ATP: Energy Currency of the Cell

Thousands of reactions take place in living cells. Many reactions require the addition of energy for the assembly of complex molecules from simple reactants. These reactions include DNA synthesis, protein synthesis, and the construction of cell walls and other cellular structures. Other cell-driven actions—such as muscle contractions in animals, the motion of flagella in bacteria (**Figure 1**), and the movement of sap within a tree—also require a supply of energy.

Since so many cellular functions require energy, cells need a constant supply of energy. Even though the species on Earth are very diverse, all cells in every organism use the same energy carrier for almost all of their energy-driven actions. This energy comes in the form of a compound called adenosine triphosphate, or ATP. ATP directly supplies the energy that powers nearly every cellular function, and it is considered the universal energy "currency." The types of work that are carried out by ATP include mechanical, transport, and chemical work (**Table 1**).

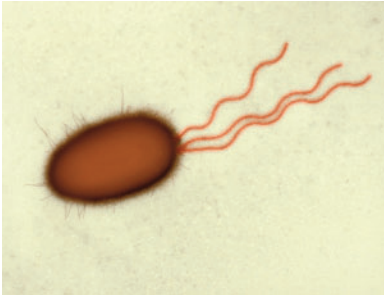


Figure 1 A bacterium with flagella

Table 1 Types of Work Performed by ATP

Mechanical work	Transport work	Chemical work
• beating of cilia or movement of flagella • contraction of muscle fibres • movement of chromosomes during mitosis/meiosis	• process of pumping substances across membranes against their concentration gradient	• process of supplying chemical potential energy for non-spontaneous, endergonic reactions, including protein synthesis and DNA replication

ATP Hydrolysis and Free Energy

Adenosine triphosphate (ATP) consists of three parts: a nitrogenous base called adenine, which is linked to a five-carbon sugar called ribose, which in turn is linked to a chain of three phosphate groups (**Figure 2**, next page). ATP contains large amounts of free energy. The energy of the molecule is high because of its three negatively charged phosphate groups. The phosphate groups crowd together, and their close proximity creates a mutual repulsion of their electrons. The mutual repulsion contributes to the weakness of the bond holding the groups together. The bonds of ATP are easily broken by a catalyzed reaction with water—a process called hydrolysis (Figure 2). The hydrolysis reaction results in the breaking off of the end (or terminal) phosphate group and the formation of two products—adenosine diphosphate (ADP) and an inorganic phosphate (P_i). In addition, an H^+ ion is released into the solution. As bonds in these new products form, free energy is released.

$$\mathrm{ATP} + \mathrm{H_2O} \rightarrow \mathrm{ADP} + \mathrm{P_i} \quad \Delta G = -30.5\ \mathrm{kJ/mol}$$

Note that the H^+ ion is not normally shown in the chemical equation, since it is understood to be associated with the formation of P_i.

Recall, from Section 3.1, that during a chemical reaction, bonds in the reactants break and new bonds in the products form. During ATP hydrolysis, bonds form when a new —OH group attaches to the phosphorus atom of the phosphate group and when an electron attaches to the oxygen that remains on the ADP molecule. Energy is also released as the H^+ ion interacts with water molecules. The bond rearrangements and the change in entropy result in an overall free energy change of –30.5 kJ/mol. When ATP splits into ADP and P_i within a cell, the phosphate group, rather than remaining free in solution, often becomes attached to another molecule, which results in a different bonding arrangement.

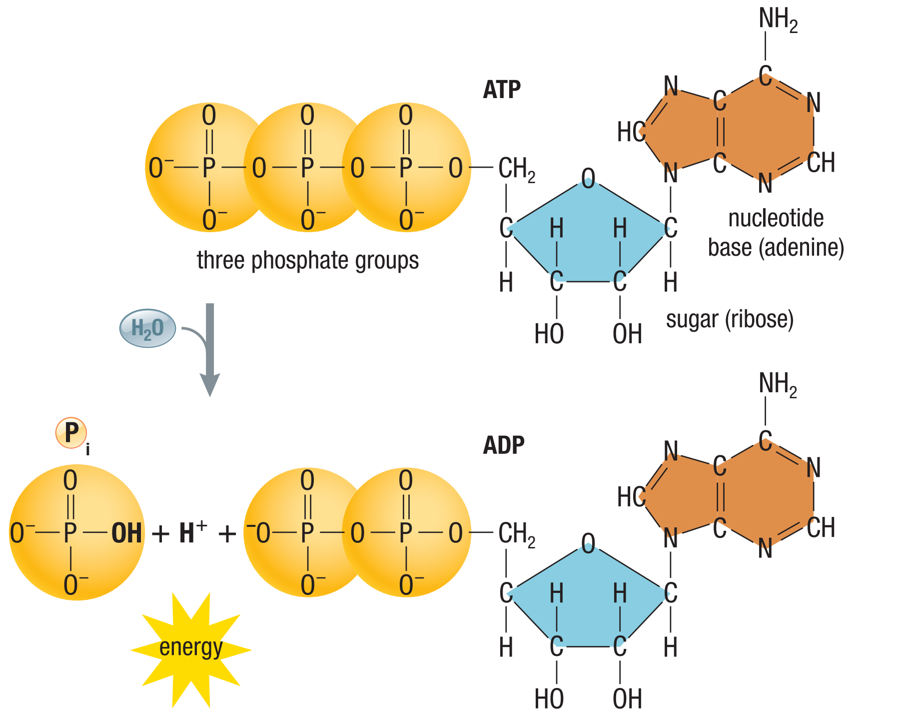


Figure 2 ATP releases large amounts of free energy during a hydrolysis reaction as new bonds form in the products. The reaction results in the addition of a new OH group to a released phosphate as well as the addition of an electron to the terminal oxygen on the ADP and the release of an H^+ ion into solution.

ATP and Energy Coupling

phosphorylation the transfer of a phosphate group, usually from ATP, to another molecule

In a process called energy coupling (Section 3.1), ATP can be moved into close contact with a reactant molecule of an endergonic reaction. Then, during the reaction, the terminal phosphate group breaks away from the ATP and transfers to the reactant molecule. Attaching a phosphate group to another organic molecule is a process called **phosphorylation**. It results in the molecule gaining free energy and becoming more reactive. Energy coupling requires an enzyme to bring the ATP molecule close to the reactant molecule of the endergonic reaction. There are specific sites on the enzyme that bind both the ATP molecule and the reactant molecule. In this way, the two molecules are brought close to one another, and the transfer of the phosphate group takes place.

Most of the work carried out in a cell is dependent on phosphorylation for energy. An example of energy coupling that is common to most cells is the reaction in which ammonia, NH_3, is added to glutamic acid (**Figure 3(a)**, next page). The resulting product of this reaction is glutamine, which is an amino acid. The reaction can be written as follows:

$$\text{glutamic acid} + \text{ammonia} \rightarrow \text{glutamine} + H_2O \quad \Delta G = +14.2 \text{ kJ/mol}$$

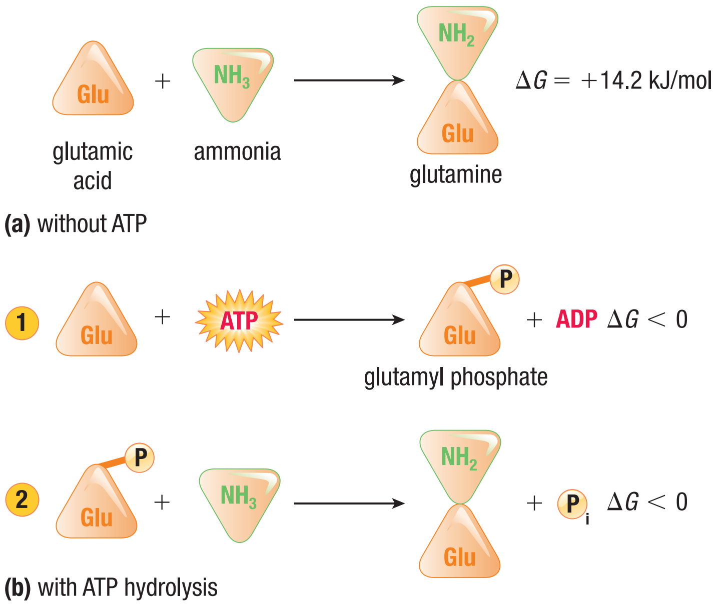
The glutamine that is produced takes part in the assembly of proteins during protein synthesis. The positive value of ΔG shows that the reaction is endergonic and cannot proceed spontaneously. Therefore, the coupling of this reaction with ATP hydrolysis gives it the necessary energy to proceed. As a first step, the phosphate group is removed from the ATP and transferred to the glutamic acid molecule, forming glutamyl phosphate (**Figure 3(b)**, next page):

$$\text{glutamic acid} + \text{ATP} \rightarrow \text{glutamyl phosphate} + \text{ADP} \quad \Delta G < 0$$

The change in free energy, ΔG, is negative for this reaction. This means that the reaction is exergonic and can proceed spontaneously. In the second step of the reaction, glutamyl phosphate reacts with ammonia:

$$\text{glutamyl phosphate} + \text{ammonia} \rightarrow \text{glutamine} + P_i \text{ (inorganic phosphate)} \quad \Delta G < 0$$

The second step of this reaction also has a negative ΔG value, so it also proceeds spontaneously. The overall ΔG value for the two-step reaction is -16.3 kJ/mol (**Figure 3(c)**). This example represents a two-step endergonic reaction that is coupled to ATP hydrolysis, but there are hundreds, thousands, or even millions of steps involved in the assembly of huge protein molecules or the synthesis of an entire DNA genome. The process is analogous to building a huge wall, one brick at a time. This step-by-step approach is what enables cells to perform these large tasks. ATP molecules provide energy every step of the way.



$$\begin{array}{lcll} \text{Glu} + NH_3 & \longrightarrow & \text{Glu} - NH_2 & \Delta G = +14.2 \text{ kJ/mol} \\ \text{ATP} & \longrightarrow & \text{ADP} + P_i & \Delta G = -30.5 \text{ kJ/mol} \\ \hline & & & \text{net } \Delta G = -16.3 \text{ kJ/mol} \end{array}$$

(c) free energy change with ATP

Figure 3 Energy coupling using ATP: (a) Ammonia is added to glutamic acid to form glutamine. This is a non-spontaneous, endergonic reaction. (b) In the presence of ATP, a phosphate is transferred to glutamic acid. This forms glutamyl phosphate, which spontaneously reacts with ammonia to form glutamine. (c) ATP provides the free energy for the overall reaction and allows it to occur spontaneously.

Regeneration of ATP

For cells to keep functioning, they must regenerate ATP molecules. In the previous section, you learned how the hydrolysis of ATP into ADP and inorganic phosphate, P_i, is an exergonic reaction that can be coupled with endergonic reactions to drive them forward spontaneously. ATP coupling reactions occur continuously in living cells and, consequently, an enormous number of ATP reactions are required.

Cells generate ATP by combining ADP with P_i. If ATP hydrolysis is an exergonic reaction, then the reverse process, ATP synthesis from ADP and P_i, is an endergonic reaction. Therefore, ATP synthesis requires the addition of free energy. The energy needed to drive ATP synthesis usually comes from the exergonic breakdown of complex molecules containing an abundance of free energy. These complex molecules are in the foods we eat: carbohydrates, fats, and proteins. All of these molecules are sources of free energy. In Chapter 5, you will learn that light energy is also a primary source of energy used to drive ATP synthesis. At least 10 million times every second, ATP molecules are hydrolyzed and resynthesized in a typical cell, illustrating that this

ATP cycle the cyclic and ongoing breakdown and re-synthesis of ATP

cycle operates at an astonishing rate. In fact, if ATP were not formed in the cell from ADP and P_i, the average human would need about 75 kg of ATP per day. The continued breakdown and resynthesis of ATP is a process called the **ATP cycle** (**Figure 4**).

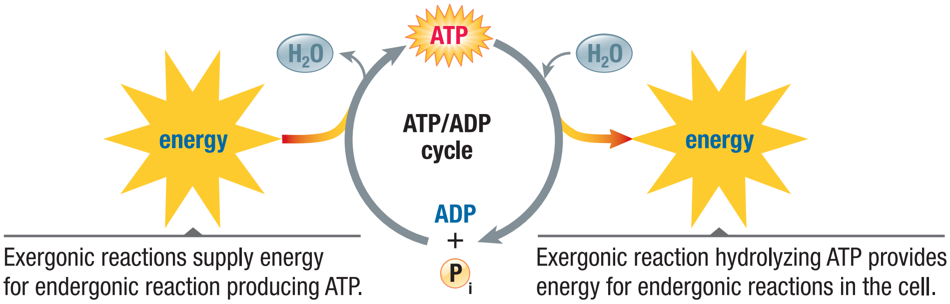


Figure 4 The ATP cycle couples reactions that release free energy (exergonic) to reactions that require free energy (endergonic).

ATP Is the Universal Energy Currency

There is very little ATP in our diet, and yet we require it as a constant energy source within our cells. ATP hydrolysis releases energy obtained from the foods we eat, and then more energy from food is used to reassemble the ATP. If cells constantly need to use energy from food to reassemble ATP, then why do cells use ATP as their energy currency to begin with? It would seem that cells could just use the food molecules directly as sources of energy. Cells use ATP as an immediate source of energy because it has specific properties that are important for the biochemical reactions that allow proper cell functioning.

ATP provides a manageable amount of energy, and couples in very similar ways to thousands of different reactions in our cells. This ability to couple to so many different endergonic reactions gives ATP its "universal" characteristic. The widespread use of ATP in all living things is an evolved characteristic. Many other molecules are energy rich, but they vary in size and shape, in the amount of energy they release, and in the types of reactions to which they can couple. Also, the availability of these molecules is not always reliable or predictable. If a certain reaction required the use of a particular food molecule—for example, glucose—as an energy source to drive a coupled reaction, and the cell did not have any glucose, it could not power the given reaction, even if there were other energy-rich molecules in the cell. The ability to assemble ATP using the energy from a variety of food molecules ensures that all vital reactions in the cell can be performed. Complex food molecules also require numerous reactions to release their energy, but ATP can be created and accessed immediately. The only requirement is that at least one of these food sources is available for generating ATP. Although ATP is the energy currency of cells and is the immediate source of energy to drive cellular processes, it is not the only energy carrier in cells. There are other phosphate carriers, such as guanosine triphosphate (GTP), that are used specifically as carriers of high-energy electrons.

In this section, you learned that cells can use ATP as a source of energy to drive endergonic reactions. There are, however, other factors that influence a cell's ability to perform endergonic and even exergonic reactions. Critical among these factors is the need to overcome the activation energy requirements for a particular reaction (Section 3.1). If the activation energy requirement is very high because the bonds in the reactants are very strong, a reaction will not start even if it is exergonic overall. As you will learn in the next section, some proteins called enzymes play an important role in lowering the activation energy for certain reactions.

3.2 Review

Summary

- ATP supplies energy directly to chemical reactions in all cells. It is the universal energy currency in living organisms.
- ATP hydrolysis results in the formation of ADP and P_i, and releases a large amount of free energy in the process.
- ATP hydrolysis can be coupled to endergonic reactions in a cell to power hundreds of reactions. This process is called energy coupling.
- Phosphorylation, the process of attaching a phosphate group to another organic molecule, causes the molecule to gain free energy and become more reactive.
- ATP is regenerated from ADP and P_i during part of the ATP cycle.

Questions

1. Provide an example of a use of ATP energy for each of the following tasks:
   (a) chemical work
   (b) mechanical work
   (c) transport work K/U
2. What does the universality of ATP in all living species suggest about the relationship of species to one another? A
3. (a) Describe the structure of an ATP molecule.
   (b) How does the structure of the ATP molecule relate to the large amounts of free energy it contains? K/U
4. Describe the process of ATP hydrolysis. K/U
5. During the hydrolysis of ATP, energy is released, but most of the molecule, the ADP portion, remains intact. How does this compare to what happens to a molecule of glucose when it is used as an energy source? T/I
6. With a classmate, explain the relationship between the ATP cycle and the coupling of exergonic and endergonic reactions. K/U C
7. Which of the following groups of molecules has more overall free energy? Explain your answer. K/U
   - Group 1: glutamic acid, NH_3, and ATP
   - Group 2: glutamine, ADP, and P_i
8. Why is it necessary for cells to “recycle” ADP and P_i rather than just release them as waste products? K/U
9. Use a flow chart or another graphic organizer to explain the ATP cycle. K/U C
10. Describe a phosphorylation reaction. K/U
11. Examine the following set of reactions: T/I
    (i) $A + B \rightarrow C$ $\quad \Delta G = +4.4$ kJ/mol
    (ii) $D \rightarrow E + F$ $\quad \Delta G = -3.0$ kJ/mol
    (iii) $M + N \rightarrow P + R$ $\quad \Delta G = -6.2$ kJ/mol
    (iv) $S + T \rightarrow V$ $\quad \Delta G = +2.1$ kJ/mol
    (a) Which of these reactions are spontaneous?
    (b) List all combinations of two reactions that would result in an overall spontaneous reaction.
12. Explain why it is advantageous for cells to use ATP as an energy source rather than using glucose, lipids, or protein directly. K/U
13. An unusual form of biological work is the production of light. Conduct research online to determine how fireflies use ATP energy to produce their well-known flashes of light (**Figure 5**). How efficient is this process? T/I

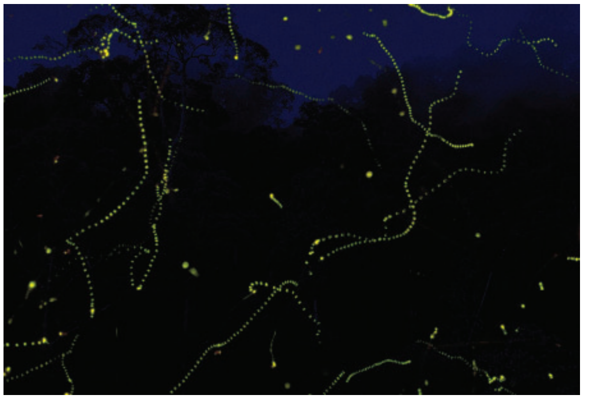


Figure 5

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