Science4All

Teaching Resources

2023

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Dr Aamod Desai

Summary of Aamod's work:

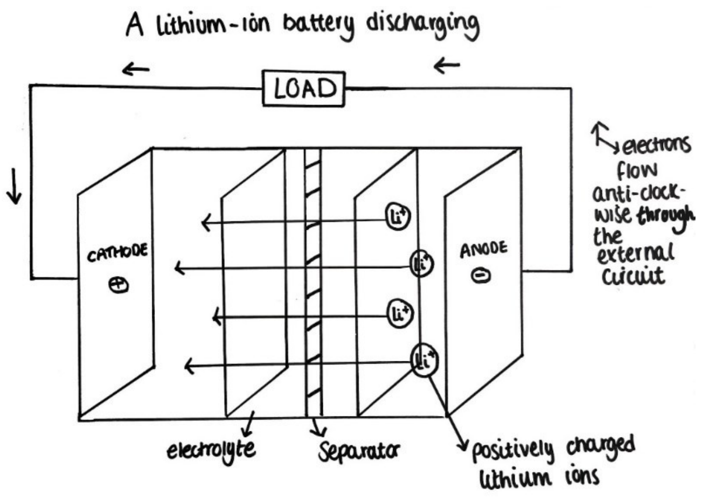
Batteries are very important to our everyday life. They power so many of our important electricals like phones, laptops and even cars. The key part of the batteries that we use today is the chemical element lithium, which also gives them their name: lithium-ion batteries. As the reserves of lithium in the Earth's crust is running out, scientists are working hard to replace the lithium in our batteries with sodium instead. These new batteries are called sodium-ion batteries. Aamod's research focuses on replacing parts of the batteries currently made from scarce materials with organic materials instead. Organic means that the compounds are primarily made of carbon. These molecules can be sourced naturally from biomass (consisting of plant and animal waste) or recycled waste. If Aamod can make them work, it will make battery production environmentally friendly and much more affordable.

Take a closer look …

Lithium-ion batteries:

Batteries consist of a negatively charged end (anode), a positively charged end (cathode), a separator, and an electrolyte. The electrolyte is a medium that ions can travel through inside the battery. An ion is an atom that becomes charged (this could be either positively or negatively charged) due to the loss or gain of electrons. Positively charged lithium ions are formed at the anode as the lithium atoms give up negatively charged electrons to the anode, giving the atoms an overall positive charge. The positively charged lithium ions move from the anode towards the cathode. The electrons that have built up at the anode also begin to move towards the cathode through an external circuit.[1] This electron flow is the basis of an electrical current which provides power to our devices, cars, laptops and many more. See Figure 1 which shows what the inside of a lithium-ion battery looks like during discharging and charging. In the figure, the device that is being powered by the battery is called the 'load'.

a)



b)

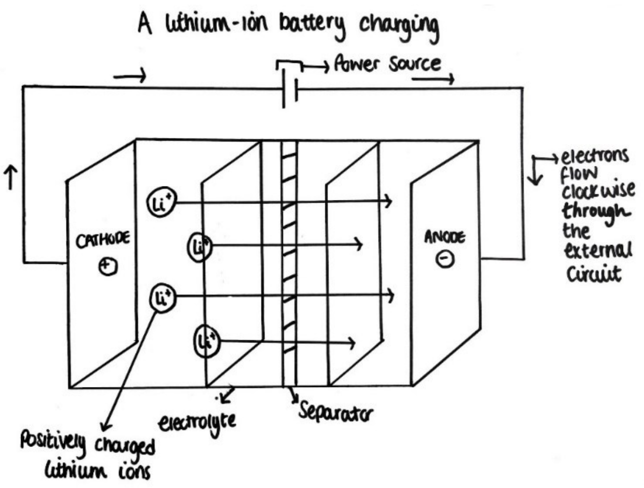


Figure 1: A diagram of the structure of a lithium-ion battery showing the movement of electrons and ions during (a) discharging and (b) charging.

An advantage of lithium-ion batteries is that they are rechargeable. When all of the positive lithium ions have reached the cathode, the battery must be recharged. When charging, positively charged lithium ions move from the cathode towards the anode. At the anode, they pick up electrons to become lithium atoms again with a neutral charge overall. The electron flow, in this case, is moving from the cathode towards the anode through the external circuit.[1]

Sodium-ion batteries:

Sodium-ion batteries work on the same principle as lithium-ion batteries. The driving force behind using sodium instead of lithium is that sodium is readily available and cheaper than lithium. Elemental sodium needed for batteries can be obtained from seawater by passing electricity through it to split sodium chloride (salt) into sodium and chlorine. This process is called electrolysis.

Lithium must be mined from the ground which usually leads to many harmful effects on the environment such as soil degradation, ecosystem damage, toxic waste products and pollution of water sources.[2] By using sodium instead of lithium we bypass many environmental concerns linked to lithium mining. Additionally, finding new environmentally friendly materials to use in sodium-ion batteries will help them to become even more sustainable and a viable low-cost energy solution for future electronics.

Organic materials:

An organic material is simply one that contains molecules made up of carbon atoms and the material that does not contain molecules made up of carbon atoms is called inorganic material. Much of life and nature as we know it is based on organic molecules. Aamod's research focuses on replacing the current inorganic material-based electrodes in batteries with organic materials, particularly anodes. It is these inorganic materials that we mine from the Earth's crust, and it is these that we are running out of. As much of our world is made from organic materials, we can source them much more easily. In fact, we can even extract the materials that we need from biomass or recycled waste, notably terephthalic acid, which we can get from waste PET (polyethylene terephthalate) bottles. By using these materials, we can bypass much of the negative environmental effects of mining the Earth's crust and make batteries more sustainable and economical. To be useful, the organic materials must be active towards reduction-oxidation reactions. This means that the chemistry needed to make the batteries work and to store battery charge should be possible (you can read more about this in Ioanna's section). Currently, inorganic electrodes work much better than organic ones. Scientists like Aamod are working hard to bring the organic electrodes up to industry standards so we can use them in the future.

Resources:

For teachers…

Let's talk science has some extra diagrams of the structure of lithium-ion batteries and the movement of electrons during use (discharging) and during charging. There is also a more detailed explanation of the chemistry involved in the batteries including redox reactions.

(https://letstalkscience.ca/educational-resources/stem-in-context/how-does-a-lithium-ion-battery-work)

The US department of energy has put together a simple guide on how lithium-ion batteries work. (https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work)

JAES Company has a good video about the history of lithium-ion batteries and details of materials used in their production. (https://www.youtube.com/watch?v=Te7JqKjz3B0)

For kids…

You can make a battery using coins. This BBC Science Focus Magazine article 'How to get electricity from coins' explains how to can build one.
(Article link: https://www.sciencefocus.com/science/how-to-get-electricity-from-coins/
Video link: https://youtu.be/-BqXBask8Og)

A new Guinness world record was set by RSC and Professor Saiful Islam for creating the highest voltage using a battery made from fruits
(Article link: https://www.rsc.org/new-perspectives/sustainability/rsc-lemon-battery-breaks-guinness-world-records/
Video link: https://www.youtube.com/watch?v=DzLqJoczEpo)

The Sustainable Energy Authority of Ireland has made a video on a potato battery experiment which is a fun way to get children interested in sustainability.
(https://www.youtube.com/watch?v=RMtRc_6FMsw)

Dr Filippo Formoso

Summary of Filippo's work:

Geology is a science which focuses on finding out the Earth's history by studying rocks and minerals. Filippo looks at what gases (such as air) do when they are trapped inside magma. Magma is a very hot liquid rock that we find under the Earth's surface. Magma that has broken the Earth's surface is called lava, which cools to form rock. Filippo makes and studies man-made magma in his lab, so he can apply lots of his findings to any planet where the laws of physics are the same as ours on Earth. His research helps us understand how elements needed to support life are released or stored by planets during their lifetimes. Additionally, some scientific techniques that Filippo and his team developed have applications in underground greenhouse gas storage. This is one of the ways that we can mitigate the effects of climate change.

Take a closer look…

As you can probably imagine, using real magma that is under the Earth's crust is quite tricky in the lab. Filippo would either need to make a very big hole in the bottom of the lab or fly to a country with active volcanoes. Fortunately, he can access huge hydraulic presses and furnaces that produce synthetic magma. Once he cools it down, the magma will form into a type of glass that Filippo can study.

When planets are still relatively young, they are made up of lots of magma. This is because the conditions that form planets are extremely hot. Just like soda, magma is a liquid that can contain gases. Notably, elements that are important to life (like nitrogen which is a vital part of DNA) get trapped in these magmas. Finding out more about how these magmas released key gases into our early atmosphere helps us better understand the origins of life. We can also get a better idea of how much gas and water is still stuck in the magma on Earth and how they move between the atmosphere and the ground.

As a lot of the best scientific discoveries are made by mistake, like penicillin and the microwave, Filippo's lab has been no exception. He found that the techniques developed for studying magma are also fantastic at studying how nitrogen is stored in aqueous fluids at high pressures and temperatures. This information can help us trap other gases in aqueous fluids, such as greenhouse gases, and store them underground. Greenhouse gases are gases that are released into our atmosphere and trap UV radiation from the sun. This creates a warming effect and leads to climate change. One of the most infamous greenhouse gases is carbon dioxide, which is commonly stored underground using carbon capture and storage technology.[3] Other greenhouse gases include methane, nitrous oxide and chlorofluorohydrocarbons (CFCs).

Resources:

For teachers…

The Royal Society of Chemistry (RSC) has a great infographic on the rock cycle. This helps explain where magma comes from and how different types of rocks are formed from lava. (https://edu.rsc.org/infographics/teaching-the-rock-cycle/4015807.article)

London School of Economics (LSE) has a very good webpage that explains more about carbon capture and storage technology and its pros and cons. (https://www.lse.ac.uk/granthaminstitute/explainers/what-is-carbon-capture-and-storage-and-what-role-can-it-play-in-tackling-climate-change/)

TedEd has a video that explains what the early Earth was like and the gases involved in the early atmosphere that help us to piece together the possible origins of life. (https://www.youtube.com/watch?v=de1hiS_XjWg)

For kids…

GlobalNews has a good video showing Iceland's lava flows from a volcano. Lava is magma that has broken the Earth's surface, so this video can show students what magma looks like underground. (https://www.youtube.com/watch?v=PrD0PfSQJwg)

GreatBigStory also has a video that shows researchers from the University of Buffalo making their own magma for their experiments. Although this is not the same way that Filippo makes his magma, it is a good demonstration of how synthetic magma can be made. (https://www.youtube.com/watch?v=Z_3X_YNsNSk)

Classroom experiment idea:

All you will need is an empty plastic bottle, baking soda, white vinegar, dish soap, sand, water, a tissue and optional food colouring. This experiment will help to visually demonstrate what happens when a volcano erupts and magma breaks the Earth's surface.

Bury your empty bottle deep into the sand. Add 60 mL of water, a few drops of dish soap, optional food colouring (red or orange would work best), and 60 mL of white vinegar to the empty bottle using a funnel. Wrap the baking soda in the tissue and drop it into the bottle. Stand back to see the volcano erupt.

How it works: In simple terms, the vinegar here is an acid whilst the baking soda is an alkali. As they come into contact, they begin to neutralise one another. This produces large amounts

of carbon dioxide gas. The dish soap collects the gas which makes lots of soapy foam which looks similar to a lava flow. Take a look at this article from ThoughtCo if you'd like to learn more about the chemistry of the reaction.
(https://www.thoughtco.com/equation-for-the-reaction-of-baking-soda-and-vinegar-604043)

Alternatively: Fun With Mama has a video showing the experiment. This is a good way to show the students the experiment whilst missing out on the clean-up! (https://www.youtube.com/watch?v=3GnaAmJCt7Y)

Video extension activity: Ask students to watch the GreatBigStory video. After they are finished, ask them if they noticed anything special about what the scientists wore. If they didn't notice anything, they can watch again. Magma is the definition of 'red hot'. It is very dangerous, so scientists need to wear lots of protective gear and pay attention to safety when working with it.

See if they can spot all the safety gear on this list:
Gloves

Visor

Helmet

Jacket

Overalls

Worksheet opportunity: The **safety worksheet** is a good opportunity to show students how scientists must be careful when working with dangerous materials. The worksheet invites students to circle the items of safety equipment among clothing that does not provide protection. This exercise practices being visually observant and helps teach the importance of safety.

Dr Hannah Lawther

Summary of Hannah's work:

Hannah's job is to be a detective in the chemistry lab. She uses a machine called a mass spectrometer to find out the chemical makeup of unknown samples. She works with a wide range of things from bacteria to dyes from old manuscripts. The mass spectrometer gives information on how heavy the molecules present in a sample are. Using this information, scientists like Hannah can match the mass of the sample molecules to the mass of molecules that we already know. The mass of a molecule is determined by the sum of the individual masses of the different atoms contained in the molecule. This gives us information on the sample's chemical makeup, which is essential to understanding things like medicine, history, food, and our environment.

Take a closer look …

Mass Spectrometry:

All elements have different masses. The periodic table is handy for telling us the different masses of the elements. We can use this information to find the mass of a molecule. Once we have determined how much of each element is present in the molecule, we can add the elements' masses to give the molecule's overall mass. We call this molecular mass. The mass spectrometer tells scientists the molecular mass of their unknown sample. The sample must be ionised (made into an ion) to do this.

Ions are charged atoms that arise due to the loss or gain of electrons. Ions can be either negatively or positively charged. Mass spectrometry works on the principle that magnetic fields deflect different positive ions to different degrees. Importantly, lighter ions are deflected more than heavier ones, and ions with more charge are deflected more than those with less.[4]

Firstly, the sample is ionised by knocking electrons off the molecules inside the sample to give positive ions. The ions are then accelerated into a beam by passing them through negatively charged plates. Lighter ions are accelerated more than heavier ones (similar to when kicking a light ball, it will travel faster than when you kick a heavier one). After this, the ions are deflected by a magnetic field. As deflection depends on mass and charge, different molecules pass through at different speeds.[4] The beam then meets an ion detector, and the information is used to make a spectrum that resembles a bar chart with m/z on the x-axis. M/z stands for mass/charge and tells us the mass of the ion fragment divided by its charge. Using databases of known molecules and the periodic table, we can match these masses up to the mass spectrum and deduce the contents of our unknown sample. Take a look at Figure 2 which shows what the inside of a mass spectrometer might look like.

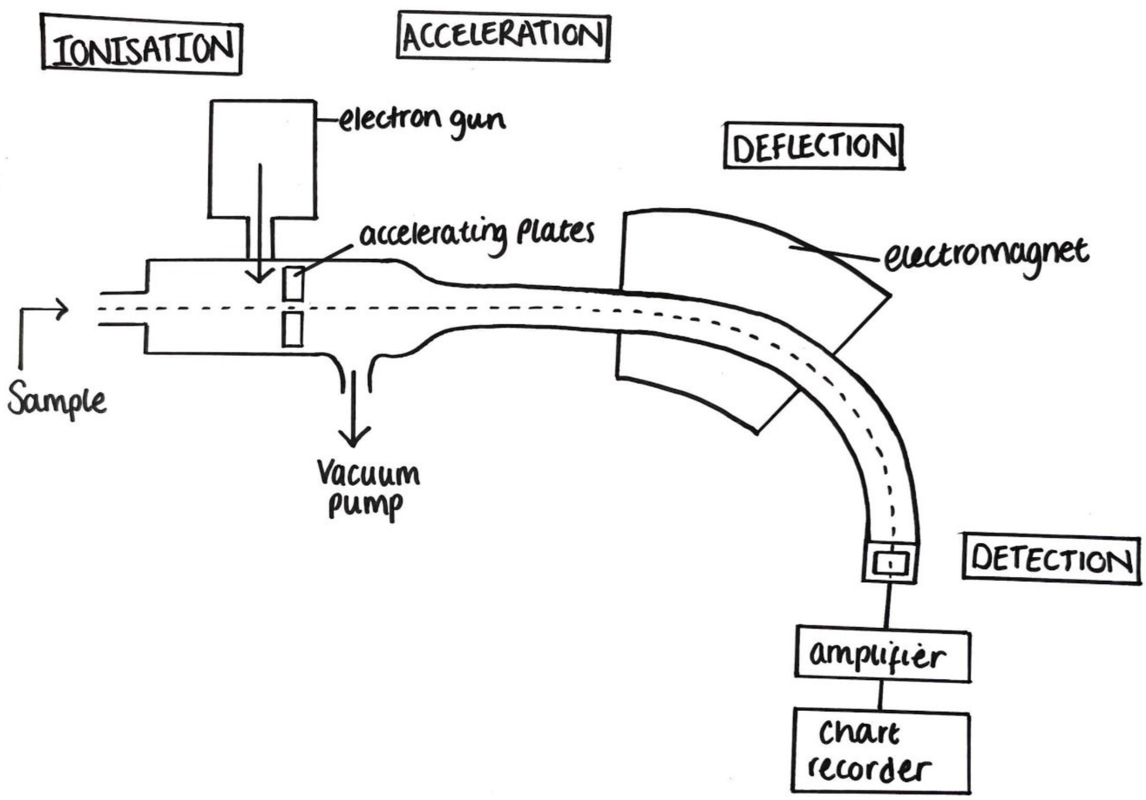


Figure 2: A diagram showing the inside of a mass spectrometer and the different stages that the sample goes through.

Resources:

For teachers…

Chem guide has an excellent and detailed guide on mass spectrometry with extra information for interest and also has diagrams of the spectrum and inner workings of a spectrometer. (https://www.chemguide.co.uk/analysis/masspec/howitworks.html)

The Royal Society of Chemistry (RSC) has a video showing a mass spectrometer working in the lab and explains how the machinery works and how scientists use the spectra. (https://www.youtube.com/watch?v=J-wao0O0_qM)

Professor Dave Explains has an interesting video on mass spectrometry which explains how a chemist might decode the spectrum given from a mass spectrometer. (https://www.youtube.com/watch?v=hSirWciIvSg)

The RSC also has an interactive online periodic table that shows changes of state at different temperatures, the groups and classification of the elements, how abundant they are, their isotopes, their uses and atomic data as well as how they were discovered and the origins of their names: (https://www.rsc.org/periodic-table)

For kids…

Worksheet opportunity: The **chemicals worksheet** introduces students to everyday chemicals and helps them to picture what they look like on a molecular level. In the activity, students are invited to count the number of different atoms in the molecules. The worksheet allows them to identify different atoms in the molecule and practice numeracy.

Mengfan He

Summary of Mengfan's work:

We encounter fragrances daily, whether in perfumes, cleaning products or air fresheners. We also encounter many natural scents, such as those from foods, pets or people. One of the most popular scents for fragrance is the natural musk found in animals. The musk from the male musk deer and civet cats are among the most sought after. Due to their desirable scents, these animals are in danger from commercial hunters. Mengfan is finding out how to make new fragrance compounds in his lab, particularly synthetic musk. This helps to protect these animals whilst allowing us to carry on enjoying their scents.

Images of the musk deer and civet cat can be found at Britannica and the World Wildlife Fund (WWF) webpages.

(https://www.britannica.com/animal/civet-mammal-Viverridae-family/images-videos#Images)
(https://www.worldwildlife.org/pages/musk-deer)

Take a closer look...

Synthetic musk:

These synthetic alternatives are modelled after muscone (deer musk) and civetone (civet musk). The main challenge for scientists like Mengfan is trying to keep the chemical structure of the musk similar enough to give the desired scent but avoiding negative chemical effects. For example, nitro musk and polycyclic musk are two classes of synthetic musk that are difficult to break down, specifically in aquatic environments. This causes danger to local marine life as the compounds stick around in the fatty tissues of the fish.

Many synthetic musk preserve the sweet and clean scent of the musk whilst avoiding the faecal notes that persist in animal musk. These synthetic counterparts are so close to the original scent that field biologists have used 'Calvin Klein's Obsession for Men' to attract jaguars into camera traps.[5] The camera traps allow biologists to take close images of the cats and collect other data without harming the animal. Additionally, the jaguars tend to rub their chin or cheeks on the scented item. The biologists then collect the hairs that the jaguar leaves behind to conduct research.[6] It is thought that the synthetic civetone resembles a territorial marking, and the accompanying scents, like vanilla, spark the big cat's curiosity.[5] This was originally discovered at Bronx Zoo where researchers studied how twenty-three different perfumes attracted tigers' attention.[6] These techniques are invaluable to conservation efforts as these big cats are endangered. Gathering information on the cats allows scientists to track them and protect them from poachers.

Resources:

For teachers…

Scientific American has a fun blog post about how field biologists are enticing the jaguars into their camera traps and the data they are recording. (https://blogs.scientificamerican.com/thoughtful-animal/youe28099ll-never-guess-how-biologists-lure-jaguars-to-camera-traps/)

Today I found Out has a great video about the history of the use of musk in fragrance and how some medical conditions can be diagnosed using scent. (https://www.youtube.com/watch?v=GwNz_5sjrHY)

For kids…

Would be good to remind students to not try this at home on their own. Also, make sure no student is allergic to any substances/pollen used in these activities.

Classroom experiment idea: With some small empty bottles, flower petals or herbs, citrus fruit, and food colouring perfume can be made easily! Firstly, invite the student to add petals and/or herbs of their choice into an empty bowl. Add some water to steep the flowers and herbs. A squeeze of citrus fruit is also a nice addition. Filter the mixture into an empty bottle and add a drop of food colouring of their choice. Now they are fragrance scientists!

Secondary idea: If the prospect of making perfume sounds like too much chaos, find some things with strong smells (for example, citrus fruit, fish, coffee grounds, mint, or lavender) and place them in containers with holes in the top. Invite students to come and smell each box blindfolded. Allow them to guess what they are smelling. Invite them to assume the role of a fragrance scientist. Which scents were the best, and what would they include in their perfume?

Dr Ioanna Maria Pateli

Summary of Ioanna's work:

Ioanna is in the business of making electricity. Her work focuses on making, testing and optimising batteries. Batteries are the key power source for many important items like watches, mobiles and even cars. We must understand how our batteries age to see how we can make them perform better or identify any safety issues. Part of Ioanna's job is to take used batteries apart and look inside them with a microscope to investigate any changes.

Take a closer look…

Batteries:

Alessandro Volta invented the first battery. It consisted of layers of silver and zinc with saltwater-soaked cloth in between. The 'volt', a unit of electric potential, gets its name from this scientist!

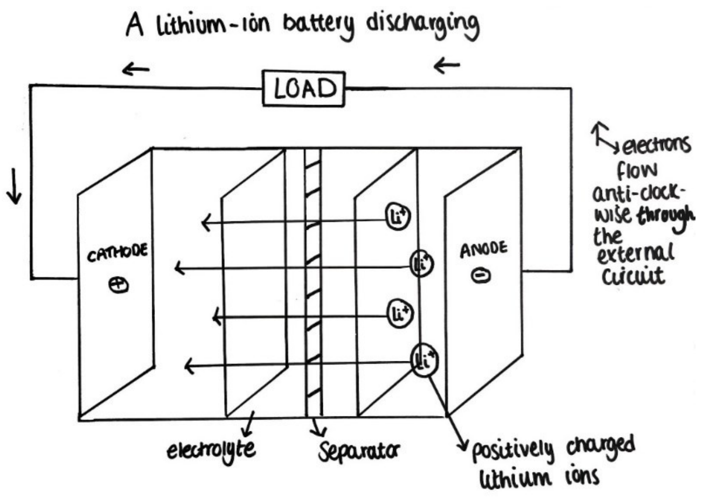
Britannica has some images of Alessandro Volta and a sketch of the first battery for interest. (https://www.britannica.com/biography/Alessandro-Volta/images-videos#Images)

Batteries convert chemical energy into electricity inside an electrochemical cell. Batteries can have one or more electrochemical cells, but they all have two electrodes separated by an electrolyte. An electrolyte is a medium which will allow ions to move through. An ion is an atom that has become charged by the loss or gain of electrons. Electrodes are at either end of the electrochemical cell. One electrode is called the anode (-, negative electrode), and one is called the cathode (+, positive electrode).

Generally, electrons accumulate at the anode due to a process called oxidation reaction, whilst the cathode can accept electrons due to a reduction reaction. The natural movement of the electrons is to flow from the negative anode to the positive cathode (think of opposites attracting). This flow of electrons is what we know as electricity and provides power to our devices.

The electrolyte is essential as it allows the positive ions to flow throughout the cell, which balances the negative charge that comes from the flow of electrons. The cells usually have a semi-permeable membrane (separator) which prevents the two electrodes from contacting each other whilst allowing ions to travel from one end of the cell to the other. See Figure 3 for a visual representation of the inside of a battery.

a)



b)

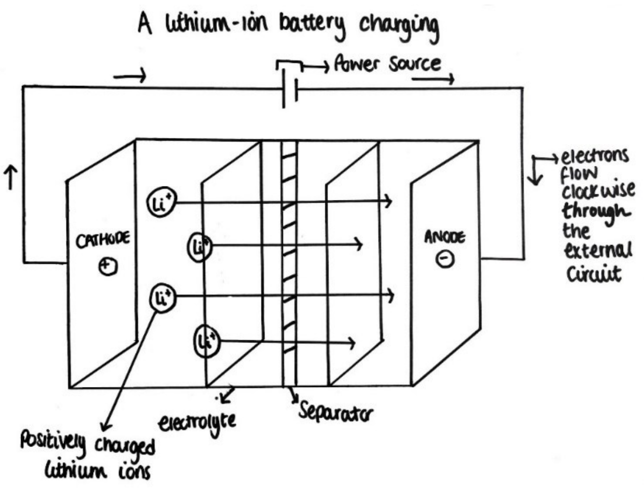


Figure 3: A diagram of the structure of a lithium-ion battery showing the movement of electrons and ions during (a) discharging and (b) charging.

When recharging a battery, this process is effectively reversed. However, the repetitive resetting of the electrochemical cell begins to degrade the electrodes little by little and causes the internal crystals to become more disordered.[7] The battery will lose performance and become less efficient. Additionally, recharging some batteries before they have been used much can lead to a 'memory effect' where the cell 'remembers' where it was up to in its discharge cycle and does not recharge properly.[7] Self-discharge can also occur within the battery, wherein chemical reactions cause it to lose energy over time even when not in use.[7] These problems are areas that Ioanna may potentially explore in her daily work. Ioanna will also use redox (reduction-oxidation) chemistry when she makes new battery cells. If you want to learn more about lithium-ion batteries, please see Aamod's section!

As part of her job, Ioanna investigates the degradation of battery electrodes. Various chemical reactions occur on the surface of the electrodes during continuous charging and discharging cycles of the battery causing degradation on the surface of the electrodes. She checks the surfaces of battery electrodes using two techniques called Scanning Electron Microscopy (SEM) and Raman spectroscopy. These techniques help understand what contaminants are formed on the electrodes and the microstructure of the surface of the electrodes.

Scanning Electron Microscopy (SEM) uses a focused beam of electrons that hit the surface of the sample. These electrons interact with the atoms on the surface of the sample and produce signals that are characteristic of the sample. The detectors on the instrument pick up these signals and produce magnified images of the surface of the sample. With SEM it is possible to obtain magnified images of the sample surface from about a hundred to about a million times!

Raman spectroscopy is a non-destructive technique that can be used to analyse the surface of a sample. It is based on the interaction of light of specific energy with the chemical bonds of the sample. This technique provides various information such as the chemical composition and structure of the sample. The output obtained from this technique is a distinct chemical fingerprint of a particular molecule or material and therefore Raman spectroscopy can be used to easy identification of chemical compounds on the surface of the sample.

More information on SEM can be found here:
https://www.scimed.co.uk/education/sem-scanning-electron-microscopy/#:~:text=Scanning%20electron%20microscopy%20works%20by,which%20act%20to%20focus%20it

More information on Raman spectroscopy can be be found here:
https://www.horiba.com/aut/scientific/technologies/raman-imaging-and-spectroscopy/raman-spectroscopy/

Resources:

For teachers…

The Australian Academy of Science has a very useful page with lots of extra information and diagrams about how batteries work.
(https://www.science.org.au/curious/technology-future/batteries)

MIT also has a helpful and concise webpage detailing the chemistry involved in batteries. (https://engineering.mit.edu/engage/ask-an-engineer/how-does-a-battery-work/)

TED-Ed has a good video on how batteries generally work.
(https://www.youtube.com/watch?v=9OVtk6G2TnQ)

For kids…

RSC has a great video for chameleon experiment demonstrating a colour-changing redox reaction between potassium permanganate and lollipop. It is a great way to show students the kind of chemistry going on within batteries (electron transfer) visually.
(https://www.youtube.com/watch?v=6gEwCn0ONFU&t=4s)

Further information on the science behind this can be found in the RSC education in chemistry page.
(https://edu.rsc.org/exhibition-chemistry/demonstrating-the-chameleon-redox-reaction-with-a-lollipop/4016633.article)

Dr Juan Gonzalez Carballo

Summary of Juan's work:

Juan gets the best of both worlds in his job by working as a scientist in the lab and in business development. Juan will attend working events to reach out to companies and make new relationships with them. These companies usually seek someone to help them develop new products, which is where the lab comes in. Juan will return to the lab and conduct experiments to produce new chemicals. Work is very varied, and he could work on anything from aircraft fuel to shampoo!

Take a closer look…

Contract research and development:

Lots of companies and institutions don't have the infrastructure necessary to do product development entirely on their own. In this scenario, companies may start reaching out to scientists such as Juan who works on behalf of Drochaid, a company specialising in scientific research services to undertake this research for them, which is generally more cost-effective and efficient than the companies attempting to do it on their own. Contracts between Drochaid and the university facilitate seamless research and development.

Scaling up from laboratory to industry:

Once it has been proved that a particular compound can be made, moving from laboratory to industrial-scale production can be challenging. This is because it is much easier to make things on a small scale when compared to a large scale. In a lab, you can generally use as much energy and time as you need to make a compound as you will only be making a small amount. In industry, the quantities are much larger, so the energy requirements, time and temperature are also scaled up.[8] This can get expensive very quickly. A significant part of Juan's work is finding ways to make new compounds that can be scaled up to an industry level easily.

Resources:

For teachers…

Dr Khan has written a detailed article on LinkedIn detailing the challenges of scaling up production in more detail: https://www.linkedin.com/pulse/challenges-scale-up-from-laboratory-production-dr-mohd-ismaeel-khan

A real-life example of research and development comes from the pharmaceutical industry. Biogen has made a video that explains the process of taking a successful molecule found in research to large scale manufacture of a biologic drug:
https://www.youtube.com/watch?v=3u7pUE6xbUo

For kids…

Worksheet opportunity: The **colour worksheet** can help students use similar problem-solving skills to those that Juan needs in his lab. Invite them to imagine that they are a colour scientist, and someone asks them how to make a range of different colours. They must colour or write in the paint blobs to show the formulas that make the new colours (for example, if they are asked to make orange: red blob + yellow blob = orange blob).

Dr Siobhan Smith

Summary of Siobhan's work:

When chemists make things in the lab, they are not always sure if their samples are pure. Additionally, chemists sometimes come across unknown samples they need to learn more about. To do this, scientists tend to use instruments such as machines that can measure things. The data from these instruments will provide enough information so scientists can find out what they need to know. Siobhan looks after these instruments in the lab and teaches people how to use them, read the data and troubleshoot if things don't look right. The instrument Siobhan looks after is called the NMR machine that works by a combination of a large magnet and a radio which give data in the form of a spectrum (this usually looks like a type of graph). Sometimes Siobhan might talk with students and help them understand their spectra. Sometimes she might need to fill the magnets with very cold liquids called cryogens (for example, nitrogen or helium) which keep the magnets working.

Take a closer look…

NMR:

A big part of Siobhan's job is working with NMR machines. NMR stands for nuclear magnetic resonance and is a type of spectroscopy that exploits the magnetic properties of certain nuclei. Spectroscopy means that the sample we are investigating will interact with electromagnetic radiation in a way that we can measure (this gives us a spectrum at the end). We can explore the properties of many nuclei with NMR, but most commonly, we focus on hydrogen and carbon as these atoms are very common in molecules and so can tell us a lot about our samples.

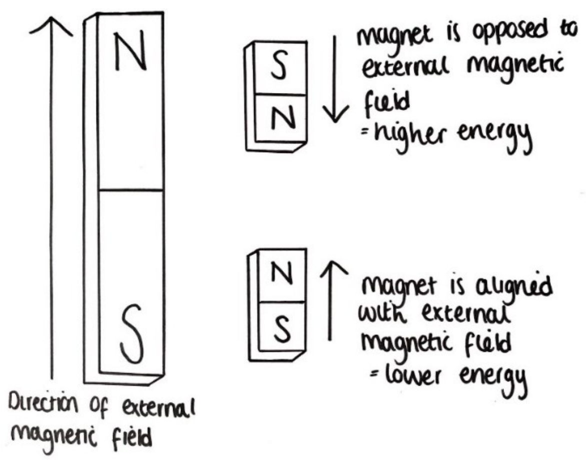


Figure 4: A diagram to help link the concept of magnets to the behaviour of carbon and hydrogen nuclei.

Hydrogen and carbon nuclei have magnetic properties, which we call nuclear spin. This makes the nuclei act as little magnets.[9] We can align the nuclear spin with the large magnet inside the NMR machine.[9]. If we apply a certain amount of energy, we can flip the direction of the nuclear spin so that it is now opposed to the large magnet in the machine.[9] Take a look at **Error! Reference source not found.** and imagine that the large magnet represents the magnet inside the NMR machine (the external magnetic field). The small magnets represent the nuclear spin of the atomic nuclei such as carbon or hydrogen. We can see that when the small magnet is opposed to the external magnetic field, it has higher energy. This is why energy needs to be supplied in order to flip the nuclear spin. Usually, the energy needed is supplied as radio waves. Each hydrogen or carbon will be in a slightly different chemical environment from the others in the molecule. This means that slightly different frequencies of radio waves are needed to flip these nuclei. Using this information, the NMR machines can generate a spectrum that chemists can analyse to deduce the sample's chemical structure.

An MRI (magnetic resonance imaging) machine also works in a very similar way. The large magnets in these machines combined with the radio wave frequencies measure how much energy is needed to slip the nuclear spins of the hydrogen nuclei in our own bodies.[10] The spectrum we get from this machine is converted into a detailed photograph of the body which can help diagnose cancers, bone and muscle problems, to name a few.[10]

Resources:

For teachers…

Chemguide has some excellent walkthrough guides of hydrogen and carbon NMR with diagrams if you would like to learn more.
(https://www.chemguide.co.uk/analysis/nmrmenu.html)

Bruker has made a helpful video that provides an overview of NMR and shows what the inside of a machine looks like.
(https://www.youtube.com/watch?v=Sn3dNMv-67k)

For kids…

If you want to explore a little bit more about the cryogens that Siobhan uses, Steve Spangler has a good video showing experiments with liquid nitrogen.
(https://www.youtube.com/watch?v=MaxZwsqstFs)

Worksheet opportunity: The **measurements worksheet** will allow students to practice measuring things for themselves, just like instruments do! Students will be able to practice filling water levels in beakers to the correct mark by drawing lines at the correct level. They can also practice adding volumes together to find the total volume.

Classroom experiment idea: Place a selection of items on a table. Give students a magnet and invite them to come up to the table. Let them test which items are magnetic and which are not. Do the magnetic items have any similarities? For example, are they all shiny? Are they all metal? Some metals that we find in our homes are magnetic, like iron and steel. Items that contain these metals will be attracted to the magnets. Here is a list of objects that you could use in your experiment:

Magnetic	**Non-magnetic**
Paper clips	Paper
Keys	Button
Stainless steel spoon	Pencil
Screws	Eraser
Saucepan	Plastic spoon

Soneni Ndlovu

Summary of Soneni's work:

Catalysts speed up the rate of reactions without getting used up. This makes them very useful in industrial processes, especially in making medicines, as they can make reactions much more economical. Soneni works on making new catalysts from environmentally friendly materials to help make laboratory and industrial chemistry more sustainable.

Take a closer look:

Catalysts:

Catalysts come in two types, homogenous and heterogeneous catalysts. Homogeneous catalysts are in the same phase as the reaction products (for example, a liquid catalyst in a reaction with liquid reactants). Heterogeneous catalysts are the opposite and exist in a different phase than the reactants. This makes heterogeneous catalysts easier to separate from the products at the end of the reaction. Soneni is particularly interested in these kinds of catalysts.

When we talk about a reaction, it is important to address activation energy. The activation energy of a reaction is the energy that the reactants need to be able to react and form products. Catalysts work by lowering the activation energy of the reaction. They do this by changing something called the 'transition state' of the reaction. In simple terms, this is the midpoint of the reaction where the reactants are partway through being transformed into products. The reactants have reorganised their bonds to look different from how they did at the start of the reaction but have not yet turned into the final product. Changing the transition state provides a lower energy pathway for the reaction. This means that a larger proportion of collisions between reactants will be successful, and the reaction will be faster. Figure 5 shows how the activation energy of a reaction varies with and without a catalyst.

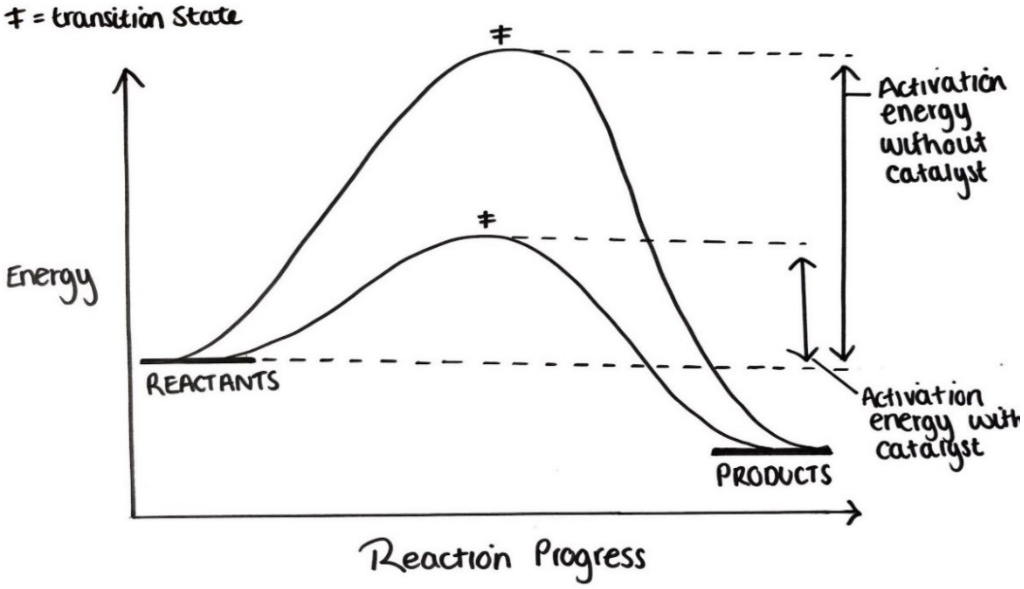


Figure 5: A diagram showing the differences in activation energy for a reaction with and without a catalyst.

An example of a catalyst is the enzymes in our body that help to convert our food to energy and play a part in respiration and many other biological functions.[11] Additionally, cars are fitted with catalytic converters that use catalysts like platinum to convert dangerous pollutants and toxic gases into less dangerous counterparts like water and nitrogen.[11]

Resources:

For teachers…

Rovira I Vigilli has a very condensed and straightforward explanation of catalysis. (https://www.youtube.com/watch?v=wyMLpY_zIM4)

FuseSchool has a video explaining how catalysts work with some examples from industry. (https://www.youtube.com/watch?v=m_9bpZep1QM)

ChemTalk has a page that summarises how catalysts work with examples of homogenous and heterogeneous catalysts.
(https://chemistrytalk.org/catalysts-activation-energy/)

Khan Academy also has a page on catalysis and goes into acid-base catalysis and the mathematics behind rates of reactions if you are interested in learning more. (https://www.khanacademy.org/science/chemistry/chem-kinetics/arrhenius-equation/a/types-of-catalysts)

For kids…

The famous elephant toothpaste reaction is caused by the decomposition of hydrogen peroxide into water and oxygen using potassium iodide or yeast and warm water as a catalyst. Here are a couple of short videos showing the experiment in action:
Youtube – Elephants toothpaste experiment 1
(https://www.youtube.com/watch?v=ezsur0L0L1c)

The genie in the bottle - the catalytic decomposition of hydrogen peroxide is an alternative for elephant toothpaste reaction.This article explains the science behind the experiment and also includes a video demonstration of the experiment.
Article: https://edu.rsc.org/exhibition-chemistry/the-genie-in-the-bottle/3009156.article
Video: https://www.youtube.com/watch?v=S3o-_tQ7MME

Classroom experiment ideas:

Yeast acts as a catalyst in breadmaking and this is explained well by Imperial College London- Catalysis - activity. (https://www.imperial.ac.uk/be-inspired/schools-outreach/secondary-schools/stem-in-action/energy-and-sustainability/catalysis--activity/)

The elephant toothpaste experiment can be done with simple household items and is guaranteed to get students' attention. You'll need hydrogen peroxide, washing up liquid, food colouring (optional), warm water, fast action yeast and an empty plastic bottle. The BBC has put together a guide with step-by-step instructions and a video to show you how to set up the experiment.
(https://www.bbcgoodfood.com/howto/guide/elephant-toothpaste)

Syed Ansar Ali Shah

Summary of Syed's work:

Syed works with catalysts just like Soneni does. Remember that catalysts are things we can add to reactions to speed them up, but they don't get used up themselves. Syed makes a special sort of catalyst called a photocatalyst. We know that plants need the sun to grow. This is because plants use the sun's energy to convert carbon dioxide and water into glucose and oxygen in a process called photosynthesis. The 'photo' part of photosynthesis and photocatalyst means 'light'. Photocatalysts work by absorbing light and converting it to energy. This energy can be used to trigger a chemical reaction. This technology can help break down pollutants in both water and air which can harm people and aquatic life. By turning these dangerous chemicals into harmless ones with a photocatalyst, scientists are helping to clean up and protect our environment.

Take a closer look…

Photocatalysts:

Photocatalysts rely on semiconducting materials to provide energy to electrons when light hits them. Electrons exist within levels inside the molecules of the semiconductor. Energy is supplied to the electrons to allow electron holes to form. This process is best described with an analogy:

Imagine a lift that goes up and down between two floors. All the electrons normally exist on the bottom floor of the building, where each electron sits on a chair. When the electrons are given more energy, they can go into the lift and travel to the upper floor of the building, leaving empty chairs behind on the bottom floor. This is exactly what happens inside the semiconductor, except that we call the bottom floor the 'valence band', the upper floor the 'conduction band' and the empty chairs 'electron holes'. These electrons and electron holes are very important as they can split water (H_2O) into more reactive radical species (OH and O_2).[12] It is these super reactive radical species that react with pollutants in the environment to help clean our air and water.[13] Figure 6 shows a schematic of this process where the energy that has been supplied to the electrons is UV light and the semiconducting material is titanium dioxide.

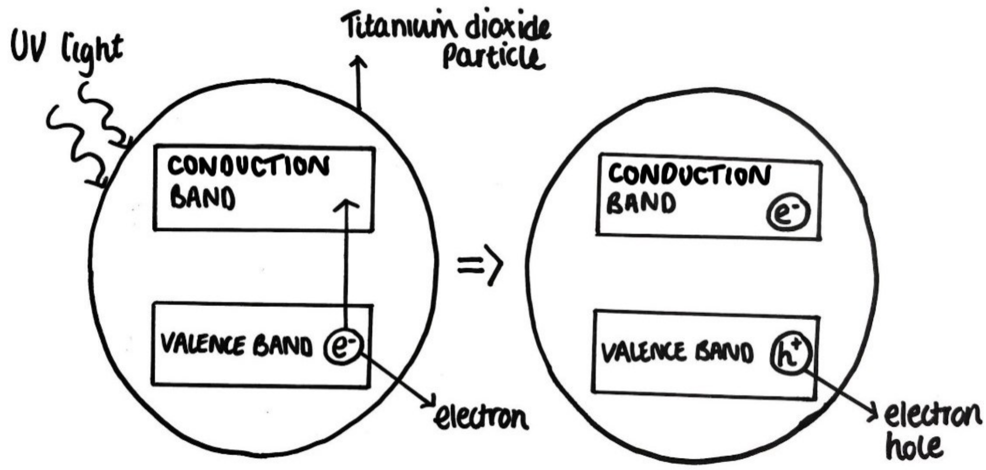


Figure 6: A diagram showing how electron holes are formed in semiconducting materials.

Titanium dioxide is the semiconducting material used in lots of photocatalysts. It is a safe, non-toxic chemical found in our sun creams and food, and is a standard pigment in white paint. An important part of this technology is that it is self-cleaning, so it is very low maintenance. We can put these catalysts in lots of different environments, and they will do their job without anyone having to clean them. Chemical species that love water, called hydrophiles, coat the surface of the titanium dioxide.[14] These hydroxyl radicals loosen the dust and dirt on the surface of the titanium dioxide so that when the rain comes and spreads out along the hydrophilic surface, the dirt is washed away.[14]

Scientists today are working hard to find alternative photocatalysts that can get the same high efficiency as titanium dioxide or even better. Syed is working on something called oxide spinels, specifically zinc aluminate ($ZnAl_2O_4$). This material is a nanomaterial, which means that its particles are between 1 and 100 nm in size. To put this into perspective, a sheet of paper is about 100,000 nm thick![15] Nanomaterials have an increased surface area, so there are more sites for chemical reactions to take place, making it more efficient.

Resources:

For teachers…

BIOMIMIC has a good summary page about photocatalysts with some excellent diagrams showing how the technology works.
(http://www.biomimic-c.com/en/service/biomimic_coat/photocatalyst/)

ChemistryDocs also has an excellent resource on photocatalysts that goes into depth about the chemical mechanisms involved if you are interested in learning more. (https://chemistrydocs.com/photocatalysis-types-mechanism-and-applications/)

Certified Germ Control has a short video about how photocatalysis has applications in germ sanitisation: (https://www.youtube.com/watch?v=6PIPXIyL_ms)

The German Federation for Applied Photocatalysis has a very good video that gives a simple explanation of how photocatalysis works.
(https://www.youtube.com/watch?v=YHys1hxD1UY)

For kids…

Photocat A/S has a video that can be used to help explain photocatalysis visually to students. The concrete slab on the right has a photocatalytic coating, whereas the slab on the left does not. Dye is applied to both and then exposed to UV light. The slab on the left has a stain, whereas the one on the right does not. This shows that the photocatalyst has worked by degrading the dye. (https://www.youtube.com/watch?v=6TYFLcdWUGI)

Dr Yi-Ying Sung

Summary of Yi-Ying's work:

The world is made up of atoms. Everything we see, touch or feel is made up of atoms, including the air we breathe and our own bodies. We can't see these microscopic building blocks of our world with our eyes; they are far too small. In fact, in just one grain of sand, there are 43 quintillion atoms. That's 43 with 18 zeros after.[16] Yi-Ying is an atom expert and uses a special machine called a scanning tunnelling microscope. By changing the tip of her microscope, she can pick up atoms and place them wherever she wants to, much like picking up toys using a claw machine at the arcade. Yi-Ying uses the machine to make different patterns with the atoms. This is useful in investigating how the arrangement of atoms on the surface of materials may affect how they behave.

Take a closer look…

Scanning tunnelling microscope (STM):

Quantum mechanics is the weird and wonderful world of rules that govern how the small things like atoms and electrons behave. Many of the rules of quantum mechanics seem counterintuitive to us as all the things we interact with are subject to the rules of general relativity instead. In short, when we start to deal with the tiny things that make up our universe, the rules that apply to our everyday lives don't apply. The STM is based on something called quantum tunnelling.[17] To explain this, we need to think of particles, in this case electrons, as waves. Suppose we put a barrier in front of the particle, quantum tunnelling is the probability that we will find it on the other side of the barrier.[18] Lighter the particles and smaller the barriers, the more probability of finding the particles on the other side of the barrier.[18]

If we apply this to the microscope, the electrons between the sample and the metal tip of the microscope can move through the air or liquid separating them (the barrier).[17] By measuring the current generated by this movement of electrons, we can figure out how close the tip of the microscope is to the sample.[17] This allows us to generate an image of the sample's surface on an atomic scale.[17] By tuning the current, we can create a bond between the tip of the microscope and an atom on the sample's surface.[19] This way, we can pick the atom up and move it wherever we want.

Resources:

For teachers…

TedEd has a fun video that puts how small an atom really is into perspective: (https://ed.ted.com/lessons/just-how-small-is-an-atom#watch)

The Royal Society of Chemistry has a brilliant webpage explaining how quantum tunnelling works. Some videos are included to help with the concept: (https://www.chemistryworld.com/news/explainer-what-is-quantum-tunnelling/4012210.article)

NanoScience has a good page about how the STM works without getting too deep into the complicated world of quantum mechanics. (https://www.nanoscience.com/techniques/scanning-tunneling-microscopy/)

La Physique Autrement has an animation that shows how the STM works with captions explaining the process involved. (https://www.youtube.com/watch?v=HE2yE8SvHmA)

For kids…

IBM was the first to use the STM for moving atoms from one place to another. Since then, IBM has won the Guinness World Record for the smallest stop-motion film by manipulating atoms using STM. This video shows the film 'A Boy and His Atom'. (https://www.youtube.com/watch?v=oSCX78-8-q0)

Worksheet opportunity: The **chemicals worksheet** introduces students to everyday chemicals and helps them to picture what they look like on a molecular level. In the activity, students are invited to count the number of different atoms in the molecules. The worksheet allows them to identify different atoms in the molecule and practice numeracy.

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