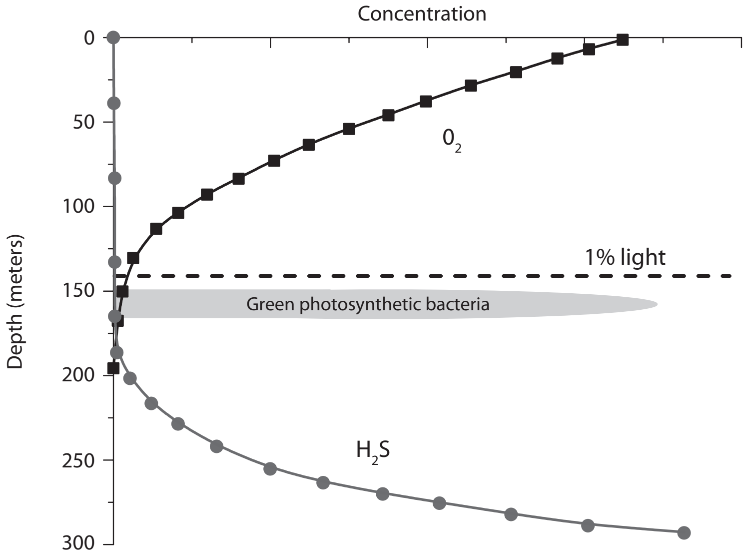

FIGURE 1. An idealized profile of dissolved oxygen and hydrogen sulfide gas (which smells like rotten eggs) in the upper 300 meters of the Black Sea. This body of water is unique in the ocean; in most ocean basins and seas, oxygen is detectable to the seafloor. Just below the depth at which 1% of the sunlight from the surface remains, there is a very narrow layer of photosynthetic bacteria that split the hydrogen sulfide with energy from the Sun, for their own growth. The metabolism of these organisms is extremely old; it probably evolved more than three billion years ago, when oxygen concentrations on the Earth's surface were extremely low.

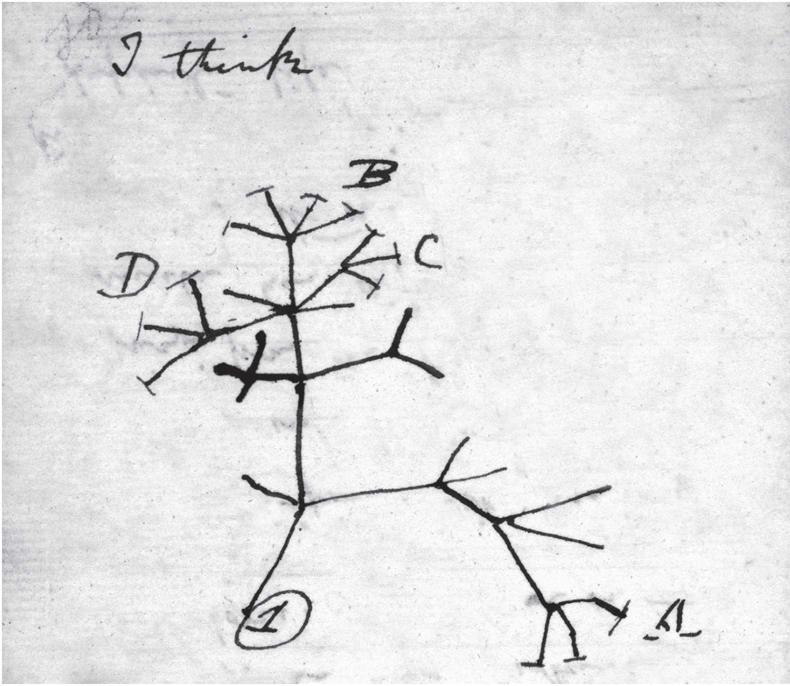

FIGURE 2. A reproduction of the doodle that Darwin sketched in Notebook B between 1837 and 1838. The basic idea is that extant species are descended from extinct species but are also related to other extant species to form a historical tree of life. This doodle was the kernel for the theory of descent with modification followed by selection—the core of Darwinian evolution. (With permission from Cambridge University Press and thanks to Peter and Rosemary Grant. Copyright © 2008 The Committee for the Publication of Charles Darwin's Notebooks.)

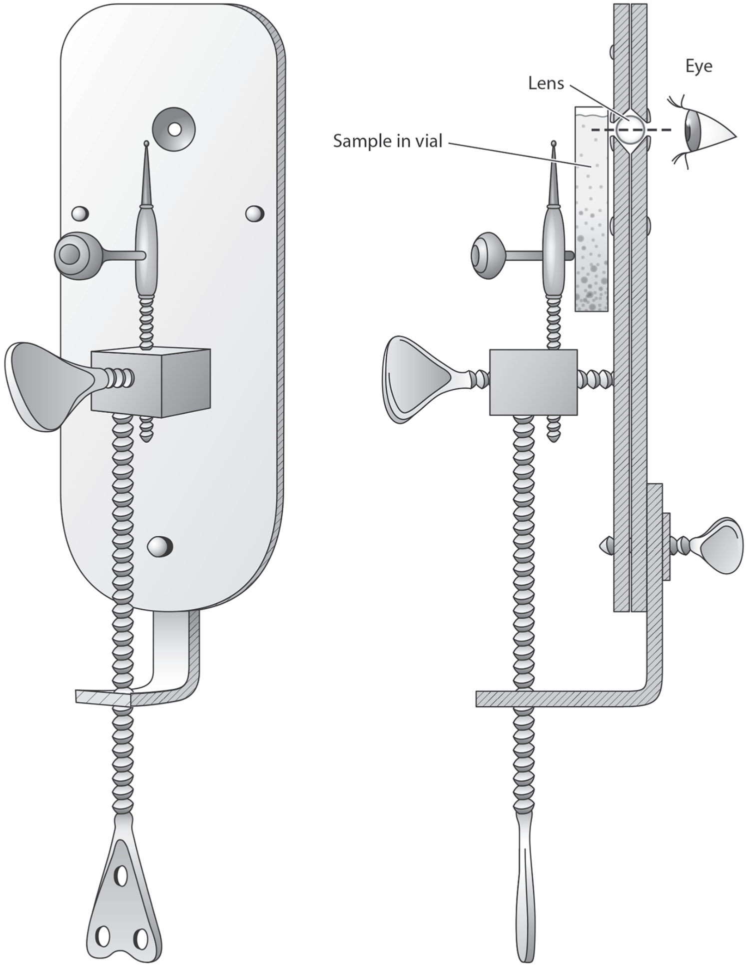

FIGURE 5. An illustration of the type of microscope invented and used by Anton van Leeuwenhoek. The single spherical lens was placed in a small hole between two plates. The sample was held close to the lens with a small screw, and the observer placed his eye close to the lens and held the microscope up the light. Despite its simplicity, this type of microscope could magnify up to 400 times, depending on the quality and size of the lens.

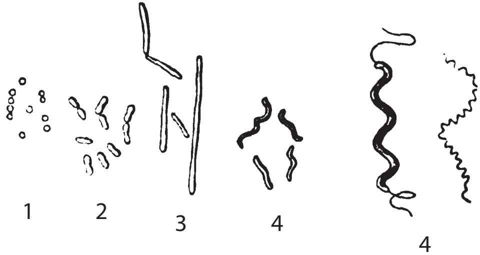

Figure 7. Illustration of the shapes of microbes described by Ferdinand Cohn in his treatise *Über Bakterien: Die Kleinsten Lebenden Wesen*, published in 1875. He characterized these organisms as related to algae and plants and assigned them to four families by shape: 1. the Spherobacteria (spherical bacteria); 2. the Microbacteria (short rods); 3. the Desmobacteria (straight filaments); and 4. the Spirobacteria (spiral filaments). This basic, simple system of descriptive classification was useful and persists to the present time.

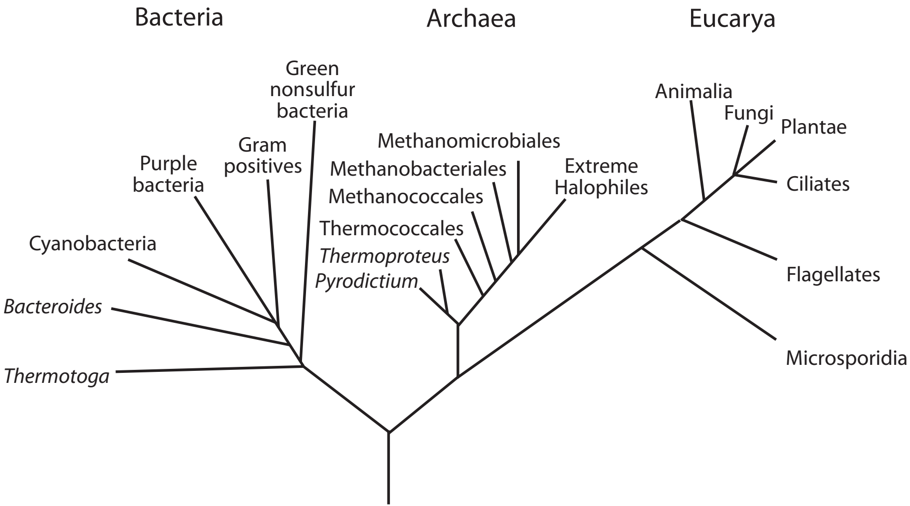

FIGURE 8. Carl Woese and George Fox's tree of life relates living organisms to each other based on ribosomal RNA sequences. Woese and Fox discovered that the bacteria are actually two super families of distinctly different organisms, Bacteria and the Archaea. Furthermore, animals and plants are subgroups within a larger family of eukaryotes, Eucarya. The vast majority of organisms in this tree of life are microbial.

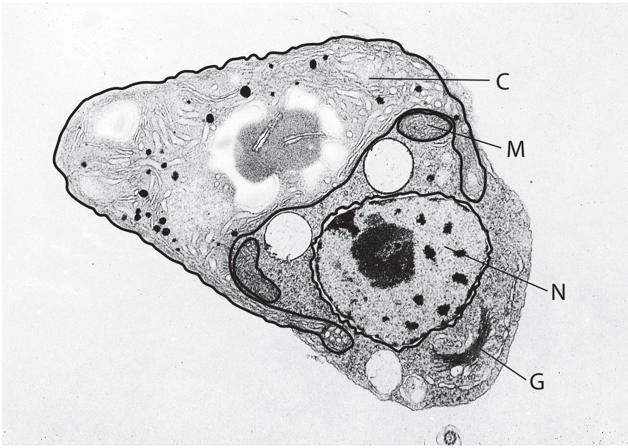

FIGURE 9. An electron micrograph of a thin section of a green algal cell. This organism is a eukaryote (see Fig. 8), and like all eukaryotes, contains several internal organelles that are bound by membranes. In this algal cell, the organelles include a chloroplast (C), mitochondria (M), a nucleus (N), and a Golgi apparatus (G). (Original photomicrograph by Myron Ledbetter and Paul Falkowski)

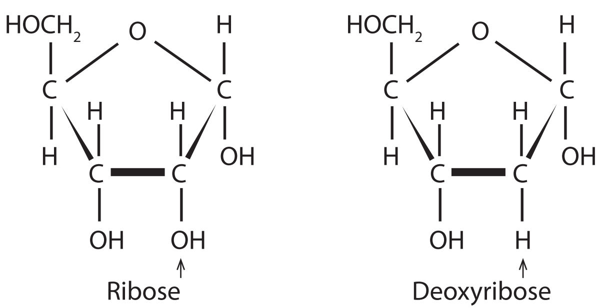

FIGURE 10. A diagram of the structures of ribose and deoxyribose. The former is found in ribonucleic acids (RNA) the latter is in deoxyribonucleic acid (DNA).

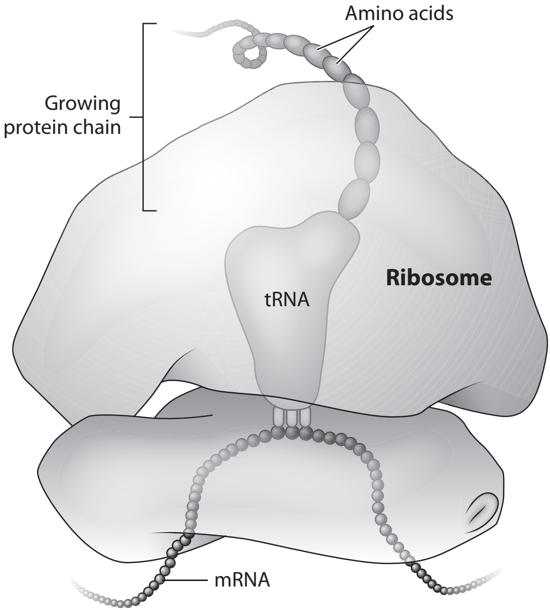

FIGURE 11. A cartoon showing the basic function of a ribosome. This nanomachine makes proteins using a template of information originally encoded in DNA and transcribed by a messenger RNA molecule. The messenger RNA molecule provides the information for the sequence of amino acids for a specific protein; each protein in a cell has a specific messenger RNA. The ribosome, which also contains RNA but is organized into a larger structure with many proteins, "reads" the information from the messenger RNA and uses a third RNA molecule with a specific amino acid attached (transfer RNA) to build up the protein one amino acid at a time. The protein emerges from the ribosome to finds its proper place within the cell.

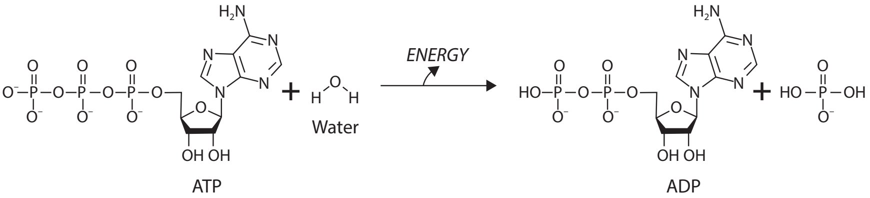

FIGURE 13. The basic currency of biological energy across the tree of life is adenosine triphosphate (ATP). When ATP is combined with water in enzymes, a phosphate group can be cleaved from the molecule to form adenosine diphosphate (ADP) and inorganic phosphate. That reaction releases the energy that all cells use for life.

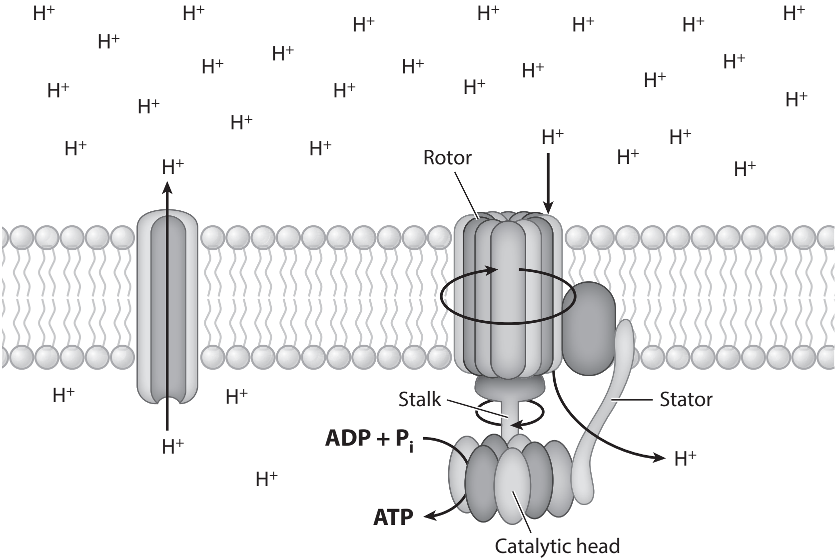

FIGURE 14. Adenosine triphosphate is made in cells by generating gradients of electrical charge across a membrane. In many cells and in two organelles, the mitochondrion and the chloroplast, the charge gradient is created by a proton gradient—that is, more protons (hydrogen ions) on one side of a membrane than the other. As the protons are funneled through a coupling factor embedded within the membrane, ATP can be made (see Fig. 15).

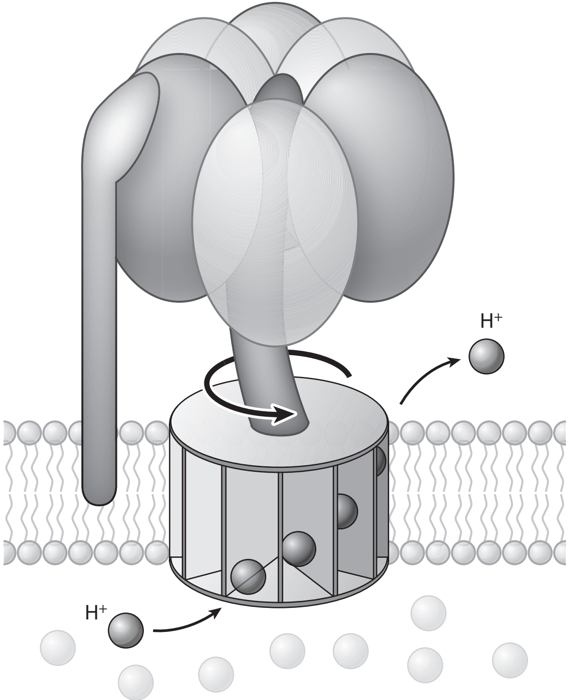

FIGURE 15. A cartoon showing the basic mechanism by which a coupling factor generates ATP from the flow of protons. The protons pass through a stalk in the membrane; as they do so, the stalk physically turns, and the head of the nanomachine, which is on the opposite side of the membrane, oscillates. The physical oscillation allows ADP and inorganic phosphate (see Fig. 13) to attach to the head group, where they are chemically bonded to form ATP.

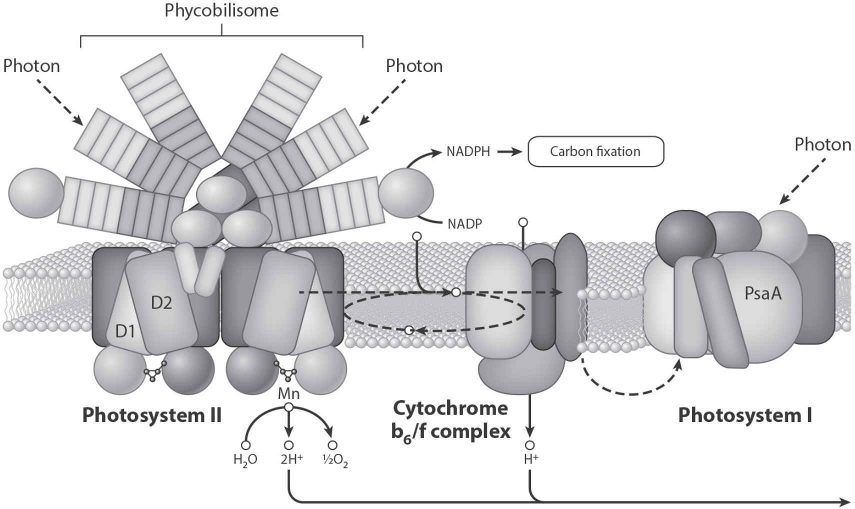

FIGURE 16. A schematic illustration of a reaction center in oxygen-evolving organisms. This is the only biological nanomachine capable of splitting water. It is composed of many proteins, and its primary role is to use the energy of the Sun to split water into oxygen, hydrogen ions, and electrons. The structure is embedded within a membrane, and the hydrogen ions from the water-splitting reaction are deposited on one side of the membrane. They flow through the coupling factor (Fig. 15) to generate ATP and eventually meet up with the electron on the other side of the membrane.

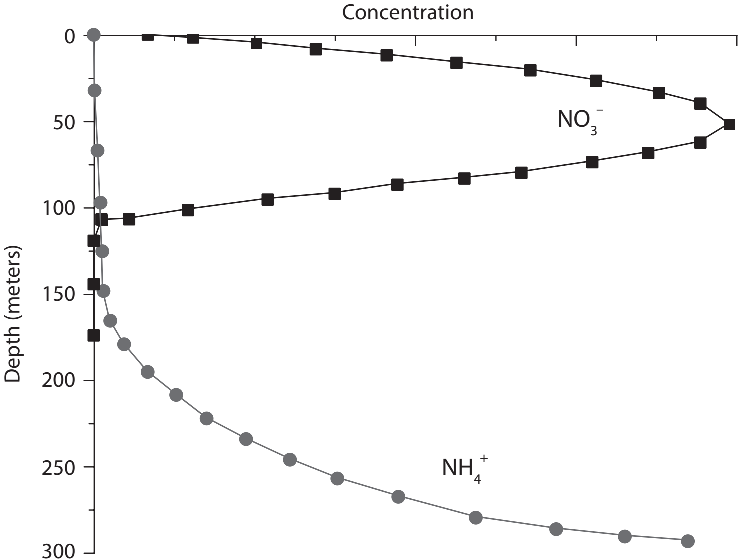

FIGURE 20. A vertical profile of the distribution of two forms of nitrogen, nitrate (NO_3), and ammonium (NH_4), in the Black Sea. Note that where oxygen becomes vanishingly low (Fig. 1), those forms of nitrogen also become extremely scarce.

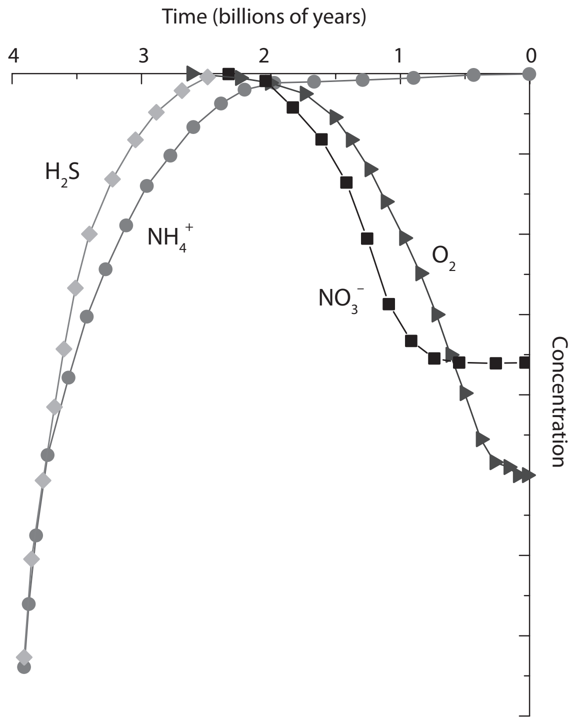

FIGURE 21. By turning the vertical profiles of oxygen, nitrogen, and hydrogen sulfide on its side, one can imagine the progression of how the chemistry of the ocean changed prior to the Great Oxidation Event, ~2.4 billion years ago, and after the oxygenation of the atmosphere and ocean.

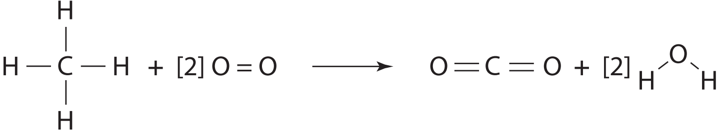

FIGURE 22. A schematic showing the difference between methane (CH_4) and carbon dioxide (CO_2). Both of these molecules are invisible, odorless gases. In the presence of oxygen, methane is converted to CO_2 and water in the atmosphere and by microbes.

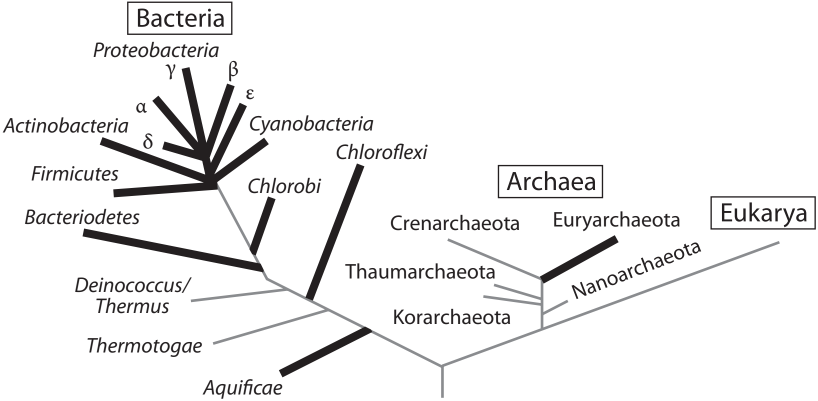

FIGURE 24. A distribution of nitrogenase genes across the tree of life. Note that pattern of the distribution does not follow that of descent from a common ancestor but, rather, is not easily predictable. The genes (and many others) were acquired by horizontal gene transfer between bacteria and between bacteria and archaeans. The genes for nitrogen fixation have never been found in the genomes of eukaryotic cells. (Courtesy of Eric Boyd)

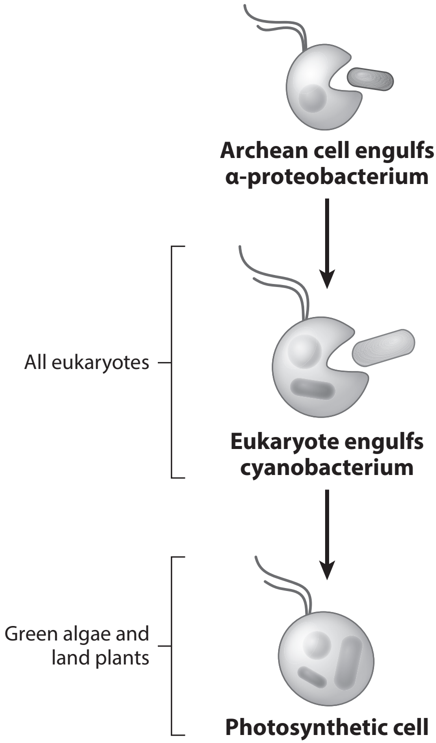

FIGURE 27. A schematic showing the two basic endosymbiotic events that led to the formation of eukaryotic cells. In the first event, the host cell (an archaean), engulfed a purple nonsulfur bacterium, which possibly was photosynthetic. The bacterium would evolve much later to become a mitochondrion. In the second event, a cell containing the protomitochondrion engulfed a cyanobacterium. The cyanobacterium would later evolve to become a chloroplast. These two primary symbiotic events are the basis of the evolution of microscopic organisms, such as green algae (Fig. 9), that were prevalent in the oceans long before the evolution of animals and plants.

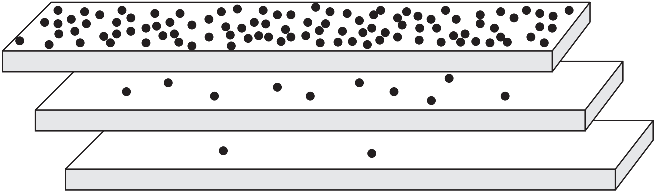

FIGURE 30. The problem of diffusion of oxygen in multicellular animals. Without some circulatory system, oxygen can only be supplied to cells via diffusion. If an animal lives on the seafloor, the only source of oxygen is from the waters above. The oxygen reaching the first layer of cells is depleted by respiration, the second layer receives far less oxygen than the first, and so on. The diffusion of oxygen almost certainly contributed to the evolutionary selection of thin animals in the early Ediacaran Period.

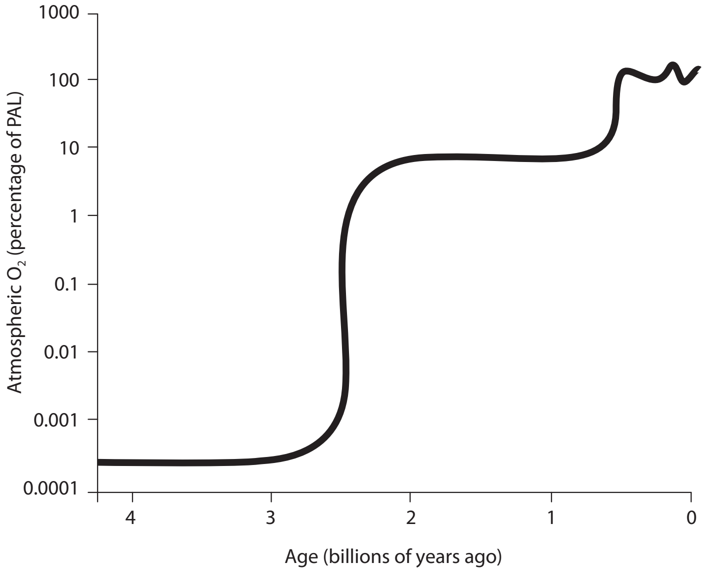

FIGURE 31. An illustration of our present-day reconstruction of oxygen over geological time. Note that the scale for oxygen is logarithmic. Oxygen concentrations during the first half of Earth's history were vanishingly low, on the order of 0.0001% of the present atmospheric level (PAL). The concentration may have risen to approximately 1% of PAL during the Great Oxidation Event, 2.4 billion years ago, and then rose again to approximately 10% during the Ediacaran and Cambrian Periods, about 600 to 500 million years ago. Over the past 500 million years, oxygen concentrations have remained relatively high and relatively stable, varying between approximately 50 and 150% of the present value.

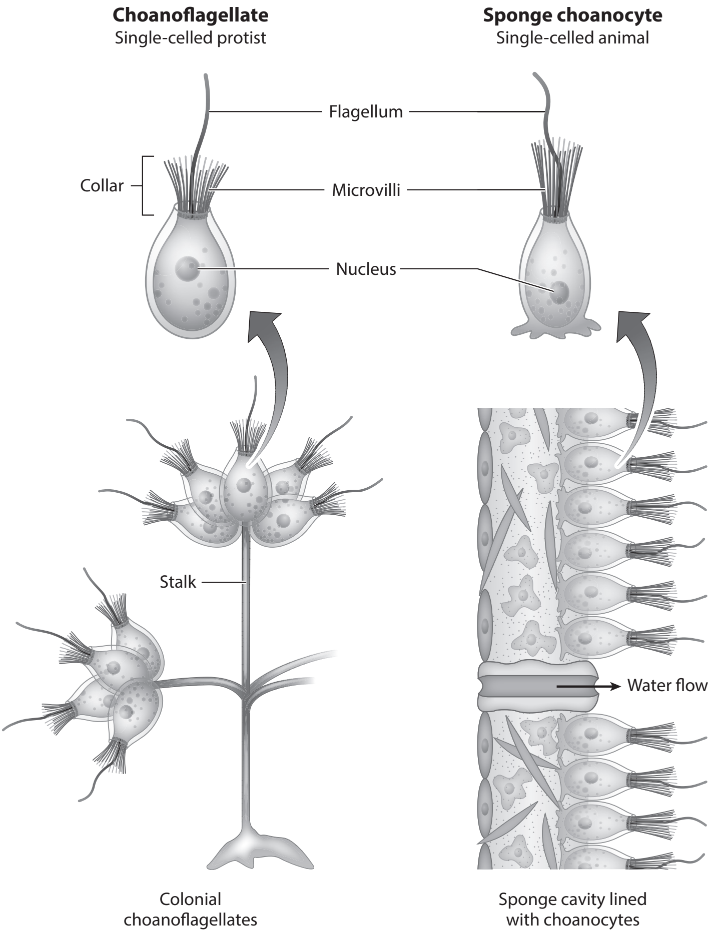

FIGURE 32. Drawings of colonial choanoflagellates (left), showing the flagella they use to push bacteria and other particles into the collar, where they are ingested, and the strikingly similar types of cells, the choanocytes, found in sponges (right).

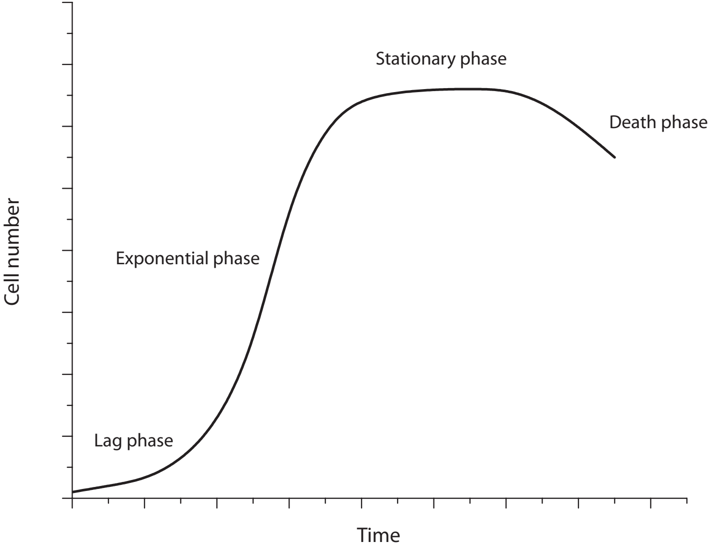

Figure 33. A typical growth curve for microbes. Upon inoculation, the cells undergo a lag phase before beginning to grow exponentially. At some point, a nutrient or other resource (for example, light in the case of algae) becomes limiting and the growth rate declines, eventually stopping. This is the stationary phase. If left for a long period of time without replenishment of nutrients and dilution, the cells will start to die.

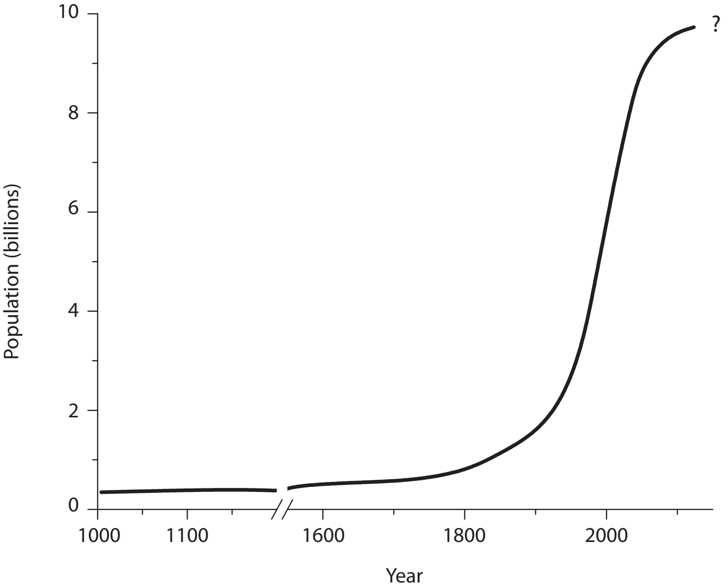

FIGURE 34. A growth curve of the human population since the year 1000 CE. Prior to the Industrial Revolution and the discovery of how to separate sewage from clean drinking water, the human population was relatively constant, analogous to the lag phase in a microbial culture (Fig. 33). From the middle of the nineteenth century, however, the human population has grown exponentially. Demographers estimate that it will plateau in the middle of the twenty-first century at approximately 9.5 to 10 billion people. Compare with Figure 33.

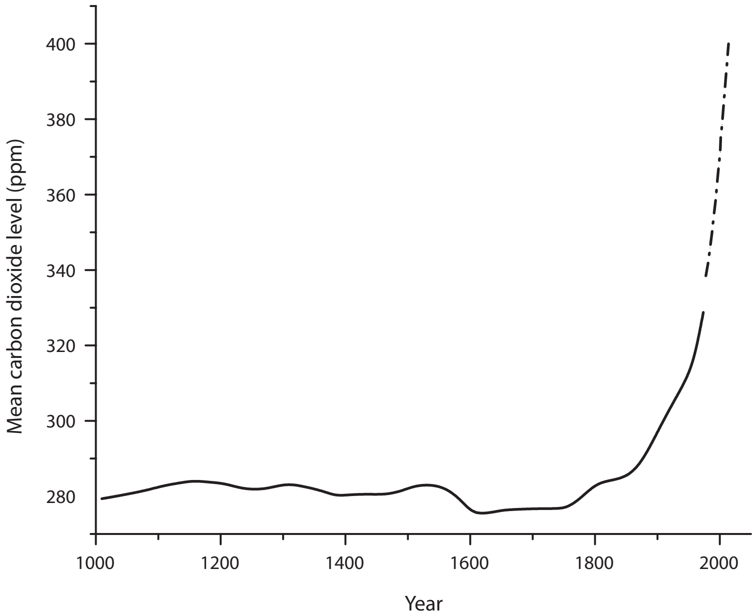

FIGURE 35. The change in concentration of carbon dioxide in Earth's atmosphere since 1000 CE. Until the Industrial Revolution, atmospheric carbon dioxide concentrations were relatively constant at approximately 280 parts per million by volume (i.e., 0.028%, compared with oxygen at 210,000 parts per million, or 21%). Since the Industrial Revolution, the concentration of the gas has risen almost exponentially, and in 2014 reached 400 parts per million. Unlike nitrogen and oxygen, carbon dioxide is a greenhouse gas and traps heat. The relatively small concentration of this gas in Earth's atmosphere is critical to controlling climate. The curve for the change in carbon dioxide is strikingly similar to the growth curve for the human population (Fig. 34).

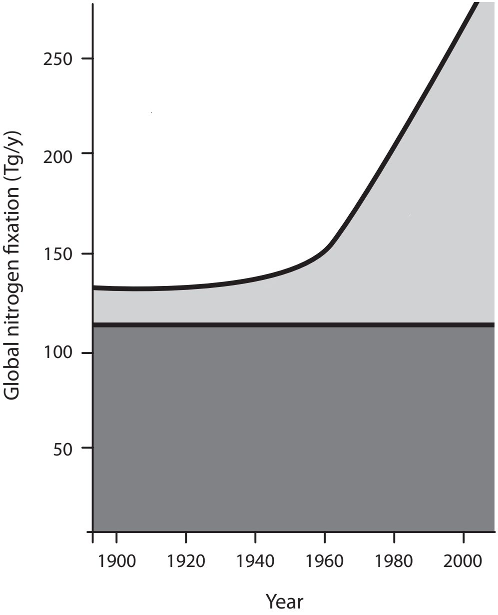

FIGURE 36. The change in the total amount of nitrogen fixed during the past century. Prior to the invention of the Haber-Bosch reaction for fixing nitrogen, all nitrogen was fixed by microbes with a small contribution from lightning. Natural biological nitrogen fixation is approximately 100 teragrams (10^{12} grams) per year (darker area). After the introduction of the Haber-Bosch reaction, human production of fixed nitrogen increased dramatically and presently exceeds natural biological nitrogen fixation by almost a factor of two (lighter area).

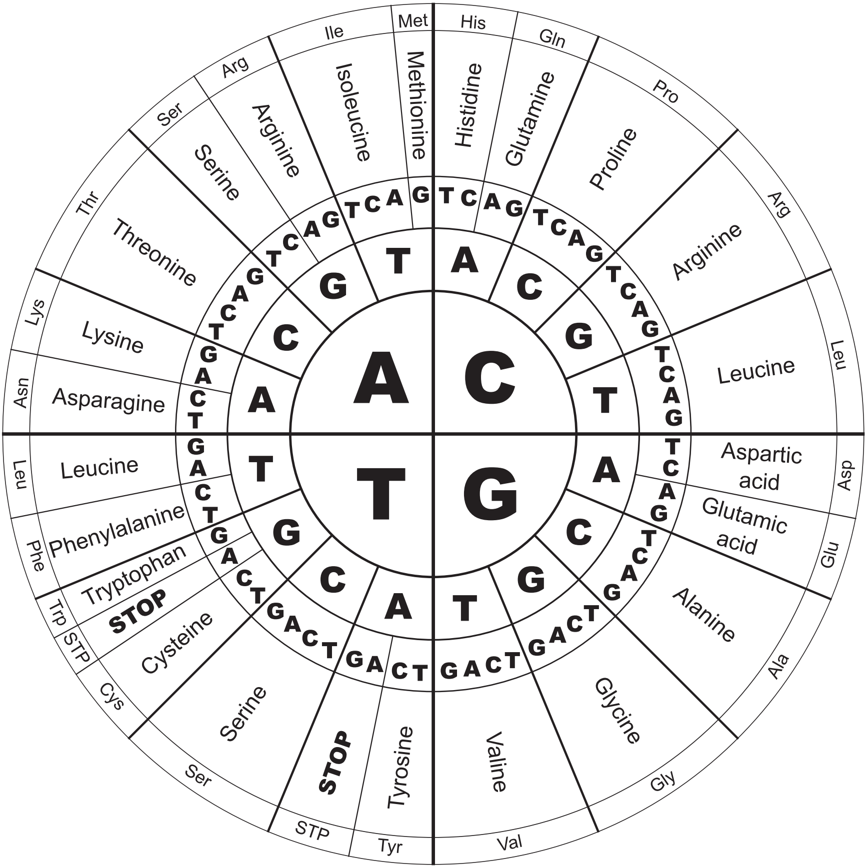

Figure 37. The codon wheel. This is the Rosetta stone of how the individual bases, or nucleotides, in DNA encode for specific amino acids in a protein. The code for each amino acid is contained in a sequence of three nucleotides called a codon. Starting in the center of the wheel and working out, one can determine which amino acid is encoded from the sequence of DNA. For example, a sequence of AGC encodes for the amino acid serine, whereas ACC encodes for threonine. With the exception of methionine and tryptophan, all amino acids have more than one possible codon.