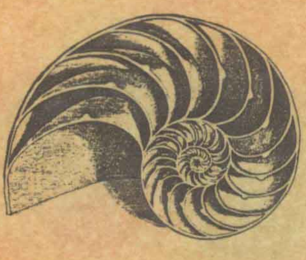
SCIENCE AS A WAY of KNOWING

The Foundations of Modern Biology



JOHN A. MOORE

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Designed by Gwen Frankfeldt

This volume is dedicated with the deepest thanks to my wife,
Betty C. Moore,
and to my friend and associate in science for nearly half a century,
Ingrith Deyrup-Olsen.
It would never have been produced without their
constant encouragement, support, and advice
based on their critical knowledge of the biological sciences.

Preface

We generally think of the Scientific Revolution of the sixteenth and seventeenth centuries as the movement that shaped the modern world. Nicolaus Copernicus (1473–1543), Andreas Vesalius (1514–1564), Francis Bacon (1561–1626), Galileo Galilei (1564–1642), Johann Kepler (1571–1630), William Harvey (1578–1657), Robert Hooke (1636–1703), Isaac Newton (1642–1727), and their like spoke for a new breed of men who rejected received truths and sought to understand the natural world in naturalistic terms. But it was a very slow revolution—two and a half centuries separated the birth of Copernicus and the death of Newton.

In marked contrast, we live in the time of a scientific revolution characterized by great speed and enormous accomplishment. During the nineteenth century, astronomy, physics, chemistry, geology, and biology began their modern development. They became more rigorous, more conceptual, and interdisciplinary. Today most major questions in science have general answers that, although not final, have been established as true beyond reasonable doubt. But science is never complete, and each new discovery produces new questions. In fact, we have now reached the point where ever more sophisticated questions can be asked and new techniques are available for seeking answers to many of them.

Science as a Way of Knowing tells the story of the development of concepts in the biological sciences—the sciences of life. The complexity of life itself has made this intellectual journey difficult. Nevertheless, in our time biology has become the most active, the most relevant, and the most personal science, one characterized by extraordinary rigor and predictive power. As the twentieth century comes to a close, we have a depth of understanding of that most distinctive and puzzling feature of life—its ability to self-replicate—that is satisfying to almost everyone, scientist and nonscientist alike. This understanding of self-replication made possible with the procedures of science has been an outstanding achievement in intellectual history. From an account of these advances in understanding in the pages that follow, we will see how long it has taken and how indirect and seemingly unrelated were the observations and experiments that eventually provided the answers.

Four major topics are developed in this volume: "Understanding Nature," "The Growth of Evolutionary Thought," "Classical Genetics," and "The Enigma of Development." Evolution, genetics, and developmental biology form the core of conceptual biology: all deal with the fundamental characteristic of life—its ability to replicate over time. Much of the material in these chapters first appeared in eight essays in the *American Zoologist* from 1984 to 1990, as part of the "Science as a Way of Knowing" project. The stimulus for that project, which was sponsored by twelve scientific and educational organizations, was the widespread feeling that human beings have become so numerous and are consuming resources so avidly that the earth cannot long continue to support our way of life. We are overwhelming the natural cycles that have made life on earth possible for well nigh 4 billion years. The "Science as a Way of Knowing" project sought to help remedy these problems by providing materials to assist in understanding. There can be no future for the human experiment unless a critical mass of involved people understands that the laws of nature constrain our activities and that our solutions to these problems must be based on knowledge and not blind adherence to fads.

The advice of many people was followed in developing the original versions of these essays. They have been acknowledged previously with sincere thanks, but I wish to note again that the advice of Betty C. Moore and Ingrith Deyrup-Olsen has been essential throughout. At Harvard University Press, Howard Boyer first suggested revising the essays for a general audience, Michael Fisher shepherded the manuscript through the review process, and Susan Wallace skillfully molded the essays into this single volume. Many thanks to all.

J.A.M.

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Contents

Introduction

Nearly 4 billion years ago, in the violent millennia of the Hadean world, some organic molecules achieved the ability to make more of themselves from the simpler chemical substances of the primeval seas in which they occurred. This ability to self-replicate at the expense of the environment was the beginning of life on earth. Life itself involves a conflict between two antagonistic phenomena: Self-replication can produce, in theory, an infinite number of products; yet, in reality, the world that supplies the materials for replication is finite. Life, then, is a tension between the infinite and the finite. It is inevitable that the finite prevails.

This struggle between the demands of life and the finite ambient world has resulted in the incredible variety of life with us today, as well as the wondrous fossils of life lived long ago found in sedimentary rocks. Each of the many kinds of life—each biological species—represents a different way of exploiting the living and nonliving world. Had the mechanisms of self-replication never changed, life on earth today, had it survived at all, would consist only of a uniform primeval ooze. But diversification ensued, and today there are untold and largely unknown millions of species, each representing a different way of making a living and leaving offspring. This diversification is a consequence not of a "desire" to diversify but of the imperfect nature of replication itself in a finite world.

But life has not been easy, and there have been many crises during the last 4 billion years. As recent as 10,000 years ago, North America was home to horses, camels, mammoths, mastodons, saber-toothed cats, and many other species that are no longer with us. They totally disappeared, leaving a much depleted variety of mammals. The cause is unknown. Approximately 230 million years ago another catastrophe exterminated approximately 90 percent of life in the sea. Again, the cause is unknown.

One of the greatest biocides may be occurring now; if not, it is a distinct possibility for the near future. In contrast with previous cases of mass extinction, the current one is taking place in decades, not in thousands of years. Its cause is that tension between the needs of organisms for resources and the limited quantity of resources in the environment. Until the time of man, there had always been an equilibrium between those needs and the ability of the environment to provide. Organisms do not destroy the chemical substances they use for life; they merely borrow them. For example, human beings take in food, water, and air, consisting mainly of compounds of carbon, hydrogen, oxygen, nitrogen, and sulfur, and during life eliminate these molecules in the form of carbon dioxide, water, urea, and feces. At death all the borrowed molecules are returned to the surrounding world. Green plants and microorganisms use the molecules eliminated by human beings and other animals for food and for the substances of their own bodies. Animals neither deplete the atmosphere of the oxygen required for their lives nor saturate the atmosphere with the carbon dioxide that is a waste product of their metabolism. This is because the photosynthetic reactions in the cells of green plants use that carbon dioxide and other molecules to synthesize organic compounds, leaving oxygen as a waste product. The activities of animals and green plants, then, are in such exquisite equilibrium that the concentrations of oxygen and carbon dioxide in the atmosphere are nearly constant. Both life and the environment are sustained because the environment is farmed, not mined.

Times have changed. Human beings are now making such extraordinary demands on the environment that the natural cycles can no longer provide a seemingly unlimited supply of resources. Our rate of borrowing has become too great. Tropical forests are being cut at a rapid rate for their timber or to make new agricultural land. The fertility of soils in many parts of the world is being depleted by poor agricultural practices. Species and their habitats are being destroyed by human activity at a rate never experienced before. There is overuse not only of the normally renewable resources—air, water, food, timber—but of nonrenewable resources as well. The minerals and fossil fuels that have become the basis of civilization are being consumed at a rate that will ensure their depletion before many more generations have passed.

And the waste products of civilization now exceed the ability of the environment to deal with them effectively. A few generations ago it was common practice for towns to use a local river for water and then to empty untreated sewage into it. Towns downstream would use that same river as a source of water and as a dumping ground for their sewage. This was possible because, as the saying goes, "A river purifies itself in 10 miles." The waste of the towns was food for the bacteria and other microorganisms that lived in the river and in the mud at the bottom. That bacterial purification system works so long as there are towns, not cities. If the human population becomes too large, the amount of sewage overwhelms the ability of the microorganisms to purify the water in a short distance.

Today there is another difficulty. Microorganisms can use human bodily wastes and garbage for food, but they cannot metabolize many of the industrial poisons that are now added to our old-fashioned wastes—a huge list of toxic substances emitted from mines, nuclear reactors, factories, automobiles, and homes. In modest amounts many can be handled by the environment, but when they are dumped in massive quantities, there may be unacceptable consequences.

What human beings seem often to lose sight of is that in the natural world different species form communities that enhance the life of the various species within the community. Plants provide places for birds to nest and food for many animals. Microorganisms cycle the substances from corpses, through themselves, and back to the plants and animals of the community. Natural communities are balances of interacting and interdependent species. Disruption of those balances may severely impact some or all of the members of the community.

One cannot overemphasize the importance of the interdependence and interrelations of organisms. Not only are they necessary for one another, but their activities mold the nonliving environment, making it a better place for life. For example, the composition of today's atmosphere is a product of life. The atmosphere of the primitive earth was devoid of oxygen, and organisms relied on anaerobic processes (those not requiring oxygen). When green plants appeared, the oxygen that was an end product of photosynthesis began to enter the atmosphere. Subsequently, organisms evolved that could use oxygen in their energy-producing metabolic reactions. The difference was dramatic. When glucose is used for energy, aerobic metabolism provides 18 times as much energy as does anaerobic metabolism. Today, nearly all complex animals and plants are aerobic.

Because of the size of modern cities and the amounts of waste products they produce, natural cycles can no longer maintain the purity of the atmosphere in most metropolitan areas. Waste gases are destroying the ozone layer, which protects living creatures from harmful radiations; others may result in a warming of the globe, the consequence being widespread disruptions of agriculture. The list of abuses of our life-support systems is long, disturbing, and growing.

These matters are discussed so prominently by the mass media that it is not necessary to elaborate further. The conclusion reached by many thoughtful scientists is that the demands human beings are now making on the environment simply cannot be continued.

Very difficult decisions will have to be made if we are to have a sustainable human society in a sustainable environment. Many of those decisions will require extensive knowledge of biology. We have reached the point in history, therefore, when biological knowledge is the *sine qua non* for a viable human future. Such knowledge will be especially necessary for the leaders of society—in government, industry, business, and education—but the tough decisions will have to be supported by an informed electorate. A critical subset of society will have to understand the nature of life, the interactions of living creatures with their environment, and the strengths and limitations of the data and procedures of science itself. The acquisition of biological knowledge, for so long a luxury except for those concerned with agriculture and the health sciences, has now become a necessity for all.

Material to help achieve that understanding is the subject of this book. First there will be an account of how human beings over the millennia have sought to understand nature. There will follow a survey of some of the basic areas of conceptual biology—evolution, genetics, and developmental biology.

This will be a long and detailed story so it is useful to provide a thumbnail sketch of the basic concepts of biology that will inform and provide perspective. Such an overview, even when simple, will allow one to fit the parts to the whole. Parts are best understood when they can be seen in relation to an entire structure—in this case the conceptual structure of biological science.

A Brief Conceptual Framework for Biology

At any moment of time life appears not as a continuum (as is the case with the air or the oceans) but sequestered in individuals. These individuals consist solely of the atoms that are common in the nonliving world, but those atoms are usually built into tremendously complex molecules, such as nucleic acids, proteins (including enzymes), carbohydrates, and fats. Life, then, is an expression of complex and dynamic chemical reactions. These reactions occur continuously, until ended at death, and involve chemical substances entering and leaving the body. Most of these reactions require energy, which in the last analysis comes almost entirely from the light of the sun. These complex reactions of life are programmed by the nucleic acids DNA and RNA.

The key characteristic of living organisms is their ability to make more of themselves—to reproduce—from chemical substances in the environment. The offspring resemble the parent(s) closely, as a consequence of their having received the hereditary substance DNA (and, in some microorganisms, the similar nucleic acid, RNA). Because the environmental resources available for making new individuals is finite, organisms have devised innumerable ways of maximizing the acquisition of resources. Green plants require only simple chemical substances—carbon dioxide, water, and salts plus light from the sun. Animals use for resources the bodies of green plants directly (they eat them) or indirectly (they eat animals that have eaten plants). Microorganisms use the bodies of dead plants and animals for resources. The interactions among these various sorts of organisms cycle renewable resources with such precision that they remain nearly constant.

The origin of species capable of exploiting different resources, or the same resources differently, is made possible by the nature of self-replication. The basic requirement for self-replication is precision. If an organism has the heredity makeup, the DNA, that enables it to survive in a particular environment, it is important to have that hereditary program transmitted to the offspring ("If it works, don't fix it"). But if the DNA were transmitted with complete accuracy, the organisms would be restricted to that particular environment and way of life for all time, or at least until some catastrophic change in the environment wiped out all of life. Fortunately for the history of life, replication of the genetic program is not completely accurate—there is some slight variation in the hereditary programs transmitted from parent to offspring. If in the long term these slight variations permit the exploitation of new resources—plants growing in a previously unexploited environment, marine animals able to live on land, normally free-living species becoming parasites, and so on—new places and ways of living become available. Over time, through a long series of variations, organisms with different structures, physiologies, and behaviors evolve. Every distinct species should be viewed as an experiment, successful for the moment, in coping with a specific habitat in a specific way.

Thus, built into the phenomenon of organic reproduction is a constant pressure to expand and to diversify life. The result is that, today, there are uncounted millions of species—each representing a slightly different way of obtaining resources and, hence, of living. Three major fields of biology are concerned with this basic phenomenon: genetics, developmental biology, and evolution.

Genetics deals with the ultimate physical basis for life—the genetic program that controls what an individual is and does, changes in that program, and the transmission of the program to the next generation. Throughout the world of life the hereditary program consists of four kinds of nucleotides of DNA (rarely RNA) arranged in a specific linear structure—in a chromosome—like letters and words of a very long book. Functional units of DNA are known as genes. During reproduction the DNA is normally replicated with precision, but, rarely, changes in the arrangement of nucleotides occur. These changes are mutations that may program an individual with a somewhat different anatomy or physiology.

A more common source of variation is a result of sexual reproduction. Reproduction, especially in the more complex plants and animals, usually involves the interaction of females and males. During sexual reproduction there is a shuffling of genes in the formation of ova in females and sperm in males. Further genetic variability arises when genetically different kinds of ova and sperm unite.

Cells are the basic structural and functional elements in organisms. They represent the simplest level of organization that can exist independently. Ova and sperm are highly specialized cells, and their union, in fertilization, can produce a new individual, with a genetic program similar to but not exactly like that of the parents.

Developmental biology deals with the events and processes that convert the single cell formed at fertilization into an adult individual that may consist of thousands or millions of cells. The basic problem of development is how is it possible for a single cell, with a single genetic program, to produce an adult with dozens or hundreds of different types of cells. The general answer is that, at different times in the course of development, different genes become active in different cell types.

Since many more offspring are produced than can secure the resources to survive, any individuals with a genetic program that better equips them to obtain resources will have an advantage over other individuals. Those better-equipped individuals are said to be "selected." **Evolution** consists, then, of the natural selection of genetic variations that give individuals a better chance of surviving and leaving offspring. Over the course of time, the individuals of a generation will come to differ greatly from their remote ancestors.

Every tree, shrub, insect, and bird has an ancestry that extends back 4 billion years to the time when life first emerged. Over the course of that long ancestry, the forms of life have diverged, and every species represents a unique way of living. The bird is not better than the bee or the oak tree. Each began from a tiny fertilized egg or a bud of some sort and underwent a complex development, guided by the hereditary program of the species, to reach the adult state. Every organism is part of an interacting and interdependent community of life. Life provides for life.

Such a thumbnail sketch of how we understand life is a relatively recent achievement. Although the antecedents of this understanding go back to the dawn of history, most of it is a product of twentieth-century science. Before turning to a detailed account of evolutionary biology, genetics, and developmental biology in the nineteenth and twentieth centuries, we will first take a look at how science became a way of knowing the natural world from prehistory to the age of Darwin.