The science of model flying: The periodic table

You have had time to recover from the electricity series. Now I am going to show you how science permeates our hobby. ‘Modern’ science has been around for a surprisingly long time and the stories are worth reading. I will be including some thumb nail sketches about the scientists and some experiments for you to try to help the ideas sink in. The first of this series is a look at one of the oldest and most fundamental of all modern scientific ideas, the periodic table.

Please be kind

I hope professional chemists and materials scientists don’t take issue with my explanations. I have attempted to explain simply without telling untruths. That said, please let me know of any mistakes and suggested additions or improvements at peter@peterscott.website. I love to learn. The full details of the various types of battery have very complex chemistries far beyond this article.

Time to lift off

The periodic table is a brilliant insight, fully clarified by Dmitri Mendeleev in 1869. The table was almost perfect science – a model that fitted the known facts and could be used to make predictions that later were proved to be true. It is important to us as flyers as it explains:

- conductivity
- radio transmission
- battery chemistry
- navigation light colours
- silicon’s importance for electronic chips
- possible dangers from the materials we use
- why we must have gold plating on our connectors
- why we should top up electrolytes when climbing slopes on a hot day
- what to do if we are in a full size electric ‘plane about to ditch in the sea

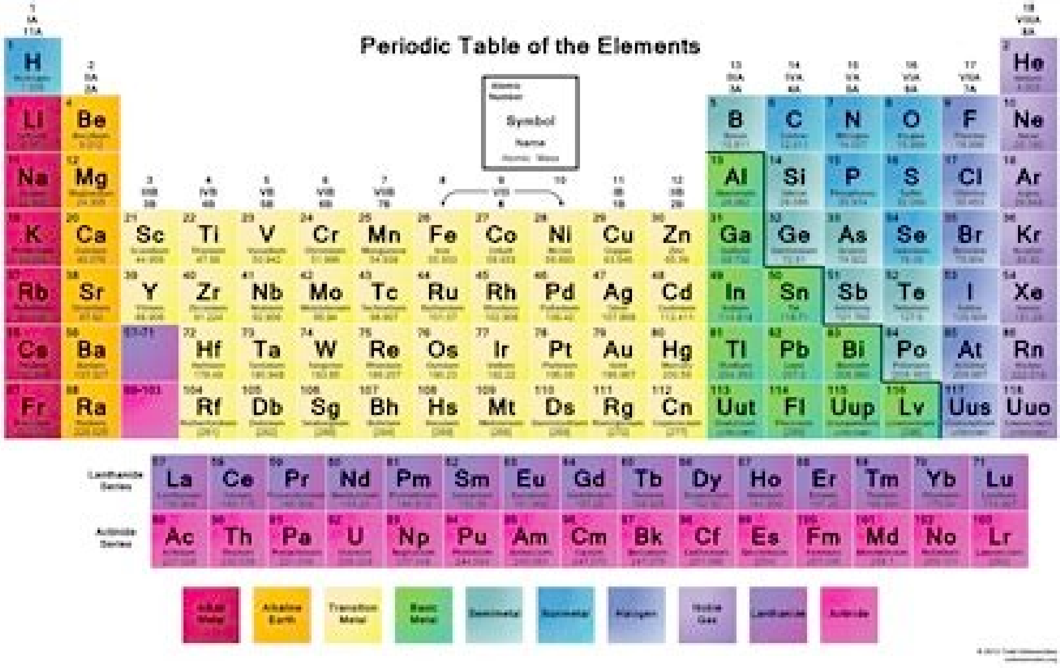
The periodic table

Look at the periodic table in Picture 1, which adorns a wall in most labs. We see all of the ninety-two naturally occurring stable elements up to uranium. In Mendeleev’s time only fifty-six were known. There were gaps in the table but the surrounding elements enabled scientists to predict the atomic weight and many of the physical properties of the missing elements. People knew what to look for and when they had found it.

Beyond uranium, and called transuranic, there are now more elements made artificially by us. Amongst many other things the table now tells us about an element are the number of electrons it has and how the electrons are arranged. Even if we fly using internal combustion power the rest of our models use electricity and that is what electrons are.

Let me again stress that the diagrams and explanations used by scientists are analogies or models. We get closest to reality in the mathematical formulae and even there we are using symbols to represent the underlying ideas. Every model has its limits and breaks down at some point. However this doesn’t mean the ideas it represents are wrong. It is just a way of helping our limited mammalian brain to grasp the idea. In the end, as Newton said, ‘If it works mathematically that is enough.’ (Remember *satis est*?)

To illustrate our limitations, as a teenager I once lay in bed (don't they all!) trying to imagine infinite space. I used the model of empty space going on for ever. I was doing well, imagining bigger and bigger when all of a sudden my brain just shut down. My hundred thousand million brain cells proved insufficient and refused in a sulky way to think about it any more. Of course Einstein gave us a get out. He insisted that space was curved so you will eventually get back to where you started. Space is infinite but bounded. Read Dr Seuss' story, 'The Big Brag', for an example.



Picture 1

Dmitri Mendeleev 1834 – 1907

Mendeleev was born in Siberia. His mother came from a family of merchants and publishers. His father was the head of a school and taught arts, politics and philosophy. How he finished up with his names is odd as any reader of Russian literature will tell you it always seems to be. The best translators include a glossary of names so you can keep track as the various versions are used for each person. His father eventually settled on the name Mendeleev after the name of a local landlord. Dmitri was the youngest of seventeen children of whom fourteen survived.

The family suffered financial disasters so they moved first to Moscow then to St Petersburg to get an education for Dmitri. After a spell in the Crimea recovering from tuberculosis, and a spell in Heidelberg working on capillary action and spectroscopy, he returned to St Petersberg. His work there, including his design of the periodic table, made it a world centre for chemistry.

Rare Earth Metals (REMs)

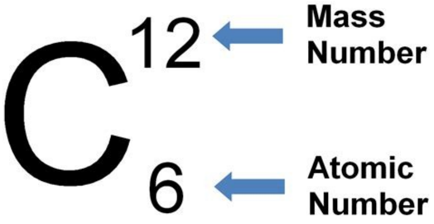
Also called Rare Earth Elements (REEs) these seventeen elements are of crucial importance both to us as humans and as model flyers. Look at the table above. Below the main body of the table are two rows. The upper one is called the lanthanides. These are fifteen of the REMs. In addition there are two more, Scandium and Yttrium, also called REMs because they have similar properties. In naming these elements Sweden gets a lion's share. Four elements names are based on the Swedish village Ytterby where they were first extracted. In addition Scandium is named for the the area.
The strangeness of the name rare earth is due to history. They are neither rare nor an earth. They are found all over the world, and are often found together. Originally they were

called ‘earths’ because they are non-ferrous metals. However they are rare in the sense that they have a very low concentration in the mined ore. This means that extraction is energy intensive and polluting, so tends to happen in poor countries where local people have little say or are desperate for any kind of income.

REMs are at the heart of modern technologies. Amongst other things they are used in lasers, magnets, electronic components, jet engine alloys, special glass, superconductors and LEDs. I even have tooth crowns made of yttrium mixed with zirconium.

Atoms

An atom has a small and very dense centre, called a nucleus, containing neutrons and protons, collectively called hadrons. The number of protons determines what element it is and its atomic number in the table. The total of neutrons and protons determine its mass. An atom is written like this (Picture 2):



Picture 2

This tells us that the element carbon has six protons (atomic number) and six neutrons making twelve nuclear particles in total (atomic mass number). It also tells us that it has six electrons, of which, as you will see later, four are free to form links with other atoms.

The nucleus is very small compared with the size of the atom having a radius about 1/2000 of the total radius of the atom. For Brits this is like an acorn on the end of Nelson’s nose where his column in Trafalgar Square is the atom’s radius. The Statue of Liberty is nearly twice as tall from the ground so I suppose a horsechestnut would be about right for size.

And now a personal dislike. I usually avoid bothering about other people’s pronunciation but one that always bugs me is noo-kewler instead of new-clear when pronouncing ‘nuclear’.

With all this empty space how can things feel solid? It is because the electrons are in a cloud surrounding the nucleus. They are kept circling by the attraction between the positive nucleus and the negative electrons. When we touch something solid the outer electrons in our fingers are strongly repelled by the outer electrons of the thing we are touching. An analogy is a spinning propellor. There is a slight chance that you might get your finger through but it is pretty certain that it will be chopped off.

The simplest elements, hydrogen (1 proton and 1 electron) and helium (2 protons 2 neutrons and 2 electrons), are found in normal glowing stars. Once the universe cooled enough from the big bang for atoms to form, hydrogen was the only atom around. The hydrogen clouds were collapsed by gravity into stars and as their potential energy turned into kinetic energy they heated up. The high temperature meant that the hydrogen atoms were smashed together at a high speed so their nuclei fused to form helium. This fusion gave off even more heat and is the technology used in hydrogen bombs. This was the moment when stars lit up for the first time. I loved the adverts from one sunglasses maker that boasted, 'Thermonuclear Protection.' We hope to use this process in fusion reactors to generate heat to make electricity as it produces no long lived or harmful pollution and the fuel is everywhere. However for the last sixty years delivery has always been 'in about thirty years' and still is. One day our batteries might be charged with fusion electricity but don't hold your breath.

Stardust

So where do all the other elements come from? Stars eventually burn up most of their hydrogen fuel, then cool down and start to collapse under gravity. They didn't collapse before because the violent movement and collisions of the hot atoms held them out against gravity. What happens then depends on how large and massive the star is. 'Massive' here has its true meaning of 'amount of mass'. We are learning rapidly about the life stories of stars of different masses and it makes a fascinating read. If in your country you can get the British Broadcasting Corporation's (BBC) Radio 4 programme 'In Our Time' on the Sounds app or as a podcast, there was an excellent account of stars on June 9th 2022. Knowledge is advancing very fast so don't bother to read anything more than a year or two old. The wonderful Hubble telescope has given us so much new information and it is a great relief that the new James Webb has not been damaged by the recent particle strike.

For very massive stars, collapse can provide enough heat energy to fuse helium and hydrogen atoms into heavier elements up to iron. Many stars go through cycles of collapse and expansion, heating and cooling, which produce these elements. Others collapse so far they squeeze out some or all of the space that the electrons are in and become in effect one big nucleus, called a neutron star or white dwarf. Some are so massive and dense that they become black holes. White dwarfs are very dense, a cubic centimetre having a mass of perhaps 1 metric tonne. Neutron stars are 10^8 times denser. The squeezing is so great that the electrons and protons are squashed together to make the neutrons. According to wikipedia one teaspoon of a neutron star has the same mass as the Great Pyramid at Giza.

Stars are often found in pairs that circle each other, called binary stars. The more massive one can drag matter from the lighter one so changing both lives, or they can collide. If two neutron stars merge they can create a huge unstable object that explodes in what is called a 'super-nova'. Such events provide the vast energy needed to fuse elements further to make the very heavy ones like gold. These events are relatively rare in the chaos of the universe but there is so much of it that we have traces of gold on our planet sufficient to back up our economies, adorn ourselves with jewellery and most important to plate our radio control connectors and boards. And of course to provide us with Aussie Gold Hunters.

The explosions scatter the elements far and wide and they later form new stars. Quite often the matter for the new star is spinning around a centre of gravity and some of the matter doesn't fall into the star but remains surrounding it. This matter collapses into planets and satellites which continue to orbit the new star. Exactly how that happens is under investigation with evidence from ever larger telescopes. All kinds of hypotheses are suggested with exotic names like The Nice Model, Late Heavy Bombardment, Dust Clumps and Pebble Accretion. It looks likely that as with stars there are several routes for the evolution of planets. The address for an excellent Quanta Magazine article is at the end.

Some planets allow life to evolve. Recent studies of matter from a comet has found amino acids from which life is made. Did you know that the name vitamin – a chemical essential for life - comes from ‘vital amine’? We are stardust – literally - exactly as Joni Mitchell sang. And when we die our atoms spread out again. Nothing is wasted nor lost.

One odd but true fact that is not relevant here but gives a feeling for the the large numbers involved is that, every time you breathe in, the air includes at least one molecule from Plato’s dying breath, or anyone else you choose. There are roughly as many air particles in a half-litre tidal breath as there are half-litres in the entire breathable atmosphere.

Shells and exclusion

Back from the stars to our world. In one atom each electron has energy that we visualise using the analogy of concentric layers, called shells. They aren’t layers of course, being just different energy states, but it works well as an analogy - a model. Each shell has a letter and a maximum number of electrons in it. There is one shell for each row in the periodic table and an energy state inside that shell for each electron. In his ‘Exclusion Principle’ Wolfgang Pauli told us that in an atom each electron must have its own energy state different from the others.

Let us look at the three innermost shells. These are the top three rows on the periodic table. The innermost shell, named K, can only contain two electrons and the other two, named L and M, can contain up to eight. So there are two, eight and eight elements in these first three rows. (M can hold 18 for heavier elements.) Each time we step across the columns of the table the number of protons in the nucleus increases by one. This is called the atomic number and determines what element it is. The number of electrons in the outermost shell also goes up by one. To be exact this is only true when the atom is well separated from others and in its lowest energy state as you will see later.

Wolfgang Pauli 1900 - 1958

Pauli was born in Vienna to a chemist father and had Ernst Mach, of Mach Number fame, as a godfather. He emerged as a great mind early in life. He was what scientists aspire to be, an internationalist. He studied and worked in many countries including the US and over his short life was a citizen of three countries, his native Austria, the United States, then Switzerland. His grandparents were from a leading Jewish family in Prague. He was brought up as a Roman Catholic but later renounced that. He was not immune to mystical ideas as he became a friend and disciple of Carl Jung, though a critical one.

One early work was a lengthy critique of relativity, which Einstein himself praised. However he is best known for his work on quantum mechanics. He proposed the idea of electron energy levels including spin and the exclusion principle which governs the way electrons are structured in terms of energy states. He worked in Gottingen, Copenhagen, Hamburg, Zurich, Michigan and Princeton in the US. He died young in Zurich of pancreatic cancer.

Columns and properties

Now we can use the periodic table model to explain things. The elements in a column, also called a group, have similar properties. In the first column group there is one electron in the outer shell of the elements, that can easily be pulled out. This makes those elements very reactive. Look at the names: hydrogen, lithium and sodium. At school you probably saw a lump of sodium dropped into water. It reacts with the water, heats up, melts into a ball, skitters around on the layer of steam on the water surface then explodes. Great fun. Sodium, which is a soft metal and shiny when cut with a knife, must be stored in oil. Lithium behaves much the same but less so. All of the elements in that column are highly reactive. That is important for our batteries.

In the next column group the elements are still reactive but less so. As we move to the right across the table the reactivity drops. As we go vertically down a column the reactivity increases.

The last but one column group contains reactive elements called halogens. It is a unique group in that it contains elements that are solid (iodine), liquid (bromine) or gas (chlorine) at room temperature. Fluorine, chlorine and bromine react with the chemicals of the human body and so are very poisonous or dangerous. Chlorine is used as chemical weapon, for example in Syria, and polytetrafluoroethylene (PTFE or teflon) will give off fluorine if overheated, for example by machining or drilling. Other plastics also can give off fumes so it pays to open your workshop door and window when shaping them. A simple cloth mask won't protect you against gases.The halogens are reactive as they have one vacant energy level in their outer shells. They are different in that they are less reactive as you move down the column. Fluorine is the most reactive. Hydrofluoric is the most powerful acid and can dissolve glass so is used to etch patterns on it. It has to be stored in rubber or plastic containers and is very dangerous to living flesh as it goes in and dissolves bones and can cause heart failure. On the Internet there are gruesome pictures of its effect.

Then we reach the last column group. The gas elements here have a full outer shell. This makes it difficult to add or remove electrons so these are very unreactive elements, usually called inert or noble. Again look at the names. Stable neon and xenon are used for gas discharge lights such as advertising displays and camera flash lights. Argon is used as an unreactive shield against oxygen in the air for argon-arc welding and as an inert, heavy gas inside double-glazed window units.

The elements in the middle of the table are mostly metals. When atoms are in a solid crystal form, electrons are more loosely attached to them and can easily be shared with other atoms. They are called 'free electrons' and behave a bit like a gas in a pipe making the materials electrical conductors. More about that later.

Quanta and radiation

When we add energy to an atom it usually only raises the energy of the electrons. They move to higher shells or energy levels. When they drop back to a lower level they radiate the energy. This might be in the form of light, heat, radio waves etc. These are all electromagnetic (EM) waves which are the subject of another article. The strange thing is that only certain jumps between two allowed energy states are possible, each called a quantum. The radiation is both waves and particles, the latter being called photons. The bigger the quantum jump, the more energy the photon has and the higher its frequency. That is why when heated some metals first glow red, then orange, then yellow and finally white when all the colours are emitted. It is also why the colour of lamp bulbs is often given as a temperature. Pure white ones are 6500 K (kelvin), which is the temperature of the outside of the sun and is described as 'daylight white'. 2500 to 3000 K is called 'warm white' similar to an old, cooler tungsten filament lamp. When we heat metals we use the colours to tell us the temperature. We are seeing the light from ever larger energy jumps.

It's why some less massive stars go from white to red as they age and cool down, as our sun will before long. Well actually in four thousand million years so you can put that bottom of your list of things to worry about.

Newton suggested that light was particles, which was thought very funny at the time. Thomas Young suggested that it was waves which seemed to match observed data better. However it turned out that they were both right. EM radiation is a wave when moving but if you stop it, so you know where it is, the wave collapses into a photon particle. This is called Heisenberg's Uncertainty Principle. You can know radiation's speed or its position but not both at the same time. And of course when emitted from an atom by an electron energy jump it starts as a particle, a photon. So our radio control signals are the result of quanta of a particular size produced by electron jumps. Young's biographical thumbnail is in the article on aerials.

Energy in electrons

Where electrons are concerned energy is measured in electron volts eV. This is a tiny amount and is the energy that one electron has when raised to one volt. That compares with the SI unit for energy, the joule, which is the energy of one coulomb (C) of charge raised to one volt (1 C = 6.2×10^{18} electrons). Max Planck showed that when an electron releases its energy the number of eV determines the frequency of the radiation, and hence its colour if it is visible. As an example, the 1.8 eV jump in gallium arsenide phosphide gives a red photon, which is why that material glows red as a light emitting diode (LED). So the port navigation light on your scale model gives out 1.8 eV photons many, many times. Many. Many. The more current that flows the more electrons there are to make the jump and emit a photon. That is why more current means more brightness. The size of the eV jumps needed for different colours is why LEDs have different voltage drops.

Examples of materials used in LEDs and the colours they produce are shown in Figure 1.

Material	Wavelength (nm)	Colour	Photon energy (eV)
GaAs	850 - 940	Infra-red	1.2
GaAsP	630 - 690	Red	1.8
GaAsP	605 - 620	Orange	2.0
GaAsP:N	585 - 595	Yellow	2.2
AlGaP	550 - 570	Green	3.5
SiC	430 - 505	Blue	3.6
InGaN	450	White	4.0

Ga gallium As arsenic P phosphorus Al aluminium Si silicon C Carbon In indium GaN gallium nitride

Figure 1

Flashing lights

You might have noticed when you move your eyes rapidly from side to side when looking at an LED that you get a row of individual flashes. The brightness of LEDs can go up and down very quickly with little energy loss. There is no metal filament to heat up nor gas to start glowing. To save energy LEDs are often rapidly switched on and off with the brightness being decided by on versus off time as well as by the current. Usually our eyes don't notice the flashing. The switching speed is one reason for the great data speeds in fibre optic communication cables that will be carrying this article at least part of the way. One gigabit/s would be impossible without the fast LEDs used to carry the data.

Max Planck (1858 - 1947)

He was born in Holstein in 1858 which was then part of Denmark. Planck's family was well educated with professors, lawyers and a judge. Holstein was annexed by what became Germany, in a messy war not unlike Ukraine now. Lord Palmerston, then the British Prime Minister, is reputed to have said, 'Only three individuals knew the cause of the tangled dispute. One was Prince Albert, who unfortunately was dead; the second was a Danish official who had gone mad; and the third was he himself, Lord Palmerston, who had forgotten it.'

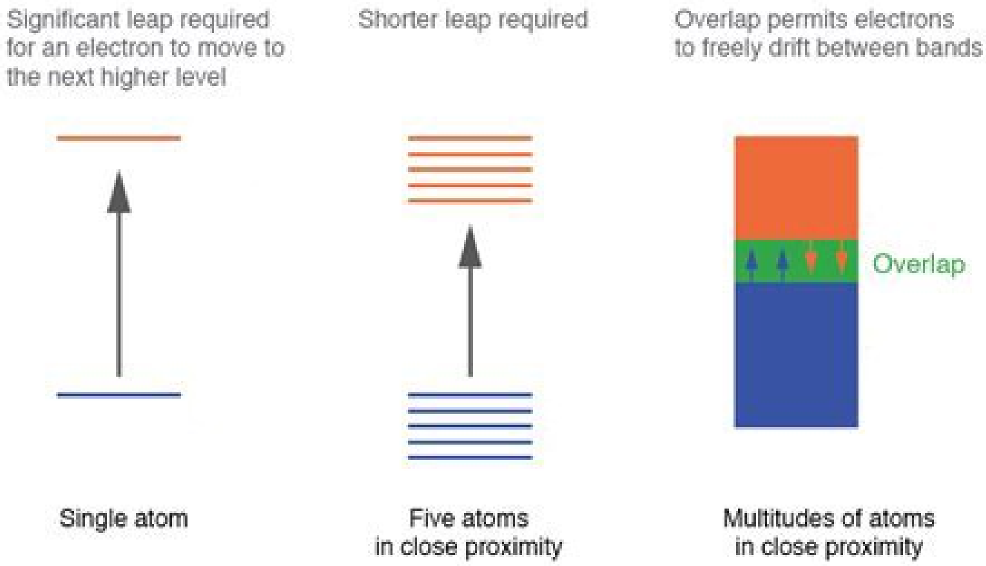
After graduating at 17, Planck could have been a talented musician. Instead he opted for Physics, against the advice of a Munich professor, who said 'In this field [Physics], almost everything is already discovered, and all that remains is to fill a few holes.' Professors! What do they know?

After several other posts he ended as Professor at Berlin University. In 1918 he won the Nobel Prize for Physics for his work in quantum physics. In 1945 his favourite son Erwin was killed for his part in an attempt to kill Hitler.

Band theory

When atoms join together to form other substances they share some of their electrons, called valency. It is the sharing that holds them together, like the sentimental clichés about human relationships. Pauli said that each electron must have its own unique energy state.

When there are many atoms close to each other the levels for the electrons must increase in number, so they form bands of allowed states with gaps between the bands called energy gaps and measured in eV as shown in Picture 3. The electrons can move around. Provided the outer band is not full this forms conductors.



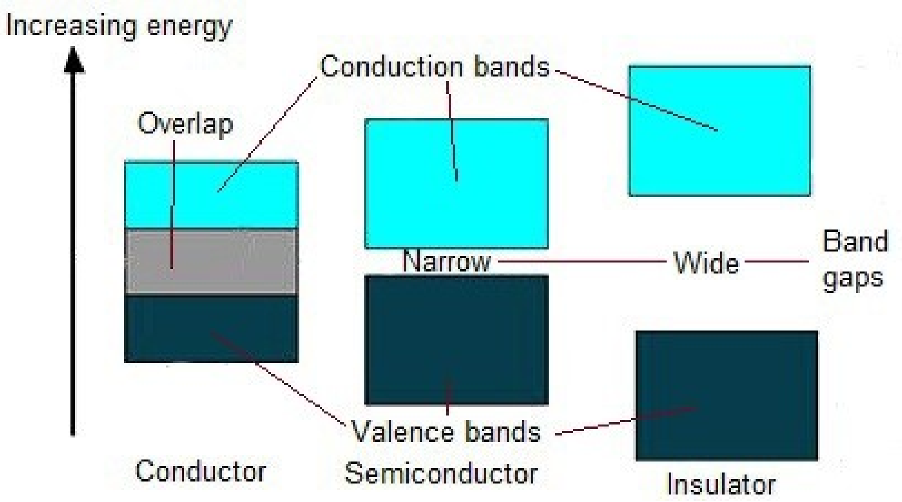
Picture 3

This is called Band Theory, though here the word theory is used in its proper sense of 'law that works' not the ill-informed sense of, 'Scientists don't really know. It's only a theory.'

Conductors, insulators and semi-conductors

Apart from the outermost conduction band all lower bands will be full. The next one down is called the valence band and we need not trouble about the others. The energy gap between the conduction and valence bands is one reason for how conductive a substance is. The other is how full the conduction band is.

In semi-conductors the energy gap is narrow. In silicon it is between 0.5 to 1.1 eV. As the material is made hotter electrons can jump this gap into the conduction band so the resistance falls. This is shown in Picture 4.



Picture 4

Crystals

A crystal is a solid that is made up of a three dimensional lattice of atoms. You see this in natural crystalline rocks where a perfect crystal will have flat faces, perfectly straight edges and a set of angles that is the same throughout. The way the atoms pack together determine the angles. Most are not like the perfect 90° format we will use later. Common table salt is, which is why it forms cube crystals.

Copper sulphate is shown in picture 5. It hasn’t been ground or cut to look like this.

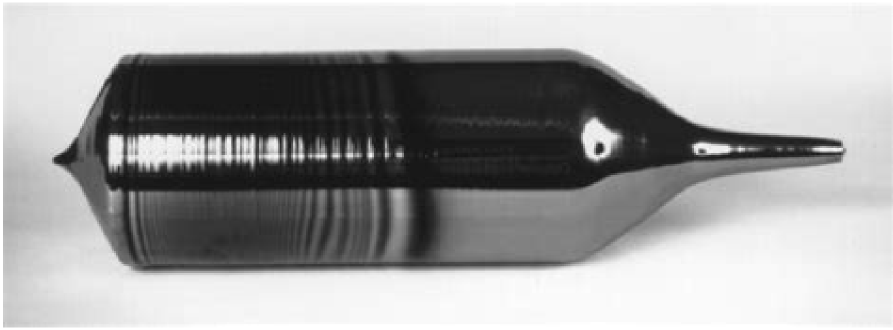
Picture 5

This is only true for perfectly pure materials. If an impurity is added, which I will call doping from now on, the doping atoms will be of a different size and/or valency and will mess up the perfect structure. By doing this is in a controlled way, with the doping atoms well spaced out, we can alter the conduction and build integrated circuits (IC, chips) by adding new energy levels. Incidentally doping can also change the colour of the crystal by messing with the crystal structure.

To make electronic integrated circuits (ICs) large crystals of silicon, called ingots, are grown by slowly drawing them out of a tank of liquid silicon. This ensures that the crystal structure is perfect. One is shown in Picture 6. They are then sliced into round wafers and polished. The silicon in the wafers is called a substrate. Then the surface is doped with a range of different elements after photographically masking off the areas to be doped with each dopant in turn. That way circuits can be built up with components that are nanometres in size. For example the latest 2 nm chips have parts on them that are 1/40 000 of the thickness of an average human hair.

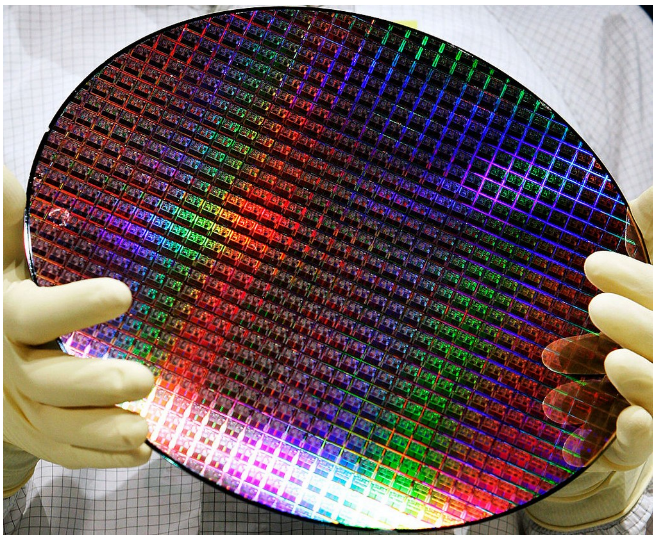
There are many rectangular chips on one wafer. The wafer is scored with a diamond just like glass, which of course is what it is. Then the small chips are broken apart and connected into packages using fine gold wires that are welded on. That's where our radio equipment and servo chips come from. And of course the mobile phone you use to say you'll be late home from flying.

A silicon ingot



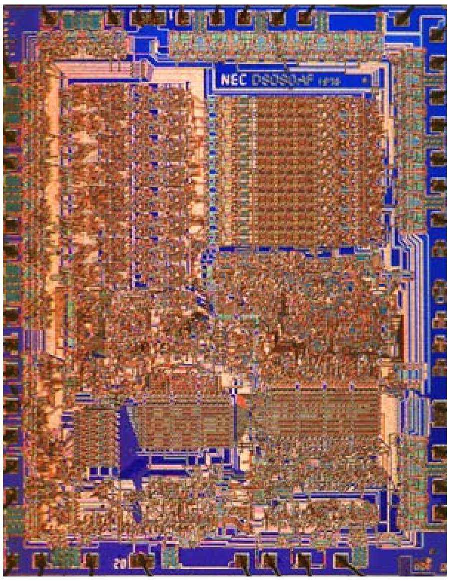
solarmarket.com.au
Picture 6

In picture 7 you see one 300 mm wafer showing a grid of integrated circuits (chips). The coloured spectra are caused by light waves reflected from the tiny patterns on the circuits.



From itechpost.com
Picture 7

And here in Picture 8 is one chip.



Picture 8
From micro.magnet.fsu.edu

Experiment one: Growing a crystal

You might have grown crystals at school where a solution slowly evaporates and deposits crystals on a string or in a container. Copper sulphate, alum or even table salt or sugar can be grown like that. Check the health and safety sheets on the internet for the materials you decide to use unless it is salt or sugar. If any are hazardous make sure you understand the risks, wear gloves and do not touch your eyes or mouth. There are lots of instructions and kits listed on the internet. One excellent example is on the Instructables site listed at the end.

Most methods will just give you a mass of small crystals. It is possible, though difficult, to grow a single large crystal. The trick is to hang a thread or piece of fishing line from a pencil or tongue depressor across the top of glass jar. Put a strong cold solution of your chosen material into the jar. Carry on stirring until no more will dissolve. The amount will surprise you. Filter the solution. You can get a funnel and papers from the supplier of the chemicals or use a kitchen funnel and a fine cloth. Tie a single small crystal on the end of the string and let it dangle in the solution near to the bottom but with enough clearance for the crystal to grow. Cover the jar loosely so the liquid can evaporate but dust can't fall in. Then wait for days or weeks. The first try might not work so dissolve the material and try again. With luck you will grow one or more largish crystals. With even more luck you might have a single separate one. However attractive they look take care not to let children handle them with bare hands.

Doping

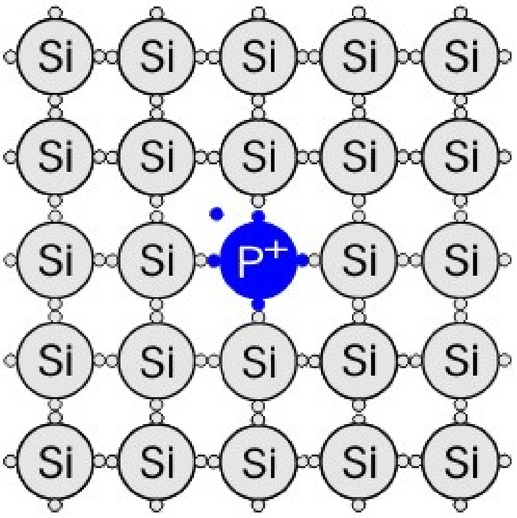
Doping allows us to fiddle with how materials conduct. Our integrated circuits or chips are made from materials where the band structure is changed by doping with other elements. In semiconductors the doping adds new levels in the narrow energy gap so the electrons behave differently. The silicon substrate can be changed to form circuits on its surface. The doping atoms are kept far apart so they do not form bands. If the energy level is close to the conduction band electrons can jump into the conduction band as additional negatives so the extra moving charges are negative and the material is called n-type. If the level is close to the valence band electrons leaving the band leave positive holes so the material is p-type having positives that move by electrons jumping in them from another atom.

Valency 4 materials are used for the substrate: silicon and previously germanium
Valency 5 materials are used for n-type doping: phosphorus, antimony, bismuth
Valency 3 materials are used for p-type doping: indium, thallium, gallium, boron

There are two ways of picturing semiconductor doping, that is by band theory and by crystal structure. If you can see how they are connected you have just completed your freshman year in Physics or Materials Science. Note that in the band diagrams the word impurity is used instead of doping.

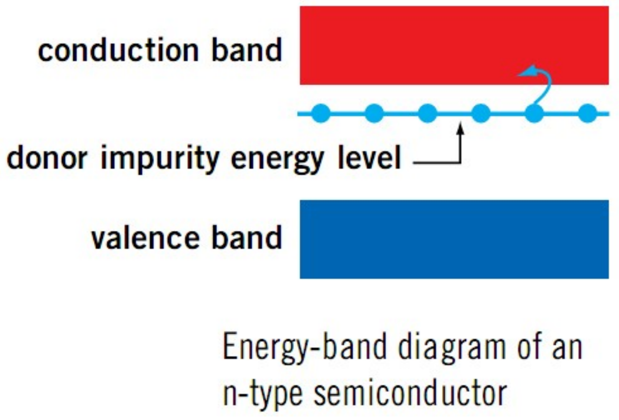
N-type phosphorus doping

Phosphorus can share five electrons with other atoms. Silicon can only share four. There is a surplus electron free for conduction. The mobile charges are negative, which is why this conductor is called n-type. In Picture 9 we see how it looks on the crystal structure diagram The structure of the crystal is not as right-angular as this.



Picture 9

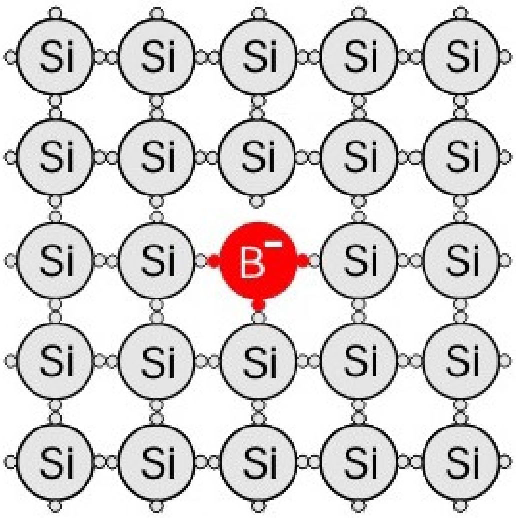
And here in Picture 10 is the band diagram



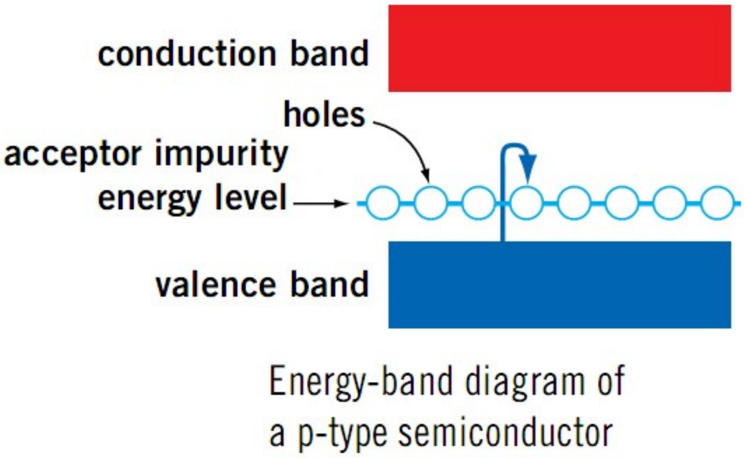
Picture 10

P-type boron doping

Boron can share three electrons. In effect there is a positive hole in the valency structure where there should be an electron. So an electron moves to fill it and the hole moves in the opposite direction. There is no surplus of electrons, so in effect the mobile charges (holes) are positive giving the material the name p-type, shown in Pictures 11 and 12.



Picture 11



Picture 12

Atoms, ions and molecules

A lone atom with no extra energy is electrically neutral, having equal numbers of electrons and protons. If one or more electrons are removed from an atom it become positive, called oxidation, and if added it becomes negative called reduction. Such charged atoms are then called ions.

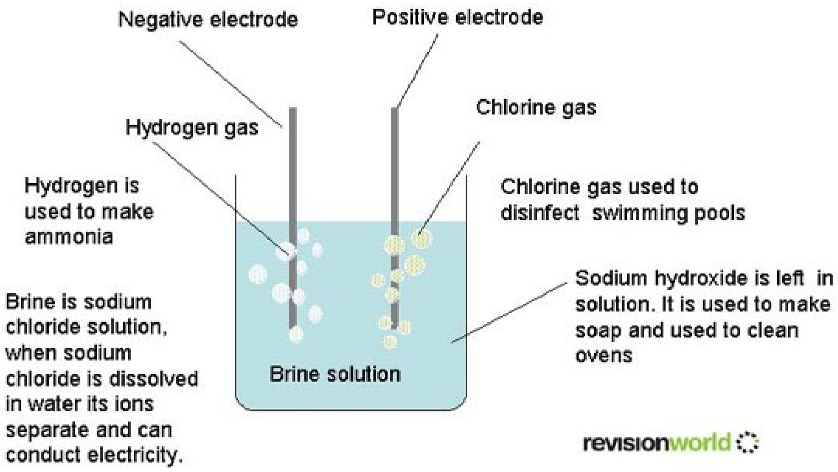
When atoms link together by exchanging electrons it is called a chemical reaction and a new substance is formed, the combined substance being called a compound. The dual process of gain and loss during a reaction is called a redox reaction (reduction-oxidation). The particles are now called molecules. The properties can change dramatically. After all a deadly green gas (chlorine) and a highly flammable metal (sodium) come together to make crystals to sprinkle on our chips (fries). In effect the atoms share one or more electrons, called valency. The number of valency electrons decides how many other atoms it can link with. The angles of the links decide what three-dimensional shape the resulting molecule will have.

Atoms that share one, two, three, four and five electrons are called univalent, bivalent, trivalent, quadrivalent, and pentavalent. The fact that carbon is quadrivalent (or tetravalent) is the main reason why it is the backbone of life and all other organic substances. The four valences and the fact that they are at wide angles to each other means that long chains of carbon atoms can be formed as a backbone to large molecules and that complex three dimensional molecules can be built. So you, and the birds that follow your gliders, exist to fly because of carbon’s valency. The existence of carbon thoughout the universe makes it highly likely that life exists elsewhere and might even prove to be a natural progression. Let’s hope aliens are all as genial as ET. In fiction aliens are usually shown as more advanced than us. Some scientists suggest that the life-supporting earth has been in existence for almost as long as it is possible, over four thousand million years. That has given a very long time for life to evolve, so we might be the most advanced life form.

Silicon is similar to carbon in its valency. Science fiction writers have suggested that it could be the basis for different silicon-based forms of life elsewhere in one of the universes. Life could exist where temperatures make carbon life impossible. ‘It’s life Jim but not as we know it.’ Notice that silicon is beneath carbon in the table and under that is germanium. Germanium was unknown to Mendeleev but from his table he predicted it and its properties, calling it ekasilicon. He proved correct, adding strength to the idea of the table. Because of its quad valency germanium got transistors started but silicon is now the basis for all electronic chips. A pub quiz bit of information is that at first the only source of germanium was the soot in chimney flues. For the benefit of non-Brits a pub quiz is run by a landlord to sell more beer. Teams compete to get the most correct answers, a modest cash prize and intense hatred. Quizzes are a national obsession. Some think that carbon in the form of graphene might be used for chips as well. Graphene is a single layer of carbon atoms and is already used in some of the batteries we use to fly.

Solvents

Some liquids, called solvents, can break molecules apart. Examples are water, alcohol and propanone (acetone). When broken apart – dissolved - in water, table salt (sodium chloride) splits into a positive sodium ion and a negative chlorine ion. In effect the solvent breaks the electron exchange link but the electrons remain with the atom they have been shared with. The ions are free to move around in the salty water so if a battery is connected an electric current flows. Salt water therefore conducts and such a liquid is called an electrolyte. When the ions reach one of the plates (electrodes) they either gain or lose electrons and become a neutral atom again, as shown in Picture 13. The sodium on one plate reacts with the water and produces hydrogen gas and the chlorine on the other plate bubbles off. Doing this to sea water using solar cell electricity is one clean way to generate hydrogen for such as house heating, car engines or aircraft turbines.



Picture 13
From revisionscience.com

The ability of a metal to take part in chemical reactions depends, in part, on the ability of the metal to lose electrons to form a metal ion. Very reactive metals lose electrons easily. Very unreactive metals do not.

When two metals are placed together, electrons tend to leave the more reactive metal and travel to the less reactive metal. A cell is a particular way of allowing electron transfer between metals so that an electric current is produced.

We can use this effect for electroplating. Imagine a solution of metal ions, for example zinc or gold. We dip two plates of cheaper metals, such as steel or copper, into the liquid and connect to battery. The metallic ions will pick up one or more electrons and become a metal again. One of the plates will become covered in a very thin layer of the metal in solution. In the case of zinc this is galvanisation. More important for us, gold plating the connectors in our electronic equipment ensures that connection will not be lost due to corrosion. Gold is very unreactive so does not rust away nor tarnish.

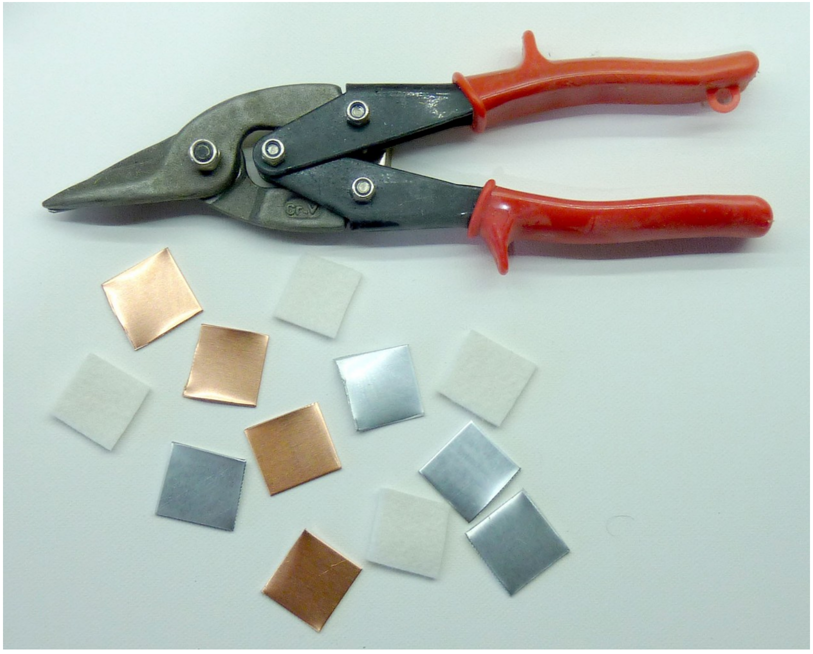
Careful how you ditch

When in 2016 the Solar Impulse electric plane flew around the world the pilots were told what to do in the event of ditching in the sea. They must jump out well before the plane was likely to hit the sea. There is a large quantity of high voltage electricity in the cells, and the salty sea water is conductive enough to electrocute the pilot.There will be similar concerns when more aircraft go aloft powered by huge batteries. Fresh water is safer having many fewer ions in it, though it was said at one time that some of the rivers in industrial Europe were so polluted that you could develop photographic film in them. Being dissolved in water, and no doubt other liquids, the impurities would be in ionic form. If you ditch an electric model in water it might be worth checking around for dead fish to barbecue over the burning wreckage of your model.

Experiment two

Buy some pure copper and zinc sheets or foil about 1 to 1.5 mm thick. You won’t need much and can find it on ebay quite cheaply. Alternatively you could use galvanised washers and copper coins. Note that many coins that look like copper are actually coloured steel. Clean the surface of the metals using alcohol, steel wool or sandpaper, then cut some 25 mm squares. Find some felt fabric a couple of mm thick and cut squares a little smaller than the metal. The felt must hold water so a natural fibre like wool is best. Mix up a saturated salt water solution using cold water. Add salt until no more will dissolve but this time there is no need to filter it.

In Picture 14 are the 25 mm squares of zinc, copper and felt and the tin snips that I used to cut them from the sheets. I then flattened them with a hammer and cleaned the surfaces.



Picture 14

Photo by Peter Scott

You will also need a voltmeter and ideally a bare light emitting diode (LED) available cheaply on ebay or ask the club's electronics guru for one. (Picture 15)

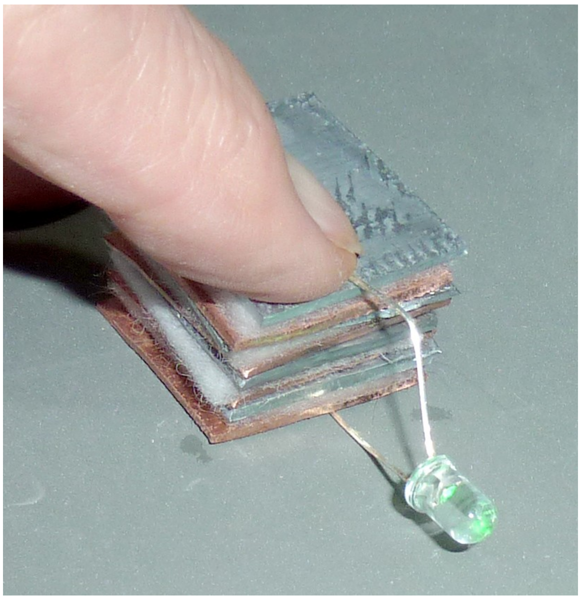
Picture 15

LED – any colour will do, though red needs the least voltage

Soak the cloth pieces in salt water, squeezing and dunking to ensure they are well saturated. Put a copper square down and put a felt square on top. Put a zinc square on top of that. Touch the voltmeter probes, one on each metal, with the red on the copper. Press down gently on the zinc to ensure good contact. You could see a voltage of about 0.7 V but possibly a bit lower.

Now stack up four layers as follows: copper, cloth, zinc, copper, cloth, zinc and so on. End with with zinc as shown in Picture 16. Again test with the meter. Try connecting the LED and see if it lights. Connect the longer leg of the LED to the copper and the shorter to the zinc. Don’t worry. If an LED fails it won’t blow up in your hand. You can always remove one of the pairs of copper and zinc to reduce the voltage.

If nothing happens it might be because salty water is running down the sides of the pile and shorting the voltages. Pick the stack up in one piece, dry the sides and try again.



Picture 16
Photo by Peter Scott

The green LED is glowing with a pile of four sets of copper/felt/zinc. What is the photon and quantum jump size? Yes, you got that right, 3.5 eV.

You have just made a Voltaic Pile (Picture 17), which was first invented in 1800 by Alessandro Volta after whom the volt, the unit of electric potential is named. Seats in Italy were often made of cold marble. (Pile. Geddit?) Each copper/felt/zinc layer is a cell and the whole pile is a battery. The cells are in series so the voltages just add up. For a long time batteries were the only way to generate electric currents in research laboratories. The Royal Institution labs in London were successful partly because of their large battery room. The metals are called plates or electrodes, with the positive copper one called an anode and the negative zinc one a cathode.

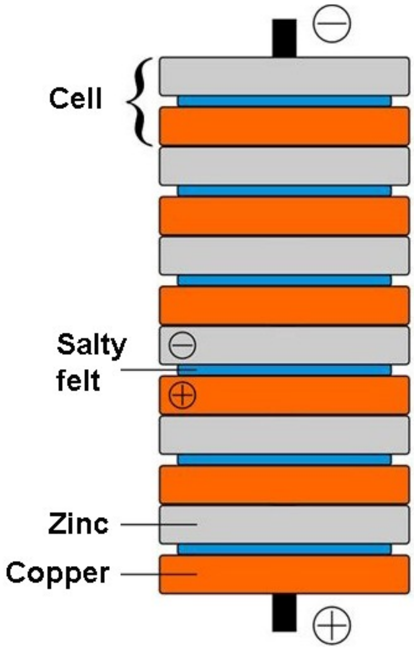
Alessandro Volta (1745 – 1827)

Volta was born in Como, a lakeside town in northern Italy. His greatest achievement was showing that electricity could be made from chemical cells. To be fair it was Luigi Galvani who, by making salt pickled frog’s legs jump on a stand made of iron and copper, first showed that different metals could produce a voltage. That inspired Mary Shelley’s book Frankenstein; or, the Modern Prometheus in 1818 with electricity bringing the creature to life. Galvani also suggested the reactivity series. However Volta’s batteries led to large amounts of electricity being available in laboratories enabling the work of Faraday, Oersted and many others. The Royal Institution in London, to which he sent his experimental reports, was an early leader in this field. He also studied methane and the electrical property we now call capacitance and showed that voltage is proportional to charge in a capacitor.

His work on cells was admired by Napoleon Bonaparte, who, when he wasn’t ravaging Europe in his appalling manner, was a great innovator, with his Code Napoleon legal system, a modern, secular education system and of course the metric system for weights and measures in 1799. Yes it has been around that long. Volta maintained a friendship with Boney and received many awards from him including the Légion d’Honneur. He spent his working life at Pavia University in Italy and was respected *by his students even though he was a private man. The SI unit of electric potential, the volt, is named after him.*

When you take your pile apart you will see from the surfaces of the metals that there have clearly been reactions. The zinc is much more affected than the copper. It is more reactive which is why it becomes more negative than the copper and so forms the cell voltage. More about that later.

Volta's original pile



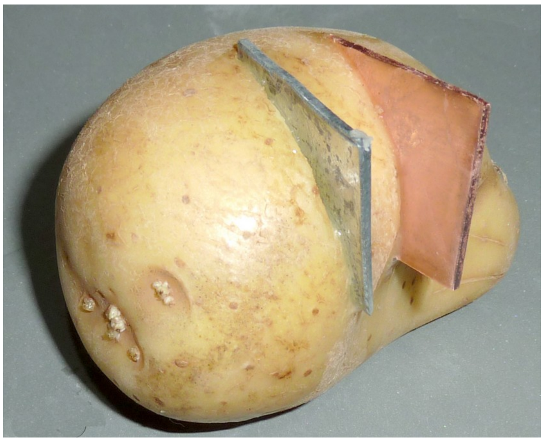
Picture 17
From wikipedia

Picture 18
From wikipedia

What voltage would you expect from the pile in Picture 18? Yes, about 6 V

Experiment three

You will now need a lemon and a raw spud (potato). Push a copper and zinc square or a copper coin and a galvanised washer into the lemon a centimetre or so apart, as shown in Picture 19. Test the voltage. The acidic juice reacts with the metals to create the voltage. The same will work with a potato which will give about 0.8 V. So if you have an electric car and you run out of charge on the way home from the supermarket all you need to do is open up the sack of potatoes you just bought and hook them all up in series. Or maybe not.



Picture 19
Photo by Peter Scott

You might have some crocodile clip leads for your voltmeter. If so try clipping them onto the zinc and copper electrodes and dipping them into other liquids. If you have some citric acid crystals in your kitchen try a saturated solution of that in water (0.85 V). Also try vinegar (0.91 V).The bracketted voltages are what I got. Both are fairly strong acids that increase the reactivity of the metals. Best avoid someone's glass of wine as it will change the flavour for the worse and dissolved copper is a poison. Don't try strong acids nor other liquids unless you are a chemist and know what you are doing.

Primary cells

All of the above cells are primary cells, meaning that the materials involved get used up and the cell cannot be recharged. Rechargeables are called secondary cells and will be described later.

The zinc-copper cell only produces only about one volt. But, as we know, some cells produce much more. A dry cell (C or D) makes 1.5, a nickel metal hydride (NiMH) cell is about 1.2 and a lithium polymer one (lipo) can reach 4.2 V. Why is that? To answer that we have to look into reactivity which will be later.

The salty felt is called an electrolyte. Yes, it's the same word used for what you are might need to top up when you are sweating a lot. Ions like sodium and potassium are essential in your body fluids to enable its many reactions and they are lost through sweating. Pet animals will lick you to get salt from your skin and large animals like cattle are given salt licks. It is one time when replacing salts is important, rather than just drinking pure water. So remember that on a long, hot day on the flying site, especially if you had to climb to get there. You can buy soluble tablets with a pleasant flavour from cycling or athletics shops. Low electrolytes can lead to tiredness, muscle cramps, confusion and dizziness.

Rechargeable or secondary cells

To be rechargeable a cell or battery must be made of materials whose chemical reactions are reversible. We add energy to the battery using a reverse current and we see this energy as a raised voltage. In different types of battery the materials change in a number of different ways. The surface of the anode and cathode, or the molecules in the electrolyte, might change, or both. The chemistry is complicated and beyond us here.

When we finish charging and connect our motor or lamp the energy returns from the electrolyte or plates as a current in the connected conducting metals.

Reactivity

At the beginning of this article I mentioned that some elements lose electrons more easily. This enables them to produce higher cell voltages and to join on to other elements to form compounds. If two metals are placed together electrons leave the more reactive metal and join the less reactive metal. So to work out what pairs of elements will make the best cells we need a list putting reactivity on order from most to least. In a cell the two elements are connected by an electrolyte. This might be liquid or paste.

This is not the full list of elements. I have just included the elements that are of interest to us in the cells we use. To find what cell voltage we can expect when using these elements we combine the potentials shown in Figure 2. Zinc (Zn) has -0.76 and copper (Cu) has +0.34. Combined these make 1.1 V which is not far from what we found in our experiments.

Standard Reduction Potentials (volts)

Ag	0.80
Fe	0.77
Cu	0.34
Pb	−0.126
Ni	−0.25
Fe	−0.44
Zn	−0.76
Al	−1.66
Mg	−2.37
Na	−2.714
Li	−3.045

Figure 2

What can we learn from this table?

Lithium is the obvious preferred choice with its large potential. Sodium is not far behind and is a sound second, or perhaps first choice, as you will learn if you read my article on cell technology. It is also cheap and plentiful. Aluminium looks promising too. You can see why the old nickel iron (NiFe) cells were low voltage (0.25 + 0.77). NiMH cells are not included because the second plate is not an element but a compound hydride. What voltage should you get if you replace the zinc with aluminium? If you try it using the method in experiments 2 and 3, sand the surface of the aluminium just before you use it as it soon combines with oxygen to form a grey insulating layer. Because of course it is reactive.

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