Reading Questions from Dawkins "The Greatest Show on Earth".

This reading is available in the exam 3 sub folder of the Geography 105 class folder. location is www.wou.edu/~mcgladm

Note that I have omitted some pages and sections to maintain brevity.

There will be a closed-note quiz over the first 14 questions the next time class meets.

1. What difference can be observed for tree growth rings of good years vs. bad years?
2. If individual trees that you have growth rings for only live 300-500 years, how could you date a specimen that lived 1500 years ago?
3. In practice, about how many years back can dendrochronology be used?
4. What are varves, and what do they have in common with tree rings and coral reefs?
5. What is the typical percentage margin of error for radioactive clocks? Using this margin, how many years off would a date gathered by this technique be, if the time frame is 10 million years, for example?
6. The number of what type of particle in the nucleus determines what element the atom is?
7. The mass number of an atom is composed of what two components?
8. An isotope of an element varies in the number of ____ it has?
9. How many neutrons does carbon-14 have? (deduce from content of page 94)
10. What happens that characterizes unstable (radioactive) isotopes?
11. Describe the first three types of radioactive decay listed by the author.
12. Fill in the blanks, from page 95: Every radioactive isotope decays at its characteristic rate, which is _____ _____.
13. Define the "half-life" of a radioactive isotope.
14. If a radioactive isotope has a half-life of 1 million years, what % of it will be left after 5 million years?
15. Why is the "potassium-argon" clock referred to as the "potassium-argon" clock?
16. What are igneous rocks? What is meant by a radioactive clock being "zeroed"?
17. When a new crystal of rock is solidified (crystallized) from igneous rock, how much argon does it have? What happens through time to the amount of potassium-40?
18. If we observe various layers of sediments, generally which ones are older?
19. What do the 37 unstable isotopes that have not gone extinct all have in common, in terms of their half-life? How is this evidence of an old earth?
20. Do the findings of the various radioactive clocks agree with each other, within the expected margins of error? How old do they indicate the earth to be?
21. Over vast periods of time, the continents and ocean basins of the earth have moved around, combined and divided. We will learn about this in the last section of the course. I hope this reading has helped you comprehend the kind of evidence scientists use to estimate how much time our planet has been around.

and for dating specimens on the sort of timescale that covers the domestication of the dog or the cabbage. At the other end of the scale, we need natural clocks that can time hundreds of millions, even billions, of years. And, praise be, nature has provided us with just the wide range of clocks that we need. What's more, their ranges of sensitivity overlap with each other, so we can use them as checks on each other.

TREE RINGS

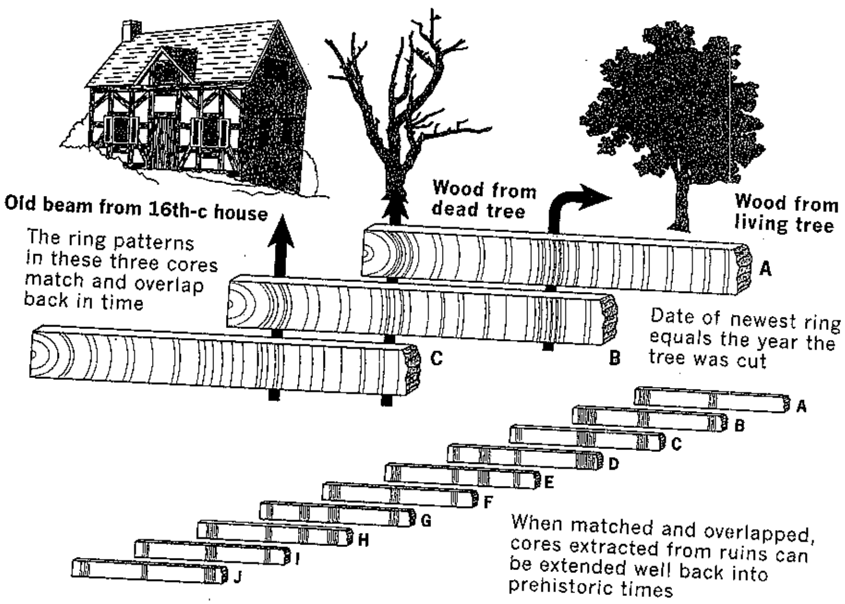
A tree-ring clock can be used to date a piece of wood, say a beam in a Tudor house, with astonishing accuracy, literally to the nearest year. Here's how it works. First, as most people know, you can age a newly felled tree by counting rings in its trunk, assuming that the outermost ring represents the present. Rings represent differential growth in different seasons of the year – winter or summer, dry season or wet season – and they are especially pronounced at high latitudes, where there is a strong difference between seasons. Fortunately, you don't actually have to cut the tree down in order to age it. You can peek at its rings without killing it, by boring into the middle of a tree and extracting a core sample. But just counting rings doesn't tell you in which century your house beam was alive, or your Viking longship's mast. If you want to pin down the date of old, long-dead wood you need to be more subtle. Don't just count rings, look at the pattern of thick and thin rings.

Just as the existence of rings signifies seasonal cycles of rich and poor growth, so some years are better than others, because the weather varies from year to year: there are droughts that retard growth, and bumper years that accelerate it; there are cold years and hot years, even years of freak El Niños or Krakatoa-type catastrophes. Good years, from the tree's point of view, produce wider rings than bad years. And the pattern of wide and narrow rings in any one region, caused by a particular trademark sequence of good years and bad years, is

sufficiently characteristic – a fingerprint that labels the exact years in which the rings were laid down – to be recognizable from tree to tree.

Dendrochronologists measure rings on recent trees, where the exact date of every ring is known by counting backwards from the year in which the tree is known to have been felled. From these measurements, they construct a reference collection of ring patterns, to which you can compare the ring patterns of an archaeological sample of wood whose date you want to know. So you might get the report: 'This Tudor beam contains a signature sequence of rings that matches a sequence from the reference collection, which is known to have been laid down in the years 1541 to 1547. The house was therefore built after AD 1547.'

All very well, but not many of today's trees were alive in Tudor times, let alone in the stone age or beyond. There are some trees – bristlecone pines, some giant redwoods – that live for millennia, but most trees used for timber are felled when they are younger than a century or so. How, then, do we build up the reference collection of rings for more ancient times? For times so distant that not even the oldest surviving bristlecone pine goes back that far? I think you've already guessed the answer. Overlaps. A strong rope may be 100 yards long, yet no single fibre within it reaches more than a fraction of that total. To use the overlap principle in dendrochronology, you take the reference fingerprint patterns whose date is known from modern trees. Then you identify a fingerprint from the old rings of modern trees and seek the same fingerprint from the younger rings of long-dead trees. Then you look at the fingerprints from the older rings of those same long-dead trees, and look for the same pattern in the younger rings of even older trees. And so on. You can daisychain your way back, theoretically for millions of years using petrified forests, although in practice dendrochronology is only used on archaeological timescales over some thousands of years. And the amazing thing about dendrochronology is that, theoretically at least, you can be accurate to the nearest year, even in a petrified forest 100 million



How dendrochronology works

years old. You could literally say that *this* ring in a Jurassic fossil tree was laid down exactly 257 years later than *this* other ring in another Jurassic tree! If only there were enough petrified forests to daisychain your way back continuously from the present, you could say that this tree is not just of late Jurassic age: it was alive in exactly 151,432,657 BC! Unfortunately, we don't have an unbroken chain, and dendrochronology in practice takes us back only about 11,500 years. It is nevertheless a tantalizing thought that, if only we could find enough petrified forests, we could date to the nearest year over a timespan of hundreds of millions of years.

Tree rings are not quite the only system that promises total accuracy to the nearest year. Varves are layers of sediment laid down in glacial lakes. Like tree rings, they vary seasonally and from year to year, so theoretically the same principle can be used, with the same degree of accuracy. Coral reefs, too, have annual growth rings, just like trees. Fascinatingly, these have been used to detect the dates of ancient earthquakes. Tree rings too, by the way, tell us the dates

of earthquakes. Most of the other dating systems that are available to us, including all the radioactive clocks that we actually use over timescales of tens of millions, hundreds of millions or billions of years, are accurate only within an error range that is approximately proportional to the timescale concerned.

RADIOACTIVE CLOCKS

Let's now turn to radioactive clocks. There are quite a lot of them to choose from, and, as I said, they blessedly cover the gamut from centuries to thousands of millions of years. Each one has its own margin of error, which is usually about 1 per cent. So if you want to date a rock which is billions of years old, you must be satisfied with an error of plus or minus tens of millions of years. If you want to date a rock hundreds of millions of years old, you must be satisfied with an error of millions. To date a rock that is only tens of millions of years old, you must allow for an error of plus or minus hundreds of thousands of years.

To understand how radioactive clocks work, we first need to understand what is meant by a radioactive isotope. All matter is made up of elements, which are usually chemically combined with other elements. There are about 100 elements, slightly more if you count elements that are only ever detected in laboratories, slightly fewer if you count only those elements that are found in nature. Examples of elements are carbon, iron, nitrogen, aluminium, magnesium, fluorine, argon, chlorine, sodium, uranium, lead, oxygen, potassium and tin. The atomic theory, which I think everybody accepts, even creationists, tells us that each element has its own characteristic atom, which is the smallest particle into which you can divide an element without it ceasing to be that element. What does an atom look like, say an atom of lead, or copper, or carbon? Well, it certainly looks nothing like lead or copper or carbon. It doesn't *look* like anything, because it is too small to form any kind of image on your retina, even with an ultra-powerful microscope. We can use analogies or models to help us visualize an atom. The most famous model was proposed by the great Danish physicist Niels Bohr. The Bohr model, which is now rather out of date, is a miniature solar system. The role of the sun is played by the nucleus, and around it orbit the electrons, which play the role of planets. As with the solar system, almost all the mass of the atom is contained in the nucleus ('sun'), and almost all the volume is contained in the empty space that separates the electrons ('planets') from the nucleus. Each electron is tiny compared with the nucleus, and the space between them and the nucleus is huge compared with the size of either. A favourite analogy portrays the nucleus as a fly in the middle of a sports stadium. The nearest neighbouring nucleus is another fly, in the middle of an adjacent stadium. The electrons of each atom are buzzing about in orbit around their respective flies, smaller than the tiniest gnats, too small to be seen on the same scale as the flies. When we look at a solid lump of iron or rock, we are 'really' looking at what is almost entirely empty space. It looks and feels solid and opaque because our sensory systems and brains find it convenient to treat it as solid and opaque. It is convenient for the brain to represent a rock as solid because we can't walk through it. 'Solid' is our way of experiencing things that we can't walk through or fall through, because of the electromagnetic forces between atoms. 'Opaque' is the experience we have when light bounces off the surface of an object, and none of it goes through.

Three kinds of particle enter into the makeup of an atom, at least as envisaged in the Bohr model. Electrons we have already met. The other two, vastly larger than electrons but still tiny compared with anything we can imagine or experience with our senses, are called protons and neutrons, and they are found in the nucleus. They are almost the same size as each other. The number of protons is fixed for any given element and equal to the number of electrons. This number is called the atomic number. It is uniquely characteristic of an element, and there are no gaps in the list of atomic numbers – the famous periodic table.* Every

* Alas, the popular legend that it came to Dmitri Mendeleev in a dream may be false.

number in the sequence corresponds to exactly one, and only one, element. The element with 1 for its atomic number is hydrogen, 2 is helium, 3 lithium, 4 beryllium, 5 boron, 6 carbon, 7 nitrogen, 8 oxygen, and so on up to high numbers like 92, which is the atomic number of uranium.

Protons and electrons carry an electric charge, of opposite sign – we call one of them positive and the other negative by arbitrary convention. These charges are important when elements form chemical compounds with each other, mostly mediated by electrons. The neutrons in an atom are bound into the nucleus together with the protons. Unlike protons they carry no charge, and they play no role in chemical reactions. The protons, neutrons and electrons in any one element are exactly the same as those in every other element. There is no such thing as a gold-flavoured proton or a copper-flavoured electron or a potassium-flavoured neutron. A proton is a proton is a proton, and what makes a copper atom copper is that there are exactly 29 protons (and exactly 29 electrons). What we ordinarily think of as the nature of copper is a matter of chemistry. Chemistry is a dance of electrons. It is all about the interactions of atoms via their electrons. Chemical bonds are easily broken and remade, because only electrons are detached or exchanged in chemical reactions. The forces of attraction within atomic nuclei are much harder to break. That's why 'splitting the atom' has such a menacing ring to it – but it can happen, in 'nuclear' as opposed to chemical reactions, and radioactive clocks depend upon it.

Electrons have negligible mass, so the total mass of an atom, its 'mass number', is equal to the combined number of protons and neutrons. It is usually rather more than double the atomic number, because there are usually a few more neutrons than protons in a nucleus. Unlike the number of protons, the number of neutrons in an atom is not diagnostic of an element. Atoms of any given element can come in different versions called *isotopes*, which have differing numbers of neutrons, but always the same number of protons. Some elements, such as fluorine, have only one naturally occurring isotope. The atomic number of fluorine is 9 and its mass number is 19, from which you can deduce that it has 9 protons and 10 neutrons. Other elements have lots of isotopes. Lead has five commonly occurring isotopes. All have the same number of protons (and electrons), namely 82, which is the atomic number of lead, but the mass numbers range between 202 and 208. Carbon has three naturally occurring isotopes. Carbon-12 is the common one, with the same number of neutrons as protons: 6. There's also carbon-13, which is too short-lived to bother with, and carbon-14 which is rare but not too rare to be useful for dating relatively young organic samples, as we shall see.

Now for the next important background fact. Some isotopes are stable, others unstable. Lead-202 is an unstable isotope; lead-204, lead-206, lead-207 and lead-208 are stable isotopes. 'Unstable' means that the atoms spontaneously decay into something else, at a predictable rate, though not at predictable moments. The predictability of the rate of decay is the key to all radiometric clocks. Another word for 'unstable' is 'radioactive'. There are several kinds of radioactive decay, which offer possibilities for useful clocks. For our purposes it isn't important to understand them, but I explain them here to show the magnificent level of detail that physicists have achieved in working out such things.

All these kinds of instability involve neutrons. In one kind, a neutron turns into a proton. This means that the mass number stays the same (since protons and neutrons have the same mass) but the atomic number goes up by one, so the atom becomes a different element, one step higher in the periodic table. For example, sodium-24 turns itself into magnesium-24. In another kind of radioactive decay, exactly the reverse happens. A proton turns into a neutron. Again, the mass number stays the same, but this time the atomic number decreases by one, and the atom changes into the next element down in the periodic table. A third kind of radioactive decay has the same

result. A stray neutron happens to hit a nucleus and knocks out one proton, taking its place. Again, there's no change in mass number; again, the atomic number goes down by one, and the atom turns into the next element down in the periodic table. There's also a more complicated kind of decay in which an atom ejects a so-called alpha particle. An alpha particle consists of two protons and two neutrons stuck together. This means that the mass number goes down by four and the atomic number goes down by two. The atom changes to whichever element is two below it in the periodic table. An example of alpha decay is the change of the very radioactive isotope uranium-238 (with 92 protons and 146 neutrons) to thorium-234 (with 90 protons and 144 neutrons).

Now we approach the nub of the whole matter. Every unstable or radioactive isotope decays at its own characteristic rate which is precisely known. Moreover, some of these rates are vastly slower than others. In all cases the decay is exponential. Exponential means that if you start with, say, 100 grams of a radioactive isotope, it is not the case that a fixed amount, say 10 grams, turns into another element in a given time. Rather, a fixed *proportion* of whatever is left turns into the second element. The favoured measure of decay rate is the 'half-life'. The half-life of a radioactive isotope is the time taken for half of its atoms to decay. The half-life is the same, no matter how many atoms have already decayed – that is what exponential decay means. You will appreciate that, with such successive halvings, we never really know when there is none left. However, we can say that after a sufficient time has elapsed – say ten half-lives – the number of atoms that remains is so small that, for practical purposes, it has all gone. For example, the half-life of carbon-14 is between 5,000 and 6,000 years. For specimens older than about 50,000–60,000 years, carbon dating is useless, and we need to turn to a slower clock.

The half-life of rubidium-87 is 49 billion years. The half-life of fermium-244 is 3.3 milliseconds. Such startling extremes serve to illustrate the stupendous *range* of clocks available. Although carbon-15's half-life of 2.4 seconds is too short for settling evolutionary questions, carbon-14's half-life of 5,730 years is just right for dating on the archaeological timescale, and we'll come to it presently. An isotope much used on the evolutionary timescale is potassium-40, with its half-life of 1.26 billion years, and I'm going to use it as my example, to explain the whole idea of a radioactive clock. It is often called the potassium argon clock, because argon-40 (one lower in the periodic table) is one of the elements to which potassium-40 decays (the other, resulting from a different kind of radioactive decay, is calcium-40, one higher in the periodic table). If you start with some quantity of potassium-40, after 1.26 billion years half of the potassium-40 will have decayed to argon-40. That's what half-life means. After another 1.26 billion years, half of what remains (a quarter of the original) will have decayed, and so on. After a shorter time than 1.26 billion years, a proportionately smaller quantity of the original potassium will have decayed. So, imagine that you start with some quantity of potassium-40 in an enclosed space with no argon-40. After a few hundreds of millions of years have elapsed, a scientist comes upon the same enclosed space and measures the relative proportions of potassium-40 and argon-40. From this proportion – regardless of the absolute quantities involved – knowing the half-life of potassium-40's decay and assuming there was no argon to begin with, one can estimate the time that has elapsed since the process started – since the clock was 'zeroed', in other words. Notice that we must know the ratio of parent (potassium-40) to daughter (argon-40) isotopes. Moreover, as we saw earlier in the chapter, it is necessary that our clock has the facility to be zeroed. But what does it mean to speak of a radioactive clock's being 'zeroed'? The process of crystallization gives it meaning.

Like all the radioactive clocks used by geologists, potassium/argon timing works only with so-called igneous rocks. Named after the Latin for fire, igneous rocks are solidified from molten rock – underground magma in the case of granite, lava from volcanoes in the case of basalt. When molten rock solidifies to form granite or basalt, it does so in the form of crystals. These are normally not big, transparent crystals like those of quartz, but crystals that are too small to look like crystals to the naked eye. The crystals are of various types, and several of these, such as some micas, contain potassium atoms. Among these are atoms of the radioactive isotope potassium-40. When a crystal is newly formed, at the moment when molten rock solidifies, there is potassium-40 but no argon. The clock is 'zeroed' in the sense that there are no argon atoms in the crystal. As the millions of years go by, the potassium-40 slowly decays and, one by one, atoms of argon-40 replace potassium-40 atoms in the crystal. The accumulating quantity of argon-40 is a measure of the time that has elapsed since the rock was formed. But, for the reason I have just explained, this quantity is meaningful only if expressed as the *ratio* of potassium-40 to argon-40. When the clock was zeroed, the ratio was 100 per cent in favour of potassium-40. After 1.26 billion years, the ratio will be 50–50. After another 1.26 billion years, half of the remaining potassium-40 will have been converted to argon-40, and so on. Intermediate proportions signify intermediate times since the crystal clock was zeroed. So geologists, by measuring the ratio between potassium-40 and argon-40 in a piece of igneous rock that they pick up today, can tell how long ago the rock first crystallized out of its molten state. Igneous rocks typically contain many different radioactive isotopes, not just potassium-40. A fortunate aspect of the way igneous rocks solidify is that they do so suddenly – so that *all* the clocks in a given piece of rock are zeroed simultaneously.

Only igneous rocks provide radioactive clocks, but fossils are almost never found in igneous rock. Fossils are formed in sedimentary rocks like limestone and sandstone, which are not solidified lava. They are layers of mud or silt or sand, gradually laid down on the floor of a sea or lake or estuary. The sand or mud becomes compacted over the ages and hardens as rock. Corpses that are trapped in the mud have a chance of fossilizing. Even though only a small proportion of corpses actually do fossilize, sedimentary rocks are the only rocks that contain any fossils worth speaking of.

Sedimentary rocks unfortunately cannot be dated by radioactivity.

Presumably the individual particles of silt or sand that go to make sedimentary rocks contain potassium-40 and other radioactive isotopes, and therefore could be said to contain radioactive clocks; but unfortunately these clocks are no use to us because they are not properly zeroed, or are zeroed at different times from each other. The particles of sand that are compacted to make sandstone may originally have been ground down from igneous rocks, but the igneous rocks from which they were ground all solidified at different times. Every grain of sand has a clock zeroed at its own time, and that time was probably long before the sedimentary rock formed and entombed the fossil we are trying to date. So, from a timekeeping point of view, sedimentary rock is a mess. It can't be used. The best we can do – and it is a pretty good best – is to use the dates of igneous rocks that are found near sedimentary rock, or embedded in it.

To date a fossil, you don't literally need to find it sandwiched between two slabs of igneous rock, although that is a neat way to illustrate the principle. The actual method used is more refined than that. Recognizably similar layers of sedimentary rock occur all over the world. Long before radioactive dating was discovered, these layers had been identified and given names: names like Cambrian, Ordovician, Devonian, Jurassic, Cretaceous, Eocene, Oligocene, Miocene. Devonian sediments are recognizably Devonian, not only in Devon (the county in south-west England that gave them their name) but in other parts of the world. They are recognizably similar to each other, and they contain similar lists of fossils. Geologists have long known the *order* in which these named sediments were laid down. It's just that, before the advent of radioactive clocks, we didn't know *when* they were laid down. We could arrange them in order because – obviously – older sediments tend to lie beneath younger sediments. Devonian sediments, for example, are older than Carboniferous (named after the coal which is frequently found in Carboniferous layers) and we know this because, in those parts of the world where the two layers coincide, the Devonian layer lies underneath the Carboniferous layer (the exceptions to this rule occur

in places where we can tell, from other evidence, that the rocks have been tilted aslant, or even turned upside down). We aren't usually fortunate enough to find a complete run of layers, all the way from Cambrian at the bottom up to Recent at the top. But because the layers are so recognizable, you can work out their relative ages by daisychaining and jigsawing your way around the world.

So, long before we knew how old fossils were, we knew the *order* in which they were laid down, or at least the order in which the named sediments were laid down. We knew that Cambrian fossils, the world over, were older than Ordovician ones, which were older than Silurian; then came Devonian, then Carboniferous, Permian, Triassic, Jurassic, Cretaceous, and so on. And within these major named layers, geologists also distinguish sub-regions: upper Jurassic, middle Jurassic, lower Jurassic, and so on.

The named strata are usually identified by the fossils they contain. And we are going to use the ordering of the fossils as evidence for evolution! Is that in danger of turning into a circular argument? Certainly not. Think about it. Cambrian fossils are a characteristic assemblage, unmistakably recognizable as Cambrian. For the moment we are using a characteristic assemblage of fossils simply as *labels* for Cambrian rocks – indicator species – wherever we may find them. This, indeed, is why oil companies employ fossil experts to identify particular strata of rocks, usually by microfossils, tiny creatures called foraminifera, for example, or radiolaria.

A characteristic list of fossils is used to recognize Ordovician rocks, Devonian rocks, and so on. So far, all we are using these fossil assemblages for is to identify whether a slab of rock is, say, Permian or Silurian. Now we move on to use the order in which the named strata were laid down, helped by daisychaining around the world, as evidence of which strata are older or younger than which. Having established these two sets of information, we can then look at the fossils in successively younger strata, to see whether they constitute a sensible evolutionary sequence when compared with each other in sequence. Do they progress in a sensible direction? Do certain kinds of fossils, for example mammals, appear only *after* a given date, never before? The answer to all such questions is yes. Always yes. No exceptions. That is powerful evidence for evolution, for it was never a *necessary* fact, never something that had to follow from our method of identifying strata and our method of obtaining a temporal sequence.

It is a fact that literally nothing that you could remotely call a mammal has ever been found in Devonian rock or in any older stratum. They are not just statistically rarer in Devonian than in later rocks. They literally never occur in rocks older than a certain date. But this didn't have to be so. It could have been the case that, as we dug down lower and lower from the Devonian, through the Silurian and then even older, through the Ordovician, we suddenly found that the Cambrian era – older than any of them – teemed with mammals. That is in fact *not* what we find, but the possibility demonstrates that you can't accuse the argument of being circular: at any moment somebody might dig up a mammal in Cambrian rocks, and the theory of evolution would be instantly blown apart if they did. Evolution, in other words, is a falsifiable, and therefore scientific, theory. I shall return to this point in Chapter 6.

Back to dating, and radioactive clocks. Because the relative ordering of the named sedimentary strata is well known, and the same order is found all over the world, we can use igneous rocks that overlie or underlie sedimentary strata, or are embedded in them, to date those named sedimentary strata, and hence the fossils within them. By a refinement of the method, we can date fossils that lie near the top of, say, the Carboniferous or the Cretaceous, as more recent than fossils that lie slightly lower in the same stratum. We don't need to find an igneous rock in the vicinity of any particular fossil we want to date. We can tell that our fossil is, say, late Devonian, from its position in a Devonian stratum. And we know, from the radioactive dating of igneous rocks found in association with Devonian strata all around the world, that the Devonian ended about 360 million years ago.

Unstable isotope	Decays to	Half-life (years)
Rubidium-87	Strontium	49,000,000,000
Rhenium-187	Osmium-187	41,600,000,000
Thorium-232	Lead-208	14,000,000,000
Uranium-238	Lead-206	4,500,000,000
Potassium-40	Argon-40	1,260,000,000
Uranium-235	Lead-207	704,000,000
Samarium-147	Neodymium-143	108,000,000
Iodine-129	Xenon-129	17,000,000
Aluminium-26	Magnesium-26	740,000
Carbon-14	Nitrogen-14	5,730

Radioactive clocks

The potassium argon clock is only one of many clocks that are available to geologists, all using the same principle on their different timescales. Above is a table of clocks, ranging from slow to fast. Notice, yet again, the astonishing range of half-lives, from 49 billion years at the slow end to less than 6,000 years at the fast end. The faster clocks, such as carbon-14, work in a somewhat different way. This is because the 'zeroing' of these higher-speed clocks is necessarily different. For isotopes with a short half-life, all the atoms that were present when the Earth was originally formed have long since disappeared. Before I turn to how carbon dating works, it is worth pausing to consider another piece of evidence in favour of an old Earth, a planet whose age is measured in billions of years.

Among all the elements that occur on Earth are 150 stable isotopes and 158 unstable ones, making 308 in all. Of the 158 unstable ones, 121 are either extinct or exist only because they are constantly renewed, like carbon-14 (as we shall see). Now, if we consider the 37 that have not gone extinct, we notice something significant. Every single one of them has a half-life greater than 700 million years. And if we look at the 121 that have gone extinct, every single one of them has a half-life less than 200 million years. Don't be misled, by the way. Remember we are talking *half-life* here, not life! Think of the fate of an isotope with a half-life of 100 million years. Isotopes whose half-life is less than a tenth or so of the age of the Earth are, for practical purposes, extinct, and don't exist except under special circumstances. With exceptions that are there for a special reason that we understand, the only isotopes that we find on Earth are those that have a half-life long enough to have survived on a very old planet. Carbon-14 is one of these exceptions, and it is exceptional for an interesting reason, namely that it is being continuously replenished. Carbon-14's role as a clock therefore needs to be understood in a different way from that of longer-lived isotopes. In particular, what does it mean to *zero* the clock?

CARBON

Of all the elements, carbon is the one that seems most indispensable to life – the one without which life on any planet is hardest to envisage. This is because of carbon's remarkable capacity for forming chains and rings and other complex molecular architectures. It enters the food web via photosynthesis, which is the process whereby green plants take in carbon dioxide molecules from the atmosphere and use energy from sunlight to combine the carbon atoms with water to make sugars. All the carbon in ourselves and in all other living creatures comes ultimately, via plants, from carbon dioxide in the atmosphere. And it is continually being recycled back to the atmosphere: when we breathe out, when we excrete, and when we die.

Most of the carbon in the atmosphere's carbon dioxide is carbon-12, which is not radioactive. However, about one atom in a trillion is carbon-14, which is radioactive. It decays rather rapidly, with a half-life of 5,730 years, as we have seen, to nitrogen-14. Plant biochemistry is blind to the difference between these two carbons. To a plant, carbon is carbon is carbon. So plants take in carbon-14 alongside carbon-12, and incorporate the two kinds of carbon atom in sugars, pages 104 & 105 omitted

I have repeatedly emphasized that there are lots of different clocks that the modern evolutionary detective can use, and also that they work best on different, but overlapping timescales. Radioactive clocks can be used to give independent estimates of the age of one piece of rock, bearing in mind that all the clocks were zeroed simultaneously when this very same piece of rock solidified. When such comparisons have been made, the different clocks agree with each other – within the expected margins of error. This gives great confidence in the correctness of the clocks. Thus mutually calibrated and verified on known rocks, these clocks can be carried with confidence to interesting dating problems, such as the age of the Earth itself. The currently agreed age of 4.6 billion years is the estimate upon which several different clocks converge. Such agreement is not surprising, but unfortunately we need to emphasize it because, astonishingly, as I pointed out in the Introduction (and have documented in the Appendix), some 40 per cent of the American population, and a somewhat smaller percentage of the British population, claim to believe that the age of the Earth, far from being measured in billions of years, is less than 10,000 years. Lamentably, especially in America and over much of the Islamic world, some of these history-deniers wield power over schools and their syllabuses.

Now, a history-denier could claim, say, that there is something wrong with the potassium argon clock. What if the present very

slow rate of decay of potassium-40 has only been in operation since Noah's flood? If, before that, the half-life of potassium-40 was radically different, only a few centuries, say, rather than 1.26 billion years? The special pleading in such claims is glaring. Why on Earth should the laws of physics change, just like that, so massively and so conveniently? And it glares even more when you have to make mutually adjusted special pleading claims for each one of the clocks separately. At present, the applicable isotopes all agree with each other in placing the origin of the Earth at between four and five billion years ago. And they do so on the assumption that their half-lives have always been the same as we can measure today – as the known laws of physics, indeed, strongly suggest they should. The history-deniers would have to fiddle the half-lives of all the isotopes in their separate proportions, so that they all end up agreeing that the Earth began 6,000 years ago. Now that's what I call special pleading! And I haven't even mentioned various other dating methods which also produce the same result, for example 'fission track dating'. Bear in mind the huge differences in timescales of the different clocks, and think of the amount of contrived and complicated fiddling with the laws of physics that would be needed in order to make all the clocks agree with each other, across the orders of magnitude, that the Earth is 6,000 years old and not 4.6 billion!