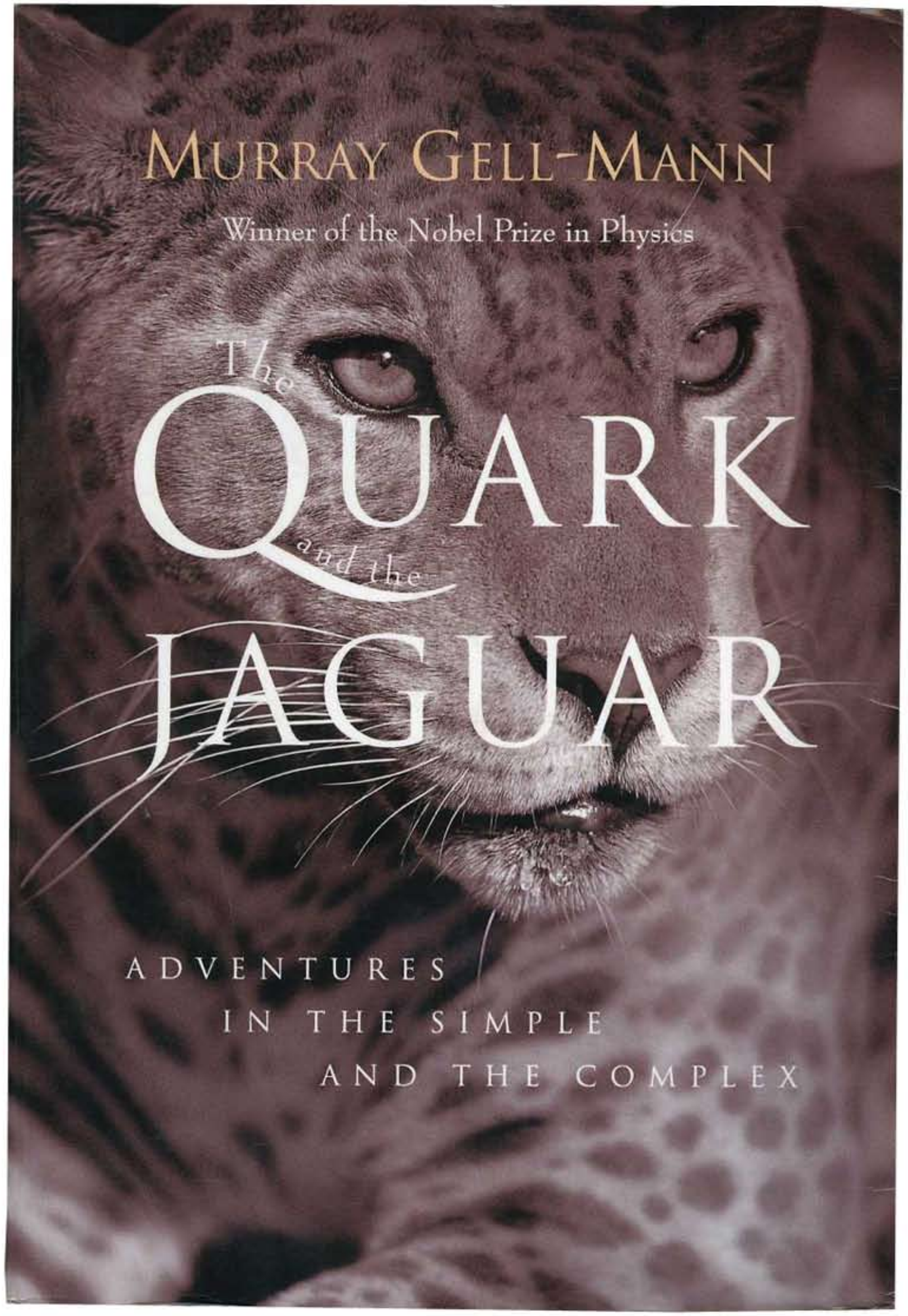

MURRAY GELL-MANN
Winner of the Nobel Prize in Physics
The QUARK and the JAGUAR
ADVENTURES IN THE SIMPLE AND THE COMPLEX

he suggested engineering. I replied that I would rather starve, and also that whatever I designed would probably fall 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 the dullest course in the curriculum, and that it was the only subject in which I had done badly. We had had to memorize such things as the seven kinds of simple machine: the lever, the screw, the 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 the 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 the 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 them, that the beauty of nature is manifested just as much in the elegance of these fundamental principles as in the cry of a loon or in trails of bioluminescence made by porpoises at night.

Complex Adaptive Systems

A wonderful example of the simple underlying principles of nature is the 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 the time of their formation, such bodies were already manifesting complexity, diversity, and individuality. But those properties took on new meanings with the emergence of complex adaptive systems. Here on Earth that development was associated with the 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 the underlying simplicity, including the theory of gravitation itself.

Research on the sciences of simplicity and complexity, as carried out at the Santa Fe Institute and elsewhere around the world, naturally includes teasing out the meaning of the simple and the complex, but also the 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 the 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 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.

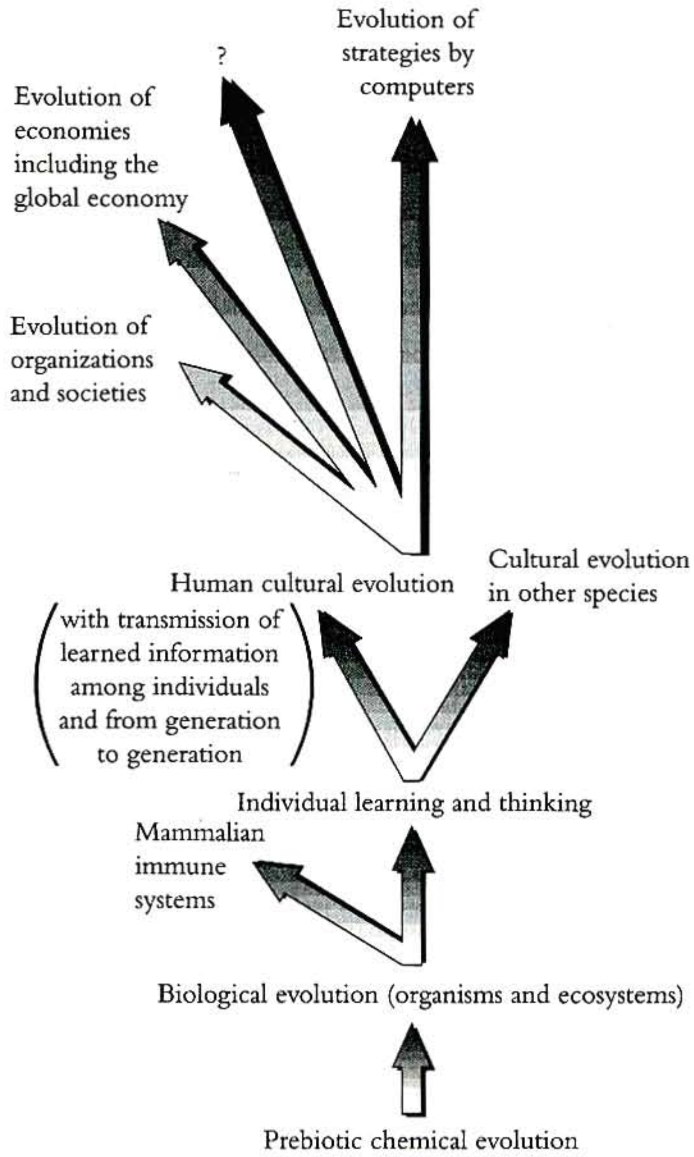
Whether putting together a business plan for a new venture, refining a recipe, or learning a language, you are behaving as a complex adaptive system. If you are training a dog, you are watching a complex adaptive system in operation and you are functioning as one as well (if it is mainly the latter that 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 the usual sense that provides examples of the operation of complex adaptive systems. Biological evolution provides many others. While human beings acquire knowledge mainly by individual or collective use of their brains, the other animals have acquired a much larger fraction of the information they need to survive by direct genetic inheritance; that information, evolved over millions of years, underlies what is sometimes rather vaguely called "instinct." Monarch butterflies hatched in parts of the United States "know" how to migrate, in enormous numbers, to the pine-clad slopes of a particular mountain in Mexico to spend the winter. Isaac Asimov, the late biochemist, popularizer of science, and science fiction author, told me that he once had an argument with a theoretical physicist who denied that a dog could know Newton's laws of motion. Isaac asked indignantly, "You say that, even after watching a dog catch a Frisbee with its mouth?" Obviously, the physicist and he were using "knowing" to mean different things: in the case of the physicist, mostly the result of learning in the cultural context of the human scientific enterprise; in Isaac's case, information stored in the genes, supplemented by some learning from the experience of the individual.

That capacity to learn from experience, whether in paramecia or dogs or people, is itself a product of biological evolution. Furthermore, evolution has given rise not only to learning but to other new types of complex adaptive systems as well, such as the 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 the 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 other 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 the following page illustrates how various complex adaptive systems on Earth are related to one another. Certain chemical reactions involving reproduction and some transmit-



Some complex adaptive systems on Earth.

ted variation led, around four billion years ago, to the 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 the immune system and the learning process. In human beings, the development of the capacity for symbolic language expanded learning into an elaborate cultural activity, and new complex adaptive systems arose within human culture: societies, organizations, economies, and the scientific enterprise, to name but a few. Now that rapid and powerful computers have emerged from human culture, we can make it possible for them to act as complex adaptive systems as well.

In the 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 the early 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 then director of the Institute for Advanced Study in Princeton), replied that he could attend only the second half of the meeting. Leo turned to me, and I said that I could attend only the first half. Murph and I then asked if we could share an invitation. Leo thought for a moment and then 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 directly to an advanced computer, (not through spoken language or an interface like a console), and by means of that computer to one or more other human beings. Thoughts and feelings would be completely shared, with none of the selectivity or deception that language permits. (Voltaire is supposed to have remarked that "Men . . . employ speech only to conceal their thoughts.") My friend Shirley Hufstedler says that being wired up together is not something she would recommend to a couple about to be married. I am not sure that I would recommend such a procedure at all (although if everything went well it might alleviate 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 with their general properties as well as with the distinctions among them. Although they differ widely in their physical attributes, they resemble one another in the way they handle information. That common feature is perhaps the best starting point for exploring how they operate.