THE ILLUSTRATED FIVE KINGDOMS

A Guide to the Diversity of Life on Earth

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Kathryn Delisle and Christie Lyons

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Cover illustration
A = African tree pangolin, *Manis tricuspis*; **B** = American elm, *Ulmus americana*; **C** = fly agaric, *Amanita muscaria*; **D** = velvet worm, *Peripatus*; **E** = cyanobacterium, *Anabaena*; **F** = colon bacterium, *Escherichia coli*; **G** = anaerobic phototrophic bacterium, *Chromatium*; **H** = bladder kelp, *Nereocystis*; **J** = chambered nautilus, *Nautilus pompilius*.

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by Lynn Margulis, Karlene Schwartz, and Michael Dolan

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THE ILLUSTRATED FIVE KINGDOMS

Dedicated to the memory of Professor HEINZ A. LOWENSTAM (1912–1993), beloved teacher, natural historian, geologist, marine biologist and founder of the field of biomineralization

Note to the Reader

As we burn rain forests for farm space, ranchland, and hardwood, as we drain ponds and level hills to accommodate housing projects and shopping malls, we encroach on the lives and living space of the other organisms with whom we share this planet. We are clearing out our planetmates faster than we are learning about them. The relentless increase of human beings at the cost of other organisms has inspired many eloquent scientists and concerned citizens to put the study of biodiversity—different kinds of life—high on the social agenda. The small guide you hold in your hands outlines the basics of biodiversity. To introduce the reader to the diminishing life on Earth, we have selected at least one member of each of the largest groupings, or phyla, of the five kingdoms and depicted it with the other members of its living community.

Designed for teachers and students, as well as the interested public, the book's spiral binding makes production of multiple copies for coloring or labeling easy. Because descriptions are subject to differing opinions and change as new information becomes available, no names or labels appear on the full-size illustrations. A reduced, labeled copy of each drawing accompanies the text that describes the organisms in their habitat. The genus (which comes first but is more like our family name) and species (second, but more like our personal name) of most organisms, as well as explanatory information, are provided. A complete list of species, genera, and phyla illustrated in this book appears in the Appendix, beginning on page 165. Members of some of the most abundant and familiar phyla (such as the molluscs, chordates, and angiosperms) are represented more than once.

Contents

Introduction

Biodiversity: All of Life

Although full of astounding beings, much of life on Earth remains a mystery. This guide introduces many unfamiliar organisms and describes many familiar ones. Through illustrations that show examples from each of the phyla, the full range of living beings is discussed. This book is a primer in biodiversity.

Unlike other books on biodiversity, this work places each organism in its habitat, i.e., its natural environmental context. From photosynthetic bacteria to amebas and slime molds, from horsetails to tube worms and velvet worms, each being is depicted in its own surroundings, which includes other members of its community. In the context of natural history, ecological, taxonomic, and structural information are presented together.

We tend to take for granted the live organisms that do not belong to our species, even though they include all of those upon whom we depend for life. Our food, shelter, and pharmaceuticals come from other living beings. Furthermore, coal and petroleum products, including gasoline, plastics, and motor oil, all come from traces of bygone that were left on Earth's surface when great algal crusts or giant forests died and were buried before they could decay entirely. Although no one knows for sure, it is estimated that there are roughly thirty million species of organisms in total, of which more than 99.9% are extinct. Most present-day species are insects or other arthropods. As many as 100,000 species of fungi and 250,000 species of protoctists are estimated to exist. There may be between 250,000 and 500,000 species of plants, but since most are in the tropics where they are least studied, no one knows for certain. As for bacteria, the biological literature lists some 10,000 different types, but most are probably still unknown.

Autopoiesis, or What Is Life?

All living beings share certain characteristics: They are composed of cells bounded by membranes composed of proteins and lipids (fatty substances). Inside the cells are biochemicals, including several thousand genes (stretches of DNA) and proteins (stretches of linked amino acids). DNA is made of small molecules hooked together in a sequence that determines the order of the amino acids in proteins. These intracellular materials actually produce the membranes, proteins, and nucleic acids that make up the cells. Thus, cells are self-making and self-maintaining. External sources of energy and nutrients provide the raw materials for the components of cells to repair their parts and make more of themselves. This process of self-maintenance and growth, a property of all live beings, is called autopoiesis.

The word used to refer to the sum of the chemical transformations that underlie the autopoietic processes is metabolism. Dead bodies, which may at first have the same composition as their live counterparts, do not metabolize; by contrast, all live organisms metabolize. Metabolism involves the exchange of gases, chemical compounds, and other materials and energy with the surroundings. Eventually cells that have grown large may reproduce. The reproduction of cells is based on the replication, or copying, of their nucleic acid molecules: DNA and RNA. Replication is a property of molecules (DNA can copy itself in a test tube); reproduction is a property of life. Although DNA and RNA molecules can replicate, nothing less complex than a cell or organism composed of cells can reproduce.

Viruses

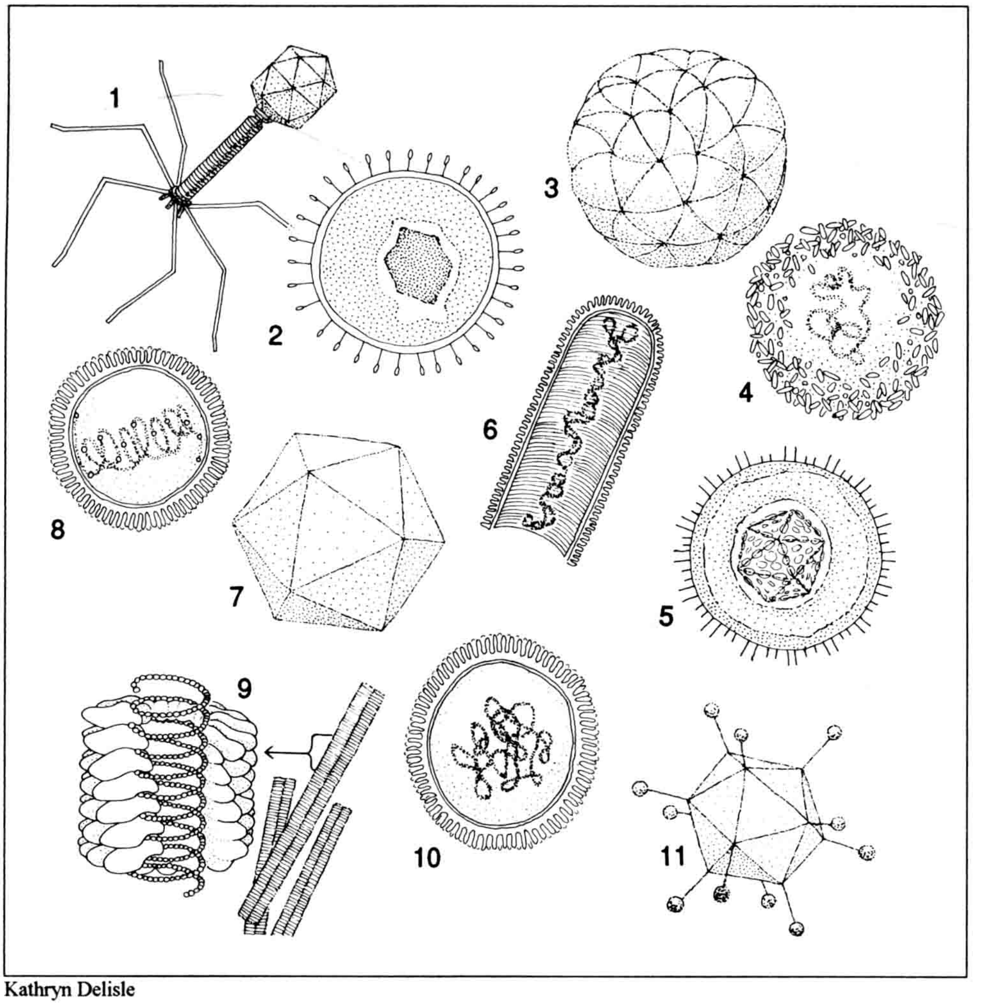
Viruses, which are much smaller and much less complex than cells, are not autopoietic. If fed, watered, and supplied with chemical or light energy, they still cannot metabolize. Viruses can replicate but cannot reproduce on their own. Even replication of viruses requires that they enter actively metabolizing cells. All members of the five kingdoms are composed either of prokaryotic (nonnucleated) cells (i.e., bacteria) or eukaryotic (nucleated) cells (i.e., protoctists, fungi, animals, and plants). Because they are not cellular entities, viruses do not belong to any of the five kingdoms of organisms. Alternatively, viruses may be thought of as inanimate parts of the cells that they infect and hence can be classified with these cells. Some viruses are depicted in Figure 1.

How Many Species Are There?

We estimate that there are more than thirty million known species, of which most are arthropods (the animal phylum to which all insects belong) or nematodes. Many thousands more species await discovery. Probably 99% of living microorganisms still are not known to science.

Cells and Movement: Flagella and Undulipodia

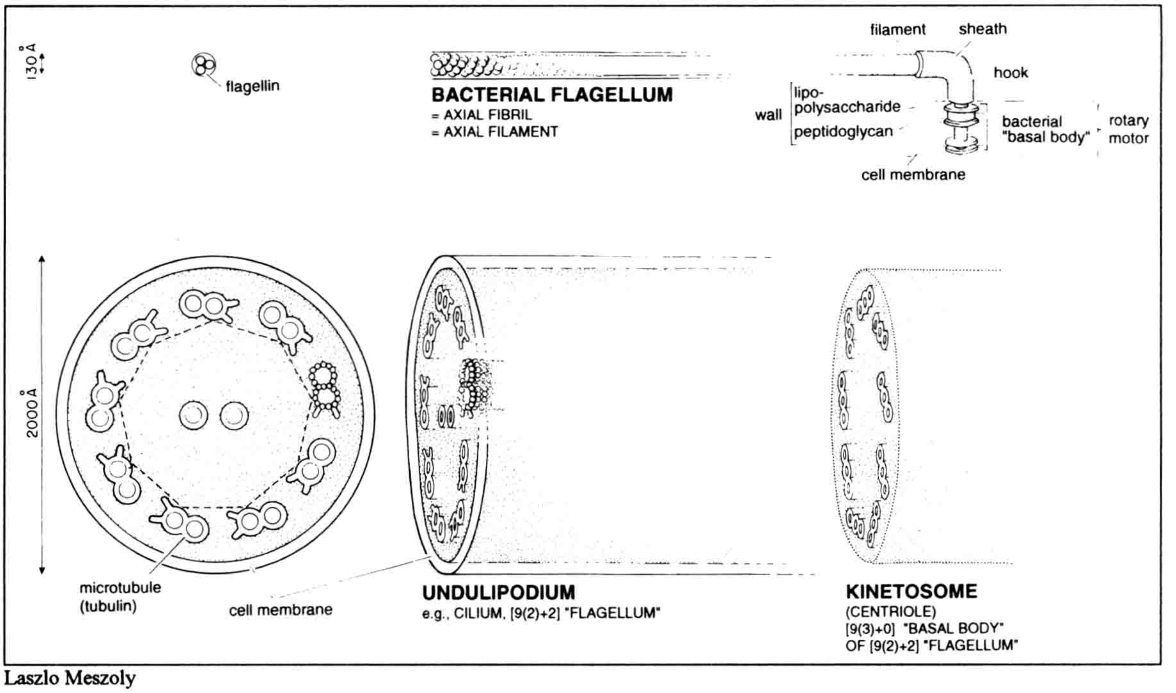
The parts of cells move. Whether the cell is prokaryotic (bacterial) or eukaryotic, its components bounce around by random jiggling called Brownian motion. In addition, bacterial cells may glide slowly if attached to a surface (by an unknown mechanism) or may swim using their rotary motor flagella (Figure 2).



Kathryn Delisle

Figure 1
Viruses are particles of DNA or RNA enclosed in a protein coat. Because they are not made of cells, viruses are not considered to be living organisms. Although they reproduce, they can do so only by entering a cell and using its living machinery to replicate themselves. Outside of the cell a virus cannot reproduce, feed, or grow. The viruses pictured here are (1) bacteriophage, (2) human immunodeficiency virus (HIV), (3) polio virus, (4) pox virus, (5) herpes virus, (6) rhabdovirus, (7) picorna virus, (8) orthomyxovirus, (9) tobacco mosaic virus (TMV), in cross section (left) and whole (right), (10) paramyxovirus, and (11) adenotype 2 virus.

Bacterial cells divide by direct division, a process called binary fission. Although eukaryotic cells also divide in two, they do not do so directly: They divide by mitosis. During many mitotic cell divisions, at the ends (poles) of the cells are two or four dotlike bodies that, magnified, show a characteristic structure of arrayed microtubules: nine triplet tubules in a cylindrical pattern. The dotlike bodies are centrioles. The centriole structure of nine groups of three microtubules each and no central microtubules is called the [9(3)+0] array. Eukaryotic cells swim using wavy structures, cilia, or other kinds of undulipodia. These



Laszlo Meszoly

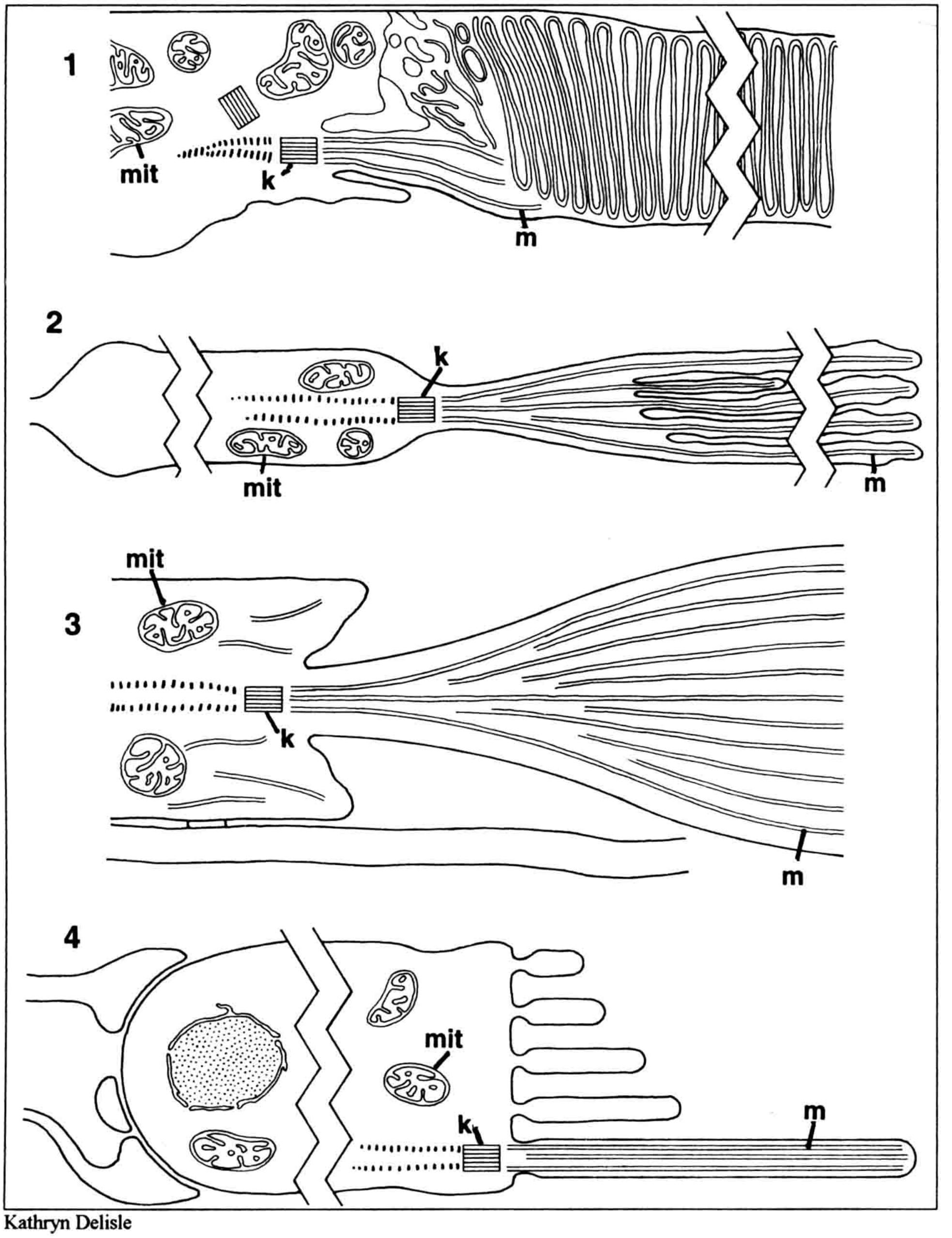
Figure 2
Although both move the organism through its environment, prokaryotic flagella (top) and eukaryotic undulipodia (bottom) differ fundamentally in structure.

undulipodia—whether oviduct cilia, sperm tails, or amebomastigote undulipodia—show the same pattern in cross section under an electron microscope. The underlying kinetosome is identical to the centriole, but the shaft, with its nine groups of two fused microtubules each, surrounding two separate central microtubules, has a slightly different array (see Figure 2).

Undulipodial shafts have [9(2)+2] cross sections made of longitudinally aligned microtubules. All undulipodia are underlain by kinetosomes (Figure 3), basal structures from which they grow. Undulipodia are modified to make a fantastic variety of functional structures, including the sensory hairs of lobster antennules and the cilia of the gills of marine animals. The term used to describe mitotic centrioles and cilia basal bodies is centriole-kinetosome. Centriole-kinetosomes, undulipodia, mitosis, and [9(2)+2] arrays are entirely absent in prokaryotes—i.e., they do not occur in members of the kingdom Monera. Although microtubules and mitosis are present in fungi, centriole-kinetosomes and undulipodia are always absent.

Because of the confusion surrounding the names of these structures, we define them as follows:

Flagella (Greek: "whip"), s. **flagellum.** Solid bacterial organelles of motility composed of flagellin, intrinsically nonmotile. Rotary locomotion is generated at the points of insertion of organelle into the cell. Flagella



Kathryn Delisle

Figure 3
Four general types of animal sensory cells based on cilia (a type of undulipodium). All contain modified undulipodia with microtubules. (1) Rod cell of the eye (vision). (2) Olfactory cell (smell). (3) Mechanoreceptor cell (touch). (4) Inner-ear cell (hearing). **k** = kinetosome; **m** = microtubule; **mit** = mitochondrion; zig-zags represent omissions in long structures.

are extracellular in that they always extend externally beyond the plasma membrane of the prokaryotic cell. Diameter: 15 to 30 nanometers. Includes the axial filaments or axial fibrils of spirochetes. In these latter microbes the flagella are situated in the periplasm, the space between the outer and the inner (plasma) lipoprotein membranes of the Gram-negative cell wall.

Undulipodia (from Latin: *undula,* "a little wave," and Greek: *podos,* "foot": "little waving feet"), **s. undulipodium.** Cilia and [9(2)+2] flagella: Long slender tubulin-containing intracellular organelles of motility of eukaryotes, intrinsically motile throughout their length, capable of movement when severed from the cell. Diameter: 0.25 micrometer (250 nanometers). The axoneme is the [9(2)+2] shaft of the undulipodium; i.e., it is the undulipodium lacking its surrounding membrane.

Many biologists retain "flagellum" and "basal body" for the ninefold symmetrical microtubular motility organelles of eukaryotes. We suspect that they are reluctant to change because they do not generally confront bacteriologists. In the past the term flagellum has referred both to the undulipodium/cilium found in animals, plant sperm, and many protoctists, as well as to the rotating bacterial organelle. This ambiguous use of the term has led to confusion, which, by using different terms, we avoid in this book.

Modes of Nutrition: Autotrophy and Heterotrophy

The existence of photosynthetic animals such as *Convoluta roscoffensis* and heterotrophic plants such as Indian pipes (*Monotropa*) makes clear that nutritional mode alone cannot be used to define the highest taxa. Indeed, microbes display a remarkable diversity of nutritional modes (Table 1). With the exceptions of photoheterotrophy and chemotrophy, every nutritional mode is represented among the protoctists.

Photoheterotrophs use organic compounds as food sources while simultaneously employing visible light to generate ATP directly, whereas chemoautotrophs can use exclusively carbon dioxide and other inorganic compounds as sources of carbon and energy. In strict chemoautotrophy (e.g., methanogenesis, methylotrophy, ammonia oxidation, sulfide oxidation, and the like), neither the source of carbon nor the source of energy is from carbon–hydrogen (organic) compounds. These two metabolic modes—photoheterotrophy and chemoautotrophy—are found only in bacteria. Thus, although they display a greater range of nutritional types than do plants, fungi, or animals, protoctists are far more limited in energy- and nutrient-gathering capability than are bacteria. Bacteria are by far the most nutritionally diverse organisms; photosynthesis and motile heterotrophy evolved in them.

All five kingdoms include organisms that exhibit biomineralization—the production of minerals by live cells and the incorporation of those minerals into their bodies or protective coverings (Table 2).

MODE/EXAMPLE	ENERGY SOURCE	CARBON SOURCE
Autotrophy		
Plants, algae, and cyanobacteria	Light	Atmospheric CO_2
Sulfide-, methane-, and ammonia-oxidizing bacteria	Inorganic compounds (H_2S, CH_4, and NH_3)	Atmospheric CO_2
Heterotrophy		
Fungi, protoctists (ciliates, mastigotes, slime nets, etc.) and animals (molluscs, hydras, fish)	Organic compounds (C, H, N, O)	Organic compounds (C, H, N, O)

Table 1: Modes of Nutrition
Organisms have evolved various ways of obtaining energy and carbon—the two requirements for growth and reproduction.

Reproduction or Sex

At least some organisms from each of the five kingdoms reproduce directly—i.e., the offspring have only one parent. Generally referred to as asexual reproduction, this process is better called simply reproduction. Reproduction is defined as any process in which the number of living beings increase. When we are wounded, our cells reproduce by mitotic division, and at least some members of most animal groups make new multicellular individuals directly from one parent (e.g., sponge gemmae, hydra buds, and coral strobili). All members of the moneran, protoctist, and fungal kingdoms reproduce by propagules that are produced by a single parent (i.e., asexuality is the norm). Animals, however, which develop from embryos formed by a sexual act (fertilization of an egg by sperm), and plants, which grow after an egg nucleus is fertilized by a sperm or pollen nucleus, are sexual.

Sexuality is entirely different from reproduction, in principle, even though the two are intertwined in the most familiar organisms: mammals and flowering plants. In biology, sex or sexuality is the formation of a new organism from more than a single genetic source, usually from the genes of two parents. Therefore, an individual who has developed from a sexual event has two biological parents rather than one. By definition, then, sex begins with two sources of DNA (the genes of the two parents) and results in the formation of a new individual (called a recombinant individual) with genes from both sources.

Bacteria engage in a peculiar form of sex in which they inject their genes into each other. Any bacterium that has its own genes and receives other genes from a fellow bacterium is, by definition, the product of a sexual event, even though the cells do not fuse. (Only the DNA molecules pass from cell to cell.) The contact of bacterial cells followed by the one-way injection of genes from donor to recipient is called conjugation, or bacterial mating. Cell fusion is limited