

## Energy Flow in Cells - 1

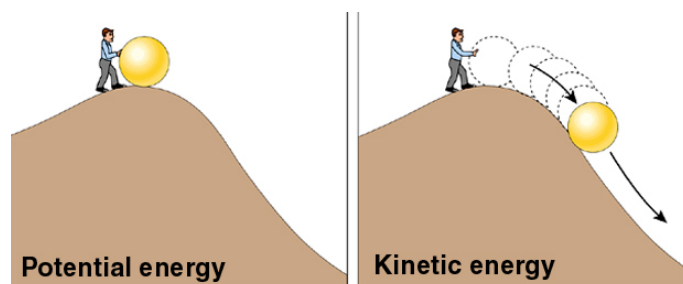
Thousands of chemical reactions occur in our cells and tissues to keep us alive (and hopefully healthy). We have discussed some of the molecules of living organisms (carbohydrates, lipids, proteins, etc.) in the context of the functions they perform in cells and tissues. These coordinated, controlled and orderly activities of cells collectively comprise the **metabolism** of living organisms. Much of metabolism involves energy transfer so it is helpful to have a common knowledge base about energy. The energy used in metabolism is **chemical energy**, the energy of electrons. This energy is used to build and maintain our cells and tissues, to move materials into and out of our cells, to process fuel molecules - to do the work of the cell.

We will briefly look at the physical laws that govern energy flow, how energy flow relates to chemical reactions and how living organisms control the chemical reactions that occur in their cells and tissues. Since **enzymes** catalyze our chemical reactions it's important to take a look at enzyme activity, too.

### Defining Energy

Energy is often defined as the capacity to do work. The two fundamental types of energy are **kinetic** (energy at work, or the movement of energy) and **potential** (stored energy waiting to do work, such as the energy in the bonds of chemicals).

**Potential energy** is energy that matter has because of its structure or location. The water stored behind a dam has potential energy because of its location. Chemical bonds have potential energy because of their structure. The water flowing through the turbines of a dam has **kinetic energy**.



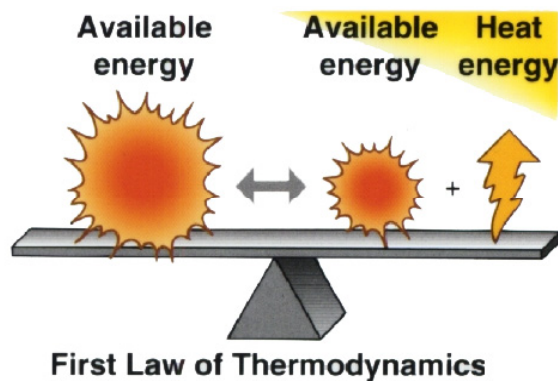
Both kinetic and potential energy can be found in many forms, such as electrical, light, chemical, heat, and mechanical. Under the right conditions, energy can be transformed from one type to another and from one form to another. This is a good thing, since different kinds of work require different kinds of energy, and as it applies to living organisms, it is often thought of as energy flow. Without energy flow, we would have no life on earth.

To make sense of this we have to understand both the **quantity of energy** available and the **usefulness of that energy** to do work, which is the study of **thermodynamics**, the field that studies energy transformations. There are two laws: one addresses the quantity of available energy and the second addresses the usefulness or availability of energy to do work. In addition, thermodynamics involves **a system and its surroundings**. The matter being studied is the system, and everything outside of the system is the surroundings.

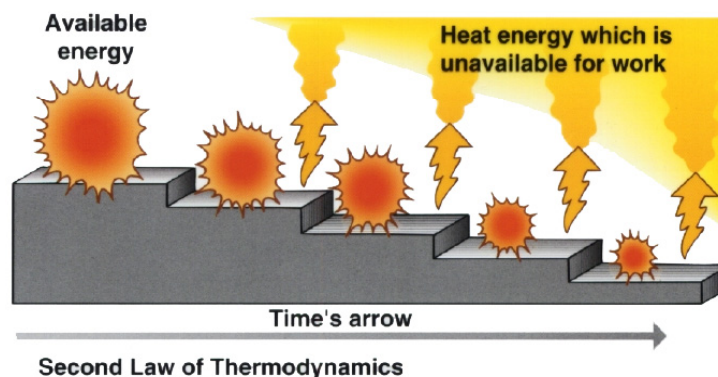
## The Two Laws of Thermodynamics

The **First Law of Thermodynamics** states the amount of energy in any process is constant, meaning that energy can neither be created nor destroyed by ordinary processes. But energy can be, and is, converted from one form to another and between potential and kinetic.

When we apply this law to living organisms (or any system) we say that the total amount of energy of a system **and** its surroundings remains constant, because energy transformations occur constantly. With each transformation within any system (such as the cells of your body) some energy escapes to the surroundings as heat energy. Which takes us to the second law.



The **Second Law of Thermodynamics** says something like "the amount of useful energy decreases when energy transformations occur", which means there is a tendency for all systems to reach the lowest possible energy or increase the amount of disorder in the system. This is the famous "**entropy**" law. Entropy is the measure of the amount of disorder (loss of higher level energy) in a system. **Useful** is the critical term here. The amount of energy doesn't change, but the ability of that energy to do the work we need accomplished diminishes. Most entropy is measured in increasing amounts of heat energy released by the system. We can also see increasing entropy when an organism decomposes. The decaying cells are far less "ordered" than when they were alive and functioning.



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To give an example, Apple trees trap light waves of solar radiation in the process of photosynthesis. They use the photosynthetic products to provide energy to maintain their cells and tissues and to produce apple fruits. Apple trees are maintaining their organized structure (and function) by obtaining "fresh" energy through photosynthesis. The apple fruit may lose its energy to you when you choose to eat an apple. The apple becomes seriously disordered as it passes through your digestive system as you process it for nutrients to maintain the organization of your cells.

This is the critical part of the second law of thermodynamics – **order**. Regions of concentrated energy, such as that found in the intact apple, tend to be more orderly than regions of more random energy, found in the individual molecules of the degraded apple in your intestine. A living organism constantly uses energy to maintain order and to prevent disorder of its cells and tissues. It does so at the expense of some other system in which entropy is increasing.

### **Laws of Thermodynamics, Energy Flow and Chemical Reactions**

At first, when we think of the Laws of Thermodynamics, we might think that life can't exist if we must always put energy into a system to sustain it and if all of the chemical reactions that occur in cells are increasing the amount of less useful energy, even when we factor in the transfer of energy from apples to humans. It seems like it's all going downhill.

### **Enter the Sun**

Life on earth relies on the sun. The sun constantly loses energy (the energy of solar radiation) which is trapped by green plants on earth in the process of photosynthesis. Living organisms use the products of photosynthesis to sustain their cells and tissues through the flow of energy within our ecosystems. We survive at the expense of the sun's increasing entropy.

So we can see that while it might seem that we must violate some law of thermodynamics to have life on earth, we really don't.

Now that we've gotten the laws down, let's turn to energy flow and chemical reactions.

### Energy Flow in Chemical Reactions

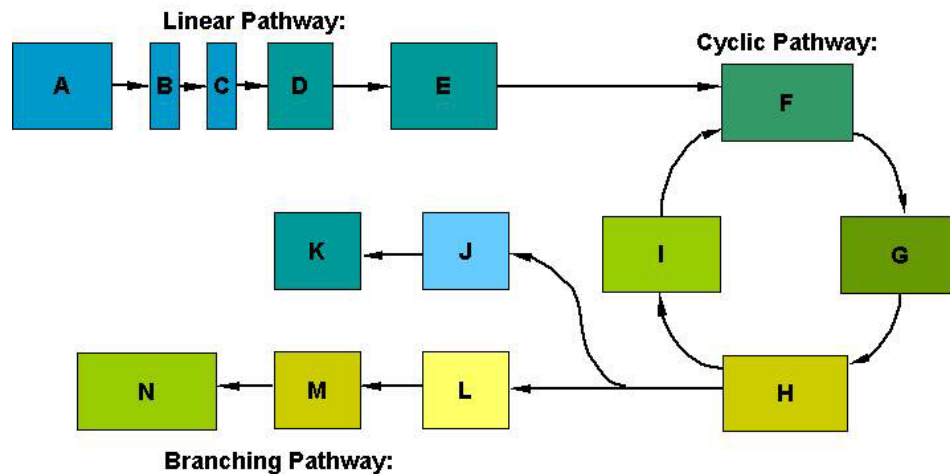
A chemical reaction takes one set of substances, called the **reactants**, (or sometimes, the **substrate**) and converts them to a different set of substances, called the **products**.

Reactants → Products

Many chemical reactions rely on **energy carriers** to activate **enzymes** and other molecules needed to do the reaction. Some enzymes need **cofactors** and **coenzymes** to work. All are important. We will discuss a few of these.

### Metabolic Pathways

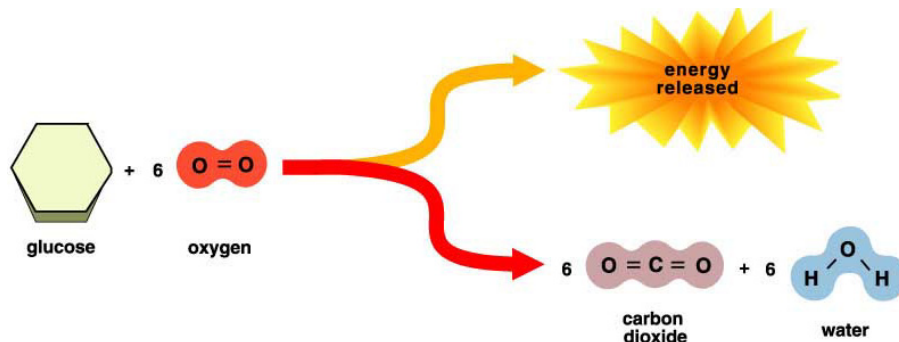
Many of our metabolic reactions take place along pathways in a series of chemical reactions that must be tightly regulated for our cells to function. Metabolic pathways are used to build complex molecules or do complex metabolic activities as well as to degrade. Pathways can be linear, branching or cyclical. Cellular respiration and photosynthesis are but two of the wonderful metabolic pathways of cells.



### Direction of Energy Flow

#### Exergonic Chemical Reactions

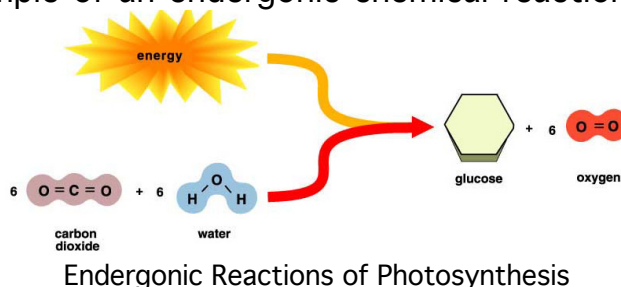
Some chemical reactions release energy -- the amount of energy in the products is less than that of the reactants. Such reactions are said to be **exergonic**.



Exergonic Reactions of Cellular Respiration

## Endergonic Chemical Reactions

Some chemical reactions require or consume energy -- the amount of energy in the products is more than that of the reactants. Such reactions are said to be **endergonic**. The dehydration synthesis that forms the peptide bond between amino acids is an example of an endergonic chemical reaction.



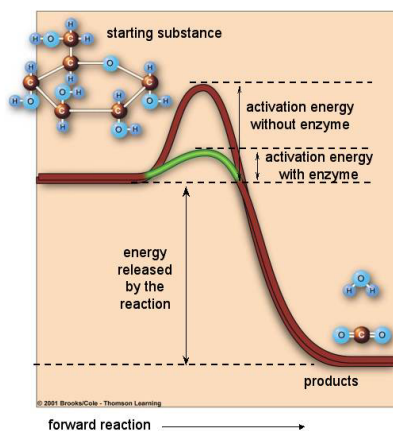
## Activation Energy

Given enough time, an exergonic reaction can (and will) occur spontaneously. Endergonic reactions require energy from some other source in order to take place. In living organisms the source of this needed energy is usually ATP, a molecule we will discuss in a few minutes.

For any chemical reaction to get started, the reactants must come together at the right bonding place at the right time. Remember that all atoms and molecules are in motion, so at some time, it is possible that the reactants will come together randomly.

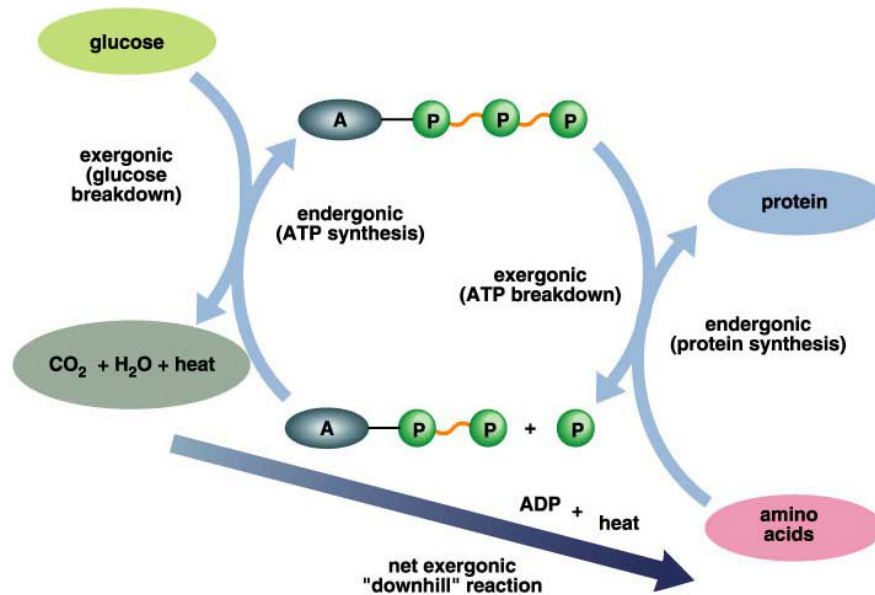
However, the rate of a chemical reaction at normal earth temperatures may be so slow that it is imperceptible. No matter how energetically favorable a chemical reaction is, some energy is needed to get the reaction started. This energy is called the **activation energy**. Activation energy is anything that increases the rate at which the reactants collide (or come together) so that any reaction can occur.

Some chemical reactions occur naturally because the activation energy needed to break the bonds of the reactants can be supplied by ambient heat energy. Most reactions cannot, which is a good thing for life. Reasonably unstable molecules such as nucleic acids and proteins would degrade spontaneously if just a small amount of heat energy was needed to overcome the activation energy.



### Applying Energy Flow to Coupled Reactions

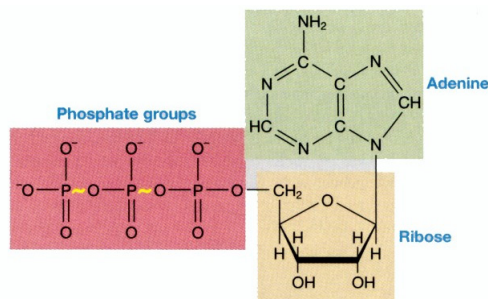
Keeping cells alive takes work and requires energy. This energy comes from exergonic reactions within the cells that provide the free energy to perform the endergonic reactions needed to keep cells and tissues functioning. We refer to these paired reactions as **coupled reactions**. For example, the release of energy from the oxidation of glucose fuel molecules, for example, is coupled to the endergonic assembly of proteins and other macromolecules in cells and tissues.



By far, the most common energy coupler in chemical reactions is the nucleotide, ATP.

### Speaking of ATP

For some reason, in order for energy to be useful to do cell work, it must be in the form of the nucleotide, **ATP**. Cells do not directly use other forms of energy, so that the energy of chemical fuel molecules must be transformed into ATP before cell work can be done. ATP is then used to provide the energy to complete an endergonic chemical reaction.



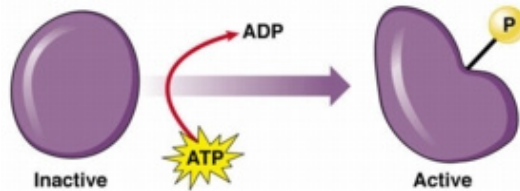
ATP has three "high-energy" phosphate bonds. The second and third phosphate bonds of ATP are unstable. When this phosphate bond is broken by hydrolysis, energy is released (an exergonic reaction). This released energy is just perfect for the amount of energy needed for many cell reactions. This is why we call ATP an energy carrier. It "carries" the energy needed to do the cell work.

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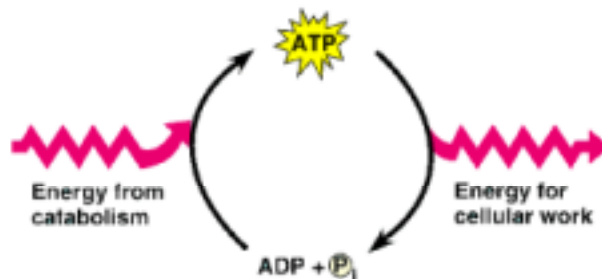
The product of the hydrolysis of ATP is a molecule of ADP and a free phosphate molecule ( $P_i$ ).



ATP may "energize" a molecule by transferring the ATP phosphate to the molecule, so that the molecule has a more favorable bonding arrangement for its activity.



The exergonic process of cell respiration makes ATP using energy obtained by "burning" or oxidizing fuel molecules, like glucose, to bond a Phosphate ( $P_i$ ) to the nucleotide ADP. Once synthesized, the ATP is broken to release its energy in the reactions to which it is coupled. This is a constant process in cells. About 88 pounds of ATP is made and broken in 24 hours just for basic cell maintenance. A cell has only about a one-minute supply of ATP at any given time. The unstable ATP cannot be "stockpiled". Keep in mind, however, that not all of that 88 pounds is useful energy. Much of the energy released when ATP is broken is in the form of less useful heat energy. So in one sense, we can say life is about making and breaking ATP.



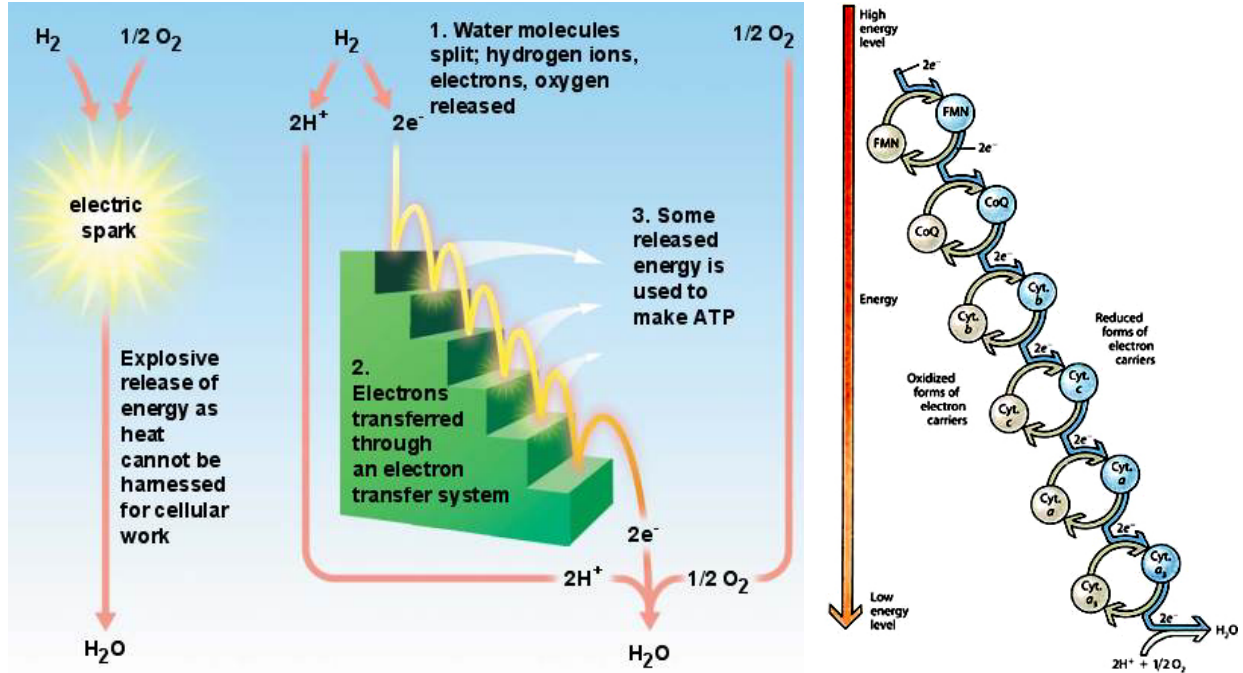
ATP can also work by transferring its third phosphate to the reacting molecule, energizing that reactant. When you are transferring phosphates ( $P_i$ ) from one thing to another it's called **phosphorylation**, a good term to know.

### Electron Carriers

Many coupled reactions involve electron transfers using series of energy carrier molecules embedded in membranes. They are often called **electron transport chains**. These electron transfer chains include a number of nucleotides, such as **NAD<sup>+</sup>**, **NADP<sup>+</sup>** and **FAD**, along with many other kinds of molecules including proteins and quinones.

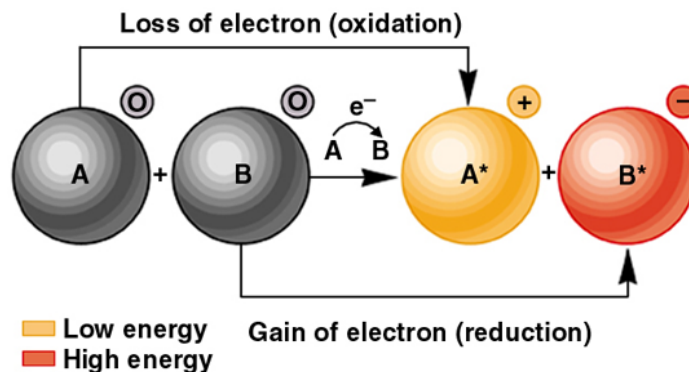
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The electron carrier molecules can capture energy released in exergonic reactions and transport it to endergonic reactions so that energy needed to cell work can be controlled and useful, rather than wasted. Often they are described as stair steps, because they can release energy step-by-step along their pathway.



## Oxidation-Reduction and Metabolism

Since energy changes in cells involve energy transfers, oxidation-reduction reactions are important. It can be useful to review them. An **oxidation** is the loss of one or more electrons. A **reduction** is the gain of one or more electrons. Oxidations and reductions are always coupled and are useful in controlling the energy released from an exergonic chemical reaction so that it can be made available for cell work. In many cell oxidation-reduction reactions, the electron oxidized is associated with a hydrogen atom, so gaining and losing hydrogens and their electrons is something we will often see in metabolic pathways, such as cell respiration and photosynthesis.



## Regulating Metabolism – Activation Energy, Catalysts and Enzymes

We need to be able to control the chemical reactions that occur in our cells and tissues, and we need to be able to do the chemical reactions of metabolism within the temperature, pressure and concentrations of molecules that are found within our cells. Many of our metabolic reactions occur in pathways that must be tightly regulated or our cells cannot function. Much regulation of metabolism depends on the use of **catalysts**, substances that affect the rate of reactions.

### Catalysts

An alternative to increasing the heat energy needed to activate a chemical reaction is to stress the bonds of the reactants to make them easier to break. Substances that can do this are called **catalysts**. A catalyst affects the bonds of the reactants in a way to reduce the activation energy needed to break the bonds, thus facilitating the rate of the chemical reaction.

### Characteristics of Catalysts

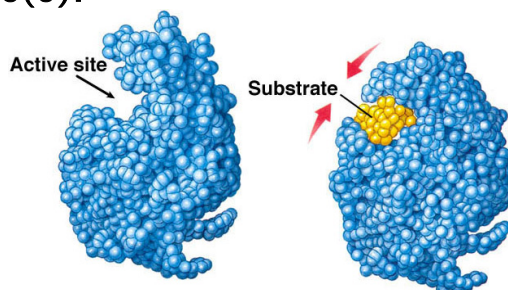
- A catalyst speeds up a chemical reaction
- A catalyst can not cause a reaction to occur that is not energetically favorable
- A catalyst does not change the chemical equilibrium of a reaction.
- A catalyst is not consumed in a chemical reaction

It is important to know that a catalyst is not part of the chemical reaction. It is neither a reactant nor a product. A catalyst facilitates the reaction. In living organisms, we mostly use a special class of catalysts, called **enzymes**. Enzymes are proteins. In addition, some chemical reactions are catalyzed by RNA molecules called **ribozymes**.

Note: Activation energy is separate from the energy input needed to sustain endergonic reactions. Any endergonic reaction needs energy added to it to keep it going, along with getting it started.

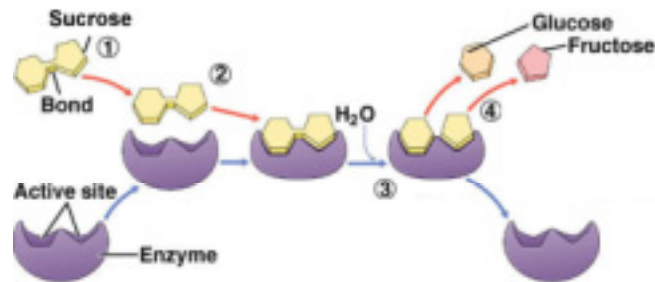
### Enter Enzymes

Enzymes are almost always globular proteins with a place on the surface where the enzyme can bind to the reactant(s). This "notch" is the **active site**, comprised of just a few amino acids (a domain of the tertiary structure). The remainder of the enzyme helps to maintain the integrity of the active site. The active site has a precise size, shape, and electrical charge that exactly complements the reactant(s) or **substrate(s)**.



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When a substrate binds to the enzyme, it "fits" into the active site, temporarily distorting the reacting molecules; this is called the **induced fit**. This distorted stage of the substrate is called the **transition state** and its bonds are more easily broken (lowered activation energy), promoting the reaction. Once the reaction occurs, the active site is altered, releasing the product. The enzyme is unaffected by the reaction.



Enzymes are highly specific. Each chemical reaction that occurs in cells has its own enzyme. Enzyme shape determines its function. The kinds of enzymes in cells determine what chemical reactions take place and what metabolic activities will occur within that cell.

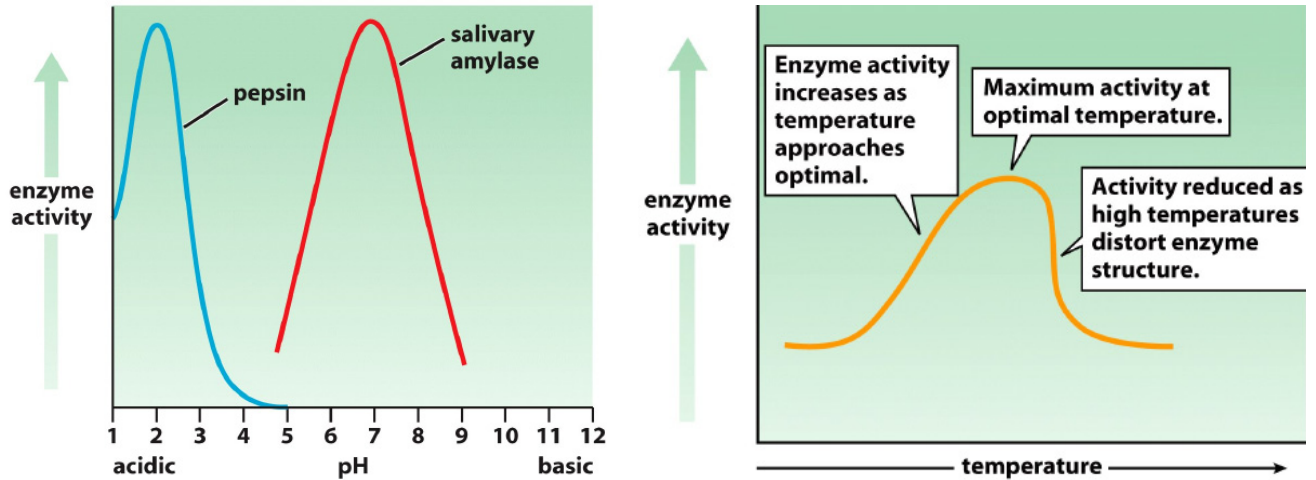
Although many enzymes are located free within the cytoplasm of the cell, others are found within complexes, typically associated with membranes of specific organelles, such as the enzymes needed for cell respiration found in the mitochondria. Such complexes provide greater efficiency and control in metabolic pathways.

Some enzymes can only work when they have associated molecules, called **coenzymes** (non-protein organic molecules) or **cofactors** (mineral ions) present.

- Many of our vitamins function as coenzymes in electron transport pathways picking up the electrons removed from the substrate and carrying them (and their associated H<sup>+</sup>) to the next reaction in the pathway in a series of **oxidation-reduction** reactions.
- Some of our minerals, notably zinc, copper and iron, function as cofactors. Cofactors in the active site attract electrons from the substrate promoting the reaction. Some metals may interfere with enzyme function. Mercury, for example, inhibits the function of many enzymes, partly by blocking the attachment of the needed cofactor.

## Enzymes and Their Environment - Enzyme Regulation

Enzyme activity is controlled by conditions of the environment. Each enzyme works at precise pH, temperature and chemical conditions, such as the amount of sodium ions in the cell.



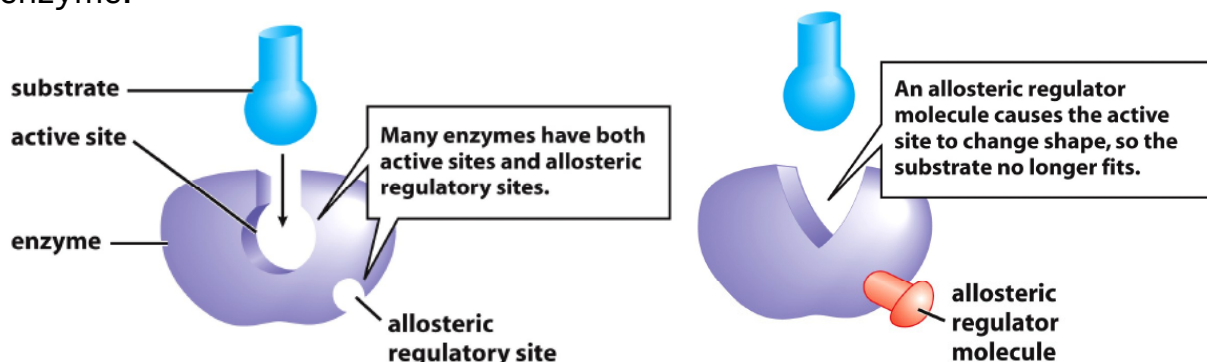
## Enzyme Regulation

Enzyme regulation is a natural part of how cells function. Homeostasis in cells and organisms involves elaborate feedback mechanisms. They are essential for control of metabolism and the orderly operation of cells. Many of these metabolic controls work by activating or de-activating enzymes at appropriate times. This is the subject of **enzyme regulation**.

- The amount of enzyme present can serve to regulate the rate of some chemical reactions. And the cell's DNA controls whether an enzyme is present.
- Some enzymes are manufactured in an inactive form, and converted to an active form only in the presence of the proper reactant (substrate).
- Regulating enzyme activity often involves "sophisticated" controls.

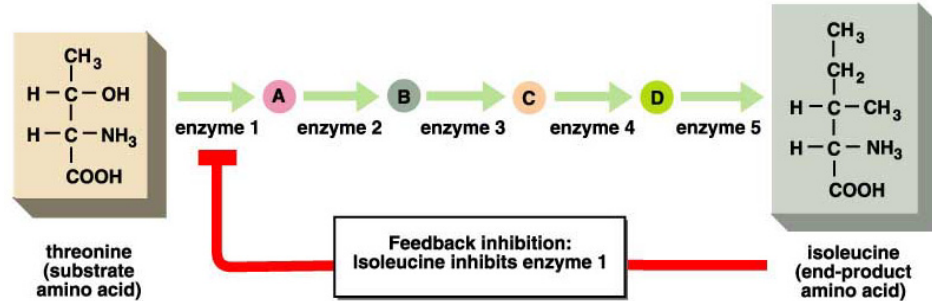
## Allosteric Regulation

Some enzymes have specific receptor sites that change its shape to either activate the enzyme or inhibit the enzyme from functioning. These molecules are known as **allosteric regulators**. The receptor site on the enzyme is called the **allosteric site**. One allosteric site may activate by stabilizing the enzyme shape for the active site and another may inhibit by stabilizing an inactive shape of the enzyme.



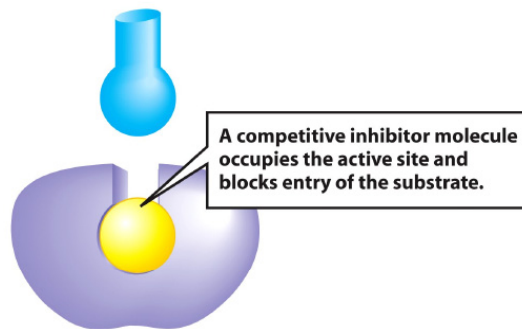
### Feedback Inhibition

Many enzymes are regulated by feedback mechanisms that tell the enzyme that its job is finished. Often the product of the reaction serves as this control. When enough product is formed, some of the product blocks the enzyme's activity, stopping the reaction. As the product is used up, its block of the enzyme is removed, and the enzyme can be active again. This process is called **feedback inhibition**.

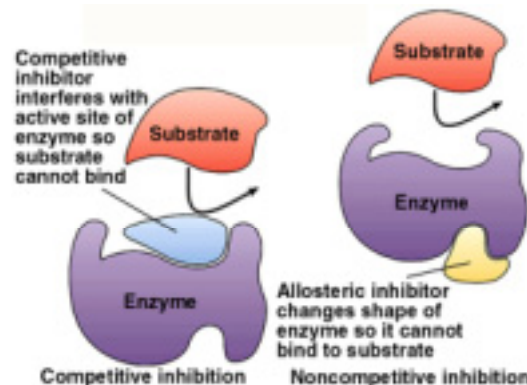


### Competitive Inhibition

Some enzyme inhibitors compete with the substrate for the enzyme's active site and wind up blocking the active site since they do not undergo a chemical reaction and get released from the enzyme. Substances that compete for the enzyme's active site are called **competitive inhibitors**. For example, both methanol and ethanol for the active site on the enzyme alcohol dehydrogenase.



Substances that bind to the enzyme at some other place changing its shape so it can no longer function effectively are called **non-competitive inhibitors**. Allosteric inhibitors are non-competitive inhibitors. A number of poisons block enzyme activity in this way. Many pesticides block essential nervous system enzymes. Mercury inhibits the function of many enzymes, partly by blocking the attachment of the needed cofactor.



### Using Enzyme Activity in Research

One of the fascinating enzyme actions is on the fluorescent molecule, luciferin. A number of living organisms have enzymes, called luciferases, that cause luciferin to fluoresce (give off light). Fireflies are infamous for this activity, although their use of flashing light is to attract mates, as do some marine worm species. Many Dinoflagellates (photosynthetic protists) fluoresce, probably as a defense activity. Genetic researchers have been able to isolate the genes for luciferase and splice this gene into any number of organisms for a variety of genetic and medical research purposes. A more novel use of this was the creation of the fluorescent rabbit for artist, Eduardo Kac (<http://www.ekac.org/>). The gene transferred was a fluorescent gene from a jellyfish.



Alba, the fluorescent bunny.

*Photo: Chrystelle Fontaine*

## **Some Vocabulary Review**

### **Endergonic**

An energy consuming chemical reaction

### **Exergonic**

An energy releasing chemical reaction

### **Reactants**

The substance undergoing a chemical reaction.

Also called: Substrate or Precursor

### **ATP**

Adenosine triphosphate, the energy currency of cells

### **Metabolism**

The chemical reactions which occur in living organisms

### **Metabolite**

Compound involved in a metabolic pathway

### **Secondary Metabolite**

Produced as a by-product or indirect product of a metabolic pathway

### **Intermediate Metabolite**

Compound in the middle of a pathway, or a compound that can branch into alternative metabolic pathways

### **Enzyme**

Protein that serves as a catalyst for a metabolic reaction

### **Cofactors**

Inorganic metal ions that work with enzymes

### **Coenzymes**

Small organic molecules (often vitamins) that work with enzymes

### **Products**

The substance(s) left or produced at the end of a metabolic reaction

A **by-product** is a product not needed for cell use at the end

### **Oxidation**

The loss of electrons (or in cell processes, a Hydrogen ion with its electron)

### **Reduction**

The gain of electrons (or in cell processes, a Hydrogen ion with its electron)