How Atoms Work, by Craig Freundenrich, PhD.

What is an Atom? The Legacy of Ancient Times Through the 19th Century

The modern view of an atom has come from many fields of chemistry and physics. The idea of an atom came from ancient Greek science/philosophy and from the results of 18th and 19th century chemistry:

- concept of the atom
- measurements of atomic mass
- repeating or periodic relationship between the elements

Concept of the Atom

From the ancient Greeks through today, we have pondered what ordinary matter is made of. To understand the problem, here is a simple demonstration from a book entitled "The Extraordinary Chemistry of Ordinary Things, 3rd Edition" by Carl H. Snyder:

1. Take a pile of paper clips (all of the same size and color).
2. Divide the pile into two equal piles.
3. Divide each of the smaller piles into two equal piles.
4. Repeat step 3 until you are down to a pile containing only one paper clip. That one paper clip still does the job of a paper clip (i.e., hold loose papers together).
5. Now, take a pair of scissors and cut that one paper clip in half. Can half of the paper clip do the same job as the single paper clip?

If you do the same thing with any element, you will reach an indivisible part that has the same properties of the element, like the single paper clip. This indivisible part is called an **atom**.
The idea of the atom was first devised by **Democritus** in 530 B.C. In 1808, an English school teacher and scientist named **John Dalton** proposed the modern atomic theory. Modern **atomic theory** simply states the following:

- **Every element is made of atoms** - piles of paper clips.
- **All atoms of any element are the same** - all the paper clips in the pile are the same size and color.
- **Atoms of different elements are different (size, properties)** - like different sizes and colors of paper clips.

- **Atoms of different elements can combine to form compounds** - you can link different sizes and colors of paper clips together to make new structures.
- In chemical reactions, **atoms are not made, destroyed, or changed** - no new paper clips appear, no paper clips get lost and no paper clips change from one size/color to another.
- In any compound, **the numbers and kinds of atoms remain the same** - the total number and types of paper clips that you start with are the same as when you finish.

Dalton's atomic theory formed the groundwork of chemistry at that time. Dalton envisioned atoms as tiny spheres with hooks on them. With these hooks, one atom could combine with another in definite proportions. But some elements could combine to make different compounds (e.g., hydrogen + oxygen could make water or hydrogen peroxide). So, he could not say anything about the numbers of each atom in the molecules of specific substances. Did water have one oxygen with one hydrogen or one oxygen with two hydrogens? This point was resolved when chemists figured out how to weigh atoms.

How Much Do Atoms Weigh?

The ability to weigh atoms came about by an observation from an Italian chemist named **Amadeo Avagadro**. Avagadro was working with gases (nitrogen, hydrogen, oxygen, chlorine) and noticed that when temperature and pressure was the same, these gases combined in definite volume ratios. For example:

- One liter of nitrogen combined with three liters of hydrogen to form ammonia (NH_3)
- One liter of hydrogen combined with one liter of chlorine to make hydrogen chloride (HCl)

Avagadro said that at the same temperature and pressure, equal volumes of the gases had the same number of molecules. So, by weighing the volumes of gases, he could determine the ratios of atomic masses. For example, a liter of oxygen weighed 16 times more than a liter of hydrogen, so an atom of oxygen must be 16 times the mass of an atom of hydrogen. Work of this type resulted in a relative mass scale for elements in which all of the elements related to carbon (chosen as the standard -12). Once the relative mass scale was made, later experiments were able to relate the mass in grams of a substance to the number of atoms and an atomic mass unit (amu) was found; **1 amu** or **Dalton** is equal to 1.66×10^{-24} grams.

At this time, chemists knew the atomic masses of elements and their chemical properties, and an astonishing phenomenon jumped out at them!

The Properties of Elements Showed a Repeating Pattern

At the time that atomic masses had been discovered, a Russian chemist named **Dimitri Mendeleev** was writing a textbook. For his book, he began to organize elements in terms of their properties by placing the elements and their newly discovered atomic masses in cards. He arranged the elements by increasing atomic mass and noticed that elements with similar properties appeared at regular intervals or **periods**. Mendeleev's table had two problems:

- There were some gaps in his "periodic table."
- When grouped by properties, most elements had increasing atomic masses, but some were out of order.

To explain the gaps, Mendeleev said that the gaps were due to undiscovered elements. In fact, his table successfully predicted the existence of gallium and germanium, which were discovered later. However, Mendeleev was never able to explain why some of the elements were out of order or why the elements should show this periodic behavior. This would have to wait until we knew about the structure of the atom.

In the next section, we will look at how we discovered the inside of the atom!

The Structure of the Atom: Early 20th Century Science

To know the structure of the atom, we must know the following:

- What are the parts of the atom?
- How are these parts arranged?

Near the end of the 19th century, the atom was thought to be nothing more than a tiny indivisible sphere (Dalton's view). However, a series of discoveries in the fields of chemistry, electricity and magnetism, radioactivity, and quantum mechanics in the late 19th and early 20th centuries changed all of that. Here is what these fields contributed:

- The parts of the atom:
  - **chemistry** and **electromagnetism** ---> **electron** (first subatomic particle)
  - **radioactivity** ---> **nucleus**
    - **proton**
    - **neutron**
- How the atom is arranged - **quantum mechanics puts it all together**:
  - **atomic spectra** ---> **Bohr model** of the atom
  - **wave-particle duality** ---> **Quantum model** of the atom

Chemistry and Electromagnetism: Discovering the Electron

In the late 19th century, chemists and physicists were studying the relationship between electricity and matter. They were placing high voltage electric currents through glass tubes filled with low-pressure gas (mercury, neon, xenon) much like neon lights. Electric current was carried from one electrode (**cathode**) through the gas to the other electrode (**anode**) by a beam called **cathode rays**. In 1897, a British physicist, **J. J. Thomson** did a series of experiments with the following results:

- He found that if the tube was placed within an electric or magnetic field, then the **cathode rays could be deflected or moved** (this is how the the cathode ray tube (CRT) on your television works).
- By applying an electric field alone, a magnetic field alone, or both in combination, **Thomson could measure the ratio of the electric charge to the mass of the cathode rays**.
- He found the **same charge to mass ratio of cathode rays was seen regardless of what material was inside the tube** or what the cathode was made of.

Thomson concluded the following:

- **Cathode rays were made of tiny, negatively charged particles**, which he called **electrons**.
- The **electrons had to come from inside the atoms** of the gas or metal electrode.
- Because the charge to mass ratio was the same for any substance, the **electrons were a basic part of all atoms**.
- Because the charge to mass ratio of the electron was very high, the **electron must be very small**.

Later, an American Physicist named Robert Milikan measured the electrical charge of an electron. With these two numbers (charge, charge to mass ratio), physicists calculated the mass of the electron as 9.10 x 10^{-28} grams. For comparison, a U.S. penny has a mass of 2.5 grams; so, 2.7 x 10^{27} or 2.7 billion billion billion electrons would weigh as much as a penny!
Two other conclusions came from the discovery of the electron:

- Because the electron was negatively charged and atoms are electrically neutral, **there must be a positive charge somewhere in the atom**.
- Because electrons are so much smaller than atoms, **there must be other, more massive particles in the atom**.

From these results, Thomson proposed a model of the atom that was like a watermelon. The red part was the positive charge and the seeds were the electrons.

Radioactivity: Discovering the Nucleus, the Proton and the Neutron

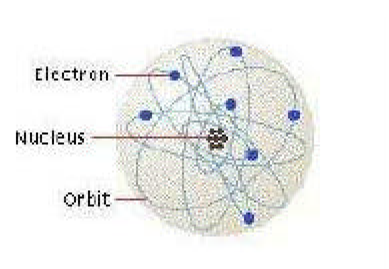
About the same time as Thomson's experiments with cathode rays, physicists such as by Henri Becquerel, Marie Curie, Pierre Curie, and Ernest Rutherford were studying radioactivity. Radioactivity was characterized by three types of emitted rays (see How Radioactivity Works for details):

- **Alpha particles** - positively charged and massive. Ernest Rutherford showed that these particles were the nucleus of a helium atom.
- **Beta particles** - negatively charged and light (later shown to be electrons).
- **Gamma rays** - neutrally charged and no mass (i.e., energy).

The experiment from radioactivity that contributed most to our knowledge of the structure of the atom was done by Rutherford and his colleagues. Rutherford bombarded a thin foil of gold with a beam of alpha particles and looked at the beams on a fluorescent screen, he noticed the following:

- Most of the particles went straight through the foil and struck the screen.
- Some (0.1 percent) were deflected or scattered in front (at various angles) of the foil, while others were scattered behind the foil.

Rutherford concluded that the **gold atoms were mostly empty space**, which allowed most of the alpha particles through. However, some **small region of the atom must have been dense** enough to deflect or scatter the alpha particle. He called this dense region **the nucleus** (see The Rutherford Experiment for an excellent Java simulation of this important experiment!); the nucleus comprised most of the mass of the atom. Later, when Rutherford bombarded nitrogen with alpha particles, a positively charged particle that was lighter than the alpha particle was emitted. He called these particles **protons** and realized that they were a fundamental particle in the nucleus. Protons have a mass of 1.673×10^{-24} grams, about 1,835 times larger than an electron!
However, protons could not be the only particle in the nucleus because the number of protons in any given element (determined by the electrical charge) was less than the weight of the nucleus. Therefore, a third, neutrally charged particle must exist! It was **James Chadwick**, a British physicist and co-worker of Rutherford, who discovered the third subatomic particle, the **neutron**. Chadwick bombarded beryllium foil with alpha particles and noticed a neutral radiation coming out. This neutral radiation could in turn knock protons out of the nuclei of other substances. Chadwick concluded that this radiation was a stream of neutrally charged particles with about the same mass as a proton; the neutron has a mass of 1.675×10^{-24} grams.
Now that the parts of the atom were known, how were they arranged to make an atom? Rutherford's gold foil experiment indicated that the nucleus was in the center of the atom and that the atom was mostly empty space. So, he envisioned the atom as the positively charged nucleus in the center with the negatively charged electrons circling around it much like a planet with moons. Although he had no



Rutherford's view of the atom

evidence that the electrons circled the nucleus, his model seemed reasonable; however, it presented a problem. As the electrons moved in a circle, they would lose energy and give off light. The loss of energy would slow the electrons down. Like any satellite, the slowing electrons would fall into the nucleus. In fact, it was calculated that a Rutherford atom would last only billionths of a second before collapsing! Something was missing!