CHAPTER 18

THE APPEARANCE OF OXYGEN

THE ORIGIN OF BIOLOGICAL (ORGANIC) MOLECULES

There are various snippets of evidence by which we think that we can identify the first signs of life on earth. For instance, some types of marine bacteria grow in peculiar large clumps. These clumps are remarkably similar to unusual rock formations, called stromatoliths, found in various fossil rocks (Fig. 18.1). Also, most carbon is tied up in chemical forms such as carbon dioxide (a gas) or calcium carbonate (chalk), with pure carbon being rather difficult to come by in the test tube. Living organisms can decay to combinations of carbon and hydrogen (oil) or to nearly pure carbon (coal), and many investigators believe that deposits of oil or coal indicate earlier life. Furthermore, living organisms carry out some chemical reactions in a decidedly non-chemical way. Since enzymes must fit perfectly around other molecules to assemble them or take them apart (see page 224), a reaction catalyzed by an enzyme can distinguish subtleties that a powdered-metal or clay catalyst cannot. For instance, because of the way that atoms bind to each other, many organic molecules are constrained to specific shapes. Some are constrained to shapes like a left-handed and right-handed glove, in which one of the three axes (up-down, left-right, back-front) is reversed relative to the other two. Nonenzymatic chemical reactions do not distinguish between the two, but enzymatic reactions do. Many molecules, such as amino acids (the building blocks of protein) and sugars, display this property, and some of them can be preserved almost indefinitely in old soils and crude petroleum. Living organisms vastly prefer, use, and manufacture the left-handed forms of amino acids, whereas chemical reactions make no distinction (Fig. 18.2). The presence of a preponderance of left-handed amino acids suggests the former presence of life. Finally, although it is very subtle, one isotope (see page 104) of carbon, carbon-13, is ever so slightly larger than the more common form, carbon-12. Enzymatic reactions can very slightly distinguish the two, preferring carbon dioxide containing carbon-12 as a substrate to make sugars over a form containing carbon-13. A compound containing a higher ratio of carbon-12 to carbon-13 than is found in surrounding rocks is an indicator that life was present. When these data are all taken together, there is some consensus that life originated on Earth approximately 3.5 billion years ago—astonishingly close to the time that the Earth was sufficiently cool enough to support life, but quite distant from the time that life really began to explode on the earth, approximately 500 million years ago (see page 277). What could have happened to cause these two transitions?

Figure 18.1. Stromatoliths. (Upper) Fossil stromatoliths from Precambrian period, found in Germany. (Lower) Contemporary stromatoliths, formed by bacteria on the west coast of Australia. Credits: Fossil stromatolith - de.wikipedia.org/wiki/Stromatolith, Australian stromatolith - http://upload.wikimedia.org/wikipedia/commons/1/1b/Stromatolites_in_Sharkbay.jpg

There are several hypotheses. These hypotheses assume very highselection pressures favoring those who could versus those who couldn't. The first transition is defined by the need for energy. One absolute requirement for life is the ability to capture energy. According to the Law of Entropy coming from Physics, everything

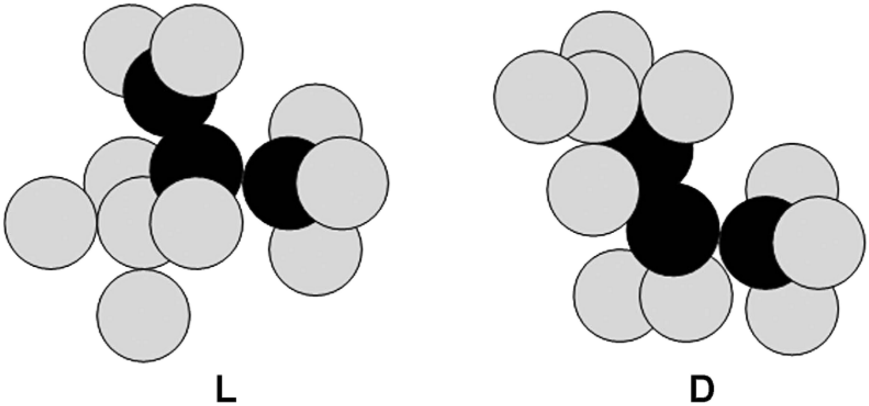

Figure 18.2. L- and D-amino acids. (The “L” and “D” are from the Latin names for “left” and “right”. These molecules contain the same atoms, but because of the way that the atoms are attached they resemble each other as left and right gloves resemble each other. Because biological reactions take place with one molecule fitting into another like a hand in a glove, biological systems usually readily distinguish between the two forms, whereas chemical reactions usually do not. The L form is commonly used in biological systems. The D form is not except in cell walls of bacteria

tends to deteriorate. Entropy is essentially disorder, and it always tends to increase. That is, order decreases. Helium contained in a balloon—ordered by being confined to a specific location—will dissipate, thus destroying that order. A watch can fall apart, but it will not spontaneously reassemble. A sand castle (a highly ordered arrangement of sand) will gradually fall apart, whether by waves, wind, or gravity, but it will not spontaneously appear. But life creates order: an egg becomes an embryo, and the embryo an animal. A seed turns into a tree. The reason that this can happen is that living creatures can use energy, which at one point is contained in a highly ordered arrangement of atoms, to build a different but new arrangement. Wood burns to create heat that causes a machine to bend a sheet of metal into an object. Turning the metal into an object creates order, but in the larger picture the destruction of the wood was a greater loss of order, the conversion of the cellulose into carbon dioxide and water, and the difference was lost as heat. Overall, the Law of Entropy holds, but for the machinist and the object, order has been created. A major adaptation of early life would have been to trap a source of energy to reproduce itself. If the early Earth contained, as we assume, some coacervate/cell structures formed amid a soup of relatively similar organic molecules, then breaking down these organic molecules would have yielded energy that the coacervate/cell (organism) could use. Many organisms continue to do this at present. Yeast can famously take a molecule such as sugar and, breaking it down to ethanol (alcohol), carbon dioxide, and water, can extract enough energy to build new yeast. Bacteria routinely perform similar conversions, often producing foul-smelling products such as butyric acid (the odor of rancid butter). Thus these reactions are possible and may have sustained the earliest forms of life. Virtually all organisms preserve this capability, which generically is known as fermentation.

However, sooner or later living creatures would have used up these resources, since with any efficiency of reaction they would have been able to consume them faster than chemical processes could generate them, and living creatures would have faced an ultimatum: find another source of energy or die. They would have been forced to manufacture their own means of support and reproduction.

THE FIRST FORMS OF PHOTOSYNTHESIS

However, luckily there is another readily available source of energy: the sun. If you focus the sun's rays through a magnifying glass onto a container of water, you raise the water to boiling, and you use the steam to drive a motor, you have captured the energy represented by the light and heat of the sun and used it to do work, to drive the motor. If the motor manufactures an object, you have created order from the energy of the sun. It is possible to capture even more of the energy from the sunlight by not letting any light escape. You can do this by adding carbon to the water so that it is an opaque black. All pigments do essentially the same thing. They absorb some of the sunlight, reflecting back the colors that we see. Thus a green leaf absorbs red and blue, while it reflects back green. It does so by containing special pigment molecules called chlorophyll. (The name "chlorophyll" translates to "the green from the leaf".) The chlorophyll is special because normally we cannot bottle sunlight, but chlorophyll not only absorbs the light but hangs onto it long enough to move the energy elsewhere (Fig. 18.3). This is the first step of photosynthesis, capturing the energy of sunlight and using that energy to manufacture complex organic molecules from simpler molecules. In the best known instance, plants capture carbon dioxide from the air and combine it with water to form sugar:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$ [9]

It takes energy to combine simple molecules into larger, more complex ones, and the genius of plants is that they can capture the energy of sunlight to do so. Animals live entirely as parasites on the plants, using the sugar of the plants as a source of energy to build their own molecules. There are a few organisms that dwell alongside volcanoes at the bottom of the ocean, capturing energy from high-energy molecules produced by the volcano, but other than these latter, all energy used by life on this planet originates in the sun.

Capturing energy from the sun does not mean that the chemical reaction is necessarily the one listed above. What is required is that, first, the sunlight be

[9] In chemist's symbolism, $6H_2O$ means six molecules of water, each consisting of two atoms of hydrogen and one atom of oxygen. $C_6H_{12}O_6$ means one molecule of sugar (here glucose), consisting of six atoms of carbon, twelve of hydrogen, and six of oxygen. Note that in the equation the numbers of atoms of hydrogen, carbon, and oxygen are equal on both sides of the equation.

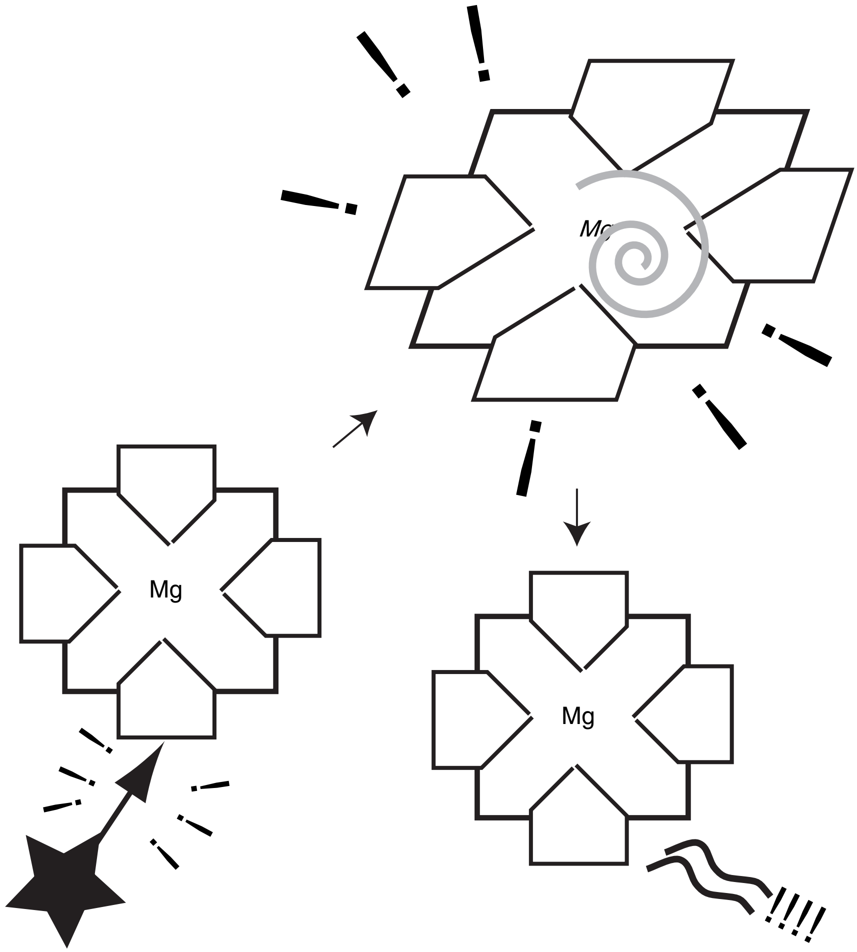

Figure 18.3. The role of chlorophyll in converting instantaneous (light) energy into storable (chemical) energy. A molecule like chlorophyll can be pictured as a large rubber sheet. When a particle of light slams into it, it stretches in a recoiling action. Moments later, it bounces back, releasing most of the energy in a form that can be captured and used to convert carbon dioxide and water into sugar

captured and second, that it be converted into a useful chemical product. The first step requires this special chlorophyll-type molecule which can, fortunately, be assembled spontaneously if conditions are right. Chlorophyll is a compound very closely related to the molecules that animals use to handle the oxygen (hemoglobin and cytochromes) used to burn the sugar, or carry it in the reverse reaction to that illustrated above back to carbon dioxide and water. This type of molecule is very good at moving energy. Its trick, as mentioned above, is to hang onto the energy long enough to use it for something else.

We all know that sunlight can do damage by, for instance, bleaching colored garments. What happens is that the pigment molecules absorb the energy, which breaks the molecules apart and causes them to lose their color. What is special about molecules like chlorophyll is that they can absorb the energy but then bounce it around, rather like a hot potato, until it can be released again without shattering the molecule. Light hitting the molecule is rather like a very fast bullet or ball slamming into a somewhat elastic net or cage. It bounces around, ricocheting around, until it loses enough energy to dribble out of the cage. You can see this property fairly easily. If you extract the chlorophyll from something like spinach into an organic solution like ethyl acetate (fingernail polish remover) and, in a dark room, illuminate the green solution with blacklight (long wavelength ultraviolet light), the solution will glow a deep red. Besides being an amusing trick for Halloween, it illustrates chlorophyll releasing the higher energy of the blacklight as lower energy visible red light. The absorbed photons are released in multiple steps, so that the total of energy gained equals the total of energy given back. So, the first success of organisms was to learn to use the properties of chlorophyll and similar molecules to capture light energy and hold it long enough to use it for constructive purposes. This is the 'photo' part of photosynthesis.

The second step is to turn the energy into a synthesized chemical product such as sugar, which can be stored and used for other purposes. This is the 'synthesis' part of photosynthesis. This would be rather like a bullet slamming into a paddle wheel and turning it—if you can capture the energy, you can turn it into useful work. For a plant, this means being able to use the energy to attach two molecules together.

We can interpret from among reactions that bacteria use today as well as from the geological record what the synthesis step must have been when photosynthesis was first achieved. We know that there was considerable hydrogen sulfide, H_2S, dissolved in the water at the time. Hydrogen sulfide is a gas producing the odor of rotten eggs, but otherwise is chemically similar to water, which differs only by having oxygen, O, in the role played by sulfur, S. Some bacteria, known as the sulfur bacteria, carry out photosynthesis using the following reaction (actually a series of reactions):

$$6CO_2 + 6H_2S \rightarrow C_6H_{12}O_6 + 12S$$

They use the energy sunlight to attach the hydrogen to carbon dioxide, synthesizing sugar. The leftover product is sulfur. Some of the bacteria alive today that can form stromatoliths, as seen in very ancient fossils, also can carry out this reaction. The resulting products are the highly ordered sugar—which can be used as fuel for other syntheses—and the element sulfur, which is a solid powder at normal temperatures. We also know that the sulfur deposits that are mined today are in very ancient rocks. These observations lead us to conclude that the earliest photosynthesis was of the sulfur-producing variety, and that it generated both the energy needed to sustain the rest of life and created the great sulfur deposits of the Andes and elsewhere in the world.

Sulfur photosynthesis, however, suffers from several embarrassments. First, the sulfur accumulates. In shallow lake beds, for instance, the accumulation of sulfur may eventually fill the lake, and the sulfur can react with water or other materials to produce truly noxious (poisonous) materials such as sulfuric acid. Second, hydrogen sulfide may be convenient for a while, but ultimately there is not much of it. If you ever have a chance to climb to the crater of an active volcano, you will encounter the foul smell of hydrogen sulfide, and you will retain a disagreeable but memorable recollection of the experience. Other than volcanoes and hot springs, thankfully H_2S is rare in our atmosphere.

PHOTOSYNTHESIS USING WATER INSTEAD OF HYDROGEN SULFIDE

This is the point. Hydrogen sulfide is generated in a few places and, once the original widely-distributed supply is gone, the marvelous invention of photosynthesis will be useless. Unless one can find a substitute for H_2S. Finding a substitute was, as both modern genetics and geology indicate, the next big achievement of plant life. They substituted water for hydrogen sulfide and produced the reaction that we know today:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

(Despite the differences between the yellow powder sulfur and the gas oxygen, the two elements react chemically in many similar ways.) Water as a reactant has several advantages over hydrogen sulfide. Water is far more abundant than hydrogen sulfide, and the waste product oxygen does not precipitate at the bottom of lakes and convert to disagreeable products. It is a gas that bubbles away into the atmosphere. At the very low levels of oxygen accumulated by the first oxygen photosynthesizers, this must have been an ideal solution to the problem of diminishing amounts of H_2S, and the organisms that had achieved this success must have proliferated rapidly. It was the first major worldwide pollution, and it changed the planet. Microscopic examination of the most ancient rocks in Australia, approximately 2.8 billion years old, reveals structures very similar to modern cyanobacteria. The cyanobacteria are so named because they are bluish in color. The blue color is a form of chlorophyll, the primary molecule that can trap light to initiate the reaction. At approximately this time, chemical products in the rocks suggest that oxygen appears in the atmosphere.

One of the most startling indicators of this activity is the so-called banded iron formations or redbeds (Fig. 18.4). These ancient rocks show striping alternating between red and the base color. The red is iron oxides (rust). In the uncolored regions, iron is present but is not iron oxide. What appears to have happened is that alternately there was free oxygen, which would react with free iron, just as iron today will rust, and alternately the oxygen disappeared. It has been speculated, though it is highly unlikely, that this alternation was seasonal. Today there is so much oxygen in the atmosphere that any iron left exposed for any length of time turns to rust, but as the waste product oxygen was first being produced, much

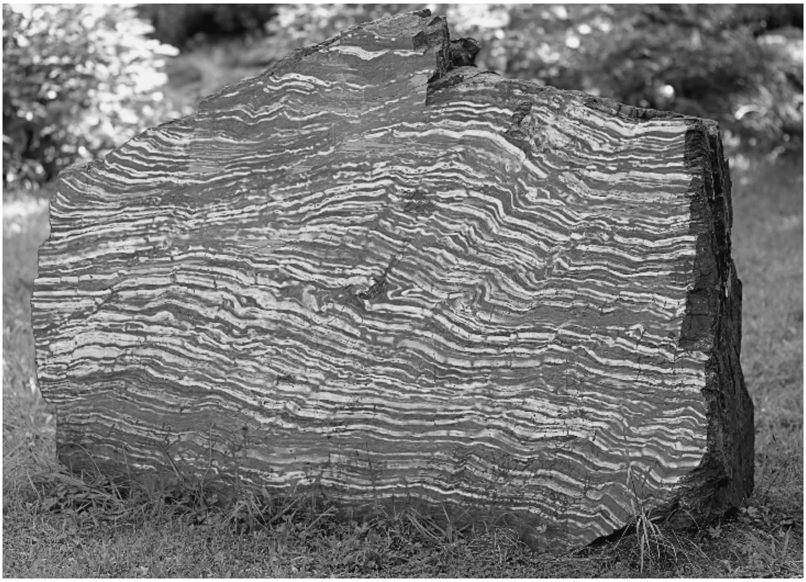

Figure 18.4. Banded iron formation. The lighter colors are red, representing back-and-forth shifts of the availability of atmospheric oxygen. Such patterns are characteristic of only a limited period of the earth's history. Today evenly distributed iron would be completely oxidized. Credits: http://upload.wikimedia.org/wikipedia/commons/5/5f/Black-band_ironstone_%28aka%29.jpg This is a file from the Wikimedia Commons

of it may have immediately reacted with iron and other materials in the soil and water, and never reached the atmosphere. During this time the amount available may have waxed and waned with the seasons and the ability of microorganisms to maintain photosynthesis, as similar-sized bands in bacterial formations similar to stromatoliths are formed by seasonal fluctuations, or there may have been other mechanisms generating the cyclicity. We are not convinced that oxygen began to build in the atmosphere until approximately one billion years ago.

THE IMPACT OF AN OXYGEN ATMOSPHERE

The accumulation of oxygen in the atmosphere changed the earth in many crucial ways. First, as you know, oxygen is highly reactive: hence all the warnings about not smoking or creating sparks when high levels of oxygen are present, since it reacts with many types of molecules. Second, it releases a lot of energy when it reacts: things burn or explode. We can snuff out fires by depriving them of oxygen, or make them burn more vigorously by adding more oxygen. The energy that is released can be captured and used, whether to drive a motor or to drive chemical reactions that living things can use. Third, oxygen can provide an important shield for living creatures. Let's consider these in reverse order.

Every fair-skinned person is aware of the danger of sunburn, and even people with greater pigmentation can burn. Ultraviolet light can be absorbed by molecules, including macromolecules, and it can shatter them. If you imagine a molecule to be a balloon, hitting the molecule with a photon (particle) of ultraviolet light would be the equivalent of stomping on the balloon. Clothes fade in sunlight because the ultraviolet light shatters the pigment molecules. We use ultraviolet lamps to sterilize small areas because the UV shatters the DNA, RNA, and proteins of the bacteria, thus killing them. Some individuals, afflicted with a disease that prevents them from repairing damage from the sun, dare not expose their skin even briefly to sunlight, but must remain indoors and fully clothed at all times. This condition demonstrates that most people routinely suffer damage to the skin (shattered molecules) from sunlight, but repair virtually all of it. Imagine what it would be like to live on an earth that received somewhere between 50 and 500 times more UV. (The number is imprecise because, owing to cloud cover, elevation, and latitude, the amount of UV that reaches the earth at any one time varies.) In the early atmosphere, water could absorb UV and protect life a few centimeters below the surface of the water, but the land surface was under continuous bombardment by an extremely powerful germicidal lamp. Life on land was not possible in the early atmosphere.

Fortunately, when oxygen reaches the upper atmosphere, it can form an unusual form of oxygen, known as ozone, and the ozone absorbs the UV very effectively. It acts essentially as a colored filter, allowing only light less energetic than UV (of longer wavelength) through, much as a red filter will not let blue light through. The black-and-white photographs with dramatic dark skies were produced by using red filters, which prevented the blue light of the sky from reaching the film, while the white light from the clouds remained. Ozone is far from a perfect filter, but by blocking 98% or more of the dangerous UV, it made the land habitable. Land offers many opportunities for life, and this was a very important transition.

It was also a very important transition because products can be burned using oxygen. Cellulose, the main constituent of wood or paper, is a macromolecule consisting of a chain of sugar molecules. If it reacts with oxygen in a fire, it is converted into carbon dioxide and water, releasing the energy that we identify as fire and heat. Photosynthesis has been invented, accumulating sugars, and some organisms can become parasites on the photosynthetic organisms, taking their sugar for themselves. We know these organisms as non-photosynthetic bacteria, fungi, and animals.

These organisms have a few means of using sugar. One of these is simply rearranging the sugar molecule. The simplest version of this is the conversion of sugar, $C_6H_{12}O_6$, into two molecules of lactic acid, $C_3H_6O_3$, or to two molecules of ethanol (grain alcohol, C_2H_6O) and two molecules of carbon dioxide (CO_2). Note that in either case you still have 6 carbons, twelve hydrogens, and six oxygens. This is rather like releasing the spring on a small toy to make it jump. The sugar represents the toy in its cocked position, and the ethanol or lactic acid the toy with the spring released. You have released some energy, which you could use to perform some work. But let's make the toy plastic. If you burned it (reacted it with oxygen), it would release a lot more heat, which you could use to do more work. As a matter of fact, you know that the byproduct of rearranging molecules, ethanol, readily burns, releasing substantial heat. This means that there is still a lot of energy in the molecule. Burning ethanol is simply reacting it with oxygen: $C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$, and it releases a lot of heat, converting all of it to carbon dioxide and water. If we could do that, we could get much more energy from the sugar, actually about 24 times as much. Think of it: organisms that can ferment sugars get only 4% of the energy available in the sugar. Once oxygen becomes readily available, the organism that can learn to use it has a huge advantage. Thus some organisms managed to adapt a modified version of the chlorophyll molecule, which can absorb energy in the same fashion as chlorophyll but in this case not using light—think of it as containing an explosion—to carry out this reaction in slow motion. The energy that is released in burning sugar to carbon dioxide and water is the same whether one burns cellulose (paper, cotton, or wood, a polymer of sugar) or whether we "digest" sugar to carbon dioxide and water. We measure it in the same fashion, in Calories or Joules. A calorie is the amount of heat needed to raise one liter of water (about one quart) one degree centigrade (about two degrees Fahrenheit). Sugar releases approximately 4 Calories per gram whether it is burned with a match or digested. The heat of our bodies is the same heat as that produced by a fire. The difference is that living creatures do the burning in slow motion and controlling it so that the body never gets too hot, and as much energy as possible is captured to be used for such purposes as making new molecules (synthesis). Again, for obvious reasons, these organisms were enormously successful. They were so successful that, as the bacteriologist Lynn Margulis suggested, other creatures decided to hang out with them.

THE INVENTION OF THE EUKARYOTIC CELL

Eukaryotic cells are those that contain true, membrane-bounded organelles such as nuclei, mitochondria, and chloroplasts ("eukaryotic" means "with a good nut [in the center]", based on the appearance of a cell and its nucleus when viewed in the microscope). The organelles serve specific functions, since different enzymes work under different conditions and the membranes create compartments in which ideal conditions can be maintained for each process. Mitochondria, which are responsible for respiration, and chloroplasts, which conduct photosynthesis, are peculiar. First, these organelles are enclosed by not one but two membranes, with the inner membrane deeply folded so that it has far more surface area (Fig. 18.5). Second, although proteins can be synthesized inside these organelles, the ribosomes (page 228) on which the proteins are synthesized are unusual. Most of the ribosomes of eukaryotes are a bit different from those of bacteria, and some antibiotics are more toxic to bacteria than to us because of this difference, but the ribosomes of mitochondria and chloroplasts are more similar to those of bacteria than to the other ribosomes inside the cell. Third, as was finally understood in the 1960's, mitochondria and chloroplasts have their own DNA and divide when the cells divide, so that each

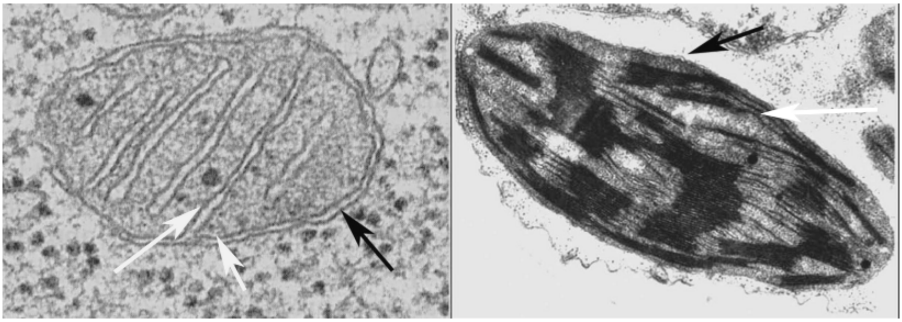

Figure 18.5. Mitochondria, chloroplasts, bacteria. Upper: Mitochondrion (left) and chloroplast (right). The outer membranes are indicated by black arrows and the inner membranes by white arrows. Credits: Mitochondria - http://web.mit.edu/esgbio/www/cb/org/mito-em.gif origin unknown, Chloroplast - http://www.nrc-cnrc.gc.ca/education/images/bio/gallery/pl_chloroplast.jpg

daughter cell has similar numbers of these organelles. Also, most mitochondria are similar in size to bacteria. Finally, some primitive eukaryotes lack mitochondria, but have symbiotic bacteria living with them. Putting all this **evidence** together, in 1966 Margulis produced a **logical** if very startling hypothesis, that mitochondria and chloroplasts were descended from respiring and photosynthetic bacteria that larger cells had taken inside of themselves to benefit from their activities! This arrangement is known on larger scale and called a mutualistic arrangement, as lichens are combinations of algae and fungi, and most animals cannot live without the products of helpful bacteria that live in their digestive tracts. However, in this case Margulis proposed that ancient cells took up these bacteria into vacuoles, or membrane-bound organelles, where the cells delivered precursor products and the bacteria, which lived happily inside the vacuoles, returned their products for the benefit of the larger cell. See Fig. 18.6. Since Margulis first proposed this hypothesis, it has become possible to sequence DNA, and the similarity of mitochondrial and chloroplast DNA to that of certain bacteria is so close that the relationship seems extremely convincing. This later evidence **falsifies** almost all alternative hypotheses. Mitochondria and chloroplasts are nevertheless very different from their original forms, and cannot survive outside of cells, but most scientists are convinced of their origin from bacteria. The mutualism was so successful that the world is now dominated by eukaryotic creatures. The origin of the nucleus is far more speculative and far less certain, but remains an interesting scientific question.

THE ORIGIN OF MULTICELLULARITY

There are many obvious advantages for the cooperative interaction of many cells. One very important advantage is efficiency. In some of the simplest organisms such as a colonial alga, some cells specialize in the photosynthesis that provides food for the organism while others take over the primary responsibility for producing the

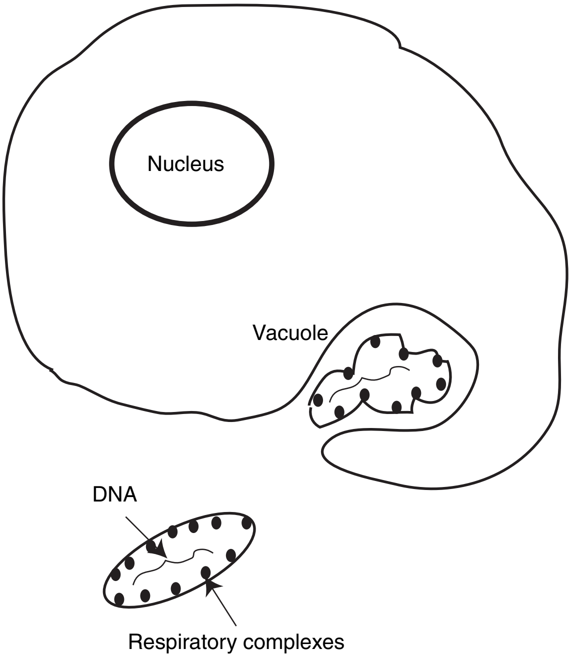

Figure 18.6. The hypothesis is that photosynthetic bacteria, and bacteria that could handle oxygen, lived commensally with larger cells, ultimately evolving to be come completely dependent on the host organism as, respectively, chloroplasts and mitochondria. Because oxygen is so reactive, molecules handling it are embedded into the cell membrane of bacteria, where they can be held in place and their reactions controlled. The bacteria are engulfed by cells that cannot handle oxygen, but they are not eaten. Their cell membranes ultimately become multiply folded to increase their capacity to process oxygen, but they retain their DNA and ability to divide within the cell. The outer membrane is the old membrane of the vacuole, and the inner membrane is the old bacterial cell membrane. Ultimately, some of what they need is produced by the host cell, and they no longer can live independently

new generation (Fig. 18.7). In an example of inefficiency, the simple multicellular organism Hydra, a freshwater relative of jellyfish, has partially specialized cells. What makes its muscle is not a true muscle cell but a cell that contains muscle components but also carries out other functions more typical of cells on the outside of the animal, called epithelial cells. The cell is called a musculo-epithelial cell. As is seen in Fig. 18.8, the cell can contract, but it has to drag along the non-contractile bag of the epithelial component, which incidentally is attached to other cells. It is a rather awkward arrangement. Thus animals and plants that have truly specialized cells, which can perform complex functions (digest, contract, send signals, excrete) very efficiently, but which depend on other cells for their support, have many advantages over multi-purpose, jack-of-all-trades cells. Also, larger size creates the advantage of having more resources to deal with and survive intermittent problems such as lack of food or water. Thus larger, multicellular creatures can do better in variable environments without having to go into deep hibernation or

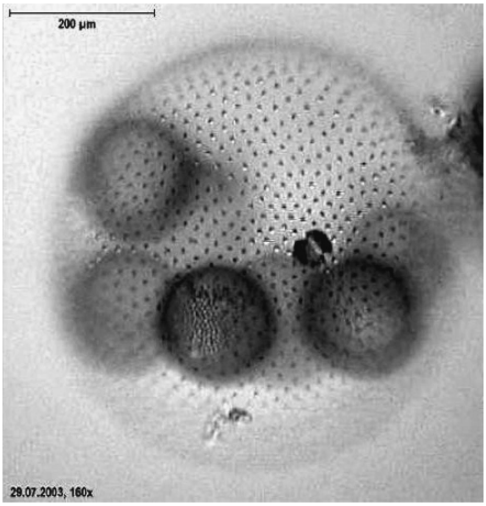

Figure 18.7. Volvox, a colonial alga. Each spot on the larger sphere is a single cell of the organism. The inner balls are collections of cells that have separated from the outer sphere to become the reproductive cells for the next generation. The outer cells will eventually die. This is one of the simplest structures for a multicellular organism. Credits: Micrograph of Volvox aureus. Copyright held by Dr. Ralf Wagner, uploaded to German Wikipedia under GFDL

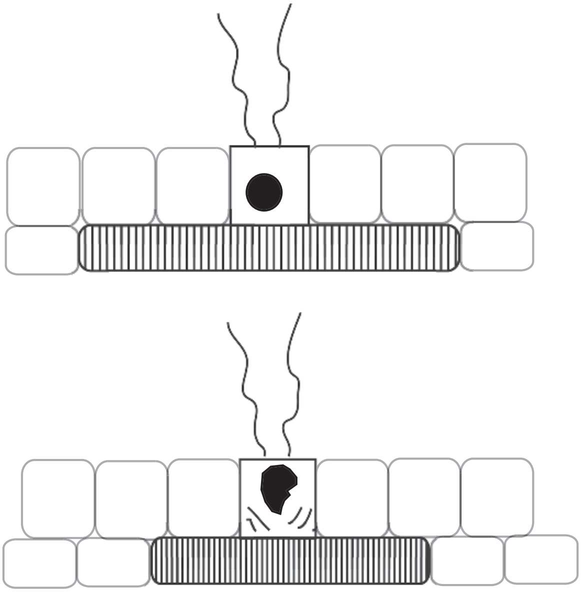

Figure 18.8. Musculoepithelial cell in a hydra. The dark unit is one cell. The upper part faces the outside of the animal and has cilia to stir up water and draw in prey. The lower part works like a normal muscle. When the muscle contracts (lower picture) the epithelial part gets pushed around and is under strain. Higher organisms have separated functions for greater efficiency

make other drastic arrangements. Presumably because of these advantages, although single-celled organisms, particularly bacteria, are enormously numerous, multicelled creatures are now very prominent in our world.

REFERENCE

Orgel, Leslie (1998) The origin of life. A review of facts and speculations. Trends in Biochemical Sciences 23: 491–495.

STUDY QUESTIONS

1. How do living organisms not violate the laws of entropy?
2. Is there more than one type of photosynthesis? Explain.
3. Does photosynthesis differ from fermentation? Explain.
4. How similar are photosynthesis and respiration?
5. What is the advantage of respiration over fermentation? What is the disadvantage?
6. What is the evidence that mitochondria and chloroplasts descended from bacteria? What is the evidence against the hypothesis?
7. Would you think that any other cellular organelles could have arisen by symbiosis? Why or why not?
8. Do you think that there might be evidence today for a commensalism that might be evolving toward complete symbiosis? What might that be?
9. Is there any advantage to being multicellular? What might that be?