ENERGY IN SCIENCE AND SOCIETY

Many people are concerned about preserving the planet's environment.

Net Zero

In 2019 the UK Government set a legally binding target of the year 2050 for the country's greenhouse gas emissions to reach net zero (meaning the new emissions put into the atmosphere don't exceed the rate they are removed). It makes up a part of the global initiative towards sustainability – three of the United Nation's sustainable development goals are tied to this effort – an emphasis on climate action, developing sustainable cities and communities, and sourcing affordable and clean energy.

To understand how the UK (and the world) intends to meet these targets, we need to look at the way we heat our homes and businesses, the way we transport people and goods, and the way our electricity is produced. Each of these areas is united by a key scientific concept – the concept of energy.

Car engines that use fossil fuels release carbon dioxide into the atmosphere.

Energy and the energy sector

As we go about our modern daily lives, we need at least some amount of energy to be transferred. Whether it's boiling water for a cup of tea, or keeping a nice warm home, or making sure our phone batteries are fully charged, we are transferring energy. People often say we're "using" energy, or that we need to "save" energy[1] but really we only ever transfer energy from one store to another. Energy is always conserved. The headache for us humans is that some stores are more useful than others.

Take cars – most cars on UK roads have engines that burn petrol. Petrol is combined with oxygen inside the engine and the release of hot gases (mostly water and carbon dioxide) forces pistons to move and that motion is carried to the car's wheels. There's also friction involved – friction from the air and the road that acts against the car when it's travelling, and friction from the brakes slowing the car down and bringing it to a stop (and at the same time heating up the car and the surroundings).

In terms of energy – you can compare the start of your journey when the car is parked with the journey's end when the car is parked up again. The energy stored in the chemicals of the petrol (and oxygen in the air) has decreased, while parts of the car and the surroundings have heated up. Energy has been transferred from a chemical store to a thermal one. Unfortunately, this process is one-way – you cannot make your car unburn the petrol.

And the other big problem is that the car engine releases carbon dioxide and other pollutants into the atmosphere. Carbon dioxide released by human activity is the biggest cause of global warming and climate change.

Some cars are electric though – you charge a battery that can then make the wheels turn and make the car go forward. But how do you charge that

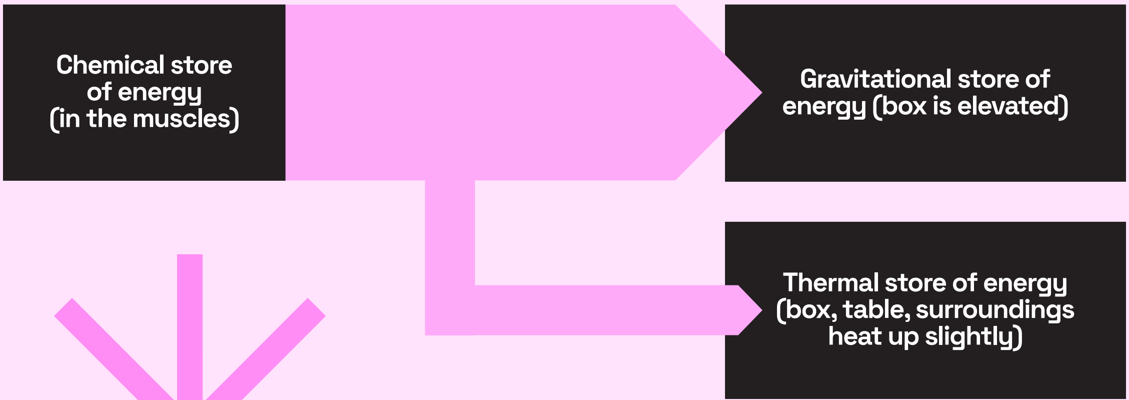
[1] Usually, what people mean is that we are using up fuel, and that we need to save or conserve fuel.

Conservation of energy

Energy cannot be created or destroyed. It can only be transferred from one energy store to another.

For example, imagine you lift a heavy box off the floor and put it on a table. Energy is being transferred from the chemical energy store of your muscles to the gravitational energy stored by the box being on top of the table.

Energy can be transferred in useful ways, like changing the height of the box from the floor. However, in any process, some energy will be dissipated – in this case it's spread out across the box, the table, and the surrounding air, which heat up slightly. Some energy has been transferred to these thermal stores. No energy has been destroyed but we often say that the dissipated energy has been "wasted", because it's difficult to transfer energy back out of these thermal stores in a useful way.



battery? In the UK, our electricity networks[2] make use of a variety of energy resources. Right now, burning fossil fuels (coal, oil, natural gas) in power stations, the use of renewable energy technology like solar or wind, and operating nuclear power plants all supply power to "the grid". And then there are future technologies like fusion. Different energy sources have different pros and cons, especially when it comes sustainability. Can we keep using them forever? And what harm are they doing right now?

The activities in the rest of this resource pack will help teachers and students explore the pros and cons of different energy resources, and learn about the potential of fusion power, as well as the career opportunities of the fusion sector. Fusion is a kind of nuclear power. Traditional nuclear power plants are really "fission powered". Fission is the process of large atoms being split into smaller atoms. Fusion is the opposite – small atoms being combined into larger atoms. Fusion power is an exciting prospect that may play a big role as the UK and the rest of the world transition to a sustainable future.

[2] There are two separate electricity networks supplying the UK: one network across mainland Britain including surrounding islands like the Isle of Wight, Isle of Man, and many Scottish isles, and a separate network covering both Northern Ireland and the Republic of Ireland. There are another three networks across mainland Europe.

Turbines and generators at the Hoover Dam hydroelectric plant on the Colorado River, USA.

Generating electricity

Most of Britain's electricity is generated by burning fossil fuels. The energy transferred by burning the fuels goes into heating up water to make steam, which then turns a turbine. At this point, the process is very similar to other forms of electricity generation.

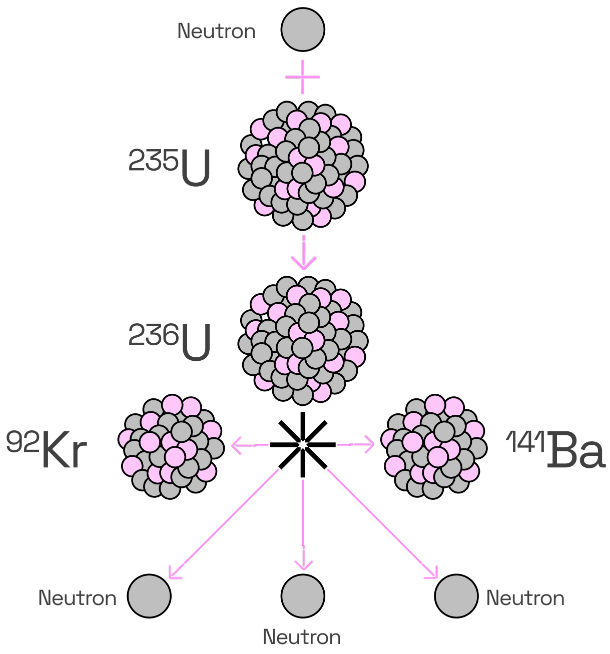
So what is a turbine? A turbine is a device that looks a bit like a windmill or desk fan. It converts the movement of a flowing liquid or gas into rotational motion, to allow useful work to be done. The simplest kinds of turbines are windmills and waterwheels. The sails of the windmill rotate in the wind, turning the machinery inside, perhaps to grind wheat into flour. Water wheels are turned by flowing water to achieve the same effect.

Modern turbines work in a similar way but are often attached to **generators,** in order to turn the rotation into electricity. A generator is a device that takes rotational motion to move wires in a magnetic field, producing an electric current. A generator is just a combination of a magnet and conducting wires that move through the field in a certain way. To understand a wind farm, you only really need to know that the turbines take wind (the motion of the air flowing past them) and turn it into rotational motion (the blades turn) and that a generator then uses this rotation to create an electric current. The same goes for hydroelectric power plants – which are just larger modern versions of the water wheel, where the motion of water downhill drives a turbine. Similarly, tidal power and most wave power is done using the motion of water to drive a turbine. It's worth knowing that people also use the word "generator" to mean portable units that link a fossil-fuel burning engine to an electric generator that can be used to power homes in an emergency or in an off-grid situation.

With other sources of electricity, most power plants are based on steam turbines – the blades turn within a casing that controls the flow of steam. What separates many types of power plant is just the method used for boiling water into steam. The heating can be provided by burning coal or gas, by nuclear fission in traditional nuclear power, or perhaps by the fusion power plants of the future.

Occasionally solar power can involve steam turbines and generators to generate electricity. However, it's more common to use "photovoltaic panels" (solar panels) to provide an electric current directly, by careful choice of the materials in the panel. There's also the option of solar water heaters that give not electricity, but domestic hot water for cleaning and bathing.

Humanity has been using the essential parts of electricity generation for over a century – what makes the future technology of fusion different?



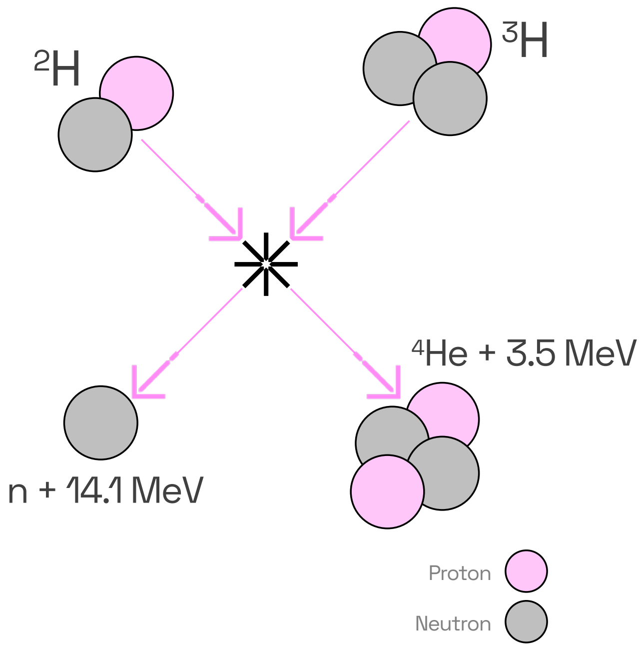


Figure 1: Every atomic nucleus larger than hydrogen-1 is a store of nuclear energy. We can use these reactions - fission on the left and fusion on the right - as a useful source of energy if the nuclear energy stored at the start is greater than the nuclear energy stored at the end. Ultimately energy is transferred out of the fusion materials by heating other components of the equipment used to drive the reactions. As in other kinds of power plants, fusion machines will heat up water to make steam that drives a turbine, in order to make electricity.

What is fusion?

Fusion is a type of nuclear reaction. Every atom is made up of a nucleus in the centre, and a number of electrons orbiting the nucleus. Most everyday changes to materials are explained by chemical reactions and by the sharing or transfer of electrons. But in a nuclear reaction, it is the atomic nucleus that is changed. In most nuclei, protons and neutrons are bound together to make up the nucleus. The number of protons tells you which element you have (hydrogen has one proton, helium has two, and uranium has 92, for example).

The simplest nucleus of all is a single proton with no neutrons – this is the most common type of hydrogen nucleus, called hydrogen-1 (sometimes called "protium"). Other forms exist called hydrogen-2 (one proton, one neutron) and hydrogen-3 (one proton, two neutrons) – but they are most commonly called "deuterium" and "tritium". These three different forms are the "isotopes" of hydrogen.

At the other end of the scale, are elements like uranium – all uranium atoms have 92 protons but there are different isotopes – uranium-238 (the most common) contains 146 neutrons, while the next most common isotope, uranium-235, has 143 neutrons.

There are two important types of nuclear reactions that we can use – fission and fusion. Fission is the splitting of a large nucleus into smaller nuclei. For example, firing a neutron at a uranium-235 nucleus causes it to split into two smaller fragments[3]), releasing more neutrons and creating a chain reaction. Fusion involves colliding two small nuclei together to create a heavier element – the same process that happens inside the sun[4]. The easiest fusion reaction for us to use is to collide one deuterium and one tritium to give one neutron and one helium-4 nucleus (also known as an alpha particle: it contains two protons, two neutrons).

[3] a krypton-92 nucleus and a barium-141 nucleus.
[4] The sun does largely transform hydrogen into helium, but the deuterium-tritium reaction detailed here is massively outweighed by other routes because of the low natural abundance of tritium.

Energy and mass (A-level Extension)

Underpinning nuclear reactions like fusion and fission is perhaps the most famous equation in the world: $E = mc^2$. However, we're going to write it as:

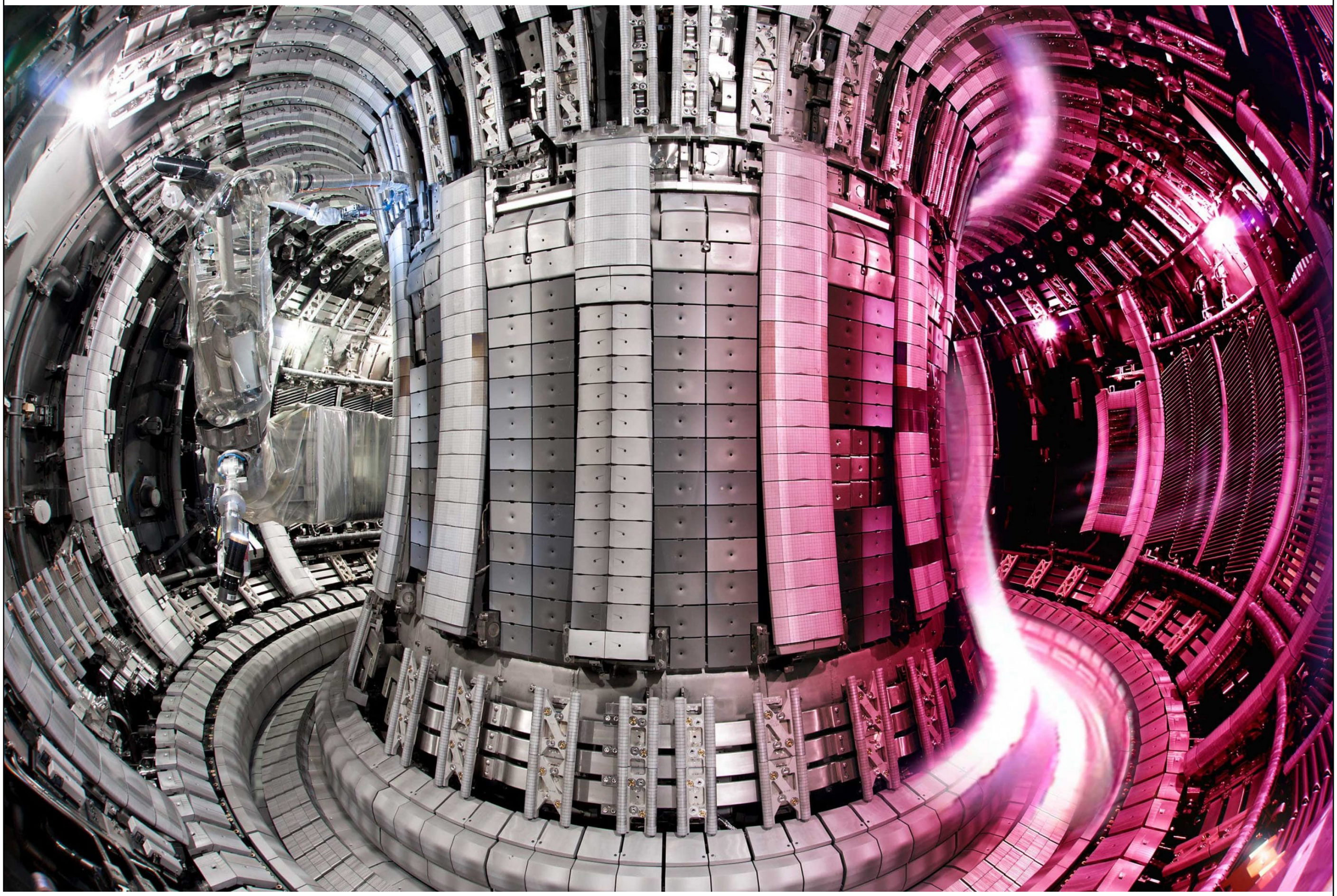
$$\Delta E = \Delta mc^2$$

Across the nuclear reaction, the total mass of the particles involved changes. The total mass of the starting particles and that of the end products is very slightly different (we can no longer assume that a proton and a neutron each have a mass of exactly 1 amu). This change in mass, Δm, is offset by a change in the kinetic energy of the particles, ΔE. The conversion factor is huge, since c signifies the speed of light, making c^2 a very large number indeed. During fusion or fission, a tiny amount of mass is lost, and the kinetic energy of the particles increases hugely. For fission of uranium-235, only around 0.1% of the original mass is lost. This idea is called "mass-energy equivalence". People often talk about mass being converted into energy or vice versa, which seems to violate the law of energy conservation. However, you can think of a particle's mass as being an energy store like any other – during fission or fusion, most of the energy involved is transferred from the energy store of the starting particle masses to the energy store of the final particle masses, and a small amount of energy is transferred to the kinetic energy stored by the particles. The exact interplay between the mass, energy, and momentum of high-speed particles can only be fully understood with Einstein's theories of relativity.

How does a fusion machine work?

In a fusion machine, it's the reaction shown in the right-hand panel of figure 1 on page 33 that's most useful – here hydrogen is turned into helium. For fusion to happen, the nuclei need to collide – and fast! Both nuclei have a positive charge, and since like charges repel, the speed of the two nuclei must be fast enough to overcome this. That means the fuel must be heated to over 100 million degrees Celsius. At room temperature, hydrogen is a gas, comprising molecules of H_2 – two hydrogen atoms sharing electron, with the molecule being neutral. Helium, under normal conditions, is a gas of individual neutral atoms (simply written He).

At the temperatures needed for fusion, the materials involved aren't even gases – they have turned into a plasma – where the electrons have separated from the nuclei, meaning the individual particles are charged. The plasma is so hot this means there are huge challenges in terms of engineering and choosing materials.



Inside the plasma chamber of experimental fusion machine JET (Joint European Torus) at Culham Centre for Fusion Energy, Oxfordshire.

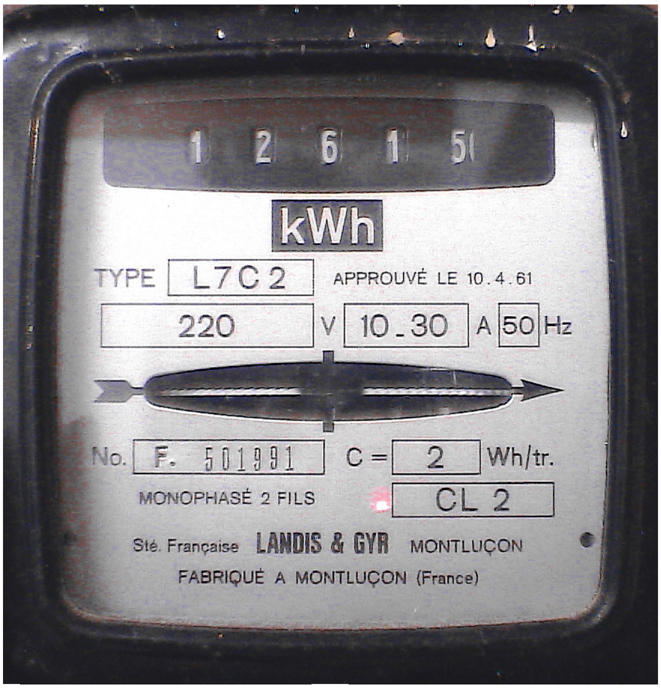
Working with fusion machines requires a whole variety of different people with different skills and knowledge and backgrounds to work together. When fusion has been achieved, the reaction produces high speed neutrons that collide with the walls of the chamber. This heats up the chamber walls, and eventually steam is produced to drive a turbine. This is the same end process as with other kinds of power plant. Whether it's burning coal or using nuclear fission, most other power stations simply heat up water to make steam, making the turbine spin, producing electricity[5].

[5] For a demonstration of this: https://www.youtube.com/watch?v=MGj_aJz7cTs

APPENDIX A

Joules, kilojoules, and kilowatt-hours

How do we talk about the amounts of energy involved in an energy transfer? The standard unit of energy is the joule (J). Let's return to our example of lifting a box. If the box weighs one kilogram, and is lifted one metre off the floor, the energy gained by the gravitational store is 10 J[6] (Your muscles' chemical energy store is depleted by more than this because the energy transferred to thermal stores is "wasted"). As another example, if you wanted to heat a litre of water by just 10 °C, you would need to transfer 42,000 J, or 42 kJ (1,000 joules equals 1 kilojoule).



An older style of electricity meter still seen in many homes, with analogue display showing total energy reading of 12,615 kilowatt-hours

When we know the details of the task, we can work out how much energy is transferred and state it in joules or kilojoules. But take an electrical appliance – it can be turned on and run for a short amount of time or for a very long time. It makes more sense to talk about the appliance's power rating – how much energy it transfers in a set amount of time. The standard unit of power is the watt (W) – the power required to transfer 1 J of energy per second. A 12 W broadband router running for 10 seconds will transfer 120 J of energy. Many household appliances are rated in kilowatts (kW), where 1 kW = 1,000 W. A kettle has a power of around 3 kW, and an electric shower might be 10 kW. Power also applies to sources of energy as well - a large offshore wind turbine out to sea might generate 5 million watts (5 MW) of electricity at peak performance, in other words transferring 5 million joules of energy every second to the electricity network.

Another unit of energy that is often used when talking about household or industrial energy needs is the kilowatt-hour. A device running at a power of 1 kW for period of 1 hour transfers 1 kilowatt-hour of energy (1 kWh), equal to 3.6 MJ. Although it's not a standard unit, the kilowatt-hour does make for simple calculations for many purposes, especially when electricity companies tell you their prices per kWh!

[6] You may know that acceleration due to gravity is 9.8 m/s², or recognise that 1 kg mass on Earth weighs 9.8 N, and will spot that here 9.8 J has been rounded up to 10 J.

APPENDIX B

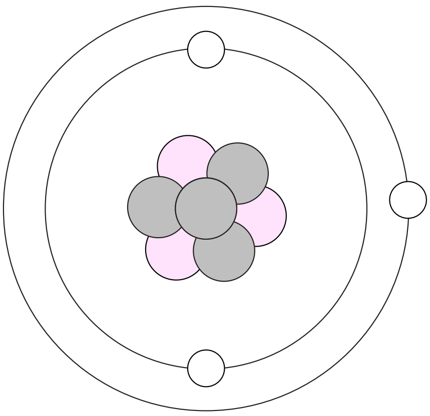
Atomic structure and periodic table

Atomic Structure

An atom has a nucleus in the centre and electrons that orbit around it. The electrons are negatively charged and are arranged in shells. The nucleus contains protons and neutrons. Each proton is positively charged (with equal but opposite charge to an electron), while each neutron has zero charge (is neutral). The nucleus has an overall positive charge and contains almost all the mass of the atom (the neutron's mass is almost identical to the mass of the proton, and the electron mass is much smaller). The size of atoms is incredibly small – not easily expressed in millimetres (thousandths of a metre) or even micrometres (microns, millionths of a metre). An atom is around one tenth of a nanometre across, or 0.1 nm (a nanometre is one billionth of a metre). A nucleus is 100,000 times smaller still, being only a few femtometres in diameter.[7]

Lithium-7

$^{7}_{3}\text{Li}$



The structure of an atom of lithium-7 (one of the isotopes of lithium). The central nucleus is orbited by electrons (white). The nucleus itself contains protons (pink) and neutrons (grey).

Knowing this basic structure is incredibly useful when learning about everything from chemical reactions to the design of a nuclear power plant.

The number of protons tells you which element you have – 3 protons mean you have an atom of lithium. The number of neutrons can vary from atom to atom – lithium most commonly has 4 neutrons, but around 5% of lithium atoms have only 3 neutrons. These different types of lithium atoms are called isotopes, and they have different masses. The isotopes are named lithium-7 and lithium-6. For example, lithium-7 has an atomic mass number of 7 (the total number of protons and neutrons added together).

The different particles that make up atoms, along with their masses and charges relative to one another. *An electron has a mass 1,836 times smaller than the mass of a proton.

	Relative Mass	Relative Charge
Proton	1	+1 (Positive)
Neutron	1	0 (Neutral)
Electron	Very small*	-1 (Negative)

[7] The units involved here are best expressed in engineering notation – e.g. millimetres (1mm = 10^{-3}m), microns or micrometres (1µm = 10^{-6}m), nanometres (1nm = 10^{-9}m), picometres (1pm = 10^{-12}m), and femtometres (1fm = 10^{-15}m). Another useful unit is the Angstrom (1Å = 0.1 nm = 10^{-10}m).

The periodic table

The periodic table is arranged to help you find out the structure of the atoms of each element. The elements generally get heavier as you go to the right along each row, and down to the row below. This means larger atoms with more protons and neutrons in the nucleus. But to find out exactly how many, you have to look at the atomic symbol of each element. The symbol's letter(s) tells you the element, e.g. H means hydrogen, Fe means iron. The numbers drawn alongside the letter(s) tell you the atomic number and the atomic mass. The atomic number is the number of protons in the nucleus (and in a neutral atom this is the same as the number of electrons). The atomic mass is a bit more complicated. For the element chlorine, there are two common isotopes – all chlorine atoms have 17 protons but some will have 18 neutrons and some 20 neutrons. The lighter atom is more commonly found in nature, so on average a chlorine atom has a mass of 35.45 atomic mass units. These isotopes of chlorine can be written in symbol form (^{35}Cl and ^{37}Cl) or given the names chlorine-35 and chlorine-37, but the overall summary for the element chlorine is drawn as this:

A periodic table tile for the element chlorine, taken from the Periodic Table on the final page. The chemical symbol for chlorine is Cl, and every atom of chlorine has 17 protons in the nucleus, meaning its "atomic number" is 17. The atomic mass is stated as roughly 35.45 atomic mass units (amu). Most chlorine atoms have either 18 or 20 neutrons, which gives an average mass for the nucleus of 35.453 amu. Some periodic tables may include additional information.

Periodic table of the elements

1 H 1.01 Hydrogen																	2 He 4 Helium
3 Li 6.94 Lithium	4 Be 9.01 Beryllium											5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 16 Oxygen	9 F 19 Fluorine	10 Ne 20.18 Neon
11 Na 22.99 Sodium	12 Mg 24.30 Magnesium											13 Al 26.98 Aluminium	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.06 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
19 K 39.10 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.87 Titanium	23 V 50.94 Vanadium	24 Cr 51.20 Chromium	25 Mn 54.94 Manganese	26 Fe 55 85 Iron	27 Co 58.94 Cobalt	28 Ni 58.69 Nickel	29 Cu 63.55 Copper	30 Zn 65.38 Zinc	31 Ga 69.72 Gallium	32 Ge 72.63 Germanium	33 As 74.92 Arsenic	34 Se 78.97 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.95 Molybdenum	43 Tc 98 Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.76 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
55 Cs 132.91 Caesium	56 Ba 137.33 Barium	57/71	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.84 Tungsten	75 Re 186.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po 209 Polonium	85 At 210 Astatine	86 Rn 222 Radon
87 Fr 223 Francium	88 Ra 226 Radium	89/103	104 Rf 267 Rutherfordium	105 Db 268 Dubnium	106 Sg 269 Seaborgium	107 Bh 270 Bohrium	108 Hs 269 Hassium	109 Mt 278 Meitnerium	110 Ds 281 Darmstadtium	111 Rg 281 Roentgenium	112 Cn 285 Copernicium	113 Nh 286 Nihonium	114 Fl 289 Flerovium	115 Mc 289 Moscovium	116 Lv 293 Livermorium	117 Ts 294 Tennessine	118 Og 294 Oganesson
Lanthanide Series		57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm 145 Promethium	62 Sm 150.36 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.92 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.05 Ytterbium	71 Lu 174.97 Lutetium	
Actinide Series		89 Ac 227 Actinium	90 Th 232.04 Thorium	91 Pa 231.04 Protactinium	92 U 238.03 Uranium	93 Np 237 Neptunium	94 Pu 244 Plutonium	95 Am 243 Americium	96 Cm 247 Curium	97 Bk 247 Berkelium	98 Cf 251 Californium	99 Es 252 Einsteinium	100 Fm 257 Fermium	101 Md 258 Mendelevium	102 No 259 Nobelium	103 Lr 266 Lawrencium	

The Periodic Table of Elements. Each tile shows an element's name, chemical symbol, atomic number, and atomic mass. When learning about nuclear physics, it's important to know that the atomic number (the number of protons in the nucleus) increases as you go right along each row, and continue onto the row below (and roughly speaking so does the atomic mass). The lightest element in the universe, hydrogen is shown at the top left, while helium is shown top right. Uranium (atomic number 92) is used in nuclear fission plants and is found towards the bottom of the table. The periodic table is often shown in this space-saving format, where elements 57-71 and 89-103 are pulled out to the bottom of the picture. https://sciencenotes.org/

CREDITS

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