

The twentieth century did contain, however, such a rich variety of mechanical views that we need to label its subdivisions. The unmitigated extreme was promoted by German émigré Jacques Loeb (1859–1924), whose 1912 book *The Mechanistic Conception of Life* described experiments demonstrating the automatic nature of certain animal behaviors. Many biologists held a moderate middle view that we may call organic mechanism, granting importance to life's great complexity of organization, which is layered in hierarchies of size from the atomic level, to the level of material within cells, to the architecture and intercommunications that make cells into tissues, organs, and organisms, on up to the relations between whole organisms that constitute the systems we call species and ecosystems. Several biologists, calling themselves holists or organicists or emergentists, have emphasized that new properties emerge out of organization. Charles Manning Child (1869–1954), chair of the biology department of the University of Chicago, opposed Loeb's mechanism by insisting on the dynamic relationship between an organism and its changing environment. Organicists early in the century often sounded like mild vitalists, while organicists later in the century were careful to exclude all but physical laws. Ludwig von Bertalanffy (1901–72), who came to Canada from Austria in 1949, urged the view that the integrated systems that tie living things together mean that ordinary mechanism is just as inadequate a description as vitalism certainly is. Thus the terminology of "organic mechanists" would not have pleased him—and there remain other viewpoints that are more difficult to classify. In 1979, James Lovelock (b. 1919) shifted the focus of attention away from the kind of organism that has always been our model, which is a single person, cat, tree, or fish. Previously, the microscope had shifted attention downward, identifying cells as deserving to be called a unit of life, but Lovelock shifted attention upward. As if viewing our globe from outer space like an astronaut, he declared that the entire planet, organic and inorganic stuff together, is truly a single organism, which he named Gaia. Most of his followers can only be called extreme vitalists, because they add a kind of soul to Gaia, but whether Lovelock's own view is organic mechanism depends upon whether or not it is reasonable to treat teleology—the planet's goal of its own survival—as an emergent property. Darwinian evolutionists say that it is, but only for individuals that are members of populations, not for single entities like a planet.

Developments in technology in the twentieth century greatly widened the kinds of phenomena that human-made objects are capable of, increasing the power of mechanical analogies and lessening the need for vitalism. Electronic communication such as the telephone, introduced late in the nineteenth century, and the automated telephone exchanges that replaced human operators in the 1920s were immediately compared to nervous systems. Information theory and cryptology that proved crucial to the military during World War II were incorporated into the thinking of molecular biologists after 1953. Computers that not only store data but can also manipulate those data by following programs provided a model for how DNA might govern the apparently goal-directed steps of **ontogeny**. With only a little help from science fiction, the lifelike capacities of late-twentieth-century machines went far toward closing the gap that Descartes had claimed would always separate humans from human-shaped machines (now called androids). In television and movies, computers could carry on flawless if humorless conversations, and authors toyed with the dilemma of whether people owe androids moral respect. Thus the great explosion of technical sophistication converged on the successes of biochemical and molecular physiology to surpass Descartes's wildest dreams.

Yet the world of Descartes had two deep flaws: It was dualist and it was effectively ahistorical. Its sharp distinction of mind and matter conflicted with common sense, for higher animals obviously display at least some mindlike qualities. Descartes himself had struggled to explain by what connections human minds can cause motions in

\* **Ontogeny.** The development of a living organism.

human bodies. At the same time, as conservative theologians recognized immediately, Cartesian dualism divorced the Creator from his creation. The watchmaker analogy that seemed so convenient to those who wanted to show that science could support rather than threaten religion was based on this same radical separation. God's responsibility was relegated to some distant past moment, when miraculous events, no longer allowed, once occurred. The historical sciences therefore posed a disturbing threat to the watchmaker Creator at every stage in their development. In Lyell's geology, ordinary events such as rainfall and erosion, shorelines and volcanoes, following natural laws as faithfully as heat and water do today, have sculpted the world into its present shape over many eons. People of profound faith had no trouble equating a naturally evolving earth with one made by God's hand, but for the literal-minded, only supernatural events seem divinely caused. Theologians who had never acceded to Descartes's dualism had less trouble accommodating to the progress of science than did laypeople who had accepted natural theology, unaware of its implicit dualism.

## Twentieth Century

### EVOLUTION

In 1900, the Darwinian view of evolution was at a low ebb. Many biologists believed in yet-undiscovered, nonrandom causes of variation that, coupled with the inheritance of acquired characters, would explain the pattern of progress they saw in the history of life. They allowed to natural selection only the minor role of culling out the maladapted. None of the founders of the new experimental science of genetics—Hugo de Vries (1848–1935), William Bateson, and Thomas Hunt Morgan—shared Darwin's belief that change originated with small, random, individual differences. But after several decades of sometimes contentious research, the facts of genetics that have now become commonplace were uncovered: that some genes are **dominant** and others **recessive** the vast number of recombinations of genes mixed by sexual reproduction, the small but constant source of new genes through **mutation**. The result was that several people working independently in the 1930s—R. A. Fisher (1890–1962), Sewall Wright (1889–1988), and J. B. S. Haldane (1892–1964)—were able to calculate by mathematical modeling that natural selection acting on random small differences could be fully as effective as Darwin had postulated. In the late 1930s and the 1940s, Dobzhansky, Julian Huxley (1887–1975), Ernst Mayr (b. 1904), and George Gaylord Simpson (1902–84) agreed on an evolutionary “modern synthesis” that tied together recent findings in genetics, paleontology, and the geographical distribution of closely related species. In the 1950s and 1960s, difficult problems such as dramatic differences in the form and behavior of the two sexes and the highly social ants and bees whose workers sacrifice themselves for the good of the colony were analyzed through mathematically rigorous comparisons. Beginning in the 1970s, the study of animal societies, called *sociobiology*, aroused both ideological and technical objections when extended onto human societies, but the science of studying kinship patterns and behavior in animals produced impressive results in the last quarter of the century. Evolutionary biologists held vigorous debates over unsettled questions, such as: Does selection work only for the good of the individual or can it promote the good of the species? How does the evolution of organisms that do not reproduce sexually differ from those that do interbreed? Over geological time, do species evolve gradually or are periods of stability broken by occasional rapid change (“punctuated equilibrium”)? Should our taxonomic system of naming kinds of living things try to reflect their evolutionary history, and if so, how? How can we check the truth of a plausible story about how a particular character evolved? The experts who vigorously

\* **Dominant/recessive.** In genetics, terms used to describe the ability of one gene to mask another.

\* **Mutation.** The process by which a gene is displaced from its position on the DNA strand.

explored a variety of answers to these and many other questions all agreed, however, that the evidence for evolution, with natural selection as the principal cause of adaptation, was as strong as any evidence in all of science.

### MOLECULAR BIOLOGY

The most important development of twentieth century biology was, without a doubt, the discovery of the structure of DNA by Francis Crick (b. 1916) and James Watson (b. 1928) in 1953. After that, molecular biology grew exponentially, and it so dominates biology in the early twenty-first century that it is hard to imagine what things were like before the double helix. Histories that show how steadily and logically events in previous decades led up to Watson and Crick's work, as they certainly did, also make it hard to imagine why it should have been such a revolutionary breakthrough. Looking back to the first half of the twentieth century, we can see that although almost all biochemists, molecular biologists, geneticists, physiologists, and **cytologists** thought of themselves as mechanists, and some were fervent antivitalists, none of them foresaw how exceedingly like miniature machinery the vital processes would turn out to be.

\* **Cytology.** Study of the structure, behavior, and reproduction of cells.

Immediately upon finding the right model for deoxyribonucleic acid (DNA), Watson, Crick, and other biologists could see how this molecule, the wonderful double helix, held the answers to some of the oldest mysteries about life. First, the freedom of order along the chain of bases explains how information could be carried, like words across a page. Second, the complementarity of its bases, each lightly attached to only one possible mate, explains life's ability to multiply, cell division after cell division, in endless replication. Third, its sturdy coiled backbones explain the great stability that genes must have if offspring are to resemble parents, generation after generation. In searching back through the writings of geneticists and others before 1953, one can find earlier suggestions that seem to have anticipated this sort of solution. Such premonitions, however, were exceptional, few, and scattered, which helps to explain why the features of the double helix had such a revolutionary impact.

Physicist Erwin Schrödinger (1887–1961), in his little book *What Is Life?* (1944), discussed the implications of x-ray experiments that caused mutations in fruit flies, which found that genes seemed to consist of only a few thousand atoms. This seemed very small for something that had such a complicated job to do. He brought up the principles of cryptography, exemplified by Morse's telegraph code of dots and dashes, to show that a large number of messages could be made from very few distinct elements. Yet neither Schrödinger nor the biologists were guessing that the gene could be as arbitrary as a cipher; it was widely assumed that since it governed the production of proteins, it must itself be protein. Thus the 1944 discovery by microbiologist Oswald T. Avery (1877–1955) and his co-workers that the genetically active ingredient in chromosomes was not their protein but their nucleic acid was surprising and puzzling, for nucleic acid molecules were thought to consist of bits of sugar, phosphate, and base in boring repetition. Avery's discovery caused biochemist Erwin Chargaff (b. 1905) to ask whether different species have different kinds of DNA, since the genes in a cow ought to differ from the genes in a mouse. Breaking apart the molecules, he confirmed his guess: The percentage of the four bases (adenine, thymine, guanine, and cytosine) was different in the DNA of each of the species he looked at. He also reported that within each species, the amount of adenine roughly equaled the amount of thymine, and the amount of guanine roughly equaled the amount of cytosine. Chargaff would certainly have seized upon these one-to-one ratios as an important clue if the question of how genes might be copied had been much discussed in the early 1950s. In fact, the ratios made sense to Watson and Crick only in the final stage of their trial-and-error model building. Once things do make sense, people soon find it difficult to remember why

they were not always obvious. Before 1953, how genes might replicate, and how they might control enzymes, was nearly impossible to conceive. But Chargaff's insight that there is not one but an enormous number of distinct molecules fitting the chemists' definition of DNA is critical.

After Watson and Crick's model and throughout the decades of the 1960s and 1970s, when the genetic code was deciphered and the role of RNA (ribonucleic acid) in bringing information from nucleus to **cytoplasm** was worked out, the intoxicating notion persisted that with the structure of DNA, the secret of life had been discovered. During those years, more than a few molecular biologists felt something close to pity or disdain for the old-fashioned biologists who were still studying plants and animals rather than bacteria and viruses, and whose questions about ecology, evolution, or worst of all, behavior, were so vague and probably unanswerable. DNA seemed to be a master molecule, and at first Watson and Crick even imagined it could copy itself without the help of enzymes. Some textbooks still give the impression that DNA is somehow life itself, so if we could send some to a distant planet, cows and trees, or at least some form of life, would sprout up there. If this were so, the dream of the ancient atomists would have been fulfilled, but this is pure fantasy. Delbrück had started his quest with the idea that by using the smallest thing capable of replication, a virus, he would be studying the smallest unit of life. Yet viruses cannot reproduce themselves; they are parasites and can replicate only by hijacking the machinery of cells. DNA by itself is as inert as a rock unless placed in the right environment. In a laboratory, for a brief time, that environment can be fragments of cells, but in nature, DNA is active only within cells. The smallest unit of life had already been discovered in the nineteenth century.

In the last decades of the twentieth century, molecular biologists, locating giant molecules within the detailed architecture that is visible with the electron microscope, began to learn more about the intricate machinery by which organized structures in the nucleus support gene action, and by which complicated bodies in the cytoplasm manage protein synthesis and deploy energy. How DNA acts to govern the development of the fertilized egg or ovum, and to control the differing vital processes of each special tissue, we have only begun to find out, although we are confident that the general picture will follow the sketch of François Jacob (b. 1920) and Monod's concept of the **operon**, that is, that the activity of some genes results in a product in the cell while the job of other genes is to switch those genes on or off. Peering today into the molecular machinery within cells is like staring at the spaceship of an advanced, alien civilization, except that this is more amazing because it all fits into the size of a pinpoint. Just as Descartes and Boyle expected, life turns out to be an automaton, made up of gears and gates and conveyor belts, moving parts stitched together out of atoms, more intricate and wonderful than any human engineer could ever have designed. Just as Paley expected, it is a factory with the capability of reproducing itself, and molecular biology is well on the way to spelling out exactly how.

The epigenecists were of course right—that all visible organisms are formed anew. They do not grow from miniatures, but from a cell containing something analogous to knowledge, giving something like instructions to the various cells that divide from the fertilized egg. But the preformationists were right also, because the egg arose by cell division, from a long line of virtually immortal ancestors. Remak's insight, that all cells come from previous cells, is more important than ever. Is Darwinian evolution, which depends on occasional small differences from parent to offspring, up to the task of explaining the complexity that molecular biology is uncovering?

The answer lies in the future. With only a few interesting exceptions, most evolutionary biologists have been focusing their attention on large, multicellular creatures, such as birds, flowering plants, mammals, dinosaurs, and clams. Ernst Haeckel thought about the trunk of the great **phylogenetic** tree from which multicellular forms must have

\* **Cytoplasm.** The interior environment of a cell, excluding the cellular structures (organelles).

\* **Operon.** A functional unit made up of a number of adjacent genes on a chromosome. Operons are switched on and off as an integrated unit.

➤ **Phylogeny.** See *Anatomy and Physiology: Nineteenth Century*.

\* Nucleated cell. A cell that has a nucleus.

\* Organelle. Any part of a cell that has a certain function: for example, the nucleus.

come, and pointed to the rich variety of single-celled protists, algae, and fungi, but the natural history of nonparasitic bacteria began to be studied only in the twentieth century (see Figure 5). The idea that bacterial symbiosis was responsible for the evolution of nucleated cells, which at first seemed fantastic, began to seem more and more likely. When, in the second half of the nineteenth century, it was shown that lichen consist of algal cells cohabiting with fungus, the phenomenon of symbiosis—two kinds of organism combining for mutual advantage—was considered an oddity. In 1927, the maverick American Ivan Wallin (1883–1969) proposed that organelles crucial to the life of

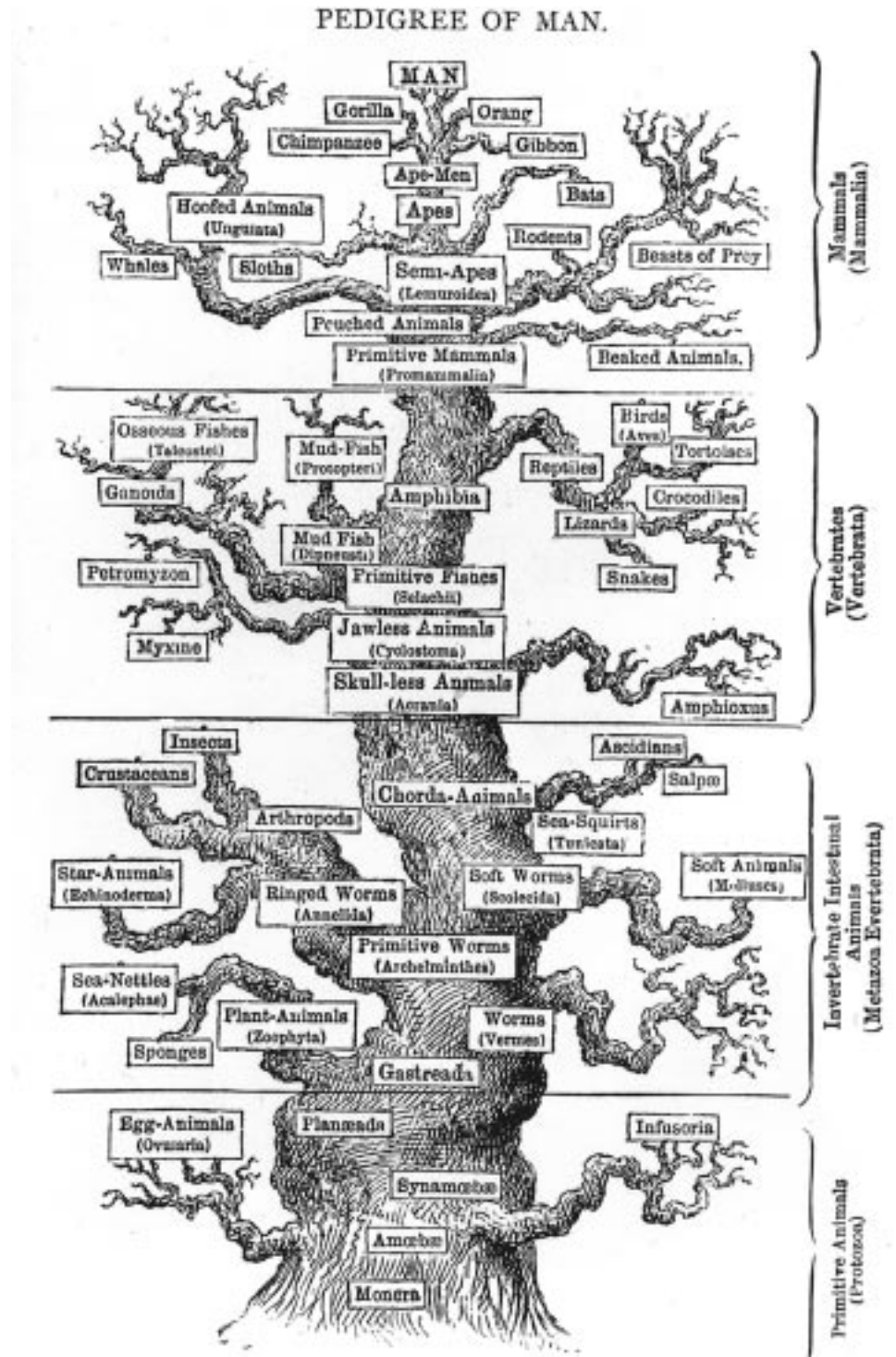


Figure 5. The tree of life. From Ernst Haeckel, *The Evolution of Man* (New York, 1879). Courtesy of the Thomas Fisher Rare Book Library, University of Toronto.

Date	Astronomy and Cosmology	Chemistry	Earth Sciences	Life Sciences
1942	Grote Reber makes the first radio maps of the universe.			
1943				
1944				Oswald T. Avery finds evidence indicating that DNA carries genetic properties.
1945				Karl Landsteiner's first study of chemical specificity in immunology is published.
1946				
1947			Willard Frank Libby develops carbon-14 dating.	Frisch shows that bees exploit the polarization of light for orientation.  Tatum and Joshua Lederberg discover genetic recombination in the bacterium <i>Escherichia coli</i> .
1948	Hermann Bondi, Thomas Gold, and Fred Hoyle develop the steady-state theory of the cosmos.  George Gamow and Robert Herman advance the Big Bang theory.			
1949	Fred L. Whipple suggests that comets are made of ice and rock dust.	Dorothy Crowfoot Hodgkin uses an electronic computer to ascertain the structure of an organic chemical.		
1950	Jan Hendrik Oort suggests that comets are caused by a cloud of material orbiting the Sun beyond the orbit of Pluto.		The first computer-assisted weather predictions are made by John von Neumann and a team of meteorologists.	Embryo transplants for cattle are carried out for the first time.
1951	A computer is used to calculate the planetary orbits of the five outer planets.			
1952	Martin Schwarzschild studies the evolution of stars.			Alfred Day Hershey and Martha Chase show, on the basis of their bacteriophage research, that DNA alone carries genetic information.

Mathematics	Physics	Technology	Culture
	Fermi makes the first controlled nuclear chain reaction. The Manhattan Project is launched.		
	Shin'ichirō Tomonaga develops quantum electrodynamics.	The first nuclear reactor is activated at Oak Ridge, Tennessee. The first electronic calculating device is constructed by Turing.	
		A quartz-crystal clock is installed at Greenwich Royal Observatory.	
		Arthur C. Clarke proposes the idea of communications satellites.	The first thermonuclear fission bomb is exploded at Alamogordo in the New Mexico desert. Hiroshima is bombed with a nuclear fission bomb on August 6. Nagasaki is bombed with a nuclear fission bomb on August 9.
		J. Presper Eckert and John W. Mauchley finish ENIAC, the first electronic computer.	
	Dennis Gabor elaborates the essential idea of holography.		The first supersonic flight takes place.
	Richard P. Feynman, Julian Seymour Schwinger, and Tomonaga develop quantum electrodynamics. The atomic clock is introduced. The transistor is invented by William B. Shockley, Walter H. Brattain, and John Bardeen.	Norbert Wiener elaborates his idea for a field of study to be called <i>cybernetics</i> .	
Claude Shannon advances his work on information theory.			
		The field ion microscope is developed.	
		Donald A. Glaser develops the bubble chamber to observe the behavior of subatomic particles, rendering the cloud chamber obsolete.	The first hydrogen bomb, Mike, is detonated. A polio epidemic affects many thousands of people in North America.