CHAPTER 17

# THE STORY OF OUR PLANET

## THE STUFF OF INHERITANCE: DNA, RNA, AND MUTATIONS

Knowing how DNA works and how proteins are synthesized can tell us that all life is related, but it does not tell us how life arose. Strictly speaking, this is not an issue for the story of evolution, since the story of evolution begins with the postulate that, once life appeared, natural selection generated the variety that it became. Whether life appeared on earth as an act of God, as dust delivered from another planet—which begs the question of how THAT life arose—or appeared as an entirely chemical process does not seriously affect the hypothesis of natural selection. Nevertheless, it is possible to speculate on the mechanics of creating life. After all, science is about the mechanics, or how things work. The only difference between a scientific analysis of how life might have begun and a religious viewpoint is that the scientific argument is, "If God created life, this is how He might have done it." As the great late Medieval Spanish Jewish philosopher Maimonides put it, "A miracle is not something that could never have happened. It is something that always could have happened, but did not without the intervention of God." Maimonides was one of the scholars who returned Aristotelian philosophy to Europe, and he was widely respected by Christian, Jewish, and Islamic philosophers. Aristotle of course emphasized mechanical explanations for phenomena.

There is much evidence to tell us about many of the steps that presumably transpired, but at present we cannot assemble the entire story. Based on evidence and logic, we can hypothesize several of the steps that probably occurred. The story is constructed as follows:

## LIFE REQUIRES CARBON AND WATER

The reason that projects such as planetary exploration search other planets for water and "organic molecules" is that virtually all scientists agree that any form of life must be based on these materials. There are many reasons for this agreement, based on the properties of "organic molecules" and the properties of water. Organic molecules are defined as complexes based on the element carbon. Carbon is unique among the over one hundred known elements in that individual carbon atoms can bond to other carbon atoms (that is, carbon can form chains of molecules) and that the carbon-to-carbon bond or linkage is flexible. Atoms are the smallest intact particles of elements, such as oxygen, carbon, sulfur, or chlorine. Molecules are combinations of different atoms, such as water (two hydrogen atoms combined to one oxygen atom), carbon dioxide (two oxygen atoms combined to one carbon atom) or propane (three carbon atoms and eight hydrogen atoms linked together). Other atoms, such as silicon, can also bond to each other and form chains, but the chains are not flexible; they tend to form very rigid structures such as sand (crystals of linked silicon and oxygen). The flexibility means that a carbon-based molecule can be built in almost any shape imaginable—including giant accumulations of atoms called macromolecules (including thousands of carbon atoms, as well as more thousands of hydrogen, oxygen, sulfur, nitrogen, and phosphorus atoms), providing the enormous variety that is essential for life. For instance, cotton, wood, sugar, and starch are all forms of carbon-based compounds called carbohydrates; fingernails, hair, antlers, steaks, egg white, milk, the blood protein hemoglobin, silk, and skin are all members of another carbon-based family, the proteins; and butane lighter fluid, gasoline, candle wax, animal fat, and cooking oil are members of the carbon-based family called lipids. No other single type of atom will do this. For this reason virtually all scientists are in agreement that life must be based on carbon, and complex carbon-based molecules are granted their own special branch of chemistry. Complex carbon-based molecules are called organic molecules, and the study of them is called organic chemistry.

The properties of carbon-based molecules also determine some conditions of life. For instance, most carbon-based molecules break down if they get too hot. This is what happens to the white of an egg when you cook it, or to your skin if you burn it. Most carbon-based molecules are unstable above 50° C (122° F), setting an upper limit to the temperature at which life could exist. (A very few creatures, such as bacteria living in hot springs and thermal vents, have made special adaptations to their proteins and DNA, to allow them to survive at temperatures near boiling. These, however, are quite rare.) The instability of carbon-based molecules is even the reason why people become delirious if the body temperature rises above 104–105° F (approximately 40° C). The properties of carbon are illustrated in Fig. 17.1.

The other crucial element is water. Water is a wonderful solvent, dissolving at least a little of a vast range of molecules ranging from salts to proteins and lipids. (The fact that you can taste the gasoline if water has come in contact with it indicates that a little of the gasoline has dissolved in the water.) It absorbs and holds onto a lot of heat, which is why coastal areas have warmer autumns and cooler springs than inland areas; it interacts quite well with many molecules, allowing them to react with each other. When it freezes, unlike most molecules, the ice is lighter than the water and floats, preventing deeper water from freezing. But most importantly, it is liquid at temperatures at which carbon-based molecules are stable and can react. Atoms do not move much in crystals such as ice, and so reactions cannot take place. (Imagine making a cocktail or any other drink that must be shaken if the whole mixture is frozen into one big chunk of ice.) Thus water is extremely useful, even essential, for life, and the freezing point of water determines a lower limit

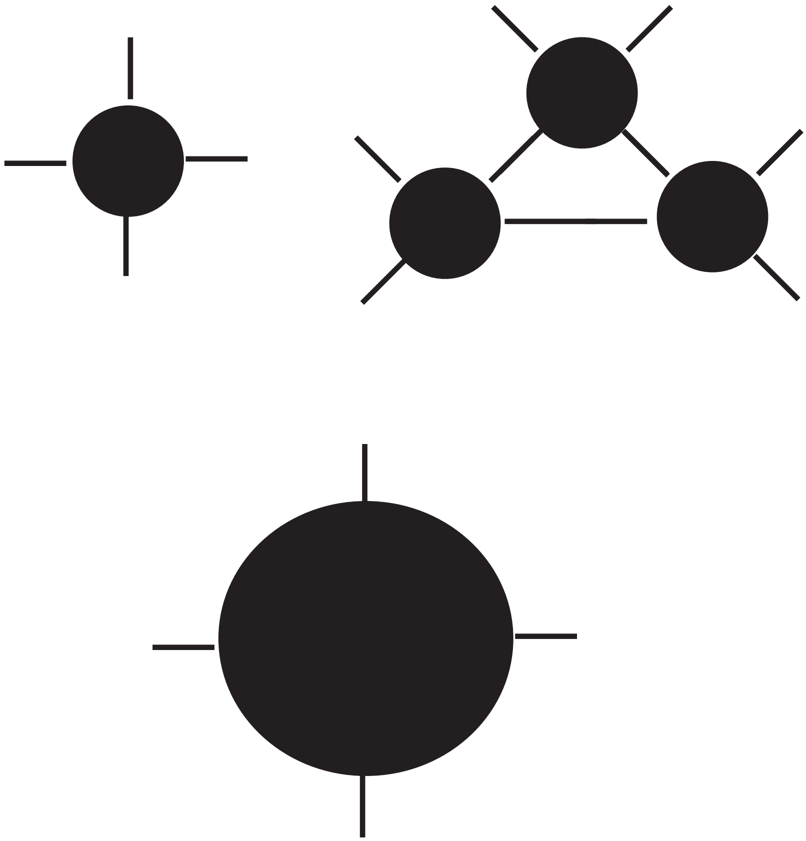

*Figure 17.1.* Upper left: The atomic structure of carbon consists of an atomic nucleus (black) and a shell of electrons surrounding it, of which four electrons can interact and form bonds with other atoms (lines). Because of the size of the nucleus relative to the shell, the electrons can interact with each other, in effect bending to form bonds in various positions (upper right). The molecule illustrated would be called cyclopropane. Because of this property, carbon atoms bonding to other carbon atoms can form molecules (complexes of atoms) with an infinite variety of shapes and forms, a requisite for being the basis of the enormous complexity that allows us to live. Also, because the bending forces the distortion of a relaxed state, different molecules store energy rather like cocked springs. The molecule cyclopropane is flammable, capable of releasing its energy as heat. (Lower). The atom silicon is similar in configuration to carbon but is much larger. Its electrons are too far apart to interact, like a cartoon character who has blown up like a balloon so that his arms and legs no longer can reach each other. The consequence is that silicon can form only rigid, linear or cuboidal structures like sand

at which life can comfortably exist. We therefore can identify three characteristics that we feel should be present if life is to exist: complex carbon-based molecules, water, and a temperature somewhere above freezing and below about 100° F. This is why probes of other planets, looking for signs of life, explore for traces of liquid water and for complex organic compounds. The structure of water is indicated in

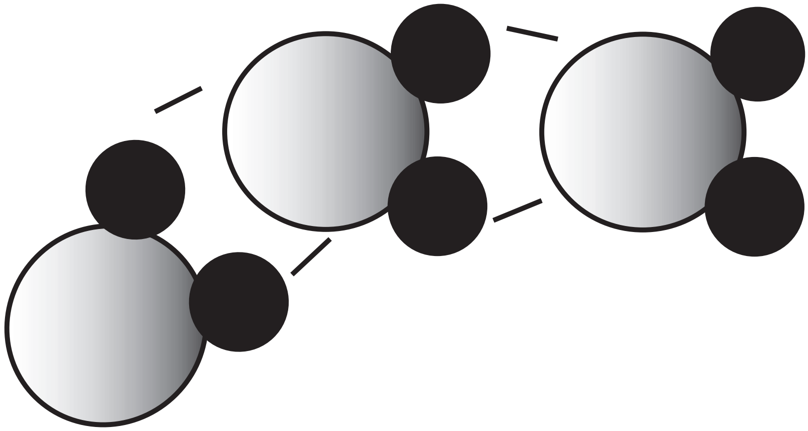

*Figure 17.2.* Water molecules. Water molecules consist of one oxygen atom (larger circle) with two hydrogen atoms (smaller circles) attached. The hydrogen atoms are separated at an angle slightly larger than a right angle. Water is not ionic. In other words, it does not have a charge and it will not move in an electric field. However, it does have a polarity like a magnet (gradient across the molecule). The oxygen end is slightly negative, and the hydrogen end is slightly positive. Thus different molecules can interact weakly with each other, again like magnets separated by slight distances, holding themselves together and making water a liquid at room temperature. By contrast, methane, a molecule of similar size but not polar, is a gas at room temperature, with its molecules not interacting at all. Approximately one in ten million water molecules do break apart, allowing water to react with many other substances. Because it can do this, water can dissolve many different types of substances. Because it is a liquid at temperatures in which carbon-based compounds are stable and because it can dissolve and interact with many substances, it is a very special molecule for the mixing and building of carbon-based compounds. It has several other properties that make it nearly unique among molecules, leading scientists to conclude that it is essential for life

Fig. 17.2. In terms of the origin of life on earth, we can assume that water and carbon dioxide were present, thus supplying the two primary ingredients. We need to ask if we can get more complex organic molecules by processes other than the metabolism of living creatures. The answer is yes.

## FORMATION OF ORGANIC MOLECULES CAN TAKE PLACE IN THE CONDITIONS PREVAILING DURING THE EARLY DAYS OF THE EARTH

There are many means of analyzing atmospheric and climatic conditions in the early earth. One can interpret the composition of the atmosphere by the chemical composition of the rocks. You are familiar with the fact that iron rusts when left in air. In fact, elemental (native) iron reacts relatively easily with oxygen to form ferric oxide (rust). If one breaks open a rock that has lain undisturbed since it was formed, and finds rust inside this rock, one may safely conclude that oxygen was present in the atmosphere the last time the iron was exposed, perhaps in lava coming out of a volcano. If the iron is metallic or in some other form, then no oxygen was present when the iron was last at the surface. It is possible to make this assessment more quantitative, since different reactions occur at different concentrations of oxygen in the atmosphere. Similarly, the shapes of crystals are different if they are formed at different temperatures or under different pressures. Diamonds, graphite, and coal are all primarily carbon, but each is formed under different conditions. Thus one can interpret the temperature at which other rocks formed.

From considerations such as these, most geologists have concluded that the early earth was hot, an argument fully consistent with the hypothesis that the earth originated from the sun. Eventually the surface cooled to below the boiling point of water, allowing incessant rain that accumulated on the earth as hot water. Because of the physics of raindrops, there must have been considerable lightning during this period. The moon was much closer to the earth, generating violent tides hundreds of feet high that swept many miles inland. The rain would have extracted soluble salts from the surface of the earth, carrying the salts to the forming sea. (The concentration of the salts in the sea at this time can also be estimated by the types of crystals that were formed: it was approximately 0.2%, about ¼ of what it is today.) All the oxygen available had already reacted with other molecules, producing sulfur dioxide, water (dihydrogen oxide), carbon dioxide, and other oxides, and there was no free oxygen in the atmosphere. There was, however, sulfur dioxide, hydrogen sulfide (the odor of rotten eggs), and ammonia.

These conclusions had been reached by 1953, when Stanley Miller and Harold Urey*explored the possibility that such conditions could create the first steps toward life. They put together the molecules hypothesized to be present in the early atmosphere, together with a salt water solution. They removed all free oxygen from the mixture and maintained it at high temperature, together with electrical discharges through the flask, simulating lightning, and allowed the mixture to "cook" for several weeks. At the end of this period, they opened the flask and analyzed the solution. What they found were the simplest molecules presumed to be necessary for life: the building blocks of proteins (amino acids), nucleic acids (nucleic acid bases), sugars, and small lipids. In other words simple organic molecules could be formed from inorganic molecules in the conditions presumed to be present in the

- Interact with hydrogen, oxygen, and water
- Mostly unstable at temperatures much above 40°C (104°F)
- Easily deformed by extremes of acidity or alkalinity
- Easily deformed by changes in salt concentration

*Figure 17.3.* Properties of organic molecules. The structure of carbon-based molecules determines that they can exist only under specific conditions of temperature, salinity, and acidity. Thus, since life depends on carbon and water, all living organisms must function within these limits. Living organisms cannot exist at temperatures at which carbon-based molecules burn or water is converted completely to steam, and organisms cannot function (and can only survive as spores or the equivalent) if the water in their bodies is solid (ice)

early earth. This would be the first step in the creation of life. The properties of organic molecules are illustrated in Fig. 17.3.

## LARGER ORGANIC MOLECULES CAN BE FORMED FROM SMALL ORGANIC MOLECULES

Macromolecules are polymers—end-to-end chains, occasionally branched, of these building blocks. If these building blocks are brought together, they can interact to link to each other. We have encountered macromolecules earlier (page 244). They include long chains of amino acids, which are proteins; long chains of nucleotides, which are the nucleic acids DNA and RNA; chains of sugars, which we know as starches, glycogen, complex sugars, and cellulose; and chains of small two-carbon molecules that form fats. More recent research has established that, under appropriate conditions of heat, salt concentration, and sometimes electricity, small molecules can interact to form macromolecules, Thus, although we are still a very long way away, we have the beginnings of something that could eventually acquire the complexity required for life. Based on evidence such as that described in Chapter 17 and elsewhere, we believe that the early seas were warm enough, salty enough, and subjected to enough lightning strikes to recreate these conditions. The reactions would have taken place very slowly. Living systems have developed enzymes, or proteins capable of speeding up reactions, to make the process much more efficient, but in the early earth, enzymes would not have existed, and since enzymes also degrade macromolecules—bacterial enzymes are what causes formerly living materials to putrefy—it would have been possible to accumulate large quantities of these organic molecules. One other element that could cause these molecules to decay was also missing. You are aware that many types of carbon-containing and some inorganic materials, of which wine and iron are primary examples, will "spoil" if exposed to air. This is because many types of molecules react easily with oxygen, turning into different types of molecules. As we will see in Chapter 18, there is also solid evidence that there was no free oxygen in the atmosphere of the early earth. Thus this limitation to the accumulation of organic molecules was also absent. Many scientists therefore feel that it would have been possible in the early earth for large amounts of organic molecules to accumulate. This of course is primarily speculative, but the point is that the mechanism is possible, and thus there is no intellectual impediment to this part of the hypothesis.

## THE LIPIDS FORMED CAN NATURALLY FORM PARTICLES THE SIZE OF BACTERIA; THESE PARTICLES HAVE A MOST STABLE SIZE AND CAN GROW AND DIVIDE

In the most precise interpretation of the sentence, the sea is not "living". It contains an immeasurable number of living organisms, but the complex salt-water solution, containing also some soluble macromolecules from plants and animals that have died and burst (sea foam, often seen when a coastline containing a lot of algae is agitated, is created because the carbohydrates—agar, as is used in biological research—are dissolved in the water). Nevertheless, it is not alive; if all living organisms are removed from the water, it will sit there more or less indefinitely. One can argue that the essence of life is control. As the father of physiology, Claude Bernard, said, "The constancy of the internal environment is the basic condition for a free life[7]," meaning that, in order for an organism to function independently of the environment, it must be able to make the conditions inside its body constant—constant body temperature, salt content, concentration of nutrients, oxygen level, etc. The reason for this is that macromolecules are delicate things. They work only when conditions are just right; otherwise they may not work, or even be damaged. Life cannot exist at temperatures at which macromolecules are not stable. Thus we become delirious at the temperature at which the membranes of our nerve cells begin to melt, and we receive burns at the temperatures at which egg whites become solid (the proteins are "denaturing" or precipitating from solution). In order for a living thing to exist, it has to isolate its macromolecules from the rest of the world, and maintain them in a medium with a constant, ideal, amount of salts, acidity, and other supplies. Again, proteins precipitate when conditions become too acid (milk curdles because of acid production by bacteria) or too alkaline. To maintain the constancy, a living creature basically has to keep the proteins inside of plastic bags into which it can allow entry and exit of only limited amounts of the salts, acids, and supplies. These plastic bags are what we know as the membranes surrounding the cell, the nucleus of the cell, and the organelles of the cell. The question is, where did cells come from?

## INTERESTINGLY ENOUGH, ORGANIC SOLUTIONS CAN SPONTANEOUSLY FORM PARTICLES WITH THE APPROPRIATE PROPERTIES

Everyone is familiar with the "shake well before using" admonition on prepackaged salad dressings, spray paints, and other items. The object of the shaking is to temporarily suspend particles or one liquid in another liquid in which it is immiscible (it does not dissolve). If the particles are small enough, they may remain nearly permanently, as in homogenized milk. In the case of milk, it is called a colloidal suspension, in which the droplets of fat are suspended in the watery milk. They basically are very tiny droplets of fat, so small that they do not settle out. The fats can form another type of suspension, in which the droplet of fat is not a full droplet, but rather a little bubble, a membrane of fat separating two watery solutions. In this configuration, a suspension of little bubbles is called a coacervate.

Coacervates have very interesting properties. First, as you can readily imagine, the conditions inside the bubble can be different from conditions outside, as a balloon may contain helium while existing in air, which is primarily a mixture of nitrogen

[7] La fixité du milieu intérieur est la condition même de la vie libre.

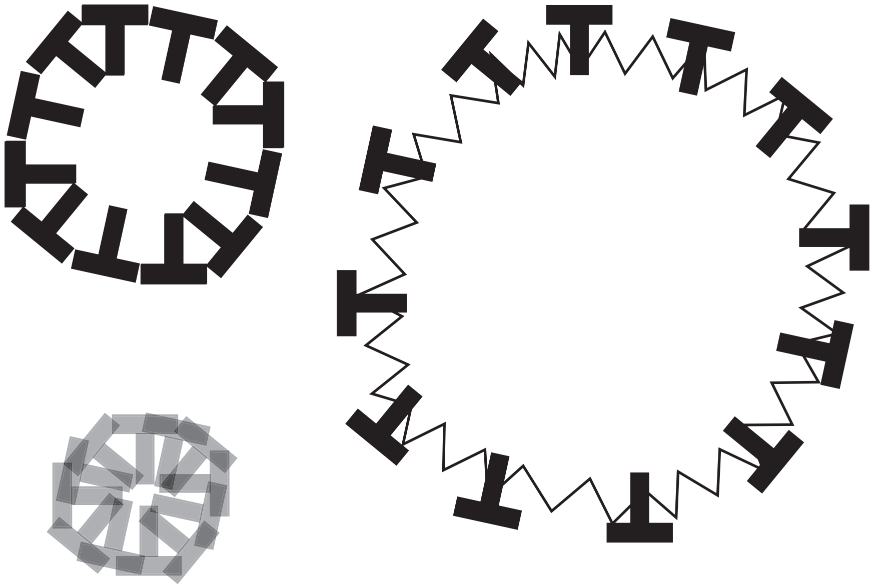

*Figure 17.4.* The molecules in a coacervate become crowded if the size of the bubble is too small. If the bubble gets too big, they are stretched apart, weakening the structure. Therefore coacervate particles are most stable at intermediate sizes. Smaller particles will fuse to grow, and larger particles will split to shrink

and oxygen. Second, they can have an optimum stable size. The fat molecules cling to each other more firmly than they cling to anything else, and they have defined shapes. If they pack too tightly, they crowd each other, while if the bubble is too big, it is not very strong (Fig. 17.4). Because of this property, in a coacervate suspension consisting of different-size bubbles, tiny bubbles will fuse to become larger and approach the more stable size and, surprisingly, larger bubbles may split to become smaller. This splitting has the appearance of a crude and simplistic type of cell division. Furthermore, the optimum stable size turns out to be approximately the size of bacteria and small cells. A coacervate even has a further interesting property: If anything can move across the membrane, it can attract some molecules, which interact well with the fats, into the inside of the bubble, causing the bubble to grow until it is larger than optimum size, whereupon it splits into two. Thus, although it is speculative, we can imagine the creation of something that would look like a dividing cell. It can even create a stable situation in which the interior of the bubbles, or coacervates, is consistently different from the outside world.

## THESE PARTICLES CAN DIVIDE, BUT CAN THEY REPRODUCE?

We would consider this process to be interesting, complex, but non-living. It is purely chemical, rather than living, because it does not control its own reproduction.

One of the defining characteristics of life is its ability to reproduce itself. Thus it is not sufficient for chemicals to tend to accumulate in preferential distribution: A living creature must define that distribution, and expend energy to maintain and reproduce that distribution even when conditions are not favorable. Thus, though it may not have been the first mechanism invented, ultimately life had to invent enzymes, or proteins that can efficiently and rapidly assemble and disassemble other molecules. In the world of physics and chemistry, everything in the long run tends to deteriorate. Living creatures capture energy to rebuild molecules and ultimately reproduce themselves. The question is, how do we move from the interesting complex chemistry of the coacervate to the directed reproduction of a living creature?

Proteins are very special molecules, the spontaneous assembly of which is highly improbable and which are therefore characteristic of living organisms. As we have seen in Chapters 14 and 15, proteins are made by a very elaborate mechanism involving DNA and RNA. One intellectual breakthrough came when in the 1980's Thomas Cech and Sidney Altman demonstrated that RNA, a macromolecule of relatively simple structure, could catalyze reactions—as Leslie Orgel, Francis Crick, and Carl Woese had suggested almost 20 years before (evidence finally coming to the aid of logic). A catalyst brings two molecules into close proximity so that they can interact, and thus speeds up reactions. The catalytic converter in automobile exhausts binds both sulfur compounds and oxygen so that the oxygen can inactivate the sulfur compounds and render them less harmful. An enzyme is a catalyst. The discovery of enzymatic RNA (ribozyme) brought a new idea to the concept of the origin of living creatures. Rather than having to establish a complex process of DNA having to code for RNA so that the RNA could make protein before life could become self-reproducing, Orgel and others suggested that if RNA could act as an enzyme, it might be possible for RNA to reproduce itself without other components. Following the logic of Occam's Razor (pages 50 and 170) this hypothesis required far fewer assumptions and was therefore inherently more appealing. The primary problem was the same as the Russian doll problem (page 200–203): if proteins are required to synthesize RNA and DNA, how do you get RNA, DNA, and proteins together spontaneously? On the other hand, if RNA were spontaneously formed, it might be able to replicate itself, as it does in certain viruses, with the aid of host energy supply and raw materials, and also and also to alter some proteins in enzyme-like mechanisms. Evidence has since accumulated that RNA can indeed act as an enzyme. It also may have been possible to build RNA under primitive earth conditions, perhaps using clay as a catalyst, much as powdered metals are used as catalysts for the catalytic converters that remove impurities from exhaust fumes.

Much of this of course is highly speculative, but is supported at least by the logic of the argument, with some evidence adduced in support of the logic. The subject is somewhat tangential here, but is discussed clearly by scientists such as Orgel (http://www.geocities.com/CapeCanaveral/Lab/2948/orgel.html).

## HOW WAS THE DNA→mRNA→PROTEIN SEQUENCE CREATED?

We know little about how we got to the DNA→mRNA→protein sequence, other than the fact that, although chemically it is easier for RNA to be made than for DNA to be made, DNA is a more stable molecule in the chemical conditions that may have existed in the early history of the earth. Thus the hypotheses are as follows:

1. RNA and protein were formed by non-living chemical means.
2. RNA could interact and alter other RNA and proteins. In other words, it was an enzyme.
3. In some of these reactions, RNA, which could form paired double helices like DNA, made copies of itself, or reproduced.
4. Occasionally the reproduction of the RNA would not be perfect and would produce mistakes. These mistakes are mutations, passed along to the next generation. Some of these mutations would improve the ability of the RNA to control its environment and reproduce more efficiently. Thus this mutation would be selected for.
5. Some of the properties of the RNA, or the proteins altered by the RNA, required specific concentrations of salts and acids. Thus there was selection also to structure coacervates such that the RNA and protein were inside, and other proteins became gates controlling what could pass through the lipid (fatty) membranes. These ultimately became the highly specific membranes that we know as cell membranes.
6. Since proteins are structurally more variable and malleable than RNA, and DNA is more chemically stable than RNA, gradually selection worked to make proteins primarily responsible for the many reactions carried out by cells, and DNA responsible for preserving the genetic information.
7. This type of selection would lead to a primitive living organism, perhaps similar to bacteria, which have a cell membrane through which they can import and export specific materials and exclude others. The DNA is naked inside the cell. In many types of bacteria, the DNA is replicated with no sexual exchange between individuals. Some bacteria have little "hairs" by which they can actively move, and some can even sense light, but otherwise there is little other structure or organization. Nevertheless, by being able to control its internal environment, to make new proteins when it wishes, and to reproduce its DNA at appropriate intervals, this type of creature has vastly greater ability to survive and propagate than any inanimate aggregate. It is alive.

Incidentally, although viruses are considerably simpler than bacteria, they are not considered to be the earliest forms of life, for the simple reason that they cannot survive without living cells. They use the mechanisms of living complete cells to manufacture new virus, as is described in Chapter 28.[8]

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[8] This is similar to a story told in religious circles about scientists creating life:
God is sitting in Heaven when a scientist says to Him, "Lord, we don't need you anymore. Science has finally figured out a way to create life out of nothing. In other words, we can now do what you did in the 'beginning'.

## REFERENCES

*http://www.geocities.com/CapeCanaveral/Lab/2948/orgel.html* (Orgel's essay on Origin of Life)
*http://www.ncseweb.org/icons/icon1millerurey.html* (The Miller-Urey experiment, from National Center for Science Education)

## STUDY QUESTIONS

1. Argue for or against the proposition that all properties of life are properties of the element carbon.
2. Argue for or against the proposition that life can exist in liquids other than water.
3. What would you consider to be the most accurate means of determining the composition of the early earth? Why?
4. What steps would you consider to be the most crucial for life to begin? Why?
5. What characteristics make a living creature, as opposed to an exceptionally adaptable molecule or collection of molecules? Why?
6. Could you imagine a form of life in which DNA directly constructed proteins, without the requirement for RNA? What would it be like? Why do you assume that it would work?
7. Could you imagine a form of life in which RNA copied itself without the aid of DNA? What would it be like? Why do you assume that it would work?
8. Can you imagine a form of life in which protein reproduced itself, without the aid of nucleic acids? What would it be like? Why do you assume that it would work?

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"Oh, is that so? Tell me..." replies God.
"Well", says the scientist, "we can take dirt and form it into the likeness of you and breathe life into it, thus creating man."
"Well, that's interesting. Show Me."
So the scientist bends down to the earth and starts to mold the soil.
"Oh no, no, no..." interrupts God, "Get your own dirt."