Radiometric Dating and the Age of the Earth

How to tell time:

- **Relative Time**: putting events in time order.
  - Law of Superposition
  - Correlation of rock layers using fossils.

“There is a wonderful order and regularity with which nature has disposed of fossils and assigned to each its peculiar stratum.”

William Smith

How to tell time:

- **Absolute Time**: Determining age in years.

How old is the Earth?

My calculations based on the Bible prove the Earth is 6000 years old!

James Ussher
Early attempts to measure the age of the Earth:

- How long would it take to deposit all the strata?
- How long would it take the oceans to get salty?

At least 75 million years. Perhaps much longer?

Thomas Huxley

Early attempts to measure the age of the Earth:

**William Thomson (Lord Kelvin) 1824–1907**

- British physicist
- Find rate at which heat is escaping from Earth's interior.
- Assume Earth started as molten rock.
- How long would it have taken the Earth to cool to its current temperature?
- 20 to 30 million years.

“When you can measure what you are speaking about and express it in numbers, you know something about it.”

30 million years is not enough time!

But how can you argue with physics?!

There must be some mistake!

How could Kelvin be wrong?
**Henri Becquerel (1852-1908)**

- 1896 - discovers that uranium emits energetic particles.
- Works with Marie and Pierre Curie to develop theory of natural radioactivity.

If it’s 1903, then that Nobel Prize is for me!

- Radioactivity heats up surrounding rock.
- Kelvin’s assumption of steady cooling is wrong, which invalidates his argument.
- So, how old is the Earth??

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**Ernst Rutherford (1871-1937) and Frederick Soddy (1902)**

- Radioactive decay changes atoms from one element to another.
- The parent isotope decays into a daughter isotope.
- The rate of decay is mathematically constant.
- The daughter isotope accumulates over time.

The progressive accumulation of daughter isotopes in a rock could provide a basis for measuring geological time.

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[Graph showing exponential decay of parent and daughter isotopes over time.]

**Number of parent atoms**

**Number of daughter atoms**

**Time**
Bertram Boltwood (1870-1927)
• Yale University radiochemist. Discovers the Uranium – Lead decay series.
• 1907 – Measures the proportions of Uranium (parent) to Lead (daughter) in minerals from 10 different localities on three continents.
• Calculates ages from 410 million to 2.2 billion years.
• The Earth is at least 10X older than geologists had suspected!

Basics of Radioactivity
• Atomic nuclei contain protons (+) and neutrons (0).
• Identity of element is given by # of protons.
• Atomic mass = # protons + # neutrons

Helium - 2 protons, 2 neutrons
Mass = 4

Carbon - 6 protons,6 neutrons
Mass = 12
$^{12}\text{C}$

Carbon - 6 protons,7 neutrons
Mass = 13
$^{13}\text{C}$
Basics of Radioactivity

Radioisotopes
- Isotopes that are too massive to be stable.
- At some point in time, they decay to a different isotope.
- Decay emits radiation.

Carbon - 6 protons, 8 neutrons
Mass = 14
$^{14}\text{C} = \text{radioactive}$

Nitrogen - 7 protons, 7 neutrons
Mass = 14
$^{14}\text{N} = \text{stable}$

The Laws of Radioactive Decay
- Each radioisotope has a constant probability of decay.
- Cannot predict when a single atom will decay.
- Can predict how long it will take half of the atoms in a sample to decay = half life.
- Each radioisotope has a unique half life.
- Nothing changes the half life.
  - Not Pressure
  - Not Temperature
  - Not Magnetism

Radiometric Dating of Rocks
During formation of Igneous and Metamorphic Rocks...
- Parent atoms are trapped during crystallization of minerals.
- Blocking temperature - mineral becomes a closed system.
- The clock starts as daughter atoms form and remain trapped in the rock.
**Decay series useful for dating rocks**

<table>
<thead>
<tr>
<th>Parent Isotope</th>
<th>Half Life</th>
<th>Stable Daughter</th>
<th>Effective Age Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium 238</td>
<td>4.5 Ga</td>
<td>Lead 206</td>
<td>&gt; 100 Ma</td>
</tr>
<tr>
<td>Uranium 235</td>
<td>.7 Ga</td>
<td>Lead 207</td>
<td>&gt; 100 Ma</td>
</tr>
<tr>
<td>Thorium 232</td>
<td>14 Ga</td>
<td>Lead 208</td>
<td>&gt; 200 Ma</td>
</tr>
<tr>
<td>Thorium 232</td>
<td>48.8 Ga</td>
<td>Strontium 87</td>
<td>&gt; 100 Ma</td>
</tr>
<tr>
<td>Potassium 40</td>
<td>1.25 Ga</td>
<td>Argon 40</td>
<td>&gt; 100,000 yr</td>
</tr>
<tr>
<td>Carbon 14</td>
<td>5,730 yr</td>
<td>Nitrogen 14</td>
<td>0 - 80,000 yr</td>
</tr>
</tbody>
</table>

**Lead – Lead dating:**

\[
\frac{207 \text{ Pb}}{206 \text{ Pb}} \text{ increases with increasing age.}
\]
Possible Sources of Error

\[
\frac{\# \text{ Daughter}}{\# \text{ Parent}} = \text{Age}
\]

- Loss of some parent atoms?
  - Sample appears older than it actually is.
- Loss of some daughter atoms?
  - Sample appears younger than it actually is.
- Addition of some parent atoms? (contamination)
  - Sample appears younger than it actually is.
- Addition of some daughter atoms? (contamination)
  - Sample appears older than it actually is.

How to check the accuracy of radiometric dates

- Date many samples from different places within the same rock layer. All dates should be similar.
- Use two different isotope series to date the same rock. Both dates should be the same.
- When different samples or isotope series give similar dates for a rock layer, the dates are called concordant.

The accuracy of radiometric dates is limited by experimental error and the sensitivity of the instrumentation.

- Radiometric dates are usually reported as + / – some uncertainty.
  - For example 208 +/- 2 Ma

Radiometric dates are used to calibrate the relative time scale based on fossils to absolute time.
Radiocarbon Dating

Radioactive $^{14}$C isotope

- Commonly used method to date organic material.
- Tissue, wood, bone, tooth, shell, hair, cloth.
- Works for samples younger than 80,000 years old.
- Often used in archeology to date artifacts.

$\text{Cosmic rays} \rightarrow n \rightarrow ^{14}\text{C}$

$^{14}\text{C} + ^{16}\text{O} \rightarrow ^{14}\text{CO}_2$
Radiocarbon Dating

- Metabolic activity continually replaces carbon in living tissue.
- Maintains same $^{14}\text{CO}_2 / 12\text{CO}_2$ ratio in atmosphere.
- Replenishment stops at death.
- Supply of $^{14}\text{C}$ begins to decay.

Atmospheric ratio

- Count number of radioactive decay events per minute.
- Compare to a standard of known age.