

# The Relation Among Physics, Chemistry and Biology in the Natural World

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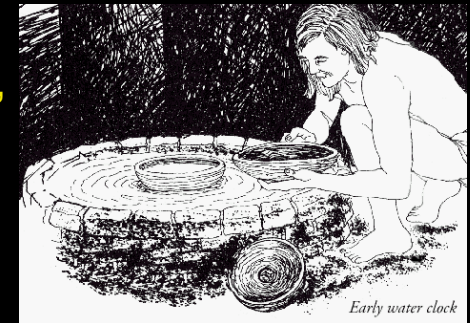
Academia Sinica

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# Mystical View of the World

- Mystical concepts of elements & reasons for change
  - Babylonian argument that **water** = “**theory of everything**”
    - Source of all life between Tigris & Euphrates
    - Capable of change from solid to liquid to gas
  - Water, Fire, Earth, Air, and Quintessence (Greece)
  - Water, Fire, Earth, Metal, and Wood (China)

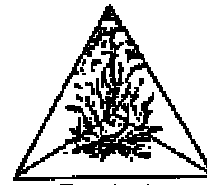


Early water clock

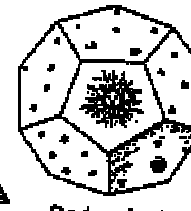
Association of five elements with five platonic solids



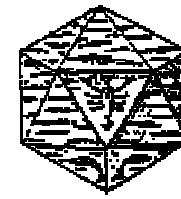
Cube  
Earth



Tetrahedron  
Fire



Dodecahedron  
the Universe



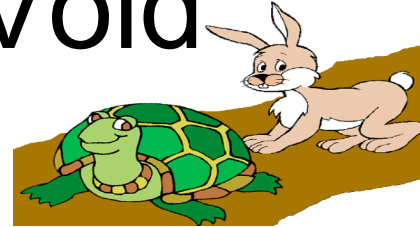
Icosahedron  
Water



Octahedron  
Air

- Association of metals/elements with planets
  - West: Sun = gold, Moon = silver, Mercury = tin, Venus = copper, Mars = iron, Jupiter = asem, Saturn = lead (7 planets = 7 day week); quicksilver ≠ metal**
  - East: Mercury = water, Venus = metal, Mars = fire, Jupiter = wood, Saturn = earth**

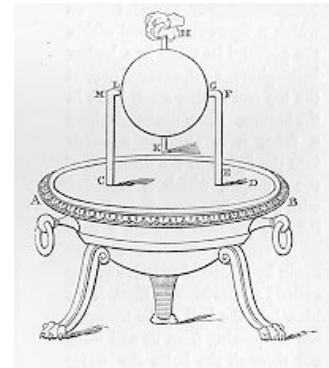
# Atoms and the Void



- Zeno's paradox, tortoise and the hare:

$$10 + 1 + 0.1 + 0.01 + \dots = 10(1 + x + x^2 + x^3 + \dots) = \frac{10}{1-x} = \frac{100}{9}.$$

- Inability to perform infinite sums proved to be an obstacle to the Greeks for serious theories of motion.
- Curious idea for escape from difficulty: Maybe matter, unlike space, is not infinitely divisible, but is composed of uncuttable units, *atoms* (Leucippus, 480-420 BC).
- Further development of idea by Democritus:  
Atoms and the Void.
- Hero (10-70 AD): Air is composed of atoms and the void. Beginning of experimentation, but it was too late. Greeks were already enslaved by Romans, who disdained both scientific theory and experimentation.



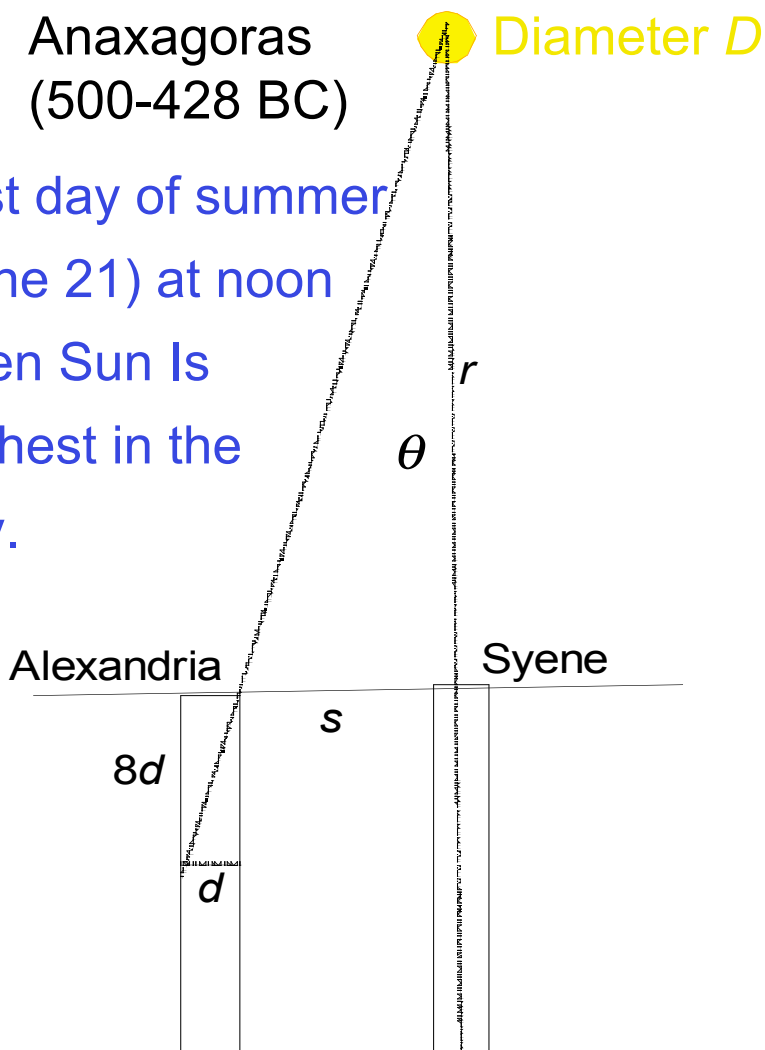
# Alchemy and the Search for Longevity/Immortality

- Basis of alchemy: belief that all metals are same element (superior refining of Athens: asem = alloy of gold and silver: quicksilver → Mercury, tin → Jupiter)
- Notion (in China) that longevity or even immortality could be achieved by ingesting gold
- However, stomach acid cannot dissolve gold -- search for potion that could aid digestion of gold
- Invention of gunpowder (**alchemy** → **chemistry**)
- Arabic discovery of aqua regia ( $\text{HCl} + \text{H}_2\text{SO}_4$ )
- Ultimate failure to turn base metals (tin, copper, iron, lead) to noble metals (silver, gold) suggests that **metals are many elements**; discovery of zinc (from brass making) in China & India ⇒ # metals > # planets, and **numerology of 3** (for eclipses), **5** (for elements), **7** (for planets), is nonsense

# Planets as Physical Bodies Rather than Gods

Anaxagoras  
(500-428 BC)

First day of summer  
(June 21) at noon  
when Sun is  
Highest in the  
Sky.



Meteorite fell from sky, hot when found.  
Must have come from the Sun.

Hypothesis: Sun is hot piece of stone.  
How big?

Pay a soldier to pace off:  $s = 800$  km.

$$r/s = 8d/d = 8 \Rightarrow r = 8s = 6400 \text{ km};$$

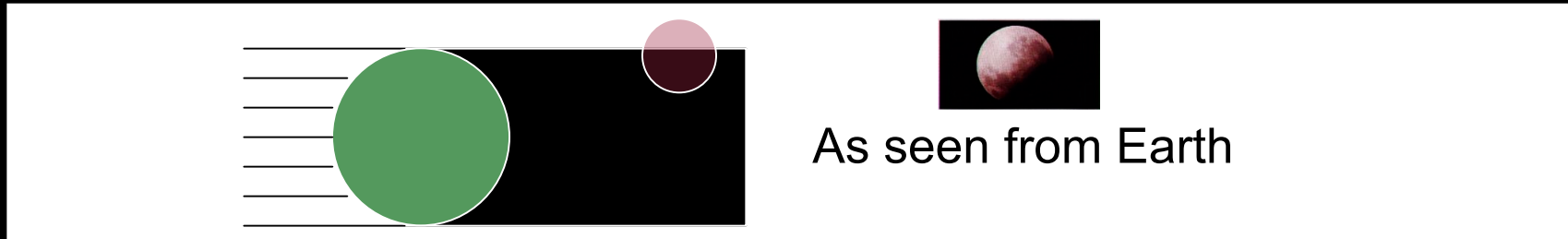
$$D/r = 0.5^\circ = 0.5^\circ(\pi \text{ rad}/180^\circ) = 0.009$$
$$\Rightarrow D = 58 \text{ km}$$

Anaxagoras concludes that Sun is a  
flaming rock smaller than Greece.

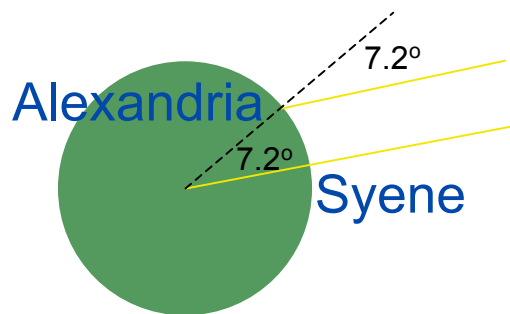
Wrong! But more important is idea that  
Sun is a physical body, not a God.

# Measure of the Earth and the Moon

During lunar eclipse, shadow cast by Earth is circular  $\Rightarrow$  Earth is a sphere.



Erastosthenes (276-194 BC): If the Sun is much farther away, its rays arrives on parallel lines. Anaxagoras's problem is then given by the bottom diagram. Alexandria lies north of Syene by a latitude angle  $\arctan(1/8) = 7.2^\circ = 360^\circ/50$ . Distance from Alexandria to Syene, 800 km, is  $1/50$  of the polar circumference around the world  $\Rightarrow 2\pi R_E = 40,000$  km  $\Rightarrow R_E = 6400$  km. What Anaxagoras got as the distance to the Sun is actually the radius of the Earth! The Sun must be much farther away!

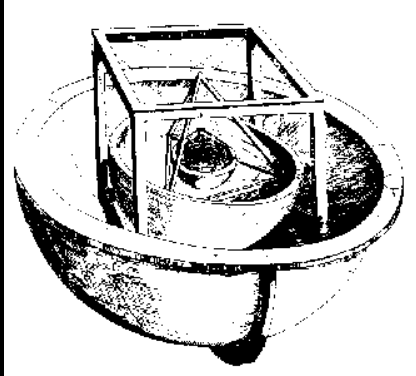


Aristarchus (310-230 BC): During lunar eclipse, shadow has inferred diameter 3.7 times larger than diameter  $D_M$  of the Moon. Thus,  $D_M = 2R_E/3.7$ . But  $D_M/r_M = 0.5^\circ = 0.009$  rad  $\Rightarrow r_M = 2R_E/[(3.7)(0.009)] = 60 R_E$ . (Crucial for Newton)  
If Sun is much farther than Moon, Sun is much bigger than Earth. **Maybe Earth circles Sun.**

# The European Renaissance

## Why Modern Science Appeared There

- Despite its brilliance in theory, Greece did not develop modern science because it (generally) refrained from experimentation.
- Despite its many successes in experimentation, China did not develop modern science because it was too practical to tolerate theory.
- Islam was crossroad of commerce between East and West.
- Islam was exposed to Western tradition (theory) and Eastern tradition (experimentation) in advancing knowledge.
- Crusades led to European re-exposure to classical knowledge.
- Islam, a more advanced culture than Europe, was subsequently destroyed by Genghis Khan and the Mongol invasion. If Islam had escaped devastation, it might well have invented modern science.
- As it was, the opportunity fell to Europe. Besides Copernicus, the two scientific giants of the Renaissance were
  - **Kepler**, transitional figure, three laws of planetary motion;
  - **Galileo**, perfect blend of theorist & experimentalist (whose like is not seen again until Fermi).

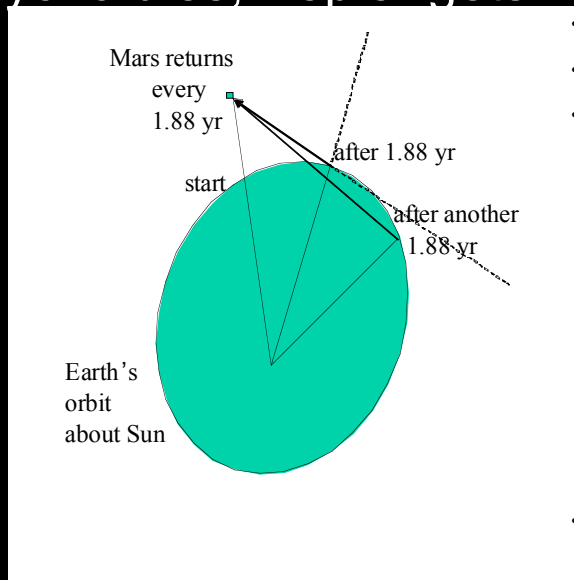


Kepler (1571-1630): Perhaps the five platonic solids provide scaffolding for the crystalline spheres of the six Copernican planets: Mercury, Venus, Earth, Mars, Jupiter, and Saturn as they circulate about the Sun.

**Misfits by only 10%.** Maybe Copernicus's orbits

are in error. Need better data. Becomes apprentice to Tycho Brahe.

- Tycho dies, Kepler gets his hands on positional data for Mars.



How to deduce orbit? Observations only of angles from moving Earth! Must get orbit of Earth first.

Crucial assumption: **All orbits are closed.** Lucky guess! Gets an **ellipse** which had been studied mathematically by Greeks! **Sun is at a focus!**

- Second law: radius vector sweeps out **equal areas in equal time.** Are magnetism of Earth (Gilbert) and rotation of Sun (Galileo) the **cause?** Attracts later contempt of Newton, who only cites third law.



# The Age of Enlightenment

- Newton (1642-1727)
  - Forces as the agents of change:  $F = ma$
  - Mass as the source of the force of gravitation:  $F = GMm/r^2$ .
    - $g = 9.8 \text{ m s}^{-2}$  for apple at surface of Earth.
    - $a = v_M^2/r_M = (2\pi)^2 r_M / P_M^2 = g/3600 = g/(60)^2$ .
    - $g = GM_E/R_E^2$ ; get  $G$  if know  $M_E$ .
  - Invention of reflecting telescope
  - Invention of calculus
  - Discovery of colors of white light
  - Invention of spectroscopy
- Epitaph by Alexander Pope: “Nature and Nature’s laws lay hid in night, God said. ‘Let Newton be,’ and all was light.”

# Most Illustrious Person in English History was a Physicist



Most Illustrious Person in English History was an Astrophysicist

# Modern Atomism

- Ideal Gases
  - Boyle's law:  $PV = \text{const}$
  - Charles and Gay-Lussac:  $PV = \nu RT$
  - Atomic/molecular derivation by Bernoulli:  $P = nkT$
- Proof of Atomism (**chemistry = physics**)
  - Integer proportions: Debate between Dalton & Gay Lussac
  - Proposal by Avogadro:  $N_A = R/k$
  - Measurement of  $k$  using Brownian motion (Einstein, Perrin) -  
- determination of  $N_A$ ; proof of atomic hypothesis
- Heating mercuric oxide produces oxygen (Priestley)
  - Survival of mice in this gas = 5x in air (oxygen is only 20% of air; **air is not an element**; **biology = chemistry**)
  - Fire results when flammable substances combine with oxygen (**fire is not an element**)
  - Oxygen combines with gas given off by certain metal-acid reactions to give a "dew" on reaction flask
  - Lavoisier: dew = water; gas that generates water with oxygen is "hydrogen" (**water is not an element**)

# Cross-fertilization of Science and Technology

- Dissection of frogs
  - Twitched when steel scapel cutting dead frog's leg accidentally touched brass hook to which frog's leg is attached (Galvani).
  - Electric current must have flowed because of potential difference of two different metals connected by electrolyte, frog's blood (Volta).
  - Replace frog's blood by brine (salt water) between alternating piles of different metallic plates -- Voltaic pile (battery)!
  - Tremendous technological advance: can produce **DC electric currents on demand!** (Advance in biology leads to advance in physics.)
  - Tremendous scientific discovery: **nervous systems of animals operate on flowing electric currents!**
- Electroplating of metals
  - Faraday's law: **amount of metal plated on an electrode is proportional to the amount of electric charge that passes through an external wire, with the proportionality being a universal constant (dependent only on the "valence state of the metal")**.
  - If Faraday knew Avogadro's number, he would have been able to determine the charge of an electron, But Faraday did not wish to commit to an atomic theory of matter. Nevertheless, Faraday proved essentially that the structure of metals (and by induction, the chemistry of all elements) is basically **electrostatic in nature**.

# Electricity & Magnetism (Classical period)

- Static electricity from rubbing amber (elektron) with wool, pick up bits of cloth (Greece) -- in modern terms, **electricity must be associated with a force**
- Iron ore mined from Magnesia are natural magnets (Greece) -- in modern terms, **magnetism must be associated with a force**
- Steel needles stored next to natural magnet become themselves magnetized (China)
- Magnetized steel needle stuck in cork and floating in a bowl of water is a **compass** that will point (approximately) to north (China). Why?



# Electricity & Magnetism (Renaissance to Maxwell)

1. Bar magnets contain two poles, north and south that repel like and attract unlike. Earth behaves as a big bar magnet. A cut bar magnet yields two bar magnets, each with north & south poles. There are no magnetic monopoles (Gilbert)
2. Charges yield electric **forces** that act on other charges (Coulomb)
3. Charges come in positive and negative forms. When sign is taken into account, electric charge is conserved. (Franklin)
4. Currents, or moving electric charges, are sources for magnetic **forces** on other currents (Oersted, Ampere). **Electricity and magnetism are related!**
5. Electric and magnetic **fields** have existence independent of the **particles** that they act upon (Faraday). Electric fields **E** driving current flow in a wire can create magnetic fields **B**. Can **B** create **E**?
6. **Time-varying B can generate E** (Faraday's law of induction, basis of AC electricity generation). Can time-varying **E** generate **B**?
7. Items 1, 2, 4, and 6 are inconsistent with 3 unless time-varying **E** can generate **B** (Maxwell, adds "displacement current to 4)
8. Can time-varying **E** and **B** sustain each other in absence of charges & currents? **Yes, EM-waves that travel at the speed of light c** (Maxwell, who postulated an aether = quintessence for **E** and **B** to wave in).

# Fifth Most Illustrious Person in US History was a Physicist



# Quantum Theory

- Kirchhoff: Radiation given off by an opaque body of uniform  $T$  has a wavelength distribution characterized only by  $T$  and does not depend on the material composition of the body.
- Planck: Found the functional form of this distribution, which introduced a new fundamental constant of nature,  $h$ , now referred to as Planck's constant.
- Einstein: light is not entirely a wave; photoelectric effect means that light also comes in energy quanta of  $h\nu$  where  $h$  is Planck's constant from theory of blackbody radiation.
- Bohr: spectroscopy of hydrogen then requires quantization of electron orbits in Rutherford's planetary model of atoms
- When add quantum mechanics (Heisenberg, Schroedinger) and electron spin (Pauli), Bohr's scheme becomes the **quantum basis for understanding Mendeleev's periodic table of the chemical elements**. (Chemistry is basically the quantum mechanics of the orbital electrons of atoms.)

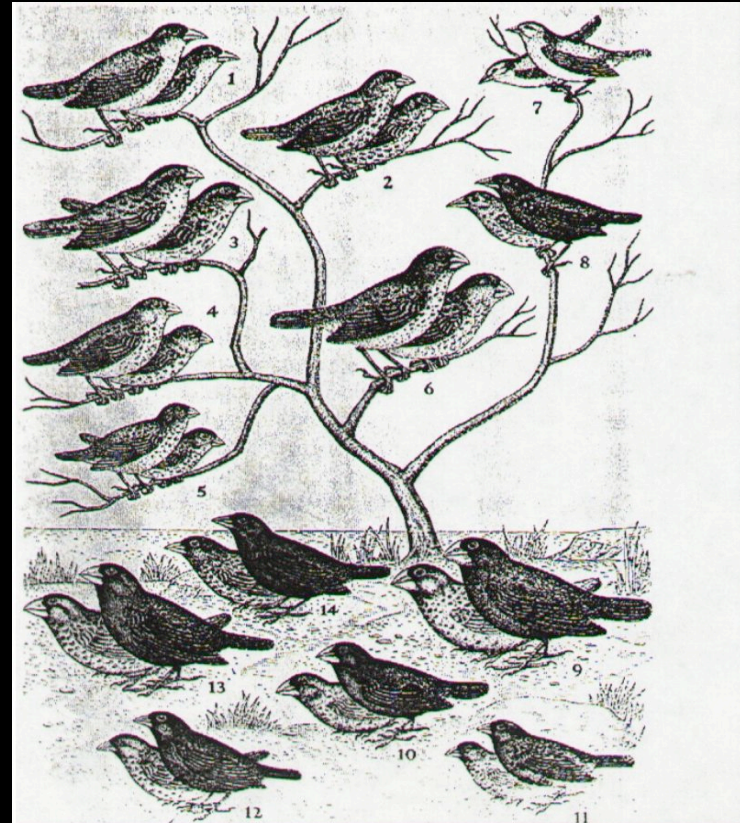


# Relativity Theory

- Einstein as schoolboy of 16: What would EM wave in a vacuum look like if one raced along it at  $c$ ? Oscillatory in space but stationary in time. **But Maxwell's equations have no such solutions in a vacuum!**
  - Why not? It must not be possible for any material body to move at  $c$ .
  - Why not? Because maybe light always travels at  $c$  no matter how fast one moves relative to the source of the light -- **Special theory of relativity**.
- Michelson-Morley: there is no aether (i.e., **no quintessence**).
- Dirac: marriage of quantum mechanics and special theory of relativity requires electrons to have spin  $1/2$  and anti-particles (positrons).
- Einstein: Newton must also be wrong about gravitation (action at a distance) as he was about absolute space and time. Maybe space and time are dynamical variables with stress-energy acting as a source of spacetime curvature (gravitation) -- **General theory of relativity**.
- Marriage of quantum mechanics and general relativity is difficult without adopting the drastic concept of extra spatial dimensions -- **String theory**. (Precursor: Kaluza-Klein theory)

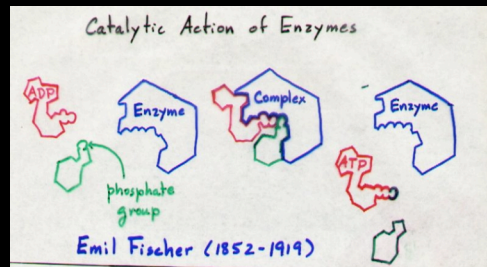
# Evolutionary Biology

- Darwin carries two books with him before boarding the *Beagle*:
  - Malthus: Essay on Population
  - Lyell: Principles of Geology
- On Galapagos Islands, find many varieties of tortoises and, especially, finches
- Surmises each variety had evolved from an original common form to adapt to local conditions of food sources on isolated islands: stout beaks to crack nuts or seeds, sharp beaks to drink nectar or peck for insects, etc.
- When environmental resources can no longer support a geometrically increasing population (Malthus), who will live and who will die? Darwin's answer: Natural selection.
- Need geologically long times (Lyell) for natural selection to work.

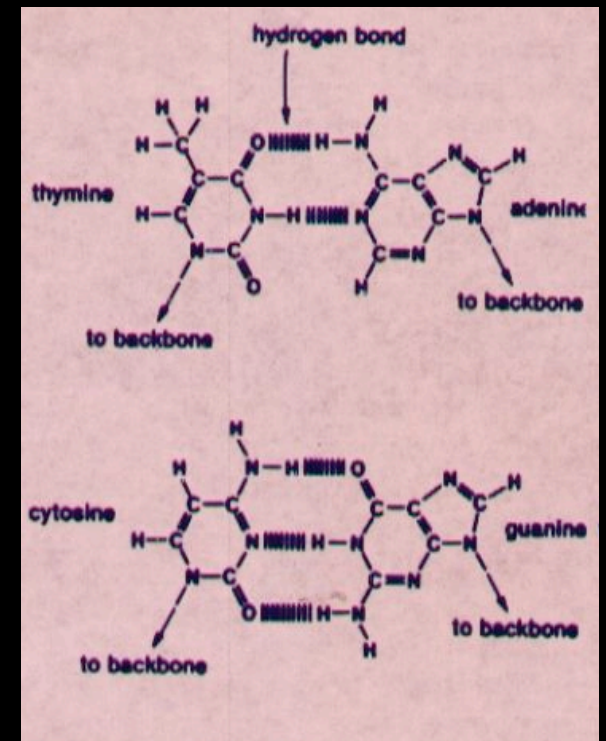


# Molecular Basis of Life

- Life characterized by growth (metabolism) and reproduction.
- Metabolic reactions often carried out by electrically neutral molecules -- only left-over short range forces -- need “**lock and key**” relationship to be effective (Fischer).

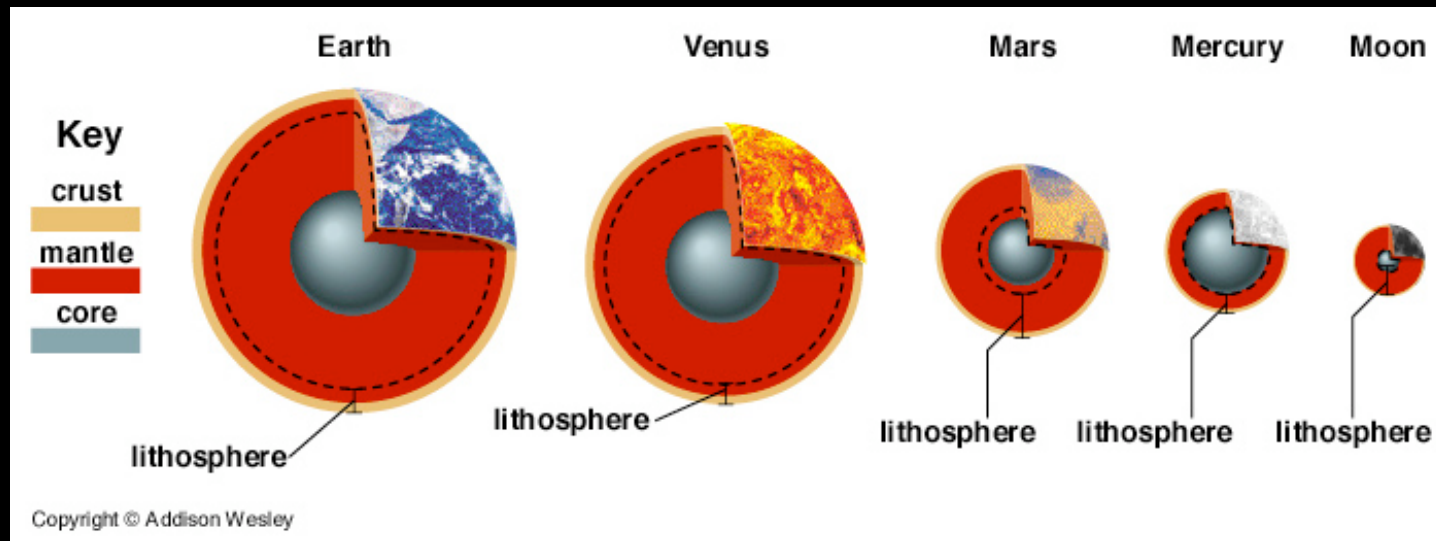


- One such force is the **hydrogen bond**, where H is attracted to an electronegative atom other than its immediate partner.
- Hydrogen bonds are key to the specific (Chargaff) base pairings: **A with T** and **G with C** at heart of Watson and Crick’s **double-helix model of DNA** that governs self-replication. **Biochemistry = chemistry of large molecules built from small ones.**



# Origin of Life in Inanimate World

- All lifeforms probably originated from a single primitive cell (Darwin).
- Earth at birth too hot (completely molten) to have supported life.



- Formation of protocell by chemical evolution of abiotic material to become first thing capable of growth and reproduction. Extension of idea of natural selection down to molecular level (Haldane & Oparin).
- No sharp line between living and non-living, between biology and chemistry. We are related not only to apes, trees, and bacteria, but to the air, water, and rocks of Earth.

# Summary

- We have made tremendous scientific progress since the earliest civilizations pondered what are the fundamental building blocks of the material world.
- Yet there are still many who cling to the old superstitious and mystical beliefs.
- The peoples of antiquity did get one thing right. They did not compartmentalize human knowledge into small pieces. Indeed, today's division into physics, chemistry, biology, astronomy, earth sciences, ... are imposed by human historical accident, not by nature.
- Because the great remaining questions are largely interdisciplinary and deal with complex systems, reform of the school curriculum away from narrow individual perspectives should be encouraged.