How radiocarbon dating works

There are 3 kinds (isotopes) of carbon. Atoms of different isotopes differ only in how many neutrons are in the nucleus. Carbon-12 (written ^{12}C) has 6 protons and 6 neutrons. Carbon-13 (^{13}C) has one extra neutron, that is, 6 protons and 7 neutrons. Carbon-14 (^{14}C) has two extra neutrons, that is, 6 protons and 8 neutrons. The three isotopes all act essentially the same in chemical processes, including the metabolism of living things.

Most carbon in the environment is ^{12}C. About 1% is ^{13}C. About 1 part per trillion is ^{14}C, which is radioactive. That is, the excess neutrons in the ^{14}C nucleus make it unstable. Sooner or later, any given ^{14}C atom will "decay", in order to settle down to a more stable configuration. When a ^{14}C atom decays, it converts into a ^{14}N (nitrogen) atom.

(Detail for the physics-minded: This decay consists of one of the neutrons in the ^{14}C nucleus spontaneously converting to a proton by emitting a high-energy electron, called a beta particle. This results in a nucleus with 7 protons and 7 neutrons, which is ^{14}N).

^{14}N is stable and is the major component of the earth’s atmosphere, so when a ^{14}C atom decays into nitrogen, it essentially gets lost in the crowd.

^{14}C has a half life of 5730 years. That is, if you have 1 gram of ^{14}C, in 5730 years, one half of it will have decayed to ^{14}N. In another 5730 years, half of the remaining half will have decayed to ^{14}N… and so on.

So why is there any ^{14}C around any more? Shouldn’t it all have decayed away?

It *has*… but new ^{14}C is constantly produced in the upper atmosphere by cosmic radiation, which is mostly high-speed particles emitted by the sun. Through a series of steps, this cosmic ray bombardment converts occasional ^{14}N atoms into ^{14}C. The relatively constant rate of production of new ^{14}C balances against the constant decay of existing ^{14}C, resulting in a constant percentage of ^{14}C in the atmosphere.

Plant and animal tissues contain a lot of carbon. Land plants get their carbon from the carbon dioxide in the atmosphere, and animals get their carbon from plants that they eat. So living terrestrial plants and animals are made of carbon that has recently come from the atmosphere, and has essentially the same fraction of ^{14}C as the atmosphere. Since most living tissues are constantly being remodeled through growth, repair, absorption, etc., they continue to have the same fraction of ^{14}C as the atmosphere as long as the plant or animal is alive.

When a plant or animal dies, the tissues stop being renewed through biological processes. The ^{14}C in the dead tissues keeps decaying away, but it is no longer replenished by fresh ^{14}C from the air or from food. This means that the amount of ^{14}C in the tissues begins to decline after death.

So, since we know what fraction of the carbon in the air is ^{14}C, we know the fraction of ^{14}C that the organic tissues started with. If we measure what fraction of the carbon in the dead tissues is ^{14}C now, we can calculate how much ^{14}C has decayed away. Since we know the rate of decay, we can then calculate how long it has been since the plant or animal died.

There are a few complications. First, the amount of ^{14}C in the atmosphere has not been exactly constant, probably due to variations in sun's output of the cosmic rays that produce ^{14}C in our atmosphere. We know this because people have radiocarbon dated wood from individual tree rings of exactly known age (essentially by counting rings back from the outer surface of a living tree). Now that thousands of such rings have been dated, we can correct for this slight variation. These corrected dates are called "calibrated" dates, written like "700 cal BC" or "cal AD 700", and they correspond well to calendar years. Calibration makes the date look older than the uncalibrated radiocarbon ages. The difference approaches 2000 years at 10,000 cal BC, around the end of the Pleistocene (the most recent Ice Age).

Another problem is that radiocarbon measures the time since a living thing died. Sometimes that is not what we are actually interested in dating. For example, say you collect some burned wood from an ancient campfire. You want to know when someone camped at the site. If you date the wood, the radiocarbon date will tell you when that branch or tree trunk died, not when the person made the campfire. The wood might have been laying around on the ground for centuries before someone picked it up to burn. If so, the radiocarbon date, even though perfectly correct, will mislead you into thinking that the campfire was made centuries before it actually was. This is known as "the old wood problem".

Radiocarbon dating has some limitations. It works on samples from about 1940 AD (just before the first atomic bomb test, which caused a huge spike in the ^{14}C content of the earth’s atmosphere) back to around 45,000 years ago. In samples older than that, too little ^{14}C is left for an accurate measurement. That is plenty old enough for studies of complex societies, but it does not go back far enough to help us with most sites related to Neanderthals, the development of the earliest modern *Homo sapiens*, or anything earlier.

In addition, because the date depends on a measurement, and there is always some uncertainty about the exact value of any measurement, an estimated error range is included with all dates. The older the date, the larger the uncertainty. A typical error range is ±60 years for a date of 2000 years ago, or ±40 for a date of 1000 years ago, although they vary higher and lower. That figure means that there is a 68% chance that the true date falls within the indicated range. For a date of 200 AD ±60, there is a 68% chance that the date lies between 140 AD and 260 AD. That means there is still a 32% chance (about one chance in three!) that it falls outside the range. If we double the error estimate, there is a 95% chance that the date falls in the doubled range. For the same date of 200 AD ±60, there is a 95% chance that the true date falls between 80 AD and 320 AD. That means we can be pretty sure of the true age of the sample (even though we will still be wrong 5% of the time, or one time out of twenty). However, doubling the error estimate usually gives a pretty broad range for the date, making detailed interpretations difficult. Running dates on a number of samples and averaging them is one way to reduce this uncertainty.

There are other dating methods based on clever physics tricks that work in certain circumstances, but radiocarbon dating is by far the most commonly used and trusted technique for the many places and periods where dendrochronology cannot be applied.