Energy is defined as **the capacity to cause change**—for instance, by doing work.

Potential energy is the energy that matter possesses because of its **location** or **structure**.

For example, water in a reservoir on a hill has potential energy because of its altitude.

When the gates of the reservoir’s dam are opened and the water runs downhill, the energy can be used to do work, such as moving the blades of turbines to generate electricity.

Because energy has been expended, the water has less energy at the bottom of the hill than it did in the reservoir.

Organic compounds possess potential energy as a result of **the arrangement of electrons** in the bonds between their atoms.

Through the activity of enzymes, a cell systematically degrades complex organic molecules that are rich in potential energy to simpler waste products that have less energy.

Some of the energy taken out of chemical storage can be used to do work; the rest is dissipated as heat.

**How do the catabolic pathways** that decompose glucose and other organic fuels **yield energy?**

The answer is based on **the transfer of electrons** during the chemical reactions.

**The relocation of electrons** **releases energy** stored in organic molecules, and this energy ultimately is used to synthesize ATP.

In a redox reaction, the loss of electrons from one substance is called oxidation, and the addition of electrons to another substance is known as reduction.

Not all redox reactions involve the complete transfer of electrons from one substance to another; some change **the degree of electron sharing in covalent bonds**. Methane combustion is an example.

The covalent electrons in methane are shared nearly equally between the bonded atoms because carbon and hydrogen have about the same affinity for valence electrons; they are about equally electronegative.

But when methane reacts with oxygen, forming carbon dioxide, electrons end up shared less equally between the carbon atom and its new covalent partners, the oxygen atoms, which are very electronegative.

In effect, the carbon atom has partially “lost” its shared electrons; thus, methane has been oxidized.

The two atoms of the oxygen molecule (O2) share their electrons equally.

But when oxygen reacts with the hydrogen from methane, forming water, the electrons of the covalent bonds spend more time near the oxygen.

In effect, each oxygen atom has partially “gained” electrons, so the oxygen molecule has been reduced.

**An electron loses potential energy** when it shifts **from a less electronegative atom toward a more electronegative one**, just as a ball loses potential energy when it rolls downhill.

A redox reaction that **moves electrons closer to oxygen**, such as the burning (oxidation) of methane, therefore **releases chemical energy** that can be put to work.

The oxidation of methane by oxygen is the main combustion reaction that occurs at the burner of a gas stove.

In general, organic molecules that have an abundance of hydrogen are excellent fuels because their bonds are a source of “hilltop” electrons, whose energy may be released as these electrons “fall” down an energy gradient when they are transferred to oxygen.

The summary equation for respiration indicates that hydrogen is transferred from glucose to oxygen.

But the important point, not visible in the summary equation, is that **the energy state of the electron** **changes** as hydrogen (with its electron) is transferred to oxygen.

In respiration, **the oxidation** of glucose **transfers electrons to a lower energy state, liberating energy** that becomes available for ATP synthesis.

The main energy-yielding foods—carbohydrates and fats—are **reservoirs of electrons** associated with hydrogen.

Only the barrier of activation energy holds back the flood of electrons to a lower energy state.

Without this barrier, a food substance like glucose would combine almost instantaneously with O2.

If we supply the activation energy by igniting glucose, it burns in air, releasing 686 kcal (2,870 kJ) of heat per mole of glucose (about 180 g).

Body temperature is not high enough to initiate burning, of course.

Instead, if you swallow some glucose, enzymes in your cells will lower the barrier of activation energy, allowing the sugar to **be oxidized in a series of steps**. At key steps, electrons are stripped from the glucose.

As is often the case in oxidation reactions, each electron travels with a proton—thus, as a hydrogen atom.

The hydrogen atoms are **not** transferred **directly** to oxygen, but instead are usually passed first to an electron carrier, a coenzyme called NAD+ (nicotinamide adenine dinucleotide, a derivative of the vitamin niacin).

NAD+ is well suited as an electron carrier because it can cycle easily between oxidized (NAD+) and reduced (NADH) states.

As an electron acceptor, NAD+ functions as an oxidizing agent during respiration.

**How does NAD+ trap electrons** from glucose and the other organic molecules in food**?**

Enzymes called dehydrogenases remove a pair of hydrogen atoms (2 electrons and 2 protons) from the substrate (glucose, in the above example), thereby oxidizing it.

The enzymatic transfer of 2 electrons and 1 proton (H+) from an organic molecule in food to NAD+ reduces the NAD+ to NADH.

The other proton is released as a hydrogen ion (H+) into the surrounding solution.

NAD+ as an electron shuttle. Most of the electrons removed from food are transferred initially to NAD+, forming NADH.

The full name for NAD+, nicotinamide adenine dinucleotide, describes its structure—the molecule consists of two nucleotides joined together at their phosphate groups. (Nicotinamide is a nitrogenous base, although not one that is present in DNA or RNA.)

Electrons lose **very little** of their potential energy when they are transferred from glucose to NAD+.

Each **NADH molecule** formed during respiration represents **stored energy**.

This energy can be tapped to make ATP when the electrons complete their “fall” in a series of steps down an energy gradient from NADH to oxygen.

**How do electrons** that are extracted from glucose and stored as potential energy in NADH **finally reach oxygen?**

It will help to compare the redox chemistry of cellular respiration to a much simpler reaction: the reaction between hydrogen and oxygen to form water.

Mix H2 and O2 , provide a spark for activation energy, and the gases combine explosively.

The explosion represents a release of energy as the **electrons** of hydrogen **“fall” closer to** the electronegative **oxygen** atoms.

Cellular respiration also brings hydrogen and oxygen together to form water, but there are two important differences.

First, in cellular respiration, the hydrogen that reacts with oxygen is derived from organic molecules rather than H2.

Second, instead of occurring in one explosive reaction, respiration uses an **electron transport chain** to break **the fall of electrons to oxygen** into **several energy-releasing steps**.

An electron transport chain consists of a number of molecules, mostly proteins, built into the inner membrane of the mitochondria

of eukaryotic cells (and the plasma membrane of respiring prokaryotes).

Electrons removed from glucose are shuttled by NADH to the “top,” higher-energy end of the chain.

At the “bottom,” lower-energy end, O2 captures these electrons along with hydrogen nuclei (H+), forming water. (Anaerobically respiring prokaryotes have an electron acceptor at the end of the chain that is different from O2.)

Electron transfer from NADH to oxygen is an exergonic reaction with a free-energy change of -53 kcal/mol (-222 kJ/mol).

Instead of this energy being released and wasted in a single explosive step, electrons cascade down the chain from one carrier molecule to the next in a series of redox reactions, losing a small amount of energy with each step until they finally reach oxygen, the terminal electron acceptor, which has a very great affinity for electrons.

Each “downhill” carrier is more electronegative than, and thus capable of oxidizing, its “uphill” neighbor, with oxygen at the bottom of the chain.

Therefore, the electrons transferred from glucose to NAD+, which is thus reduced to NADH, fall down an energy gradient in the electron transport chain to a far more stable location in the electronegative oxygen atom.

Put another way, oxygen pulls electrons down the chain in an energy-yielding tumble analogous to gravity pulling objects downhill.

In summary, during cellular respiration, most electrons travel the following “downhill” route:

glucose → NADH → electron transport chain → oxygen.

The harvesting of energy from glucose by cellular respiration is

a cumulative function of three metabolic stages.

1. GLYCOLYSIS
2. PYRUVATE OXIDATION and the CITRIC ACID CYCLE
3. OXIDATIVE PHOSPHORYLATION: Electron transport and chemiosmosis

Biochemists usually reserve the term cellular respiration for stages 2 and 3 together.

In this text, however, we include glycolysis as a part of cellular respiration because most respiring cells deriving energy from glucose use glycolysis to produce the starting material for the citric acid cycle.

glycolysis and pyruvate oxidation followed by the citric acid cycle are the catabolic pathways that break down glucose and other organic fuels.

Glycolysis, which occurs in the cytosol, begins the degradation process by breaking glucose into two molecules of a compound called pyruvate.

In eukaryotes, pyruvate enters the mitochondrion and is oxidized to a compound called acetyl CoA, which enters the citric acid cycle.

There, the breakdown of glucose to carbon dioxide is completed. (In prokaryotes, these processes take place in the cytosol.)

Thus, the carbon dioxide produced by respiration represents fragments of oxidized organic molecules.

Some of the steps of glycolysis and the citric acid cycle are redox reactions in which dehydrogenases transfer electrons from substrates to NAD+, forming NADH.

In the third stage of respiration, the **electron transport chain** accepts electrons (most often via NADH) from the breakdown products of the first two stages and passes these electrons from one molecule to another.

At the end of the chain, the electrons are combined with molecular oxygen and hydrogen ions (H+), forming water.

**The energy** released at each step of the chain **is stored** in a form the mitochondrion (or prokaryotic cell) can use to make ATP from ADP.

This mode of ATP synthesis is called oxidative phosphorylation because it is powered by **the redox reactions of the electron transport chain.**

In eukaryotic cells, the inner membrane of the mitochondrion is the site of electron transport and chemiosmosis, the processes that together constitute oxidative phosphorylation. (In prokaryotes, these processes take place in the plasma membrane.)

Oxidative phosphorylation accounts for almost 90% of the ATP generated by respiration.

A smaller amount of ATP is formed directly in a few reactions of glycolysis and the citric acid cycle by a mechanism called substrate-level phosphorylation.

This mode of ATP synthesis occurs when an enzyme transfers a phosphate group from a substrate molecule to ADP, rather than adding an inorganic phosphate to ADP as in oxidative phosphorylation.

“Substrate molecule” here refers to an organic molecule generated as an intermediate during the catabolism of glucose.

For each molecule of glucose degraded to carbon dioxide and water by respiration, the cell makes up to about 32 molecules of ATP, each with 7.3 kcal/mol of free energy.

Respiration cashes in the large denomination of energy banked in a single molecule of glucose (686 kcal/mol) for the small change of many molecules of ATP, which is more practical for the cell to spend on its work.