Chapter 7

Biosynthesis

7.1 Introduction

The collective activities of living things on a world can influence the planetary surface environment in many ways. For example, green forests can reduce the planet’s albedo and help warm the atmosphere. On the other hand, the water vapor from forest trees helps to cool the forest by encouraging the formation of clouds. As the roots help make soil from solid rock, they speed up a process called rock weathering which helps cool the planet by removing atmospheric carbon dioxide. But these changes in the environment are caused by life acting on the mechanical level — pumping water, breaking rocks, absorbing light. Life also can profoundly influence the planetary surface environment by acting on the chemical level.

Life possesses a diverse toolbox of chemical activity. If present in abundance, life’s chemistry can influence the planetary surface environment in interesting ways. Living things exploit the chemical properties of several substances found in the Earth’s physical environment — the air, water and soil. Organisms use these planetary materials to build, maintain, operate and reproduce themselves. “Biosynthesis” is the term used to describe the biochemical processes in which living things assemble many different kinds of new molecules. As a consequence of this assembly process, life establishes its potential to chemically change the planet.

The overall biosynthesis process has two main consequences that can lead life toward planet-changing stature:

1) By exchanging materials with the Earth’s environment, biosynthesis establishes life’s potential to change the chemical environment
2) By possessing the ability to assemble useful molecules, biosynthesis supports the dispersal of life. Biosynthesis does this in two ways: a) by establishing the basis for ecological processes like competition and predation — which in turn drive dispersal itself and the evolutionary phenomenon of natural selection; and b) by synthesizing special molecules that help living things to survive in the Earth’s many different environments.

Therefore, the purpose of this chapter is to describe the overall process of biosynthesis on Earth. Its occurrence gives life the potential to chemically influence the planetary surface environment.

7.2 Living things build themselves mostly from just a few elements

Living things are remarkable constructions of tiny parts called molecules (see panel 7.1). The molecules of life are amazingly diverse in terms of their size, shape, makeup and what they do. For example, sugar molecules (see panel 7.2) are small. Their main benefit is the ability to store energy. By contrast, enzyme molecules (a type of protein) are relatively large. They speed up the chemistry of life. All living things are endlessly engaged in a process of self-construction (growth), self-maintenance and other energy-consuming operations like moving materials around inside (like pumping blood), or moving themselves to another location. All of the activities of life that we observe ultimately are dependent upon the presence and action of the parts of life — the molecules. To the extent that a living thing runs out of a particular part, its health is diminished. This idea is very understandable to anyone whose car has broken down. Cars, like living things, are collections of parts that work together as a whole system. The big difference is that living things, unlike cars, build, fix and reproduce themselves. And in order to do that, living things need building materials. They get those from the planet.

Living things build the molecules of life mainly out of smaller parts called atoms (panel 7.1). There are about a hundred different kinds of atoms. Each variety of atom is called an atomic element. Atoms are the most basic form of matter (if we ignore the subatomic particles for the moment). Life mainly uses only about six different kinds of atoms — six different elements. These main elements of life are shown in Table 7.1

Please note, living things require many other kinds of elements in addition to the “main elements” shown in Table 7.1. Still, this chapter will focus on the six main elements of life: carbon, hydrogen, oxygen, nitrogen, phosphorous, and sulfur. Not only are they the most useful to life, they also are the most significant in terms of life’s chemical influence on the planet. Their use on a grand scale by living things has resulted in important consequences to the planetary surface environment.
What is an atom?
To put it simply, an atom is the most fundamental, independent unit of matter. They are extremely tiny. Atoms have recognizable chemical properties and are identified by them. For instance, there are over 100 different kinds of atoms. Chemists call these the atomic elements and they give each kind of atom a name. Life builds itself out of a handful of elements, namely carbon, hydrogen, oxygen, nitrogen, phosphorous and sulfur. On Earth, atoms usually don’t exist totally free. They are usually attached to other atoms making crystals or molecules.

What is a molecule?
A molecule is the smallest particle of a substance that expresses the chemical properties of that substance. Generally, molecules are groups of atoms that are held together with strong bonds. For example, a water molecule is made up of two hydrogen atoms attached to a single oxygen atom. Water’s molecular formula is H$_2$O. The oxygen you breathe actually is a molecule composed of two oxygen atoms stuck

What is a chemical reaction?
A chemical reaction involves two or more chemical substances in which all participants are chemically changed in some way. For example, chemical reactions can be represented in the form of a reaction equation. At right is a reaction equation for photosynthesis. The chemical reaction starts with the reactants, shown on the left side of the reaction equation. The chemical reaction finishes with the products, shown on the right side of the reaction equation. Notice that the products are different substances from the reactants. That means that the reactants are no more, they have been transformed into the products. A chemical reaction is not a mixing of chemicals, it is a rearranging of the parts of chemicals, turning them into something completely different.
7.3 Life gathers materials from different environmental realms of the planetary surface environment

Living things gather the elements they need by consuming certain materials from the atmosphere, water, and soil in different forms (panels 7.1 & 7.2). For example, on Earth plants remove carbon dioxide ($\text{CO}_2$) from the atmosphere. They use the $\text{CO}_2$ to build sugars and other molecules. Plants also consume oxygen from the atmosphere, where it exists as molecular oxygen ($\text{O}_2$). The $\text{O}_2$ then combines with hydrogen inside the plant to become water ($\text{H}_2\text{O}$). Nitrogen is pulled out of the atmosphere by bacteria that live in the soil or in the waters of lakes and oceans. Sulfur and phosphorous mainly are taken out of the soil. Sulfur also spends some time in the atmosphere after it is used up by living things.

7.4 Biosynthesis involves the assembly of many kinds of useful molecules

Biosynthesis is a term that refers to the biological assembly of hundreds of thousands of different kinds of useful molecules. The molecules produced by biosynthesis include: carbohydrates (including sugars and starches); proteins (including enzymes); nucleic acids (including DNA); and lipids (including cell membranes). Additional molecules synthesized by life include vitamins, hormones, alkaloids (like cocaine and caffeine), various pigments (like melanin and carotene) and many kinds of poisons (like glycosides and aflotoxins). These special molecules have interesting adaptive value and will be discussed in chapter 13. For now, I wish to focus on the central “purpose” of biosynthesis, the making of carbohydrates, proteins, nucleic acids, and lipids.

Living things tend to conduct biosynthetic activities very vigorously — as long as they can get the materials and energy they need from their surroundings. Which brings us to the connection between life and the Earth.
It is appropriate now to make a statement that is very obvious, but I want to make it anyway, for emphasis. Here it is. Living things do not inhabit the Earth as totally independent entities, free from Earthly needs. Instead, they exist in a state of constant need for materials and energy. Why? Because biosynthetic processes endlessly consume building materials and energy resources. Biosynthesis is responsible for driving life’s demand for the Earth’s resources. Biosynthesis, in its vigorous efforts to make new living molecules, chemically interacts with the world. It is life’s point of contact with the Earth — the gateway between the physical world and the living world, in which materials are passed back-and-forth. Biosynthesis is the link and the reason behind the link. Therefore, in order to understand the root cause for life’s overall influence on the planet, we need to know more about how life does biosynthesis — its diverse operations, its benefits to living things, and its potential consequences to the planet.

7.5 Our approach to biosynthesis is organized around a four-part model

Biosynthesis is an inherently complex set of processes that involves thousands of different kinds of biochemical reactions. It includes dozens and dozens of intermediate products and thousands of different enzymes. It happens in different places in the cell, and differently in different kinds of organisms. Achieving a comprehensive understanding of biosynthesis would involve a lifetime of study in the fields of biochemistry, molecular biology, cell biology and microbiology. Our objective here is much more limited. The planetary biologist is interested in biosynthesis, but only to the extent that it helps explain the planet. Therefore, many of the details of biosynthesis do not concern us, and we will ignore them. This is largely because our perspective on biosynthesis is necessarily so much different from that of traditional biology. Our goals are to understand: 1) the many ways biosynthesis interacts with the global environment 2) the basic kinds of molecules that biosynthesis builds and how they are useful to living things — keeping in mind that their production, availability and acquisition are important drivers of ecological processes.

In order to condense this huge field of study into a more manageable and appropriate planetary perspective, I invented a new model (figure 7.1). This model organizes all of the processes of biosynthesis into four main components:
1) Planetary Materials 2) Contact Biosynthesis 3) Intermediate Pool 4) Deep Biosynthesis

Although on its face this model is anything but simple looking, it is based upon some very basic principles that should make understandable.

The Earth is made up of many materials, some of which are important biologically. These include: nitrogen gas, oxygen gas, carbon dioxide gas, water, sulfur minerals and phosphate minerals (see panel 7.2). Living things make use of these materials in order to build, maintain, operate and reproduce themselves. Using energy from the sun and energy contained in some of the Earth’s own materials, living things take in the planetary chemicals and assemble them into large molecules. This overall assembly process is called biosynthesis and it happens in three main stages. According to this model, the first stage of biosynthesis is called “Contact Biosynthesis”.

Contact Biosynthesis includes all the major kinds of biosynthetic processes that directly exchange materials with the environment. Included in this stage are familiar processes like photosynthesis and respiration, as well as nitrogen fixation and sulfur oxidation. The products of Contact Biosynthesis include sugar, ATP (an energy-carrying molecule), carbon chains, ammonia and hydrogen sulfide (see panel 7.2). These products flow into the “Intermediate Pool”.

The Intermediate Pool is a hypothetical holding area which then feeds the products of Contact Biosynthesis back to some types of Contact Biosynthesis and to the ultimate destination of biosynthesis — “Deep Biosynthesis”.

Deep Biosynthesis uses chemical energy and materials from the Intermediate Pool to assemble the large molecules of life — proteins, nucleic acids, lipids, carbohydrates and much more. Living things use the large molecules to build, maintain, operate and reproduce themselves.

A consequence of this process is that while biosynthesis is happening, living things are exerting their potential to change and redistribute planetary materials. In addition, pursuit of the means for biosynthesis and the products themselves contribute to dispersal of life by driving ecological processes that in turn drive evolutionary processes.
7.6 Contact Biosynthesis directly exchanges materials with the planet

Contact Biosynthesis is unique when compared to the other stages of biosynthesis because it includes processes that directly exchange materials with the planetary surface environment. Life makes contact with the planet through the chemical processes of Contact Biosynthesis. It brings non-living materials into the living world. It also converts living materials into non-living materials which are then returned to the planet. The main function of Contact Biosynthesis is to take in energy and materials from the physical environment and convert them into forms that can be used to support Deep Biosynthesis. The products of Contact Biosynthesis have two destinations. Some are released back to the planet, while others are fed into the Intermediate Pool.

In terms of life’s influence on the planet, Contact Biosynthesis is the most interesting to the planetary biologist. These processes define the nature of life’s planet-changing capabilities. What follows are brief discussions of the most important forms of Contact Biosynthesis.

The different processes of Contact Biosynthesis fall into three main categories: 1) Carbon fixation; 2) Energy extraction from sugar; and 3) Ammonia production. There are also other interesting processes that do not fit into these categories, such as calcium carbonate precipitation (Panel 7.3), and dimethylsulfide production (Panel 7.4).

7.7 Carbon Fixation attaches hydrogens to carbon to make carbon chain

Carbon fixation is the biosynthetic process that attaches atoms of hydrogen to atoms of carbon, making small carbon chains. Carbon chains are made up of several carbon atoms surrounded by hydrogen attachments. Some carbon chains are later assembled into sugar molecules. Otherwise, the carbon chains go on to make many different kinds of useful molecules.

Since living things build themselves out of carbon, hydrogen and oxygen, the process of carbon fixation is an essential first step. There are several ways to go about fixing carbon into carbon chains. I will present the following ways below: 1) photosynthesis (oxygenic and anoxygenic); 2) sulfur oxidation; and 3) nitrification.

Regardless of the particular pathway toward carbon fixation, certain processes are common:

1) Carbon fixation requires a source of energy and a source of reducing power. The energy usually comes in the form of the energy-carrying molecule, ATP. Reducing power means the ability to attach hydrogen atoms to carbon atoms. The NADPH molecule usually provides the reducing power for carbon fixation.

2) Before proceeding with carbon fixation, ATP and NADPH must first be manufactured by the organism. This is done in a variety of ways, as we will see below.
3) After the manufacture of ATP and NADPH, the actual process of carbon fixation follows, usually carried out by a recycling series of reactions known as the Carbon Fixation Cycle (Figure 7.2 — otherwise known as the Calvin Cycle).

4) Upon completion of the Carbon Fixation Cycle, fixed chains of carbon may proceed to the final synthesis of sugar. But sometimes the Carbon Fixation Cycle doesn’t complete itself. Instead, smaller chains of carbon may spin off in midstream of the cycle. Those smaller chains don’t become sugar molecules. Instead, they join the Intermediate Pool of carbon chains available for other forms of biosynthesis.

The synthesis of sugar has two important biological benefits:

1) The sugar molecule is a physical object of energy storage. The chemical energy it contains can be moved around and stored
2) Once fully formed, sugar also can serve as a source of carbon chains during its later disassembly in the processes of glycolysis, respiration, and fermentation (section 7.8). In any case, both the energy and carbon chains that come from the synthesis and disassembly of sugar are ultimately fed into Deep Biosynthesis.

**7.7.1 Photosynthesis uses the sun’s energy to fix carbon**

Photosynthesis is one of the most important and powerful processes of Contact Biosynthesis. Its source of energy for carbon fixation is the sun. Photosynthetic organisms, make a large molecule that has the ability to capture light energy. The molecule is called chlorophyll, and it is what makes plants look green. Using chlorophyll, the process of photosynthesis captures light energy from the sun and uses it to make ATP and NADPH.

As we will see below (section 7.9.2), the process of photosynthesis also spins off the energetic molecule, NADPH, which is used by green plants to convert nitrate into the more useable ammonia (in assimilative nitrate reduction).

Photosynthesis contributes to big changes in the global environment, mainly as a producer of oxygen gas. Virtually all of the oxygen gas in our atmosphere came from photosynthesis. Photosynthesis also has played a minor role as a remover of carbon dioxide gas from the atmosphere (calcium carbonate precipitation greatly overshadows it).

Photosynthesis occurs in two main ways: 1) oxygenic photosynthesis (which produces O$_2$ gas); and 2) anoxygenic photosynthesis (which doesn’t produce O$_2$ gas).

**7.7.2 Oxygenic Photosynthesis uses water as a source of hydrogens to fix carbon**

Oxygenic photosynthesis is the most familiar and widespread form of photosynthesis. On the continents, it occurs mostly in green plants (Figure 7.3). It is also prevalent in aquatic environments, like lakes, rivers and oceans. There, oxygenic photosynthesis is performed by algae, many protozoans, and cyanobacteria. Also, corals, lichens, giant clams and at least one kind of tiny marine slug are photosynthetic because they are inhabited by symbiotic, photosynthetic microorganisms.
Oxygenic photosynthesis is a complex process that involves a cascade of biochemical reactions. In essence, however, it is fairly simple. The general reaction equation for oxygenic photosynthesis is shown below.

\[ 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{Sunlight} \rightarrow C_6\text{H}_{12}\text{O}_6 \text{(carbon chain)} + 6\text{O}_2 \]

[Carbon dioxide plus water plus sunlight react to make carbon chains plus water plus oxygen gas.]

This reaction equation shows that the process of photosynthesis takes in carbon dioxide gas from the atmosphere, water from the soil (in the case of green plants), and light energy from the sun. Photosynthesis then uses these resources to make carbon chains. The carbon chains later can be used to make a variety of molecules including sugar. Note that water is used as a source of hydrogens. Oxygen gas is given off as a waste product.

I want to draw your attention for a moment to the issue of hydrogens. It turns out that much of the diversity in Contact Biosynthesis centers around the problem of what to do with hydrogen atoms. In order to make organic molecules from carbon dioxide, you need a source of hydrogens. And later, in order to break down those molecules, you have to get rid of those hydrogens. As we will see, the processes of photosynthesis, respiration and fermentation have developed unique ways of dealing with hydrogens. How these processes manage hydrogen also has important biological, ecological and planetary consequences.

**7.7.3 Anoxygenic Photosynthesis uses hydrogen sulfide as a source of hydrogens to fix carbon**

Anoxygenic photosynthesis is probably the oldest form of photosynthesis, perhaps originating within a hundred million years or so after the appearance of life 3.8 billion years ago. Its biochemistry is somewhat simpler than oxygenic photosynthesis. Anoxygenic photosynthesis occurs today in purple bacteria and green sulfur bacteria (Figure 7.4) that inhabit shallow, oxygen-free waters and muds in lakes, swamps, and oceans. Anoxygenic photosynthesis is different from oxygenic photosynthesis in two main ways: 1) The chemical compound, hydrogen sulfide (H\textsubscript{2}S) is used instead of water as a source of hydrogens; and 2) Mineral sulfur (S) is produced instead of oxygen gas. The general reaction equation for anoxygenic photosynthesis is shown below.

\[ 6\text{CO}_2 + 12\text{H}_2\text{S} + \text{Sunlight} \rightarrow C_6\text{H}_{12}\text{O}_6 \text{(carbon chains)} + 6\text{H}_2\text{O} + 12\text{S} \]

[Carbon dioxide plus hydrogen sulfide plus sunlight react to make carbon chains plus water plus mineral sulfur.]

There are major limitations on the geographic distribution of anoxygenic photosynthesis. In order for it to occur, the environment must have a combination of three things: 1) It must be free of oxygen gas; 2) Hydrogen sulfide must be available; and 3) Sunlight must be available. An oxygen-less, hydrogen sulfide-rich environment (typical of deep lake waters or deep in muddy environments) is difficult to find with good exposure to sunlight.

**7.7.4 Nitrification uses the chemical energy in ammonia to fix carbon**

Instead of light energy, the nitrifying bacteria use chemical ammonia (\textsubscript{NH}_3) as an energy source for the synthesis of ATP. Nitrifying bacteria are abundant in soils and shallow muds. Ammonia is present in these environments due to the actions of the nitrogen-fixing bacteria (section 7.9.1). Ammonia possesses a small amount of chemical energy which the nitrifying bacteria can extract and use to make ATP. Once the ATP is synthesized, it has two possible fates: 1) The ATP can act as a general energy provider to the cell, helping in biosynthesis or other operations; or 2) The ATP can be used to synthesize NADPH.

In the case of nitrifying bacteria, much of the ATP produced is used to energize the synthesis of NADPH. Then ATP and NADPH proceed to the Carbon Fixation Cycle and support the synthesis of carbon chains.

The composite reaction equation for nitrification and carbon fixation is shown below.

\[ 6\text{CO}_2 + 6\text{NH}_3 + 6\text{O}_2 \rightarrow C_6\text{H}_{12}\text{O}_6 + 6\text{HNO}_3 \]

[carbon dioxide plus ammonia plus oxygen gas react to make carbon chains plus hydrogen nitrite]
Nitrification is important ecologically since it replenishes supplies of nitrate in the soil which then can be used by the denitrifying bacteria (section 7.8.4). Nitrate also can be easily absorbed by plants which use it in their biosynthesis. However, the conversion of ammonia to nitrate by nitrifying bacteria presents an inconvenience to the process of biosynthesis. This is because nitrate must be reconverted back to ammonia before nitrogen can be used in biosynthesis. The reconversion process is carried out by plants in a process called assimilation (section 7.9.2).

Globally, nitrification is another process that requires molecular oxygen. As a result, nitrification has the potential to: 1) assist in the ultimate return of nitrogen gas to the atmosphere (by supplying nitrate to the denitrifying bacteria); and 2) reduce the quantity of oxygen gas in the atmosphere.

7.7.5 Sulfur-Oxidation uses the chemical energy in hydrogen sulfide to fix carbon

Certain kinds of purple bacteria have the ability to extract the small amount of chemical energy stored in sulfur minerals, including hydrogen sulfide (H₂S) and mineral sulfur (S). Bacteria with these abilities are called the sulfur-oxidizing bacteria. Sulfur-oxidizing bacteria mainly inhabit oxygen-containing muds in aquatic environments like ponds, lakes and oceans. They sometimes live in acid pools. This is no small wonder since one of the main products of sulfur oxidation is sulfuric acid.

They can tolerate high heat too. One species (Thermotrix) lives in sulfur hot springs at temperatures up to 185° F (Figure 7.5). Sulfur-oxidizing bacteria form the ecological base of deep sea hydrothermal vent communities. These ocean bottom hot springs spew out sulfur and hydrogen sulfide. Since they occur on ocean bottoms over 6000 feet deep, there is no sunlight whatsoever. Photosynthesis is not even remotely possible. Instead, the sulfur-oxidizing bacteria perform the job normally done by photosynthesis. Overall, their energy management scheme is very similar to that of the nitrifying bacteria just discussed. The sulfur-oxidizing bacteria use the chemical energy in sulfur minerals to make ATP. The ATP then can either be used to support other biosynthetic activities, or to make NADPH. Then the ATP and NADPH together feed the Carbon Fixation Cycle in which carbon dioxide is ultimately fixed to make sugar.

The general reaction equation for sulfur-oxidation and carbon fixation using hydrogen sulfide is shown below.

\[
6 \text{CO}_2 + 3 \text{H}_2\text{S} + 6 \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 3 \text{H}_2\text{SO}_4
\]

[carbon dioxide plus hydrogen sulfide plus water react to make carbon chains plus hydrogen sulfate, otherwise known as sulfuric acid]

NOTE: This reaction equation, like all shown in this chapter, is a summation and consolidation of a series of many reactions. Although not shown here, molecular oxygen (O₂) is a necessary ingredient in the initial reactions leading to sulfur oxidation. Therefore, this process does best in environments that have O₂.

7.8 The energy stored in sugar is extracted in order to make ATP

Once sugar molecules are made following carbon fixation, they have several possible fates:

1) They can be fed directly into Deep Biosynthesis. There, they can be chained together to make durable energy storage molecules like starch or glycogen. Or they can be used to make rugged structural materials like cellulose.

2) Sugar molecules can be utterly disassembled in the energy-extraction processes of glycolysis, respiration, and fermentation. These processes remove the energy stored in sugar and use it to make energy-carrying ATP molecules which are universally and instantly useful (Figure 7.6). ATP molecules provide energy for the biosynthetic process and for the operation of the molecules that result from biosynthesis.

Sugar molecules also can be fed into Deep Biosynthesis by indirect means — but they are first broken apart into carbon chains. For example, the processes of glycolysis, respiration and fermentation spin off several different kinds of carbon chains that later are useful in the synthesis of proteins, nucleic acids and lipids.

7.8.1 Glycolysis precedes respiration and fermentation

Glycolysis is the biochemical process that precedes the two main processes that will be discussed below. They are:

1) respiration
2) fermentation
Respiration occurs in two main forms: 1) the Krebs cycle, and respiratory chain are in place — that follow, it is assumed that the components of the respiration. Therefore, in the discussions of respiration into a single process, which I will refer to simply as respiratory chain. Instead, I have consolidated them thermodynamic details of the Krebs cycle and fascinating and abundant biochemical and the global environment, I have chosen to ignore the intricate details of this system, as most biology books do, will not advance our efforts. So that we do not planetary biological perspective, I think that dwelling on this reason, I believe it is appropriate to consider respiration as a necessary part of the biosynthetic machine.

Also, from a biochemical point of view, respiration is usually seen as only one part of a larger, multiple-part energy extraction process consisting of: 1) the Krebs cycle; and 2) the respiratory chain. Reasserting our following important functions:

1) Respiration totally disassembles sugar molecules (or other small organic molecules) and releases carbon dioxide
2) During sugar disassembly, respiration extracts the energy from sugar and uses it to build ATP molecules
3) In the end, respiration must somehow get rid of waste hydrogen atoms. Different solutions to the dilemma posed by the waste hydrogens distinguishes aerobic respiration from anaerobic respiration. If the hydrogens are not disposed of, then the whole process clogs up like a big traffic jam. A popular but less efficient side route around congested respiration is the process of fermentation, discussed later (section 7.8.5).

7.8.2 Respiration is the most efficient producer of ATP

The discussion of respiration that follows is somewhat unconventional as biology books go. Typically, respiration is treated mainly, and often exclusively, as an energy management system and nothing more. Its role in biosynthesis frequently is overlooked. Perhaps due to its total destruction of sugar molecules, many biologists do not consider respiration to be a mechanism of biosynthesis. However, because of its role in spinning off important carbon chains and in supplying ATP energy, respiration plays a vital part in supporting later biosynthesis — Deep Biosynthesis. For this reason, I believe it is appropriate to consider respiration as a necessary part of the biosynthetic machine.

Consequently, aerobic respiration is shown below (Note: for brevity, ADP and P are not shown):

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

[Sugar plus water plus molecular oxygen react to make carbon dioxide plus water plus ATP]

In this reaction, sugar is utterly dismantled yielding chemical energy along the way. The chemical energy liberated by respiration is captured in the form of the universally redeemable ATP molecule. ATP then is fed into the Intermediate Pool.

7.8.3 Aerobic respiration uses molecular oxygen (O_2) to get rid of waste hydrogens

With aerobic respiration, molecular oxygen \( O_2 \) takes away the waste hydrogens by reacting with them to make water. The reaction equation for aerobic respiration is shown below (Note: for brevity, ADP and P are not shown):

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

[Sugar plus water plus molecular oxygen react to make carbon dioxide plus water plus ATP]

In this reaction, sugar is utterly dismantled yielding chemical energy along the way. The chemical energy liberated by respiration is captured in the form of the universally redeemable ATP molecule. ATP then is fed into the Intermediate Pool.

7.8.4 Anaerobic respiration uses nitrate to get rid of waste hydrogens (Denitrification)

Anaerobic respiration happens in oxygen-free environments. When oxygen is not available, other substances are used to dispose of waste hydrogens. For example, denitrifying purple bacteria use the substance, nitrate, when molecular oxygen is not available. The general reaction equation for anaerobic respiration using nitrate is shown below.

\[ 5 C_6H_{12}O_6 + 24 HNO_3 \rightarrow 30 CO_2 + 42H_2O + 12 N_2 + ATP \]
[sugar plus hydrogen nitrate react to make carbon dioxide plus water plus nitrogen gas plus ATP]

The denitrifying bacteria mostly are purple bacteria of the widely distributed genus Pseudomonas. These bacteria are interesting in that when molecular oxygen is available, they use aerobic respiration. But if molecular oxygen is not available, they shift over to anaerobic respiration using nitrate. They are also interesting to the planetary biologist since, in addition to carbon dioxide, they return nitrogen gas to the atmosphere. This may be a very important service to life on the continents by replenishing the nitrogen gas removed by nitrogen-fixing bacteria (section 7.9.1).

7.8.5 Fermentation is a popular but sluggish detour when oxygen is not available

In environments where molecular oxygen is not available, the process of fermentation can take over. Fermentation occurs as a standby backup energy extraction process in all aerobic bacteria, protozoans, algae, fungi (including yeasts), plants, and animals. But it is the main mode of getting energy from sugar in many anaerobic bacteria (except the methanogenic bacteria, sulfate-reducing bacteria and aceticogenic bacteria — sections 7.8.6 and 7.8.7).

Basically, fermentation kicks in when there is a buildup of waste hydrogen gases at the end of the respiration process. Normally, molecular oxygen or nitrate are the removers of waste hydrogens. If they are absent, such as in deep muds, soils, or stagnant water, then respiration stops because the hydrogens clog the system, causing a traffic jam. The carbon chain products of glycolysis (pyruvate) then are diverted onto a side street called fermentation which continues their disassembly and ATP formation. The big difference is that for each sugar molecule, fermentation produces about 20 time less ATP than respiration. So, fermentation does not support vigorous activity.

For example, after you do sit-ups for awhile, you start getting tired. That’s because your muscles are demanding oxygen faster than your blood can supply it (the oxygen you breathe in is used to support respiration in your cells). Since they can’t support respiration any longer (because of lack of oxygen), your muscle cells shift over to fermentation. But since fermentation is much less efficient, your ability to continue sit-ups quickly falls off, and you are finally too weak to continue.

Another big difference about fermentation compared to respiration is the large variety of waste products fermentation makes. They include lactic acid, ethanol (the type of alcohol in beer and wine), and acetic acid (the acid that gives vinegar its sour “bite”). Fermentation in your tired muscles yields lactic acid. Although a buildup of lactic acid generally is not good for you (it can contribute to the making of sore muscles), lactic acid fermentation in bacteria is useful in the making of yogurt and cheese (Figure 7.7). Ethanol and CO₂ are produced by yeast and bacteria. This is how champagne gets its sparkle, and its notorious alcoholic ‘kick’. Bakers also benefit from the fermentation process as the production of CO₂ by fermenting yeast cause the bread to rise from an otherwise solid blob of dough (Figure 7.8).

The waste products of fermentation occasionally represent carbon chains which are useful in the biosynthesis of larger molecules. More likely, however, fermentation wastes end up being released to the environment where they either cause a contamination problem (such as the death of yeast caused by the accumulation of ethanol in a corked bottle of grape juice/wine), or they are used by other microorganisms as a source of energy.

Some of the waste products of fermentation still contain chemical energy. They are used by special groups of bacteria including the methanogenic bacteria, and the sulfate-reducing bacteria who have no ability to perform glycolysis or fermentation themselves. Both of these types of bacteria live strictly in oxygen-free environments. They are interesting ecologically because they cannot use sugar directly. Instead, methanogenic bacteria and sulfate-reducing bacteria live in close association with other kinds of bacteria that produce fermentation waste products.

7.8.6 Sulfate-reducing bacteria extract energy from fermentation waste products

Most sulfur in the Earth’s crust is found in the form of sulfate minerals, mainly gypsum (Calcium sulfate) and sulfide minerals, like iron pyrite (FeS₂). In the oceans, sulfur exists mainly in the form of dissolved sulfate. Certain bacteria, called sulfate-reducing bacteria, use sulfate to dispose of waste hydrogens.

The sulfate-reducing bacteria live only in environments that have no molecular oxygen. They are widely distributed in oxygen-free environments. For example, if you have ever dug up the black mud from a pond or standing pool of water (Figure 7.9), you probably remember smelling something like rotten eggs. That was the hydrogen sulfide produced by the sulfate-reducing
bacteria living in the mud. Sulfate-reducing bacteria use sulfate to get rid of waste hydrogens. The general reaction equation for anaerobic respiration using sulfate is given below.

\[ \text{C}_2\text{H}_4\text{O}_2 + \text{H}_2\text{SO}_4 \longrightarrow 2 \text{CO}_2 + 2 \text{H}_2\text{O} + \text{H}_2\text{S} + \text{ATP} \]

Note that in this reaction equation I have shown acetic acid as the energy-carrying molecule. Acetic acid is one of many different kinds of waste materials generated from the process of fermentation.

Hydrogen sulfide can go straight into Deep Biosynthesis for the formation of amino acids and proteins. Sulfate-reducing bacteria are important ecologically because they return hydrogen sulfide to the environment, making it available again for anoxygenic photosynthetic bacteria and sulfur-oxidizing bacteria. Regarding the global environment, sulfate-reducing bacteria are important because they return \( \text{CO}_2 \) to the atmosphere.

### 7.8.7 Methanogenic bacteria extract energy from fermentation waste products

Methanogenic bacteria live deep underground and in muds along with sulfate-reducing bacteria. They flourish in the growing accumulations of municipal garbage dumped in landfills. But they also are abundant in the guts of animals like cows, termites (Figure 7.10) and humans. These environments are thriving communities of different kinds of bacteria. Methanogenic bacteria take in waste hydrogens, waste carbon dioxide, or waste acetic acid that are produced by fermentative bacteria. The methanogenic bacteria use these wastes as a source of energy, then produce a new waste of their own — methane gas. The general reaction equation for methanogenesis is shown below.

\[ \text{C}_2\text{H}_4\text{O}_2 \longrightarrow \text{CH}_4 + \text{CO}_2 + \text{ATP} \]

[acetic acid reacts to make methane plus carbon dioxide plus ATP]

Another reaction equation for methanogenesis is given below.

\[ 4\text{H}_2 + \text{CO}_2 \longrightarrow \text{CH}_4 + 2 \text{H}_2\text{O} + \text{ATP} \]

[hydrogen gas plus carbon dioxide react to make methane plus water plus ATP]

Methanogenic bacteria live in the rumen (sort of a multiple stomach) of cows and other grazing animals, like deer and Wildebeest. These animals burp out huge amounts of methane produced by the methanogenic bacteria living inside. Termites harbor methanogenic bacteria in their intestines and are one of the largest single sources of methane emissions on the planet. Humans also serve as host to methanogenic bacteria which live in our intestines. Their busy work inside of us is manifested occasionally in the most embarrassing way, as we release methane from the end of our digestive tract.

In terms of the global environment methane production is very important since methane is a powerful greenhouse gas. Emissions of methane have been on the rise because of increases in cattle populations worldwide, and the increased cultivation of rice whose flooded fields support mud-dwelling methanogenic bacteria.
This DRAFT document is an excerpt from *Principles of Planetary Biology*, by Tom E. Morris.

7.8.8 *In summation, energy extraction processes provide energy and supplies to Deep Biosynthesis*

This concludes the section on energy extraction from sugar. Altogether, the biological aim of these processes is the production of the Intermediate Pool substance, ATP. ATP then is available as an energy source for Deep Biosynthesis. In the process of disassembling sugar molecules, living things employ several interesting solutions to deal with the problem of disposing of waste hydrogens. Aerobic respiration uses molecular oxygen. Anaerobic respiration uses nitrate. Fermentation releases whole carbon chains with the hydrogens still stuck to them. Sulfur-reducing bacteria intercept the fermentation wastes, then use sulfate to dispose of waste hydrogens. Methanogenic bacteria also consume fermentation wastes and dispose of waste hydrogens by making methane. Also, while sugar is being disassembled in this energy extraction process, some of the carbon chains spin off to become useful carbon chains.

In terms of the global environment, the energy extraction process in all forms represents one of life’s most diversified and vigorous planet-changing engines. It involves the mass movements of nitrogen gas, oxygen gas, carbon dioxide gas, water, and sulfate.

7.9 *Ammonia production makes nitrogen accessible to Deep Biosynthesis*

Nitrogen is a very important element that is used to make proteins, nucleic acids, membranes and other useful molecules like ATP. On Earth, the greatest pool of nitrogen is in the atmosphere in the form of nitrogen gas (N₂). But just plain nitrogen gas cannot be used by living things. Instead, it first must be converted to ammonia (NH₃). This is where the problem starts.

Unlike carbon, getting nitrogen into the living world is not so easy. Nitrogen gas tends to be a very stable substance that rarely combines with other kinds of atoms. So, breaking it up and attaching hydrogens to it (making ammonia) is a difficult task that only certain kinds of bacteria are capable of. The process of making ammonia from nitrogen gas is called *nitrogen fixation*. Nitrogen is much more reactive while part of the ammonia molecule. So, once the ammonia is produced, the nitrogen it carries can be easily incorporated into large molecules in Deep Biosynthesis. The most aggressive ammonia consumers are the nitrifying bacteria (section 7.7.4). They use ammonia as a source of hydrogens in the fixation of carbon. The nitrifying bacteria produce nitrate as a waste product. That doesn’t do other living things much good since the nitrate must again be changed to ammonia. The process of changing nitrate to ammonia is called assimilative nitrate reduction, and it is performed by green plants. Let’s discuss nitrogen fixation first.

7.9.1 *Nitrogen fixation pulls nitrogen out of the air to make ammonia*

Nitrogen fixation is an extremely important biological process. In this process, several different kinds of bacteria remove nitrogen gas (N₂) from the atmosphere and convert it to ammonia (NH₃). Only certain kinds of bacteria can perform nitrogen fixation, including some cyanobacteria, purple bacteria, the symbiotic bacterium, *Rhizobium*, and the gram positive bacterium, *Clostridium*. Nitrogen is necessary in the biosynthesis of ATP, NADPH, proteins, cell membranes (a type of lipid), nucleic acids and many other kinds of molecules. But biosynthesis cannot use nitrogen gas directly. So nitrogen fixation is important because it converts nitrogen gas into a form that can be used by biosynthesis — ammonia. The general reaction equation for nitrogen fixation is shown below:

\[
\text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{H}_2\text{O} + 4\text{N}_2 \rightarrow 6 \text{CO}_2 + 8 \text{NH}_3
\]

[sugar plus water plus nitrogen gas react to make carbon dioxide plus ammonia]

Note that sugar is the ultimate source of hydrogens in this reaction. And, this reaction actually consumes more energy than it puts out.

In the sea, the main nitrogen fixers are the cyanobacteria. On land, nitrogen is fixed by bacteria in the soil or mud. The bacterium, *Rhizobium*, lives in special root nodules of legume plants (like peas, beans, clover, alfalfa, and soybeans). Inside these nodules, *Rhizobium* fixes nitrogen to ammonia which is absorbed directly by the plant roots. In addition to the symbiotic *Rhizobium*, there are many free-living bacteria that fix nitrogen gas. However, the ammonia produced by free-living soil bacteria is quickly consumed by another band of bacteria, the nitrifying bacteria (section 7.7.4, above).

7.9.2 *Assimilative nitrate reduction converts nitrate to ammonia*

The consumption of ammonia by nitrifying bacteria reduces the amount of ammonia in the soil. After using ammonia, the nitrifying bacteria release nitrate as a waste. As a result of this conversion process, the primary source of nitrogen to most plants is nitrate. Nitrate is a kind of salt that can dissolve in water and be taken in by the roots of plants.
But once inside, the nitrate must be converted back to ammonia for use in biosynthesis. The process that converts nitrate back to ammonia for this purpose is called assimilative nitrate reduction. This is an energy-consuming reaction.

Assimilative nitrate reduction happens inside the chloroplasts (tiny green objects inside leaf cells -Figure 7.11) of green plants and uses light as its source of energy. It is a sort of side reaction that happens alongside photosynthesis. Remember that in photosynthesis, NADPH is made with the help of light energy. The main function of NADPH is to transfer hydrogen atoms to carbon atoms in the Carbon Fixation Cycle. Assimilative nitrate reduction adds a different twist to this process. In assimilative nitrate reduction, several NADPH molecules are diverted away from the Carbon Fixation Cycle and their hydrogens are transferred to nitrogen instead of carbon. The result is the production of ammonia which then can be used in Deep Biosynthesis. The general reaction equation for assimilative nitrate reduction is shown below.

\[ 2 \text{HNO}_3 + 2 \text{H}_2\text{O} + \text{Sunlight} \rightarrow 2 \text{NH}_3 + 4 \text{O}_2 \]

[Hydrogen nitrate plus water plus sunlight react to make ammonia plus oxygen gas.]

This reaction equation should look very similar to that of oxygenic photosynthesis. Water is consumed and used as a source of hydrogens and sunlight provides the energy. Notice too that molecular oxygen is produced. However, this does not really represent a net increase in oxygen production. Remember that two related processes, nitrification/carbon fixation and aerobic respiration both consume molecular oxygen. So, if there is perfect coupling between these three reactions, all materials are completely recycled.

7.10 The reactions of Contact Biosynthesis are coupled such that they recycle all materials

Looking at the many different kinds of processes in Contact Biosynthesis you should begin to sense that, collectively, living things make elegant use of planetary materials. As complicated as a single living things is, there are really only a few kinds of materials that it needs. And these same kinds of materials are used in very similar ways by all living things. For example, on Earth, carbon dioxide is the ultimate source of carbon for the construction of biological molecules. It is also the main carbon waste product from the dismantling of biological molecules during energy extraction. By the same token, water is the overwhelming favorite source of hydrogens when building sugar, and it is returned to the physical world when disassembling sugar for energy. So, carbon dioxide and water are recycled by biological processes.

If we look at other processes, a very interesting pattern begins to emerge. We start to see opportunities for recycling amongst all of the diverse biochemical operations we have dealt with so far. Table 7.2 (next page) organizes the various reaction equations into sets of coupled reactions in which all of the reactants and products are completely recycled. Notice that in each set of coupled reactions is a source of energy, almost always sunlight.

So, driven by the sun’s energy, the biochemical processes of Contact Biosynthesis have the potential to churn the planet. Left to their own devices, it seems that biosynthetic processes will continuously recycle planetary materials as long as three conditions for ideal recycling (Figure 7.12) are met:

1) Reaction sets are perfectly coupled
2) Coupled reactions are not somehow uncoupled or otherwise interfered with
3) There is a steady input of sunlight energy.

If all three conditions are satisfied, then life should have little or no recognizable chemical impact on a planet. It would just turn things round and round and there would be no large net movement of materials between the air, the water or the soil. But this is not what we see in the history of Earth.

7.11 Geological burial of biosynthetic products uncouples reaction sets

Instead of an unchanging planet, Earth’s chemical environment has evolved in many ways. For instance, the atmosphere has experienced big increases in oxygen gas and big decreases in carbon dioxide, and life has been largely responsible. But how could this be if the coupled reactions so perfectly recycle materials? In order for life to cause such big changes, the ideal recycling process must be interrupted, the coupled reactions uncoupled. Such disruptions cause net movements of materials out of one realm and into another. The perfect circle is sometimes broken.
### Table 7.2
Examples of Coupled Contact Biosynthetic Reactions

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Chemical Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon Fixation by Oxygenic Photosynthesis</strong></td>
<td>$6\text{CO}_2 + 6\text{H}_2\text{O} + \text{Sunlight} \rightarrow \text{C}<em>6\text{H}</em>{12}\text{O}_6 + 6\text{O}_2$</td>
</tr>
<tr>
<td><strong>Aerobic Respiration</strong></td>
<td>$\text{C}<em>6\text{H}</em>{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}$</td>
</tr>
<tr>
<td><strong>Carbon Fixation by Nitrification</strong></td>
<td>$6\text{CO}_2 + 6\text{NH}_3 + 6\text{O}_2 \rightarrow \text{C}<em>6\text{H}</em>{12}\text{O}_6 + 6\text{HNO}_3$</td>
</tr>
<tr>
<td><strong>Assimilative Nitrate Reduction</strong></td>
<td>$2\text{HNO}_3 + 2\text{H}_2\text{O} + \text{Sunlight} \rightarrow 2\text{NH}_3 + 4\text{O}_2$</td>
</tr>
<tr>
<td><strong>Aerobic Respiration</strong></td>
<td>$\text{C}<em>6\text{H}</em>{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}$</td>
</tr>
<tr>
<td><strong>Carbon Fixation by Oxygenic Photosynthesis</strong></td>
<td>$6\text{CO}_2 + 6\text{H}_2\text{O} + \text{Sunlight} \rightarrow \text{C}<em>6\text{H}</em>{12}\text{O}_6 + 6\text{O}_2$</td>
</tr>
<tr>
<td><strong>Fermentation &amp; Methane Production</strong></td>
<td>$\text{C}<em>6\text{H}</em>{12}\text{O}_6 \rightarrow 3\text{CH}_4 + 3\text{CO}_2$</td>
</tr>
<tr>
<td><strong>Spontaneous Chemical Breakdown</strong></td>
<td>$3\text{CH}_4 + 6\text{O}_2 \rightarrow 3\text{CO}_2 + 6\text{H}_2\text{O}$</td>
</tr>
<tr>
<td><strong>of Methane in Environment</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Carbon Fixation by Anoxygenic Photosynthesis</strong></td>
<td>$6\text{CO}_2 + 12\text{H}_2\text{S} + \text{Sunlight} \rightarrow \text{C}<em>6\text{H}</em>{12}\text{O}_6 + 12\text{S} + 6\text{H}_2\text{O}$</td>
</tr>
<tr>
<td><strong>Fermentation and Mineral Sulfur Reduction</strong></td>
<td>$\text{C}<em>6\text{H}</em>{12}\text{O}_6 + 12\text{S} + 6\text{H}_2\text{O} \rightarrow 6\text{CO}_2 + 12\text{H}_2\text{S}$</td>
</tr>
<tr>
<td><strong>Carbon Fixation by Sulfur Oxidation</strong></td>
<td>$6\text{CO}_2 + 3\text{H}_2\text{S} + 6\text{H}_2\text{O} \rightarrow \text{C}<em>6\text{H}</em>{12}\text{O}_6 + 3\text{H}_2\text{SO}_4$</td>
</tr>
<tr>
<td><strong>Fermentation and Sulfate Reduction</strong></td>
<td>$\text{C}<em>6\text{H}</em>{12}\text{O}_6 + 3\text{H}_2\text{SO}_4 \rightarrow 6\text{CO}_2 + 3\text{H}_2\text{S} + 6\text{H}_2\text{O}$</td>
</tr>
<tr>
<td><strong>Carbon Fixation by Oxygenic Photosynthesis</strong></td>
<td>$24\text{CO}_2 + 24\text{H}_2\text{O} + \text{Sunlight} \rightarrow 4\text{C}<em>6\text{H}</em>{12}\text{O}_6 + 24\text{O}_2$</td>
</tr>
<tr>
<td><strong>Nitrogen Fixation</strong></td>
<td>$3\text{C}<em>6\text{H}</em>{12}\text{O}_6 + 18\text{H}_2\text{O} + 12\text{N}_2 \rightarrow 18\text{CO}_2 + 24\text{NH}_3$</td>
</tr>
<tr>
<td><strong>Carbon Fixation by Nitrification</strong></td>
<td>$24\text{CO}_2 + 24\text{NH}_3 + 24\text{O}_2 \rightarrow 4\text{C}<em>6\text{H}</em>{12}\text{O}_6 + 24\text{HNO}_3$</td>
</tr>
<tr>
<td><strong>Denitrification (Nitrate Respiration)</strong></td>
<td>$5\text{C}<em>6\text{H}</em>{12}\text{O}_6 + 24\text{HNO}_3 \rightarrow 30\text{CO}_2 + 42\text{H}_2\text{O} + 12\text{N}_2$</td>
</tr>
</tbody>
</table>

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7.12 Oxygen builds up in the atmosphere because of the burial of fixed carbon

For example, in order for oxygen gas to build up in the atmosphere, there has to be less fixed carbon for it to react with in the oceans and on the continents. This is accomplished by geologic processes that bury the remains of living things (Figure 7.13). The burial process results in a one-way movement of carbon dioxide and water into the Earth’s crust (in the form of fixed carbon), and a one-way movement of oxygen gas into the atmosphere. As a result, fixed carbon accumulates deep in the Earth's crust, and oxygen gas accumulates in the atmosphere. It turns out that for the processes we have discussed so far, the potential for life to chemically influence the planet ironically is dependent upon the planet interfering with the chemical cycles of life. It does this by disrupting the connections between coupled reactions. But there are other forms of biosynthesis which exert their influence in slightly different ways — namely, the precipitation of calcium carbonate, and the production of dimethylsulfide.

7.13 Calcium carbonate precipitation is a non-coupled biosynthetic process

The precipitation (solidification) of calcium carbonate is a form of non-coupled biosynthetic process. There is virtually no recycling of solid calcium carbonate back to calcium and carbon dioxide. Therefore, the biological precipitation of calcium carbonate is by far the greatest permanent remover of atmospheric carbon dioxide of all planetary processes. Please read about it in Panel 7.3 (next page).

7.14 The potential influence of dimethylsulfide depends on sulfur cycling

The influence of dimethylsulfide (DMS) is greatest while the coupled reactions of the sulfur cycle remain intact. DMS is released as a waste product from the metabolism of sulfur compounds. Once in the atmosphere, DMS undergoes additional reactions that may increase the production of clouds over the open ocean. Read about it in Panel 7.4.

Panel 7.4. Potential environmental consequences of DMS production

There has been recent interest in the biological production of a substance called dimethylsulfide (DMS). DMS is emitted in large quantities over the oceans. Once in the atmosphere, DMS undergoes a series of reactions that convert it to airborne sulfate. The sulfate particles in the air then act as nuclei for the condensation of the tiny water droplets that make up clouds. So, the more DMS emitted, the more clouds. And clouds have the potential to warm the planet or cool it, depending upon how they form.

So, what is the biological reason for DMS production? It turns out that DMS is made following the degradation of dimethylsulfonium proprianate (DMSP). DMSP is made from the sulfur-containing amino acid methionine and it helps microscopic marine algae regulate their internal water balance. When individual algae are consumed by marine bacteria (for example, after they die), the bacteria can use DMSP as an energy source. In this way, DMSP is degraded to DMS and released to the atmosphere. The general flow for this process is shown below.

Methionine ————> DMSP ————> DMS

[Amino acid] [Helps in salt/water balance] [waste from DMSP breakdown]
The biosynthetic precipitation of calcium carbonate is different from the processes we have looked at so far because it is almost entirely a non-coupled process. Calcium carbonate is a very hard substance. The sea shells you pick up at the sea shore are constructed out of it. Calcium carbonate makes up coral reefs and the shells of hundreds of different kinds of aquatic organisms, big and small.

In order for calcium carbonate to be used as a solid, it first must be precipitated from its dissolved form. Chemical precipitation is a process that makes a solid out of a substance that is otherwise dissolved in water. For example, the soap scum that accumulates on the sides of your bathtub is a result of the precipitation process. Soap that is usually dissolved in water sticks to the bathtub walls as a solid.

In the waters of the oceans, lakes and rivers, calcium carbonate is dissolved. Calcium carbonate almost never precipitates on its own (except for the whitings of the Bahamas). In nearly all circumstances, living things are responsible for the precipitation of calcium carbonate according to the following process.

\[ \text{CaCO}_3 \text{(Dissolved)} \rightarrow \text{CaCO}_3 \text{(Solid)} \]

[Dissolved calcium carbonate is precipitated to solid calcium carbonate.]

The carbonate (\( \text{CO}_3^{3-} \)) is formed beforehand from carbon dioxide gas in the atmosphere.

In terms of planetary biology, the significance of the biosynthetic precipitation of calcium carbonate is that it is a non-coupled consumer of atmospheric carbon dioxide. That means it has great power to remove carbon dioxide from the atmosphere and never recycle it. This is what has happened on Earth in great measure, starting about 2.5 billion years ago. Solid calcium carbonate has been very useful to living things because of its high strength and durability. And because of its toughness, calcium carbonate tends to last a long, long time. In fact, calcium carbonate precipitated by living things lasts hundreds of millions of years. So, once solidified, calcium carbonate tends to accumulate in the environment, settling on ocean bottoms. Today, it forms the huge volume of limestone deposits in the Earth's crust. It is estimated that there are about 4.4 x 10^19 pounds of calcium carbonate deposits in the crust (Holman in Butcher et al.). That is 44 billion billion pounds, an amount equivalent to the entire surface of the Earth covered in Cadillac cars 320 deep.

Since carbon dioxide is a greenhouse gas, its removal in such large amounts by calcium carbonate precipitation probably had profound effects on the Earth's global climate.

Unlike sugar, solid calcium carbonate is not a consumable substance that can be used by Deep Biosynthesis or any other biochemical process. In other words, once calcium carbonate is formed, it stays calcium carbonate and is not biologically recycled back into free calcium and carbon dioxide. Thus is the nature and power of non-coupled biosynthetic reactions to cause the one-way, net movement of materials from one realm to another. In the case of calcium carbonate precipitation, carbon dioxide leaves the realm of the atmosphere and is permanently stored in the realm of the lithosphere (the Earth's crust). (NOTE: After hundreds of millions of years, the carbon stored in limestone can be slowly recycled back into the atmosphere from volcanoes following the tectonic processes of subduction.)
7.15 In summary, uncoupled or non-coupled contact biosynthetic processes have the greatest potential to change the planet

Let us review for a moment here. We have seen that the processes of Contact Biosynthesis establish their planet-changing potential mostly when they are occasionally uncoupled (as in burying fixed carbon) or when they occur in non-coupled form (as in the precipitation of calcium carbonate). As a result, these uncoupled or non-coupled biosynthetic reactions do not recycle materials. Instead, they cause a one-way movement of materials from one realm to another. As a consequence, uncoupled or non-coupled biosynthetic reactions have the greatest potential to change the chemical environment of the planet by eventually causing gross re-distributions of planetary materials. We will see in chapter 15 that certain changes to the chemical environment are among the most important ways that life influences the planet.

Table 7.3 (next page) summarizes all of the reactions discussed so far.

---

### Table 7.3

<table>
<thead>
<tr>
<th>Planetary Materials</th>
<th>Intermediate Pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar, ATP, NADH</td>
<td>Sugar, ATP, NADH</td>
</tr>
<tr>
<td>Phosphate Minerals</td>
<td>Phosphate Minerals</td>
</tr>
<tr>
<td>Carbon Skeletons</td>
<td>Carbon Skeletons</td>
</tr>
<tr>
<td>Hydrogen Sulfide (H₂S)</td>
<td>Hydrogen Sulfide (H₂S)</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>Ammonia (NH₃)</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Nitrate</td>
</tr>
</tbody>
</table>

---

7.16 The Intermediate Pool feeds Deep Biosynthesis with energy and supplies

The Intermediate Pool is a theoretical holding area for the products of Contact Biosynthesis. As we have already seen, some of the Intermediate Pool materials (like sugar) feed back to support different Contact Biosynthetic processes. But ultimately, the materials of the Intermediate Pool are drawn upon by the needs of Deep Biosynthesis.

Deep Biosynthesis uses materials almost exclusively from the Intermediate Pool to assemble very large molecules. The processes of Deep Biosynthesis are all but entirely dependent upon the products of Contact Biosynthesis as a source of supplies and energy.

Deep Biosynthesis typically happens in two main stages (Figure 7.14). Stage one uses Intermediate Pool energy and supplies to make an assortment of building block molecules. During stage two, these building block molecules are assembled into very big molecules, including proteins, nucleic acids, lipids, and
### Table 7.3. Potential Environmental Consequences of Contact Biosynthesis

<table>
<thead>
<tr>
<th>Biochemical Process</th>
<th>Biological Usefulness</th>
<th>Organisms</th>
<th>Requires</th>
<th>Removal from Physical Environment</th>
<th>Addition to Physical Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon Fixation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>By Oxidative Photosynthesis</td>
<td>Sugar stores energy &amp; source of carbon skeletons; Q: useful later in respiration</td>
<td>Cyanobacteria, Chloroplasts in plants, algae, lichens, phytoplankton, corals</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>By Anaerobic Photosynthesis</td>
<td>Sugar stores energy &amp; source of carbon skeletons</td>
<td>Anaerobic Purple, Brown or Green Sulfur bacteria</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>By Sulfur Oxidation</td>
<td>Using energy from hydrogen sulfide to make ATP &amp; NADPH to make sugar</td>
<td>Sulfur-oxidizing purple bacteria</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>By Nitritation</td>
<td>Using energy from ammonia to make ATP &amp; NADPH to make sugar</td>
<td>A few kinds of autotrophic bacteria (Nitrospora)</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td><strong>Extracting Energy from Sugar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerobic Respiration</td>
<td>Extraction and use of energy stored in sugars, starches, fats; O2 carries off waste hydrogen as H2O</td>
<td>Aerobic bacteria, Mitochondria in algae, fungi, protozoans, plants, animals</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>Denitritiation (Anaerobic, Nitrification)</td>
<td>Extraction and use of energy stored in sugars, starches, fats</td>
<td>Anaerobic, denitrifying bacteria (Pseudomonas)</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>Fermentation &amp; Methane Production (Composite)</td>
<td>Extraction of energy stored in sugars, proteins, fatty acids in the absence of O2</td>
<td>Anaerobic free-living bacteria; yeasts: Fungi; symbiotic bacteria in animal guts</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>Fermentation and Sulfate Reduction (Composite)</td>
<td>Extraction of energy stored in organic compounds released by fermenters</td>
<td>Anaerobic, purple bacteria and archaeobacteria</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>Fermentation and Mineral Sulfur Reduction</td>
<td>Extraction of energy stored in organic compounds released by fermenters</td>
<td>Anaerobic, purple bacteria and archaeobacteria</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td><strong>Ammonia Production</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen Fixation</td>
<td>Prepares nitrogen for the making of proteins, DNA, cell membranes; N2 carries off waste H as NH3</td>
<td>Cyanobacteria, and soil bacteria (Rhizobium)</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>Assimilative Nitrate Reduction</td>
<td>Converts nitrate to ammonia for making proteins, DNA, and lipids</td>
<td>Occurs in the chloroplasts of green plants</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td><strong>Calcium Carbonate Precipitation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biologically Enhanced Rock Weathering</td>
<td>Speeded up because land plants increase amount of CO2 in the soil</td>
<td>Respiration by roots. Decay of plant material by soil bacteria</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>Biological Precipitation of Calcium Carbonate</td>
<td>Calcium carbonate is used for shells and other structural support</td>
<td>Aquatic invertebrates (like corals and clams: algae)</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td><strong>Dimethyl Sulfide Production</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthesis of Methionine (a sulfur-containing amino acid)</td>
<td>Synthesis of important amino acid used in making proteins</td>
<td>Bacteria and some higher plants</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
<tr>
<td>Decomposition of Methionine to Dimethyl Sulfide (DMS)</td>
<td>DMS for salt/water balance. Used by bacteria for energy, who release DMS</td>
<td>Plants, Marine algae (cocco-throphores, dinoflagellates)</td>
<td>![ ]</td>
<td>![ ]</td>
<td>![ ]</td>
</tr>
</tbody>
</table>

### Consequences to the Global Environment

- **Reduces the greenhouse effect.** The burial of dead organisms denies O2 reaction opportunities, creating an O2 surplus.
- **Helps tie up hydrogen atoms in the bodies of living things.** The burial of dead organisms also can remove hydrogen from atmospheric circulation. May help planet conserve water.
- **Increases the greenhouse effect.** The more CO2, the warmer the planet. Biological processes that cycle CO2 in & out of the atmosphere have the potential to influence the global temperature.
- **Increases production of stratospheric ozone.** Supports biological processes and life forms that are dependent upon O3-based biochemistry, such as many bacteria, protists, fungi, plants and animals.
- **Releasing N2 back into the atmosphere allows nitrogen to recirculate over the continents, making large, continental ecosystems possible.** Otherwise, the planet’s nitrogen would eventually all end up in the oceans.
- **Once released into the atmosphere, DMS undergoes additional reactions to make a sulfate particle.** Tiny particles encourage cloud formation. Clouds (esp. low clouds) can have a cooling effect on the planet.
polysaccharides (chained carbohydrates). These big molecules then are capable of performing the important biological functions that help organisms complete their life cycles. Stage two represents the final assembly process.

7.17 The products of biosynthesis are biologically useful in a variety of ways

We have spent so much time on the processes of biosynthesis. Let’s now think about the products of biosynthesis. After all, what is the point? The end result of the biosynthetic process is the production of molecules that are biologically useful. As I have mentioned before, they help living things grow, operate, maintain and reproduce themselves. The molecular products of biosynthesis can be assembled in interesting ways to make organs (such as a root system or an eye), make useful structures (such as hard shells, or a seed casing), or provide useful services (such as storing energy, expediting chemical reactions, or fighting off infections). Some of these constructions enable organisms to survive in harsh environments. For example, hot spring bacteria possess heat-tolerant enzymes, creosote bushes tolerate hot and dry conditions, and emperor penguins tolerate the extreme cold of Antarctic winters.

These useful molecules are the products of evolution by natural selection. We will consider them as molecular adaptations in chapter 13.

7.18 Biosynthesis has profound ecological consequences

Let us review our interest in biosynthesis. Biosynthesis, in conjunction with geologic processes, establishes life’s potential to alter the planet’s chemical environment. But the expression of this planet-altering potential will remain small if living things are confined to only a few small geographic areas. Nonetheless, we know that life has dispersed to essentially cover the surface of the Earth, despite its extremely diverse environments. The process of evolution has spun new adaptive molecules and shaped them into new features that have helped things live even in the harshest of physical environments. The “wheel” of evolution is fanned by environmental stresses such as competition, predation, parasitism, and tolerance to the physical environment.

Many environmental stresses are simply manifestations of whole organisms seeking the means by which to satisfy their own biosynthetic needs. In other words, biosynthesis is the reason for the pursuit of resources, and the pursuit of resources is the basis of many environmental stresses.

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