23. How Life Works

There are millions of organic molecules, but only a few are used for the essential activities of life. In man and alfalfa plants alike, the molecules of life use the same chemical schemes to arrive at their ends. Having examined the structures of sugars, amino acids, proteins, and nucleic acids, we now endeavor to show how these structures are used.

The term life means different things to different people. The title of this chapter perhaps promises more than it will deliver. This chapter will focus on only two important characteristics of life at the molecular level: growth and reproduction. There is certainly much to life that we do not address here. For example, no one knows how consciousness might (or might not) be rooted in physical law.

In his book Knowledge and Wonder, Victor Weisskopf contrasts living and nonliving organic systems. He imagines a one-celled organism and a similar plastic, sausage-shaped skin filled with a jellylike substance such as fat or gelatin. Each is about 0.0001 inch long. In outward appearance both look very much alike. Yet one is a living organism, and the other is not. If both were placed in a nutrient solution consisting mostly of sugar, phosphates, ammonia and traces of other chemicals, one would appear inert and the other would exhibit noticeable activity. Some of the contents of the plastic bag might leak out and some nutrients might leak in, but little else would happen. However, there would be substantial change in the organism. It would assimilate the nutrients, form them into macromolecules (proteins, DNA, etc.), grow, and ultimately divide into two one-celled organisms. This activity would continue until the nutrients were exhausted.

The processes of growth and replication are characteristic of life. Nowhere else is the behavior observed. (Although inorganic crystals exhibit a kind of growth, they do not produce independent replicas.) Can these processes be understood in terms of the fundamental laws and principles that govern atoms and establish the laws of chemistry? If so, we must understand two essential things that the one-celled organism must do:

1. The organism must build the 20 kinds of amino acid molecules and the five nucleotides from sugar, ammonia, and phosphates.
2. The organism must combine the amino acids in the correct order to form the thousands of different proteins needed for structure and function, and it must combine the nucleotides for the replication of nucleic acids in the process of division.

How Does the Cell Get Its Nutrients?

The one-celled organism we imagine is immersed in a nutrient solution consisting of sugar, phosphates, ammonia, and perhaps traces of other minerals. The nutrients, with the exception of sugar, are relatively simple (we could say “primitive”) molecules. But without them, the organism is doomed.

We can classify the required nutrients as follows:

1. Energy sources. These are organic substances (usually carbohydrates like sugar) that have energy-rich carbon-hydrogen bonds.
2. Materials for building and repairing. Every living thing needs carbon since carbon forms the backbone of the molecules of life. Methane, CH₄, and carbon dioxide, CO₂, form primitive sources of carbon, but most animals get their carbon by ingesting and breaking down carbohydrates, fats, and proteins. Likewise, nitrogen is needed as a building block for the amino acids. We provide ammonia, NH₃, in the nutrient bath for this purpose, but many organisms digest proteins of other organisms to obtain nitrogen.
3. Water. Water dissolves the various chemicals and provides a “soup” within which they have mobility. Sixty to 95 percent of living matter is water.
4. Other elements. Other elements are needed in varying amounts. For example, sulfur ties together two amino-acid chains in insulin.
One of the prime sources of energy for living things is sugar. Some organisms (heterotrophs) cannot manufacture sugar from sunlight, carbon dioxide, and water, but must rely on other organisms for nutrition. Where, then, do these other organisms get their sugar?

The answer is plants. Plants are autotrophs, which can produce their own organic carbon compounds from water and sunlight. The process can be summarized

\[ 6H_2O + 6CO_2 + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2. \]

However, it must be understood that this is a summary of a series of very complicated chemical reactions. The source of energy for this reaction is sunlight. Chlorophyll is a molecule found only in autotrophs and is one of the reactants in the complicated series of reactions that synthesize sugar. Plant cells produce amino acids and proteins like any other cell. But they also, at the command of their DNA, produce chlorophyll.

Next to DNA, chlorophyll is the most crucial molecule for the existence of life on earth. It is not so complicated in structure as DNA, but it is not simple either (Fig. 23.1). Chlorophyll permits plants to live without sugar in their nutrient solution. Plants are quite capable of synthesizing their own sugar from the primitive molecules of carbon dioxide and water. Without the sugar produced by chlorophyll in the autotrophs, all of the heterotrophs would eventually die. And without the sun as a source of energy, the autotrophs would die.

**How Does the Organism Fabricate Amino Acids and Nucleotides?**

The cell is provided with a host of enzymes. As nutrients seep into the cell, specific enzymes decompose the nutrient molecules into simpler pieces. Other enzymes (at least one kind for each of the 20 needed amino acids and at least one kind for each of the five nucleotides) then assemble the respective molecules. (If an organism is incapable of producing a particular needed amino acid, the amino acid is called an essential amino acid and must be provided in the nutrient.) Enzymes are complicated proteins, but no enzyme is complex enough to string amino acids together to form proteins.

**How Do the Enzymes Get Energy to Do Their Tasks?**

The energy to fabricate the amino acids and nucleotides must come from somewhere. No building project proceeds without energy. In this case the energy must come from the nutrients. Therefore, in this sense the organism essentially depends on some outside source. The nutrients may contain glucose, because this is the ultimate chemical source of energy for living systems. The glucose reacts with oxygen and releases carbon dioxide, water, and energy.

\[ C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}. \]

Here the organism runs into two problems. Its first problem is with the Law of Increasing Disorder. If the energy were released directly as in the above reaction, it would be such disordered energy as to be virtually unusable for purposeful molecular construction. Its second problem is that the amount of energy thus released is much too large for the processes at hand.

To solve these problems, there exists a pair of molecules called ATP (adenosine triphosphate) and ADP (adenosine diphosphate), which are closely related to one of the RNA nucleotides. All living things, including humans and alfalfa, use ATP and ADP in the same way. ATP contains more chemical energy than ADP does. When glucose is converted to carbon dioxide and water, the energy released converts many ADP molecules into ATP. The ATP moves through the organism to some other site where energy is needed. The ATP then gives up its energy to whatever chemical process requires it and returns to ADP. Nature has survived the confrontation with the Law of Increasing Disorder by storing the energy in an ordered form in ATP. Moreover, the energy is stored in small packages, because the energy from one sugar molecule is typically divided among about 40 ATP molecules.

![Figure 23.1. A form of the chlorophyll molecule.](image-url)
How Does the Cell Make Its Proteins?

We have seen how the organism makes the amino acids and nucleotides. We have seen how the organism handles its energy requirements. But the most important step remains: How does the cell string together the amino acids to form exactly the proteins it uses? The step of putting the pieces together to form the macromolecules contains many secrets of the life of the organism, since it is the different types of proteins that perform all the important functions in the chemical life of a cell.

The master plans for building proteins are contained in the nucleus of the cell. The blueprints are written in a coded language on the strands of DNA. The creation of the protein is carried out in the ribosomes—tiny particles in a cell designed for protein synthesis. Hence, a copy of the blueprints and raw materials (the amino acids) must be delivered to the ribosomes. The process by which this is accomplished is fascinating!

How Are the Blueprints Delivered to the Ribosomes?

Let us see how the cell creates a protein by following the process for a conjectured DNA blueprint. On the strands of DNA are sequences of the bases adenine, thymine, guanine, and cytosine. We will refer to these, respectively, as A, T, G, and C as we did in the last chapter. The sequences are read by grouping them in sets of three adjacent bases. We choose the sequence ATC GCC CCC CGA ATC as our conjectured DNA blueprint.

The blueprints are carried from the DNA to the ribosome by a specialized RNA molecule, messenger RNA (mRNA). The master blueprint is exposed when the DNA molecule “unzips” along the base-base bonds that tie together the two “backbones.” In our case a very short segment would unzip, exposing the code for our imagined protein,

<table>
<thead>
<tr>
<th>GCC</th>
<th>CCC</th>
<th>CGA</th>
</tr>
</thead>
</table>

and a “complementary” copy is made in messenger RNA. Enzymes catalyze the unzipping and the copying. The exposed bases of the DNA molecule provide a template against which the mRNA is fabricated from available raw materials. Cytosine (C) in the DNA molecule will attract and hold guanine (G) in place while thymine (T) will attract and hold adenine (A). However, A in the DNA will attach and hold U (not T) in the mRNA because RNA uses U instead of T. The mRNA molecule will thus be assembled and linked together opposite the half-DNA molecule:

<table>
<thead>
<tr>
<th>GCG</th>
<th>GCC</th>
<th>GCA</th>
</tr>
</thead>
</table>

The single-strand mRNA then moves away, and the DNA zips closed again and remains behind. The mRNA is free to carry a copy (albeit a kind of negative copy) of the blueprint to the ribosomes.

The mRNA copy of our conjectured DNA blueprint is AUG CGG GGG GCU UAG. The AUG and UAGs are punctuation marks that specify the beginning and ending of the sequence of bases in the mRNA molecule. Each ordered group of three bases corresponds to an amino acid from among the set of 20 used by living organisms. For example, CGG means arginine, GGG means glycine, and GCU means alanine. Think of the mRNA as containing a coded description of a protein molecule that is to be built. The “builder” will read the description, starting from one end of the mRNA molecule. As it reads the code for each successive amino acid, it adds the amino acid to the protein it is building. When it encounters CGG (cytosine-guanine-guanine) in the blueprint, it will add arginine to the protein chain because CGG is nature’s code for arginine.

In most cases one amino acid is expressed by more than one triplet. For example, CGG and GGC both mean glycine. The triplets AUG, UGA, UAA, and UAG are “punctuation marks,” meaning “start here” or “stop here.” The dictionary for the code of life shown in Table 23.1 is used by almost all living things, including both humans and alfalfa plants. Starting with one punctuation mark and ending with another, the sequence of bases in a RNA molecule, read three at a time:

<table>
<thead>
<tr>
<th>Amino Acids</th>
<th>Code Triplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycine</td>
<td>GGG GGC GGA GGU</td>
</tr>
<tr>
<td>Alanine</td>
<td>GCG GCC GCA GCU</td>
</tr>
<tr>
<td>Glutamic Acid</td>
<td>GAG GAA</td>
</tr>
<tr>
<td>Aspartic Acid</td>
<td>GAC GAU</td>
</tr>
<tr>
<td>Valine</td>
<td>GUG GUC GUA GGU</td>
</tr>
<tr>
<td>Arginine</td>
<td>CGG CGC CGA CGU AGA AGG</td>
</tr>
<tr>
<td>Proline</td>
<td>CCG CCC CCA CCU</td>
</tr>
<tr>
<td>Glutamine</td>
<td>CAG CAA</td>
</tr>
<tr>
<td>Histidine</td>
<td>CAC CAU</td>
</tr>
<tr>
<td>Leucine</td>
<td>CUG CUC UCA CUU UUA UUG</td>
</tr>
<tr>
<td>Serine</td>
<td>UCG UCC UCA UCU AGC AGU</td>
</tr>
<tr>
<td>Threonine</td>
<td>ACC AGC ACA ACU</td>
</tr>
<tr>
<td>Lysine</td>
<td>AAG AAA</td>
</tr>
<tr>
<td>Methionine</td>
<td>AUG</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>AUC AUA AUU</td>
</tr>
<tr>
<td>Tryptophane</td>
<td>UGG</td>
</tr>
<tr>
<td>Cystine</td>
<td>UGC UGU</td>
</tr>
<tr>
<td>Tyrosine</td>
<td>UAC UAU</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>UUU UUC</td>
</tr>
<tr>
<td>Asparagine</td>
<td>AAC AAU</td>
</tr>
<tr>
<td>Punctuation</td>
<td>AUG UGA UAA UAG</td>
</tr>
</tbody>
</table>

Table 23.1. Dictionary for the genetic code. (The code is as it appears on messenger RNA.)
time, stands for an ordered set of amino acids. In our example,

\[
\text{AUG CGG GGG GCU UAG}
\]

might be considered an mRNA blueprint for a very short protein consisting of

Start-arginine-glycine-alanine-Stop.

The millions of nucleotides in RNA molecules, separated into shorter sequences by punctuation marks, are sufficient for all of the proteins needed for the functioning of an organism.

**How Are the Raw Materials Delivered to the Ribosomes?**

For each of the 20 kinds of amino acids there exist specialized RNA molecules, transfer RNA (tRNA), that attach to a specific amino acid and transfer it to the ribosome for protein synthesis. Transfer RNA is a nucleic acid and it carries a code. On one end of the tRNA molecule is "written" (in the three-base code) the name of the amino acid it carries. For example, the tRNA molecule that carries arginine has the code GCC, the one with glycine has CCC, and the one with alanine has CGA. The three tRNA molecules, each carrying an amino acid, could be represented:

![tRNA molecules]

These pieces move independently of one another to the ribosomes, thus delivering the raw materials for protein construction.

**How Do the Ribosomes Execute the Final Assembly?**

The mRNA is “inserted” into ribosomes. As the mRNA slides through the ribosomes (which look somewhat like beads on a string), the blueprint is read and the protein is assembled. As depicted in Figure 23.2, the mRNA attracts the tags written on the tRNA. Once the amino acids are positioned, they hook up to form the desired protein, and the protein moves away free to perform its function. The tRNA are then free to go and pick up other amino acids and transfer them to ribosomes; the blueprint in the mRNA is free to be read again.

**How Does the Cell Copy the Blueprints before Division?**

The cell is a factory that turns out protein. In time, enough protein has been synthesized to support two cells. But before the cell can divide, the blueprints must be copied so that each new cell will have a complete set. A specific enzyme unzips the DNA molecule. Another enzyme assembles, from raw materials at hand, the pieces to restore each of the separated halves into a complete DNA molecule (Fig. 23.3). With the blueprints available for two cells, the cell divides and two independent “factories” continue their work. The work of the cell is to reproduce itself. Each new cell will have its share of the enzymes, ribosomes, RNA, proteins, and so on, which the parent cell has been producing from its DNA blueprints. The cells must produce the machinery they use including the reproduction machinery and the material for growth.
How Do Complex Organisms Develop?

The DNA molecules of a human contain the instructions to make a human. If we wrote out the code, which in principle we could do, it would look like page after page of the letters A, G, C, and T. The book of instructions to build a human would run, according to one estimate, about 1,000,000 pages! This book of 1,000,000 pages is written again and again in every cell of the human body. Everybody’s “book” is unique. Moreover, there are many more possible “books,” each unique, that have never yet been written, even though about 60 billion people have lived at one time or another. A human, unlike a virus or a one-celled organism, is a complex organism consisting of many different kinds of cells. When a one-celled organism reproduces, an identical cell is produced. In a human there are many quite different cells. In some way, parts of the DNA code are switched on and others switched off by the different kinds of cells in the body so that liver cells reproduce liver cells and brain cells reproduce brain cells, even though both kinds of cells contain the full blueprints for the entire human body.

Some parts (genes) of the DNA lie dormant in a cell until activated by the attachment to the genes of proteins that the cell itself produces. A certain set of genes arranged on the chromosomes in the same order as the longitudinal structure of a tiger or a worm produces proteins to turn on the genes in order to produce a head at one end and a tail at the other. Remarkably, these controlling genes seem to be the same for all animals. At the beginning of the development of the embryo, only those parts of the DNA are active that produce the early cells. The presence of the newly created proteins in these cells then switches off one section of DNA and switches on another, thus creating a new set of proteins and, hence, a new kind of cell. The new proteins, in turn, do their own switching. The process continues until a differentiated organism forms.

What Are Favorable Conditions for Life?

We have direct knowledge of only one place in the universe where life exists and thrives. But we see through our telescopes a hundred billion stars in our galaxy and ten billion galaxies besides our own. The chances are good that there are other planets orbiting other stars on which life, as we know it, might exist. We can look at our own planet and identify some conditions that might be important for life:

1. The planet must be large enough so that its gravitational force can hold an atmosphere to its surface. Hence, it must be about the size of earth or larger.
2. The primitive atmosphere must contain water, methane, carbon dioxide, ammonia, and hydrogen sulfide. These compounds were once commonly found in the atmosphere on earth and are presently found on the larger planets of our solar system. However, the primitive atmosphere should not contain free oxygen. These active molecules swiftly interact with the lengthening organic chains and inhibit their further development.
3. The planet must be neither too close nor too far away from its energy source, a star. If too close, the energy will be too intense and destroy the molecular chains as they form and vaporize the water in the atmosphere so that it does not serve the purpose of providing a “soup” in which the molecules can move about. If the star is too far away, the energy will be inadequate to drive the chemical reactions, and the water will be in the unsuitable form of ice.
4. The orbit of the planet must be nearly circular so that wide variations in temperature do not occur on the planet’s surface.
5. The planet should rotate on its axis in such a way that its surface is equally exposed to the star from which it derives its energy. Otherwise, temperature extremes will develop on the planet that will drive destructive weather patterns.
6. The parent star, the source of energy, must not be too large. Large stars burn much faster and die. Such a star would not allow the long time span necessary for the complex molecules of life to be built up. But neither can the parent star be too small, for then it radiates too weakly to sustain life.

Given the billions upon billions of known stars, many feel that it is likely that conditions suitable to life might exist many times over in our universe.

Is Life Inevitable?

For our simple organism, the characteristics of life were growth and reproduction. If we take these as an admittedly limited definition of life—let us call it organic life—then some scientists (but not all) now believe that “organic life” is inevitable. It was built into the universe at the time of its creation. Organic life is in the laws of physics, in the shapes of the orbitals that govern the atoms and that make them chain together in complicated structures.

The raw materials are everywhere. Hydrogen, methane, ammonia, carbon dioxide, hydrogen sulfide, and water have all been observed in abundance as we have sent out space probes to the planets and moons of
our own solar system. Moreover, we can see the identifying light spectrum of these same molecules in the clouds of material in interstellar space. They are literally everywhere. It seems the formation of the primitive molecules is unavoidable in a universe created as ours was, with an abundance of organized energy.

In the early 1950s, Stanley Miller, a graduate student studying with chemist Harold Urey, performed experiments that have been repeated again and again with the same results. He mixed together hydrogen, water, methane, and ammonia in a flask in roughly the proportions we imagine existed on the early earth. He then caused electrical discharges in the mixture. The sparks provided energy to break up the bonds of the primitive molecules. On the early earth the energy would have been provided by ultraviolet radiation from the sun or from lightning discharges.

In a matter of hours a brown scum formed that contained a rich variety of organic molecules, including several amino acids. In subsequent experiments amino acids have been observed, under primitive earth conditions, to chain together to form molecules resembling proteins. Some of these molecules feebly control useful chemical reactions, as enzymes do. Nucleotides have been put together into strands of nucleic acid a few dozen units long. Under the right circumstances in the laboratory, these short nucleic acids can synthesize identical copies of themselves.

But it also must be clearly understood that viruses, the simplest of living things, have DNA with hundreds of nucleotide links. No one has ever mixed together the gases and waters of the early earth and at the end of the experiment had something crawl out of the test tube. Nevertheless, some scientists (often physicists who may underestimate the complexities of life) think that life might already be spread throughout the galaxy. Others, who consider the extremely unlikely chance of events that would be required for spontaneous generation of life, are convinced that, from a scientific point of view, our earth provides the sole instance of life in our galaxy and, perhaps, in the universe.

If organic life were truly inevitable, then there is a second inevitability. As the molecules of life copy one another, mistakes will surely happen. Perhaps two chains will accidentally get stuck together at the ends to form a double chain.

Most accidents are a disaster. But occasionally, given enough time, an accident will occur that is beneficial to the survival of the organism. Such an accident will probably mean an added degree of complexity in the DNA molecule. Therefore, some feel that given time, organized energy, and the inevitable accidents, the protein chains will grow longer, the resulting proteins will become more complex, and the organisms made of the proteins will change. It is possible that organic life will evolve.

Summary

Organic life possesses the capability of growth and reproduction. In these chemical processes, the nucleic acid molecules and chlorophyll play a central role. DNA is the “master molecule” containing the blueprints of the organism. Enzymes, transfer RNA, messenger RNA, and ATP each carry out a specific task.

In our example, primitive molecules and sugar are supplied to a one-celled organism in a nutrient bath. The fundamental source of energy for living things is sunlight. Chlorophyll is a molecule found in plants and is one of the reactants in the complicated series of reactions that synthesize sugar. Sugar from plants is a source of energy for those organisms which themselves cannot make direct use of sunlight. The energy from sugar can be broken down into smaller amounts and distributed throughout an organism by ATP. By storing and transporting energy in ATP, the organism maintains the energy in an organized form.

The genetic code for producing protein for an organism is written in a code along strands of nucleic acid. Proteins are assembled in the ribosomes of a cell. Messenger RNA is a specialized RNA molecule which carries a copy of the code from the DNA in the nucleus of the cell to the ribosomes outside the nucleus. Transfer RNA is a specialized RNA molecule which transports amino acids to the ribosomes.

In this chapter we list a number of conditions on a planet which are essential for life as we know it. Some scientists study the conditions under which simple molecules might react to form the more complicated molecules of life and speculate that life might be common throughout the galaxy or the universe. Others are convinced that the chain of events for life to arise spontaneously is so unlikely that, from a scientific point of view, life on earth is almost certainly the only instance in the galaxy, if not the universe.

STUDY GUIDE
Chapter 23: How Life Works

A. FUNDAMENTAL LIFE WORKS

B. MODELS, IDEAS, QUESTIONS, OR APPLICATIONS
2. What are some of the required conditions for the “creation” of life?
3. What was done and what was learned in the famous Urey-Miller experiment?
4. How do covalent bonds form?
5. What are carbon chains?
6. How are amino acids and nucleotides made?
7. How are proteins made?
8. How is information describing a life form stored, read, and copied?
9. What is a ribosome?
10. What is the function of transfer RNA?
11. What is the function of messenger RNA?

C. GLOSSARY
1. ATP, ADP (adenosine triphosphate, adenosine diphosphate): Specialized molecules used by living systems to store and transport energy to sites where it is needed.
2. Autotroph: Organisms which produce their own organic carbon compounds from water, carbon dioxide, and sunlight.
3. Essential Amino Acid: An amino acid that an organism cannot produce for itself and must have supplied as an external nutrient.
4. Heterotroph: Organisms that cannot manufacture organic compounds from sunlight, carbon dioxide, and water and must rely on ready-made organic compounds.
5. Messenger RNA: A specialized form of RNA which carries a copy of the genetic instructions for building protein from the nucleus of the cell to the ribosomes.
6. Organic Life: In the context of this chapter, a limited definition of life that restricts itself to the essential characteristics of growth and reproduction.
7. Ribosome: Substructure in a cell which is the site where proteins are built.
8. Transfer RNA: A specialized form of RNA which transports amino acids to the ribosomes after they enter the cell from its surrounding nutrient bath.

D. FOCUS QUESTIONS
1. Describe how amino acids and nucleotides are made.
   a. What are enzymes?
   b. Use the mechanical analogy and diagram used in the book (Fig. 22.12) to help illustrate how amino acids and nucleotides are constructed.
2. Describe how a protein is made. Where does the assembly take place? What is messenger RNA and how does it function? What is transfer RNA and how does it function?
3. Describe how DNA is copied to create another DNA molecule. What purpose does the organism have for copying its DNA in this way?

E. EXERCISES
This chapter is organized as the answers to a series of questions. Here we repeat the questions, but break them down into smaller associated questions.

23.1. Where does the cell get its nutrients?
   a. What is a heterotroph?
   b. What is an autotroph?
   c. What is the importance of chlorophyll?

23.2. How does an organism fabricate amino acids and nucleotides?
   a. Where do the raw materials come from?
   b. What are the raw materials?
   c. What special class of proteins catalyze the reactions?

23.3. How do the enzymes get energy to do their task?
   a. What problem does the Law of Increasing Disorder pose?
   b. How is the problem solved?
   c. How is the energy subdivided into usable amounts?
   d. What special molecule is involved? (The three-letter acronym will do.)

23.4. How does the cell make its proteins?
   a. Where are the master plans kept?
   b. How are they coded?
   c. Where are the proteins built?

23.5. How are the blueprints delivered to the ribosomes?
   a. What role does mRNA play?
   b. How does it work?

23.6. How are the raw materials delivered to the ribosomes?
   a. What role does tRNA play?
   b. How does it work?

23.7. How do the ribosomes execute the final assembly? How do they work?

23.8. How does the cell copy the blueprints before division? How does it work?

23.9. What are some favorable conditions for organic life to exist on a planet and thrive?

23.10. Why do some people think that organic life is inevitable in our universe? Why do others think it not inevitable?

23.11. Why do many people think that, given organic life, it is inevitable that it should evolve?