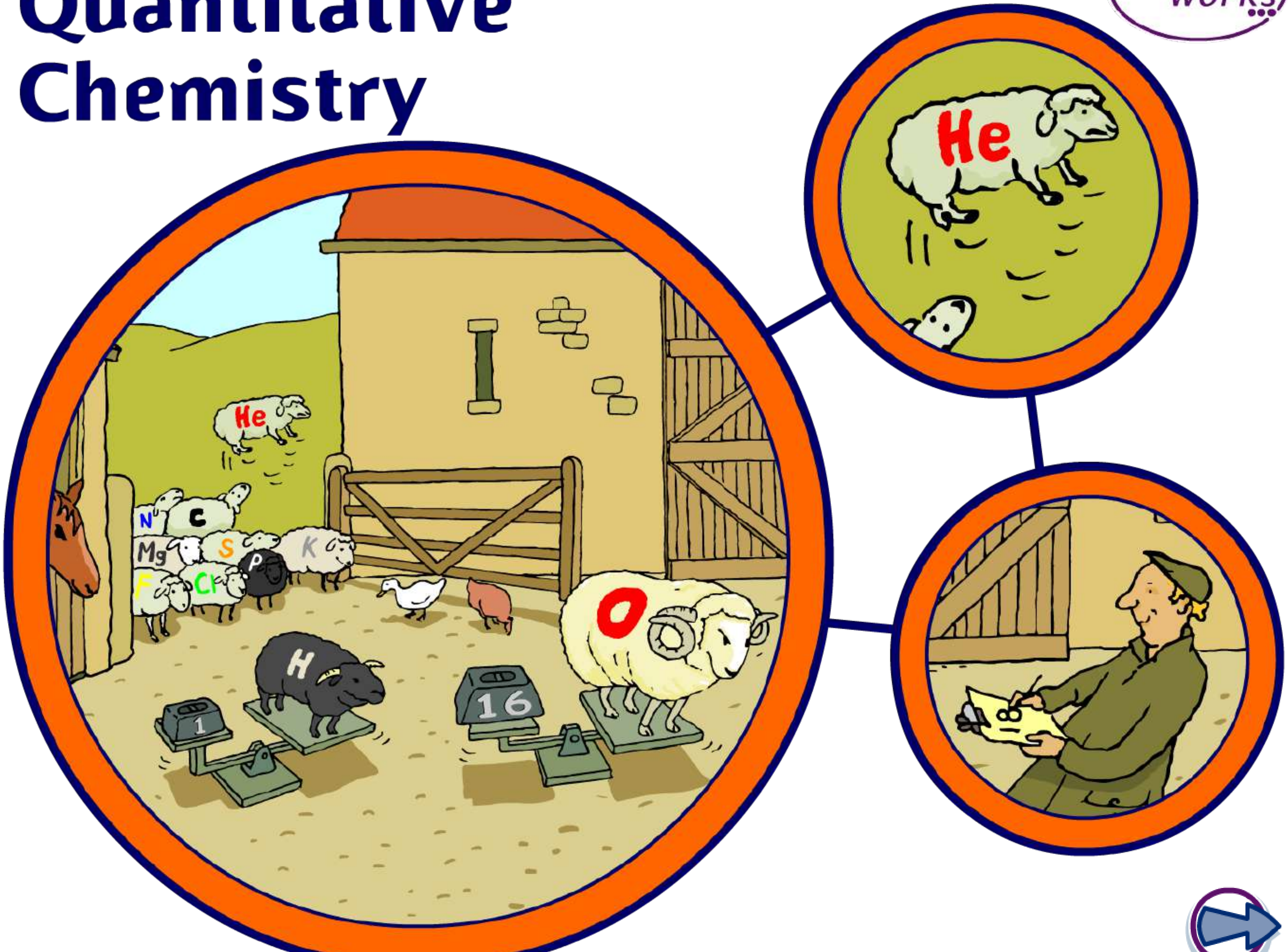
GCSE Additional Science

Quantitative Chemistry



Quantitative Chemistry

Contents

How is the mass of atoms measured?

One grain of sand contains millions of atoms, so atoms must be really small. How is the mass of an atom measured?

Atoms are so small that their masses are not measured directly.

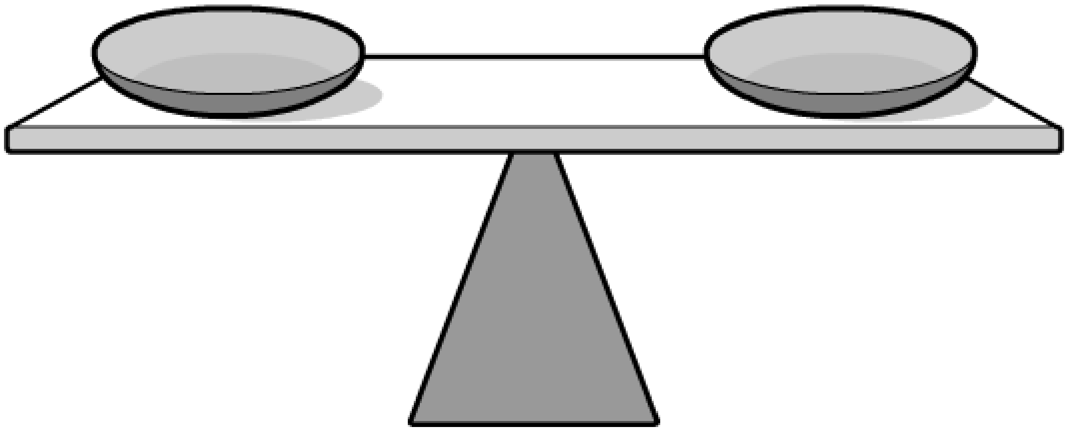
Instead, all atoms are compared with the mass of carbon-12.
The mass of an atom on this scale is called its **relative atomic mass**.

What is relative atomic mass?

The **relative atomic mass** (r.a.m.) of an element is the mass of its atoms compared with the mass of an atom of carbon-12.

Each element has a different r.a.m. value.

Click "**play**" to find out more .

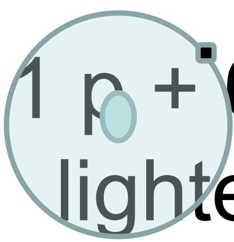
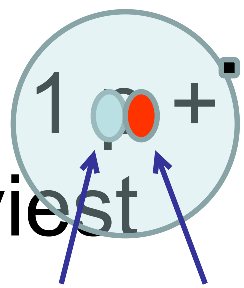
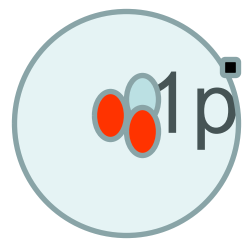


Isotopes

Not all atoms of the same element are identical.

For example, there are 3 types of hydrogen atoms.

^{1}H ^{2}H ^{3}H

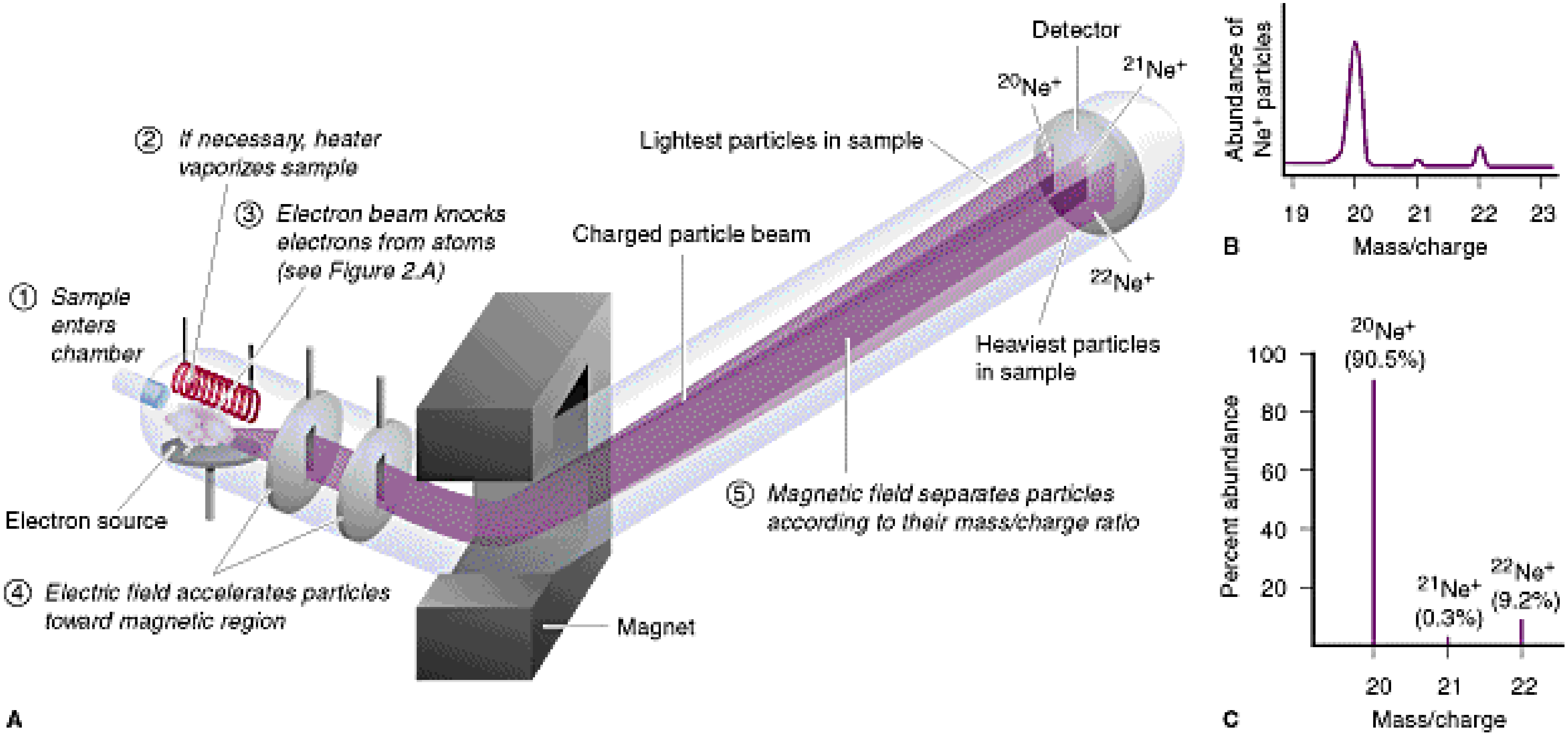




1 p + 0 n 1 p + 1 n 1p + 2 n

lightestheaviest

Mass Spectrometers

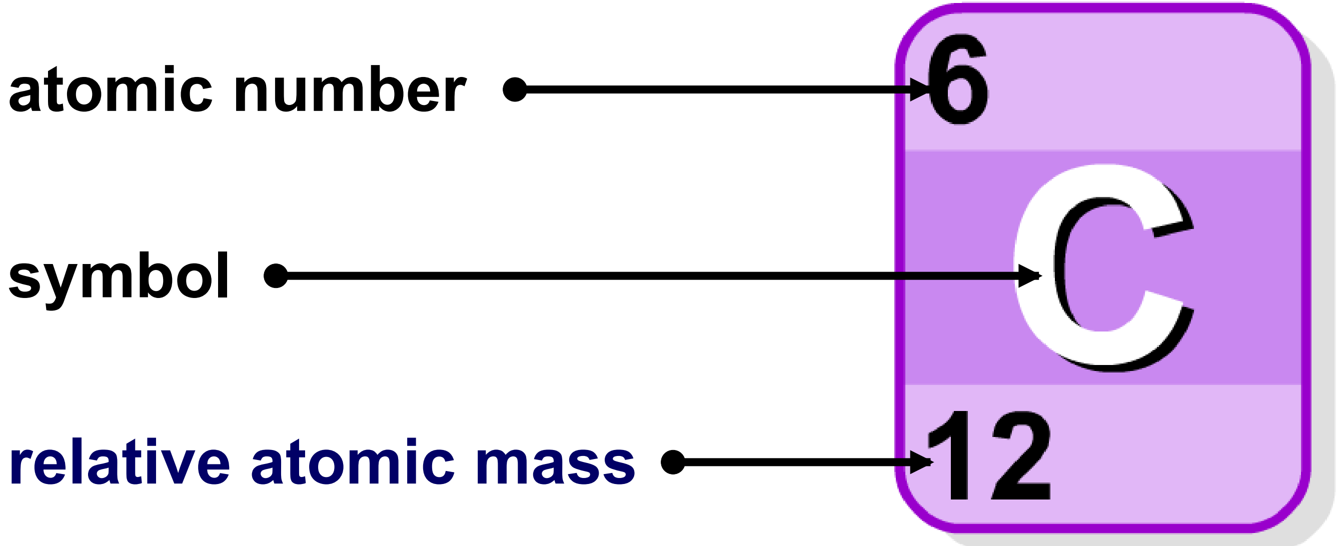
A device known as a **mass spectrometer** can be used to determine the **relative abundance** and **mass** of the **isotopes** of elements.



Detector
$^{20}Ne^+$
$^{21}Ne^+$
$^{22}Ne^+$
Lightest particles in sample
② If necessary, heater vaporizes sample
③ Electron beam knocks electrons from atoms (see Figure 2.A)
Charged particle beam
① Sample enters chamber
Heaviest particles in sample
Electron source
⑤ Magnetic field separates particles according to their mass/charge ratio
④ Electric field accelerates particles toward magnetic region
Magnet
A
Abundance of Ne^+ particles
19
20
21
22
23
B
Mass/charge
$^{20}Ne^+$ (90.5%)
$^{21}Ne^+$ (0.3%)
$^{22}Ne^+$ (9.2%)
Percent abundance
100
80
60
40
20
20
21
22
C
Mass/charge

Where are r.a.m. values found?

The values of relative atomic mass (r.a.m.) are usually given in a data book or found in the periodic table. So you don't have to work them out or remember them all!



When looking up relative atomic mass in the periodic table, remember that it always the larger of the two numbers given.

What is the other number?

Identifying relative atomic mass

What is the relative atomic mass of each element?

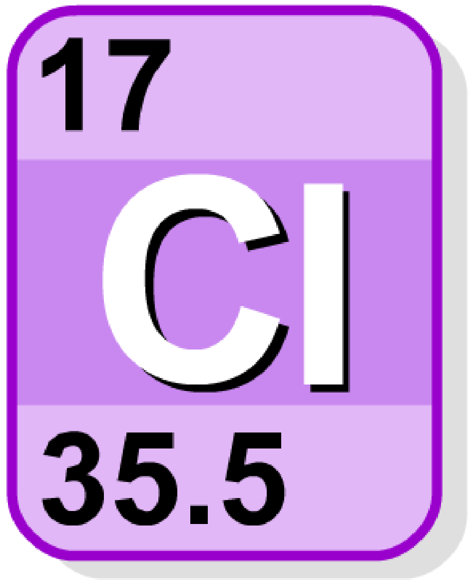
4	helium (He)
9	silver (Ag)
16	oxygen (O)
40	molybdenum (Mo)
84	calcium (Ca)
96	krypton (Kr)
108	beryllium (Be)

?

solve

Why isn't r.a.m. always a whole number?

Relative atomic mass (r.a.m.) is not always a whole number. For example, the r.a.m. of chlorine is **35.5**.



The standard r.a.m. value of each element is actually the **average** relative atomic mass, which takes all the isotopes of each element into account.

Chlorine has two isotopes:
chlorine-35 (75%) and **chlorine-37** (25%).

average r.a.m. of chlorine = (35 x 75%) + (37 x 25%)
= (35 x 0.75) + (37 x 0.25)
= 26.25 + 9.25
= **35.5**

Calculating average r.a.m. from isotopes

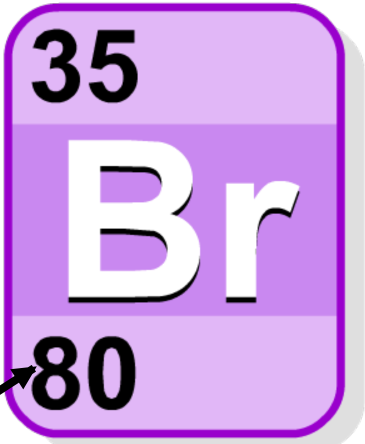
To calculate the average r.a.m. of a mixture of isotopes, multiply the percentage of each isotope(as a decimal) by its relative atomic mass and then add these together.

Naturally-occurring bromine is composed of two isotopes: bromine-79 (50.5%) and bromine-81 (49.5%).

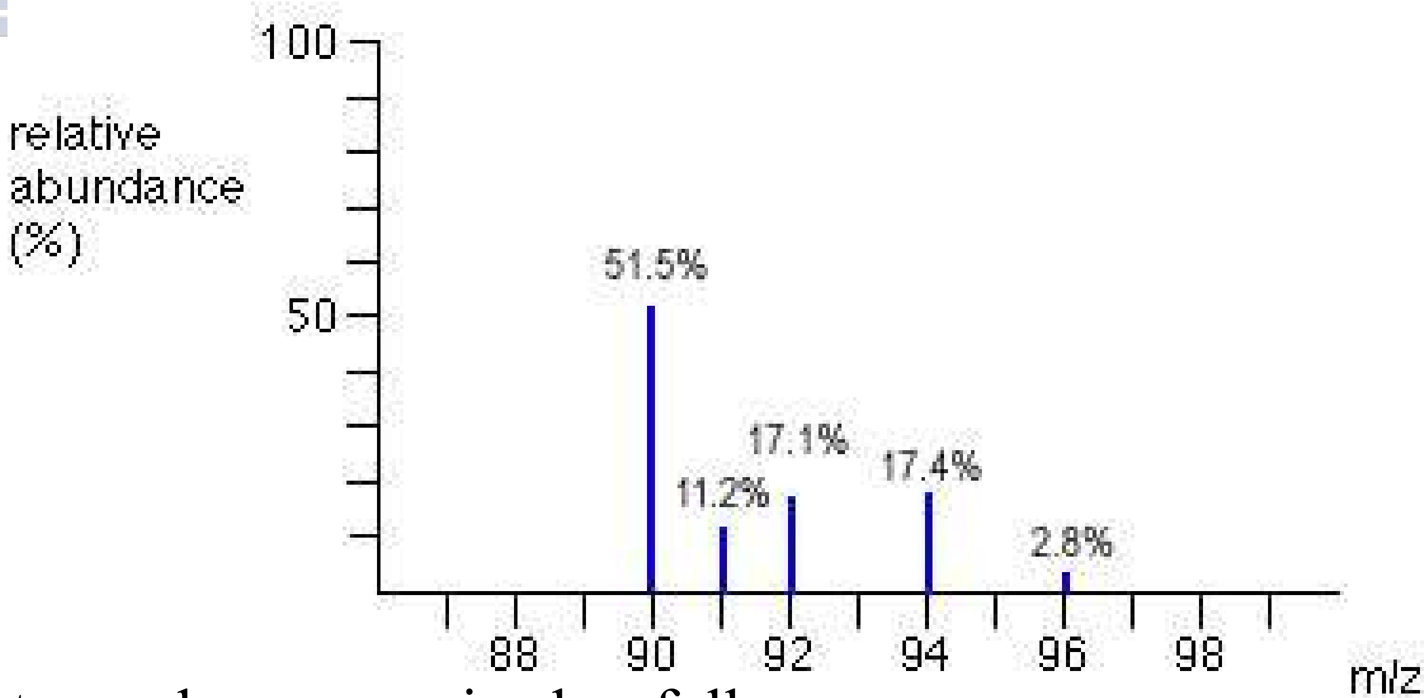
What is the average r.a.m. of naturally-occurring bromine?

average r.a.m. = (79 x 50.5%) + (81 x 49.5%)
= (79 x 0.505) + (81 x 0.495)
= 39.895 + 40.095
= **79.99**

This figure can be rounded up.



The Mass Spectrum of the Element "Zirconium"



The data can be summarized as follows:

Isotope	Mass`Abundance
^{90}Zr 90.00 amu	51.5 %
^{91}Zr 91.00 amu	11.2 %
^{92}Zr 92.00 amu	17.1 %
^{94}Zr 94.00 amu	17.4 %
^{96}Zr 96.00 amu	2.80 %

atomic mass of isotope **100 %**

Isotope	Mass`	Abundance
^{90}Zr	90.00 amu	51.5 %
^{91}Zr	91.00 amu	11.2 %
^{92}Zr	92.00 amu	17.1 %
^{94}Zr	94.00 amu	17.4 %
^{96}Zr	96.00 amu	2.80 %

STEP 1.

Change each percent of each isotope to a decimal by dividing by 100.
Multiply by the mass.
Add it all together.

Isotope	Mass` Abundance		
^{90}Zr90.00 amu	51.5 %	=	.515
^{91}Zr91.00 amu	11.2 % =.112		
^{92}Zr92.00 amu	17.1 % =.171		
^{94}Zr94.00 amu	17.4 %=.174		
^{96}Zr96.00 amu	2.80 %=.028		

Calculate the weighted average mass of zirconium using the data below.

Change each percent to a decimal by dividing by 100.
Multiply by the mass.
Add it all together.

Isotope	Mass`	Abundance
^{90}Zr	90.00 amu	51.5 %
^{91}Zr	91.00 amu	11.2 %
^{92}Zr	92.00 amu	17.1 %
^{94}Zr	94.00 amu	17.4 %
^{96}Zr	96.00 amu	2.80 %

0.515

(percent)(mass)

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^{96}Zr	96.00 amu	2.80 %

0.515(90.00)

(percent)(mass)

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^{94}Zr	94.00 amu	17.4 %
^{96}Zr	96.00 amu	2.80 %

$0.515(90.00) + 0.112$

(percent)(mass)

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0.515(90.00) + 0.112(91.00)

(percent)(mass)

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0.515(90.00) + 0.112(91.00) + 0.171

(percent)(mass)

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^{94}Zr	94.00 amu	17.4 %
^{96}Zr	96.00 amu	2.80 %

$$0.515(90.00) + 0.112(91.00) + 0.171(92.00)$$

(percent)(mass)

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0.515(90.00) + 0.112(91.00) + 0.171(92.00) + 0.174

(percent)(mass)

Calculate the weighted average mass of zirconium using the data below.

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^{92}Zr	92.00 amu	17.1 %
^{94}Zr	94.00 amu	17.4 %
^{96}Zr	96.00 amu	2.80 %

0.515(90.00) + 0.112(91.00) + 0.171(92.00) + 0.174(94.00) + 0.0280

(percent)(mass)

Calculate the weighted average mass of zirconium using the data below.

Change each percent to a decimal by dividing by 100.
Multiply by the mass.
Add it all together.

Isotope	Mass`	Abundance
^{90}Zr	90.00 amu	51.5 %
^{91}Zr	91.00 amu	11.2 %
^{92}Zr	92.00 amu	17.1 %
^{94}Zr	94.00 amu	17.4 %
^{96}Zr	96.00 amu	2.80 %

$$0.515(90.00) + 0.112(91.00) + 0.171(92.00) + 0.174(94.00) + 0.0280(96.00)$$

(percent)(mass)

Calculate the weighted average mass of zirconium using the data below.

Change each percent to a decimal by dividing by 100.
Multiply by the mass.
Add it all together.

Isotope	Mass`	Abundance
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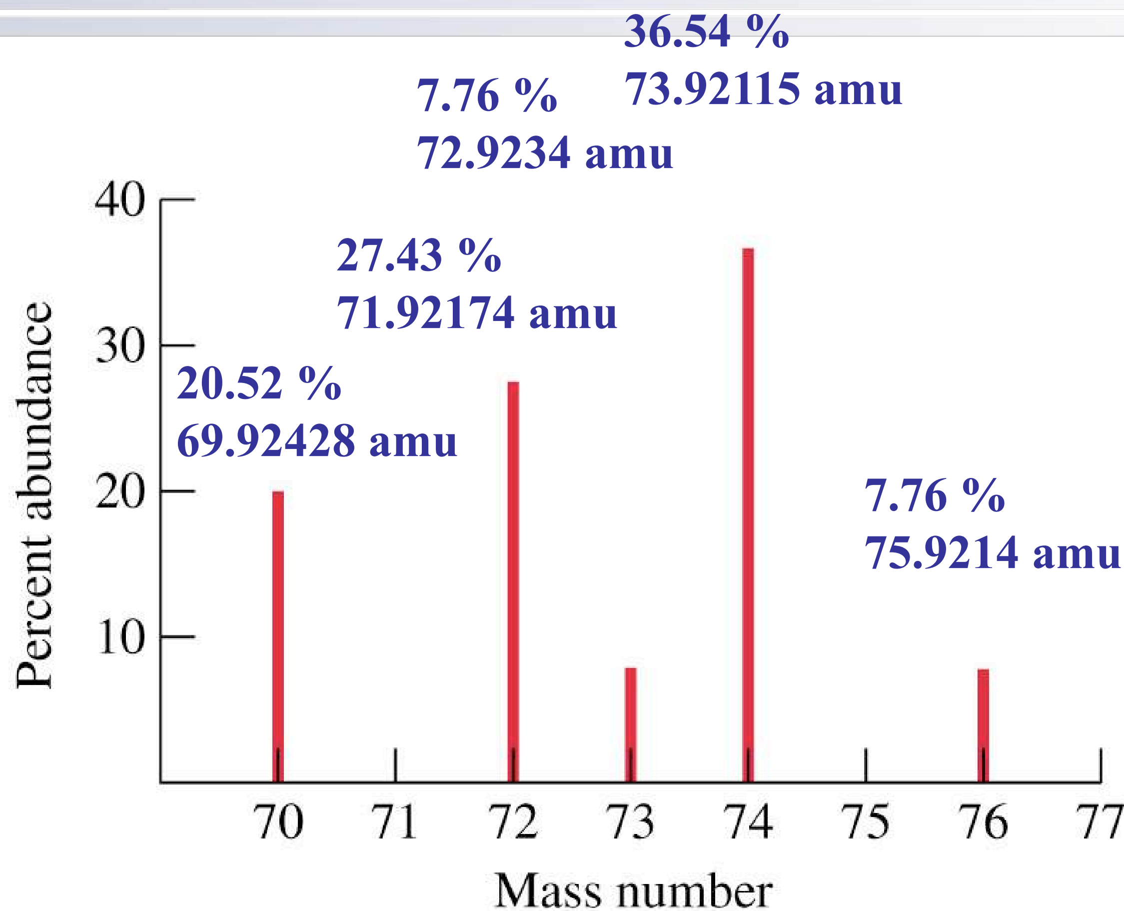
^{94}Zr	94.00 amu	17.4 %
^{96}Zr	96.00 amu	2.80 %

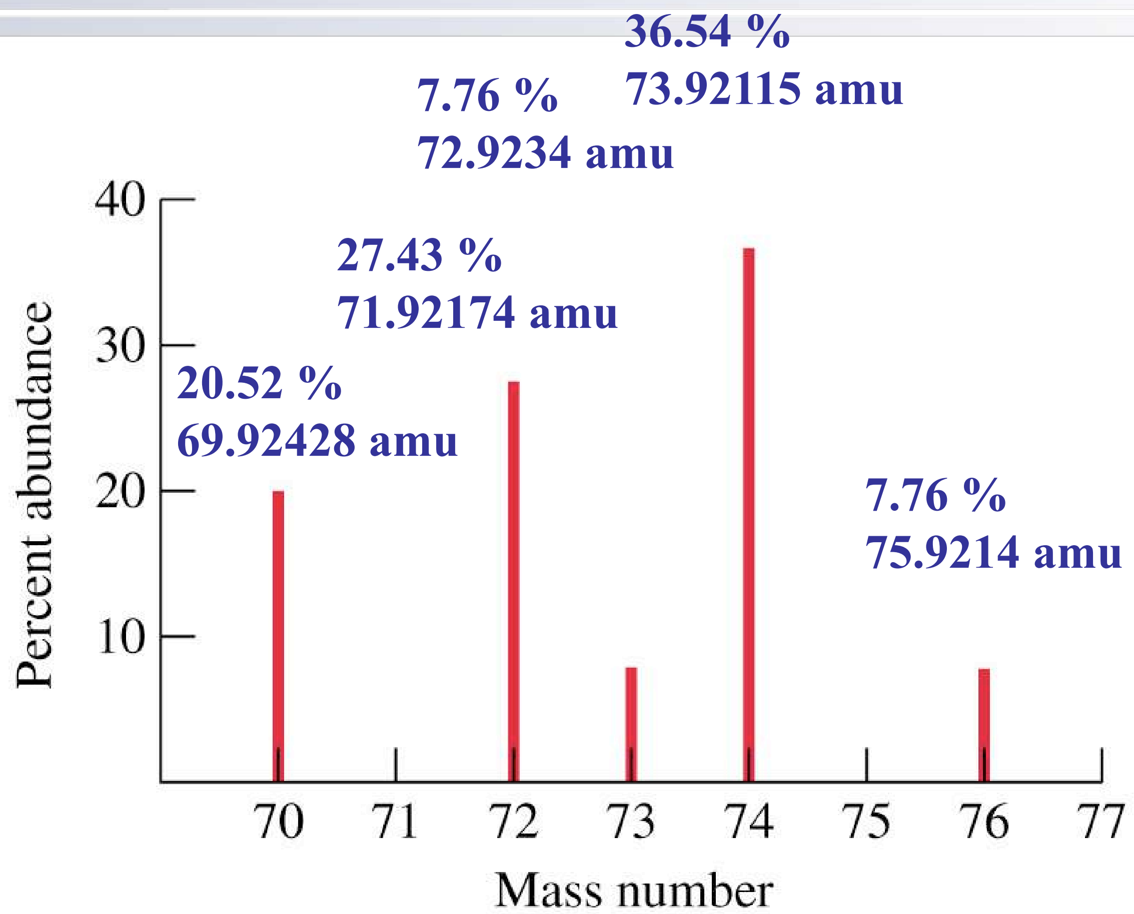
0.515(90.00) + 0.112(91.00) + 0.171(92.00) + 0.174(94.00) + 0.0280(96.00)

=91.3 amuround to the smallest number of sig figs!

Calculate the average atomic mass for Germanium

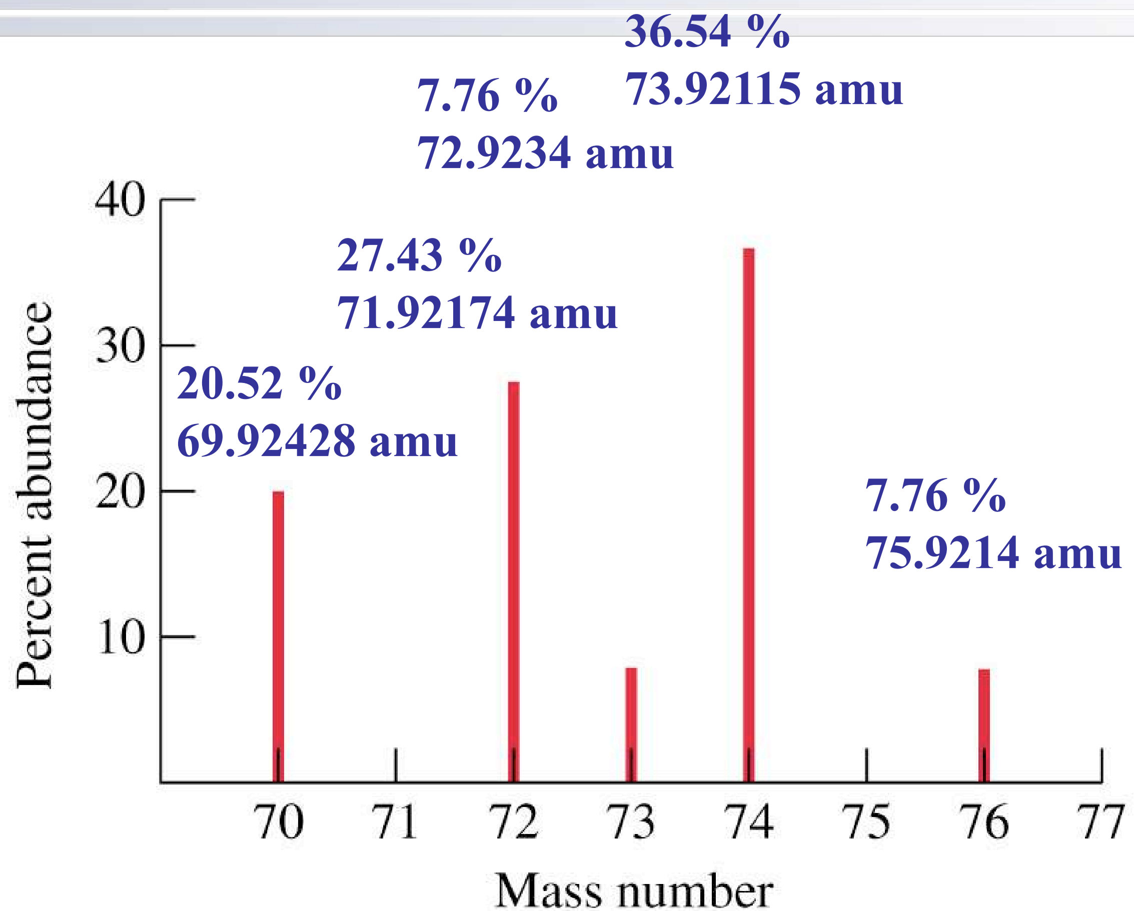


Calculate the average atomic mass for Germanium



$$(0.2052)(69.92428) + (0.2743)(71.92174) + (0.0776)(72.9234) + (0.3654)(73.92115) + 0.0776)(75.9214) =$$

Calculate the average atomic mass for Germanium



(0.2052)(69.92428) + (0.2743)(71.92174) + (0.0776)(72.9234) + (0.3654)(73.92115) + 0.0776)(75.9214) =

=**72.6 amu**

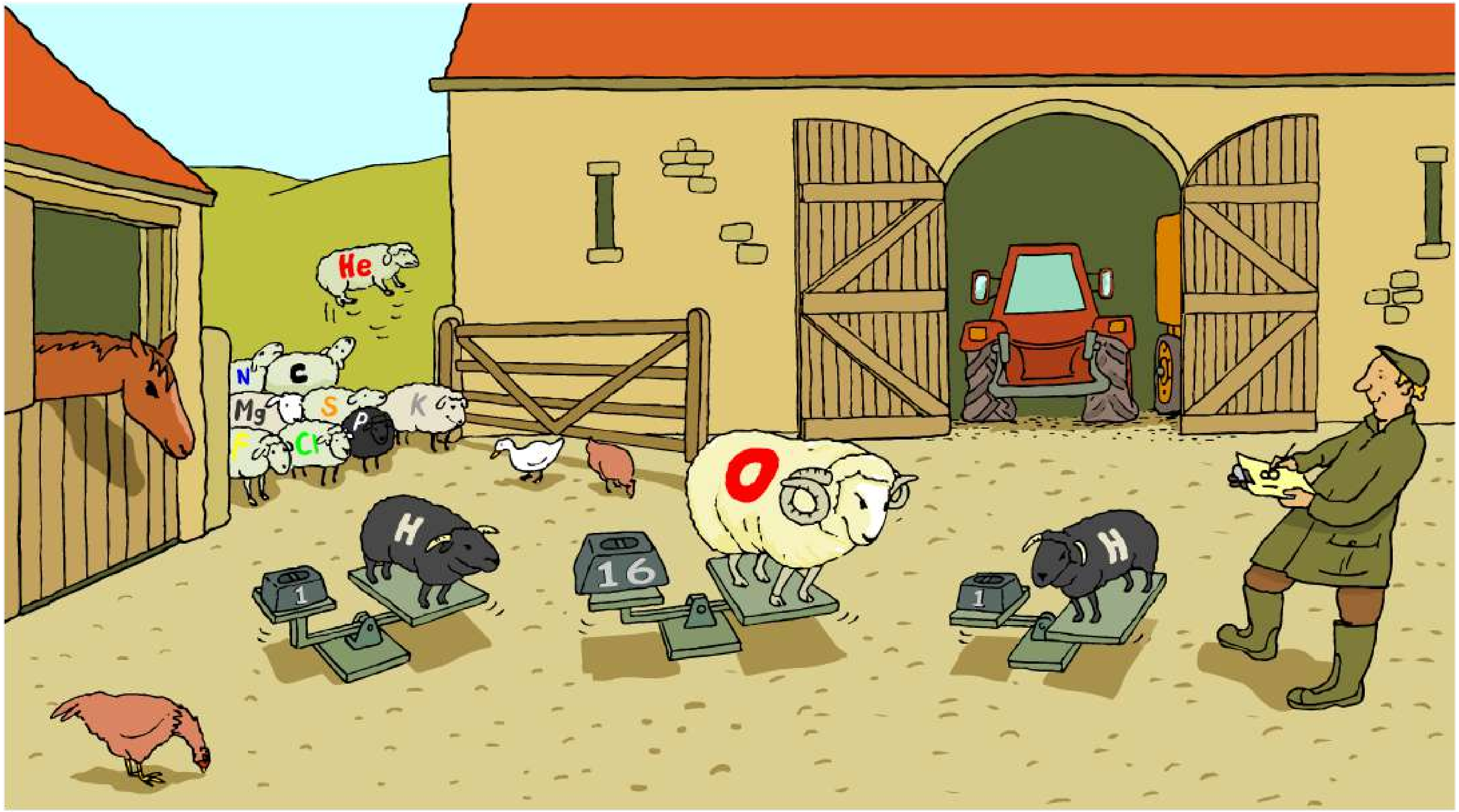
What about the mass of compounds?

Most substances are made of molecules, not individual atoms. Molecules are really small too, so can we work out their masses in the same kind of way?

Of course! The mass of a molecule is called the **relative formula mass**. This is calculated by adding up the relative atomic masses of all the atoms in the molecule.

What is relative formula mass?

How is r.a.m. used to find the relative formula mass of H_2O?



How is relative formula mass calculated?

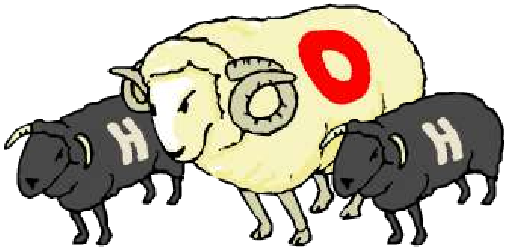
To find the **relative formula mass** of a compound, add up the relative atomic masses of all the atoms in its formula.

Step 1: Write down the formula of the molecule.

Step 2: Find the r.a.m. of each type of atom in the molecule.

Step 3: Multiply each r.a.m. by the number of atoms of that element and add these values together.

What is the relative formula mass of water?



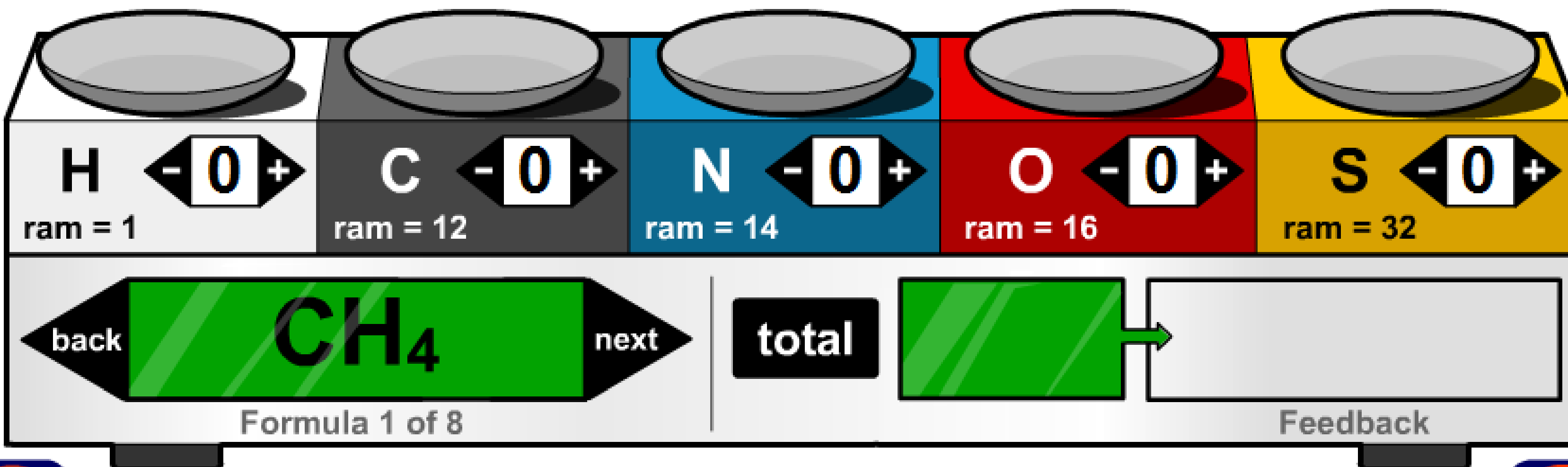
Step 1: formula of water is H_2O

Step 2: r.a.m. values: hydrogen = 1, oxygen = 16

Step 3: relative formula mass = (2 x 1) + (1 x 16) = **18**

Relative formula mass 'calculator'

What is the relative formula mass?



Calculating relative formula mass

What is the relative formula mass of each substance?

Substance	Formula	Relative formula mass
iodine	I_2	?
sodium chloride	NaCl	?
aluminium oxide	Al_2O_3	?
potassium nitrate	KNO_3	?
ammonium carbonate	$(NH_4)_2CO_3$	?

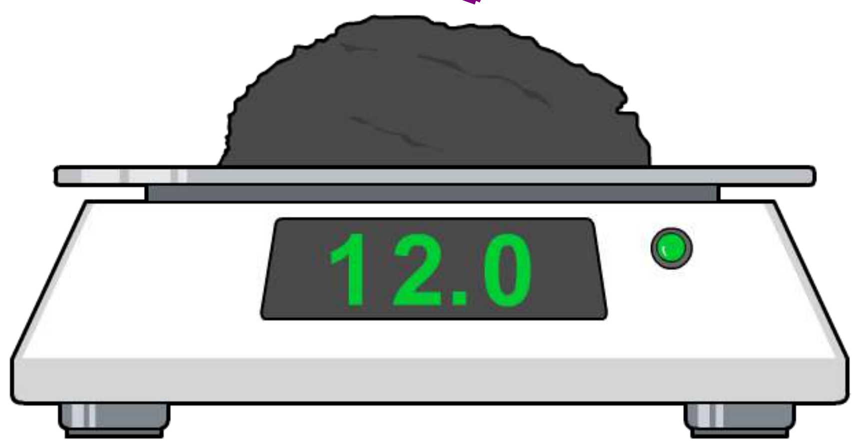
43 | 58.5 | 96 | 127 | 254 | 101 | 36.5 | 69 | 102

solve

What is a mole?

The term **mole** is also used to talk about mass. **One mole** of a substance is its relative atomic mass, or relative formula mass, in **grams**.

For example, the relative atomic mass of carbon is 12, so **one mole of carbon atoms weighs 12 grams**.



What is the mass of one mole of hydrogen atoms?

What is the mass of one mole?

Fe

H_2O

Mg

solve

Relative atomic mass – true or false?

Are these statements about masses of atoms true or false?

1.	The relative atomic mass of carbon is 1.	
2.	Relative atomic mass is always a whole number.	
3.	Adding the relative atomic masses of all the atoms in a molecule gives its relative formula mass.	
4.	The relative formula mass of water is 18.	
5.	The units of relative atomic mass are grams.	
6.	One mole of sodium has a mass of 23 grams.	

true false

? solve

Quantitative Chemistry

Contents

Can you work out which fertilizer is best?

My uncle uses fertilizers on his allotment to grow his prize-winning pumpkins.

How can he work out which fertilizer contains the most nitrogen?

Different fertilizers contain different compounds. Your uncle needs to find out the **percentage by mass** of nitrogen in each compound.

How is percentage by mass calculated?

Scientists use **percentage by mass** calculations to help them work out how useful a substance is, how pure it is or even to identify an unknown substance.

The percentage by mass of an element in a compound is sometimes known as the **percentage composition**. Percentage by mass is calculated using r.a.m. and r.f.m.

$$\textbf{\% element} = \frac{\textbf{r.a.m. of element x number of atoms}}{\textbf{r.f.m of compound}} \textbf{ x 100}$$

Calculating percentage by mass – example 1

What percentage by mass of **nitrogen** is in ammonia (**NH_3**)?
(r.a.m.: H = 1, N = 14)

Step 1: Work out the relative formula mass (r.f.m.) of NH_3.

r.f.m. of NH_3 = 1 nitrogen atom + 3 hydrogen atoms
= (1 x 14) + (3 x 1)
= 17

Step 2: Work out the percentage by mass of nitrogen.

$$\text{\% of nitrogen in } NH_3 = \frac{\text{r.a.m.} \times \text{number of atoms}}{\text{r.f.m. of compound}} \times 100$$

$$= \frac{(14 \times 1)}{17} \times 100$$

= 82%

What percentage by mass of **hydrogen** is in ammonia (**NH_3**)?
(r.a.m.: H = 1, N = 14)

Step 1: Work out the relative formula mass (r.f.m.) of NH_3.

r.f.m. of NH_3 = 1 nitrogen atom + 3 hydrogen atoms
= (1 x 14) + (3 x 1)
= 17

Step 2: Work out the percentage by mass of hydrogen.

$$\%\text{ of hydrogen in } NH_3 = \frac{\text{r.a.m. x number of atoms}}{\text{r.f.m. of compound}} \times 100$$

$$= \frac{(1 \times 3)}{17} \times 100$$

= 18%

How much oxygen?

What is the percentage by mass of oxygen in each compound?

Compound	Relative formula mass	% of oxygen
MgO	?	?
K_2O	?	?
$NaOH$	?	?
SO_2	?	?

How much nitrogen?

How much nitrogen does each fertilizer contain?

My uncle still can't decide which fertilizer to buy. There are three to choose from, each containing a different source of nitrogen.

What is the percentage of nitrogen in each one?

start

Comparing fertilizers

?

C

solve

Which fertilizer is the best?

Fertilizer	Compound	% nitrogen
MEGA pumpkin	NH_4NO_3	35%
Supergro	$(NH_4)_2SO_4$	21%
Plant-B-big	CON_2H_4	47%

Quantitative Chemistry

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Introduction to reacting masses

My asthma inhaler uses a chemical called salbutamol. Millions of people have asthma, so how do manufacturers work out how to make enough salbutamol?

Many useful substances are made by chemical reactions. Scientists decide how much product they want to make and then work out the amount of reactants needed.

The first step is to write a **balanced symbol equation** for the reaction.

Symbol equations – balanced or not?

Are these symbol equations balanced or not balanced?

balanced	not balanced

$Fe + Cl_2 \rightarrow FeCl_4$

?

C

solve

Balancing symbol equations

→

→

→

KBr → Br$_2$ + 2KF

E H$_2$ + NO → 2H$_2$O + N$_2$

F

?

C solve

Why are balanced equations useful?

The balanced equation for a chemical reaction shows the **ratio of reactants and products** involved.

magnesium + oxygen → magnesium oxide

$$2Mg + O_2 \rightarrow 2MgO$$

The balanced equation for this chemical reaction shows that the ratio of **Mg : O_2 : MgO** is **2 : 1 : 2**.

This ratio can be used to calculate the masses of reactants needed and the mass of product that will be made.

These amounts are called the **relative reacting masses**.

Using reacting masses – example 1

If you have 48 grams of magnesium, what mass of oxygen will react with this?

magnesium + oxygen → magnesium oxide

$$2Mg + O_2 \rightarrow 2MgO$$

- The balanced equation shows the ratio of **Mg : O_2** is **2 : 1**.
- The relative atomic mass of **Mg = 24** and the relative formula mass of **O_2 = 32**.
- Combining these two sets of information gives the ratio of reacting masses.

Mg : O_2 = (2 x 24) : (1 x 32) = **48 g : 32 g**

So, 48 g of magnesium will react with 32 g of oxygen.

Using reacting masses – example 2

If you have 48 grams of magnesium, what mass of magnesium oxide will be produced?

magnesium + oxygen → magnesium oxide

$$2Mg + O_2 \rightarrow 2MgO$$

- The balanced equation shows the ratio of **Mg : MgO** is **2:2**.
- The relative atomic mass of **Mg = 24** and the relative formula mass of **MgO = 24 + 16 = 40**.
- Combining these two sets of information gives the ratio of reacting masses.

Mg : MgO = (2 x 24) : (2 x 40) = 48 g : 80 g

So, 48 g of magnesium will produce 80 g of magnesium oxide.

Reacting masses

What are the masses involved in these reactions?

Balanced equations, relative atomic masses and relative formula masses are used to calculate the ratio of reacting masses.

Remember to include the **ratio of reactants and products** from the balanced equation in your calculations.

Click "**start**" to begin.

start

Using reacting masses – example 3

If you have 480 grams of magnesium, what mass of magnesium oxide will be produced?

magnesium + oxygen → magnesium oxide

$$2Mg + O_2 \rightarrow 2MgO$$

- From previous calculations, the ratio of reacting masses for **Mg : MgO = (2 x 24) : (2 x 40) = 48 g : 80 g**.
- Starting with 480 g of magnesium, means you have to work out the scale factor for the ratio of reacting masses.
  scale factor = 480 g ÷ 48 g = 10
- Applying this scale factor to the amount of magnesium oxide in the ratio of reacting masses gives the answer.

mass of MgO to be produced = 80 g x 10 = 800g

What are the rules for reacting masses?

The rules for working out **reacting masses** are:

- **Step 1**. Write down the balanced symbol equation.
- **Step 2**. Write down the relative atomic/formula masses of the reactants and products.
- **Step 3**. Use the balanced equation to write down the ratios of reactants and products.
- **Step 4**. Convert to ratio of reacting masses.
- **Step 5**. Calculate the scale factor and apply this to the ratio of reacting masses.

Reacting masses – worked example

If 28 g of iron reacts with copper sulphate solution, what mass of copper will be made?

- **Step 1**. Write down the balanced symbol equation.

  $$Fe + CuSO_4 \rightarrow Cu + FeSO_4$$

- **Step 2**. Write down the relative atomic/formula masses.

  Fe = 56 Cu = 64

- **Step 3**. Write down the ratio of reactants and products.

  Fe : Cu = 1 : 1

- **Step 4.** Convert to ratio of reacting masses.

Fe : Cu = 1 : 1 = 56 g : 64 g

- **Step 5**. Calculate the scale factor and apply this to the ratio of reacting masses.

  scale factor = 28 g / 56 g = 0.5

  mass of Cu made = 64 g x 0.5 = 32 g

What are the masses involved in these reactions?

Balanced equations, relative atomic masses and relative formula masses are used to calculate the ratio of reacting masses.

Remember to work out the **scale factor** and apply this to the ratio of reacting masses in your calculations.

Click "**start**" to begin.

start

What about reacting masses in industry?

Industrial processes use tonnes of reactants, not grams.

Balanced equations and relative atomic/formula masses are still used to calculate the masses of reactants and products – but the **units** of grams are swapped for tonnes or kilograms.

For example, what mass of calcium oxide (r.f.m.= 56) can be made from 200 tonnes of calcium carbonate (r.f.m.= 100)?

r.f.m. values give ratio of reacting masses

$$CaCO_3 \rightarrow CaO + CO_2$$

100 (tonnes) : 56 (tonnes) : 44 (tonnes)

So, by equivalence, 100 tonnes of calcium carbonate produces 56 tonnes of calcium oxide, and, therefore, **200 tonnes** produces **112 tonnes** of calcium oxide.

Reacting masses in industry

What are the masses involved in these industrial reactions?

Balanced equations, relative atomic masses and relative formula masses are used to calculate the ratio of reacting masses.

Remember that the unit of **grams** can be swapped for **kilograms or tonnes** in your calculations.

Click "**start**" to begin.

start

Quantitative Chemistry

Contents

Introduction to yield and atom economy

I'm worried about the environment and using up resources. How do manufacturers make sure they don't waste chemicals?

All manufacturers want reactions to be as **efficient** as possible. They don't want to waste resources or energy, and they want to make as much product as possible.

To work out how efficient reactions are, scientists use **yield** and **atom economy**.

What are the different types of yield?

The **percentage yield** of a chemical reaction shows how much product was actually made compared with the amount of product that was expected.

To calculate the percentage yield, you need to work out the **theoretical yield** and the **actual yield**.

The **theoretical yield** is the maximum mass of product expected from the reaction, using reacting masses.

The **actual yield** is the mass of the product that is actually obtained from the real chemical reaction.

Why is the actual yield usually less than the theoretical yield?

What factors affect the actual yield?

Do these factors reduce the yield of useful products or not?

reduce yield	do not reduce yield

The products are more stable than the reactants.

?

C

solve

How is percentage yield calculated?

The percentage yield of a reaction is the actual yield written as a percentage of the theoretical yield.

The equation for working out the percentage yield is:

$$\textbf{percentage yield} = \frac{\textbf{actual yield}}{\textbf{theoretical yield}} \times 100$$

The percentage yield is always less than 100%.

Why is the percentage yield never 100%?

What does it mean if the percentage yield of a reaction is 0%?

Calculating percentage yield – example

I reacted copper sulphate solution with some iron. Using reacting masses, I worked out that the theoretical yield of the reaction was 50 grams of copper.

I lost some copper when I filtered the solution and ended up with 40 grams. What is the **percentage yield** of my reaction?

$$\textbf{percentage yield} = \frac{\textbf{actual yield}}{\textbf{theoretical yield}} \times 100$$

$$\textbf{percentage yield} = \frac{40\,g}{50\,g} \times 100 = 80\%$$

What is the percentage yield?

$$\text{percentage yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$

1. A chemical factory was planning to make 500 tonnes of calcium oxide by heating calcium carbonate. They produced 450 tonnes. What was the percentage yield?

answer 1

2. A pharmaceutical company carried out a test reaction, aiming to make 1 g of a new cancer drug. The reaction only produced 0.7 g of the drug. What was the percentage yield?

answer 2

3. A teacher burned 24 g of magnesium in oxygen, hoping to make 40 g of magnesium oxide, but actually only produced 30 g of this product. What was the percentage yield?

answer 3

What is atom economy?

Atom economy is another measure of the efficiency of a chemical reaction.

It is the amount of starting materials that end up as useful products.

In an ideal chemical process, all the starting materials end up as useful products and no atom is wasted.

If most of the starting materials end up as useful products, the reaction is said to have a **high atom economy**.

Why is it important for sustainable development and for economical reasons to use reactions with high atom economy?

Why is high atom economy important?

A chemical reaction with a **high percentage yield** has a **high atom economy**.

This is important for the chemical industry for many reasons:

- to minimise waste of non-renewable reactants
- to make as much useful product as possible
- to reduce pollution from waste products
- to minimise energy use in heating chemical reactions
- to minimise energy use in running factories
- to reduce use of water for cooling chemical reactions.

Atom economy – true or false?

Are these statements about yield and atom economy true or false?

1.	The actual yield of a reaction is the amount of product that you expected to make.	
2.	The percentage yield of a reaction can be over 100%.	
3.	If some product has been lost, the percentage yield of a reaction will be less than 100%.	
4.	The percentage yield of an industrial reaction should be as high as possible to maximise energy use.	
5.	A high atom economy means that most of the starting materials end up as waste products.	
6.	A chemical reaction with a high percentage yield is an efficient reaction.	

true

false

?

solve

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Contents

Glossary (1/2)

- **actual yield –** The real amount of product obtained from a chemical reaction.
- **atom economy –** The amount of starting materials that end up as useful products.
- **isotopes –** Atoms of the same element with a different relative atomic mass.
- **mole –** The relative atomic mass or relative formula mass of a substance in grams.
- **percentage by mass –** The amount of an element in a compound written as a percentage of the relative formula mass. It is also known as the percentage composition.
- **percentage yield –** The actual yield of a chemical reaction written as a percentage of the theoretical yield.

Glossary (2/2)

- **reacting mass –** The mass of a substance needed to react with or produce a given mass of another substance.
- **relative atomic mass –** The average mass of an element compared with $\frac{1}{12}$ of the mass of carbon-12.
- **relative formula mass –** The sum of the relative atomic masses of all the elements in a substance.
- **theoretical yield –** The maximum amount of product that could be made in a chemical reaction.

Anagrams

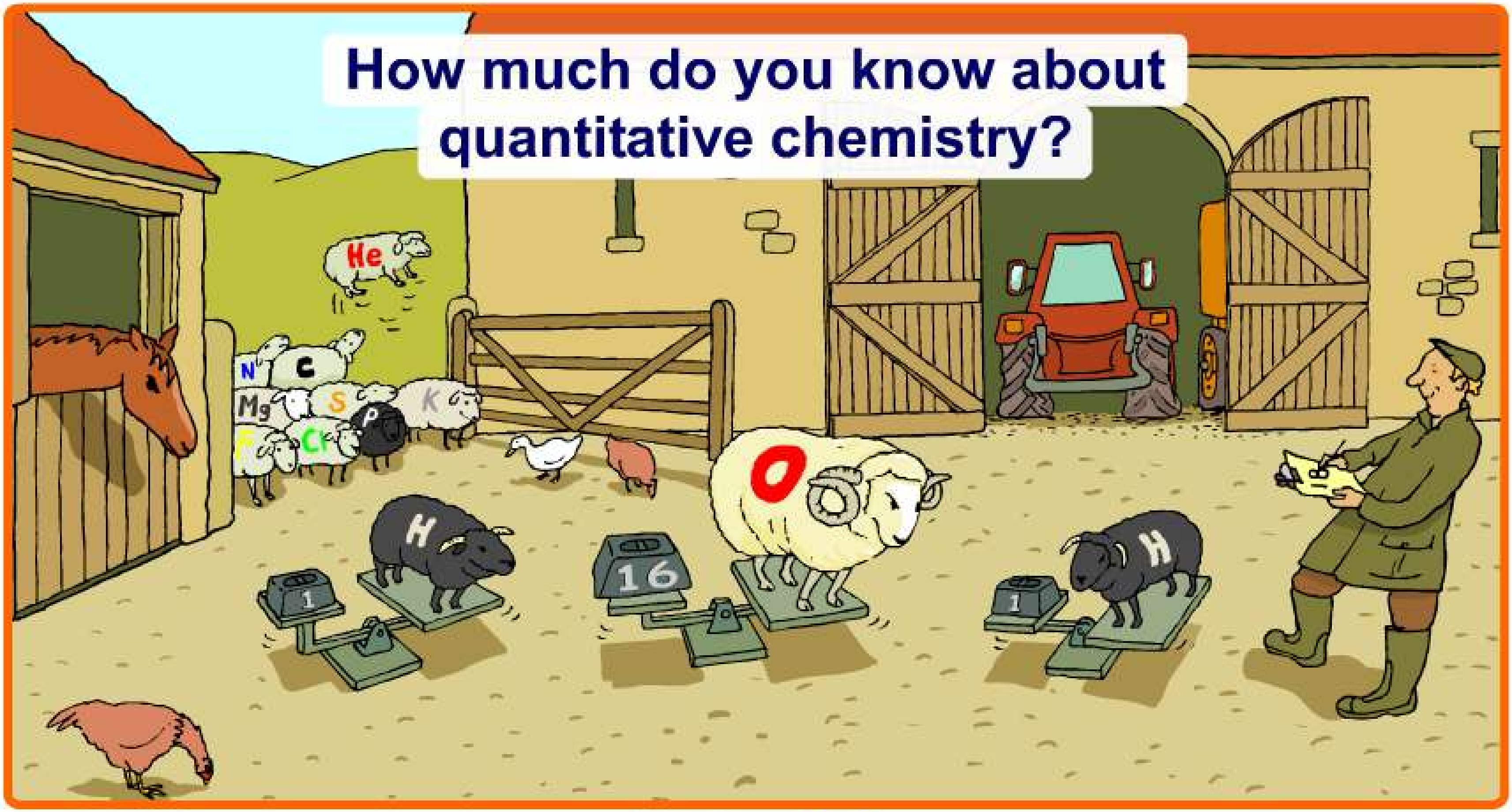
How quickly can you unscramble anagrams of words about

q u a n t i t a t i v e

c h e m i s t r y ?

start

Multiple-choice quiz



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