Chapter 2-9: Structures of Photosynthesis

Photosynthesis is the biochemical process through which plants convert the sun's energy into a usable chemical form. During photosynthesis, a plant produces carbohydrates that provide energy for the plant and are modified in numerous ways to serve as important cellular components.

Photosynthesis is also essential to animals, including humans, who obtain all their food either directly or indirectly from plants. In addition, photosynthesis replenishes the atmospheric oxygen used in animal metabolism.

The reactions of photosynthesis take place within the chloroplasts of plant cells and in the cytoplasm of cyanobacteria. This plate focuses on chloroplasts and describes their structure and function in photosynthesis.

In this plate, we present a series of diagrams starting with the leaf and progressing to the submicroscopic structures involved in photosynthesis.

We will begin with a survey of the main photosynthetic structure of the plant, the **leaf (A)**. Although the leaf is considered the center of photosynthesis, this process also occurs in cells of the plant stem.

In diagram 2, we show a cross section of the leaf. The surface of the leaf is covered by a thin waxy layer called the **cuticle (B)**, under which lie the cells of the **epidermis (C)**. Beneath the epidermis are several layers of cells called **mesophyll cells (D)**. Some of these cells are tall and stacked against each other; these make up the palisade layer of mesophyll cells, while others are more cubical and loosely packed; these comprise the spongy layer of the mesophyll. Mesophyll cells contain the main structures that carry on photosynthesis. At the lower portion of diagram 2 are stomates, where carbon dioxide necessary for photosynthesis enters the leaf.

We have begun our survey of photosynthetic structures by focusing on the leaf and some of its details. We will now take a single cell of the leaf and display its photosynthetic structures. Continue your reading as you color the plate.

Take a look at the single plant cell in diagram 3. This cell is rectangular compared to an animal cell, because plant cells have cell walls that maintain their box-like rigidity.

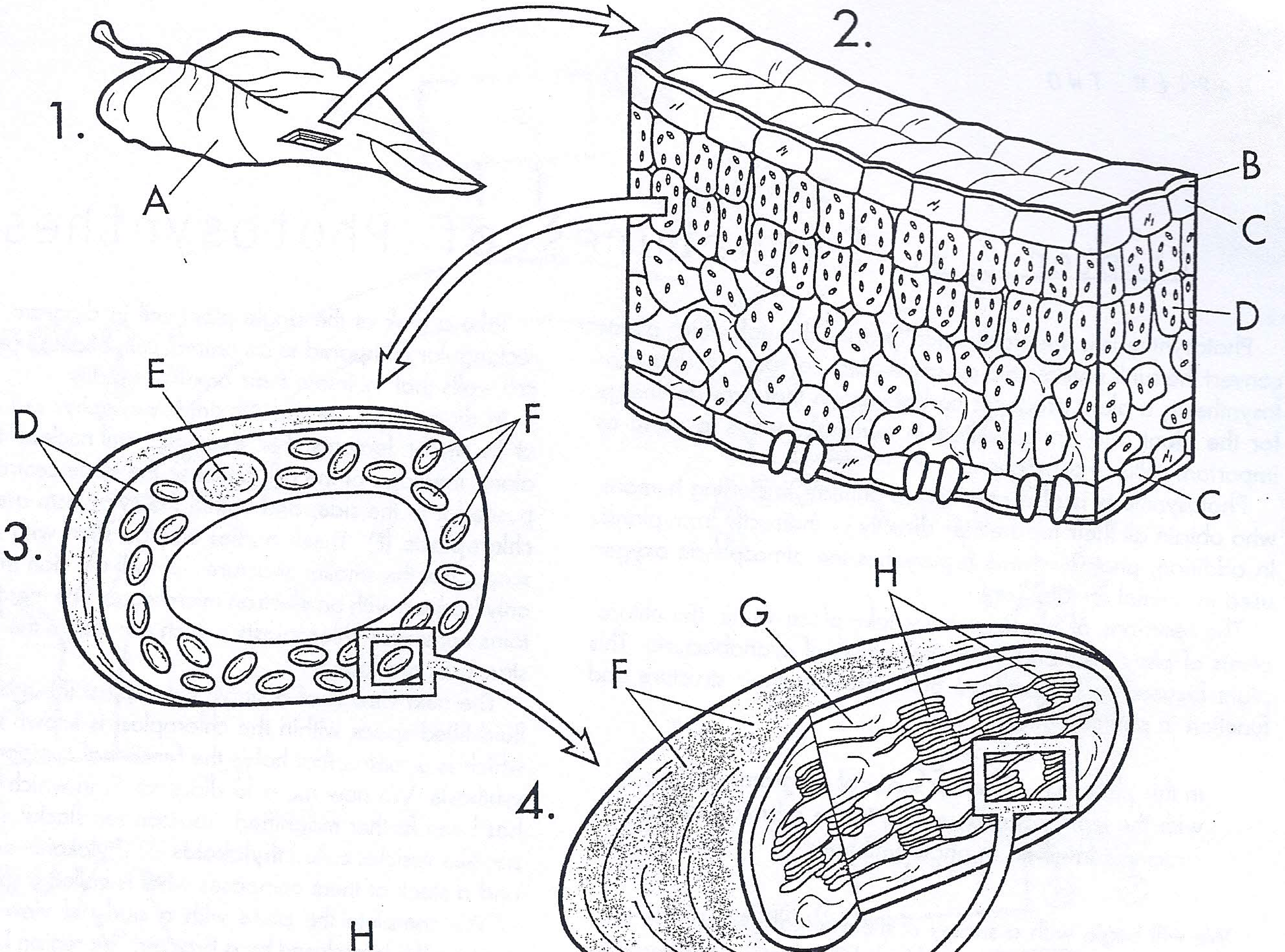
In diagram 3, we show a single mesophyll cell (D) and some of its major features. For example, the **nucleus (E)** is situated along the edge of the cell because the large central vacuole has pushed it to the side, and within the cytoplasm are a number of **chloroplasts (F)**. These bodies can be seen with a light microscope, but the smaller structures we will mention in this plate can only be seen with an electron microscope. The mesophyll cell contains numerous chloroplasts, which are where the photosynthetic structures are found.

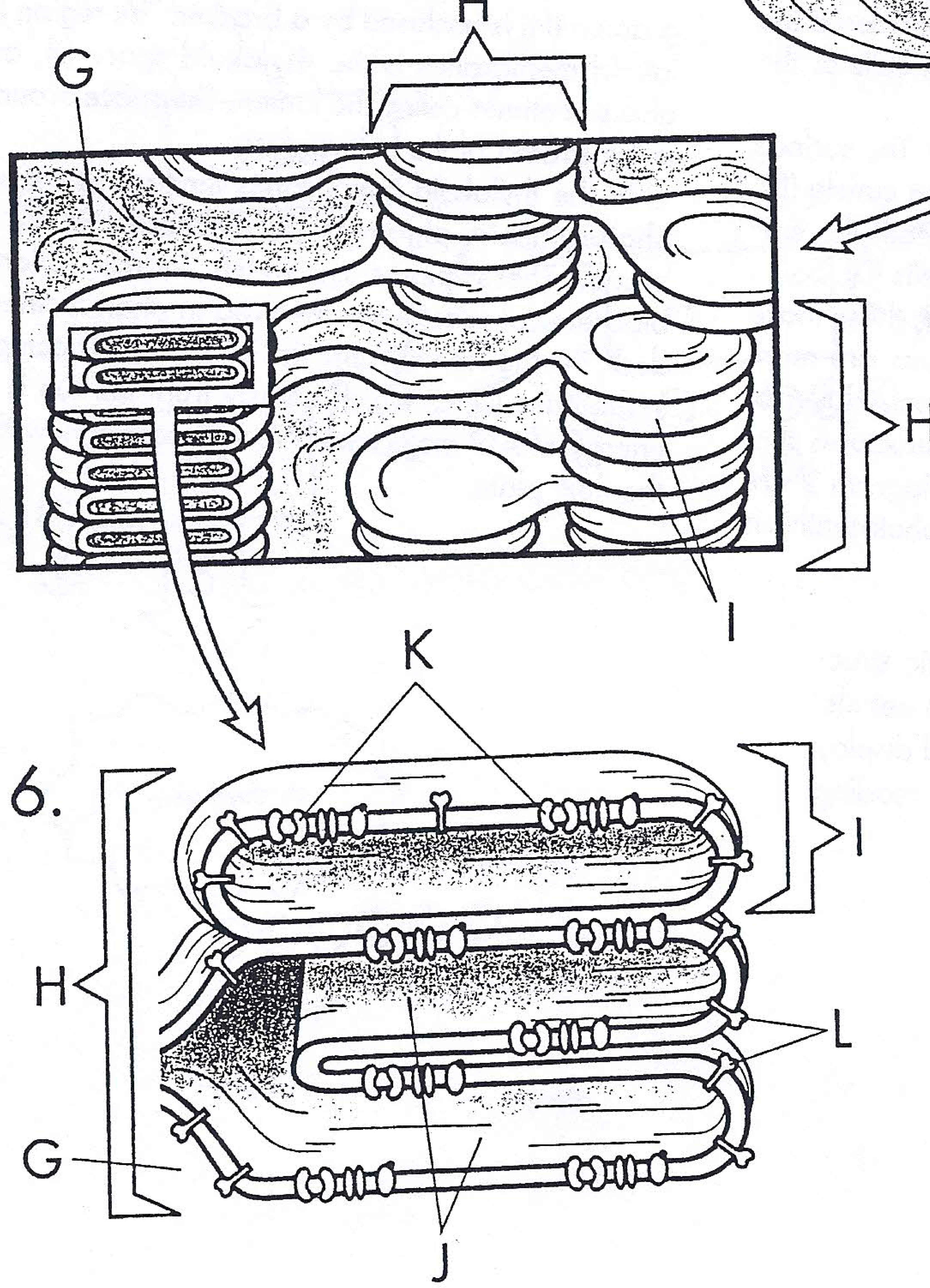
The next view is of a single chloroplast (F) in diagram 4. The fluid-filled space within the chloroplast is known as **stroma (G)**, which is a matrix that holds the functional components of photosynthesis. We now move to diagram 5, in which the chloroplast has been further magnified. You can see stacks of membranous, sac-like vesicles called **thylakoids (I)**. Thylakoids are disc-shaped, and a stack of them composes what is called a **granum (H)**.

We complete the plate with a study of view 6, in which a granum (H) is enclosed by a bracket. The region between the thylakoid membranes is the **thylakoid space (J)**, and this space is also sometimes called the lumen. The space around the thylakoids is the stroma of the chloroplast.

In the thylakoid membranes themselves we see a number of **photosynthetic pigments (K)** embedded in the thylakoid membrane. These pigments, which include chlorophyll, are the biochemical substances involved in photosynthesis. Also embedded in the membrane is a chemical complex called **ATP synthetase (L)**, at which energy from the sun is converted to the energy of ATP molecules. We will explain how this takes place in the next plate.

Structures of Photosynthesis





Structures of Photosynthesis

- ◯ Leaf ....A
- ◯ Cuticle ....B
- ◯ Epidermis C
- ◯ Mesophyll Cells ....D
- ◯ Nucleus ....E
- ◯ Chloroplasts ....F
- ◯ Stroma ....G
- ◯ Granum ....H
- ◯ Thylakoid I
- ◯ Thylakoid Space ....J
- ◯ Photosynthetic Pigments ....K
- ◯ ATP Synthetase L

Chapter 2-10: Photosynthesis—The Light Reactions

Photosynthesis is the biochemical process by which sunlight, oxygen, and water are converted into energy contained in the chemical bonds of carbohydrates. Photosynthetic organisms include green plants, algae, and certain species of bacteria. These organisms are key elements in the cycles of life on Earth, since all atmospheric oxygen and a large quantity of food come from photosynthesis.

The two main processes of photosynthesis involve a series of energy-fixing (light) reactions and a series of carbon-fixing (dark) reactions. In the light reactions, energy from sunlight is trapped in the chemical bonds of ATP, while in the second process, this ATP is used to form carbohydrate molecules. The dark reactions are the subject of the next plate.

This plate contains three diagrams that depict the energy-fixing reactions of photosynthesis. The biochemistry of these reactions can be difficult to comprehend, so go through the reading slowly.

Photosynthesis takes place inside chloroplasts in specialized membranes called thylakoids (which were mentioned in the last plate). In the main diagram of this plate, we show a large leaf. If you want to color it, use a very pale color.

The process of photosynthesis begins with the sun's **light energy (A)**. This energy enters leaf cells and is absorbed and transferred to a series of chlorophyll molecules within a complex cluster called a photosystem. The first photosystem involved in this transfer is **photosystem II (B)**, and this photosystem contains chlorophyll molecules that absorb light that has a wavelength of 680 nanometers (nm).

When the complex in photosystem II is activated by light energy, it gives up **electrons (C)**, which are then absorbed by an **electron acceptor (D)**. This electron acceptor is part of what is called an energy transfer system, through which the electrons move until they reach **photosystem I (F)**. During these transfers, hydrogen ions are pumped from the stroma into the interior of the thylakoid. As hydrogen ions leak back across the membrane through special carrier proteins called ATPases, **ADP (E_1)** is phosphorylated, forming **ATP (E)**.

Now photosynthesis continues. Light energy (A) is absorbed by photosystem I (F), whose chlorophyll pigments absorb light energy that measures 700 nm. Once again, energy is transmitted by the chlorophyll in the complex, and an electron is given off to an electron acceptor, ferredoxin.

The electron acceptor then transfers the electron to a molecule of nicotinamide adenine dinucleotide phosphate, or **NADP (G_1)**, which takes on a **hydrogen ion (H)** to become **NADPH (G)**. NADPH is used in carbon fixation in the next plate.

We complete the process of photosynthesis by referring back to the original P680 molecule, which has lost an electron that must be replaced. A **water molecule (I)** breaks down, forming free hydrogen ions and **diatomic oxygen (J)**, and contributing an electron to the P680 complex. The oxygen is released to the atmosphere.

We have completed the discussion of the energy-fixing reactions of photosynthesis, and will now spend a moment on an alternative one called the cyclic reaction.

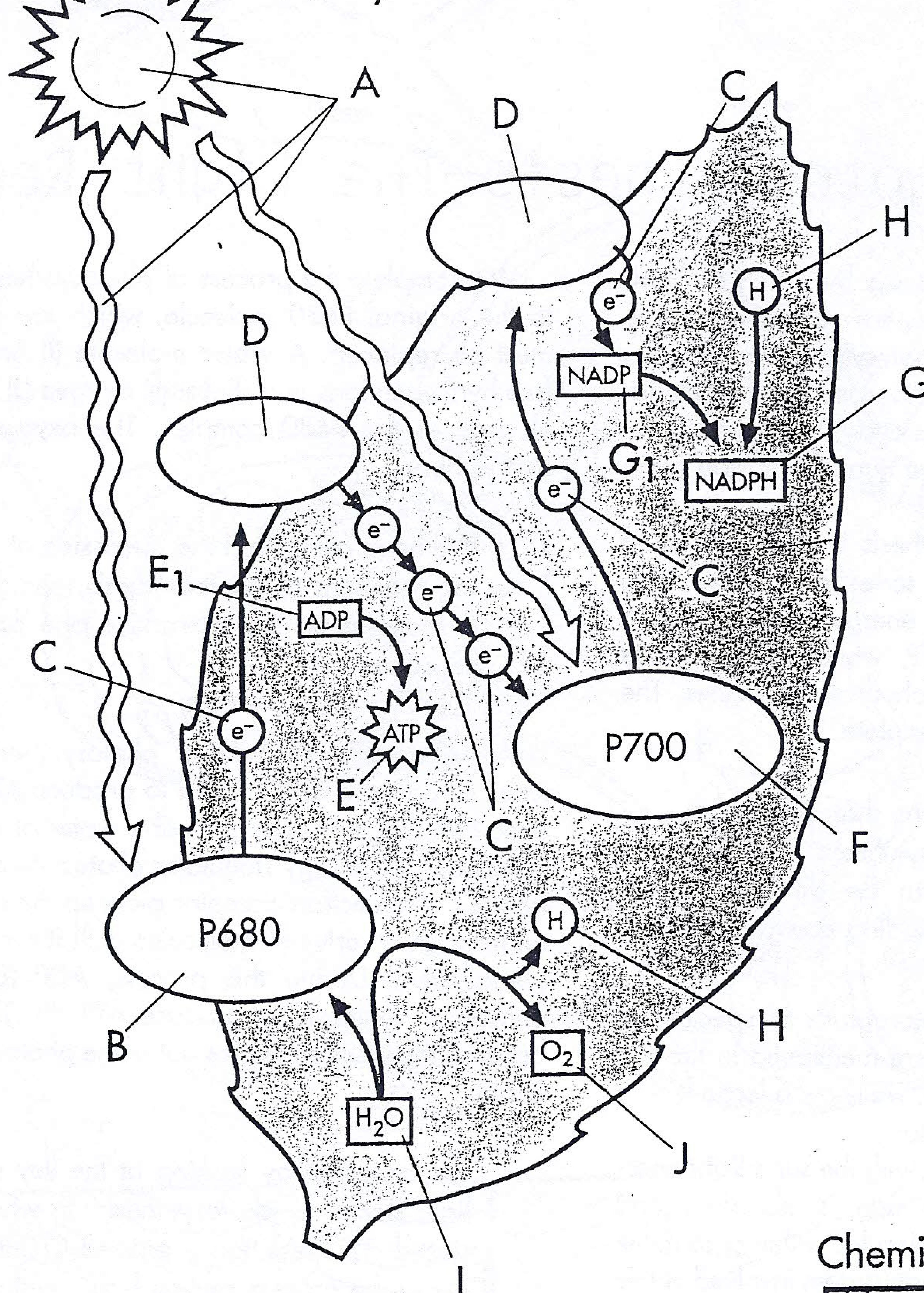
An alternative process of photosynthesis occurs in certain types of bacteria and is used to produce ATP, but does not produce NADPH, nor does it involve water or oxygen. In this cyclic reaction, light energy stimulates photosystem I (F) to emit an electron (C). An electron acceptor picks up the electron and passes it on through a series of molecules until it eventually returns to the photosystem. During this process, ADP (E_1) combines with a phosphate molecule to produce ATP (E). This reaction is cyclic because the electron moves out of the photosystem and then back into it.

We conclude by looking at the key elements of the light stages of photosynthesis, in which ATP is produced. This reaction is entitled Chemiosmosis. Read about the process as you focus on the final diagram of the plate.

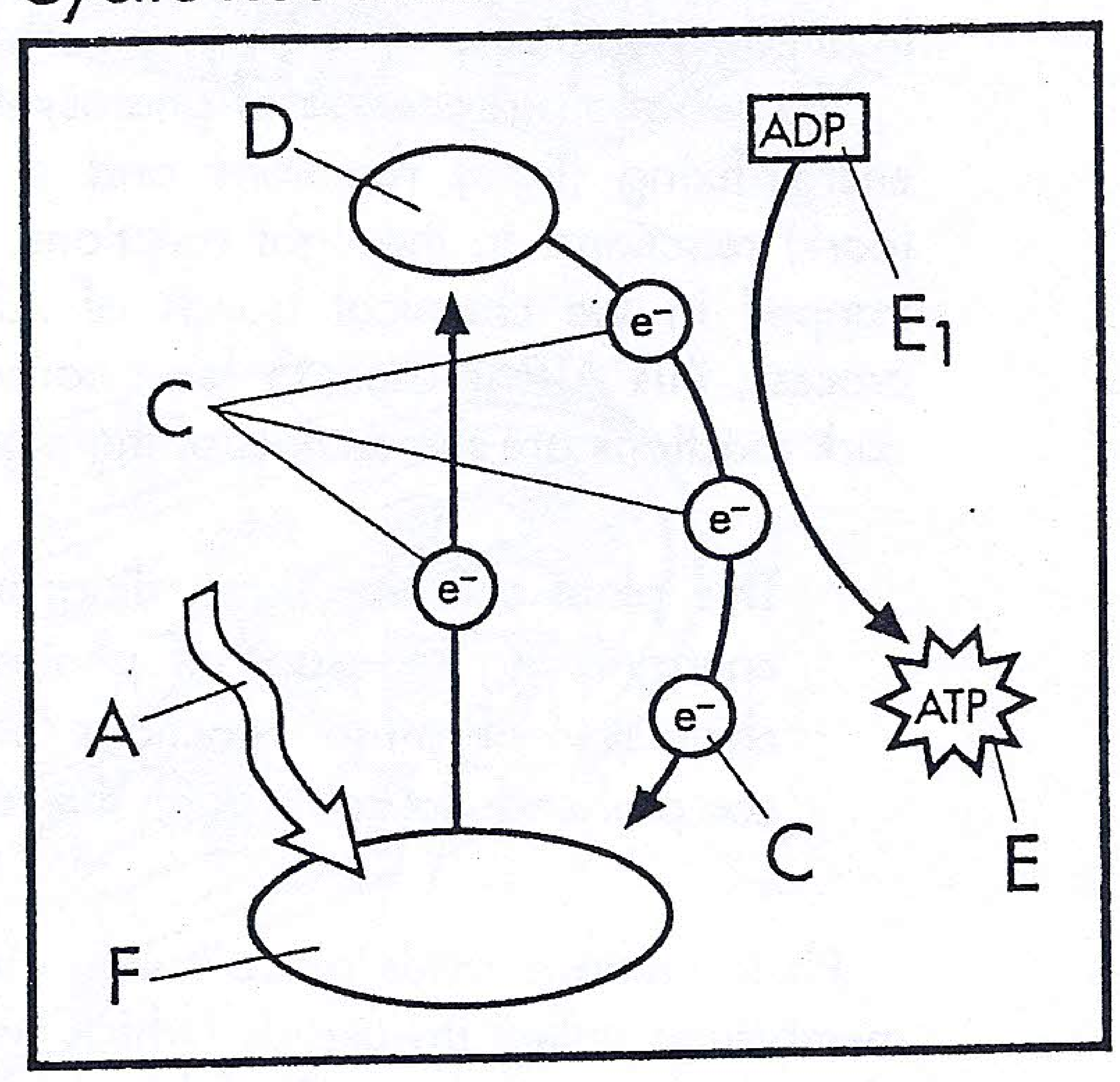
Chemiosmosis is the mechanism through which ATP is produced in the chloroplast of the plant cell. Light energy (A) enters a specific **chlorophyll molecule (B_1)** of photosystem II, and then we see **energy flow (L)** as this energy moves into photosystem I (F). All of this takes place within the **thylakoid membrane (K)**. During this transferal of energy, there is **hydrogen ion flow (M)** across the membrane, from the **stroma (P)** into the **thylakoid space (O)**.

As hydrogen ions move back into the stroma, they travel through an enzyme complex called **ATP synthetase (N)**. The hydrogen ion flow coincides with the formation of molecules of ATP (E) from ADP. The ATP formed in chemiosmosis is an essential factor in the carbon-fixing reactions of photosynthesis, which are discussed in the next plate.

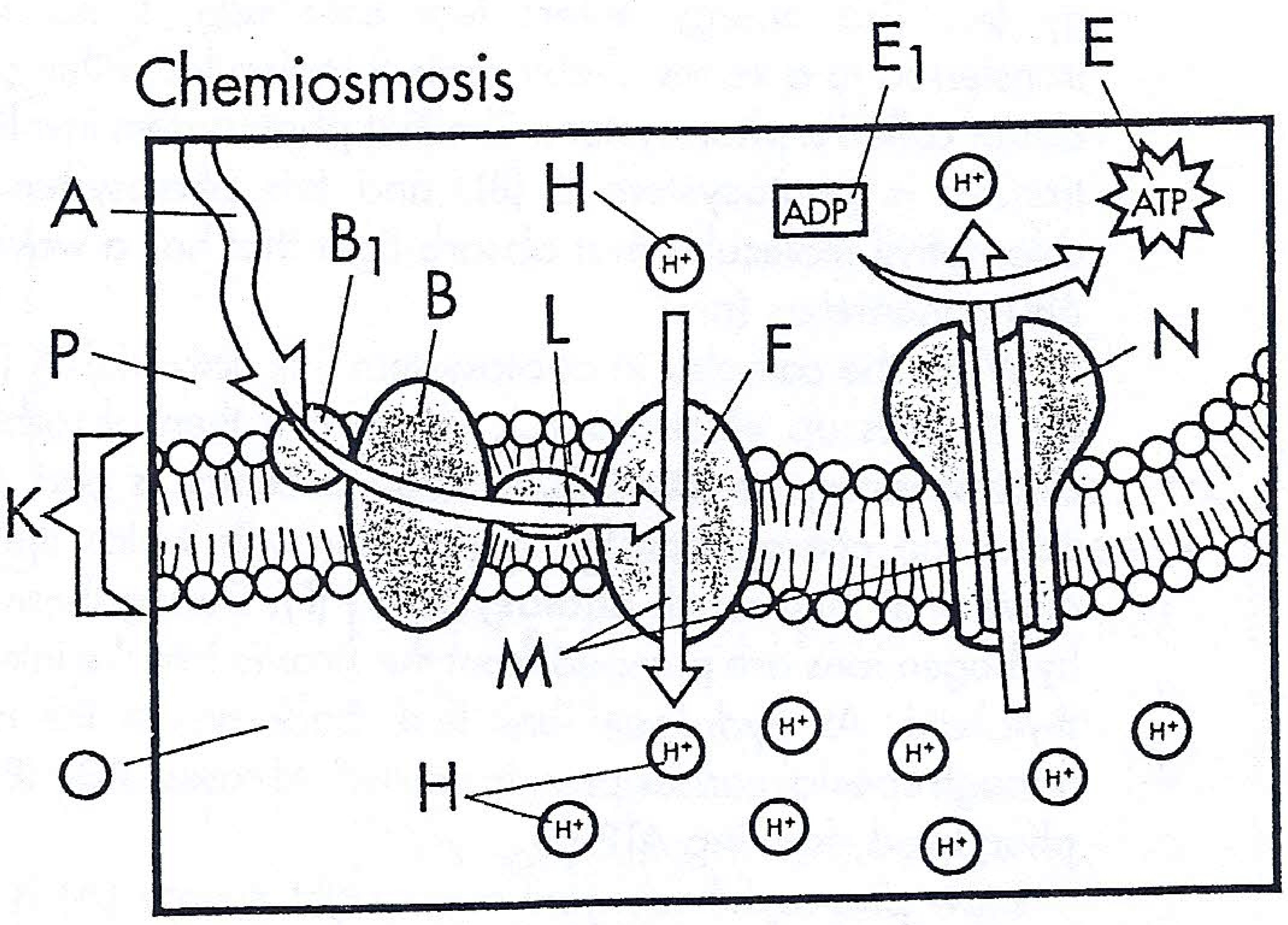
Noncyclic Reaction



Cyclic Reaction



Chemiosmosis



Photosynthesis—The Light Reactions

- ○ Light Energy .... A
- ○ Photosystem II .... B
- ○ Chlorophyll .... B_1
- ○ Electron C
- ○ Electron Acceptor .... D
- ○ ATP .... E
- ○ ADP .... E_1
- ○ Photosystem I .... F
- ○ NADPH .... G
- ○ $NADP_1$ .... G
- ○ Hydrogen Ion .... H
- ○ Water Molecule I
- ○ Diatomic Oxygen .... J

- ○ Thylakoid Membrane .... K
- ○ Energy Flow L
- ○ Hydrogen Ion Flow .... M
- ○ ATP Synthetase .... N
- ○ Thylakoid Space .... O
- ○ Stroma .... P

Chapter 2-11: Photosynthesis—The Dark Reactions

The term photosynthesis refers to two major processes that are made up of complex series of biochemical events. The first process (which is made up of the energy-fixing reactions) was discussed in the last plate. ATP and NADPH are generated in those reactions, and are used in the second process, the carbon-fixing reactions, which we will now discuss. The carbon-fixing reactions are sometimes referred to as the dark reactions, since they do not require light. They can occur in both its presence and absence, since their energy source is ATP.

In the carbon-fixing reactions, organic molecules are formed. Carbon dioxide provides the carbon backbone for the new molecules, and fuels the reactions. The process is often called the Calvin Cycle, after Melvin Calvin, who discovered some of the key reactions.

In this plate, we present a cycle in which carbon dioxide provides the carbon necessary for the synthesis of organic compounds such as carbohydrates. The series of reactions is cyclic, meaning that it follows a circular biochemical pathway.

In the second major process of photosynthesis, energy from sunlight is converted to the chemical energy contained in the bonds of carbohydrates. These reactions occur at the outer surface of the thylakoid membrane, and the resulting carbohydrates are stored in plant cells to be used in cellular respiration, or distributed to other cells.

We begin this process with three molecules of **carbon dioxide (A)**, which you can see at the top of the cycle. In reaction 1, carbon dioxide combines with a molecule called **ribulose bisphosphate (B)**, abbreviated as RuBP. This molecule contains five carbon atoms and two phosphate groups, which are indicated by the P's. When the two molecules combine, a six-carbon molecule is formed. This molecule is split immediately into molecules of **3-phosphoglyceric acid (PGA) (C)**. Note that the PGA molecules each have three carbon atoms. This completes the first step of the carbon-fixing reactions.

We have seen how carbon dioxide from the atmosphere is incorporated into the cycle of carbon-fixing reactions. Essentially, a five-carbon molecule combines with the carbon dioxide molecule to yield a six-carbon molecule that immediately splits into two three-carbon molecules. We will now look at reaction 2.

In the second reaction of the process, the six PGA molecules are converted to six molecules of **1,3-diphosphoglyceric acid, or DPGA (D)**. An **ATP molecule (E)** provides the energy needed to make this reaction proceed, and in the process is converted to **ADP (F)**. This ATP was formed in the energy-fixing reactions described in the previous plate, so you can see that the energy-fixing reactions are essential for the carbon-fixing reactions. Only two DPGA molecules are shown.

We now move to reaction 3. Here the DPGA molecules convert to molecules of **phosphoglyceraldehyde, or PGAL (G)**. The **NADPH (H)** formed in the energy-fixing reactions is used up in this conversion and becomes **NADP (I)**. Note also that one phosphate group has been lost from the DPGA in the formation of PGAL.

In reaction 5 we see that some of the PGAL molecules are used to form **carbohydrates (J)**, including glucose, lactose, cellulose, and others. The interconversions that lead to these carbohydrates are extremely complex, but it is at this point that the carbon of carbon dioxide is incorporated into carbohydrate molecules, which all plants and animals use as energy. In other words, this is where the energy from the sun is incorporated into the energy of carbohydrates.

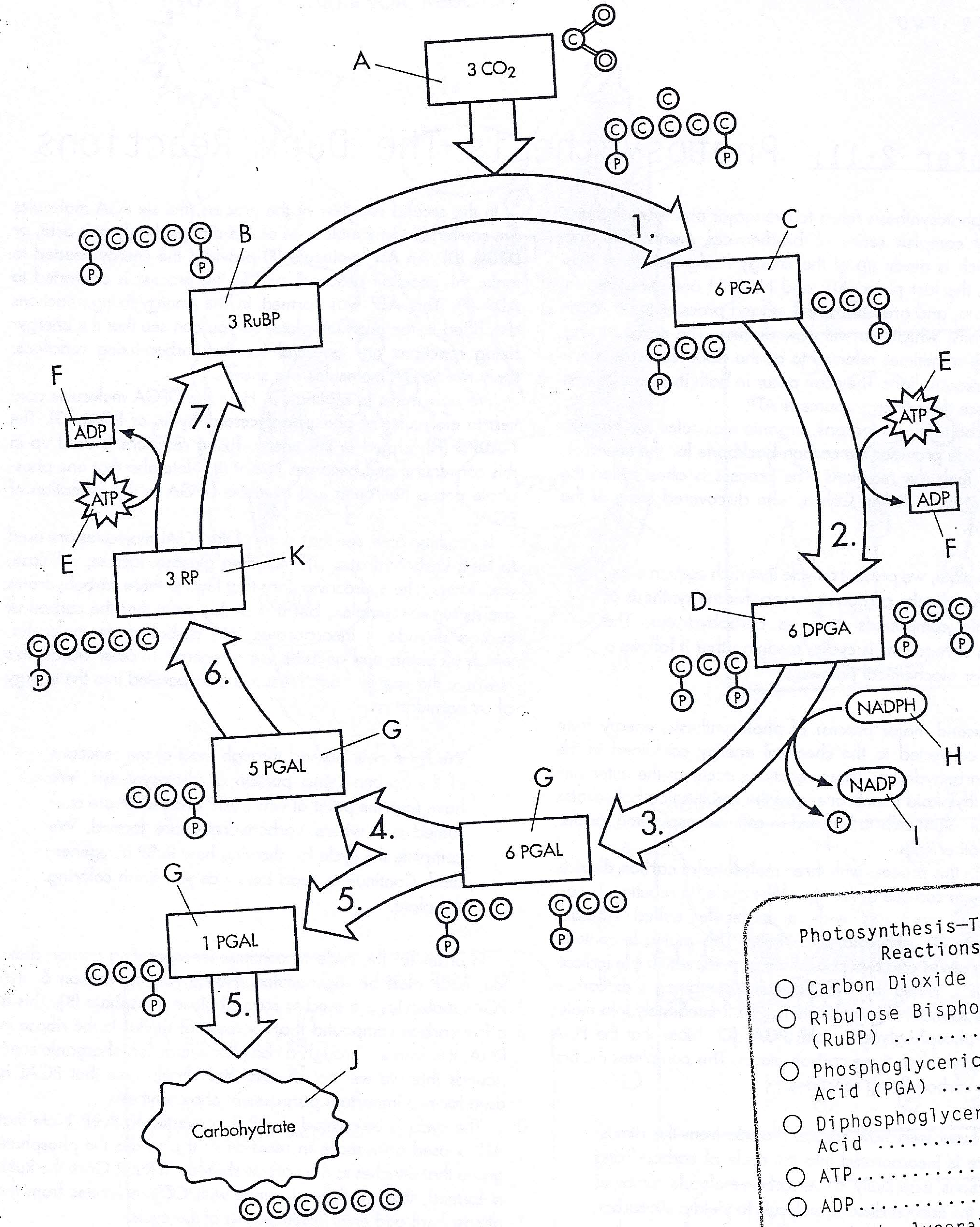
We have now passed through most of the reactions of the carbon-fixing portion of photosynthesis. We have seen the point at which ATP and NADP are consumed and where carbohydrates are formed. We complete the cycle by showing how RuBP is regenerated. Continue to read below as you finish coloring the plate.

In order for the cycle to continue incorporating carbon dioxide, RuBP must be regenerated. Notice that in reaction 6, five PGAL molecules are used to form **ribulose phosphate (K)**. This is a five-carbon compound that's somewhat similar to the ribose in RNA. It is formed through a complex interaction of organic compounds that we will not discuss. You should note that PGAL is used for two important purposes in photosynthesis.

The cycle is completed as RP is converted to RuBP. Note that ATP is used once more in reaction 7; it provides the phosphate group that attaches to the carbon skeleton in RuBP. Once the RuBP is formed, it is available to unite with CO_2 molecules from the atmosphere and enter another turn of the cycle.

The carbon-fixing reactions of photosynthesis are quite complex. Light energy is converted first to ATP energy, and then ATP energy is used in the formation of carbohydrates.

Photosynthesis–The Dark Reactions



Photosynthesis–The Dark Reactions

- ○ Carbon Dioxide ....A
- ○ Ribulose Bisphosphate (RuBP) ....B
- ○ Phosphoglyceric Acid (PGA) C
- ○ Diphosphoglyceric Acid ....D
- ○ ATP ....E
- ○ ADP ....F
- ○ Phosphoglyceraldehyde ..G
- ○ NADPH...................H
- ○ NADP I
- ○ Carbohydrate ....J
- ○ Ribulose Phosphate ....K