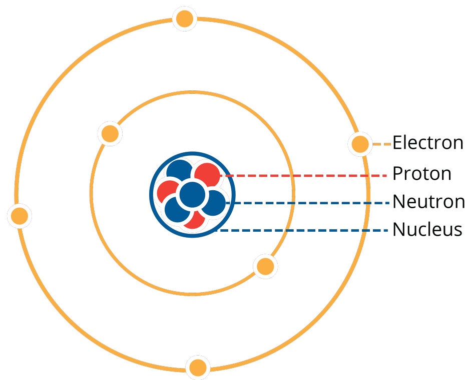
Chapter 1

Matter and Energy

All things (including the air around you) are made of atoms. Atoms are very tiny – there are more atoms in a drop of water than there are drops of water in all the oceans.

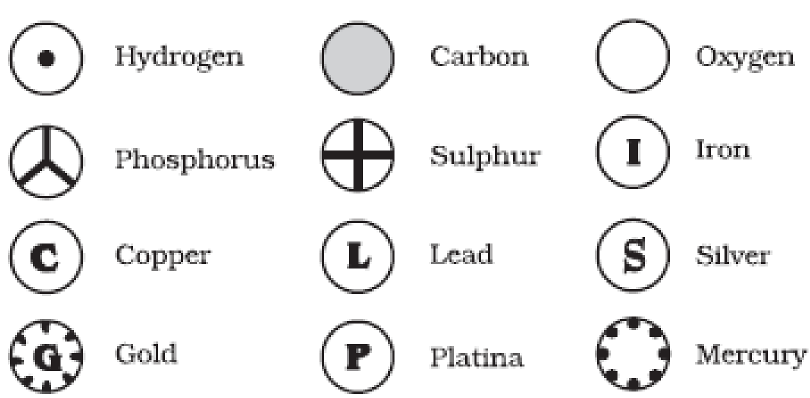
Every atom has a nucleus that contains protons and neutrons. Orbiting around the nucleus is a cloud of electrons. However, the mass of the atom comes mainly from the protons and neutrons, since they are about 2000 times as massive as an electron.



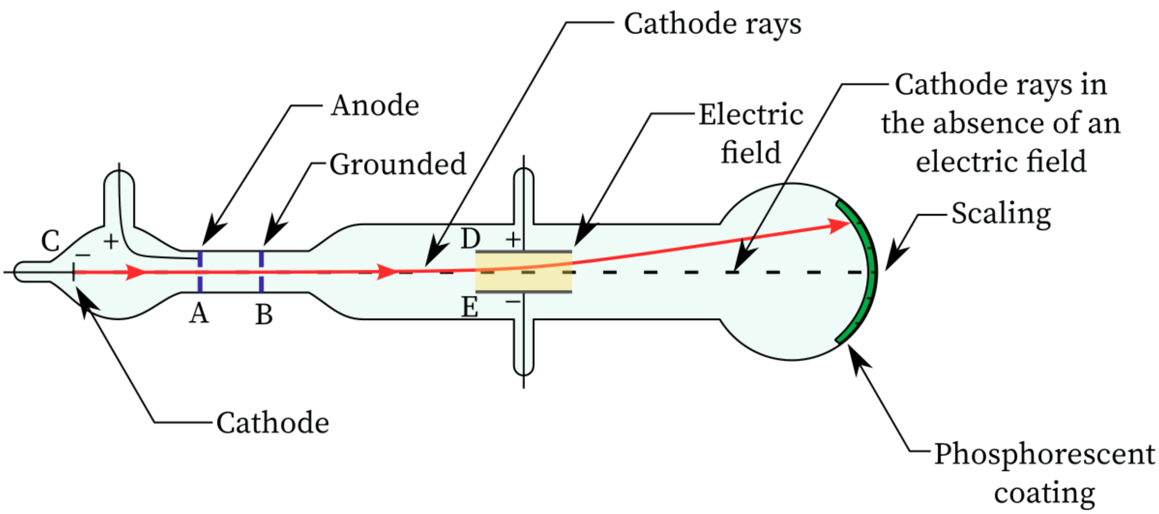
1.0.1 Models of the Atom

Over the history of science, there have been many ideas about the structure of atoms. This history is a good example of how science develops: how unexpected results drive scientists to update their models, moving us closer and closer to a true model of the atom.

During his investigations into the behavior of gases, John Dalton (lived 1766-1844) noted that different elements combine in strict ratios. For example, he noted that nitrogen and oxygen combine in a 1:1 and 1:2 fashion, but no ratio in between.

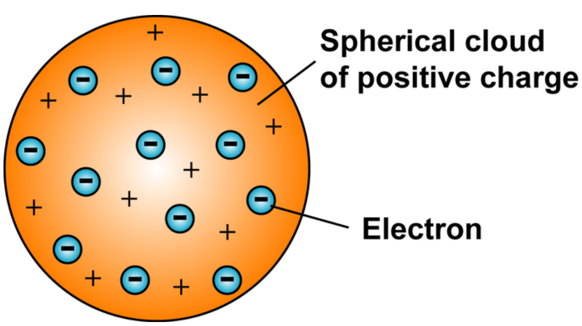


This first model of the atom is very rudimentary: each element is a unique atom, and atoms cannot be subdivided. The atom is modeled as one large, solid, uniform, and neutral object. Some scientists, including the British physicist J.J. Thomson (1856-1940) thought that larger atoms (like lead) might be able to be broken down into smaller atoms (like hydrogen). Thomson had been experimenting with cathode ray tubes and discovered that the these rays traveled much faster than thought possible for a particle the size of a hydrogen atom.



This, combined with the observation that cathode rays could be deflected by electrical charge, led him to postulate two things:

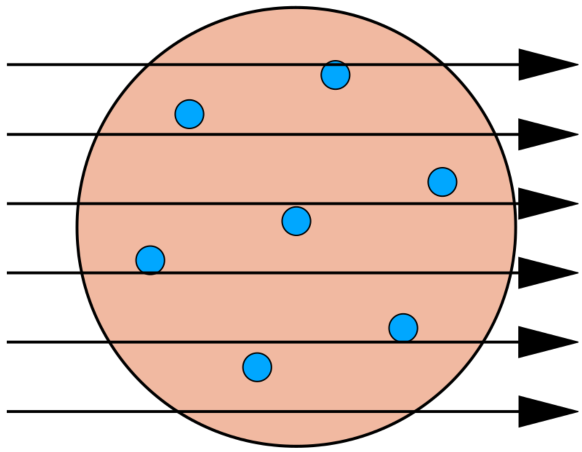
1. Atoms can be broken into parts much smaller than a hydrogen atom
2. Whatever part of atoms that composes cathode rays is negatively charged



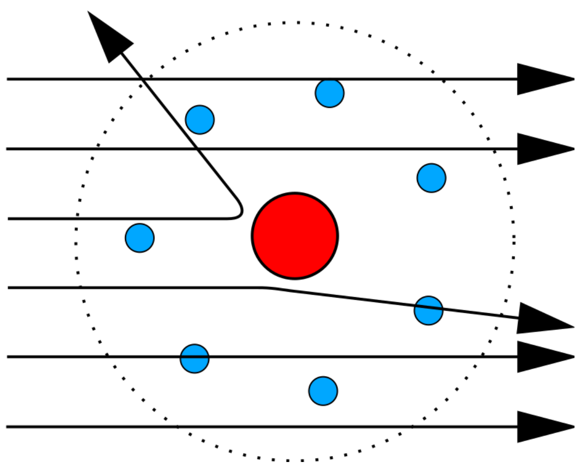
The presence of "corpuscules" (as Thomson called them) that were negatively charged and smaller than a hydrogen atom contradicted Dalton's theory. Thomson updated his model of the atom: adding small, negatively charged subatomic particles (now called electrons) that were embedded in a larger, uniform, positive sphere. Suddenly, the atom went from neutral and indivisible to made of different types of charged particles.

At the time, physicists were very interested in the mass-to-charge ratios of various particles (Thomson was able to determine the mass-to-charge ratio of the electron during his experiments), and Ernest Rutherford (1871-1937) was investigating the mass-to-charge ratio of alpha particles. (Alpha particles, we now know, are composed of two protons and two neutrons. They are emitted from certain radioactive elements, including uranium.)

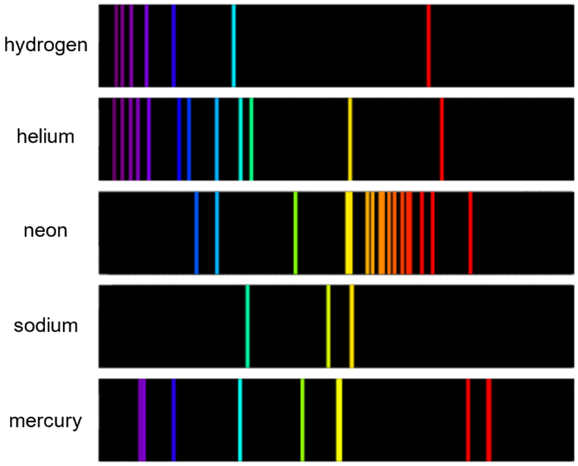
Rutherford needed consistent scattering of alpha particles in order to collect the data necessary to determine the particles' mass-to-charge ratio. He achieved this by bombarding extremely thin gold foil with alpha particles. The Thomson model of the atom would predict that particles would be slightly deflected, as illustrated below:



However, a small but significant portion of the alpha particles were deflected over 90 deg! To explain this, Rutherford modeled the atom as mostly empty space with a small, dense, positive center (we now call this the nucleus).



At the same time that Rutherford was conducting his gold foil experiments, Niels Bohr was investigating the hydrogen line series. FIXME insert figure of hydrogen lines. When hydrogen is electrically excited, it emits specific bands of color, not a complete spectrum. Every element has a unique emission spectrum.



Bohr, upon learning of Rutherford's experiments, embraced the Rutherford model over the Thomson model and postulated that electrons existed only at discrete distances from the nucleus. When electrified, a hydrogen atom's electrons would gain energy and "jump" up one or more levels. The electron would be unstable in this energized state, and eventually "fall" back to the lowest energy level, emitting the extra energy as light. different colors of light have different energies: violet being the most energetic and red being the least. The different levels had differing amounts of energy between them, resulting in only those colors corresponding to the exact energy step between levels being emitted. This model, called the Bohr model or the Rutherford-Bohr model, expands on the Rutherford model by limiting electrons to specific distances from the nucleus, and is often compared to a model of the solar system FIXME add image of Bohr model.

This is likely the model you are most familiar with seeing, and it is the one we will use often in this text.

The previous graphic is slightly untrue. While it is a convenient model for thinking about atoms, in reality electrons don't neatly orbit the nucleus. Scientists don't know exactly where an electron will be in relation to the nucleus, but they do know where it's most likely to be. They use a cloud that is thicker in the center but fades out at the edges to represent an electron's position.

We classify atoms by the numbers of protons they have. An atom with one proton is a hydrogen atom, an atom with two protons is a helium atom, and so forth (refer to periodic table on pg..). We say that hydrogen and helium are *elements* because the classification of elements is based on proton number. And we give each element an atomic symbol. Hydrogen gets H. Helium gets He Oxygen gets O. Carbon gets C, etc.

Often two hydrogen atoms will attach to an oxygen atom. The result is a water molecule. Why do they cluster together? because they share electrons in their clouds.

A molecule is described by the elements it contains. Water is H_2O because it has two hydrogen atoms and one oxygen atom.

There are many kinds of molecules. You know a few:

- Table salt is crystals made of $NaCl$ molecules: a sodium atom attached to a chlorine atom.
- Baking soda, or sodium bicarbonate, is $NaHCO_3$.
- Vinegar is a solution including acetic acid (CH_3COOH).
- O_2 is the oxygen molecules that you breathe out of the air (Air, a blend of gases, is mostly N_2.).

1.0.2 Reading the Periodic Table

The Periodic Table organizes what we know about the structure of different elements. Each element has its own block or tile on the Periodic Table, and the information on the tile tells us about the structure of that atom. Take a look at the tile for carbon: (FIXME add carbon tile)

There are two key numbers: the atomic number and the average atomic mass. The atomic number tells how many protons there are in the nucleus of any atom of carbon. All carbon atoms have 6 protons. The other number is the average atomic mass. Have you heard of carbon-14 dating? The phrase "carbon-14" refers to a rare type of carbon that decays radioactively. By seeing how much carbon-14 has decayed, scientists can estimate the age of organic materials, such as bone or ash. Carbon-14 is a radioactive isotope (or version) of carbon. The 14 refers to the mass number - the total amount of protons AND neutrons in the nucleus. The most common isotope of carbon is carbon-12, with 6 protons and 6 neutrons in its nucleus. Carbon-14, on the other hand, has 8 neutrons, which makes the nucleus unstable, leading to radioactive decay. FIXME tow models comparing the structure of C-12 and C-14. FIXME resource: atom builder PhET. The average atomic mass is the weighted average of all the carbon atoms in existence. Since the vast majority of carbon is carbon-12, the average atomic mass is very close to 12. You cannot determine the mass number of an individual atom from the periodic table: it only tells you the average of all the isotopes. However, especially for light atoms (atoms in the first two rows of the periodic table), you can usually determine the mass number of the most common isotope by rounding the average atomic mass to the nearest whole number.

1.1 Chemical Reaction

Sometimes two hydrogen atoms form a molecule (H_2). Sometimes two oxygen atoms form a molecule (O_2). If you mix these together and light a match, they will rearrange themselves into water molecules. This is called a *chemical reaction*. In any chemical reaction, the atoms are rearranged into new molecules.

Some chemical reactions (like the burning of hydrogen gas described above) are *exothermic* – that is, they give off energy. Burning hydrogen gas happens quickly and gives off a lot of energy. If you have enough, it will make quite an explosion.

Other chemical reactions are *endothermic* – that is they consume energy. Photosynthesis, the process by which plants consume energy from the sun to make sugar from CO_2 and H_2O requires an endothermic chemical reaction.

1.2 Mass and Acceleration

Each atom has a mass, so everything that is made up of atoms has a mass, which is pretty much everything. We measure mass in grams. A paper clip is about 1 gram of steel. An adult human can weigh 70,000 grams, so for larger things we often talk about kilograms. A kilogram is 1000 grams.

The first interesting thing about mass is that objects with more mass require more force to accelerate. For example, pushing a bicycle so that it accelerates from a standstill to jogging speed in 2 seconds requires a lot less force than pushing a train so that it accelerates at the same rate.

Newton's Second Law of Motion

The force necessary to accelerate an object of mass m is given by:

$$F = ma$$

That is the force is equal to the mass times the acceleration.

What are the units here? We already know that mass is measured in kilograms. We can measure velocity in meters per second, but that is different from acceleration. Acceleration is the rate of change in velocity. So if we want to go from 0 to 5 meters per second (that's jogging speed) in two seconds. That is a change in velocity of 2.5 meters per second every second. We would say this acceleration is $2.5m/s^2$.

What about measuring force? Newton decided to name the unit after himself: The force necessary to accelerate one kilogram at 1m/s^2 is known as *a newton*. It is often denoted by the symbol N

Exercise 1 Acceleration

Working Space

While driving a bulldozer, you come across a train car (with no brakes and no locomotive) on a track in the middle of a city. The train car has a label telling you that it weighs 2,400 kg. There is a bomb welded to the interior of the train car, and the timer tells you that you can safely push the train car for 120 seconds. To get the train car to where it can explode safely, you need to accelerate it to 20 meters per second. Fortunately, the track is level and the train car's wheels have almost no rolling resistance.

With what force, in newtons, do you need to push the train for those 120 seconds?

Answer on Page 11

1.3 Mass and Gravity

The second interesting thing about mass is that masses are attracted to each other by the force we call *gravity*. The force of attraction between two objects is proportional to the product of their masses, and inversely proportional to their distance squared. Meaning as objects get farther away, the force decreases. That is why you are more attracted to the earth than you are to distant stars, which have much more mass than the earth.

Newton's Law of Universal Gravitation

Two masses (m_1 and m_2) that are a distance of r from each other, are attracted toward each other with a force of magnitude:

$$F = G\frac{m_1 m_2}{r^2}$$

where G is the universal gravitational constant. If you measure the mass in kilograms and the distance in meters. G is about 6.674×10^{-11}. That will get you the force of the attraction in newtons.

Exercise 2 Gravity

Working Space

The earth's mass is about 6×10^{24} kilograms.

Your spacecraft's mass is 6,800 kilograms.

Your spacecraft is also about 100,000 km from the center of the earth. (For reference, the moon is about 400,000 km from the center of the earth.)

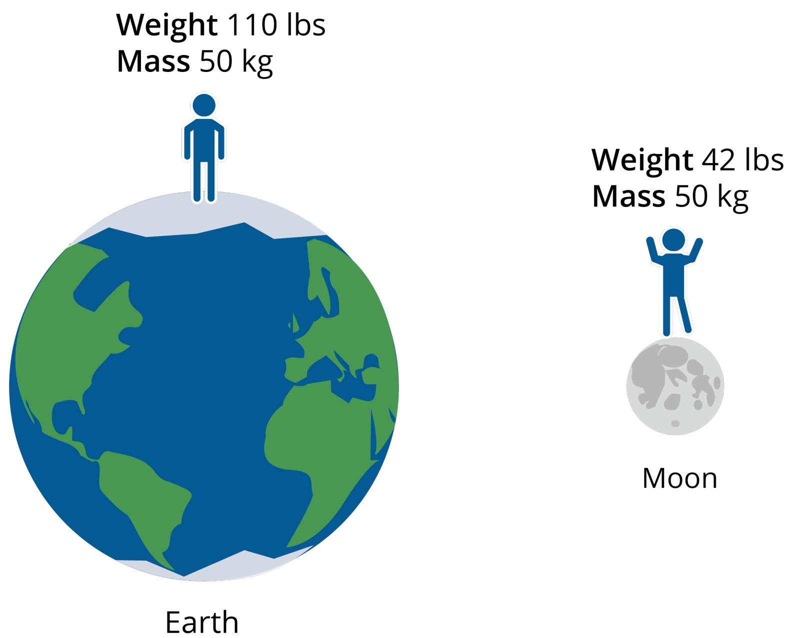
What is the force of gravity that is pulling your spacecraft and the earth toward each other?

Answer on Page 11

1.4 Mass and Weight

Gravity pulls on things proportional to their mass, so we often ignore the difference between mass and weight.

The weight of an object is the force due to the object's mass and gravity. When we say, "This potato weighs 1 pound," we actually mean "This potato weighs 1 pound on earth." That same potato would weigh about one-fifth of a pound on the moon.



But that potato has a mass of 0.45 kg anywhere in the universe.

FIXME Global layout note: Let's discuss adding Title's and Captions to all graphics.

For example:
TITLE: Mass versus Weight
CAPTION: Human Earth weight: 150lbs / Moon weight:??lbs
Potato Earth weight: .25lbs / Moon weight: ??lbs

FIXME: Allison thinks it would be funny if the person in the graphic were holding a potato and we also added the weight and mass of the potato to the caption. No worries if this type of edit isn't in the budget!

FIXME: What are your thoughts about using the metric system consistently – in which case we'll replace pounds here with kilos. Max notes: we should explicitly use kilos for mass and pounds or newtons for weight. Kilos are a scalar measure of the amount of matter and pounds are a vector force of gravity on a particular piece of matter. Many students struggle to differentiate between mass and weight at a theoretical level due to casual comparison between pounds and kilos.

Appendix A

Answers to Exercises

Answer to Exercise 1 (on page 7)

To get the train to 20 meters per second in 120 seconds, you must accelerate it with a constant rate of $\frac{1}{6}m/s^2$. You remember that $F = ma$, so $F = 2400 \times \frac{1}{6}$. Thus, you will push the train with a force of 400 newtons for the 120 seconds before the bomb goes off.

Answer to Exercise 2 (on page 8)

$$F = G\frac{m_1 m_2}{r^2} = (6.674 \times 10^{-11})\frac{(6.8^3)(6 \times 10^{24})}{(10^5)^2} = 6.1 \times 10^6$$

About 6 million newtons.

Index