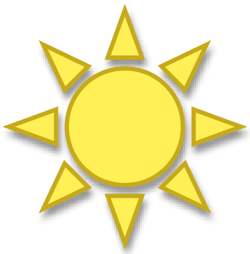
The Fire Within

Module 6 • i2P • La Ruta de Sal

Source: Matthew Bowden

> “ Chemistry itself knows altogether too well that - given the real fear that the scarcity of global resources and energy might threaten the unity of mankind - chemistry is in a position to make a contribution towards securing a true peace on earth.
>
> - Kenichi Fukui



FIRE

Figure 1: Prometheus and the eagle (source: Rheinisches Bildarchiv)

In Greek mythology mortal man had no knowledge of fire; it was solely the possession of the Gods until one day Prometheus, a lesser God, stole fire from the king of the Gods, Zeus, and gave it to mortal man. For his crime Zeus punished Prometheus by binding him to a rock, and having a great eagle eat his liver, only to have the organ regenerate overnight to be eaten again, day after day.

The Oxford English Dictionary defines fire as “the state of burning, in which substances combine chemically with oxygen from the air and give out bright light, heat, and smoke” (Oxford).

Whether a gift of the Gods or a chemical reaction, fire is a cornerstone of modern life. We burn gasoline to propel cars and planes. We burn wood to heat houses, and burn fuel to cook food. It is by burning candles that we light our way. The act of burning is called *combustion*. Combustion is valuable for the two byproducts it produces: heat and light. Heat and light are forms of energy that humans harness to do work, keep us warm and illuminate our environment.

Fire requires three essential ingredients to occur:

- Oxygen
- Heat
- Fuel

Fire is a chain reaction that is started using an ignition source (eg. heat, spark, lightning, fire) and continues as long as the reactants - or fuel - and oxygen are both available. A fire ‘burns’ at the rate at which the fuel and oxygen are both available. Fire is an example of a chemical process where energy is released when a molecule of fuel is transformed into different molecules. These are called *product molecules*.

Figure 2: A Wood Fire (source: Einar Helland Berger

OXYGEN

Over the history of the planet, oxygen has not always been abundant. Without it, there is no fire. According to the fossil record, evidence of fire (seen in charcoal - a proxy for fire) first appears on Earth 420 million years ago. Scientists have established that the amount of charcoal in the fossil record is proportional to the atmospheric oxygen. Currently oxygen molecules (O_2) form 21% of the atmosphere, but this amount has varied significantly over geological time. The fossil record reveals that fire was found on the planet when atmospheric oxygen reached a threshold of 13% and increased in incidence as oxygen levels rose, vanishing when the oxygen content of air surpassed 35% (see: oxygen).

Did You Know?

The Fire Window:

Experimental data provide the following observations about O_2 levels and fire in the fossil record: At levels <13%, except under exceptional circumstances, wildfires will not ignite and spread irrespective of moisture content. Between 13% and 16% fires would be rare and would only burn very dry plant material. Between 18% and 23% fire occurrences would be similar to those under current conditions where plant matter (fuel) must have low moisture content; dry seasons help to effect this decline in fuel moisture and permit the rapid spread of the flame front and fire propagation. At >25% fires would become widespread, especially in wetter climatic areas, because of the prevalence of lightning strikes. At levels >30% fire activity would be globally distributed. However, at levels >35% plants have been predicted to burn irrespective of drying, resulting in an upper limit of O_2 beyond which fires could not be extinguished . These limits define the fire window, within which O_2 levels are constrained where charcoal, a pyrolysis product of fire, is found in the fossil record.

see: charcoal

Of all the elements in the periodic table, why is fire dependent on oxygen? The answer lies in the structure of the oxygen molecule. Atmospheric oxygen consists of two oxygen atoms bonded together (O_2). If you remember from earlier modules, the bonding capacity of an atom or molecule depends on the number of electrons available to be shared. Electrons that are in pairs are not available to be shared. Unpaired electrons, called *free radicals,* are eager to pair up with an electron from another atom to form a bond. Atmospheric oxygen (O_2) has two free radicals, and as such it is a *diradical*. When fuel molecules (such as wood or gasoline) are exposed to an ignition source (eg. a spark or flame), the stable bonds in those molecules are broken and radicals are produced. These radicals react with the O_2 diradical. In this manner, anything that burns is able to react with oxygen.

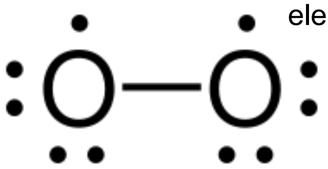


Figure 3: This structural model of an oxygen molecule illustrates its two unpaired electrons (source: Leyo)

HEAT

Did You Know?

Combustion need not involve oxygen; e.g., hydrogen burns in chlorine to form hydrogen chloride with the liberation of heat and light, characteristic of combustion.

The chain reaction of fire requires heat to start. Heat causes stable bonds in the fuel to become unstable and react with oxygen diradicals. This breaking of bonds releases more heat and more bonds are broken, causing the chain reaction. If heat is removed a fire will stop. Water extinguishes a fire by cooling the environment so that no further unstable bonds are formed and the chemical reaction of fire stops.


Figure 4: Spark plug (source: Vlad UA)

Humans have developed simple technologies to start fire, like lighters and matches that are designed to supply heat. A match introduces heat from friction generated when it is struck. Heat from a spark plug alights the gasoline that is burned to drive an internal combustion engine.


Figure 5: A burning match (source: Sebastian Ritter)

FUEL

The basic unit of fuel is the chemical bond, which stores energy. Chemical bonds come in various forms, and hold varying magnitudes of energy. Combustion is one way of harnessing this energy. Combustion is a chemical reaction in which complex molecules are broken down into smaller, more stable molecules. The conversion of complex energy-rich molecules to simple energy-poor molecules, releases excess energy in the form of heat and light.

THE FIRE WITHIN

There are microscopic fires underway in all the cells of our bodies. Like a campfire, our bodies use fuel, oxygen and heat to generate energy. For us, food is the fuel; and it's burned in a controlled manner in our cells, to generate the energy and heat that sustains us. Just as fire requires oxygen to burn, humans use oxygen to generate heat and energy from food. Deprived of oxygen, human beings die rapidly for the very same reasons that a fire deprived of oxygen stops burning. Death by suffocation results from the sudden deprivation of energy resulting in the shutdown of all body systems.

When food is broken down, a series of chemical reactions convert it into a molecule called adenosine triphosphate (ATP). ATP is an energy-rich molecule, and is the universal currency of energy for human beings. The bonds between the atoms of ATP carry a great deal of energy and heat when they are broken to power and sustain cellular function.

Did You Know?

Imagine if heat were not needed and fire was produced with fuel and oxygen alone. Much of the world would be burning as fuel and atmospheric oxygen are always in contact. The wood you place in your fireplace, although bathed in oxygen, requires the addition of heat to combust.

Source: Grm wnr

When the i2P team members stop to eat during a run, the food they ingest begins a long chemical journey from fuel to energy and heat. Let's imagine a bite of an apple. The apple is first ground up by the teeth, and the carbohydrate (sugar) in it is broken down by the saliva in the mouth before passing down the throat. Complex sugar molecules released from the apple are broken into simple sugar molecules as it moves through the stomach and into the small intestine. The most common simple sugar is glucose, which is absorbed by cells that line the small intestines. It is then passed into the blood stream and distributed to cells throughout the body.

The bonds between atoms of a glucose molecule contain energy, and it is this energy that is used to produce ATP. This chemical process is called cellular respiration. In cellular respiration the combination of one glucose and six oxygen molecules produces thirty-eight ATP, six molecules of water and six molecules of carbon dioxide. The chemical reaction is written as follows:

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 38\ ATP + 6\ CO_2 + 6\ H_2O$

ATP produced in cellular respiration supplies the energy to drive all body functions. Understanding this reaction helps explain what is occurring when the i2P team is running. They will need food energy ($C_6H_{12}O_6$) and to breath in O_2 (inhaling) to produce energy (ATP) to power the muscle cells. They will also need to breath out (exhale) to rid the body of CO_2. In fact, breathing is an automatic reflex that is not controlled by lack of O_2, but rather by an increase in CO2 in the body.

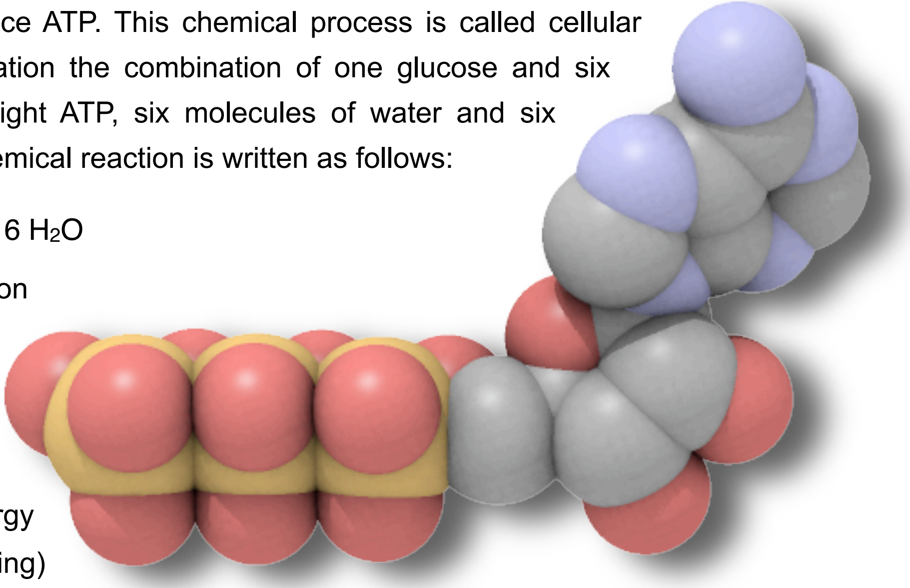


Figure 6: An ATP molecule (source: ALoopingIcon)

ANAEROBIC RESPIRATION

When the i2P team are running as much as 90% of the oxygen they breath will be used to create energy for their muscle cells. Team members will be able to elevate the rate at which they can process oxygen to about twenty times resting value. What occurs however, when energy needs surpass oxygen supply?

Class Exercise

This experiment shows how sweating helps keep your body cool.

see: [Sweat]

Did You Know?

Carbohydrates, protein and fats can be burned to produce energy in the human body. Fats are a more efficient molecule for storage of energy as each gram of lipid yields more than twice the energy found in carbohydrates or proteins. A normal person has enough energy stored as fats to run hundreds of miles, but only enough stored carbohydrate to run about 20 miles!

During extreme physical exertion the oxygen needs of the human body can exceed the supply. This is seen in sporting events such as the 800-metre run, 200-metre swim, downhill ski racing, and 1500-metre speed skating. In these situations the human body has the capacity to produce energy without oxygen, a process called *anaerobic metabolism*. The body relies primarily on anaerobic metabolism for the energy required to perform intensive exercise of greater than 12- 15 seconds and less than 3 minutes duration.

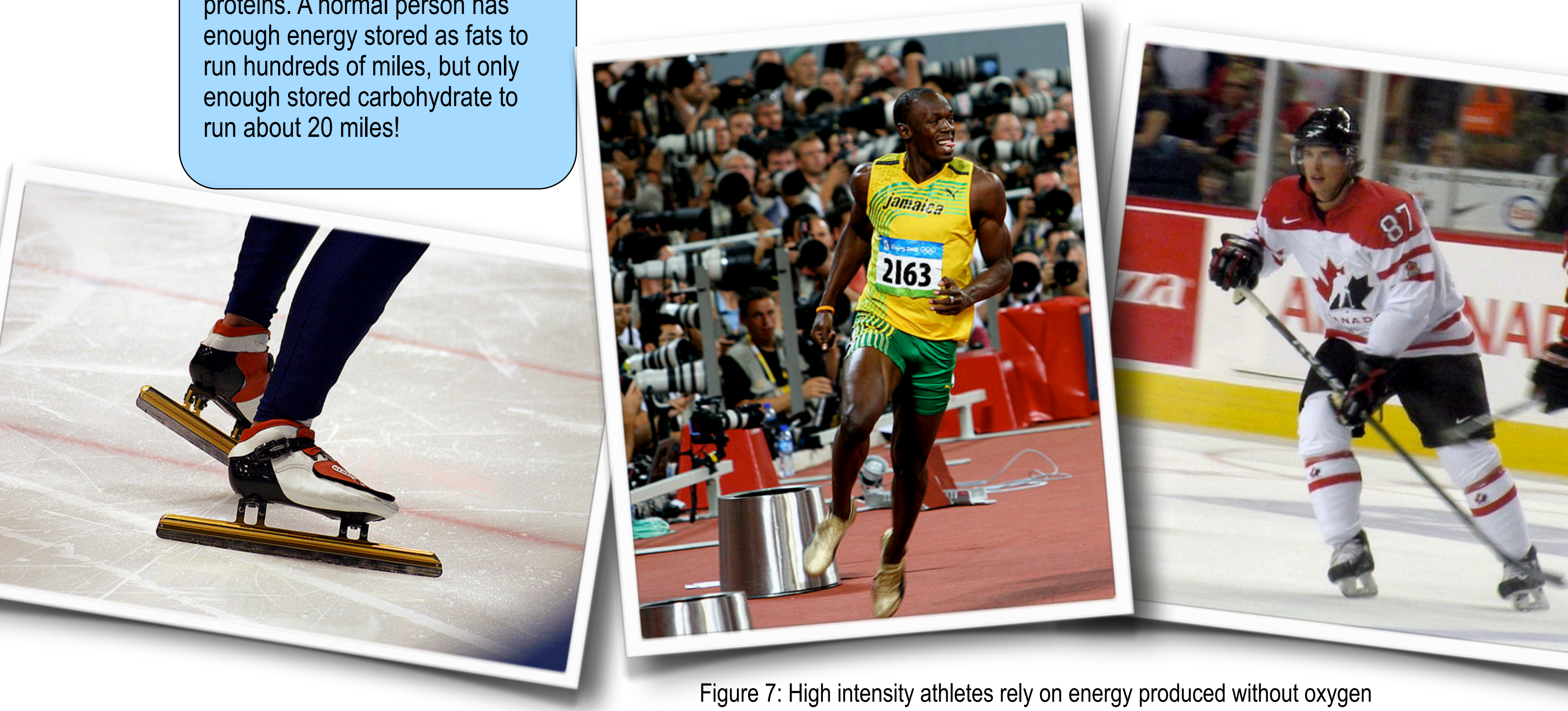


Figure 7: High intensity athletes rely on energy produced without oxygen (sources: Vincent Baas , Richard Giles, Resolute)

In anaerobic metabolism cellular enzymes break down the chemical bonds in glucose in the absence of oxygen. Anaerobic metabolism is much less efficient than aerobic metabolism, as only two ATP molecules are produced for every one molecule of glucose. Most of the energy generated in this reaction does not result in ATP synthesis, but is dissipated as heat. That is why intensive exercise over the aerobic threshold (the level at which oxygen dependent energy production is surpassed) causes an athlete to become very hot and sweat a great deal.

Class Exercise

Students can weigh themselves before and after 30-60 minutes of aerobic exercise (like a soccer game or jumping rope for example). This will show how much body mass is lost with sweat when we exercise. (Hint, you'll get thirsty, so you'll likely want to replenish your body with water. You should weight your water bottle before and after exercising. Should the weight of water you drank bee added or subtracted from your post-exercise weight?

Another byproduct of anaerobic energy production is lactic acid. The exercise intensity at which lactic acid begins to accumulate within the blood has been commonly referred to as the anaerobic threshold. In practical terms, the anaerobic threshold can be thought of as the point during exercise when the person begins to feel discomfort and a burning sensation in their muscles. Have you ever noticed that professional hockey players keep their time on the ice to about 40 seconds? This is because lactic acid builds up in the muscle tissues on longer shifts slowing the player down. The shifts are short so the athletes have time for that lactic acid to be removed form their muscles.

THE SUN

If you trace the ultimate origin of the energy that will be fueling the i2P team members running across the Salar de Uyuni it leads to the sun. The sun is the source of virtually all energy in the world. The sun produces radiant light and heat that is captured on the planet in a variety of ways. Wind, rain, thunderstorms, flowing water, and ocean currents are all a byproduct of the sun's energy. Human beings cannot extract energy directly from the sun, and must rely upon plants, algae and bacteria to do so through *photosynthesis*. Photosynthesis is a chemical process that captures the

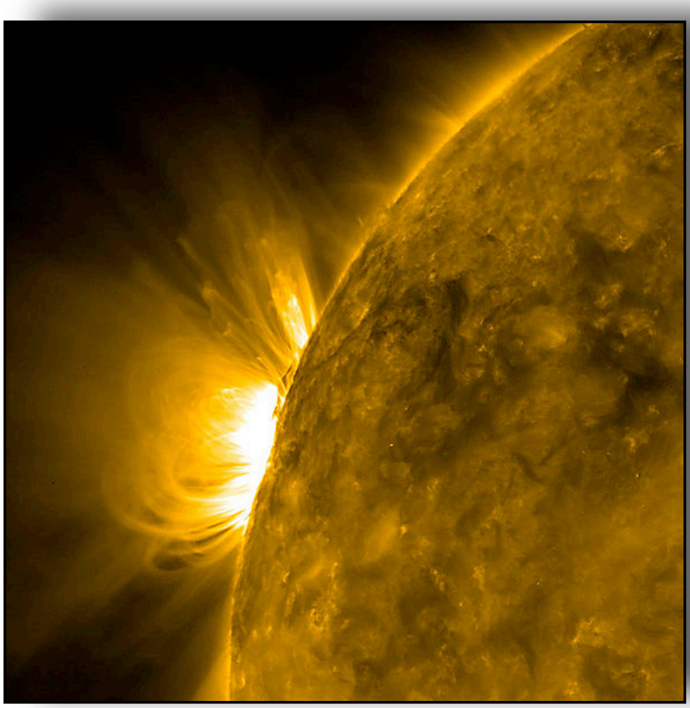


Figure 8: A solar flare seen on the surface of the sun (source: NASA)

radiant energy of the sun and stores it in carbon compounds. These carbon compounds form the material of all living things, including the food we eat.

The warmth and light from an evening campfire after the i2P teams long run, is the release of the sun's energy bound in the chemical bonds of wood molecules. From the burning of jet fuel that carried the team to Bolivia, to the energy bars that drive the muscles of the runners, all are gifts of the sun. Although the sun is often referred to as a ball of fire, the energy it produces is generated by a process that differs from the chemistry of fire. The sun produces energy by fusing atoms together (not by breaking the bonds apart), which releases the energy that make life on Earth possible (nasa).

Figure 9: A forest fire: fuel (wood), oxygen and heat