MATTER AND ATOMS
Philosophical Ideas on Matter

• Ancient Greeks discussed the “nature” of matter
  – Is there a fundamental “building block” of matter?
  – How many times can a leaf be torn in half? Infinity?
  – Are there different “types” of matter? (e.g. Oil vs. Water)

• Aristotle: Four fundamental “ingredients” of matter:
  – Earth (solid), Air (gas), Water (liquid), Fire (plasma)
  – Can be mixed in different combinations like a recipe

• Limited Technology → Limited Experiments
  – For thousands of years!
  – Until the 19th and 20th centuries
The Atomic Hypothesis

- Observed features of matter to be explained:
  - Exerts pushing, pulling, and friction forces
  - Absorbs and transmits heat, in some cases it combusts
  - Change of “phase”: freezing, melting, vaporizing

- Hypothesis: Energy can be captured in matter
  - As if it contained imaginary springs!
  - Compress / stretch the springs $\rightarrow$ forces
  - Break the springs $\rightarrow$ melting
  - But... what is at the ends of the “springs”?
  - A fundamental building block called an “atom”
Early Experiments on Matter

• "Scattering" experiments
  - Bombard matter with light and/or other bits of matter and detect what comes out

  - Information learned:

  - Confirmed hypothesis: matter consists of tiny atoms

  - Atoms have an even smaller center (called a nucleus) which carries a positive electric charge
Electrons, Orbits, and “Clouds”

- Matter is **usually** electrically neutral
  - But nucleus has **positive** electric charge
  - There must be **negative** charge to balance it out!

- The **electron** (e⁻)
  - Tiny particle with **very** small mass and **negative** charge
  - Orbits around the nucleus of the atom (**very** fast!)

- Electron “clouds”
  - High speed of e⁻ → impossible to “track” electron in its orbit around the nucleus
  - Orbit appears to be a “**cloud**” → e⁻ is everywhere at once
Atomic Structure

- **e⁻ cloud diameter** $\approx 10^{-10}$ meters
  - There are a billion billion billion atoms in a human body!

- **Nucleus diameter** $\approx 10^{-15}$ meters
  - 100,000 times smaller than the atom!
  - The atom is 99.9999999999999 % empty space!

- **Nucleus is relatively heavy**
  - Holds 99.9 % of the atom's mass
“Seeing” Atoms

• Close your eyes and shout
  – Sound waves reflect back from objects in front of you
  – Easy to detect a wall this way
  – Impossible to detect a fly this way
  – Size of detectable objects depends on wavelength of sound

• Using visible light → impossible to see anything smaller than $10^{-7}$ meters
  – We can never “see” an atom directly!!

• Electron microscope: Fire beams of $e^-$ at material
  – And detect what bounces back!
Electron Microscope Images
Inside The Nucleus

• Atomic nucleus is made up of smaller particles
  - Protons (positively charged) and neutrons (neutral)

The electric charge of a nucleus is determined by how many protons it contains

A nuclear reaction is a process which changes the number of protons or neutrons in a nucleus

Some nuclei are unstable and will decay on their own into smaller nuclei
The Elements

For matter to be electrically neutral:
- Negative charge of e\(^-\) balances nucleus' positive charge

Different nuclei can have different numbers of protons:
- And different numbers of e\(^-\) orbiting around them
- This causes very different behavior

Number of protons in a single nucleus:
Range: 1 → about 100
Elements and Isotopes

- **Chemistry**: # of protons → “element”
  - Each element has a specific # of protons in each nucleus

- **Example**: Oxygen → 8 protons in nucleus

- An element can have different numbers of neutrons
  - These are called “isotopes” of the same element

- **Example**: Carbon
  - “Carbon 12” → 6 neutrons; “Carbon 14” → 8 neutrons
Organizes the elements into “families” with similar behaviors

Classified based on “atomic number” (i.e. number of protons)
Molecules

When two atoms collide:

- Their nuclei can enter each other's e\(^{-}\) clouds
- If the conditions are right, one (or both) e\(^{-}\) clouds change their shape to enclose two (or more) nuclei
- The nuclei “share” the e\(^{-}\) cloud
- This is called a “chemical bond”
- The whole system is now called a molecule
Chemical Bonds and Energy

• Motivation for the atomic hypothesis:
  – Matter can store energy at the microscopic level
  – Acts as if there were tiny “springs” between atoms

• Chemical bonds explain this behavior
  – Nuclei have a preferred “equilibrium” separation distance
  – Squeezing or stretching the separation between nuclei causes an opposing force
  – Just like a spring!

• Energy can be stored in chemical bonds
  – It can also be released during chemical reactions
Antimatter

- Early 20th century theoretical physics
  - Seemed to predict the existence of “antiparticles”
  - Anti-protons, anti-neutrons, anti-electrons (positrons)
  - Just like regular particles with opposite electric charge

- Experiment: 1st positron observed in 1932
  - Today we can produce antimatter in particle accelerators
  - The first “anti-atom” was created in 1995
  - Has a negative nucleus with positron orbiting around it
Antimatter and Energy

● When a particle collides with its antiparticle
  – The two particles “annihilate” (disappear!)
  – Mass of two particles is converted into pure energy (light)

● Bad consequences
  – Antimatter is very difficult to create and store
  – Antimatter is very dangerous

● Good consequences
  – Could be an extremely efficient way to store energy
  – IF humans could control it! (Science fiction)
Matter and The Universe

- Where did the matter in the universe come from?
  - Physicists → particles were created as universe cooled and expanded after “The Big Bang”

- 1940's and 1950's → Theoretical calculations
  - Predicted the amount of “small” elements in the universe
  - Results match with observation → evidence for Big Bang

- What about “heavy” elements?
  - Produced inside stars by nuclear fusion
  - Including the atoms inside your body!
Dark Matter

• Physics → strong understanding of gravity
  – Can predict the motions of stars and galaxies

• Problem: Motions don't match up
  – The matter we can see is not enough to explain motions
  – Something else must be pulling on stars and galaxies
  – “Dark Matter” – exerts gravity but can't be seen
  – Still a mystery in physics! (About 25% of universe)