Science (All of It)

… in Only *Three* Questions!

Chapter 1
Three Big Questions

I guess you're reading this book because you're interested in science.

Or maybe someone like your mum or dad or granny told you that you had to read it because you *ought* to be interested in science, but actually you're not all *that* interested.

But I reckon you might be *a little bit* interested, because otherwise you'd just be pretending to read it while actually thinking about playing football or chatting with your friends or whatever it is you'd prefer to be doing.

Let's just *imagine* that you like science, even if only a bit. So here's a little quiz for you:

1. **What is the proper medical name for your anklebone?**
2. **What's the atomic weight of the element argon?**
3. **What is the speed of sound?**
4. **How does a gyroscope work?**
5. **Name five moons of Saturn.**

How well did you do?

Oh, and do you still like science as much now?

If you didn't know the answers to *any* of these questions, don't worry. Because I'll tell you a secret: neither do I. Writing about science is my job, and I have degrees in chemistry and physics – but I couldn't give exactly the right answer to a single one of those questions.

Oh, I'm not too bothered that I couldn't answer those questions. And I'll tell you why.

Look at Question 3. It was part of a test made up by the famous American inventor Thomas Edison about a century ago. Edison gave the test to people who wanted a job in his company, which made light bulbs and other electrical stuff.

Some of the questions were published in American newspapers in 1921, and a rumour went around that the most famous and brilliant scientist in the world, named Albert Einstein, had taken the test and failed it. Einstein didn't even know what the speed of sound was!

What Einstein said was this: there's no point carrying around a number like the speed of sound in my head, because I can always look it up.

But that's cheating! When you do an exam, you can't take books in with you that tell you the answer.

No, but if you ask me, that's *exactly* what you should be allowed to do. If it was a good exam, having the books with you wouldn't make any real difference to how well you did. The best students would still get the best marks.

You see, I don't think any scientist needs to know the answers to my quiz. The trouble is, we often get told that we *do* need to know things like that. People are always saying to me things like "You call yourself a scientist and you don't even know the botanical name for a daisy!" (And it's true: I don't.) But I say to them what Einstein said: why should I, if I can just look it up?

If you're actually not so keen on science, I reckon there's a good chance it's because you've got the idea that this is what science is: learning a whole load of facts. There's a long list of the chemical elements called the Periodic Table, and there's about 90 of them in it. How on earth can you be expected to remember them all? In biology there are all those parts of the body: the humerus, the tibia, the spleen, the prefrontal cortex. Help!

And in physics you have to know the meaning of words like mass and acceleration, and why these aren't the same as weight and velocity. There's just so *much*! How can anyone expect you to remember all that?

Well, they shouldn't expect you to. You can just look it up. Scientists do that all the time. They forget facts, even quite basic ones, and have to look them up. True, they might do this in secret, hoping no one is going to find them out. But really they needn't be embarrassed. Einstein wasn't.

If it feels to you that science is a quiz like the one I just gave you, but which seems to go on *forever*…

Yup, that's *just* how it feels
– sometimes.

Well then, it's not surprising if you're not too keen on science. I was lucky when I was young, because I had quite a good memory for facts and so I could get pretty good scores in exams. But I've forgotten most of what I knew then, and I bet that you know some things I don't about science, like the names of dinosaurs or constellations or plants. Maybe you even know the speed of sound! If you do, that's fantastic, and it might be dead handy if you decide to be a scientist. But I'm afraid it isn't what will make you a *good* scientist.

We're obsessed with quizzes like this. You probably get lots of them in school, and you might hate them – so it probably seems a bit weird that some adults think they are cool and clever. On the British television program called *Mastermind*, contestants have to sit in a chair and answer lots of questions about a subject that they've studied. If they get most of the questions right, people think they must be an "expert" on the subject. I even went on a show a bit like that myself once, in which most of the questions are *really* hard. And I admit that I was terrified that I'd get some really simple question about science wrong, like "How do you spell carbon?", because I was so frightened by the lights and the cameras and my mind had gone blank. And then everyone would see me on TV making this awful mistake laugh and they'd say, "Ha, he's not a real scientist at all!"

I shouldn't have been afraid of that (even though I was) – because knowing lots of facts doesn't make you an expert. Not in science, nor in anything else. It helps, but it's not essential. Because you can always look up facts. That's not cheating, it's just sensible. It's why we have books, and the internet. If you don't believe me, you should believe Einstein.

He said this:

Imagination is more important than knowledge.

Imagine that! He's saying that to be a good scientist, you don't need to know lots of stuff, but you need to be imaginative.

I thought you only had to be imaginative if you were an artist... or a writer or something.

Lots of people think that, but they're wrong. The best scientists are the imaginative ones. You'll probably never come up with new ideas, or new inventions, unless you're good at imagining what *could be*, even if you don't know yet if it's true or if it can really be made.

I wrote this book because I think that if, by the time you finish your schooling, you think that science is a load of facts that are hard to remember, that would be a real shame. Worse than that: it would mean that you hadn't been taught very well. Most teachers are brilliant, and they don't want to teach you like that at all. But it's harder and harder for them not to, because everyone has got obsessed with exams that expect you to carry a load of facts around in your head. And that, like I say, isn't what makes you an expert.

I'm not going to pretend that you don't need to know *anything* because it's all in books that you can look up. That's not true either. What you should really be taught isn't facts, but *how to think*.

This is exactly what Einstein said when he failed the Edison test. "The value of a college education", he said, "is not the learning of many facts but the training of the mind to think."

How can you be trained to think?

Well, here's the kind of thing I mean. I don't know the speed of sound, but I do know that when lightning strikes, the sound of thunder arrives a bit later than the flash. That's because light travels faster than sound. Now, I *do* happen to know by heart the speed of light, but that doesn't matter –

That's a kind of weird thing to know by heart, to be honest.

I know, I know. But what's really important is that I know light travels so fast that we can think of it as taking almost no time at all to get from the lightning bolt to my eye.

This means that we can think of the flash that I see as happening at pretty much the same moment that lightning strikes. So the flash tells us when the lightning struck.

Now, I'd say a distant thunderstorm is probably a few kilometres away. It could be one kilometre, it could be ten. But it's not a centimetre (because the lightning would fry me before I got to hear any thunder) and it's not a thousand kilometres (because that would be too far away to see and hear – it would be in another country). And I reckon there's usually a delay of a few seconds between the flash and the rumble. So the sound must travel a few kilometres in a few seconds. That makes its speed about one kilometre a second. It could be a bit more or a bit less, but it's not going to be a *lot* more or less.

Now I just looked up what the speed of sound really is. And guess what: it's 340 metres per second, or about a third of a kilometre a second. So my estimate wasn't bad! At least I didn't estimate a metre a second, or a million kilometres a second. I could get a fair idea of the number just thinking about stuff that I *do* know – and which I reckon you know too, once you think about it.

But if an exam asked the speed of sound and I just said "About a kilometre a second", that wouldn't be good enough. It would be marked wrong!

Maybe. But first of all, no sensible exam should be asking you "What is the speed of sound?" And second, if *I* were marking an exam like that, I would give as good a mark to someone who worked out from scratch, with reasons like those I just gave, that the speed of sound was about a kilometre a second as I would give to someone who'd memorized that it was 0.34 km per second. And I'd suspect that the first person shows more signs of being a good scientist than the second, which means much more (or should do) than what exam mark you got. (By the way, sometimes Albert Einstein didn't get very good exam marks either.)

So if you don't need to know lots of facts to do science, but you do need to know something, what's that "something"?

That's what this book is about.

And here's the answer – sort of. I'm going to tell you that, to have a pretty good grasp of science, it's not about what you *know*. It's about what questions you *ask*.

You mean, all I have to do to learn science is ask questions?

Again – sort of. Because here's the thing: the best scientists are not those who know all the answers, but the ones who think up the best questions.

If that sounds encouraging, you might like this next bit even better. Because I'm going to suggest to you that, to have a good grasp of science, there are only *three* questions that you need to ask. It's that simple.

Three! That's really easy!

Who said it was easy?

You did! You said –

Simple. I said simple. That's not the same as easy.

Ah, you're just messing about with words now…

We'll see. By the way, you are…?

Mel.

Short for – ?

Just Mel.

Got it. Hi Mel, nice to meet you.

You too. So what are these three questions then?

Oh, I'm not going to tell you that. Not just let. I have a few more things to say about them first. Besides, *I'm* actually not going to tell you what the questions are at all.

What??!!

No, I'm going to get some help for that. I'm going to let three scientists tell them to you. There's Rani, a physicist, and Sam, a chemist, and Yun Yun, a biologist.

Er, I'm not too sure what the differences are between different sorts of scientist…

Don't worry, they'll tell you what they do. But before they arrive, let me tell you a secret: they're not *really* sure what the differences are either. I'll explain why at the end of the book.

So yes, there are some things you need to know about these three questions. First, when I say three, I must admit that some of them have more than one part…

Well, think of the speed of sound. The exact number (0.34 kilometres per second) didn't matter so much. The important point is that it wasn't 1 kilometre a second, or a million. So don't get too hung up on "three questions." One question isn't enough, but there aren't a hundred of them either.

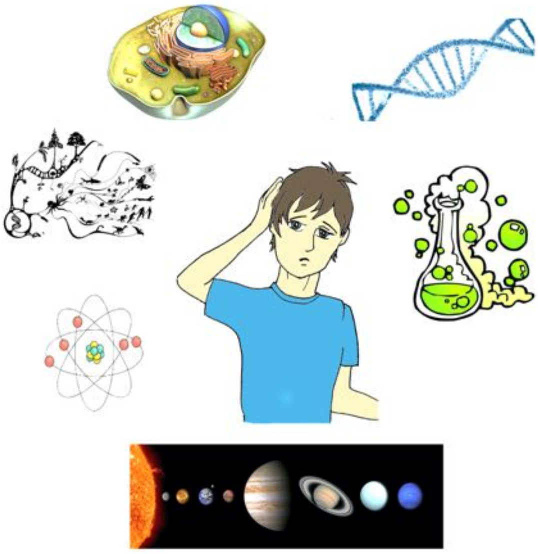
But the most important thing is that, when you ask these questions, you probably won't just be able to look up the answer in a book. You'll need to start figuring out the answer for yourself. *That's* what will make you think like a scientist.

And that's why I'm not saying it's easy, or that you don't need to know anything apart from the questions themselves. You need to know what the questions mean, and why they matter, and how to *think* about what the answer might be, even if you can't actually work the answer out.

And you also need to know when these questions *aren't* going to help you much in understanding what's going on. Because there's a lot of stuff in the world, and there's only so much that three questions can do. But these ones can do a lot.

So this is what I promise you. If you understand why these are important questions, and what they mean, and you can start to figure out just a little of how to answer them, you will be what is called "scientifically literate" – which is really a way of saying that you have the kind of basic skill in science that is like being able to read or write or add up.

This is true *even if* you get bad marks in your science tests. I'm not saying that it makes it OK to get bad marks in your science tests. But it means that you won't be bad at science even if you do. Maybe you just find science tests hard. If you understand these questions, then once you finish school you'll be ready to think about science when you meet it in life. That's more important than memorizing facts to pass exams – like the speed of sound.



Not many people *do* know the speed of sound. But quite a few don't know either whether the sun goes around the earth or the earth goes around the sun.

I do think it would be good if everyone knew the answer to that. If you don't, don't worry; I'll tell you right now. The earth goes around the sun. There. Will you remember that tomorrow? I reckon you will. Will you remember it next week? Probably. Next year? Maybe…

Some adults don't remember it at all. Is that because they were never taught the answer? Maybe, but I doubt it. Is it because they didn't pay attention? Maybe. Is it because they are stupid…?

I always assume that when someone doesn't know what seems like an "easy" question about science (or about anything else), it is *never* because they are stupid. I don't really know what "stupid" means, except that it is always a word used to be unkind about someone (or perhaps you might say it just because you're frustrated with them). It's *never* used to say something about someone that is true. I don't think people who don't know that the earth goes around the sun are stupid.

Then why don't they know it?

I reckon it might be because it was just taught to them as one fact among loads of others about science, and they tried to put that fact away in a little box in their brain and then they lost the box. They lost it because all the boxes looked the same. They didn't have any way of organizing them.

The reason I'm going to tell you – or rather, why Rani, Sam and Yun Yun are going to tell you – about these three questions is that they should give you a way of organizing boxes. If they do, then if you lose a box, you might be able to find your way back to it. Or if you still can't, the questions might help you figure out where you can look up the answers.

And if anyone tells you that you shouldn't be looking up the answers, just tell them that Albert Einstein told you to.

Chapter 2
What Is Science?

Before we get to the Three Big Questions, I've got an even bigger one:

What is science anyway?

Any ideas?

Ummm.... Doing experiments?

OK, that's a very important part of it. Anything else?

Wearing white lab coats.

Well, maybe. If you're doing experiments in the lab, it's not a bad idea to have a lab coat on, just like you might put on an apron to do cooking. But plenty of scientists don't wear white coats at all, or not much. It's not like a uniform or anything.

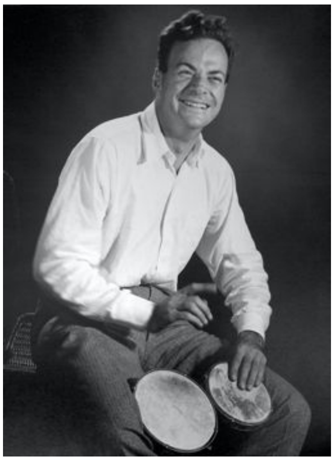
After all, some scientists do all their work on a computer, and some do it all in their heads, or with a pen and paper. Some go diving into the oceans, or climbing volcanoes, or even into space, where you need to have other, special kinds of clothing. So you really don't have to wear a white coat – unless you think they look good, I suppose.

They really don't look good.

No, I guess they don't, do they? It *is* possible to be a stylish scientist, but perhaps not all the time. They can look like this:

Or like this:

Or even this:



Huh? A bongo-playing scientist?

Yes, they do exist. This scientist was very famous.

For playing the bongos?

Among other things.

What else do you know about doing science?

Do you have to be good at maths?

Not necessarily. In some subjects it helps. In others you don't need to be great at maths at all. There are two qualities that are usually more important for being a good scientist than being good at maths. One is that – remember, I told you this just now – you have to be good at asking questions.

Well, I'm always asking questions!

I noticed. And that's why I reckon you could be a good scientist.

But we don't get to ask many questions in science at school. Usually they're asking us questions, and they expect us to know the answers.

Well then, I should tell you something. No scientist ever did anything, or not anything really important, because they knew the answer. They do it because they *don't* know the answer. What's the point of doing an experiment if you know what's going to happen?

In the experiments we do at school, the teacher always knows what's going to happen. At least, what's supposed to happen. Sometimes the experiments don't work.

And do the teachers tell you why they don't work?

No, they tell us what should have happened.

But if it *should* have happened, why *didn't* it happen?

Maybe they did something wrong?

Maybe they did. Like when you bake a cake but you forget to add something, such as the baking powder. Or sometimes an experiment might not do what you hoped it might because a piece of the equipment was broken, just as the cake might not work out if the oven's timer is broken and you cook it for far too long. When experiments don't work for reasons like that, it's a bit boring.

But sometimes an experiment won't do what you expected and you've got no idea why. You check everything twice, ten times, and still you don't get the result you expect.

That sounds like a nuisance.

Perhaps. But it can also be the best thing that can happen. Because then you might discover something new. You might discover that things don't work the way you thought they did.

Here's an example. Once, more than a hundred years ago, two scientists set out to measure how much the speed of light changes when it travels in different directions. They thought that space was filled with something called ether, and light was waves in the ether, just like sound is waves in the air. So as the earth moves through the ether as it goes around the sun, light should be slowed down when it goes in the same direction, a bit like a cyclist being slowed down when she pedals into the wind. But the light had the same speed in every direction. And that really puzzled everyone, because it's not what they expected.

Then years later, Einstein came along and explained what was going on. There was no ether after all! It was one of the biggest discoveries of the 20th century.

So you see, many of the experiments you do at school aren't like the ones scientists have done. They aren't really experiments at all – they're *demonstrations*. Someone has done them before, so we know what will happen if everything is done right. The reason you do them is to show you something, to help you learn or understand it.

But when scientists do an experiment, they don't know what's going to happen. And that's the point!

But then how do they know why they get the results that they get?

Maybe they don't know why. But they try to figure it out. That might sound hard, but they don't do an experiment randomly. They have planned it carefully, so that they know what they're looking for.

I'll explain what I mean, but first I should mention what the second thing is that makes you a good scientist. The first was that you like asking questions – which means that you're a curious person. Curiosity is good in science.

Why do people say that curiosity killed the cat?

Actually no one knows where that came from. But long ago people thought curiosity was bad – that we should just know what we're told, and not ask or expect to know more than that.

But that's no way to learn anything new.

Well, the second thing you need is attentiveness.

I don't know if I've got that, because I'm not sure what it means.

It means paying attention. I don't mean paying attention in class, although that won't do any harm. What I really mean is: being a good watcher. Being good at noticing things. Sometimes it's the little things that pop up in an experiment that really matter, that lead to something new and important.

There was once – this was in the middle of the nineteenth century – a chemistry student called William Perkin. He was eighteen years old, and he was studying at the top chemistry college in London. Well, his teacher told him to try and make an important chemical called quinine, which was used as a drug to cure the disease called malaria.

The trouble is, the experiment didn't work. Instead of making quinine, he made a kind of black gunk.

But he was curious about it, and he was attentive. Instead of throwing it away, he experimented with it some more and found he could dissolve it in alcohol, and it was a deep purple colour. And because he was attentive, he knew that lots of people were trying to kind coloured chemicals that they could use as dyes for making brightly coloured clothes. So he dipped a bit of silk into his purple liquid, and it stained the silk purple.

It was one of the most important dyes ever discovered, and soon there was a huge industry making dyes like Perkin's. It looks like this:

That was a Victorian thing.

So you see, Perkin's experiment didn't really go "wrong" at all. It just turned out differently from what he expected. And because he was a good scientist – even though he was only a teenager – he learnt something new and important from it. It made him rich too, but don't count on that!

Another famous scientist from that time, called Louis Pasteur – he's the fellow who discovered how to pasteurize milk, which is named after him – once said something about that. He said:

Fortune favours the prepared mind.

What he meant was that you might, in your experiment or in your theories, stumble by accident over something big, like Perkin did – just by accident. But if your mind has been well prepared to think like a scientist, you'll be more likely to notice and make the most of it. Lots of important discoveries have been made by accidents like this.

Now, not all science is about doing experiments, as I said. But experiments are one of the most important things about science. Because when you do an experiment, you're asking the world a question. And the world gives you an answer, and the world never lies.

I mean that the world doesn't care what you thought you were doing, or what you thought would happen, or what you wanted to happen. The world just follows its own rules, whatever those are. They determine what happens in the experiment. So we can discover those laws by doing experiments and paying careful attention to the results.

Actually, that's the *only* way we can discover those laws of nature. You can have as many ideas and theories as you like. But no other scientist is likely to believe you unless you do an experiment that shows you're right.

So if a scientist said, My theory is that if I add these two chemicals together they'll go purple, and then he does that experiment and they go purple, everyone decides he's right?

Sort of. But there's a little more to it than that. You need to design your experiment carefully so that it's as clear and convincing as possible.

Think about what Perkin was trying to do: make a drug called quinine that cures malaria. Now, if his mixture hadn't gone black but instead created a clear liquid, which is what dissolved quinine looks like, could he have decided that he'd succeeded in making quinine?

Well, I suppose lots of liquids are clear. Like water. So he might have made something, but he couldn't be sure it was quinine just from looking at it, right?

Right. So what could he have done to test it?

He could give it to someone with malaria to drink, and see if they got better.

That's one option. But what if he hadn't made quinine, but a deadly poison instead?

Oh. Then I suppose drinking it to see if it works isn't such a good idea. Does quinine smell?

Good thinking. If it smells like quinine, then it might actually be quinine. But not necessarily. It might be something else that just happens to smell like quinine. Even if he then took the risk of giving it to a malaria patient who got better afterwards, he couldn't be sure that he hadn't made a different drug that also cured malaria and happened to smell like quinine.

That would be a bit of a coincidence!

But it's not impossible, you see. And if you're trying to convince people that your experiment has turned out the way you predicted, you have to rule out as many other explanations as you can.

Anyway, sometimes people just recover from malaria naturally. So if he got someone to drink his liquid and they got better, there's no proof that it was the liquid that cured them.

Wow, you're hard to convince! Proving to you that I'm right would be really tough!

Lots of scientists would say that you can never prove that you're right. You can only prove that you're wrong. For example, if what he had made didn't look or smell at all like quinine, then probably he hadn't made it at all.

What's the point in proving that you're wrong?

Well, you hope you're not wrong. But if you do lots of tests, and none of them show that you're wrong, others are going to start thinking you might well be right. And that's often as good as it gets in science: other scientists say yes, I'm pretty convinced that you're right.

But if someone gets better after drinking your mixture, are you saying that you can never be sure it was the mixture that cured them?

You can be pretty sure, but you have to work hard to get there. It's not enough to give your medicine – what you think and hope is a medicine – to one person and see what happens. You have to give it to lots of people and see what happens. And you have to compare that with what happens to another group of people with the disease that receive no medicine at all. The best way to do that is to give them something that looks like your medicine but isn't –it's something that you know has no effect at all. Those people are called the control group.

Then, if many more people get better from taking your medicine but don't in the control group, you can be fairly confident that you've made a drug that works. Of course, before doing any of that, you have to be sure that the drug isn't a deadly poison.

All the drugs we use today have been tested like this, usually on thousands of people. It's really expensive to carry out all these experiments and it takes a long time, but that's the only way we can be sure both that the drug works and that it won't have nasty side effects, like damaging your kidneys.

Now, you can see from all this that science isn't just about finding out about the world around us. Some scientists do that. But others try to make useful things, like drugs. Some try to discover things that might help solve a big practical problem, like how to turn sunlight into electricity so that we can get our energy in a cleaner way, without so much pollution. Others just want to know stuff, such as how stars are formed, even though it's not obvious why that should ever be useful to us (though you never know!). It's fine to do science to solve problems and help humanity, *and* to do science that has no practical value at all. Both are science, and if we have any sense then we'll make sure we let scientists do both.

Let me just say, though, that chemists today have much better ways of finding out what they've made by mixing chemicals together than smelling them or drinking them.

Thank goodness for that!

Well yes. They have machines that can show us exactly what the chemicals are.

So no scientists come up with experiments randomly. No chemist looks at her shelves and says "I wonder what would happen if I mix that jar and this one?" They have much more focused goals than that. They might want to make a chemical that is known to be useful, like a drug, or some new material with particular properties, like being really hard. Then they might think up an experiment that, according to what they've learnt, ought to make that chemical, and they see if it works.

By the way, that's one experiment where often you really *can* prove that you're right, because the scientists might use ways of figuring out, accurately and reliably, just what the chemical is – and whether it is what you predicted it would be.

Some other experiments are to test theories. Einstein came up with a theory about gravity which said that, when gravity is very strong, it can bend light. Until then, everyone thought that light travelled in straight lines. So an astronomer called Arthur Eddington did an experiment to see if Einstein was right. He sailed across the world to a place where there was going to be a total solar eclipse – that's when the moon moves exactly in front of the sun and blocks out all the light, turning the world dark for a few minutes until the moon moves on. During the moments of darkness, Eddington was able to see stars that were actually known to be behind the sun, because their light got bent around it, just as Einstein said it would be.

That was some experiment, when you think about it – an experiment using the sun and another star.

So let me get this straight. If you're a scientist, you have an idea and then you think up an experiment to see if the idea is right?

That's more or less it. Sometimes you won't do all of that yourself. There are some scientists who really just come up with ideas, and some scientists who mostly do experiments to test ideas that others have had. But plenty of scientists do a bit of both.

And it might not be an experiment exactly. You might go out into the world to make measurements and observations. That's what astronomers do – scientists who study stars and space. It's kind of hard to make an experiment to figure out what's inside a star. But if you look closely at stars, if you measure their starlight really carefully, you can figure out what they're made of.

Or if you're a geologist and you have an idea about how a range of mountains was made, you might go up the mountain to look at the rocks up there and see if you can find clues that can tell if you're right or not. Some biologists go into jungles looking for new types of animals or plants.

But even when you're looking at the natural world like this, you probably have some idea of what you're looking for, of what you expect to see. You might not find it – you might find something else entirely – but usually a scientist starts with an idea.

And where do you get ideas from? No one has ever taught me that at school.

Well, it's not easy to teach it. But for a scientist, it is really, really important to find ideas. You have to use your imagination.

You mean you just imagine stuff?

In a way, yes. But that doesn't mean you just make it up. You look at what other people have found out before you, and then you might find that you have an idea about something they never looked at. It might be only a really small idea. You might think, well, if this chemical kills germs, maybe this other one will too – and maybe it'll do it even better.

Or you might have a really big idea, like how life got started on Earth.

Hey, but then how can you do an experiment to find out if that's right? Life started on earth absolutely ages ago, right? So how can you find out anything about it now?

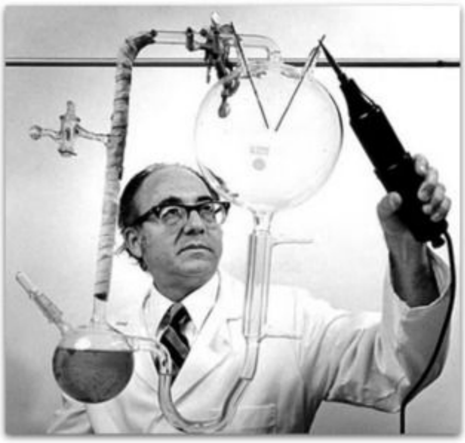
Yes, life started more than three and a half billion years ago, and so you're right: it's really hard to think up experiments to test ideas like that! But sometimes you can.

Over 60 years ago, two scientists in America had the idea that maybe the chemicals you need to make life – like the ones that make up really simple living things like bacteria – maybe they got made on the earth all that time ago from even simpler chemicals in the air. Back then the air was different: it contained different kinds of chemicals.

How do we know that?

It's a bit complicated to explain, but partly we know by looking at really old rocks. So anyway, these two scientists, called Urey and Miller – Miller was just a young student, but Urey was already very famous – they thought up an experiment to test their idea.

They made a mixture of the chemicals that most scientists back then thought were in the atmosphere of the earth just after it formed. And they had to give the chemicals some extra energy to make them turn into different ones. They figured that maybe lightning did that, and so they sent electrical sparks through their mixture inside a big glass bubble. Here is Miller with that experiment:



Old dude in white lab coat alert!

Yeah, I know. They were quite big on white coats back then. And ties, if you were a man.

Well, only a day after Urey and Miller started their experiment running, they found that these very simple chemicals had turned into some really quite complicated ones – and those were just like some of the chemicals from which living things are made.

You mean they made life?

No, they were a long way off doing that.

Aw. They weren't Frankensteins then.

No, but they made some of the main ingredients of life.

I have to tell you that many scientists today don't think life started the way Urey and Miller suspected. They don't think it got its ingredients from lightning in the atmosphere. But that's science for you – you might do an experiment that shows your idea could be right, then someone else comes along with a better experiment, or better observations, and it turns out that your idea probably isn't right after all.

But that's fine. Being wrong sometimes is OK in science. Even if you're wrong, your ideas might have inspired someone to do better experiments and find out more. Actually most ideas turn out to be wrong eventually. But that's kind of what we want, because it means our ideas get better and better – they get to be more and more accurate ways of understanding the world.

Are you saying that scientists usually get things wrong?

Not wrong, exactly. They might come up with an explanation for what they see that works pretty well, but then someone notices a new thing that no one had seen before and scientists realise that their ideas – their theories – were only roughly right.

Let's say someone asks you how to get from your road to your school, and you tell them to take the number 54 bus. But then when they go to the bus stop, there's a sign saying the 54 bus has been cancelled that week. Was what you told them wrong?

No! How was I to know the bus had been cancelled?

You weren't. So no, you weren't exactly wrong. But still, what you told them wasn't going to work on that occasion, even though it might work fine most of the time. This week, what you said was wrong. You're looking sulky now.

Well, I don't think that was a fair example. I don't think it's fair to say I was wrong.

OK look, let's say they asked me and *I* told them that. Well, you won't blame me, will you?

No. It wasn't your fault either.

That's right, it wasn't. And when scientists find that their theories and explanations don't always work, it's not their fault. Perhaps it's just that something new has turned up. Remember what I said about Arthur Eddington testing Einstein's theory of gravity?

By looking at the sun during an eclipse? And... something about starlight...

Right – and seeing rays of starlight getting bent by the sun's gravity. Well, before then there was already a theory of gravity, which was thought up by Isaac Newton about two hundred years earlier. It seemed to work fine for all that time. It could explain why the planets go around the sun, and why the moon goes round the earth, and how things fall when they're thrown up into the air.

So it was a pretty good theory. But it wouldn't have been able to explain why Eddington saw gravity bend light. So it wasn't the complete truth. Einstein's theory explained all of the things that Newton's theory did, but some other things too. Not just why the sun bends starlight, but also things people discovered later, like black holes, which you'll hear about in a bit.

So Newton's theory wasn't exactly wrong. Actually, it was still good enough to use to plan the space missions that took men to the moon, long before you were born. Still, in some situations Newton's theory of gravity isn't going to work, and you need Einstein's instead.

Sometimes people say that science isn't about getting things right, but about getting them less wrong than before.

And it's usually by doing some kind of experiment that we find out what it is about our theories that needs fixing. We find something that we can't explain using our theory. Maybe all it needs is bit of patching up. Or sometimes we might need a whole new theory.

Over two hundred years ago, lots of chemists thought that when things burn, they give off a kind of gas, called phlogiston.

Called what?!

They did think up a few weird names back then, didn't they? You say it "fluh-jist-on". The theory seemed mostly to work kind of okay – it seemed to explain why, say, a big lump of wood turns to a little pile of ash. But a French chemist called Lavoisier wasn't too happy with the idea of phlogiston. For one thing, he saw that when metals are burnt – when you make them hot – they get a bit heavier. How can they do that, if they're *losing* phlogiston? Lavoisier realised that what really happens when things burn is that they are changed by the air itself, or by one of the gases in the air, which he called oxygen. So the whole theory of phlogiston had to be kicked out and replaced with Lavoisier's theory of oxygen.

And by the way, Lavoisier's theory of oxygen is probably about as right as we're ever going to be about burning. Not every theory in science is just waiting to be replaced by a better one. There are something's we scientists have worked out which are probably always going to be right.

But you see, Lavoisier worked this out by doing experiments, looking at them very carefully – measuring what happens, like how things change weight when they're burnt in air – and then thinking about it.

There's a real skill to making a good experiment. You don't just try out any old thing. You start with an idea you want to test. And then you ask: what should happen if I'm right? What might happen if I'm wrong? You might have to do some maths to work out what you think you should measure, and then compare it with what you *do* measure.

I think I'm getting it. So science is about asking questions, and thinking what the answer might be, and then doing an experiment to test your idea? And you don't even have to wear a white coat?

That's right. And no, you don't – though sometimes you don't want to wear your best clothes either.

But you've got to think carefully about how to make it a good test. I told you that, if you want to see if a new medicine works, you can't just give it to someone with the illness and see if they get better. They might have got better anyway.

So you should get a whole bunch of people with the illness…

... and give them all the medicine and see if they all get better!

Actually not quite. It would be even better to give half of them the medicine, and half not. Then you see if more people who took the medicine got better than those who didn't. The ones who don't get it are called the control group.

That doesn't seem fair. If the medicine works, the people you don't give it to don't get better.

Well, you're right, and that makes it tricky. If the illness isn't very serious, and there are already some other medicines that work, you could give the control group those medicines later. But for serious illnesses, it's not easy to find a fair way of testing new medicines. You might be trying to cure an illness for which there's no known cure yet, and so you tell a group of people that this new medicine might or might not work, and they might or might not be in the control group that doesn't get it anyway, but do they want to be part of the study? And often plenty of people think they would, because it might help to find a new medicine that could cure others too.

But to be more sure about your results, you don't just give the control group nothing. Everyone in the test gets given something – a pill, say. But only half of the pills actually contain the medicine you're testing.

You trick people?

No, you tell them before that you'll do it this way, and they'll not know if they're getting the medicine or not. You have to do that, because there are many illnesses where some people would recover simply if they *think* they're getting a medicine. It's really just the power of the mind that makes them better.

That doesn't sound like science! It sounds like, I don't know, mind control or mind reading or something.

I know, it seems odd. But it really does happen. What we think and feel can affect our health. So scientists have to think about things like that.

But they need to be even more careful about their experiment. What if one of their groups was mostly men and the other one mostly women, or one mostly young and the other mostly old? Then more people in the group that gets the medicine might get better than in the control group just because they're younger and healthier, and nothing to do with the medicine itself. Or the medicine might not seem to work, but only because it works better on women than on men, and there are more women in the control group.

So they have to take care that the two groups are as similar as possible – except that one gets the medicine and one doesn't. That way, they can be more sure that any differences that they see between the two groups was caused by the medicine.

Well, all these things are especially important for testing medicines, but you have to think in the same kind of way for any experiment. You have some kind of control to compare what happens when you do something and when you don't do it. And you try to make sure that the results can't be caused by anything except the thing you change yourself in the experiment. You have to be constantly asking yourself, Well, could something else be causing this result? Is there some way I could be fooling myself into seeing just what I expected to see?

It sounds like scientists don't trust themselves!

In a way that's true. They are trained to be doubters. And the easiest person to fool is yourself. That bongo-playing scientist said that, by the way.

You see, often in life we see things happen and we jump to conclusions. We think, Oh, that obviously happened because of this. Or we hear things that sound like they could be true, or which we'd like to be true. But if we're good scientists, we don't immediately assume that they *are* true.

What star sign are you?

I'm a Libran. Um, do scientists believe in star signs, then?

Do you?

Kind of. Librans are meant to be fair and tactful – you know, careful with what they say to people. And I am like that! Well, most of the time. And my best friend is a Scorpio, and they're meant to be determined. And she is! So doesn't that show star signs are true?

Well, do you think you have to be a Libran to be fair and tactful? And a Scorpian to be determined?

I suppose not...

So the question is, are Librans more fair and tactful than everyone else? Well, that's not an easy thing to find out. How do you measure how fair someone is? But maybe you can think of a way of doing it – maybe you could see how people play games where you can cheat. Still, it's not easy. But to be sure that

Librans are fairer than other people, you'd need to do that test – not just with you, but with lots of Librans and non-Librans. Ideally you'd test a few hundred or each. Until you do that, you can't say for sure that Librans are especially fair.

But if you're thinking about the question like a scientist, you should also ask yourself: does it seem *likely* to be true? Can I think of a way it might be? Why would Librans be more fair than anyone else?

I think astrologers say it's because the stars affect our moods. I read about one who says that the moon affects the tides, so why can't the stars affect our bodies?

OK, let's think about that. Do you know why the moon affects the tides?

Errr... is it gravity?

Right! It's that old law of gravity that Isaac Newton came up with. A huge great thing like the moon, so close to the Earth, has gravity strong enough to make the oceans slosh and cause tides. Actually the Sun's gravity affects the tides a little bit too. The Sun is much further away from us than the moon, and an object's gravity gets weaker the further you are from it. But the Sun is also much bigger than the moon, and an object's gravity is stronger the more massive it is. So even though it's further away, the Sun is huge enough still to tug at the oceans a bit and help to cause tides.

Well now, stars are just like our Sun, but are much, much further away. It's hard even to imagine how far away they are. So Newton's law of gravity lets us work out how strong their gravity is here on earth. And you know what? It is really, really weak. The force of gravity from a truck driving past your house is stronger than the force of gravity you feel from even the nearest star. So if the force of gravity from stars was affecting your moods, it should be also getting changed all the time, and much more strongly, from everything around you.

Besides, why would just the stars of Libra affect Librans, and those in the constellation of Scorpio affect Scorpions? It's even worse than that. The stars in the constellation of Libra aren't all the same distance from earth. Some are much further away than others. So the idea that constellations of stars can have an influence on our personality just doesn't seem to make sense according to any science we know about.

That's a good reason to be pretty doubtful right from the start about whether astrology works. There are no laws of science that we know of that could explain *how* it could work.

That doesn't mean we have to throw away the idea that Librans are more fair, on the whole, than other people. Librans are born in early autumn, right? So maybe there's something about being born in early autumn that could make people like to be especially fair. It's hard to see what that could be, though. Maybe there's something about early autumn that could have an effect on newborn babies, which would affect their personalities for life, but it seems pretty unlikely. And anyway, early autumn in the Southern Hemisphere, like South America and Australia, is in March and April, not September and October.

Still, we wouldn't know for sure whether there's anything in it unless we did some kind of experiment to test people. No one has ever found any evidence that your star sign has any particular effect on your personality, though. So scientifically, there's absolutely no reason to think that astrology is true, or even any good reason to think it *might* be true.

I suppose I see what you mean. But I did kind of like the idea that I am fair and tactful because I'm a Libran.

Sure. We like to have explanations for things. But we can't be sure they are good explanations unless we do experiments and tests. And by good, I don't just mean that they seem to make sense to us. I mean that the explanation allows us to correctly predict something about the world that we didn't already know.

Like predicting that if someone we just met is a Libran, they'll turn out to be fair and tactful?

Not just that. Most people are pretty fair and tactful, I reckon, whether they're Librans or not. So you'd need to predict that they are likely to be fairer and more tactful than average. Like I say, that's not at all easy to measure!

It sounds like a lot of work to do good scientific tests.

It is. You have to keep asking, But what if my results are caused by this or that? And you try to figure out experiments that would answer that question. So you might need to do lots and lots of experiments before you feel confident about deciding what they mean.

For example, in 2012 some physicists announced that they had found a new particle: a new tiny bit of stuff that no one had seen before. It was called the Higgs boson, and…

The what? You said scientists thought up weird names long ago, but it sounds like they're still at it.

Well, you have to call it something. Years before that experiment, a scientist called Peter Higgs, and some others too, said that this particle might exist. But if it did, it would be really, really rare. The only way to make it in an experiment was to smash two other particles into each other, and see if any of the new particles turned up in the debris. Well, they did. But to be sure of that – to be sure that their results weren't just happening by chance, and weren't caused by Higgs bosons at all – the scientists had to carry out not just several experiments, or even hundreds or thousands. They had to carry out 300 trillion. So they needed some of the world's most powerful computers to help them sort out the results and see if there was any sign of the Higgs boson here.

Scientists don't usually have to carry out quite that many experiments! But they do always have to be careful: to make sure, say, that an experiment that seemed to work once, and give the answer they expected, will work a second time, and a third…

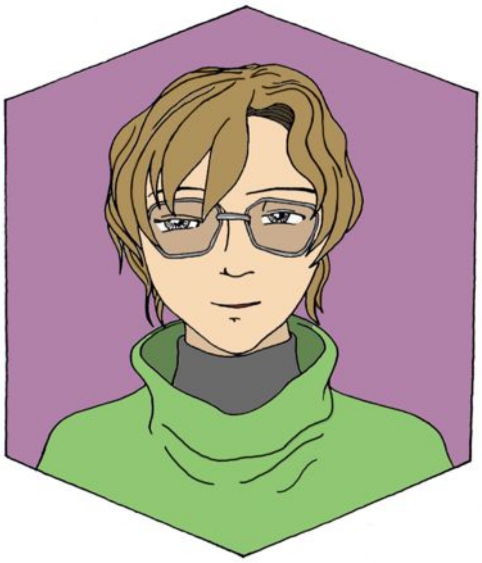
It sounds like very hard work. Is this the only way to find stuff out?

If you're trying to find out things like how the world works, or what it's made of, or whether some material or chemical or drug or machine does what we want it to do, then there's nothing like science for giving you answers that you can trust. Of course, that doesn't mean science can answer every question. If I want to know if it will rain on this day next year, it's hard to see how you could do a science experiment to find out the answer. Science could tell you what the chances are – you just need to look at whether it rained one this day for as far back as you have weather records. But that won't tell you for sure.

And some questions aren't really scientific at all. Some just come down to facts: you can't work out from an experiment on which day Henry VIII died. And some don't really have a particular answer – like, is it better to be a fair person or a kind person? That's really a question for philosophy, not science. It's an interesting question, but not one that science can answer.

So it's important to choose the right questions: to know what science can answer and what it can't. We mustn't expect too much from it. But the main idea – to ask a question and then design experiments to help us find the answer – is amazingly powerful. It's why we have medicines that really work, and aeroplanes that really fly. It's how we know why stars are hot, how plants grow, what the weather will probably be like tomorrow. It's why we can do science.

Chapter 3
What Makes the World Go Round?



Hello. My name is Rani, and I'm a physicist.

You probably know that's a kind of scientist. So what does a physicist study?

Well, physics, obviously.
Duh!

Right. And at this point I'm probably supposed to tell you what physics is. But it's kind of hard to do that. If you study physics in school, you'll learn about stuff like forces and gravity and energy and perhaps planets and stars. All that is physics.

But here's why it's hard for me to say exactly what physics is: because there's physics in everything. It's in computers and cars, but also in trees and birds, and–

Isn't that biology?

Well yes, it's biology too.

But how can it be part of two subject

We cut up science into these chunks like physics and biology and chemistry, but that's just like we cut up the ocean into the Atlantic and the Pacific and so on. It's all just a load of water, and the water flows between the different oceans and seas and doesn't notice when it goes from one to the other. There isn't some kind of wall or red line dividing them up. It's the same with the world: if we want to understand it, we can use science, and it doesn't much matter that we might say "This bit's physics" and "This bit's biology" and so on.

My friends and I will show you later what I mean. The fact is, physics is the hardest of all the sciences to define, because it leaks into everything. If you play the piano, there's physics involved. If you play video games, there's physics. If you climb a tree or throw a ball or even if you're just sitting there thinking – there's physics going on in your brain.

Remember that we said every one of the main science subjects has its own core question? I'm going to tell you right away what the question is for physics. Here it is:

How did that happen, and why?

You can ask it about pretty much anything, like why it rained, or why your phone works (or why it broke), or why stars are born and die.

And of course there will be lots of different answers, and it might seem that there's nothing connecting them all. But very often, the answer will have something to do with physics. And there's a good chance that you can understand a lot of it by asking two further, more physics-y, questions:

Where is the energy? What are the forces?

Oh wow! Those are really tough questions. I don't even really know what energy and forces are.

That's OK. That's what I'm here for – to tell you what the question means. But I bet you've heard those words before: "energy" and "force". Am I right?

Yes I have. Energy is like when I say "Oh, I don't have the energy to do my homework". And force... It's like in Star Wars: "Feel the force, Luke!" Or when I say something like "...and you can't force me to do my homework either!" But I don't suppose that really counts, does it?

It completely does count. Those are great examples. So you see that energy is like an "oomph" that lets you do stuff. And force is something that *makes* you do stuff. Unless you resist, of course, in which case you'll be exerting a force of your own.

Hey, I can think of loads of other examples now. Energy bars. Nuclear energy – I'm not sure what that is though. It says something about energy on the back of cereal packets. And then, "force of nature" – like, "she was a real force of nature". Force nine gales. The armed forces, the police force. Don't force it, or it'll break.

Right. So we talk about energy and forces quite a lot. A force sounds like something strong – like a kind of strength. And energy is something… energetic! Bouncy, like Tigger.

I just thought of another word a bit like these. It's power. Nuclear power. That's a powerful movie. Power tools. I'm feeling powerless – or powerful!

Yep, you've got it: power is related to force and energy. They're all to do with *making things happen*. We'll get to power in a bit.

But I'm going to be honest with you now. It's not easy to say exactly what force and energy are. I don't mean it's hard for me to tell you. I don't completely understand them myself. Nobody does, not if you really try to get to the bottom of them.

Wait. You're saying that the big question for physics is "where is the energy?", but you don't even know what energy is?

Sort of. But don't be discouraged. All I'm saying is that if you find them hard to grasp, what's just because everyone does, including physicists. Still, they get used to it, and so can you. Once you get used to thinking about energy, you're not so worried about being able to say exactly what it is.

Think of it a bit like the colour red. Can you say what it is?

The colour of tomatoes!

Yes, but can you say just what it is without talking about things that are red?

Is this a trick question?

A good scientist should never need to ask trick questions.

But it's really hard to do, isn't it? Still, I bet you never have any trouble knowing just what you mean when you talk about the colour red! Energy is a word a bit like that. There are quite a few words in science like that. Actually, most of the really basic things in science, like gravity or mass or temperature, are like that. We get used to using them, but it's not at all easy to say exactly what any of them is.

We get to understand them not by defining them in a dictionary, but by using them.

Now, remember that we said you're not going to learn *everything* from these three questions. Not all of physics is about understanding forces and energy. All the same, if you really know what we mean by force and energy, and if you know how to look at something that happens – it could be anything, like burning the toast or a meteorite hitting the moon – and you can think about it in terms of the energy and the forces involved, then you are a long way toward being able to think like a physicist.

So let's start with energy.

Have a biscuit.

Really?

Yes, go on. It'll be good for your learning. You can tell your parents or teachers or whoever that I said that.

Are chocolate ones best for my learning?

Yes. OK, yes they really are. Tell them I said that too. Not best for your body, of course. But best for energy.

Because that's what you get when you eat a biscuit. It gives you energy.

Like you said, we sometimes say that we've got lots of energy – that we feel energetic. And that's because we have. And food is where we get it. Food is an energy store.

Sugar is particularly good at storing energy, which is why there's a lot in chocolate biscuits. It's not a bad idea to eat something like a chocolate biscuit before you do something that needs lots of energy, like playing sports, because then your body has plenty of it to keep you going. Food, and especially food with lots of energy in it, is a kind of fuel, like the petrol we put in cars.

And like cars, we get the energy from burning that fuel.

Yes, the sugar in the biscuit releases the energy it has stored in it when it is burnt up inside your body. And *that's* why it's not such a grand idea to eat too many chocolate biscuits, or to eat them when you're not exercising. Because then your body isn't going to burn up all the sugars to get their energy, but instead it will store up the energy itself – by turning the sugars into fat. Then it can burn up the fat later if it needs to. If it doesn't need to, the fat just stays as fat – and that's not so great for your body, if there's too much of it.

But where is the energy in sugar?

Good question. The energy is stored up inside the sugar. My friend Sam, who is a chemist, will tell us more about how that works. The only thing we need to think about right now is that the energy gets released when the sugar gets combined with oxygen in your blood –

Oh, now you're getting into biology! Or is it chemistry?

Well, I *did* warn you. But look, there's a good way to show that there's energy stored in a biscuit that gets released when it is burned. And that's to burn the biscuit.

No way! I want to eat it.

I know, but this is for the sake of science. If you're lucky, you might get another one for lunch. But this one's for burning.

Look, you can light a biscuit with a match or a candle. And it catches fire. It's a bit smelly, but it's not a bad smell really – kind of caramel-ish, because that's really all caramel is: slightly burnt sugar, mixed with a bit of butter. So you could use biscuits as a real kind of fuel. You could make a fire with them, and heat up a pan of water with it. Then the energy in the biscuits has gone into the water and made it warm. It has become heat energy.

How come we don't get hot when the biscuit burns inside us?

Well, actually we do! Our bodies are usually warmer than their surroundings. You can measure that with a thermometer. We measure temperature in degrees, right? In most countries we use the Centigrade scale. So a comfortable room is about 20 degrees Centigrade, whereas our bodies should be about 36.5 degrees. And the reason they're warmer is because they are burning up food. If they weren't, we'd gradually get as cool as the room. And that would be very bad news, because if our bodies get colder than about 35 degrees, we're in danger.

So some of the energy in food is converted to heat energy too, which keeps us warm. But some of the energy is what we use to do active things, like running. Or thinking.

Thinking takes energy?

Yes, thinking uses a surprising amount of energy. About a fifth of all the energy we take in as food is used up in the brain.

But here's the really important thing. I said that, when sugar is burned, the energy it stores is converted to heat energy. And this is what happens with energy: it can get converted into different types. There are lots of types of energy, and in our everyday world it is constantly being changed from one form to another.

In sugar, and in all food, the energy is stored as chemical energy. All that means is that it is held inside the chemicals in the food. Burning is one way to release that energy, and most of it is then turned into heat energy, which makes things hotter.

But some of the energy is used for the actions themselves. If something is moving, it has a kind of energy called *kinetic energy* – that literally just means "movement energy". So you have kinetic energy when you run or walk. Even if you just move your arm, it has kinetic energy, which it gets from the chemical energy of food. Even your beating heart has kinetic energy, because parts of it are moving to and fro like a pump.

It's pretty easy to work out how much kinetic energy a moving thing has. The kinetic energy is the mass of the object times its velocity squared, divided by two.

I just knew you'd spring some maths on me.

So if a tennis ball and a basketball are moving at the same speed, the baseball has more kinetic energy because it has more mass. But if the tennis ball gets faster and faster, eventually there will come a point where it has the same kinetic energy as the slower basketball, because the kinetic energy depends on velocity too.

Think of an elephant walking along. For a mouse to get the same kinetic energy as the elephant, it would need to travel at about five thousand miles an hour.

That's one speedy mouse!

It certainly is.

There are other sorts of energy. When you walk upstairs, you're converting some of the chemical energy of the food into a kind of energy called gravitational potential energy.

Ooh, sounds complicated...

It's really just a kind of energy that gets stored in things that are lifted higher off the ground. When they're high up, we can get this gravitational potential energy out of them by letting them fall. We might be able to use or store that energy.

That's how one kind of water wheel works. The water runs onto the top of the wheel, where it fills buckets attached to it. And the weight of the water makes the wheel turn as the water descends. Then the gravitational potential energy of the high-up water is being turned into kinetic energy of the moving water wheel. And we can use that movement to do something useful, like rotating a grindstone to grind wheat into flour.

This conversion of energy from kinetic energy to gravitational potential energy, and back again, is what happens if you throw a ball directly up into the air. It goes up and up, and all the time it's moving it has some kinetic energy. But gradually it goes slower and slower as the kinetic energy is turned to potential energy. Right at the top of the throw, the ball actually stops moving for a brief moment, and then all of its kinetic energy has become potential energy. Then –

down it comes! And the gravitational energy gets turned back to kinetic energy as the ball falls faster and faster.

There are other kinds of energy too. For example, what else stores energy?

A battery?

Good! And in a battery the energy is stored as electrical energy. If you connect the battery in a circuit, that electrical energy gets released. One way to think about what goes on is that it is turned into the kinetic energy of the tiny little particles that make up the electrical current, called electrons. They move along the wire. Now what happens if there's a light bulb in the circuit?

It lights up.

Of course. And then some of that electrical energy becomes light energy. Because light is a form of energy too. But what else happens to the bulb?

Hmm...

What's it like to touch?

It might be hot.

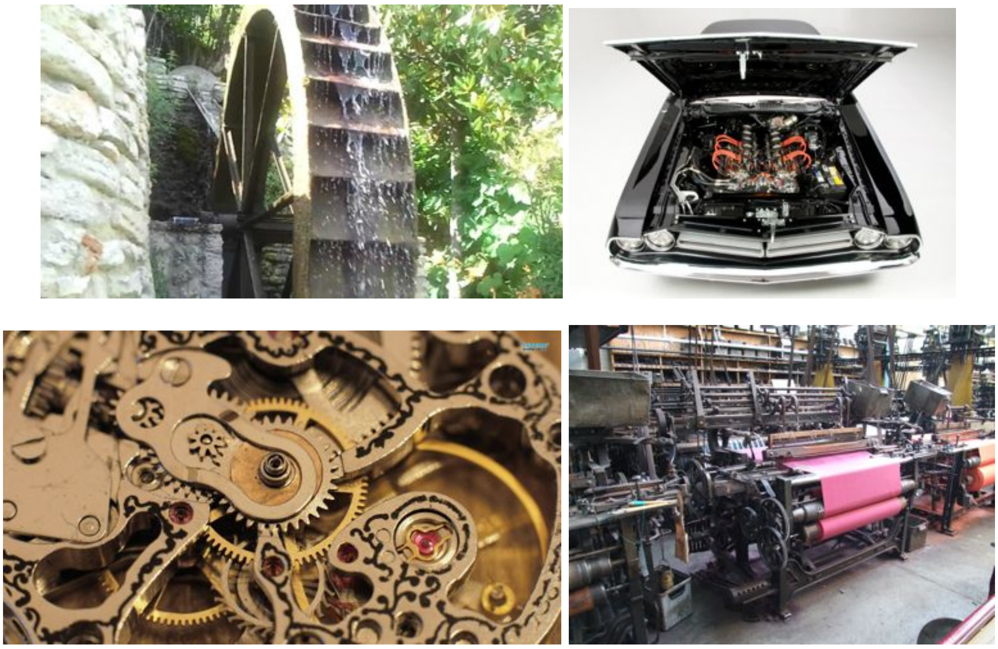
Right – which is why it's best *not* to touch a glowing lightbulb. So some of the electrical energy becomes heat energy too. In fact, just about every conversion of energy from one form to another produces some heat. We saw that this happens in your body: when you run around, you get kinetic energy but you also get hot. Even when a ball is thrown up into the air, it gets a tiny bit warmer, because the rubbing of the ball against the air it passes through, which is called friction, produces some heat.

When we want to burn fuel to warm up water, we're perfectly happy to make heat – that's exactly what we want. But we can't get all the heat to go into the water, no matter how clever we are. Some will leak away and be wasted. Same with the light bulb: we just want to make light, but we can't help making heat too. And with our moving bodies: we just want to move, but we get hot too. We want to keep our bodies warmish, but getting really hot when we run around doesn't help us at all. We just can't help it – we can't stop some of the food energy being turned to heat.

It's the same with cars. If you ever felt the bonnet of a car after it's been driven, you'll know that it's warm. In fact, the engine under the bonnet might be dangerously hot to touch. And that's just wasted energy – we didn't *need* the engine to get warm, it's just that we can't help it when we burn the fuel. All we want is for the fuel's energy to get turned into movement of the car – kinetic energy – but some makes heat instead. Actually we can sometimes use that heat, to keep the car warm in winter, so it might not be totally useless. But on a hot summer's day, that's the last thing you want.

There's a word for describing how much energy gets turned into a form we want and can use, and how much is wasted as heat. The word is *efficiency*. The more efficient a car is, the more of the fuel's energy goes into making it move, and less goes into warming it up.

Machines, like cars, are generally things that turn one form of energy into another – and in doing that, they do something useful. They *do work*. A water wheel is a machine for turning the kinetic and gravitational potential energy of water into work, for example to grind wheat. The "work" that a car does is to move around – that's its job. A bicycle is a machine for turning the energy of your moving legs into movement of the wheels. And the better a machine is at turning a source of energy, like running water or coal or chocolate biscuits, into useful work, the more efficient it is.



Machines do work by converting one form of energy into another.

Slow down! I'm having to work pretty hard myself here...

Sure, let's stop to look at the ideas we've got so far.

There are many types of energy, and one type can be converted into another. One of those forms of energy is heat.

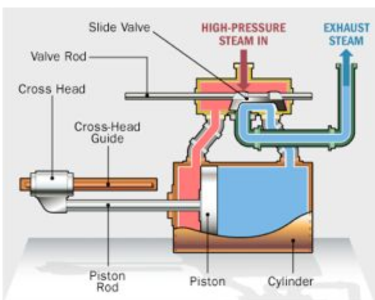
Machines convert energy from one form into another – generally they need a source of energy, called a fuel.

And machines do work – which means putting the energy of the fuel to good use. How well they convert that energy to useful work is called their efficiency.

Phew... OK, go on.

Well, about machines. You might have learnt in history about the Industrial Revolution. This was the time from around 1760 until the 1850s when lots of new machines were invented for doing work, and they began to be used in factories for making things on a big scale, like textiles spun on weaving machines.

During the Industrial Revolution, people first figured out how to make engines that run on steam. The basic idea is to turn fuel energy into movement: chemical to kinetic energy. The way steam engines do that is to burn the fuel to heat up water until it boils. Then it evaporates as steam. The steam is a gas, and takes up a lot more space than the water, and so it can create a kind of pressure, like what you get when you blow air into a balloon. In a steam engine, that pressure pushes at something called a piston, which is usually a cylinder inside a bigger cylinder, and the piston moves forward. That movement can be used in a machine.



Steam engines were used for many things, from powering machinery like weaving looms to making steam trains run along their tracks. But engineers wanted to know how to make their machines and engines efficient, so that they could do more work with less fuel. And in particular they were keen to know what was the most efficient machine possible – because as I said, no machine is *perfectly* efficient. Some energy is always wasted as heat that leaks away into the surroundings and can't be used.

And so they invented a new branch of science, which was all about how energy gets converted from one form into another, and how much heat gets made in the process. This science was called *thermodynamics*, which just means "movement of heat".

Now I'm going to tell you a secret.

When I was learning physics, I thought thermodynamics was one of the most boring parts of it.

Oh great. And now I have to learn about it?

But you see, I was wrong. I learnt some more physics, and I discovered that thermodynamics is *amazing*. Why? Because it can help you to understand things like why time only goes in one direction, and how the universe will end, and what happens to stars when they run out of fuel and go bananas.

Stars go bananas? I quite like the sound of that.

Well, I'm going to get to it. You'll just have to trust me for now: thermodynamics is amazing.

Here's all you really need to know for now about thermodynamics: it has three laws. And actually, you only need to know the first two of them anyway.

OK, I'll give you a little peek of the third law too. It says something a bit like there's a limit to how cold things can get. You can't keep cooling them forever.

So there's like, an Ultimate Coldness?

There is, and outer space is almost that cold, mostly. But nothing is really that cold. It's impossible to ever get to the Ultimate Coldness.

Good name for a band, though.

Well, let's look at the first two laws of thermodynamics, which are the most important. The first law tells you the *most important thing* about energy, and it's this: you can never create or destroy energy, you can only convert it from one form to another.

In other words, the total amount of energy in the universe is fixed. It never changes.

How do we know? We don't.

What?!! You're saying it's a law but it might not be true?

I suppose I am saying that. What I'm saying is that pretty much every scientist and engineer in the world believes it to be true, and we've never seen anything that breaks the law. But we can't *prove* that it's true. Sometimes that's the best we can do in science: to assume that something is true because, every time we check, it does *seem* to be true.

The first law of thermodynamics means that, for everything that ever happens, if you add up all the energy that you start with, and all the energy that you end up with, they're the same. You never lose any energy, and nor do you gain any. This is called the *conservation of energy*. Conservation here doesn't have anything to do with the conservation of pandas or tigers, except that it's a word meaning that something is saved. And that's true of the energy: all of it is saved, none is lost. It is conserved.

What this also means is that you can never make energy from nothing. There's no machine that will just keep working forever, unless you give it some fuel. It would be wonderful if such a thing existed, because then we wouldn't have to keep generating energy by doing things like burning coal and oil, which harms the environment. We wouldn't need fuels at all. A machine that would run forever without fuel is called a perpetual motion machine, meaning that it never stops moving of its own accord. But the law of conservation of energy says that a perpetual motion machine is impossible. That hasn't stopped people from trying to make one, because they figure that if they could do it then they would get very, very rich from their invention. There are still some people trying to do that today. But sadly, it looks like they'll never succeed.

Still, we can *imagine* perpetual motion machines. Here is one: this waterwheel will keep on turning as water flows round and round the loop.

Uh – how does that work?! I can't quite figure it out.

That's the idea. It's just a clever optical illusion that the artist dreamed up. It looks as though the water is moving downhill all around the loop, but that's impossible because it could never then get back to where it started.

Now it's time for the second law. This one is *really cool*. It says that heat always flows from hot things to cold things.

That is not really cool, not even as a bad pun. It is obvious, and it sounds dead dull.

I know what you mean. If I make a cup of tea and leave it to stand, it's going to get cold, right? It won't get even hotter, just be standing there. That's the second law. Well duh, again.

But wait. Some things do get colder, not hotter, as they stand there. Like a fridge. When you buy it from the shop, it's the same temperature as everything around it, inside and out. And then you plug it in and switch it on, and the inside gets *colder*. That doesn't seem to be obeying the second law, does it?

No. But I've got a feeling you're going to tell me that it does.

I am. Have you ever been round the back of a fridge?

Can't say that I have. But we once had mice who lived in the back of our fridge.

Aha. And do you know why they made their nest there?

Because then we couldn't catch them?

Well, partly that. But also, because it was warm.

There are some tubes and stuff round there, and I won't explain exactly how it all works except to say that the fridge uses electricity to squeeze and expand a liquid inside the tubes, and what this ends up doing is drawing heat out of the inside of the fridge but dumping it, *and more heat too,* into the room. One bit of the fridge gets colder, but overall the fridge produces heat. As all machines have to.

All right. But that still doesn't seem to fit with your second law. You said that heat always flows from hot to cold. But if that's true, the inside of the fridge could never get colder than the room it's in, once you switch it on.

You're smart, Mel. And you're right. I gave you a slightly lazy version of the second law. What I should really have said is that heat never flows from cold to hot of its own accord. We can *make* it do that, just as we can make water flow uphill if we pump it. We can make heat pumps, and that's really what a fridge is. But if we pump heat from cold to hot, we're always going to need energy to do it, and we're always going to waste some of that energy as heat. And overall, if we add up all the flows of heat, we'll find that we've ended up making the universe a little bit warmer as a result. We've made some heat.

And this is what the second law is really saying. Every time you convert one type of energy to another, you end up making some heat. And that heat energy just leaks away, and you've lost it. You can never get all the energy back: you can't make the conversion completely efficient.

Well, that seemed bad news for engineers. But hey, it wasn't *so* bad. We can live with a bit of inefficiency, a bit of energy wasted as useless heat.

But when scientists first came up with these laws of thermodynamics – this was around the middle of the nineteenth century – they realized something a bit ominous. If, every time *anything* happens to convert one type of energy into another, some of that energy is lost forever as heat, eventually we'll run out of energy. It will all be turned into heat. It's like moving all the water from one bathtub to another. If you can't ever do that without some of the water splashing and leaking away, then eventually you'll have lost it all. Well, you can always run more water into the bath – but you can't get more energy from anywhere. Remember that the first law says that the total amount of energy in the universe is fixed. So when we reach the point where all the available energy has been turned into useless heat, there's none left to do any work.

No more work! Cool.

Well perhaps – but that also means no more life. Once that happens, the universe is dead.

Oh. So not so cool.

Not really. You see, energy is needed to make *anything* happen. We need sources of energy to live. If all the energy stored in food has been turned to heat, and all the energy of the sun has been turned to heat, and so on, then there can't be any life because there's no energy to keep it going. There's no energy to keep anything going. *Nothing can happen, nothing can change!*

As long as there are patches of the universe that are hotter than other patches, things can happen, because then heat energy is on the move, going from warmer to colder places – and some of that energy can be captured to do some work. But eventually that movement of heat will smooth away all the temperature differences until everything is the same temperature, all over the universe. And then that's it. From there on, it's nothing, all the way to eternity. The nineteenth-century scientists called it the heat death of the universe.

It sounds like the ultimate boredom trip.

It is. Those scientists were a bit horrified by the idea, and some of them looked for ways to escape from it. But they couldn't find one.

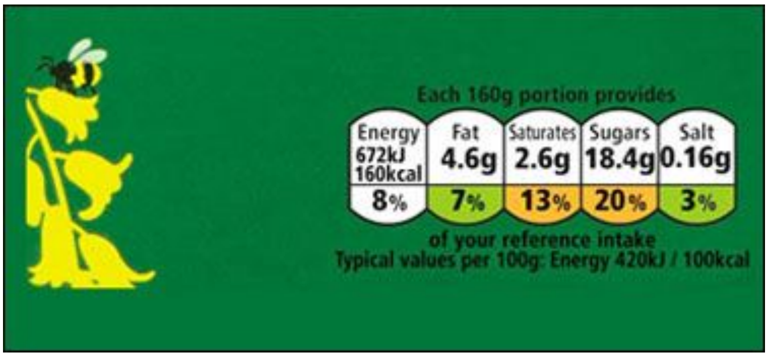
So we're all going to die of the heat death?

Well, the truth is that no one knows. These are hard questions that physicists are still trying to understand. But what's surprising is that it all came out of thinking about how to make better steam engines.

And burning biscuits.

Yes, and that too. Which, by the way, I want to say something more about. I quite like a chocolate biscuit myself, but I know that I'm not going to be in good shape if I have too many. But I can use the laws of physics to figure out how to burn off all the energy that one of them contains. Here's how.

First, I need to find out how much energy is in a biscuit. Now, I could just look on the back of the packet, because these days the packets will usually tell you how much energy a food contains. Energy is sometimes measured in units called calories (cal for short), and sometimes in joules (J). A food packet will tell you how many calories of energy are in the food – look:



If this information wasn't there on the packet, though, I could work out roughly how much energy is in the biscuit by burning it to heat a glass of water, and seeing how hot the water gets. There's a maths equation that tells me how much energy is needed for each degree of temperature rise in the water.

So let's say that I eat a biscuit and all that energy goes into me. Now I want to burn it up. Let's say I want to convert it all to gravitational potential energy by walking up the stairs in a tall building. How high does the building need to be? There's a formula for working out the potential energy of an object, and it says that the energy is equal to the mass of the object times its height above the ground times the strength of gravity. I know my mass, and I know the strength of gravity – it's pretty much the same all over the earth. So then I can work out the height that produces exactly as much potential energy as the biscuit contained. How about that? Just from physics, I can figure out how to eat chocolate biscuits and stay slim.

And how high do you have to go?

I did the calculation, and it came out as 200 metres, which is the height of a pretty tall skyscraper. But you see, it's not quite that bad, because I have to think about how efficient my muscles are: how good they are at converting the chemical energy of a chocolate biscuit into potential energy. According to biology textbooks, they're not very efficient: maybe only a quarter of the energy gets converted to potential energy. Most of the rest gets turned into heat – I'll get very hot going up all those steps. But it does mean that I only need to go as quarter as high, because I lose the rest of the energy as heat. So that makes it 50 metres. I reckon I could manage that – it's about as high as an average office block.

Well, so much for energy. But now what is it, exactly, that makes it hard for me to walk up those stairs?

You're not very fit?

Ouch. But maybe it's partly that. What am I working against, though, when I climb the stairs?

Oh, I get it! Gravity.

That's it. The *force* of gravity drags me downwards.

So here we come to forces. Now, the thing about forces is–

I bet I know what you're going to say. No one knows what a force is.

Well, I kind of was going to say that, but do you know what? If you think of a force as a push or a pull, that's actually good enough.

Just as there is energy everywhere – inside us, in the air, in light – so too there are forces all around and in us. You could say forces are a part of life.

We're not always aware of them though. If you're sitting in a chair reading, you probably don't feel like you're being pushed or pulled. But you are. For one thing, the force of gravity is pulling you down towards the floor. If it wasn't, you'd float off, as astronauts do inside space stations.

So how come you're not having to fight against this downwards force of gravity? Well, you are. If your spine wasn't pushing up your skull, you'd collapse in a heap. But you're getting help from the chair, because the chair is pushing back too.

The chair is pushing? That's weird.

It does sound odd. But that's one of the laws of forces: if something pushes on something else, the something else pushes back just as hard. Gravity makes your body push against the chair, and the chair pushes back. This has a name: Newton's Third Law. It was discovered by Sir Isaac Newton in England more than three hundred years ago.

So wait – I suppose if it's his third law, this Isaac Newton had two other laws about forces too? At least two others!

Yes, he did. Just two others.

Still, so many laws!

Yes, but at least Newton's laws are pretty much all you need to know about forces. Once you know them – they're called his laws of motion – and if you understand them, then you'll have grasped kind of the central ideas in physics.

OK, but don't think I've grasped much yet. I don't see where the pushing and pulling come from. If I tie a rope to a tree and pull on it, then I can see that I'm making a pulling force, and the tree will bend. But how does gravity pull? It's invisible.

That's a brilliant question. So brilliant that I can't completely answer it, because no one knows. But the best answer we have at the moment is a pretty strange one. It's because gravity bends space.

What?! How can space be bent?

I know, it's pretty hard to see what it means. But here's a way to think about it.

Isaac Newton was also the first person to get a really good idea of what gravity is, though even he didn't think of it as bent space. He said that he thought about it by watching an apple fall off a tree and down to the ground. He figured that gravity is something caused by mass, which really means, by stuff. Any piece of stuff has gravity that pulls other stuff towards it. How come? Newton didn't know. He just figured out that, the more massive an object is, the stronger its gravity. So the apple is falling down because of the force of gravity from the entire earth, which is pulling it down.

We could just leave it at that: we could just say, well, gravity is a force that mass creates, which pulls stuff to itself. That was pretty much how people thought about gravity for two hundred years or so. Then Albert Einstein – remember him? – came along, and he said that the reason objects have gravity is that their mass bends space.

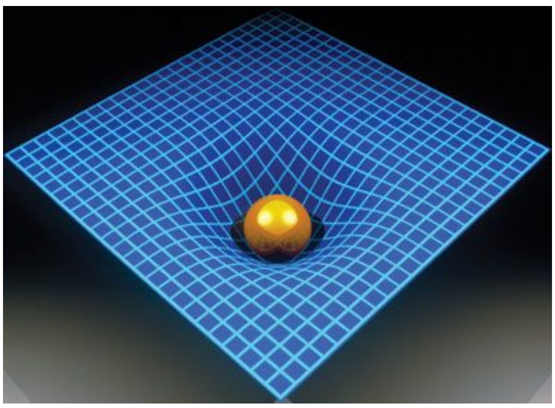
Here's how it works. I want you to imagine space as a flat sheet. If Einstein is right that space is bendy, we can think of it as a sheet of rubber. But it's flat. Now think of the earth as a football and Newton's apple as a pea. Of course, if the earth were really the size of a football then the apple would have to be much, much smaller than a pea to stay in the right proportion. But never mind that.

Earth

Apple

So the football and the pea sit on the bendy sheet of space. According to Newton, the football just kind of sends out this force that pulls the pea towards it. That's an OK way to think about gravity, but like you say, it's a bit odd because it's then just this mysterious, invisible force.

But according to Einstein, the football sitting on the rubber sheet will bend the sheet because of its mass: it will make a big bowl-shaped dip.



And then the pea will just roll down the dip until it hits the surface of the ball. And there you are: the pea has fallen onto the surface of the ball because the ball has bent space, and that produces gravity.

So how come space doesn't look bent around the earth?

Well, the bending is very, very small, and you can't see it anyway when you're in it too, just as you can't see that the earth itself is curved. But if you stand a long way off from a bit of curved space then you *can* see it is curved, just as you can see that the earth is round if you step back from it – on a space station, say.

This is what a British scientist named Arthur Eddington did in 1919 to show that Einstein was right about gravity bending space. Einstein said this around 1916, and it meant that light has to follow a curved path too when it goes through a piece of curved space. Eddington saw that light from a distant star is actually bent slightly as it skims the sun before reaching a telescope on earth. The sun is usually far too bright to see a star behind it, but Eddington looked at the sun during a solar eclipse, when the moon blocks out all the sun's light, and he saw that the star didn't seem to be where it *should* be according to what astronomers say, because its light was bent by the sun's gravity.

So gravity is the force that keeps the earth in orbit around the sun. Without the sun's gravity, the earth and the other planets would just drift away into space. And the earth's gravity is what holds the moon in orbit around the earth. What Newton realized is that the force that pulls an apple to the ground is the same as the force that binds the earth and moon together – it's gravity.

Then how come the earth doesn't just fall onto the surface of the sun, and the moon doesn't fall onto the surface of the earth, like the apple?

The reason is that the earth is moving. If it wasn't, then we would be pulled into the sun and frazzled in an instant. Think of that dimple of bent space again. The pea just rolls down the slope and hits the football. But what if the pea is already moving sideways? Then it can roll around the football along the rim of the dimple. If it is going fast enough, it can stay up on the rim and never fall in. And that's like the earth going round the sun.

But what keeps the earth moving? If I want to keep a car moving, I have to give it energy – it needs fuel. So what's fuelling the earth to keep moving around the sun?

This is the amazing thing. Nothing is fuelling the earth!

How can it keep moving then?

This brings us to Newton's other laws. His first law says that something that is moving to begin with will keep on moving in the same direction forever if no other forces act on it. If it's motionless to begin with, it'll stay motionless. And it doesn't take any energy to do this. After all, we saw that the kinetic energy of an object depends on its velocity. So if the velocity stays the same, so does the energy. You don't need any more energy to keep the velocity the same.

So you're saying that if something is moving, we don't need to keep pushing it to keep it moving?

That's right.

No it's not! If I push a marble so that it rolls across the carpet, it won't keep rolling forever. It'll slow down and stop eventually.

Yes. But I said that an object will keep moving forever in the same direction only if no forces are acting on it. But there *is* a force acting on the marble. It's the force of friction between the marble and the carpet. If one thing moves across the surface of another thing, there is always this force called friction between them. And it's a force that pushes back against the moving object. That force makes the velocity get smaller and smaller until it shrinks to nothing.

There's also a force of friction on something moving through water, like a swimmer or a boat. There's even a force of friction for an object moving through the air, which we call air resistance. You can think of it as coming from the object bumping into the tiny particles called atoms that are what air really is, and slowing it down.

Because of friction, things that are moving do stop eventually unless we keep pushing. And that takes energy. Friction turns some of the kinetic energy into heat energy: the moving object and the surface it moves over both get a bit warmer. Because of this, many people thought that Newton's first law sounded odd and wrong, just as you did. But you have to think about all the forces that might be involved. In space, where there is no air and so no friction, an object that is moving *will* keep moving forever. Well, more or less – even space isn't completely empty. And so you can't easily see Newton's first law working on earth.

So the earth keeps moving around the sun because of Newton's first law? Because it is moving in empty space, and so there's nothing to slow it down?

Not quite. Remember I said that, in Newton's first law, if there are no forces acting on a moving object then it keeps on moving *in the same direction* – in a straight line. But the earth doesn't go in a straight line. It is changing direction all the time, as it moves in a circle – well, a slightly flattened circle, called an ellipse – around the sun. And what this means is that there *is* a force acting on the moving earth, which is not slowing it down but is changing its direction. And what do you think that force is?

I suppose... it must be gravity?

Right! Gravity isn't strong enough to pull the earth into the sun, thank goodness – but it *is* strong enough to bend the path of the earth away from a straight line and into a circle.

Think of it this way. If you throw a ball up into the air, eventually gravity pulls it back down again. If you throw it harder and faster, it will travel further, but still it will fall in the end.

But what if you throw it so fast that it falls over the horizon? Then you can send it into orbit. You can think of it as falling over the horizon forever. It's going so fast that it never actually falls back to the earth's surface. But it's not fast enough to actually escape the earth's gravity altogether and float off into space. What this means is that the object is falling forever. And the earth is like that in its orbit around the sun. We are falling into the sun forever.

Freaky!

It is, isn't it?

So what I've just told you is that a force acting on a moving object makes it change its velocity. Now, we have to be careful here. We often use the words "speed" and "velocity" as if they mean the same thing, but they don't quite. Velocity is speed in a particular direction. If an object changes direction then it changes its velocity, even if it keeps up the same speed. That's what is happening to the earth: it's going round the sun at the same speed all the time – which is why a year is always 365 days, because it takes that long to complete an orbit. (Well, actually about 365¼ days, which is why we have to have a leap year with an extra day every four years.) But it is constantly changing its velocity, because of the force of the sun's gravity.

And Newton's second law tells us by how much an object's velocity changes when a force acts on it. All it really says is that the bigger the force, the faster the velocity changes.

This is kind of obvious. Say you have a toy car sitting on the carpet. Its velocity is zero, OK? If you give it a little shove – a small force – then you change its velocity a bit: it's not zero any more. But if you give it a bigger shove, you change the velocity more: it sets off at a faster speed.

So here's the main thing about Newton's laws of motion. If an object is motionless, or if it's moving at a steady speed in a straight line, then overall no forces are acting on it. You sit still on your chair, because the downward force of gravity, making your bottom push on the chair, is perfectly balanced by the upward force, called thrust, that the chair exerts on your bottom. When a car is moving down a road at a steady speed of 20 miles and hour, there *are* forces of friction and air resistance that would slow it down – but it is burning fuel to produce a force from the engine that drives the wheels. And if its speed is steady, those two forces are perfectly balanced.

If, though, an object is speeding up or slowing down or changing direction, then there's some overall force acting on it.

And so when you see something happen – remember that first Big Question we started with? – you can ask: what were the forces that made things move in that way? And how was energy changed during the process?

You bend down and pick up your schoolbag. You used energy from the food you ate to make your muscles get shorter, and that pulled on your bones and let you bend down. Then you grabbed the bag, moving muscles in your fingers, and a different set of muscles shortened and relaxed to let you stand up. The forces in your body pushed up and overcame the force of gravity holding the bag to the floor. As the bag rose, it gained both kinetic energy (because it was moving) and gravitational potential energy (because it was getting higher). And that energy was coming from the chemical energy in your body. All the while, some heat is being produced: there's friction in all the movements, and your body gets a tiny bit warmer because of the exertion. To describe all this in detail – to figure out how chemical energy causes muscles to tense and shorten, say – is very complicated. But we can see that the motion is being caused by forces that change object's velocities, and those changes causes energy to be transformed from one type to another.

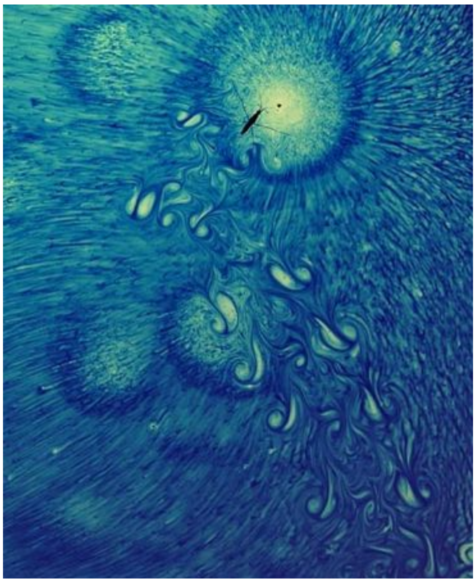
And that's physics?

A fair bit of it, yes. Thinking about forces helps us make sense of what we see happen too. An apple falls from the tree to the ground - it's the force of gravity! But then a leaf falls off, and it falls more slowly. Why’s that? Because there's air resistance pushing back up as the leaf falls. The apple feels air resistance too, but it is round and heavier, and the air resistance is too weak to make much difference. Because the force of gravity depends on how much mass the object has, gravity pulls less on a small and light leaf than it does on the apple. Also, the leaf is broad and flat, and so there's plenty of air just beneath it to push back. So the total downward force on the leaf is smaller than on the apple, and it doesn't accelerate so fast.

A leaf also flutters and sways as it falls, though. Why?

Good point. That's because of all the swirling in the air as the leaf moves through it.

How air - or anything the flows, like water - moves when it is pushed or pulled is really complicated, and very hard to predict. Just look at all the swirling that goes on in a fast-flowing river: all that chaos is called turbulence. Even so, we can still understand how gases and liquids flow using Newton's laws. The answer is complicated because in this case every bit of the fluid is pushed by and pushes back on every other bit. It's a little like a crowd of people, all jostling one another - the movements get quite random. Sometimes, though, these swirls can become surprisingly organised, like in little trails of spiraling flow called eddies. Here are some of them made by the movement of a water strider's legs as it moves over the surface of water:



And here is the same kind of thing, billions of times bigger, in the swirling gases of Jupiter's atmosphere:

They look like freaky paintings!

They really are beautiful, aren’t they? Nature is quite an artist.

Sometimes a falling leaf might produce quite organized eddies like this in the air, and then it might sway regularly from one side to the next as it falls. You can see the same thing in bubbles when they rise up through a fizzy drink: sometimes they move in a kind of zigzag, because of eddies forming first on one side of the moving bubble and then on the other.

And you know, sometimes crowds really do move like a kind of fluid too. There's something called crowd turbulence, which can happen in dense crowds when everyone is pushing and shoving too hard. It’s a bit scary and dangerous. But sometimes crowds can end up making more organized movements too, just thanks to the forces of each person pushing against the next. Here's one of them:

Hey, that's a mosh pit!

Ah, you know about mosh pits then - where people in the audience at rock concerts all jostle up like crazy and nobody cares? Yes, that's what this is, and here it's turned into a kind of wild round-and-round dance. Nobody planned to move that way - it's just what came out of the forces in the crowd. Some physicists wrote about it in an article called "Collective motion of moshers at heavy metal concerts".

Are you serious? Scientists went to heavy metal concerts to study moshers?

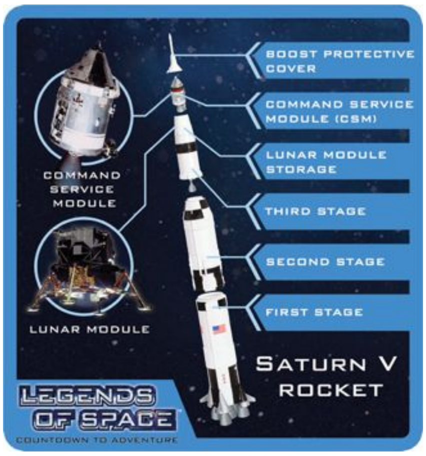
Well, they just looked at some Youtube videos, I think. But who said science can't be fun?

Some of the coolest physics of forces and energy is what goes on in space. What I've told you already helps to explain how to get there. We need to create a big force to push a rocket up from the ground and get it free from the earth's gravity. To do that, we basically make a big but slow explosion, which is sort of what a rocket engine is.

Rocket fuel is made of chemicals that store lots of energy, which gets released when they burn. There are many kinds of rocket fuel, but some of them, like the stuff called RDX and HMX, are basically explosives. They get mixed with another chemical called an oxidizer, which contains a lot of energy to help the fuel burn quickly. Then – Boom!

The reason this propels the rocket is because of Newton's third law. The burning produces really hot exhaust gases, and these stream out through a nozzle at high speed, with lots of energy. Remember that if all this mass of stuff is being pushed in one direction, Newton's third law says that it will push back with equal force in the opposite direction. So as the exhaust gases get fired out of the rocket engine, the rocket gets pushed the other way, which is called thrust force. And up it goes.

But most of a rocket is fuel: it's like a cylinder of explosives with a little cabin on top, where the astronauts sit. And just about all that fuel is needed to create the force that will get the rocket away from earth's gravity. Out in space, it barely needs any fuel. That's because of Newton's first law. As there's no air resistance, you don't need to keep up a thrust force. Once the rocket is moving, it will just keep moving without needing more energy. So the early moon rockets threw off most of their mass once they were in space, getting rid of the fuel canisters. Here's the Saturn V rocket that the Apollo missions used, and all the first three stages were jettisoned by the time the rocket was outside the earth's gravity. All you need in space is little thrusters for steering with: moving a bit this way, a bit that way.



The latest rocket engines don't burn fuel at all to get their thrust. They use something called ion drives–

You sure that's not just something out of Star Trek?

It does sound a bit like that! But they're real. The engines produce electrically charged atoms called ions, and then use strong electrical fields to pull the ions along until they're moving really fast. Then the ions get spat out of the exhaust, and thanks to Newton's third law that creates a thrust. Ion drives need less energy, and can potentially make rockets go much faster.

You see, basically rocket science is mostly about force and energy.

I guess even the Starship Enterprise used the same sort of physics to explore the universe. But that can be a dangerous mission. There are some pretty fierce things out there: things that release lots of energy. One of them is exploding stars, called supernovas. Stars going bananas.

At last!

Stars, you see, have life cycles, rather like animals, although the star isn't really alive. Still, they're born, they grow, they get old and they die. And understanding that cycle is all about seeing where the energy is and what the forces are.

Stars are born because of gravity. Space is filled with dust and gas – I mean, most of space is more or less completely empty, but every so often there are these clouds, just like there can be clouds here and there in a clear sky. And the gas and dust in the clouds clumps together because of its gravity. The denser the clump gets, the stronger the gravity, and that gas goes on getting squeezed and squeezed, and as it is squeezed it gets hotter and hotter. Eventually it's a ball of super-hot and super-dense gas – and then it can start to burn, and it's a bright shining star.

But it's not burning like the gas on a cooker. It burns because of another kind of energy, which I haven't mentioned yet, called nuclear energy. My friend Sam the chemist will say a bit more about it when she talks about what atoms are like. All you need to know for now is that nuclear energy is locked away inside atoms, but there are ways of getting it out. One is when two atoms smash into each other and merge into a bigger one. That's called nuclear fusion: fusion is really just another word for merging. And when two atoms fuse, some of the nuclear energy inside them can get released. In young stars, some nuclear energy escapes when two atoms of the stuff called hydrogen get squeezed together. They merge and turn into another kind of stuff called helium – Sam will tell you what these substances are.

Stars start off as balls almost entirely of hydrogen, and bit by bit this gets turned into helium by nuclear fusion. The nuclear energy that escapes becomes heat and light energy. That's why the sun is hot and bright, because the sun is a star. Every other star in the sky is more or less like our sun, though some are bigger and some are smaller, some are older and some younger.

As a star gets older and most of its hydrogen is turned into helium, the helium atoms merge together too to make even heavier ones, and that releases nuclear energy too. The atoms go on merging, making heavier and heavier atoms like carbon and calcium, all the way until they become iron.

Stars *make* stuff?

They do. But as they make ever bigger atoms, they produce less and less heat and light. So old stars grow dimmer, and turns red. Eventually the star has run out of stuff to burn, and then it's ready to die.

Stars get born – they make stuff – and then they die? Like us?

Kind of, yes. But there are several ways a star might die. All of them begin by collapsing. While a star is hot, the heat and light it makes produces a kind of push which stops the star's gravity from tugging all the gas into an even tighter and denser ball. But when that heat and light fades, gravity takes over and the star starts shrinking. What happens next depends on how big it was to begin with.

Our own sun will shrink until it's only a bit bigger than the earth – but it will be much, much denser. The shrinking heats it up again, and it will glow white-hot. Shrunken stars like this are called white dwarfs.

If the star is a bit bigger than our sun, then it shrinks so fast and so much that it gets really, really hot and it explodes. That's a supernova. All the outer layers of the star get blasted out into space – all those substances that it made from merging atoms are scattered across the cosmos. But the very centre of the star gets crushed even denser by the blast, and it turns into a really weird star called a neutron star.

Gravity is so strong in a neutron star that it mashes all of the star's atoms together into one big mass – a bit like a saucepan of peas being boiled into a gloop of mushy peas. There aren't any actual atoms left in the neutron star gloop, but just bits of atoms called neutrons.

This neutron gloop is amazing. When we say something is dense, we mean that it has a lot of stuff squeezed into a small space. Well, neutron-star stuff has the most extraordinary amount of stuff in a tiny, tiny space. Imagine taking a mountain and squeezing it. How small do you think you need to make it to get it to the density of a neutron star?

OK, just guessing here. The size of my school.

Smaller.

The size of my house?

Smaller.

Oh wow. The size of me?

It's the size of a thimble.

A mountain squeezed into a thimble? How is that even possible?

That's what the force of gravity can do, in the right circumstances. It's an amazing squeezer.

So a neutron star, then, is only about as wide as a big city – maybe 20 miles across. But it has the same amount of stuff in that space as a star. Its nuclear energy is all used up, so neutron stars are dark. But some of them are spinning, and send out jets of energy as they spin: two beams like those in a rotating lighthouse, not of light but of radio waves, which astronomers can see using instruments called radio telescopes. These spinning neutron stars seem to be blinking on and off steadily, sometimes many times a second because they are spinning so fast. Because of this pulsing, they are called pulsars.

A twin beam of radio waves streaming from a pulsar.

The gravity on neutron stars would squash us as flat as a sheet. It pulls the neutron star into a perfect ball, as smooth as a snooker ball. But that's not the limit to how strong the force of gravity can be.

You see, if a star starts off even bigger than the ones that make supernovas and neutron stars, then they have too much stuff in them, and so too much gravity, to ever stop shrinking at the ends of their lives. They keep collapsing in and in, until they vanish.

What? They just disappear?

Yes, they really do. Einstein's theory of gravity, which I told you about earlier, says that there's no limit to how dense stuff can get. Gravity can go on pulling it tighter and tighter until it shrinks to nothing. Now, most scientists think that probably it can't *really* shrink to nothing, because there's a different theory in physics which says that this shouldn't be possible. So probably some day someone will come up with a better theory than Einstein's which tells us what really happens here.

Einstein's theory is wrong then?

Most theories in science are wrong – or rather, they only work up to a point, and then they break down. That's how it was with Newton's theory of gravity: it's good enough to tell us how the earth goes round the sun, but not how stars collapse at the end of their lives. Science isn't so much about getting the "right" answer, but getting an answer that is good enough.

So then, the stuff in these stars gets so dense that you can't even really imagine it. And then a strange thing happens.

I told you that Einstein said that gravity is bent space. Well, in one of these completely collapsed stars, the gravity is so strong that space gets curled right up on itself, and nothing inside can get out again. Even light. So light can fall on the collapsed star, but it just gets sucked in by the force of gravity and never escapes. And that's why these stars are called black holes.

Because they're black, and space is black too, it's not easy to see a black hole. But astronomers have done. They look like this:

The stuff around the hole is very hot, and so it glows – that's how we can see the hole in the middle! Scientists have even seen two black holes collide, which releases such a lot of energy that it shakes space itself.

It shakes space? What does that even mean?

It's hard to imagine what it means, but Einstein's theory of gravity said it could happen, and now we've proved that it does.

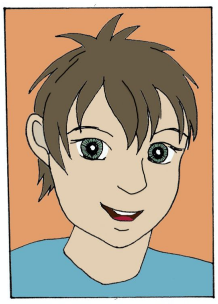
Making black holes must be one of the weirdest things that forces can do. If you fell into a black hole, the force of gravity would suck you into a long, thin strand like spaghetti. But it gets even stranger. Because Einstein's theory of gravity says that, not only is gravity bent space, but also it slows down time. In a part of space that feels a force of gravity, times goes more slowly. The stronger the gravity, the slower time passes, compared with space outside the reach of the force. And the thing is that, at the point around a black hole where not even light can escape from its gravity, time is slowed down so much that it stops altogether. If an astronaut was watching something – let's say it's a shoe –

The astronaut has lost her shoe?

Don't think about it too hard. It's a space shoe, or something. Anyway, this shoe is falling into the black hole, but it looks to the astronaut as though it never actually gets to the middle. It just slows down and stops at the place where space is fully curled up, as though it is frozen there. Forever.

Forever?

Well, perhaps. The English physicist Stephen Hawking had a theory that black holes shrink – they evaporate. He's probably right, but we don't know for sure. Other scientists think that some black holes might be shortcuts that join up two different parts of space. They call them wormholes.



Shortcuts in space? So you could step through them and come out in a different part of the universe? Like in *Doctor Who*?

Maybe. It's not clear if it's possible to go through a wormhole, if they exist at all. Or even if it is, you might not survive the journey.

Like, you might get sucked out of shape by gravity?

Exactly. It's not something you'd want to find out by trial and error, let's say.

You see, there's still plenty we don't know about black holes. They're such extreme things that they take us right to the edge of what physicists know, and they remind us that we don't know everything.

And that's why doing science is fun. Because there's still plenty to find out.

Chapter 4

What's It Made Of?

Seven hundred and sixty five trillion, twenty nine billion, four hundred and sixty two million, eight hundred and thirteen thousand, three hundred and twenty *seven*…

Seven hundred and sixty five trillion, twenty nine billion, four hundred and sixty two million, eight hundred and thirteen thousand, three hundred and twenty *eight*…

Seven hundred and sixty five trillion, twenty nine billion, four hundred and sixty two million, eight hundred and thirteen thousand, three hundred and twenty *nine*…

What are you doing?

I'm… Seven hundred and sixty five trillion… I'm counting atoms… Twenty nine billion…

Why?

…four hundred and sixty two… was it two?...

Why?

Wait, I just… and sixty two million, um… No, I've lost it.

Oh, I put you off. I'm sorry

It doesn't matter. I was only making it up.

What?!

I just wanted to give you some idea of how many atoms there are in things. No, if I'd really counted up to seven hundred trillion and something, then I'd have had to start quite a long time ago.

Oh. How long?

Well let's see. If I count one atom every second – and I can't even say the numbers that fast when they're so big, but let's pretend I could – then to get to seven hundred trillion I'd have had to have been counting for… let's see… oh, about 20 million years.

You're joking.

I'm not. That's long before humans even existed.

I have a question. What's an atom? Rani talked about them, but I don't really understand what they are.

Atoms are the pieces of stuff that everything is made of. They're like the building blocks of everything. Just like houses are made of bricks, so bricks – and bread and basketballs and even you – are made up of atoms. If you had a sharp knife, sharper than the sharpest knife you can imagine, and you kept cutting up a piece of bread, eventually you'd cut it into atoms. That's what "atom" means: it comes from a Greek word meaning "uncuttable". Though actually you *can* cut atoms up, but we'll get to that later.

So I guess if there are seven hundred trillion atoms in a loaf of bread, they must be really small?

Oh, they're much smaller than that. Seven hundred trillion atoms wouldn't even make something as small as a grain of sand. Not by a long shot. To make a grain of sand, you'd need something like 50 quintillion atoms. That's about 50 million trillion.

I didn't even know quintillion was a real word. It's a cool one, though. What about gazillion?

No, that's not a real word. But I like it too.

That's mad, though, isn't it? I can't even imagine numbers that big.

No, you're right. We can't imagine it. The truth is that, if I tried to count the number of atoms in a grain of sand and I started when the universe began, I wouldn't even be close to finishing yet. And what that means is that atoms are really, really small. That's how so many of them can fit into a single grain.

It sounds a bit bonkers. Why should atoms be so small?

Who says they're small? They're only small compared to you. You could just as well say, why should humans be so big? Though of course, we're not really big. Not compared to the world, let alone the universe. We're kind of quite neatly in the middle, between the tininess of atoms and the hugeness of the universe. Which is kind of interesting.

I'm Sam, by the way. I'm a chemist.

One of the things chemists do is think about what things are made of. What kinds of atoms they have in them.

Oops, I've blown it already. That was going to be my Big Question, you see. First of all, the question is:

What is it made of?

And then you ask it in the way that a chemist might, which is like this:

Which are the atoms? How are they arranged, and what are they doing?

Atoms *do* stuff?

Certainly they do. If they didn't do stuff, like move around and change places with each other, then you wouldn't do stuff either. Your body is made of atoms doing stuff, and what they're doing keeps you alive. Even in a grain of sand, which is like a tiny little chip of rock, atoms are doing stuff – though to be honest, it's not such interesting stuff as what the atoms in you do. And so a grain of sand isn't alive.

But first of all, let's go back to the first question. What is it made of?

What is *what* made of?

Anything you like.

My shoes.

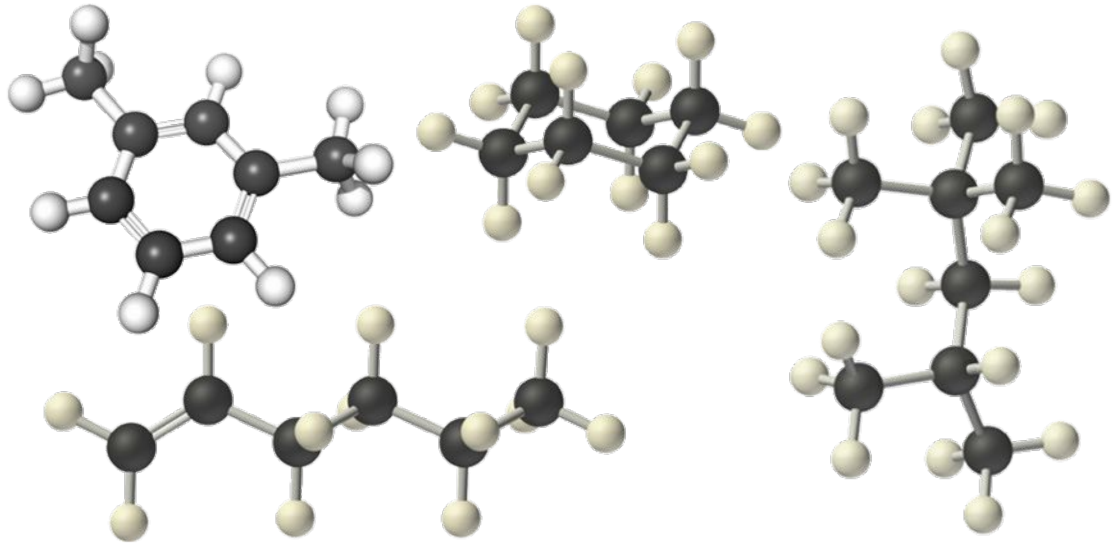
OK, your shoes. You tell me – what are they made of?

They're mostly plastic, actually. Kind of rubbery plastic.

Right. So let's think about plastic. Now, plastics like this are made by chemistry. They're made by rearranging the atoms you find in oil. That's the kind of oil you can find deep in the ground, which is black and smelly.

There are mostly just two kinds of atoms in oil: atoms of carbon and atoms of hydrogen. These two are called elements, and I'll tell you more about elements in just a moment. For now, let's just think of these two kinds of atoms as being like tiny balls with different sizes and different colours. Let's say carbon atoms are black, and they're bigger than hydrogen atoms, which are white. These two kinds of atom aren't really black and white, but that's how I'll draw them.

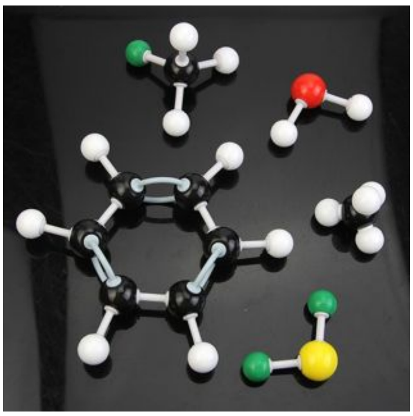
In oil, the atoms are joined together into little groups, and each little group of atoms is called a molecule. It's a strange word: you say the first "e", so it's pronounced "moll-uh-cule". There are lots of different kinds of molecules in oil, but most of them are just different kinds of groups of carbon and hydrogen atoms joined together. Here's what some of them look like:



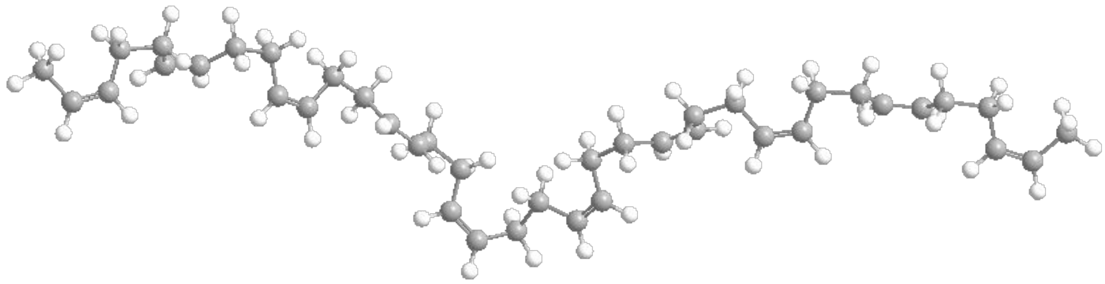
There aren't really sticks linking the atoms together, but I'm using them here so you can see which atoms are joined to which.

They look like the kind of building kits I used to play with!

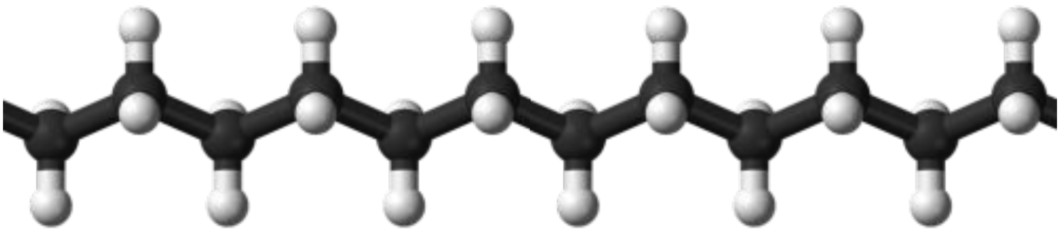
They do, and chemists still play with kits like that, to figure out what molecules they might be able to make and what shapes they would have. They have kits like these:



So then, molecules have different shapes. And chemists have worked out how to make the atoms join together in different ways. So they can change the molecules in oil into different ones, like the molecules in rubbery plastic. Here's what those look like:



You see, these molecules are like long strings of atoms, a bit like beads on a necklace. Long stringy molecules can get scrunched up and stretched out, so the stuff that's made of them is sort of squishy and springy: it's the rubbery plastic in the soles of your shoes. Most plastics are made of these chain-like molecules. Here's a bit of the molecule in another plastic: polythene, which chemists call polyethylene. It's what shopping bags are made from:



Molecules like this that are long chains of atoms are called polymers. The word means "many bits", because the molecules are made from the same groups of atoms, linked together again and again. Lots of stuff in your body, like skin and hair and muscle, is also a kind of polymer.

One of the main parts of a chemist's job is figuring out how to make molecules: how to take groups of atoms and rearrange and reassemble them into different groups. Chemists love making molecules!

But let's go back to atoms. Like I said, in plastics like these there are just two kinds of atoms: carbon and hydrogen atoms. There are around 90 or so different kinds of atoms that you can find in the world around us. Some, like these ones, are quite common, and other sorts are pretty rare.

So everything is made up of just those 90 different kinds of atom?

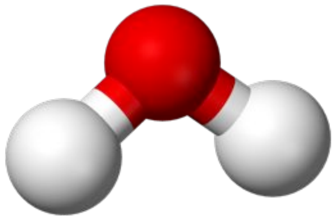
Pretty much. Actually most stuff is made from just a few dozen common types of atom.

But there's more than 90 different kinds of stuff.

There certainly is. There's things like wood, bone, water, rocks, air, iron, gold – you name it. But it's all made from those 90 or so different types of atom, mixed and joined together in different ways.

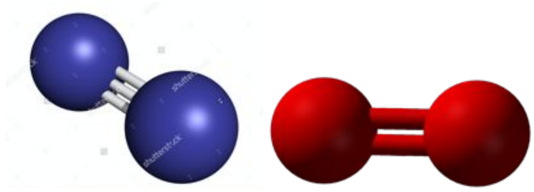
Each different type of atom is called an element. Carbon is an element, and so is hydrogen. Elements are the basic stuff of the universe.

Most stuff around you, like rock and wood and air and water, and plastics and food too, is made up of atoms of several different kinds of element. Water is made up of molecules that contain one atom of the element oxygen and two atoms of hydrogen. The molecules look like this:



Here I'm drawing the oxygen atoms as red balls. Again, they're not really red. Stuff like water made from molecules with more than one kind of atom are called compounds.

Yes, air is a mixture of several different kinds of molecule. Most of the air is nitrogen molecules, which are made from two atoms of the element nitrogen joined together. That's about four fifths of the air. The other fifth is made of oxygen molecules, which each have two oxygen atoms. So they look like this:



Oxygen *Nitrogen*

As a quick way of writing elements, chemists use symbols of just one or two letters. Some of them are kind of obvious: O for oxygen, N for nitrogen. As each of these two molecules has two atoms, we can write them as N_2 and O_2.

There are tiny amounts of other molecules in air too, especially carbon dioxide, which has two oxygen atoms joined to one carbon (CO_2). Now, remember that these atoms and molecules are far, far too small to see just with our eyes – we need special microscopes to do that. And in air, all the molecules are a long way from each other, so there's lots of empty space between them. So much that we can't really see anything there, although we can feel it: when the wind blows, say. The feeling of the wind blowing is the feeling of molecules pushing against you.

Even so, there are lots of these molecules in air. In the air inside a matchbox, there are about 500 billion trillion molecules.

Don't start that counting again!

OK. But you know, air isn't *perfectly* invisible. The air in a room is invisible, but all the air in the earth's atmosphere isn't. It's what turns the sky blue. Light bounces off the oxygen and nitrogen molecules, and that bouncing about is stronger for blue light than it is for the other colours. So sunlight bouncing off all the air molecules in the atmosphere make it look blue.

It can be hard to remember that all stuff is made of atoms and molecules. Or maybe it's just hard to believe it. When you look at water, say, it doesn't feel like it is grainy: it's perfectly smooth. But that's just because the molecules are so small. Really, water *is* grainy, but the grains – the molecules – are really, really small.

Now I'm going to tell you what makes the atoms of one element different from another element. To understand that, we have to see what atoms themselves are made of.

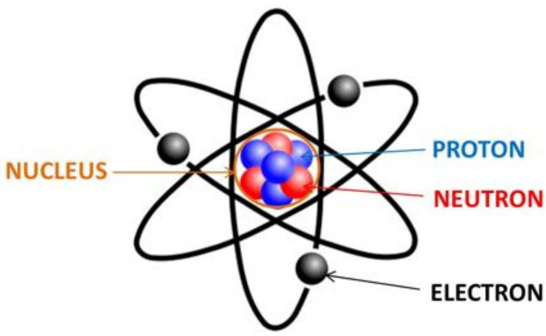
Atoms are made of stuff too?

Yes. I told you that the word "atom" means "uncuttable" – but atoms were called that before anyone knew that atoms actually *are* cuttable. They're not really like little balls, but are made from even smaller things called subatomic particles. Fancy name, but it just means "smaller-than-atoms" particles.

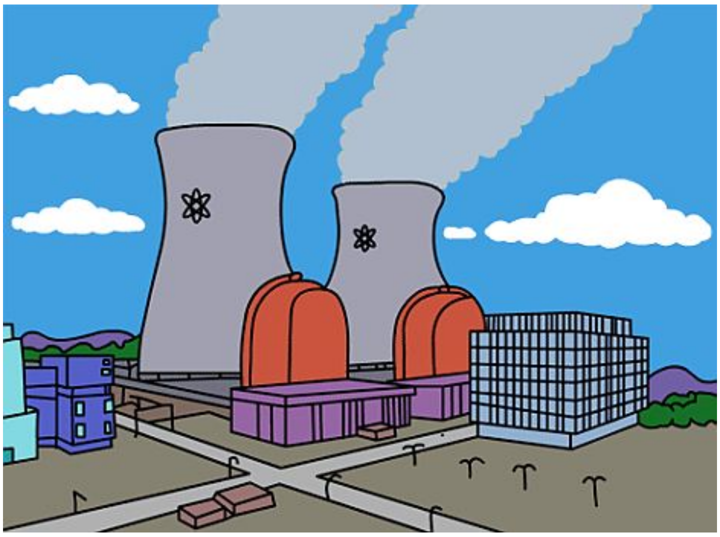
There are three kinds of subatomic particles in atoms, and these are called protons, neutrons and electrons–

Rani told me about neutrons! They're what neutron stars are made of – well, obviously, I suppose...

Right. And the protons and neutrons are about the same size, and they are stuck together in a lump in the middle of an atom, called the nucleus. The electrons are much smaller, and they kind of buzz around the nucleus like bees around a hive.



That's the picture everyone uses to look sciencey. I saw it on the Simpsons!



Ah, that's Springdale nuclear power station, right? It's where they split atoms apart to get nuclear energy, which is the energy inside the nucleus.

All the protons, neutrons and electrons in every atom are identical. It's just the *number* of them that's different in different atoms. Each element has a different number of protons in their nucleus. Hydrogen has one, helium has two, carbon has six and oxygen has eight. And the number of electrons they have is always exactly the same as the number of protons.

Protons and electrons both have an electrical charge. You know when you rub a balloon with a woolly jumper, and then it can make your hair stand on end when you bring it close? Well, that's because the rubbing gives the balloon an electric charge. Electrons and protons have electrical charge, and it makes them stick together, just as the charge on a rubbed balloon can make your hair stick to it, or can make the balloon stick to the ceiling.

What about neutrons? Don't they have an electrical charge too?

No, they don't. They are said to be electrically neutral, which means that they have no charge. That's where their name comes from, like a shortened version of "neutral one".

Listen. A neutron goes into a bar and orders a drink. He says to the bartender, "How much do I owe you?" The bartender says "For you, no charge."

I can't believe how bad science jokes are. Do they really make scientists laugh?

Only because they are so terrible.

I don't really know what charge is anyway. Electrical charge, I mean. I know what it means when shopkeepers charge you. Or when a bull charges you. Or when someone charges you around. But those are all different, I guess.

They are. But here's how to think about electrical charge. If you go and find a battery, you'll see that one end of it is labelled with a plus sign, and the other with a minus sign.

These say that the ends of a battery have an electrical charge too. One end has a positive or plus charge, like a proton, and the other has a negative charge, like an electron. In fact, if you link up the two ends of the battery with a wire, electrons can come out of the negative end and move along the wire.

And protons come out of the positive end?

Good guess, but no. Electrons can go *into* that end. But don't worry about that.

So that's what an atom is like: it's got protons and neutrons in its centre, and electrons around it. The nucleus with the protons and neutrons in it is much, much smaller than an atom. If the atom were the size of a football stadium, then the nucleus would be like a walnut on the centre spot. Most of it is just empty space.

Hang on – if atoms are mostly empty space, then how come we're not see-through?

That's a good point. It's really because light bounces off the electrons, so you never get to see all the empty space. A balloon is mostly empty space too, right? But the light can't get inside to show us that: balloons aren't see-through.

Okay... I guess. 

Well, now I've told you the difference between elements. They have different numbers of protons in their nucleus.

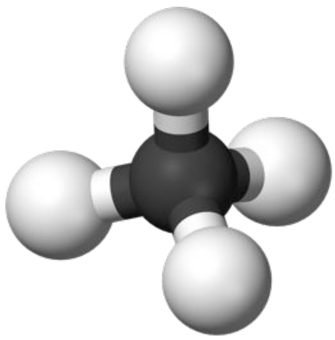
That's the only difference?

Yes it is.

Seems kind of strange. So oxygen is this invisible gas, and gold is this heavy shiny metal, but they're both made of exactly the same parts? Except one sort of atoms has more of those parts than the other?

That's right. But you see, it also means that the atoms have different numbers of electrons. And that makes a *big* difference, because the number of electrons is what decides how an atom joins up with other atoms – so it can affect whether, say, the atoms just link in pairs, like in oxygen molecules, or stack up all together to make a solid metal like gold.

It's also because of their different numbers of electrons that oxygen atoms will join up with two hydrogen atoms in water, whereas carbon atoms can join up with up to four other hydrogen atoms. A molecule made from one carbon atom joined to four hydrogens is called methane, and it looks like this:



And we write it in chemical shorthand as CH_4. You remember those hydrocarbons earlier? Well, methane is another one – the simplest one of all. You can get some methane out of oil too. But mostly methane is found in natural gas, which is the stuff piped to gas cookers. It burns really well.

You said there are about 92 different elements. What are the others?

You will have heard of some of them. Lots of metals are pure elements: that means that the metals just contain one kind of atom. Metal elements are things like iron, copper, silver, gold, tin and lead. But there are some elements you've probably never heard of, like gadolinium, boron, praseodymium and tellurium.

How am I going to keep track of all of those? I can't even spell them. I can't even say them!

Don't worry, you don't have to keep track of them all. You don't really have to be able to spell them all either, unless you become a chemist (although to tell you the truth, there are plenty of chemists who don't know how to spell praseodymium, or even how to say it).

There are only about 30 or so common elements in nature, and only about ten or so in your body. Most of the molecules in your body are made of just carbon, hydrogen, oxygen and nitrogen, with a bit of the elements called phosphorus and sulfur.

But if you *do* want to make some sense of all those elements, there's a way to do it.

You see, the list of all the elements isn't *just* a list. The elements have families.

Here's one family: lithium, sodium, potassium, rubidium, caesium, francium.

Lithium

Sodium

Potassium

Rubidium

Francium is very rare, so I can't show you a picture of it.

No offence, but they don't look like a very interesting family.

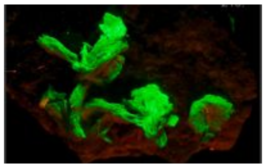
OK, try this one: fluorine, chlorine, bromine, iodine, astatine, tennesssine.

Fluorine

Chlorine

Bromine

Iodine



Astatine

Tennessine is even rarer – we've only ever got a handful of its atoms, and we had to make those ourselves.

Well, bromine looks cool. Like real chemistry. I'd never heard of it before. I hope it smells.

Yes, it smells terrible.

I have a dumb question. Do things smell the way they do because of the elements in them?

Now why would that be a dumb question?

I don't know. It's just that I don't know if it's a good question or not.

All questions are good ones, if you really want to know the answer. In science, it's never a good idea not to ask a question because you are worried it will be a dumb one. Actually, every time someone says to me "this might be a dumb question, but…", they always ask a good one. Yours is a good question too.

Phew. So the answer is?

The answer is that lots of smells depend on the shapes of the molecules that cause the smell. But we don't really know the rules for what makes a molecule smell a certain way. Usually it doesn't depend on what elements are in it – or not in any obvious way. But just occasionally it does. Molecules that contain a sulfur atom joined to a hydrogen atom – it's called a thiol group – often smell like rotten eggs, or like garlic. One, called methyl mercaptan, smells awful – a bit like bad cabbage. It's often one of the molecules in bad breath, and also in… you know what I'm going to say, don't you?

Farts!

You got it.

Ah – maybe we should get back to element families. The point is that, like in many families, the elements in each of these groups are quite similar. They do similar things.

Such as?

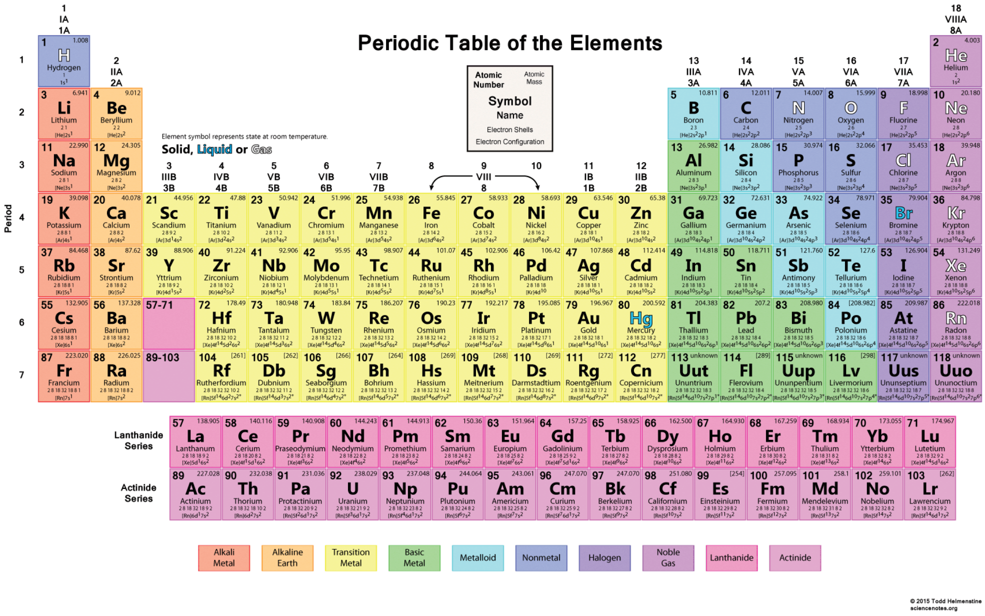
Well, the first family is called the alkali metals. The elements are all metals – they're all silvery. And if you put them into water, they all fizz and steam. Actually, they mostly do more than that: sodium, potassium and caesium explode.

Yay! Way to go!

Just don't do it at home! But it shows they're not as boring as they look.

The second group is called the halogens, and one way they're quite similar is that they're smelly and quite poisonous. Breathing chlorine could kill you – it was used as a poison gas in the First World War. It is a green gas, and it's dissolved in the water in some swimming pools to kill off bacteria, so that we don't catch each other's germs. They only use a little bit of chlorine – not enough to do us any harm, but you can still smell it. Bromine is a liquid, but it boils and evaporates – which means it turns into a gas – even with just a little bit of warming. And it makes a brown smelly gas which doesn't do you much good either.

All the elements can be placed in some family or other. And chemists show these families in the Periodic Table of the Elements, which is a kind of stack of all the elements in their families. It looks like this:



Why is it such a funny shape? Why not just list all the elements in a big square block?

Because of the families. Think of it a bit like a street, and each stack of elements is a family. The last house in the row, number 18, has seven people in it, with helium the smallest. Number 17 is Halogen House, where six elements live. And number 11 has only four. They're quite rich, though, because silver and gold is in that family.

Um... I can't find them here...

That's because their chemical symbol comes from their Latin names: *argentum* and *aurum*, shortened to Ag and Au. Those elements were named long ago, when people with fancy educations wrote in Latin.

Now, if you read the Periodic Table from left to right, starting at the top row and going gradually down, you see that all the elements are in order of their number of protons. Each step to the right increases the number of protons by one. So up in the top left is hydrogen, whose atoms have just one proton. Next, in the top right, is helium, with two protons. Then you go down to the next row, starting with lithium with three protons. And so on.

But if you read the Periodic Table in columns from top to bottom, that's when you get the families – the alkali metals, the halogens and all the others. To make this pattern work, you have to leave some big gaps in the first few rows, so it has this strange sort of shape with towers at each end. Still, when the elements are listed this way, we can see that they're not just a list with random kind of properties, but have this orderly pattern of families.

Why do elements come in families? I'm guessing it's not because lithium and sodium got married and had a daughter called potassium.

You're right. The real reason has to do with the rules of how the electrons in atoms can be arranged. Remember that I told you the kinds of thing an element does – like how many other atoms it will make bonds with – depend on how the electrons are arranged. So there's a regularly repeating pattern in this arrangement, which means that every so often you get another member of the alkali-metal family, or the halogen family, and so on.

This is making my head spin. There's too much going on in the Periodic Table.

I know what you mean. It takes chemists quite a time to learn all the patterns in there, not to mention all the elements. But as I say, you don't need to remember them all.

Still, in chemistry it's good to know a few things about the Periodic Table. For one thing, the atoms get heavier the further down the Table you go, because each atom has more protons. So the densest elements – the ones that weigh the most, if you take a same-sized lump of them – are lower down in the Table. They're elements like gold and lead.

The second handy thing to know is that on the left and in the middle of the table, the elements are metals, like sodium or iron or copper. And on the right, the elements are mostly not metals – maybe they're gases like chlorine, oxygen and helium.

You make it sound like all the elements have a sort of – I don't know, a personality or something? Like each has its own special quirks.

That's a great way to see it. And actually, chemists often find that they have favourites. I like molybdenum, because it has a fun name.

That's what chemists call fun?

Maybe it *is* a bit weird. I like molybdenum's big brother tungsten too. He's really heavy.

Well, the main point is that it's all here – all the stuff you'll ever touch and see and smell and eat is here. Everything there is – all the stuff in our world, like wood and paint and clothes – is made of atoms that are somewhere in the Periodic Table, joined together in some way. We've seen some of those groups of atoms already, like the chain-shaped molecules in plastics.

I have a question about those molecules. What joins atoms together? Are they sticky?

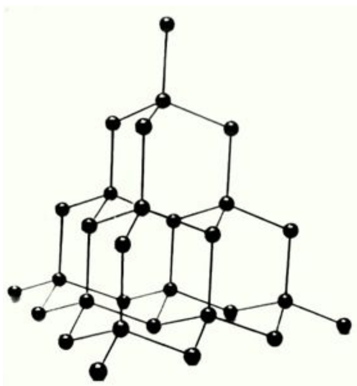
They sort of *are* sticky, yes.

The glue between atoms is called a chemical bond. It's a glue made from those electrons that are buzzing round the nucleus in atoms. Electrons like to be in pairs, and if an electron can't find a partner in its own atom, it will look for one on other atoms. They pair up and the atoms stick together.

Take hydrogen. Its atoms only have one electron each. The electrons on two hydrogen atoms can pair up, and that links the atoms themselves into a pair by a chemical bond. And there you have the hydrogen molecule, which we write as H_2.

Carbon atoms have six electrons. You might think they could form three pairs, but actually they can't. Only two of the electrons can pair up, and so the other four have to find partners elsewhere. In methane, each of them pairs up with an electron in a hydrogen atom.

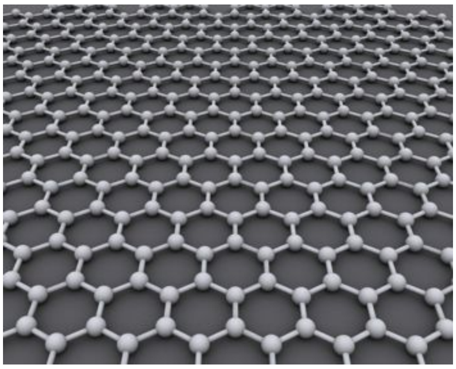
But carbon atoms can also link up with each other. Each carbon atom can join with four others, and so they stick together in this big network of bonds that goes on and on. A piece of it looks like some fancy climbing frame:



When carbon atoms join up this way, the framework of bonds is really strong and hard to bend or break. And the stuff it makes is diamond.

So diamond is made of carbon atoms?

Yes, it is pure carbon. The funny thing is, though, that carbon atoms can join up in another way too so that all their electrons are paired up. You see, some atoms can form more than one bond with another atom. They might pair up two or three or even more of their electrons with the same atom. Well, if carbon atoms pair up one electron each with two others, and then pair up the two remaining lone electrons with a third carbon atom, they can link up into hexagon-shaped rings:



This is called graphene. Now the framework of bonds is flat: the carbon atoms are joined into sheets, just one atom thick. All the same, the sheets are really strong. You can see them under a microscope, folding over and wrinkling. Scientists have only quite recently worked out how to make single sheets of graphene, and they're really excited about it, because the sheets aren't just strong, they conduct electricity. So it might be possible to use them in electrical devices like mobile phones.

But in a way we've known about graphene for centuries. Because when lots of graphene sheets are stacked on top of each other, they make graphite, which is the stuff in the "lead" of pencils. Long ago people really used the metal lead in pencils, but then they replaced it with graphite, because lead is poisonous.

What seems odd is that, although diamond is clear, hard and bright, graphite is blackish, soft and dull – which is why it is good for writing with! And yet they're both made of pure carbon. It's just that the atoms are joined together in different ways.

And that's what I mean with the question "How are the atoms arranged?" Once you know that, you can start to understand why stuff is the way it is. In graphite, the carbon atoms in a single sheet of graphene are bound strongly together, but there are no bonds left over to join up a sheet to the other sheets above or below it in the stack. So they can slide over each other, and the material is soft. In diamond, though, all the atoms are linked into one big lump, and it's the hardest material we know.

So if we want to understand why some material is the way it is, it's always a good place to start by asking how its atoms are arranged. Just like those rubbery polymers we talked about, made of chains of carbon atoms. They're rubbery and stretchy because the chains can bend and scrunch up…

Look, I'm kind of fond enough of rubber, because it's in my sneakers. But to be honest, I'd really like to hear about the chemistry of some other things I like more. Like chocolate. And fries. And cake.

Those are great subjects for chemistry! All cookery is. That's what cookery is, really: when you cook something, you're making a chemical reaction, and things change. Hopefully in ways that make them tastier.

Like fries. Made from potatoes, right?

Yes – but they're way tastier than the boiled ones.

I'll tell you why. Potatoes contain a lot of something called starch. It's a polymer, made from lots of molecules of sugar joined together. If you've ever eaten raw potato, you know it doesn't taste great.

But when you heat up the starch in potatoes by putting them in hot oil, some of the starch falls apart into sugar. So fries taste a bit sweet. And some of the sugar molecules stick together in new ways to make molecules with a brownish colour and a caramel flavour – it's actually called caramelization, and is what happens when you make toffee.

I'm getting hungry.

There's more. You see, potatoes also contain molecules called amino acids. And when they're heated up together, amino acids and sugars have a complicated chemical reaction too, where their atoms get rearranged. The molecules they make are also brown, and they taste – well, put it this way. This reaction of sugar and amino acids is called the Maillard reaction, and it's also what makes biscuits and roasted peanuts and grilled steak taste the way they do. Basically, it's the Yum Reaction.

OK, my tummy's rumbling now. But never mind – tell me about chocolate. I can take it.

Oh, I meant to mention that too. The Maillard reaction happens in cocoa beans when they're roasted to make into chocolate.

I think I've found my favourite chemical reaction.

I don't blame you. But there's a lot more to chocolate too. Did you ever go to eat an old chocolate bar and found it was all crumbly and not half as nice as you expected?

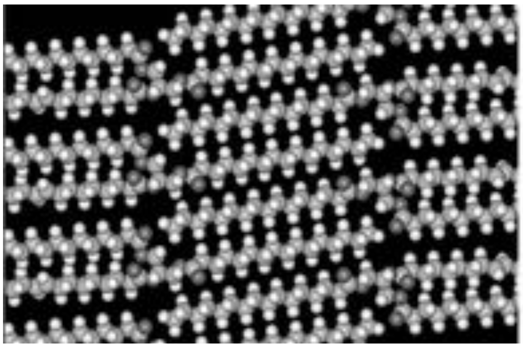
My chocolate bars don't have a chance to get old. But – don't tell – I once found an old Easter egg that my brother had forgotten about at the back of the kitchen cupboard. I sneaked it up to my room, all excited. And yes, it was like that. Of course, I ate it anyway, just on principle.

Chocolate is a great example of why it's useful to think about where the atoms are. One of the main ingredients is a kind of fat called cocoa butter. It's what gives chocolate that creamy feel in your mouth.

Well, cocoa butter is made of fat molecules.

Even the *molecules* in chocolate are fat?

Yes, but I don't mean they are chubby. I mean they're the actual stuff called fat. There are lots of different kinds of fats, and cocoa butter is one of them. The molecules are like short chains, and they look like this:



This picture shows several of the fat molecules, and you can see that they're all closely packed together. This is how the molecules are arranged in solid chocolate. But there's more than one way you can stack them together. One way of stacking is best when the chocolate is really cold, another way when it's a comfortable temperature, and another way when it's a hot day.

But here's the thing: only *this* way of stacking the cocoa-butter molecules makes chocolate with that silky, firm texture, that goes snap when you break a chunk off. That's the form that's really yummy.

If you leave chocolate for a long time, or if you put it in the fridge, the molecules can shift into a different way of stacking. And then it doesn't feel so good in your mouth – it can be crumbly. What's more, when the molecules rearrange they can squeeze some white fat onto the chocolate surface. Did your brother's old chocolate look like this?

Urgh, yes it did!

Well, that's what had happened. And sweet-makers really don't want chocolate to go like that. They want it to look like this:

Ooooh, so do I!

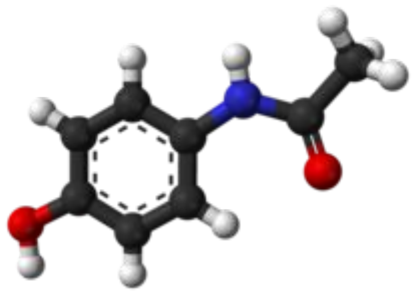
So chocolate companies have to take an awful lot of care to make sure that the molecules are arranged in the right way in their chocolate. They employ chemists to make sure that they are.

Now, those chemists are dealing with molecules that nature has already made: the fats in cocoa butter that can be extracted from cocoa beans. And nature is the best chemist we know: it gives us all kinds of useful molecules, which we can use as medicines, say, or as dyes for clothes, or flavorings for food and so on.

But chemists also make molecules that don't exist in nature. They find ways of putting atoms together into new arrangements, like those rubbery polymer chains that they make from oil for your sneakers.

And this is like cooking. Like I said, sometimes it really *is* cooking: heating up potatoes turns some of their starch and amino acids into tastier molecules. But usually chemists try to be more precise: to know *exactly* what it is they're making.

Let me show you an example. Here's the molecule in paracetamol that makes it a pain-killer:



We can't find this molecule in nature – in plants, say – although there are natural ones a bit like it. So we have to make it ourselves.

I'm guessing that's a bit harder than building it from those molecular kits, right?

You're dead right – because no tools are small and precise enough to pick up atoms and put them together the way we want them. And even if we did have tools like that – some scientists are making them! – it's no good trying to make billions and billions of molecules that way. So we chemists have to find ways of getting other, simpler molecules that we *do* have already stick together to make the molecule we want. This is called chemical synthesis.

Often this takes many steps. We start with something really simple that we can find in nature – a methane molecule, say, like the ones in natural gas, or benzene, which we can get from oil. Then we do something to it that changes it to a different kind of molecule – perhaps with an oxygen or chlorine atom stuck onto it, say. And bit by bit we can build it up into the molecule we're trying to make.

Each of those steps is a chemical reaction. We start off with some types of molecule, called the reactants, and we might mix them together and do something like heat them up, and this makes the atoms rearrange to make other molecules, called the products. Ideally we'll know exactly which product molecules we'll get in any given reaction.

It sounds like hard work.

It can be, and sometimes it's frustrating because a reaction doesn't go the way we want it to. But chemists have found out by trial and error what will work and what won't. This is really the heart of chemistry: it's about producing changes, transforming one lot of molecules to another.

Is that how you chemists make things explode?

Sometimes we do, though hopefully not just by accident. I know lots of people like chemical explosions…

I do! Tell me a good one.

Well… OK. They can be dangerous unless you know what you're doing, but OK. One of the simplest is burning hydrogen gas. Remember that hydrogen molecules have two atoms each in them – H_2?

Yes…

And oxygen molecules in the air also have two atoms: O_2? Well, it turns out that these two molecules react together very well, if there's a bit of heat to help them on their way. You can think of the heat as loosening up the atoms so that they're able to let go of their partners and find a new arrangement. What happens is that two hydrogen atoms stick to each oxygen: they make water, which is H_2O.

A reaction that makes water? Sounds a bit dull – don't we have lots of that already?

Yes, but the bit that makes it more exciting is that when hydrogen combines with oxygen like this, it also produces a lot of energy – it explodes! If you fill a test-tube with hydrogen and put a flame to the end, there's a loud pop as the hydrogen reacts. With a lot of hydrogen, the results can be pretty dramatic – and very dangerous.

Hydrogen is lighter than air, and so hydrogen-filled balloons will float in the atmosphere. People used to make hydrogen-filled airships, until one caught fire and exploded in 1937, killing many of the passengers. Now we realise that hydrogen is too inflammable and explosive in air to be used safely for airships.

But that energy produced when hydrogen burns could be useful. These days, we get a lot of the energy we need – for powering cars, say, or making electricity – by burning coal and oil. The problem is that this reaction has carbon dioxide as one of its products. It's a problem because the carbon dioxide mostly goes into the atmosphere, where it soaks up heat from the sun and makes the worlds warmer. That's called the greenhouse effect, and it is why the planet's climate is getting hotter. Ten of the past 15 years have been the warmest ever recorded.

What's wrong with that? Isn't it nice to have warmer weather?

It can be, sure. But there are all kinds of bad things that happen if the earth gets warmer. For one thing, we don't just have summers that are a tiny bit warmer: they can have scorching heatwaves that cause droughts and fires. Also, the ice at the poles is beginning to melt, which can raise the sea level and flood coasts and make it hard for some polar animals to survive. And there are more storms in a warmer world. And so on… Lots of problems.

So we would like to find a way of producing energy without producing carbon dioxide. We could do that if, instead of burning coal and oil, we could burn hydrogen, which just makes water.

Why don't we do it then?

Because there's not much hydrogen gas around. There are lots and lots of hydrogen *atoms*, especially all those in the H_2O molecules of sea water. But they're no good in that form: they've reacted with oxygen already!

So chemists and other scientists are interested in finding ways to get the hydrogen out of sea water and turn it into hydrogen gas, which we could use as fuel. It's the opposite to what happens when hydrogen burns in oxygen – we want to split water *back* into hydrogen and oxygen!

How can you do that?

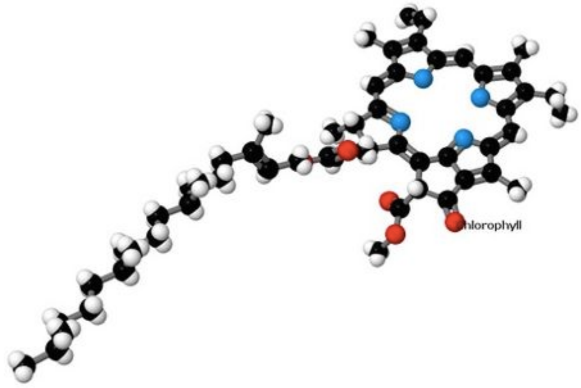
Well, if the reaction of hydrogen and oxygen also produces energy, then to drive the reaction in the other direction you need to *put in* energy. That's the problem. We know how to do it, but it's no good making hydrogen this way for fuel if it uses up all the energy that you gain by burning the fuel.

So it's hopeless?

No, it's not. You see, plants do something like this all the time. They're constantly splitting water molecules into hydrogen and oxygen. They don't want the oxygen – it just becomes oxygen molecules, which the plants spit out. That's where the oxygen in our atmosphere, which we breathe, comes from! Plants can use the hydrogen atoms, though, in clever ways that let them make sugar molecules, which they use as their own fuel, or to produce polymer molecules called cellulose that make up the walls of their cells.

This is a process called photosynthesis. It's "synthesis" because it's about making molecules. But it's the "photo" part that's the key, because that means "light". The energy that the plants need to split water like this comes from sunlight. It's energy for free, because it is streaming over the earth from the sun every day! The plants have molecules called chlorophyll – you pronounce it "klor-uh-fill" – which can absorb the energy of sunlight and use it for splitting water molecules.

A chlorophyll molecule looks like this:



Ooh, it even looks a bit like a flower!

Yes it does! That’s just coincidence, though, and the chlorophyll is actually in the green parts of the plant – in the leaves. The part of the molecule that absorbs the light is that “flower head” at the end of the stalk. In the middle of it, there’s an atom of magnesium.

So we chemists hope we can learn from nature here. If we can figure out how plants capture the sun’s energy and use it to drive the chemical reaction that splits water into oxygen and hydrogen, we might be able to make our own chemical systems that can do it too – but which actually make hydrogen molecules, which we can store for fuel. It would be a kind of artificial photosynthesis.

We already know a lot about how nature does this, and can do it ourselves too – but not well enough to produce lots of hydrogen cheaply. That’s the goal some of us chemists are trying to reach. And understanding how to do it is all about asking those questions, whether about plants or about our human-made chemical systems: which are the atoms, how are they arranged, and what are they doing?

Chapter 5
What Is Life?

It's funny what most people imagine aliens look like. They've got spindly little bodies, and long, thin fingers. Their heads are egg-shaped and bald, with big foreheads, dark almond-shaped eyes, and tiny noses. Right?

Yes – they always make aliens like that! Why?

Well, just look at them. They're like us, except weedier and greener. Or purpler:

Or – wait, maybe they're like the aliens we see in *Star Wars*, which means that they're even more people-shaped, but with funny rubber heads:

Or perhaps they're a really scary sort of lizard people:

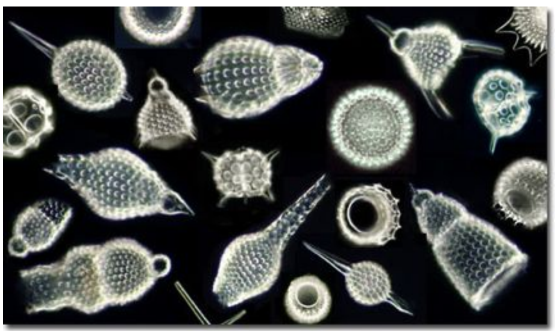
Waaah! Way too scary!

Yeah, you're right. But even so, I reckon aliens like these just show that we're vain and unimaginative. We seem to find it hard to imagine that beings from other planets would be very different from us.

Or perhaps it's just that, when we show aliens in films, they have to be roughly this shape so that the actors will fit into their alien costumes.

But if you want to see *really* weird living things, you only need to look around you. The shapes and sizes of the creatures in nature are truly amazing. Some of the smallest organisms are bacteria, and they weigh ten thousand million million million times less than the largest, which are blue whales. This means that a blue whale is much more massive compared to a bacterium, than the entire earth is compared to a blue whale. To put that another way: to a bacterium, a blue whale is like an entire planet.

And what strange shapes animals can have! Look at these ones – they're called radiolarians:



They're pretty! Like Christmas-tree decorations.

Yes, although they're so small that you can only see them in the microscope.

Trigger warning: if you don't like spiders, then this next one will freak you out. It's called a jumping spider:

Here you can only see four of its eyes. It actually has four more at the back of its head – so eight all together.

You're right, it's totally gross. Plus, I don't like the "jumping" bit. You'd better not be saying that they go jumping on things to eat them.

That's exactly what they do, I'm afraid.

Great. So much for my dreams tonight.

Sorry about that, Mel. Let's move on quickly to another strange animal. Sponges look like weird sea plants, but they are actually a kind of animal too, and so are corals.

And the odd things animals do! You probably learnt long ago that caterpillars turn into butterflies – remember that book The Very Hungry Caterpillar when you were a toddler? But you might not have been told how strange it is what happens inside the cocoon when the caterpillar is transforming. Its entire body dissolves into a kind of goo. What I mean is, the caterpillar digests itself.

Huh? Like we digest the food in our guts?

Pretty much like that.

That is truly and seriously disgusting.

But out of that digested gloop, the butterfly grows.

I'm Yun Yun, by the way, and you probably guessed that I study living things, which means I'm a biologist.

Well, you see what I'm saying here Mel? Life on Earth is absolutely amazing! Much more amazing than what we imagine aliens to be like.

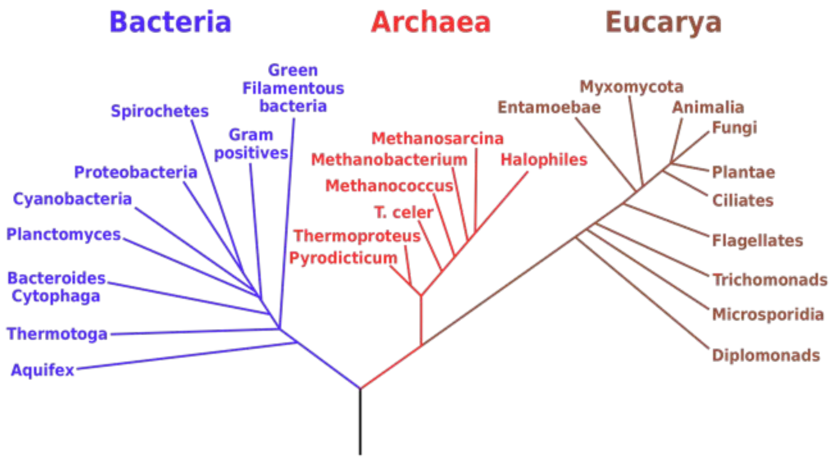
This is fabulous, but it's also puzzling. Why are there so many different kinds of creature on earth, and why are they *so* different?

Actually, when I say "creature" then I'm really just talking about animals. There are other kinds of living things too, of course. Like plants – they're amazing too. There are plants that eat insects, and plants that live for thousands of years, and plants that dance.

Oh come off it! Dance?

Really: they move their leaves to catch more sunlight, but they'll also move them to music.

And there are loads of other types of living thing that aren't animals *or* plants. Like fungi, for instance: mushrooms. Mostly these others have complicated names, and you've probably never heard of most of them. Here's a picture showing lots of the different families of living things and how they're related. Can you see that all the ordinary plants, animals and fungi are each just the tips of one branch, up on the right?



Eek, I can't even read most of those names! But wait – you said "related". You mean animals like us are related to mushrooms?

Yes. Every living thing on the planet is related.

That's mad. I mean, I'm related to my parents, and grandparents, and great-grandparents and so on. But are you saying my great-great-great-great grandfather was a mushroom?

Well, you'll have to go back *much* further in your family tree to find how you were related to mushrooms. And that relative wouldn't necessarily look any more like a mushroom than it looks like you.

Then what would she – it – look like?

Hmm. Probably like slime.

Hey, that's my relative you're talking about!

There's nothing wrong with slime.

Well, this has gone weird pretty quickly, Yun Yun. When I've been taught biology before, it's all about nature: cute things like foxes and rabbits and ponds and insects. Not this stuff about us being related to slime.

Well look, I love all that stuff about wildlife too. It's what made me want to become a biologist. I used to collect wild flowers and beetles.

Wild flowers – OK. Beetles? Bit weird, if I'm honest.

Do you think so? How many different kinds of beetle do you think there are?

I can probably think of a few. Stag beetle. Dung beetle – I only know that one because it's funny. Um... that's it. But I bet there are dozens more, right?

A few more than that. Scientists have found about 350,000 different kinds of beetle. Here are some of them.

Yeah, very funny. But – you don't mean 350,000 beetles, do you? You mean that many different KINDS of beetle. Wow.

That's just the ones we've found. There are lots more that no one has found yet.

How do you know that, if no one's found them yet?

We know where we haven't looked yet. We figure that, if there are this many in all the places we *have* looked, and if there is roughly the same amount of variety in those other places we haven't explores, there must be about four to eight million different types of beetle on Earth.

A famous biologist once said that God must be really keen on beetles, because he created so many kinds of them. Though actually he didn't really think that God made them at all.

So what did make them?

That's the Big Question for biology. I mean, not "what made all the beetles?", but "what made everything?" We think that all living things appeared on Earth – all this amazing richness of life – because of something called evolution. And that's why, whenever you come across anything to do with life, it's always a good question to ask:

What has evolution got to do with it?

You see, this thing called evolution has got something to do with just about everything in biology. It can help us to understand why the living world is the way it is. Why you have two arms and legs, say. Why birds fly and lay eggs, why foxes hunt rabbits, why leopards have spots and trees are tall. A famous biologist – not the one I mentioned before, a different one – once said "Nothing makes sense in biology until you ask what evolution has got to do with it."

He didn't quite say it that way, but that's what he meant.

So, I should probably say what evolution is, right?

Yes please.

It's basically the reason for what I said before: that we're all related. Every living thing on Earth is related because evolution is what turned slime into mushrooms and us, and trees and turtles.

I still don't see how I can be related to a tree, or a mushroom.

It sounds odd, I know. But you are. And I do mean related in the same way as you are related to your parents and grandparents.

Remember that family tree I showed your earlier of all living things? Well, that's just like our own personal family trees, but goes back a *lot* longer. If you go back down your family tree, you'll get to your great-great-grandparents, say, right?

I don't know who they were though. I only knew my grandparents. My great granny was still alive when I was born, but I was just a baby when she died.

Yes, not many people ever get to meet their great-great grandparents, unless those folks live for a *really* long time. But of course you can keep going back even further, and there'll be ancestors you have who were alive hundreds of years ago. But the same is true for ancestors thousands of years ago. And if you go back say about fifty thousand years ago, they'd have been living in the last ice age…

Then they'd be cavemen! And cavewomen too, I don't know why we always just hear about caveMEN.

You're right Mel, those caveman wouldn't have got far without cavewomen, for sure. Actually not all people back then lived in caves, but some did.

So were they humans?

Oh yes. Humans – what scientists call Homo sapiens – have lived since around two or three hundred thousand years ago.

And before that they were apes, right?

Well… technically we are still one of the types of animals known as Great Apes, along with gorillas, chimpanzees, orangutans and a kind of chimp-like ape called the bonobo.

I'm... an ape?

Well, those other apes do look quite like us, right?

Um...

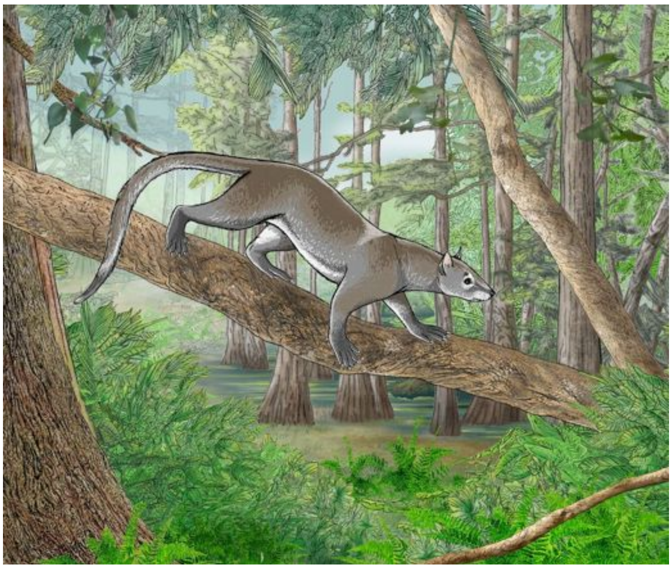
It's a compliment. Apes are amazing.

But you see, those ancestors from long ago before humans weren't like any of these modern-day apes. They were the *common ancestor* of all of us great apes – the ancestor we all have in common. They probably looked a bit like chimps, though.

So you see, you really did have ancestors back then that weren't human. And we can keep going back, on *down* the family tree, and you find we and the great apes share a common ancestor with monkeys, and then further back all the mammals share a common ancestor – us, cats, dogs, horses and so on.

Woah! What did that look like?

It was quite cute really – a bit like a big squirrel with a monkey tail:



I've never seen one of those. What's it called?

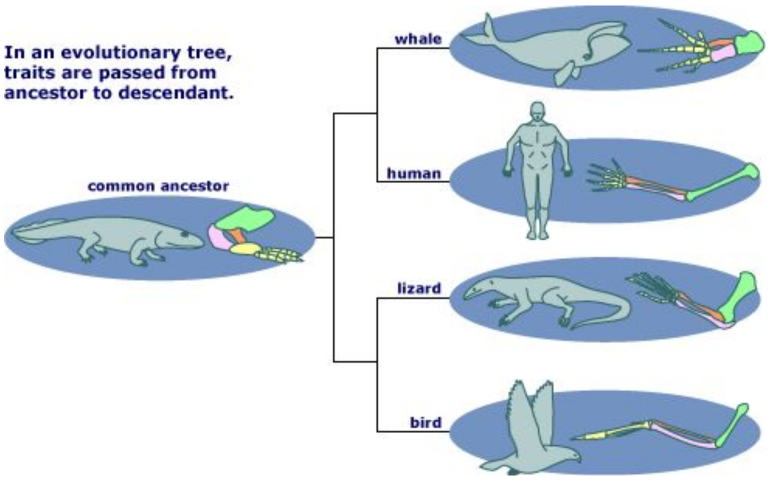
You've never seen one because they don't exist any more. They lived about 56 million years ago but went extinct long ago, like the dinosaurs. So it doesn't have a simple name, but only one of the long, hard-to-say Latin names that scientists use for extinct things.

How do we know it looked like that, if it's been extinct for millions of years?

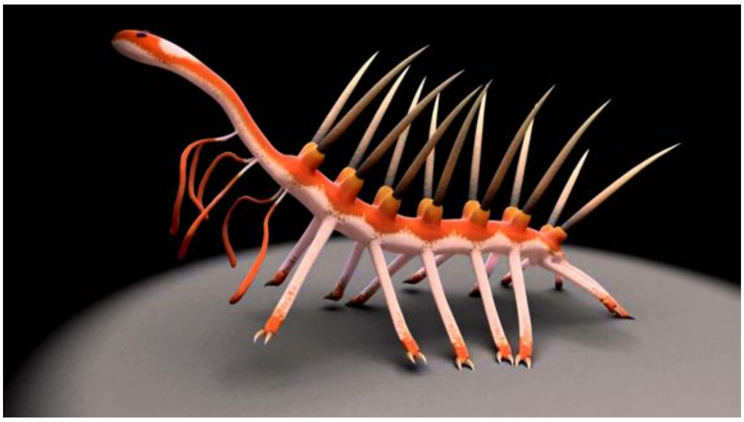
Because scientists have found fossils of it – that is, fossils of its bones. From the bones, they can work out what the creature probably looked like. And they have special methods of finding out how old the bones are, so can figure out when the creature lived. Of course, they might not have got the fur colour exactly right. That doesn't tend to survive in fossils.

They can also comparing the shape of the bones with those of other animals, both living and extinct, and that's how they can work out where this extinct creature fits into the family tree – at least, more or less, because it can be hard to be sure sometimes if all you have are fossilized bones. Scientists who do this sort of work with fossils are called palaeontologists – you say it "pay-lee-ontologist. They're a kind of biologist too.

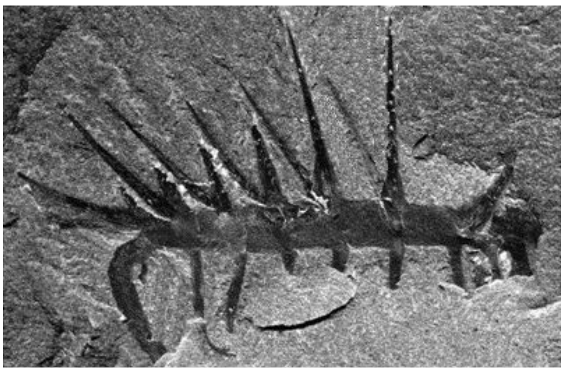
Fossils can tell us what even older ancestors were like. For example, there were creatures from which both mammals and birds evolved. They were reptiles, a bit like small crocodiles, and they lived around 300 million years ago. And so on.



And so you can keep going back further. Eventually you get back to some really weird-looking creatures, like this one:



Well, to be honest we're not always sure exactly what these creatures looked like, because usually all we have to go on is a blurry fossil imprint in a rock. Here's what the fossil for this one looks like:



And before that?

Before that we can find fossils of tiny worms and jellyfish-like things. We can only get some inkling of what they looked like if we can find fossils, and so we only know what a tiny fraction of all the things that ever lived look like, because lots of them didn't leave any fossils that still survive.

As we look back like this, we see points where the branches split on this tree of life. If we go about a billion and a half years back, we get to the part of the tree before animals and fungi and plants have become separate types of living thing. We find the common ancestor of them all. We don't really know what they looked like, but it was probably not like much at all, just tiny blobby things.

If we go even further back before this ancestor of us and trees, we get to smaller and smaller living things until you find, a few billion years ago, ones so small you can only see them in a microscope. They're simple organisms, really just tiny jelly-like drops of living stuff called cells. Bacteria are like this. Under a microscope they look something like this:

All life on Earth started as things like this, about three and a half billion years ago.

But how can something like a tiny little blob of jelly ever change into something like a fish, or like us? How can it grow arms and legs?

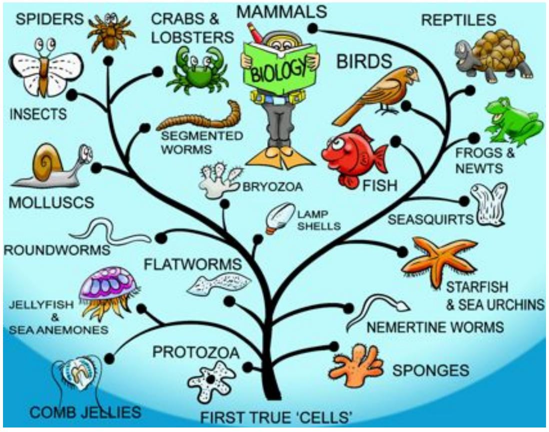
Very, very slowly. What I mean is that the offspring – I mean the children, sort of, but it's odd to call blobs of jelly "children" –

Wanna bet? You should see my baby sister. I'm JOKING, Sis!

So, those offspring look a tiny bit different from their parents, and so do *their* offspring, and so on. Little by little, over millions of generations, some of them have become animal-like – a bit like a sea sponge or an eel, maybe.

This slow change of one kind of living thing into other things that look very different is what we call evolution.

Evolution joins us all into a single family tree, which looks something what I showed you earlier. But here's a version that looks a bit more friendly:



Look: everything alive today is at the end of a branch. All the other things – the ones at the places where branches join – are extinct, and all we can hope for is to find a fossil of them. But the branch tips are only a small fraction of the whole tree. Almost all species that ever lived – more than 99 percent of them – are extinct.

Wait. If those old creatures went extinct, how can anything be descended from them? How come they're not still around too?

Good question Mel. You see, it's a bit like – do you know any Ancient Egyptians?

No! They wouldn't be Ancient Egyptians if I did. They'd be – I don't know – modern Egyptians, I suppose. People who live in Egypt.

Right. So this is sort of the same. There aren't any Ancient Egyptians, or Vikings, today. But there are descendants of Ancient Egyptians and Vikings. And cave people. And so on, back to these reptiles that all died out long ago.

Why did they die?

All kinds of reasons – ran out of food, or the climate got too hot or too cold for them, or they got gobbled up by predators. But mostly these extinct organisms didn't exactly die off: they evolved into something else. Just as we will.

What? We'll evolve?

Of course. Everything evolves. It's how nature works.

What will we evolve into?

No one knows. That's the thing about evolution: scientists can find out something about how it happened in the past (although there is lots they still don't know), but no one can predict how it will go in the future. Some people think that, because we have technology and medicines that make life easier for us, so that we don't have to be strong and fast to catch prey and avoid predators, we might end up looking a bit like those aliens, with big heads and weedy bodies. But that's just a guess.

Urgh! I hope not.

Well, whatever we become, it'll just seem normal to our descendants, just as it seems normal to you that we're not very hairy, like our ancient ancestors, and we walk on two legs instead of four.

Even if it can be a bit disturbing, evolution tells us where we came from. It explains why there are so many different types of living thing on our planet – it's because there are so many different places for them to live, and so many ways they can adapt to their environment. All of those species of beetles, for example.

Why do creatures change though? Why don't the children look like the parents? I mean, I don't look exactly like my mum, but we're both human, even if sometimes I pretend she isn't. She's no more like a tree or a seaweed than I am.

That's exactly the right question, Mel: why do they change? Some people already suspected, over two hundred years ago, that something like evolution happens, so that living things slowly change – evolve – into different ones. But no one could understand *why* that should happen.

Then two scientists figured it out, at about the same time in the middle of the nineteenth century. Their names were Charles Darwin and Alfred Russel Wallace.

They both figured it out at the same time, after people had been wondering for ages? That's a bit of a coincidence, isn't it?

It certainly is. But sometimes that's just how it goes in science. It's as if all that hard thinking all comes together at once, and so several people see the answer at the same time. Have you ever had the same idea as a friend, just at the same time?

Yeah, but it's usually a bit predictable – like, Oh, here's the sweet shop, shall we go in?

Well, that's how it happened: Darwin and Wallace both realised how evolution could work.

Some scientists think it was the smartest idea anyone ever had.

But before I get to that, I want to ask you another question. What do we mean when we say something is alive?

Ooh... It moves?

But so does the wind. And the sea. Are they alive?

Um, OK then... It eats?

That's a good start. Plants don't exactly eat, but they do need to get nutrients – from the soil, say. What we and plants, and everything that's alive, *really* need is energy. We get it from food, but plants and some bacteria get it from sunlight.

There's another important thing about being alive too. Nothing that's alive lives forever, so somehow living things have to make new living things. We make babies, and so do other animals. Plants make seeds that new plants can grow from. It's called reproduction. Living things need to reproduce.

Just tell me now: is this about to get gross again?

I'll try to make sure it doesn't.

So biology is about living things, right? Actually, that's exactly what the word means – it comes from the ancient Greek words that mean "the study of life".

Now, you'd probably think we scientists would have a nice, neat definition of what life is. But we don't. We can't say *exactly* what it is. We pretty much agree on whether something is alive or not, although some scientists argue whether the germs called viruses are really alive – I'll come back to them later. But we can't say quite what it is that makes a living thing alive.

Still, being able to find sources of energy, and being able to reproduce, are two of the most important things about being alive.

And it's really those two things that make evolution happen.

If living things – let's think about animals – are going to survive, then they need to get energy: they need food. Some animals eat plants – they're called herbivores, which just means "plant eaters". And some eat other animals, and they're called –

Carnivores. And if they eat both, they're omnivores.

Good! And those words mean "meat eaters" and "everything eaters". So off animals go, looking for things to eat. The trouble is, so are all the other animals. They're all trying to get to the food first, without getting eaten themselves. It's a pretty tough life for most animals. Cows have to spend six hours a day eating grass, and then another eight hours chewing what they've already eaten, because grass doesn't have much nutrition in it and it's really hard to digest.

But at least if you're a cow in a field, there should be plenty of grass around and you don't have to work hard to get it. Many animals have to spend most of their lives searching for food, maybe trying to catch another animal that's doing its best to escape. Lots of animals just starve, and lots get eaten.

So nature is a competition: a kind of race. It's a really tough one, too. If you're going to survive, you have to get to the food before the others. And you have to escape from things that might eat *you*. So it's often the fastest, or the most sharp-eyed, or the craftiest and most well-hidden animals that do best.

It sounds really mean. Like the bullies win.

Well, nature is hard, it's true. But it's not really mean. If a bird catches a worm and eats it, the bird isn't trying to be nasty to the worm. Nothing in nature is really cruel.

My kitten caught a mouse once, and played with it for ages before killing it. I was furious with her, but she kept running off with it.

Ah yes, cats. Nature isn't cruel, but sometimes I do wonder about cats.

Even plants compete. Mostly all they do is stand around soaking up sunlight, and hoping that no herbivore comes along to munch on them. But imagine there you are, a bush basking in the light, and then a seed drops down next to you, carried on the wind. And it grows into a bush that's taller than you are, and the bush spreads its branches and starts getting all the light while you're left in the shade. Trees grow tall so that they can get the sunlight first. They get taller and taller, but eventually there comes a point where they're not steady enough to grow any more – like a tower that's too high, they risk toppling over.

So nature is full of all this life struggling to outdo anything that will compete with it for sources of food and energy. The ones who are best at the race – the fastest, biggest or whatever – are said to be the fittest. And they're the ones that survive.

> **That makes nature sound horrible! Like a class full of really pushy kids wanting to be top.**

It does, doesn't it? But I'm afraid a lot of nature is like that: it's eat or be eaten. This doesn't mean that some animals can't live together, though. And some will even help each other. Evolution can explain why they do that too.

Animals aren't just trying to survive, though. What they're really trying to do is survive long enough to have children. The real aim is to reproduce.

OK... I know that most people do want to have kids - and I suppose most animals might be the same. But now I think about it, I wonder why. Why not just try to live as long as you can and leave it at that? I suppose little children are kind of cute - some of them, anyway. But do ants think their kids are cute? Seems unlikely.

You're right, I doubt very much if they do. Lots of animals just leave their children to survive as best they can. If the children hatch from eggs, like ants or frogs do, the parents might not ever even see them.

Huh! Sounds like the ultimate bad parents.

I suppose you could say different situations need different kinds of parenting.

But animals aren't having children because they're cute. They do it because they have a natural urge – what we call an instinct – to do it. All animals have instincts, which make them do some things automatically. An ant doesn't have much in the way of a brain, but still it looks for food and eats it when it finds it. As far as we can tell, an ant doesn't actually have thoughts in the way that we do. It won't suddenly think "I'm starving!" It's almost like a little robot that's just programmed to look for food. Though to be honest, no one knows what it's really like to be an ant – there might well be more going on in insect minds than we think.

We've got that same food instinct too. We might feel it in a more complicated way: "I'm famished, I'll go and look in the fridge for a piece of pie". But underneath it all is an instinct you're born with: "I must eat."

Animals also have an instinct to reproduce. They want to find another animal to mate with and have babies. Not all humans want to do that, but we're quite unusual as animals go: we're very complicated because of our big brains, and it seems that not everyone's instinct to reproduce is strong enough to make that a priority for them. But for most of us, it is.

I don't see how this stuff about instincts really explains anything though. Aren't you just saying "Animals reproduce because they want to reproduce"?

That's a really good point, Mel. But one of the great things about evolution is that it can explain where these instincts come from.

I said that evolution comes from two things. First, we want food, but have to compete for it. Second, we want to reproduce – and we have to compete for that too.

> **You mean like – steal someone else's boyfriend? Like in soap operas? Ah, and I suppose in real life too, sometimes.**

Yes, that kind of thing. It happens in the animal world too. It's easier if you're a bacterium, because then you don't need a partner to do it. You can just split in two, and each half is a new bacterium.

Oooh... Shame we don't have that choice too.

Well, it would be interesting, for sure – though not exactly easy for big creatures like us. But there are advantages of needing two of us to reproduce.

But there's actually a third thing that's crucial for evolution too. When we reproduce, our children are quite like us.

> **I do look a bit like my mum, I suppose. And we're both left-handed – people say, You got that from your mum. But she likes fried liver, and I can't stand it.**

There you go: I said "quite like us". We're not exactly like our birth parents. We couldn't be, really, because we have two of them: mother and father. And we might be like our mother in some ways, and our father in others, and like neither of them in other ways. But we do get a fair bit of how we are from one parent or another. It's likely that you really did get your left-handedness from your mother.

And green eyes from my dad!

There you go again. So some of the things we inherit – that's the word for getting features from a parent – are about how we look. Others are about how we behave. It seems that we can sort of inherit things like how good we are at maths, or music, or sports. Those things don't all come from our parents, and they might not do at all – you might find that two sporty parents have a child who hates sport. But most people have a lot of traits like this that come from one parent or the other. Aren't relatives always saying tiresome things like "Oh, you're just like your mother!"?

> **Sometimes they say that about me and my brother: Oh, don't they look alike? I can't stand it. I don't look a bit like him.**

That must be tough. But you probably *will* be alike in some ways. I mean, some of those similarities are just because your parents brought you up, so you speak the same language and eat the same kind of food and so on. But some of the similarities are ones you're born with. Those are the inherited ones.

It's because of this similarity between parents and children that evolution can happen. Let me give you an example.

Suppose there's a group of foxes, and they feed on rabbits. The rabbits are pretty good at running away, but the foxes will catch them if they're fast enough.

Which rabbits will be more likely to survive: the slow ones or the fast ones?

I hope this isn't a trick question. I'd say the fast ones.

It's not a trick question. Good scientists–

...don't ask trick questions. Yeah, Rani told me.

Good. So the faster rabbits survive – which means that they'll produce more babies, because they're less likely to get caught and eaten by foxes before they can reproduce. And the babies will inherit their parents' ability to run fast – because their legs muscles grow bigger, say. So gradually, the slow rabbits die out and virtually all the population runs fast.

But what about the poor foxes? They'll starve.

Maybe, but maybe not. Because after all, some of *them* will be faster too, just by chance. And the faster ones will catch more rabbits, and so will be less likely to starve. So they'll make more baby foxes, which will be fast runners too.

You see what I mean about nature being all about competition and races?

But there’s more to this tale. You see, as more and more rabbits get born, they start to wander further and further in search of grass, because there’s less and less to go round where they’re born. They spread north, to where it’s colder, and I’m afraid that some of the rabbits freeze to death in the winter.

But some have fur that grows a bit longer than the others, and it keeps them warmer. So they survive better. And then their children…

...have longer fur too!

Yes. So gradually the northern rabbits become long-haired rabbits, unlike their distant cousins in the south.

Well, they keep on spreading until some reach the far north, where it is snowy for much of the year. And by the way, the foxes have been doing the same, so even up in the north some rabbits are getting caught and eaten by foxes.

But every so often a light-haired rabbit is born. Again, just by chance – it turns out that their bodies don’t produce so much of the stuff that makes their fur brown. And because they’re lighter-coloured, they’re harder to see against the snow. So the foxes don’t catch them so easily, and they survive better and have more babies. The lighter their coats, the more they survive. In the end, the rabbits of the far north not only have long hair, they have white hair.

Trouble is, the same happens to the foxes. With white fur, those foxes can hide more easily against the snow, and so they’re more likely to catch rabbits and not starve. This is just what we find in the Arctic, up near the north pole: there are Arctic foxes and Arctic hares, and both are white. When an animal is coloured in a way that makes it hard to see against its usual background, it’s called camouflage.

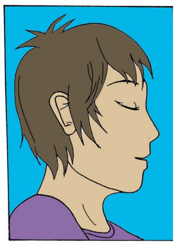
That’s the cutest fox in the world. I wish I could have one.

Sure it is – if you're not an Arctic hare.

This is evolution at work. These different groups of animals, living in different places, have evolved so that they're different from each other. Only a little bit, but in ways that help them to survive and breed. Those differences are called adaptations: the Arctic hares and foxes are *adapted* to a snowy, white environment.

Maybe you can see now that these changes can go on and on, so that creatures that were once all the same thing – brown rabbits, say – end up becoming completely different things. It might take thousands and thousands, or even millions of years, but eventually the descendants might look nothing like their ancestors. The foxes in one place might grow as big as bears, or become spotty like leopards, or even grow wings. And that's evolution.

Foxes aren't spotty, by the way, but some animals do evolve to have spotty or stripy skins and fur.



Like leopards?

Yes, and the leopards' spots are probably another form of camouflage. We don't know that for sure, but it seems likely that the spotty markings on their pelts make them harder to spot among bushes or rocks. So they are adapted for sneaking up on their prey.

Now, the crucial thing here that makes evolution possible is that bit of randomness in how inheritance works – which makes some hares faster or lighter-furred, say. Evolution picks out any random differences between each generation that help in survival – it could be bigger size, or smaller, or better camouflage or better eyesight, all kinds of things. But if a difference doesn't give any advantage in survival or reproducing, then it doesn't catch on – evolution ignores it, you might say.

Evolution's way of picking out and spreading changes that help survival is called *natural selection*, and it's what makes living things adapted to where they live. It's also why, little by little, groups of animals living in different places become different from one another.

This natural selection is what Charles Darwin and Alfred Wallace Russel discovered. Before them, plenty of people believed that evolution happens – that living things gradually change into other living things. But now natural selection explained how and why.

And what's really cool about evolution is that it can help us understand not just the way nature once was – remember that family tree of how one sort of living thing evolved into another. It can also explain the way the living world is now. We can see why Arctic foxes are white.

So that they're camouflaged and can catch their prey better!

Yes – although if we put it that way, it sounds like someone must have designed them to be that way, to help them survive. But no one did! Natural selection did it, all on its own. Arctic foxes only *look* designed for life among the snow. But it's not a design – it's an adaptation.

Some of these adaptations are amazing. Camouflage is a good example. Can you spot the moth here?

No... wait! That lighter leaf is... a moth?

Yes. It has evolved to look just like a dead leaf, to help it hide from predators like birds.

Now, why have giraffes got long necks?

So they can reach the highest leaves?

Well, kind of – but again, no one actually designed them for that. It's better to say that among the ancestors of giraffes, some were lucky enough to have longer necks. They were the best adapted for feeding off leaves, because they could get to the ones others couldn't reach. So they had more chance of surviving, and of having more children,

You can ask all kinds of questions about why creatures are the way they are, and the right way to think about the answer is to ask what evolution had to do with it. Why are fish torpedo-shaped? Because they're better adapted for swimming through water. How come spiders make such amazing webs for catching prey? The ones that had the instincts and the ability to spin good fly-catching webs survived.

But now look at this:

That's how extravagant evolution can get sometimes. A bit crazy, right?

It's like he – it's a he, right – like he's just showing off.

Right! In a way, that's just what he's doing. But why do peacocks have these huge, colourful tails?

Because when you think about it, it doesn't seem such a great idea. A big tail like that makes it harder for you to escape from something that wants to eat you. But the peacock's tail is great for grabbing the attention of a female – a peahen – so that she will mate with you and have your babies. The peacock spreads its great colourful feathers, and the peahen falls for it.

Bah, boys!

I know. But actually the peahen is smarter than that. She isn't just being easily impressed by the fancy tail. She figures that, if a peacock can carry round a cumbersome tail like that *and still* avoid predators, he must actually be pretty good at survival. So the tail doesn't just attract attention – it tells the peahen that the male is a good survivor, and so his children should be too.

It sounds like evolution will make everything sort of super-duper and massive.

It does sound like that. But that's not quite true. It's better to say that evolution only makes organisms as good as they need to be to survive. If all you want to do is win the race, and you know you're faster than everyone else, would you bother training and training to get faster still? Why do that? As long as evolution can make an organism that's adapted better than its competitors, that's all it takes. In fact, evolution *can't* do any better than that, because it only works when there's competition to pick out the fittest. If you're already better than everyone else, there's no competition and so there's no natural selection.

Let me show you what I mean. A dead-leaf moth does a pretty good imitation of a dead leaf, doesn't it? But it's not perfect – you could still spot it, after a moment. Why doesn't evolution make it perfect? Because it doesn't need to! Maybe the eyesight of its predators isn't so great, so it can't tell the difference between a dead-leaf moth and a dead leaf even if the resemblance isn't perfect. Then, if by chance one day a moth hatches from its chrysalis (remember that's how moths are made?) with wings that look even more like a dead leaf, it doesn't have any advantage over the others: to a predator, they're all equally hard to spot. So natural selection can't get to work spreading that change through the moth population.

Or maybe the improvements that natural selection makes get limited by other things. Remember those rabbits getting faster and faster with each generation? How come, then, you don't end up with supersonic rabbits, travelling as fast as jet aircraft? It's just not physically possible. The laws of physics can't produce rabbit muscles capable of that much speed. For one thing, the rabbits would need more energy to reach that speed than they could never get by eating, even if they did it all day without sleeping.

That's a shame. I'd love to see a supersonic rabbit.

It's also possible for living things to evolve *without* natural selection. If the offspring change by chance in a way that doesn't make any difference to their chances of survival and reproduction, it doesn't give them any advantage but it doesn't give them a disadvantage either. So the change doesn't spread, but neither does it get wiped out. That way, populations of creatures can end up all looking a bit different.

Remember those radiolarians I showed you earlier – the Christmas-decoration creatures? They are tiny sea creatures that make themselves an "outside skeleton", a sort of shell, of hard bony stuff. Those shells have lots of holes in them, like a kind of cage, and this is a good design because the holes make the shells lighter but still strong and protective. So holey shells are adaptations.

But there are all kinds of different shapes and designs that radiolarians use for their shells, and none is really any better than the other. They've just come up with these variations by chance, and natural selection didn't have any reason to choose between them. The oceans are full of this wonderful array of different radiolarians, not because of natural selection but just because of random chance. Sometimes people talk about evolution and natural selection as if they're the same thing, but they're not quite.

And you know, sometimes evolution even gets things wrong. What I mean is that it ends up doing something quite badly, not the best way at all.

Huh? But if it does something wrong or badly, won't that be a problem for survival?

Maybe, but maybe not. Here's what I mean.

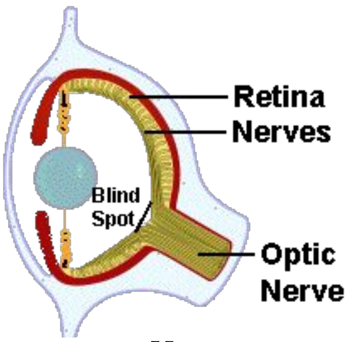
If an engineer was going to design your eyes, she'd never do it the way evolution has. Evolution's "design" has a big "mistake".

Light comes in through the front of our eyes, like it does through the lens of a camera, and the light strikes a kind of screen at the back, called the retina. The screen contains molecules that can absorb light, and when they do, signals travel from the retina along a kind of cable called the optic nerve into our brains. There the signal gets read and turned into an image in our minds. And that's how we see. So far, so good.

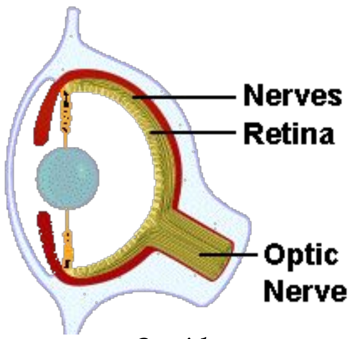
But the way the eye is wired up to the brain by the optic nerve is ridiculous. If you were going to have this light-sensitive screen, the retina, connected to the brain behind it, then wouldn't it make sense to put all the wiring on the back of the screen, where it won't get in the way of the light? Yes it would. But in our eyes the wiring comes out of the *front* of the screen! This means that the light has to pass through all this tangle of wiring to reach the screen at all. OK, so evolution has made the wiring transparent, but even so this seems to be making life difficult for itself.

But it's worse still. If the wires come out of the *front* of the screen, but they have to connect up to the brain *behind* the screen, then they have to pass back *through* the screen. There has to be a hole in it where they pass through. This means that one part of the screen, where the hole is, can't absorb light, and so there's always one part of the scene in front of you that you can't actually see. This is called the blind spot.

Squids and octopuses don't have a blind spot, because their eyes are wired more sensibly, from the back.



Humans



Squid

My friend says you should say "octopi".

Lots of people think that, but it's not true. If you're going to be picky, you should say octopodes.

I refuse to say octopodes. That's just a ridiculous word.

Fair enough.

We usually don't notice the blind spot because our brain fills in what we see there with a guess about what we *should* see.

You can discover your blind spot for yourself, though. Look at this dot and cross with your right eye closed, starting from about two feet away.

Focus on the cross, and slowly move the book closer. Eventually you'll see that the dot seems to disappear.

And here's how you can catch your brain "filling in" the gap. Do the same thing here: right eye closed, left eye now focusing on the red dot, and move the book closer. There's a point where the two blue lines seem to become one, with no gap, because you've hit your blind spot and your brain is telling you that it should be a blue bar all the way, with no gap.

Hang on – you said "your brain is telling you." But if my brain's the thing that's thinking, who is it telling?

Wow, you don't let anything slip past, do you Mel! You're quite right. What I should have said is that your brain creates that experience of a blue bar without a gap. There's no one inside your brain that gets told anything.

So we can cope with the blind spot. But why have it at all? Why not just wire up the retina from behind? We don't know quite how evolution got into this clumsy muddle with us, but not squid –

or octopodes...

Right. But once that bad design happened, it stuck. There was no going back, because making such a big change in the structure of the eye is really hard. It's not impossible, but our distant ancestors' badly wired eyes worked well enough, so there wasn't enough reason for natural selection to improve them.

But if we and octopuses – I'm going with that – are both related to the same long-lost relative, whatever that was, how can we have ended with different eye designs?

Because that long-lost relative probably didn't have real eyes at all. It was before eyes evolved. So eyes evolved separately more than once – it happened once on the branch of the tree leading to us, and a different time on the branch that led to the octopus. Sometimes that happens in evolution: it finds the same design several times. In fact, biologists think eyes might have evolved in different animals on up to 50 or so different occasions.

Now I need to say something about how we inherit things from our parents, and why this inheritance isn't perfect. When Charles Darwin suggested the idea of natural selection, he didn't know *why* inheritance happens – why we can look and maybe behave a lot like our parents.

And the other one – was it Wallace?

You're right, he often gets overlooked. And he didn't know either.

But over the past hundred years or so, scientists have worked out how inheritance happens. It's all to do with genes.

You might have heard about genes. Sometimes people say things like "It's in her genes."

She's got dancing in her genes.

That sort of thing. What they mean is, she must have been born that way, with a talent and passion for dancing. Often they don't actually mean it, or if they do then they're often wrong. It doesn't seem very likely that anyone is born with a special talent for dancing, though some people might be born with particularly good balance or coordination. But the idea is that everything you're born with, that you don't learn or get from how you live – dark hair, say, or dark skin or tallness – is "in your genes".

Mum says I have the stubborn gene. But is a stubborn gene really a thing?

No, it isn't. If really are stubborn, it's not exactly because of your genes, though they might have a part to play in making you headstrong or whatever.

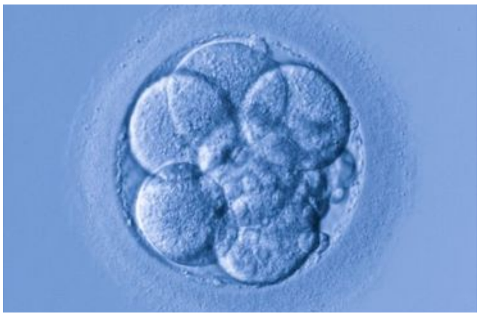
So I can tell her it's her fault – a bit?

Possibly. It's worth a try.

Let's see what genes really are, though.

We all grew from an egg: a human egg, about the size of this full stop. That egg got fertilized by a sperm: the egg was in your biological mother, and the sperm came from your biological father. When the sperm got into the egg, it triggered the egg to start growing into you.

The fertilized egg is a cell. It divided into two, and each of those two divided into four, and within a few days it became a cluster of cells, called an embryo. It looks like this – *you* looked like this, and so did we all:



The cells went on dividing, and the shape of the embryo changed to start looking a bit like a human. Some cells became a head, others little bud-like limbs that would grow into arms and legs, and so on. When the embryo becomes more like a kind of tiny, roughly shaped baby, it is called a fetus.

The fetus goes on developing and changing until it really is a baby, inside the mother's womb.

We learnt about all this. I know it's what happens, but I still find it a bit weird and creepy. I mean, once it starts looking like a baby it's OK. But when it's a blob or a kind of shrimp, it's freaky.

Yes, it really is hard to get used to. It's no wonder lots of people once believed we grew from a tiny human, with arms and legs and everything but smaller than a full-stop.

Yeah, that's sort of weirder. Like Ant Man!

Anyway, we know now that you started off as a single cell: a fertilized egg. Now, let's say your mother had black hair and you inherited it. But how could that be, if the fertilized egg doesn't *have* any hair? What you inherited, and what was inside that fertilized egg, was an instruction for making black hair once the baby was ready to grow it. That instruction is a gene, or a group of genes.

There is a whole lot of instructions like this for making a human being – about 20 thousand. Well, maybe it sounds like a lot, but the odd thing is that how many instructions – how many genes – you have doesn't seem to depend so much on how complicated you look when you've grown. I say that because onions and bananas have more genes than we humans do. No one knows why.

But actually, 20 thousand instructions isn't really that many for making a creature as complicated as us. It surprised biologists when they discovered, less than 20 years ago, that we only have this many genes, and not more.

What are these instructions in genes? It's not like there's a little booklet inside the fertilized egg (and who would be able to read it anyway?). No – the instructions, the genes, are written in a kind of code. That code is written on molecules called DNA.

Dee-enay?

The letters. D. N. A.

What does DNA stand for?

The full name is deoxyribonucleic acid.

OK, so now I know what DNA stands for: Do Not Ask.

Remember how Sam the chemist told us that some molecules, called polymers, are long strings of atoms joined together, like beads on a string? Well, DNA is

like that too. It's a polymer, but one that is made naturally inside cells. You can think of it as being made of four different kinds of bead, each bead being a different group of atoms. They have special chemical names which we often shorten to just the first letters: A, T, G and C. The instructions are written in this four-letter code on strands of DNA. A little part of the code might look like this:
AATCTTCCCGAGAGCTT
… and so on, for three billion beads.

Each piece of DNA actually has two strands, wrapped around each other in a coil called a helix:

Both of these strands contain the same message, but encoded differently: on one strand there is always an A where the one opposite has a T, and a C where the other has a G, and vice versa.

A single gene is a short sequence of these beads. Each gene is usually between a few hundred and few thousand beads long. You could think of the beads as being like words, and the gene is like a very long sentence.

Now, I need to warn you here. People often say that your DNA is an instruction book for making you, but it's not really.

Isn't that what you just said?

Yes, I suppose it sort of was. But I was trying to keep things simple. It's really a whole lot more complicated than that. What the code in most genes says is not things like "Make this person tall" or "Give her dark hair". They're actually instructions for making other molecules, called proteins.

Proteins are the molecules that make chemical reactions happen in the right way in cells. Somehow, thanks to all these proteins and other molecules bumping into each other and reacting, a cell is able to grow and divide, and to develop into a tall, dark-haired person, or whatever you happen to be. We biologists are a long way from understanding quite how that works, and it's certainly not all just controlled by instructions in genes that make proteins. It's really difficult to figure it all out.

But maybe we can think of it a bit like a recipe in a cookbook. The recipe probably doesn't tell you absolutely everything you need to do, like exactly how to crack the eggs. And in any case the cook might decide to add or leave out a few things anyway. The genes just give you the basics, and if two people use the same recipe then what they make is likely to be pretty similar.

That's what happens with identical twins: they have the same genes, because they both came from the same fertilized egg, which ended up dividing into two separate embryos. But identical twins are never really identical, and in fact often they get more and more easy to tell apart as they get older. They've got the same genetic instructions, but life makes little adjustments here and there.

There are identical twins in our class. But I can tell them apart because Toni lets her hair get messy and Bryony keeps it perfect. Also, Toni hates cheese, which is deeply weird.

Well there you go.

It's your genes that control what you inherit from your biological parents. There was DNA from your mother inside the egg that you grew from, and DNA from your father in the sperm that fertilized the egg. Inside the fertilized egg, these two sets of genes join up, so you get two copies of each gene, one from each parent. Sometimes the mother's gene wins out – you're left-handed like your mother. Sometimes the father's does instead, so you might get his eye colour.

Even though it contains all these thousands of genes, your DNA can be folded and scrunched up very, very small, so that it will fit comfortably inside a cell. If the DNA in just one of your cells was unravelled and laid in a straight line, it would be as long as an adult is tall – about six feet, or two metres. That's just in *one* cell. And you have trillions of cells in your body! So all the DNA in one adult human, stretched out into a line, would reach to the Sun and back – about 70 times.

Oh come on, that can't be possible!

It really is. All that DNA will fit inside us because it is so incredibly thin.

So then, you inherit some traits from your parents because you inherit their genes. I should say, though, that you're not simply "half your mother, half your father". Your genes are, but because of the complicated ways that genes work together to make you, you'll also end up with your own unique personality and looks and so on. No one can predict how you'll end up just by looking at your genes, although they *can* predict some things and make good guesses at others. They could estimate how tall you'll be, for example. But probably not how good a dancer you'll be.

It was over 50 years ago that scientists discovered that DNA looks like a double helix, and now we know what many of the genes in our cells do. Today it's possible to read the genes' code in anyone's DNA, pretty fast and accurately, and it costs only few hundred dollars or so. It's getting cheaper and cheaper to do it, and soon probably all babies will have their genes read when they're born.

Why would anyone do that?

The main reason is that it could tell you whether they might have, or get, some diseases. Lots of diseases are caused by genes that don't work quite as they should. The people who have one of these diseases might have a slightly different sequence of beads from healthy people in one or more of their genes, which means that their bodies make some proteins that don't work as they ought to.

Only a few of these genetic diseases are caused by a single faulty gene, though. That's how it is with cystic fibrosis, which is a really nasty disease that causes serious problems with breathing and digestion. More often, genetic diseases are caused by several or many faulty genes. By reading the code of our DNA we can figure out if we're at high or low risk of getting these diseases. If we know that, we might be able to do something to make a high risk smaller. So knowing about your genes could be really useful for keeping you healthy.

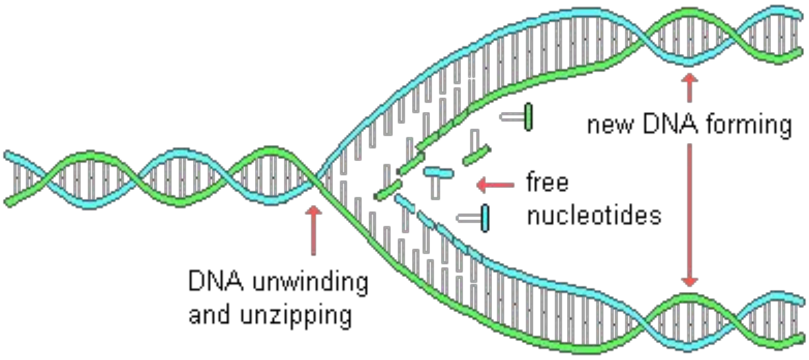
I should say that not all diseases are caused by faulty genes. Many are caused by other things, like germs: by getting an infection, say. Some diseases come from a bit of both. Because we inherit genes from our parents, sadly we can inherit genetic diseases too.

Why do some genes go wrong like that?

Well, that's an important question. And not just for understanding health but for understanding evolution. This is the last bit of the explanation for how evolution works, and it's the bit that Charles Darwin couldn't explain, because he didn't know about genes or DNA.

You see, cells, like all other living things, have to reproduce: they don't live forever. But whereas animals reproduce by having sex, our cells have a much simpler way. Like bacteria, they just split in half. Nearly all of the cells in your body can do that. When they do, each of the two new cells formed from the one that divided must have a complete copy of all the DNA in the original cell, so that they have all the genes they need. This means that, before a cell divides, it must make a copy of all of its DNA.

How that happens is very clever. Those two strands coiled around each other in the DNA molecule unzip, and each of the single strands acts as a kind of mould for putting together a second strand. There are protein molecules that assemble all the parts and join them up in the right order. You start off with one DNA double-helix and end up with two. And each of the new cells gets one copy.



Now, imagine if I asked you to make a copy of a list of three billion letters. Do you think you could do it without making any mistakes?

I doubt if I could do it without going mad.

And it's hard for cells to get it perfectly right too. The proteins that make DNA are pretty good at it, and there are even other proteins that come and check they've done their job well. But even so, a few mistakes slip through: like putting a G bead where there should be a T. Whenever the whole of a cell's DNA – that's called its genome – is copied in this way, the two new DNA double-helices end up with some mistakes.

Lots of these mistakes don't matter – just as the meaning of a sentence is clear enough even if there are a few speeling mistakes –

A few what?

Speeling mistakes. I did that one on purpose. But you knew I meant "spelling mistakes", didn't you? My mistake didn't really matter.

I'll tell my English teacher that, next time he says I spelt something wrong.

Hmm, good luck with that Mel.

Sometimes, though, the errors do matter – and you end up with those proteins that don't do their job properly, which can cause diseases like cystic fibrosis.

> **I don't think I get it. You said that evolution works by picking out organisms that have the right genes to survive, while ones with genes that aren't so good die out – right?**

Yes.

> **So how come there are still these gone-wrong genes around that people can inherit, so that they get diseases?**

Well spotted. You'd think evolution would get rid of them, wouldn't you? Especially for the faulty gene that causes cystic fibrosis, because children with that disease used to die young, before they even had a chance to grow up and have their own children. Nowadays we have treatments, but it's still a horrible disease.

But here's the thing. I said that every time a cell divides, its DNA gets copied and the two new cells each get a copy. Well, that's true – but the truth is that all of our cells start with two copies of all our genes to begin with. We get one of those copies from our mothers, and one from our fathers. So the new cells get a copy of *both* of these pairs of genes.

But only one of those genes is actually used by the cell. The other is a kind of backup. The faulty genes that cause diseases are often the backup. So the fact that they're faulty usually never matters, because they're never actually used. Then you only get the disease if *both* of your copies of that gene are faulty. Your mother and your father could both have a faulty copy, and if you're unlucky, you inherit both of their faulty genes and neither of their good ones.

In the case of cystic fibrosis, only about one in every three thousand babies has the disease, but about one out of every 25 people has the faulty gene as one of its copies. Those people are called "carriers". They don't get the disease themselves, and can have children and be perfectly healthy – so natural selection doesn't notice the fact that they have this faulty gene. But if they have a baby with another person who is a carrier, there's a chance that the baby could inherit both of the bad genes, and then sadly it has cystic fibrosis.

Now, it sounds like bad news that genes can be mis-copied when cells divide. But as far as evolution goes, those errors can be a good thing. They're actually what makes evolution possible at all.

They are called mutations. And they happen all the time. When your complete genome has been replicated three times, there will be one mutation on average. That's actually pretty good going: it means that when they copy their DNA, cells only make one mistake on average for every ten billion beads copied. If you were copying out the information in the genome by hand, I reckon you'd make a lot more mistakes than that.

Now, usually, a gene mutation is either bad news or makes no difference. It could stop the gene from doing its job, or maybe the mutation happens in a part of the gene that doesn't matter very much and so the gene works pretty much as well as before.

But just occasionally – it's rare, but it happens – a mutation makes a gene *better*. Let's say the gene affects how muscles grow. If a mutation makes muscles grow a bit bigger, then the animal might be stronger or faster, and it will get an advantage over the others for catching food. And so natural selection will start to spread that mutated gene through the animal population, until most animals have that mutant. It's the same story with those white-haired Arctic hares and foxes: they have genes that make their fur white. Actually in that case it means they just don't switch on genes that make the dark stuff that colours the fur of other hares and foxes.

I've got a nasty feeling you're really saying that we're all mutants.

Of course we are. That's the only way we could evolve beyond slime.

Well, no offence to slime, but then I guess I'd rather be a mutant.

But look Yun Yun, I'm wondering how we know all this happens? You said that evolution is really, really slow. Our ape-like ancestors lived how long ago?

Depends how ape-like you mean. There were creatures looking like modern humans that lived about 200 thousand years ago.

Right. So we haven't really evolved much since then?

Not really, as far as we know. I mean, different population groups got to look a bit different – people in the east, like me, had eyes shaped differently from people in the west, like you. And different populations of people got different amounts of skin pigments, so some are darker and some lighter. That can be useful: it's good to have darker skin in hotter, sunnier climates. Also some groups of people are adapted to live up in mountainous places or highlands: they have more red blood cells, which are the cells that trap and move oxygen around in the body. That way, they can stay healthy even when the air is thinner.

But these are just little differences. We're all basically the same: we're all humans, all part of the same species. Humans are identical in nearly all of our genomes – all our differences come from a difference of just one thousandth in our genes.

Still, you asked how we know that evolution happens this way. Well, one way to answer that is that we can *see* it happening. You're right that it takes absolutely ages for 'good' mutations to happen and spread in humans, because we only reproduce about once every 30 years. It takes many, many generations for evolution to make big changes, which means many thousands of years.

But some organisms reproduce much more quickly. Bacteria do. They divide to make two new cells – a new generation – about every 20 minutes or so. That means there could be around 250 generations of bacteria in a week. Your own ancestors from 250 generations ago lived during the time of ancient Egypt, when the pyramids were built – about five thousand years ago.

So you see, bacteria can evolve much faster than us. And they do.

You know that some bacteria make us ill, right?

Urgh. Like a stomach bug?

Yes, it's often bacteria that gives you those. But some bacteria give us much worse diseases, like tuberculosis, which damages our lungs.

Fortunately, now we have drugs that can kill off the bacteria that make us ill. They're called antibiotics.

> **Hey, I had to take them once. I got a chest infection that wouldn't get better until I took these pills – the doctor said they were those, antibi-... what you said.**

Antibiotics. Well, I'm sorry to tell you this, but there was once a time when infections like that might have killed children like you. Charles Darwin's first daughter died when she was only ten, and some historians think it was tuberculosis that killed her.

Operations or bad injuries were very dangerous too, because the wound could get infected by bacteria. But now antibiotics stop that.

But here's the problem: bacteria evolve very quickly. And they will evolve so that antibiotics don't kill them any more.

Remember how it works. Let's say that, just by chance, a bacterium appears with a gene mutation that means it won't get killed by the drug. A germ like that is called resistant. Well, then it has an advantage over all the others – but only if they have to face the drug at all. If they never come across that antibiotic, the resistant bacterium never even knows it's resistant – it doesn't know about its advantage.

Once they meet the drug, though, all the other bacteria will be killed but the resistant one will survive and spread, and all its offspring will have the resistance gene too. So pretty soon you have a whole population of resistant bacteria, and the antibiotic won't work any more.

That's what is happening now. Several antibiotics that used to kill off dangerous bacteria don't work any more, and we have to invent new ones. Bacteria that can resist antibiotics are often called superbugs.

I don't like the sound of those superbugs.

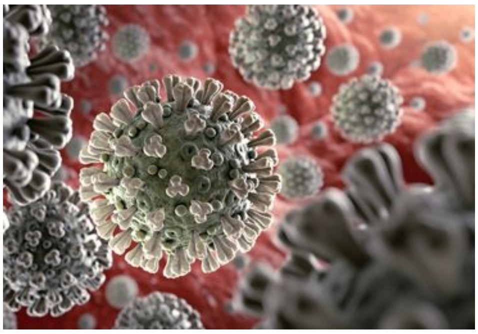
No, they are very bad news. And the thing is, they thrive in just the places you don't want them, like hospitals – because that's where there are often lots of antibiotics being used, which is just what it takes to help superbugs evolve.

But they're not just in hospitals, because we use antibiotics too much all around us too. We give them to farm animals even if they have not diseases, just in case. And doctors give them to patients who don't really need them, perhaps just so they'll feel happy about having got a medicine.

I don't get it. You say that giving people too many antibiotics is a bad idea, because it helps to create superbugs that antibiotics can't kill. But then you said that doctors do often give people too many antibiotics. Why would they do that?

They do it because they didn't understand evolution well enough, or didn't think about it carefully enough. They didn't stop and think that they were creating the conditions that would let superbugs spread.

I know – you're used to thinking the doctors know best. Usually they do, about medicine anyway. If a doctor gives you a medicine, it's best to take it.
But doctors weren't used to thinking that what medical treatments they gave would have anything to do with evolution. So they made a mistake. They forgot our question: what has evolution got to do with it?
Now they know that giving out too many antibiotics is a bad idea, and they try not to. But lots of damage is already done, and superbugs exist.
It's the same story with the coronavirus that gives people Covid-19. Viruses are even smaller than bacteria – here's what they look like.



They can be very infectious, like the flu virus. This coronavirus is really infectious. But as it spread, the virus evolved too, and now we have new forms of it that spread even faster.

Because they do, they have an advantage over other forms of the virus, and so natural selection picks them out – and they become the most common form of the virus. So you see, evolution has made things very hard for us to defeat Covid.

Hopefully we can keep finding new drugs that will kill superbugs, and vaccines that will protect us against viruses like the coronavirus. But these nasty bugs have taught us a really important lesson. It's that evolution is not just about the past, about fossils and dinosaurs and our hairy apelike ancestors. It's real, and it's still happening – to us and all around us. And we'd better not forget it!

Chapter 6
(A short one!!)
Science Is Everywhere

So that's it? All of science?

Well – not really.

Oh, well I know there's lots more. But those are all the subjects, right?

Those are just the ones you're likely to learn at school. But there are many more sciences.

As well as physics, chemistry and biology? Like what?

You can do science about any of the things that happen in the world. There are scientists who look at how clouds form and winds blow – they might be atmospheric scientists, or meteorologists. Some look at how the Earth works – how rocks and mountains are formed, say. They're usually called geologists. Or there are scientists who try to understand the oceans, and they are called oceanographers.

There are lots of ways to split up biology. Some scientists think mostly about medicine, some think mostly about evolution, some study how animals behave. Engineers are people who make things – it could be bridges, it could be vaccines, it could be plastics – so there are structural engineers, and bioengineers and chemical engineers.

OK, OK, so lots of 'ologists.

Yes, and some of those study how human minds work – they might be psychologists. There's a science of how all of society works, called –

Let me guess. Societology?

Very close! It's called sociology, or sometimes people just talk about the "social sciences". Those scientists might look at how people behave in groups, or study families, say, or how people make decisions.

What is there to know about how people make decisions?

Well, here's a question. A runaway train is coming hurtling down the track, and you're standing at a junction in the railway. If you pull a lever, you can switch the path of the train from one track to another. If you don't pull the lever, the train will run over five people on the track ahead of you. If you pull it, the train will change tracks and run over just one.

So what will you do?

Are you serious? That's a question scientists thought up? That's crazy! Hey, they don't do experiments on this, do they?

Not real experiments with real people. But they might test a whole bunch of people by just asking them the question and seeing what they say they'd do.

Many people think: well, if I don't pull the lever, those five people will die but it wasn't my fault. But if I do pull the lever, that one person will die because of me. So maybe I shouldn't.

But isn't it better for just one person to die than five?

Yes, many people think that too. And maybe it's a fair way to think. But even so, it feels somehow worse to be doing something that kills someone, rather than not doing something even if it means several people will die.

Hmm. So what's the right answer?

There is no right answer. Different people decide different things.

So why ask? Who's ever in that situation anyway?

Hopefully, no one is. But sometimes we do have to face tough choices like that. Say you're running a hospital and you don't have enough doctors or medicines to help everyone who needs it. How do you decide who gets treated and who doesn't?

Oh, I see what you mean. That's tough.

Yes, it is. And so it's good to find out how most people think. Then you might want to ask, well, what if the five people are old but the one is young.

You mean it's better to let the old people die than the young one? Isn't that... well, mean?

I don't know. It's a really hard decision. But if we understand how people think and reason about problems like that, we might be able to make plans about very difficult situations like that which most people would think are good ones – and perhaps how the decisions should change when the situation changes, like if the people are of different ages, or some are sicker than others.

So you see, once you get to social sciences, science is starting to get pretty mixed up with other subjects, like philosophy, or history or archaeology…

I've heard of that. Is it about digging old things up?

Sometimes, yes. Archaeology is about trying to understand how people in the past lived, usually from the things they've made that are still around. Do you know about the Roman city of Pompeii in Italy?

That was - wait, did lots of people die there in a volcanic eruption?

That's right. It happened almost 2000 years ago, and many of the citizens of Pompeii got smothered in the volcanic ash and suffocated. The city got preserved under all the ash – even some of the paintings on the walls are still there today. Like this one:

And so are some of the bodies, which were preserved in the ash layer almost like mummies. Here's one of them:

Yikes! Bit gross, tbh.

So archaeologists study Pompeii, but to understand what happened there they need to talk to historians who know about Ancient Rome, as well as geologists who know about volcanoes

So you get to dig up all those old bones and then have pizza and ice cream afterwards?

Well, archaeology isn't always as glamorous as that. Sometimes it means digging in a cold and wet field and not finding a thing. But yes, it's a pretty cool subject.

Do all these others kinds of science have their one big question too? Which could, you know, actually be two or three big questions, but whatever?

I suppose they probably do, though I haven't thought what they'd be.

You see, the real point is that we have to divide up what there is to study and know into these different subjects so that you get different lessons at school, and so there can be different departments at universities and so on. But that doesn't mean the actual world is divided up the same way. If you ask a question, it'll lead you where it wants to go. Even art and science aren't completely separate things. If you want to know about the history of art, you might need to know about the chemicals that painters used to make their different colours. If you want to know about music, you might want to find out about the science of sound, or even the science of our brains.

Remember what I said at the start: curiosity is good in science. Ideally, curiosity about everything. About the world and the things we find in it, about where they come from, about where *we* come from.

It's not about answers. It's about questions.