

## Overview of Energy and Thermodynamics

In physics, energy is an indirectly observed quantity that is often understood as the ability of a physical system to do work on other physical systems. However, this must be understood as an overly simplified definition, as the laws of thermodynamics demonstrate that **not all energy can perform work**.

Depending on the boundaries of the physical system in question, energy as understood in the above definition may sometimes be better described by concepts such as exergy, energy and thermodynamic free energy. In the words of Richard Feynman, "It is important to realize that in physics today, we have no knowledge what energy is."

However, it is clear that energy is an indispensable requisite for performing work, and the concept has great importance in natural science.

Work = Force x distance

The main concept we are trying to understand is what energy is and how energy moves within a system. A system can be a place or an imaginary space. Physicists consider open and closed systems. An open system will allow energy and matter in and out of the system. An isolated system will let no energy or matter in and out. Biologists call a system an ecosystem. An ecosystem is a community of living organisms (plants, animals and microbes) in conjunction with the nonliving components of their environment (things like air, water and mineral soil), interacting as a system. These components are regarded as linked by how energy flows through the system...energy can be in the form of sunlight or food. They are open systems.

Now that we have learned the basics of how stars evolve and some of the basic geometry of our universe we can use our knowledge to return to Earth and understand how Earth evolves. In the next month or so, we will investigate what governs how our world works and how our lives evolve. One of the central issues will be how energy fits into the picture. Where does the energy on Earth go? How does life depend on energy? How do we humans use energy to maintain life?

In thermodynamics, a closed system can exchange energy (as heat or work) but not matter, with its surroundings. An isolated system cannot exchange any heat, work, or matter with the surroundings, while an open system can exchange heat, work and matter. If a coffee mug was a system and it was an open system, you could heat the mug and add coffee. If it were an isolated system, you could neither heat nor cool the mug nor add or remove coffee. If it was a closed system you could heat or cool the mug but add or remove no coffee. For an isolated system inside of which it is undergoing chemical reactions, there may be all sorts of molecules being generated and destroyed by the reaction processes but the total amount of energy remains the same.

We will begin with the three laws of the movement of heat. Scientists call these three laws, The Three Laws of Thermodynamics. The laws can be stated in many ways; the most common are so esoteric that you probably would not understand what they are trying to communicate.

- The first law of thermodynamics, also called conservation of energy, states that “the total amount of energy in a system is constant.” This means that all of the energy has to end up somewhere, either in the original form or in a different form. It also means that energy cannot simply be created or disappear. We can use this knowledge to determine the amount of energy in a system, the amount lost as waste heat, and the efficiency of the system. A consequence of this law is that you cannot get more energy out of something than you put in. At the very most you can only get the same amount out that’s in the system. You can’t win...

-The second law of thermodynamics states that the amount of usable energy in any system is always decreasing. Another way to describe this loss of usable energy is to say that there is an increase in the disorder of the system because to keep a system in order requires usable energy. After cleaning your locker, it has a tendency to become messy again. This is a result of the second law. The word for disorder in physics is ENTROPY. A consequence of the second law is that the universe, as an isolated system will eventually run out of usable energy and end up as a cold dark dead expanse...creepy éh. You can’t break even.

formal way of stating this law is “The increase in the internal energy of a thermodynamic system is equal to the amount of heat energy added to the system minus the work done by the system on the surroundings.”

- The third law of thermodynamics tells us that all molecular movement stops at a temperature we call absolute zero, or 0 Kelvin (-273°C). Since temperature is a measure of molecular movement, there can be no temperature lower than absolute zero.

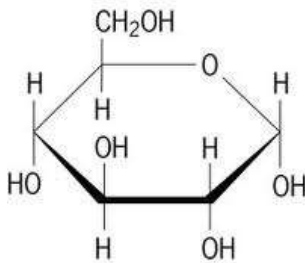
### Perpetual Motion

Generations of inventors have tried to create a machine, called a perpetual motion machine, that would run forever without fuel. Such a machine is not forbidden by Newton’s laws of motion, which are built around the concepts of force and inertia. Force is free, and can be multiplied indefinitely with pulleys, gears, or levers. The principle of inertia seems even to encourage the belief that a cleverly constructed machine might not ever run down. But friction has a way of creeping into all moving systems. The rotating Earth might seem like a perfect perpetual motion machine, since it is isolated in the vacuum of outer space with nothing to exert frictional forces on it. In fact our planet’s rotation has slowed drastically since it first formed, and the Earth continues to slow its rotation, making today just a little longer than yesterday. The very subtle source of friction is the tides. The Moon’s gravity raises bulges in the Earth’s oceans, and as the Earth rotates the bulges progress around the planet. Where the bulges encounter land, there is friction, which slows the Earth’s rotation very gradually.

## Roles of Organisms

Organisms in an ecosystem can be either *producers* or *consumers* based on whether they gather energy from the Sun to make sugar. Producers convert energy from the environment (usually the Sun) into carbon bonds and hydrogens bonded to carbons, such as those found in the sugar glucose. The hydrogens are actually the most important chemical storage of potential energy in most biological molecules. *Plants* are the most obvious examples of producers; plants take electromagnetic energy from the sun and use it to convert carbon dioxide into sugars. Other producers include bacteria living around deep-sea vents. These bacteria take energy from chemicals coming from the Earth's interior and use it to make sugars. Another word for producers is *autotrophs*.

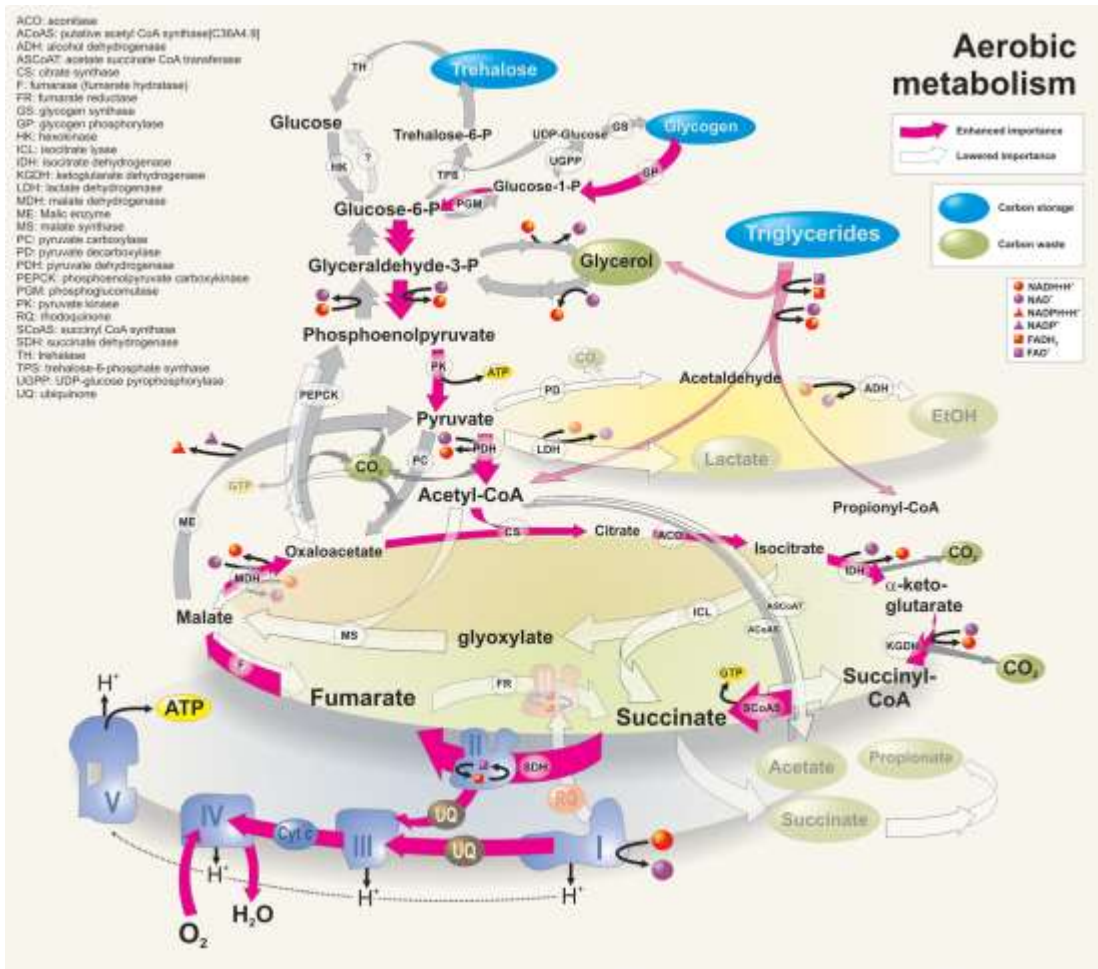
Consumers get their energy from the hydrogens bonded to carbon-based molecules such as sugar made by the producers.



This is a molecule of glucose — the most common sugar in the human body. When the mitochondrion of a eukaryotic organism breaks down sugar and utilizes its chemical energy, it is slowly taking the bond energy stored in the hydrogens bonded to the carbons. This is done in a complex series of chemical reactions.

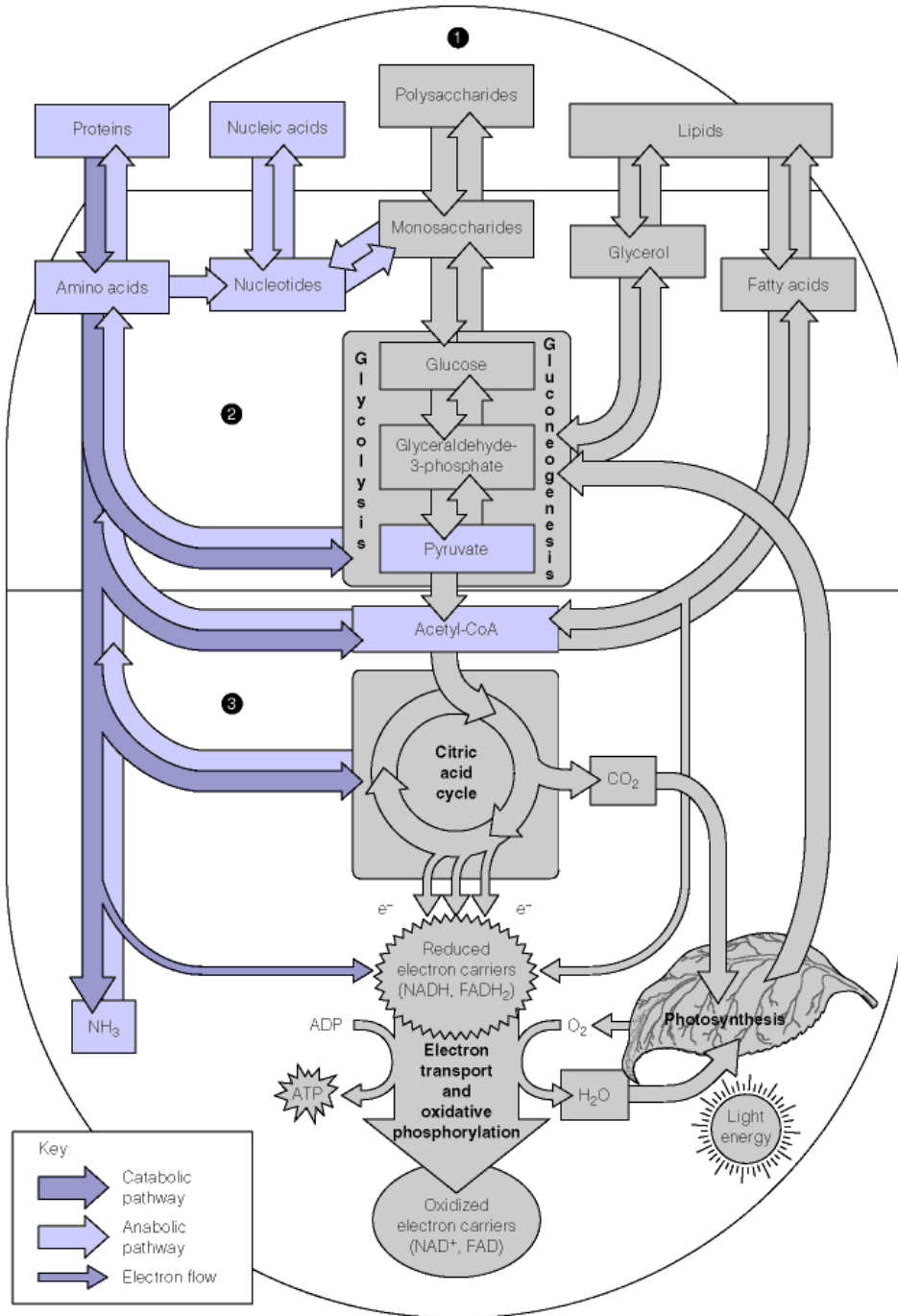
A very simplified image of the reaction paths in a human cell to make energy is shown below in what is called metabolism. Metabolism is a series of stepwise chemical reactions that transform molecules in cells. Some parts of metabolism are for producing energy, some are for storing energy, and some are for making molecules to build muscle, bone and nerves.

**Do Not Worry About Memorizing any of these illustrations... Just Appreciate how Complex Life IS**



Each of the arrows in this model of metabolism represents a conversion from one chemical to another and that conversion requires an enzyme. The enzymes' names are listed in the upper left. Every enzyme here is a protein and for every protein you need a gene to make the protein. Now you can see why we need a lot of genes. A somewhat more complete set of reactions to use and produce energy, in a human body is shown below:

Here is a more generalized model of Energy Flow...Can you find the Sun?



The four biological molecules at the top: From left to right they are Proteins, nucleic acids, polysaccharides (carbs) and lipids (fats and oils).

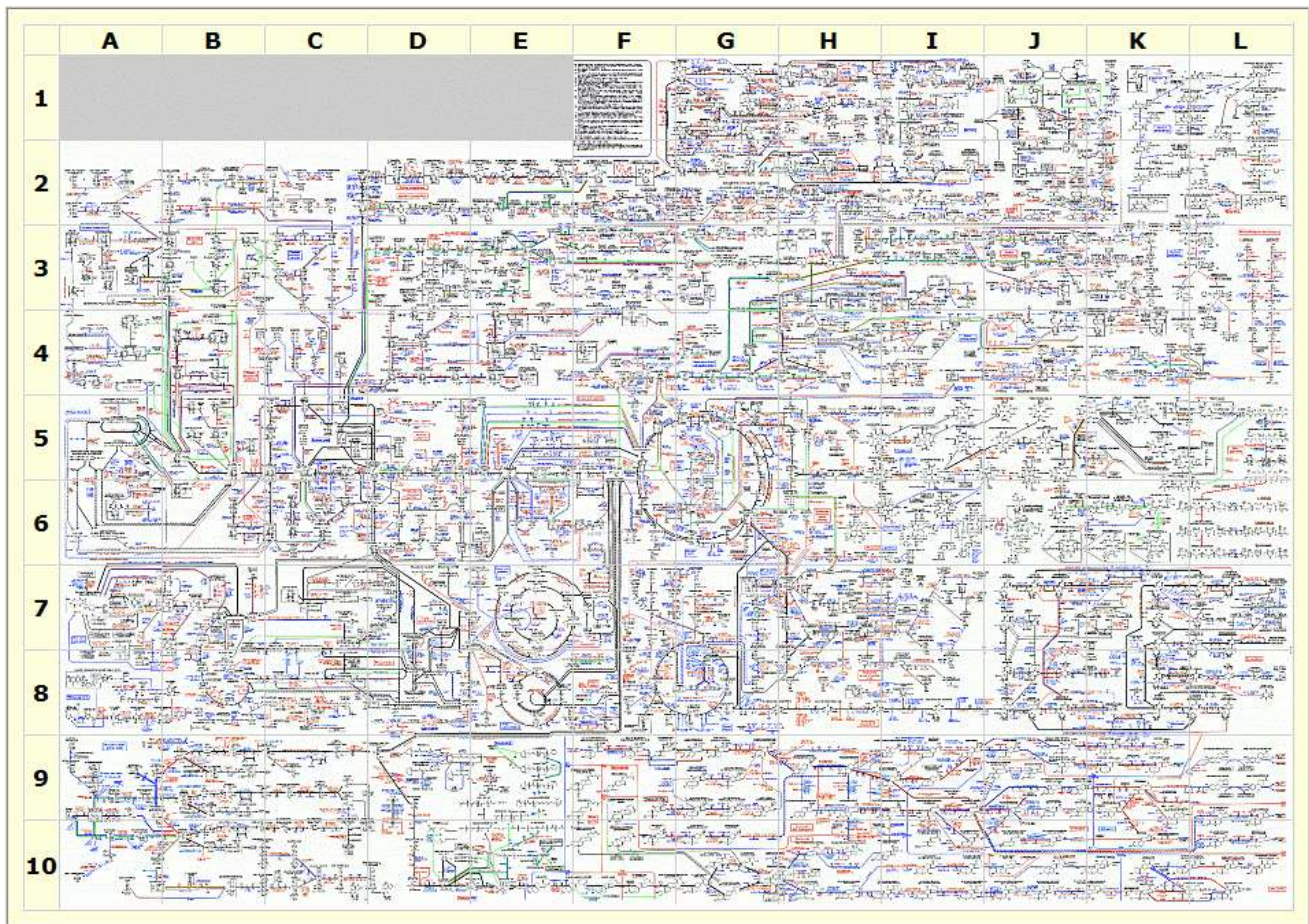
We see that CO<sub>2</sub> and water are used to make sugars. The sugars are fed into the center box that can then generate either amino acids, polysaccharides, or fatty acids. Some of the amino acids are used to make nucleotide bases that are part of DNA.

In the mitochondria, glucose can be broken down in the Citric Acid Cycle to make ATP, NADH, FADH<sub>2</sub> and CO<sub>2</sub>.

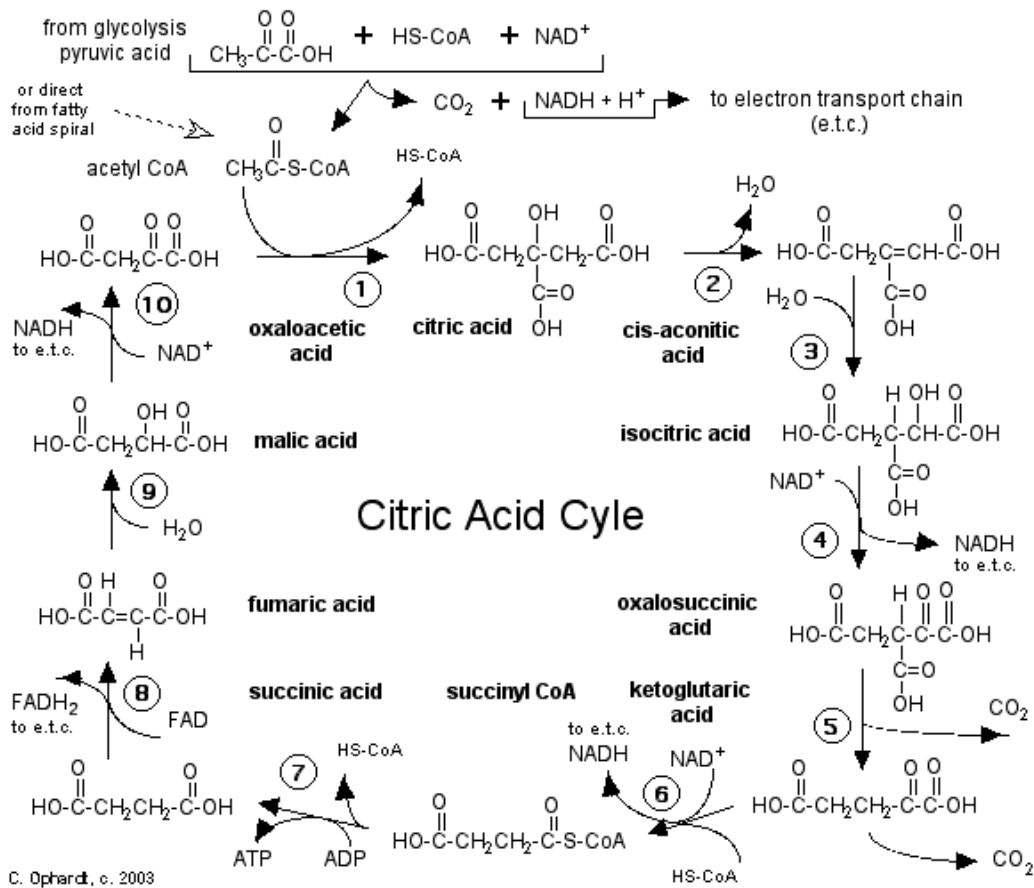
The NADH & FADH<sub>2</sub> combine with O<sub>2</sub> to make more ATP and water in the mitochondria.

This image tries to show how many of the chemical reactions in our body are entwined.

The reason I wish you to see it is to appreciate how complex living systems are. Each one of the hundreds of reaction here requires an enzyme and each of those enzymes requires a gene...humans have over 20,000 genes in each one of their nucleated cells.



If we take a close up peak at part of block G5 it looks like the series of reactions below that illustrates how our bodies breakdown sugar for energy...note the release of CO<sub>2</sub> in the process.



Again...just appreciate how complex life systems are!

The secret to living things is that they have a series of clever steps where they capture energy that is used by them to beat back the second law. But the living “system” cannot cheat the second law...for every joule of energy spent to keep a living system ordered...at least half of that joule of energy is lost to entropy, or stated another way, in every step of this system some of the energy stored in the molecules is lost as unusable heat...an increase in entropy.

As we said, organisms can be either *producers* or *consumers* in terms of energy movement in an ecosystem. Producers convert energy from the environment into carbon bonds and hydrogens bonded to carbons, such as those found in the sugar glucose.

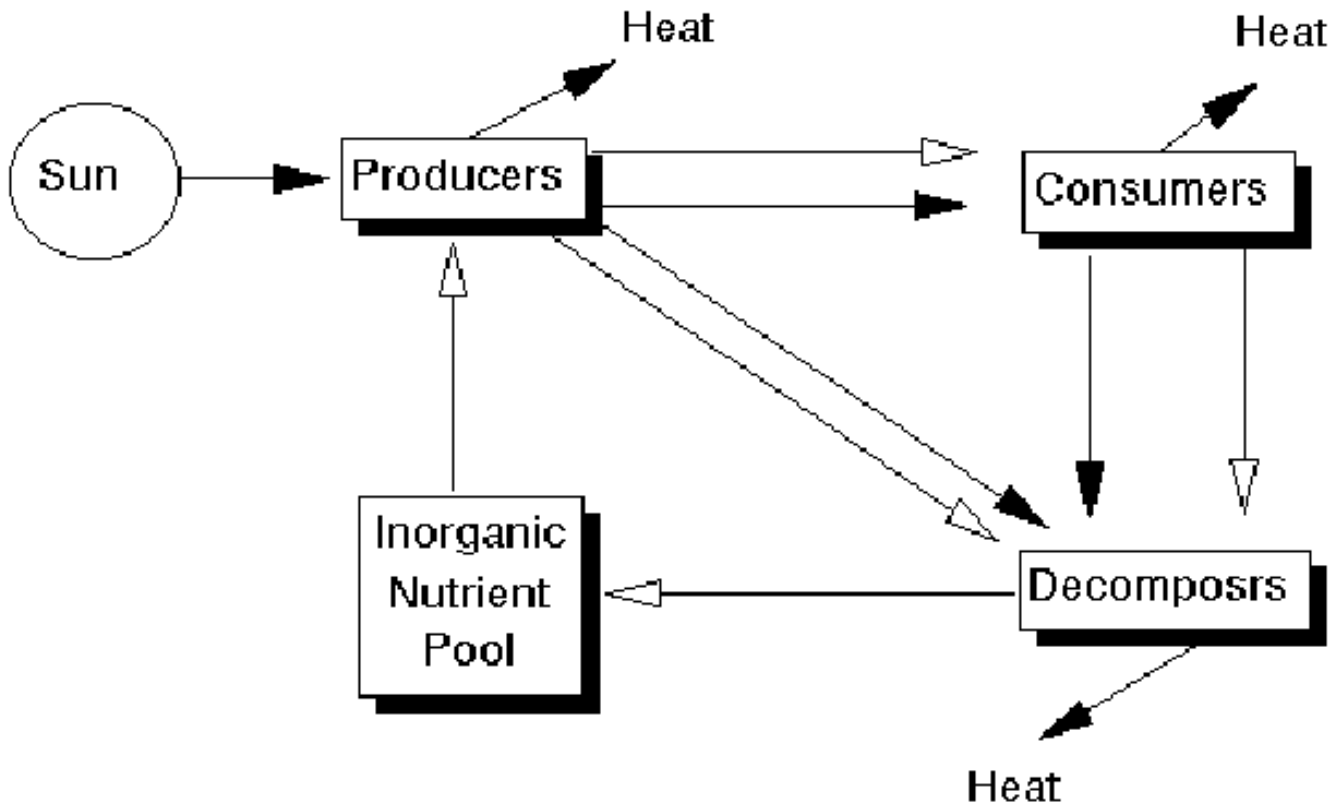
Another word for a consumer is a *heterotroph*. Based on what they eat, we can distinguish between 4 types of heterotrophs:

<u>Consumer</u>	<u>Trophic level</u>	<u>Food source</u>
Herbivores	primary	plants
Carnivores	secondary	animals that digest other animals
Omnivores	all levels	plants & animals
Detritivores	-----	detritus

A *trophic level* refers to the organisms position in the food chain. Autotrophs are at the base. Organisms that eat autotrophs are called *herbivores* or *primary consumers*. An organism that eats herbivores is a *carnivore* and a *secondary consumer*. A carnivore which eats a carnivore which eats a herbivore is a *tertiary consumer*, and so on. It is important to note that many animals do not specialize in their diets. *Omnivores* (such as humans) eat both animals and plants. Many “carnivores” when they have to will eat organisms of any trophic level. Frogs, for instance, don't discriminate between herbivorous and carnivorous bugs in their diet. If it's the right size, and moving at the right distance, chances are the frog will eat it. It's not as if the frog has brain cells to waste wondering if it's going to mess up the food chain by being a secondary consumer one minute and a quaternary consumer the next.



## Energy Flow Through the Ecosystem



The diagram above shows how energy and inorganic nutrients flow through an ecosystem. We need to define some terminology first. Energy "flows" through the ecosystem in the form of carbon-hydrogen bonds. When respiration occurs, the carbon-hydrogen bonds are broken and the electrons associated with the hydrogens will be captured to make ATP. The carbon atoms are combined with oxygen to form carbon dioxide molecules (we breath out carbon dioxide). The ATP is used to make muscles move. More than 50% of the energy in any glucose molecule will be lost as heat. The dark arrows represent the movement of usable energy. Note that the original source of energy is the Sun, and that in every conversion in the system some energy is lost as heat. Some of the energy does not recycle!!

The other component shown in the diagram are the inorganic nutrients. They are considered inorganic because they do not contain carbon-carbon bonds. These inorganic nutrients include the calcium in your teeth and bones, the iron in red blood cells, and the nitrogen in your amino acids (the building blocks of protein). The movement of the inorganic nutrients is represented by the open arrows. The organisms that die or parts of organisms that are dead become detritus, food for the decomposers.

There is also the notion of “limiting nutrients” in life systems. A limiting nutrient is a element or molecule that is in such short supply that the life in a system is limited in its ability to flourish or reproduce. Some common limiting nutrients for plants are iron, nitrogen and phosphorus. Iron is often so limiting to phytoplankton that scientists have contemplated dumping tons of it in our oceans to stimulate phytoplankton to reduce the greenhouse gas carbon dioxide...as plants grow they remove carbon dioxide from the atmosphere. Since the base of the food/energy web is phytoplankton, they make up a large part of all the carbon dioxide removal on the planet Earth.

To summarize: In the flow of energy and inorganic nutrients through the ecosystem, a few generalizations can be made:

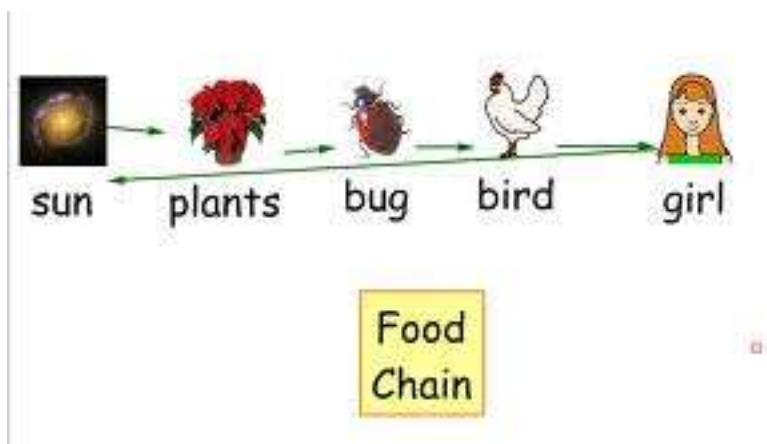
The ultimate source of energy is the Sun.

During any exchange of energy in an ecosystems some of the energy is lost as heat.

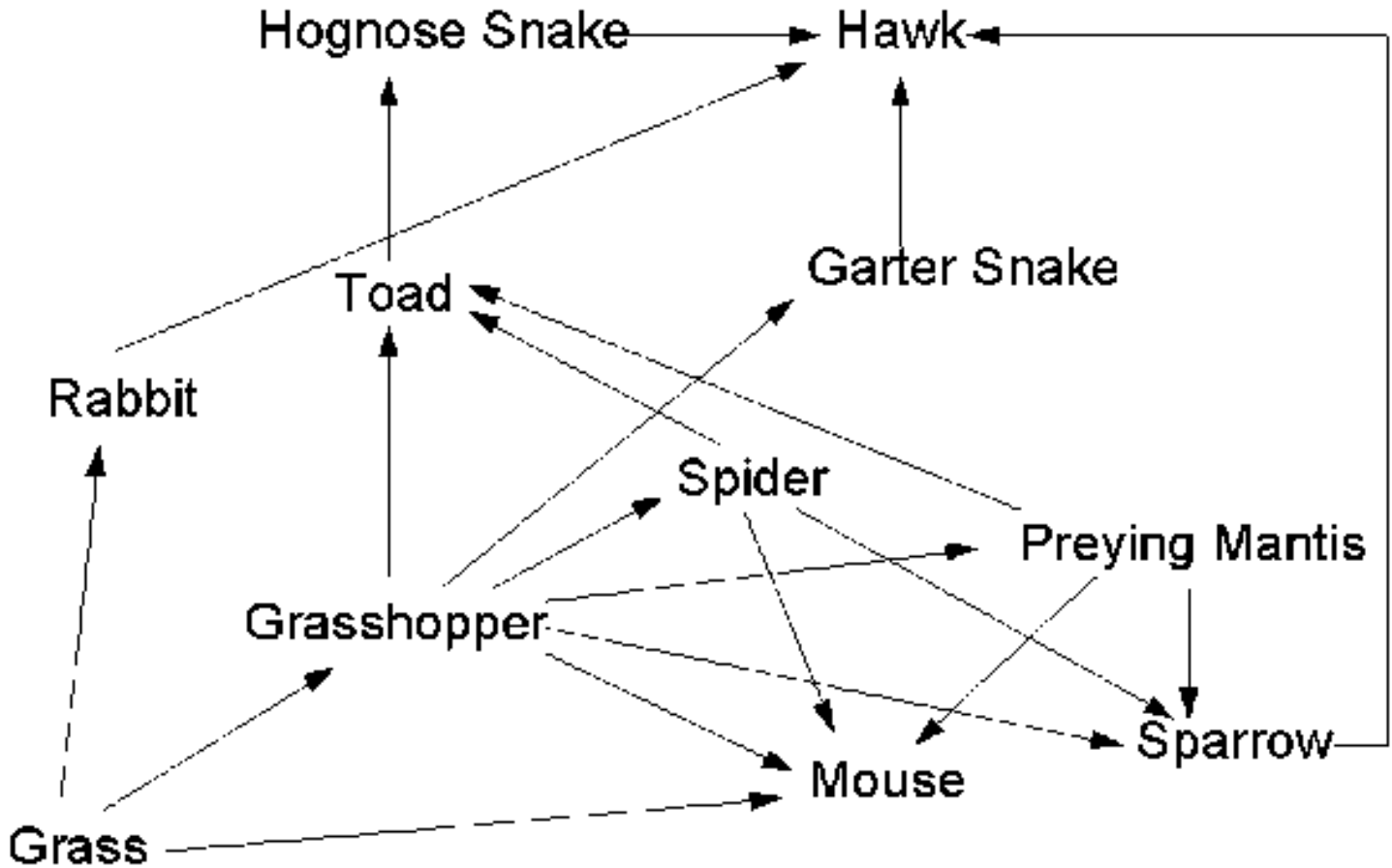
Energy and nutrients are passed from organism to organism through the food web as one organism eats another.

### Food Chains and Webs:

A food chain is the path of food from a given final consumer back to a producer. For instance, a typical food chain in a field ecosystem might be:



Food chains are just a way for us to model what is going on in nature, but they are lonely a notion in our minds. Most organisms do not specialize in their diets (koala bears are a specialist... they eat only eucalyptus leaves). Hawks don't limit their diets to snakes, snakes eat things other than mice, mice eat grass as well as grasshoppers, and so on. A more realistic depiction of who eats what is called a food web shown below:



When we have a picture of a food web in front of us, the definition of food chain makes more sense. We can now see that a food web consists of interlocking food chains, and that the only way to untangle the chains is to trace *back* along a given food chain to its source.

*Recall that in any system entropy must increase and as it does the amount of usable energy to keep order decreases. For our universe, being the largest system, this has great implications. It suggests that our universe will eventually be cold, dark and devoid of any order. What puzzles scientists is that in the chaotic evolution of the universe that there are pockets of extremely high order and thus very low entropy. We can take this as a chance occurrence rather like rolling double sixes many times in a row, or meeting a dozen people in one day with the same unusual name. As Boltzmann explained this, we are an unusual occurrence of a highly ordered system in an otherwise largely chaotic universe. It might further be proposed that this unlikely fluctuation, where order rules, requires our presence...or put a less emphatic way, only in a universe that allows life to exist will there be life to observe it... strangely tautological. But there seems to be a sort of "fine tuning" or self-selection that has occurred for this sort of universe to exist. To understand this point, we return to our physical constants and make a note that all the physical constants are tightly entwined. The equations for each of them explain the*

*others and their values are equally entwined. Modern science calculates that if any of the pure constants were to vary slightly from their current value, life would not exist and most organized matter as we know it (or could observe it) would not exist, stars would not have formed, and the elements of matter required for life would not have evolved in their absence. It is somewhat ironic that this idea arose at a meeting celebrating the 500th birthday of Copernicus where the Copernican Principle which states that humans do not have some sort or privileged place in the universe. That might be so but it is possible consciousness might. That we exist in a special time in the evolution of the universe is self evident, for if it were otherwise, we would not exist.*