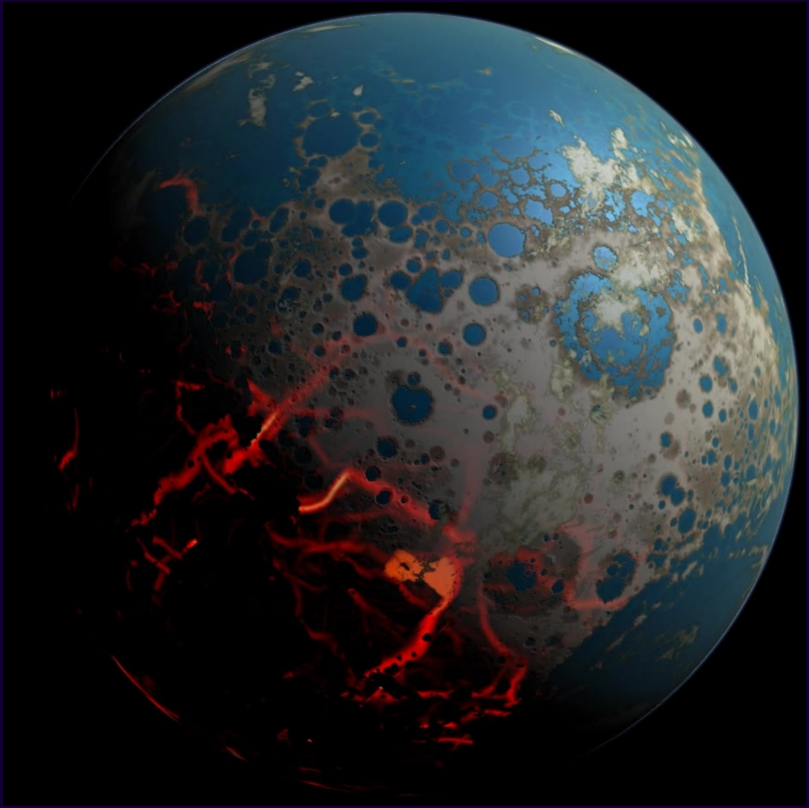
The history and ages of the planets

Astronomy 101
Syracuse University, Fall 2017
Walter Freeman

November 13, 2017



Exam 3 grades

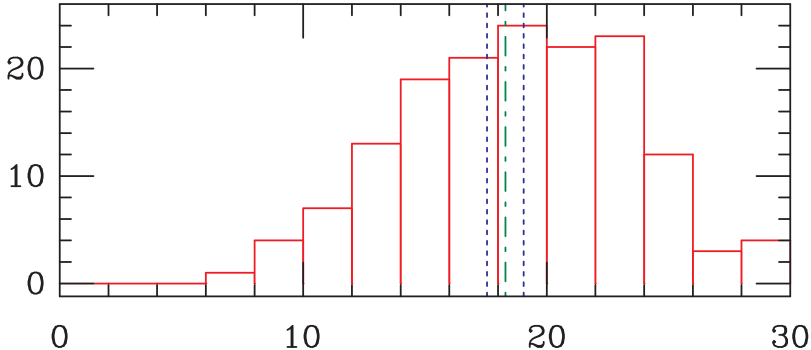
Some of you expressed a concern: students who had lab on Monday had an advantage on the exam.

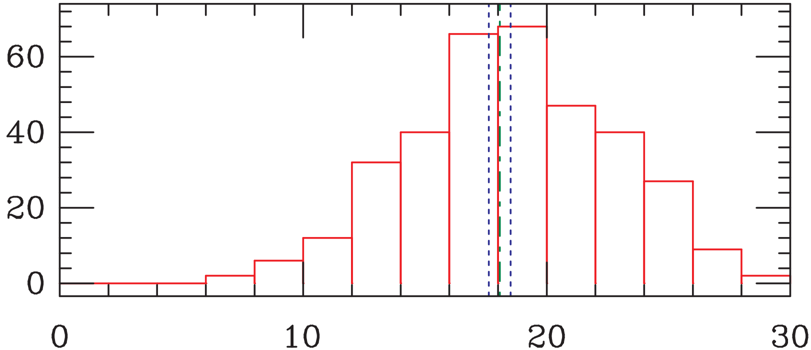
Exam 3 grades

Some of you expressed a concern: students who had lab on Monday had an advantage on the exam.

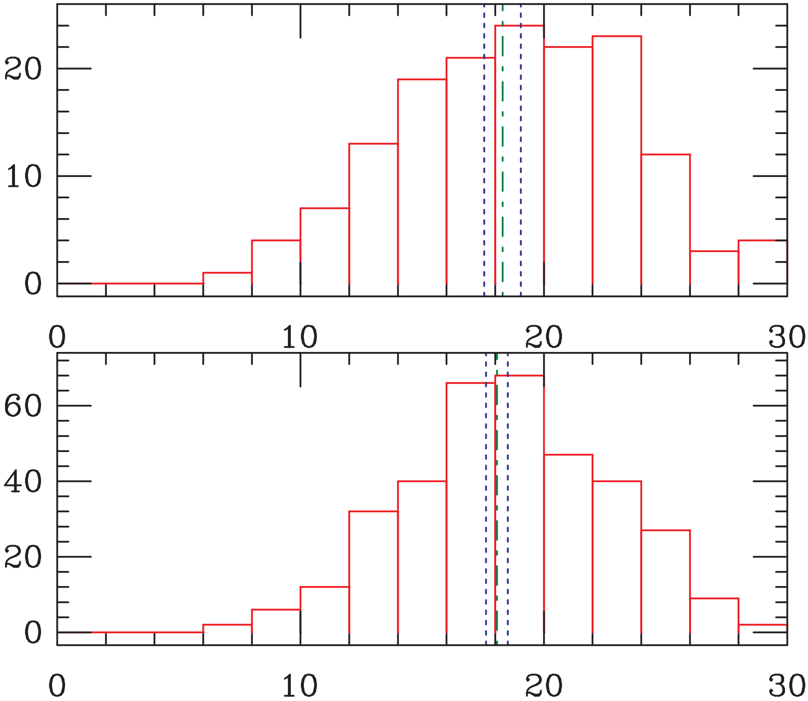
How can we determine if this is true?

Exam 3 grades





Exam 3 grades



Exam 3 grades

The difference was less than 1%, well within the margin of error.

Exam 3 grades

The difference was less than 1%, well within the margin of error.

However, it looks like there might be some effect on moderately-high scoring students.

When I compare only those students scoring over 50%, the averages differ by 2%.

Exam 3 grades

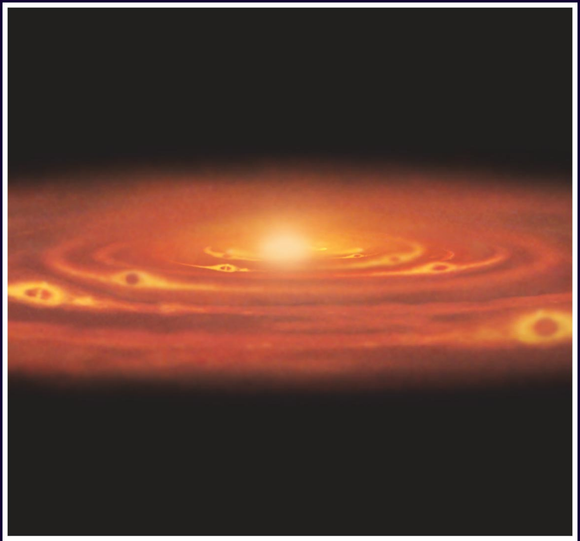
The difference was less than 1%, well within the margin of error.

However, it looks like there might be some effect on moderately-high scoring students.

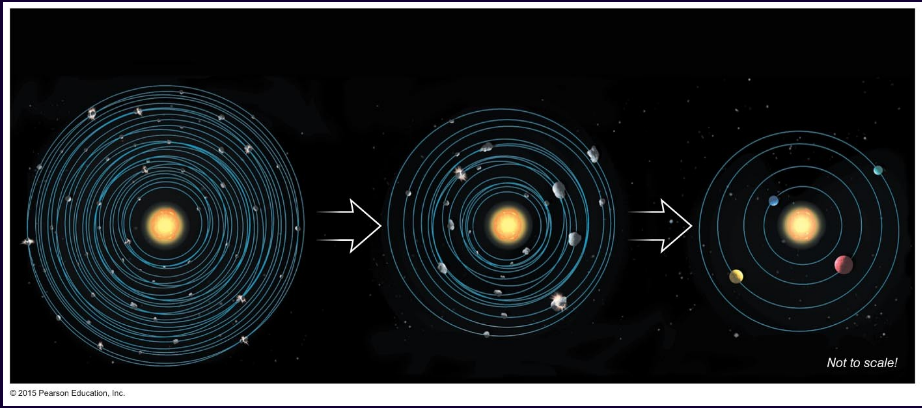
When I compare only those students scoring over 50%, the averages differ by 2%.

I've decided to give everyone a one-point freebie – essentially, scoring the exam out of 29 rather than 30.

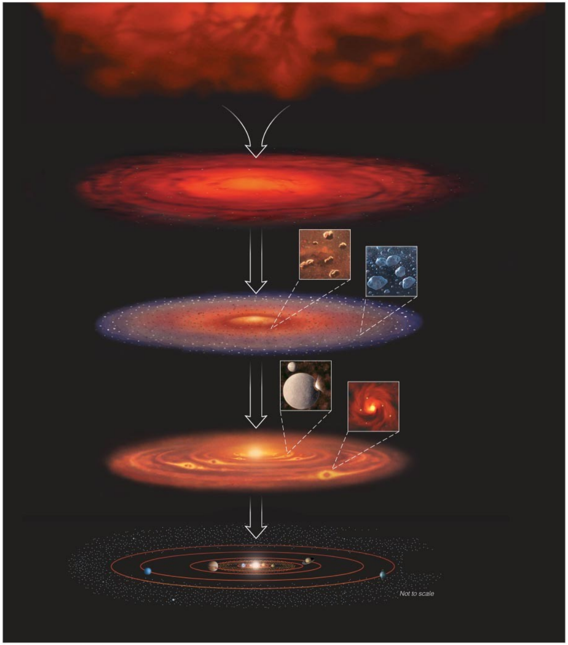
A spinning cloud of gas...



… bits coalesce into planets



The full picture



Complete *Lecture Tutorials* pp. 111-112.

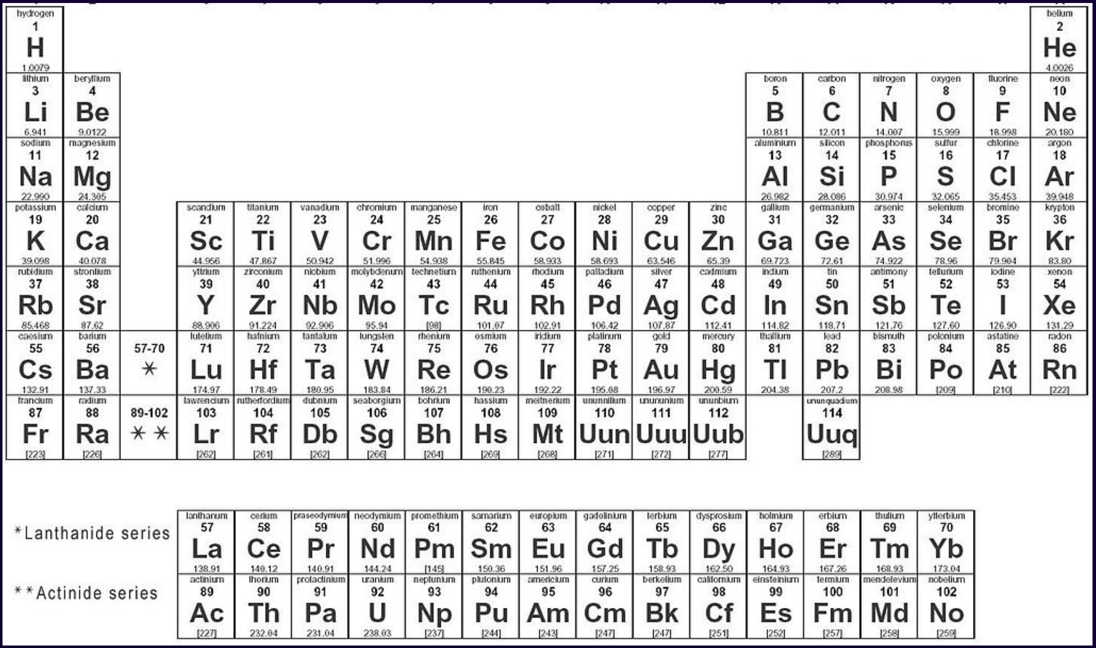
… but how long ago was this?

The process used to figure out the ages of the planets is the same as the process used for more recent objects.

“Carbon dating”: use the radioactive decay of carbon to figure out how old things are.

- Useful for things up to about 50,000 years old

We can use the decay of other isotopes to age much older things, though – like planets!


hydrogen 1 H 1.0079
helium 2 He 4.0026
lithium 3 Li 6.941
beryllium 4 Be 9.0122
boron 5 B 10.811
carbon 6 C 12.011
nitrogen 7 N 14.007
oxygen 8 O 15.999
fluorine 9 F 18.998
neon 10 Ne 20.180
sodium 11 Na 22.990
magnesium 12 Mg 24.305
aluminium 13 Al 26.982
silicon 14 Si 28.086
phosphorus 15 P 30.974
sulfur 16 S 32.065
chlorine 17 Cl 35.453
argon 18 Ar 39.948
potassium 19 K 39.098
calcium 20 Ca 40.078
scandium 21 Sc 44.956
titanium 22 Ti 47.867
vanadium 23 V 50.942
chromium 24 Cr 51.996
manganese 25 Mn 54.938
iron 26 Fe 55.845
cobalt 27 Co 58.933
nickel 28 Ni 58.693
copper 29 Cu 63.546
zinc 30 Zn 65.39
gallium 31 Ga 69.723
germanium 32 Ge 72.61
arsenic 33 As 74.922
selenium 34 Se 78.96
bromine 35 Br 79.904
krypton 36 Kr 83.80
rubidium 37 Rb 85.468
strontium 38 Sr 87.62
yttrium 39 Y 88.906
zirconium 40 Zr 91.224
niobium 41 Nb 92.906
molybdenum 42 Mo 95.94
technetium 43 Tc [98]
ruthenium 44 Ru 101.07
rhodium 45 Rh 102.91
palladium 46 Pd 106.42
silver 47 Ag 107.87
cadmium 48 Cd 112.41
indium 49 In 114.82
tin 50 Sn 118.71
antimony 51 Sb 121.76
tellurium 52 Te 127.60
iodine 53 I 126.90
xenon 54 Xe 131.29
caesium 55 Cs 132.91
barium 56 Ba 137.33
57-70 *
lutetium 71 Lu 174.97
hafnium 72 Hf 178.49
tantalum 73 Ta 180.95
tungsten 74 W 183.84
rhenium 75 Re 186.21
osmium 76 Os 190.23
iridium 77 Ir 192.22
platinum 78 Pt 195.08
gold 79 Au 196.97
mercury 80 Hg 200.59
thallium 81 Tl 204.38
lead 82 Pb 207.2
bismuth 83 Bi 208.98
polonium 84 Po [209]
astatine 85 At [210]
radon 86 Rn [222]
francium 87 Fr [223]
radium 88 Ra [226]
89-102 **
lawrencium 103 Lr [262]
rutherfordium 104 Rf [261]
dubnium 105 Db [262]
seaborgium 106 Sg [266]
bohrium 107 Bh [264]
hassium 108 Hs [269]
meitnerium 109 Mt [268]
ununnilium 110 Uun [271]
unununium 111 Uuu [272]
ununbium 112 Uub [277]
ununquadium 114 Uuq [289]
*Lanthanide series
lanthanum 57 La 138.91
cerium 58 Ce 140.12
praseodymium 59 Pr 140.91
neodymium 60 Nd 144.24
promethium 61 Pm [145]
samarium 62 Sm 150.36
europium 63 Eu 151.96
gadolinium 64 Gd 157.25
terbium 65 Tb 158.93
dysprosium 66 Dy 162.50
holmium 67 Ho 164.93
erbium 68 Er 167.26
thulium 69 Tm 168.93
ytterbium 70 Yb 173.04
**Actinide series
actinium 89 Ac [227]
thorium 90 Th 232.04
protactinium 91 Pa 231.04
uranium 92 U 238.03
neptunium 93 Np [237]
plutonium 94 Pu [244]
americium 95 Am [243]
curium 96 Cm [247]
berkelium 97 Bk [247]
californium 98 Cf [251]
einsteinium 99 Es [252]
fermium 100 Fm [257]
mendelevium 101 Md [258]
nobelium 102 No [259]

Radioactive decay: key points

- Each element on the periodic table has a fixed number of protons and electrons
- The chemical properties don't depend on the number of neutrons
- "Ordinary" carbon is called "carbon-12"
    - It has six protons and six neutrons, for a total of twelve nucleons in the nucleus

Radioactive decay: key points

- Each element on the periodic table has a fixed number of protons and electrons
- The chemical properties don't depend on the number of neutrons
- "Ordinary" carbon is called "carbon-12"
  - It has six protons and six neutrons, for a total of twelve nucleons in the nucleus
- A different form of carbon is called "carbon-14"
  - It has six protons and eight neutrons, for a total of fourteen nucleons in the nucleus
- These different forms of elements, with different numbers of neutrons, are called **isotopes**

Radioactive decay: key points

- Many isotopes are *radioactive*: they will decay into other isotopes of other elements after some time, eventually reaching a stable one
- For instance: potassium-40 decays into argon-40; carbon-14 decays into nitrogen-14; uranium-235 decays (eventually) to lead-207
- We can characterize how fast they decay by a number called the “half-life”
- One half-life: how long it takes for half of the substance to decay
  - “Carbon-14 has a half-life of 5730 years”
- We can use these decays as a clock

You give someone ten thousand pennies. Starting at noon, every hour she puts the pennies in a bucket and throws them on the floor, then removes all the ones that came up heads.

You notice that at some point she has 2493 pennies left. About what time is it?

A: 1:00
B: 1:30
C: 2:00
D: 2:30
E: 3:00

You give someone ten thousand pennies. Starting at noon, every hour she puts the pennies in a bucket and throws them on the floor, then removes all the ones that came up heads.

You notice that at some point she has 2493 pennies left. About what time is it?

A: 1:00
B: 1:30
C: 2:00
D: 2:30
E: 3:00
F: Please, please, don't make this a lab

- Every hour half of her pennies come up heads and are removed

- Every hour half of her pennies come up heads and are removed
- After one hour she'll have about 5,000 pennies left

- Every hour half of her pennies come up heads and are removed
- After one hour she'll have about 5,000 pennies left
- After two hours she'll have about 2,500 pennies left

- Every hour half of her pennies come up heads and are removed
- After one hour she'll have about 5,000 pennies left
- After two hours she'll have about 2,500 pennies left
- After three hours she'll have about 1,250 pennies left

- Every hour half of her pennies come up heads and are removed
- After one hour she'll have about 5,000 pennies left
- After two hours she'll have about 2,500 pennies left
- After three hours she'll have about 1,250 pennies left
- $\rightarrow$ Her pennies have a half-life of 1 hour
- The more pennies she started with, the more accurately I can tell time this way
- There are **far more** atoms in a sample than pennies here

Important difference with radioactive decay:

- Radioisotopes don't decay every hour (or year or whatever); they decay continuously

Radioactive decay: key points

There aren't many of these unstable isotopes around, as you might expect.

- Some of them, like carbon-14, are continually produced.
- Some of them, like uranium-235 and potassium-40, are left over from the supernova that produced them

If we can figure out what fraction of the original amount of a radioisotope is left in an object, we can figure out how long ago it formed.

Carbon dating

Carbon-14 has a halflife of 5730 years and is continually produced in the atmosphere.

The fraction of carbon-14 in the atmosphere was historically nearly constant – until recently. Why might that be?

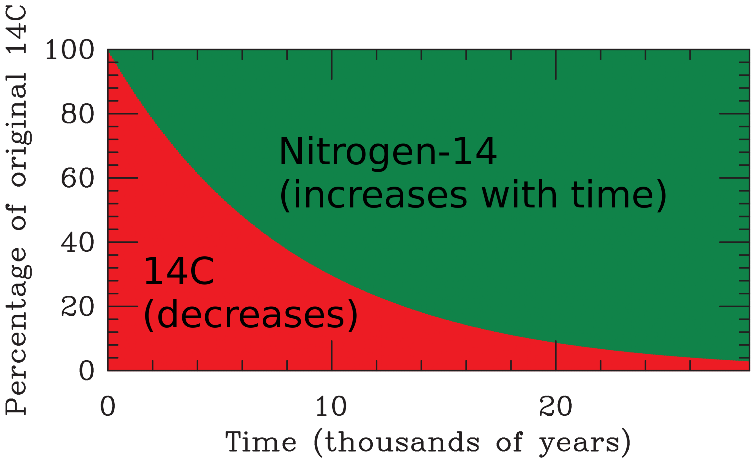
A: Explosion of nuclear weapons has increased the amount of radioactivity in the atmosphere

B: CO_2 emissions from burning fossil fuels have added only carbon-12 to the atmosphere, not carbon-14

C: The amount of cosmic rays hitting the atmosphere has changed because of the solar cycle

D: The metabolisms of plants and animals have changed with the rise of humans, absorbing carbon-12 but not carbon-14

Carbon dating

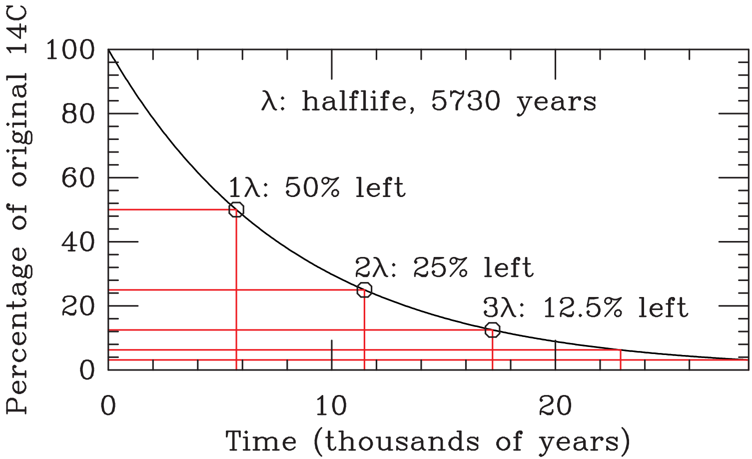


Living things constantly recycle their carbon, so their 14C fraction is the same as the atmosphere.

But once they die and stop breathing, over time 14C is replaced by 14N.

This lets us use the amount of 14C as a clock to see how long ago they died.

Carbon dating

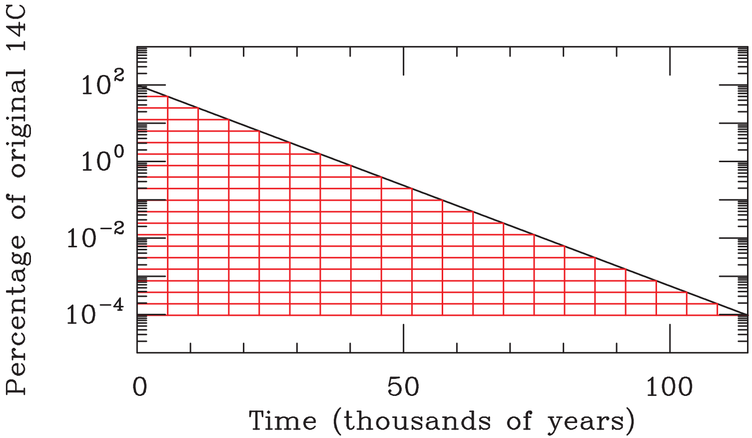


Living things constantly recycle their carbon, so their 14C fraction is the same as the atmosphere.

But once they die and stop breathing, over time 14C is replaced by 14N.

This lets us use the amount of 14C as a clock to see how long ago they died.

Carbon dating



We can use this procedure on things up to about 50,000 years old.

Past that, the 14C fraction is too small to give an accurate picture.

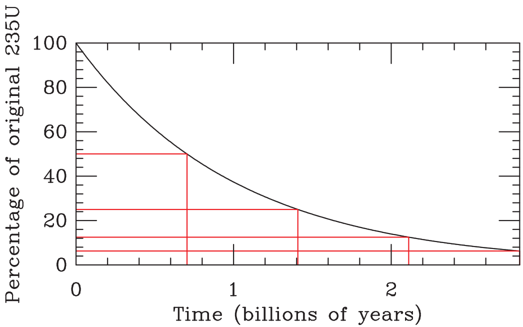
We need some older process to date the planets!

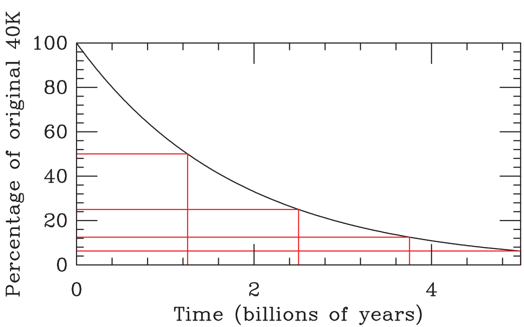
Other radioisotopes

There are longer-lived isotopes we can use here:

- Potassium-40: half-life of 1.251 Gyr (“gigayears” – billion years). Decays into argon-40.
- Uranium-235: half-life of 0.7038 Gyr. Decays into lead-207.

This radioactive decay works the same way:





Uranium-lead dating

Crystals of the mineral zircon readily incorporate uranium into their structure, but *not* lead, while they are forming.

Thus any lead present in zircon got there through the decay of uranium-235.

Uranium-lead dating

Crystals of the mineral zircon readily incorporate uranium into their structure, but *not* lead, while they are forming.

Thus any lead present in zircon got there through the decay of uranium-235.

A zircon crystal contains as many atoms of lead-207 as uranium-235. About how old is it? (The halflife of U-235 is about 0.7 billion years.)

A: 0.7 Gyr

B: 1.4 Gyr

C: 2.1 Gyr

D: 2.8 Gyr

Uranium-lead dating

Crystals of the mineral zircon readily incorporate uranium into their structure, but *not* lead, while they are forming.

Thus any lead present in zircon got there through the decay of uranium-235.

Uranium-lead dating

Crystals of the mineral zircon readily incorporate uranium into their structure, but *not* lead, while they are forming.

Thus any lead present in zircon got there through the decay of uranium-235.

A zircon crystal contains seven atoms of lead-207 for every atom of uranium-235. About how old is it? (The halflife of U-235 is about 0.7 billion years.)

A: 0.7 Gyr

B: 2.1 Gyr

C: 4.9 Gyr

D: 5.6 Gyr

Potassium-argon dating

Argon is a noble gas. It doesn't chemically bond readily.

Thus any argon-40 present in zircon got there through the decay of potassium-40. Potassium-40 has a half-life of about 1.251 Gyr.

These two processes – lead/uranium dating and potassium/argon dating – rely on different assumptions, so they are a nice crosscheck.

Now, let's date some rocks!

Now, let's date some rocks!

(no, not like that)

- Oldest Earth rocks: 4 Gyr (a few grains are a bit older)
- Oldest Moon rocks: 4.4 Gyr
- ... can we get anything older than that? What are the most primordial things in the Solar System?

Now, let's date some rocks!

Some meteorites found on Earth date to 4.55 Gyr old – the age of the condensation of the first rocks in the Solar System.

What about other planets?

https://www.caltech.edu/news/first-rock-dating-experiment-performed-mars-41496

We've done argon/potassium dating on Mars, giving the same results as Earth: a bit more than four billion years.