How to Measure the Length of a Molecule

In Chapter 3 of the book, Table 3.2 referred to the dimensions of a molecule. The values are so small that it is impossible to measure these sizes directly with school equipment, or even to see a molecule. This is a major stumbling block to learning chemistry.

However, there is a procedure that can be carried out in schools that gets close to these values. It makes use of a monolayer of a chemical on the surface of water. The effect can be seen on the surfaces of rivers and canals when uncaring companies and people discharge fuels[1] (Figure 1).

Figure 1

The wavelength of light reflected from the upper and lower surfaces of the oil film is the same as the thickness of the film. The colours in Figure 1 show that the thickness of the oil on the surface is between 400 and 700 nm, (4×10^{-5} to 7×10^{-5} cm). Students will have seen iridescence in soap bubbles, butterfly wings, bird feathers, seashells and rocks (opals). But even these values are over 100 times larger than the length of this molecule, oleic acid.

Nuffield chemistry introduced an experiment where a drop of oleic acid ($C_{18}H_{34}O_2$, Mr = 282.7 g·mol^{-1}) solution (see Figure 2) in pentane was dropped on the surface of water covered in a fine powder. Both oleic acid and pentane are insoluble in water. The fine powder shot out into a circle (the monolayer), which would then decrease in size as the pentane evaporated leaving a monolayer of oleic acid on the surface. The long hydrophobic carbon chain sticking up in the air and the hydrophilic carboxylic group at the end of the chain attracted to the surface water molecules (see Figure 3)

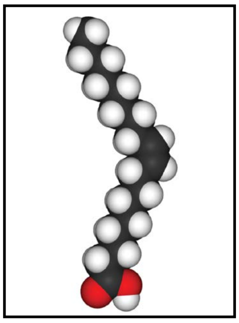

Figure 2: Space-filling model of oleic acid showing the long hydrophobic carbon chain and the (red) hydrophilic carboxylic acid group.

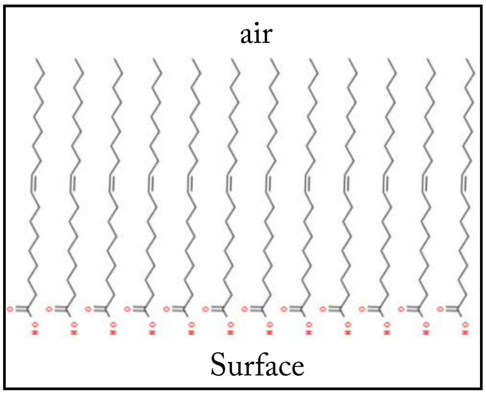

Figure 3: Oleic acid molecules line up as a monolayer on the surface of water. The height of the cylinder is the length of the molecule.

The suggested surface powder at the time was lycopodium powder, the spores of clubmoss plants. The spores cause skin allergies and breathing difficulties. In addition, the plant is an endangered species in the UK. Another suggestion was the use of flowers of sulfur. Both of these powders clagged into clumps, making the appearance of the circle difficult to measure. Here are two alternatives:

1. Grated cork: Cork is from a tree and discarded corks are easily obtained. The particles are prepared using a cheese grater.
2. Biodegradable glitter: This is suitable for demonstrations as it is easily seen when projected from a visualiser. It is important to use the biodegradable materials[2] as the plastic glitter can end up as microplastics in waste.

The solvent for the oleic acid has been changed to ethanol[3] as this dissolves instantaneously into the body of water.

Appreciation of the small size of particles is an important feature in the understanding of chemistry. It would be educationally useful to introduce this procedure to younger students, but there some concepts are difficult to grasp:

- *Large and small numbers*. If the molecules are only 9×10^{-10} m in length, then there are 34,867,844 molecules lying end to end in 1 cm length of molecules. This is difficult to visualise.
- The structure formula of the oleic acid is difficult to understand for beginners in chemistry.
- It is difficult to imagine the formation of a monolayer on the surface of water because it is invisible.
- It is difficult to compare the idea of a monolayer to that of a cylinder, with the height of the cylinder equivalent to the length of the oleic acid molecule.

This is then a suitable activity for older students who have experience with rearranging mathematical formulae and coping with more complex molecular structure.

Outline requirements

- Oleic acid, which is a viscous liquid at room temperature
- Ethanol (industrial denatured alcohol is suitable)
- Bowl of water
- Volumetric flask (100 cm^3)
- Balance weighing to at least 2 dec places
- 1 cm^3 syringe with blunt needle
- Transfer pipette
- Grated cork/Biodegradable glitter

Outline method with an example calculation[4]

1. Sink a plastic ruler in a shallow tray or bowl and add tap water. Let the surface settle and try not to move the bowl any more.
2. On the settled surface of water, sprinkle the grated cork so that it floats. (Eco-glitter is an alternative, more suited for a demonstration under a visualiser.)

Finding the volume of oleic acid in 100 cm^3 ethanol

1. Find the mass of a 100 cm^3 volumetric flask, add 1 or 2 drops of oleic acid from a 1 cm^3 transfer pipette and reweigh the volumetric flask. This will provide you with the mass of oleic acid used (m_{oleic}).
2. Use the density of oleic acid (0.895 g cm^{-3}) in the formula ($v_{olceic} = m_{oleic}/0.895$) to find the volume of the oleic acid.
3. Fill the volumetric flask with ethanol, stopper it and invert the flask several times to ensure good mixing. You now know the volume of oleic acid in 100 cm^3 of ethanol.

2 drops of oleic acid weighed 0.067 g (0.07 g on the 2 place balance). The density of oleic acid is 0.895 g cm^{-3}. The volume of acid must be 0.067/ 0.895 or 0.075 cm^3. This is the volume of oleic acid dissolved in 100 cm^3 of ethanol.

Finding the volume of oleic acid in one drop of the ethanol solution added to the surface of water.

1. With a 1 cm^3 transfer pipette, suck up the ethanolic oleic acid solution. Make sure that it is not dripping uncontrollably, and practise adding one drop.
2. Weigh a vial on a balance. Hold the pipette vertically above the vial. Add 10 drops of ethanolic oleic acid solution, note the reading. You might like to repeat this procedure 4 times so that 50 drops have been added. If you divide the mass of ethanolic oleic acid in the vial by 50, you have the mass of one drop of the oleic acid in ethanol (m_{drop}).

3. The density of ethanol is 0.789 g cm^3. Use the formula (v_{drop} = m_{drop}/0.789) to find the volume (cm^3) of a drop of the ethanol solution (v_{drop}). This is the volume of ethanol containing a small amount of oleic acid that will be placed on the surface of water in the next steps.
4. Volume of oleic acid in 1 drop of ethanolic oleic acid solution is $v_{oleic\ in\ drop} = v_{drop} \times v_{olceic}/100$.

50 drops of the solution weighed 0.791 g.

One drop had a mass of 0.0158 g.

The density of ethanol is 0.789 g cm^{-3}. The volume of one drop of ethanol with oleic acid is 0.0158/0.789 or 0.020 cm^3.

There is 0.075 cm^3 of oleic acid dissolved in 100 cm^3 of ethanol. So, in one drop (0.020 cm^3), there is 0.020 × 0.075/100 or 1.5×10^{-5} cm^3 of oleic acid.

Finding the length of the oleic acid molecule in one drop of the ethanol solution added to the surface of water

1. Move the pipette with ethanolic oleic acid about 5 cm vertically over the grated cork on the surface of the water and add 1 drop.
2. Measure the diameter (approx.) of the circle and halve the value for the radius (r) (see Figure 4).
3. So you now have $v_{oleic\ in\ drop} = \pi r^2 h_{olieic\ acid}$. Rearrange this equation $h_{olieic\ acid} = v_{oleic\ in\ drop}/\pi r^2$ to find the length of the oleic acid molecule.

For cork, the radius of the circle is 6 cm.

$1.5 \times 10^{-5} = \pi \times 6^2 \times h$; So **h = 1.33×10^{-7} cm or 1.3 nm**.

For eco-glitter:

$1.5 \times 10^{-5} = \pi \times 8.5^2 \times h$; So **h = 6.70×10^{-8} cm or 0.7 nm**.

As a carbon-carbon bond length is 0.15 nm in these are not bad results.

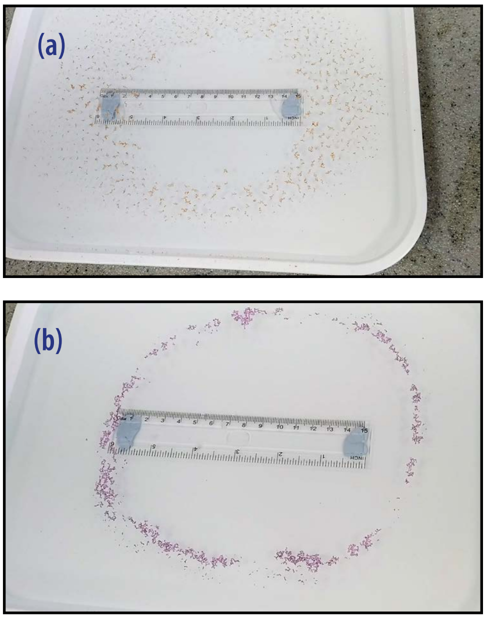

Figure 4: (a) Maximum diameter of the circle is about 12 cm. (b) Maximum diameter of the circle is about 17 cm.

Trouble with small numbers

Chapter 3 in the book showed that the number of stars in the Universe came to the same number as the number of molecules in 18 g (1 mole) of water (a mind-blowing fact if ever there was one), and visualising this in the mind requires a vivid imagination. There is a similar issue with size and distance.

Science deals regularly with much larger and smaller numbers than students generally encounter in 'life'. All students will be familiar with the distance of 2 cm on a ruler. Table 1 shows how this is represented in other units, from metres to picometres.

Table 1. Dimensions for small numbers.

	m (metre)	**cm (centimetre)**	**mm (millimetre)**	**µm (micron)**	**nm (nanometre)**	**pm (picometre)**
Standard notation	0.02	2	20	20,000	20,000,000	20,000,000,000
Scientific notation	2×10^{-2}	2	2×10^{1}	2×10^{4}	2.0×10^{7}	2.0×10^{10}
Found on calculators	2.0 E-2	2	2.0 E+1	2.0 E+4	2.0 E+7	2.0 E+10
In metres	1	0.01	1×10^{-3}	1×10^{-6}	1×10^{-9}	1×10^{-12}

- The size of the rod-shaped bacterium, *Escherichia coli K12* used in biology is 0.5 µm wide and a few microns long.
- The average size of a coronavirus is between 80 to 120 nm.
- The length of the oleic acid molecule is in the region of 1 nm.
- The size of the water molecule is about 0.282 nm or 282 pm.
- The diameter of a hydrogen atom is about 0.07 nm or 70 pm.
- The diameter of the proton in hydrogen is 0.0000017 nm (1.7×10^{-6} nm), 0.0017 pm (1.7×10^{-3} pm or 1.7 fm (which is a femtometre, i.e. 1×10^{-15} m).

From which it can be seen that a hydrogen atom (diameter 70 pm) is 40,000 times larger than the 1-proton nucleus diameter (0.0017 pm) and therefore the atom is mostly empty space.

To visualise this further, a logarithmic scale is often used, but there is another clash with the background of students:

Log scales

There is no mention of logarithms in the present English GCSE mathematics exam specifications. However, chemistry teachers have already introduced a log scale to young students with the pH scale for acids and alkalis. Physics teachers use them to show how far stars and planets are from the Earth. Biology teachers will be interested in the size of bacteria, viruses and DNA, and protein molecules in comparison to smaller molecules.

Log scales are a convenient way of condensing vast numbers, vast distances and large and small sizes into manageable diagrams. Figure 6 shows a logarithmic scale for the size of particles. The design for this diagram was started on PowerPoint and the distance from the 1 metre mark to the 10^{-1} mark was set at 1 cm. If the diagram had not used a log scale, the femtometre mark would be 10^{15} cm away. The Sun is 1.5×10^{11} m away from the Earth and is known as the astronomical unit (AU)). That femtometre mark would have had to be placed 6,600 AU away: the dwarf planet Pluto is about 40 AU away from the Sun. Mind-blowing facts again.

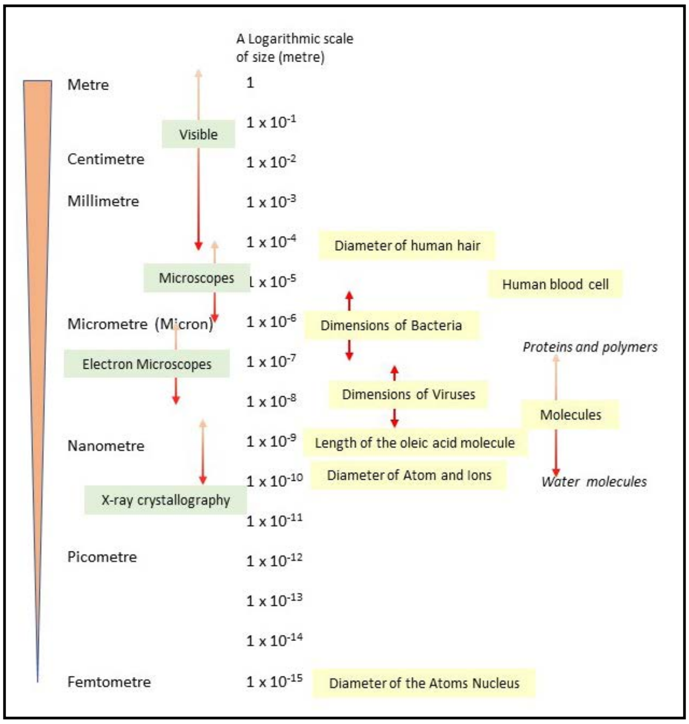

Figure 6: Visualising size on a log scale diagram.

Teacher note

Make wall charts illustrating log scales of size and pH.

Here is a crude version of the oil drop experiment, *Finding the average height of charcoal on a A4 piece of paper*. Measure the dimensions of the paper and calculate the surface area (A_{paper}). Weigh a piece of artist's charcoal before and after making a sweep of the charcoal over the paper. Do not worry if you cannot see the black colour in certain areas, we are looking for an average height. The density of carbon is 2.26 g cm^{-3}, which means that the volume of carbon can be calculated (V_{carbon}). Imagine the carbon as the height of a carbon cube to include the dimensions of the side and the length. As $V_{carbon} = h_{carbon} \times A_{paper}$), the height of the carbon can be calculated.

I got sizes down to 10^{-4} m.

References

[1] Photo from: Are you disposing of your oil or fuel correctly? - GOV.UK (www.gov.uk)

[2] For instance: About Bioglitter (sparkletown.co.uk)

[3] See e2a34898423e48da95c4a489d14a9197 (flinnsci.com)

[5] A video is available on https://youtu.be/8V72z_HYL1M

[6] 'It was as if you fired a 15-inch shell at a sheet of tissue paper and it came back to hit you.' This is a famous quote used by Sir Ernest Rutherford in his lectures. See Rutherford's alpha scattering experiment | IOPSpark.