How "Z" got its chemical name…

Summary

Most of us and our students face difficulty in learning atomic theory and the concepts of molecular formulae. On one level, we can see it as a problem of memorization, or of learning a new language (of chemistry) with a new set of symbols. But actually the problem is not just of the new symbols but lies much deeper. The formulae are not a set of facts to be memorized, but in reality are conclusions that were derived from experiments done over decades for each substance by large number of scientists, who sometimes helped each other, and sometimes even opposed or fought with each other. On one hand, these aspects show that the formalism of chemical formulae is a result of human thought process and dynamics, while on the other hand prepare us to understand subsequent changes in the disciplines of modern science. Historical study can be of profound help in teaching-learning of this dimension of science.

This unit walks through some of the historical developments that went in establishment of molecular formula of a substance. These developments were in form of experimental findings as well as theoretical assumptions which contributed to foundations of modern atomic theory. The unit consists of passages containing historical information and problems of logic in these followed by a set of questions. The students are expected to answer the questions based on information provided prior to the question only. It is important that students go through the unit in sequential manner, which will help them learn construction of logic and theoretical framework.

Minimum Time required: 4 sessions of 40 min
Type of LU: Classroom
Material required: Only this worksheet and a pen/pencil.

Links to Curriculum: Atomic theory of matter; Concepts of Elements, compounds and Mixtures

Learning Objectives:

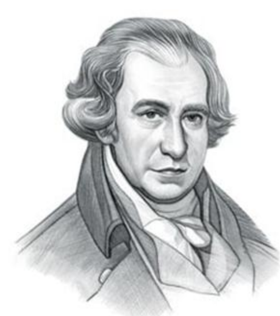
1) To see an example of how masses and volumes measurements of gases played a big role in development of modern chemical understanding of substances.
2) To differentiate between experimental results, assumptions and conclusions.
3) To realizing that molecular formula of a substance is not an ever-known fact but a conclusion derived based on certain assumptions and certain experimental findings. A change in assumptions or theoretical framework may change this.
4) To learn why some of the ideas alternate to modern atomic theory were not taken forward in modern science.

In this learning unit, we shall read about how people tried to understand chemical nature of a substance, and how these efforts led to knowledge we read about the nature of matter in our books today. Read the information given and try to answer the question given after it.

Task 1: The "Z"

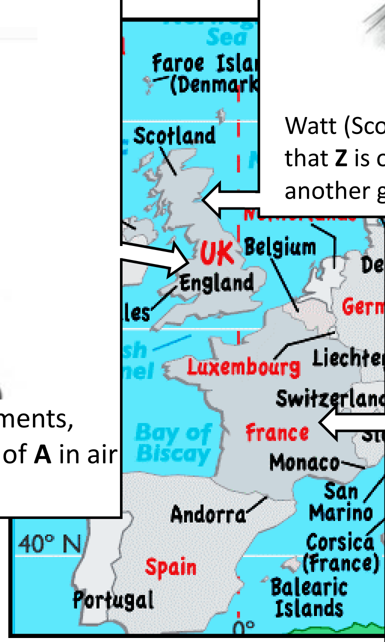
For ages, there was something which everyone had seen but no one knew what it is made of. Some said it was one of the purest substances of nature. Hence, they said it had nothing else in it. Many people tried breaking it down into components but were unsuccessful. Even heating it to high temperatures did not break it into components but converted it to an invisible form. People in different countries called it by different names. We will call it **Z**.

In 1777, a chemistry professor Mr. Macquer in France saw that on burning a gas in air, a liquid was formed on the lower surface of a dish held above it. Let us call this gas "**A**". Mr. John Warltire in England also observed the same phenomena. Due to cold climate in Europe, Macquer thought the liquid to be just water condensing from air. Four years later, an English priest, Dr. Priestly observed the same phenomena again. He wondered if burning of **A** in air is producing **Z !** and so he told it to his friends. At least three persons in Europe found this observation new and did experiments on it— Mr. Cavendish (a physicist in England), Mr. James Watt (an Engineer in Scotland), and Mr. Antonie Lavoisier (a tax collector and scientist in France).



Watt (Scotland) published his findings in 1784 that **Z** is obtained by combining **A** and another gas **B**.

Cavendish after detailed experiments, concluded in 1783 that burning of **A** in air indeed produces **Z**.



Lavoisier (France) heard the findings of Macquer and experimented with igniting **A** with gas **B** using spark and obtained **Z**. By 1783, he was the first to share this findings publically.

Q 1. What were the differences and similarities between the findings by Mr. Lavoisier, Mr. Watt, and Mr. Cavendish mentioned in the picture above?

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> The experiments done by the three scientists were different. Henry Cavendish burned **A** in air, James Watt combined **A** and **B** (probably by burning), whereas Antonie Lavoisier mixed **A** and **B** and ignited with a spark. Hence, James Watt and Lavoisier were familiar with the role of gas **B** in forming **Z**. They all found that the substance formed was indeed the substance **Z**.

Mr. Lavoisier also measured the mass of **Z** formed and found it to be same as the sum of masses of **A** and **B** used.

Around that time, many scientists had found a new kind of energy which could break down liquids, they called it electricity. After lot of effort by several people, by 1800, an English surgeon Anthony Carlisle and his colleague William Nicholson showed that by electrolysis, the liquid "**Z**" could also be broken down into two substances "**A**" and "**B**".

> Electrolysis of **Z** was successfully done by several people before 1800 also, but there could not obtain 2 separate gases form it. Moreover, getting back **A** and **B** from **Z** and the mass equivalence established that **Z** consists of **A** and **B** only, and nothing else.

Thus, experiments done by many people in many countries together established that **Z** was not an element but ____. (***Complete the sentence***)

> Let students write whatever that think about **Z**. Do not insist on writing that it was compound, because so far we have not mentioned about fixed proportion of **A** and **B** in **Z**. Even if students say it to be a mixture, it is ok. Most important is that they should realize that **Z** contains (only) **A** and **B**.

Task 2: The Mystery of Mass Ratio: The Concept of Atoms

Mr. Cavendish made more accurate mass measurements than Mr. Lavoisier and found that **Z** always had 11% **A** and 89% **B** by mass.

Q 1. Calculate the ratio of mass of **A** to mass of **B** in **Z** in terms of smallest whole numbers.

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> 1:8; Students may divide 89 by 11 and get a fractional number. It is important to discuss here that Cavendish was trying to find a relationship between the masses of reacting substances by keeping it a simple whole number ratio.

Q 2. People have always tried to write shortcut notations to represent information. If people wanted to write the information about the mass ratio of **A** and **B** in **Z** as shorthand notation, how should they write it as?

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> Here students may write many different answers such as A1-B8, 1**A**-8**B**, or $\mathbf{AB}_8$, or **A**(1): **B**(8), or (**A**, **B**) = (1, 8).

Many gases and liquids usually mixed in any proportions. However, **Z** had fixed proportion of masses of **A** and **B**. What did the fix mass ratio tell about **A**, **B**, and **Z**?
Many philosophers since ancient history said that all matter consist of particles (called atoms) but no one had seen or measured mass of individual particles of **A** or **B**. Now even if they assumed that **A**, **B** and **Z** consisted of particles, the fixed mass ratio was still a problem.
If these substances consisted of particles, then there were two possibilities:

(i) different particles of a given substance had same mass.
(ii) different particles of a given substance had different masses.

Q 4. If different particles of **A** had different mass just like particles of sand, would the number of particles in any 100 g sample of **A** be always the same? Explain.

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> If all particles of **A** had exactly same mass, the number of particles in any sample of 100 g of **A** would be always the same. But if the particles have different masses then usually the number of particles in two 100 g samples same or may not be the same.

Q 3. In which of the above two possibilities, the mass ratio of **A** and **B** in **Z** would always be the same? Explain. What other condition about the particle combinations in **Z** is necessary to explain the constant mass ratio of **A** and **B** in **Z**?

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> If all particles of **A** are of same mass, and all particles of **B** are of same mass, then the mass ratio of **A** and **B** in **Z** would be always the same. If the particle masses of a substance vary then then in some samples, mass ratio may be approximately same, but it will not be always same. Another condition is that the ratio of number of particles of **A** and **B** in every particle of **Z** should always the same
> It should be noted that assuming particles of a substances to be identical was big leap of imagination and contradictory to common experience, because in nature no two particles of any substance are identical. Like a heap of potatoes will always have potatoes of different masses, and two particles of sand or soil are never identical.

Around 1800, a pharmacist in France, Mr. Joseph Louis Proust gave a hypothesis that a fixed composition of elements is a characteristic property for compounds. Thus compounds were different from mixtures, which could have varying composition. Since many substances were known by then that had fixed composition, this hypothesis of Mr. Proust came to be known as the law of constant proportion for compounds.

If all particles in an element have same mass, then masses of **A** and **B** in a certain amount of **Z** can be written as

Mass of **A** in **Z** = mass of 1 particle of **A** × number of **A** particles in **Z**

Mass of **B** in **Z** = mass of 1 particle of **B** × number of **B** particles in **Z**

and ratio of mass of **A** to mass of **B** in **Z** can be expressed as:

$$\frac{\text{Mass of } \mathbf{A} \text{ in } \mathbf{Z}}{\text{Mass of } \mathbf{B} \text{ in } \mathbf{Z}} = \frac{\text{mass of 1 particle of } \mathbf{A}}{\text{mass of 1 particle of } \mathbf{B}} \times \frac{\text{number of } \mathbf{A} \text{ particles in } \mathbf{Z}}{\text{number of } \mathbf{B} \text{ particles in } \mathbf{Z}}$$

The ratio on the left hand side for **Z** was fixed (as obtained from the experiments). Therefore, if one knew the mass ratio of individual particles of **A** and **B**, then the ratio of number of **A** and **B** particles could be obtained, and vice versa.

Two students, Kamal and Amina were reading this history and were trying to find possible ratio of number of particles of **A** and **B** in **Z**.

Q 4. Amina wanted to take the simplest possibility that the mass of an **A** particle is same as that of a **B** particle. For Amina's assumption, find the ratio of number of particles of **A** to **B** in **Z**.

(1:8)

Q 5. Amina chose shorthand symbol of **Z** as $\mathbf{A}_x\mathbf{B}_y$, where x and y are number of particles of **A** and **B** in a particle of **Z**, respectively. Then what would Amina write the symbol of **Z** as?

($\mathbf{A}_1\mathbf{B}_8$)

Q 6. Kamal assumed that the mass of an **A** particle is 2 times the mass of a **B** particle. For Kamal's assumption, what would be the symbol of **Z**?

($\mathbf{A}_1\mathbf{B}_{16}$)

Now let us go back in 18^{th} century and see what assumptions the scientists made about **Z**.

In 1787, a 21 year old professor of mathematics and natural philosophy in England, Mr. John Dalton, developed an unusual interest in nature of the atmosphere. He continued study on atmospheric gases even after losing his job in 1789. Based on his experiments, he also proposed that all substances are made of particles. He also made a very unusual and bold assertion giving a face to the modern atomic theory:

- all particles of a substance are alike with respect to mass and properties.
- particles of different elements are different in mass.

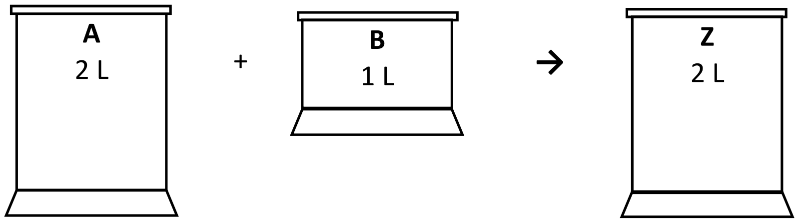
In 1804, Mr. Dalton published a book "*A New System of Chemical Philosophy*". In this book, he wrote that, the ratio of the number of particles of elements in a compound can be expressed as a simple whole number ratio. For **Z**, he made an assumption that the ratio of number of particles of **A** and **B** should be 1:1, and the symbol of **Z** should be **AB**.

Q 7. With Dalton's assumed symbol (**AB**) for **Z** and assuming that the mass of a particle of **A** is 1 unit, what would be the mass of a particle of **B**?

> Mass of **B** particle = 8 units, because in **Z**, mass ratio of **A**: **B** is 1:8.

Task 3: The Mystery of Volume Ratios: The Concept of Molecules

Around the same time in England only, Mr. Cavendish and Mr. Priestly found a relationship between volumes of reacting gases used to make **Z**. This finding was later confirmed in 1808 by a French Chemist Mr. Joseph Gay-Lussac. They found that to form **Z**, the volume of **A** used at atmospheric pressure was 2 times than that of **B** used at the same temperature. Further, 2 L of **A** combined with 1 L of **B** to give 2 L of gaseous **Z** at the same temperature.



The volume ratio of **A** and **B** that was obtained from electrolysis of **Z** was also found to be same (2:1) and fixed at a given temperature and atmospheric pressure.

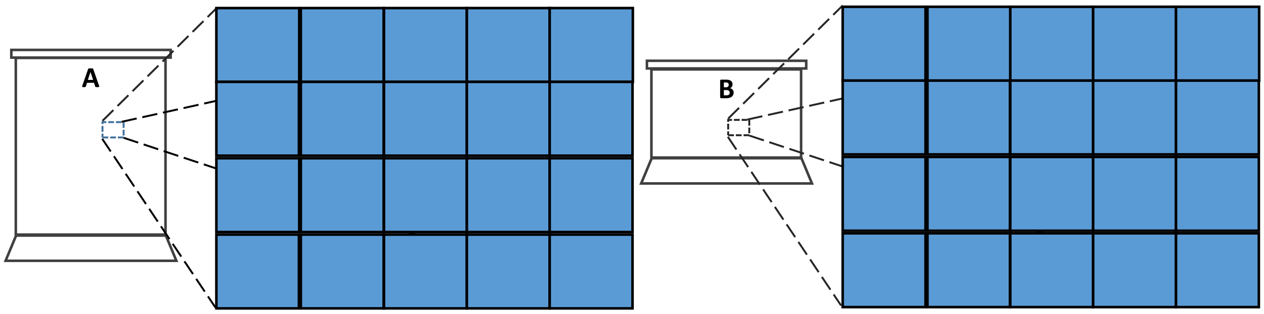
Q 1. Above information indicates that the average volume occupied by particles of **A** at atmospheric pressure and same temperature is always the same! Explain how?

> This is exactly like the argument for mass ratio. The volume ratio **A** and **B** obtained from **Z** would be constant ALWAYS only if average volume occupied by particles of **A** is same and particles of **B** is same. If particles of **A** can have different spacious extent, then volume of **A** obtained from same volume of **Z** would vary.
> In terms of idea, however, this is a more complex ideas because it involves the question of whether particles are stacked on the top of each other or have spaces in between. If we imagine that particles are stacked on each other, then it is enough to imagine that size of particles of a substance is always the same. But if we imagine the particles have spaces in between, then we also need to imagine that the average space in which particles move around at a given temperature and pressure is also constant. Imagining this is difficult if we assume random distribution of particles in space.

This was puzzling because mass percentage of **B** used for **Z** was higher and volume was lower than that of **A**. Mr. Dalton struggled to imagine how particles in different substances were arranged in space which could lead to this volume ratio. Since no one had ever seen how particles are arranged in space in gases, he and other imagined particles to occupy cubical spaces. He also thought that the particles must be stacked over each other.

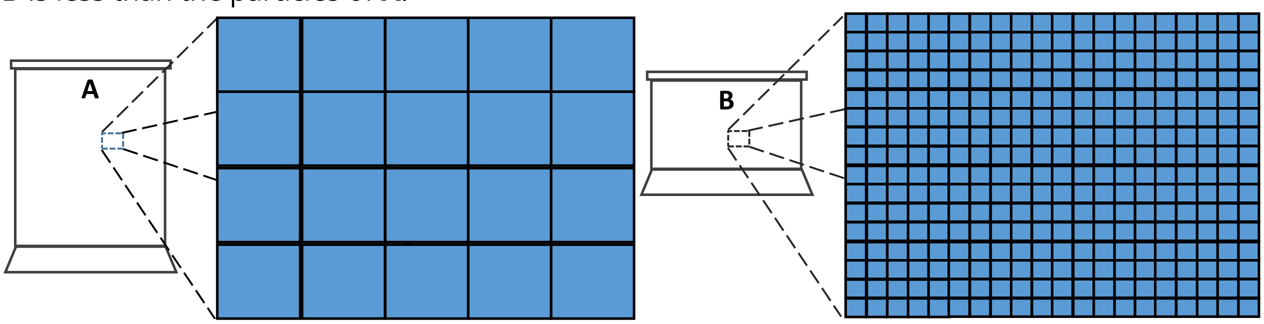
If we consider above experimental data, the following possibilities emerge:

Possibility I: The average size of a particle of **B** was same as that of a particle of **A** but particles of **B** are heavier than **A**.



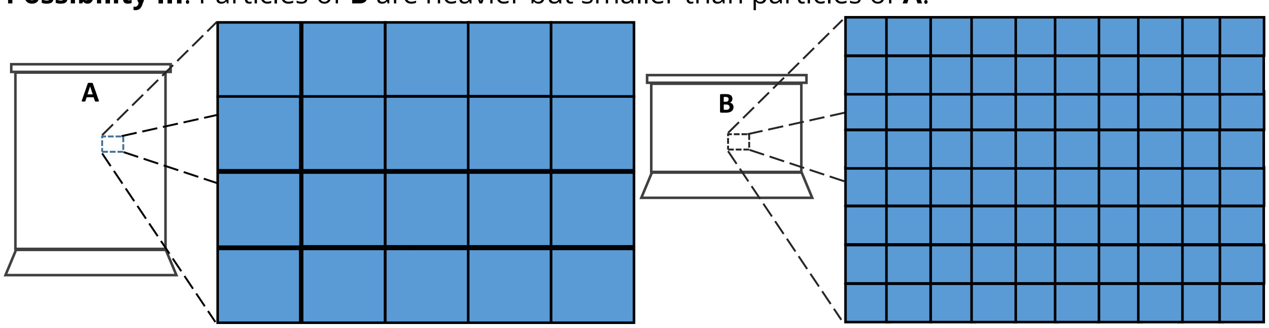
Particles of A **Particles of B**

Possibility II: Particles of **B** have same mass as particles of **A** but the average size of particles of **B** is less than the particles of **A**.



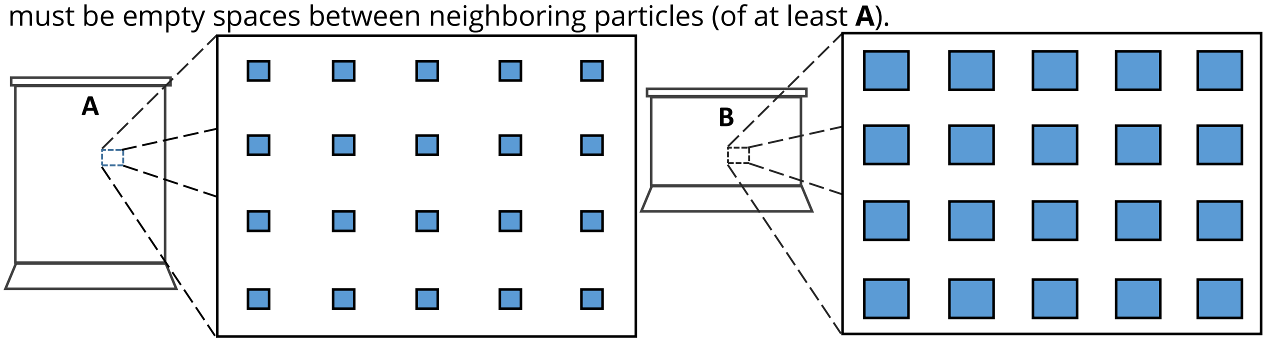
Particles of A **Particles of B**

Possibility III: Particles of **B** are heavier but smaller than particles of **A**.



Particles of A **Particles of B**

Possibility IV: Particles of **B** are heavier as well as bigger than particles of **A**. In such case, there must be empty spaces between neighboring particles (of at least **A**).



Particles of A **Particles of B**

Q2. Which of the above possibility is likely to be more correct and why?

> All four are likely possibility here based on data provided here. There was no evidence if particles of **B** are heavier, lighter, bigger or smaller than that of **A**. It is important to realize here that without any strong reason or evidence, none of the possibilities can be ruled out.
> The most important purpose of this question is to help students realize that the data about volume ratio prompted a problem about stacking of particles particularly for gases. Mr. Dalton also could not think of empty spaces between particles and he saw gases consisting of particles stacked together (possibility **II** and **III**). The real problem in this picture was in explaining diffusion of one gases into another gases, which requires particles to move in between other particles. He explained diffusion of two dissimilar gases by saying that particles of different sizes (of the two gasses) stacked on one another would keep on tumbling and hence keep on mixing.

Q 3. Draw any other picture of arrangement of particles of **A** and **B** you can think of:

Particles of A **Particles of B**

> Here students can draw any other possibilities that comes to their mind. It can be different shapes of the particles, whether are ordered or random, have space within or not, etc. Pedagogically, it can help see alternate conceptions in mind of students.

Unfortunately, the data presented so far was insufficient to establish the chemical symbol for **Z**. No one could count the number of particles in a given mass or volume of a gas. Based on other experiments, Mr. Gay-Lussac hypothesized that equal volumes of different gases should be containing equal number of particles.

Q 4. If equal volumes of two gases have same number of particles, then which of the above possibilities (**I** to **IV**) have to be WRONG?

> Possibilities **II** and **III** have to be wrong.

Q 5. With the above assumption, 2 L of **A** should contain twice the number of particles as in 1 L of **B**. If two particles of **A** combine with one particle of **B** to give 1 particle of **Z**, then how many L of gaseous **Z** should be obtained with 2 L of **A** and 1 L of **B** . Explain.

> The number of particles of **Z** formed would be same as the number of particles of **B**, thus 1 L of **Z** should be obtained.

Mr. Dalton did not accept Mr. Gay-Lussac's reasoning because if 1 L of **A** had same number of particles as 1 L of **B**, and if two particles of **A** combine with one particle of **B** then 2 L of gaseous **Z** could not be obtained. He argued that if particles of different elements had different masses then their sizes should also be different.

Q 6. If particles of different elements have different sizes, then which of the above possibilities (**I** to **IV**) have to be WRONG?

> Possibility **I** has to be wrong.

In 1811, an Italian physics professor Mr. Amedo Avogadro published a solution to the volume problem. He wrote that if the particles of elements could break into two half particles, then two particles of **A** would combine with one particle of **B** to give two particles of **Z**. Thus, Professor Avogadro brought the idea of molecules and that molecules can break into two smaller particles (which now everyone knows as atoms). In other words, what was being considered as (fundamental) particles so far were molecules, which could break further to give atoms.

In addition, Mr. Avogadro also supported Mr. Gay Lussac's reasoning and showed the necessity to assume that "equal volumes of all gases at the same pressure and temperature contain equal number of particles" to explain the above experimental observations.

Q 7. If we accept Mr. Avogadro's hypothesis about half-particles (atoms), then what must be the ratio of number of half-particles of **A** and **B** in **Z**. Thus, what should be the chemical symbol of **Z**?

> Ratio of number of half-particles of **A**: **B** = 2:1, chemical symbol: $\mathbf{A_2B}$

Task 4: The Major Learnings

Q 1. If the formula of **Z** is as per Avogadro's hypothesis and mass of an atom of **A** is taken to be 1 unit, then what must be the mass of an atom of **B**.

2 atoms of **A** have mass of 2 units.
Mass of **B** in **Z** is 8 times that of **A**. Thus mass of atom of **B** is $8 \times 2 = 16$ unit

Q 2. How many years did it take after the first laboratoty synthesis of **Z** to establish its modern chemical formula?

About 30 years.

Q 3. Can you now figure out what is compound **Z**?

Z is water, **A** is hydrogen and **B** is oxygen. This students can possibly predict from currently known atomic masses of elements.

Q 4.List the major experimental facts and assumptions that were necessary to arrive at the modern chemical symbol (which we also know as chemical formula) of **Z**.
Experimental Observations:

a) **Z** consists of two different substances **A** and **B** (gases), hence it is not an element.
b) Ratio of masses of **A** and **B** in **Z** is always 1:8.
c) 2 L of gaseous **A** combines with 1 L of gaseous **B** to give 2 L of gaseous **Z** at the same temperature and at atmospheric pressure.

Assumptions:

a) All substances (including liquids and gases) consist of particles.
b) Particles of an element are exactly alike in mass and properties, and particles of different elements are different in mass and properties.
c) Equal volumes of all gases consist of equal number of particles at the same temperature and atmospheric pressure.
d) In many elements, the particles (molecules) can break into half particles (atoms) which can combine to give new particles (molecules) of another substances (called compounds).

Suggested Readings:

- Aaron J. Idhe (1984), The development of Modern Chemistry, Dover Publications, Inc, New York. This book presents a very detailed history of various developments leading to modern chemistry.
- Anirban Hazra (2006), The Story of Chemistry, Vigyan Prasar. Available online at: http://scipop.iucaa.in/Literature/storyofchemistry.pdf. This book is a comic book written and illustrated for young children to make the story of chemistry interesting for them.
- Sushil Joshi, Uma Sudhir (2014), The story of Atomic Theory of matter, Eklavya, Bhopal. This book has detailed description of experiments and ideas that went into development of atomic theory with some interesting illustrations and suggested experiments.

References:

a) Henry Cavendish's 1784 paper on synthesis of water: http://rstl.royalsocietypublishing.org/content/74/119.

b) James Watt's 1784 paper on synthesis of water: http://rstl.royalsocietypublishing.org/content/74/329.

c) Antoine Lavoisier' 1783 report: Observations sur la Physique, 23, 452-455 (1783) on water being a compound.

d) Pictures were sourced from http://www.pci.tu-bs.de/aggericke/Personen/Gaylussac_Biography.html, www.worldatlas.com/webimage/countrys/eu.htm, fr.wikipedia.org/wiki/Fichier:Antoine_Laurent_de_Lavoisier.png