving reproduction and some transmit-

 Evolution of economies including the global economy Evolution of organizations and societies Evolution of strategies by computers Cultural evolution Human cultural evolution m omer species ^with transmission of \ tj learned information \' among individuals] and from generation / to generation / Individual learning and thinking Mammalian immune systems Biological evolution (organisms and ecosystems) ft Prebiotic chemical evolution Some complex adaptive systems on Earth. ted variation led, around four billion years ago, to die appearance of the first life forms and then to diverse organisms constituting ecological communities. Life then gave rise to further complex adaptive systems

 such as die immune system and die learning process. In human beings, the development of die capacity for symbolic language expanded learning into an elaborate cultural activity, and new complex adaptive systems arose within human culture: societies, organizations, economies, and die scientific enterprise, to name but a few. Now diat rapid and powerful computers have emerged from human culture, we can make it possible for diem to act as complex adaptive systems as well. In die future, human beings may create new kinds of complex adaptive systems. One example, which has appeared in science fiction, was first brought to my attention as a result of a conversation that took place in die eady 1950s. The late, great Hungarian-American physicist Leo Szilard invited a colleague and me to attend an international meeting on arms control. My colleague, "Murph" Goldberger (later president of Caltech and dien director of die Institute for Advanced Study in Princeton), replied that he could attend only die second half of die meeting. Leo turned to me, and I said that I could attend only die first half. Murph and I dien asked if we could share an invitation. Leo thought for a moment and men told us, "No, it is no good; your neurons are not interconnected." Some day, for better or for worse, such interconnections might be possible. A human being could be wired direcdy to an advanced computer, (not dirough spoken language or an interface like a console), and by means of diat computer to one or more odier human beings. Thoughts and feelings would be completely shared, widi none of die selectivity or deception diat language permits. (Voltaire is supposed to have remarked diat "Men .. . employ speech only to conceal dieir droughts.") My friend Shirley Hufstedler says diat being wired up togedier is not somediing she would recommend to a couple about to be married. I am not sure diat I would recommend such a procedure at all (aldiough if everything went well it might aUeviate some of our most intractable human problems). But it would certainly create a new form of complex adaptive system, a true composite of many human beings. Gradually, students of complex adaptive systems are becoming familiar widi dieir general properties as well as widi die distinctions among diem. Aldiough diey differ widely in dieir physical attributes, diey resemble one anodier in die way they handle information. That common feature is perhaps die best starting point for exploring how diey operate.

3 INFORMATION AND CRUDE COMPLEXITY In studying any complex adaptive system, we follow what happens to the information. We examine how it reaches the system in the form of a stream of data. (For example, if a subject in a psychological experiment is shown a sequence of images, they constitute the data stream.) We notice how the complex adaptive system perceives regularities in die data stream, sorting them out from features treated as incidental or arbitrary and condensing them into a schema, which is subject to variation. (In the example, the subject makes up and continually modifies conjectured rules that are supposed to describe the regularities governing the sequence of images.) We observe how each of the resulting schemata is then combined with additional information, of the same kind as the incidental information that was put aside in abstracting regularities from the data stream, to generate a result with applications to the real world: a description of an observed system, a prediction of events, or a prescription for behavior of the complex adaptive system itself. (In the psychological experiment, the subject may combine a tentative schema based on die past succession of images with die information provided by die

based on the past succession of images with the information provided by the next few and thus make a prediction about what images will be shown later. In this case, as often happens, the additional special information comes from a later portion of the same 13

 data stream as the one from which the schema was abstracted.) Finally, we see how the description, prediction, or behavior has consequences in the real world that feed back to exert "selection pressures" on the competition among the various schemata; some are demoted in a hierarchy or eliminated altogether, while one or more manage to survive and may be promoted. (In the example, a schema that makes predictions contradicted by the succeeding images is presumably discarded by the subject, while one that gives correct predictions is retained and assigned a high value. Here the testing of the schemata is carried out using later portions of the very same data stream that gave rise to the schemata in the first place and that supplied the additional special information used in making predictions.) Hie operation of a complex adaptive system can be represented by a diagram such as the one on page 25, in which the flow of information is emphasized. Like everything else, complex adaptive systems are subject to the laws of nature, which themselves rest on the fundamental physical laws of matter and the universe. Moreover, of all the physical situations permitted by those laws, only specific conditions permit complex adaptive systems to exist. When studying the universe and the structure of matter we can follow the same practice that we follow when studying complex adaptive systems: concentrate on the information. What are the regularities and where do accidents and the arbitrary enter in? Indeterminacy from Quantum Mechanics ana rrom Chaos According to classical physics of a century ago, exact knowledge of the laws of motion and of the configuration of the universe at any one moment in time would, in principle, permit the complete history of the universe to be predicted. We now know that to be quite false. The universe is quantum-mechanical, which implies that even if its initial state and the fundamental laws of matter are known, only a set of probabilities for different possible histories of the universe can be calculated. Moreover, the degree of this quantum-mechanical "indeterminacy" goes far beyond what is usually discussed. Many people are familiar with the Heisenberg uncertainty principle, which prohibits, for

 Consequences (real world) Description, prediction, behavior (real world) Present data C Unfolding Selective effect on viability of schema and on competition among schemata

Selective effect on viability of schema and on competition among schemata Schema that summarizes and is capable of predicting (one of many competing variants) Identification of regularities and compression Previous data, including behavior and its effects How a complex adaptive system works. example, exact specification of both the posidon and momentum of a particle at the same time. While that principle has received wide publicity (sometimes in quite misleading terms) over many decades, the additional indeterminacy that quantum mechanics requires is rarely mentioned. We shall take it up in some detail further on. Even when the classical approximation is justified and quantum- mechanical indeterminacy is correspondingly ignored, there remains the widespread phenomenon of chaos, in which the outcome of a nonlinear dynamical process is so sensitive to initial conditions that a minuscule change in the situation at the beginning of the process results in a large difference at the end. Some contemporary statements about classical determinism and classical chaos were anticipated in this passage written in 1903 by the French mathematician Henri Poincare in his book Science and Method (as cited by Ivars Peterson in Newton's Clock):

 If we knew exacdy the laws of nature and the situation of the universe at the initial moment, we could predict exacdy the situation of that same universe at a succeeding moment. But even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation approximately. If that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so; it may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon. One of the papers that called attention to chaos in the 1960s was written by a meteorologist, Edward N. Lorenz. In fact, meteorology often supplies examples of chaos that strike close to home. Although satellite photography and calculations using powerful computers have made weather prediction fairly reliable for many purposes, meteorological reports still cannot always tell us correctly what many of us most want to know—whether or not it will rain here tomorrow. Exacdy where a given storm system will pass and when it will drop rain may be arbitrarily sensitive to the details of winds and of the position and physical state of clouds a few days or even a few hours earlier. The slightest imprecision in the meteorologist's knowledge of those data can render a prediction of tomorrow's weather useless for planning a company picnic. Since nothing can ever be measured with perfect accuracy, chaos gives rise to effective indeterminacy at the classical level over and above die indeterminacy in principle of quantum mechanics. The interaction between these two kinds of unpredictability is a fascinating and still rather poorly studied aspect of contemporary physics. The challenge of understanding die relationship between quantum unpredictability and the classical chaotic kind even impressed the editorial staff of the Los Angeles Times so much that in 1987 they printed an editorial on the subject! The writer pointed to the apparent paradox diat some theorists studying the quantum mechanics of systems that exhibit chaos in die classical limit have been unable to find the chaotic kind of indeterminacy superposed on the quantum-mechanical kind. ■

Fortunately, the issue is now being clarified through die work of various theoretical physicists, including a student of mine named Todd Brun. His results seem to confirm diat for many purposes it is useful to regard chaos as a mechanism that can amplify to macroscopic levels die indeterminacy inherent in quantum mechanics. Recendy, diere has been a great deal of careless writing about chaos. From the name of a technical phenomenon in nonlinear dynamics, die word has been turned into a kind of catchall expression for any sort of real or apparent complexity or uncertainty. When I give a public lecture on complex adaptive systems, for example, and mention the phenomenon perhaps once, or maybe not at all, I am bound to be congratulated at the end on having given an interesting talk about chaos. It seems to be characteristic of the impact of scientific discovery on the literary world and on popular culture diat certain items of vocabulary, interpreted vaguely or incorrecdy, are often die principal survivors of die journey from die technical publication to die popular magazine or paperback. The important qualifications and distinctions, and sometimes the actual ideas diemselves, tend to get lost along die way Witness die popular uses of "ecology" and "quantum jump," to say nodiing of die New Age expression "energy field." Of course, one can argue diat words like "chaos" and "energy" antedate dieir use as technical terms, but it is die technical meanings diat are being distorted in the process of vulgarization, not die original senses of die words. In die face of what appear to be increasingly efficient literary mechanisms for turning certain useful concepts into meaningless cliches, an effort should be made to prevent die same fate from befalling die various notions of complexity. We will have to tease some of diem apart and try to see where each one applies. Meanwhile, what about die word "complex" in die term "complex adaptive system" as it is used here? Really, "complex" need have no precise significance in this phrase, which is merely a conventional one. Still, the presence of die word implies the belief diat any such system possesses at least a certain minimum level of complexity, suitably defined. Simplicity refers to die absence (or near-absence) of complexity. Whereas die former word is derived from an expression meaning "once folded," die latter comes from an expression meaning "braided togedier." (Note diat both "plic-" for fold and "plex-" for braid come from die same Indo-European root "pfefc.")

 Different Kinds of Complexity What is really meant by die opposing terms simplicity and complexity? In what sense is Einsteinian gravitation simple while a goldfish is complex? These are not easy questions—it is not simple to define "simple." Probably no single concept of complexity can adequately capture our intuitive notions of what the word ought to mean. Several different kinds of complexity may have to be defined, some of which may not yet have been conceived. What are some cases where the question of defining complexity comes up? One is die computer scientist's concern about the time a computer requires to solve a certain kind of problem. In order to keep that time from depending on the cleverness of die programmer, scientists focus on die shortest possible solution time, which is often called die "computational complexity" of die problem. Even die minimum time still depends on die choice of computer, however. Such "context dependence" keeps cropping up in attempts to define different kinds of complexity. But die computer scientist is particularly interested in what happens to a set of problems that are similar except for size; furthermore, his or her main concern is with what happens to computational complexity as the size of the problem gets larger and larger without limit. How does the minimum solution time depend on size as the size tends to infinity? The answer to such a question can be independent of the details of the computer. Computational complexity has proved to be quite a useful notion, but it does not correspond very closely to what we usually mean when we employ the word complex, as in a highly complex story plot or organizational structure. In those contexts, we may be more concerned with how long a message would be required to describe certain properties of the system in question than with how long it would take to solve some problem on a computer. For example, a debate has been going on for decades in the science of ecology over whether "complex" ecosystems like tropical forests are more or less resilient than comparatively "simple" ones such as the forest of oaks and conifers resilient than comparatively "simple" ones such as the forest of oaks and conifers found high in the San Gabriel Mountains behind Pasadena. Here resilience refers to the likelihood of surviving (or even deriving benefit from) major disturbances from climate

change, fire, or some other environmental alteration, whether human in origin or not. Currently those ecological scientists seem to be winning the argument who claim that, up to a point, the more complex ecosystem is more resilient. But what do they mean by simple and complex? The answer is certainly related in some way to the length of a description of each forest. To arrive at a very elementary notion of complexity for forests, ecologists might count the number of species of trees in each type (less than a dozen in a typical high-mountain forest of the temperate zone venus hundreds in a lowland tropical forest). They might also count the number of species of birds or mammals; again, the comparison would greatly favor the tropical lowlands. With insects the results would be even more striking —imagine how many insect species there must be in an equatorial rain forest. (The number has always been thought to be very large, and recendy the estimates have been gready increased. Starting with the work of Terry Erwin of the Smithsonian Institution, experiments have been carried out in which all the insects in a single rain forest tree are killed and collected. The number of species was found to be on the order of ten times that previously estimated, and many of the species were new to science.) One need not count only species. Ecologists would also include interactions among organisms in the forest, such as those between predator and prey, parasite and host, pollinator and pollinated, and so on.

Coarse Graining

But down to what level of detail would they count? Would they look at microorganisms, even viruses? Would they look at very subde interactions as well as obvious ones? Evidendy, they have to stop somewhere. Hence, when defining complexity it is always necessary to specify a level of detail up to which the system is described, with finer details being ignored Physicists call that "coarse graining." The image that inspires the name is probably that of the grainy photograph. When a detail in a photograph is so small that it needs to be gready enlarged to be identified, the enlargement may show the individual photographic grains. Instead of a clear picture of the detail, there will then be only a few dots to convey a rough image of it. In the Antonioni film Blow-Up,

the title refers to just such an

enlargement. The graininess of a photograph supplies a bound on the amount of information it can yield. If the film is very grainy; the best the whole picture can do is to give a rough impression of what was photographed; it is exhibiting very coarse graining. If a spy satellite takes a picture of a previously unknown weapons "complex," the measure of complexity that can be assigned to it will depend on die graininess of the photograph. Having established the importance of coarse graining, we are still faced with the question of how to define the complexity of the system being investigated. For instance, what characterizes a simple or a complex pattern of communication among a certain number of people (say, N people)? Such a question might arise for a psychologist or a student of organizations who is trying to compare how well or how rapidly some problem is solved by the N people under different conditions of communication. At one extreme (call it case A), each person works alone and there is no communication at all. At the other extreme (call it case F), each person is free to communicate with every other person. Case A is obviously simple. Is case F much more complex or is it about as simple as case A? As to level of detail (coarse graining), suppose all the people are treated alike, having no individual characteristics, and are represented in a diagram simply as dots, in such a way that the positions of the dots do not matter and all the dots are interchangeable. Communication between any two people is either allowed or not allowed, with no gradations in between, and each two-way communication link is represented as a line (with no directionality) connecting two dots. The resulting diagram is what mathematicians call an "undirected graph." The Length or the Description With the level of detail specified in this way, it is possible to explore what is meant by the complexity of a pattern of connection. First take die case of a small number of dots, say eight (N = 8). Here it is easy to draw some of the patterns, including some trivial ones. The diagrams on page 31 show some of the possible communication patterns among eight individuals. In A, none of the dots is connected to any other. In B, some of the dots, but not all, have connections. In C, all die dots are

 Some patterns of connection of eight dots. connected, but not in all possible ways. In D, the connections that are present in C are absent and those that are absent in C are present; D is what we might call the complement of C and vice vena. Similarly, E and B are complements of each other. So are F and A: Pattern A has no connections, while F has all possible connections. Which patterns are to be assigned higher complexity than which others? Everyone will agree that A, with no connections, is simple, and that B, with some connections, is more complex or less simple than A. But what about the others? One particularly interesting case is that of F. An initial reaction to F might be that it is the most complex of all, since it has the most connections. But is that sensible? Isn't the property of having all dots connected just as simple as that of having no dots connected? Maybe F belongs at the bottom of the complexity scale, along with A.

 Such reasoning brings us back to the suggestion that at least one way of defining the complexity of a system is to make use of the length of its description. Pattern F would then really be about as simple as its complement, pattern A, since the phrase "all dots connected" is of about the same length as the phrase "no dots connected." Moreover, the complexity of E is not all that different from that of its complement, B, since adding the word "complement" doesn't make the description significantly longer. The same is true of D and C. In general, complementary patterns will have about the same complexity. Patterns B and E are evidently more complex than A and F, and so ate C and D. The comparison of B and E with C and D is trickier. It may seem that C and D are more complex, using the simple criterion of description length, but whether they really are depends to some extent on die vocabulary available for die description. Before going further with die notion that complexity is related to die length of a description, it is worth noting that die same diagrams that we have applied to patterns of communication among people can also be applied to another situation, one that is of great significance in science, technology, and business today. These days, computer scientists are making rapid progress in die construction and utilization of "parallel processing" computers, which are much more effective in solving certain kinds of problems dian conventional machines. Instead of a single giant computer that works away steadily at a problem until it is finished, parallel processing uses an array of many smaller computing units, all operating simultaneously, with some pattern of communication links joining certain pairs of units. Here again one can ask, What does it mean for one pattern of communication hookups to be more complex dian anodier? In fact, it was a physicist designing a parallel processing computer who asked me diat very question years ago and renewed my interest in the problem of defining complexity. We previously considered die possibility of counting die number of species, interactions, and so form in order to define simple and complex ecological communities. If all die kinds of trees occurring in die community were listed, for example, die length of diat part of die description would be roughly proportional to die number of tree species. Hence, in diat case would be roughly proportional to die number of tree species. Hence, in diat case too die length of die description was effectively being used as a measure.

 Context Dependence If complexity is defined in terms of the length of a description, then it is not an intrinsic property of the thing described. Obviously, the length of a description may depend on who or what is doing the describing. (That reminds me of James Thurber's story Tlte Glass in the Field, in which a goldfinch gives a concise account to other birds of a collision with a pane of glass: "I was flying across a meadow when all of a sudden the air crystallized on me.") Any definition of complexity is necessarily context-dependent, even subjective. Of course, the level of detail at which die system is being described is already somewhat subjective—it too depends on the observer or the observing equipment. In actuality, then, we are discussing one or more definitions of complexity diat depend on a description of one system by another system, presumably a complex adaptive system, which could be a human observer. Suppose, for present purposes, diat the describing system is, in fact, a human observer. To refine the notion of the length of a description, we should avoid describing something by pointing to it; clearly it is just as easy to point to a complex system as to a simple one. Therefore, we are concerned with a description that is being communicated to someone at a distance. Also, it is easy to give a name like "Sam" or "Judy" to something extremely complicated, making its description trivially short. The descriptive language must be previously agreed upon and not include special terms made up for the purpose. Of course, many kinds of arbitrariness and subjectivity still remain. The length of the description will vary with the language used, and also widi the knowledge and understanding of the wodd that die correspondents share. If, for example, a rhinoceros is to be described, the message can be shortened if both parties already know what a mammal is. If the orbit of an asteroid is to be described, it makes a great deal of difference whether both know Newton's law of gravitation and his second law of motion—it may also matter to the length of the description whether the orbits of Mars, Jupiter, and die Earth are already known to both parties.

 Conciseness and Crude Complexity But what if a description is unnecessarily long because words are being wasted? I recall the story of die grade school teacher who assigned a 300-word composition to her class as homework. A pupil who had spent the weekend playing managed to scribble on Monday morning die following essay: "Yesterday the neighbors had a fire in their kitchen and I stuck my head out of

"Yesterday the neighbors had a fire in their kitchen and I stuck my head out of the window and yelled, 'Fire! Fire! Fire!...'" The child repeated the word "fire" until the essay was 300 words long. However, if it hadn't been for that requirement, the child could have written instead, "... yelled 'Fire!' 280 times" and conveyed die same meaning. For our definition of complexity we are therefore concerned with the length of the shortest possible message describing a system. These points can be integrated into a definition of what may be called "crude complexity": the length of the shortest message that will describe a system, at a given level of coarse graining, to someone at a distance, employing language, knowledge, and understanding that both parties share (and know they share) beforehand. Certain familiar ways of describing a system do not yield anything like the shortest message. For example, if we describe die parts of a system separately (say die pieces of a car or the cells in a human body) and also tell how the whole is composed of the parts, we have ignored many opportunities to compress die message. Those opportunities would make use of similarities among the parts. For example, most of die cells in a human body share the same genes and have many other features in common, while the cells in a given tissue are even more similar. The shortest description would take that into account. ritnmic Information Content Certain experts in information theory utilize a quantity that is much like crude complexity, although their definition is more technical and naturally involves computers. They envisage a description to a given level of coarse graining diat is expressed in a given language and then encoded by some standard coding procedure into a string of Is and 0s. Each choice of a 1 or 0 is known as a "bit." (Originally, that was a Ako

 contraction of "binary digit." It is binary because there are only two possible choices, whereas with the usual digits of the decimal system there are ten: 0,1,2,3,4,5,6,7,8,9.) It is that string of bits, or "message string," with which they are concerned. The quantity they define is called "algorithmic complexity," "algorithmic information content," or "algorithmic randomness." Nowadays the word "algorithm" refers to a rule for calculating something and, by extension, to a program for computing something. Algorithmic information content refers, as we shall see, to the lengdi of a computer program. Originally, algorithm meant something different. The word sounds as if it is derived from the Greek, like "arithmetic" but, in fact, that is only the result of a disguise. The "th" was introduced by analogy with the "th" in "arithmetic," although it doesn't really belong there. A spelling that better reflects the etymology would be "algorism." It comes from the name of the man whose book introduced the idea of zero into Western culture. He was the ninth century Arab mathematician Muhammad ibn Musa al-Khwarizmi. The surname indicates that his family came from the province of Khorezm, south of the Aral Sea, now part of the newly independent republic of Uzbekistan. He wrote a mathematical treatise the ode of which contains the Arabic phrase "aljabr," meaning "the transposition," from which we get the word "algebra." Originally, the word "algorism" referred to the decimal system of notation, which is thought to have passed from India to Europe largely through the translation into Latin of al-Khwarizmi's "Algebra." Algorithmic information content (AIC) was introduced in the 1960s by three authors working independendy. One was the great Russian mathematician Andrei N. Kolmogorov. Another was an American, Gregory Chaitin, who was only fifteen years old at the time. The third was another American, Ray Solomonoff. Each assumes an idealized all-purpose computer, treated as essentially infinite in storage capacity (or eke finite but able to acquire additional capacity as needed). The computer is equipped with specified hardware and software. They then consider a particular message string and ask what programs will cause the computer to print out that string and then stop compudng. The length of the shortest such program is the AIC of the string.

 We have seen that subjectivity or arbitrariness is inherent in the definition of crude complexity, arising from such sources as coarse graining and the language used to describe the system. In AIC, additional sources of arbitrariness have been introduced, namely the particular coding procedure that turns the description of the system into a bit string, as well as the particular hardware and software associated widi the computer. None of this arbitrariness bothers the mathematical information theorists very much, because they are usually concerned with limits in which finite arbitrariness becomes comparatively insignificant. They like to consider sequences of similar bit strings of increasing length, studying how die AIC behaves as the length approaches infinity. (That is reminiscent of how computer scientists like to treat the computational complexity of a sequence of similar problems as the problem size approaches infinity.) Let us return to the idealized parallel processing computer made up of units, represented by dots, connected by communication links represented by lines. Here Kolmogorov, Chairin, and Solomonoff would not be very interested in die AIC of various possible patterns of connections among a mere eight points. Instead, they would ask questions about the connections among N points as N tends to infinity. Under those conditions, certain differences in the behavior of the AIC (for example, between the simplest pattern of connections and the most complex) dwarf any differences that result from the use of one computer instead of another, one coding procedure instead of another, or even one language instead of another. An information theorist cares whether a certain AIC keeps growing as N approaches infinity and, if so, how fast. He or she is not much concerned with die comparatively negligible differences between one AIC and another diat are introduced by various kinds of arbitrariness in the descriptive equipment. We can learn an interesting lesson from those theorists. Even if we don't confine ourselves to systems diat become infinitely large, it is important to understand diat discussions of simplicity and complexity tend to become more and more meaningful as the bit strings become longer and longer. At the other extreme, say for a string of one bit, it is evidendy meaningless to differentiate between simplicity and complexity.

 Information Denned It is high time to make clear die distinction between algorithmic information content and information, as discussed, for example, by Claude Shannon, die founder of modern information dieory. Basically, information is concerned widi a selection from alternatives, and it is most simply expressed if those alternatives can be reduced to a sequence of binary choices, each of which is between two equally probable alternatives. For example, if you learn that a coin toss resulted in tails instead of heads, you will have learned one bit of information. If you learn that three successive coin tosses resulted in heads, men tails, men heads again, you will have acquired three bits of information. The game Twenty Questions provides a beautiful opportunity to express the most varied sorts of information in the form of successive binary choices between equally probable alternatives, or as close to equally probable as die questioner can get It is played by two people, die first of whom dreams up something that die second player has to guess in twenty questions or less, after having been told whether it is animal, vegetable, or mineral. The questions have to be answered either "yes" or "no"; each is a binary choice. For die second player, it is advantageous to make die questions as close as possible to a choice between equally probable alternatives. Knowing that die tiling is mineral, for example, die questioner would be ill-advised to ask right away whether it is die Hope diamond. Instead, he or she might ask, "Is it natural [as opposed to being manufactured or modified by humans]?" Here, die probabilities of affirmative and negative responses are about equal. If die answer is "No," die next question might be, "Is it a specific object as opposed to a class of objects?" When die probabilities of a yes and no answer are equal, each question will elicit one bit of information (the most diat answer are equal, each question will elicit one bit of information (the most diat such a question can extract). Twenty bits of information correspond to a choice from among 1,048,576 equally probable alternatives, die product of multiplying together 20 factors of 2. That product is die number of different bit strings of lengdi 20.) Note that bit strings are employed differendy depending on whedier AIC or information is being discussed. In the case of algoridi- mic information content, a single bit string (preferably a long one) is

 considered, and its internal regularities are measured by die length (in bits) of die shortest program that will cause a standard computer to print out the bit string and then stop. By contrast, in die case of information, one may consider a choice among all die different bit strings of a given lengdi. If diey are all equally probable, dieir lengdi is die number of bits of information. One can also deal widi a set of bit strings, for example equally probable ones, each with a particular value of AIC. In diat case it is often useful to define an amount of information, determined by the number of strings, as well as a value of AIC averaged over the set. Compression ana Random Strings Algoridimic information content has a very curious property. To discuss it, we have to look first at the relative "compressibility" of different message strings. For a bit string of a given lengdi (say a very long one), we can ask when the algorithmic complexity is low and when it is high. If a long string has the form 110110110110110110 ... 110110, it can be produced by a very short program that says to print 110 a particular number of times. Such a bit string has a very low AIC, even though it is long. This means it is highly compressible. By contrast, it can be shown mathematically diat most bit strings of a given lengdi are incompressible. In odier words, the shortest program diat will produce one of diose strings (and then have the computer stop) is one diat says PRJNT followed by the string itself. Such a string has a maximum AIC for its lengdi. There is no rule, no algoridim, no dieo- rem diat will simplify the description of diat bit string and allow it to be described by a shorter message. It is called a "random" string precisely because it contains no regularity that will permit it to be compressed. The fact diat algorithmic information content is maximal for random strings explains die alternative name algoridimic randomness. The UncomputaLiliiy or AIC The curious property is diat AIC is not computable. Even though most bit strings are random, there is no way of knowing exacdy which ones are. In fact, we cannot, in general, be sure diat die AIC of a given string isn't lower than we think it is. This is because there may always be a theorem we will never find, an algorithm we will never discover, that would permit the string to be further compressed. More precisely, there is no procedure for finding all the theorems that would permit further compression. That was proved some years ago by Greg Chaitin, in work that is reminiscent of part of a famous result of Kurt Godel. Godel was a mathematical logician who stunned the world of mathematics in the early 1930s with his discoveries about the limitations of systems of axioms in mathematics. Until his time, mathematicians had hoped it might be possible to formulate a system of axioms for mathematics that could be proved consistent and used in principle to derive the truth or falsity of all mathematical propositions. Godel showed that neither of those goals is attainable. Negative results like that often represent monumental advances in mathematics or in science. We might compare Albert Einstein's discovery that there can be no absolute definition of time or space, but only a combined space-time. In fact, Godel and Einstein were good friends. At the Institute for Advanced Study in Princeton, New Jersey, in the early 1950s, I used to see them walk to work together, and they made a strange-looking couple, like Mutt and Jeff. Godel was so tiny that he made Einstein look quite tall. Did they discuss deep mathematical or physical questions? (Godel worked from time to time on problems related to general relativity.) Or was their conversation mainly about the weather and their health problems? The part of Godel's conclusion that is relevant to our discussion is the one about undecidability: given any system of axioms for mathematics, there will always be propositions that are undecidable on the basis of those axioms. In other words, there are propositions that cannot, in principle, be shown to be either true or false. The most celebrated kind of undecidable proposition is a statement that is independent of the axioms. One can use such a proposition to enlarge the set of axioms by introducing either the proposition or its contrary as a new axiom. But there are other undecidable propositions that have a different character. Suppose, for example, that an undecidable proposition relating to positive whole numbers is of the form, "Every even number greater than 2 has the following property. . . ." If there were any exception to such a proposition, in principle we could find it, given

 enough time, by trying out every even number in succession (4,6,8,10, ...) until we hit a number not possessing the property in question. That would immediately disprove die proposition, but it would also contradict its undecidability, since undecidability means precisely that die proposition cannot be proved or disproved. Thus, there is no exception to die proposition. In die ordinary sense of die word "true," die proposition is true. We can make diis more concrete by considering a proposition diat has never been proved, after centuries of effort, aldiough no exception to it has ever been found. The proposition is Goldbach's conjecture, which states diat every even number larger than 2 is die sum of two prime numbers. A prime number is a number greater dian 1 that is not divisible by any number except itself and 1. The first few prime numbers, dierefore, are 2,3,5,7,11,13,17,19,23,29,31, and 37. It is easy to see from diis list how every even number between 4 and 62 can be expressed in at least one way as die sum of two primes. Computer calculations have verified diat every even number up to some unbelievably large value has die same property. However, no such computation can prove die conjecture, which could always fail for some still larger even number. Only a rigorous madiematical demonstration can turn die conjecture into a proved dieorem. There is no reason to believe diat Goldbach's conjecture is un- decidable, but suppose it is. It would dien be true, even diough unprovable, because diere could be no exception to it. The existence of any even number greater dian 2 diat is not die sum of two primes would disprove die conjecture and dierefore contradict its undecidability. The fact diat such true but unprovable dieorems are always lurking in die background means, as Chaitin has shown, diat diere may be one diat will permit a long message string to be compressed when we diink it is incompressible, or to be further compressed when we diink we have found die shortest program diat will cause die computer to print it out and dien stop. Thus, in general, one cannot be sure of die value of algoridimic information content; one can only place an upper bound on it, a value that it cannot exceed. Since die value may be below diat bound, AIC is unconfutable. The property of uncomputability may be awkward, but a different property is what prevents us from using algoridimic information content to define complexity. Aldiough AIC is useful for introducing useful

notions like coarse graining, compressibility of message strings, and the length of a description generated by an observing system, it has one really bad flaw: the alternative name algorithmic randomness gives it away. Algorithmic information content is largest for random strings. It is a measure of randomness, and randomness is not what is usually meant by complexity, either in ordinary discourse or in most scientific usage. Thus AIC is not true or effective complexity. It turns out that care is required when discussing randomness, however, because the word does care is required when discussing randomness, however, because the word does not always mean exactly the same thing. I first became aware of that pitfall a long time ago, in my contacts with the RAND Corporation.

4 RANDOMNESS When I first came to work at Caltech in die 1950s, I needed a consulting job to pay some bills. Caltech professors are allowed to consult once a week, and I inquired among my colleagues to find out what the possibilities were. One or two suggested the RAND Corporation, located in Santa Monica near the famous pier and Muscle Beach. The RAND Corporation had started out, shordy after die Second World War, as Air Force Project RAND (said to be an acronym for research and no development). It was to advise the U.S. Air Force on matters such as matching strategy to mission (that is, to the tasks assigned to die service), and devising rational methods of procurement. After a while, its role was broadened to include advice to government on a variety of matters, many of diem connected with defense strategy. Project RAND continued to be important, but it provided only part of the financial support for die organization, which became a not-for- profit corporation and branched out into civilian work of many kinds. RAND employs specialists in a great many fields, including political science, economics, physics, mathematics, and operations research. The physics department, consisting mosdy of theoreticians, hired me as a consultant, and I started to earn money doing unclassified research. Three of us from Caltech formed a car pool and spent every Wednesday at RAND.

44 • THE SIMPLE AND THE COMPLEX The Meanings of "Random" One of the things I remember best from my early visits to RAND was being handed a small pile of recendy produced reports, so that I could become familiar with some of the work that was going on. One of the reports in the stack was the "RAND Table of Random Numbers," which was undoubtedly useful though not very exciting to read (I am told, however, that the subtide, "And 100,000 Normal Deviates," led some librarians to shelve it under abnormal psychology). What I found interesting about the report was a small piece of paper (a "Wow-in") that fluttered out of it and fell to the floor. I picked it up and found it was an errata sheet. The RAND mathematicians were supplying corrections to some of the random numbers! Were they catching random errors in the random numbers? For a long while, I regarded this incident as just one more scene in the human comedy, but as I speculated about it later it focused my attention on an important fact: even to mathematicians and scientists the word "random" means several different things. As we have been using the word, applied for instance to a single string of a thousand bits, random means that the string is incompressible. In

string of a thousand bits, random means that the string is incompressible. In other words, it is so irregular that no way can be found to express it in shorter form. A second meaning, however, is that it has been generated by a random process, that is, by a chance process such as a coin toss, where each head gives 1 and each tail 0. Now those two meanings are not exactly the same. A sequence of a thousand coin tosses could produce a string of a thousand heads, represented as a bit string of a thousand Is, which is as tar from being a random bit string as it is possible to get. Of course, a sequence of all heads is not at all probable. In fact, its chance of turning up is only one in a very large number of about three hundred digits. Since most long strings of bits are incompressible (random) or nearly so, a set of a thousand tosses will often lead to a random bit string, but not always. One way to avoid confusion would be to refer to chance processes as "stochastic" rather than random, reserving the latter term mainly for incompressible strings. But what does random signify in the RAND table of random numbers? How could the table be equipped with an errata sheet? And of what use is a table of random numbers in the first place?

 One of die activities of die RAND physics department in 1956 and 1957 was an unclassified project, with applications to astrophysics, that required a calculation in rather basic physics. I undertook to carry it out, receiving some help from another consultant, an old friend named Keith Brueckner. Part of the calculation involved doing a couple of difficult sums approximately, and one of die most interesting RAND physicists, Jess Marcum, offered to do diem by what is known as die Monte Carlo method, utilizing die table of random numbers. Random Numbers and the Monte Carlo Method The mediod was very suitable for Jess because he was a gambler as well as a physicist. In his early years, he had won a good deal of money at blackjack in casinos. He used die "student mediod," betting lighdy on most games, when the odds were slighdy against him, and then heavily when die odds were in his favor, for example when all die ten-counting cards (tens and picture cards) were in one part of the deck. That mediod of play was possible only as long as a single deck was being used. After a while, all the casinos adjusted dieir procedure (adapting to die "students") and began to use many decks at a time. Jess moved on to odier pursuits. At one point, he took a leave of several months from RAND to play die horses. His mediod was to handicap die handicappers. He didn't claim to be an expert on die horses diemselves, but merely studied die racing forms to see how well die odds given by each handicapper corresponded with die actual results. He dien followed die advice of die successful handicappers. However, he added anodier wrinkle.Just before each race, he checked die tote board to see whether the quoted odds (reflecting the bets received up to diat time) corresponded with diose of the good handicappers. If diey didn't, it meant diat die crowd was following other advice, probably that of bad handicappers. Jess rushed into die gap between die quoted odds and die odds given by the best predictors, betting heavily. In diis way, he made steady money at die racetrack. But after a while he concluded diat his RAND salary paid at least as much widi less risk, and so he went back to work. That is how Jess happened to be available to help me.

46 • THE SIMPLE AND THE COMPLEX The Monte Carlo method of doing sums is applied when there is a really huge set of quantities to be added; a rule (an algorithm!) is given for computing the first quantity from the number 1, the second quantity from the number 2, die third quantity from die number 3, and so forth; die rule is such diat die quantity varies radier smoothly from one number to die next; and die computation of each quantity from die corresponding number is long and tedious, so diat one does not want to do any more of diose computations than necessary. (These days, with enormously rapid and powerful computers easily available, many such sums are computed direcdy,aldiough the computers of diirty-five years ago required tricks like the Monte Carlo method.) Suppose we have to add 100 million quantities after calculating each of them from the corresponding number, which runs, of course, from 1 to 100 million. To employ die Monte Carlo approximation, we use a table of random numbers to obtain, say, 5,000 numbers between 1 and 100 million, chosen by chance. In each of die 5,000 cases, every number between 1 and 100 million has an equal probabiUty of turning up. We then calculate the quantities corresponding to die 5,000 numbers and add diem up, taking diem to be a representative sample of die whole 100 million quantities to be added. Finally, we multiply the result by 100 million divided by 5,000 (that is, 20,000). In this way, we have approximated our lengthy calculation by a much shorter one. Random or Pseudorandom? The table of random numbers is supposed to be a set of whole numbers between one and some fixed large value, widi each number chosen by a chance process in which every number in die range has an equal probability of occurring. In fact such a table is not usually generated that way, but is instead a table of pseudorandom numbers! These are reeled off by a computer using some definite madiematical rule, but one so messy that it is supposed to simulate a chance process (for example, a rule might be used that is chaotic in die technical sense). The resulting list of numbers may men be tested to ascertain whether it meets

some of die statistical criteria diat a list obtained by a true chance process would be expected to meet in most cases. In die case of the RAND table, were die numbers really pseudorandom? Did a last minute check reveal diat one such criterion was not quite satisfied? Was diat why an

 errata sheet had to be "blown in"? It turns out that the answers to these questions are in the negative. After all, a table of random numbers can be generated by a truly stochastic process, for example, one that makes use of quantum-mechanical phenomena. In fact, the RAND table was prepared in a stochastic way, using noise from a vacuum tube. Moreover, the errata sheet referred to the 100,000 normal deviates, and not to the table of random numbers itself! The mystery that was so instructive was really no mystery at all. Stochastic methods require a great deal of work, however, and it is more convenient to let a computer reel off a sequence using a deterministic rule and then to ensure that the resulting unwanted regularities in the sequence are comparatively harmless in the situations where the numbers are to be used. Still, experience has shown that using such pseudorandom sequences as if they were random can be dangerous. I read recently about a set of pseudorandom numbers used in numerous laboratories that turned out to be seriously nonrandom. As a result, certain kinds of calculations performed with those numbers came out badly in error. This incident can serve to remind us that sequences of numbers arising from deterministic chaotic or near- chaotic processes can possess a considerable amount of regularity. Regularities in Price Fluctuations Sometimes sequences thought to be stochastic turn out to be partially pseudorandom instead. For example, many neoclassical economists have preached for years that the price fluctuations in financial markets around the values dictated by market fundamentals constitute a "random walk," a stochastic process. At the same time, advice on market investments has been available from "chartists" who pore over squiggles in graphs of prices versus time and claim to derive from those squiggles better-than-chance predictions of how prices will behave in the near future. I once read an article by an economist who expressed his fury at the very idea of someone pretending to utilize such evidence in defiance of economists' insistence that the fluctuations amount to nothing but a chance process. But it has now been shown convincingly that the chance process idea is wrong. These fluctuations are in part pseudorandom, as in deterministic chaos; in principle, they contain enough regularities for

 one to make money off them. That

 one to make money off them. That does not mean that every financial nostrum peddled by chartists will make you a fortune; much of their advice is probably worthless. But die idea that price fluctuations amount to more than a chance process is not in itself a crazy one, as that angry economist believed. (Doyne Farmer and Norman Packard, two physicists belonging to die Santa Fe Institute family, have actually quit their jobs in scientific research to start an investment firm. They used to work on die theory of deterministic chaos and of nearly chaotic processes. They moved on to study computer-based adaptive systems such as die neural nets and genetic algorithms described in Chapter 20. Now diey use systems like those to find regularities in price fluctuations (especially changes in volatility), and diey invest accordingly. They started off by practicing for a few months with play money and men went on to invest real funds provided by a large bank. So far, they are doing quite well.) We have encountered diree different technical uses of me word random: 1. A random bit string is one so irregular that there is no rule for compressing its description. 2. A random process is a chance or stochastic process. In generating long bit strings of a given lengdi, it will often produce random, completely incompressible strings; sometimes strings containing a few regularities so that they are somewhat compressible, and very occasionally strings that are exceedingly regular, highly compressible, and not at all random. 3. A table of random numbers is usually generated by a pseudorandom process —a deterministic computational process that does not really use chance at all, but is so messy (chaotic, for example) that it simulates a stochastic process fairly well for many purposes, and satisfies some of die statistical criteria diat a stochastic process would usually satisfy. When such pseudorandom processes are used to generate bit strings, die strings resemble to a considerable extent the results of a chance process of generation. Shakespeare and the Proverbial Monkeys Now we are equipped to discuss why algorithmic randomness or algorithmic information content does not fully match our intuitive idea of

 what complexity is. Consider the famous monkeys at die typewriters, who it is assumed would hit die various keys in a stochastic manner, with an equal chance of typing any symbol or a space with each stroke. I doubt if real monkeys would behave that way, but for our purposes it doesn't matter. The question is, what are die chances mat the monkeys would, in a certain period of rime, type the works of Shakespeare (or else all die books in die British Museum —die part now called die British Library). Obviously, mere is a non-zero chance mat if a certain number of monkeys were each to type sufficiendy many pages, die total text would include a connected passage comprising die works of Shakespeare (say die Folio Edition). However, mat chance is inconceivably small. If all die monkeys in the world were typing eight hours a day for ten diousand years, die chance that die resulting text would include a connected part that was die Folio Edition of Shakespeare is utterly negligible. In a story by Russell Maloney called Inflexible Logic, which appeared in The New Yorker magazine some years ago, six chimpanzees began systematically typing die books in die British Museum, one after anodier, with no hesitation and no mistakes. However, diose apes came to a bad end: a scientist killed diem in order to preserve his conception of die laws of probability. The last chimp, in his deadi agonies, "was slumped before his typewriter. Painfully, widi his left hand, he took from the machine the completed last page of Florio's Montaigne. Groping for a fresh sheet, he inserted it, and typed widi one finger, 'UNCLE TOM'S CABIN, by Harriet Beecher Stowe. Chapte ...' Then he, too, was dead." Consider a non-Netv-Yorker monkey of die proverbial kind typing material equal in length to die Folio Edition, and compare a typical product of that monkey widi die work of Shakespeare. Which has die greater algorithmic information content? Obviously, die work of die monkey. By means of a chance process (the second of our meanings of random), die monkey is extremely likely to produce a random or near-random sequence of symbols (in die first sense of random). If die work of die monkey is encoded in some standard manner as a bit string, the chances are excellent that die bit string will have maximal or nearly maximal algorithmic randomness for a string of its length. The works of Shakespeare are obviously less random. The rules of English grammar, spelling conventions (despite Shakespeare's sloppy use of an already sloppy system), die need to make sense, and many other factors all

 contribute to nonrandomness in Shakespeare's text, thus giving it a much lower algorithmic information content (or algorithmic randomness) than any probable, equally long passage typed by the monkey. And all mat is true of any author in English; we have not yet taken into account the uniqueness of Shakespeare! Effective Complexity Evidendy, AIC or algorithmic randomness, even though it is sometimes called algorithmic complexity, does not correspond to what is meant by complexity in most situations. To define effective complexity, one needs something quite different from a quantity that achieves its maximum in random strings. In fact, it is just the nonrandom aspects of a system or a string mat contribute to its effective complexity, which can be roughly characterized as the length of a concise description of the regularities of that system or string. Crude complexity and AIC fail to correspond to what we usually understand by complexity because they refer to the length of a concise description of the whole system or string—including all its random features—not of the regularities alone. In order to discuss more fully the concept of effective complexity, it is essential to examine in detail the nature of complex adaptive systems. We shall see that their learning or evolution requires, among other things, the ability to distinguish, to some extent, the random from the regular. Effective complexity is then related to the description of the regularities of a system by a coiriplex adaptive system that is observing it.

5 A CHILD LEARNING A LANGUAGE When my daughter was learning to speak, one of her first sentences was "Daddy go car-car/' which she would recite every morning when I left for work. I was flattered that the sentence was about me and delighted that she was actually talking, even if her English still needed some work. It has struck me only recendy how certain features of English grammar were already present in that utterance. Take word order, for example. In English, die subject comes before the verb (while in some other languages, such as Welsh, Hawaiian, and Malagasy, it does not). The order of subject and verb was already correct, as was the position of the phrase "car-car." In the grammatical English sentence "(Daddy] [is going away] [in his car]," the order of the three elements is exacdy the same as in the baby's approximation. As my daughter grew older, her grammar naturally kept improving and in a few years, like other children, she was speaking correcdy. Any normal young child with a caregiver, such as a parent, who speaks a particular language and uses it regularly to address the child, will learn, over a period of years, how to speak that language grammatically. (Of course, some Americans think that this statement fails to apply to many U.S. high school students.) In fact, most children are capable of learning two or even three languages with native fluency, especially if each of

 two or three caregivers uses just one of the languages correcdy and habitually with die child. This is true even if a child's only exposure to a language is through a single speaker of it. But how does the child come to know, for a given language, which ways of constructing a sentence are grammatical and which are not? Imagine that there are only fifty thousand possible sentences, and that a mother and child systematically try out fifty new ones every day for a thousand days, the mother patiendy indicating

"OK" or "bad sentence" for each one. If we assume this absurd scenario, plus a perfect memory on the part of the child, then after three years the youngster would know exactly which of the fifty thousand sentences are grammatical. A computer scientist might say that this fictitious child had constructed in his or her mind a "look-up table" in which each candidate sentence was listed, alo|ng with the label "grammatical" or "ungram- matical." Clearly a real, child does not prepare such a table. For one thing, fifty thousand sentences are far too few. In any human language, there are an unlimited number of possible sentences, which can contain arbitrarily many clauses, each loaded with modifying words and phrases. Sentence length is limited only by the time available and by the patience and memory capacity of the speaker and listener. Moreover, there is typically a vocabulary of many thousands of words to work with. There is no chance that a child will hear or try to speak every possible sentence and enter it in a look-up table. Yet at the end of the real learning process, a child can tell whether a previously unheard sentence is grammatical. Children must make up, without being fully aware of it, provisional sets of rules for what is grammatical and what is not. Then, as they continue to hear grammatically correct sentences and (occasionally) try out a sentence and have it corrected, they keep altering the set of rules, again without necessarily being fully aware of it. For example, in English it is easy for a child to acquire the regular or "weak" construction of the simple past tense by adding -ed or -d to a verb. Then, after running across "sing" and "sang" (the present and past of a "strong" verb) the child tries a modified set of rules that includes this exception. That new set, however, may lead the child to say "bring" and "brang," which will eventually be corrected to "bring" and "brought." And so on. Gradually, the internal set of rules is improved. The child is constructing a kind of grammar in its mind.

 A child learning a language does indeed make use of grammatical information, acquired over the years from examples of grammatical and ungrammatical sentences. But instead of constructing a look-up table, a child somehow compresses this experience into a set of rules, an internal grammar, which works even for new sentences that have never been encountered before. But is the information obtained from the outside world, for example from a parent who speaks the language in question, sufficient to construct such an internal grammar? That question has been answered in the negative by Noam Chomsky and his followers, who conclude that the child must come already equipped at birth with a great deal of information applicable to the grammar of any natural human language. The only plausible source of such grammar of any natural human language. The only plausible source of such information is a biologically evolved innate proclivity to speak languages with certain general grammatical features, shared by all natural human languages. The grammar of each individual language also contains additional features, not biologically programmed. Many of those vary from language to language, although some are probably universal like the innate ones. The additional features are what the child has to learn.

Grammar as a Partial Schema

Of course, whether a declarative sentence is grammatical is largely independent of whether it is factual. Speakers of English know that it is grammatically correct to say "the sky is green, with purple and yellow stripes," even though it is unlikely to be true, at least on Earth. But there are many circumstances other than mere veracity that influence the choice of which grammatical sentence one utters on a particular occasion. In constructing an internal grammar, a child effectively separates grammatical features from all the other factors, some of them stochastic, that have led to the particular sentences he or she hears. Only in that way is compression into a manageable set of grammatical rules possible. The child who does this has exhibited the first characteristic of a complex adaptive system. He or she has compressed certain regularities identified in a body of experience into a schema, which includes rules that govern that experience but omits the special circumstances in which the rules have to be applied.

Grammar, however, does not encompass all the regularities encountered in a language. There are also the rules of sounds (constituting what linguists call the "phonology" of a language), the rules of semantics (relating to what makes sense and what does not), and others. The grammatical schema is therefore not the entire set of rules for speaking a language, and grammar is not all that is left when arbitrary features of the linguistic data stream have been put aside. Nevertheless, a child's acquisition of grammar is an excellent example of the construction of a schema—a partial schema. The process of learning grammar also demonstrates the other features of a complex adaptive system in operation. A schema is subject to variation, and the different variants are tried out in the real world. In order to try them out, it is necessary to fill in details, such as the ones that were thrown away in creating the schema. That makes sense, since in the real world the same kind of data stream is encountered again as that from which the schema was abstracted in the first place. Finally, what happens in the real world influences which variants of the schema survive. In the acquisition of English grammar the schema is varied, for example, when the rule for constructing the simple past tense of a verb with -

ed or -d is modified by exceptions such as those for sing-sang and bring-brang. In order to try out these variants, the child must use the schema in an actual sentence, thus restoring special circumstances of the sort pared away to make the schema possible. For example, the child may say, "We sang a hymn yesterday morning." That sentence passes muster. If, however, the child says, "I brang home something to show you," the parent may reply, 'it's very nice of you to show me that cockroach you found at Aunt Bessie's, but you ought to say 'I brought home something...'." That experience would probably result in the child's trying out a new schema, one that allows for both sing-sang and bring-brought. (In very many cases, of course, a child tries out a schema simply by waiting for someone else to speak.) Complex Adaptive Systems and Effective Complexity The operation of a complex adaptive system was shown in the diagram on page 25. Since a complex adaptive system separates regularities from

randomness, it affords die possibility of defining complexity in terms of the length of die schema used by a complex adaptive system to describe and predict the properties of an incoming data stream. Those data typically relate, of course, to the functioning of some odier system that the complex adaptive system is observing. Utilizing the length of a schema does not signify a return to die concept of crude complexity, because die schema is not a complete description of the data stream or of die observed system, but only of the identified regularities abstracted from the available data. In some cases, such as grammar, only regularities of a certain type are included while the rest are put aside, so die result is a partial schema. One may dunk of grammatical complexity in terms of a textbook of grammar. Roughly speaking, the longer the textbook, the more complex the grammar. This agrees very well with the notion of complexity as the lengdi of a schema. Every nasty litde exception adds to the length of die book and the grammatical complexity of die language. As usual, there are sources of arbitrariness such as coarse graining and shared initial knowledge or understanding. In the case of a textbook of grammar, the coarse graining corresponds to the level of detail achieved by the text. Is it a very elementary grammar that leaves out many obscure rules and lists of exceptions, covering only the main points needed by a traveler who doesn't mind making a mistake now and then? Or is it a weighty academic tome? If so, is it one of the old, familiar kind or a currendy fashionable generative grammar? Obviously the length of the book will depend on such distinctions. As to the level of initial knowledge, consider an old-fashioned grammar of a foreign language written in English for English speakers. It will not have to introduce so many new grammatical ideas to the reader if it is a grammar of Dutch (faidy similar to English and closely related) rather dian of Navajo, which is very different from English in structure. The grammar of Navajo should be longer. Similarly, a hypothetical grammar of Dutch written for speakers of Navajo would presumably have to be longer than a grammar of Dutch written for English speakers. Even taking these factors into account, it is still reasonable to relate the grammatical complexity of a language to the length of a textbook describing its grammar. However, it would be more interesting if it were possible instead to look inside the brain of a native speaker (as advancing technology may some day make possible) and see how the grammar is encoded there. The length of the schema represented by

 that internal grammar would provide a somewhat less arbitrary measure of grammatical complexity. (Naturally, the definition of length in this case may be a subtle one, depending on how the bits of grammatical information are actually encoded. Are they inscribed locally in neurons and synapses or distributed somehow over a whole network?) We define the effective complexity of an entity, relative to a complex adaptive system that is observing it and constructing a schema, as the length of a concise description of the entity's regularities identified in the schema. We can use the term "internal effective complexity" when the schema somehow governs die system under discussion (as grammar stored in the brain regulates speech), rather than merely being used by an external observer, such as the author of a grammatical text.

Separating Regularity from Randomness

The usefulness of the concept of effective complexity, especially when it is not internal, depends on whether the observing complex adaptive system does a good job of identifying and compressing regularities and discarding what is incidental. If not, the effective complexity of the observed system has more to do with the particular observer's shortcomings than with the properties of the system observed. It turns out that the observer is often fairly efficient, but the concept of efficiency raises deep issues. We already know that the notion of optimal compression may run into the obstacle of uncomputability. But what about the actual identification of regularities, apart from compression? Is it really a well-defined problem to identify the regularities in a stream of data? The task would be easier if the data stream were in some sense indefinitely long, as in the case of speech or text so extended that it comprises a representative sample of the possible sentences (up to a given length) that can be uttered in a given language. Here, even a rare to a given length) that can be uttered in a given language. Here, even a rare grammatical regularity would show itself over and over under similar conditions and thus tend to be distinguishable from a false rule arising from a mere chance fluctuation. (For instance, in a short English text the past perfect tense might not occur, suggesting wrongly that it does not exist in English. In a very long text, that would not be likely to happen.)

Identifying Certain Cla sses or Regularities

A number of theoretical physicists, such as Jim Crutchfield of the University of California at Berkeley and the Santa Fe Institute, have made considerable progress in understanding how to distinguish regularity from randomness for an indefinitely long bit string. They define particular broad classes of regularities and show how a computer could be used, in principle, to identify any regularities belonging to those categories. Even their methods, however, do not provide an algorithm that would pick out every kind of regularity. There is no such algorithm. They show, however, how a computer, having found in a bit string regularities belonging to certain classes, can deduce that new regularities belonging to a broader class are present and can be identified. That is called "hierarchical learning." Typically, a class of regularities corresponds to a set of mathematical models of how a data stream might be generated. Suppose the data stream is a string of bits known to be generated by a process that is, at least in part, stochastic—say coin tosses are involved. A very simple example of a set of models would then be a sequence of biased coin tosses, in which the probability of heads (yielding Is in the bit string) has some fixed value between zero and one for each model, while the probability of tails (yielding Os in the bit string) is one minus die probability of heads. If die probability of heads is one-half, then any apparent regularity in such a sequence would be the effect of chance alone. As die data stream gets longer and longer, the probability of being fooled by such chance regularities gets smaller and smaller, and the likelihood increases of recognizing that the sequence stems from the equivalent of unbiased coin tosses. At the opposite extreme, take a two-bit string. The chance of both bits being Is (a case of perfect regularity) is one out of four for unbiased tosses. But such a sequence could just as well come from tossing a two-headed coin. Thus, a short bit string arising from a sequence of unbiased coin tosses can often be mistaken for a heavily biased sequence. In general, the advantage of an indefinitely long data stream is that it gready increases the chances of discriminating among models, where each model corresponds to a particular class of regularities.

 Another example of models, slighdy more complicated dian sequences of biased coin tosses, might have the additional provision that all sequences in which two heads occur in succession would be thrown away. The resulting regularity, that the bit string never has two ones in a row, would be quite easy to recognize in a long string. A still more complicated model might consist of sequences of biased coin tosses in which any sequence containing an even number of heads in succession would be discarded. When a complex adaptive system receives an arbitrarily long data stream, say in the form of a bit string, it can search systematically for regularities of given classes (corresponding to models of given classes), but there is no such procedure for searching for every type of regularity. Whatever regularities are identified can then be incorporated into a schema describing the data stream (or a system giving rise to that stream). Dividing the Data Stream into Parts—Mutual Information When identifying regularities in an incoming data stream, a complex adaptive system typically divides that stream into many parts mat are in some way comparable to one another and searches for their common features. Information common to many parts, called "mutual information," is diagnostic of regularities. In the case of a stream of text in a given language, sentences could serve as die parts to be compared. Mutual grammatical information among the sentences would point to grammatical regularities. However, mutual information is used only to identify regularities, and the quantity of it is not a direct measure of effective complexity. Instead, once regularities have been identified and a concise description of them given, the length of the description measures the effective complexity. Large Effective Complexity and Intermediate AIC Suppose there are no regularities in the system being described, as will often (but not always!) be die case in a passage typed by the proverbial

 Largest possible effective complexity Minimum, very near zero Maximum Algorithmic information content for given message length Increasing disorder Completely regular Completely random A sketch showing roughly how die largest possible effective complexity varies with AIC. monkeys. A properly operating complex adaptive system would then be unable to find any schema, since a schema summarizes regularities and there aren't any. To put it differendy, the only schema will have length zero, and the complex adaptive system will assign zero eflfective complexity to the random junk it is studying. That is entirely appropriate; a grammar of pure gibberish ought to have zero length. Although the algorithmic information content of a random bit string is maximal for its length, the information content of a random bit string is maximal for its length, the eflfective complexity is zero. At the other end of the scale of AIC, when it is near zero, the bit string is entirely regular, consisting, for example, only of Is. The eflfective complexity—the length a concise description of the regularities of such a bit string—should be very close to zero, since the message "all Is" is so short. For eflfective complexity to be sizable, then, the AIC must be neither too low nor too high; in other words, the system must be neither too orderly nor too disorderly. The sketch on this page illustrates crudely how the largest possible

effective complexity of a system (relative to a properly functioning complex adaptive system as observer) varies with AIC, attaining high values only in the intermediate region between excessive order and excessive disorder. Many important quantities that occur in discussions of simplicity, complexity, and complex adaptive systems share the property that they can be large only in that intermediate region. When a complex adaptive system observes another system and identifies some of its regularities, the algorithmic information content of the data stream coming from the observed system is expressed as the sum of two terms: the apparendy regular information content and the apparently stochastic information content. The effective complexity of the observed system is essentially the same as the apparendy regular portion of the information content. For a random data stream, recognized as such, that effective complexity is zero and the whole of the AIC is recognized as the product of chance. For a perfectly regular data stream, recognized as such (a long bit string consisting entirely of Is, for example), the entire AIC is regular (with no stochastic portion) but extremely small. The interesting situations lie between these extremes, where the AIC is sizable but not maximal (for the length of the data stream), and is the sum of two appreciable terms, the apparendy regular portion (the effective complexity) and the apparendy stochastic portion.

Learning with the Genes or the Brain

Although our examination of complex adaptive systems began with the example of learning in a human child, it is not necessary to invoke anything so sophisticated to illustrate the concept. Our fellow primates—the ones caricatured in the typewriter story—could be used just as well. So could a dog. In fact, one way we encounter learning in other mammals is through training our pets. Teaching a dog to stay involves applying an abstraction to a great many different situations: staying in a sitting position on the ground, staying in a car when the door is opened, staying nearby instead of pursuing a tempting squirrel. The dog learns, by means of rewards and/or punishments, the schema for the command to stay. Alternative schemata, for example, one that makes an exception for chasing cats, are

 (at least in theory) rejected as training proceeds. But even if the dog adopts a schema with the exception, a complex adaptive system is still at work. A schema other than the one the trainer intended has survived, as a result of competing pressures from training and the instinct to chase cats. When given the command to stay, the trained dog fills in the details appropriate to die particular situation and carries die schema into die real world of behavior, where the reward or punishment occurs and helps to determine whether the schema survives. However, the tendency to chase cats or squirrels, which also influences the competition among schemata, has not been learned by the individual dog. Instead, it has been genetically programmed as a result of biological evolution. All organisms have such programs. Consider an ant wandering around in search of a morsel of food. It is following a built-in procedure evolved over millions of years. Herbert Simon, the distinguished expert on psychology, economics, and computer science at Carnegie-Mellon University, long ago used the ant's movements to illustrate the meaning of what I call effective complexity. The path followed by the ant may appear complex, but the rules of the search process are simple. The intricate path of the ant manifests a great deal of algorithmic complexity (AIC), of which only a little comes from the rules, which correspond more or less to the regularities of the search. That small part, though, constitutes (at least approximately) the entire effective complexity. The remainder of the AIC, the bulk of the apparent complexity, comes from incidental, largely random features of the terrain that the ant is exploring. (Recently I discussed the ant story with Herb, who exclaimed with a grin, "I got a lot of mileage out of that ant!") In a sequence of less and less sophisticated organisms, say a dog, a goldfish, a worm, and an amoeba, individual learning plays a smaller and smaller role compared to diat played by the instincts stored up through biological evolution. But biological evolution itself can also be described as a complex adaptive system, even in the humblest organisms.

6 BACTERIA DEVELOPING DRUG RESISTANCE

When I was young, I had the habit of browsing through encyclopedias (a habit that persists to this day, provoking merriment in my family). At one point I ran into an article on the bronze disease, which started me thinking for the first time about some of the issues central to this book. The bronze disease is a set of chemical reactions that can corrode bronze surfaces, creating greenish-blue spots that grow and spread.

Under moist conditions, the reactions can actually spread the disease through the air from one surface to another and ruin a whole collection of bronze objects. Since Chinese bronze vessels of the Shang dynasty, for instance, may be worth a million dollars apiece, protection against the bronze disease is not an unimportant matter. However, when I first read about it, as a poor boy, I was obviously not thinking from the collector's point of view. Instead I was wondering, "How is the bronze disease different from a plague caused by a living organism? Is it that the bronze disease is merely obeying the laws of physics and chemistry?" But even as a child I rejected, as serious scientists have done for generations, the idea that life is characterized by any special "vital forces" outside of physics and

 chemistry. No, a bacterium too obeys the laws of physics and chemistry. But then what is the difference? It occurred to me that bacteria (like all other living things) exhibit variation that is heritable and subject to natural selection, whereas for the bronze disease there is no evidence of any such thing. Indeed, that distinction is critical. To explore the same distinction further, consider the example of a turbulent flow of fluid down a pipe. For more than a century it has been known that energy is dissipated from large turbulent eddies into smaller and smaller ones. In describing those eddies, physicists have often quoted Jonathan Swift: So, Nat'ralists observe, a Flea Hath smaller fleas that on him prey, And these have smaller fleas to bite 'em, And. so proceed ad infinitum. Moreover, the physicist and polymath L. F. Richardson created his own bit of doggerel specifically applicable to eddies: Big whorls have little whorls, Which feed on their velocity; And little whorls have lesser whorls, And so on to viscosity. In a sense, the larger eddies give birth to smaller ones. If the pipe has bends and constrictions, there may be some large eddies that come to grief without having offspring, while others survive to spawn many smaller ones, which generate still smaller ones, and so on. The eddies thus seem to exhibit a kind of variation and selection. Yet no one has ever suggested that they resemble life. What important feature do the turbulent eddies lack that living organisms possess? What really distinguishes turbulent flow from biological evolution? The difference lies in how information is handled in the two cases. There is no indication that in turbulent flow any significant information processing goes on, any compression of regularities. In biological evolution, however, the experience represented by past variation and natural selection is handed down to future generations in a highly compressed package of information, the "genome" (or set of genes) of an organism. Each gene can have different alternative forms, which in some connections are called "alleles." The set of particular alleles of all the genes in a given organism is known as the "genotype." Biologists emphasize the distinction between the genotype, which describes die inherited information contained in the genes of an individual organism, and the phenotype, which describes the appearance and behavior of die organism during the course of its lite history. Changes in the genotype, such as an alteration in a given gene from one allele to another, can, of course, affect the phenotype duough the gene's influence on chemical processes in die organism. But die phenotype is also influenced during the development of the organism by a huge variety of odier circumstances, many of them random. Think of all the accidental circumstances that affect the development of a human being, from the single-cell and fetal stages through infancy and childhood, before procreation becomes possible in aduldiood. The genotype of an individual human being is like a basic recipe, allowing for wide variations in die actual dish prepared by die cook. A single genotype permits one of many different possible alternative adults to emerge from the development process. In the case of identical twins, who always share the same genotype, two of die different alternative adults co-exist. When raised separately, they can supply precious information about the roles of "nature" and "nurture" in the formation of the adult phenotype. In the course of biological evolution, random changes take place in the genotype from generation to generation. They contribute, along with die accidents of development that occur in a given generation, to phenotypic changes that help to determine whether an organism is viable and able to reach maturity, to reproduce, and to pass on its genotype, in whole or in part, to its descendants. The distribution of genotypes in the population is thus the result of chance combined with natural selection. The Evolution of Drug Resistance in Bacteria One case of biological evolution of great significance for contemporary humanity is the development of resistance to antibiotics in bacteria. For example, after a number of decades of widespread use of penicillin

 to control certain species of pathogenic (disease-producing) bacteria, strains of those organisms have appeared that are not particularly sensitive to the drug. In order to cope with the diseases caused by these altered germs, new types of antibiotics are required, and much human suffering and even death may occur while new drugs are being perfected. Similarly, the bacillus that causes tuberculosis yielded for decades to perfected. Similarly, the bacillus that causes tuberculosis yielded for decades to certain antibiotics, but in recent years has developed resistant strains. Tuberculosis is again a major health menace, even in places where it was formerly controlled. In the acquisition of drug resistance by bacteria, an important role is often played by the exchange of genetic material between two individual bacteria as they come together, merge, and then separate again. This process, which is as close to sexual activity as such primitive organisms get, was first observed by Joshua Lederberg when he was a graduate student at Yale. I was an undergraduate there at the time, and I remember how much public attention was drawn to the discovery of sex in the realm of germs; there was even an item in Time magazine. Josh was launched on his career, which led eventually to the presidency of Rockefeller University. In discussing bacterial drug resistance, I shall, for the sake of simplicity, ignore sex (with apologies to Josh). For the same reason, I propose to ignore another very important mechanism for transfer of genetic material between cells, in which the carrier is a virus—a bacteriophage (or "phage")—that infects bacteria. Experiments on this process, called transduction, were precursors of the first work in genetic engineering. Careful research on bacteria has centered on the species Escherichia coli (or E. coif), common, harmless, and even useful in the human intestines, but often pathogenic when infecting other parts of the body (and also, in certain mutant forms, dangerous even in the digestive tract). Each E. coli organism is a single cell with genetic material consisting of a few thousand genes. A typical gene is a sequence of something like a thousand "nucleotides" (known collectively as DNA). Those DNA constituents, which make up all genes in all organisms, come in four kinds, called A, C, G, and T for the initial letters of their chemical names. Any gene is part of a longer strand composed of nucleotides and paired with another strand in the famous double helix. The double helix structure was worked out in 1953 by Francis Crick and James Watson, utilizing the work of Rosalind Franklin and Maurice Wilkins. In E. coli, there are two helical strands of around five million nucleotides each.

 The nucleotides strung out along one strand are complementary to those on the other strand in die sense that A and T always occur opposite each other, as do G and C. Since either helix is determined by the odier, we need look at only one of them in order to read die complete message. Suppose die number of nucleotides in the strand is really five million. A can be encoded as 00, C as 01, G as 10, and T as 11, so diat die five million nucleotides are represented by a string often million 0s and Is, in other words, by a bit string with ten million bits. That string stands for the informatio words, by a bit string with ten million bits. That string stands for the information diat each E. coli bacterium transmits to its progeny, which come into being by means of the splitting of the cell into two cells, the double helix giving rise to two new double helices, one for each new cell. Each of die several thousand genes in die bacterium can exist in many forms. The madiematical possibilities are extremely numerous, of course. For a string of one thousand nucleotides, say, die number of different conceivable sequences equals 4x4x4x...x4x4, with a thousand factors of 4. This number, when written in die usual decimal system, has around six hundred digits! Only a tiny fraction of diose theoretically possible sequences can be found in nature (die existence of all of diem would require far more atoms than the universe contains). In practice, at any given time, each gene may have some hundreds of different alleles that actually occur widi significant probability in die bacterial population and are distinguished by their different chemical and biological effects. Any gene can undergo mutation from one form to anodier as a result of various kinds of accidents, for example, die random passage of a cosmic ray or the presence of some strong chemical in die environment. Even a single mutation can have a significant effect on cell behavior. For example, die mutation of a certain gene in an E. coli cell to a certain new allele could, in principle, lead to die resistance of that cell to a drug such as penicillin. That resistance would men be passed on to the cell's progeny, as diey multiply dirough repeated cell divisions. Mutations are typically chance processes. Suppose a single bacterium in a host tissue produces a colony of descendants, all of die same genotype. Mutations can men occur in diat colony, with die mutant forms giving rise to colonies of dieir own. In that way the population of bacteria in die tissue comes to contain various genotypes. If penicillin is introduced in sufficient quantity, only die colonies resistant to it

 will continue to grow. The important point is that the resistant mutant bacteria are often already there by chance, usually through a mutation in an ancestor, when the drug starts to exert selection pressure in their favor. Even if they are not already present, they exist somewhere else, or at the very least they have come into existence from time to time through chance processes and then disappeared. The mutations are not induced by the penicillin, as Lederberg showed long ago. The mutation of a gene to an allele corresponding to drug resistance presumably has some unfavorable effects on die operation of an E. coli cell. Otherwise that allele would almost certainly have been present already in a large number of E. coli bacteria, and penicillin would not have worked in the first place. However, as penicillin continues to be widely used, the survival of die penicillin-resistant strain is favored, while the selective disadvantage, whatever it is, is outweighed by the advantage of drug resistance. (A different antibiotic, not occurring so widely in nature as penicillin, might serve even better as an example, since the species of bacterium would have had fewer contacts widi it before it was introduced into medicine.) The development of drug resistance takes place, then, dirough a change in the genotype, the string of some ten million bits that is transmitted by the cell to its descendants. It is dirough the genes that the bacterium "learns" to cope widi this menace to its survival. But the genotype contains a huge amount of other information that permits the bacterium to function. The genes contain the lessons learned over billions of years of biological evolution about how to survive as a bacterium. The experience of the species E. coli and its ancestral life forms was not merely recorded for reference in a look-up table; regularities in that experience were identified and compressed into the string represented by the genotype. Some of them are regularities experienced only re- cendy.like the prevalence of antibiotics. Most of them are quite ancient. The genotype varies to some extent from individual to individual (or from one colony of genetically identical individuals to anodier), and mutations can occur by accident at any time and be transmitted to progeny. This kind of learning differs in an interesting way from die kind that takes place through the use of a brain. We have emphasized mat mutant forms of a bacterium exhibiting resistance to an antibiotic may easily be present by chance when die drug is introduced and diat in any

 case those forms have existed from time to time in the past. Ideas, however, more often arise in response to a challenge rather than being already available when the challenge is presented. (There is some slight evidence for genetic mutations in biology occasionally arising in response to need, but if the phenomenon really exists it is comparatively insignificant compared to chance mutation.) Evolution as a Complex Adaptive System To what extent can the evolutionary process be described as the operation of a complex adaptive system? The genotype satisfies the criteria for a schema, encapsulating in highly compressed form the experience of the past and being subject to variation through mutation. The genotype itself does not usually get tested directly by experience. It controls, to a great extent, the chemistry of the organism, but the ultimate fate of each individual depends also on environmental conditions that are not at all under the control of the genes. The phenotype, in other words, is co-determined by the control of the genes. The phenotype, in other words, is co-determined by the genotype and by all those external conditions, many of them random. Such an unfolding of schemata, with input from new data, to produce effects in the real world is characteristic of a complex adaptive system. Finally, the survival of a particular genotype for a single-celled organism is related to whether cells with that genotype survive until they divide, whether their offspring survive until they divide, and so form. That fulfills the requirement of a feedback loop involving selection pressures. The bacterial population is certainly a complex adaptive system. The effective complexity of the bacterium, in our sense of the length of a schema, is evidently related to the length of the genome. (If parts of the double DNA helix are just fillers and contribute no genetic information, as seems to be the case in higher organisms, the length of those parts would not be counted.) The length of the relevant part of die genome provides a crude internal measure of effective complexity. It is internal because it relates to the schema that the organism uses to describe its own heritage to its descendants, rather than a schema devised by some outside observer. (This measure resembles the length of the internal grammar in the brain of a child learning its native language.

as opposed to the length of a book describing die grammar of that language.) It is only a crude measure because biological evolution, like other complex adaptive systems, performs die task of compression of regularities with varying efficiency in different cases. Sometimes such variations can invalidate die measure, as in certain organisms that are obviously radier simple but have anomalously long genomes, which do not give a concise description of the relevant regularities. But a comparison of die genomes of different organisms reveals deficiencies in the whole notion of using effective complexity, based on the lengdi of a schema, as the only measure of the complexity of a species. For instance, in considering subtle but important differences such as diose that distinguish our species from closely related great apes, we have to include more sophisticated ideas. Those comparatively few genetic changes diat permit an apelike creature to develop language, advanced dunking, and elaborate culture, all manifesting great effective complexity, have greater significance dian most comparable sets of alterations in the genetic material. The effective complexity of the new (human) genome, as measured crudely by its lengdi, is not by itself a satisfactory measure of the complexity of die corresponding organisms (people), since die slighdy altered genome can give rise to so much effective complexity of a novel kind (cultural complexity). We will therefore find it necessary to supplement effective complexity with the concept of potential complexity. When a modest change in a schema permits a complex adaptive system to create a great deal of new effective complexity over a certain period of time, die modified schema can be said to have a gready increased value of potential complexity widi respect to diat time interval. We shall pursue this subject later on, but for now let us return to the idea of adaptation to drug resistance as a complex adaptive system and compare diat picture with an incorrect theory of how such resistance comes about. Direct Adaptation Today it seems obvious diat drug resistance develops largely dirough a genetic mechanism such as we have been considering. However, that was not always die case. In the 1940s, when penicillin was just coming into use and the sulfa drugs were still the glamorous weapons in the batde against bacterial infection, drug resistance was already a problem.

 and some scientists offered very different models for its development. One of those was the distinguished English chemist Cyril (later Sir Cyril) Hinshelwood. I remember seeing his book on the subject when I was a student, and being quite skeptical, even then, of his ideas on this particular subject Hinshelwood's erroneous theory of drug resistance was, naturally, a chemical theory. His book was full of equations describing the rates of chemical reactions. The general idea was that the presence of the drug caused changes in the chemical balance of the bacterial cell that were detrimental to the cell's reproduction. However, prolonged exposure of the bacteria to high doses produced, by direct chemical means, adjustments in the cell's metabolism that limited the detrimental effect of the drug and permitted cells to survive and divide. In cell division, the theory went, this simple form of drug resistance was passed on mechanically to the daughter cells through the chemical composition of the ordinary cell material. The proposed mechanism was straight negative feedback in a set of chemical reactions. (If your car starts to go off the road and you supply a corrective turn of the steering wheel, that is another example of negative feedback.) In Hinshelwood's theory, the bacterial genes were not involved. There was no complex adaptive system underlying the development of bacterial drug resistance: no compression of information, no schema, no chance variation, and no selection. In fact, a chapter of the book is devoted to refuting the idea of selection of spontaneous variants. We can describe Hinshelwood's theory as involving "direct adaptation." Such processes are very common. Consider the operation of a thermostat set for a particular temperature; the device causes a heating system to go on when the temperature falls below the set point and off when it reaches it again. In place of a set of competing and evolving schemata, the thermostat has a single fixed program, and a very simple one at that. The device just keeps mumbling to itself, "It's too cold. It's too cold. It's a litde too hot. It's too cold ...," and acting accordingly. It is useful to contrast direct adaptation with the operation of complex adaptive systems, but I do not mean to suggest that direct adaptation is uninteresting. Indeed, most of the excitement about cybernetics in the aftermath of the Second World War was related to processes of direct adaptation, especially the stabilization of systems by means of negative feedback. The basic principle is the same as that of a diermostat, but the problems it presents can be much more challenging.

Direct Adaptation, Expert Systems, and Complex Adaptive Systems

The word "cybernetics" was introduced by a great but eccentric mathematics professor at the Massachusetts Institute of Technology, Norbert Wiener, who as a child had been considered a prodigy and never got over the need to show off in bizarre ways. As a graduate student at MIT, I would occasionally find him asleep on die stairs, creating a real obstacle to traffic with his pordy figure. Once he stuck his head in the door of my dissertation adviser, Viki Weisskopf, and uttered some words mat Viki found completely incomprehensible. "Oh, I thought all European intellectuals knew Chinese," said Wiener, and hurried off down the hall. The word is derived from the ancient Greek kubemetes meaning helmsman.That word begins with the Greek letter "kappa" and it is responsible for the "kappa" in "Phi Beta Kappa," the academic honor society, the motto of which means "Philosophy, life's helmsman." After borrowing from Greek into Latin and later from French into English, the same word gave rise to the verb "govern," and indeed cybernetics relates to both steering and governing, as in controlling a robot. But in the days of cybernetics robots were not usually able to create an evolving schema out of their sense impressions. Only now are we entering the age of robots that are really complex adaptive systems. Take a mobile robot, for instance. In the early cybernetic era, it might have been equipped with sensors to indicate the presence of a nearby wall and to activate a device for avoiding it. Other sensors might have detected bumps just ahead and caused the form of locomotion to change in some predetermined way so die robot could get over them. The point of the design was to provide a direct response to environmental signals. The next era was that of the "expert system," in which information supplied by human experts in a field was fed into a computer in the form of an "internal model" mat could be used to interpret incoming data. The advances in robot design achieved by be used to interpret incoming data. The advances in robot design achieved by such methods were not dramatic but an example from a different field can be used to illustrate the approach. Medical diagnosis can be automated to some extent by obtaining the expert advice of physicians and constructing a "decision

tree" for the computer, with a definite rule for decision-making at each branch based on particular data concerning the patient. Such an internal model is fixed, unlike the schemata of complex adaptive systems. The computer can diagnose illnesses, but it does not learn more and more about diagnosis from its experience with successive patients. It continues to use the same internal model developed by consulting die experts. The experts can be consulted again, of course, and the internal model redesigned to take account of the successes and failures of die computer diagnoses. In that case, the extended system consisting of die computer, the model designers, and the experts can be regarded as a complex adaptive system, an artificial one with "humans in die loop." Today we are entering die era of computers and robots functioning as complex adaptive systems without humans in the loop. Many future robots will have elaborate schemata subject to variation and selection. Consider a six-legged mobile robot having in each leg a set of sensors that detect obstacles and an information processor that responds in some prearranged manner to the signals from those sensors to control the motions of that leg, moving it up or down and forward or backward. Such legs resemble a set of old-fashioned cybernetic devices. Nowadays robot design might include a form of communication among the legs, but not dirough a governing central processing unit. Instead, each leg would have the capacity to influence die behavior of the odiers by means of communication links. The pattern of strengths of influence of the legs on one another would be a schema, subject to variations produced, for example, by input from a generator of pseudorandom numbers. The selection pressures influencing the adoption and rejection of candidate patterns might originate from additional sensors that measure what is happening not just to an individual leg, but also to the robot as a whole, such as whether it is moving forward or backward and whether its belly is far enough off die ground. In this way die robot would tend to develop a schema diat yielded a gait suited to the terrain on which it was traveling and diat was subject to alteration when the character of that terrain changed. Such a robot may be regarded as at least a primitive form of complex adaptive system. I am told that a six-legged robot something like diis has been built at MIT and that it has discovered, among other gaits, one that is commonly used by insects: die front and back legs on one side move

 together with die middle leg on the odier side. When die robot uses that gait depends on the terrain. Now consider, in contrast to a robot that learns a few useful properties of die terrain it needs to traverse, a complex adaptive system exploring die general properties, as well as a host of detailed features, of a much grander terrain, namely die whole universe.

7 THE SCIENTIFIC ENTERPRISE The concept of the complex adaptive system is beautifully illustrated by the human scientific enterprise. The schemata are theories, and what takes place in the real world is the confrontation between theory and observation. New theories have to compete with existing ones, partly on the basis of coherence and generality, but ultimately according to whether they explain existing observations and correctly predict new ones. Each theory is a highly condensed description of a whole class of situations and, as such, needs to be supplemented with the details of one or more situations in order to make specific predictions. The role of theory in science should be fairly obvious, and yet in my own case it took me a long time to get a real feeling for it, even though I was to devote my whole career to theoretical science. It was only when I entered graduate school at MIT that it finally dawned on me how theoretical physics works. As an undergraduate at Yale, I had managed to get high grades in science and math courses without always understanding the point of what I was learning. Sometimes, it seemed, I was able to get by merely by regurgitating on examinations what I had been fed in class. My views changed when I attended one of the sessions of the Harvard- 15

 MIT theoretical seminar. I had thought of the seminar as some sort of glorified class. In tact, it was not a class at all, but a serious discussion group on subjects in theoretical physics, particularly the physics of atomic nuclei and elementary particles. Professors, post-docs, and graduate students from both institutions attended; one theorist would lecture and then there would be a general discussion of the topic he had presented. I was unable to appreciate such scientific activity properly because my way of thinking was still circumscribed by notions of classes and grades and pleasing the teacher. The speaker on this occasion was a Harvard graduate student who had just completed his Ph.D. dissertation on the character of the lowest energy state of a nucleus called boron ten (B j, composed of five protons and five neutrons. By an approximation method that seemed promising but was not guaranteed to work, he had found that the lowest state should have a "spin" angular momentum of one quantum unit, as was generally believed to be the case. When he finished his talk, I wondered what kind of impression his approximate derivation of the expected result had made on the distinguished theoreticians in the front row. The first person to comment was not a theoretician at all, however, but a litde man with a three days' growth of beard who looked as if he had just crawled out of the basement of MIT. He said, "Hey, da spin ain't one. It's t'ree. Dey measured it!" Suddenly, I understood the main function of the theoretician: not to impress the professors in the front row but to agree with observation. (Of course, experimentalists can make mistakes; in this case, however, the observation to which the scruffy man referred turned out to be correct.) I was ashamed of not having been fully aware earlier that the scientific enterprise worked that way. The process by which theories are selected according to their agreement with observation (as well as their coherence and generality) is not so different from biological evolution, where genetic patterns are selected according to whether they tend to lead to organisms that have progeny. But I was not to appreciate fully the parallel between the two processes until many years later, when I had learned more about simplicity and complexity and about complex adaptive systems. Today most physicists are either theoreticians or experimentalists. Sometimes the theoreticians are ahead, having formulated a highly successful body of theory capable of making predictions that are re-

peatedly confirmed by observation. At other times the experimentalists find an unexpected result, and the theoreticians have to go back to the drawing board. But the existence of these two distinct classes of researchers should not be taken for granted. It was not always the case in physics, and in many fields—including cultural anthropology, archaeology, and most parts of biology—there are still only a few professional theorists and they are not necessarily treated with great respect. In molecular biology, a very prestigious subject today, most theoretical puzzles that have turned up have yielded rather easily to the ingenuity of the experimenters. As a result, many prominent molecular biologists are not impressed with the need for theorists in biology. By contrast, the field of population biology has a long and honorable tradition of mathematical theory, personified in such distinguished figures as Sir Ronald Fisher, J. B. S. Haldane, and Sewall Wright Through their work and that of many other theorists, numerous detailed predictions have been made and confirmed by observation in population genetics, and even the mathematical literature has been enriched. Theory tends to emerge as a profession as a science matures and as the depth and power of theoretical methods increase. But the roles of theory and observation should be regarded as distinct whether or not there are separate classes of practitioners for the two activities. Let us see how the interaction between the two fits in with the notion of a complex adaptive system. Theories typically arise as a result of a multitude of observations, in the course of which a deliberate effort is made to sort out the wheat from the chaff, to separate out rules from special or accidental circumstances. A theory is formulated as a simple principle or set of principles, expressed in a comparatively short message. As Stephen Wolfram has emphasized, it is a compressed package of information, applicable to many cases. There are, in general, competing theories, each of which shares these characteristics. To make predictions about a particular case, each theory must be unfolded or re-expanded; that is, the compressed general statement that constitutes the theory must be supplemented with detailed information about the special case. The theories may then be tested by further observations, often made in the course of experiments. How well each theory does, in competition with the others, at predicting the results of those observations helps to determine whether

it survives. Theories in serious disagreement with the outcome of careful and well-designed experiments (especially experiments that have been repeated with consistent results) tend to be displaced by better ones, while theories that successfully predict and explain observations tend to be accepted and used as a basis for further theorizing (that is, as long as they are not themselves challenged by later observations).

Ealsiriability ana Suspense

It has often been emphasized, particularly by the philosopher Karl Popper, that the essential feature of science is that its theories are falsifiable. They make predictions, and further observations can verify those predictions. When a theory is contradicted by observations that have been repeated until they are worthy of acceptance, that theory must be considered wrong. The possibility of failure of an idea is always present, lending an air of suspense to all scientific activity. Sometimes the delay in confirming or disproving a theory is so long that its proponent dies before the fate of his or her idea is known. Those of us working in fundamental physics during the last few decades have been fortunate in seeing our theoretical ideas tested during our lifetimes. The thrill of knowing that one's prediction has actually been verified and that the underlying new scheme is basically correct may be difficult to convey but it is overwhelming. It has often been said that theories, even if contradicted by new evidence, die only when their proponents die. Although that contradicted by new evidence, die only when their proponents die. Although that remark is usually directed at the physical sciences, my impression is that, if it applies at all, it is more to the difficult and complex life sciences and behavioral sciences. My first wife Margaret, a student of classical archaeology, found it applicable to her field in the 1950s. She was astonished to discover that many physicists actually change their minds when confronted with evidence contradicting their favorite ideas. When suspense seems to be lacking in a particular field, controversy may erupt about whether it is really scientific. Psychoanalysis is fre- quendy criticized as not falsifiable, and I tend to agree. Here I mean psychoanalysis as a theory describing how human behavior is influenced by mental processes outside of conscious awareness and how

those mental processes themselves are initiated by experiences, especially early ones. (I will not discuss treatment, which is an almost entirely separate issue. Treatment could be helpful because of a constructive relationship between analyst and analysand without confirming the ideas of psychoanalysis. Likewise treatment might be ineffective even if many of those ideas are correct.) I believe that there is probably a considerable amount of truth in the body of lore developed by psychoanalysis, but that it does not constitute a science at the present time precisely because it is not falsifiable. Is there any statement that might be made by a patient, or any behavior that might be demonstrated by a patient, that could not somehow be reconciled with the underlying ideas of psychoanalysis? If not, those ideas cannot really amount to a scientific theory. Back in the 1960s, I toyed with the idea of switching from theoretical physics to observational psychology or psychiatry. I wanted to isolate a subset of the ideas of psychoanalysis that were falsifiable and could therefore amount to a theory, and then try to find ways of testing such a theory. (The set of ideas might not correspond exacdy to those of a particular psychoanalytic school, but at least they would be closely related to those of psychoanalysis in general. They would be concerned with the role of mental processes outside of awareness in the everyday life of reasonably normal people as well as in the patterns of repeated, apparendy maladaptive behavior exhibited by people labeled neurotic.) For some months I visited various distinguished psychoanalysts and academic psychologists (at that time still strongly influenced by behaviorism—cognitive psychology was only in its infancy). Both discouraged me, although for opposite reasons. Many of the psychologists tended to feel that unconscious mental processes were unimportant or too difficult to study or both, and that psychoanalysis was so silly that it was not worth any serious attention. The analysts tended to feel that their discipline was so well established that it did not require any elaborate effort to incorporate some of its ideas into science, and that any research needed to refine its precepts could best be carried out by psychoanalysts themselves in the course of their work with patients. I finally gave up and continued to work in physics, but many years later I had the opportunity to make an indirect contribution to a renewed

 effort aimed at incorporating into science certain ideas about conscious and unconscious mental processes and their effects on patterns of behavior. That effort is yielding some encouraging results. Selection Pressures on the Scientific Enterprise In practice, die scientific enterprise does not precisely conform to any clearcut model of how it ought to work. Ideally, scientists perform experiments either in an exploratory mode or in order to test serious theoretical proposals. They are supposed to judge a theory by how accurate, general, and coherent a description it gives of the data. They should not exhibit such traits as selfishness, dishonesty, or prejudice. But the practitioners of science are, after all, human beings. They are not immune to the normal influences of egotism, economic self- interest, fashion, wishful thinking, and laziness. A scientist may try to steal credit, knowingly initiate a worthless project for gain, or take a conventional idea for granted instead of looking for a better explanation. From time to time scientists even fudge their results, breaking one of the most serious taboos of their profession. Nevertheless, the occasional philosopher, historian, or sociologist of science who seizes upon these lapses from scientific rectitude or ideal scientific practice in order to condemn the whole enterprise as corrupt has failed to understand the point of science. The scientific enterprise is, by its nature, self-correcting and tends to rise above whatever abuses occur. Extravagant and baseless claims like those made for polywater or cold fusion are soon discounted. Hoaxes like the Piltdown man are eventually exposed. Prejudices such as those against the theory of relativity are overcome. A student of complex adaptive systems would say that in the scientific enterprise the selection pressures that characterize science are accompanied by the familiar selection pressures that generally occur in human affairs. But the characteristically scientific selection pressures play the crucial role in advancing the understanding of nature. Repeated observations and calculations (and comparisons between them) tend to weed out, especially in the long run, imperfections (that is, features that are imperfect from the scientific standpoint) introduced by the other pressures.

THE SCIENTIFIC ENTERPRISE • 81 While the historical details of any scientific discovery are usually somewhat messy, the net result can sometimes be a brilliant and general clarification, as in the formulation and verification of a unifying theory. Theories That Unity ana Synthesize Sometimes a theory accomplishes a remarkable synthesis, compressing into a brief and elegant statement the regularities found in a whole range of phenomena previously described separately and inadequately. A splendid example from basic physics is the work done by James Clerk Maxwell in the 1850s and 1860s on the theory of electromagnetism. Since ancient times some people had been familiar with certain simple phenomena of static electricity, for instance that amber (elektron in Greek) has the power, when rubbed on a cat's fur, of attracting fragments of feathers. Likewise they had known about certain properties of magnetism, including the fact that the mineral magnetite (an iron oxide named after Magnesia in Asia Minor, where it is common) is capable of attracting bits of iron and also of magnetizing them so that they can do the same to other bits of iron. The early modern scientist William Gilbert included some important observations on electricity in his famous treatise on magnetism in 1600. But electricity and magnetism were still regarded as separate classes of phenomena; they were not understood to be closely related until the nineteenth century. The invention by Alessandro Volta of the first battery (the voltaic pile) around 1800 resulted in experiments on electric currents that opened the way for the discovery of the interaction between electricity and magnetism. In about 1820, the subject of electromagnetism was born when Hans Christian 0rsted discovered that an electric current in a wire produces a magnetic field that curls around the wire. In 1831, Michael Faraday found that a changing magnetic field can induce an electric current in a loop of wire; this effect was later interpreted to mean that a magnetic field changing with time gives rise to an electric field. By die 1850s, when Maxwell began his work on a comprehensive mathematical description of electromagnetic effects, most of the individual pieces of the electromagnetic puzzle had been formulated as

82 • THE SIMPLE AND THE COMPLEX scientific laws. What Maxwell did was to write down a set of equations that reproduced those laws, as shown here on the facing page'. In textbooks for undergraduates today, they are usually written as four equations. The first one restates Coulomb's law describing how electric charges produce an electric field. The second equation embodies Ampere's conjecture that there are no true magnetic charges (and hence all magnetism can be attributed to electric currents). The third equation

reformulates Faraday's law describing the generation of an electric field by a changing magnetic field. The fourth equation, as Maxwell first wrote it, merely reproduced Ampere's law describing how an electric current gives rise to a magnetic field. Looking at his four equations, Maxwell saw that there was something wrong with them and he corrected the flaw by altering the last equation. The reasoning that he actually used at the time looks fairly obscure to us today, but there is a modified version of his argument that appeals to the contemporary mind and makes clear what kind of alteration was needed. The conservation of total electric charge (its constancy in time) is a beautiful and simple law, well established by observation, that was already an important principle in Maxwell's time. However, his original equations did not conform to that principle. What kind of change in the equations would make them obey it? The third equation has a term describing the generation of an electric field by a changing magnetic field. Why couldn't a corresponding term be inserted into the fourth equation that would describe the generation of a magnetic field by a changing electric field? Sure enough, for a particular value of the coefficient (multiplier) of the new term, the equation became consistent with the conservation of electric charge. Moreover, that value was small enough that Maxwell could safely put in the term without contradicting the results of any known experiment. With the new "displacement current" term, Maxwell's equations were complete. The subjects of electricity and magnetism were fully unified by means of an elegant and consistent description of electromagnetic phenomena. The consequences of the new description could now be explored. It soon turned out that the equations, with the new term included, had "wave solutions"—electromagnetic waves of all frequencies were generated in a calculable way by accelerating electric charges. In a vacuum, the waves would all travel at the same speed. Computing that speed, Maxwell found it to be identical, within the margin of error that prevailed at the time, to the famous speed of light, about 186,000 miles

 In notation somewhat like that used in undergraduate textbooks of today: In more compressed relativistic notation: V • E = 4irp V-B = 0 VxE+JB=0 VxB-±E = ^j (1) (2) (3) (4) In less compressed notation like that used when Maxwell began his work: dEx dEv dE> -± + -l + -± = 4Ttp (1) oar ay az oBx oBv oB* oar ay az dEY dEx 1 • dEx dEz i • az ax c ^ J (3) dBY dBx i ^ 4-tf _ ^ dx dy <E* <}z oBz oBv 1 • 4 it z — ' _ _ p — -Hi; dy dz <Ex <Jx dBx dB~ \ . 4^ % dz 3.v cEY~ cJr J > (4) (1 and 4) (2 and 3) Three ways of writing Maxwell's equations. per second. Could light consist of ways of writing Maxwell's equations. per second. Could light consist of electromagnetic waves in a certain band of frequencies? That conjecture had been made before, in a vaguer form, by Faraday, but it gained enormously in clarity and plausibility from Maxwell's work. Although it took years to prove by experiment, the idea was absolutely correct. Maxwell's equations also required the existence of waves of higher frequencies than those of visible light (what we now call ultra-violet rays, X-rays, etc.) and of lower frequen-

 cies dian die visible (what we now call infrared rays, microwaves, radio waves, etc.). Eventually all those forms of electromagnetic radiation were discovered experimentally, not only confirming die theory but also leading to die extraordinary achievements in technology widi which we are all familiar. Trie Simplicity of Great Unifying Tneories Maxwell's equations describe die behavior of electromagnetism throughout die universe in a few lines. (The exact number depends on die compactness of die notation, as in the figure.) Given die boundary conditions and die charges and currents, the electric and magnetic fields can be calculated. The universal aspects of electromagnetism are captured by die equations—only die special details need to be supplied. The equations identify die regularities with precision and compress diem into a tiny madiematical package of immense power. What could be a more elegant example of a schema? As die lengdi of die schema is practically zero, so too is die effective complexity, as we have defined it. In odier words, die laws of electromagnetism are extremely simple. A critic might complain that while Maxwell's equations are indeed short, it nevertheless takes some education to understand die notation in which diey are expressed. When Maxwell first published the equations, he used a less compressed way of writing diem than is used in teaching undergraduates today and die set of equations was somewhat longer. Correspondingly, we can now use a relativistic notation that makes diem shorter. (Bodi die longer and die shorter versions are illustrated.) The critic might demand that in each case we include in die schema not only die equations but also an explanation of the notation. This is not an unreasonable demand. We have already said, in connection with crude complexity, mat it would be misleading to employ special language just to reduce die lengdi of a description. In fact, die undedying madiematics of Maxwell's equations is not particularly difficult to explain, but even if diat were not die case, it would still require only a finite amount of interpretation. This pales into insignificance when we consider diat die equations apply to all electric and magnetic

 fields everywhere in the universe. The

 fields, everywhere in the universe. The compression achieved is still enormous. Universal Gravitation—Newton ana Einstein Another remarkable universal law is that of gravitation. Isaac Newton developed the first version, which was followed two and a half centuries later by the more accurate general-relativistic gravitational theory of Albert Einstein. Newton gained his brilliant insight into the universality of gravitation when he was a young man of 23. In 1665 Cambridge University was forced to close because of the plague and Newton, a fresh B.A., returned to his family home in Woolsthorpe, Lincolnshire. There, in 1665 and 1666, he began to develop the integral and differential calculus, as well as the law of gravitation and his three laws of motion. In addition, he carried out the famous experiment with a prism, showing that white light is made up of the colors of the rainbow. Each one of those pieces of work was a major innovation, and though historians of science like to emphasize nowadays that Newton didn't complete them all in one annus mirabilis, or marvelous year, they still admit that he made a good start on each of them during that time. As my wife, the poet Marcia Southwick, likes to say, he could have written an impressive essay entided "What I Did During My \&cation." Legend associates Newton's conception of a universal law of gravitation with die fall of an apple. Was diere really such an incident? Historians of science are not sure but diey do not rule it out, because diere are four independent sources diat refer to it. One of diem, Conduct, wrote: In die year 1666 he retired again from Cambridge ... to his modier in Lincolnshire & whilst he was musing in a garden it came into his diought that die power of gravity (wch brought an apple from the tree to die ground) was not limited to a certain distance from die earth but diat diis power must extend much farther than was usually diought. Why not as high as the moon said he to himself & if so that must influence her motion & perhaps retain her in orbit, whereupon he fell a calculating what would be die effect of diat supposition but being absent from books & tak-

 ing die common estimate in use among Geographers & our seamen before Norwood had measured die eardi, that 60 English miles were contained in one degree of latitude on the surface of the Earth, his computation did not agree widi his dieory & inclined him dien to entertain die notion diat togedier widi the force of gravity there might be a mixture of diat force wch the moon would have if it was carried along in a vortex ... In this story we see a number of processes at work diat may occur from rime to time in die life of a dieoretical scientist. An idea strikes at an odd moment. It makes possible a connection between two sets of phenomena previously diought to be distinct. A dieory is dien formulated. Some of its consequences can be predicted; in physics die theorist "falls a calculating" in order to make diose predictions. The predictions may fail to agree widi observation even though die theory is correct, either because of an error in the reported observations (as in Newton's case) or because the theorist has made a conceptual or madiematical mistake in applying die dieory. The theorist may dien modify die correct theory (with its simplicity and elegance) and cobble togedier a more complicated one to accommodate die error. Witness die bit at the end of die Conduitt quotation about the messy "vortex" force diat Newton diought of adjoining to the force of gravity! After a long while, the discrepancy between dieory and observation was straightened out and Newton's theory of universal gravitation was accepted, until it was replaced in about 1915 by Einstein's general-rela- tivistic theory, which agrees exacdy widi Newton's in die limit in which all bodies are moving very slowly compared widi die speed of light. In die solar system, planets and satellites move at speeds on die order often miles per second, while die speed of light is about 186,000 miles per second. The Einsteinian corrections to Newton's dieory are dierefore very tiny and have so far been detectable only in a very few observations. In all die tests that have been conducted, Einstein's theory checks out. The replacement of an excellent theory by an even better one is described in a particular way by Thomas Kuhn in his book 77ie Structure .of Scientific Revolutions, and his point of view has become extremely influential. He pays special attention to "paradigm shirts," using "paradigm" in a tamer special sense (some might say he is misusing the word!). His approach emphasizes changes in matters of principle as die improved dieory takes over. In the case of gravitation, Kuhn might point to the fact that Newton's theory employs "action at distance," mat is, a gravitational force mat acts instantaneously, whereas in Einstein's theory gravitational influences propagate, like electromagnetic ones, at die speed of light. In Newton's nonrelativistic dieory, space and time are treated as separate and absolute, and gravitation is not connected widi geometry; in Einstein's dieory space and time are mixed togedier (as they always are in relativistic physics), and Einsteinian gravitation can be regarded as intimately connected with the geometry of space-time. Also, general rehtivity, unlike Newtonian gravitation, is based on die principle of equivalence, which states diat it is impossible to distinguish locally between a gravitational field and an accelerated frame of reference (as in an elevator); the only diing one can feel or measure locally is die difference between one's acceleration and die local acceleration of gravity. The paradigm shift approach is concerned with such profound differences in philosophy and language between an old theory and a new one. Kuhn does not like to stress the fact (although he mentions it, of course) that the old theory may still provide a sufficiendy good approximation for calculations and predictions in die domain for which it was developed (in diis case die limit of weak fields and very low relative velocities). I should like to call special attention to diat feature, however, in order to point out diat in the competition of schemata in the scientific enterprise, die triumph of one schema over another does not necessarily mean diat die loser is abandoned and forgotten. In fact, it may be utilized far more often than its more accurate and sophisticated successor. That is certainly true for Newtonian versus Einsteinian mechanics of the solar system. Victory in the competition between scientific theories may be more a matter of demotion of die old theory and promotion of the new one over its head than a matter of die deadi of the vanquished. (Of course, it does often happen instead that die old theory no longer has any value at all, and then it is mainly historians of science who bodier to discuss it.) Einstein's general-relativistic equation iv *s OJIK l jiv

 does for gravitation what Maxwell's equations do for electromagnetism. The left-hand side of die equation relates to die curvature of space- time (and dius to die gravitational field) and die right-hand side to die energy density, etc., of matter other than die gravitational field. It expresses in a single short formula the universal features of gravitational fields throughout die cosmos. Given die masses, positions, and velocities of matter, one can calculate die gravitational field (and thus die effect of gravitation on die motion of a test body) at any place and time. We are dealing widi a remarkably powerful schema, which has compressed into a brief message die general properties of gravitation everywhere. Again, a critic might demand that we include as part of die schema not only die formula but also an explanation of die symbols. My fadier, who struggled as an educated layman to understand Einstein's dieory, used to say, "Look how simple and beautiful this theory is, but what are Tpv and G^v?" As in die case of electromagnetism, even if a course of study is included in die schema, Einstein's equation is still a bargain in terms of compression, since it describes die behavior of all gravitational fields everywhere. The schema is still remarkably short, and its complexity low. Hence, Einstein's general-relativistic dieory of gravitation is simple.

8 THE POWER OF THEORY The mind-set of die theoretical scientist is useful not only for probing die ultimate secrets of die universe but for many odier tasks as well. All around us are facts diat are related to one another. Of course, diey can be regarded as separate entities and learned mat way. But what a difference it makes when we see diem as part of a pattern! Many facts dien become more dian just items to be memorized—their rehtionships permit us to use a compressed description, a kind of dieory, a schema, to apprehend and remember them. They begin to make some sense. The world becomes a more comprehensible place. Pattern recognition comes naturally to us humans; we are, after all, complex adaptive systems ourselves. It is in our nature, by biological inheritance and also through the transmission of culture, to see patterns, to identify regularities, to construct schemata in our minds. However, those schemata are often promoted or demoted, accepted or rejected, in response to selection pressures that are far different from diose operating in die sciences, where agreement with observation is so critical. Unscientific approaches to the construction of models of die world around us have characterized much human thinking since time immemorial, and diey are still widespread. Take, for example, die version of sympathetic magic based on the idea diat similar things must be connected. It seems natural to many people around the world that, when in need of rain; diey should perform a ceremony in which water %9

 is procured from a special place and poured on die ground. The similarity between die action and die desired phenomenon suggests diat mere should be a causal connection. The selection pressures that help to maintain such a belief do not include objective success, the criterion that is applied in science (at least when science is working properly). Instead, odier kinds of selection are operating. For instance, diere may be powerful individuals who carry out the ceremony and encourage the belief in order to perpetuate dieir audiority. The same society may also be familiar widi sympadietic magic that works dirough an effect on people, say eating a lion's heart to increase die bravery of a warrior. Now that can achieve some objective success, simply by psychological means: if a man believes he has eaten something that will increase courage, that may give him die confidence to act bravely. Similarly, destructive witchcraft (whether based on sympadietic magic or not) can be objectively successful if die victim believes in it and knows that it is being practiced. Say diat you want me to suffer pain and you make a wax effigy of me, widi some hair and nail parings of mine embedded in it, and you dien stick pins into die effigy. If I believe, even a little, in die efficacy of such magic and I know you are engaged in it, I may feel pain in die appropriate places and become ill (and, in an extreme case, perhaps even die) dirough psychosomatic effects. The occasional (or frequent!) success of sympadietic magic in such cases may dien encourage die belief that such magic works even when, as in die ceremony for die production of rain, it cannot achieve objective success except by chance. We shall return to die subject of unscientific models, as well as the many reasons for dieir appeal, in die chapter on superstition and skepticism, but for now we are concerned widi die value of dieorizing in the scientific manner about die world around us, seeing how connections and working relationships fall into place. "Merely Theoretical" Many people seem to have trouble widi die idea of dieory because diey have trouble widi die word itself, which is commonly used in two quite distinct ways. On die one hand, it can mean a coherent system of rules and principles, a more or less verified or established explanation ac-

counting for known facts or phenomena. On the odier hand, it can refer to speculation, a guess or conjecture, or an untested hypothesis, idea, or opinion. Here the word is used with the first set of meanings, but many people think of the second when they hear "theory" or "theoretical." One of my colleagues on the board of directors of die John D. and Cadierine T. MacArthur Foundation is likely to comment, when some fairly bold research project is proposed for funding, "I diink we should take a chance and support that, but let's be careful not to spend money on anything theoretical." To a professional theorist those ought to be fighting words, but I understand that he and I use dieoret- ical in different senses. Theorizing about Place Names It can be useful to theorize on almost any aspect of the world around us. Take place names. In California, people familiar with the Spanish place names along the coast are not surprised that many of diem relate to die Roman Catholic religion, of which die Spanish explorers and setders were usually devout communicants. However, I believe few people ask why each place has been given its particular name. Yet it is not unreasonable to inquire whedier diere might be some system behind the giving of saints' names like San Diego, Santa Catalina, and Santa Barbara, as well as odier religious names such as Conception (Conception) or Santa Cruz (Holy Cross), to islands, bays, and points of land along the coast. A hint is available when we notice on die map Point Ano Nuevo (New Year). Could odier names also refer to days of the year? Of course! In die Roman Catholic calendar we find, in addition to die New Year on January 1, die following: San Diego (Saint Didacus of Alcala de Henares) November 12 Santa Catalina (Saint Catherine of Alexandria) November 25 San Pedro (Saint Peter of Alexandria) November 26 Santa Barbara (Saint Barbara, Virgin and Martyr) December 4

 San Nicolas (Saint Nicholas of Myra) December 6 La Purisima Concepcion (The Immaculate Conception) December 8 Perhaps on a voyage of discovery die geographical features were named in order from soudieast to northwest, according to die days on which diey were sighted. Sure enough, scholars have verified from die historical record that in 1602 die explorer Sebastian Viscaino named San Diego Bay on November 12, Santa Catalina Island on November 25, San Pedro Bay on November 26, die bay at Santa Barbara on December 4, San Nicolas Island on December 6, and Point Concepcion on December 8. Point Ano Nuevo was apparently die first point sighted in the new year 1603, aldiough on January 3 radier than New Year's Day. On January 6, die day of the Three Kings, Viscaino named Point Reyes (Kings). The theory works, but is it general? What about Santa Cruz? The day of die Holy Cross is September 14, which doesn't fit in widi the sequence. Was it named on a different voyage of discovery? The schema is beginning to acquire a little complexity. In fact, many of the Spanish religious names along die coast correspond to dates on just a few voyages of discovery, so die effective complexity is not diat great. In this kind of dieorizing, die construction of rough schemata to describe the results of human activity, arbitrary exceptions may be encountered, which fortunately do not plague schemata such as Maxwell's equations for electromagnetism. San Quentin, for example, located north of San Francisco and well known for its state prison, sounds as if it might have been named by some early Spanish explorer on Saint Quentin's Day. However, research by place-name experts reveals that die "San" was added in error to the earlier name Quentin, for die Spanish Quintin, die name of an Indian chief who was captured mere in 1840. Empirical Tkeory-Z ipr s Law In die place-name example, dieorizing has led not only to die identification of regularities but also to a plausible explanation of diem and a

 confirmation of that explanation. That is die ideal situation. Often, however, we encounter less than ideal cases. We may find regularities, predict that similar regularities will occur elsewhere, discover that die prediction is confirmed, and dius identify a robust pattern: however, it may be a pattern for which die explanation continues to elude us. In such a case we speak of an "empirical" or "phenomenological" dieory, using fancy words to mean basically diat we see what is going on but do not yet understand it. There are many such empirical dieories that connect together facts encountered in everyday life. Suppose we pick up a book of statistical facts, like die World Almanac. Looking inside, we find a list of U.S. metropolitan areas in order of decreasing population, togedier widi the population figures. There may also be corresponding lists for die cities in individual states and in other countries. In each list every city can be assigned a rank, equal to 1 for the most populous city, 2 for the next most populous, and so on. Is diere a general rule for all these lists diat describes how die population decreases as die rank increases? Roughly speaking, yes. Widi fair accuracy, die population is inversely proportional to die rank; in odier words, the successive populations are roughly proportional to 1,1/2, 1/3,1/4,1/5,1/6,1/7,1/8,1/9,1/10,1/11,and so on. Now let us look at die list of the largest business firms in decreasing order of volume of business (say die monetary value of sales during a given year). Is diere an approximate rule diat describes how die sales figures of die firms vary with their ranks? Yes, and it is the same rule as for populations. The volume of business is approximately in inverse proportion to die rank of die firm. How about die exports from a given country in a given year in decreasing order of monetary value? Again, we find die same rule is a fair approximation. An interesting consequence of that rule is easily verified by perusing any of die lists mentioned, for example a list of cities widi their populations. First let us look at, say, die third digit of each population figure. As expected, die diird digit is randomly distributed; die numbers of 0s, Is, 2s, 3s, etc. in the third place are all roughly equal. A totally different situation

2s, 3s, etc. in the third place are all roughly equal. A totally different situation obtains for die distribution of first digits, however. There is an overwhelming preponderance of Is, followed by 2s, and so forth. The percentage of population figures widi initial 9s is extremely small. That behavior of the first digit is predicted by die rule, which , if

 Rank it 1 7 13 19 25 31 37 49 61 73 85 97 City New York Detroit Baltimore Washington, DC New Orleans Kansas City, Ma Virginia Beach, Va. Toledo Arlington,Texas Baton Rouge, La. Hialeah, Fla. Bakersfield, Calif. Population (1990) 7^22,564 1,027,974 736,014 606,900 496,938 434,829 393,089 332,943 261,721 219,531 188,008 174,820 Unmodified Zipfs law 10,000,000 divided by it 10,000,000 1,428371 769,231 526316 400,000 322,581 270,270 204,082 163.934 136.986 117,647 103,093 Modified Zipf slaw 5,000,000 divided by («-2/5)3/4 7,334,265 1.214,261 747,639 558,258 452,656 384,308 336,015 271,639 230,205 201,033 179,243 162,270 Populations of U.S. cities from die 1994 WotidAlmanac compared with Zipfs original law and a modified version of it. exactly obeyed, would give a proportion of initial Is to initial 9s of 45 to 1. What if we put down die World Almanac and pick up a book on secret codes, containing a list of die most common words in a certain kind of English text arranged in decreasing order of frequency of occurrence? What is die approximate rule for die frequency of occurrence of each word as a function of its rank? Again, we encounter the same rule, which works for odier languages as well. Many of diese relationships were noticed in the early 1930s by a certain George Kingsley Zipf, who taught German at Harvard, and diey are all aspects of what is now called Zipfs law. Today, we would say diat Zipfs law is one of many examples of so-called scaling laws or power laws, encountered in many places in the physical, biological, and behavioral sciences. But in the 1930s such laws were still something of a novelty.

 In Zipfs law the quantity under study is inversely proportional to the rank, that is, proportional to 1, 1/2, 1/3, 1/4, etc. Benoit Mandelbrot has shown that a more general power law (nearly die most general) is obtained by subjecting diis sequence successively to two kinds of modification. The first alteration is to add a constant to die rank, giving 1/(1 + constant), 1/(2 + constant), 1/(3 + constant), 1/(4 + constant), etc. The further change allows, instead of diese fractions, dieir squares or dieir cubes or dieir square roots or any odier powers of them. The choice of die squares, for instance, would yield die sequence 1/(1 + constant)2 1/(2 + constant)2 1(3 +

instance, would yield die sequence 1/(1 + constant)2,1/(2 + constant)2,1(3 + constant) , 1(4 + constant)2, etc. The power in die more general power law is 1 for Zipf s law, 2 for die squares, 3 for die cubes, 1/2 for die square roots, and so on. Madi- ematics gives a meaning to intermediate values of die power as well, such as 3/4 or 1.0237. In general, we can think of die power as 1 plus a second constant. Just as die first constant was added to die rank, so die second one is added to die power. Zipf s law is then the special case in which those two constants are zero. Mandelbrot's generalization of Zipfs law is still very simple: die additional complexity lies only in the introduction of the two new adjustable constants, a number added to the rank and a number added to die power 1. (An adjustable constant, by the way, is called a "parameter," a word that has been widely misused lately, perhaps under the influence of the somewhat similar word "perimeter." The modified power law has two additional parameters.) In any given case, instead of comparing data widi Zipfs original law, one can introduce diose two constants and adjust them for an optimal fit to die data. We can see in the chart on page 94 how a slighdy modified version of Zipfs law fits some population data significandy better than Zipfs original rule (widi both constants set equal to zero), which already works fairly well. "Slighdy modified" means that die new constants have radier small values in die altered power law used for die comparison. (The constants in the chart were chosen by mere inspection of the data. An optimal fit would have yielded even better agreement widi the actual populations.) When Zipf first described his law, at a time when very few other scaling laws were known, he tried to make an important issue of how his principle distinguished die behavioral from the physical sciences, where such laws were supposedly absent. Today, after so many power laws have been discovered in physics, diose remarks tend to detract from

% • THE SIMPLE AND THE COMPLEX New rank 2» corresponding to halved populations * * 0 0 10 ". / 9 8 7 6 5 4 3 2 1 / / * i r j i 12 3 4 5 6 Original rank n 7 How a power law (in this case Zipfs original law) exhibits scaling. Zipfs reputation rather than enhance it. Another circumstance is said to have worked against his reputation as well, namely that he indicated a certain sympathy with Hider's territorial rearrangements of Europe, perhaps justifying his attitude by arguing that those conquests tended to make the populations of European countries conform more closely to Zipfs law. Whether the story is true or not, it teaches an important lesson about the applications of behavioral science to policy: just because certain relationships tend to occur, that doesn't mean they should necessarily be regarded as always desirable. I encountered this issue at a recent Aspen Institute seminar, where I mentioned the tendency of distributions of wealth or income to follow scaling laws under certain conditions. I was immediately asked whether such a situation should be regarded as a good thing. As I remember, I shrugged my shoulders. After all, the steepness of the distribution, which determines the sharpness of the inequalities in wealth or income, depends on what power occurs in the law.

 ZipPs law remains essentially unexplained, and the same is true of a great many other power laws. Benoit Mandelbrot, who has made really important contributions to die study of such laws (especially their connection to fractals), admits quite frankly diat early in his career he was successful in part because he placed more emphasis on finding and describing the power laws than on trying to explain diem. (In his book T7ie Fractal Geometry of Nature he refers to his "bent for stressing consequences over causes.*^ He is quick to point out, however, that in some fields, especially in die physical sciences, quite convincing explanations have developed. For instance, die phenomenon of chaos in nonlinear dynamics is closely associated with fractals and power laws, in ways that are quite well understood. Also, Benoit has from time to time constructed models in which power laws occur. For instance, he calculated die word frequencies in texts typed by die proverbial monkeys. They obey a modified version of ZipPs law, widi die power approaching 1 (ZipPs original value) as the number of symbols gets larger and larger. (He also noticed, by the way, diat when word frequencies in actual texts written in natural languages are fitted by a modified ZipPs law, die power can differ significandy from 1, widi die deviation depending on die richness of die vocabulary in die text in question.) Scale Independence In die last few years, increasing progress has been made toward an explanation of certain power laws. One such effort involves what is called "self-organized criticality," a concept proposed by the Danish dieoretical physicist Per Bak, in collaboration with Chao Tang and Kurt Wiesenfeld. Their initial application of die idea was to sand piles, such as those we might see on a desert or a beach. The piles are roughly conical, and each has a fairly well-defined slope. If we examine diose slopes, we observe diat they are mosdy the same. How does diat come about? Suppose winds keep depositing additional sand grains on die piles (or a physicist in the laboratory keeps dribbling sand from a container onto experimental piles). As each pile builds up, its sides can become steeper, but only until die slope attains a critical value. Once that critical slope is reached, die addition of more sand starts to produce avalanches diat reduce the height of die pile.

 If die slope is greater than die critical value, an unstable situation results, in which avalanches of sand occur very readily and reduce die slope until it reverts to die critical value. Thus die sand piles are naturally "attracted" to die critical value of die slope, widiout any special external adjustment being necessary (hence "self-organized" criticality). The size of an avalanche is usually measured by die number of sand grains that participate. Observation reveals diat when die slope of the pile is near its critical value, die sizes of die avalanches obey a power law to a good approximation. In this case die constant added to die ZipPs law power is very large. In odier words, if die avalanches are assigned numerical ranks in order of size, dien the number of participating sand grains decreases very rapidly widi the rank. The distribution of avalanches in sand piles is an example of a power law diat has been successfully studied by dieoretical as well as experimental means. A numerical simulation of die avalanche ptocess by Bak and his coUeagues reproduced bodi die law and an approximate value of die large power. Despite die sharp decline in size as rank increases, neady all scales of avalanche size are present to some degree. In general, a power law distribution is one diat is "scale-independent," That is why power laws are also called "scaling laws." But what exacdy does it mean for a distribution law to be scale-independent? The scale independence of power laws is well illustrated by ZipPs original rule, according to which populations of cities, for instance, are proportional to 1/1:1/2:1/3:1/4:1/5... For die sake of simplicity, take them to be one million, one half million, one-third million, and so on. Let us multiply diose populations by a fixed fraction, say 1/2; the new populations, in millions, become 1/2,1/4,1/6,1/8,1/10 ... They are just die original populations previously assigned ranks 2,4,6,8,10 ... So a reduction by a factor of two in all die populations is equivalent to doubling die ranks of die cities from die sequence 1,2,3,4,... to die sequence 2,4,6,8,... If die new ranks are plotted on a graph against die old ones, a straight line results, as in die diagram shown on page 96. That straight line relationship can serve as the definition of a scaling law for any type of quantity: reduction of all die quantities by any constant factor (1/2 in die example) is equivalent to choosing new ranks in die original set of quantities, such that die new ranks graphed against die old ones yield a straight line plot. (The new ranks will not always come out whole numbers, but in every case die formula for size

 against rank will give a simple smooth curve that can be used to interpolate between whole numbers.) In the case of sand pile that can be used to interpolate between whole numbers.) In the case of sand pile avalanches, since their sizes are distributed according to a power law, a reduction of all the sizes by any common factor is equivalent to a simple reassignment of the ranks in die original sequence of avalanches. It is evident that in such a law no particular scale is being picked out, except at die two ends of the size spectrum, where the obvious limitations are encountered. No avalanche can have less dian one grain participating; evidently, the power law must break down at the scale of a single grain. At die odier end of die spectrum, no avalanche can be larger dian the sand pile in question. But die largest avalanche is picked out anyway by having rank one. Thinking about die largest avalanche recalls a frequent feature of power law distributions for sizes of events in nature. The largest or most catastrophic ones, with very low numerical ranks, even though they fall more or less on die curve dictated by the power law, can be regarded as individual historical events with a great many noteworthy consequences, while small events of very high numerical rank are usually considered merely from die statistical point of view. Huge earthquakes, registering around 8.5 on the Richter scale, are recorded in screaming newspaper headlines and in history books (especially if large cities are involved). The records of the multitudes of earthquakes of size 1.5 on the Bichter scale languish in the data banks of seismologists, destined mosdy for statistical studies. Yet the energy releases in earthquakes do obey a power law, discovered long ago by Charles Bichter himself and his mentor Beno Gutenberg, bodi deceased Caltech colleagues. (Gutenberg was die professor who was so deep in conversation widi Einstein about seismology one day in 1933 that neidier of them noticed the Long Beach eardiquake shaking the Caltech campus.) Similarly, the very small meteorites diat are always striking the Earth are noted mainly in statistical surveys by specialists, while the huge collision that helped to cause the Cretaceous extinction sixty-6ve million years ago is considered a major individual event in the history of die biosphere. Since power laws have been shown to operate in cases of self-organized criticality, die already popular expression "self-organized" has gained even greater currency, often coupled with die word "emergent." Scientists, including many members of the Santa Fe Institute family, are trying hard to understand the ways in which structures arise without the imposition of special requirements from die outside. In an

 astonishing variety of contexts, apparently complex structures or behaviors emerge from systems characterized by very simple rules. These systems are said to be self-organized and their properties are said to be emergent. The grandest example is die universe itself, die Rill complexity of which emerges from simple rules plus die operation of chance. In many cases die study of emergent structures has been greatly facilitated by modern computers. The emergence of new features is often easier to follow by means of such machines dian by writing equations on a piece of paper. The results are often especially striking in cases where a great deal of real time elapses during die course of emergence, because die computer can effectively speed up die process by a gigantic factor. Still, die computation may require a great many steps, and diat raises a whole new issue. Depth and Crypticity In our discussions of complexity so far, we have considered compressed descriptions of a system or its regularities (or short computer programs for generating encoded descriptions), and we have related various kinds of complexity to the lengths of those descriptions or programs. However, we have paid little attention to die time, labor, or ingenuity necessary to accomplish die compression or to identify die regularities. Since die work of a dieoretical scientist consists precisely of recognizing regularities and compressing dieir description into dieories, we have effectively been setting at nought die value of a dieorist's labor, clearly a monstrous crime. Something must be done to rectify diat error. We have seen diat several different concepts are needed to capture adequately our intuitive notions of what complexity is. Now it is time to supplement our definition of effective complexity with definitions of odier quantities, which will characterize how long it takes a computer to get from a short program to a description of a system and vice versa, (lb some extent these quantities must resemble die computational complexity of a problem, which we defined earlier as die shortest time in which a computer can produce a solution.) Such additional concepts have been studied by a number of people, but diey are treated in an especially elegant way by Charles Bennett, a brilliant thinker at IBM, who is given time to generate ideas, publish

 diem, and give talks about diem here and there. I like to compare his peregrinations widi diose of a twelfth-century troubadour traveling from court to court in what is now die soudi of France. Instead of courtly love, Charlie "sings" of complexity and entropy, of quantum computers and quantum encipherment. I have had die pleasure of working widi him in Santa Fe and also in Pasadena, where he spent a term visiting our group at Caltech. Two particularly interesting quantities, labeled "depdi" and "cryp-ticity" by Charlie, are bodi related to computational complexity and have a reciprocal relation to each odier. The study of each quantity throws light on die case of an apparendy complex system that nevertheless has low algorithmic information content and low effective complexity because its description can be generated by a brief program. The catch lies in the answers to die following questions: 1) How laborious is it to go from die brief program or a highly compressed schema to a full-blown description of die system itself or of its regularities? 2) How laborious is it, starting widi die system, to compress its description (or a description of its regularities) into a program or schema? Very roughly, depdi is a measure of die first kind of difficulty and crypticity is a measure of die second. Evidendy, it is crypticity diat is related to die value assignable to die work of a dieorist (aldiough a subder description of dieorizing might include an attempt to distinguish between die ingenious and die merely laborious). A Hypothetical Example To illustrate how a good deal of simplicity may be associated with great depdi, let us return to Goldbach's conjecture that every even number greater than 2 is the sum of two prime numbers. As mentioned earlier, the conjecture has never been proved or disproved, but it has been verified for all even numbers up to some huge bound, set by die capabilities of die computer used and die patience of die investigators. Previously we allowed ourselves to imagine diat Goldbach's conjecture was technically undecidable (on die basis of die axioms of number dieory) and therefore really true. This time let us imagine instead that Goldbach's conjecture is false. In diat case, some gigantic even number £ is die smallest even number greater dian 2 that is not die sum of two prime numbers. That hypothetical number g has a very simple descrip-

 tion, which we have just given. Likewise, there are very short programs for calculating it. For example, one can simply search methodically for larger and larger prime numbers and test Goldbach's conjecture on all even numbers up to 3 plus die largest prime found. In diat way, the smallest even number g violating Goldbach's conjecture will eventually be discovered. If Goldbach's conjecture really is false, it is likely diat die running time for any such short program to findg is very long indeed. In diis hypothetical case, dien, die number g has a fairly low algorithmic information content and effective complexity but very considerable depdi. A Deeper Look at Depth Charlie's technical definition of depdi involves a computer, die same kind diat we introduced in connection widi algorithmic information content: an ideal all-purpose computer diat can increase its memory capacity as much as it needs to at any time (or diat has infinite memory to begin widi). He starts widi a message string of bits describing die system being studied. Then he considers message string of bits describing die system being studied. Then he considers not just die shortest program diat will cause die computer to print out diat string and dien stop (as in die definition of algoridimic information content), but a whole range of fairly short programs diat have die same effect. For each of diese programs, he asks how much computing time is required to go from die program to die message string. Finally, he averages diat time over die programs, using an averaging procedure diat emphasizes the shorter programs. Bennett has also recast the definition in a slighdy different form, using Greg Chaitin's metaphor. Imagine diat die proverbial monkeys are set to work typing not prose but computer programs. Let us concentrate our attention just on diose rare programs diat will cause the computer to print out our particular message string and then halt. Out of all such programs, what is the probability diat die computer time required will be less than some particular time 7? Call diat probability p. The depdi d will then be a particular kind of average of T, an average diat depends on die curve of p versus T. The illustration on page 103 gives a rough picture of how die probability p varies widi the maximum permitted computer time T. When T is very small, it is very unusual for die monkeys to produce a program diat will compute the desired result widiin such a short time,

THE POWER OF THEORY • 103 i t Probability P A U I « i Tiepthd- * TimeT Depth as a rise time. so p is near 0. When T is extremely long, the probability naturally approaches 1. The depth d is, roughly speaking, die rise time of die curve of T against p. It tells us what maximum permitted running time T is required in order to pick up a good fraction of die programs that will cause die computer to print out the message string and dien halt. Depth is thus a crude measure of how long it takes to generate die string. When a system occurring in nature has a great deal of depdi, that is an indication that it took a long time to evolve or that it stems from something diat took a long time to evolve. People who show an interest in the conservation of nature or in historic preservation are trying to protect both depth and effective complexity, as manifested in natural communities or in human culture. But depth, as Charlie has shown, tends to communicate itself to by-products of long processes of evolution. We can find evidence of depdi not only in today's life forms, including humans; in glorious works of art produced by human hands; and in fossilized remains of dinosaurs or Ice Age mammals; but also in a beer can pull tab on a beach or in die graffiti spray-painted on a canyon wall. Preservationists need not defend all manifestations of depth. Deptn and AIC Aldiough depdi is an average of running time over program lengths, with die average weighted so as to emphasize the shorter programs, we

 i Largest possible depth (IA / I \ / \ \ Maximum Algorithmic information content (AIC) ^£3 Order Disorder f~^- Largest possible depth crudely sketched as a function of algorithmic information content. can often get a good idea of depth by looking at die running time for the shortest program. Suppose, for example, that the message string is completely regular, with algorithmic information content near zero. Then die running time of the shortest program is not very long—die computer doesn't have to do much "thinking" to execute a program such as "PRINT twelve trillion zeroes" (of course, die printing may take some time if die printer is slow). If the algorithmic information content is very low, the depdi is low. What about a random string, which has maximal algorithmic information content for a given message length? To go from die shortest program—PRINT followed by the string—to actually printing out the string will again require no "thinking" on die part of the computer. So the depdi is low when die algoridimic information content is maximal, as well as when it is very small. The situation bears some resemblance to

 the way die maximum effective complexity varies with algorithmic information content, as in die sketch on page 59. Here, we can see very roughly how die maximum depth varies widi algorithmic information content. It is low right near both ends but can be sizable anywhere in between, in die intermediate region between order and disorder. Of course, in diat in-between region, die depdi doesn't have to be large. Note that this figure has a different form from die one on page 59. Even diough both are just crude sketches, diey show that depdi can be great even for values of AIC fairly close to complete order or complete disorder, where effective complexity is still small. Crypticity and Theorizing The definition of crypticity refers to an operation diat is die reverse of the one figuring in die definition of depdi. The crypticity of a message string is die minimum time required for die standard computer, starting from the string, to find one of die shorter programs that will cause die machine to print out the string and dien stop. Suppose die message string results from the encoding of a data stream studied by a theorist. The crypticity of die string is dien a rough measure of die difficulty of the theorist's task, which is not so very different from diat of die computer in die definition. The dieorist identifies as much regularity as possible, in the form of mutual information relating different parts of the stream, and dien constructs hypotheses, as simple and coherent as possible, to explain die observed regularities. Regularities are the compressible features of die data stream. They stem partly from die fundamental laws of nature and partly from particular outcomes of chance events diat could have turned out odier- wise. But the data stream also has random features, which arise from chance events diat have not resulted in regularities. Those features are incompressible. Thus die dieorist, in compressing die regularities of the data stream as much as is practicable, is at die same time discovering a concise description of die entire stream, a description made up of compressed regularities and incompressible random supplementary information. Similarly, a brief program that causes the computer to print out the message string (and then stop) may be arranged

 to consist of a basic program, which describes die regularities of die string, supplemented by inputs of information describing specific accidental circumstances. Aldiough our discussions of theory have only scratched the surface of die subject, we have already mentioned dieorizing about place names, about empirical formulae for statistics, about the heights of sand piles, and about classical electromagnedsm and gravitation. While there is a great deal of formal similarity among diese various kinds of dieorizing, they involve discoveries at many different levels, among which it is useful to distinguish. Are the basic laws of physics being studied? Or approximate laws that apply to messy physical objects such as sand piles? Or rough but general empirical laws about human institutions like cities and business firms? Or specific rules, widi many exceptions, about place names used by people in a particular geographical area? Clearly diere are important differences in accuracy and in generality among die various kinds of dieoretical principles. Frequently diose differences are discussed in terms of which are more fundamental dian odiers. But what does diat mean?

9 WHAT IS FUNDAMENTAL? The quark and the jaguar find themselves almost at opposite ends of die scale of what is fundamental. Elementary particle physics and cosmology are the most basic scientific disciplines, whereas the study of very complex living things is much less basic, aldiough obviously of die greatest importance. In order to discuss this hierarchy of die sciences, it is necessary to disentangle at least two different direads, one having to do with mere convention and die odier widi real relationships among the different subjects. I have been told diat die faculty of sciences of a French university used to discuss die business related to die various subjects in a fixed order: first

mathematics, then physics, dien chemistry, then physiology, and so on. It would seem that die concerns of die biologists must often have been somewhat neglected under diat arrangement. Similarly, in die will of die Swedish dynamite magnate Alfred Nobel, who established the Nobel prizes, the science prizes are listed with physics first, chemistry second, and physiology and medicine third. As a result, the physics prize is always awarded at die beginning of die ceremony in Stockholm. If diere is just one physics prize winner and diat winner is a married man, it is his wife who comes into dinner on the arm of the King of Sweden. (When my friend Abdus Salam, a citizen of Pakistan and a Muslim, received a share of the physics prize in 1979, he turned up in Sweden widi his two wives, no doubt causing \0?

 some problems of protocol to arise.) The winner or winners in chemistry rank second in protocol, and those in physiology and medicine third. Madiematics is omitted from Nobel's will for reasons diat are not really understood. There is a persistent rumor that Nobel was angry widi a Swedish immematician, Mittag-Leffler, for stealing die affections of a woman, but, as far as I know, it is only a rumor. This hierarchy of subjects can in part be traced to die nineteendi- century French philosopher Auguste Comte, who argued diat astronomy was die most fundamental scientific subject, physics the second, and so fordi. (He regarded madiematics as a logical tool radier than a science.) Was he right? And if so, in what sense? Here it is necessary to put aside questions of prestige and try to understand what such a hierarchy really means in scientific terms. The Special Character or Mathematics First of all, it is true diat madiematics is not really a science at all, if a science is understood to be a discipline devoted to die description of nature and its laws. Madiematics is more concerned with proving die logical consequences of certain sets of assumptions. For this reason, it can be omitted altogedier from die list of sciences (as it was from Nobel's will) and treated as an interesting subject in its own right (pure madiematics) as well as an extremely useful tool for science (applied madiematics). Anodier way to look at mathematics is to regard applied madiematics as concerning itself widi die structures diat occur in scientific theory, while pure mathematics covers not only diose structures but also all the ones diat might have occurred (or might yet turn out to occur) in science. Madiematics is dien die rigorous study of hypodietical worlds. From diat point of view, it is a kind of science—the science of what might have been or might be, as well as what is. Treated in diat way, is madiematics then die most fundamental science? And what about die remaining subjects? What is meant by fundamental science? And what about die remaining subjects? What is meant by die statement diat physics is more fundamental dian chemistry or chemistry more fundamental dian biology? What about die different parts of physics: aren't some more fundamental dian odiers? In general, what makes one science more fundamental dian anodier?

I suggest that science A is more fundamental than science B when 1. The laws of science A encompass in principle die phenomena and die laws of science B. 2. The laws of science A are more general than diose of science B (mat is, diose of science B are valid under more special conditions than are diose of science A). If mathematics is considered to be a science, it is men, according to diese criteria, more fundamental man any odier. All conceivable madi- ematical structures lie within its province, while die ones diat are useful in describing natural phenomena are only a tiny subset of diose that are or may be studied by madiematicians. Through that subset, die laws of madtematics do cover all die dieories used in die other sciences. But what about those odier sciences? What are die relations among diem? Chemistry and the Physics of the Electron When die remarkable English dieoretical physicist Paul Adrien Maurice Dirac published his relativisdc quantum-mechanical equation for die electron in 1928, he is said to have remarked diat his formula explained most of physics and die whole of chemistry. Of course he was exaggerating. Still, we can understand what he meant, particularly regarding chemistry, which is mosdy concerned with the behavior of objects such as atoms and molecules, diemselves composed of heavy nuclei widi light electrons moving around diem. A great many of die phenomena of chemistry are governed largely by the behavior of die elections as diey interact widi die nuclei and widi one anodier dirough electromagnetic effects. Dime's equation, describing die electron in interaction widi the electromagnetic field, gave rise within a very few years to a fiill-blown relativisdc quantum-mechanical dieory of the electron and electromag- netism. The dieory is quantum electrodynamics, or QED, and it has been verified by observation to a huge number of decimal places in many experiments (and so fully deserves its abbreviation, which reminds some of us of our school days, when we used "QED" at die end

of a mathematical proof to mean quod erat demonstrandum, Latin for "which was to be demonstrated"). QED does explain, in principle, a huge amount of chemistry. It is rigorously applicable to those problems in which die heavy nuclei can be approximated as applicable to those problems in which die heavy nuclei can be approximated as fixed point particles carrying an electric charge. Simple extensions of QED permit die treatment of nuclear morions and nonzero size as well. In principle, a dieoretical physicist using QED can calculate die behavior of any chemical system in which die detailed internal structure of atomic nuclei is not important. Wherever calculations of such chemical processes are practical using justified approximations to QED, diey are successful in predicting die results of observation. In most cases in fact, one particular well-justified approximation to QED will do. It is called the Schrodinger equation widi Coulomb forces, and it is applicable when die chemical system is "nonrelativistic," meaning that die electrons as well as die nuclei are moving very slowly compared to the speed of light. That approximation was discovered in the very early days of quantum mechanics, three years before die appearance of Dirac's relativistic equation. In order to derive chemical properties from fundamental physical dieory, it is necessary, so to speak, to ask chemical questions of the dieory. One must put into die calculation not only the basic equations but also die conditions that characterize the chemical system or process in question. For instance, the lowest energy state of two hydrogen atoms is the hydrogen molecule H^An important question in chemistry is die amount of binding energy in that molecule; that is, how much lower die energy of the molecule is than the sum of the energies of die two atoms of which it is composed. The answer can be calculated from QED. But first it is necessary to "ask the equation" about die properties of die lowest energy state of that particular molecule. The conditions of low energy under which such chemical questions arise are not universal. In die center of the sun, at a temperature of tens of millions of degrees, hydrogen atoms would be ripped apart into dieir constituent electrons and protons. Neidier atoms nor molecules are present mere widi any significant probability. There is, so to speak, no chemistry in die center of the sun. QED meets the two criteria for being considered more fundamental dian chemistry. The laws of chemistry can in principle be derived from QED, provided die additional information describing suitable

 chemical conditions is fed into die equations; moreover, diose conditions are special—they do not hold throughout die universe. Chemistry at Its Own Level In practice, even with die aid of die largest and fastest computers available today, only die simplest chemical problems are amenable to actual calculation from basic physical dieory. The number of such amenable problems is growing, but most situations in chemistry are still described using concepts and formulae at die level of chemistry rather than diat of physics. In general, scientists are accustomed to developing dieories diat describe observational results in a particular field widiout deriving diem from die dieories of a more nindamental field. Such a derivation, though possible in principle when die additional special information is supplied, is at any given time difficult or impossible in practice for most cases. For example, chemists are concerned widi different kinds of chemical bonds between atoms (including die bond between die two hydrogen atoms in a hydrogen molecule). In die course of dieir experience, diey have developed numerous practical ideas about chemical bonds diat enable diem to predict the behavior of chemical reactions. At die same time, dieoretical chemists endeavor to derive diose ideas, as much as they can, from approximations to QED. In all but die simplest cases diey are only partially successful, but diey don't doubt that in principle, given sufficiendy powerful tools for calculation, diey could succeed with high accuracy. Staircases (or Bridges) and Reduction We are dius led to die common metaphor of different levels of science, with die most fundamental at die bottom and the least fundamental at the top. Non-nuclear chemistry occupies a level "above" QED. In very simple cases, an approximation to QED is used to predict directly die results at die chemical level. In most cases, however, laws are developed at die upper level (chemistry) to explain and predict phenomena at diat level, and attempts are dien made to derive those laws, as much as

 possible, from the lower level (QED). Science is pursued at both levels and in addition efforts are made to construct staircases (or bridges) between diem. The discussion need not be restricted to non-nuclear phenomena. Since QED was developed around 1930, it has been gready generalized. A whole discipline of elementary particle physics has grown up. Elementary particle theory, on which I have worked for most of my life, has as its task die description not only of die electron and electromag-netism, but of all die elementary particles (die fundamental building blocks of all matter) and all die forces of nature. Elementary particle theory describes what goes on inside die atomic nucleus as well as among die electrons. Therefore, the relationship between QED and die part of chemistry that deals widi electrons can now be regarded as a special case of die relationship between elementary particle physics (as a whole) at die more fundamental level and chemistry (as a whole, including nuclear chemistry) at die less fundamental one. The process of explaining die higher level in terms of die lower is often called "reduction." I know of no serious scientist who believes that mere are special chemical forces that do not arise from underlying physical forces. Akhough some chemists might not like to put it this way, the upshot is that chemistry is in principle derivable from elementary particle physics. In that sense, we are all reductionists, at least as far as chemistry and physics are concerned. But die very fact that chemistry is more special man elementary particle physics, applying only under die particular conditions that allow chemical phenomena to occur, means that information about those special conditions must be fed into die equations of elementary particle physics in order for die hws of chemistry to be derived, even in principle. Widiout that caveat, die notion of reduction is incomplete. One lesson to be learned from all this is mat, while die various sciences do occupy different levels, diey form part of a single connected structure. The unity of that structure is cemented by die relations among die parts. A science at a given level encompasses die hws of a less fundamental science at a level above. But the latter, being more special, requires further information in addition to die hws of die former. At each level mere are laws to be discovered, important in dieir own right. The enterprise of science involves investigating those laws at all levels, while also working, from die top down and from die bottom up, to build staircases between diem.

 Such considerations apply within physics, too. The laws of elementary particle physics are valid for all matter, throughout the universe, under all conditions. Nuclear physics, however, was not really applicable during the earliest moments of the expansion of die universe because die density was too high to allow separate nuclei, or even neutrons and protons, to form. Still, nuclear physics is crucial for understanding what goes on in die center of the sun, where diermonu- clear reactions (somediing like diose in a hydrogen bomb) are producing the sun's energy, even diough the conditions diere are too harsh for chemistry Condensed matter physics, which is concerned widi systems such as crystals, glasses, and liquids, or superconductors and semiconductors, is likewise a very special subject, applicable only under the conditions (such as low enough temperature) that permit die existence of die structures diat it studies. Only when those conditions are specified is condensed matter physics derivable, even in principle, from elementary parade physics. Trie Information Required for Reduction or Biology What about the relation to physics and chemistry of anodier level in die hierarchy, mat of biology? Are there today, as there used to be in past centuries, serious scientists who believe that diere are special "vital forces" in biology that are not physico-chemical in origin? There must be very few, if any. Virtually all of us are convinced that life origin? There must be very few, if any. Virtually all of us are convinced that life depends in principle on die laws of physics and chemistry, just as die laws of chemistry arise from diose of physics, and in that sense we are again reductionists of a sort. Still, like chemistry, biology is very much wordi studying on its own terms and at its own level, even as die work of staircase construction goes on. Moreover, terrestrial biology is extremely special, referring as it does to living systems on diis planet, which may differ widely from many of the diverse complex adaptive systems that surely exist on planets revolving around distant stars in various parts of die universe. On some of diose planets, perhaps die only complex adaptive systems are ones diat we would not necessarily describe as alive if we encountered diem. (To take a trivial example from science fiction, imagine a society composed

 of very advanced robots and computers descended from ones built long ago by an extinct race of beings mat we would have described as "living" while diey existed.) Even if we restrict our attention to "living" beings, however, many of them presumably exhibit very different properties from diose on Earth. An enormous amount of specific additional information must be supplied, over and above die laws of physics and chemistry, in order to characterize terrestrial biological phenomena. To begin with, many features common to all life on Earth may be die results of accidents diat occurred early in die history of life on the planet but could have turned out differendy. (Life forms for which diose accidents did turn out differendy may also have existed long ago on Earth.) Even die rule diat genes must be made up of die four nucleotides abbreviated A, C, G, and T, which seems to be true of all life on our planet today, may not be universal on a cosmic scale of space and time. There may be many odier possible rules, followed on odier planets; and beings obeying odier rules may also have lived on Earth a few billion years ago until diey lost out to life based on die familiar A, C, G, andT.

Biochemistry—Effective Complexity Versus Depth

It is not only die particular set of nucleotides characterizing the DNA of all terrestrial life today diat may or may not be unique. The same question is debated in connection widi each general property diat characterizes die chemistry of all life on Earth. Some dieorists claim diat die chemistry of life must take numerous forms on different planets scattered dirough die universe. The terrestrial case would then be die result of a large number of chance events, each having contributed to die remarkable regularities of biochemistry on Earth, which would diereby have acquired a good deal of effective complexity. On die odier side of die question are diose who believe diat biochemistry is essentially unique, diat die laws of chemistry, based on die fundamental laws of physics, leave little room for a chemistry of life odier dian diat found on Earth. The proponents of diis view are saying in effect diat going from die fundamental laws to die laws of biochemistry involves almost no new information, and dius contributes very

litde effective complexity. However, a computer might have to do a great deal of calculating to derive die near-uniqueness of biochemistry as a dieoretical proposition from die fundamental laws of physics. In that case, biochemistry would still have a good deal of depdi, if not much effective complexity. Anodier way to phrase die question about die near-uniqueness of terrestrial biochemistry is to ask whedier biochemistry depends mainly on asking die right questions about physics or also depends in an important way on history. Lire: High Effective Complexity—Between Order and Disorder Even if die underlying chemistry of terrestrial life depends litde on history, diere is still an enormous amount of effective complexity in biology, far more than in such subjects as chemistry or condensed matter physics. Consider the immense number of evolutionary changes that have occurred by chance during die four billion years or so since the origin of life on Earth. Some of diose accidents (probably a small fraction, but still a great many) have played major roles in die subsequent history of life on this planet and in die character of die diverse life forms that enrich the biosphere. The laws of biology do depend on die laws of physics and chemistry, but diey also depend on a vast amount of additional information about how diose accidents turned out. Here, much more than in die case of nuclear physics, condensed matter physics, or chemistry, one can see a huge difference between die kind of reduction to die fundamental laws of physics that is possible in principle and die trivial kind that die word "reduction" might call up in the mind of a naive reader. The science of biology is very much more complex man fundamental physics because so many of die regularities of terrestrial biology arise from chance events as well as from die fundamental laws. But even die study of complex adaptive systems of all kinds on all planets is still radier special. The environment must exhibit sufficient regularity for die systems to exploit for learning or adapting, but at die same time not so much regularity that nothing happens. For example, if the environment in question is die center of die sun, at a temperature of tens of millions of degrees, mere is almost total randomness, nearly

maximal algorithmic information

content, and no room for effective complexity or great depth—nothing like life can exist. Nor can there be such a thing as life if die environment is a perfect crystal at a temperature of absolute zero, widi almost no algoridimic information content and again no room for much effective complexity or great depth. For a complex adaptive system to function, conditions are required that are intermediate between order and disorder. The surface of die planet Earth supplies an environment of intermediate algoridimic information content, where depdi and effective complexity can both exist, and that is part of die reason why life has been able to evolve here. Of course, only very primitive forms of life evolved at first, under die conditions diat prevailed on Earth several billion years ago, but men diose living diings diemselves altered die biosphere, particularly by adding oxygen to die atmosphere, producing a situation more like die present one and permitting higher forms of life, widi more complex organization, to evolve. Conditions in between order and disorder characterize not only die environment in which life can arise, but also life itself, widi its high effective complexity and great depdi. Psychology and Neurobiology—Tne Mind and me Brain Complex adaptive systems on Eardi give rise to several levels of science that lie "above" biology. One of die most important is die psychology of animals, and especially of die animal widi die most complex psychology, die human being. Here again, it must be a rare contemporary scientist who believes that mere exist special "mental forces" that are not biological, and ultimately physicochemical, in nature. Again, virtually all of us are, in this sense, reductionists. Yet in connection widi such subjects as psychology (and sometimes biology), one hears die word "reductionist" hurled as an epidiet, even among scientists. (For example, die California Institute of Technology, where I have been a professor for almost forty years, is often derided as reductionist; in fact I may have used the term myself in deploring what I regard as certain shortcomings of our Institute.) How can that be? What is die argument really about?

 The point is that human psychology—while no doubt derivable in principle from neurophysiology, die endocrinology of neurotransmitters, and so forth—is also worth studying at its own level. Many people believe, as I do, that when staircases are constructed between psychology and biology, die best strategy is to work from die top down as well as from the bottom up. It is this proposition that does not receive universal agreement, for example at Caltech, where very little research on human psychology takes place. Where work does proceed on bodi biology and psychology and on building

Where work does proceed on both biology and psychology and on building staircases from bodi ends, die emphasis at die biological end is on the brain (as well as die rest of die nervous system, die endocrine system, etc.), while at die psychological end die emphasis is on die mind—that is, die phenomenological manifestations of what die brain and related organs are doing. Each staircase is a brain-mind bridge. At Caltech, it is mosdy die brain diat is studied. The mind is neglected, and in some circles even die word is suspect (a friend of mine calls it the M-word). Yet very important psychological research was carried out some years ago at Caltech, particularly die celebrated work of die psychobiologist Roger Sperry and his associates on die mental correlates of die left and right hemispheres of die human brain. They used patients in whom, as a result of accident or of surgery for epilepsy, die corpus callosum connecting die left and right brains had been cut It was known that speech tends to be associated widi the left brain, along widi control of die right side of die body, while control of die left side of die body is usually associated widi the right brain. They found, for example, diat a patient whose corpus callosum has been cut can show inability to express verbally information relating to die left side of the body, while giving indirect evidence of possessing diat information. As Sperry became less active widi increasing age, die research he had begun was continued at odier institutions by his former students and post-docs and by many new recruits to die field. Further evidence was found diat die left brain excels not only in verbal language but also in logic and analysis, while the right brain excels in nonverbal communication, in die affective aspects of language, and in such integrative tasks as face recognition. Some researchers have linked die right brain to intuition and to seeing die big picture. Unfortunately, popularization has exaggerated and distorted many of diose results, and much of die resulting discussion has ignored Sperry's cautionary remark that "die

two hemispheres in die normal intact brain tend regularly to function closely together as a unit " Nevertheless, what has been discovered is quite remarkable. I am particularly intrigued with die continuing investigation of the extent to which die claim is true that amateurs typically listen to music predominandy with die right brain, while professional musicians usually listen mosdy widi die left brain.

Concentration on Mechanism or Explanation—"Reductionism"

Why does so little research in psychology go on at Caltech today? Granted, die school is small and can't do everything. But why so little evolutionary biology? (I sometimes say in jest diat a creationist institution could scarcely do less.) Why so little ecology, linguistics, or archaeology? One is led to suspect that diese subjects have something in common that puts off most of our faculty. The scientific research agenda at Caltech tends to favor the study of mechanisms, underlying processes, and explanations. Naturally I am sympadietic to that approach, since it is the one diat characterizes elementary particle physics. Indeed, the emphasis on underlying mechanisms has led to many impressive successes in a variety of fields. T. H. Morgan was brought to Caltech to found die biology division in die 1920s when he was mapping the genes of die fruit fly, dius laying die groundwork for modern genetics. Max Delbriick, who arrived in the 1940s, became one of die founders of molecular biology. If a subject is considered too descriptive and phenomenological, not yet having reached die stage where mechanisms can be studied, our faculty regards it as insufficiendy "scientific." If Caltech had existed widi diose same proclivities in Darwin's time, would it have invited Aim to join die faculty? After all, he formulated his dieory of evolution without many dues to die underlying processes. His writings indicate diat if pressed to explain die mechanism of variation, he would probably have opted for something like die incorrect Lamarckian idea (Lamarckians believed that cutting the tails off mice for a few generations would produce a strain of tailless mice, or diat die long necks of giraffes are explained by generations of ancestors stretching dieir necks to reach higher into die yellow diorn acacias.) Yet his contribution to

 biology was monumental. In particular, his theory of evolution laid die groundwork for die simple unifying principle of die common descent of all existing organisms from a single ancestor. What a contrast to die complexity of die previously widespread notion of the stability of species, each specially created by supernatural means. Even if I agreed that subjects like psychology are not yet sufficiendy scientific, my preference would be to take them up in order to participate in the fun of making diem more scientific. In addition to favoring, as a general rule, die bottom-up mediod of building staircases between disciplines—from die more fundamental and explanatory toward die less fundamental—I would, in many cases (not just that of psychology), encourage a top-down approach as well. Such an approach begins widi the identification of important regularities at die less fundamental level and defers until later understanding of die underlying, more fundamental mechanisms. But die atmosphere of the Caltech campus is permeated by a strong bias in favor of the bottom-up approach, which has produced most of die spectacular achievements responsible for die reputation of the institution. That bias is what invites die charge of reductionism, with its pejorative connotation.

Subjects such as psychology, evolutionary biology, ecology, linguistics, and archaeology all bear on complex adaptive systems. They are all studied at die Santa Fe Institute, where a great deal of emphasis is bid on die similarities among diose systems and on the importance of studying their properties at dieir own levels, not just as consequences of more fundamental scientific disciplines. In that sense, die founding of the Santa Fe Institute is part of a rebellion against the excesses of reductionism. Simplici V and Complex! V from Quark to Jaguar While I believe Caltech is making a serious mistake by neglecting most of the "sciences of complexity," I have been pleased by the support given diere to elementary particle physics and cosmology, die most fundamental sciences of all, involving die search for die basic laws of die universe. One of die great challenges of contemporary science is to trace die mix of simplicity and complexity, regularity and randomness,order and

120 • THE SIMPLE AND THE COMPLEX disorder up die ladder from elementary particle physics and cosmology to the realm of complex adaptive systems. We also need to understand how die simplicity, regularity, and order of die early universe gave rise over time to die intermediate conditions between order and disorder that have prevailed in many places in later epochs, making possible, among odier things, die existence of complex adaptive systems such as living organisms. To do this, we have to examine fundamental physics from the point of view of simplicity and complexity and ask what role is played by die unified dieory of die elementary particles, die initial condition of die universe, the indeterminacies of quantum mechanics, and die vagaries of classical chaos in producing die patterns of regularity and randomness in die universe within which complex adaptive systems have been able to evolve.

^"'/ THE QUANTUM UNIVERSE

cM.hPTElf 10 SIMPLICITY AND RANDOMNESS IN THE QUANTUM UNIVERSE How do the fundamental bws of matter and die universe stand today? How much is well established and how much is conjecture? And how do diose bws look with respect to simplicity and complexity or regularity and randomness? The fundamental bws are subject to the principles of quantum mechanics, and at every stage of our thinking we will have to refer to the quantum approach. The discovery of quantum mechanics is one of the greatest achievements of die human race, but it is also one of die most difficult for die human mind to grasp, even for diose of us who have used it daily in our work for decades. It viobtes our intuition—or rather our intuition has been built up in a way that ignores quantum- mechanical behavior. That circumstance makes it all die more necessary to explore die meaning of quantum mechanics, especially by examining some recendy developed ways of thinking about it. It may dien be easier to understand why our intuition seems to pay no attention to something so important. The universe consists of matter, and matter is composed of many different kinds of elementary particles, such as electrons and photons. These particles lack individuality—every electron in die universe is \2j

 identical to every other, and all photons are likewise interchangeable. However, any particle can occupy one of an infinite number of different "quantum states." There are two broad classes of particle. Fermions, such as dectrons, obey the Pauli exclusion principle: no two partides of the same kind can occupy the same state at die same time. Bosons, such as photons, obey a kind of antiexclusion principle: two or more partides of die same kind exhibit a preference for being in the same state at the same time. (That property of photons makes possible die operation of die laser, where photons in a given state stimulate die emission of more photons in that same state. All diose photons have die same frequency and travel in die same direction, forming die laser beam. "LASER" was originally an acronym for "light amplification by stimulated emission of radiation.") Bosons, because of their proclivity for crowding together in die same quantum state, can build up their densities so diat diey behave almost like classical fields, such as diose of electromagnetism and gravitation. Particles diat are bosons can dierefore be regarded as quanta — quantized packets of energy—of those fields. The quantum of die electromagnetic field is die photon. Similarly, dieory requires die existence of die quantum of die gravitational fidd, a boson called the graviton. In fact, any fundamental force must be associated with an elementary particle diat is the quantum of the corresponding field. Sometimes the quantum is said to "carry" die corresponding force. When matter is described as being composed of elementary particles—that is, of fermions and bosons—it should be emphasized diat under certain conditions some of the bosons may behave more like a fidd than like particles (for example, in die dectric field surrounding a charge). Fermions too can be described in terms of fields; although diose fields do not ever behave classically, they are nevertheless associated, in a sense, with forces. All matter possesses energy, and all energy is associated with matter. When people refer carelessly to matter being converted into energy (or vice versa), they mean simply diat certain kinds of matter and energy are being converted they mean simply diat certain kinds of matter and energy are being converted into other kinds. For example, an electron and a related (but oppositely charged) particle called a positron can come together and turn into two photons, a process often described as "annihilation" or even "annihilation of matter to give energy." However, it is merely the transformation of matter into odier matter, of certain forms of energy into other forms.

Tke Standard Model

All die known elementary particles (except die graviton demanded by dieoretical considerations) are provisionally described today by a dieory that has come to be called die standard model. We shall look into it in some detail a little later on. It seems to be in excellent agreement widi observation, aldiough diere are a few features that have not yet been confirmed by experiment. Physicists had hoped that diose would be tested (along widi exciting newer ideas diat go beyond die standard model) at die high energy particle accelerator diat was partially completed in Texas (die "superconducting supercollider" or "SSC"). But that was scrapped by die U.S. House of Representatives in a conspicuous setback for human civilization. Now die only hope for verification of fundamental theoretical ideas lies in die lower energy accelerator facility being created (by converting an existing machine) at CERN near Geneva, Switzerland. Unfortunately, its energy may be too low. Those of us who helped put togedier the standard model are naturally radier proud of it, since it brought a good deal of simplicity out of a bewildering variety of phenomena. However, diere are a number of reasons why it cannot be die ultimate dieory of die elementary particles. First, the forces have very similar forms and cry out for unification by means of a dieory in which diey appear as different manifestations of the same underlying interaction; yet in die standard model diey are treated as different from one anodier and not unified (contrary to claims that are sometimes made). Second, die model is not yet simple enough; it contains more than sixty kinds of elementary particles and a number of interactions among diem, but no explanation for all that variety. Third, die model contains more dian a dozen arbitrary constants describing diose interactions (including die constants diat yield die various masses of die different kinds of particles); it is hard to accept as fundamental a dieory in which so many important numbers are uncalculable in principle. Finally, gravitation is not included, and any attempt to incorporate it in a straightforward manner leads to disastrous difficulties: the results of calculations of physical quantities turn out to include infinite corrections, rendering them meaningless.

So-called Grand Unified Theories

Elementary particle theorists have tried to cope with these defects in two ways. The more straightforward way involves generalizing the standard model to what some have called a "grand unified theory," although mere is little justification for that name. Let us see what such a generalization does about die four problems listed. First, die interactions in the standard model that required unification are in fact seen to be unified, along with new ones, at very high energies, widi a natural description of how, at die lower energies of today's experiments, die interactions appear to be separate. Second, all die elementary particles of the dieory are grouped into just a few sets, widi die members of each set closely related; thus a good deal of simplification is achieved, even though die number of kinds of particles is substantially increased (widi some of die new ones having masses so high that diey cannot be observed in die foreseeable future). Third, the theory contains even more arbitrary constants dian die standard model, soil uncalculable in principle. Finally, gravitation is still omitted, and it is just as difficult as before to incorporate it Such a dieory may possibly be approximately valid over a wide range of energies. The third and fourth points, however, make dear that it is not credible as die fundamental dieory of die elementary particles.

Einstein's Dream

The search for that fundamental unified dieory leads to die second way of transcending the standard model. The quest recalls Einstein's dream of a field dieory that would unify in a natural way his general-relativis- tic dieory of gravitation and Maxwell's dieory of electromagnetism. In his old age, Einstein published a set of equations that claimed to accomplish that task, but unfortunately dieir appeal was purely madiemati- cal—they did not describe plausible physical interactions of gravitation and electromagnetism. The greatest physicist of modern times had lost his powers. In 1979, at die celebration in Jerusalem of die hundreddi anniversary of Einstein's birth, I deplored die fact that a special commemorative coin had been struck with diose wrong equations on the reverse—what a shame for a scientist who had produced such beautiful,

correct, and crucially important equations when he was younger. I am likewise disturbed that so many pictures and statues of Einstein (such as the sculpture at die headquarters of die National Academy of Sciences in Washington) show him in old age when he was no longer making important contributions and not as die radier handsome, well-dressed younger man who had made all die remarkable discoveries. Einstein's attempt at a unified field theory was doomed not only by the general decline of his skills, but also by specific flaws in his approach. Among odier things, he his skills, but also by specific flaws in his approach. Among other things, he ignored diree important features of the problem: The existence of odier fields besides die gravitational and electromagnetic (Einstein knew in a general way diat there must be odier forces but did not attempt to describe diem). The need to discuss not only die fields that quantum theory reveals as being composed of bosons like die photon and gravitoh, but also fermions (Einstein believed diat die electron, for example, would somehow emerge from die equations). The need to construct a unified theory widiin die framework of quantum mechanics (Einstein never accepted quantum mechanics, aldiough he had helped to lay the groundwork for it). Still, we dieoretical physicists have been inspired by Einstein's dream, in a modern form: a unified quantum field theory embracing not only die photon, die graviton, and all the odier fundamental bosons, widi dieir associated electromagnetic, gravitational, and other fields, but also die fermions such as the electron. Such a dieory would be contained in a simple formula explaining die great multiplicity of elementary particles and dieir interactions and yielding, in die appropriate approximations, Einstein's equation for general-relativistic gravitation and Maxwell's equations for electromagnetism. Superstring Tkeory-Tke Dream Perhaps Realized Now that dream may have been realized. A new type of dieory called "superstring" dieory seems to have die right properties for accomplishing die unification. In particular, "heterotic superstring theory" is die

 first viable candidate ever for a unified quantum field dieory of all die elementary particles and dieir interactions. Superstring dieory grew out of an idea called die bootstrap principle after die old saw about die man who could pull himself up by his own bootstraps. The notion was diat a set of elementary particles could be treated as if composed in a self-consistent manner of combinations of diose same particles. All die particles would serve as constituents, all die particles (even die fermions in a certain sense) would serve as quanta for force fields binding the constituents togedier, and all die particles would appear as bound states of die constituents. When I tried, many years ago, to describe die idea to an audience at die Hughes Aircraft Company, the engineer who dien headed die synchronous satellite program, Harold Rosen, asked me whedier it was anything like what he and his team had found when diey tried to explain an intrusive signal in die circuits diey were building. They finally succeeded by assuming die signal was diere and showing that it would dien produce itself. I agreed diat the bootstrap idea was indeed something of die same sort: die particles, if assumed to exist, produce forces binding diem to one anodier; die resulting bound states are die same particles, and they are die same as die ones carrying die forces. Such a particle system, if it exists, gives rise to itself. The earliest form of superstring dieory was proposed by John Schwarz and Andre Neveu in 1971, widi support from some ideas of Pierre Ramond. Akhough die dieory seemed far-fetched at die time, I invited bodi Schwarz and Ramond to Caltech, believing that super- strings were so beautiful that diey had to be good for something. Schwarz and various collaborators, especially Joel Scherk and Michael Green, developed die dieory further over die next fifteen years or so. At first die dieory was applied to just a subset of particles, die same ones that dieorists had attempted to describe using die bootstrap principle. It was only in 1974 diat Scherk and Schwarz suggested that superstring dieory could describe all die elementary particles. What convinced diem was the discovery diat die dieory predicted die existence of die graviton, and dius of Einsteinian gravitation. Almost ten years later four physicists at Princeton, known collectively as the "Princeton string quartet," found die particular form called the heterotic superstring theory.

 Superstring dieory, in particular the heterotic form, may really be die long-sought unified quantum field dieory. In a suitable approximation, it implies, as it should, Einstein's theory of gravitation. Moreover, it incorporates Einsteinian gravitation and die other fields into a quantum field dieory widiout running into die usual difficulties widi infinities. It also explains why diere is a great multiplicity of elementary particles: die number of different kinds is actually infinite, but only a finite number (some hundreds, probably) have sufficiendy low masses to be discoverable in die laboratory. Also, die theory does not, at least on die face of it, contain any arbitrary numbers or lists of particles and interactions, aldiough some arbitrariness may reappear on closer examination. Finally, superstring theory emerges from a simple and beautiful principle of self-consistency, originally presented as the bootstrap idea. Not the Theory or Everything Of all the important questions about die heterotic superstring dieory, the one that particularly interests us here is die following: Assuming that it is correct, is it really the dieory of everything? Some people have used that expression, and even the abbreviation TOE, in describing it. However, that is a misleading characterization unless "everydiing" is taken to mean only die description of die elementary particles and their interactions. The theory cannot, by itself, tell us all that is knowable about the universe and the matter it contains. Odier kinds of information are needed as well. The Initial Condition and the Arrow(s) or Time

One of diese pieces of additional information is die initial condition of the universe at or near die beginning of its expansion. We know diat die universe has been expanding for around ten billion years. That expansion appears in dramatic form to astronomers using powerful telescopes to observe distant clusters of galaxies, but it is not at all obvious when we look closer at hand. The sohr system is not expanding, nor is our galaxy or the cluster of galaxies to which it belongs. The other galaxies and clusters are not expanding eidier. But the different clusters ate

receding from one anodier, and diat is what reveals die expansion of the universe, which has been compared to an idealized picture of the baking of raisin bread. Under die influence of die yeast, die bread (die universe) expands but die raisins (die clusters of galaxies) do not, al- diough diey move apart. The behavior of die universe since die beginning of the expansion obviously depends not only on die laws diat govern die behavior of die particles composing die universe but also on die initial condition. Nor is diat initial condition something that shows up only in abstruse problems in physics and astronomy. Far from it. It has an enormous influence on what we observe around us every day. In particular, it determines die arrow (or arrows) of time. Imagine a film of a meteorite speeding into the Earth's atmosphere, glowing widi heat as it streaks across die sky, most of its substance consumed by fire, and dien, much diminished in size and weight, crashing into the Earth. If we were to run diat film backwards, we would see a rock, partially buried in die earth, rising of its own accord into the air, growing in size and weight as it arcs dirough die atmosphere, collecting material on die way, and finally, large and cold, flying off into space. The time-reversed film is clearly an impossible sequence of events—we can identify it immediately as a film run backwards. That asymmetry of die behavior of die universe between forward and backward time is known as die arrow of time. Sometimes various aspects of die asymmetry are discussed separately and labeled as different arrows of time. However, diey are all related; diey all have die same ultimate origin. Now, what is diat origin? Could die explanation for die arrow or arrows of time be found in die fundamental laws of die elementary particles? If changing the sign of die time variable leaves die form of die equations describing diose laws unchanged, die equations are said to be symmetrical between forward and backward time. If reversing the time variable alters the form of die equations, an asymmetry between forward and backward time, or a violation of time symmetry, is said to exist. Such a violation could, in principle, account for the arrow of time. In fact a small violation of that could, in principle, account for the arrow of time. In fact a small violation of that kind is known to exist, but it is much too special an effect to give rise to such a general phenomenon as the arrow of time. Instead, die explanation is diat if we look in bodi directions of time, we find diat about ten or fifteen billion years away in one of diose

directions, die universe is in a very special state. That direction of time has an arbitrary name: die past. The other direction is called die future. In die state corresponding to the initial condition, the universe was tiny, but that tininess by no means completely characterizes the state, which was also especially simple. If, in the very distant future, die universe stops expanding and starts to recontract, eventually becoming tiny again, diere is every reason to believe that its resulting final state will be quite different from the initial one. The asymmetry between past and future will dius be maintained.

A Candidate for the Initial Condition

Since a viable candidate has emerged for the unified law of die elementary particles, it is reasonable to ask whether we also have a plausible theory for the initial condition of die universe. Actually there is one. It was suggested by James Harde and Stephen Hawking in about 1980. Hawking likes to call it die "no-boundary boundary condition." This is an apt name but it doesn't convey what is particularly interesting about die proposal with respect to "following the information." If die elementary particles are indeed described by a unified dieory (which Harde and Hawking did not explicidy assume), then die appropriately modified version of dieir initial condition can be calculated in principle from diat unified theory, and the two fundamental hws of physics, for die elementary particles and the universe, become a single law.

Instead 01 Everything, Just Probabilities tor Histories

Whedier or not die Harde-Hawking idea is correct, we can still ask die following: If we specify both the unified theory of die elementary particles and die initial condition of the universe, can we, in principle, predict die behavior of the universe and every diing in it? The answer is no, because die laws of physics are quantum-mechanical, and quantum mechanics is not deterministic. It permits theories to predict only probabilities. The fundamental laws of physics allow, in principle, only die calculation of probabilities for various alternative histories of die uni-

Decreasing exponential 7op:The decreasing exponential curve for the fraction of radioactive nuclei remaining undecayed after time I. Bottom: A rising exponential.

verse that describe different ways events could play themselves out given die initial condition.

different ways events could play themselves out given die initial condition. Information about which of those sequences of events is actually occurring can be gathered only from observation, and is supplementary to the fundamental laws themselves. Thus there is no way that die fundamental hws can supply a theory of everything. The probabilistic nature of quantum theory can be illustrated by a simple example. A radioactive atomic nucleus has what is called a "half- life," the time during which it has a 50% chance of disintegrating. For example, the half-life ofPu239,the usual isotope ofplutonium.is around 25,000 years. The chance that a Pu239 nucleus in existence today will

 still exist after 25,000 years is 50 percent; after 50,000 years, die chance is only 25 percent; after 75,000 years, 12.5 percent; and so on. The quantum-mechanical character of nature means that for a given Pu239 nucleus, diat kind of information is all we can know about when it will decay; there is no way to predict die exact moment of disintegration, only a curve of probability against time such as die one on die racing page. (That curve is what is known as a decreasing exponential; die reverse curve, a rising exponential, is also shown. Any exponential curve gives, at equal time intervals, a geometric progression, such as 1/2,1/4, 1/8,1/16..., for die decreasing case or 2,4,8,16... for die rising one.) While the moment of radioactive disintegration cannot be predicted accurately, the direction of decay is completely unpredictable. Suppose die Pu 9 nucleus is at rest and will decay into two electrically charged fragments, one much larger than die odier, traveling in opposite directions. All directions are dien equally likely for die motion of one of die fragments, say die smaller one. There is no way to tell which way die fragment will go. If so much is unknowable in advance about one atomic nucleus, imagine how much is fundamentally unpredictable about the entire universe, even given the unified dieory of die elementary particles and the initial condition of the universe. Above and beyond diose presumably simple principles, each alternative history of die universe depends on the results of an inconceivably large number of accidents. Regularities and Effective Complexity torn Frozen Accidents Those accidents have chance outcomes, as required by quantum mechanics. The outcomes have helped to determine die character of individual galaxies (such as our Milky Way), of particular stars and planets (such as the sun and the Earth), of terrestrial life and die particular species diat evolved on our phnet, of individual organisms such as ourselves, and of die events of human history and our personal lives. The genotype of any human being has been influenced by numerous quantum accidents, not only mutations in the ancestral germ plasm, but even events affecting die fertilization of a particular egg by a particular sperm.

 The algorithmic information content of each alternative history of die universe evidently receives a tiny contribution from the simple fundamental laws, along widi a gigantic contribution from all the quantum accidents mat arise along the way. But it is not only the AIC of die universe mat is dominated by those accidents. Although diey are chance events, dieir effects contribute heavily to effective complexity as well. The effective complexity of die universe is die lengdi of a concise description of its regularities. like die algorithmic information content, die effective complexity receives only a small contribution from die fundamental laws. The rest comes from die numerous regularities resulting from "frozen accidents." Those are chance events of which the particular outcomes have a multiplicity of long-term consequences, all related by dieir common ancestry. The consequences of some such accidents can be far-reaching. The character of die whole universe was affected by accidents occurring near die beginning of its expansion. The nature of life on Earth depends on chance events that took place around four billion years ago. Once die outcome is specified, die long-term consequences of such an event may take on the character of a law, at any but the most fundamental level. A law of geology, biology, or human psychology may stem from one or more amplified quantum events, each of which could have turned out differendy.The amplifications can occur through a variety of mechanisms, including die phenomenon of chaos, which introduces, in certain situations, indefinitely large sensitivities of outcome to input. To understand fully die significance of chance events, it is necessary to look deeper into die meaning of quantum mechanics, which teaches us that chance plays a fundamental role in die description of nature.

11 A CONTEMPORARY VIEW OF QUANTUM MECHANICS Quantum Mechanics ana the Classical Approximation When quantum mechanics was first discovered, people were struck most forcibly by the contrast between its probabilistic character and die certainties of die older classical physics, in which exact and complete information about an initial situation would in principle permit, given the correct dieory, exact and complete specification of die outcome. Determinism of diat kind is never perfecdy applicable in quantum mechanics, but it often does apply approximately under die frequently encountered conditions—what may be called die quasiclassical domain—where

classical physics is nearly correct. That domain may be crudely characterized as involving die behavior of heavy objects. For instance, die motion of die planets around the sun can be calculated, for any practical purpose, widiout quantum corrections, which are utterly negligible for such a problem. If the quasiclassical domain were not so relevant, physicists would never have developed and used classical physics in die first place, and classical dieories such as those of Maxwell and Einstein would not have achieved dieir wonderful successes in predict- \3s

 ing die results of observations. This is anodier case where die old paradigm (as Kuhn would call it) is not discarded when a new one is adopted, but remains a valid approximation in a suitable limit (like Newton's dieory of gravitation, which remains immmensely useful as an approximation to diat of Einstein when speeds are slow relative to die velocity of light). Still, classical physics is only an approximation, while quantum mechanics is, as far as we know, exacdy correct Al- diough many decades have elapsed since die discovery of quantum mechanics, physicists are only now approaching a really satisfactory interpretation, one diat affords a deep understanding of how die quasi- classical domain of everyday experience arises from die underlying quantum-mechanical character of nature. Tne Approximate Quantum Mechanics or Measured Systems When first formulated by its discoverers, quantum mechanics was often presented in a curiously restrictive and andiropocentric fashion, and it is frequendy so presented to this day. It is assumed, more or less, that some experiment (such as the detection of die radioactive decay of a particular kind of nucleus) is performed in identical fashion over and over again. The outcome of die experiment is observed each time, preferably by a physicist using some apparatus. It is supposed to be important that die physicist and die apparatus be external to die system being studied. The physicist records die fractions of occurrence of the different possible outcomes of die experiment (such as die times of die decays). As die number of trials gets larger widiout limit, diese fractions tend to approximate the probabilities of the various outcomes, which are predicted by die quantum-mechanical dieory. (The probability of radioactive decay as a function of time is closely related to die proportion of nuclei remaining undecayed after various time intervals. That proportion is shown in die curve on page 132. The probability of decay follows a similar curve.) This original interpretation of quantum mechanics, restricted to repeated experiments performed by external observers, is far too special to be acceptable today as die fundamental observers, is far too special to be acceptable today as die fundamental characterization, especially since it has become increasingly clear diat quantum mechanics must

 apply to die whole universe. The original interpretation is not wrong, but it is applicable only to die situations it was developed to describe. Moreover, in a wider context diat interpretation must be regarded as not only special but approximate. We can refer to it as die "approximate quantum mechanics of measured systems." Trie Modern Approach For describing die universe, a more general interpretation of quantum mechanics is clearly necessary, since no external experimenter or apparatus exists and there is no opportunity for repetition, for observing many copies of die universe. (In any case die universe presumably couldn't care less whedier human beings have evolved on some obscure planet to study its history; it goes on obeying die quantum-mechanical laws of physics irrespective of observation by physicists.) That is one reason why what I call die modern interpretation of quantum mechanics has been developed over the last few decades. The odier principal reason is die need for a clearer understanding of die relationship between quantum mechanics and die approximate classical description of die world around us. In early discussions of quantum mechanics it was often implied, and sometimes explicidy stated, diat diere was a classical domain apart from quantum mechanics, so diat basic physical dieory somehow required classical laws in addition to quantum-mechanical ones. To a generation brought up on classical physics, diat arrangement may have appeared satisfactory, but to many of us today it seems bizarre as well as unnecessary. In die modern interpretation of quantum mechanics, it is proposed diat die quasiclassical domain emerges from die quantum-mechanical laws, including die initial condition at die beginning of die expansion of die universe. Understanding how diat emergence comes about presents a major challenge. The modern approach was pioneered by die late Hugh Everett III, a graduate student of John A. Wheeler at Princeton and later a member of die Weapons Systems Evaluation Group at die Pentagon. A number of dieoretical physicists have worked on it since, including James Harde and me. Harde (of die University of California at Santa Barbara and die Santa Fe Institute) is a distinguished dieoretical cosmologist and an

 expert on Einstein's general-relativistic dieory of gravitation. In die early 1960s, when he was my doctoral student at Caltech, his dissertation was on elementary particle dieory. Later, he and

Caltech, his dissertation was on elementary particle dieory. Later, he and Stephen Hawking wrote the seminal paper entided "The Wave Function of the Universe," which played a vital role in shaping die field of quantum cosmology. Since 1986,Jim and I have been working togedier to help clarify how quantum mechanics should be conceived, particularly in relation to the quasiclassical domain. We consider Everett's work to be useful and important, but we believe diat diere is much more to be done. In some cases too, his choice of vocabulary and diat of subsequent commentators on his work have created confusion. For example, his interpretation is often described in terms of "many worlds," whereas we believe that "many alternative histories of die universe" is what is really meant. Furthermore, die many worlds are described as being "all equally real," whereas we believe it is less confusing to speak of "many histories, all treated alike by die theory except for their different probabilities." To use die language we recommend is to address die familiar notion diat a given system can have different possible histories, each widi its own probability; it is not necessary to become queasy trying to conceive of many "parallel universes," all equally real. (One distinguished physicist, well versed in quantum mechanics, inferred from certain commentaries on Everett's interpretation that anyone who accepts it should want to play Russian roulette for high stakes, because in some of die "equally real" worlds die player would survive and be rich.) Anodier linguistic problem is diat Everett avoided die word "probability" in most connections, using instead die less familiar but madie- matically equivalent notion of "measure"; Harde and I see no advantage in diat. Words aside, however, Everett left a number of important questions unanswered, and the main challenge is not a matter of language but of filling those gaps in our understanding of quantum mechanics. Jim Harde and I are part of an international group of dieorists trying in various ways to construct die modern interpretation of quantum mechanics. Among those who have made especially valuable contributions are Robert Griffiths and Roland Omnes, whose belief in the importance of histories we share, as well as Erich Joos, Dieter Zeh, and Wojciech ("Wojtek") Zurek, who have somewhat different points of view. The formulation of quantum mechanics in terms of histories was developed by Dick Feynman, who built on earlier work by Paul Dirac.

 That formulation not only helps to clarify the modern interpretation; it is also particularly useful in describing quantum mechanics whenever Einsteinian gravitation is taken into account, as it must be in quantum cosmology. The geometry of space-time is then seen to be subject to quantum-mechanical indeterminacy, and the method based on histories handles that situation particularly well. The Quantum State or tne Universe Basic to any treatment of quantum mechanics is the notion of a quantum state. Let us consider a somewhat simplified picture of me universe in which each particle has no attributes other than position and momentum and the indistinguishability of all particles of a given type (the interchangeability of all electrons, for example) is set aside. Then what is meant by a quantum state for the whole universe? It is best to start by discussing the quantum state of a single particle and then of two particles before tackling the whole universe. In classical physics it would have been legitimate to specify exactly both the position and the momentum of a given particle at the same time, but in quantum mechanics that is forbidden, as is well known, by the uncertainty, or indeterminacy, principle. The position of a particle can be specified exactly, but its momentum will men be completely undetermined; that situation characterizes a particular kind of quantum state for a single particle, a state of definite position. In another kind of quantum state the momentum is specified but the position is completely undetermined. There is also an infinite variety of other possible quantum states for a single particle, in which neither position nor momentum is exactly specified, only a sineared-out probability distribution for each. For example, in a hydrogen atom, which consists of a single (negatively charged) electron in the electric field of a single (positively charged) proton, the electron may find itself in the quantum state of lowest energy, in which its position is smeared out over a region of atomic size and its momentum is distributed as well. Now consider a "universe" of two electrons. It is technically possible for meir quantum state to be such that each electron is in a definite quantum state. However, that does not often occur in reality, because the two electrons interact, especially through the electrical repulsion between them. The helium atom, for example, consists of two electrons

 in the field of a central nucleus with a double positive charge. In the lowest energy state of the helium atom, it is not true that each of the two electrons is in a definite quantum state of its own, although that situation is sometimes discussed as an approximation. Instead, as a result of the interaction between the electrons, their joint quantum state is one in wliich the states of the two electrons are entangled (correlated) with each other. If you are interested in just one of the electrons, you can "sum over" all the positions (or momenta or values of any other attribute) of the other electron, and then the limited information available about your electron is described as follows. Your electron is not in a definite ("pure") quantum state, but instead has a set of probabilities for being in a variety of such states; it is said to be in a "mixed quantum state." We can now proceed directly to the consideration of the whole universe. Even if the universe is in a pure quantum state, this state is such that the states of the individual particles are entangled with one another. If we sum over all the situations in some parts of the universe, then the rest of the universe (what is "followed," what is not summed over) is in a mixed quantum state. The universe as a whole may actually be in a pure quantum state. Hartle and Hawking, making that assumption, have proposed a particular form for the pure state that existed near the beginning of the expansion of the universe. As remarked earlier, their hypothesis—suitably generalized to a unified theory of elementary particles—specifies that initial quantum state of the universe in terms of the theory. Moreover, the same unified theory determines how the quantum state varies with time. But a complete specification of the quantum state of the whole universe, not only initially but at all times, still does not supply an interpretation of quantum mechanics. The quantum state of the universe is like a book that contains the answers to an infinite variety of questions. Such a book is not really useful without a list of those questions to be asked of it. The modern interpretation of quantum mechanics is being constructed by means of a discussion of the appropriate questions to ask of the quantum state of the universe. Since quantum mechanics is probabilistic rather than deterministic, those questions are inevitably about probabilities. Hartle and I, like Griffiths and Omnes, make use of the fact that the questions always relate ultimately to alternative histories of the universe. (By "history" we do not mean to emphasize the past at the expense of the future; nor do we refer mainly to written records as in human history. A history is

merely a narrative of a time sequence of events—past, present, or future.) The questions about alternative histories may be of die type "What is die probability of occurrence of this particular history of die universe rather than those others?" or else "Given diese assertions about a history of the universe, what is die probability of diose additional statements being true?" Often die latter type of question takes the familiar form, "Given diese assertions about die past or die present, what is die probability of diose statements about die future coming true?"

Alternative Histories at the Race Track

One place to encounter probabilities is at die race track, where diey are related to what we may call true odds. If die true odds against a horse's winning a race are 3 to 1, dien diat horse's odds. If die true odds against a horse's winning a race are 3 to 1, dien diat horse's probability of winning is 1/4; if the true odds are 2 to 1, die probability is 1/3, and so on. (Of course the odds actually quoted at a race track are not true odds and do not correspond in this way to true probabilities. We shall return to diat point.) If there are ten horses in die race, each one has some positive probability of winning (or zero probability in a really desperate case!), and diose ten probabilities add up to 1 if diere is to be exacdy one winner among die horses. The ten alternative outcomes are dien mutually exdusive (only one can occur) and exiiaustive (one of diem must occur). An obvious property of die ten probabilities is diat diey are additive, die probability that eidier die third or die fourth horse will win, for example, is just die sum of die two individual probabilities of victory of die third and die fourth horses. A closer parallel between die race track experience and histories of die universe can be drawn by considering a sequence of races, say eight races widi ten horses in each. Suppose for die sake of simplicity that only winning matters (not "place" or "show") and that diere is just one winner of each race (no dead heats). Each list of eight winners is dien a kind of history, and those histories are mutually exclusive and exhaustive, as in die case of a single race. The number of alternative histories is die product of eight factors of ten, one for each race, or a hundred million all together. The probabilities of die different sequences of victories have die same additive property as do the probabilities of individual horses

winning a single race: die probability that one or anodier particular sequence of victories will take place is die sum of die individual probabilities for the two sequences. A situation in which either one sequence or anodier happens may be called a "combined history." Let us label two individual alternative histories A and B. The additive property dictates that die probability of die combined history "A or B" is die probability of A plus die probability of B. In other words, die probability diat I will go to Paris tomorrow or stay home is die sum of die probabilities of my going to Paris and my staying home. A quantity diat doesn't obey this rule is not a probability. Alternative Histories in Quantum Mechanics Suppose a set of alternative histories of die universe is specified, and diat diose histories are exhaustive and mutually exclusive. Does quantum mechanics always assign a probability to each one? Surprisingly, it does not always do so. Instead, it assigns to every pair of such histories a quantity called D, and it supplies a rule for calculating D in terms of die quantum state of die universe. The two histories in a given pair may be different, like the alternatives A and B, or diey may be die same, say A and A.

The value of D will be indicated by an expression such as D(A, B), pronounced D of A and B. If die two histories in die pair are both A, dien we have D(A, A). If bodi of diem are die combined history A or B, dien die value of D is designated D(A or B, A or B). When die two histories in die pair are die same, D is a number between zero and one, like a probability. In fact, it can, under certain conditions, be interpreted as die probability of die history, lb see what diose conditions are, let us examine die relationship among die following quantities: D(AorB,AorB). D(A,A). D(B,B). D(A,B)plusD(B,A). The first diree quantities are numbers between zero and one and dius resemble probabilities. The last quantity can be positive or negative or zero and is not a probability. The rule for calculating D in quantum

 mechanics is such that the first quantity is the sum of the other three. But, if the last quantity is always zero when A and B are different, men D(A or B, A or B) is just equal to D(A, A) plus D(B, B). In omer words, if D is always zero when the two histories are different, then D of a history and that same history always possesses die additive property and can dierefore be interpreted as die probability of that history. The fourth quantity in die list is called die interference term between die histories A and B. If it is not zero for every pair of different histories in die set, men mose histories cannot be assigned probabilities in quantum mechanics. They "interfere" widi each odier. Since die best mat quantum mechanics can do in any situation is to predict a probability, it can do nothing in die case of histories mat interfere with each other. Such histories are useful only for constructing combined histories mat do not interfere. Rne-Grainea Histories of the Universe Completely fine-grained histories of die universe are histories mat give as complete a description as possible of the entire universe at every moment of time. What does quantum mechanics have to say about them? Let us continue to use the simplified picture of the universe in which particles have no attributes other than their positions and momenta and the indistinguishability between particles of a given type is put aside. If classical deterministic physics were exacdy correct, the positions and momenta of all the particles in the universe could be specified exacdy at any given time. Classical dynamics could men, in principle, predict widi certainty die positions and momenta of all the particles at all future times. (The phenomenon of chaos produces situations in which the slightest imprecision in initial positions or momenta can lead to arbitrarily large uncertainties in future predictions, but in classical dieory perfect determinism would still be correct in principle, given perfect information.) What is die corresponding situation in quantum mechanics, to which classical physics is only an approximation? For one thing, it is no longer meaningful to specify bom the exact position and die exact momentum of a particle at the same time; that is part of the celebrated uncertainty principle. In quantum mechanics, therefore, die condition

of die simplified universe at a given time could be characterized by specifying just the positions of all die particles (or by die positions of some and die momenta of odiers, or by die momenta of all, or in an infinite number of other ways). One kind of completely fine-grained history of die simplified universe in quantum mechanics would consist of die posidons of all die particles at all times. Since quantum mechanics is probabilistic radier man deterministic, one might expect it to supply a probability for each fine-grained history. However, mat is not die case. The interference terms between fine-grained histories do not usually vanish, and probabilities cannot therefore be assigned to such histories. Yet at die race track, the bettor does not have to worry about any interference term between one sequence of winners and anodier. Why not? How is it mat die bettor deals with true probabilities diat add up properly, while quantum mechanics supplies, at die fine-grained level, only quantities for which die addition is encumbered by interference terms? The answer is that in order to have actual probabilities, it is necessary to consider histories that are suffiriendy coarse-grained. Coarse- Grained Histories The sequence of eight horse races serves not only as a metaphor, but also as an actual example of a very coarse-grained history of die universe. Since only die list of winners is considered, die coarse graining consists of die following: 1. Ignoring all times in die history of die universe except diose at which die races are won. 2. At the times considered, following only die horses entered in die races and ignoring all odier objects in die universe. 3. Of diose horses, following only die one that wins each race; every part of die horse is ignored except die tip of its nose. For histories of die universe in quantum mechanics, coarse graining typically means following only certain tilings at certain times and only to a certain level of detail. A coarse-grained history may be regarded as a class of alternative fine-grained histories, all of which agree on a particular account of what is followed, but vary over all possible behaviors of what is not followed, what is summed over. In die case of die

horse races, each coarse-grained history is die class of all fine-grained histories that share die each coarse-grained history is die class of all fine-grained histories that share die same sequence of eight winning horses on mat particular afternoon at that particular track, aldiough die fine-grained histories in die class vary over all possible alternatives for what happens to any odier feature of the history of die universe! All die fine-grained histories of die universe are dius grouped into classes such that each one belongs to one and only one class. Those exhaustive and mutually exclusive classes are coarse-grained histories (such as die different possible sequences of winners of eight races when mere are no ties). Suppose that a given class comprises just two finegrained historiesj and K; die coarse-grained history will men be "J or K," meaning that eidier J or K occurs. Likewise, if die class comprises many fine-grained histories, die coarse-grained history will be die combined history in which any of diose fine-grained ones occurs. Madiemadcians would call diese coarse-grained histories "equivalence classes" of fine-grained histories. Each fine-grained history belongs to one and only one equivalence class, and die members of die class are treated as equivalent. Imagine that die only things in die universe are die horses in die eight races and a certain number of horse flies, and diat all each horse can do is eidier win or not win. Each fine-grained history in this ludicrously oversimplified world consists of die sequence of winning horses and some particular story about die flies. If die coarse-grained histories follow only die horses and dieir victories and ignore die flies, dien each such history will be die set of fine-grained histories in which mere is a particular sequence of winning horses and any fate whatsoever for die flies. In general, each coarse-grained history is an equivalence class of fine-grained histories characterized by a particular narrative describing die phenomena followed and any of die possible alternative narratives describing everything that is ignored. Coarse Graining Can Wash Out Interference Terms For die quantum-mechanical histories of die universe, how can die grouping of fine-grained histories into equivalence classes yield coarsegrained histories widi true probabilities? How is it that suitably coarsegrained histories have no interference terms between diem? The answer

 is that die interference term between two coarse-grained histories is die sum of all die interference terms between pairs of fine-grained histories belonging to diose two coarse-grained ones. The sum of all diose terms, with their positive and negative signs, can produce a great deal of cancellation and give a small result of eidier sign, or zero. (Recall that D of a history and itself is always between zero and one, like a real probability; when such quantities are added, diey cannot cancel out.) Any behavior of anything in die universe diat is ignored in die coarse-grained histories can be said to have been "summed over" in this summation process. All die details diat are left out of coarse-grained histories, all die times and places and objects that are not followed, are summed over. For instance, equivalence classes could group togedier all die fine-grained histories in which certain particles have specified positions at every moment while all die odier particles in the simplified universe can be anywhere at all. We would then say diat die positions of die first set of particles are followed at every moment, while diose of die second set of particles are ignored or summed over. Further coarse graining might consist of following die positions of die first set of particles only at certain times, so that everything that happens at all odier times is summed over. Deconerence of Coarse-Grainea Histories— True Probabilities If die interference term between each pair of coarse-grained histories is zero, eidier exactly or to an exceedingly good approximation, dien all die coarse-grained histories are said to decohere. The quantity D of each coarse-grained history and itself is dien a true probability, widi die additive property. In practice, quantum mechanics is always applied to sets of decohering coarse-grained histories, and that is why it is able to predict probabilities. (D, by die way, is called die decoherence fimctional; die word "functional" indicates diat it depends on histories.) In die case of die afternoon at die races, die coarse graining employed can be summarized as follows: die fate of everything in die universe is summed over except die winners of races at a particular track, and events at all times are summed over except die moments at which victories in die eight races occur on a particular day. The result-

 ing coarse-grained histories decohere and have true probabilities. Because of our everyday experience it does not surprise us diat things work out diat way, but we should be curious about how it happens. Entanglement and Mechanisms of Deconerence What is die underlying explanation for decoherence, die mechanism diat makes interference terms sum to zero and permits die assignment of probabilities? It is the entanglement of what is followed in die coarse-grained histories widi what is ignored or summed over. The horses and jockeys in die races are in contact widi air molecules, bits of sand and horse dung on die track, photons from die sun, and horse flies, all of diem summed over in the coarse-grained histories of die races. The different possible outcomes of die races are correlated widi different rates for everything ignored in die coarse-grained histories. But those fates are summed over, and quantum mechanics tells us diat in die summation, under suitable conditions, interference terms vanish between histories involving different fates for what is ignored. Because of die entanglement, die interference terms between different results of die races also give zero. It is mind-boggling to consider, instead of diose decohering coarsegrained histories, an extreme case of fine-grained histories widi nonzero interference terms and no true probabilities. Such histories might follow, over die whole period of die races, every elementary particle contained in every horse and in everything that came into contact widi each horse. We do not have to go to extremes, however, to find histories diat are sufficiendy free of entanglement diat diey interfere widi each odier. Take die famous experiment in which a photon from a tiny source can pass freely dirough eidier of two sKts in a screen on its way to a given point on a detector—diose two histories interfere and cannot be assigned probabilities. It is dien meaningless to say what slit die photon came through. Probabilities and Quoted Odds It should be stressed once more for die sake of clarity diat die probabilities given, for sufficiendy coarse-grained histories, by quantum me-

 chanics together with a correct physical dieory are die best probabilities that can be calculated. For a sequence of races, diey correspond to what we have called true odds. The odds actually quoted at a race track, however, are quite different in character. They merely reflect bettors' opinions about forthcoming races. Moreover, die corresponding probabilities do not even add up to 1, since die track needs to make a profit. Decokerence {or an Object in Orbit lb illustrate die generality of decoherence, we can pass from die mundane to die celestial for another example: an approximate description of die orbit of an object in die solar system. The object can range in size from a large molecule to a planet; in between, it may be a dust grain, a comet, or an asteroid. Consider coarse-grained histories in which die fates of all odier things in the universe are summed over, as are all die internal properties of die object itself, leaving only its center-of-mass position at all times. In addition, suppose that position itself is treated only approximately, so that only small regions of space are considered and all die possibilities for die position inside each region are summed over. Finally, suppose die coarse-grained history sums over what happens at most times, following die approximate position of die object only at a discrete sequence of times, widi short intervals between diem. Say die object in orbit has mass M, the linear dimensions of die small regions of space are of order X, and die time intervals are of order T. The different possible coarse-grained histories of die object in die solar system will decohere to a high degree of accuracy over wide ranges of values of die quantities M X, and T The of accuracy over wide ranges of values of die quantities M,A, and T.The mechanism responsible for diat decoherence is again frequent interaction widi objects die fates of which are being summed over. In one famous example, those objects are die photons composing die background electromagnetic radiation left over from die initial expansion of die universe (die so- called big bang). Our orbiting object will repeatedly encounter such photons and scatter off diem. Each time that happens, object and photon will emerge from the collision widi altered motions. But die different directions and energies of all die photons are summed over, and that washes out the interference terms between such directions and energies, and consequendy die interference terms among different coarsegrained histories of die object in orbit.

 The histories (specifying die successive approximate positions of the center of mass of die object in die solar system at die particular instants of time) decohere because of die repeated interactions of die object widi things diat are summed over, like die photons of die background radiation. This process answers a question Enrico Fermi often put to me in die early 1950s, when we were colleagues at die University of Chicago: Since quantum mechanics is correct, why is the planet Mars not all spread out in its orbit? An old answer, diat Man is in a definite phce at each time because human beings are looking at it, was familiar to bodi of us, but seemed just as silly to him as to me. The actual explanation came long after his deadi, widi die work of such dieorists as Dieter Zeh, Erich Joos, and Wojtek Ziirek on mechanisms of decoherence, such as the one involving die photons of die background radiation. Photons from the sun diat scatter off Man are also summed over, contributing to die decoherence of different positions of the planet, and it is just such photons diat permit human beings to see Mars. So, while die human observation of Man is a red herring, die physical process that makes diat observation possible is not a red herring at all, and can be regarded as being partially responsible for die decoherence of different coarse-grained histories of die motion of die planet around die sun. Decokerent Histories R>rm a Brandling Tree Such decoherence mechanisms make possible the existence of die qua- siclassical domain diat includes ordinary experience. That domain consists of decoherent coane-grained histories, which can be envisaged as forming a tree-like structure. Jorge Luis Borges, in one of his brilliant short stories, described a representation of such a structure as a "garden of forking padis." At each branching, diere are mutually exclusive alternatives. A pair of such alternatives has often been likened to a fork in a road, as in Robert Frost's poem "The Road Not Taken." The structure first road, as in Robert Frost's poem "The Road Not Taken." The structure first branches into alternative possibilities right at, or just after, die beginning of die expansion of die universe. Each branch dien splits again a short time later into further alternatives, and so on for all time. At each branching, there are well-defined probabilities for die alternatives. There is no quantum interference between diem.

 This is well illustrated by what happens at the race track. Each race involves a branching into ten alternatives for die different winners, and for each winner mere is a further branching into ten alternatives for the winner of die next race. At die track, there is not usually a great deal of influence exerted by die outcome of one race on the probabilities for die next one (for example, a jockey's becoming depressed over having lost a previous race). However, in die branching tree of alternative histories of die universe, die outcome at one branching may profoundly afreet die probabilities at subsequent branchings, and may even affect the nature of die alternatives in subsequent branchings. For example, die condensation of material to form die planet Mars may have depended on a quantum accident billions of years ago; in those branches where no such planet appeared, it follows that further branchings explicidy related to alternative fates of Mars would not occur. The tree-like structure of alternative decohering coarse-grained histories of die universe is different from evolutionary trees like those for human languages or for biological species. In die case of evolutionary trees, all die branches are present in die same historical record. For example, die Romance languages all branch off from a hte version of Latin, but they are not alternatives. French, Spanish, Portuguese, Italian, Catalan, and odiers are spoken today, and even die now extinct Romance languages, such as Dalmatian, were actually spoken at one time. By contrast, die branches of die tree of alternative decohering histories are mutually exclusive, and only one branch is accessible to an observer. Even die interpreters of Hugh Everett's work who speak of many worlds, equally real, do not claim to have observed more than one of diose branching worlds. High Inertia ana Nearly Classical Behavior Decoherence alone (giving rise to branching of histories into distinct alternatives widi well-defined probabilities) is not die only important property of die quasiclassical domain that includes everyday experience. The domain also exhibits largely classical behavior—hence "quasiclassical." Not only do die successive positions of die planet Mars at a sequence of closely spaced times have true probabilities. Those positions at diose times are also very highly correlated widi one another (probabilities extremely close to one) and they correspond, in an excellent approximation, to a well-defined classical orbit around die sun. That orbit obeys Newton's classical equations for motion in die gravitational field of the sun and die odier planets, widi tiny corrections for Einstein's improved (general-relativistic) classical theory and a very small frictional force from collisions with light objects like the background photons. Recall that diose objects are ignored and thus summed over in. die coarse-grained histories that follow die motion of Mars, which is die reason why the coarse-grained histories decohere. How can die planet follow a deterministic classical orbit when it is continually being buffeted by random blows from die photons it encounters? The answer is diat die heavier an object in an orbit, the less it will exhibit erratic behavior and die more it will peacefully follow its orbit. It is die mass M of the planet, its inertia, that resists die buffeting and permits it to behave classically to a very good approximation. An atom or small molecule is too light to follow an orbit widi any degree of consistency in the presence of all die objects in die solar system widi which it could collide. A large dust grain is heavy enough to follow an orbit fairly well, and a small spacecraft does so still better. But even such a spacecraft is knocked around a litde by die solar wind, composed of elections emitted by die sun. Collisions of die craft widi diose electrons would be sufficient to disturb certain very delicate experiments used to test Einsteinian gravitation; for this reason, it would be desirable for those experiments to make use of a radar transponder on Mars instead of on a space probe. Aldiough we have ascribed quasiclassical behavior to die heaviness of objects, it would be more accurate to ascribe it to motions associated widi sufficiendy high inertia. A batch of very cold liquid helium can be both large and heavy and nevertheless, because some of its internal motions have low inertia, exhibit bizarre quantum effects such as creeping over die edge of an open container. Fluctuations Physicists sometimes try to distinguish between quantum and classical fluctuations, where die latter could be, for example, diermal fluctuations associated widi die motions of molecules in a hot gas. The coarse

 graining required to achieve decoherence in quantum mechanics implies that many variables must be summed over, and diose variables may easily include some of the ones that describe such molecular motions. Thus classical diermal fluctuations tend to get lumped together widi quantum fluctuations. A heavy object that follows a classical orbit fairly well is resisting the effects of both kinds of fluctuations at once. Likewise a lighter object may be significandy affected by both. Erratic motion caused by repeated collisions widi tiny things was noticed in the early nineteenth century by die botanist Robert Brown, after whom die phenomenon is named Brownian motion. It can easily be observed by putting a drop of ink into water and watching die ink granules under a microscope. Their jerky movements were explained quantitatively by Einstein as being caused by fluctuations in collisions widi water molecules, thus making molecules effectively susceptible to observation for the first time. Scnroainger's Cat In a quasiclassical domain, objects approximately obey classical laws. They are subject to fluctuations, but those are individual events superimposed on a pattern of fairly classical behavior. Once it occurs, however, a fluctuation in die history of an odierwise classical object can be amplified to an arbitrary degree. A microscope can enlarge the image of an ink particle struck by a molecule and a photograph can preserve die magnified image indefinitely. This brings to mind die famous diought experiment involving Schrodinger's cat, in which a quantum event is amplified so as to control whedier or not a cat is poisoned. Such amplification is perfecdy possible, if not very nice. A device can be hooked up that makes the life or deadi of die cat depend, for example, on die direction of motion of a nuclear fragment emitted in a radioactive decay. (Using thermonuclear weapons, one could nowadays arrange for die fate of a city to be determined in die same way.) The usual discussion of Schrodinger's cat goes on to describe alleged quantum interference between die live and dead cat scenarios. However, die live cat has considerable interaction widi die rest of die world, dirough breathing, for example, and even the dead cat interacts widi die air to some extent. It doesn't help to have die cat placed in a

 box, because die box will interact widi die outside world as well as widi die cat. Thus there is plenty of opportunity for decoherence between coarse-grained histories in which die cat lives and coarse-grained histories in which it dies. The live and dead cat scenarios decohere; diere is no interference between diem. Perhaps it is the interference aspect of the cat story that makes Stephen Hawking exclaim, "When I hear about Schrodinger's cat, I reach for my gun." He is, in any case, parodying the remark (often attributed to one or another Nazi leader, but actually occurring in the eariy pro-Nazi play Schlageter by Harms Johst) "When I hear die word 'Kultur,' I release die safety catch on my Browning." Suppose die quantum event that determines die fate of die cat has already occurred, but we don't know what happened until we open a box containing die cat. Since die two don't know what happened until we open a box containing die cat. Since die two outcomes decohere, this situation is no different from a classical one where we open a box inside of which die poor animal, arriving after a long airplane voyage, may be eidier dead or alive, widi some probability for each. Yet reams of paper have been wasted on the supposedly weird quantum-mechanical state of die cat, bodi dead and alive at the same time. No real quasiclassical object can exhibit such behavior because interaction widi the rest of die universe will lead to decoherence of die alternatives. Additional Coarse Graining (or Inertia and Quasiclassicality A quasiclassical domain naturally requires histories that are sufficiendy coarse-grained to decohere to an excellent approximation; it also requires that diey be even further coarse-grained so diat what is followed in the histories has enough inertia to resist, to a considerable extent, die fluctuations inevitably associated widi what is summed over. There dien remain continual small excursions from classical behavior and occasional large ones. The reason additional coarse graining is required for high inertia is that sizable chunks of matter can dien be followed, and diose chunks can have large masses. (If some stable or nearly stable elementary particles with huge masses were available, diey would provide a different source of high inertia. Such particles have not been encountered in our experience, although diey might exist and, if so, could have played

 an important role in the earliest moments of die expansion of die universe.) Measurement Situations and Measurements A quantum event may become fully correlated widi somediing in die quasidassical domain. That is what happens in die sensible part of die cat story, where such an event becomes correlated widi die fate of die animal. A simpler and less fanciful example would be a radioactive nucleus diat occurs as an impurity in a mica crystal and decays, say, into just two electrically charged fragments moving in opposite directions. The direction of motion of one fragment is completely undetermined until die decay occurs, but dien it correlates perfecdy widi a track left in die mica. Quasidassical histories, which sum over dungs like die soft radiation emitted when die track was formed, leave the different directions, widi some small spread in each one, decoherent. Such a track, at ordinary temperatures, lasts for tens of diousands of years or more, and of course mere persistence is an example (albeit a trivial one) of a classical history. The radioactive decay has made contact with die quasi- classical domain. The accumulation in minerals of tracks left by die disintegration products of spontaneous nuclear fission is sometimes used to date diose minerals; die mediod is known as fission-track dating, and it can be applied to rocks that are hundreds of diousands of years old. Suppose a physicist engaged in such research looks at a particular track. While pursuing die work on dating, he or she can also be said to have made a measurement of die direction of decay of die radioactive nucleus. The track, however, has been diere ever since it was formed; it does not come into existence when die physicist looks at it (as some clumsy descriptions of quantum mechanics might suggest). A measurement situation has existed since die nucleus decayed and die track was formed; diat is when a strong correlation was established widi die quasidassical domain. The actual measurement could have been carried out by a cockroach or any odier complex adaptive system. It consists of "noticing" diat a particular alternative has occurred out of a set of decoherent alternatives widi various probabilities. Exactly the same tiling occurs at the racetrack when a particular horse is "observed" to win one of die races. A record of die victory, already present somewhere

 in die quasiclassical domain, is further registered in die memory of die observer, whedier that observer is of high or low intelligence. However, many sensible, even brilliant commentators have written about die alleged importance of human consciousness in die measurement process. Is it really so important? What do noticing and observing really mean? An IGUS—A Complex Adaptive System as Observer An observation in this context means a kind of pruning of the tree of branching histories. At a particular branching, only one of the branches is preserved (more precisely, on each branch, only that branch is preserved!). The branches that are pruned are thrown away, along widi all die parts of die tree diat grow out of die branches that are pruned. In a sense, die mica widi die fission tracks has already performed a pruning operation by registering die actual direction of motion of die fission fragment and dius discarding all odier directions. But a complex adaptive system observing die track prunes in a more explicit way, by including me observation in die data stream that gives rise to die evolution of its schemata. The subsequent behavior of die system can then reflect its observation of die particular track direction. A complex adaptive system acting as an observer probably deserves a special name. Jim Hartle and I call it an IGUS, for information gathering and utilizing system. If die IGUS possesses consciousness or self-awareness to a significant degree (so that it notices itself noticing die direction of a fission track), so much die better. But why is that necessary? Does a measurement made by an arbitrary human being, even one of very low intelligence, really have any greater significance than one made by a gorilla or a chimpanzee? And if not, dien why not substitute a chinchilla or a cockroach for die ape? When it comes to pruning die branching tree of histories, perhaps a distinction should be made between a human observer who knows something about quantum mechanics (and is dierefore aware of die origins of the tree) and one who does not. In a sense, die difference between diem is greater dian that between a human ignorant of quan-. turn mechanics and a chinchilla.

 An IGUS can do something else besides eliminating alternative branches when a particular outcome is known: it can bet on that outcome beforehand, using some approximate version of the probabilities supplied by quantum mechanics. Only a complex adaptive system can do that. Unlike a piece of mica, an IGUS can incorporate its estimated probabilities of future events into a schema and base its future behavior on that schema. A desert-dwelling mammal, for instance, may walk a long way to a deep water hole some days after the last rain, but not to a shallow one, since the probability is greater that mere will still be water remaining in die deep hole. The pruning of branches replaces what, in die traditional interpretation of quantum mechanics, is usually called die "collapse of die wave function." The two descriptions are not unrelated madiematically; but the collapse is often presented as if it were a mysterious phenomenon peculiar to quantum mechanics. Since pruning, however, is just the recognition that one or anodier of a set of decohering alternatives has occurred, it is quite familiar. It is exemplified by noticing, for example, that I have not gone to Paris after all but stayed home. All die branches of history that depended on my going to Paris have been discarded; dieir probabilities are now zero no matter what diey were before. The point often left unclear in discussions of die so-called collapse is diat even if die pruning involves die measurement of a quantum event, it is still an ordinary discrimination among decohering alternatives. Quantum events can be detected only at me level of die quasi- classical domain. There die situation is just one of classical probabilities, as in dirows of dice or tosses of a coin, widi die probabilities changing to one and zero when die outcome is known. The quasiclassical domain admits die possibility of reasonably persistent records of die outcome, records that can be amplified or copied over and over in a quasiclassical chain of near-certain agreement of each record widi die previous one. Once a quantum event is correlated widi die quasiclassical domain (creating a measurement situation), die particular outcome in a given branch of history becomes a fact. Selt-awaxeness and ReeWill Since die issue of consciousness has been raised, let us digress briefly and explore it a bit further. The human brain has gready enlarged

frontal lobes compared widi diose of our close relatives die great apes. Neurobiologists have identified areas of die frontal lobes diat seem to be associated with self-awareness and intention, diought to be especially well-developed in human beings. In conjunction widi die many parallel processing strands in human thought, consciousness or attention seems to refer to a sequential process, a kind of spodight diat can be turned from one idea or sensory input to anodier in rapid succession. When we believe we are attending to many different things at once, we may really be employing die spodight in a time-sharing mode, moving it around among die various objects of our attention. The parallel processing strands differ in dieir accessibility to consciousness, and some sources of human behavior lie buried in layers of thought diat are difficult to bring to conscious awareness. Nevertheless, we do say diat utterances and odier actions are to a considerable degree under conscious control, and diat statement reflects not only die recognition of die spodight of awareness but also die strong belief that we have a degree of free will, diat we can choose among alternatives. The possibility of choice is an important feature, for example, of "The Road Not Taken." What objective phenomena give rise to diat subjective impression office will? To say a decision is taken freely means diat it is not stricdy determined by what has gone before. What is die source of diat apparent indeterminacy? A tempting explanation is that it is connected with fundamental indeterminacies, presumably diose of quantum mechanics enhanced by classical phenomena such as chaos. A human decision would dien have unpredictable features, which could be labeled retrospectively as freely chosen. One might wonder, however, what feature of die human brain cortex makes die contribution of quantum fluctuations and chaos particularly prominent diere. Instead of invoking only diose straightforwardly physical effects, we might also consider processes more directly associated widi die brain and die mind. Recall that, for a given coarse graining, all die phenomena diat are summed over (not followed) can contribute apparent indeterminacies (for instance diermal fluctuations) diat are lumped in widi quantum fluctuations. Since diere are always many strands of diought not illuminated by die searchlight of consciousness, diose strands are being summed over in the extremely coarse-grained histories that are consciously remembered. The resulting indeterminacies would seem more likely to contribute to die subjective impression of free will than die indeterminacies narrowly associated widi physics. In odier words, human beings probably act on hidden motives more often than diey use die results of an internal random or pseudorandom number generator. But die whole matter is pooriy understood, and for die time being we can only speculate. (Speculation about such questions is far from new, and is usually radier vague. Nonedieless, I see no reason why die subject should not be pursued in terms of scientific inquiry into the possible role of various indeterminacies in die functioning of die human brain cortex and the corresponding mental processes.) What Characterizes the Familiar Quasiclassical Domain? In die coarse-grained histories of die quasiclassical domain that incorporates familiar experience, certain kinds of variables are followed while die rest are summed over, which means that diey are ignored. Which kinds are followed? Roughly speaking, die usual quasiclassical domain follows gravitational and electromagnetic fields and exacdy conserved quantities such as energy or momentum or electric charge, as well as quantities diat are approximately conserved, like die number of dislocations (irregularities) in a crystal produced by die passage of a charged particle. A quantity is said to be conserved when die total amount existing in a closed system remains unchanged dirough time; it is approximately conserved when die total amount in a closed system varies only a little as time passes. A conserved quantity like energy cannot be created or destroyed, only transformed. The dislocations in a crystal, however, obviously can be created, by the passage of a charged particle, for example; still, they can last for tens or hundreds of diou- sands of years, and in diat sense diey are nearly conserved. The familiar quasiclassical domain involves summing over everything except ranges of values of diese fields and conserved and nearly conserved quantities within small volumes of space, but volumes large enough to have die inertia necessary to resist the fluctuations associated widi die effects of all die variables diat are summed over. That is to say, die fluctuations are resisted sufficiendy so diat die quantities followed exhibit quasiclassical behavior.

 Those quantities must be followed at rime intervals that are not too close together, so die alternative coarse-grained histories can decohere. In general, if die graining becomes too fine (because die time intervals are too short, the volumes too small, or die ranges of values of die quantities followed too narrow), die danger small, or die ranges of values of die quantities followed too narrow), die danger of interference between histories rears its head. Let us consider a set of alternative coarse-grained histories that are maximally refined, so that any fiirther fine graining would ruin either the decoherence or die nearly classical character of the histories or bodi. The small volumes in which the conserved and nearly conserved quantities are followed at suitable intervals of time can then cover the whole universe, but widi a coarse graining in space and dme (and in ranges of values of die quantities) mat is just adequate to yield deco- herent and nearly classical alternative histories. The experience of human beings and of die systems widi which we are in contact is of a domain that is very much more coarse-grained than such a maximal quasiclassical domain. A huge amount of additional coarse graining is required to go from that maximal quasiclassical domain to the domain accessible to actual observation. The accessible domain follows only very limited regions of space-time, and the coverage of die variables in diose regions is very spotty. (The interiors of stars and of other planets are almost entirely inaccessible, for instance, and what happens on dieir surfaces can be detected only in a very coarsegrained manner.) In contrast, die coarse-grained histories of the maximal quasi- classical domain need not sum over, and so ignore, all die variables inaccessible to human observation. Instead, diose histories can include descriptions of alternative outcomes of processes arbitrarily remote in space and time. They can even cover events near die beginning of die expansion of die universe, when there were presumably no complex adaptive systems anywhere to act as observers. In summary, a maximal quasiclassical domain is an exhaustive set of mutually exclusive coarse-grained histories of die universe that cover all of space-time, that are decoherent with one anodier and nearly classical most of the time, and diat are maximally refined consistent widi die odier conditions. In this particular kind of maximal quasiclassical domain we are discussing, die quantities followed are ranges of values of conserved and nearly conserved quantities over small volumes. The actual domain of familiar human experience is obtained from such a

 maximal domain by the application of an extreme amount of additional coarse graining, corresponding to the capabilities of our senses and instruments.

The Branch Dependence 01 Followed Quantities

It is important to reemphasize that die specific quantities followed at a given time may depend on die outcome of a previous branching of histories. For instance, the distribution of mass in the Earth, as represented by the amount of energy contained in each of a huge number of small volumes within die planet, will presumably be followed by coarse-grained histories as long as die Earth exists. But what if the Earth is one day blown to smithereens by some presendy unforeseen catastrophe? What if diat catastrophe vaporizes die planet, as in some B movie? Presumably, for die histories in which diat happens, die quantities subsequendy followed by die coarse-grained histories will be different from what diey were before die catastrophe. In other words, what is followed in die case of a given coarse graining of histories may be branch-dependent. Individual Objects We have discussed die quasidassical domain diat includes familiar experience in terms of ranges of values of fields and of exacdy or approximately conserved quantities in small volumes of space. But how do individual objects like a planet come into die story? Early in die history of die universe, masses of material began to condense under die influence of gravitational attraction. The narratives of die various alternative coarse-grained histories after that time are much more concise when described in terms of the objects dius formed. It is much simpler to record die motion of a galaxy dian to list separately all die coordinated changes in the densities of matter in a trillion trillion small volumes of space as die galaxy moves. As galaxies gave rise to stars, planets, rocks and in some places to complex adaptive systems like die living things on Earth, die existence of individual objects became a more and more striking feature of die quasidassical domain. Many of die regularities of die universe are most

concisely described in terms of such objects; dius die properties of individual things represent a great deal of die effective complexity of die universe. In most cases die description of individual objects is simplest when die definition allows for die accretion or loss of comparatively small amounts of matter. When a planet absorbs a meteorite or a cat breadies, die identity of die planet or die cat is not altered. But how is individuality to be measured? One way is to look at a set of comparable objects and, for a given coarse graining, to describe as briefly as possible die properties that distinguish diem (such as die lost feathers of die eleven California condors I saw feasting on a calf). The number of bits in die description of a typical individual can dien be compared widi die number of bits necessary to count die individuals in die set. If, for die particular coarse graining involved, the description contains many more bits than die enumeration, die objects in die set are exhibiting individuality. Consider die set of all human beings, now numbering about five and a half billion. Assigning a different number to each person takes around 32 bits, because 2 multiplied by itself 32 times is 4,294,967,296. But even a cursory look at each person dose up, accompanied by a brief interview, can easily reveal many more than 32 bits of information. When studied more closdy, die people will exhibit far more individuality. And imagine how much additional information will be available when dieir individual genomes can be read. The stars in our galaxy, not counting possible dark kinds diat astronomers may some day discover, number some 100 billion. Assigning each one a serial number would take about 37 bits. For die sun, which is dose by, much more information than diat is available to astronomers, but die graining for odier stars is much coarser. Position in die sky, die brightness, die spectrum of light emitted, and motion can all be measured to some extent, more or less accurately depending on distance. The total number of bits of information is not typically very much greater than 37, and in some cases it may be less. As viewed today by astronomers, stars other than die sun do exhibit some individuality, but not a great deal. The particular coarse graining characteristic of today's observations can be avoided by switching to a maximal quasidassical domain, which consists of alternative histories, covering all of space-time, that are not

 only decoherent and neady classical, but also in some sense maximally fine-grained given dieir decoherence and quasiclassicality. Where appropriate, those histories may be expressed in terms of individual objects, which are followed in extraordinary detail and exhibit a correspondingly high degree of individuality. In die usual maximal quasiclassical domain, die information about any star is enormously greater than what we now know about die sun. Likewise, the information about any human being is much richer than what is available to us today. In fact, no complex adaptive system observing a star or a human being could possibly make use of such a gigantic quantity of information. Moreover, much of die data would refer to random or pseudorandom fluctuations of matter densities in a stellar interior or inside some bone or muscle. It is hard to imagine what use a complex adaptive system could make of die bulk of such information. Yet regularities in die data could be very useful; in fact, physicians make use of just such regularities when diey employ magnetic resonance imaging (MRI) or X-ray computer-assisted tomography (CAT scans) to diagnose illness. As usual, a descriptive schema formulated by an observing complex adaptive system is a concise listing of regularities, and die lengdi of such a list is a measure of die effective complexity of die thing observed. Tne Protean Character of Quantum Mechanics Like classical probabilistic situations such as a series of horse races, the coarse-grained alternative histories of die universe diat constitute the maximal quasiclassical domain form a branching tree-like structure, widi well-defined probabilities for die different possibilities at each branching. How dien does quantum mechanics differ from classical mechanics? One obvious difference is that in quantum mechanics the coarse graining is necessary for die dieory to yield anything useful, whereas coarse graining is introduced in classical mechanics only because of die imprecision of measurements or some odier practical limitation. But anodier difference may account, more than anything else, for die counter-intuitive nature of quantum mechanics—it is protean. Recall diat Proteus, in classical mythology, was a reluctant prophet who could transform himself into one type of creature after anodier. To get

 him to make predictions, it was necessary to hold him fast as he went though a great many changes of form. Say we return to our simplified fine-grained histories of die universe, which specified the position of every particle in the universe at every instant. In quantum mechanics position is an arbitrary choice. While the Heisenberg uncertainty principle makes it impossible to specify both die position and the momentum of a given particle at die same time with arbitrary accuracy, it does not prevent momentum instead of position from being specified at some of diose instants. Consequendy, fine-grained histories can be chosen in a great many different ways, widi each particle being characterized at certain times by its momentum and at die remaining times by its position. Moreover, there is an infinite variety of odier, subder ways of constructing finegrained histories of die universe. Are There Many Inequivalent Quasiclassical Domains? For each of diose sets of fine-grained histories it is possible to consider many different coarse grainings and to ask which ones, if any, lead to a maximal quasiclassical domain characterized by decoherent coarsegrained histories that exhibit nearly classical behavior, widi continual small excursions and occasional large ones. Furthermore, one can ask whedier there are really significant distinctions among die domains or whether they are all more or less the same. Jim Harde and I, among odiers, are trying to answer diat question. Unless the contrary is demonstrated, it will remain conceivable that there is a large set of inequivalent maximal quasiclassical domains, of which die familiar one is just a single example. If diat is true, what distinguishes the familiar quasiclassical domain from all die odiers? Those who espouse die early view of quantum mechanics might say that human beings have chosen to measure certain quantities and that our choice helps to determine die quasiclassical domain widi which we deal. Or, a little more generally, diey might say diat human beings are capable of measuring only certain kinds of quantities and that die quasiclassical domain must be based, at least in part, on such quantities.

Home for Complex Adaptive Systems

It is true that quasiclassicality guarantees to all human beings and to all systems in contact with us die possibility of comparing records, so that we are all dealing with die same domain. But do we collectively select that domain? Such a point of view may be needlessly anthropocentric, like odier aspects of die old-fashioned interpretation of quantum mechanics. Anodier, less subjective approach is to start widi a maximal quasi- classical domain and note mat along certain branches, during certain epochs of time, and in certain regions of space, it can exhibit just die kind of mixture of regularity and randomness mat favors die evolution of complex adaptive systems. The nearly classical behavior supplies die regularity, while die excursions from determinism—the fluctuations—supply the element of chance. Mechanisms of amplification, including ones mat involve chaos, permit some of diose chance fluctuations to come into correlation widi the quasiclassical domain and give rise to branchings. Hence, when complex adaptive systems evolve, they do so in connection widi a particular maximal quasiclassical domain, which need not be regarded as having somehow been chosen by diose systems according to their capabilities. Instead, die location and capabilities of die systems determine die degree of additional coarse graining (in our case, very coarse indeed) mat is applied to die particular maximal quasiclassical domain in order to arrive at die domain perceived by the systems. Suppose mat the quantum mechanics of the universe allows mathematically for various possible maximal quasiclassical domains mat are genuinely ^equivalent. Suppose, too, that complex adaptive systems actually evolved to exploit some coarse graining of each of those maximal quasiclassical domains. Each domain then provides a set of alternative coarse-grained histories of die universe, and information gathering and utilizing systems (IGUSes) record in each case the outcomes of various probabilistic branchings in the tree of possible histories, a tree that would be quite different in the two cases! If there is some degree of agreement in the phenomena followed by die two odierwise distinct quasiclassical domains, the two IGUSes might become aware of each other and even communicate to some

extent. But a great deal of what is followed by one IGUS could not be apprehended directly by the other. Only through a quantum-mechanical calculation or measurement might one IGUS achieve any appreciation of the full range of phenomena perceived by the other (this may remind some people of the relation between men and women). Could an observer utilizing one domain really become aware that other domains, with their own sets of branching histories and their own observers, were available as alternative descriptions of the possible histories of the universe? This fascinating issue has been raised by science fiction writers (who sometimes use the expression "goblin worlds," according to the Russian meorist Starobinsky), but it is only now receiving enough attention from theorists of quantum mechanics to be properly studied. Those of us working to construct the modern interpretation of quantum mechanics aim to bring to an end the era in wliich Niels Bohr's remark applies: "If someone says that he can think about quantum physics wimout becoming dizzy, that shows only mat he has not understood anything whatever about it."

12 QUANTUM MECHANICS AND FLAPDOODLE While many questions about quantum mechanics are still not fully resolved, there is no point in introducing needless mystification where in fact no problem exists. Yet a great deal of recent writing about quantum mechanics has done just that Because quantum mechanics predicts only probabilities, it has gained a reputation in some circles of permitting just about anything. Is it true that in quantum mechanics anything goes? That depends on whether events of very, very low probability are included. I remember as an undergraduate being assigned die problem of calculating die probability diat some heavy macroscopic object would, during a certain time interval, jump a foot into die air as a result of a quantum fluctuation. The answer was around one divided by die number written as one followed by sixty-two zeroes. The point of die problem was to teach us that there is no practical difference between that kind of probability and zero. Anything diat improbable is effectively impossible. When we look at what can really happen widi significant probability, we find diat many phenomena diat were impossible in classical physics are still effectively impossible in quantum mechanics. However, public understanding of this has been hampered in recent years by a rash of misleading references in books and articles to some elegant

 theoretical work done by die late John Bell and to the results of a related experiment. Some accounts of die experiment, which involves two photons moving in opposite directions, have given readers die false impression that measuring die properties of one photon instantaneously affects die odier. Then die conclusion has been drawn that quantum mechanics permits faster-than-light communication, and even that claimed "paranormal" phenomena like precognition are diereby made respectable! How can this have happened? Einstein's Objections to Quantum Mechanics The story begins, in a way, with die attitude of Albert Einstein toward quantum mechanics. Akhough he had helped to prepare die way for it early in die twentiedi century widi his brilliant work on photons, in which he took seriously die original quantum hypodiesis of Max Planck, Einstein never liked quantum mechanics itself. At die Solvay Conference in Brussels in 1930, Einstein gave what purported to be a demonstration that quantum mechanics was inconsistent. Niels Bohr and his allies worked frantically for die next few days to find die flaw in die great man's argument. Sure enough, before die conference ended, diey were able to show diat Einstein had omitted something; remarkably, it was die effect of general relativity that he had forgotten. Once diat was included, die alleged inconsistency disappeared. After diat, Einstein gave up trying to show that quantum mechanics was internally inconsistent. Instead, he concentrated on identifying die principle it violated that he believed a correct dieoretical framework should obey. In 1935, togedier widi two young associates, Podolsky and Rosen, he published a paper describing that principle and a hypodieti- cal experimental situation in which quantum mechanics would fail to conform to it. The principle, which he called "completeness," challenged die essential nature of quantum mechanics. What Einstein required was roughly die following. If, by means of a certain measurement, die value of a particular quantity Q could be predicted widi certainty, and if, by an alternative, quite different measurement, die value of anodier quantity R. could be predicted widi certainty, men, according to die notion of completeness, one should be able to assign exact values simultaneously to bodi of die quantities Q

 and R. Einstein and his colleagues succeeded in choosing the quantities to be ones that cannot simultaneously be assigned exact values in quantum mechanics, namely the position and momentum of the same object. Thus a direct contradiction was set up between quantum mechanics and completeness. What is the actual relationship in quantum mechanics between a measurement that permits the assignment of an exact value to a particle's position at a given time and another measurement that permits its momentum at the same time to be exactly specified? Those measurements take place on two different branches, decoherent specified? Those measurements take place on two different branches, decoherent with each other (like a branch of history in which one horse wins a given race and another branch in which a different horse wins). Einstein's requirement amounts to saying that the results from the two alternative branches must be accepted together. That clearly demands the abandonment of quantum mechanics. Hidden Variables In tact, Einstein did want to replace quantum mechanics with a different kind of theoretical framework. In remarks made elsewhere, he indicated his belief that the successes of quantum mechanics stemmed from theoretical results that were only approximately correct and that represented a kind of statistical average over the predictions of another sort of theory. Einstein's idea assumed a more definite form when various theorists, at different times, suggested that quantum mechanics might be replaced by a deterministic, classical framework—but one in which there is a very large number of "hidden variables." Those variables may be imagined as describing invisible flies buzzing about everywhere in the universe, more or less at random, interacting with the elementary particles and affecting their behavior. As long as the flies are undetectable, the best the theorist can do in making predictions is to take statistical averages over their motions. But the unseen flies will cause unpredictable fluctuations, creating mdeterminacies.The hope was that the indeterminacies would somehow match those of quantum mechanics, so that die predictions of die scheme would agree widi

quantum-mechanical predictions in die many cases where observation confirms die latter. Bokm and Einstein I knew one theorist who vacillated, at least for a time, between believing in quantum mechanics and thinking that it might have to be replaced by somediing like a "hidden variable" approach.That was David Bohm, who was preoccupied during his whole career with understanding die meaning of quantum mechanics. In 1951, when I was a fresh Ph.D. and a post-doc at the Institute for Advanced Study in Princeton, David was an assistant professor at Princeton University. We were bodi bachelors and sometimes spent the evening walking around Princeton togedier discussing physics. David told me that as a Marxist he had had difficulty believing in quantum mechanics. (Marxists tend to prefer dieir dieories to be fully deterministic.) Since quantum mechanics was immensely successful and not contradicted by any observation, he had tried to convince himself diat it was, after all, philosophically acceptable. In attempting to reconcile quantum mechanics with his Marxist convictions, he had written an elementary textbook on quantum theory, emphasizing the problem of interpretation. That book was about to appear, and David was anxious to show Einstein the relevant chapters and see if he could overcome the great man's objections. David asked me to arrange an appointment. I replied that I was not die best person to do so, since I hardly knew Einstein, but diat I would talk with Miss Dukas, Einstein's formidable secretary, and see what could be done. When I met David a day or two later and started to tell him diat I was working oh his appointment, he interrupted me excitedly to report that it was unnecessary. His book had appeared and Einstein had already read it and telephoned him to say that David's was die best presentation he had ever seen of die case against him and diat they should meet to discuss it. Naturally, when next I saw David I was dying to know how dieir conversation had gone, and I asked him about it. He looked rather sheepish and said, "He talked me out of it. I'm back where I was before I wrote the book." From then on, for more than forty years, David tried to reformulate and reinterpret quantum mechanics so as to overcome his doubts. Very recently, I learned widi great sadness that he had died.

The EPRB Experiment

Many years ago David Bohm proposed replacing die hypothetical "completeness" experiment of Einstein, Podokky, and Rosen (which need not be described here) by a modified and more practical version. Bohm's experiment (called EPRB after die four physicists) involves die decay of a particle into two photons. If the particle is at rest and has no internal "spin," dien die photons travel in opposite directions, have equal energy, and have identical circular polarizations. If one of die photons is left-circularly-polarized (spinning to the left), so is the odier; likewise if one is right-circularly-polarized (spinning to die right), so is die odier. Furthermore, if one is plane-polarized along a particular axis (that is, has its electric field vibrating along diat axis), then die other one is plane-polarized along a definite axis. There are two cases, depending on the character of the spinless particle. In one case the plane polarization axes of the two photons are die same. In the odier diey are perpendicular. For simplicity let us take the former case, even diough in the practical situation (where die decaying particle is a neutral pi meson) die latter case applies. The setup is assumed to be such diat nodiing disturbs eidier photon until it enters a detector. If die circular polarization of one of die photons is measured by the detector, die circular polarization of die other is certain—it is the same. Similarly, if the plane polarization of one of die photons is measured, that of die other photon is certain—again, it is the same as diat of die first photon. Einstein's completeness would imply that both die circular and plane polarization of die second photon could dien be assigned definite values. But the values of die circular polarization and the plane polarization of a photon cannot be exacdy specified at the same time (any more dian the position and momentum of a particle can be so specified). Consequendy, die requirement of completeness is just as unreasonable in this case, from die point of view of quantum mechanics, as in die case discussed by Einstein and his colleagues. The two measurements, one of circular and die odier of plane polarization, are alternatives; diey take place on different branches of history and diere is no reason for die results of both to be considered togedier.

 EPRB and liie Hidden Variable Alternative Later on, some theoretical work of John Bell revealed that the EPRB experimental setup could be used to distinguish quantum mechanics from hypothetical hidden variable theories, by means of certain polarization measurements on both photons. Bell's theorem (also called Bell's inequalities) concerns a particular quantity that specifies die correlation between die polarizations of die two photons. In quantum mechanics, that quantity can attain values that are not allowed in a classical hidden variable dieory. After die publication of Bell's work, various teams of experimental physicists carried out die EPRB experiment. The result was eagerly awaited, aldiough virtually all physicists were betting on the correctness of quantum mechanics, which was, in fact, vindicated by die outcome. One might have expected that interested people all over die world would heave a sigh of relief on hearing die news and dien get on with dieir lives. Instead, a wave of reports began to spread alleging diat quantum mechanics had been shown to have weird and disturbing properties. Of course, it was the same old quantum mechanics. Nothing was new except its confirmation and die subsequent flurry of flapdoodle. Tne Story Distorted The principal distortion disseminated in die news media and in various books is the implication, or even die explicit claim, diat measuring the polarization, circular or plane, of one of die photons somehow affects the odier photon. In fact, die measurement does not cause any physical effect to propagate from one photon to die other. Then what does happen? If, on a particular branch of history, die plane polarization of one photon is measured and diereby specified widi certainty, dien on the same branch of history die plane polarization of die odier photon is also specified widi certainty. On a different branch of history die circular polarization of one of die photons may be measured, in which case die circular polarization of both photons is specified widi certainty. On each branch, die situation is like that of Bertlmann's socks, described by John Bell in one of his papers. Berdmann is a madiematician who always wears one pink and one green sock. If you see is a mathematician who always wears one pink and one green sock. If you see just one of

 his feet and spot a green sock, you know immediately that his other foot sports a pink sock. Yet no signal is propagated from one foot to die other. Likewise no signal passes from one photon to the odier in die experiment mat confirms quantum mechanics. No action at a distance takes place. (The label "nonlocal" applied by some physicists to quantum-mechanical phenomena like die EPRB effect is thus an abuse of language. What they mean is that if interpreted classically in terms of hidden variables, the result would indicate nonlocality, but of course such a classical interpretation is wrong.) The false report that measuring one of the photons immediately affects die odier leads to all sorts of unfortunate conclusions. First of all, the alleged effect, being instantaneous, would violate die requirement of rehtivity dieory that no signal—no physical effect—can travel faster dian the speed of light. If a signal were to do so, it would appear to observers in some states of motion that die signal was traveling backward in time. Hence die limerick: There was a young lady named Bright Who could travel much faster than light. She set out one day, in a relative way, And returned home die previous night. Next, certain writers have claimed acceptability in quantum mechanics for alleged "paranormal" phenomena like precognition, in which the results of chance processes are supposed to be known in advance to "psychic" individuals. Needless to say, such phenomena would be just as upsetting in quantum mechanics as in classical physics; if genuine, they would require a complete revamping of die laws of nature as we know them. A third manifestation of flapdoodle is die submission of proposals, for example to the U. S. Department of Defense, for using quantum mechanics to achieve faster-than-light communication in military contexts. One wonders whedier die advent of this new category of far-out requests means a declining number in more old-fashioned areas, like antigravity and perpetual motion. If not, die bureaucracy diat deals with them must be growing.

 Axes for plane polarizations used in quantum cryptography. Serious Potential Applications or EPRB Meanwhile, serious researchers have begun to think about ways in which the EPRB effect might actually be put to use. Instead of crackpot ideas, they have come up with some fascinating potential applications. For example, Charlie Bennett, Gilles Brassard, and Artur Ekert have been working on a form of quantum cryptography in which the EPRB effect is used over and over again to generate a cryptography in which the EPRB effect is used over and over again to generate a string of randomly generated bits known to two people and to no one else. That string can then be used as die basis of an unbreakable cipher for transmitting messages secretly between die two individuals. The method works roughly as follows. Suppose a steady supply of EPRB photon pairs is available to Alice and Bob. Of each pair, one photon goes to Alice and one to Bob. They agree in advance to make a long series of plane polarization measurements of their respective photons, on half the occasions distinguishing between two perpendicular directions called a* and y, and on die other half distinguishing between two other mutually perpendicular directions (halfway between a* and y) called X and V. (The Xand Vaxes are rotated 45 degrees from the x and y axes, as shown in the illustration above.) Alice chooses at random, for

 each of her photons, whether it will be subjected to an x versus y or an X versus Y measurement. Bob does the same, separately and indepen- dendy.) Once the work is finished, Alice tells Bob which kind of measure- i * ment she made on each of her photons, x versus y or X versus Y, and Bob gives Alice die analogous information. (The conversation can take pbce over a public telephone and be overheard by spies without doing any harm.) They learn on which occasions diey both made the same kind of measurement (that will have happened about half die time). For each such common measurement, the results obtained by Alice and Bob must be identical, because of the EPRB effect. The results of diose common measurements are then known to both of them and to no one else (assuming each made; the measurements in secret and did not divulge die results). Those ,results can be represented as a string of Is (standing for x or X) and Os (standing for y or V) known only to Alice and Bob. That string can then serve as the basis for an unbreakable secret cipher to be used between diem. If Alice and Bob are especially worried about security, diey can waste the results of a few of the measurements they made in common, comparing die corresponding Is and Os over an open telephone line to make sure they are really identical (while using die rest of the Is and Os for dieir secret messages). Any spy who had somehow been making his or her own measurements on die photons would diereby have destroyed die perfect agreement between Alice's and Bob's results. The comparison of some of diose results would reveal the work of die spy. Quantum cryptography does not actually require the EPRB effect. Subsequendy, a group of six physicists (including Bennett) has invented a clever procedure, in which'EPRB is essential, for destroying a photon and creating one in die same state of polarization but elsewhere (i.e., with a different probability distribution in space). As we have continued to learn more and more about the elementary particle system, a remarkable interplay has developed between die apparent complexities revealed by experiment and the simplification achieved by theory. The discovery of many different kinds of particles and several different types of interaction among them has created and reinforced the impression that particle physics is complicated. At the same time, on the theoretical side, progress toward unification in die description of particles and interactions has uncovered more and more of the underlying simplicity.'Although elementary particle physics is

 much less than a century old, we may already be at die stage where die unity of die subject is beginning to reveal itself, in the form of a single principle that is expected to predict die existence of die observed diversity of elementary particles.

13 QUARKS AND ALL THAT: THE STANDARD MODEL All respbctable theorizing about the elementary particles is carried out within the framework of quantum field theory, which includes both the standard model and superstring theory. Quantum field theory is based on three fundamental assumptions: the validity of quantum mechanics, the validity of Einstein's relativity principle (special relativity when gravitation is not included, and general .relativity otherwise), and locality (meaning that all fundamental forces arise from local processes and not by means of action at a pistance). Those local processes involve the emission, and absorption of particles. 1 ' QED-r-Quantum Electrodynamics The firsti successful exampl: of quantum field theory was quantum electrodynamics (QED), the theory of the electron and the photon. The it obeys the Pauli exclusion principle) and unit of electric charge (labeled "negative" electron is a fermion (that is, it possesses one fundamental according Ito a convention that dates back to Benjamin Franklin). The photon is^a boson (in other words, it obeys the antiexclusion principle) and it is electrically neutral. \7?

 Two electrons exchanging a virtual photon, which gives rise to the electromagnetic force between them. In quantum electrodynamics die electromagnetic force between two electrons comes about through the emission of a photon by one electron and its absorption by the other. If you know some classical physics, you may object that for an electron to emit a photon (that is, to turn into an electron plus a photon) violates die principle of the conservation of energy, die conservation of momentum, or both; likewise for die absorption of a photon. If you know some quantum physics, however, you are probably aware that conservation of energy need not hold over finite time intervak, only in the long ran. That property of quantum mechanics can be regarded as a manifestation of Heisenberg's uncertainty principle applied to energy and time. The system can borrow some energy for a while to permit the first electron to emit a photon, and the energy can then be returned when the odier electron absorbs die photon. Such a process is called the "virtual" exchange of a photon between electrons. The photon is emitted and absorbed only in the Pickwickian sense of quantum mechanics. For any quantum field theory, we can draw funny litde pictures, invented by my late colleague Dick Feynman, which give the illusion of

 understanding what is going on. In die one on die facing page electrons are virtually exchanging a photon to give die electromagnetic force between diem. Each electron is labeled "e," with a minus sign attached to indicate its single unit of negative electric charge. The photon similarly carries a nought superscript to indicate its electrical neutrality. An "e" widi a positive sign would represent die positron, the antipardcle of the electron. But what is ah antiparticle? Particle-Antiparticle Symmetry Quantum field dieory turns out to imply a fundamental symmetry of die elementary particle system between particles and dieir "antipar-ticles." For every particle there is a corresponding antiparticle, which behaves like die particle moving backwards in space and time. The antipardcle of the antiparticle is die particle itself. If two particles are antiparocles of each other, they have opposite electrical charges (that is, charges of equal magnitude but opposite sign) and die same mass. The antiparticle of die electron is called die positron because of its positive electric charge. Some electrically neutral particles, such as the photon, are dieir own antiparticles. When Dirac published his relativistic equation for die electron in 1928, he opened the way for die discovery of quantum electrodynamics, which followed soon afterwards. The interpretation of die Dirac equation pointed to the necessity of die positron, but initially Dirac did not actually predict the existence of that particle. Instead, he indicated diat somehow the1 expected positively charged object might be identified widi die proton, which was well known experimentally but is almost two diousand times heavier dian die electron (from which it differs in odier important ways as well). When 1 asked him, many decades later, why he had not immediately predicted die positron, Dirac replied in his usual pidiy manner, "Pure cowardice." It was left to experimentalists to make die discovery. The positron turned up in 1932 in the laboratories of my late colleague Carl Anderson at Caltech and Patrick Blackett in England; they shared a Nobel prize in physics a few years later. Their experiments established that die pardcle-antiparticle symmetry of quantum field theory is a real phenomenon.

 To a great extent die standard model can be regarded as a generalization of quantum electrodynamics. The electron and positron are supplemented by many odier particle-antiparticle pairs of fermions, and die photons are supplemented by odier quanta. Just as die photon is the carrier or quantum of die electromagnetic force, so die odier quanta carry other fundamental forces. Quarks For a long time it was diought that among the particles accompanying die electron on die list of fundamental fermions would be the neutron and proton, die constituents of atomic nuclei. However, that turned out to be false; die neutron and proton are not elementary. Physicists have learned on odier occasions as well that objects originally diought to be fundamental turn out to be made of smaller things. Molecules are composed of atoms. Atoms, aldiough named from die Greek for uncut- table, are made of nuclei widi electrons around diem. Nuclei in turn are composed of neutrons and protons, as physicists began to understand around 1932, when die neutron was discovered. Now we know diat the neutron and proton are diemselves composite: they are made of quarks. Theorists are now quite sure that it is die quarks that are analogues of die electron. (If, as seems unlikely today, die quarks should turn out to be composite, men die electron would have to be composite as well.) In 1963, when I assigned die name "quark" to die fundamental constituents of die nucleon, I had the sound first, widiout die spelling, which could have been "kwork." Then, in one of my occasional perusals oiFinnegans Wake, by James Joyce, I came across die word "quark" in die phrase "Three quarks for Muster Mark." Since "quark" (meaning, for one thing, die cry of a gull) was clearly intended to rhyme with "Mark," as well as "bark" and other such words, I had to find an excuse to pronounce it as "kwork." But die book represents die dream of a publican named Humphrey Chimpden Earwicker. Words in die text are typically drawn from several sources at once, like die "portmanteau words" in Through the Looking Glass. From time to time, phrases occur in die book that are partially determined by calls for drinks at die bar. 1 argued, dierefore, that perhaps one of die multiple sources of die cry "Three quarks for Muster Mark" might be "Three quarts for Mister quarks for Muster Mark" might be "Three quarts for Muster

 Mark," in which case the j pronunciation "kwork" would not be totally unjustified. In any case, the number three fitted perfectly the way quarks occur in nature. 1 The recipe for making a neutron or proton out of quarks is, roughly speaking, "Take three qujarks." The proton is composed of two "w quarks-' and one "</ quark]" while the neutron contains two "</ quarks" and one "w quark." The u and d quarks have different values of the electrid charge. In the same units in which the electron has an electric charge jof-1, the proton pas a charge of+1, while the neutron has charge p. The charge of the m quark in those same units is 2/3 and that of the d quark -1/3. Sure enough, if we add 2/3,2/3, and -1/3, we get 1 for the charge of the proton; and if we add -1/3,-1/3, and 2/3, we get 0 for the charge of the neutron. The u and d are said to be different "flavors" of quark. Besides flavor, the quarks have another, even more important property that is called "color,i although it has no more to do with real color than flavor in this context&has to do with the flavors of frozen yoghurt. While the name color is (mostly a joke, it also serves as a kind of metaphor. There are three colors, labeled red, green, and blue after the three basic colors of light in a simple theory of human color vision. (In the case of paints, the three primary colors are of n taken to be red, yellow, and blue, but for mixing lights instead of paints for their effect on human observers, yellow is replaced by green) The recipe for a neutron or proton is to take one quark of each color, that is, a red quark, a green quark, and a blue quark, in such a way that color averages out. Since, in vision, white can be regarded as a mixture of red, green, and blue, we can use the metaphojfi to say that the neutron and proton are white. Quarkp Confined Quarks Have the remarkable property of being permanently trapped inside "white" particles such as the neutron and proton. It is only white particles that are directly observable in the laboratory. Color is averaged out in the observable particle; and only inside them can colored objects exist. Likewise the electric cnarge of an observable object is always a whole nufnber (such as 0,1.--1, or 2), and fractionally charged particles can exist only inside.

 When I proposed die existence of quarks, I believed from the beginning that diey were permanendy confined in some way. I referred to such quarks as "mathematical," explaining carefully what I meant by die term, and contrasted diem widi what I called "real quarks," which would be capable of emerging so that diey could be detected singly. The reason for die choice of hnguage is that I didn't want to face arguments widi philosophically inclined critics demanding to know how I could call quarks "real" if diey were always hidden. The terminology proved unfortunate, however. Numerous authors, ignoring my explanation of die terms "madiematical" and "real," as well as die fact that die situation I was describing is die one now generally accepted as correct, have claimed that I didn't really believe die quarks were diere! Once such a misunderstanding becomes established in popular literature, it tends to perpetuate itself, because die various writers often simply copy one another. Colorful Gluons For quarks to be confined as diey are, the forces between diem must be very different from familiar forces like electromagnetism. How does diat difference arise? Just as die electromagnetic force between electrons is generated by the virtual exchange of photons, so die quarks are bound to one another by a force diat comes from die exchange of other quanta, called gluons because diey glue die quarks together to make observable white objects like die neutron and die proton. The gluons pay no attention to flavor—we might say diey are "flavor-blind." However, they are very sensitive to color. In fact, color plays the same kind of role for diem diat electric charge plays for the photon: die gluons interact widi color much as the photon interacts widi electric charge. The triple nature of color requires die gluons to have a property not shared by die photon: for different color situations, diere are different gluons. In die top sketch on die facing page, a red quark is shown turning into a blue one widi the virtual emission of a red-blue gluon, which is virtually absorbed by a blue quark, turning it into a red one. Anodier color situation is exhibited in the lower sketch, where a blue quark turns into a green one, virtually emitting a blue-green gluon,

 Forces between quarks from gluon exchange. the virtual absorption of which turns a green quark into a blue one. (Note, by the way, that the andparticle of a gluon is also a gluon; for example, blue-green and green-blue gluons are antiparticles of each other.) The flavor labels have been chosen to be different in die two sketches to illustrate the irrelevance of flavor to die color processes mediated by gluons. Quantum Ctiromodynamics Around 1972, a number of us contributed to die formulation of a definite quantum field theory of quarks and gluons. 1 named it quantum chromodynamics, using die Greek root chromo meaning color. It seems to be die correct dieory and is generally recognized as such, although a considerable amount of madiemadcal work is still required before we can be sure diat its detailed quantitative predictions agree with observation—confirming that die quarks, antiquarks, and gluons (of which all nuclear objects such as the neutron and proton are composed) truly behave according to die rules of quantum chromodynamics.

184 • THE QUANTUM UNIVERSE QED Fermions Quanta (bosons) Photon0 Fermions e* Rd2" 35l/3. Comparison of QED and QCD. The quarks and antiquaries are coupled to the photon through their electric charges, but the electron and positron are not coupled to the ghions. QCD ut2" dBm Colorful gluons0 To compare quantum electrodynamics (QED) and quantum chro-modynamics (QCD), we can construct the sort of dictionary shown above. In QED, electrons and positrons interact dirough the virtual exchange of photons, while in QCD quarks and antiquaries similarly interact through die virtual exchange of gluons. The electromagnetic force arises from electric charges; we can dunk of die color force as arising from color charges. Bodi electric and color charges are perfectly conserved—just as electric charge cannot be created or destroyed, neither can color charge. However, mere is a crucial difference between die two dieories: in QED die photon, which carries the electromagnetic interaction, is electrically neutral, while in QCD die gluons, which carry die color force, are themselves colorful. Because die gluons are not without color,

QUARKS AND ALL THAT: THE STANDARD MODEL • 185 they interact among themselves in a way mat photons do not, and that gives ree to terms in the equations of QCD that have no analogue in QED. q& a result, die color force turns out to behave very differently from elpctromagnetism or any odier previously known force: at large distances, it does not die away. That property of QCD explains why colored! quarks and antiqijarks and colorful gluons are permanently confined inside white objects such as die neutron and proton. The color force ads something like a spring holding them together. Although quarks are trapped forever and cannot be directly detected in the laboratory, beautiful experiments have been performed that confirm their existence inside die proton. For example, a beam of high-energy electrons can be used to make a kind of electron micrograph of'the proton's interior, and sure enough the quark structure is revealedil was delighted wh,en my friends Dick Taylor,Henry Kendall, and Jerry Friedman shared the Nobel prize in physics for such an experiment. (I only wish I had noticed in advance diat this would be a good way to confirm die existence of quarks.) Simplicity Revealed 3y QCD i In an atotnic nucleus, neutrons and protons are bound together (unlike quarks, they are not confined and can be extracted individually). Now that those particles are knowp to be composed of quarks, how are die nuclear forces between diem to be described?

When I was a graduate student, the character of thos; forces was one of the great mysteries we hoped some day to solve. M ost dieorists now believe that QCD has supplied the solution, although the relevant calculations are by no means copiplete. The situation is analogous to that of the forces between atoms or molecules, which were explained in the late 1920s after the discovery of quantum mechanics. Those forces are not in any way fundamental, but only indirect consequences of die electromagnetic force treated quantum-mechanically Similarly, the nuclear force is not fundamental but arises as an indirect effect of the color force, which in iturn comesj from the quark—gl uon interaction. The neutron and proton ire not the only observable (white) nuclear particles, although they are the best known. Hundreds of other

nuclear particle states have been discovered since die late 1940s in high energy collisions, first in cosmic ray experiments and then at high energy particle accelerators. They have all now been explained as composites ofquarics, antiquaries, and gluons. The quark scheme, embodied in the explicit dynamical theory of quantum chromodynamics, has thus exposed the simplicity underlying an apparendy very complicated pattern of states. Moreover, those states all interact with one another through the "strong interaction," which includes the nuclear force. The many manifestations of the strong interaction are all drought to be describable as indirect consequences of the fundamental quark-gluon interaction. Quantum chromodynamics has thus revealed the simplicity of the strong interaction as well as that of the nuclear particle states, which are the participants in that interaction. Electron and Electron Neutrino—The Weak Fbrce Important as they are, we know that there is more to matter than the nuclear particles and their fundamental constituents. The electron, for example, does not possess color and pays no attention to the color force or to the resulting nuclear fbrce. In a heavy atom, the innermost electrons that surround the nucleus actually spend a good deal of their time inside, but do not feel the nuclear force, although naturally they are susceptible to electromagnetic effects such as the electrical pull of the protons. Although the electron does not possess color, it does have flavor. Just as the d quark has the u quark as its flavor partner, so the electron has the electron neutrino as its partner. The electron neutrino is something of a silent partner because, being electrically neutral, it ignores not only the nuclear force (as the electron does), but also the electromagnetic force. It can pass through the earth, for example, with very little probability of interacting. The neutrinos produced by the thermonuclear reactions in the center of the sun reach the surface of the by the thermonuclear reactions in the center of the sun reach the surface of the earth by raining down on us during the day, but at night they come up at us through the earth. When the writer John Updike read about that aspect of neutrino behavior, he was inspired to write the following, entitled "Cosmic Gall":

QUARKS AND ALL THAT: THE STANDARD MODEL • 187 Neutrinbs, they are very small. They have no charge and have no mass And do hot interact at all. The earth is just a silly ball To them, through which they simply pass, Like dusl maids down a drafty hall Or photons through a sheet of glass. Thev snub the most exquisite gas, Ignore the most substantial wall, Cola-shoulder steel and sounding brass, Insult the stallion in his stall, And, scorning barriers of class, Infiltrate you and me! Like tall And painless guillotines, they fall Down through our heads into the grass. At night, they enter at Nepal And pierce the lover and his lass From underneath the bed—you call It wonderful; I call it crass. (In the third line it is tempting to employ scientific license and alter "do not" to "scarcely") Unfortunately detection of solar neutrinos is still fraught with many problems. The rate of detection seems to be lower than predicted, leading physicists to propose{various explanations of varying degrees of plausibility. My colleague Willy Fowler once went so far as to suggest that mayfcje the nuclear furnace at the center of the sun went out some time ago, but the energy transfer mechanisms in the sun are so slow that the news has not yet reached the surface. Not many people believe that is the correct explanation, bit if it is, then we are heading for a real energy crisis some day. How can neutrinos be produced in the center of the sun and how can they be detected in laboratories here on earth if they are subject neither toj the strong force nor to the electromagnetic one? Another [force, the'so-called weak force, is responsible. The electron neutrino | does participate in that interaction, along with the electron. Hence the suggested revision ofjohn Updike's phrase "do not interact at all."

 An electron turning into an election neutrino while a m quark turns into a A quark. Two versions of the same Feynman diagram. The weak force gives rise to reactions like the following: 1. An electron turns into an electron neutrino while a proton turns into a neutron. This reaction is an example of how neutrinos can be produced; die proton involved is part of a heavy nucleus and die electron is in one of die innermost electron states around that nucleus, inside of which it spends a sizable fraction of its time. 2. The inverse process, in which an electron neutrino turns into an electron while a neutron turns into a proton. This illustrates how a neutrino can be detected, with die target neutron being inside a nucleus. Since neither die neutron nor the proton is elementary, however, such reactions are not die basic processes, which involve quarks instead: 1. An electron turns into an electron neutrino while a u quark turns into a d quark.

 2. An electron neutrino turns into an electron while a d quark turns into a u quark.j i These reactions involve a change of flavor, both for the electron turning into an electron neutrino (or vice versa) and for the u quark turning into a d quark (or vice versa). As in any such process in quantum field theory, a quantum is being exchanged. For each of the two reactions, (the first of which is illustrated on the facing page) there are two versions of the same Feynman diagram, one version involving the exchange of a positively charged quantum and the other the exchange of a negatively charged quantum. The existence of such quanta was first discussed by some of us in the late 1950s, and they were discovered at CERN twenty-five years later, in experiments that procured a Nobel Prize for Carlo Rubbia ahd Simon van der Meer. The quanta are usually called W * and W~, as they were designated in a celebrated paper by T. D. Lee and C. N. Yang, but I still often refer to mem by the names X+ and X' mat Dick Feynman and I used to employ. Quantum Flavor Dynamics ana die Neutral Weak Force Bom the electromagnetic and weak forces can be regarded as flavor forces, since the electric charge varies with flavor and the weak force involves the changing of flavor. During the 1950s and 1960s, a sort of quantum flavor dynamics was formulated, incorporating both quantum electrodynamics and a theory of the weak force. Quantum flavor dynamics (associated particularly with the names of Sheldon Glashow, Steven Weinberg, and Abdus Salam) successfully predicted, among other things, the existence of a nevjr flavor force that causes simple scattering of electron neutrinos off neutrons or protons, without change of flavor.

More basically, in terms of quarks, the new force causes scattering of electron neutrinos off u and. d quarks, again without any change of flavor. The scattering takes place through the exchange of a new, electrically neutral quantum called 2?, as illustrated on page 190. The existence of that quantum, too, was confirmed by Rubbia, van der Meer, and their colleagues.

The scattering of an election neutrino off a d quark. Families 01 Fermions The diagram on page 191 summarizes what we have said so far about particles and forces. There is a family of fermions composed of the electron and its neutrino and two flavors of tricolored quarks; a corresponding antifamily consists of the positron and the anti-electron-neutrino and two flavors of tricolored antiquaries. Coupled to the color variable (which does not exist for the electron and its neutrino and their antiparticles) are the colorful gluons of quantum chromodynam- ics. Coupled to the flavor variable, which does exist for the entire family and for the entire antifamily, are the four quanta of quantum flavor dynamics. That fermion family, it turns out, does not stand alone. There are two more such families, with very similar structure. Each consists of an electron-like particle, a corresponding neutrino, and two flavors of quark with the electric charges -1/3 and +2/3, like the d and u respectively. The electron-tike particle in the second family is the muon, discovered by Carl Anderson and Seth Neddermeyer at Caltech in 1937. It is a heavy version of the electron, about two hundred times heavier, and it

has its own neutrino—the muon neutrino. The quarks in the second fermion family are the "strange" s quark (analogous to d) and the "charmed" c quark, (analogous to i<). Like the muon, they are heavier than their analogues in the! first family. A third family of fermions is also known, consisting of the tauon (about twenty times as heavy as the muon); the tauon neutrino; the b (or "bottom") quark, with a charge of-1/3; and the t (or "top") quark, with a charge of +2/3, for| which two independent teams of experimentalists have recently provided convincing evidence. If they had not confirmed the existence of the top quark, we theorists would have had to "tall on our fountain J pens," as my former colleague Marvin "MurphV Goldberger used to put it. These days, though, fountain pens are scarce. Besides, the ancient Roman hero who wanted to kill himself after a defeat had a trusty retainer to hold his sword—it is not clear if a pen could be held steady enough by a graduate student. Can there be additional fermion families besides the three that are known? Light was thrown on that question by families besides the three that are known? Light was thrown on that question by a recent experiment on the rate of disintegration ofi the 2l° quantum. The result was in agreement with theoretical predictions that allow for the decay of 2l° into any of three different kinds of neutrino-antineutrino pairs, corresponding precisely to electron, muon, and tauon neutrinos. There is no room for a fourth kind of neutrino unless it has a gigantic mass, unlike the r v? 'Color forces, carried by colorful gluons0 QUANTUM COLOR DYNAMICS i Flavor forces, carried] by, photon0, X*. Z° i QUANTUM FLAVOR DYNAMICS Elementary particles and forces discussed so far. (The antiparticles of the fermions are omitted from the diagram for die sake of simplicity.) "*" 16" «ft * " "ft dcui «£2'3 A=U3 ..±2/3 .

 other three, which are very light. A fourth family is dius excluded, unless its neutrino is very different from die odiers. With die three families of fermions, meir antiparticles, and die quanta of die electromagnetic, weak, and gluonic interactions we have come nearly to die end of our description of the standard model, and it is still a fairly straightforward generalization of QED. The photon is accompanied by odier quanta and the electron by odier fermions. The patterns of those quanta and fermions, including meir various masses and die strengths of die forces mediated by me quanta, show some apparent complexity. But die standard model is not yet die fundamental dieory, and only at die fundamental level should die full simplicity of die underlying dieory be revealed. The Zero-Mass Approximation One way to bring out the simplicity diat die standard model does possess is to consider an approximation in which all die particles mentioned so far are assigned zero mass, meaning diat diey always travel at die speed of light and can never be brought to rest. When die quanta of die weak interaction are treated as massless, die fundamental similarity of die diree interactions is made manifest. Quantum flavor dynamics and quantum chromodynamics have related madiematical structures; diey belong to die same class of dieories—so-called gauge dieories, or Yang-Mills theories (as generalized by Shelly Glashow and me long ago). When die fermions are assigned zero mass as well, a great deal of symmetry appears in die system of fermions. In particular, die three families men have identical properties. The question diat immediately arises is how die zero-mass approximation gets broken. But before describing die mechanism diat induces nonzero masses, we should take a look at die actual values. Masses (or Energies) Large and Small In dealing widi masses and energies, it is essential to make use of Einstein's celebrated relation between mass and energy, which states diat a particle widi nonzero mass, when at rest, has an energy equal to its

 mass times c squared, where c is the velocity of light. This equivalence of mass and rest energy can be used to assign an energy equivalent to any mass. The neutron and proton masses, when thus converted to energy, are both rather close to the energy unit known as the GeV or giga-elec- tron-volt. The prefix giga- is used to indicate a billion; a GeV is thus the energy that would be acquired by an electron accelerated from rest by an electrical potential difference of one billion volts. It is a convenient unit in which to measure the energy equivalents of particle masses. The nonzero masses of the elementary particles in the standard model are mostly quite different from one another. The electron mass is around one two-thousandth1 of a GeV. The neutrino masses, if they are not actually zero, are at most on the order of a hundred-millionth of a GeV. The tauon mass is approximately 2 GeV. The X (or W) plus and minus and 2? bosons have.masses in the vicinity of 100 GeV. The heaviest quark, the (quark, is expected to have a mass around 170 GeV All these masses violate the special symmetries of the zero-mass approximation. Spontaneous Symmetry Violation What makes those masses nonzero, and what makes them so different from one another? The mechanism that operates in the standard model is at least partially understood. It is connected with the existence of a new kind (or new kinds) of boson. At least one such type of boson may be observable at energies available now or soon to be available at the new accelerator at CERN. Such a particle is called a Higgs boson (or higgson). It was actually discussed not only by Peter Higgs of Edinburgh (in a beautiful piece of theoretical work), but also, in various ways, by several other elementary particle physicists, including Tom Kibble, Gerald Guralnik and> C. R. Hagen, and Robert Brout and Francois Englert. In addition,! it was proposed in general terms even earlier by my friend Philip Anderson, a theoretical condensed matter physicist and currently Vice-Chairman of the Science Board of the Santa Fe Institute. He won a Nobel prize for his work in condensed matter physics, but his anticipation of the general idea of the Higgs boson has not been widely recdgnized by elementary particle physicists. I cannot avoid a sneaking suspicion that if his contribution had been

 more generally acknowledged we would be spared some of his eloquent public arguments against die construction of new par dele accelerators. Is mere any way he could strongly oppose a machine that is built, in part, to try to find die Anderson-Higgs boson, or even the Higgs-

Anderson boson? For die sake of fairness, I suggest we retain die term "higgson" but use die name "Anderson-Higgs" to label die mechanism that breaks die symmetry of die zero-mass approximation and is responsible for the various different non-zero particle masses in die standard model. The Anderson-Higgs mechanism is a special case of a more general process called spontaneous symmetry breaking. For a familiar example of that process, think of an ordinary magnet, in which all die tiny atomic magnets are aligned with one another. The equations for die elementary particles composing the magnet, in interaction with one anodier but subject to no outside influence, are per- fecdy symmetrical widi respect to directions in space: they are indifferent, so to speak, to die direction in which die magnet points. But then any external influence, however feeble, (say a very weak external magnetic field), can determine the magnet's orientation, which would omerwise be totally arbitrary. The equations for die particles composing die magnet possess a symmetry because they treat all directions alike, but each individual solution of die equations violates die symmetry by pointing in a definite direction. The set of all those unsymmetrical solutions does, however, possess die symmetry because every direction corresponds to a solution and die set of all directions is perfecdy symmetrical. The essence of spontaneous symmetry breaking lies in this very circumstance: equations widi a particular symmetry can have solutions that individually violate diat symmetry, although the set of all solutions is symmetrical. The greatest virtue of die Anderson-Higgs mechanism of spontaneous symmetry breaking is that it permits die fermions and the quanta of die weak interaction to acquire nonzero masses widiout introducing disastrous infinities into die calculations of quantum flavor dynamics. Particle dieorists had searched for some time for such a "soft" mechanism for producing nonzero masses before it was shown that the higgson would do die job.

 Violation of Time Symmetry i The Anderson-Higgs mechanism may be responsible not only for die nonzero masses in the standard model but also for the observed small deviation from symmetry under reversal of time in elementary particle physics. The equations of! die underlying fundamental theory would then be symmetrical under time reversal. (Indeed, heterotic superstring theory, the only serious candidate for die unified theory of elementary particles, does possess mat | symmetry.) The violation would represent another, instance of symmetrical equations having a symmetrical set of unsymmetrical solutions, just one of which is found in nature. In diis case there would be two solutions, differing in the direction of time. This violation of time symmetry at the elementary particle level does not in any case seem capable of explaining the arrow (or arrows) of time—die conspicuous differences that we continually observe between events moving forward in time and the corresponding time- reversed version of those events. Those conspicuous differences arise instead from die special initial condition at the beginning of the expansion of the universe, as we have already mentioned and as we shall discuss in more detail later on. Violation or Matter—Antimatter Symmetry If the mathematical operation that interchanges forward and backward time is combined widi die interchange of left and right and also widi the interchange of matter and antimatter, die resulting operation (called CPT) is an exact symmetry of quantum field dieory. Thus it should not come as a complete surprise that die spontaneous violation of time symmetry also violates die 'symmetry between matter and antimatter. Can that violation be responsible for die gross asymmetry of die wodd around us, where just aboiit everything is composed of matter, and antimatter is produced only, in rare collisions at high energy? That proposal was made years ago by Andrei Sakharov, die late Russian .physicist well knoyrn for his coming up (along with Ya. B. Zel'dovich) widi die crucial idea for die Soviet hydrogen bomb and later for his struggles on behalf of peace and human rights in die Soviet

 Union. Sakharov put together a package of ideas that has undergone considerable modification at the hands of other theoretical physicists but has always included the following point. The very early universe was symmetrical between matter and antimatter, but soon produced the present asymmetrical situation through the same effect that produces spontaneous violation of time symmetry. Sakharov's proposal appeared quite strange at first, but in its successive transformations has looked better and better. It does seem that spontaneous symmetry violation is responsible for die predominance of matter over antimatter. Spin The higgson involved in die Anderson-Higgs mechanism of spontaneous symmetry violation is a different kind of boson from die quanta of die gluonic, weak, and electromagnetic interactions. A very important distinction lies in the value of die spin angular momentum (spin for short), which quantifies how much die particle rotates about its own axis. Quantum mechanics supplies a natural unit for spin, and in terms of diat unit a boson can have a spin of 0 or 1 or 2, and so on, while a fermion can have a spin of 1/2 or 3/2 or 5/2, and so on. All die elementary fermions of die standard model have spin 1/2. All die quanta of quantum chiomodynamics and quantum flavor dynamics have spin 1. The higgson, however, must have spin 0.

quantum flavor dynamics have spin 1. The higgson, however, must have spin 0. How Can There Be So Many Elementary Particles? The huge multiplicity of observed nuclear particle states was explained by die discovery diat they are composites, formed according to die rules of quantum chiomodynamics, from elementary quarks, antiquaries, and gluons. But the quarks, widi their three colors and six flavors, and die gluons, which come in eight (radier than nine) color combinations, are already radier numerous. Moreover, outside the realm of die strongly interacting nuclear particles, we encounter in addition the electron and its neutrino, die muon and its neutrino, and die tauon and its neutrino.

 And all die fermions have antiparticles distinct from themselves. In addition, we have the photon, and die three intermediate bosons of die weak interaction. The higgson completes our list of elementary particles demanded by the standard model. Let us add up die total number. We have eighteen quarks, diree electron-like particles, and three neutrinos, making twenty-four fermions in all. Widi dieir antiparticles, we have forty-eight. Then mere are the known quanta: die eight gluons, die photon, and the three intermediate bosons for die weak interaction, bringing die total to sixty. Widi the higgson (if there is only one), we get sixty-one. To a lay observer, it seems crazy to suppose mat die basic law of all matter in the universe could rest on such a large and heterogeneous collection of fundamental! objects. The expert in elementary particle physics can only agree. The solution to die puzzle must lie in die incorporation of die standard model into a larger theory containing less arbitrariness, preferably a unified dieory of all die particles and all dieir interactions. While die standard model is supported by copious evidence from experiment, any unified dieory must at present, in die absence of direct support from observation, be regarded as speculative. A unified theory must of course be testable, mat is, able to make predictions that can be verified by observation. But how can such a theory deal with the profusion of elementary particles widi which we are now faced in die standard model? There would seem to be diree ways out. The first is to suppose that today's elementary particles are really composite, and that die ultimate description of matter involves a smaller number of new, truly elementary constituents. I do not believe mere is any theoretical or experimental evidence today that points in such a direction. Moreover, the hypothetical new constituents would diemselves have to be rather numerous in order to explain the great variety of properties of the known elementary particles. Hence the reduction achieved in die number of elementary objects would] not be dramatic. A related idea is that <die process

just discussed, of explaining die apparendy elementary objects at one level as composites of still more elementary objects at the inext level down, will go on forever. Such an endless chain of composition was advocated in die People's Republic of China by die late Chairman Mao (if he seems an unlikely recruit to this field of endeavor, remember that Lenin wrote about die electron and

 Stalin intervened in numerous controversies in the sciences, humanities, and arts, sometimes with most unfortunate consequences for those he attacked). In accordance with die Chairman's ideas, the quark was for a time called "layer child" in Chinese, recalling the coinage "foundation child" for atom. Under die rule of Mao and die Gang of Four, it was no doubt inadvisable for Chinese scientists to disagree too violently with the idea of an infinite sequence of layers. Under the milder regimes mat have followed, however, die late Chairman's foray into theoretical physics has largely been ignored. The third possibility is that a simple theory underlies die elementary particle system, according to which die number of such particles can be regarded as infinite, with only a finite number accessible to experimental detection at available energies. Superstring theory falls into this category of explanation.

14 SUPERSTRING THEORY: UNIFICATION AT LAST? For the first time in history, we have in superstring theory—and specifically injj heterotic superstring theory—a serious proposal for a unified theory of all the elementary particles and their interactions and, therefore, of tall the forces of nature. The next step is to extract predictions from thb theory and compare them with what is known, as well as with what will soon be measurable, about the elementary particles. A striking feature (of that comparison is the occurrence in the equations of a characteristic energy or mass (the Planck mass), close to which the full unity of superstring theory starts to manifest itself direcdy. But the energy [equivalent of the Planck mass is enormous compared to the energy scale of phenomeni detectable in the laboratory. Therefore, the elementary particles that :an be studied more or less direcdy in the laboratory all belong to the "low-mass sector" of the theory. The Low-Mass Sector A large but finite number dred) nave masses low experiments of the foreseeable rions constitute the low-i of particles (say between one and two hun- ehough that they will appear in accelerator future. Those particles and their interac- rrlass sector of superstring theory.

 All die other elementary particles (an

infinite number of diem) are enormously more massive, so that their presence can be verified only through virtual effects (such as die generation offerees by die virtual exchange of quanta). Some of those virtual effects may be of critical importance, such as die ones diat enable Einsteinian gravitation to be part of die theory widiout engendering crippling infinities. The standard model, including die three fermion families, dieir antiparticles, and the twelve known quanta, forms part of die low-mass sector of die unified dieory. The graviton, widi zero mass, obviously belongs to die low-mass sector as well, as do other predicted particles. Renormalizability of the Standard Model The standard model is distinguished from, say, die dieory of the graviton by a wonderful property called renormalizability. This means it can be separated off in an excellent approximation from the rest of die unified dieory widiout encountering infinities mat make calculations meaningless. A renormalizable portion of die unified dieory can be used on its own, almost as if it were die final dieory. However, mere is a price to be paid for diat separation, which in die case of the standard model is die occurrence of more than a dozen arbitrary numbers diat cannot be calculated and must be taken instead from experiment. Those numbers represent the dependence of die model on the rest of die fundamental unified dieory, including the infinite set of high-mass states. Comparison with Observation Not at All Impossible Because die ratios of die Planck mass to die nonzero masses of the low-mass sector are so large, a few dieoretical physicists and a number of lay audiors have claimed diat die predictions of die dieory are difficult or impossible to check against observation. However, such arguments are not correct. There are many possible ways of confronting die dieory with experimental results.

 1. To begin with, superstring theory already predicts, in a suitable limit, Einstein's general-relativistic theory of gravitation. The automatic incorporation of Einsteinian gravitation into a unified quantum field theory without encountering the usual difficulties (with infinities) is already a major triumph. 2. The next challenge is to determine whether superstring theory can predict, in an appropriate approximation, the standard model. 3. But recall mat the standard model has a great many arbitrary constants (parameters), the values of which the theory should be capable of predicting. 4. The low mass sector of superstring theory contains additional, new particles, the predicted properties of which can be checked against observation. 5. In particular, the standard model is embedded in a larger renormalizable model that is part of the low-mass sector. The properties of that larger theory, including its particle content and the constants describing

the masses and interactions of the particles, can all be compared with the results of experiments. 6. In addition, the virtual effects of the high-mass sector may introduce some observable corrections to the physics of the low- mass sector. 7. Finally, superstring theory may have consequences for cosmology that are verifiable by astronomical observation. So we need not despair of finding ways to compare the predictions of the theory with the facts of nature, but theoreticians must proceed with the difficult task of extracting those predictions. Basic Units of Energy and Oilier Quantities What is the huge energy that characterizes superstring theory and where does it come from? It is the basic unit of energy, derived from the fundamental, universal constants of nature. There are three such constants: c, the velocity of light in empty space; h, the quantum constant of Max Planck; and G, the gravitational constant of Isaac Newton.

 The constant h is the universal ratio of the energy of any quantum of radiation to the vibration frequency of that radiation. In practice, it is usually employed in the form ft, which means h divided by two pi, where two pi is the familiar ratio of the circumference of any circle to its radius. (Werner Heisenberg used to wear a tie pin in the form of ft as a way of showing his pride in having discovered quantum mechanics. That symbol is so familiar to physical scientists mat my late friend, the brilliant and amusing mathematician Stanistaw Ulam, used to describe the t, the "dark" Polish / in his first name, as / divided by two pi. G is the universal constant in Newton's formula for the gravitational force between any two point particles, which is equal to G times the product of the two masses divided by the square of the distance between mem. (Newton showed mat the same formula applies to two spherically symmetrical bodies if the distance used is the distance between their centers, so mat the formula can be employed approximately for the sun and the planets and for satellites like the moon.) By multiplying and dividing suitable powers of the three universal constants, c, ft, and G, one can construct the fundamental unit of any physical quantity, such as length, time, energy, or force. The fundamental length is about a centimeter divided by a number written as 1 followed by thirty-three zeroes. Dividing that length by the velocity of light yields the fundamental unit of time, on the order of a second divided by a number written as 1 followed by forty-four zeroes. By way of contrast, the units to which most people are accustomed are arbitrary; they are not constructed from the universal constants of nature. Although the foot is no longer (if it ever was) the average length of the shod feet of the first ten men to leave church on Sunday, it is still not fundamental. Neither is the meter, defined formerly as the

Sunday, it is still not fundamental. Neither is the meter, defined formerly as the length of a specific bar of metal in a vault near Paris and nowadays as a certain multiple of the wavelength of the light emitted by a krypton atom in a particular state of excitation. Particle Masses and the Basic Unit The fundamental unit of mass, the Planck mass, is about a hundred thousandth of a gram. It may not seem enormous on a human scale, but on the scale of the neutron and proton masses (bom approximately

 equal to a GeV) it is large indeed—about twenty billion billion times as big. Turning the relation around, we can say that the masses of neutron and proton are extremely tiny in terms of fundamental units. The mass of the electron is about two thousand times smaller still. Why do these very small numbers occur? The short answer is that we do not yet know. Heterotic superstring theory does not explicitly contain any adjustable parameters. If it is indeed the correct theory, it must somehow generate by itself the tiny ratios of the masses of the known particles to the fundamental unit of mass. Verifying by calculation that it does so will be one of the most severe tests of the theory. So far, mere are only hints of how the small numbers may arise in the theory. A fairly obvious guess is mat mere is a useful approximation in which all the particles of the low-mass sector are assigned a mass of zero. Symmetry-breaking corrections to mat approximation (including those induced by the Anderson-Higgs mechanism) men become responsible for the actual tiny but nonzero masses. A few mass values, including those of the photon and graviton, receive no correction at all and remain zero. Energies available in current experiments are on the order of a thousand GeV; soon they may be something like ten times greater, but no more. They are still very small compared with the fundamental unit of energy, around twenty billion billion GeV. Since experimentalists cannot produce in the laboratory particles with masses higher than the energies available at their accelerators, they will be dealing directly only with particles that belong to the low-mass sector. Trie Meaning of tke Term Superstring What general observations can be made about the particle content of heterotic superstring theory? The answer to mat question is connected with the meaning of the word string and of the prefix super-. String indicates that the theory can be regarded as describing particles in terms of tiny loops instead of points; the typical dimension of each loop is approximately the fundamental unit of length, around a billionth of a trillionth of a trillionth of a centimeter. Those loops are so small that for many purposes mere is an equivalent description in terms of point particles, actually an infinity of kinds of point particles. How

 are those different particles related to one another? In particular, how are those of die low-mass sector related to those mat have masses comparable to the Planck mass or greater? A good analogy is with a violin string, which has a lowest mode of vibration and an infinite number of odier modes (harmonics) of higher and higher musical frequency. But in quantum mechanics energy is like frequency multiplied by Planck's constant h. The panicles of me low- mass sector can be visualized as die lowest modes of die various sorts of loops of string occurring in superstring theory, while particles with masses comparable to die fundamental unit of mass represent die next- lowest modes, and still heavier panicles represent higher modes, and so on forever. The prefix super- indicates that die theory has approximate "super- symmetry," which means in turn mat for every fermion in die list of panicles mere is a corresponding boson and vice versa. If the super- symmetry of die elementary panicle system were exact, each fermion would have precisely die same mass as its related boson. However, supersymmetry manages to get itself "broken," in a way diat is still only dimly understood, causing die masses of die corresponding fermions and bosons to be separated by what I like to call a "supergap." This is not exactly die same for each fermion-boson couple, but it is probably always of die same general order of magnitude. If die supergap is anything like die fundamental unit of mass, we can despair of observing direcdy in die laboratory die superpartners of die known elementary panicles. Superpartners ana New Accelerators If, however, die energy equivalent of die supergap is only hundreds or even thousands of GeV, superpartners may be observable in die next few years, provided die new CERN accelerator is built. (The chance of observing diem would have been greater if the higher energy SSC had been completed.) The theoretical analysis of certain experimental results indicates mat die supergap is probably of die right size to have been bridged by the SSC and may perhaps be bridged by die CERN machine. Assuming those indications are correct, I believe die prospect of discovering superpartners is die most exciting of all die specific motivations for building new accelerators. (There is always in addition

 die nonspecific goal of exploring die unknown and seeing if some unforeseen phenomenon turns up.) The names assigned to die hypothetical superpartners follow two different patterns. When die known particle is a boson, die related fermion is given a name ending in die Italian diminutive -ino, first employed (in a different way) by Fermi in naming the neutrino. Thus die expected partner of die photon is the photino, diat of the graviton die gravitino, and so forth. Since die electrically charged bosons transmitting the weak interaction are often called Wplus and W minus, die corresponding predicted fermions have acquired the bizarre appellation "winos." In die case where die known particle is a fermion, die boson partner is called by the same name as the fermion but widi the letter "s" prefixed (presumably standing for super). Thus one gets rattier weird terms like squarks and selections. (I should like to emphasize that I am not responsible for these names, aldiough I must admit, reluctantly, to having been present when die -ino suffix was chosen for die fermion partners of known bosons.) Since die superpartner of a boson is a fermion and vice versa, die spins of die two superpartners must always be different, one a whole number and die odier a whole number plus 1/2. In fact, die two spins must differ by 1/2. The Higgs bosons (or higgsons) have spin 0 and their partners (higgsinos) have spin 1/2. The three families of fermions have spin 1/2 and their partners (squarks, selections, and so on) have spin 0. The quanta (gluons, photons, X or W bosons, and Z°) have spin 1 and their partners (gluinos, photinos, and so on) have spin 1/2. The graviton has spin 2 and its partner, the gravitino, spin 3/2. In superstring dieory, die standard model is incorporated into a larger renormalizable dieory, which we may call die superstandard model, containing die twelve quanta, die usual fermions, and some higgsons, along widi die superpartners of all those particles. The prediction of die validity of die superstandard model provides a great many experimental tests of superstring dieory. Trie Approach to the Planck Mass As energy increases and die low mass sector—the sector directly accessible to experiment—is left behind, superstring dieory predicts diat the gluonic, the electromagnetic, and die weak interactions all approach

 one another in strength and reveal their close relationship. (Extrapolation of present experimental results to high energies yields the same conclusion provided broken supersymmetry is assumed, with a super- gap that is not too large. Thus there is already some indirect evidence for supersymmetry.) At the same dme, the symmetries among the fer- mions also assert themselves. Now let energy continue to increase. It may or may not turn out, at an energy interval just below the Planck mass, that the superstandard model gives way temporarily to a supersymmetric version of a "grand unified theory" before exhibiting, in the vicinity of the Planck mass, the first excited modes of the superstring. Although none of us will live to see energies modes of the superstring. Although none of us will live to see energies comparable to the Planck mass produced in the laboratory, such energies were available in the infant universe as it began to expand. The fundamental unit of time, about a hundred millionth of a trillionth of a trillionth of a trillionth of a second, measures the period during which the tiny universe experienced the full physical effects of the superstring theory. Is there any cosmic evidence remaining today that could test the validity of superstring theory through its effects at that crucial but remote moment of time? Theorists are not sure whether such evidence remains or not. That brief interval was almost certainly followed by a period of inflation, an explosive expansion of the universe that was succeeded by the more gradual expansion still going on. Inflation nearly wiped out many features of the very early universe, and may thus have suppressed numerous consequences of superstring theory. But the constraints it imposes on the character of the inflation may permit the theory to be tested after all by cosmological means. The same kind of reasoning applies to the initial condition of the universe, which, according to the proposal of Harde and Hawking, is tied to the unified quantum field theory. Assuming their idea and superstring theory are both correct, the initial condition is uniquely determined, but its effects on the later universe are filtered through the process of inflation. Apparent Multiplicity or Solutions Besides the great disparity between the characteristic energy scale of the superstring theory and the energies available for elementary particle

 experiments, there is another reason why a few physicists have expressed doubts about whether the theory will be testable. This has to do with the discovery of numerous approximate solutions of the equations of heterotic superstring theory. Each such solution supplies, among other things, a list of the parades that have zero mass in the approximation used. It is plausible to assume mat those particles are the same ones that make up the low-mass sector of the theory when the small nonzero mass corrections are included. The zero-mass particle content of each approximate solution can men be compared with the content of the superstandard model. For certain solutions, mere is indeed agreement: the low-mass sector contains the superstandard model and a few additional particles, including the graviton and gravitino. The trouble is that thousands of other approximate solutions have turned up, and it looks as if many more will be found. It is therefore not at all impossible that the observed situation is compatible with a solution of the superstring theory, but what is to be done with all the other solutions? There are several possible answers. One, of course, is that the theory is wrong, but I see no reason whatever to draw such a drastic conclusion from the existence of a plethora of approximate solutions. A second possibility is that the difficulty stems entirely from the approximation (which is by no means fully justified, but merely convenient), and that when the approximation is improved, all the solutions but one will be seen to be spurious and can be thrown away. (A modified version of that possibility is mat only a few genuine solutions will survive.) Action lb discuss the remaining possible answers to the problem of multiple solutions, it is helpful to bring up a most important quantity called action, usually designated by the symbol S. It was introduced into classical Newtonian physics ages ago and proved quite useful, but with the advent of quantum mechanics it became not only useful but essential. (Action has the dimensions of energy times time; It, Planck's constant divided by two pi, has the same dimensions and can be regarded as the fundamental unit of action.) Recall that the probabilities for coarsegrained histories in quantum mechanics are sums over values of the

 quantity D for pain of completely fine-grained histories. A meory in quantum mechanics assigns to each fine-grained history a particular value of die action S, and it is diose values of die action (along widi the initial condition) that determine die values of D. It is clearly highly desirable to find the formula for die action S in heterotic superstring dieory. So far, however, diat has proved an elusive goal. What seems to be widiin reach today—as a result of work by my former student Barton Zwiebach, by Michio Kaku, and by a group in Kyoto—is to express die action as die sum of an infinite series, but the summation of that series remains a formidable task. It may be illuminating to compare die situation to an exercise diat my late colleague Dick Feynman went dirough in 1954. (He discussed his project widi me at die time I visited Caltech back in 1954, when I was offered and accepted a job there. I had, in fact, started a similar project myself.) Feynman began by imagining diat Einstein had never had his brilliant insight into die nature of gravitation around 1914, the realization diat it would have to obey die invariance principle of general relativity and relate to die geometry of spacetime. Dick asked whedier it would be possible, widiout diat insight, to construct the dieory by brute force. He found diat it could be done. However, the action came out in die form of an infinite series, and summation of diat series was virtually impossible in die absence of the geometrical point of view and the invariance principle. That principle, general relativity, yields die answer direcdy, widiout any need for die brute force method or the infinite series. In fact, once Einstein understood, on die basis of general relativity, what kind of formula he needed in order to describe gravitation, he was able to learn die relevant madie- matics from an old classmate, Marcel Grossmann, and write down the formula for the action, from which die equation on page 87 can be derived. Perhaps die situation in superstring dieory is similar. If theorists understood the invariance principle of superstring dieory, diey might be able to write down die formula for die action in short order, widiout resorting to die summation of die infinite series. (While we are waiting for it to be discovered, what should we call diat principle? Field marshal relativity? Generalissimo relativity? Certainly it goes far beyond general relativity.) In any case, a deep understanding of superstring dieory will go hand in hand widi finding die formula for die action S.

As noted earlier, the idea motivating the work that led to super- string theory in the first place was the "bootstrap" principle of self- consistency, a simple and powerful idea but not yet formulated in die right language for discovering the action or the full symmetry principle underlying the action. When superstring theory is expressed in die language of quantum field theory and when its action and its symmetries have been discovered, it will truly have come of age. Effective Action Starting from the action, one can in principle calculate a related quantity, which I denote by the symbol 3. A dieorist might call it something like "quantum-corrected Euclideanized action." It is a kind of average of a modified version of the action 3, where die modification involves altering the character of die time variable. We can refer to the quantity 3 as the "effective action." It plays a most important role in the interpretation of die dieory. In die first place, it is in terms of 3 that Harde and Hawking would express dieir initial condition for the universe. In the second place, it is to the quantity 3 diat we must look for guidance if mere really are many solutions to die superstring theory. Somehow that quantity, calculated for the different solutions, must discriminate among them. Reasoning from classical physics, where the principle of least action provides an elegant means of formulating classical dynamics, some theorists might argue that die correct solution for physical purposes—die one that characterizes the real universe—would have to be the one with the smallest value of the effective action 3. That could indeed be the right criterion for picking out the correct solution. Since we are dealing with quantum mechanics, however, it may turn out diat there is no single correct solution for the universe, but rather a probabilistic situation in which all the true solutions are possible alternatives, each with its own which all the true solutions are possible alternatives, each with its own probability, which gets smaller as die value of 3 gets larger. In fact, die formula for the probability in terms of 3 would be a decreasing exponential, described by a curve like die one on page 132. The solution with die least value of 3 would men have die highest probability of characterizing die universe, but odier solutions would have some chance as well.

 A Particular Solution Determined by On ancef The particular solution that applies to the universe would then determine the structure of the system of elementary particles. In faa, it would do more than that. Remarkably enough, it would even determine the number of dimensions of space. One way to diink of me spatial aspect of me heterotic superstring is that the theory starts out describing a spacerime widi one time dimension and nine spatial dimensions; various solutions men correspond to the collapse of some of me spatial dimensions, leaving only me remaining ones observable. If the probabilistic interpretation of 3 applies, men the three-dimensional character of space in our universe is a consequence of the chance occurrence of a particular solution to the super- string equations (as is, for instance, the existence of a particular number of fermion families containing particular sets of particles). Such a probabilistic situation is the most intriguing possible outcome of me current attempts to solve the puzzle posed by the many apparent solutions to the equations of superstring theory. Suppose it is the right outcome. We can men think of me branching tree of alternative coarse-grained histories of me universe, with a probability for each one, as beginning wim a first branching that selects a particular solution of me superstring equations. The predictions of superstring theory, whether or not they depend on such a probabilistic "choice" of solution, will have to be compared wim our experience of three-dimensional space as well as all the properties of the elementary particle system. If heterotic superstring theory does turn out to make correct predictions in all die cases where it is feasible to test it, the problem of the fundamental meory of the elementary particles will presumably have been solved. The underlying dynamics for the evolution of the state of the universe will be known. But the description of the history of the universe depends on the initial condition as well and also on me chance outcomes of all the branchings of the tree of universal history. Multiple Universes? So far the quantum cosmology we have discussed has referred to alternative histories of the universe, treated as a single entity embracing all

 matter everywhere. But quantum cosmology is in a state of flux and abounds in everywhere. But quantum cosmology is in a state of flux and abounds in speculative ideas of great interest, die status of which is still in question; some of those ideas refer, in one way or another, to multiple universes. Since uni- means one, mat sounds like a contradiction in terms, and perhaps a new word will help to avoid at least the linguistic confusion that could arise if some of those ideas turn out to be even partially correct. We can employ die term "multiverse" to refer to die entire ensemble of universes, of which our familiar universe is a member. The introduction of multiple universes is pointless unless our universe is largely autonomous. One proposal is that die odier universes are "baby universes" virtually created and destroyed in quantum processes, much like the virtual quanta mat carry forces in quantum field dieory. As viewed by Stephen Hawking and odiers, die virtual creation and destruction of baby universes alter die results of calculations in elementary particle theory, but do not necessarily challenge in an essential way the concept of a branching tree of history for our universe. Anodier suggested possibility is mat numerous universes exist, many of them comparable in size wim our own, but that our universe has only limited contact, if any at all, with the odiers, even if such contact might have occurred in die distant past or might become possible in the far future. In one such picture, the universes are like bubbles in the multiverse, bubbles mat separated from one another very long ago, thus inaugurating an era wim no communication among die universes, an era that would last for an exceedingly long time. If diis kind of multiple universe picture turns out to have any validity, one may try to identify what goes on in die various bubbles with different possible branches of die history of the universe. The door is men opened to die notion mat fantastically many branches of the tree of coarse-grained histories are actually all realized, but in different bubbles. The probability of each history would men be essentially a statistical probability, the fraction of die various "universes" in which the particular history takes place. Now suppose the probabilistic interpretation of the many approximate solutions of superstring dieory is right, so that mere are many true solutions associated with various elementary particle patterns and various dimensions of space. Then, if numerous universes really exist as bubbles in a multiverse, sets of them could be characterized by different solutions ofsuperstring theory, wim numbers of occurrences declining exponentially with die value of die effective action 3.

 Even if such theoretical speculations are shown to be without foundation, the notion of multiple, largely independent universes still provides a nice (if rather abstract) way of thinking about probabilities in quantum cosmology. "Anuiropic Principles" Some quantum cosmologists like to talk about a so-called anthropic principle that requires conditions in the universe to be compatible with the existence of human beings. A weak form of the principle states merely that the particular branch of history on which we find ourselves possesses die characteristics necessary for our planet to exist and for life, including human life, to flourish here. In mat form, the anthropic principle is obvious. Suppose the correct cosmology really involves a multiverse with a probabilistic distribution of universes displaying various solutions of the fundamental equations. Perhaps those who like to invoke an anthropic principle believe that the solution corresponding to our universe is an improbable one, while the more probable ones do not admit human life in any of their branching histories. But in that case we would still have to say that our universe must be compatible with the existence of everything observed, including human life, whether probable or not. Again, such a weak anthropic principle is a triviality. In its strongest form, however, such a principle would supposedly apply to the theory of the elementary particles and the initial condition of the universe, somehow shaping those fundamental laws so as to produce human beings. That idea seems to me so ridiculous as to merit no further discussion. Nevertheless, I have tried to find some version of the idea of an anthropic principle mat is neither trivial nor absurd. The best I can come up with is the following. Among the various solutions of the fundamental equations (if there are in fact multiple exact solutions) and among the various branches of history, certain solutions and certain histories create favorable conditions in many pbces for the evolution of complex adaptive systems, which can act as IGUSes (information gathering and utilizing systems), observers of the outcomes of quantum- mechanical branchings. (Those conditions include the prevalence of a situation suitably intermediate between order and disorder.) The char-

 acterization of those solutions and branches poses a theoretical problem of great interest, which could, I suppose.be called die search for IGUSic conditions. A minor incidental feature of those conditions favorable to IGUSes would be mat the existence of Earth, of life on Earth, and of human life in particular would be permitted and could occur on certain branches. One application of such theoretical research would be die refinement of calculations of die probability of receiving signals from intelligent complex adaptive systems on planets orbiting distant stars (as in die SETI project, die search for extraterrestrial intelligence). There are many factors entering into such calculations. One of them is the probable length of time mat a technical civilization would last and be capable of and interested in transmitting signals, since catastrophic war or die decline of technology could put an end to diem. Another factor is die probability that a planet can harbor complex adaptive systems, for example ones resembling living beings on Earth. Here a number of subtle considerations may enter in. For instance, Harold Morowitz, investigating die requirements on the Earth's atmosphere at die time of the prebiodc chemical reactions mat initiated life, has concluded that some fairly restrictive conditions had to apply in order for those reactions to take place. Odier experts, however, are not so sure. It seems that in place of some awesome "andiropic principle" we are faced with a set of fascinating but rather conventional questions in theoretical science about die conditions necessary for the evolution of complex adaptive systems on various branches of history and at various times and places, given die fundamental dieory of elementary particles and the initial quantum state of the universe. The Role of the Initial Condition We have encountered several times die role of die initial condition in supplying die order in die early universe mat made possible the subsequent evolution first of celestial objects like galaxies, stars, and planets and men of complex adaptive systems. We have also discussed one of die most dramatic consequences of the initial condition, mat time flows steadily forward diroughout the universe. Let us now explore the flow of time in more detail.

15 TIME'S ARROWS Forward and Backward Time Remember the meteorite passing through the atmosphere and landing. If a film of the whole sequence of events were run backwards, we would know instantly mat time was being reversed. We understand that the ultimate reason for die unidirectionality of time is mat the universe was in a very special state some ten or fifteen billion years ago. Looking through time toward mat simple configuration, we are contemplating what we call the past; looking in the other direction, we are seeing what we call the future stretched out before us. The compactness of the initial state (at the time of what some like to call the big bang) does not fully characterize its simplicity. After all, cosmologists consider it possible, even probable, mat at some almost inconceivably distant time in the future the universe will recollapse to a very tiny structure. If so, however, that structure will be quite different from the one that existed in the past. During the period of recollapse, the universe will not be running through its expansion in reverse. The notion that the expansion and contraction would be symmetrical with each other is what Stephen Hawking calls his "greatest mistake."

 Radiation an J Records It is easy to think of many ways in which forward time and backward time are different. For example, hot objects like stars and galaxies radiate energy outward. The most familiar form of radiated energy consists of photons—such as diose of light, radio waves, and gamma rays—which make possible optical astronomy, radio astronomy, gamma ray astronomy, and so on. In addition to the observation of photons, neutrino astronomy is just coming into its own, and some day soon we will have gravitational wave astronomy. All are based on detecting the outward flow of energy in the form of particles and waves. Likewise, when we see the light coming from a fire or an electric light bulb, our eyes are detecting a stream of emitted photons. If time were reversed, energy in each of these cases would instead be flowing inward. The outward flow of energy can carry signals; if a star turns into a supernova and suddenly becomes enormously brighter for a while, that information is propagated outward at the speed of light Another difference between the past and the future is the existence of records of the past, like die tracks left in mica by the charged particles emitted when radioactive nuclei disintegrated long aga Similar records of future disintegrations are conspicuous by their absence. That asymmetry between past and future is so obvious that we tend to overlook it. We humans make use of radiation to send signals and of records to learn about the past. We even make and keep records ourselves. But the existence of signals and records in general is quite independent of die existence of complex adaptive systems—like us—that employ some of them. The Initial Condition ana Causality The time asymmetry of signals and records is part of physical causality, die principle that effects follow their causes. Physical causality can be traced directly to die existence of a simple initial condition of die universe. But how does that initial condition enter into die dieory? The quantum-mechanical formula for die quantity D, which yields die probabilities of alternative histories of die universe, already contains the asymmetry between past and future. At one end, corresponding to what we call the past, it contains a specification of a quantum state for

 the early universe, which we call the initial condition. At die other end, corresponding to the remote future, the formula contains a summation over all possible states of the universe. That summation can be described as a condition of complete indifference as to the state of the universe in the distant future. If the initial condition were also one of complete indifference, there would be no causality and not much history. Instead, the initial condition is a special and simple one (perhaps even the one described by initial condition is a special and simple one (perhaps even the one described by Harde and Hawking, which requires no information beyond die dynamical law governing the system of elementary panicles). If die future condidon were not one of complete indifference, violations of causality would result and events would occur mat were inexplicable (or at least exceedingly improbable) in terms of the past but were required (or nearly so) by die condidon specified for die distant future. As die age of die universe increased, more and more such events would occur. There is no evidence for such a situation reflecting predestination and considerable evidence against it; therefore in die absence of any convincing new argument, we can disregard the possibility diat die future condition is anything but one of indifference. However, while relegating it to the domain of science fiction or superstition, we can still consider a special condition on die future as an interesting contrary-to-fact case contrasting widi die causal situation we strongly believe to be correct. From die basic quantum-mechanical formula for die probabilities of histories, with a suitable initial condition, it is possible to deduce all the familiar aspects of causality, such as signals and records pointing from die past to die future. All die arrows of time correspond to various features of coarse-grained histories of the universe, and the formula exhibits the tendency of all those arrows to point forward radier dian backward everywhere. Entropy and the Second Law Of die arrows that mark die distinction between forward and backward time, one of the most famous is the tendency of the quantity called entropy to increase (or at least not to decrease) in a closed system, yielding die principle known as die second law of diermodynamics. (According to an old physics joke, die first law of thermodynamics says

 you can't win, while die second law says you can't break even. Both laws are frustrating for someone who wants to invent a perpetual mo- don machine.) The first law merely states the conservation of energy: the total energy of a closed system stays die same. The second law, requiring die increase (or constancy) of entropy, is subde, and yet entropy is really very familiar to all of us in our daily lives. It is a measure of disorder, and who would deny that disorder tends to increase in a closed system? If you spend all afternoon at a table sorting pennies according to date or nails according to size, and somediing knocks over die table, isn't it overwhelmingly likely diat die pennies or nails will get mixed up? In a household where children make peanut butter and jelly sandwiches, isn't there a tendency for die peanut butter in die jar to acquire an admixture of jelly and for die jelly jar to get some dollops of peanut butter in it? If a chamber is divided into two parts by a partition, die left-hand side containing oxygen gas and die right-hand side containing an equal amount of nitrogen, isn't the removal of the partition almost certain to yield a mixture of oxygen and nitrogen in bodi parts? The explanation is that diere are more ways for nails or pennies to be mixed up man sorted. There are more ways for peanut butter and jelly to contaminate each odier's containers dian to remain completely pure. And diere are more ways for oxygen and nitrogen gas molecules to be mixed up than segregated. To die extent diat chance is operating, it is likely diat a closed system that has some order will move toward disorder, which offers so many more possibilities. Microstates ana Macrostates How are diose possibilities to be counted? An entire closed system, exacdy described, can exist in a variety of states, often called microstates. In quantum mechanics, these are understood to be possible quantum states of die system. These microstates are grouped into categories (sometimes called macrostates) according to die various properties that are being distinguished by die coarse graining. The microstates in a given macrostate are men treated as equivalent, so diat only dieir number matters.

 Consider the chamber containing equal numbers of nitrogen and oxygen molecules separated by a partition, which is then removed. Now all die possible microstates of die nitrogen and oxygen molecules can be grouped into macrostates such as the following: diose in which the left-hand part of the chamber has less man 10 percent nitrogen and the right-hand part less than 10 percent oxygen, diose in which die contaminations lie between 10 and 20 percent, those in which diey tie between 20 and 30 percent, and so form. The macrostates in which the contamination lies between 40 and 50 percent (or between 50 and 60 percent) contain the most microstates. Those are also the most disordered macrostates, the ones in which the gases are mixed widi each other to the greatest extent. Actually, counting the number of different ways in which a closed system can be in a particular macrostate is closely related to die technical definition of entropy (as measured in die most convenient unit, called Boltzmann's constant). The entropy of a system in a given macrostate is, roughly speaking, the amount of information—die number of bits—necessary to specify one of the microstates in that macrostate, with the microstates all treated as if diey were equally likely. Recall that the game of twenty questions, played perfectly, is capable of eliciting 20 bits of information beyond whedier the unknown is animal, vegetable, or mineral. Twenty bits correspond to the information needed to distinguish 1,048,676 different, equally probable alternatives, where that number is just 2 multiplied by itself 20 times. Likewise 3 bits correspond to 8 equally likely possibilities, because 8 is 2 multiplied by itself 3 times. Four bits correspond to 16 possibilities, 5 bits to 32 possibilities, and so forth. If the number of possibilities lies between 16 and 32, men the number of bits lies between 4 and 5. Thus, if die number of microstates in a macrostate is 32, then die entropy of a system in that macrostate is 5 units. If the number is 16, the entropy is 4 units, and so on. Entropy as Ignorance Entropy and information are very closely related. In fact, entropy can be regarded as a measure ofignorance. When it is known only that a system is in a given macrostate, the entropy of the macrostate measures the

 degree of ignorance about which die microstate system is in, by counting die number of bits of additional information needed to specify it, with all die microstates in die macrostate treated as equally probable. Now suppose die system is not in a definite macrostate, but occupies various macrostates widi various probabilities. The entropy of the macrostates is men averaged over diem according to dieir probabilities. In addition, die entropy includes a further contribution from die number of bits of information it would take to fix die macrostate. Thus the entropy can be regarded as die average ignorance of the microstate within a macrostate plus the ignorance of die macrostate itself. Specification corresponds to order and ignorance to disorder. The second law of diermodynamics tells us merely mat, odier diings being equal, a closed system of low entropy (considerable order) will tend, at least for a very long time, to move toward higher entropy (more disorder). Since mere are more ways for disorder to occur than order, die tendency is to move toward disorder. The Ultimate Explanation: Order in the Past A deeper question is why the same argument is not applicable when die direction of time is reversed. Why should a film for a system run backwards not show it moving toward probable disorder instead of toward order? The ultimate answer to that question lies in the simple initial condition of the universe at die beginning of its expansion some ten billion years ago, contrasted with die condition of indifference mat is applied to die distant future in die probability formula of quantum mechanics. It is not only die causal arrow of time that points from past to future as a result but also die odier arrows, including die order- disorder or "diermodynamic" arrow of time. The original condition of the universe leads, later on, to the gravitational condensation of matter and die formation of young galaxies. As galaxies of certain kinds age, young stars and planetary systems are formed inside diem. Then the stars and planets age. The arrow of time is communicated from universe to galaxy to star and planet. It points forward in time everywhere in the universe to galaxy to star and planet. It points forward in time everywhere in the universe. On Earth it is communicated to the origin of terrestrial life and its evolution and to die birth and aging of every living diing. Most large-scale order in the universe arises from order in the past

 and ultimately from the initial condition. That is why the transition from order to the statistically much more probable disorder tends to proceed everywhere from past to future and not the other way around. We can think of the universe metaphorically as an old-fashioned watch that is fully wound at the beginning of its expansion and then gradually runs down while spawning smaller, partially wound watches that slowly run down in their turn, and so on. At every stage, as a new entity is formed, it inherits from existing structures the property of being at least partly wound. We can identify the aging of each approximately isolated entity with the running down of its corresponding watch. How do galaxies and stars and planets behave as they grow older? Consider what happens to certain familiar categories of stellar objects. At the center of stars like the sun thermonuclear reactions take place, at temperatures of tens of millions of degrees, that convert hydrogen to helium, with the release of energy that finally emerges from the surface in the form of sunlight or starlight. Eventually the star runs out of its nucjear fuel and changes its character, often in dramatic ways. If it is heavy enough, it may turn suddenly into a supernova and then, after shining with great brilliance for a couple of months, collapse into a blaik hole. Clearly such a process is unidirectional in time! When we humans set up a pattern of order (with pennies, say) and leave it alone except for an agent that can upset it (a dog, for example), the closed system (pennies on a table plus clumsy dog) will evolve toward disorder because disorder is so probable. That change will occur forward in time because we humans behave causally, like everything else acting forward in time, and we created the pattern of order first and then left it alone with the dog. Such a situation involving an increase of entropy is not so very different from what is going on in the stars and galaxies. What is somewhat distinctive is the setting up of the pattern of order in the first place: sorting the pennies or re-sorting them after the dog knocks them over. That is clearly a decrease of entropy for the set of pennies, although it doesn't violate the second law of thermodynamics, because the set of pennies is not closed. In fact, the second law snys that the entropy of the environment and of the person doing the sorting has to increase by at least as much as the entropy of the pennies

 decreases. How does that work? What are

 decreases. How does that work? What are die symptoms of increasing entropy in die person doing die sorting and in the surroundings? Maxwell's Demon In trying to answer diose questions, it is useful to discuss a hypodietical demon that spends its time sorting, namely Maxwell's demon, dreamt up by die same James Clerk Maxwell who found die equations for electromagnetism. He was treating a very common (and perhaps the earliest) application of die second law of thermodynamics: to a hot body and a cold body in proximity to each other. Imagine a chamber divided into two parts by a removable partition. On one side is a hot sample of gas and on die odier side a cold sample of die same gas. The chamber is a closed system widi a certain amount of order, because the statistically faster moving molecules of die hot gas on one side of die partition are segregated from statistically slower moving molecules of die cold gas on die odier side. Suppose first that the partition is made of metal, so mat it conducts heat. Everyone knows that the hot sample of gas will men tend to get cooler and die cold sample warmer until the two reach the same temperature. That is clearly what the second law requires, since die orderly segregation of hotter and colder gas disappears and entropy thus increases. Now suppose that the partition fails to conduct heat, so mat the segregation of hotter and colder gas is maintained. Entropy will then remain constant, which is also compatible with the second law. But what if mere is a demon at work sorting molecules into faster and slower ones? Can it decrease the entropy? Maxwell's demon guards a trap door in the partition, which is still assumed not to conduct heat. It spots molecules coming from either side and judges dieir speeds. The molecules of the hot gas are only statistically faster than those of the cold gas; each sample of gas contains molecules moving at very different speeds. The perverse demon manipulates die trap door so as to allow passage only to the very slowest molecules of the hot gas and die very fastest molecules of the cold gas. Thus die cold gas receives extremely slow molecules, cooling it further, and die hot gas receives extremely fast molecules, making it even hotter.

 In apparent defiance of the second law of diermodynamics, the demon has caused heat to flow from the cold gas to die hot one. What is going on? Because die law applies only to a closed system, we must include the demon in our calculations. Its increase of entropy must be at least as great as the decrease of entropy in the gas-filled halves of the chamber. What is it like for die demon to increase its entropy? A New Contribution to Entropy Leo Szilard began to answer mat question back in 1929 by introducing the relation between entropy and information. Later, after the Second World War, Claude Shannon set forth clearly the mathematical notion of information, which was further clarified by die French theoretical physicist Leon Brillouin. In die 1960s, the concept of algorithmic complexity or algorithmic information content was introduced by Kolmogorov, Chaitin, and Solomonoff. Finally, Rolf Landauer and Charlie Bennett of IBM worked out in detail how information and algorithmic information content are connected to die activity of a person, demon, or device that decreases the entropy of a physical system while increasing its own entropy by an equal or a greater amount. Bennett considered a device acquiring appropriate information about a physical system and then recording it (say on paper or computer tape). The information refers to alternative possible sets of data, with a probability for each set. Bennett made use of those probabilities to study what happens on die average over all the different alternative results. He found that die device can really use the recorded information (about which alternative actually occurred) to make heat flow from a cold object to a hot one, as long as the device has blank paper or tape available. The entropy of die system composed of die hot and cold objects is thus decreased, but at the price of using up die paper or tape. Previously, Landauer had shown mat erasing die records, leaving no copy, produces an increase of entropy mat at least makes up for die decrease. Eventually the device must run out of recording space, and thus in the long run, when records are erased to make room for more, die second law of diermodynamics will be restored. We have just mentioned mat it is the erasure of die last copy of die

 information that must produce an increase of entropy at least sufficient to restore die second law. Actually, erasing any copy is likely to lead in practice to a similar entropy increase, but it is only the last copy mat must do so in principle. The reason is that if at least two copies exist, methods are available under certain conditions for using one of diem to "uncopy" another one reversibly, without any increase of conventional entropy. Meanwhile, it is possible to maintain die second law in some form—even during die period when die records exist—by modifying die definition of entropy of die entire system. This can be done by adding a term equal to die amount of relevant information registered in die surviving records. That amount is not affected by die existence of extra copies of die records. All mat matters is whether mere exists at least one record of which alternative really occurred. The usual entropy is a measure of ignorance, and die modified definition adds to it die amount of recorded information. Thus, when new data are obtained and registered, ignorance is reduced—on the average—by a certain amount, while the information in the records is increased by the same amount. When erasure takes place, die information in die records is decreased but ignorance of the situation of the entire closed system is increased by at least as much. The desirability of using a modified definition of entropy in this connection was first pointed out by Wojtek Zurek of Los Alamos National Laboratory and die Santa Fe Institute. The definition discussed here is a slighdy different one suggested by Sedi Lloyd. Erasure and Shredding As die demon performs its task of sorting, it must do something with the information it is acquiring about the individual molecules. To the extent that it stores the information, it will eventually run out of storage space. To the extent that die information is erased, die act of erasure increases die entropy of die demon and its surroundings. What does it mean, though, for die erasure to be completed? Think of a notation in pencil being effaced by an ordinary gum eraser. The eraser sheds tiny bits of itself, each bearing a small portion of the notation, and these are dispersed all over die desk and even onto the

floor. That kind of dispersal of order is itself an increase of entropy. In reality, the messy process of erasure typically produces an entropy increase much larger than the amount of information being rubbed out and much of that entropy production has a quite conventional character (for instance, the generation of ordinary heat). In order to make a point, however, we have been ignoring that extra entropy increase and concentrating on the minimum increase that must accompany the destruction of the information-bearing records. It matters whether the destruction is irreversible. If the process can be reversed by reconstructing the notation from the fragments of eraser, then the entropy increase specifically associated with erasure has not taken place—but neither has the erasure taken place: a copy of the information still exists in the fragments. It may be objected mat such a reconstruction is always possible in principle, that it is just a practical question whether the information can be recovered from the nasty little bits of eraser. A dramatic example of such a situation was provided when the "students" who invaded and occupied the U.S. Embassy in Teheran in 1979 garnered up the strips of classified documents that had been shredded at the last moment by embassy employees and patiendy pieced them together, so that the documents could be read and their contents made public. Although present-day shredders cut up documents in bom dimensions, making such reconstruction very much more difficult, it is still not totally impossible in principle. How then can we talk about irreversible erasure totally impossible in principle. How then can we talk about irreversible erasure or dispersal of information, or indeed about the disruption of any sort of order? Why is the whole idea of increase of entropy, of the conversion of order into disorder, not a fraud? Entropy Useless Without Coarse Graining Let us return to the oxygen molecules mixing with the nitrogen molecules. We can ask in what sense the mixing of the gases really increases disorder, since every oxygen and nitrogen molecule is sometvltere at every moment (at least in the classical approximation), and therefore the situation at any time is just as orderly as at any previous time (provided die position of every molecule is described and not just the distribution of oxygen and nitrogen).

The answer is that entropy, like effective complexity, and algorithmic information content, and other quantities mat we have discussed, depends on the coarse graining—die level of detail at which the system is being described. Indeed, it is mathematically correct that the entropy of a system described in perfect detail would not increase; it would remain constant In fact, however, a system of very many parts is always described in terms of only some of its variables, and any order in those comparatively few variables tends to get dispersed, as time goes on, into omer variables where it is no longer counted as order. That is the real significance of die second law of thermodynamics. A related way to diink of coarse graining is in terms of macrostates. A system that is initially described as being in one or a few macrostates will usually find itself later on in a mixture of many, as die macrostates get mixed up with one another by die dynamical evolution of the system. Furthermore, those macrostates that consist of die largest numbers of microstates will tend to predominate in the mixtures. For both those reasons, the later value of entropy will tend to be greater than the initial value. We can try to connect coarse graining here with coarse graining in quantum mechanics. Recall mat a maximal quasiclassical domain consists of alternative coarse-grained histories of the universe mat are as fine-grained as possible consistent with being decoherent and nearly classical. Thus die quasiclassical domain mat includes familiar experience is associated at each rime with a set of highly refined macrostates, which provide a possible coarse graining for defining entropy. The resulting entropy seems to have suitable physical properties, with a tendency to increase as required for the thermodynamic arrow of time. The Arrows or Time ana the Initial Condition Given an appropriate coarse graining, we can trace back die thermodynamic arrow of dme to the simple initial condidon of the universe and die final condidon of indifference in the quantum-mechanical formula for probabilities of decohering coarse-grained histories of die universe. The same can be said of die arrow of rime associated with outward radiation, and likewise of what I call the true cosmological arrow of rime, which involves the aging, die running down, of the universe and

 its component parts. (Stephen Hawking defines his cosmological arrow of time by the expansion of the universe, but that is not a true arrow of time according to my definition. If, after a fantastically long time, the universe contracts, the contraction will take place forward in time as well—the aging will continue, as Hawking himself emphasizes.) The arrow of time associated with the formation of records also derives ultimately from the simple initial condition of die universe. Finally, the so-called psychological arrow of dme, referring to the experience of the forward flow of dme on the part of human beings and all other complex adaptive systems, arises from the same condition. Memories are just records, and they obey forward causality just as other records do. emergence of Greater Complexity: Frozen Accidents The passage of time seems to open up opportunities for complexity to increase. Yet we know that complexity can also decline in a given system, such as a society forced to retreat to simpler social patterns because of severe stress from climate, enemies, or internal strife. Such a society may even disappear altogether. (The Classic Maya collapse certainly involved a reduction of complexity, even if many individuals survived.) Nevertheless, as time goes on, higher and higher social complexity keeps appearing. The same tendency occurs in biological evolution. Although some changes may involve decreases in complexity, the trend is toward higher maximum complexity. Why? Recall that effective complexity is the length of a concise description of the regularities of a system. Some of those regularities can be traced back to the fundamental physical laws governing the universe. Others arise from the fact that many characteristics of a given part of the universe at a given time are related to one another through their common origin in some past incident. Those characteristics have features in common; they exhibit mutual information. For example, automobiles of a given model resemble one another because they all originate from the same design, which contains many arbitrary features that could have been chosen differently. Such "frozen accidents" can make

 themselves felt in all sorts of ways. Looking at coins of King Henry VIII of England, we may reflect upon all the references to him not only on coins but in charters, in documents relating to the seizure of abbeys, and in history books and how those would all be different if his elder brother Arthur had survived to mount the throne instead of him. And how much subsequent history may depend on that frozen accident! We can now throw light on a class of fairly deep questions mentioned near the beginning of this book. If we find a coin bearing the image of Henry VIII, how can we employ the fundamental dynamical equations of physics to deduce that other such coins should turn up? Finding a fossil in a rock, how can we deduce from the fundamental laws that there are probably more fossils of a similar kind? The answer is: only by using the initial condition of the universe as well as the fundamental dynamical laws. We can then utilize the tree of branching histories and argue, starting from the initial condition and the resulting causality, that the existence of the found coin or fossil means that a set of events occurred in the past that produced it, and those events are likely to have produced other such coins or fossils. Without the initial condition of the universe, the dynamical laws of physics would not be able to lead us to such a conclusion. A frozen accident may also explain, as we discussed earlier, why the four nucleotides abbreviated A, C, G, and T constitute the DNA of all living organisms on Earth. Planets orbiting distant stan may harbor complex adaptive systems that closely resemble terrestrial life but utilize genetic material composed of other molecules. Some theorists of the origin of life on Earth conclude that there may be thousands of such possible alternatives to the set A, C, G, and T. (Others, it should be noted, speculate that the familiar set of nucleotides may be the only possibility.) An even more likely candidate for a frozen accident is the occurrence of certain right-handed molecules that play important roles in the chemistry of terrestrial life, while the corresponding left-handed molecules are not found in those roles and in some cases may be entirely lacking in life forms on Earth. It is not hard to understand why various kinds of right-handed molecules would be compatible with one another in biochemistry, and the same for left-handed molecules, but what determined the choice of one or the other? Certain theoretical physicists tried for a long time to connect this left-right asymmetry with the striking behavior of the weak interac-

 tion, which exhibits left-handedness in ordinary matter (made of quarks and electrons) and right-handedness in antimatter (made of antiquaries and positrons). Their efforts do not appear to have borne fruit, and so it seems probable that the biochemical left-right asymmetry is a frozen characteristic of the ancestor of all surviving terrestrial life, and that it could just as well have turned out the other way. The biological left-right asymmetry illustrates in a striking way that many frozen accidents can be regarded as instances of spontaneous symmetry breaking. There may be a symmetrical set of possibilities (in diis case right- and left-handed molecules), only one of which actually occurs in a particular part of the universe during a particular time interval. In elementary particle physics, typical instances of spontaneous symmetry breaking are thought to apply to the whole universe. (There may also be others, even in elementary particle physics, that apply only over gigantic regions of the universe; if so, even that subject would to some extent have the character of an environmental science!) The tree-like structure of branching histories involves a game of chance at every branching. Any individual coarse-grained history consists of a particular outcome of each of those games. As each history continues through time, it registers increasing numbers of such chance outcomes. But some of those accidents become frozen as rules for the future, at least for some portion of the universe. Thus the number of possible regularities keeps increasing with time, and so does the possible complexity. This effect is by no means restricted to complex adaptive systems. The evolution of physical structures in the universe shows the same trend toward the emergence of more complex forms through the accumulation of frozen accidents. Random fluctuations gave rise to galaxies and clusters of galaxies in the early universe; the existence of each of those objects, with its individual characteristics, has been from the time of its birth a regularity of great importance for its part of the universe. Likewise the condensation of stars, including multiple stars and stars with planetary systems, out of gas clouds in those galaxies provided new regularities of great local importance. As the entropy—the overall disorder—of the universe increases, self-organization can produce local order, as in the arms of a spiral galaxy or the multiplicity of symmetrical forms of snowfbkes. The complexity at a given time of an evolving system (whether a complex adaptive system or a nonadaptive one) does not supply a

 measure of what levels of complexity it or its descendants (literal or figurative) may attain in the future. To fill that need, we introduced earlier the concept of potential complexity. To define it, we consider the possible future histories of the system and average the system's effective complexity at each future time over those histories, with each one weighted according to its probability. (The natural unit of time for this purpose is the average interval between random changes in the system.) The resulting potential complexity, as a function of time in the future, tells us something about the likelihood that the system will develop into something highly complex by that time, perhaps even by spawning a whole new kind of complex adaptive system. In the example we discussed earlier, potential complexity would distinguish emerging humans from the other great apes, even though their effective complexity at the time was not much different. Likewise, a planetary surface with a significant probability of generating life within a certain time would be distinguished from one on which life was not a serious possibility. Will tke Emergence or Greater Complexity Continue Rorever? After an enormously long time (even by cosmological standards), the universe, as it continues to expand, will become very different. Stars will die; black holes, having become more numerous than they are now, will decay, and probably even protons (and heavier nuclei) will decay as well. All the structures with which we are now familiar will disappear. It may be, therefore, that regularities will become fewer and fewer and the universe will be describable mostly in terms of randomness. The entropy will then be very high and so will the algorithmic information content, so that effective complexity will be low and depth fairly low as well (see pages 59 and 104). Between now and then, if that picture is correct, the emergence of more and more complex forms will come gradually to a halt and the regression to lower complexity will become the rule. Furthermore, conditions will no longer be conducive to the existence of complex adaptive systems. Even individuality may decline, as well-defined individual objects become progressively scarcer. This gloomy image is by no means entirely free of controversy. More theoretical research on the very distant future is needed. Although

not directly of much practical value, such research will throw light on the significance of the era of complexity in which we find ourselves. Also the universe may be headed, after a very long time indeed, for recollapse, and theorists are investigating that phenomenon as well, attempting to describe what it would be like for entropy to continue increasing in a shrinking universe and what the prospects are for complexity during that possible phase of cosmic evolution. Meanwhile, here on Earth the characteristics of our planet and our sun have provided frozen accidents that profoundly affect the rules of geology, meteorology, and other "environmental" sciences. In particular, they furnish the background for terrestrial biology. The evolution of the Earth, of the weather on its surface, of the prebiotic chemical reactions that led to the emergence of life, and of life itself, all illustrate the accumulation of frozen accidents that have become regularities for restricted regions of space and time. Biological evolution, especially, has given rise to the emergence of higher and higher effective complexity.

SELECTION AND FITNESS

16 SELECTION AT WORK IN BIOLOGICAL EVOLUTION AND ELSEWHERE All kinds of complex adaptive systems, including biological evolution, operate in accordance widi the second law of thermodynamics. However, it is occasionally claimed by anti-evolutionists that biological evolution contradicts the second law, on die grounds mat the emergence ofmore and more complex forms represents an increase of order widi die passage of dme. There are a number of reasons why mat argument is wrong. First, in the evolution of nonadapdve systems like galaxies, stars, planets, and rocks, more and more complex forms emerge widi die passage of rime, for reasons that we described earlier, widiout any conflict widi die increase of entropy. The structures all age in accordance widi die second law, but as time goes on mere is also a broader and broader distribution of complexity, with the maximum complexity gradually increasing. Second, die second law of diermodynamics applies only to closed (that is, completely self-contained) systems. One crucial mistake made by diose who claim a contradiction between that law and biological evolution lies in looking only at what happens to certain organisms and not taking into account die environment of diose organisms. 035

236 • SELECTION AND FITNESS The most obvious way in which living systems fail to be closed arises from die need for sunlight as a direct or indirect source of energy. Strictly speaking, we cannot expect die second law of thermodynamics to hold unless we include that absorption of energy from die sun. Furthermore, energy flows out as well as in; ultimately it leaves in the form of radiation to die sky (dunk of die diermal radiation transmitted from your house to the cold, dark night sky). The flow of energy dirough a system can produce local order. Even apart from diat effect, however, the influence of information from die terrestrial environment must be taken into account. To see what happens when diat environmental information is included, consider an oversimplified case in which the influence exerted by the environment is steady and the interaction among different kinds of organisms is ignored. A population of a given kind of organism is then evolving in die presence of a consistent environment. As time goes on, die population tends to become better adapted to its surroundings, since different genotypes widiin the population compete with

one anodier and some are more successful dian odiers in creating pheno- types diat survive and reproduce. Consequently, a kind of discrepancy in information between the environment and the organism is gradually reduced. That process is reminiscent of die way that the temperatures of a hot object and a cold object placed in contact widi each anodier approach diermal equilibrium, in conformity widi die second law. Biological evolution, far from contradicting diat law, can provide instructive metaphors for it. The process of adaptation of a population is a kind of winding down in die presence of its environment. In hot sulfur springs all over the world (and in die ocean depths where hot vents mark die boundaries between tectonic plates), primitive organisms called extremophiles (or crenarchaeota) dirive in an environment diat most living things would find extremely hostile. In die life of extremophiles at the bottom of die ocean, sunlight plays a limited role, confined mosdy to processes diat supply oxidizing chemicals. For instance, sunlight helps to maintain odier life forms, nearer die surface of die water, diat keep dropping organic material down to where die extremophiles live. Strong indirect evidence points to die existence, more dian three billion years ago, of organisms diat were similar, at least metabolically, to modern extremophiles. No one knows whedier die entire underlying genotypes were also very similar, or whedier parts of die genome have

undergone substantial drift, leaving the practical result in the real world of selection pressures much the same. In either case, we can say that the rather difficult problem of living in that hot, acidic, sulfurous environment was solved when the Earth was young. The extremophiles reached a kind of steady state, something like an evolutionary equilibrium with their surroundings. Rarely, though, are the surroundings so stable. Most natural situations are more dynamic, with the environment undergoing significant changes as time goes by. For example, the composition of the Earths atmosphere as we know it owes a great deal to the presence of life. The presence today of significant amounts of oxygen can be attributed, at least in great part, to the plants that have proliferated on the surface of the planet. Co-evolving Species Moreover, the environment of any given species of organism includes a huge number of other species, which are themselves evolving. The genotype of each organism, or else the cluster of genotypes that characterizes each species, can be regarded as a schema that includes a description of many of the other species and how they are likely to react to different forms of behavior. An ecological community consists, then, of a great many species all evolving models of other species' habits and how to a great many species all evolving models of other species' habits and how to cope with them. In some cases it is a useful idealization to consider just two species co-evolving and dealing with the developments in each others capabilities. For example, in walking through forests in South America, I have often encountered a species of tree that provides nutriment for a particularly nasty species of stinging ant. In return, the ant repels many kinds of animals, including us humans, that might otherwise want to harm the tree. Just as I have learned what that tree looks like, to avoid bumping into it by mistake, so have other mammals learned to recognize it and not munch on it. Such a situation of symbiosis must have been produced by a substantial period of co-evolution. In the same forest, one may encounter offensive-defensive competitions that also proceed by the evolution of two species adapting to each other. A tree may evolve the capacity to exude a toxic substance that repels a destructive kind of insect. That insect species, in turn, may

 evolve a means of metabolizing the poison, which is then no longer a threat. Further evolution of the tree may result in modification of the poison so that it again becomes effective, and so on. Such chemical arms races can result in the natural production of chemical agents mat are very potent biologically. Some of those can be of great utility to human beings, in medicine, integrated pest management, and other fields. In the realistic situation, viewed without simplification, many species evolve together in an ecological community, with nonliving surroundings that gradually (or even rapidly) alter with time. That is much more complicated than the idealized examples of symbiosis or competition of two species, just as they are more complicated than the even more idealized case of a single species evolving in a fixed environment. In each case, the process of biological evolution is compatible with the thermodynamic arrow of time, as long as the whole system is taken into account; but only in the simplest situations, like that of extremophiles, does evolution lead to a kind of informational steady state. In general, the process is one of continuing dynamic change, just as it is for a complex physicochemical system like a galaxy, a star, or a planet without life. All are aging, winding down as time goes forward, albeit in a complicated manner. In an ecological community, the process/ of mutual adjustment through evolution is an aspect of that aging. Biological evolution is part of the winding-down process by which the informational gap between the potential and the actual tends to be reduced. Once a complex adaptive system exists, the discovery and exploitation of opportunities is not only possible but probable, because mat is the direction in which the system is pushed by the selection pressures operating on it. Punctuate J Equilibrium Biological evolution does not usually proceed at a more or less uniform rate, as some specialists used to imagine. Instead, it often exhibits the phenomenon of "punctuated equilibrium," in which species (and higher groupings or taxa, such as genera, families, and so forth) stay relatively unchanged, at least on the phenotypic level, for long periods of time and then undergo comparatively rapid change over a brief

period. Stephen Jay Gould, who proposed the idea in technical publications co-authored with his colleague Niles Eldredge, has also written a great deal about punctuated equilibrium in his engaging popular articles and books. What causes the comparatively rapid changes that constitute the punctuation? The mechanisms thought to be responsible can be divided into various categories. One comprises alterations, sometimes widespread alterations, in die physicochemical environment. At the end of the Cretaceous Period about sixty-five million years ago, at least one heavy object collided with die Earth, die one that formed the huge crater of Chicxulub on the edge of the Yucatan peninsula. The resulting atmospheric changes helped to produce the Cretaceous exdncdon, which did away widi the large dinosaurs and very many other forms of life. Hundreds of millions of years earlier, during the Cambrian Period, great numbers of ecological niches opened up and were filled by new life forms (somewhat the way a new and popular technology leads to numerous job opportunities). The new life forms created still more new niches, and so on. Some evolutionary theorists have tried to connect that explosion of diversity with an increase in the oxygen content of the atmosphere, but that hypodiesis is not generally accepted today. Another kind of rapid change that may punctuate apparent evolutionary equilibrium is largely biological in character. It does not require dramatic sudden changes in die physical environment. Instead, it results from the tendency of genomes to change gradually widi rime in ways that do not profoundly affect the viability of the phenotype. As a result of that process of "drift," a cluster of genotypes constituting a species may move toward an unstable situation in which fairly small genetic changes can radically alter the phenotype. It may happen at a certain time that a number of species in an ecological community are approaching that kind of instability, creating a situation that is ripe for the occurrence of mutations that do lead to important phenotypic changes in one or more organisms. Those changes can initiate a series of linked events, in which some organisms become more successful, others die out, the whole community is altered, and new ecological niches open up. Such an upheaval can then provoke change in neighboring communities, as, for example, new kinds of animals migrate there and compete successfully with established species. A temporary apparent equilibrium has been punctuated.

 Gateway Events Particularly dramatic biological events are sometimes responsible for critical instances of punctuated equilibrium in die absence of radical change in die physicochemical surroundings. Harold Morowitz of George Mason University and die Santa Fe Institute points out the great significance of breakdiroughs or gateway events that open up whole new realms of possibility, sometimes involving higher levels of organization or higher types of function. Harold has particularly emphasized cases where diese gateways are unique or nearly so, and where they are dependent on a biochemical innovation. To begin with, he theorizes about possible chemical gateways in the course of die prebiotic chemical evolution diat led to die origin of life on Earth. Those gateways include: 1. one that led to energy metabolism using sunlight and so to the possibility of a membrane isolating a portion of matter such as diat represented later on by die cell; 2. one diat supplied the catalysts for the transition from keto acids to amino acids and dience to die production of proteins; and 3. chemical reactions that resulted in molecules called dinitrogen heterocycles and so led to the nucleotides diat constitute DNA, dius permitting die genome, the biological schema or information package, to come into existence. In all diese cases Harold emphasizes the narrowness of die gateway. Typically just a few special chemical reactions make possible die entry into a new realm; sometimes just a single reaction is responsible. (The specificity of such reactions does not mean they are necessarily improbable—even a unique reaction may take place easily.) Analogous gateway events occurred in biological evolution, following the development of die life form ancestral to all organisms alive today. Many of diose events opened up new levels of organization. One example is die evolution of eukaryotes, organisms in which die cell possesses a true nucleus (containing the principal genetic material) and also other "organelles"—mitochondria or chloroplasts. The transformation of more primitive organisms into single-celled eukaryotes is diought by many researchers to have come about dirough their incor-

porating other organisms, which became endosymbionts (meaning that they lived on inside and in symbiosis with the cell) and then evolved into organelles. Another example is the evolution of animal-like single-celled eukaryotes (presumably the ancestors of true animals). It is thought that plant-like eukaryotes came first, each engaging in photosynthesis and equipped with a cell wall composed of cellulose, as well as a membrane inside that wall. (The membrane required a biochemical breakthrough, the formation of sterols, related to cholesterol and to human sex hormones.) Evolution then led to organisms possessing the membrane without the wall and thus able to dispense with photosynthesis by devouring photosynthesizing organisms instead. The emergence of that capability was the key to the later appearance of true animals. The evolution of many-celled organisms from single-celled ones, presumably through aggregation, was made possible by another biochemical innovation—a glue mat can hold the cells together. Harold Morowitz and others believe mat, at least in many cases, a small change in the genome, brought about by one mutation or just a few, but coming on top of a long series of earlier changes, can trigger a gateway event and start one of the revolutions mat punctuate in major ways the relative stability of evolutionary equilibrium. In entering the realm opened up by the gateway event, an organism acquires new and very significant regularities, which raise it to a higher level of complexity. As with physical disturbances such as earthquakes (or collisions of the Earth with other objects in the solar system), such major events can be regarded either as individual occurrences of great significance or else as unusual events of great magnitude lying on the tail of a distribution comprising events that are mostly of much smaller magnitude. Aggregation Resulting in Higher Levels of Organization In the evolution of an ecological community or an economy or a society, opportunities for increased complexity keep arising, as they do in biological evolution, and result in a tendency for the maximum complexity to drift upward. The most fascinating increases in complex-

ity are those that involve a transition from a level of organization to a higher one, typically through die formation of a composite structure, as in the evolution of many-celled plants and animals from single-celled organisms. Families or bands of human beings can come together to form a tribe. A number of people can pool their efforts to make a living by constituting a business firm. In the year 1291, three cantons, soon to be joined by a fourth, founded the Swiss Confederation, which grew over dme into modern Switzerland. The thirteen North American colonies joined in a confederation and then, by ratifying die constitution of 1787, turned themselves into die federal then, by ratifying die constitution of 1787, turned themselves into die federal republic called die United States of America. Cooperation leading to aggregation can be effective. Although competition among schemata is a characteristic of complex adaptive systems, die systems themselves may indulge in a mixture of competition and cooperation in their interactions with one another. It is often beneficial for complex adaptive systems to join together to form a collective entity that also functions as a complex adaptive system, for instance when individuals and firms in an economy operate under a government that regulates their behavior in order to promote values important to die community as a whole. Cooperation of Schemata Even among schemata, competition leavened with cooperation is sometimes both possible and advantageous. In die realm of theories, for instance, competing notions are not always mutually exclusive; sometimes a synthesis of several ideas comes much closer to die truth than any of diem does individually. Yet proponents of a particular theoretical point of view can often reap rewards in academic life and elsewhere by claiming their proposal to be completely correct and entirely new, while arguing that competing points of view are wrong and should be discarded. In some fields and in certain cases, that approach may be justified. Often, however, it is counterproductive. In archaeology, for example, and in other parts of anthropology, disputes have long raged over diffusion of cultural traits versus independent invention. Yet it seems obvious that both occur. The invention of the zero in India (whence it was brought to Europe through die work

of al-Khwarizmi) seems overwhelmingly likely to have been independent of its invention in Mesoamerica (where it was employed, for example, by the Classic Maya). If contacts of some kind were responsible instead, how strange that the wheel was almost entirely lacking in the New World in pre-Columbian times (it has been found only on a few toys from Mexico, I understand) when it had been known for so long in die Old World. The bow and arrow seem to have diffused from Norm America to Mesoamerica, while numerous other cultural developments, such as die domestication of maize, spread in die opposite direction. How can scholars still be berating one another as dif- fusionists and anti-dirfiisionists? Some cultural anthropologists like to point out ecological and economic rationales for tribal customs that may appear at first sight arbitrary or irrational. In doing so, they perform a valuable service, but sometimes they go on to poke fun at the very idea mat irrationality and arbitrary choice play important roles in belief systems and patterns of social behavior. Surely that is going too far; a reasonable point of view would temper ecological and economic determinism with a measure of allowance for die vagaries of tribal schemata. For instance, a particular dietary prohibition, say against eating okapis, may make sense for a certain tribe given die nutritional needs of die population and die amount of labor needed to hunt the okapi versus producing other foods in the ecological context of the surrounding forest. However, die restrictions might also stem from a former identification with the okapi as the totem of die tribe; or a mixture of both causes may be at work. Is it wise to insist that one point of view or the other is always the right one? One of die virtues of die Santa Fe Institute is that an intellectual climate has been created in which scholars and scientists feel drawn to one another's ideas and seek, much more man at their home institutions, to find ways of harmonizing those ideas and creating useful syntheses out of them when that seems indicated. On one occasion, a seminar at the Institute was attended by several professors from die same department of die same university, who found mat they could somehow converse constructively in Santa Fe about issues mat merely provoked disputes at home. In biological evolution, die closest dung to cooperation among schemata is probably die genetics of sexual reproduction, in which die

genotypes of parent organisms become mixed in their descendants. We shall soon turn to sexual reproduction, but first let us explore further die trend toward higher complexity. Is There a Drive Toward Higher Complexity? We have seen diat the dynamics of biological evolution can be complicated. Yet it has often been portrayed in simplistic ways. The emergence of ever more complex forms has sometimes been mistaken for a steady progression toward some kind of perfection, which in turn may be identified with die species, and perhaps even die race or gender, of the author. Fortunately, mat kind of attitude is on die wane, and today it is possible to look upon evolution as a process rather dian regarding it as teleological, a means to an end. Nevertheless, even now, and even among some biologists, die idea persists to a certain extent that a "drive" toward complexity is inherent in biological evolution. As we have seen, what actually takes place is a bit more subde. Evolution proceeds by steps, and at each step, complexity can either increase or decrease, but die effect on the whole set of existing species is mat die greatest complexity represented has a tendency to grow larger with time. A similar process takes place in a community mat is growing wealdiier in such a way that any individual family may see its income grow or decline or stay the same, even though the range of incomes is growing wider, so mat the largest family income tends to keep increasing. If we were to ignore any advantages conferred on species by increased complexity, we could regard die changing distribution of complexities as a kind of diffusion, exemplified by a "random walk" on a line. A great many fleas start from die same point and keep jumping, at random, by die same distance each time, either away from the starting point or toward it (initially, of course, they all jump away). At any given moment thereafter, one or more fleas will have jumped die furthest from die starting point. Which particular fleas have gone die greatest distance may keep changing, naturally, depending on which have achieved by chance die greatest number of net jumps away from die

 1 Number of fleas i 1 Near beginning T\ Later on IV ^SsslStffl later on Distance from starting point Changing distributions of distances in a random walk. starting point. The greatest distance that any flea has moved from that point tends to keep increasing as time goes on. The distribution of the distances of the fleas from the starting point spreads out as the fleas undergo diffusion toward greater and greater distances, as shown above. The movement toward higher maximum complexity can proceed in a manner that resembles diffusion, especially in nonadaptive systems like galaxies. In complex adaptive systems such as biological evolution, though, it often happens that selection pressures favor higher complexity in certain situations. The distribution of complexities in such cases will differ, in shape as a function of time, from the result of a random walk. Although there is still no reason to believe in a steady drive toward more complex organisms, the selection pressures that favor higher complexity may often be strong. To characterize those systems and environments in which complexity is highly advantageous presents an important intellectual challenge.

 Gateway events in the course of biological evolution typically give rise to large increases in complexity and also to very significant advantages. The opening of a critical gateway results in an explosion of ecological niches, the filling of which may well look as if it were caused by a drive toward greater complexity. Since we humans are the most complex organisms in the history of biological evolution on Earth, it is understandable that some of us look upon the whole process of evolution as leading up to Homo sapiens sapiens. Even though that view is anthropocentric foolishness, there is a sense in which the role of biological evolution does end with us, or at least is now suspended. Our effect on the biosphere is so profound and our ability to now suspended. Our effect on the biosphere is so profound and our ability to transform lite (not just by ancient and slow procedures like dog breeding but by modern methods like genetic engineering) will soon be so great that the future of life on Earth really does depend in large part on crucial choices made by our species. Barring some spectacular renunciation of technology (very difficult to accomplish in view of the enormous human population we are already committed to sustaining), or the self-destruction of most of the human race—followed by the reversion of the rest to barbarism—it looks as if the role of natural biological evolution in the foreseeable future will be secondary, for better or for worse, to the role of human culture and its evolution. The Diversity of Ecological Communities Unfortunately, it will be a long time before human knowledge, understanding, and ingenuity can match—if they ever do—the "cleverness" of several billion years of biological evolution. Not only have individual organisms evolved their own special, intricate patterns and ways of life, but the interactions of huge numbers of species in ecological communities have undergone delicate mutual adjustments over long periods of time. The various communities consist of sets of species that differ, depending on the region of the globe and, within each region, on the physical environment On land, the character of the community varies according to factors such as the altitude, the rainfall and its distribution

 over the year, and the temperature and its pattern of variation. The regional differences are related to species distributions that have in many cases been affected by movements of continents over millions of years and by accidents of ancient migrations and dispersals. Thus forests tend to differ gready from one another, even within the tropics. Not all tropical forests are lowland rainforests, as certain news releases would have us believe. Some are lowland dry forests, others are montane cloud forests, and so form. Furthermore, one can distinguish hundreds of distinct rainforests, all containing significantly different flora and fauna. Brazil, for instance, is home not only to the vast expanse of Amazonian lowland rainforest, itself varying considerably in composition from place to place, but also to die very different Atlantic rainforest, now reduced to only a small percentage of its former territory. At its southern end, die Atlantic forest merges with the Alto Parana forest of Paraguay and die tropical forest of Misiones province in Argentina. The progressive destruction of die Amazonian forest is now a matter of general concern, although a huge amount of it still remains standing (sometimes, unfortunately, in a degraded condition that is not easily detectable from the air), but die preservation of what is left of die Atlantic forest is even more urgent. Likewise, deserts differ from one another. In the Namib Desert of Namibia, the flora and fauna are, in great part, different from those of the Sahara Desert at die other end of Africa, and from those of die spiny desert in southern Madagascar. The Mojave and Colorado deserts of southern California are quite distinct from each other and neither shares many species with, say, the Negev in Israel. (Note, though, that the famous cactus of Israel, the sabra, is just an import from Mexico and California.) On visits to die Colorado Desert and to die Negev, superficial looks will reveal many resemblances in appearance of die flora, but much of that similarity is attributable not to close relationship of species but to evolutionary convergence, die result of the operation of similar selection pressures. Likewise, many euphorbias of the arid high plains of East Africa resemble New World cacti, but only because they have adapted to similar climates; they belong to different families. Evolution has produced a number of distinct but similar solutions, in various parts of die globe, to die problem of a community of organisms living under a given set of conditions.

 Faced with such a wide variety of natural communities, will human beings have the collective wisdom to make appropriate policy choices? Have we acquired die power to effect enormous changes before we have matured enough as a species to use that power responsibly? The Biological Concept of Fitness Ecological communities made up of many complex individuals, belonging to a large number of species, all evolving schemata for describing and predicting one another's behavior, are not systems likely to reach or even closely approach an ultimate steady state. Each species evolves in die presence of constandy changing congeries of other species. The situation is about as different as it could be from mat of die oceanic extremophiles, which evolve in a fairly constant physicochem- ical environment and interact with other organisms mainly through the organic matter mat descends to their level through die water. Even a comparatively simple and nearly self-contained system such as mat of die extremophiles cannot usually be assigned a rigorously defined numerical attribute called "fitness," and certainly not one that continues to increase, as evolution proceeds, until a steady state is achieved. Even in such a simple case, it is much safer to concentrate direcdy on me selection pressures, die effects that favor one phenotypic character over another and thus affect me competition among die different genotypes. Those selection pressures may not be expressible in terms of a single, well-defined quantity called fitness. They may require a more complicated description, even in the idealized case of a single species adapting to a fixed environment. It is even less likely, then, that a truly meaningful measure of fitness can be assigned to an organism when die environment is changing, and especially when it belongs to a highly interactive ecological community of organisms adapting to one another's peculiarities. Still, a simplified discussion of biological evolution in terms of fitness can often be instructive. The idea underlying die biological concept of fitness is mat propagation of genes from one generation to die next depends on survival of die organism until it reaches die stage of reproduction, followed by die generation of a reasonable number of

offspring mat in turn survive to reproduce. Differential rates of survival and reproduction can often be roughly described in terms of a fitness quantity, defined so that that there is a general tendency for organisms with higher fitness to propagate their genes more successfully than those with lower fitness. At the extreme, organisms with genetic patterns that are consistently associated with failure to reproduce have very low fitness and tend to disappear. Fitness Landscapes One general difficulty becomes apparent when we introduce the crude notion of a "fitness landscape." Imagine the different genotypes to be laid out on a horizontal two-dimensional surface (standing for what is really a multidimensional mathematical space of possible genotypes). Fitness or unfitness is represented by height; as the genotype varies, the fitness describes a two-dimensional surface, with a great many hills and valleys, in three dimensions. Biologists conventionally represent fitness as increasing with increasing height, so that maxima of fitness correspond to the tops of hills and minima to the bottoms of pits; however, I shall use the reverse convention, which is customary in many other fields, and turn the whole picture upside down. Now fitness increases with depth, and the maxima of fitness are the bottoms of depressions, as shown on page 250. The landscape is very complicated, with numerous pits ("local maxima of fitness") of widely varying depths. If the effect of evolution were always to move steadily downhill— always to improve fitness— then the genotype would be likely to get stuck at the bottom of a shallow depression and have no opportunity to reach the deep holes nearby that correspond to much greater fitness. At the very least, the genotype must be moving in a more complicated manner than just sliding downhill. If it is also jiggling around in a random way, for example, that will give it a chance to escape from shallow holes and find deeper ones nearby. There must not be too escape from shallow holes and find deeper ones nearby? There must not be too much jiggling, however, or the whole process will cease to work. As we have seen in a variety of connections, a complex adaptive system functions best in a situation intermediate between order and disorder.

250 • SELECTION AND FITNESS A fitness landscape, with increasing fitness corresponding to greater depth. Inclusive Fitness A further complication in utilizing the concept of fitness arises in higher organisms that make use of sexual reproduction. Each such organism conveys only half its genes to a given offspring, while die remaining half derive from the odier parent. The offspring are not clones, but merely dose relatives. And die organism has odier close relatives, die survival of which can also contribute to the propagation of genes similar to its own. Thus biologists have developed die notion of "inclusive fitness," which takes account of the extent to which relatives of a given organism survive to reproduce, weighted according to die closeness of die relationship. (Of course inclusive fitness also takes account of the survival of the organism itself.) Evolution should have a general tendency to favor genotypes exhibiting high inclusive fitness.

SELECTION IN BIOLOGICAL EVOLUTION AND ELSEWHERE • 251 especially through inherited patterns of behavior that promote the survival of an organism and its close relatives. That tendency is called "kin selection," and it fits in nicely with a picture of evolution in which organisms are merely devices "used" by genes to propagate themselves. That point of view has been popularized under the name of the "selfish gene." The Selfish Gene ana the "Truly Selfish Gene" An extreme form of the selfish gene phenomenon can occur in what is called "segregation distortion." As described by the sociobiologist Robert Trivets, segregation distortion could result from the operation of a "truly selfish gene." He means a gene that works directly, not through the resulting organism, to promote its success in competition with rival genetic patterns. Such a gene present in a male animal may cause the sperm bearing it to outrace or even poison other sperm, and so to win out more easily in the competition to fertilize the eggs of the female. A truly selfish gene need not, however, confer any advantage on the resulting organism, and may even be somewhat harmful. Apart from such remarkable possible exceptions, selection pressures are exerted indirectly, through the organism produced by the sperm and the egg. That is more in line with the notion of a complex adaptive system, in which the schema (in this case the genome) is tested in the real world (in this case by means of the phenotype) rather than directly. Individual ana Inclusive case by means of the phenotype) rather than directly. Individual and Inclusive Fitness A fascinating case in which ordinary individual fitness and inclusive fitness both seem to be involved is die so-called altruistic behavior of certain species of birds. The Mexican or gray-breasted jay lives in arid habitats in northern Mexico, southeastern Arizona, and southwestern New Mexica Ornithologists observed years ago that a given nest of that species was often tended by many birds, not just the couple that produced die eggs. What were mose other jays doing there? Were they really behaving altruistically? The research of Jerram Brown revealed that the helpers were in most cases themselves offspring of the nesting

 pair; they were helping to raise their own siblings. That behavior seemed to provide a striking example of evolution of social behavior via inclusive fitness. Evolution had favored a behavior pattern in which young jays, postponing their own reproduction, helped to feed and guard their younger siblings, thus assisting die propagation of genes closely related to their own. More recently, the picture has become more complicated as a result of the work of John Fitzpatrick and Glen Woolfenden on a related kind of jay, the Florida scrub jay, which is found in the rapidly disappearing arid oak scrub habitat of soumern Florida. Until now mat bird has usually been considered one of many subspecies of me scrub jay, which is very common in the southwestern United States, but Fitzpatrick and Woolfenden are proposing that it be treated as a separate species, on account of its appearance, vocalizations, behavior, and genetics. The behavior includes helping at the nest, as in the case of the gray-breasted jay. Here again the helpers are apt to be offspring of the nesting pair, but the observations of the Florida researchers indicate mat the helpers are serving their own interests as well as their siblings'. Nesting territories in the oak scrub are large (on the order of thirty acres), fiercely defended, and not easy to come by. The helpers are in the best position to inherit all or part of the territory where they are working. In Florida, at least, it looks as if ordinary individual fitness plays a very important role in "altruistic" scrub jay behavior. I have introduced the scrub jay story not in order to take sides in a controversy among ornithologists, but just to illustrate the subtlety of the whole idea of fitness, whether inclusive or not Even when fitness is a useful concept, it is still a bit circular. Evolution favors the survival of the fittest, and the fittest are those who survive, or whose close relatives survive. Tlie Rtness of Sex The phenomenon of sexual reproduction poses some special challenges to theories of selection pressures and fitness. Like numerous other organisms, higher animals tend to reproduce sexually. Yet in many cases the same animals are not incapable of parthenogenesis, in which females give birth to female offspring with identical genetic material, except for

possible mutations. The services of a male are not required. Even the eggs of an animal as complex as a frog can be stimulated, say with a needle prick, to produce tadpoles that grow into adult frogs. In a very few cases, such as the whiptailed lizards of Mexico and the southwestern United States, whole species of vertebrates seem to manage using parthenogenesis alone, with no males at all. Why sex then? What is the enormous advantage that sexual reproduction confers? Why is it usually selected over parthenogenesis? What are males really good for? Sexual reproduction introduces diversity into the genotypes of offspring. Roughly speaking, the chromosomes (each containing a string of genes) come in corresponding pairs and an individual inherits one of each pair from the father and one from the mother. Which one it inherits from each parent is largely a matter of chance. (In identical twins, these otherwise stochastic choices come out the same for both.) The offspring of organisms with many chromosome pairs generally have different sets of chromosomes from those of either parent. In addition, sexual reproduction introduces a whole new mechanism, other than ordinary mutation, for change in the chromosomes. In the process called "crossing-over," illustrated on page 254, a pair of corresponding chromosomes from either the father or the mother can get partially switched with each other in the formation of a sperm or an egg, respectively. Say the crossing-over occurs in the case of the egg, contributed by the mother. The egg acquires a mixed chromosome consisting of a part contributed by the mother's father and the rest by the mother's mother, while another egg may receive a chromosome consisting of the remaining parts of the maternal grandfather's and grandmother's chromosomes. The evolutionary theorist William Hamilton, now the holder of a chair at Oxford, has suggested a simple explanation for the value of sexual reproduction. Roughly speaking, his idea is mat enemies of a species, especially harmful parasites, find it harder to adapt to the diverse attributes of a population generated by sexual reproduction man to the comparative uniformity of a population produced by parthenogenesis. The mingling of chromosomes contributed by father and mother and also the process of crossing-over allow all sorts of new combinations to occur among the offspring, forcing the parasites to cope with a wide variety of hosts, presenting different body chemistry, different habits, and so form. As a result, the enemies have trouble and the hosts are safer.

254 • SELECTION AND FITNESS #**BfcS»*5«Sffie Chromosome from mother's father (2 DNA strands) Chromosome from mother's mother (2 DNA strands) Doubled chromosome from mother's rather (2 "sister chromatids" comprising 4 DNA strands) Doubled chromosome from mother's mother (2 "sister chromatids" comprising 4 DNA strands) First new doubled chromosome for mother (4 DNA strands) Second new doubled chromosome for modier (4 DNA strands) ^""in'iflf-^* '■»*—"^ New single chromosomes for mother's germ cells ^^..■AUdfeMMBI (2 DNA strands each) wm&mt&sme Crossing-over of chromosomes in sexual reproduction. The theory indicates that species without sexual reproduction should have other mechanisms for coping with parasites, especially in die case of whole groups of lower animals that have been without sex for tens of millions of years. The bdelloid rotifers form such a group. They are wheel animalcules inhabiting places, like beds of moss, that are moist most of the time but become dry every few weeks or months, depending on vagaries of the weather. A student of Hamilton's, Olivia Judson, is studying those rotifers and trying to establish how they deal with parasites. She suggests that their habit of desiccating and blowing away when their surroundings dry up may afford them enough protection from parasites that they can dispense with sex.

SELECTION IN BIOLOGICAL EVOLUTION AND ELSEWHERE • 255 In any case, the advantages of sexual reproduction must be considerable to outweigh die obvious disadvantage of breaking up die successful genotypes of parents and grandparents that survived long enough to reproduce. These advantages accrue to die population as a whole, however, while many evolutionary biologists insist mat selection pressures are exerted only on individuals. Perhaps mat need not be a rigid rule. At a recent Santa Fe Institute meeting, John Maynard Smith, who teaches at the University of Sussex, was commenting on mis issue, when Brian Arthur, chairing the session, recalled the occasion when they first met Both men have a background in engineering. Maynard Smith became an aircraft designer and men took up evolutionary biology, to which he has made some remarkable contributions. Brian, who grew up in Belfast, went into operations research and then economics, becoming a professor at Stanford and die founding director of die economics program at the Santa Fe Institute. They first encountered each odier at a scientific meeting in Sweden, where Maynard Smidi remarked in die course of a lecture mat while sex had obvious advantages for a population, it was not clear what it did for the individual. Brian called out from the audience, "What a very English view of individual. Brian called out from the audience, "What a very English view of sex!" Maynard Smith, without missing a beat, replied, "I gamer from your accent that you're Irish. Well, in England at least we have sex." Death, Reproduction, ana Population in Biology While sex is by no means universal in biology, death comes pretty close to being so. The deadi of organisms is one of the more dramatic manifestations of die second law of diermodynamics. As such, it is in a sense common to all complex adaptive systems. However, it is especially significant in biological evolution, where die interplay between deadi and reproduction is at the forefront of die adaptive process. Competition between clusters of genotypes translates to a considerable degree into competition for population size among die corresponding kinds of organisms. To die extent mat fitness is well defined in biological evolution, it is connected widi population size. Comparison of various types of complex adaptive systems reveals systems in which deadi, reproduction, and population are less important than in biology. For example, take an individual human being deep in

 thought, solving a problem. The schemata in that case are ideas instead of genotypes. The analogue of death is forgetting. No one can deny the prevalence or the significance of forgetting, but it hardly plays the same role as death in biology. If mere were no need for forgetting, no need to "erase the tape," the character of thinking would not change dramatically. Recording an idea is useful, and it counteracts the efiea of forgetting, but the number of identical or nearly identical memoranda does not characterize the fitness of an idea to the same extent that population tends to correlate with fitness in biology. As ideas spread through a society (even the scientific community), the number of people sharing a given idea does have importance. In democratic elections, to the extent that they are concerned with ideas, the majority opinion prevails. Still, it is notorious that even overwhelming numbers of adherents do not necessarily render an idea correct, and may not even guarantee its survival in the long run. For a case more like that of biological evolution, we can turn to the competition among human societies in the past, lb a great extent, fitness was measured by population. In Southeast Asia, for instance, some ethnic groups practiced irrigated rice agriculture while others raised dry rice, often by slashing and burning the forest. The irrigated- rice peoples, such as the Central Thai, the Lao, or the Vietnamese, were able to put many more individuals on the ground per unit area than their neighbors. Denser population helped mem to dominate the dry- rice peoples, and in many cases to drive them back into remote hilly terrain. Looking toward the future, we may well ask whether it is desirable for density or total numbers to continue to determine winners and losers in the same way. The Riling of Nick es Biological evolution, with its emphasis on death and population, is fairly efficient in the long term at filling ecological niches as they arise. When there is an opportunity to make a living in a certain way, it is probable that some organism will evolve to exploit it, even if that way of living may seem rather bizarre to a human observer. The analogy between an ecological community and a market economy is relevant in this connection. As opportunities for making a profit arise in such an economy, individuals or firms are likely (akhough by no

means certain) to come along to take advantage of diem. The analogue of death in this case is going broke, and wealth instead of population is a crude measure of die fitness of a firm. In both economics and ecology, die advent of a new business or a new organism (or of a new type of behavior in an existing firm or organism) will alter die fitness landscape for the other members of die community. From die point of view of a business or a species, that landscape is constandy changing (besides not being altogedier well defined in die first place). Bodi of diese cases illustrate how a complex adaptive system, once established, can fill niches, create new ones in the process, fill diose in turn, and so on, spawning new complex adaptive systems along die way. (As indicated in the diagram on page 20, biological evolution has given rise to mammalian immune systems, to learning and thinking, and, through human beings, to societies that learn and adapt, and recendy to computers that function as complex adaptive systems.) Always exploring, seeking out opportunities, experimenting widi novelty, die complex adaptive system tries out increases in complexity and occasionally discovers gateway events that open up die possibility of whole new structures, including new kinds of complex adaptive systems. Given enough time, die likelihood of the evolution of intelligence would seem to be high. Astronomers and planetary scientists are not aware of any reason why planetary systems should be especially rare in our galaxy or in other similar galaxies elsewhere in die universe. Nor have theorists of the origin of life come up widi anything so remarkable about die conditions on our own planet some four billion years ago that die origin of life (or something like life) on a planet would be a particularly improbable event. It is likely that complex adaptive systems abound in die universe and that a great many of diem have evolved or will evolve intelligence. As mentioned earlier, die principal statistical unknowns in die Search for Extraterrestrial Intelligence (SETI) are die number ofplanets per unit volume of space on which inteUigent beings have arisen and die length of time diat dieir period of technical civilization, widi emission of wireless signals, typically lasts. Given the immense amount we can learn from die diversity of natural communities on Earth, to say nodiing of die diversity of human societies, it is mind-boggling to imagine (as science fiction writers sometimes do) die

 lessons that contact with extraterrestrials could teach us about the variety of circumstances mat complex adaptive systems can exploit. Deception Among Birds For amusing examples of the exploitation of opportunities by species interacting with other species, we can turn to lying as practiced by animals other than humans. Deception by mimicry is well known; the viceroy butterfly, for instance, resembles the monarch and thus profits by die bad taste of the latter. The cuckoo (in the Old World) and the cowbird (in the New World) practice another kind of deception by laying their eggs in the nests of other birds; the intrusive chicks men do away with the eggs or chicks that belong in the nest and monopolize me attention of the foster parents. But actual lying? We are accustomed to hearing people lie, but it is somehow more surprising in other organisms. When the Argentine Navy spots a mysterious periscope in the estuary of me Rio de la Plata just before the budgets of the armed forces are to be considered by the legislature, we suspect that deception is being practiced so as to capture additional resources, and we are not particularly astonished. But the analogous behavior among birds is more unexpected. One such case was discovered recently by my friend Charles Munn, an ornithologist studying mixed feeding flocks in the lowland tropical forest of Manu National Park in Peru. Some species forage together in the understory or lower canopy of the forest and others in the middle canopy, where they are sometimes joined by colorful fruit-eating tana- gers from the upper canopy. (Among the species found in those flocks in winter are a few Norm American migrants. Further north in South and Central America mere are many more. We residents of North America know mem as nesting species in the summer and are intrigued to find mem leading a very different life in a distant land. If they are to return year after year to nest, their habitats in the southern countries must be protected. Likewise, their return to those countries will be jeopardized if Norm American forests are chopped up into still smaller parcels than the ones now remaining. For one thing, thinning out the forests permits further inroads by parasitic cowbirds.) In each mixed feeding flock, mere are one or two sentinel species, which move about in such a way mat they are usually near the center of the flock or just below. The sentinels warn die odiers by a special call of approaching birds that might turn out to be raptors. Charlie nodced that the sendnels for the understory flocks sometimes gave die warning signals even when no danger was apparent. Looking more closely, he found that the fake alarm often permitted the sentinel to grab a succulent morsel mat another member of die flock might otherwise have eaten. Careful observation revealed mat die sendnels were practicing decepdon about 15 percent of die dme and often profiting by it. Wondering if the phenomenon might be more general, Charlie examined die behavior of die middle canopy flocks and found die sendnels there doing die same thing. For die two species of sendnels, die percentage of false signals was about the same. Presumably, if die percentage were much higher, the signals would not be accepted by the rest of the flock (recall the story Vie Boy Wlio Cried "Wolf"), and if it were much lower, the opportunity for the sendnel to obtain extra food by lying would be partially or wholly wasted. I am intrigued by die challenge of deriving by some kind of madiemadcal reasoning die figure of about 15 percent; in a plausible model, might it come out one divided by two pi? When I asked that question of Charles Bennett, he was reminded of something his fadier had told him about Royal Canadian Air Force units based in England during the Second World War. They found it useful, when sending out a fighter and a bomber togedier, to attempt occasionally to deceive the Luftwaffe by positioning die fighter below the bomber rather dian above. After a good deal of trial and error, diey ended up following that practice at random one time in seven. Small Steps ana Large Changes In our discussion of gateway events, we listed some examples of developments in biological evolution that look like enormous jumps, but we also pointed out that diose are rare occurrences at one end of a whole spectrum of changes of various magnitudes, the small changes near die other end of the spectrum being much more common. Whatever die magnitude of die event, biological evolution typically proceeds by working widi what is available. Existing organs are adapted to new uses. Human arms, for example, are just slighdy modified forelegs. Structures are not suddenly discarded in a revolutionary redesign of the whole

 organism. The mechanisms of mutation and natural selection do not favor such discontinuities, which would typically be lethal. Yet revolutions do occur. We discussed how, in the phenomenon of "punctuated equilibrium," the comparatively sudden changes can have several "punctuated equilibrium," the comparatively sudden changes can have several different origins. One is a change in the physicochemical environment that alters selection pressures significantly. Another is the result of "drift," in which neutral mutations, ones that do not disturb the viability of the phenotype (and sometimes do not much alter it) gradually lead to a kind of instability of the genotype. In this situation, one mutation or just a few can make a significant difference to the organism and prepare the way for a cascade of changes in a variety of other species as well. Sometimes small changes set off gateway events, often biochemical in character, that open up whole new realms of life forms. In some cases, these revolutionary changes stem from aggregation of organisms into composite structures. But in every case the basic unit of change is a mutation (or recombination, with or without crossing-over) that operates on what is already present Nothing is invented out of whole cloth. How general is that principle for complex adaptive systems? In human thinking, for instance, is it necessary to proceed by small steps? Does the process of invention entail just making strings of minor changes in what already exists? Why shouldn't a human being be able to invent a device that is totally new, totally different from anything known? In science, why not conceive a completely new theory, which bears no resemblance to previous ideas? Research (as well as everyday experience) seems to indicate that in fact human thought usually does proceed by association and in steps, at each of which specific alterations are made in what has already been thought Yet remarkable new structures do sometimes emerge, in invention, in science, in art, and in many other fields of human endeavor. Such breakthroughs remind us of gateway events in biological evolution. How do they come about? Does human creative thinking follow different patterns in these different areas of activity? Or are mere some general principles involved?

c*hPTEf, 17 FROM LEARNING TO CREATIVE THINKING Let us begin with some observations on creative achievement in theoretical science and then explore its relationship to certain kinds of creative achievement in other fields. A successful new theoretical idea typically alters and extends the existing body of theory to allow for observational facts that could not previously be understood or incorporated. It also makes possible new predictions that can some day be tested. Almost always, the novel idea includes a negative insight, the recognition that some previously accepted principle is wrong and must be discarded. (Often an earlier correct idea was accompanied, for historical reasons, by unnecessary intellectual baggage that it is now essential to jettison.) In any event, it is only by breaking away from the excessively restrictive received idea that progress can be made. Sometimes a correct idea, when first proposed and accepted, is given too narrow an interpretation. In a sense, its possible implications are not taken seriously enough. Then either the original proponent of that idea or some other theorist has to return to it, taking it more seriously than when it was originally put forward, so that its fall significance can be appreciated. a6/

 Both the rejection of a wrong received idea and the return to a correct idea not applied broadly enough are illustrated by Einstein's first paper on special relativity, which he published in 1905, at the age of 26. He had to break away from the accepted but erroneous idea of absolute space and time. Then he could take seriously as a general principle the set of symmetries of Maxwell's equations for electromagnetism—the symmetries that correspond to special relativity. Hitherto they had been viewed narrowly as applying to electromagnetism but not, for example, to the dynamics of particles. An Example from Personal Experience It has been my pleasure and good fortune to come up with a few useful ideas in elementary particle theory, not of course in a class with Einstein's, but interesting enough to give me some personal experience of the act of creation as it applies to theoretical science. One example, from very early in my career, will suffice as an illustration. In 1952, when I joined the faculty of the University of Chicago, I tried to explain the behavior of the new "strange particles," so called because they were copiously produced as though strongly interacting and yet they decayed slowly as though weakly interacting. (Here "slowly" means a half-life of something like a ten billionth of a second; a normal rate of decay of a strongly interacting particle state would correspond to a half-life more like a trillionth of a trillion th of a second, roughly the time it takes light to cross such a particle.) I surmised correctly that the strong interaction, responsible for the copious production of the strange particles, was prevented by some law from inducing the decay, which was men forced to proceed slowly by means of the weak interaction. But what was the law? Physicists had long speculated about conservation by the strong interaction of a quantity called isotopic spin /, which can have values 0,1/2,1,3/2,2,5/2, and so on. Experimental evidence in favor of the idea was being gathered at mat time by a group of physicists down the hall, led by Enrico Fermi, and I decided to see if the conservation of isotopic spin could be the law in question. The conventional wisdom was that nuclear (strongly interacting) particle states that are fermions like the neutron and proton would have

 to have values of/ equal

to 1/2 or 3/2 or 5/2, and so on, following the example pf the neutron and proton, which have / = 1/2. (The idea was reinforced by die fact that fermions must have spin angular momentum equal to 1/2 or 3/2 or 5/2, and so on.) Likewise it was believed mat the bosonic strongly interacting particles, the mesons, would have to have / = 0 or 1 or 2, and so forth, like me known meson, me pion, which has 7=1. (Again the parallel with spin angular momentum, which must be a whole number for a boson, strengthened belief in the received idea.) One' set of strange particles (now called sigma and lambda particles) consists of strongly interacting fermions decaying slowly into pion (7 f 1) plus neutron or proton (7 s 1/2). 1 thought of assigning these strange particles isotopic spin / = 5/2, which would keep the strong interaction from inducing me decay. But mat notion failed to work because electromagnetic effects such as me emission of a photon could change / by one unit at a time and thus evade the law mat would otherwise forbid rapid decay. I was invited to talk at the Institute for Advanced Study in Princeton on my idea and why it didn't succeed. In discussing me sigma and lambda particles , I was going to say "Suppose they have 7 = 5/2, so mat me strong interaction cannot induce their decay" and then show how electromagnetism would wreck the argument by changing 7=5/2 into 7 - 3/2, a value that would permit me decay in question to proceed rapidly by means of the strong interaction. By a slip of the tongue I said "/ = 1" instead of"/ = 5/2." Immediately I stopped dead, realizing that / = 1 would do the job. Electro- magnetism could not change 7 = 1 into 7 = 3/2 or 1/2, and so me behavior of me strange particles could now be explained after all by means of conservation of/. But what about the alleged rule mat fermionic strongly interacting particle, states had to have values of / like 1/2 or 3/2 or 5/2? I realized instantly mat the the rule was merely a superstition; mere was no real need for it. It was unnecessary intellectual baggage that had come along with the useful concept ofisotopic spin /, and the time had come to get rid of it. Then isotopic spin could have wider applications man before. The explanation of strange particle decay mat arose through that slip of the tongue proved to be correct. Today, we have a deeper understanding of the explanation and a correspondingly simpler way of stating it: die strange particle states differ from more familiar ones such as neutroh or proton or pioris by having at least one s or "strange" quark

 in place of a u or d quark. Only the weak interaction can convert one flavor of quark into another, and that process happens slowly. eriences or Conceiving Creative Ideas Around 1970 I was one of a small group of physicists, biologists, painters, and poets assembled in

Aspen, Colorado to discuss the experience of getting creative ideas. We each described an incident in our own work. My example was the one involving the slip of me tongue during die lecture in Princeton. The accounts all agreed to a remarkable extent We had each found a contradiction between the established way of doing things and something we needed to accomplish: in art, the expression of a feeling, a thought, an insight; in meoretical science, the explanation of some experimental facts in me face of an accepted "paradigm" that did not permit such an explanation. First, we had worked, for days or weeks or months, filling our minds with me difficulties of the problem in question and trying to overcome mem. Second, mere had come a time when further conscious thought was useless, even though we continued to carry the problem around wim us. Third, suddenly, while we were cycling or shaving or cooking (or by a slip of the tongue, as in the example I described) the crucial idea had come. We had shaken loose from the rut we were in. We were all impressed with the congruence of our stories. Later on I learned that this insight about the act of creation was in fact rather old. Hermann von Helmholtz, me great physiologist and physicist of the late nineteenth century, described me three stages of conceiving an idea as saturation, incubation, and illumination, in perfect agreement with what the members of our group in Aspen discussed a century later. Now what goes on during the second stage, that of incubation? For the psychoanalytically oriented, among others, an interpretation mat comes immediately to mind is that mental activity continues during the incubation period, but in the "preconscious mind," just outside of awareness. My own experience wim the emergence of the right answer in a slip of the tongue could hardly fit better wim that interpretation. But some academic psychologists, skeptical of such an approach, offer an alternative suggestion, that nothing really happens during incubation

 except perhaps a weakening of one's belief in the raise principle that is obstructing die search for a solution. The real creative dunking takes place, in their view, just before die moment of illumination. In any case, an .appreciable dme interval typically elapses between saturation and illumination, and we can think of mat interval as a period of incubation whether we picture intense thought out of awareness or just allowing some prejudice gradually to lose its capacity for hindering a solution. In 1|908, Henri Poincare added a fourth stage, important although rather obvious—verification. He described his own experience in developing a theory of a certain kind of mathematical function. He worked! on die problem theory of a certain kind of mathematical function. He worked: on die problem steadily for two weeks without success. One night, sleepless, it seemed to him diat "ideas rose in crowds; I felt diem collide until pairs interlocked, so to speak, making a stable combination." Still he did not have die solution. But, a day or so later, he was boarding a bus that was to take him and some colleagues on a geological field trip. "The idea came to me, widiout anydiing in my thoughts seeming to have paved die way for it, diat die transformations I had us^d to define these functions were identical with those of non- Euclidean geometry. I did not verify die idea, and on taking my seat, went on widi a conversation already begun, but I felt a perfect certainty. On my|return to Caen, for consciences sake, I verified the result." The psychologist Graham Wallas formally described die four-stage process in 1926, and it has been standard ever since in the relevant branch'of psychology, diough I think none of us at die Aspen meeting had ever heard of it. I first came across it in a popular book by Morton Hunt entitled The Universe Within, from which die above translated quotations are drawn. I ! ; Can Incubation Be Hastened or Circumvented? i Now, is it necessary to go through diat process? Can die stage of incubation be hastened or circumvented so diat we do not have to wait so Ions for die requisite new idea to come? Can we find a quicker way to escape from an intellectual rut in which we are trapped? A jiumber of people who offer special programs to teach thinking skills believe diat one of die skills they can enhance is creative thinking.

Some of their suggestions for helping to get the thinking process out of a rut fit in quite well with a discussion of that process in terms of complex adapdve systems. Learning and thinking in general exemplify complex adapdve systems at work, and perhaps the highest expression on Earth of that kind of skill is human creative thinking. A Crude Analysis in Terms or a Fitness Landscape As in other analyses of complex adaptive systems, it is instructive to introduce the notions of fitness and fitness landscape although, even more than in the case of biological evolution, those concepts are oversimplified idealizations. It is unlikely that a set of selection pressures occurring in the thinking process can be expressed in terms of a well- defined fitness. That is especially true of an artist's search for creative ideas. In science, the concept is probably more nearly applicable. The fitness of a theoretical idea in science would be a measure of the extent to which it improves existing theory, say by explaining new observations while maintaining or increasing the coherence and explanatory power of that existing theory. In any case, let us imagine that we have a fitness landscape for creative ideas. We shall continue to associate decreasing height with increasing fitness (compare the diagram on page 250). As we saw in the case of biological evolution, it is too simplistic to suppose that a complex adaptive system merely slides downward on the landscape. When entering a depression, the system would move steadily downhill until it reaches the bottom, the local maximum of fitness. The region from which downhill motion leads to that spot is called the basin of attraction. If the system did nothing but slide downward, it would be overwhelmingly likely to get stuck at the bottom of a shallow basin. On a larger scale there are many basins, and a number of them may be deeper (and therefore more fit, more "desirable") than the one the system has found, as shown on page 250. How does the system get to explore those other basins? One method of getting out of a basin of attraction, as discussed earlier for biological evolution, involves noise, that is to say, chance motion superimposed on the tendency to descend. Noise gives the system a chance to escape from a shallow depression and seek out a

 deeper one nearby, and to perform mat operation over and over, until the bottom of a really deep basin is reached. The noise must be such that the amplitudes of the chance excursions are not too great, however. Otherwiise there would be. too much interference with the process of descent,, and the system would not remain in a deep basin even after finding one. Another possibility is to have pauses in the steady downhill crawling process j that allow for freer exploration of the vicinity. Those might permit the discovery of deeper depressions nearby. To some extent such pauses correspond to the incubation process in creative thinking, in which the methodical search for the needed idea is suspended and exploration may continue outside of awareness. Some Prescriptions tor How to Escape into a Deeper Basin Some of the suggestions for speeding up the process of conceiving a creative idea fit in well with the picture of using a controUed level of noise to avoid getting stuck in too shallow a basin of attraction. One can try, to escape from the original basin by means of a random pertur- bation-|—for example Edward DeBono recommends trying to apply to a problem, whatever it is, the last noun on the front page of today's newspaper. Another method is akin to brainstorming, which has been used throughout the postwar era. Here several people try to find solutions to a problem by meeting for a group discussion in which one is encouraged to build on someone else's suggestion but not to attack it, no matter how bizarre it is. A crazy or self-contradictory proposal can represent an unstable state of thinking leading to a solution. DeBono likes to cite as an example a discussion of river pollution control, in which1 someone might say, "What we really need is to make sure mat factories are downstream! from themselves." That is a manifesdy impossible suggestion, but someone else might men come up with a more serious proposal, saying "You can do something like that if you require the inrake of water at each factory to be downstream from the effluent." The crazy idea can be regarded as a rise on a fitness landscape that can lead to a much deeper basin man the one from which the discussion started.

 Transfer of TWking Skills? Edward and many others have prepared teaching materials for special courses in dunking skills for schools, as well as for companies and even for groups of neighbors. Some of those skills relate to getting creative ideas. A number ofsuch courses have been tried out in various parts of die world. For example, a recent president of Venezuela created a Ministry of Intelligence to encourage die teaching of dunking skills in the schools of mat country. Under die auspices of die new ministry, a great many students have been exposed to various courses in thinking. Frequendy the materials for such courses emphasize thinking skills in particular contexts. For example, many of Edward's exercises have to do widi what I would call policy analysis or policy studies. They refer to choices among courses of action, at the level of die individual, family, organization, village or city, state or province, nation, or transnational body. (Such an exercise may begin, for instance, with the hypothesis mat a particular new law has been passed; possible consequences of die law are then discussed.) The materials typically relate to finding and analyzing arguments for and against various known options and also to the discovery of new ones. One question mat naturally arises is to what extent dunking skills learned in one connection are transferable to others. Does exercising one's mind by thinking up new policy options (or ways to weigh the relative merits of old ones) help one to discover good new ideas in a field of science or to create great works of an? Does exercising the mind in such a fashion help one to learn in school about science or mathematics or history or languages? Some day it may be possible to give answers to such questions. Meanwhile, only very preliminary information is becoming available. Testing Whether Various Proposed Methods Actually Work When someone takes a course in dunking skills, it is an especially difficult challenge to determine whether any improvement has in fact taken place in the student's capacity for creative thinking. Ideally, a test

 would be more or less

 would be more or less standardized, so that interested parties such as parents, school and government officials, and legislators would be impressed by die results. But how can a standardized test begin to measure creative thinking? One partial answer is provided by design problems. For example, I am told diat in Venezuela, at one point, students of thinking were asked to design a table for a small apartment. It is conceivable that die answers to such problems, if graded carefully and imaginatively, might give some indication of whether the students were absorbing creative thinking skills. David Perkins, of the Harvard Graduate School of Education, who i was involved in assigning die table problem, is especially interested in infusing the whole school curriculum with the teaching of thinking skills rather than using special courses. He emphasizes that the need for creative ideas does not arise only in die stratospheric realms of science and art, but also in everyday life. He cites the example of a friend who saves die day, at a picnic where no one has diought to bring a knife, by slicingjdie cheese neatly widi a credit card. David points out that research has identified a number of characteristics of people who can repeatedly succeed, in die domain of ideas, in escaping from a basin of attraction into another, deeper one. Those characteristics include a dedication to die task, an awareness of being trapped in an unsuitable basin, a degree of comfort with teetering on the edge between basins, and a capacity for formulating as well as solving problems. It seems unlikely mat in order to possess those traits one has to be born with diem. It may well be possible to inculcate them, but it is far from clear that today's schools do so to any important degree. For example, as David notes, schools are just about die only places where one typically finds problems already formulated. Problem Formulation an J me True Boundaries of a Problem j Problem formulation involves finding die real boundaries of die problem. To illustrate what I mean by that, I shall take some cases that my friend, former neighbor, and Yale classmate Paul MacCready likes to use in his public lectures as examples of novel solutions to problems. (Paul is the inventor of the bicycle-powered aircraft, the solar-powered air-

 craft, the artificial flapping pterodactyl, and other devices on what he modesdy calls the "backwards frontier of aerodynamics.") Although I use the same examples as he does, the lesson that I draw from them is somewhat different. Consider the famous problem illustrated on the facing page: "Connect all the nine dots by drawing the smallest possible number of straight lines without taking the pencil off the paper." Many people assume that they have to keep the lines within the square formed by the outer dots, although that constraint is not part of the problem as stated. They will then require five lines to solve it. If they allow themselves to extend the lines beyond the square, then they can get away with four, as illustrated. If this were a problem in the real world, a crucial step in formulating it would be to find out whether there is any reason to confine the lines inside the square. That is part of what I call determining the boundaries of the problem. If the problem allows the lines to be extended beyond the square, perhaps it allows some other kinds of latitude as well. What about crumpling up the paper so that the dots are all in a row and driving a pencil straight through them all in a single stroke? Several such ideas are taken up by James L. Adams in his book Conceptual Blockbusters. The best one is contained in a letter he received from a little girl, reproduced on page 272. The main point is in her last sentence: "It doesn't say you mustn't use a thick line." Is a thick line forbidden or not? What are the rules in the real world? As always, determining the boundaries of the problem is a principal issue in problem formulation. That point is made even more strongly in "The Barometer Story,"* written by a physics professor, Dr. Alexander Calandra of Washington University in St. Louis. Some time ago, I received a call from a colleague who asked if I would be the referee on the grading of an examination question. It seemed that he was about to give a student a zero for his answer to a physics question, while the student claimed he should receive a perfect score and would do so if the system were not * From Teacher's Edition of Current Sdente, Vol. 49, No. 14, January 6-10, 1964. Courtesy of Robert L. Semans.

 Connecting nine dots in a square with four straight lines widiout lifting the pencil from the paper. set up against the student. The instructor and the student agreed to submit this to an impartial arbiter, and I was selected I went to my colleague's office and read the examination question, which was, "Show how it is possible to determine the height of a tall building with the aid of a barometer." The student's answer was, "Take the barometer to the top of the building, attach a long rope to it, lower the barometer to the street, and then bring it up, measuring the length of the rope. The length of the rope is the height of the building." Now this is a very interesting answer, but should the student get credit for it? I pointed out that the student really had a strong case for fall credit, since he had answered the question completely and correcdy. On the other hand, if fall credit were given, it could well contribute to a high grade for the student in his physics course. A high grade is supposed to certify that the student knows some physics, but the answer to the question did not confirm this. With this in mind, I suggested that the student have another try at answering the question. I was not surprised that my colleague agreed to this, but 1 was surprised that the student did.

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At this point, I asked my colleague if he would give up. He conceded and I gave the student almost fall credit. In leaving my colleague's office, I recalled that the student had said that he had other answers to the problem, so I asked him what they were. "Oh, yes," said the student. "There are many ways of getting the height of a tall building with the aid of a barometer. For example, you could take the barometer out on a sunny day and measure the height of the barometer, the length of its shadow, and the length of the shadow of die building, and by the use of simple proportion, determine the height of the building." "Fine," I said. "And the others?" "Yes," said the student. "There is a very basic measurement that you will like. In this method, you take the barometer and begin to walk up the stairs. As you climb the stairs, you mark off the length and mis will give you the height of the building in barometer units. A very direct method." i "Of course, if you want a more sophisticated method, you can tie the barometer to the end of a string, swing it as a pendulum, and determine the value ofjj [the acceleration ofgravity] at the street level and at the top of the building. From the difference between the two values ofg, the height of the building can, in principle, be calculated." Finally, he concluded, "If you don't limit me to physics solutions to this problem; there are many other answers, such as taking the barometer to the basement and knocking on the superintendent's door. When the superintendent answers, you speak to him as follows: "Dear Mr. Superintendent, here I have a very fine barometer. If you will tell me the height of this building, I will give you this barometer...."

 In contrast to the distinctive selection pressures that characterize the scientific enterprise (at least science at its best), very different kinds of selection have also affected die evolution of theoretical ideas on the same subjects diat now form the province of science. An example is provided by the appeal to authority, independent of comparison with natureiln medieval and early modern Europe, appeals to authority (for instance Aristode, to say nothing of the Roman Catholic Church) were standard in fields where the scientific mediod was later to be widely applied. When the Royal [Society of London was founded in 1661, die motto'chosen was Nullius in verba. I interpret that phrase as meaning "Don't believe in anyone'; words" and as being a rejection of the appeal to authority in favor of die appeal to nature that distinguished the relatively new discipline of "experimental philosophy," which is now called [natural science. We referred earlier to systems of belief, such as sympathetic magic, that respond predominan dy to selection pressures quite different from the comparison of predctions with observation. Over the last few centuries the scientific enterprise has prospered and carved out a realm where! authority and msgical diinking have largely given way to a partnership of observatiqn and dieory. But outside that realm older ^^s

 ways of thinking are widespread and superstitious beliefs flourish. Is the prevalence ofsuperstidon alongside science a phenomenon peculiar to human beings or should intelligent complex adaptive systems elsewhere in die universe be expected to have similar proclivities? Mistakes in trie Identification or Regularities Complex adaptive systems identify regularities in the data streams they receive and compress those regularities into schemata. Since it is easy to make two types of error—mistaking randomness for regularity and vice versa—it is reasonable to suppose that complex adaptive regularity and vice versa—it is reasonable to suppose that complex adaptive systems would tend to evolve toward a roughly balanced situation in which correct identification of some regularities would be accompanied by bodi kinds of mistakes. Contemplating patterns of human thought, we can, in a crude fashion, identify superstition widi one kind of error and denial with the other. Superstitions typically involve seeing order where in fact mere is none, and denial amounts to rejecting evidence of regularities, sometimes even ones that are staring us in die face. Through introspection and also by observation of other human beings, each of us can detect an association of bodi sorts of error with fear. In the one case, people are scared by die unpredictability and especially die uncontrollability of much diat we see around us. Some of diat unpredictability stems ultimately from die fundamental indeterminacies of quantum mechanics and die furdier limitations of prediction imposed by chaos. A huge amount of additional coarse graining, with consequent unpredictability, comes from die restricted range and capacity of our senses and instruments: we can pick up only a minuscule amount of die information about the universe that is available in principle. Finally, we are handicapped by our inadequate understanding and by our limited ability to calculate. The resulting scarcity of rhyme and reason frightens us and so we impose on die world around us, even on random facts and chance phenomena, artificial order based on false principles of causation. In diat way, we comfort ourselves with an illusion of predictability and even of mastery. We fantasize that we can manipulate the world around us by appealing to die imaginary forces we have invented.

 In the case of denial, we are able to detect genuine patterns but they scare us so much that wej blind ourselves to their existence. Evidently the most threatening regularity in our lives is the certainty of death. Numerous beliefs, including some of the most tenaciously held, serve to alleviate anxiety over death. When specific beliefs of that kind are widely shared in a culture, their soothing effect on the individual is multiplied. But such beliefs typically include invented regularities, so that denial is jaccompanied by superstition. Moreover, taking another look at superstitions such as those of sympathetic magic, we see that belief in them can be maintained only by denying their manifest defects, especially their frequent failure to work. The denial of real regularities and the imposition of false ones are thus seen to be two sides of the same coin. Not only are human beings prone to both, but the two tend to accompany and support each other. If this sort of analysis is justified, then we can conclude that intelligent complex adaptive systems on planets scattered throughout the universe should tend to err in both directions in identifying regularities in their input data. In more anthropomorphic terms, we can expect intelligent complex adaptive systems everywhere to be liable to a mixture of superstition and denial. Whether it makes sense, apart from human experience, to describe that mixture in terms of the alleviation of fear is another matter. AI slightly different way of looking at superstition in a complex adaptive system suggests that perhaps superstition might be somewhat more I prevalent than denial. The system can be regarded as having evolved in great part to discover patterns, so that a pattern becomes in a sense its own reward, even if it confers no particular advantage in the real world. A pattern of that kind can be regarded as a "selfish scheme," somewhat analogous to the selfish gene or even the truly selfish gene. Examples from human experience are not difficult to find. A few years ago I was invited to meet with a group of distinguished academics from out of town who had come to discuss a fascinating new discovery. It turned out that they i were excited about some features in recent NASA photographs of the surface of Mars mat had a vague resemblance to a human face. I cannot imagine what advantage this foray into improbability could have conferred on those otherwise bright people, other than die sheer joy of finding a mysterious regularity.

 The Mythical in Art and Society For human beings, especially at die social level, numerous selection pressures in die real world, besides die alleviation of fear, favor distortions in die process of identifying regularities. Superstitious beliefs may serve to reinforce die power of shamans or priests. An organized belief system, complete widi mydis, may motivate compliance widi codes of conduct and cement die bonds uniting the members of a society. Over die ages, belief systems have served to organize mankind into groups that are not only internally cohesive, but sometimes intensely competitive widi one anodier, often to die point of conflict or persecution, sometimes accompanied by massive violence. Examples are unfortunately not difficult to find in today's world. But competing beliefs are just one basis on which people divide themselves into groups that fail to get along with one another. Any label will do. (A label, to quote from die comic strip B.C., is "something you put on [people] so you can hate diem widiout having to get to know diem first.") Many large-scale atrocities (and individual cruelties) have been perpetrated along edinic or odier lines, often widi no particular connection to beliefs. Alongside die devastating effects of systems of belief, dieir positive achievements stand out sharply as well, especially die glorious music, architecture, literature, sculpture, painting, and dance diat have been inspired by particular mythologies. Just the example of archaic Greek black figure vases would suffice to bear witness to the creative energies released by myth. In die face of die overwhelming greatness of so much of die art related to mythology, we need to re-examine the significance of false regularities. In addition to exerting a powerful influence on human intellect and emotions and leading to die creation of magnificent art, mythical beliefs clearly have a further significance that transcends dieir literal falsity and their connection with superstition. They encapsulate experience gained through centuries and millennia of interaction with nature and widi human culture. They contain not only lessons but also, at least by implication, prescriptions for behavior. They are vital parts of die cultural schemata of societies functioning as complex adaptive systems.

 Tke Search tor Patterns in the Arts Belief jin myths is only one of many sources of inspiration for the arts (just as it is only one of many sources of hatreds and atrocities). It is not only in connection with the mythical mat the arts are nurtured by patterns of association and regularity unrecognized by science. All the arts thrive on the identification and exploitation of such patterns. Most similes and metaphors are patterns that science might ignore, and where would literature, and especially poetry, be without metaphor? In the visual | arts, a great work often leads the viewer to new ways of seeing. The recognition and creation of patterns are essential activities in every kind of art. The resulting schemata are subject to selection pressures that are open (though not always) far removed from those operating in science, with wonderful consequences. We can look upon myth and magic, men, in at least three different and complementary ways: 1. as attractive but unscientific theories, comforting but false regularities imposed on nature; 2. as cultural schemata that help to give identity to societies, for better or for worse; and 3. as part of the grand search for pattern, for creative association, ithat includes artistic work and that enriches human life. A Moral Equivalent of Belief? The question naturally arises whether there is any way to capture the splenjdid consequences of mythical beliefs without the associated self- delusion and without the intolerance mat often accompanies it. Around a century ago, die concept of "me moral equivalent of war" was widely discussed. As I understand it, the point is that war inspires loyalty to comrades, self-sacrifice, courage, and even heroism, and it provides an outlet for the love of adventure, but war is also cruel and destructive to an extraordinary degree. Hence the human race is challenged to find activities with die positive characteristics of war and without the negative find activities with die positive characteristics of war and without the negative ones. Some organizations try to accomplish that goal by introducing to the challenges of outdoor adventure young people who might

not otherwise have the opportunity to live the outdoor life. It is hoped that such activity can provide a substitute not only for war but also for delinquency and crime. One can ask, in connection with superstition instead of war and crime, whether a moral equivalent of belief can be found. Can humans derive the spiritual satisfaction, comfort, the social cohesion, and the brilliant artistic creations that accompany mythical beliefs from something less than acceptance of the myths as literally true? Part of the answer might lie in the power of ritual. The Greek word muthos, from which myth is derived, is said to have referred in ancient dmes to die spoken words that accompanied a ceremony. The acts were central, in some sense, and what was said about them was secondary. Often, in fact, the original significance of the ritual had been at least partially forgotten, and the surviving myth represented an attempt at explanation by trying to interpret icons from the past and by putting together fragments of old traditions referring to a stage of culture that was long gone. The myths were subject to change, then, while continuity of the ritual was what helped hold the society together. As long as rituals persist, could literal belief in mythology wither away without causing too much disruption? Another part of the answer might relate to how fiction and drama are perceived. The characters in great literature seem to have a life of their own, and their experiences are regularly cited, much like those of mythical characters, as sources of wisdom and inspiration. Yet no one claims that works of fiction are literally true. Is there some chance, then, that many of the social and cultural benefits of belief can be preserved while the aspect of self-delusion gradually fades away? Still another partial answer might be provided by mystical experiences. Is it possible that some of the spiritual benefits often derived from superstitious beliefs can be gained instead, at least by some people, through learning techniques that facilitate such experiences? Unfortunately, in many places in the contemporary world, literal belief in mythology, far from dying out, is on the increase, as fundamentalist movements gather strength and threaten modern societies with the imposition of old-fashioned limitations on behavior and on freedom of expression. (Moreover, even where the strength of mythical beliefs is declining, no great improvement in the relation between different groups of people need occur as a result, since slight differences of almost any kind can be sufficient to sustain hostility between them.)

SUPERSTITION AND SKEPTICISM • 281 For a thoughtful discussion of the entire subject of superstitious belief, I recommend WingS{ of Illusion by John F. Schumaker, even though he tends to despair of our being able to dispense, as a species, with our assemblage of comforting and often inspiring illusions. The Skeptics' Movement During the last couple of decades, the prevalence of old-fashioned superstitions has been accompanied, at least in Western countries, by a wave of ipopularity for so-called New Age beliefs, many of which arc just contemporary and pseudoscientific superstitions, or sometimes even old superstitions with new names, like "channeling" in place of "spiritualism." Unfortunately these are often portrayed, in the news media arid in popular books, as if they were factual or very probable, and a movement has originated to counter such claims, the skeptics' movement. Local groups of skeptics have been formed in communities around the world. (Three places where I have spent a good deal of time arc ones that can use a healthy dose of skepticism: Aspen, Santa Fe, and Southern California.) The local skeptics' organizations are loosely connected to a committee that is based in the United States but includes members from other parts of the world; it is called CSICOP, the Committee for Scientific Investigation of Claims of the Paranormal. CSICOP, which publishes a journal called the Skeptical Inquirer, is not a membership organization open to the public, but a body to which one must be elected. Despite some reservations about die organization and its journal, I accepted election some years ago because I like much of its work. Claims of the so-called paranormal surround us on all sides. Some of the most ridiculous are found in headlines from tabloid publications sold at supermarket counters: "Cat eats parrot... now it talks ... Kitty wants a cracker." "Hundreds back from dead describe heaven and hell." "Incredible fish-man; can breathe under water." "Siamese twins meet their two-headed brother." "Space alien made me pregnant." CSICOP doesn't bother to take on such manifest nonsense. But its niembets do get upset when mainstream newspapers, magazines, or radio arid television networks treat as routine and unchallenged, as established or very probable, things that are not at all established: alleged

282 • SELECTION AND FITNESS phenomena such as hypnotic regression to previous lives, valuable assistance provided to the police by psychics, or psychokinesis (in which the mind is supposed to cause external objects to move). These claims challenge the accepted laws of science on the basis of evidence that careful investigation reveals to be very poor or entirely lacking. Keeping after the media not to present such things as real or probable is a useful activity

after the media not to present such things as real or probable is a useful activity of CSICOP. Claims of the Paranormal? What Paranormal? Some questions arise, nevertheless, if we look carefully at the implications of the name of the organization. What is meant by claims of the paranormal? Of course, what most of us working in science (and in fact most reasonable people) want to know first about any alleged phenomenon is whether it really happens. We are curious about the extent to which the claims are true. But if a phenomenon is genuine, how can it be paranormal? Scientists, and many nonscientists as well, are convinced that nature obeys regular laws. In a sense, therefore, there can be no such thing as the paranormal. Whatever actually happens in nature can be described within the framework of science. Of course, we may not always be in the mood for a scientific account of certain phenomena, preferring, for example, a poetic description. Sometimes the phenomenon may be too complicated for a detailed scientific description to be practical. In principle, though, any genuine phenomenon has to be compatible with science. If something new is discovered (and reliably confirmed) that does not fit in with existing scientific laws, we do not throw up our hands in despair. Instead, we enlarge or otherwise modify the laws of science to accommodate the new phenomenon. This puts someone in a strange logical position who is engaged in the scientific investigation of claims of the paranormal, because in the end nothing that actually happens can be paranormal. Perhaps this situation is related to a vague sense of disappointment that I sometimes feel upon reading that otherwise excellent journal the Skeptical Inquirer. I experience a lack of suspense. Seeing the title of the article usually gives away the content, namely that whatever is in the tide isn't true. Nearly everything that is discussed in the journal ends up debunked. Moreover, many of the authors seem to

 feel that they have to explain away every last case, even though in the real world an investigation of anything complex usually leaves a few matters somewhat cloudy. I am, it is true, delighted to see such things as psychic surgery and levitation through meditation debunked. But I do think a slight redefinition of the mission would help the organization and the journal to be more lively and interesting, as well as more soundly based. I believe the real mission of the organization is to encourage the skeptical and scientific examination of reports of mysterious phenomena, especially ones that seem to challenge the bws of science, but without making use of the bbel "paranormal," with its implication that debunking is most likely required. Many of these phenomena will turn out to be phoney, or to have very prosaic explanations, but a few may turn out to be basically genuine and interesting as well. The concept of the paranormal does not seem to me to be a helpful one; and the debunking spirit, while it is entirely appropriate for most of the subjects involved, is not always a perfectly satisfactory approach. Often! we are faced with situations where conscious fraud is involved, credulous people are cheated of their money, seriously ill patients are'diverted to worthless fake cures (like psychic surgery) from legitimate treatments that might work, and so form. In such cases, debunking is a service to humanity. Even men, however, we should spare some thought for the emotional needs of the victims that are being met by the quackery and how those might be satisfied without self-delusion. I would recommend that skeptics devote even more effort than they do now to understanding the reasons why so many people want or need to believe. If people were less receptive, the news media would not find it profitable to emphasize the so-called paranormal. In fact, it is not just misapprehension about how much good evidence there is for a phenomenon that underlies the tendency to believe in it. In my discussions with people who believe six impossible things before breakfast every day, like the White Queen in Through the Looking Glass, I have found that their main characteristic is the dissociation of belief from evidence. Many of those people, in fact, freely confess that they believe what it makes them feel good to believe. Evidence doesn't play much of a role] They are alleviating their fear of randomness by identifying regularities that are not mere.

 Menial Aberration ana Suggestibility Two subjects that must be included in any discussion of strange beliefs are suggestibility and mental aberration. Polls now reveal, for example, that an astonishing percentage of respondents not only believe in the existence of "aliens from flying saucers" but also claim to have been abducted by mem and closely examined or even sexually molested. One seems to be dealing here with people who for some reason have difficulty distinguishing reality from fantasy. It is natural to ask whether some of them are afflicted with serious mental illness. One might also speculate that a number of believers in such weird events may simply have an unusually high degree of susceptibility to trance, so that they pass in and out of states of suggestibility with the greatest ease. Such subjects can have beliefs imposed upon them when pbced in a trance by a hypnotist; perhaps a related process can occur more or less spontaneously. High trance susceptibility may be a potential liability, but it can also be advantageous, because it can facilitate hypnosis, self-hypnosis, or deep meditation, permitting a person to achieve useful forms of self-control that are difficult (although not impossible) to achieve in other ways. In many traditional societies, people endowed with very high susceptibility to trance may find roles as shamans and prophets. So may others who suffer from certain kinds and degrees of mental disturbance. Bom categories of people are thought to be more likely than others to undergo mystical experiences. In modern societies, both are said to be found among the most creative artists. (Of course, all these presumed correbtions need to be carefully checked.) Some research is taking place on the mental characteristics of people who believe in outrageously improbable phenomena, especially individuals who claim to have had personal involvement with them. So far, surprisingly little evidence has turned up either for serious mental illness or for high trance susceptibility. Rather, it appears that in many cases strong belief serves to influence the interpretation of ordinary experiences with physical phenomena or with sleep- or drug-induced mental states. The subject is clearly in its infancy, however. It seems to me desirable to intensify gready the study of such beliefs and belief systems among human beings and of the underlying causes, since in the long run the subject plays such a crucial role in our common future.

Skepticism ana Science

Suppose it is agreed that the-skeptics' movement, apart from studying the subject of belief and engaging in such activities as exposing fraud and trying to keep the media honest, is engaged in the skeptical and scientific examination of reports of mysterious phenomena that seem to defy the laws of science. Then the degree of skepticism that is applied should be. appropriate to the challenge that the alleged phenomenon presents to the accepted laws. Here one has to be very careful. For example, in complicated fields such as meteorology or planetary science (including geology), bizarre natural phenomena may be alleged to occur that challenge certain accepted principles in those fields but don't appear to iviolate fundamental laws of nature like conservation of energy. The empirical or phenomenological laws in such fields are sometimes quite difficult to relate to the laws of more basic sciences, and new observational discoveries are being made all the time that require revision of the empirical laws. An alleged phenomenon that violates those laws is not so suspect as one that violates conservation of energy. Only 'thirty years ago most geologists, including almost all die distinguished geology faculty at Caltech, were still contemptuously rejecting die idea of continental drift. I remember because I often argued with them about it at die time. They disbelieved in continental drift despite mounting evidence in its favor. They had been taught that it was nonsense mainly because evidence in its favor. They had been taught that it was nonsense mainly because die geological community hadn't thought of a plausible mechanism for it. But a phenomenon may perfectly well be genuine even though no plausible explanation has yet turned up. Particularly in that kind of subject, it is unwise to dismiss an alleged phenomenon out of hand just because experts can't think right away of what might make it happen. Planetary scientists a couple of centuries ago committed die notorious mistake of debunking meteorites. "How can rocks fall from the sky," they objected, "when there are no rocks jn die sky?" ; Today there is a strong tendency among my friends in the skeptics' movement, as well as my colleagues in physics, to dismiss rather quickly claims of] elevated incidence of rare malignancies in people who are exposed more man others to comparatively weak electromagnetic fields from 60 cycle alternating current devices and power lines. The skeptics may well be right in dunking that die claims are spurious, but it is not

so obvious as some of them say. Although the fields are too weak to produce gross effects such as substantial increases in temperature, they might still be capable of producing much more subtle effects on certain highly specialized body cells that are unusually sensitive to magnetism because they contain appreciable quantities of magnetite. Joseph Kirschvink of Caltech (who has an unusual set of interests for a Caltech professor) is investigating mat possibility experimentally and has found some preliminary indications that such a connection of magnetism with those rare malignancies might be more man a fantasy.

Tke KugelLlita—Ball Lightning

A number of phenomena alleged to take place in the atmosphere remain in a sort of limbo to this day. One of mem is the "kugelblitz"— ball lightning. Certain observers claim to have seen, in stormy weather, a bright sphere, suggesting lightning in the form of a ball. It may pass between widely spaced slats of a fence; or it may enter a room through a window, roll around inside, and men disappear, leaving slight burns. All sorts of anecdotal reports abound, but there is no incontrovertible evidence, nor is mere any really satisfactory theory. One physicist, Luis Alvarez, suggested that the kugelblitz was just a phenomenon of the observer's eyeball. That explanation, however, doesn't agree very well with the anecdotal evidence, for instance as compiled by a scientist from interviews with employees of a national laboratory. Some serious theorists have done research on the phenomenon. While the great Russian physicist Pyotr L. Kapitsa was under house arrest for refusing to work on thermonuclear weapons under the direction of Stalin's secret police chief Lavrenti P. Beria, he and one of his sons wrote a theoretical paper on a hypothetical mechanism for ball lightning. Others have tried to reproduce the phenomenon in the laboratory. But I would say mat the results are still inconclusive. In brief, nobody knows what to make of it. Around 1951, the mention of ball lightning disrupted a seminar at die Institute for Advanced Study in Princeton at which Harold W. ("Hal") Lewis, who is now a professor of physics at the University of California at Santa Barbara, presented a piece of theoretical work on which he and Robert Oppenheimer had collaborated. 1 think it was Robert's last research effort in physics before he became Director of the Institute, and he was very anxious that people listen carefully to Hal's

 account of die work, contained in the paper of Oppenheimer, Lewis, and Woiithuysen on meson production in proton-proton collisions. In the course of die discussion after the lecture, someone mentioned that Enrico Fermi had proposed a model in which die two protons stick together for a long time, for unknown reasons, and emit mesons in a statistical manner. Many of us joined in with suggestions about what could cause that kind of behavior. The learned Swiss theoretical physicist, Markus Fierz, interjected die remark that it is not always clear why things stick togedier. "For example," he said, "take the kugelblitz, ball lightning." (Oppenheimer,started to turn purple with fury. Here was his last paper in physics being presented and Fierz was diverting the discussion to ball lightning.) Fierz went on to say that a friend of his was employed by the Swiss government and given a special railroad car so that he could travel around die country and follow up on anecdotal reports of the kugelblitz. Finally, Robert couldn't stand it anymore and stalked out muttering, "Fire balls, fire balls!" I don't think our understanding of die phenomenon has improved much since then (even though Hal Lewis himself has written an interesting article about it). Rsk Balls One of my favorite examples of mysterious phenomena has to do widi fish and frogs falling from die sky. Many of the accounts are quite circumstantial and given by credible observers. Here is one, by A. B. Bajkov, describing a fish fall in Marksville, Louisiana, on October 23, 1947: ' I was conducting biological investigations for the Department of Wildlife and Fisheries. In die morning of diat day between 7:00 and 8:00 fish ranging from two to nine inches in length fell on die streets and in yards, mystifying the citizens of that soudiern town. I was in the restaurant with my wife having breakfast when die waitress informed us that fish were falling from die sky. We went immediately to collect some of die fish. The people in town were excited. The Director of the Marksville Bank,

J. M. Barham, said he had discovered upon arising from bed diat fish had fallen by hundreds in his yard and in the adjacent yard of Mrs.J. WJoffrion.The cashier of the same bank, J| E. Gremillion, and two merchants, E. A. Blanchard and J. M.

 Brouillette, were struck by falling fish as they walked toward their places of business about 7:45 a.m (quoted by William R. Corliss from Science, 109,402, April 22,1949). All the meteorologists that I have consulted assure me that their science does not provide any conclusive objection to the possibility of such creatures being raised up, transported considerable distances, and then dropped as a result of meteorological disturbances. Although one may only speculate about specific mechanisms, such as waterspouts, it is perfectly possible that the phenomenon actually occurs. Conceivably, transport by flocks of birds might provide another explanation. Moreover, if fish or at least their spawn come down alive, that could make a serious difference to zoogeography, the study of the distribution of animal species. Ernst Mayr actually mentioned in one of his papers on zoogeography that there are many puzzles about the distribution of freshwater fishes that might be resolved if those creatures could be transported by unconventional means, such as fish falls from the sky. The foregoing discussion makes clear that if fish really do tumble from the heavens, the process doesn't do any damage to the accepted laws of science; in fact it probably helps. Likewise, if one of those "cryptozoological" creatures, like the supposed giant ground sloth in the Amazonian forest, should turn out to be real, it might not harm the laws of science either, any more than the coelacanth that was discovered in the waters off southern Africa fifty years ago although it was thought to be long extinct. But what about alleged phenomena that seem to challenge the fundamental laws of science as we know them? Alleged Ph enomena That Challenge the Known Laws of Dcience Although such phenomena are not ipso facto nonexistent, a very high standard of skepticism must be applied to them. Nevertheless, if any of them ever turns out to be genuine, the scientific laws will have to be modified to accommodate it. Consider the alleged phenomenon (in which, by the way, I don't believe) of telepathy between two people who are very close personally and also closely related, say mother and child or identical twins. Almost

 everyone has heard anecdotes about such pairs of people, according to which, in moments of extreme stress for one of them, the other becomes alarmed, even if they are very far apart. Most likely these reports are occasioned by a combination of coincidence, selective memory (forgetting false alarms, for example), distorted recollection of die circumstances (including exaggeration of simultaneity), and so on. Besides, it is very difficult to investigate such phenomena scientifically, although in principle not impossible. For instance, one can imagine an experiment, cruel and therefore forbidden by ediical considerations, but not otherwise impractical, in which one hired many pairs of identical twins, separated1 them by long distances, and then subjected one of each pair to severe stress to see if die other twin would react. (There are some gullible people, including a number of my New Age acquaintances in Aspen, who believe that such an experiment was actually performed with animals while the submarine Nautilus was under die polar ice. They diuik diat a mother rabbit was monitored in the submarine and showed signs of anguish when some of her little baby rabbits were being tortured in Holland!) In any case, suppose for, a moment that, contrary to my expectations, such a telepadiic phenomenon turned out to be genuine, say for human identical twins. Fundamental scientific theory would have to be profoundly altered, but eventually, no doubt, an explanation could be found. For example, theorists might end up postulating some kind of cord, of a nature not now understood, probably involving important modifications of the laws of physics as presently formulated. Such a cord connecting the twins would carry a signal between them when one of them was in serious trouble. That way the effect could be largely independent of distance, as many of the anecdotes suggest. Let me emphasize again that I am quoting this example not because I believe in telepadiy but only to illustrate how scientific theory might be modified to accommodate even very bizarre phenomena in die unlikely event that they turned out to be genuine. i A Ger uine Ability—pReading Record Grooves Occasionally CSICOP finds! that a seemingly crazy claim is really justified. Such cases are duly reported in die Skeptical Inquirer and discussed

 at meetings, but in my opinion.they should be given more attention than they have received. Then it would be much clearer that the point is to attempt to distinguish genuine claims from false ones and not simply to engage in debunking. Scientists have, on the whole, a rather poor record of success in investigating suspected takers. All too often, even well-known savants have been taken in, sometimes becoming promoters of charlatans they should have exposed. CSICOP relies primarily on a magician, James Randi, to devise tests for people who claim extraordinary powers. Randi knows how to put things over on an audience, and he is equally good at figuring out how someone is trying to put things over on him. He gets a thrill out of unmasking fakers and demonstrating how they have obtained their effects. When it came to the attention of Discover magazine that a man was claiming to be able to glean information from the grooves on phonograph records, the obvious move was to dispatch Randi to investigate. The man in question, Dr. Arthur Lintgen of Pennsylvania, said he could look at a record of fully orchestrated post-Mozart classical music and identify the composer, often the piece, and sometimes even the performing artist. Randi subjected him to his usual rigorous tests and discovered that he was telling the exact truth. The physician correctly identified two different recordings of Stravinsky's Rite of Spring, as well as Ravel's Bolero, Hoist's The Planets, and Beethoven's Sixth Symphony. Naturally Randi showed him some other records as controls. One, labeled "gibberish" by Dr. Lintgen, was by Alice Cooper. On seeing another control, he said, "This is not instrumental music at all. I'd guess that it's a vocal solo of some kind." In fact it was a recording of a man speaking, titled So You Want to Be a Magician. This odd claim that turned out to be genuine violated no important principle. The necessary information was present in the grooves; the question was whether someone had really been able to abstract that information by inspection. Randi confirmed that indeed someone had.

19 ADAPTIVE AND MALADAPTIVE SCHEMATA One story that skeptical inquiry has successfully debunked is that of the "hundredth monkey." The first part of the account is true. One member of a monkey colony on an island in Japan learned to wash sand off her food, first in a stream leading down to the sea and men in the sea itself. She communicated the skill to other members of the colony. So far, so good. A New Age legend, however, picks up on those facts and claims further that when a hundred monkeys had picked up the trick, then suddenly, by some mysterious means, members of the species everywhere knew about it and began to practice it. For that, there is no credible evidence whatever. The trie part of the story is quite interesting in itself, as an example of cultural transmission of learned behavior in animals other than humans. Another example is provided by the behavior of some great tits (birds related to the chickadees of North America) in certain English towns several decades ago. Those little birds learned to open milk bottles. More and more great tits acquired die behavior, and a few members of other tit species as well. The physical activity required was already in the birds' repertory; all diey needed was the knowledge that the milk bottle contained a suitable reward. There are many other known cases of novel animal behavior transmitted in this way. a9/

292 • SELECTION AND FITNESS Cultural DNA Human cultural transmission can, of course, be considerably more sophisticated. The explanation presumably lies not only in superior intelligence, but also in the character of human languages, every one of which permits arbitrarily complex utterances. Using those languages, human societies exhibit group learning (or group adaptation or cultural evolution) to a much greater degree than troops of other primates, packs of wild dogs, or flocks of birds. Such collective behavior can be analyzed to some extent by reducing it to the level of individuals acting as complex adaptive systems. However, as usual, such reduction sacrifices the valuable insights that can be gained by studying a phenomenon at its own level. In particular, simple-minded reduction to psychology- may not sufficiendy stress die fact diat, besides the general characteristics of individual human beings, additional information is present in the system, including die specific traditions, customs, laws, and myths of the group. To use die picturesque phrase of Hazel Henderson, all of these can be regarded as "cultural DNA." They encapsulate die shared experience of many generations and comprise die schemata for the society, which itself functions as a complex adaptive system. In fact, die English biologist Richard Dawkins coined the term "merae" to signify a unit of culturally transmitted information

analogous to a gene in biological evolution. Adaptation actually takes place on at least diree different levels, and that sometimes causes confusion in the use of die term. First of all, some direct adaptation (as in a thermostat or cybernetic device) takes place as a result of the operation of a schema that is dominant at a particular time. When the climate turns warmer and drier, a society may have the custom of moving to new villages high up in die mountains. Alternatively, it may resort to religious ceremonies for bringing rain, under the supervision of a priesthood. When its territory is invaded by an enemy force, the society may react automatically by retreating to a well-fortified town, already stocked widi provisions, and sustaining a siege. When the people are frightened by an eclipse, there may be shamans ready with some appropriate hocus-pocus. None of this behavior requires any change in the prevailing schema.

The next level involves changes in the schema, competition among various schemata, and proniotioiji or demotion depending on the action of selection pressures in die real wojrld. If rain dances fail to bring relief from a drought, the relevant priesthood may fall into disgrace and a new religion may take over. Where die tradit onal response to climate change has been movement tjo a higher elevation, poor results from that schema may lead to the adoption of odier practices, such as new methods of irrigation or die planting of'new crops. If the strategy of retreat to a fortress fails to deal adequately widi a series of eneny attacks, die next invasion may provoke the sendingiof an expeditionary force to die enemy's heartland. The third level of adaptation is die Darwinian survival of the fittest. A society may simply cease to exist as a consequence of the failure of its schemata to cope with events!. The people need not all die, and the remaining individuals may join other societies, but die society itself disappears, tarrying its schemata into extinction with it. A form of natural selection has taken place at the societal level. Examples of schemata leading to extinction are not difficult to find. Some communities (such as the Essenes in ancient Palestine and the Shakers in the nineteenth century United States) are said to have prac- iced sexual abstinence. All die members of the community, not just a ew monks and nuns, were supposed to refrain from sexual activity. jiven suchja schema, the survival of the community would require that onversions outnumber deaths. That does not seem to have happened. The Essenes disappeared and die Shakers are now few in number. In ny case, the prohibition of sexual intercourse was a cultural trait that ontributed in an obvious way to the extinction or near-extinction of he community. The collapse of the Classic Maya civilization in the tropical forests community. The collapse of the Classic Maya civilization in the tropical forests >f Mesoan\erica during the tenth century is a striking example of the xtinction of an advanced culture. As indicated near the beginning of lis book, die causes of the collapse are a matter of dispute today; rchaeologists are uncertain Which schemata failed—those related to le class structure of society, agriculture in the jungle, warfare among le cities, of other facets of the civilization. In any case, it is m ought that lany individuals survived the collapse and that some of the people leaking Mayan languages in the area today are dieir descendants. But le construction of stone buildings in the forest cities came to an end,

as did the erection of stelae to commemorate the passage of key dates in the Maya calendar. The subsequent societies were very much less complex than those of the Classic Period. The three levels of adaptation take place, generally speaking, on different time scales. An existing dominant schema can be translated into action right away, within days or months. A revolution in the hierarchy of schemata is generally associated with a longer time scale, although the culminating events may come swiftly. Extinctions of societies usually take place at still longer intervals of time. In theoretical discussions in the social sciences, for instance in the archaeological literature, the distinctions among the different levels of adaptation are not always clearly maintained, and a good deal of confusion frequently results. The Evolution or Human Languages In the case of languages, as well as that of societies, evolution or learning or adaptation takes place in various ways on different time scales. As we discussed earlier, a child's acquisition of language represents a complex adaptive system in operation. On a much longer time scale, the evolution of human languages over centuries and millennia can be regarded as another complex adaptive system. On a time scale of hundreds of thousands or millions of years, biological evolution produced the capacity of human beings (Homo sapiens sapiens) to communicate by means of languages of the modern type. (All of those languages have certain common properties such as sentences of arbitrary length, elaborate grammatical structure, and such universal grammatical features as pronouns, genitive constructions of various kinds, and so forth.) When considering the evolution of grammar, it is important to take the various levels of adaptation into account. Since the pioneering work of Joe Greenberg, a considerable amount of information has been accumulated on the grammatical features that are common to all known human languages ("grammatical universals") and those that apply in almost all cases ("grammatical near-universals").In accounting for these general features, one must obviously pay attention to the biologically evolved, neurologically pre-programmed constraints emphasized by

 Chomsky and his followers. However, one must also consider the results of linguistic evolution over centuries and millennia, which must reflect to some extent selection pressures favoring grammatical features adaptive for conjununication. Finally, there may be frozen accidents, "founder effects,'] stemming from arbitrary choices of grammatical features in languages (or even a single language) ancestral to all modern tongues, ;hoices with consequences that persist everywhere to this day. (Recall :hat in biology the asymmetry between right- and left-handed molecules may be such a frozen accident.) In discussions of linguistics at the Santa Fe Institute, emphasis is laid on the necessity of including all these .ontriburions together in trying to explain grammatical universals and lear-univeikals. In studying evolution of any complex adaptive system, it is essential o try to pick apart these three strands: die basic rules, frozen accidents, nd the selection of what is adaptive. And of course the basic rules may hemselves look like frozen accidents when viewed on a cosmic scale of pace and time. I Adaptation Versus Wnat Is or Appears Adaptive tistinguisbing different levels' and different time scales of adaptation ill leaves the set of puzzles associated with why adaptive complex 'stems like societies seem so often to be stuck with maladaptive schema. Why haven't diey just developed better and better schemata and regressed to higher and higher fitness? Some of the reasons have ready been encountered in earlier chapters. Societies, like odier complex adaptive systems, are often subject to lection pressures diat are not-accurately described by any fitness func- 3n. And fitness, as we have seen, is not something that simply increases ith time jeven when it is well-defined. Also, mere is not a simple •rrespondence between features that are adaptive and features that ive arisen through the various forms of adaptation. None of these ues is restricted to societies. They are widespread in biology and diey s sometimes particularly acute in the experience of individual human ings. What are some of the mechanisms that permit maladaptive liemata to survive?

 Maladaptive Schemata—External Selection Pressures One very general mechanism for the persistence of apparently maladaptive behavior has already been discussed at some length, especially in connection with superstition versus science. The selection pressures affecting the promotion and demotion of theories in science relate mainly to the success of those theories in explaining coherently and predicting correcdy the results of observation, at least when the scientific enterprise is working properly. When it is not working well, it is because other selection pressures, many of them stemming from the human weaknesses of scientists, are strong. In the case of superstitious theorizing, nonscientific kinds of selection pressures play dominant roles. Let us recapitulate the pressures we have mentioned. They include the reinforcement of the authority of powerful individuals and also the maintenance of social cohesion, which confers an advantage in societal evolution. In addition the imposition of a structure of false order and regularity on mostly random events or disconnected tacts can provide a degree of comfort; the illusion of understanding and especially mastery relieves fears of the uncontrollable. Related to these selection pressures is the very general kind that we have associated with the catch phrase "the selfish scheme": any complex adaptive system has evolved to discover patterns and so a pattern is in a sense its own reward. The common element in all these selection pressures is that they are largely external to what is considered adaptive in science, namely success in describing nature. Likewise they are mostly external to what is considered adaptive in engineering, namely controlling nature tor some human purpose. Nevertheless, such selection pressures play critical roles in the evolution of cultural DNA. Clearly there is a general lesson to be learned here. The system being discussed is often defined in such a way diat it is not closed. Selection pressures of great importance are exerted from outside. A simple example is provided by one of the processes that take place in the evolution of human languages. Suppose certain tribes or nations speaking different languages come into contact and, after a tew generations, some of the languages survive, with certain modifications, while

 others become extinct. Which ones die out depends less on the relative merits of the various tongues as means of communication than on quite different considerations, such as die relative military strength or cultural attainment^ of die different tribes or nations. Those are selection pressures exerted outside die linguistic realm. In die i domain of biological evolution, where selection normally takes place at the phenotypic level, there may be, as we discussed earlier, exceptional cases where it acts direcdy on the germ cells: a "truly selfish gene"promoting, for sperm carrying it, the successful fertilization of an egg, even though that gene may not be helpful, and could even be harmful, to die resulting organism. What all of these examples suggest is mat the apparent persistence of maladaptive schemata these examples suggest is that the apparent persistence of maladaptive schemata in complex adaptive systems may often arise simply from too narrow a choice of criteria for what is considered adaptive, given all the selection pressures that are operating. Pressures Exerted by Influential Individuals In studying the evolution of human organizations, it is not always advantageous to consider the individual members of the organization merely as simplified generic agents. Often the particular decisions made by specific individual human beings make a great deal of difference to future histpry. While it may be that in the long run many such effects prove to be temporary aberrations mat are "healed" through the operation of long-term trends, still it is impossible to ignore the fact that individuals do matter. Thus the element of design enters into the pic- :ure. The constitution of a state or federation is written by individuals. Even though many of die conflicts that arise in the course of its drafting represent {he competition of large-scale interests, still the specific com- sromises tjhat are worked out are forged by particular statesmen. Likewise a business firm is directed by individuals, and the character and deas of the boss or bosses (and sometimes of other individuals as well) ire critical to the success or failure of the enterprise. At the1 same time, an organization does behave in many ways as a omplex adaptive system, with schemata and selection pressures. A busi- less firm operates according to a certain set of practices and procedures, ets goals {for its various departments or divisions, makes plans for the

 future, and generates mental models for the functioning of the whole enterprise. The models, together with the goals, plans, practices, and procedures, constitute schemata, subject to direct pressures exerted by managers at various levels, from the boss to the foremen or office managers. The actual selection pressures on the firm in the real world, however, have to do with profits, with survival in the marketplace. It matters whether customers are attracted and then satisfied. In general, when organizations are regarded both as complex adaptive systems and as theatres for the exercise of the management skills of individuals, the question arises as to the relationship between the ultimate selection pressures that govern the survival of the organization and the internal selection pressures exerted by the individual managers. W. Edwards Deming, the American statistician (with a Ph.D. in physics) who advised the Japanese on the reconstruction of their industries after the Second World War, became something of a hero in Japan as a result of his wise recommendations. For a decade or more before his recent death at the age of 93, he was finally honored in his native country, where his ideas are now widely disseminated and accepted by many industrial firms. Perhaps best known is his emphasis on "total quality management" or TQM. Of the many facets of TQM, it is perhaps most useful to cite here his strictures on the internal pressures exerted by managers, including middle managers. Those are the people who dispense rewards and sanctions. By creating incentives for employees to act in particular ways, they direcdy affect some of the principal schemata for the organization. But are those direct effects consonant with the selection pressures exerted in the real world? Are the employees being rewarded for activity that actually leads to satisfied customers? Or is it just the whim of some manager that they are satisfying? Are managers apt to behave like the truly selfish gene, acting direcdy on the survival of die schema in a way that may not promote the survival of the organism? Adaptive Systems witn Humans in tne Loop The case of managers in a business firm exemplifies die more genera situation of adaptive systems widi one or more human beings in th< loop—systems subject to what is sometimes called directed evolution in which selection pressures are exerted by individual human beings.

 The simplest situations involve direct adaptation, with no variant schemata.!Consider an eye examination by an optometrist. You look with one jeye at a chart covered with rows of letters as well as vertical and horizontal lines. The optometrist presents you with a sequence of binary choices. For each pair jof images, you are asked if the left- or the right-hanjl one is clearer. Before long you have converged on the right prescription to take care of whatever combination of astigmatism, myopia, and presbyopia the eye in question presents. The single eye-chart schema has adjusted itself to your eye. A lessicut-and-dried example of a human in the loop is provided by the work) of Karl Sims, now at Thinking Machines, a company that designs and manufactures parallel processing computers. Sims utilizes a computer screen consisting of 256 by 256 pixels, in each of which the color can vary over the whole spectrum. Patterns result from specifying the color of each pixel. Using Sims's program, the computer starts with a particular pattern and then generates a set of variant patterns, using a particular! algorithm. The person "in the loop" chooses the variation that looksibest to him or her. The computer then offers another set of choices, apd so on. After not very long, the system has converged on a picture that appeals to the human being involved. I am told that the results art often quite remarkable and also that participation in the process is addictive. One 'can imagine elaborations of this method in which chance would play a role in the algorithm for computing the choices that are offered at! each stage. Or, in what amounts to nearly the same thing, the computet could employ a pseudo-random process as part of the algorithm. At a Santa Fe Institute Science Board Symposium, Chris Langton gave a brief description of Sims's work. Bob Adams, the archaeologist who was then the Secretary of die Smithsonian Institution, raised die point that the algorithm governing the way the computer keeps offering sets of choices could itself be subject to variation. If so, it would become a kind of schema, each variant of which could be regarded as a different search process for hunting through the enormously long list of possible patterns. The particular search process adopted (which may or may not include an element of chance), together with the results of the :hoices made by the human subject, would determine the pattern on ;he computer screen.

 The patterns could then be transferred to a permanent medium and subjected to selection pressures, for example sale in the marketplace or comments by critics. The computer programs that led most often (through the human subjects) to pictures commanding relatively high prices or relatively favorable comments might be promoted, and the others demoted. Likewise the tastes (conscious or unconscious) of the human subject might change under the influence of the prices or comments. The program, the computer, the human subject, and the marketplace or critic would then constitute a complex adaptive system, with human beings in the loop. In fact, such a system may serve as a kind of crude caricature of how the creative process of real artists sometimes functions. We are all familiar with another complex adaptive system that operates in this way, namely the breeding of animals or plants for human use. Plant and animal breeding played an important role in the history of modern biology. Darwin repeatedly referred to them in his Origin of Species under the rubric of "artificial selection," with which natural selection was compared and contrasted. The Mendelian laws of genetics were discovered by the monk Gregor Mendel in the course of his breeding of peas. In addition, at the turn of the century, around the time when Mendel's work was rediscovered and disseminated to the world, the Dutchman de Vries discovered mutations while breeding tulips. The breeder exerts selection pressures by choosing for further breeding only some of the organisms produced. Of course, natural 'selection is at work as well, and many of the animals or plants fail to survive or procreate for reasons that have nothing to do with the breeder's decision. The genome is a schema, as usual in biological evolution, but here the evolution is in part directed and the breeders principles also form a schema, albeit of a different kind. When a horse breeder puts a horse up for sale or enters it in a race (or kind. When a horse breeder puts a horse up for sale or enters it in a race (or both), his methods, analogous to Karl Sims's computer program plus the choices made by his human subject, are being exposed to the selection pressures of the marketplace and the race track. Thus a complex adaptive system with a component of directed evolution can become part of a higher order complex adaptive system in which the character of the human direction can itself evolve. However, suppose a wealthy amateur breeder doesn't care how his horses perform at the race track or whether anyone wants to buy them.

 In diat case, in die context of the higher order complex adaptive system, the results of die horse breeding methods will probably appear to be maladaptive. Like managers who offer incentives for behavior unlikely to attract or keep customers, such a dilettante horse breeder may be pleasing himself but he is not acting like a businessman. From a purely business point of view, die breeding is a failure, yet it can go on. Persistence or Maladaptive Schemata: Windows 01 Maturation Maladaptive schemata sometimes persist because die relevant kind of adaptation has come to a halt, or nearly so. Young children form relationships with important people in their lives: parents, stepparents, siblings, nannies, mothers' boyfriends, and so on. According to Dr. Mardi Horowitz, die attitudes and behavior of a child in such a relationship are governed by a "person schema" relating to die child's perceptions of the individual in question. At first such a schema is subject to alteration, but later in childhood it becomes very resistant to change. As die child grows up, those person schemata may profoundly affect die way he or she relates to other people. We are all familiar, for example, with adults who keep reenacting with various surrogates a childhood relationship with a parent. Often person schemata appear quite maladaptive, and living in accordance with them amounts to what is often called neurotic behavior, notoriously difficult to cure. One useful way to look at such situations is in terms of "windows of maturation" versus "plasticity." An extreme example of a window of maturation is the phenomenon of imprinting, which was made famous by Konrad Lorenz in his book King Solomon's Ring. A newborn greylag goose regards the first suitable animal that it sees as its parent and follows it around. If that animal is Lorenz or another human being, men the goose comes to regard itself in some sense as a human and its ability to live as a normal goose is permanently compromised. The window of maturation is the very short period after birth during which the gosling identifies its "mother" and after which the identification is fixed for good. The typical gosling sees its real mother early on, and the genetic program of imprinting is then phenotypically successful. For the rare gosling that adopts an ethologist like Lorenz as its mother, the

 program is evidently a failure. In such a case the learning schema supplied by imprinting is maladaptive for the particular individual involved. Because that learning schema works out fine for most individuals, however, the genetic schemata that lead to imprinting have not been eliminated in biological evolution. Still, genetic schemata providing for such windows of maturation must also confer some general advantage in order to have survived. Presumably that advantage comes from die possibility, when die window closes down, of turning off the machinery for acquiring certain new information. Windows of maturation are known in human beings, too. For instance, some babies are born with visual problems mat must be corrected early if recovery is to be possible (at least widiout some new, so far undiscovered form of intervention). In odier cases, the windows are not absolute, so to speak. The consequences of various forms of neglect during crucial periods of infancy and early childhood may be serious if nothing is done to reverse the damage, but under suitable conditions there may be significant possibilities of recovery. Those possibilities are discussed under die rubric of plasticity, die capacity of die nervous system to reorganize itself so that patterns mat might odierwise persist indefinitely can in fact be changed. A major public policy issue, particularly in die United States, involves die extent to which deficits in learning ability acquired before the age of two and a half can be remedied by programs like Head Start, which give children special help during die following two and a half years or so. Some investigators claim that an early window of maturation plays a crucial role here and that remedial programs at die later ages are not nearly so effective in die long run as improving die learning environment of babies. Others claim to have shown mat mere is enough plasticity in this case to permit substantial and long-lasting reversal of learning deficits by means of interventions such as Head Start, provided diey are carried out (as often diey are not) widi sufficient intensity and duration. Whatever die merits of the arguments about general learning deficits in young children, it is known that for die acquisition of a first language the early years of life are critical. The few known cases of children raised widi litde or no human language contacts indicate that the innate machinery for mastering die grammar of a language ceases to be effective. Apparendy a true window of maturation is involved.

 Persistence ot

Maladaptive Schemata: Time Scales One of die most common reasons, and perhaps die simplest, for die existence of maladaptive schemata is that they were once adaptive but under conditions that no longer prevail. The environment of the complex adaptive system has changed at a faster rate than the evolutionary process can accommodate. (Windows of maturation are in a sense an extreme example of such a mismatch of time scales.) In the realm of human thought, it often happens that we are confronted with a rapidly changing situation diat overtaxes our ability to alter our thought patterns. Gerald Durrell, the founder of the zoo on the island of Jersey, who has written so many charming books on his expeditions to bring back rare animals, recounts what happened once when he was holding a certain West African snake in his hands. He was not taking any special precautions because he "knew" it to be a harmless blind snake (with only vestigial eyes). Suddenly, Durrell noticed its eyes and realized that it was not blind at all, but he did not react quickly enough to the new information that the snake belonged to an unknown and possibly dangerous species. In fact it was poisonous, and Durrell was bitten and nearly killed. Rather than change our way of diinking, we tend to cling tenaciously to our schemata and even twist new information to conform to them. Many years ago, two physicists associated with the Aspen Center for Physics were climbing in the Maroon Bells Wilderness. While descending, they lost their bearings and came down on the south side of the mountains, instead of the north side near Aspen. They looked below them and saw what they identified as Crater Lake, which they would have spotted from the trail leading home. One of them remarked, however, that there was a dock on the lake, which Crater Lake does not possess. The other physicist replied, "They must have built it since we left this morning." Needless to say, that desperate defense of a failed schema turned out to be incorrect. The physicists were looking at Avalanche Lake on the wrong side of the mountains, and it took them a couple of days to get home. Realizing that the snake, since it was not actually blind, could be poisonous fits the description that we gave of having a creative idea in everyday life, escaping from one basin of attraction into another. So

 does reflecting that the lake, with its dock, was unlikely to be Crater Lake and was therefore elsewhere in the mountains. The present discussion emphasizes that the process of getting such ideas may, in many cases, not keep pace with the need for them. It is notorious that business firms often have trouble adjusting their practices rapidly enough to changing market conditions. Right now, in the United States, the reduced appropriations for military preparedness mean that industries hitherto devoted mainly to defense have to find civilian customers in a hurry. Often those industries have formed their ideas of marketing through decades of dealing with the armed services and related government agencies. The prevailing schema for selling a product may be to go to lunch with an admiral, not necessarily a winning move in the competition for civilian business. Moreover, the mechanisms for varying such schemata and responding to selection pressures often take many years to operate, whereas the demand for defense-related systems may be drastically reduced over a year or two. If the managers (or new managers replacing them) do not introduce new mechanisms with a faster response time, the prospects for their company are not bright. The challenge of circumstances that change more rapidly than a given evolutionary process can accommodate is one that profoundly affects the prospects for the biosphere and for the human race as a whole. Human cultural evolution, especially through advances in the technological sphere, has made possible in a brief span of time an extraordinary expansion of the human population and of the capacity of each person to affect adversely other people and the environment. Biological evolution, in humans and in the other organisms, has no chance of keeping up. Our own genetic schemata reflect in great part the world of fifty thousand years ago and cannot, through the normal mechanisms of biological evolution, undergo important changes in just a few centuries. Likewise, other organisms and whole ecological communities cannot evolve quickly enough to cope with the changes wrought by human culture. The implication is that cultural change itself is the only hope for dealing with the consequences of a gigantic human population armed with powerful technologies. Both cooperation (in addition to healthy competition) and foresight are required to an unprecedented degree if human capabilities are to be managed wisely. The need for cooperation

and foresight will be even greater if reliance is placed, for dealing with some of the most urgent concerns, on artificial transformations of human beings and other organisms, utilizing future developments in genetic and other engineering. Given the immense complexity of the numerous interlocking issues facing humanity, foresight demands the ability to identify and gather great quantities of relevant information; the ability to catch glimpses, using that information, of the choices offered by the branching alternative histories of the future, and the wisdom to select simplifications and approximations that do not sacrifice the representation of critical qualitative issues, especially issues of values. Powerful computers are of critical qualitative issues, especially issues of values. Powerful computers are essential for assistance in looking into the future, but we must not allow their use to bias die formulation of problems toward the quantifiable and analyz- able at die expense of the important It is appropriate at this point to take a brief look at the kinds of simplified models of complex problems that computers can provide. Computers acting as complex adaptive systems can serve us both by learning or adapting themselves and by modeling or simulating systems in die real world mat learn or adapt or evolve.

CflAPT^ 20 MACHINES THAT LEARN OR SIMULATE LEARNING
Computers can Function as complex adaptive systems. Either the hardware can be designed so diat they do, or else computers with ordinary hardware can be programmed to learn or adapt or evolve. So far, most such designs or programs have depended on imitating a simplified picture of how some living complex adaptive system works. Neural Net Computation One well known type of computer complex adaptive system is the neural net, which can be implemented either with software or hardware. Here die analogy is with a crude model of how the brain of a mammal (especially a human being) might operate. One starts with a set of many nodes or units (often called neurons, although it is far from clear to what extent they really correspond to individual neurons in a brain). Each unit is characterized at every instant of time by a bit (0 or 1) diat is supposed to indicate whether the "neuron" is firing or not. Each unit is connected to some or all of the others, and the strengdi of the influence of any unit on any other is some positive or negative

t number depending on the two units. That number is positive if the first unit excites die second and negative if it inhibits die second. As the learning progresses, those strengths keep changing. Neural net computation can be carried out on conventional computers; in diat case the software is responsible for die units and their excitatory or inhibitory effects on one another. The units then exist only as elements of the computation. It is also possible to employ special computer hardware to realize the network, which is then composed of separate computing units arranged in a parallel processing format Of the many problems to which neural net computation has been applied, one example is learning to read an English text aloud with correct pronunciation. Since English spelling is notoriously far from phonedc, that is not a trivial exercise. The computer has to discover a huge number of general rules together with their exceptions, which can be regarded as special additional rules. Given enough text, not only the general rules but the special ones as well will crop up enough times to function as regularities. For the neural net computer to learn to read English aloud, it has to function as a complex adaptive system. It must try out various tentative identifications of sets of regularities in a batch of text, compress the information about them into schemata, and apply those schemata to more text, letting them compete with one another to come closest to the correct pronunciation, which is supplied by a "teacher." This kind of learning is called supervised learning, as opposed to the kind where, for example, schemata for pronunciation would be tried out on English speakers to see if they understood, but no teacher would be available to supply right answers. Supervision allows fitness to be defined, in terms of the amount of difference between the correct pronunciation of a text and the pronunciation resulting from the schema. In NETtalk, as developed by Terry Sejnowski and C. R. Rosenberg in 1987, the input data consisted of seven consecutive characters (each of which could be one of the 26 letters or else a space, a comma, or a period) from some written English text, presented in a moving window that gradually scanned the whole passage. The output was a pronunciation code for the middle character of the seven; that code was fed into a speech generator. The inputs were identified with die bits attached to a set of 7 times 29 (= 203) units, and the outputs with bits associated with 26 other

 units. There were 80 additional units to help with the learning. The schemata were represented by sets of interaction strengths, where the interactions were restricted to effects of input units on helper units and effects of helper units on output units. All other interaction strengths were fixed at zero, just to keep the process manageable. The network was trained using the characters constituting a text of 1024 words, accompanied by the "teacher," which was the sequence of pronunciation codes for all those characters, giving correct English pronunciation of the text. In the first training run through the text, the strengths would start out at some arbitrary values and then change (by a kind of learning) as the center of the seven-letter window moved letter by letter through the text At each step, the inputs and the strengths would be fed into a simple formula yielding candidate output values indicating attempted pronunciations. The discrepancy between the correct and the candidate outputs was then reduced by modifying the strengths, using a related simple formula. The strengths at the end of the first training run were used as the initial strengths for a second training run with the same 1024 word text. And so on. Success meant that the strengths, instead of fluctuating wildly from run to run, would zoom in, with only minor deviations, toward values giving a fair approximation to correct pronunciation. In the event, ten training runs on the 1024 words were enough to give intelligible speech, while after fifty training runs the pronunciation accuracy was estimated at 95 percent. After training, the resulting strengths were used to pronounce another batch of English text, with no further teaching. Intelligible speech, at an accuracy level of 78 percent, was achieved. There are many other versions of neural nets and a plethora of problems to which they have been applied, often with considerable success. The schema is always represented by a set of interaction strengths, each representing the effect of one unit on another. My Caltech colleague John Hopfield pointed out in 1982 a condition that, if artificially imposed on those strengths, would permit fitness not only to be well defined but to increase steadily during the learning process. The strength of the effect of any unit A on another unit B is required to be the same as that of B on A. This condition is almost certainly unrealistic for real brains and is also violated by many successful neural nets, including NETtalk. It is instructive, however, that there are situa-

 dons in which fitness is both well-defined and steadily increasing and others in which it is not. As usual when fitness is well defined, the learning process consists of exploring valleys on a fitness landscape. If fitness is also steadily increasing, so that height keeps decreasing, then the problem of getting stuck in a shallow depression when there are deep pits nearby crops up as always and can be ameliorated by introducing noise. That could be accomplished, for example, by altering the strengths slighdy, in a random way, from time to time. Such random changes in the schema resemble those proposed to jog the mind out of a rut when one is seeking a creative idea. As usual, there is an optimum level of noise. Genetic Algorithms as a Complex Adaptive System Since neural nets are based on a crude analogy with learning in higher animals, one might ask whether there are also computer-based complex adaptive systems suggested by an analogy with biological evolution. Indeed there are. They were pioneered by John Holland of the University of Michigan, a mainstay of the Santa Fe Institute, and they make use of "genetic algorithm" software, a special "classifier system," and conventional computer hardware. So far, these systems have been used mosdy for problems in which fitness is well defined, such as devising strategies tor winning at checkers or methods of installing wiring systems that minimize costs. However, there is no reason why the systems cannot be applied to other kinds of problems as well. A highly the systems cannot be applied to other kinds of problems as well. A highly simplified description of genetic algorithm software would go something like this. Each schema is a computer program for a candidate strategy or method. Every such program is composed of a number of computer instructions. The variation in schemata is accomplished by changing those instructions, say by having two of them undergo a crossing-over process (as shown on the facing page) like the one (illustrated on page 254) that occurs in the sexual reproduction of living organisms. The two instructions are both divided at a certain point into a beginning and an end. Crossing-over causes two new instructions to emerge. One of those is composed of the beginning of the fust old instruction and the end of the second. The other new one consists of the beginning of the second old one and the end of the first.

 Instructions 001110101110 and 101001100001 001101100001 and 101010101110 Can yield Crossover point 001110100001 and 101001101110 etc Crossing-over for computer instructions. Modifying a computer program by replacing one or more instructions with new ones generated in this manner sometimes improves the fitness of program and sometimes degrades it. Only by trying out the different programs on the problem to be solved can the computer judge the worth of each modification. (Making that kind of difficult judgment is known as "credit assignment") John Holland's classifier system provides a kind of marketplace in which competing instructions are bought and sold. Those that have a record of improving the performance of programs command higher prices than those that lead to no improvement or to worse performance. In that way an ordered list of instructions is established. New instructions are continually entered, and the ones at the bottom of the list are deleted to make room for them. The instructions at the top of the list are the ones used in the modified programs that constitute the mutated schemata. This is only the crudest sketch of what is a quite sophisticated procedure. Even so, it should be clear that programs evolve as a result,

 and that fitness tends to increase in the course of the evolution. The feedback from the performance of a program to the promotion and demotion of die instructions diat make it up is not a rigid rule, however, but a general tendency affected by market conditions. Hence mere is enough noise in the system to permit escape from minor basins of fitness so that depths nearby can be plumbed. Typically, the system is exploring a huge space of possible methods or strategies and not reaching a steady state—an absolute optimum. The optimum strategy for playing chess, for example, has not been optimum. The optimum strategy for playing chess, for example, has not been found. If the game in question were tic-tac-toe, however, die machine would soon find die best way to play and die search would be over. Although the generic algorithm method has been applied mainly to search and optimization problems where fitness (or "payoff") is well defined, it can also be used in other cases, just as neural nets can be employed in bodi kinds of situation. Both neural nets and genetic algoridims yield computer-based complex adaptive systems diat can evolve strategies no human being ever devised. It is natural to ask whether there is anything special about these two classes of techniques, suggested by vague analogies widi the functioning of brains and of biological evolution respectively. Can another class be invented diat is based on an analogy with mammalian immune systems? Is there in fact a huge but well-defined set of computer-based complex adaptive systems diat includes those diat are known or hypothesized and many others besides? Can such an overarching category be described in practical terms so diat a potential user could search through the different possible computer-based systems to find one appropriate for his or her problem? Such questions are among the ones diat students of computer-based complex adaptive systems are trying hard to answer. Simulation of Complex Adaptive Systems The use of computers in connection with complex adaptive systems is by no means restricted to developing hardware or software for computer-based complex adaptive systems used to solve problems. Another vast area of computer applications is the simulation of the behavior of complex adaptive systems.

 The most striking feature of those simulations is the emergence of complex behavior from simple rules. Those rules imply general regularities, but the working out of an individual case exhibits special regularities in addition. This situation is similar to that of the whole universe, governed by simple laws allowing for an infinity of scenarios, each of which exhibits its own regularities, especially for a given region of space and epoch of time, so that more and more complex forms can emerge as time goes on. The trick in designing a manageable simulation is to prune the rules so as to make them even simpler, but in such ways that the most interesting kinds of emergent behavior remain. The designer of a simulation must then know a good deal about the effects of changes in the rules on behavior in many different scenarios. Some designers, such as Robert Axelrod, a political scientist at the University of Michigan, have developed a keen intuition that helps them guess how to simplify without throwing the baby out with the bath water. Naturally, that intuition is based partly on a priori reasoning and partly on experience of fiddling with the rules and then watching what happens under the modified rules in particular computer runs. Still, the design of simple simulations rich in interesting consequences remains more of an art than a science. Can the study of sets of rules and their consequences be made more scientific? Additional experience is needed, together with the formulation of inspired empirical guesses about what kinds of rules lead to what kind of behavior. Then rigorous theorems may be conjectured, and finally some of those theorems may be proved, presumably by mathematicians. In that way, a kind of science of rules and consequences may emerge, with the computer runs functioning as experiments and the conjectured and proved theorems constituting the body of theory. In fact, with the advent of rapid and powerful computers, more and more simple simulations are being run, and on more and more subjects. The raw material for the future science is already accumulating. In the end, though, what really matters is the relevance of the simubtions to the real-world situations that they imitate. Do the simubtions supply valuable intuition about real situations? Do they suggest conjectures about real situations that could be tested by observation? Do they reveal possible behaviors that had not been thought

 about before? Do they indicate new possible explanations of known phenomena? In most fields simulations are still too primitive for these questions to be answered in die affirmative. Nevertheless, it is astonishing how, in certain cases, a very simple set of rules can give insight into the operation of a complex adaptive system in the real world.

A Simulation ot Biological Evolution

A splendid and by now quite celebrated example is the TIERRA program written by Thomas Ray of die University of Delaware and die Santa Fe Institute. He was an ecologist working in die lowland rain forest of Costa Rica at die biological research station called La Selva. Ecological research attracted him because he wanted to study evolution. Unfortunately, not much biological evolution takes place during a human lifetime and so he began to find his field work frustrating. He dierefore decided to simulate evolution on a computer. He was planning to develop a suitable program in stages, starting widi a highly oversimplified one and men gradually building in more features, such as punctuated equilibrium or die existence of parasitism. He taught himself painfully to write a program in "machine language" and managed to get a single very simple one written and debugged. That initial program was TIERRA, and it has turned out to be extraordinarily rich. Running it over and over and understanding die lessons of all die different runs has occupied him ever since. Moreover, a number of features he was planning to build in later, including both punctuated equilibrium and die prevalence of parasitism, emerged from TIERRA itself. The program even turned up something very much like sex. TIERRA uses "digital organisms," which are sequences of machine instructions diat compete for space in die memory of die computer and for time on die central processing unit, which diey use for self-replication. The community of complex adaptive systems provided by TIERRA is degenerate in a sense because die genotype and die phenotype of each digital organism are both represented by die same object, namely die sequence of instructions. That sequence is what undergoes mutation and it is also what is acted upon by selection

 pressures in die real world. Still, it is a good idea (as emphasized by Walter Fontana) to keep the two functions separate when thinking about the system, even though both are performed by die same entity. (According to some theories of the origin of life on earth, an early stage of that process had die same degenerate character, with RNA playing the roles of both genotype and phenotype.) Mutations are introduced in two ways. First, from time to time bits are flipped (from 0 to 1 or vice versa) at random anywhere in the whole set of organisms (much as real organisms are affected by cosmic rays). The rate used is around one bit flipped for every ten thousand instructions executed. Second, in die course of replication of digital organisms, bits are flipped at random in the copies. Here die rate is set somewhat higher, about one bit flipped for every couple of thousand instructions copied. These are average rates; die errors are irregularly timed to avoid periodic effects. The importance of death in biology was not neglected in the design of TLERRA. Memory space is severely limited, and in the absence of death self-replicating creatures would soon fill it up, leaving no room for further replication. Hence the "reaper," which kills off organisms on a regular basis according to a rule that depends on the age of the organism and on errors it made in executing certain instructions. Tom Ray designed a self-replicating sequence of eighty instructions, which is always used as die ancestor—the initial digital organism—in any run of TIERRA. When he ran die system the first time, he expected a long period of trouble and trouble-shooting to ensue. Instead, interesting results started to emerge right away, many of them suggestive of real biological phenomena, and that situation has prevailed ever since. One intriguing development was the appearance, after a long period of evolution, of a refined version of the ancestor. It has only thirty- six instructions instead of eighty and version of the ancestor. It has only thirty- six instructions instead of eighty and yet manages to pack into them a more complex algorithm. When Tom showed this trick of compression to a computer scientist, he was told that it was an example of a known technique called "unrolling the loop." In TIERRA, evolution had figured out how to unroll the loop. Tom writes, "The optimization technique is a very clever one invented by humans. Yet it is implemented in a mixed-up but functional style that no human would use (unless perhaps very intoxicated)."

 How do such organisms with other man eighty instructions arise? Mutations cannot produce diem direcdy. Initially, die system contains only the ancestor and its eighty-instruction descendants. (They multiply until die memory is nearly full; mat is when the reaper starts its work. The changing population of organisms then continues to occupy most of die memory.) Eventually, mutations appear diat alter the genotype of an eighty-instruction organism in a special way: when the organism examines itself to determine its size, so that it can pass on diat size to its descendants, the answer comes out wrong and a new size is passed on instead. In diat way, die population comes to contain organisms of many different sizes. If so many insights have emerged from die first attempt to model biological evolution in this way, diere must be a huge territory still waiting to be explored New ways of simulating how evolution, operating over enormous stretches of time, has generated the information now stored in organisms and natural communities diroughout the world may help not only to improve our understanding of existing diversity, but also to create a climate of ideas in which that diversity can be better protected. A Tool tor Teaching About Evolution TIERRA, together with related computer simulations of biological evolution to be developed in the future, will be especially valuable for conveying to nonscientists a feeling for how evolution works. Most people find it easy to appreciate, even without computer simulations, how comparatively minor variations combined with a few generations of selection can produce changes in a population. Personal experience widi die breeding of dogs, budgerigars, horses, or roses can easily convince almost anyone of die reality of evolution on a small scale. But evolution on a longer time scale, widi the emergence of new species, genera, families, and still higher taxa is a different matter. Even the comparatively close relationship of the elephant to the rock hyrax is hard for most people to grasp. It is still more difficult to visualize the interrelationship of all forms of life, including die immense changes diat can be wrought over billions of years. What is especially hard for many people to accept is that chance plus selection pressures can lead from a simple initial condition to highly

complex forms and to complex ecological communities comprising such forms. They cannot really bring themselves to believe that such evolution can take place without some kind of guiding hand, some kind of design. (Others balk especially at die evolution of consciousness, the self-awareness of which we humans are so proud; they feel somehow diat consciousness cannot arise widiout antecedent consciousness.) Never having entertained any of those doubts, I can only view them from the outside. But it seems clear to me mat one way to relieve them is to let people experience die remarkable transformations effected by millions of generations of largely random processes combined with natural selection. That can be done only by simulation, as in TIERRA, which can run through a huge number of generations in a manageable period of time, and in more sophisticated and realistic simulations diat will be available in the future. In describing biological evolution in terms of chance and selection, we ate treating die various mutation processes as purely stochastic A few investigators have claimed, however, to find deviations from chance behavior. They have interpreted certain observations as indicating diat sometimes mutations arise in nonrandom ways, even in ways that seem biased in favor of increasing fitness in response to changing selection pressures. In at least one case, die evidence adduced has been satisfactorily explained widiout such an interpretation. Perhaps all die alleged cases can be similarly explained. But even if certain organisms should turn out to have evolved mechanisms permitting occasional exceptions to chance behavior of mutations, our description of biological evolution would, as far as we know, be largely unchanged. Before Tom Ray had developed TIERRA, I convened a small group of thoughtful people at die Santa Fe Institute to discuss whether we could invent a computer game diat might become popular and would convince die players of die immense power of die evolutionary process extended over very many generations. One excellent result of die meeting was diat when John Holland went home he invented ECHO, a rich computer simulation of an ecology of simple organisms. However, die game diat was to be a teaching aid was not forthcoming. Then, shortly afterward and quite independendy, came Tom Ray's TIERRA, which, although not really a game, may ultimately produce die same effect. Some participants in die meeting pointed out that a pocket in die cover of die first paperback edition of Dawkins's book The Blind Watchmaker holds software for a computer game illustrating evolution. That kind of game is not, however, exacdy what I had in mind. The point is

that in real biological evolution mere is no designer in the loop. But Dawkins, whose book is devoted to making that very point in an elegant manner, has invented a game in which the player keeps supplying die selection pressures as evolution proceeds, much like the user of Karl Sims's software for producing pictures. (The game does come with a "drift" option, in which the player can let die organisms alone, but diey are still not subject to selection pressures from an ecological community to which they belong.) Using die (only partially justified) language of fitness, one can say that in Dawkins's game, the fitness is exogenous, supplied from the outside, whereas in nature (as his book explains) die fitnesses are endogenous, ultimately determined, without external interference, by die character of die earth and the sun and by chance events, including the evolution of huge numbers of particular species. Can a game be designed in which die players, like Tom Ray using TIERRA, supply only an initial situation and a set of rules for biological evolution while chance and natural selection do merest? Simulation ot Collectivities or Adaptive Agents Any serious simulation of evolution must include the interaction of populations belonging to numerous species; die environment of each of those species comprises all die other organisms as well as the physicochemical surroundings. But what if we are trying to understand what happens to such an ecological community over a comparatively short period of time, during which not much biological evolution is taking place? We are then attempting a simulation of ecological processes. A number of theorists associated with the Santa Fe Institute have used computer models to learn about the properties of those complex adaptive systems that are collectivities of co-adapting adaptive agents, which construct schemata to describe and predict one another's behavior. Those researchers have come up with a body of lore about such systems, consisting of plausible conjectures together with results demonstrated for particular models. The picture that emerges is one in which the region of intermediate algorithmic information content, between order and disorder, may contain a regime resembling that of

self-organized criticality, exemplified by sand piles. In that regime, key quantities may be distributed according to power laws. Most important of all, diere may be a tendency for the whole system to evolve toward the condition in which those power laws apply. Stuart Kauffinan has done a good deal of theoretical research power laws apply. Stuart Kauffman has done a good deal of theoretical research on these ideas, as has Per Bak. Stuart is among those who describe them by using the term "adaptation toward (or to or at) the edge of chaos," where "edge of chaos" is used somewhat metaphorically to indicate a critical condition between order and disorder. The entire expression, which is now widespread in popular literature, was first employed by Norman Packard (using the preposition "toward") as the tide of a paper on the approach to such a critical condition by a very simple computer- based learning system. Related research was carried out independently around the same time by Chris Langton. In the ecological and economic domains where some of the obvious applications lie, such power laws are well known from observation, particularly ones governing the distribution of resources. The famous empirical law of wage distribution in a market economy, discovered in the nineteenth century by the Italian economist Vilfredo Pareto, approximates a power law for the higher incomes. Pareto also discovered a rough power law for individual wealth, again applicable to the high end of the spectrum. Ecologists often look at the share of resources utilized by all the individuals of a given species taken together, considered as a function of the various species in a natural community. They too find empirical power laws. For example, along the rocky part of the shore of the Sea of Cortes near its nothern extremity just south of the U.S. border, the intertidal zone contains a number of different organisms, such as barnacles and mussels, occupying various proportions of the surface area of the rocks. The total areas occupied by the different species obey a power law to a fairly good approximation. Preying on these rock dwellers are other creatures, higher in the food chain. Among them, at or near the top of the chain, is a 22-armed starfish, Heliaster kubiniji. What would happen if the starfish were removed from the picture? That actually occurred, dirough some catastrophe, over a certain stretch of the coastline, and ecologists were able to observe the consequences. The result was that the system consisting of the remaining organisms readjusted itself, with new values for the total rock areas covered by the various species clinging to them. However, the approximate power law once

again held. There may dius be some empirical support for die idea diat systems of coadopting agents are attracted to a kind of transition regime characterized by power laws for resource distribution.

Rule- ana Agent-Based Mathematics

In much of today's research on complex adaptive systems, madiematics plays a very significant role, but in most cases it is not the kind of madiematics diat has traditionally predominated in scientific theory. Suppose diat die problem is one in which a system is evolving in time so diat at each moment its state changes according to some rule. Many of die striking successes of scientific dieory have been achieved with die aid of continuum madiematics, in which the time variable is continuous and so are die variables describing die state of die system. That state changes from moment to moment according to a rule diat is expressed in terms of die continuous variables that characterize the system. In technical language, die time development of die system is said to be described by a differential equation or a set of such equations. Much of the progress in fundamental physics over die last several centuries has taken place widi die aid of such laws, including Maxwell's equations for electromagnetism, Einstein's equations for general-rela- tivistic gravitation, and Schrodinger's equation for quantum mechanics. When such equations are solved widi die aid of a digital computer, it is usual to approximate die continuous time variable by a so-called discrete variable, which takes on values separated by finite intervals instead of all possible values between die initial and final instants diat bound die time period under study. Moreover, die continuous variables characterizing die state of die system are also approximated by discrete ones. The differential equation is replaced by a difference equation. As die intervals between die nearby values of die discrete variables, including time, become smaller and smaller, die difference equation looks more and more like die differential equation it is replacing, and die digital computer comes closer and closer to solving die original problem. The kind of madiematics diat is often used in die simulation of complex adaptive systems resembles die discrete madiematics used on a digital computer to approximate continuous differential equations, but

now the discrete mathematics is used for its own sake and not just as an approximation. Furthermore, die variables describing die state of die system may take on just a few values, with die different values representing alternative events. (For instance, an organism may or may not eat another organism; or two organisms may or may not engage in combat, and, if they do, one or die other will win; or an investor can buy, hold, or sell shares of a stock.) Even the time variable may run over only a few thousands of values, representing, for instance, generations of a species or financial transactions, depending on the kind of problem. In addition, die changes in the system at each of those discrete moments are, for many problems, determined by a rule that depends not only on die state of die system at the time, but also on die result of a chance process. Discrete mathematics of die kind we have been discussing is often called rule-based. It is a natural kind of mathematics for digital computers, and it is often applied to die simulation of complex adaptive systems composed of many individual adaptive agents, each of which is itself a complex adaptive system. Typically, die agents —such as organisms in an ecological community or individuals and businesses in an economy—are evolving schemata describing the behavior of other agents and how to react to it. In such cases, rule-based mathematics becomes agent-based mathematics, as used, for example, in TIERRA. Making Economics Less Dismal Exercises using agent-based mathematics are among die tools that have been employed recendy to guide economics toward a more evolutionary approach to its subject matter. A preoccupation with a kind of ideal equilibrium, based on perfect markets, perfect information, and perfect rationality of agents, has characterized a great deal of economic theory during the past few decades. That is true despite die efforts of some of the best economists to incorporate imperfections of all diree kinds into the post-World War II neoclassical synthesis. In a story that has long circulated among economists, a neoclassical theorist and his well-behaved litde granddaughter are walking along the street in a large American city. The girl spots a twenty-dollar bill on

 the pavement and, being very polite, asks her grandfather if it is all right to pick it up. "No, Dear," he replies, "if it were real someone would already have picked it up." For several years, a number of scholars, including die members of an interdisciplinary network assembled by die Santa Fe Institute, have directed their efforts toward studying economies as evolving complex adaptive systems composed of adaptive economic agents endowed only with bounded rationality, possessing imperfect information, and acdng on die basis of chance as well as perceived economic self-interest. The fairly successful predictions of equilibrium dieory then appear as approximations, while die newer approach admits departures from those predictions, and especially fluctuations around them, in better agreement with reality. In one exceedingly simple model, developed by Brian Arthur,John Holland, and Richard Palmer (a physicist at Duke University and die Santa Fe Institute), investors in a single security (say a stock) are represented by adaptive agents dealing with one another through a central clearinghouse. A share of stock pays a yeariy dividend, which may vary with time in some arbitrary way. The going annual rate of interest is a constant, and die ratio of die dividend to diat interest rate determines, more or less, die fundamental value of the share. The actual price of die share may, however, deviate gready from die

The actual price of die share may, however, deviate greatly from die fundamental value. Each agent keeps constructing elementary schemata, based on the history of die stock price, diat tell him or her when to buy or hold or sell. At any time, different agents may be using different schemata. Moreover, a given agent may have a list of several schemata and switch from one to anodier depending on performance. In diis way price fluctuations are generated, sometimes wild ones involving speculative booms and busts, widi die slowly changing fundamental value supplying a kind of rough lower bound for die jagged curve of price versus time. Such fluctuations, reminiscent of what goes on in real markets, turn up here in an evolutionary model, with agents diat are far from perfect but try to learn. A number of the participants in die movement to reform economics have shown that perfect rationality is not only in obvious contradiction with die facts of human affairs, but is actually inconsistent widi any situation in which market fluctuations occur. I personally have always been astonished by die tendency of so many academic psychologists, economists, and even anthropologists to treat human bangs as

 entirely rational or nearly so. My own experience, whether engaging in introspection or observing others, has always been that rationality is only one of many factors governing human behavior and by no means always die dominant factor. Assuming diat humans are rational often makes it easier to construct a dieory of how diey act, but such a dieory is often not very realistic. There, alas, is die chief flaw in much of today s social and behavioral science. When it comes to theories of complex phenomena, making diem more analyzable may be convenient but does not necessarily make diem better at describing die phenomena—and may easily make diem much worse. The great contribution of economic dieory to understanding human affairs is, in my opinion, simply the repeated emphasis on incentives. In any situarion, what are die incentives for different courses of action? When die first Dead Sea Scrolls were discovered and archaeologists wanted more scraps of the scrolls to be found and turned in by wandering Arab shepherds, die misguided scholars offered a fixed reward per soap, thereby making it likely diat die fragments would be broken up into tiny pieces before being delivered. Economists study, often in sophisticated ways, how incentives operate throughout society and they point out the flaws in scheme after scheme, in government or business, analogous to die flaws in the reward system for die Dead Sea Scrolls. Incentives provide selection pressures in an economy. Even when die responses to diem are not fully rational, and even if mere are other pressures at work, economic incentives still help to determine which schemata for economic behavior will prevail. Human ingenuity will often find some way to profit by die incentives that exist, just as biological evolution will frequendy manage eventually to fill some vacant ecological niche. Approaching economics in an evolutionary way and recognizing the bounded rationality of human beings can only improve economists' insights into die ways in which incentives operate. The economics program has been one of the most successful activities of die Santa Fe Institute, in terms of stimulating new theoretical and modeling activities of high quality. Ultimately, of course, success must be measured, as in all theoretical science, by explanations of existing data and by correct predictions of die results of future observations. The Institute is still too young and die problems it studies too difficult for very much success of diat kind to have been achieved so far. The next few years will be critical for judging die results of the Institutes

 work, and economic modeling is likely to be one of the efforts that result in verified predictions. However, there are other reforms that are much needed in economic theory. Attempts to deal with some of those were contemplated in parts of the original plan for the Institute's economics program that have not yet been implemented. One vital problem has to do with taking proper account of values difficult to quantify. Economists have sometimes been lampooned as people who would measure the value of love by the price of prostitution. The value of some things is easy to assess in terms of money, and the temptation is strong to count only such things in cost-benefit calculations and to ignore everything else. If the construction of a dam is proposed, old- fashioned cost-benefit analyses take into account benefits like electrical power and flood control. In addition, the resulting reservoir may be assigned a recreational value measured by the cost of the marinas and docks that will be built for power boats. The cost of the buildings in the valley that will be drowned by the rilling of the reservoir may be counted against the dam, but not the value of the plants and animals in that same valley, nor the historical associations that the valley may have had, nor the community ties that are destroyed. It is difficult to assign a monetary value to such things. The apparendy hard-headed practice of ignoring values difficult to quantify is often advertised as being value-free. On the contrary, it represents the imposition on any analysis of a rigid system of values, favoring those that are easily quantifiable over others that are more fragile and may be more important. All our lives are impoverished by decisions based on that kind of thinking. Many economists and political scientists have recommended leaving fragile values to the political process. But if that is done, all the quantitative studies, with their careful calculations of what happens to easily quantified values, have to be weighed by decision makers against qualitative arguments that are not similarly bolstered by impressive numbers. Nowadays the idea is gaining ground of actually polling people to see what kind of value they would assign to such things as a given improvement in air quality or the preservation of a park or neighborhood. In economic theory, people's preferences are usually treated as well-defined, fixed, and given. Respect for the preferences of large numbers of people is in harmony with democratic ideals. But is the fate of the planet just a matter of widespread untutored opinions? Couldn't

 new understanding change those opinions? Doesn't science have some insights to offer? Natural science would seem to be particularly relevant when changes are contemplated that are irreversible or nearly so. Does economics as presendy formulated pay sufficient attention to irreversibility? In physics, die first law of thermodynamics is the conservation of total energy, and keeping track of energy in physics somewhat resembles the process of keeping track of money in economics. But where is the analogue in economics of the second law of thermodynamics, the tendency of entropy to increase (or remain the same) in a closed system? Entropy helps to define irreversibility in physics, and many drinkers have tried to define a corresponding notion in economics, so far widiout conspicuous success. Perhaps the quest is not hopeless, however. And perhaps it is worth pursuing, since it might lead to an improvement on the widespread notion that whatever is nearly used up can be replaced by some substitute, such as plastic trees. Meanwhile, leading economic thinkers have developed concepts that address some of the concerns about following only things mat are easily monetized. The notion of "psychic pay" takes account of the fact that people gain satisfaction from, and can be paid in, coin that is intangible, such as pride in helping others. The "cost of information" addresses the fact that people may not know how to make reasonable free market decisions (for instance about purchases) if they don't have the necessary facts or insights. The "social rate of discount" is supposed to deal with the debt between the generations—how steeply a given generation discounts the future is related to how much it is planning to leave to future generations. However, working economists in business, government, and international agencies may not find it easy to include such advanced concepts in their reports and recommendations. Furthermore, it such advanced concepts in their reports and recommendations. Furthermore, it may be very difficult to quantify some of those concepts even though they have supposedly been introduced into the theory. In both theory and practice, then, there seems to be some room for improvement in the way economics addresses questions of fragile values, especially in cases where those values are in danger of disappearing irreversibly. Any improvements that are made can be particularly valuable in connection with the preservation of biological and cultural diversity.

^RT^ DIVERSITY AND SUSTAINABILITY

c*KPTEjf 21 DIVERSITIES UNDER THREAT We have examined how simple rules, including an orderly initial condition, together with the operation of chance, have produced the wonderful complexities of die universe. We have seen how, when complex adaptive systems establish themselves, they operate through the cycle of variable schemata, accidental circumstances, phenotypic consequences, and feedback of selection pressures to die competition among schemata. They tend to explore a huge space of possibilities, with openings to higher levels of complexity and to die generation of new types of complex adaptive system. Over long periods of time, they distill out of their experience remarkable amounts of information, characterized by both complexity and depth. The information stored in such a system at any one time includes contributions from its entire history. That is true of biological evolution, which has been going on for four billion yean or so, and also of the cultural evolution of Homo sapiens sapiens, for which the time span is more like a hundred thousand years. In this chapter we take up some of the problems and dilemmas encountered in trying to preserve, at least in great part, the diversity that those two kinds of evolution have produced. In contrast to the previous chapters, the emphasis here will be more on actions and policies than on knowledge and understanding for their own sake. Likewise, the voice will be as much that of the advocate as of #9

 the scholar. In die next chapter we move on to the broad context within which a sustainable and desirable future could be sought, and how that context might be studied. While much of our discussion will focus on science and scholarship and the role of experts, we must bear in mind that in the long run attempts to impose solutions on human societies from above often have destructive consequences. Only through education, participation, a measure of consensus, and the widespread perception by individual people that they have a personal stake in the outcome can lasting and individual people that they have a personal stake in the outcome can lasting and satisfying change be accomplished. The Conservation of Biological Diversity We have mentioned the importance of conveying to everyone (for instance by means of computer simulations) a feeling for how a single ancestor could give rise, dirough transmission errors and genetic recombination accompanied by natural selection, to the effective complexity represented by the astonishing diversity of life forms in existence today. Those life forms contain an extraordinary amount of information, accumulated over geologic time, about ways to live on the planet Earth and ways for different life forms to relate to one another. How litde of that information has been gathered so far by human beings! Yet humans, dirough procreation combined with a high environmental impact per person (especially per rich person), have started to produce an episode of extinction that might eventually compare in destrucdveness with some of die great extinctions of the past. Does it make any sense to destroy in the course of a few decades a significant fraction of die complexity that evolution has built up over such a long period? Are we humans going to behave like some other animals, filling up every available nook and cranny in response to a biological imperative, until our population is limited by famine, disease, and conflict? Or are we going to make use of the intelligence diat, we like to boast, distinguishes our species from the others? The conservation of biological diversity is one of die most important tasks facing humanity as the twentieth century nears its end. The

enterprise involves people in many walks of life and in various parts of die world, using diverse methods to decide what needs to be done and especially what needs to be done first Although die choice of how to assign priorities will vary from place to place, mere are some principles and practices that may be widely applicable. Tke Importance of tKe Tropics It seems that the greatest need for conservation efforts (especially on land) is in die tropics, where there is die greatest species diversity and also die greatest pressure to utilize natural resources to meet die needs of a poor and rapidly growing human population. This conjunction— more to lose and more danger of loss—makes biological conservation in die tropics especially urgent. The tropics are different from the temperate world not only in the number of species now threatened, but also in how much is known about them. In temperate latitudes it is generally possible to define conservation needs by looking at individual species (at least for die "higher" plants and animals) and determining which ones are in difficulty on a local, national, or world level.

When biomes (ecological communities) are considered, as they should be, they can be defined as associations of known species. In the tropics, numerous species are still unknown to science and some whole biomes remain underexplored. Under those conditions, it is impractical, as a general rule, to state die aims of conservation in terms of species. Instead, one usually has to concentrate on saving representative systems in which die individual species are represented, and die definition of those systems is not always easy. The Role of Science Science plays a crucial role in tropical conservation. That is especially clear when we remember mat the aim of science is not just to accumulate facts but to promote understanding by finding structure (that is, regularities) in die information and also, where possible, mechanisms (dynamical explanations) for phenomena.

332 • DIVERSITY AND SUSTAINABILITY A whole spectrum of approaches is available for gathering, organizing, and interpreting data about the status of natural communities throughout the tropics. Systematic biologists (those who study the classification and distribution of plants and animals) tend to favor long- term research, which may take place over many decades and produce knowledge that will be important for a long time to come. At the other end of the scale are techniques such as satellite imagery and aerial photography, which yield immediately some crude indications of differences in ground cover, lb understand what those differences mean, one needs to establish "ground truth," which can be more or less detailed, but typically involves expeditions and a good deal of taxo- nomic work. Such efforts are situated in the middle of the spectrum, between long-term studies on the ground and rapid surveys from air or space. There is no longer any serious disagreement diat a large-scale, man-made episode of extinction has begun in the tropics. To some, it is self-evident that we should not wantonly destroy the product of billions of years of evolution. Others need additional reasons to protect what is in danger of being lost Those reasons include the potential utility to human beings of species that we are exterminating before we even know they exist, to say nodiing of the value to future generations of understanding the operation of complex ecosystems in a comparatively undegraded condition. One of the important tasks for scientists is to explain those arguments in detail. Science can provide not only guidance for setting priorities in conservation but also an understandable rationale for those priorities. In other words, preservation of biological diversity requires more scientific knowledge so that conservationists have a good idea how to proceed and also so that they can demonstrate that what they are doing makes sense.

Accurate, well-marshaled information is a powerful tool that can help mobilize the broader social will needed to protect viable examples of the various ecological communities. In this endeavor, I would venture to guess, it is important to use and develop the discipline ofbiogeography. Biogeography is the study of the distributions of plants and animals and how those distributions evolved, taking into account the influence of geology and topography. It is concerned with processes of variation, dispersal, survival, and extinction, including developments over past

 time as well as ongoing processes that determine die limits of distributions for the various organisms today. Biogeography, in close association with both systematics and ecology, can provide a body of theory that helps to organize the data on occurrences of plant and animal species. It may assist in providing a classification of biomes and it can be of great utility in planning the configuration of a viable system of protected areas and in identifying gaps in existing systems. Rapid Assessment From the point of view of science, it is essential to maintain the long- term research that does not provide quick results but can give lasting ones. Obviously, however, conservation action cannot always wait for those results. By the time field biologists have completed a careful, thorough study of flora and fauna in a particular area of the tropics, it may be too late to recommend the preservation of natural communities in all or part of that area, because those communities may no longer exist. Pursuing the whole spectrum of scientific activities essential for conservation requires taking creative advantage of all potential resources. In particular, a few individual field biologists (botanists, ornithologists, and herpetologists, for example) have learned from their personal training, field experience, and scientific knowledge how to take a quick, rough census of the species in their fields of study present in an area of a given tropical region. They have acquired an idea of the composition of various biomes and they have also developed rapid methods of determining the degree of degradation of an environment. Their knowledge and their wisdom can and should be utilized in conservation work. By estimating the biological diversity of a particular area, as well as the state of preservation of its natural communities, and by helping to determine which biomes are restricted to small regions and which ones are gravely threatened, they can give immensely valuable advice to those who set priorities for protection. The same field biologists can also contribute gready to the success of short-term expeditions that provide ground truth for aerial and satellite photography, as well as to the success of long-term studies in systematic satellite photography, as well as to the success of long-term studies in systematic biology and

 biogeography. It is particularly important to train more scientists like them, especially among nationals of the tropical countries themselves. Through the John D. and Catherine T. MacArthur Foundation, of which I am a director, I helped set up the Rapid Assessment Program under the auspices of Conservation International. A core group was assembled, consisting of an ornithologist, a mammalogist, and two botanists. In association with other field biologists, they formed teams to explore particular places (so far mosdy in the Americas). The teams have by now examined areas of many different kinds, including dry forest, montane cloud forest, and lowland rain forest, initially identified by aerial survey, in order to find out whether they possessed enough biological diversity and were sufficiently undisturbed to warrant protection. In 1989 I participated in one of those aerial surveys along with Spencer Beebe, men an official of Conservation International, and Ted Parker, die program's ornithologist. We found a remarkably large and well-preserved area of forest in Bolivia, the Alto Madidi, and identified it as an early target for the program. The terrain stretches from lowland Amazonian rain forest (drained by tributaries of the Amazon, although many hundreds of miles distant from the great river itself) to high mountain forest of several kinds. Later on, the team visited the region and studied it on the ground, finding it even more striking in diversity and quality than we had guessed while looking at it from the air. Now the Bolivian Academy of Sciences and the Bolivian government are considering the possibility of extending protection to the Alto Madidi. Walking through South American forests with Ted Parker, I found myself agreeing with the superlative opinions I had heard expressed about him. Of all the highly skilled field ornithologists I have accompanied, he was the most impressive. He knew by heart and could recognize the songs and call notes of more than three thousand New World bird species. For days on end, he would identify every forest sound as made by a frog, an insect, or a particular species of bird. When we recorded the birds and called mem in by playing their songs back to mem, his identifications would always be proved correct. But then, one day, he might exclaim, on hearing a faint "Psst" from the underbrush. "I don't know what that is!" Sure enough, it would be a new bird for the area or the country, or even, very occasionally, a species new to science.

 Listening at dawn, he could estimate, from the calls and songs he heard, both the ornithological diversity and the from the calls and songs he heard, both the ornithological diversity and the quality of the habitat. His colleagues in mammalogy (Louise Emmons) and botany (Alwyn Gentry and Robin Foster) could perform comparable feats in their specialties. Recendy, tragedy struck diis outstanding team. Ted and Alwyn were killed, along with an Ecuadorian colleague, Eduardo Aspiazu, when their plane crashed during an aerial survey. The pilot was killed too. The biologists, as usual, were urging the pilot to fly lower so that they could inspect the forest carefully from the air. (They were looking for a small stretch of remaining dry forest near Guayaquil that might be protected before it was all gone.) Suddenly the aircraft entered a cloud, visibility was lost, and they collided with a nearby mountain. While mourning the loss of our friends, who seemed almost indispensable, those of us involved in tropical conservation hope that the work of the Rapid Assessment Program will somehow continue. We hope that their places will be taken by other specialized field biologists, nearly as skilled, and that new ones will be trained, especially citizens of tropical countries. In general, die future of the preservation of ecological diversity in the tropics depends to a great extent on the activities of the growing body of scientists and conservationists from the tropical countries themselves. By and large, major conservation decisions will be made on the national level, and an increasing number of citizens' organizations in the various countries are providing leadership in the protection of biological diversity. Internationally known scientists from temperate countries can sometimes exert a useful influence, but conservation will not happen without local and national support. Participation ot Local People In fact, conservation needs the support both of influential individuals, many of them in large cities, to get projects started and of local rural populations to maintain nature reserves over time. Long-term protection of large areas cannot succeed unless it is regarded with favor by the local people. This means emphasis on the contributions of conservation

 to aspects of rural development. For instance, agriculture often depends on die protection of watersheds, and die long-term availability of forest products for use and sale often requires die maintenance of nearby protected forest. Local people must have an economic stake in conservation, and they need to understand that stake. Often they can be direcdy involved with protected areas, for example through nature tourism or opportunities to serve as guides or rangers in national parks. It is particularly important to involve local indigenous people, such as die American Indians of die neotropics. In many cases, their cultural continuity and even their physical existence are more threatened than are die plants and animals of die areas where they live. Their knowledge about their environment, accumulated over many centuries, can help to identify human uses for native organisms, as well as mediods of earning a living without destroying die ambient ecological communities. In some cases, indigenous peoples have taken die lead in conservation efforts, for example, die Kuna of Panama, who have made a park out of a large fraction of their mainland territory. (Many of die Kuna live on die San Bias Islands, where they are well known as die makers of the colorful molas, often used to decorate dresses and handbags.) The struggle for survival of organisms in tropical forests leads to chemical arms races and other processes that generate chemical substances with potent biological effects, many of diem useful to human beings, especially in medicine. Such chemicals are being sought by two different means. One method, ethnobotany, exploits the knowledge of indigenous peoples, obtained by trial and error over hundreds or thousands of years, and thus makes use of cultural evolution as well as die biological evolution diat produced die chemicals in die first place. The other method is direct chemical prospecting, in which specimens of plants and animals (insects, for example) are brought from the forest to the laboratory, where new chemicals are isolated using modern methods of extraction. Here, the results of biological evolution are exploited without die helpful intervention of indigenous cultures. Both methods aim to find at least a few chemicals that will finally be utilized, say by drug manufacturers, often in developed countries. Even when such chemicals are used in modified or synthetic form, ways must be found for a significant fraction of the profits to be returned to the people of the forest or the surrounding areas. Only then can die process of exploration and utilization give those local people an additional stake in the

 preservation of die forest. The same is true of the many schemes for marketing other nontimber forest products, such as nuts and succulent tropical fruits. As usual, incentives create selection pressures on the schemata for human behavior. A Spectrum or Conservation Practices The collection of certain nontimber forest products (such as those that require hunting) can be carried out, like the harvesting of timber itself, only in areas that are at best partially protected. One scheme that has been widely adopted and endorsed by the United Nations is the creation of biosphere reserves. A typical biosphere reserve has a core area, often a wild watershed, that is folly protected, and a surrounding region in which some harvesting practices are permitted but with careful attention to conservation. Still further out, but still within the reserve, mere may be areas in which agriculture and other forms of normal economic activity are allowed, but with some restrictions. Clearly, the establishment of a system of fully protected natural areas, including some in biosphere reserves, is only part of what needs to be done. A wide variety of conservation practices is required outside of those areas. These include reforestation (with native species wherever that is practical); implementing wise energy and water policies; coping with the environmental effects of agriculture, mining, and manufacturing; and attending to the all-important matter of population growth. It is highly desirable, moreover, to develop integrated national and regional conservation strategies. Many aspects of conservation in this broad sense require financial expenditures that the poorer tropical countries cannot afford by themselves. For the developed nations of the temperate zone to assume a large part of the burden is in their long-term, enlightened self-interest. All of us on the surface of this planet will be much worse off if the biological riches of the tropics continue to be wasted. Whenever resources are transferred from the developed countries, whether through gifts, loans, or partial forgiveness of debt, a sizable fraction should be earmarked for conservation in the broad sense. An agreement to practice conservation in exchange for aid is part of what has sometimes been called the "planetary bargain." In recent years, a number of "debt

 swaps" have been carried out, in which debts owed by a tropical country, deeply discounted on the world financial market, are bought up by conservation organizations and then recognized at face value by the government of the country concerned for use in buying up land for protected areas. (The same principle can be applied to other desirable objectives, such as economic development of a less developed country or higher education abroad for its nationals.) Debt swaps are excellent examples of the planetary bargain in operation. If one were to stand back and estimate the prospects for a successful, comprehensive program of conservation of biological diversity in the tropics, the results might not be encouraging. However, history shows clearly that humanity is moved forward not by people who stop every little while to try to gauge the ultimate success or failure of their ventures, but by those who think deeply about what is right and then put all their energy into doing it Trie Preservation or Cultural Diversity Just as it is crazy to squander in a few decades much of the rich biological diversity that has evolved over billions of years, so is it equally crazy to permit the disappearance of much of human cultural diversity, which has evolved in a somewhat analogous way over many cultural diversity, which has evolved in a somewhat analogous way over many tens of thousands of years. Yet human unity (as well as solidarity with the other life forms with which we share the biosphere) is now a more important goal than ever before. How can those concerns be reconciled? I first became aware of the tension between unity and diversity at an early age. When I was a child, I raised with my father the old question of whether humanity could promote universal peace by using only a single world language. He described to me, in reply, how two hundred years ago, in the era of the Enlightenment and the French Revolution, the German thinker Herder, a pioneer of the Romantic Movement as well as a figure of the Enlightenment, wrote about the need to preserve linguistic diversity by saving the endangered Latvian and Lithuanian languages—so archaic, so close to the ancestral Indo- European. With the aid of native writers of that time, such as the Lithuanian poet Donelaitis, the work of conserving those chunks of cultural DNA was accomplished. Now Latvia and Lithuania are once

again independent countries, and those tongues saved from extinction two centuries ago are their national languages. The most challenging problems of cultural conservation involve indigenous peoples, especially those who are sometimes called primitive, largely because of the state of their technology. In many cases, these indigenous peoples are being either physically exterminated by disease and violence or else displaced or dispersed and culturally annihilated. A century ago, in some parts of the western United States, a few people were still shooting "wild Indians" on weekends. That is how Ishi, the last Yahi, lost his family and friends, as recounted by Alfred and Theodora Kroeber. Today, North Americans deplore similar atrocities being committed in other countries. Let us hope that the present desperate situation can be quickly ameliorated so that those peoples have better opportunities to survive and to choose, either to be left more or less alone for the time being or eke to undergo an organic kind of modernization, with a degree of cultural continuity and memory of the past. The rich lore, as well as institutions and ways of life, of indigenous peoples around the world constitute a treasure house of information about the possibilities of human organization and modes of thought. Many of them also possess precious knowledge of how to live as part of a tropical ecological community. (Others, it should be noted, have been destructive of nature, particularly peoples who have lived on previously uninhabited islands, large or small, for less dian a millennium or two. In some cases, the notion of indigenous peoples living in harmony with nature turns out to be wishful thinking.) Imagine, though, the knowledge of the properties of plants in the minds of certain tribal shamans. Many of those witch doctors are now dying without replacement. The great Harvard ethnobotanist, Richard Schultes, who spent many years studying medicinal plants in the Amazon Basin, says that every time such a shaman dies, it is as if a library had burned down. Schultes has trained many younger ethnobotanists, who are engaged in salvaging as many secrets as possible from those libraries before they disappear altogether. One of them, Mark Plotkin, recendy published a delightful account of his adventures, under the tide Tales of a Shamans Apprentice. Human beings have distilled, over hundreds or thousands of years of learning by trial and error, a remarkable amount of information about the uses of organisms for food, medicine, and clothing. Sometimes the

 process of learning must have been quite dramatic, as in the case of the bitter manioc of the Amazonian rain forest. Not many plants grow on the forest floor because so much of the sunlight is captured by the trees of the upper, middle, and lower canopies. Under those conditions, the bitter manioc (the tuber from which tapioca is made) is a valuable resource, edible and nutritious. However, the raw tuber contains a good deal of prussic (hydrocyanic) acid and is therefore highly poisonous. Only when heat is used to break up and drive off* the acid is the flesh of the tuber edible. A number of people must have lost their lives as hungry members of the various Amazonian bands and tribes learned how to make use of the bitter manioc. It is not only in such less developed regions that discovery by trial and error has revealed useful properties of plants and plant preparations. Folk medicine has made a great deal of difference to people's lives all over the planet Naturally, not all the claims of folk medicine are justified, but modern science has confirmed some of them. An experience of my own father provides an example. When he was a boy, the son of a forester, living in the beech woods of what was then eastern Austria, near the Russian border, he accidentally chopped off the last joint of one of his fingers with an axe. He retrieved the fallen joint, rinsed it off, and replaced it on the finger, which he then wrapped with a poultice made of bread. He bore the circular scar for the rest of his life, but the joint stayed on. It was to be many years before modern science recognized the bacteriostatic properties of the bread mold Penidllium notatum, but undoubtedly those same properties saved my father's finger. In the adaptive process by which groups of people made such useful discoveries, the selection pressures must have involved some questions fairly similar to those that are asked by science. Does the process actually work? Can people eat this food safely? Do wounds heal when wrapped this way? Does this herb help a woman to begin labor when her child is overdue? The folk remedies stemming from sympathetic magic present a different picture. Among the purported cures based on similarity is one for jaundice (actually a symptom of liver disease) that involves staring into the golden eye of a stone curlew. If my father had tried that, it would hardly have been very useful, except perhaps for a slight psychosomatic effect. In the development of sympathetic magic, so widespread among the peoples of the earth, the selection pressures, as we have

 emphasized earlier, were mostly very different from those pertaining to objective success. Yet those peoples did not necessarily draw any sharp distinction between magic on die one hand and die discovery of real uses of plant and animal products on the other. Witch doctors were still witch doctors, even if they did teach modern people to use materials such as cinchona bark, which yields quinine for use against malaria. Cultural traditions are not always easy to dissect into the parts that fit in easily with modern ideas and those that are in conflict with them. Tke Tension Between Enlightenment and Cultural Diversity The tension continues today between our need for the universality envisioned by the Enlightenment and our need for the preservation of cultural diversity. In discussing the future of the planet, using the results of scientific investigation and attempting to employ rational ways of thinking about the implications of those results, we are hampered by the prevalence of superstition. The persistence of erroneous beliefs exacerbates the widespread anachronistic failure to recognize the urgent problems that face humanity on this planet. We are, of course, severely threatened by philosophical disunity and especially by destructive particularism in all its many forms. Such particularism is still manifested in many places in the ancient form of tribalism, but today it may be related to differences in nationality, language, or religion or to other differences, sometimes so small that an outsider can scarcely detect them, but still sufficient to give rise to deadly rivalry and hatred, especially when exploited by unscrupulous leaders. Yet at the same time, cultural diversity is itself a valuable heritage that should be preserved: that Babel of languages, that patchwork of religious and ethical systems, that panorama of myths, that potpourri of political and social traditions, accompanied as they are by many forms of irrationality and particularism. One of the principal challenges to the human race is to reconcile universalizing factors such as science, technology, rationality, and freedom of thought with particularizing factors such as local rationality, and freedom of thought with particularizing factors such as local traditions and beliefs, as well as simple differences in temperament, occupation, and geography.

Universal Popular Culture

The erosion of local cultural patterns around the world is not, however, entirely or even principally the result of contact with the universalizing effect of scientific enlightenment. Popular culture is in most cases far more effective at erasing distinctions between one place or society and another. Blue jeans, fast food, rock music, and American television serials have been sweeping the world for years. Moreover, universalizing influences cannot be categorized simply as belonging either to scientific or to popular culture. Instead, they form a continuum, a whole spectrum of different cultural impacts. Occupying an intermediate position between high and popular culture are institutions like Cable News Network. In some places and on some occasions, CNN broadcasts are a valuable, timely source of memorable images and reasonably accurate information not otherwise obtainable. In other situations, they seem to represent a form of entertainment, part of the universalizing popular culture. In any event, news broadcasts received around the world and news articles that appear in daily and weekly publications in many countries are considered to be part of the worldwide "information explosion," along with an astonishing proliferation of other nonfiction periodicals and of books, to say nothing of the rapidly growing electronic mail network and the coming explosion of interactive multimedia communications.

Tke Information (or Misinformation?) Explosion

Unfortunately, that information explosion is in great part a misinformation explosion. All of us are exposed to huge amounts of material, consisting of data, ideas, and conclusions—much of it wrong or misunderstood or just plain confused. There is a crying need for more intelligent commentary and review. We must attach a higher prestige to that very creative act, the writing of serious review articles and books that distinguish the reliable fiom the unreliable and systematize and encapsulate, in the form of reasonably successful theories and other schemata, what does seem reliable. If an academic publishes a novel research result at the frontier of knowledge in science or scholarship, he or she may reap a reward in the form of a professorship or a promotion, even if the result is later

shown to be entirely wrong. However, clarifying the meaning of what has already been done (or picking out what is worth learning from what is not) is much less likely to advance an academic career. Humanity will be much better off when the reward structure is altered so that selection pressures on careers favor the sorting out of information as well as its acquisition. Tolerating the Intolerant—Is It Possible? But how do we reconcile the critical examination of ideas, including the identification and labeling of error with tolerance—and even celebration and preservation—of cultural diversity? We have discussed how each specific cultural tradition has ideas and beliefs embedded in it as artistic motifs, defining and unifying social forces, and sources of personal comfort in the face of tragedy. As we have emphasized, many of those ideas and beliefs are ones that science would label erroneous (or at least unjustified by evidence), while others represent precious discoveries about the natural world and about possible forms of human individual and social development (including, perhaps, the exploration of new realms of mystical experience and the formulation of value systems mat subordinate the appetite for material goods to more spiritual appetites). The preservation of cultural diversity, however, must somehow transcend that distinction. The patterns or schemata that are elements of cultural DNA cannot readily be divided into those that are worth preserving and those that are not. Yet the difficulty goes far deeper. Many of the local patterns of thought and behavior are associated not only with harmful error and destructive particularism but specifically with harassment and persecution of those who espouse the universalizing scientific and secular culture, with its emphasis on rationality and the rights of the human individual. And yet it is within that very culture that one often finds people concerned, as a matter of principle, with the preservation of cultural diversity. Somehow the human race has to find ways to respect and make use of the great variety of cultural traditions and still resist the threats of disunity, oppression, and obscurantism that some of those traditions present from time to time.

22 TRANSITIONS TO A MORE SUSTAINABLE WORLD Concern for the preservation of biological diversity is inseparable from concern about the future of die biosphere as a whole, but the fate of die biosphere is in turn closely linked with virtually every aspect of die human future. I intend to describe here a kind of research agenda on the future of die human race and die rest of the biosphere. That agenda does not call, however, for open-ended forecasting. Instead, it calls for people from a great many institutions and a wide variety of disciplines to think together about whether there may be evolutionary scenarios that lead from die present situation toward a more nearly sustainable world during die twenty-first century. Such an approach is more focused than simple speculation about

what might happen in die future. Why should anyone try to think on such a grand scale? Shouldn't one plan a more manageable project that concentrates on a particular aspect of the world situation? We live in an age of increasing specialization, and for good reason. Humanity keeps learning more about each field of study; and as every specialty grows, it tends to split into subspecialties. That process happens over and over again, and it is necessary and desirable. However, there is also a growing need for specialization to be supplemented by integration. The reason is mat no complex, nonlinear system can be adequately

described by dividing it up into subsystems or into various aspects, defined beforehand. If those subsystems or those aspects, all in strong interaction with one another, are studied separately, even with great care, the results, when put together, do not give a useful picture of the whole. In that sense, there is profound truth in the old adage, "The whole is more man the sum of its parts." People must therefore get away from the idea that serious work is restricted to beating to death a well-defined problem in a narrow discipline, while broadly integrative thinking is relegated to cocktail parties. In academic life, in bureaucracies, and elsewhere, the task of integration is insufficiendy respected. Yet anyone at the top of an organization, a president or a prime minister or a CEO, has to make decisions as if aft aspects of a situation, along with the interaction among those aspects, were being taken into account. Is it reasonable for the leader, reaching down into the organization for help, to encounter only specialists and for integrative thinking to take place only when he or she makes the final intuitive judgments? At the Santa Fe Institute, where scientists, scholars, and other thinkers from all over the world, representing virtually all disciplines, meet to do research on complex systems and on how complexity arises from simple underlying laws, people are found who have the courage to take a crude look at the whole in addition to studying the behavior of parts of a system in the traditional way. Perhaps the Institute can help to spark collaborative research, by institutions from around the globe dedicated to the study of particular aspects of the world situation, on potential paths toward a more nearly sustainable world. The aspects in question will have to include political, military, diplomatic, economic, social, ideological, demographic, and environmental issues. A comparatively modest effort has already begun, under the name of Project 2050, under the leadership of the World Resources Institute, the Brookings Institution, and the Santa Fe Institute, with participation of people and institutions from many parts of the world. Now with participation of people and institutions from many parts of the world. Now what is meant here by sustainable? In Through the Looking Glass, Humpty Dumpty explains to Alice how he uses words to mean anything he wants, paying mem for the privilege each Saturday night (the end of the nineteenth-century work week). These days a great many people must be paying wages to the word "sustainable." For example, if the World Bank finances some old-fashioned massive devel-

opment project destructive of the environment, that project may well be labeled "sustainable development" in the hope of making it more acceptable. This practice reminds me of the Monty Python routine in which a man enters an office to get a license for his fish, Eric. Told that there is no such thing as a fish license, he points out that he had received the same reply when he asked about cat licenses, but that he has one anyway. Producing it, he is told, "That's not a cat license. That's a dog license with the word 'dog' crossed out and the word 'cat' written in with a pencil." Today many people are busy writing in the word "sustainable" in pencil. The definition is not always clear. Thus it is not unreasonable to try to assign a meaning here. The literal signification of the word is evidently not adequate. The complete absence of life on Earth might be sustainable for hundreds of millions of years, but that is not what is meant. Universal tyranny might be sustainable for generations, but we do not mean that either. Imagine a very crowded and highly regimented, perhaps extremely violent world with only a few species of plants and animals surviving (those with intimate connections with human society). Even if such conditions could somehow be kept going, they would not correspond to what is meant here by a sustainable world. Clearly, what we are after embraces a modicum of desirability along with sustainability. Remarkably, there is a certain measure of theoretical agreement today on what is desirable, on the aspirations of the human race, as embodied, for example, in declarations of the United Nations. What kind of future, then, are we envisaging for our planet and our species when we speak of sustainability, tempering our desires with some dose of realism? Surely we do not mean stagnation, with no hope of improvement in the lives of hungry or oppressed human beings. But neither do we mean continued and growing abuse of the environment as population increases, as the poor try to raise their standard of living, and as the wealthy exert an enormous per capita environmental impact. Moreover, sustainability does not refer to environmental and economic concerns alone. In negative terms, the human race needs to avoid catastrophic war, widespread tyranny, and the continued prevalence of extreme poverty, as well as disastrous degradation of the biosphere and destruction of

 biological and ecological diversity. The key concept is die achievement of quality of human life and of the state of die biosphere that is not purchased mainly at the expense of the future. It encompasses survival of a measure of human cultural diversity and also of many of die organisms with which we share the planet, as well as die ecological communities diat they form. Some people may be technological optimists, believing mat we humans do not need to change course very much in order to avoid a disastrous future, that we can achieve approximate sustainability without special effort, merely through an endless series of technological fixes. Some may not believe in the goal of sustainability at all. Nevertheless, we can all think about it. Even those of us who do not accept sustainability as a goal can still ask whedier there are ways to approach it during die next fifty to a hundred years and if so, what those ways might be and what the world might look like as a result. Discussion of the questions does not require sharing die values of those who posed diem. Historians tend to be impatient with people who say, "This is a unique period in history," because diat claim has been made about so many eras. Still, our time is special in two well-defined and closely related ways. First, the human race has attained die technical capability to alter die biosphere through effects of order one. War is old, but the scale on which it can now be fought is entirely new. It is notorious diat a full-scale thermonuclear war could wipe out a significant fraction of life on die planet, not to mention die trouble mat could be caused by biological or chemical warfare. Moreover, through population growth and certain economic activities, humans are altering die global climate and exterminating significant numbers of plant and animal species. Actually, human beings caused more destruction in the past than is usually admitted. Deforestation by die axe and by goats and sheep, followed by erosion and desiccation, is thousands of years old and was remarked, for example, by Pliny die Elder. Even the tiny numbers of people living in North America ten thousand years ago may have contributed to die extinction of die North American ice-age mega- fauna, such as mammoths and giant sloths, dire wolves, sabre-toothed cats, and species of camels and horses. (One theory blames some of the extinctions at least partially on die habit of driving whole herds of animals over cliffs in order to use die meat and skins of just a few.)

 Nevertheless,

today the potential for damage to the entire biosphere is much greater than ever before. Human activity has already created a multiplicity of environmental problems, including climate change, ocean pollution, diminishing quality of fresh water, deforestation, soil erosion, and so on, with strong interactions among them. As with conflict, many of the environmental ills are old ones, but their scale is unprecedented. Second, the rising curves of world population and natural resource depletion cannot go on rising steeply forever; they must soon pass through inflection points (when the rate of increase starts to decrease). The twenty-first century is a crucial time (in the original sense of a crossroad) for the human race and the planet. For many centuries, total human population as a function of time hewed closely to a simple hyperbolic curve that reaches infinity in about the year 2025. Ours is obviously the generation in which world population must start to peel away from that hyperbola, and it has already begun to do so. But will the population curve flatten out as a result of human foresight and progress toward a sustainable world, or will it turn over and fluctuate as a result of the traditional scourges of war, famine, and pestilence? If the curves of population and resource depletion do flatten out, will they do so at levels that permit a reasonable quality of human life, including a measure of freedom, and the persistence of a large amount of biological diversity, or at levels that correspond to a gray world of scarcity, pollution, and regimentation, with plants and animals restricted to a few species that co-exist easily with mankind? A similar question can be posed about the progressive development of the means and scale of military competition. Will people allow large-scale, thoroughly destructive wars to break out, or will they use intelligence and foresight to limit and redirect competition, to damp down conflict, and to balance competition with cooperation? Will we learn, or have we perhaps already learned, to manage our differences in ways short of catastrophic war? And what of smaller conflicts arising from political disintegration? Gus Speth, who was the first president of the World Resources Institute (which I am proud to have played a role in founding), has suggested that the challenge to the human race over the next few decades is to accomplish a set of interlinked transitions. I propose to amplify slighdy his conception of those transitions so as to incorporate

 more political, military, and diplomatic considerations in addition to die social, economic, and environmental ones that he emphasizes. With those modifications, die rest of this chapter is organized around that crude but useful notion of a set of transitions. The Demographic Transition We have seen that the coming decades must witness a historic change in the curve of world population versus time. Most authorities estimate diat world population will level off during the next century, but at a figure somediing like twice die present number of 5.5 billion or so. Today, high rates of population growdi (associated particularly with improvements in medicine and public health without corresponding declines in fertility) still prevail in many parts of the world. That is especially true of tropical, less developed regions, including countries, such as Kenya, diat can least afford it ecologically or economically. Meanwhile, die developed countries have generally achieved rather stable populations, except for the effects of migration, which will certainly be a major issue in the coming decades. Scholars have engaged in much discussion of the factors thought to be responsible for the decline in net fertility that has taken place in most of the developed countries. They now suggest measures diat may help to produce similar declines in various parts of the tropical world. Those measures include improved provisions for women's health, literacy, further education, and opportunities to participate in the work force, as well as other advancements in the position of women; reduced infant mortality (which initially works in the opposite direction, of course, but may later prevent couples from compensating for expected deaths by producing more children than they really want); and social insurance for the elderiy, still a distant goal in many developing countries. Naturally the availability of safe and effective contraception is crucial, but so is the erosion of traditional incentives for having large families. In some parts of die world die average couple (and especially die average male) still wants to have many children. What kinds of rewards can be offered to one- and two-child families? How can people be persuaded, in culturally appropriate ways, that in the modern world such families are in die common interest, with higher levels of health, education, prosperity, and quality of life than would be possible for

 families with many children? With swings of fashion having such importance in human affairs, what can be done to help the idea of small families to become popular? These questions are still sadly neglected in many places, even by organizations that claim to be helping to solve the world population problem. If human population is really going through an inflection point and will level off, globally and in most places, in a few decades, not only is that a historical process of the greatest significance, but its timing and the resulting numbers are likely to be of critical importance as well. The exact character and magnitude of the effect of population growth on environmental quality depend on many variables, such as population growth on environmental quality depend on many variables, such as patterns of land tenure, and are worth careful study in various different areas. Nevertheless it already seems overwhelmingly probable that, on the whole, population growth encourages environmental degradation, whether through the huge consumption rates of the wealthy or through the desperate struggle of the poor to survive at whatever cost to the future. The environmental consequences are likely to be much more serious if the world simply waits for improved economic conditions among impoverished populations to effect reductions in net fertility, as opposed to trying to encourage such reductions in parallel with economic development. The total environmental impact per person is likely to be considerably greater after economic improvement than before, and the fewer the numbers when relative prosperity is finally achieved, the better for the people and for the rest of the biosphere. The Technological Transition Decades ago some of us (particularly Paul Ehrlich and John Holdren) pointed out the fairly obvious fact that environmental impact, say in a given geographical area, can be usefully factored into three numbers multiplied together: population, conventionally measured prosperity per person, and environmental impact per person per unit of conventional prosperity. The last factor is the one mat particularly depends on technology. It is technological change that has permitted today's giant human population to exist at all, and while billions of people are desperately poor, quite a few others manage to live in reasonable comfort as a consequence of advances in science and technology, including

 medicine. The environmental costs have been huge, but nowhere near as great as they may be in the future if the human race does not exercise some foresight. Technology, if properly harnessed, can. work to make the third factor as small as can be practically arranged, given the laws of nature. How much the prosperity factor can be improved, especially for the very poor, depends to a considerable extent on how much is squandered on the first factor, mere numbers of people. Evidence of the beginning of the technological transition is starting to show up in many places, even though the bulk of it is yet to occur. Even apparently simply technological fixes, however, can end up posing extremely complex problems. Consider the example of eradicating malaria in human populations. Not too long ago, the draining of swamps was still the principal method of control. But now it is understood that the destruction of wedands is to be avoided whenever possible. Meanwhile, science has identified the Plasmodia responsible for malaria and the mosquito vectors diat carry them. Spraying with chemical pesticides like DDT to eliminate the mosquitos seemed to be a step forward, but turned out to have serious environmental consequences. For one diing, birds at the top of the aquatic food chain got very concentrated doses of die metabolic product DDE, which caused thinning of egg shells and reproductive failure in many species, including the American national bird, the bald eagle. Twenty years ago, DDT was phased out in the developed world, and the threatened bird populaaojis started to recover. It is still used elsewhere, although resistant strains of the mosquito vectors are starting to appear. It then turned out that some of the immediately available replacements for DDT were fairly dangerous to humans. Nowadays, however, much more sophisticated methods are available for reducing the populations of the vectors, including the use of chemicals diat specifically target them, as well as the release of sterile mating partners and other "bio-environmental controls." Such measures can be coordinated in what is called "integrated pest management." So far, they are still fairly expensive, if deployed on a large scale. In die future, cheaper and equally gende techniques may be developed. Insect repellents are also available, -of course, but they are expensive too and cause problems of their own. Meanwhile, a simple, behavioral approach that is effective in many places is to use mosquito netting and stay under it for half an hour at

 dawn and half an hour at dusk, when die vector mosquitoes are biting. Unfortunately, in many tropical countries, die rural poor are very busy outdoors at those times and cannot stay under netting. Some day antimalarial vaccines will probably be developed, which may even wipe out the various forms of the disease entirely, but then another difficulty will arise: important wild areas that had been protected by the dangers of malaria will be exposed to unwise development. I have no doubt spent too long on this apparendy simple example, in order to expose some of its complexities. Analogous complexities can be expected to crop up anywhere in the technological transition to lower environmental impact, whether in industrial production, the extraction of minerals, food production, or energy generation. Like the conversion from defense industries to civilian production, the technological transition requires financial assistance and retraining for workers as opportunities close down in one kind of employment and develop in another. Policy makers may be well advised to consider these different types of conversion as posing related challenges. Thus, ceasing to manufacture chemical warfare agents would be regarded as similar to phasing out logging in the old growth forests of the Pacific Northwest of the United

States. Moreover, such policy issues come up again when society tries to reduce the consumption of products injurious to human health, whether legal, like tobacco, or illegal, like crack cocaine. However, on the demand side the three kinds of conversion present somewhat different problems. In the case of chemical weapons, the principal challenge was to persuade governments not to order them any more and to ferret out and destroy the stocks that exist. In the case of drugs, the issues are matters of angry dispute. In the case of the technological transition to lower environmental impact, the question is what the incentives are to develop gender technologies and to use them. That brings us to the economic transition. Economic Transition If the air or water is treated as a free good in economic transactions, then polluting it, using up its quality, costs nothing; the associated

 economic activity is carried on by stealing from the environment and from die future. Authorides have attempted for centuries to deal with such problems by means of prohibitions and fines, but those were often ineffective. Today regulation is being attempted on a massive scale in some places, and some successes have been achieved. However, it seems that the most efficient way for governments to deal with such issues is to charge, more or less, for the cost of restoring quality. That is what economists call internalizing externalities. Regulation, with its fines and other punishments, is itself a form of charging. Regulators, however, usually require specific actions by polluters, whereas internalizing costs encourages restoring quality, or avoiding its degradation in the first place, by whatever means is cheapest. The engineers and accountants of the industry concerned are the ones who prescribe the measures to be taken. Micromanagement by bureaucrats is unnecessary. Attempting to charge real costs is a principal element of the required economic transition from living in large part on nature's capital to living mainly on nature's income. While charging is usually better than regulation, it is certainly much better than mere exhortation. For one thing, it reduces ambiguities. Suppose you are engaged in awarding green medallions to products with low environmental impact. Soon you encounter a problem. A particular detergent may be lower in phosphates than another and thus produce less eutrophication (growth of algae) in lakes, but it may require greater energy use because it needs hotter water in the wash. As you go on you find more such tradeoffs. How do you balance one consideration against another? If at least a crude attempt is made to charge producers for eutrophication caused by their detergents and if the cost of the energy needed for a wash is clearly marked on the package, a consumer can just energy needed for a wash is clearly marked on the package, a consumer can just use total expenditure to make decisions, and the market will work out the prices. The green medallion may become unnecessary. The great difficulty in charging true costs, of course, is estimating them. We discussed earlier how economics has never really succeeded in coming to grips with subtle problems of quality and irreversibility, issues analogous to those that arise in connection with the second law of thermodynamics in natural science. Such problems can, of course, be shoved over into the political arena and treated as matters of public opinion only, but surely in the long run science will have something to

say about them too. Meanwhile, the simplest approach is to estimate the cost of restoring whatever is lost. In the case of the irreplaceable, some form of strictly enforced prohibition may be necessary, but otherwise the sustainability of quality is closely tied to the idea of paying to restore it, and the definition of quality will be dealt with by science and public opinion in interaction with each other. A critical part of any program to charge true costs is the elimination of subsidies for destructive economic activity, much of which would not be economic at all were it not for those subsidies. In the work of the World Commission on Environment and Development (the Brunddand Commission), composed of distinguished statesmen from many parts of the world, it took the brilliant Secretary-General of the Commission, Jim MacNeill of Canada, to point out that in order to see what is happening to the environment, one must look not so much at the activities of the Environment Ministry as at the Ministry of Finance and the budget. It is there that the destructive subsidies can be hunted down and sometimes, albeit with great political difficulties, killed. Discussion of budgets leads directly to the question of whether national accounting procedures include the depletion of nature's capital. Usually they do not. If the president of a tropical country contracts with a foreign lumber company to have a large chunk of the nation's forests cut down for a low price and a bribe, the national accounts show the price as part of the national income, and maybe even the bribe as well if it is spent at home and not sent to a Swiss bank, but the disappearance of the forest, with all its benefits and potential, does not appear as a corresponding loss. Nor is it only tropical countries that sell their forests too cheaply, as attested by the fate of the temperate rain forests of the U.S. Pacific Northwest, British Columbia, and Alaska. Clearly the reform of national accounting systems is a major need in all countries. Fortunately, efforts to accomplish that reform are already being undertaken in some places. Our example also makes clear that the struggle against major corruption is a key element in achieving the economic transition. Another indicator of the level of concern over living on nature's capital is the discount rate. I understand that the World Bank, in financing projects with large environmental impacts, still applies a discount rate of 10 percent per year to the future. If that is true, it means that the loss of some great natural asset thirty years in the future is discounted

 by a factor of 20. The natural heritage of the next generation is valued at 5 percent of its assigned value today, if indeed it is counted at all. The discount rate, used in this way, is a measure of what is called intergenerational equity, which is crucial to the notion of sustainable quality. Discounting the future too steeply amounts to robbing the future. If the notion of discount rate is generalized somewhat, it can be used to encapsulate much of what is meant by sustainability. The Social Transition Some economists make much of possible tradeoffs between intergenerational equity and intragenerational equity, diat is, between concern for the future and concern for today's poor, who need to exploit some resources in order to survive. Although some of the degradation of the biosphere today is caused by the very poor scrabbling for a living, much of it can be attributed to the wealthy squandering resources on frills. A great deal of it, however, is connected with massive projects that are supposed to help, for example, the rural poor of a developing country, but often do so, if at all, rather inefficiently and destructively. In contrast, the same people can often be aided very effectively through large numbers of small efforts, applied locally, as for example in the practice known as microlending. In microlending, a financial institution is established to provide very small loans to local entrepreneurs, many of them women, to start small enterprises that provide a living locally to a number of people. Frequently such businesses provide comparatively nondestructive employment and contribute to intergenerational as well as intragenerational equity. Fortunately, microlending to support sustainable economic activity is becoming more widespread. It is hard to see how quality of life can be sustainable in the long run if it is very inequitably shared, if there are large numbers of people starving, lacking shelter, or dying young of disease when they can see a more comfortable existence attained by billions of other people. Clearly, large-scale moves in the direction of intragenerational equity are needed for sustainability. As in the case of microlending for sustainable development, there is often more synergy than conflict between intergenerational and intragenerational equity. Policies diat really help the rural poor in developing countries are much more compatible with

those that preserve nature than is often claimed. Policies that truly benefit die urban poor certainly include provisions for avoiding urban environmental catastrophes. Such policies also include measures to resolve the problems in die countryside that are producing large-scale migrations to the cities, many of which are already swollen to such proportions as to be almost unmanageable. In fact, the social transition clearly must include die alleviation of some of die worst problems of die megacities. Today, even more than in the past, no nation can deal with problems affecting either urban or rural economic activity without taking account of international issues. The emergence of die global economy is a dominant feature of die contemporary scene, and die desire to participate more actively in that economy is a major force affecting die policies of governments and businesses around the world. Together with rapid transport, global communications, and global environmental effects, die prominence of global economic issues means that a greater degree of worldwide cooperation is essential to deal with die serious and interlocking issues mat face the whole human race. That brings us to the institutional or governance transition. The Institutional Transition The need for regional and global cooperation is hardly restricted to environmental matters, or even environmental and economic matters. The maintenance of peace, so-called international security, is at least as important. Recendy, with die dissolution of die Soviet Union and die "Soviet bloc" of nations, and with a greater degree of cooperation on the part of China, it has become possible for world institutions, including organs of the United Nations, to function more effectively dian in die past. For the UN. to organize die monitoring of elections or to sponsor negotiations for ending a civil war is now a matter of routine. "Peacekeeping" activities are in progress in many parts of die world. The outcomes are by no means always satisfactory, but at least the processes are becoming established. Meanwhile, transnational cooperation is taking place in many other ways, and indeed die role of die national state is necessarily weakened in a world where so many important phenomena increasingly tran-

scend national boundaries. In many spheres of human activity, transnational and even universal (or nearly universal) institutions, formal or informal, have been functioning for a long time. Now there are many more. Typically, they channel competition into sustainable

Now there are many more. Typically, they channel competition into sustainable patterns and temper it with cooperation. Some are more important or more effective than others, but they are all of some significance. A few diverse examples are the air travel system; the International Postal Union; the Convention on Broadcasting Frequencies; Interpol; migratory bird treaties; CITES (the Convention on International Trade in Endangered Species); the Convention on Chemical Weapons; The International Union of Pure and Applied Physics, The International Council of Scientific Unions, etc.; World Congresses of Mathematics, Astronomy, Anthropology, Psychiatry, etc.; PEN, the international writers' organization; financial institutions such as the World Bank and the International Monetary Fund; multinational corporations, including McDonald's as well as IBM; UN. Agencies such as WHO, UNEP, UNDP, UNFPA. UNICEF, and UNESCO; and the Red Cross, Red Crescent, Red Shield of David, and Red Sun and Lion. Moreover, the increasing importance of English as an international language should not be ignored. Gradually, bit by bit, the human race is beginning to come to grips, on a global or highly transnational basis, with some of the problems of managing the biosphere and human activities in it. Here the effect of the changed situation in the former Soviet Union and in Eastern Europe is extremely encouraging. It results in the probability of near-universality for numerous activities for which there was little hope of anything like universality before. Also, negotiations are going forward on issues of the global commons—those aspects of the environment that are not recognized as belonging to anyone and therefore belong to all, where selfish exploitation without cooperation can only lead to results bad for all parties. Obvious examples are the oceans, space, and Antarctica. Agreements between more and less developed countries can follow the pattern of the planetary bargain, which we encountered earlier in connection with the conservation of nature. Here it assumes a more general significance: resource transfers from wealthier countries to poorer ones carry an obligation for the poorer ones to take measures that advance sustainability in the broad sense, so that avoiding nuclear

proliferation is included along with activities such as protecting wilderness areas. (Another manifestation of the planetary bargain is that electric utilities in temperate countries offset their emissions of carbon dioxide by paying to preserve forests in tropical countries.) However, the problem of destructive particularism—the sharp and often violent competition among peoples of different language, religion, race, nation, or whatever—has come into even sharper focus than usual in the last few years, especially with the lifting of some of the lids that had been put on these competitions by authoritarian regimes. Dozens of violent ethnic or religious struggles are under way in different parts of the globe. Many different brands of fundamentalism are on the march. The world is experiencing simultaneous trends toward unity and toward fragmentation within that unity. We have mentioned that seemingly no difference is so small that it cannot be used to divide people into harshly antagonistic groups. Look, for example, at the bitter struggle going on in Somalia. Language difference? No, all speak Somali. Religious difference? Virtually all Muslims. Different sects within Islam? No. Clan differences? Yes, but they are not causing so much trouble. It is mainly subclatts that are at war with each other, under rival war lords, as legal order has collapsed. The Ideological Transition What will happen to these trends? If our long-outdated proclivities toward destructive particularism are excessively indulged, we will have military competitions, breeding competitions, and competitions for resources at levels that will make the sustainability of quality difficult or impossible to achieve. Seemingly a dramatic ideological transition is needed, comprising the transformation of our ways of thinking, our schemata, our paradigms, if we humans are to approach sustainability in our relations with one another, to say nothing of our interactions with the rest of the biosphere. Scientific research has not yet made clear to what extent human attitudes toward other people who are perceived as different (and toward other organisms) are governed by inherited, hard-wired tendencies developed long ago in the course of biological evolution. It may be that to some degree our propensities to form groups that don't get

 along with one another and to wreak unnecessary destruction on the environment have such origins. They may be biologically evolved tendencies that were perhaps once adaptive but are so no longer, in a world of interdependence, destructive weapons, and gready increased capacity to degrade the biosphere. Biological evolution is too slow to keep up with such changes. Still, we know that cultural evolution, which is much more rapid, can modify biological propensities. Sociobiologists emphasize that we humans, like other animals, inherit a tendency to protect ourselves and our close relatives so that we and they can survive to procreate and pass on some of our genetic patterns. But in human beings that instinct to promote inclusive fitness is profoundly transformed by culture. A sociobiologist, invoking the image of someone jumping into a river to save another person from a crocodile, would argue that such "altruistic" behavior is more likely if the other person is a close relative. A cultural anthropologist might point out that in many tribes certain relatives, including fairly distant relatives, are "dassificatory" siblings or parents or offspring, who are treated in many respects as if they really were those close relatives. Perhaps members of such a tribe are just as willing to risk their lives to save their dassificatory brothers and sisters as their real ones. In any event, sociobiologists now agree that patterns of altruistic behavior in humans are gready affected by culture. A certain willingness to risk one's life for another human being can easily extend to all the members of one's tribe. Such behavior occurs at higher levels of organization as well. On the scale of a nation state, it is known as patriotism. As people have aggregated into larger and larger sodeties, the concept of "us" has tended to grow in scope. (Unfortunately, stress can reveal lines of weakness in the social fabric that cause it to tear apart again into smaller units. That is what has happened, for example, in the vicinity of Sarajevo, where one resident was quoted as saying: "We have lived next door to those people for forty years, and we have intermarried with them, but now we realize that they are not fully human.") Despite such setbacks, the undeniable trend is toward a more and more inclusive sense of solidarity. The greatest ideological question is whether, on a short time scale, that sense of solidarity can come to encompass the whole of humanity

 and also, in some measure, die other organisms of the biosphere and the ecological systems to which we all belong. Can parochial and short- term concerns be accompanied increasingly by concerns that are global and long-term? Can family consciousness undergo a rapid enough cultural evolution to planetary consciousness? When political unity has been achieved in the past, it has often come about dirough conquest, sometimes followed by attempts to suppress cultural diversity, because cultural diversity and ethnic competition are two sides of the same coin. To meet the requirement of sustainable quality, however, evolution toward planetary consciousness must accommodate cultural diversity. The human race needs unity in diversity, with the diverse traditions evolving so as to permit cooperation and the accomplishment of the many interlinked transitions to sustainability. Community is essential to human activity, but only communities motivated to work together are likely to be adaptive in the world of the future. Meanwhile, human cultural diversity has given rise to a multiplicity of ideologies or paradigms, schemata that characterize ways of thinking across the globe. Some of those ways of looking at the world, including particular views of what is the good life, may be especially conducive to sustainable views of what is the good life, may be especially conducive to sustainable quality. It is desirable that such attitudes become more widespread, even though cultural diversity would suffer duough die decline of other attitudes with more destructive consequences. As usual, die preservation of cultural diversity can engender not only paradoxes but conflict with other goals as well. A few years ago I attended a remarkable lecture given at UCLA by Vaclav Havel, then president of the soon-to-be-divided Czech and Slovak Federated Republic and now president of the Czech Republic. His topic was the environmental damage to his country during the last decades, with serious effects on human health. He blamed the damage on anthropocentrism, especially the notion that we humans own the planet and have enough wisdom to know what to do with it. He complained diat neither greedy capitalists nor dogmatic communists have sufficient respect for the larger system of which we are merely a part. Havel, of course, is a writer and a fighter for human rights as well as a politician. Most ordinary politicians refrain from attacking anthropocentrism, since the voters are all human. But it may indeed be

healthy for our species to attribute intrinsic worth to nature and not only perceived utility for a particular kind of primate diat calls itself sapiens.

The Informational Transition

Coping on local, national, and transnational levels with environmental and demographic issues, social and economic problems, and questions of international security, as well as the strong interactions among all of diem, requires a transition in knowledge and understanding and in the dissemination of diat knowledge and understanding. We can call it the informational transition. Here natural science, technology, behavioral science, and professions such as law, medicine, teaching, and diplomacy must all contribute, as, of course, must business and government as well. Only if there is a higher degree of comprehension, among ordinary people as well as elite groups, of die complex issues facing humanity is there any hope of achieving sustainable quality. It is not sufficient for diat knowledge and understanding to be specialized. Of course, specialization is necessary today. But so is the integration of specialized understanding to make a coherent whole, as we discussed earlier. It is essential, therefore, diat society assign a higher value than heretofore to integrative studies, necessarily crude, diat try to encompass at once all the important features of a comprehensive situation, along with their interactions, by a kind of rough modeling or simulation. Some eariy examples of such attempts to take a crude look at the whole have been discredited, partly because the results were released too soon and because too much was made of diem. That should not deter people from trying again, but with appropriately modest claims for what will necessarily be very tentative and approximate results. An additional defect of those early studies, such as limits to Growth, the first report to the Club of Rome, was mat many of die critical assumptions and quantities diat determined die outcome were not varied parametrically in such a way that a reader could see die consequences of altered assumptions and altered numbers. Nowadays, with die ready availability of powerful computers, die consequences of varying parameters can be much more easily explored. The sensitivity of the

results to different assumptions can be checked, and die structure of die study can thus be made more transparent. Moreover, part of the study can take the form of games, such as SimCity or SimEarth, which are commercial products developed by the Maxis Corporation under die leadership of Will Wright. Games permit a critic to revamp the assumptions to suit his or her own taste and see what results. Peter Schwartz, in his book Hie Art of the Long View, relates how die planning team of the Royal Dutch Shell Corporation concluded some years ago that the price of oil would soon decline sharply and recommended mat the company act accordingly. The directors were skeptical, and some of them said diey were unimpressed with the assumptions made by die planners. Schwartz says that the analysis was then presented in the form of a game and that the directors were handed the controls, so to speak, allowing them to alter, within reason, inputs diey thought were misguided. According to his account, die main result kept coming out the same, whereupon the directors gave in and started planning for an era of lower oil prices. Some participants have a different recollection of what happened at Royal Dutch Shell, but in any case die story beautifully illustrates the importance of transparency in the construction of models. As models incorporate more and more features of die real wood and become correspondingly more complex, die task of making them transparent, of exhibiting the assumptions and showing how they might be varied, becomes at once more challenging and more critical. Those of us participating in a study such as Project 2050, aimed at sketching out paths that may lead toward a more sustainable world in the middle of the next century, face difficult questions. How can these transitions toward sustainable quality be accomplished, if at all, during the next fifty to one hundred years? Can we hope to understand, even crudely, the complex interactions among die transitions and especially the issues that arise from their delicate relative and absolute timing? Is there any1 hope of taking sufficient account of the wide variations in conditions around the world? Are there other transitions, or other ways of looking at the whole set! of issues, diat are more important? These questions' concern die period, around the middle of die twenty-first century, when the various transitions may be partly accomplished or at least well under way. Thinking usefully about that era is difficult, but not necessarily impossible. As Eilert Lovborg said, in Ibsen's Hedda Gabler,

 when surprise was expressed that his history book had a continuation describing the future, "there is a thing or two to be said about it just the same." As to the more distant future, what kind of global conditions might prevail, after the middle of the next century, that would really approach the sustainability of quality? What are our visions of such a situation? What would we see and hear and feel if we were there? We should really try to envision it, especially a world with growdi in quality finally predominating over growth in quantity. We should imagine a world in which, Utopian as it sounds, the State of the World Report and the World Resources Report do not look worse every year, population is stabilizing in most places, extreme poverty is disappearing, prosperity is more equitably shared, serious attempts are made to charge true costs, global and other transnational institutions (as well as national and local ones) are beginning to cope with the complex interlocking issues of human society and the rest of the biosphere, and ideologies favoring sustainability and planetary consciousness are gaining adherents, while ethnic hatreds and fundamentalisms of all kinds are losing out as divisive forces even though a great deal of cultural diversity remains. We can scarcely hope to attain anything approaching such a world if we cannot even imagine what it would look like or estimate on a quantitative basis how it might function. Of the three ranges of time, it is naturally hardest to get people to think about the long-term vision of a more sustainable world, but it is vital that we overcome our reluctance to make concrete images of such a world. Only then can our imagination escape from the confines of the practices and attitudes that are now causing or threatening to cause so much trouble, and invent improved ways to manage our relations with one another and with the rest of the biosphere. As we try to envision a sustainable future, we must also ask what kinds of surprises, technological or psychological or social, could make that fairly distant future totally different from what we might anticipate today. A special team of imaginative challengers is required to keep posing that question. The same team could also ponder the question of what new serious problems might arise in a could also ponder the question of what new serious problems might arise in a world where many of today s worst fears are somewhat allayed. Just a few years ago, most pundits were not predicting that the Cold War era would soon turn into a new age with different

 problems, but even those few that were predicting it were not speculating serioiusly on which concerns would replace the familiar ones that were no longer dominant. What of the short term, the next few decades? What kinds of policies and activities in the immediate future can contribute to the possibility of approaching sustainable quality later on? It is not at all difficult r!o get discussions going about the near future, and some of the problems we face in the short run are becoming clear to many observers. Perhaps the chief lesson to be learned from contemporary experience is one that we touched on when we mendoned microlending. It is the importance of bottom-up as opposed to top-down initiatives. If local people are deeply involved in a process, if they help to organize it, and if they have a perceived stake, especially an economic stake, in the outcomejthen the process often has a better chance of success than if it is imposed by a distant bureaucracy or a powerful exploiter. In helping tropical apeas to achieve objectives in the preservation of nature along with at lepst partially sustainable economic development, conservationists have found that what pays off the most is investment in local groups and local leadership, and particularly in training for local leaders. Althoiigh it is fairly easy to persuade people to discuss the middle range of; time—the era during which the interlinked transitions must be largely accomplished if anything like sustainability is to be achieved-j-the extraordinary complexity of the challenge may be daunting. All those transitions must be considered, each with character and timing to be determined, perhaps different in different parts of the world, and all strongly coupled to one another. Still, that very complexity may lead to a kind of simplicity. Certainly it is true in physical science (which is much less difficult to analyze, to be sure, but may still have somej lessons to teach) that in the neighborhood of a transition, say from a gas to a liquid, near a mathematical singularity, there are only a few crucial parameters on which the nature of the transition depends. Those parameters cannot always be characterized in advance, however; they must'emerge from a careful study of the whole problem. It is true in general that the behavior of highly complex nonlinear systems may exhibit simplicity, but simplicity that is typically emergent and not obvious at the outset. Integrated policy studies jof possible paths toward a more nearly sustainable world can be exceedingly valuable. But we must be careful

 to treat all such studies as "prostheses for die imagination," and not to attribute to them more validity than they are likely to possess. Trying to fit human behavior, and especially problems of society, into die Procrustean bed of some necessarily limited mathematical framework has already brought much grief to die world. For instance, die science of economics has often been used in that way with unfortunate consequences. Besides, ideologies destructive of human freedom or welfare have often been justified by arguments loosely based on science, and especially on analogies between sciences. The social Darwinism preached by some political philosophers of die nineteendi century is one of many examples, and by no means die worst. Nevertheless, taken in die proper spirit, a multiplicity of crude but integrative policy studies, involving not just linear projection but evolution and highly nonlinear simulation and gaming, may provide some modest help in generating a collective foresight function for die human race. An early Project 2050 document puts it this way: We are all in a situation that resembles driving a fast vehicle at night over unknown terrain diat is rough, full of gullies, with precipices not far off. Some kind of headlight, even a feeble and flickering one, may help to avoid some of die worst disasters. If humanity does equip itself somehow with a measure of collective foresight—some degree of understanding of die branching histories of die future—a highly adaptive change will have taken place, but not yet a gateway event. The accomplishment of die interlinked transitions to greater sustainability, however, would be such an event. In particular, the ideological transition implies a major step for humanity toward planetary consciousness, perhaps with die aid of wisely managed technical advances now only dimly foreseeable. After the transitions, humanity as a whole —together with die other organisms inhabiting the planet— would function, much more dian now, as a composite, richly diverse complex adaptive system.

c*KPTEjf 23 AFTERWORD In this brief chapter, I try to respond to the need for a kind of executive summary, not of every topic in the whole book, but of the central theme df simplicity, complexity, and complex adaptive systems—the theme that connects the quark, the jaguar, and humanity. The Quark and the Jaguar is not a treatise. It is comparatively nontechnical, and it reaches into a large number of areas that it cannot explore thoroughly or in depth. Furthermore, much of the work that is described in some detail is work in progress, which means that even if it were treated in foil, with equations and more scientific jargon than already employed, it would still leave a great many important questions unanswered. Evidently, die main function of the book is to stimulate thought and discussion. Running through the entire text is the idea of the interplay be-. rween the fundamental laws of nature and the operation of chance. The laws governing the elementary particles (including quarks) are beginning to reveal their simplicity. The unified quantum field theory of all the particles and forces may well be at hand, in the form of superstring theory. That elegant theory is based on a form of the bootstrap principle, which requires that the elementary particles be describable as made up out of one another in a self-consistent manner. The other fundamental la^ir of nature is the simple initial condition of the universe at the time its expansion began. If the proposal by Hartle and Hawking is *6?

 correct, then mat condition can be expressed in terms of the unified theory of die particles, and die two basic laws become one. Chance necessarily enters die picture because die fundamental laws are quantum-mechanical, and quantum mechanics supplies only probabilities for alternative coarse-grained histories of die universe. The coarse graining must be such as to permit probabilities to be well defined. It also allows for an approximately classical, deterministic description of nature, with frequent small excursions fiom classicality and occasional large ones. The excursions, especially the larger ones, result in die branching of histories, with probabilities for the different branches. In fact all die alternative coarse-grained histories form a branching tree, or "garden of forking paths," called a "quasiclassical domain." The indeterminacy of quantum mechanics thus goes far beyond die famous uncertainty principle of Heisenberg. Moreover, diat indeterminacy can be amplified in nonlinear systems by the phenomenon of chaos, which means that die outcome of a process is arbitrarily sensitive to die initial conditions, as often happens, for example, in meteorology. The world we human beings see around us corresponds to a quasiclassical domain, but we are restricted to a very much coarser- grained version of mat domain because of the limited capabilities of our senses and instruments. Since so much is hidden fiom us, die element of chance is still further enhanced. On certain branches of history and at certain times and places in die universe die conditions are propitious for die evolution of complex adaptive systems. Those are systems (as illustrated in the diagram on page 25) mat take in information—in die form of a data stream—and find perceived regularities in diat stream, treating die rest of die material as random. Those regularities are compressed into a schema, which is employed to describe die world, predict its future to some extent, and to prescribe behavior for die complex adaptive system itself. The schema can undergo changes that produce many variants, which compete with one another. How they fare in diat competition depends on selection pressures, representing die feedback fiom die real world. Those pressures may reflect die accuracy of die descriptions and predictions or die extent to which die prescriptions lead to survival of die system. Such relationships of die selection pressures to "successful" outcomes, however, are not rigid correlations but only tendencies. Also, the response to die pressures can be imperfect. Thus die process of adaptation

of the schemata leads only approximately to "adaptive" results for the systems. "Maladaptive" schemata can occur as well. Sometimes maladaptation is only apparent, arising because important selection pressures are overlooked in defining what is adaptive. In other cases, genuinely maladaptive situations occur because adaptation is too slow to keep up with changing selection pressures. Complex adaptive systems function best in a regime intermediate between order and disorder. They exploit the regularities provided by die approximate determinism of the quasiclassical domain, and at the same time they profit from the indeterminacies (describable as noise, fluctuations, heat, uncertainty, and so on), which actually can be helpful in the search for "better" schemata. The notion of fitness, which could give a meaning to the word "better," is often difficult to pin down, in which case it may be more useful to concentrate on the selection pressures that are operating. Sometimes a fitness quantity is well defined because it is "exogenous," imposed from the outside, as in the case of a computer programmed to search for winning strategies in a game like checkers or chess. When fitness is "endogenous," emerging from the vagaries] of an evolutionary process that lacks any external criterion for success, jit is in many case quite ill defined. Still, the idea of a fitness landscape is useful, if only as a metaphor. The fitness variable corresponds tjo height (which I take arbitrarily to be lower when fitness is greater),'and all the variables specifying the schema are imagined to be laid outjsay on a horizontal line or plane. The search for fitter schemata then corresponds to exploring a wiggly line or two-dimensional surface, hunting for very low places. As illustrated in the figure on page 250, that search would most likely lead to getting stuck in a comparatively shallow depression if it were not for some appropriate amount of noise (or heat, obeying what Seth Lloyd calls the Goldilocks principle—not too hot, not too cold, but just right). The noise or heat can shake thf system out of a shallow pit and permit it to discover a much deeper cine nearby. The variety of complex and permit it to discover a much deeper one nearby. The variety of complex adaptive systems here on Earth is illustrated in the diagram on page 20; which shows how one such system has a tendency to give rise to others. Thus the earthly systems, all of which have some connection with life, range from the prebiotic chemical reactions that first produced; living things, through biological evolution and the I cultural evolution' of humanity, all the way to computers

equipped with appropriate hardware or software and to possible future developments treated in science fiction, such as composite human beings formed by wiring people's brains together. When a complex adaptive system describes another system (or itself), it constructs a schema, abstracting from all the data the perceived regularities and expressing those in concise form. The length of such a concise description of the regularities of a system, for instance by a human observer, is what I call the effective complexity of the system. It corresponds to what we usually mean by complexity, whether in scientific usage or in everyday discourse. Effective complexity is not intrinsic but depends on the coarse graining and on the language or coding employed by the observing system. Effective complexity, whether internal or not, is insufficient by itself to describe the potentialities of a complex system, adaptive or nonadap- tive. A system may be comparatively simple, but capable of evolving with high probability, within a given time interval, into something much more complex. That was true, for example, of modern human beings when they first appeared. They were not much more complex than their close relatives the great apes, but because they were likely to develop cultures of enormous complexity, they possessed a great deal of what I call potential complexity. Similarly, when, early in the history of the universe, certain kinds of matter fluctuations occurred that led to the formation of galaxies, the potential complexity of those fluctuations was considerable. Effective complexity of a system or a data stream should be contrasted with algorithmic information content (AIC), which is related to the length of a concise description of the whole system or stream, not just its regularities but its random features as well. When AIC is either very small or near its maximum, effective complexity is near zero. Effective complexity can be large only in the region of intermediate AIC. Again the regime of interest is that intermediate between order and disorder. A complex adaptive system discovers regularities in its incoming data stream by noticing that parts of the. stream have features in common. The similarities are measured by what is called mutual information between the parts. Regularities in the world arise from a combination of the simple fundamental laws and the operation of chance, which can produce frozen accidents. Those are chance events

 that turned out a particular way, although they could have turned out differently, and produced a j multiplicity of consequences. The common origin of all those consequences in an antecedent chance event can give rise to a great deal of mutual information in a data stream. I used the example of the succession to the English throne of Henry VIII—after the death of his older brother—resulting in the existence of a huge number] of references to King Henry on coins and in documents and books. All those regularities stem from a frozen accident Most accidents, for example a great many fluctuations at the molecular level, take place without being amplified in such a way as to have significant repercussions, and they do not leave much regularity behind. Those accidents can contribute to the random part of the data stream reaching a complex adaptive system. As time goes on, more and more frozen accidents, operating in conjunction with the fundamental laws, have produced regularities. Hence, complex systems of higher and higher complexity tend to emerge With the passage of time through self-organization, even in the case of nonadaptive systems like galaxies, stars, and planets. Not everything keeps increasing in complexity, however. Rather, the highest complexity to be found has a tendency to increase. In the case of complex adaptive systems, that tendency may be significantly strengthened by selection pressures that favor complexity. The second law of thermodynamics tells us that the entropy (measuring disorder) of a closed system has a tendency to increase or stay the same. For example, if a hot body and a cold body are in contact (and not interacting much with the rest of the universe), heat tends to flow from the hot one to the cold one, thus reducing the orderly segregation of temperature in the combined system. Entropy is a useful concept only when a coarse graining is applied to nature, so that certain kinds of information about the closed system are regarded as important and the rest of the information is treated as unimportant and ignored. The total amount of information stays the same ana, if it is initially concentrated in important information, some of it will tend to flow into unimportant information that is not counted. As that happens, entropy, which is like ignorance of important information, tends to increase. A kirid of fundamental coarse graining of nature is supplied by the histories forming a quasiclassical domain. For the universe observed by

 a complex adaptive system, die

effective coarse graining can be taken to be very much coarser, because die system can take in only a comparatively tiny amount of information about die universe. As time goes on, die universe winds down, and parts of die universe that are somewhat independent of one anodier tend to wind down too. In every part, die various arrows of time all point forward, not only the arrow corresponding to die increase of entropy, but also those corresponding to the sequence of cause and effect, die outward flow of radiation, and die formation of records (including memories) of the past and not die future. Sometimes people who for some dogmatic reason reject biological evolution try to argue that die emergence of more and more complex forms of life somehow violates die second law of thermodynamics. Of course it does not, any more dian die emergence of more complex structures on a galactic scale. Self-organization can always produce local order. Moreover, in biological evolution we can see a kind of "informational" entropy increase as living dungs come into better adjustment with dieir surroundings, thus reducing an informational discrepancy reminiscent of the temperature discrepancy between a hot and a cold object. In fact, complex adaptive systems all exhibit diis phenomenon— die real world exerts selection pressures on die systems and die schemata tend to respond by adjusting die information they contain in accordance with diose pressures. Evolution, adaptation, and learning by complex adaptive systems are all aspects of the winding down of die universe. We can ask whether the evolving system and die surroundings come into equilibrium, like a hot body and a cold body reaching die same temperature. Occasionally they do. If a computer is programmed to evolve strategies to play a game, it may find die optimal strategy and the search is over. That would certainly be die .case if die game is tic-tac-toe. If die game is chess, die computer may discover die optimal strategy some day, but so far diat strategy is unknown, and die computer continues to hunt around in a huge abstract space of strategies seeking better ones. That situation is very common. We can see a few cases where, in the course of biological evolution, a problem of adaptation seems to have been solved once and for all eariy in the history of life, at least on the phenotypic level. The extremophiles living in a hot, acidic, sulfurous environment deep in die ocean at the boundaries between tectonic plates are probably quite similar, at least

 metabolically, to organisms diat lived in that environment more dian three and a half billion years ago. But most problems of biological evolution are not in the least like tic-tac-toe, in fact not even like chess, which will no doubt be a solved problem some day. For one thing, the selection will no doubt be a solved problem some day. For one thing, the selection pressures are not at all constant. In most parts of the biosphere, the physicochemical environment keeps changing. Moreover, in natural communities the various species form parts of the environment of other species. The organisms are co-evolving, and there may not be any true equilibrium to be attained. At various times and places, approximate and temporary equilibria do seem to be reached, even for whole communities, but after a while those are "punctuated," sometimes by physicochemical changes and sometimes by a small number of mutations following a long period of "drift,"! meanmS sequences of genetic changes diat affect phenotypes only slightly and in ways diat don't matter much to survival. Drift can have thfe effect of preparing the way for very small alterations in the genotype to cause important phenotypic changes. From time to time such comparative modest changes in genotypes can lead to gateway events, in which whole new kinds of organisms come into being. An example is the appearance of single-celled eukary- otes, so [called because the cell possesses a true nucleus and also other organelles—chloroplasts or mitochondria—which are thought to be descended from originally independent organisms incorporated into the celh Another example is the origin of multi-celled animals and plants Horn single-celled organisms, presumably by aggregation, with the aid of a biochemical breakdirough, a new kind of glue-like chemical that tield the cells together. Wh6n a complex adaptive system gives rise to a new kind of complex adaptive system, whether by aggregation or otherwise, diat can be considered a gateway event A familiar example is the evolution of the mammalian immune system, the operation of which somewhat resembles biological evolution itself, but on a much more rapid time scale, so that invaders of the body can be identified and attacked in hours or days, as compared with the hundreds of thousands of years often needed to evolve new species. Many of die same features diat are so conspicuous in biological evolution are found, in rather similar form, in other complex adaptive systems, such as human thought, social evolution, and adaptive comput-

 ing. All these systems keep exploring possibilities, opening up new padis, discovering gateways, and occasionaUy spawning new types of complex adaptive system.Just as new ecological niches keep turning up in biological evolution, so new ways to make a living continue to be discovered in economies, new kinds of theories are invented in the scientific enterprise, and so on. Aggregation of complex adaptive systems into a composite complex adaptive system is an effective way to open up a new level of organization. The composite system then consists of adaptive agents constructing schemata to account for and deal with one another's behavior. An economy is an excellent example, and so is an ecological community. A good deal of research is being carried out on such composite systems. Theories are developed and compared with experience in various fields. Much of that research indicates that such systems tend to settle into a well-defined transition zone between order and disorder, where they are characterized by efficient adaptation and by power law distributions of resources. Sometimes that zone is called, rather metaphorically, the "edge of chaos." There is no indication that there is anything terribly special about the formation of a planetary system like the solar system or about its including a planet like the Earth. Nor is there any evidence diat the chemical reactions that initiated life on this planet were in any way improbable. It is likely, therefore, that complex adaptive systems exist on numerous planets scattered through the universe and that at least some of those complex adaptive systems have many features in common with terrestrial biological evolution and the resulting life forms. It is, however, still a matter of dispute whether the biochemistry of life is, on the one hand, unique or nearly so, or, on the other handjust one of a great many different possibilities. In other words, it is not yet certain whether it is determined mosdy by physics or owes its character in great part to history. The nearly four billion years of biological evolution on Earth have distilled, by trial and error, a gigantic amount of information about different ways for organisms to live, in the presence of one another, in the biosphere. Similarly, modern humans have, over more than fifty thousand years, developed an extraordinary amount of information about ways for human beings to live, in interaction with one another and with the rest of nature. Both biological and cultural diversity are

 now severely threatened and working for their preservation is a critical task. ! The preservation of cultural diversity presents a number of paradoxes and conflicts with other goals. One challenge is the very difficult one or reconciling diversity with the pressing need for unity among peoples1 now faced with a variety of common problems on a global scale. Another is presented by the hostility that a number of parochial cultures evince toward die universalizing, scientific, secular culture, which supplies many of the most vigorous advocates of the preservation of cultural diversity. The conservation of nature, safeguarding as much biological diversity as possible, is urgendy required, but that kind of goal seems impossible to Achieve in the long run unless it is viewed within the wider context of environmental problems in general, and those in turn must be considered together with the demographic, technological, economic, social, political, military, diplomatic, institutional, informational, and ideological problems facing humanity. In particular, the challenge in all of these fields can be viewed as the need to accomplish a set of interlinked transitions to a more sustainable situation during the course of the coming century. Greater sustainability, if it can be attained, would mean a leveling off of population, globally and in most regions; economic practices that encourage charging true costs, growth in quality rather than quandty, and living on nature's income rather than its capital; technology that has comparatively low environmental impact; wealth somewhat more equitably shared, especially in the sense that extreme poverty would no longer be common; stronger global and transnational institutions to deal with the urgent global problems; a public much better informed about the multiple and interacting challenges off the future; and, perhaps most important and most difficult of all, the prevalence of attitudes that favor unity in diversity—cooperation and nonviolent competition among different cultural traditions and nation states—as well as sustainable coexistence with the organisms that share the biosphere with humankind. Such a situation seems Utopian and perhaps impossible to achieve, but it is wordiwhile to try to construct m odels of the future—not as blueprints but as aids to the im- aginatioi i—and see if paths can be sketched out that may lead to such a sustainatle and desirable world late in the next century, a world in which h imanity as a whole and the rest of nature operate as a complex adaptive system to a much greater degree than they do now.

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