12.001: Origin and Interior of the Earth
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Begin with the story of Fritz Haber, and how he followed up his discovery of a procedure for industrial Nitrogen fixation by spending years trying to extract gold from seawater. A few centuries earlier, Newton's alchemy experiments occupied the bulk of his time. Why were they so fixated on this? Why is gold so valuable? This brings us to the broader question of what determined the distribution of the elements in Earth and other planets. And that leads us to the question of how the planets formed, and what's on the inside. Today's lecture will be in 2 parts: Formation of the planets, and Earth's interior [PPT: 2 images and questions].

Part I: Formation of the planets

What do we need to build a habitable planet? A popular (n=1) recipe:

1. Stable Energy source: Central star should not be too hot, not too cold (4000-7000 K), active for billions of years, no significant changes in luminosity over short timescales.
2. A stable habitable zone defined by the presence of liquid water (zone might be redefined once we find different life forms)
3. Star must have high metallicity, in order to increase the likelihood of producing planets in the first place, and so the resulting planets have a density that will help them retain the right kind of atmosphere…i.e., an atmosphere that buffers the surface temperature.
4. The mass of the planet must be large enough to retain internal heat that maintains geological activity (small planets cool and are geologically dead….). Geological processes are important for life. Why?
    a. Convection in the outer core is essential for the magnetic field of the earth, which shields our tissues from radiation.
    b. Plate tectonics fosters biodiversity and steers the course of evolution and biogeography (spatial species distribution)
    c. Plate tectonics, and resulting processes ranging from erosion to volcanic eruptions, regulate atmospheric composition, which in turn regulates climate.
5. Radioactive elements produce heat that keeps plate tectonics running. ^{40}K, ^{238}U, ^{232}Th.

How did we get to this happy state in which we have all the right ingredients? Let's map out the sequence of events that led to the formation of the Solar system, and eventually the Earth.

1. The big bang produced elements through fusion, but only up to the mass of ^7Be. Heavier elements like C have to be produced through triple collisions of ^4He, which take a lot longer to happen.
2. The remaining heavy elements, many of which are so important for the aforementioned reasons, were produced by:
    a. Fusion of H and He in stars (like our sun). This gets us as far as ^{56}Fe.
    b. Supernovae
    c. Red giants

   At this point we've strayed past the boundary of what we cover in 12.001. Take 12.002 for more on nucleosynthesis!
3. Now we have all the elements, but how do we parse them up into sun, planets, moons, etc.? The starting point was a haze of very diffuse matter produced by the above processes. How do we know? The abundance of elements in the Sun and in one of the most primitive (i.e. least changed) meteorite classes, the "carbonaceous chondrites" is very similar to the abundance predicted by nucleosynthesis – a nice confirmation of that hypothesis, and a useful assay of what everything in the solar system is made of. (The sun is 99.85% of the mass of the solar system and the planets are only 0.135%, so the sun tells us more or less what's here.)
4. A perturbation was required to start to concentrate this matter into what eventually became the solar system. What could have supplied this perturbation? Leading hypothesis: shockwave from a nearby supernova. Evidence: meteorites contain products of radioactive decay of short-lived elements that would have been produced in a supernova, apparently < 1 Myr before the meteorites formed.
5. Gravity takes over, and as this "nebula" contracts, it begins to rotate [PPT]. The rotation flattens it out into a disk [PPT].
6. How does the disk become star, planets, etc.? In particular, which part becomes Earth? The disk differentiates. Most of the mass is at the center of the disk, which becomes the sun. In addition to the gravitational effects, two things happen that affect the temperature and the physical distribution of material:
    a. The outer part of the disk starts to cool, and material begins to condense (gas → solid or liquid), starting with denser, less "volatile" materials, and then progressing to more volatile materials. A quick overview [PPT]:

Table 2 Cosmochemical and geochemical classification of the elements.

	Elements	
	Lithophile (silicate)	*Siderophile + chalcophile (sulfide + metal)*
Refractory	$T_c = 1{,}850$–$1{,}400$ K Al, Ca, Ti, Be, Ba, Sc, V, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta, Th, U, Pu	Mo, Ru, Rh, W, Re, Os, Ir, Pt
Main component	$T_c = 1{,}350$–$1{,}250$ K Mg, Si, Cr, Li	Fe, Ni, Co, Pd
Moderately volatile	$T_c = 1{,}230$–640 K Mn, P, Na, B, Rb, K, F, Zn	Au, As, Cu, Ag, Ga, Sb, Ge, Sn, Se, Te, S
Highly volatile	$T_c < 640$ K Cl, Br, I, Cs, Tl, H, C, N, O, He, Ne, Ar, Kr, Xe	In, Bi, Pb, Hg

T_c, condensation temperatures at a pressure of 10^{-4} bar (Wasson, 1985; for B, Lauretta and Lodders, 1997).

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b. The inner part of the disk becomes so dense and hot that nuclear fusion begins, and radiation and matter is emitted. This early "solar wind" exerts a pressure that drives gases away from the proto-sun. This preferentially strips volatiles out of the disk near the sun. This irradiated, volatile-poor desert zone is home.
c. A side note: Knowledge of elemental abundance in the Sun plus condensation temperature of the elements is very powerful. Can use to infer, for example, the composition of the core. Today's in-class exercise focuses on composition of the mantle.

7. The differentiated disk accretes into planets through a combination of hydrodynamic effects, collisions, and gravity [PPT]. Close to the sun, planets grow primarily through collisions of progressively larger clumps – "planetesimals." Further from the sun, gravitational and hydrodynamic accretion of gases onto planetesimals dominated [PPT].
8. These different compositions lead to dramatically different structures [PPT]. The "terrestrial planets" (M, V, E, M, some asteroids) have metallic cores and rocky exteriors. The gas giants (J, S, U, N) have rocky and metallic cores, but massive gaseous exteriors.
9. By the way, models suggest that all of this probably happened really fast, geologically speaking – perhaps as fast as 10 million years! So the Earth and the Solar system are almost the same age. The current estimate is 4.543 billion years (Gyr) (Bowring, 11th floor). There are no rocks on Earth this old, so this is based on dating the cooling ages of meteorites that never accreted into planets. More on that in a future lecture!

Now that we've gone through the textbook sequence of events, we can do the Behind the Music version. The artistic illustrations in your textbook transform magically from nebula to protoplanetary disk to planets, invoking mechanisms qualitatively along the way. In reality, the detailed explanations for how all these transitions occurred are actively being researched. For example, the transition from protoplanetary disk to planetismals is poorly understood. Laboratory experiments have produced millimeter-sized objects that stick together because of static interaction or van der Waals forces. Gravity only becomes important for km-sized objects. What happens in between to keep accretion going is unresolved.

Part II: Interior structure of Earth

We don't delve into the Earth's interior structure in great detail in this course – again, take 12.002 for this – but there are a few things that are absolutely essential to know if we are to understand geologic aspects of the crust and surface. I told you a few minutes ago that terrestrial planets have metallic cores and rocky exteriors. How do we know? And how did the planets differentiate in this way?

Let's start with the observations. The three main questions to answer are:

1. What is the composition of Earth's interior?
2. What state of matter?
3. What are the physical properties (density, strength, etc.)?

Composition:

- We only have direct samples from relatively shallow depths – mostly from the crust, a few from the mantle [PPT: peridotite xenolith]. The crust is a very small fraction of Earth's mass, so it is not a very useful indicator of bulk composition.
- The most important information about composition comes from looking around us in the Solar system. Much of what we know about Earth's bulk composition was inferred from primitive meteorites, chunks of material left over from the early stages of accretion that were never incorporated into planets [PPT: chondrite].
- We combine this information about bulk composition with measurements of Earth's mass and moment of inertia (tells us about how elements are distributed within the interior).
- For the moment, we won't go beyond bulk elemental composition, because that would require knowledge of minerals, which we'll be discussing next.
- Your exercise today will illustrate how we can use meteoritic composition to estimate the composition of the mantle, which makes up most of Earth's mass. So…what's the mantle?

State of matter:

- Given the difficulty of direct measurement, we have to rely on indirect measurements of Earth's interior. The most valuable indirect observations are seismic wave speeds and paths.
- Seismic waves propagate at speeds of roughly 6-8 km/s, and there are two main types: compressional (P, for primary arrival, because they're faster), and shear (S, for secondary arrival, because they're slower).
- After a big earthquake with a known location, Seismologists noticed some interesting patterns in where different types of seismic waves were detected. [Sketch: P-wave and S-wave shadow zones.] The S-wave shadow zone is most striking. What does this mean? S-waves don't propagate through liquids, which can't sustain shear. This also explains the P-wave shadow zone, because seismic waves refract when they pass into a slower medium, like a liquid. So part of the interior must be liquid! But everything above it is solid. [PPT]
- What about deeper down? Is the entire core liquid? No: we know from more detailed observations of P-waves that there is a solid inner core. [Same PPT]
- Seismic wave speed also depends on density, so we can combine seismic observations with constraints on bulk composition to assemble a model of Earth's interior.

After many more detailed studies, here is the picture that has emerged [PPT: Figs. 14.7, 14.8]. Note: You should know the general compositional and mechanical zones, the approximate radii of the boundaries between them, and their physical states!

Key points:

- There are both compositional and mechanical transitions in the interior, but they don't always correspond to one another.
- The main compositional layers:
  - Crust: rocky, lighter, Fe- and Mg-poor, Si-rich, and relatively thin. ~7 km in the oceans, ~30 km on the continents. Solid!
  - Mantle: rocky, denser, Fe- and Mg-rich, less Si-rich. Extends down to ~3000 km depth. Solid, but flows like a fluid over very long timescales due to temperature, density, and pressure differences!
    - Upper mantle: above 660 km, lots of changes in seismic velocity and mineral phase transitions.
    - Lower mantle: below 660 km, relatively homogeneous in terms of average seismic velocities.
  - Outer core: ~3000-5000 km. Almost entirely Fe and Ni. Liquid! The outer core also convects (circulates due to a temperature and density gradient), but much faster than the mantle. This generates Earth's magnetic field.
  - Inner core: ~5000-6370 km. Almost entirely Fe and Ni. Solid!
- The main mechanical layers:
  - Lithosphere: Includes the crust and upper mantle, down to ~100 km. Behaves elastically, meaning it does not flow over any relevant timescale.
  - Asthenosphere: Weak, low-viscosity layer (but still solid!) extending down to ~400 km. This is the shallowest depth at which convection occurs, and it is generally thought that the asthenosphere is what allows tectonic plates to move (more on this later in the course).
  - Below the asthenosphere, the compositional and mechanical boundaries generally coincide.

How did the interior get to be this way? Differentiation occurred while Earth was forming [PPT]. May have melted entirely due to large collisions, and denser metals migrated to interior, while lighter elements migrated to shallower depths. Discovery of meteorites made almost entirely of Fe+Ni supports the idea that differentiation occurred in other bodies too, even those smaller than the terrestrial planets.

A related, critical issue: Earth probably lost some of its volatiles during accretion and through degassing as it differentiated. So where'd we get all this water? Three main ideas:

1. Some of the initial water inventory was retained, despite losses during accretion and differentiation. This probably did occur to some extent.

2. Water was delivered by comets, which have very eccentric orbits and therefore can bring volatile-rich material from further out in the Solar system where it condensed.
3. Water arrived was delivered by more volatile-rich planetesimals that migrated or were scattered inwards toward the terrestrial planets due to the influence of other bodies, especially Jupiter and Saturn.

The debate continues, with some geochemical, isotopic, and dynamical evidence in support of each hypothesis. Whichever mechanisms delivered the water, we're sure glad they did!

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