History of Atomic Theory Study Guide

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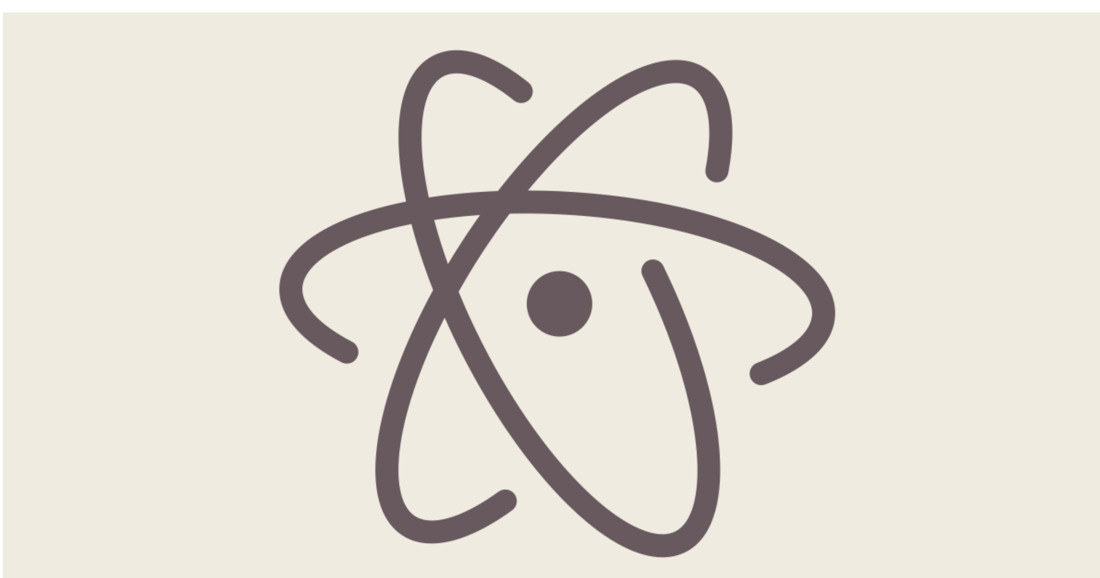
Discover the ideas that led to our current understanding of the structure of the atom. This journey begins well over 2000 years ago in Asia with categories of matter and continues through the Dark Ages where the quest for riches and everlasting life was sought through alchemy. These early concepts and accidental discoveries are the beginning of modern science and our current understanding of the minute particles that are the foundation of all matter.

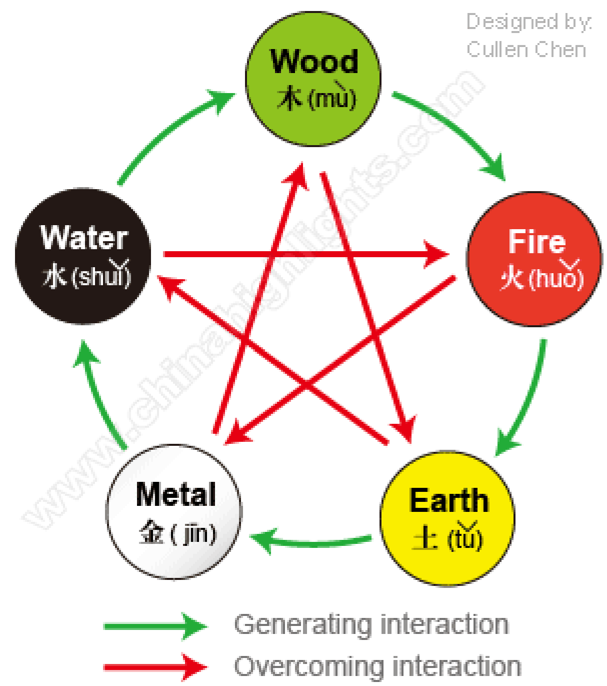


Early Concepts About Matter

Five Element Theory

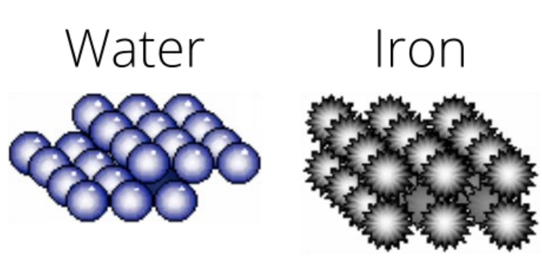
Some of the earliest recorded ideas about matter come from China and India. Philosophers developed five categories of matter: fire, water, earth, metal and wood. This system did not include the idea of atoms but we can see an attempt to differentiate matter into categories. In chemistry we classify matter based on phases (gas, liquid and solid) or based on the atomic make-up (mixture, pure substance or element).

The Five element theory is still alive and many alternative therapies connect to it.



Democritus gives atoms the name 'Atomos'

Democritus lived in Greece in 4th century BC. He developed a theory of matter based on 'atomos' which he described as tiny indivisible particles. His theory was that the atoms that made different materials were physically different from one another such as in the images below. Other philosophers of that time that that subscribed to the idea of atoms include Leucippus and Lucretius. Lucretius wrote a poem which has been translated into English called 'On the Nature of Things' which includes the idea of atoms. Even though many philosophers subscribed to the idea of atoms, these views were not widely accepted until the 16th century.



Why do you think the idea of atoms took so long to become the dominant theory? You may want to use other sources such as the link provided below to gain more information to answer this question.

https://courses.lumenlearning.com/cheminter/chapter/democritus-idea-of-the-atom/#:~:text=Democritus.&text=Aristotle%

The Email Lab

It is difficult for us to imagine how challenging it would have been to come up with the idea of the atom since this concept is ubiquitous in our education, but we can observe other ways of trying to connect pieces of information or develop a story with limited information. Read four emails from the email lab in the appendix and create a story or two of how they fit together. Consider the details of the emails such as dates, locations, names etc. Next choose two more emails from the appendix and consider if they fit with any of the stories that you have proposed. Keep adding emails and adjusting your story.

2000 Years of Alchemy: Failed Attempts to Create Gold

Alchemy can be described as a pseudoscience or medieval chemistry that was predominantly interested in turning easily available metals into gold and finding universal cures. Through trial and error, alchemists discovered elements such as mercury, sulphur and antimony.

An alchemist named Hennig Brand of the 17th century, accidently discovered phosphorus while trying to create gold. He thought the golden colour of urine indicated that urine contained gold so he collected large amounts of urine and boiled it down. (Imagine how unpleasant this would have smelled!) Hennig failed to find gold but he discovered something that was new to world of alchemy and he named it 'phosphorus'. He kept it secret for six years before sharing his discovery.

There were many alchemists in this time period that were doing their own experiments to find gold and/or cures to people's ailments. The number of failed experiments may have been huge but most of these weren't recorded. There may have been many other successes similar to Hennig's but alchemists were very secretive because they did not want to share their knowledge with their competitors. Hennig's failure to find gold has been recorded because he eventually shared his discovery and his discovery of phosphorus is important and relevant to modern society.

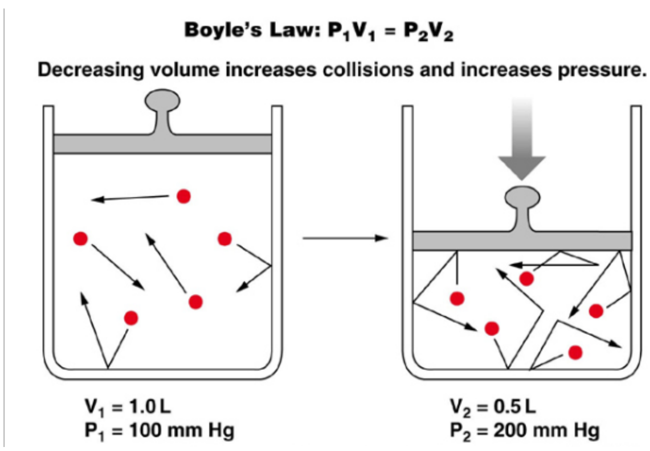
From Alchemy to Chemistry

Contributions from alchemy include metalworking, ceramics, dyes, and extracts. Although it brought many valuable discoveries the practice was losing favor in the 17th century to chemistry. Chemistry is detached from spiritual beliefs and uses a precise and empirical framework based on the scientific method.

Robert Boyle (1627—1691) is often stated as being the father of chemistry. He was born into a very wealthy British Anglican family, had a studious nature and was well-educated. Since he was well-educated he had access to philosophical writing from ancient times and more recent. He believed in a form of atomism called corpuscularism. Corpuscularism claims that everything is made of minute particles of a single universal matter.

Boyle made many important contributions to theology and philosophy. Some of his most important contributions to chemistry include:

* experiment on the properties of air, discovering that air has mass and is a mixture
* Wrote 'The Sceptical Chymist', a writing that promoted the idea that matter was made of minute particles and presented methods of chemical analysis.
* Discovered the relationship between air pressure and volume, known as 'Boyle's Law'



Research Robert Boyle and answer the following questions:

1. Who were the scientists and philosophers that he conversed with, learned from and shared his ideas with?
2. What other discoveries were being at this time related to chemistry that would have influenced Boyle?

A Tale of Two Scientists

No two scientists are alike. They differ in their personalities, influences and approaches to scientific experimentation. An example of two scientists that are starkly different and yet both made important contributions to the advancement of scientific knowledge are Antoine Lavoisier and Joseph Priestly.

Joseph Priestly (1733—1804) lived in England until 1794 where he worked as a minister. He was keenly interested in science and experimented with electricity and gases. He believed that the accumulation of facts was more important for scientific progress than the insights of a few great thinkers. He has been described as being a maverick for his independent and unorthodox views and approaches to experimentation. His contributions to chemistry include the relationship between electricity and chemical change and the discovery of oxygen.

Antoine Lavoisier (1743—1794) lived in France and worked as a tax collector. He was very interested in scientific experimentation and his wealth provided him the ability to design and build expensive apparatus and pay talented researchers to work in his lab. His experiments were largely focussed on quantitative analysis. Through quantitative analysis he established the law of conservation of mass and determined that combustion and respiration are caused by chemical reactions.

The two men met in 1774 and Priestly shared information on his experiments with air. Lavoisier repeated Priestly's experiment and through the process discovered and named the element oxygen.

The documentary 'The Mystery of Matter: Out of Thin Air' provides a charming portrayal of these two scientists. The documentary is available on youtube through the following link:

https://www.youtube.com/watch?v=z3Gt5IOjAuc

Antoine Lavoisier is often pictured with his young wife, Marie Anne Paulze. Marie was known to be highly intelligent and assisted Antoine in his scientific experiments.

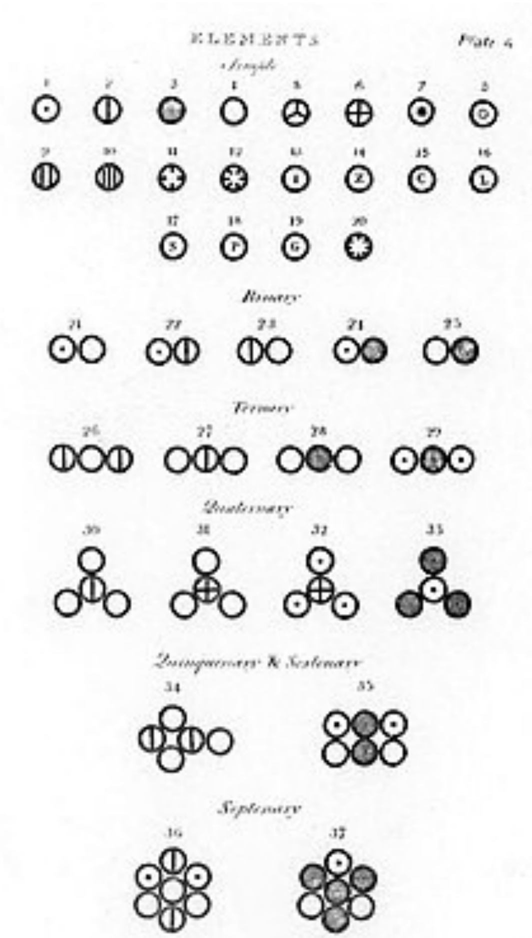
The Modern Atomic Theory

In 1808, John Dalton published the first complete attempt to describe all matter through the lens of atoms. It was called 'A New System of Chemical Philosophy' and included the following four statements:

1. Each element is made up of tiny particles called atoms.
2. The atoms of a given element are identical; the atoms of different elements are different in some fundamental ways.
3. Chemical compounds are formed when atoms combine with each other. A given compound always has the same relative numbers and types of atoms.
4. Chemical reactions involve reorganization of the atoms—changes in the way they are bound together. The atoms themselves are not changed in a chemical reaction.

The theory about matter that Dalton put forth is mostly consistent with how we understand matter today. The theory builds on the principles laid out by other chemical scientists of the time such as Cavendish, Proust and Lavoisier as well as physical scientists such as Newton. What is remarkable about Dalton's Theory is that it goes beyond what could be deduced from experimental evidence of the time and it holds true today. Dalton had abolished the idea that was held for thousands of years that atoms of all kinds of matter are alike and proposed that atoms of different elements have different sizes and mass.

Acceptance of the atomic theory was slow but he was recognized in his lifetime. He is considered to be one of science's great thinkers and differs from the style and approaches of Joseph Priestly and Antoine Lavoisier.



This list of elements was created by John Dalton and was included in 1808.

He attempted to determine the masses and some combinations of elements that formed compounds

What parts of Dalton's theory do not agree with our current understanding of atoms and compounds?

Roles, Expectations and Constraints

Throughout history we can find examples of people that moved outside the roles and expectations that society had for them. A man born into a wealthy family in the 17th century, for example, had different opportunities and limits than a man born into a working class family. For women, the roles and constraints were more limiting than for men. Women had less access to education, fewer options for living independently and less political power than men. Despite these constraints, some women were able to move outside of their expected roles and make great contributions to science.

Choose one or more of the following female scientists to research and answer the question 'What factors and influences were important for her to overcome the constraints on women of her time and place?'

Marie Curie (1867—1934) was a chemist who conducted pioneering research on radioactivity.

Lise Meitner (1878—1968) was a physicist who made important discoveries in nuclear fission.

Mary Sommerville (1780—1872) was a science writer and did original research on sunlight and its magnetizing effects

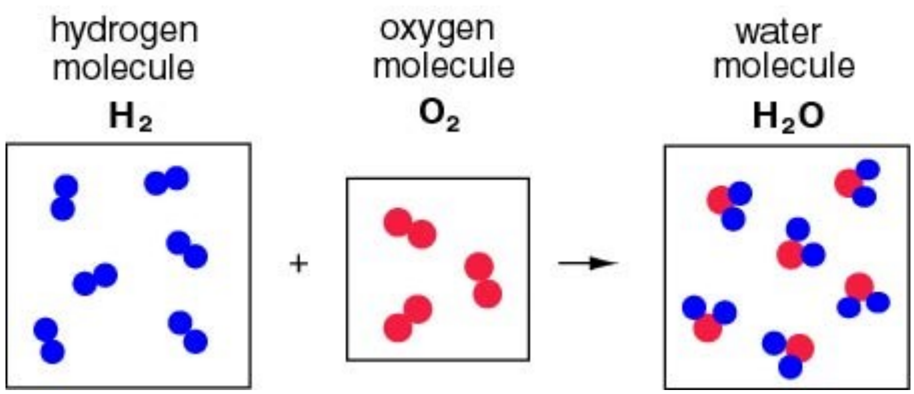
Ada Lovelace (1815—1852) has been called 'the first computer programmer' and invented the first algorithm.

Confusion Reigns Over Atomic Masses and Compounds

In the early 19th century French chemist Joseph Gay-Lussac (1778—1850) was performing experiments that utilized the relationship between temperature, pressure and volumes of gases. For example, he found that 2 volumes of hydrogen react with 1 volume of oxygen to form 1 volume of gaseous water. He also recorded other examples of reactions of gases. An Italian chemist named Amedeo Avogadro (1776—1856) interpreted Gay-Lussac's results and made the following hypothesis:

'At the same temperature and pressure, equal volumes of gases contain the same number of particles'

Based on this hypothesis, the following relationship would be true:



This representation shows the volume of the water is the same as the volume of the hydrogen gas and the number of particles of hydrogen are the same as the number of particles of gaseous water. This hypothesis was not accepted by most chemists at the time because of a belief that only atoms of different elements could attract one another and therefore, diatomic molecules such as the hydrogen and oxygen molecules could not exist. Avogadro died before his hypothesis was accepted

Many scientists were measuring masses of elements and compounds during the first half of the 19th century. However, there was no consensus about the interpretations of these measurements and many different tables of atomic masses were proposed. This confusion was cleared up by Italian chemist, Stanislao Cannizzaro (1826—1910). Cannizzaro believed that Avogadro's hypothesis was correct. He proceeded to collect data on relative masses of elements and compounds. He collected such large quantities of data and reported consistent results that eventually the scientific community came to agree that his interpretations made sense. His work led to the approximate values of the atomic masses.

Today, Avogadro is recognized with the number 6.02×10^{23} It is called Avogadro's number and it represents the number of atoms or molecules in a mole of substance.

The Gas Laws

Many of the early experiments that allowed scientists to better understand atoms and chemical reactions were done with gases. The PhET simulation linked here, called 'Gases Intro' is great tool to experiment with to learn the relationships between gas volume, pressure and temperature.

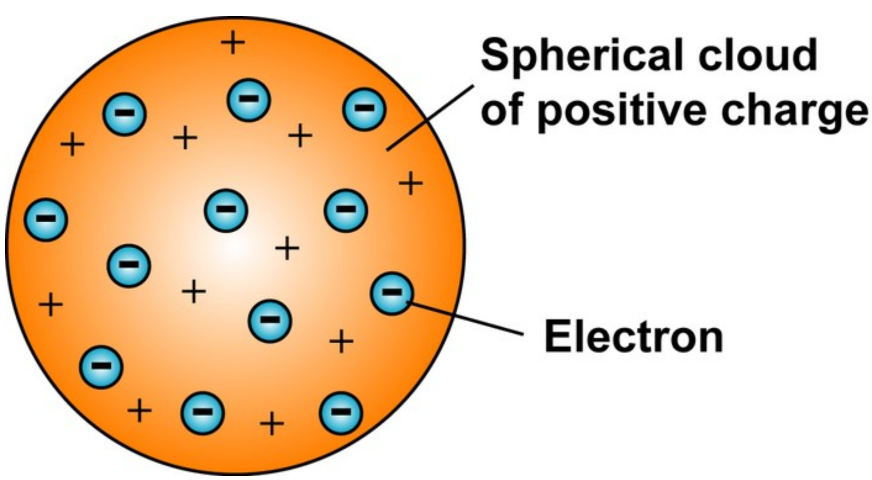
https://phet.colorado.edu/en/simulation/gases-intro

Subatomic Particle is Discovered

Electricity had been discovered by Benjamin Franklin in 1750 and he proposed that an electrical current consisted of a stream of extremely small particles but it wasn't until the late 19th century that the small particles were named electrons. J.J. Thomson (1856–1940) was experimenting with a cathode ray tube. The technology behind the cathode ray tube had been around for over 100 years, it consisted of an electrical machine and an air pump. Many inventions came from the combination of these two technologies including flourescent light bulbs and TV picture tubes but Thomson combined them to discover the electron. He ran an electrical current through a vacuum chamber and deflected the current with a small magnet. Go to the link on the Physics Aviary Website provided here to play with a simulation of the cathode ray tube.

https://www.thephysicsaviary.com/Physics/Programs/Labs/ThompsonetomLab/index.html

Thomson's genius was in drawing profound conclusions from simple observations. From the cathode ray tube experiment he reasoned that electrons were produced from the metal electrodes therefore all atoms must contain electrons. Also, since atoms were known to be electrically neutral, he thought they must also contain a positive charge. The plum pudding model of the atom was born.



Plum pudding was a popular English dessert that included raisins in a pudding mixture. Thomson's model of the atom had electrons, like raisins, in a positively charged cloud, like the pudding. Sometimes this is referred to a blueberry muffin model since this is more relatable today than plum pudding.

Changing the Concept of the Atom's Structure

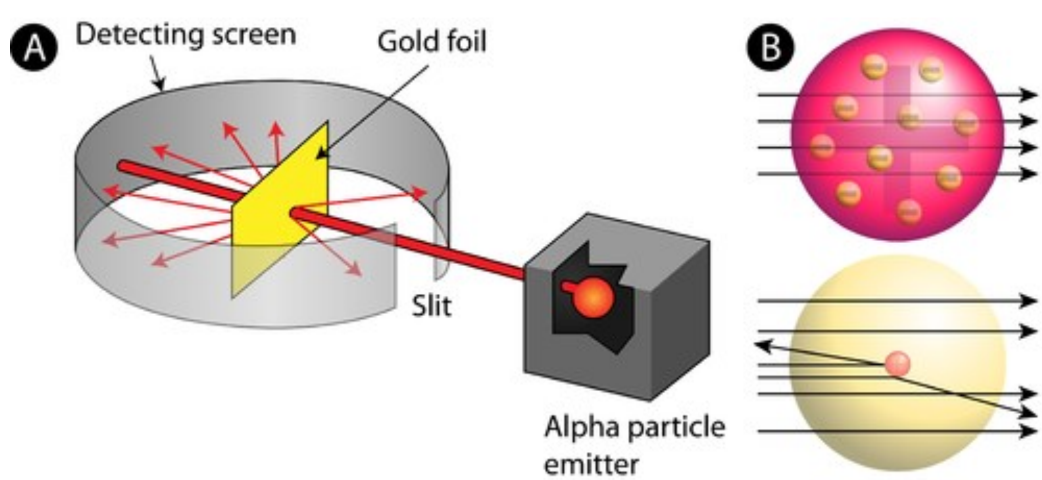
Ernest Rutherford (1871—1937) was a junior assistant in Thomson's lab when Thomson discovered the electron. Despite being directly influenced by Thomson and the exciting work on discovering subatomic particles, Rutherford's research interest was stronger in radioactivity. Radioactivity had been recently discovered in France and was being researched by Marie Curie as well as many other scientists. Three types of radioactive emissions had been identified at this time: gamma rays, beta particles and alpha particles. The alpha particle proved to be crucial in Rutherford's research. Alpha particles consist of two protons and two neutrons bound together creating a positively charged particle. However, in the early 20th century all that was known about them is that they were positively charged and had a mass about 7300 times the mass of an electron. For a more in depth look at alpha particles, try this simulation from PhET:

https://phet.colorado.edu/en/simulation/legacy/alpha-decay

Rutherford was studying the scatter patterns of alpha partilces from uranium sources. He found that most alpha particles travel straight with some minor deflection after passing through thin targets. When he moved the detector next to the source of the beam of particles, he was astonished to see the some particles reflected back. He noted that it was as surprising as shooting a cannonball at a piece of paper and seeing the cannonball bounce back. These results did not fit with Thomson's plum pudding model of the atom, which would have resulted in the alpha particles passing straight through the gold foil. Rutherford spent nearly a year contemplating the results before concluding that the atom must have a highly dense, positively charged nucleus.

The simulation called 'Rutherford Scattering' on the PhET website is useful to see how Rutherford's experiment worked:

https://phet.colorado.edu/en/simulation/rutherford-scattering



The above figure shows Rutherfords gold foil experiment (A) and the difference between between Thomson's model of the atom and Rutherfords (B)

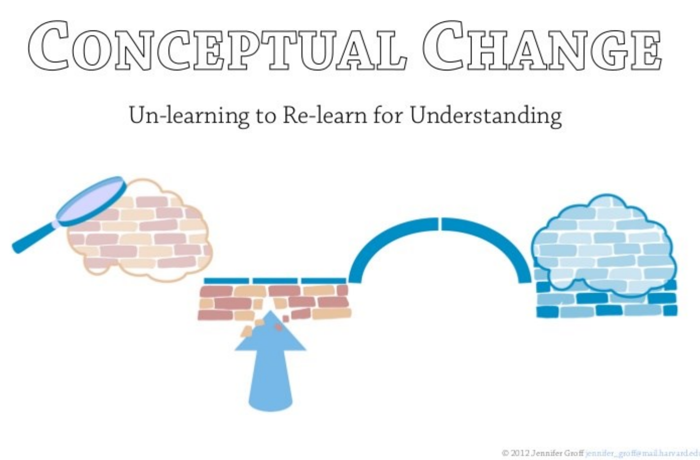
<u>The Challenge of Conceptual Change</u>

There are multitudes of examples in science history of a concept taking hold only to be replaced by a new concept. This process often takes a lot of time. Avogadro's new idea about gases did not get accepted by the broader scientific community because it conflicted with a mistaken concept that atoms that are alike cannot attract each other to make molecules. Unfortunately Avogadro did not live long enough to see his hypothesis get accepted. Lavoisier was challenged by the scientific community for his ideas about air since there was a pre-existing concept of phlogiston. He noted that the younger chemists fully accepted his theory but older scientists resisted it.

When Rutherford saw the results from his gold foil experiment he took a year to propose the new concept of an atom as having a positively charged nucleus. During this time he would have repeated the experiment many times and examined it for errors. Was the equipment faulty? Was there another source of alpha particles in the room? Was the gold foil contaminated? After he exhausted the potential sources of error, he had to change his concept of the atom to fit with the experimental results.

Changing a concept in our mind can be compared to renovating a house. A kitchen renovation may effect many other areas of the house if wiring and plumbing need to be updated and design elements need to be carried into other parts of the home. A concept in our mind is connected to other concepts so changing one will create change elsewhere. If the concept change is really big it can be compared to creating a new travel corridor in a city. The process takes a lot of effort and time and has impacts that are difficult to foresee.

As learners, we are constantly faced with conceptual change. Sometimes the instructional material is purposely designed with simple concepts being replaced by more complex ones. In chemistry we are first taught that chemical reactions are reactants changing to products and that all the molecules react. Next we are told to discard the idea that all molecules react and to determine the percent yield. Further along we are taught that many reactions go in both directions at the same time. Each time we have to deconstruct a previously held con- cept to make way

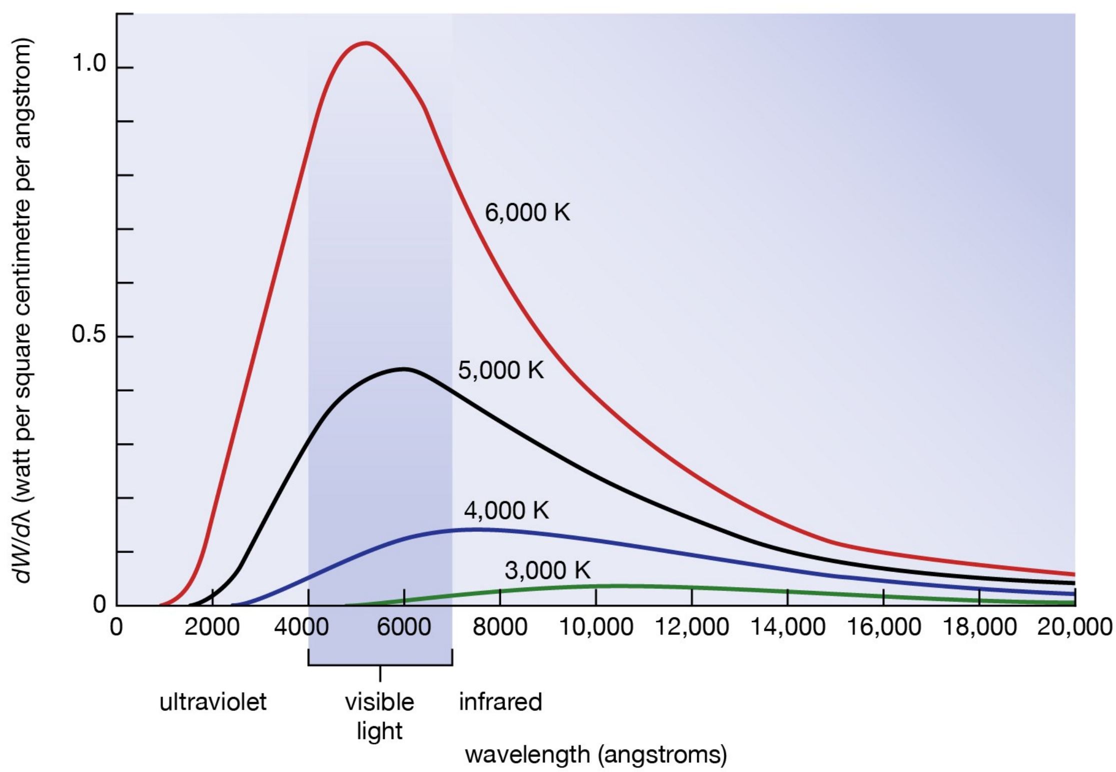


Quantized Energy

By the end of the 19th century scientists were feeling confident about their understanding of matter and energy. Matter was thought to consist of particles and energy was described as a wave.

Max Planck (1858—1947) was studying electromagnetic radiation profiles of solid iron that was heated to incandescence. The radiation profiles that were expected would have no maximum but that is not what was found. From this result, Planck hypothesized that energy could only be gained or lost in packets called 'quantum'.

The graph below is an example of blackbody radiation at different temperatures. As the temperature is increased, the shorter wavelengths increase. This helps to describe the vis-

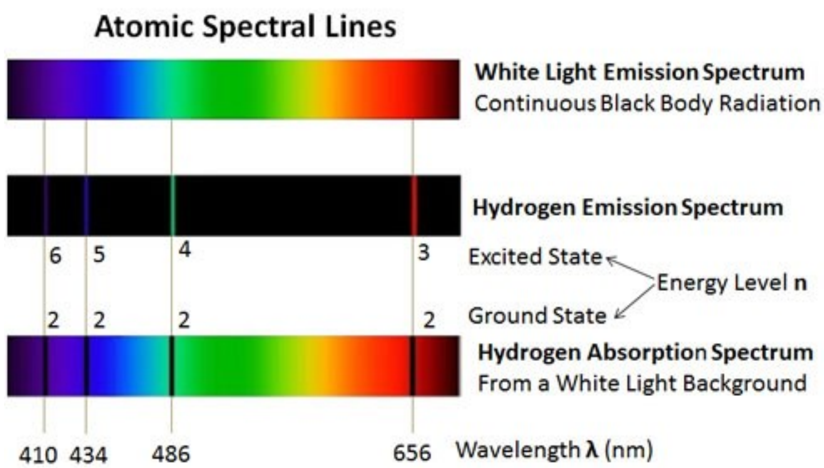


Shortly after Planck's discovery, Albert Einstein (1879—1955) was observing how light shining on certain metals releases electrons. If light is made of waves, it didn't make sense that a wave could knock an electron out of a metal atom but if he thought about light as particles in the form of bundles, then with enough energy it made sense that electrons were released. Einstein built on Planck's concept. Planck was concerned with the emission of light in bundles and Einstein went further to propose that matter always consists of bundles.

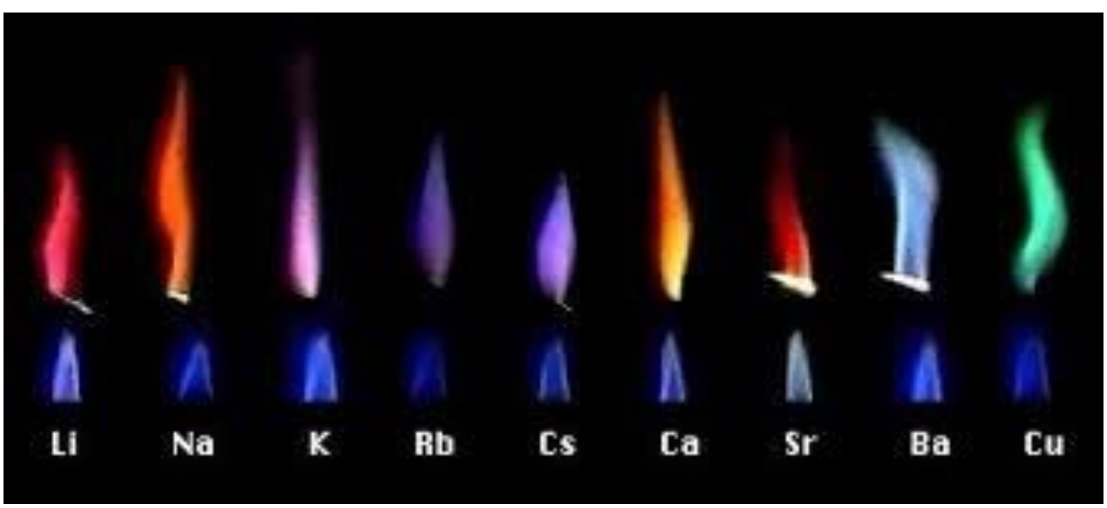
Putting the Pieces of the Puzzle Together

In the 19th century, scientists discovered that each element has its own unique emission spectrum. Spectral analysis became an important tool to discover and identify new elements but why these patterns existed was not known. It is now understood that these patterns result from electrons transitioning from higher to lower energy states and releasing photons that correspond to the difference in energy between the higher and lower states. Each element has many possible transitions.

Previous to quantum theory, it was thought that any atom could absorb any amount of energy and release any amount of energy. Atomic emission and absorption spectra demonstrate that energy is absorbed and released in discrete amounts. The energy levels of the electrons were not revealed through the atomic spectra, just the difference between energy levels.



The unique colours produced by chemical salts when exposed to a flame, are due to the emission spectra of the elements.

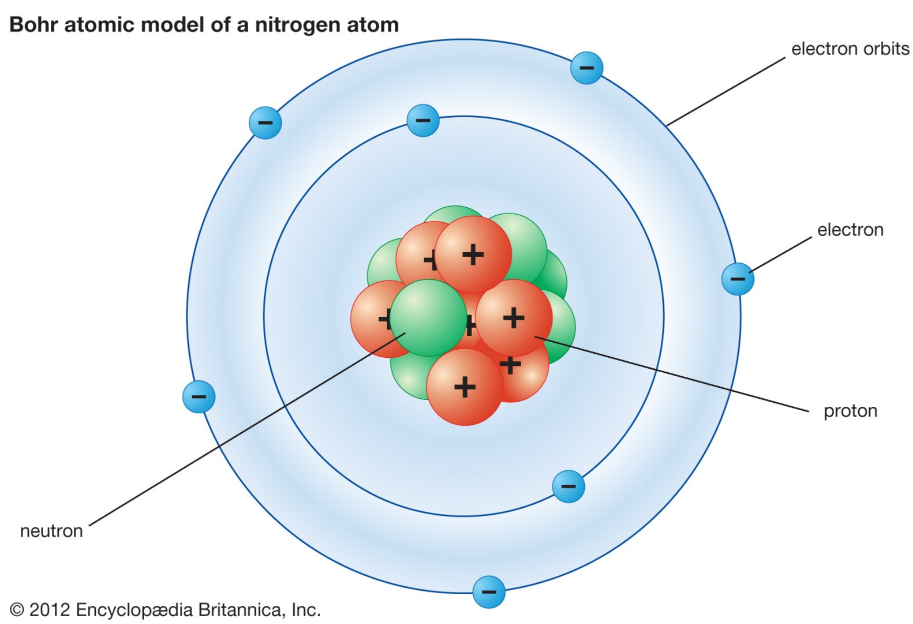


<u>The First Model of the Atom to Incorporate Quantum Theory</u>

Niels Bohr (1885—1962) was the first scientist to apply the concept of quantum theory to the structure of the atom. The Bohr model of the atom has the following characteristics:

* principle energy levels (shells) hold the electrons
* electrons closer to the nucleus have lower energy
* electrons farther from the nucleus have higher energy
* each energy level has a maximum number of electrons it can hold
* a ground state atom has its energy in the lowest state possible

Previous to this quantum model, a planetary model of the atom was hypothesized. The planetary model is easy to grasp since it is based on our solar system therefore this model is still widely displayed in images of the atom today. Bohr's model kept the circular orbits of the planetary model but he related the radii to the discrete wavelengths in the emission spectra of hydrogen.



<u>The Electron, the Photon and the Platypus</u>

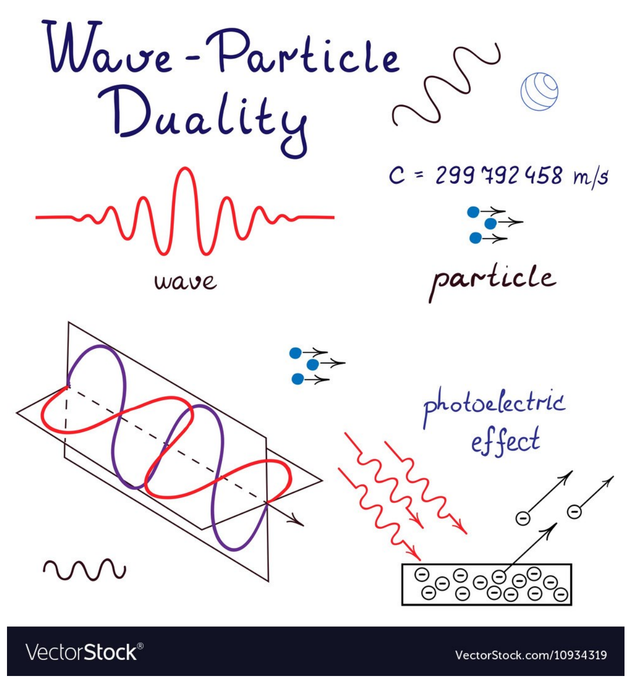
At the end of the 18th century, Europeans were introduced to an exotic animal from Australia called the platypus. The animal's unique attributes made it difficult for anatomists to categorize. It was thought to be a mammal because it was discovered to have mammary glands but then it was observed to lay eggs like birds, reptiles and fish. Until this time, animals fit nicely into the categories that anatomists created but these are human created categories to describe nature and nature does not follow human concepts. A new category was needed for this miraculous creature.

The story of the platypus is the same in many ways to the story of the electron and the photon. For hundreds of years scientists have argued over which category light belongs to: wave or particle. Einstein finally proposed that it is both, breaking away from the categories that were entrenched in people's minds. Not long after, Schrodinger proposed the same fate for the electron.

Photons and electrons are much more abstract than the platypus which makes them incomprehensible in many ways. Heisenberg noted that the structure of the atom is inaccessible to observation and that it can't be described in familiar terms. When he was asked "How can we picture the atom?", he responded "Don't try."

The following website includes a couple of short videos that provide some descriptions for comprehending the particle wave duality.

https://www.britannica.com/science/wave-particle-duality



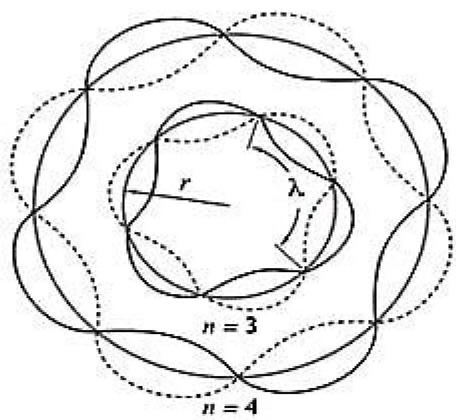
<u>Waves in the Atom</u>

The challenge with the Bohr model of the atom was that it only worked for hydrogen. Louie De Broglie (1892—1987) improved upon the Bohr model by adding the wave nature of electrons. De Broglie created an equation that demonstrated the relationship between one of the wave-like properties of matter and one of its properties as a particle. He found that most particles are too heavy to observe their wave properties but an electron has a small enough mass to exhibit both particle and wave properties. When he applied his theory to the Bohr model of the atom he found that only certain specific orbits allowed the electron to satisfy both its particle and wave duality.

The De Broglie Wavelength

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

λ = wavelength
h = Planck's constant (6.63×10^{-34} J · s)
p = momentum
m = mass
v = speed



The next model of the atom was developed by Erwin Schrodinger (1887—1961). He treated the electron like a wave and describes regions in space, called orbitals, where electrons are likely to be found. This model doesn't tell exactly where the electron is but where it is likely to be found. The following image demonstrates the De Broglie model of the atom. If you have been introduced to electron configuration of atoms and ions you should recognize the labels of the orbitals.