Hello, everyone. Welcome to another episode of Science and Technology Q&A for kids and others.

I'm starting a little bit late today, and

Have to finish fairly early, so we'll be a bit quick today.

Let's see, I see a number of… questions here.

It's a question here from Luke.

Why can't we build a perpetual motion machine?

Okay, so what is a perpetual motion machine? It's something that keeps on running.

And… and producing power of some kind forever.

And the question is, why can't we do that? Well, so the first thing to say is that there are… if we have, let's say, a wheel that's spinning around, some axle that's spinning around, then the thing that will stop that spinning is typically friction.

The thing will just… it'll spin for a while, but gradually, there will be… it will lose energy as a result of friction, and it will eventually stop.

But there are things…

that you can construct that are, have almost no friction, and will just keep going and keep going.

So we see that in…

In astronomy, for example, the, you know, the Earth has been happily going around the Sun for the last four and a half billion years, and it'll keep on going around the Sun, sort of, without much friction, so to speak, until

Until the sun, for another few billion years, until the sun gets so big that it engulfs the Earth. So there's, in a sense, in astronomy, we're used to having, in some sense, perpetual motion. Things just keep… keep going, because there isn't sort of friction to slow them down. Now, there is, in fact, even in astronomy, in some sense, a bit of friction.

even when So, for example, with the Moon going around the Earth.

the Moon is gradually kind of slowing down and is gradually getting further and further away from the Earth as a result of what amounts to friction

associated with, kind of, the, the Moon being deformed by the, by the gravity of the Earth and so on, and gradually, sort of, losing energy. What… what happens when, when

when, you know, the axle is, is spinning down, or something like this. What's happening is, what was

Kind of large-scale mechanical motion, like a wheel turning around, turns into heat.

Which is kind of the small-scale microscopic motion of molecules, and so on. So, it's… the energy that was associated with, kind of, the large-scale motion of the wheel gets turned into energy that's associated with small-scale motion of molecules.

And the problem is, you can't get it back from that form.

So, kind of the, the,

The one sort of version of why you don't get perpetual motion is because energy tends to degrade from being kind of large-scale mechanical… associated with large-scale mechanical motion to being associated with this very microscopic motion that we call heat. And

It is a sort of principle of physics, the so-called second law of thermodynamics, that once energy has degraded into the form of sort of this microscopic heat.

It doesn't get to organize itself again to come back and make kind of large-scale mechanical motion.

So, kind of in recognition of the fact that that's a phenomenon associated with the second row of thermodynamics, that form of perpetual motion of getting from, sort of, getting energy back from heat is usually called the perpetual motion machine of the second kind.

Let's talk actually a little bit about a perpetual motion machine of the first kind, which is… can be thought of as being associated with the first store of thermodynamics. The first store of thermodynamics basically just says, energy is conserved. There are different forms of energy. There can be energy from kinetic energy of motion, there can be energy that's stored in chemical bonds, there can be energy that's stored in nuclei.

There can be energy that's stored in the gravitational field and so on, but all those different forms of energy have to be… that you can convert between them, but in the end, energy in some… in all forms altogether is conserved.

So…

One of the, so, sort of the most extreme form of perpetual motion machine is a machine that just sort of makes energy from nothing.

And so the… it is… the current sort of belief about physics is that there is a principle of physics that energy is conserved.

And that's, that's a good principle, and so far as we can tell from experiments we've done, it's a correct principle. It has some footnotes, though, which are pretty tricky. So, for example, one footnote is, when it comes to the whole universe, it's not really quite right to say that energy is conserved.

It's kind of hard to say exactly what we mean by energy when you're dealing with, sort of, things like the whole universe, but it's tricky to make that claim. And for example, the expansion of the universe and the effect of the expansion of the universe does things which look like

Can be thought of as looking like not conserving energy, putting energy into things.

Now, you can sort of get around that by saying, well, the energy was really associated with the gravitational field that was produced, and changing the configurations of that and so on, but it's a little bit not kind of like ordinary energy conservation. But that's an incredibly small effect on the scale that we're dealing with.

There are other places.

So… Another, sort of, place that,

is tricky, is, well, how much energy is there just sort of bubbling around in the vacuum? How much energy is… what is the zero of energy?

You know, we say, this thing is, is, you know, it has no… like, the vacuum, does the vacuum have zero energy?

Well, you might think that was a reasonable thing to say, the vacuum has zero energy, but is that really right? Is there only one form of vacuum that can always be said to be the same and to have zero energy?

And the answer is that's a very tricky question.

And when, particularly, we know that when, sort of, the vacuum is… so what's in the vacuum? You say, well, there's nothing in the vacuum. Well, that's not really right.

In, sort of, traditional views of physics.

there are lots of quantum fluctuations happening in the vacuum. In my view of how physics works, the very existence of space is a consequence of, kind of, a lot of

Processes going on that go on even in the vacuum.

In which… One's taking the very structure of space is…

sort of knitted together by things that are happening even in the vacuum. So there's an analogy. If you think about something like a glass of water.

And you ask, what kind of holds together, what, what makes water be something that is, sort of a, a, well, actually, the more extreme case, imagine you have a blob of water in, on the…

space station. And without gravity, it doesn't sort of sit in a cup, it just makes a blob out, you know, you can put it… you can just make a blob of water, and it will just sit there. It doesn't fall in according to gravity.

What makes that blob of water be a thing that sort of has a… is coherently a blob?

Well, it's all the little interactions between the molecules of water inside that blob. If it wasn't for those interactions, the blob wouldn't be a blob, it wouldn't hang together. It wouldn't be something where you could, for example, expect to move a piece of it from here to there, and sort of have that… have that be a continuous motion.

Well, my belief is that that's the way that physical space works, sort of at the very lowest level. It's this kind of network of atoms of space that are all, that are… that are…

being reconnected and so on, very, very rapidly, and it's that process of reconnection and so on that kind of knits together the structure of space. So there's an incredible amount of activity going on in the vacuum.

In fact, if you look at the activity that's associated with knitting together the structure of space, it is unbelievably much larger than the activity associated with everything that we are sort of, kind of perceive, like the electrons and photons and things that are in the physical world.

It, it's, it's something where, the,

The, the… just sort of keeping space together is 100 orders of magnitude more activity than everything that we sense in the world.

So, in fact, even in traditional views of physics from the last hundred years or so, the same kind of thing happens, although in a slightly less extreme way. One is not dealing with knitting together the very structure of space, but one is dealing with the fact that there are always these kind of

this collection of virtual particles that exist in… even in the vacuum. So, the way in the uncertainty principle in quantum mechanics works, it says that things you might measure

like, energy or… or something. They are… it's, unless you wait

Sort of a very long time, you could never be sure about the precise value of the thing you measure.

There's always some uncertainty in the thing you measure.

And that's true even when the thing you're measuring is how many particles are there. And so the uncertainty principle says there will be sort of uncertainty about the number of particles that exist. And so that means that there's sort of constantly, in the vacuum, these so-called zero-point fluctuations where particles are sort of popping into existence and then disappearing very rapidly.

Well, that process, which is a feature of quantum field theory, is… is something happens throughout the vacuum. That's another thing where the vacuum is not sort of a featureless kind of thing where nothing's going on. In fact, lots is going on, even in traditional quantum field theory.

Actually, there's yet another effect, yet another thing in the vacuum.

which is the so-called Higgs mechanism, invented in the 1960s. It's kind of an explanation of how particles like electrons and so on get mass. Particles like photons are massless. They go at the speed of light, they have no mass.

But particles like electrons have mass, and the particles that make us up, the atoms with protons, neutrons, electrons, and so on, those particles have mass. That's why we're not zipping around the universe at the speed of light. We're just able to kind of sit still, because we have particles that have mass.

The way that it's imagined that mass is created is by the interaction of those particles with this so-called Higgs field, and sort of the concept that's existed in… for the last, I don't know, 50 years or so, has been that the way those particles get mass is by continually interacting with this kind of Higgs field that fills the universe.

There's a certain sort of density of Higgs field that exists in the universe, and as particles move through the universe, they're continually interacting with that Higgs field. Very much the same way that light, when it goes through a block of glass, will continually interact with the atoms of the glass, and it's continually being… the photons of light are being absorbed and re-emitted with a small time delay.

And that's sort of slowing down the light going through the glass. So similarly, it's the… sort of… the picture is that particles like electrons going through the vacuum which contains this Higgs field, they're continually interacting with this Higgs field and kind of being slowed down, and that's what leads to them… them having… having the appearance of having mass, so to speak.

I tend to think that picture is not quite right. I tend to think there's a sort of closer connection between what knits together the structure of space and what produces the effects of… produces things like mass. In traditional physics, those things are very separated. One doesn't even talk about how space is knitted together. One just says space is the way it is. And then one says that this Higgs field is responsible for mass.

And that that's yet separate from the vacuum fluctuations, the zero-point energy that's associated with, with the… with what happens in, from virtual particles in the vacuum. So in… in both standard physics and physics, I now think, is… is the way things work, the vacuum is a very… a place where lots and lots of stuff is going on. So, an obvious question is, can you mine the vacuum for energy?

Could it be the case that you say, well, you know, there's this giant reservoir of things going on? If we just change it a bit, could we extract lots of energy from it?

that would be a way of kind of, you're not… in that case, you're not saying you're making energy from nothing, you're just saying, I'm going to trade off some of the energy that's associated with all of that activity in the vacuum for energy that I'm going to organize in a way that gives me something that's useful to me.

So, just like in the case of the second order of thermodynamics and heat, the… the energy associated with, sort of, motion of… of… of… of molecules and so on, can either be very organized, where all the molecules are sort of moving together as part of a wheel, or the motion is very randomized. And one has the impression that it's the same kind of thing with the energy associated with the vacuum.

But it's sort of a good question in both these cases. Can you go back from the sort of microscopic structure, the energy that's been sort of ground up into all these microscopic pieces, and can you assemble it into something that's actually kind of a thing that you can make use of for some practical purpose? You know, you can run a car that way, or something like this.

In the case of, heat, kind of the second law of thermodynamics story.

the thing that you could say is, well, if you could have a machine that could figure out, oh, this molecule's going to go there, this molecule's going to go there, and so on, and you could kind of decode all the randomness associated with the motion of those molecules, if you could decode all of that, then you could potentially make use of it, because you could say, well, I know this molecule is going to go there, and so I'm going to put a little pin up there that that molecule's going to hit.

this other one's going to go the other direction, I'll put some other pin up there, and we'll put… we'll arrange these pins in such a way that we've kind of decoded the randomness of the motion of these molecules, and we'll be able to get some sort of systematic motion from that.

So, the… the thing is that for, sort of, Preachers like us.

with the technology we build, we're just not able to do the amount of decoding that's necessary to take, sort of, the practical number of atoms that exist in typical, everyday objects and so on, and do that decoding. We're talking about trillions and trillions and trillions of atoms, where we'd have to decode all of their motions to be able to sort of reorganize

What is otherwise this random heat.

On a very small scale, when we're dealing with just tens of atoms, for example, one can do that kind of decoding. One can go from something which was just sort of randomness to something which is systematic, at least at the level of tens of atoms.

So that's… so that means you can't kind of make… that failure to be able to decode is the reason that we can't make perpetual motion machines where we take the randomness of heat and turn it into systematic mechanical motion.

So now the question is, well, what about all the stuff that's happening in the vacuum? Could we somehow make use of that in some systematic way? The answer is nobody knows for sure, but… Nobody's yet figured out a slam-dunk kind of way to make that work. If one did, one will be able to kind of mine the energy of the vacuum to get, sort of, as much energy as one could possibly need.

One doesn't know how to do it. There are some slightly tantalizing signs. So there's a phenomenon called the Casimir Effect, which was originally talked about in the 1940s, I think. It's the following effect.

So… If you took… put two metal plates

In a vacuum, they're just sitting there, there's no… they don't have electric charge, they don't have any… they're just metal plates sitting there.

There is a very small force of attraction between those metal plates, and it's the result of these vacuum fluctuations. And basically, the reason is that between the metal plates, there's sort of a restriction on which… what kinds of vacuum fluctuations can happen. Those restrictions don't exist outside the metal plates, so there's sort of more vacuum fluctuations happening outside than inside, so there's a small force that pushes these plates together.

At least that's a first approximation of the intuition that you can get. That intuition isn't quite right, because if you make… if you take, instead of metal plates, you make a metal box.

You'll discover that, well, no, actually, then, in that case, for complicated reasons of sort of working out the physics, the mathematical physics of the thing, instead of there being a force of attraction, there's actually a force of repulsion instead.

In fact, back in the 1950s, even, people had wondered whether maybe electrons could be little tiny sort of metal balls, in effect, where although they have this electric charge that would be repelling one part of the electron from another.

that still this Casimir force might be such… associated with vacuum fluctuations might be such that it would sort of hold the electron together. But it turns out the exact opposite is true.

If the electron was a little metal ball, and you were looking at its Casimir forces, they would blow the thing apart, independent of the fact that the charge on the electron would… would blow it apart.

So… but…

the question that's sort of a tantalizing thing, because there's kind of like this little force that just comes from the vacuum. Now, by the way, I said it's sort of an obscure effect with metal plates. Actually, a microscopic version of that leads to the so-called van der Waals forces between molecules. So, many molecules in, I don't know, something like water, for example. Well, actually, not so much water, it's another liquid.

there will be, van der Waals forces, which are associated with, which you can think of as being associated with vacuum fluctuations. Here's how that works.

They have two molecules. They have no electric charge.

But…

the… the… what happens is vacuum fluctuations cause those molecules to have a small separation of positive and negative charges, and that's always fluctuating, so sometimes it's this going this way, sometimes it's going the other way, and so on. It's fluctuation very, very rapidly, but the molecule will have a little temporary separation of positive and negative charge.

Well, that… that separation of positive and negative charge

will induce in another molecule also a separation of positive and negative charges, and it's… those… those pairs of positive and negative charges will have a small force of attraction between them. Doesn't last long, it's sort of fluctuating all the time, but that leads to a small force of attraction between even molecules that don't have electric charges.

It's the so-called van der Waals force, and if you look at… if the molecules are a distance r apart, that force is roughly 1 over R to the 6th, or 1 over R to the 7th kind of force law. So that's a kind of microscopic manifestation of the Casimir effect that happens between these big metal plates that you can think of as being the result of vacuum fluctuations, zero-point energy in the vacuum.

So the question then is, can you make some very clever device that will just sort of constantly mine energy from the vacuum?

And, as I say, nobody really knows whether that's, you know, you can't prove that it's impossible.

The kind of,

The… you might say, well, it seems like what's happening in the vacuum is sort of too random, and like the second law of thermodynamics, and extracting energy, systematic energy from heat, that you'll have the same issue, that you can't go back from this sort of random arrangement of how energy is being used to something systematic that we can actually make use of on a large scale. But that's not… that's not known for sure.

And that would be a great way to kind of get energy for the world, if we could kind of trade off sort of all the energy that humans could ever possibly need, I might say, at least I don't know what humans will ever need in the future, but all the energy we have traditionally needed

Is, if we were kind of mining that out of the quantum vacuum.

the effect on the quantum vacuum will be absolutely, completely infinitesimal, and we'd still be able to satisfy all of our energy needs. But we don't know how to do that yet.

And maybe it's simply not possible. Maybe it's the same type of situation as happens with the second order of thermodynamics, where it's, Where it's sort of a computational fact that we kind of can't decode all those microscopic molecular motions and organize them so that they do things which are sort of mechanically useful for us.

I have to say, people have,

kind of, wondered about perpetual motion machines for a long time, and people have often sort of said, I've got this magic way that I can make motion from, you know, I can make motion go on forever, and I can make energy from nothing, or I can make useful energy from nothing. And, it's… it's usually kind of a… a, no, it doesn't really work in the end. You know, you do an experiment, and it seems like you're getting energy from nothing, but actually you forgot that, you know, you were heating one side of the thing and cooling the other side, and that was effectively where your energy came from.

people, from time to time will send me, kind of, letters about, you know, I've invented a perpetual motion machine. Those used to come in physical letters, and I remember one very peculiar one of these was, and here's a kit.

for making the perpetual motion machine, it involved a piece of string and a paperclip and so on, and it's like, well, it will be… it will be good for the world, I suppose, if it was that easy, but it's not.

So, that's kind of the story of perpetual motion machines.

Let's see…

John is asking, what about the accelerated expansion of the universe being associated with the concept of negative pressure? Actually, it's really associated with the concept of negative mass. Usually, kind of… The force of gravity just pulls things together.

But if you… and everything that exists as either zero mass if it's a photon or something, or positive mass if it's any kind of material object. But one of the theories that

to explain observations in cosmology is that there is dark energy, which is essentially negative mass matter. Sounds much better as dark energy. If you say negative mass matter, it sounds like what I think is actually the case, that it's kind of not really the right theory, that it's kind of a kludge to explain something. But yes, the idea

If there is negative mass matter, Then, that will give you

then there are indeed ways that that sort of pushes things apart. Actually, I haven't thought it through, it's a good question, whether you can easily make kind of a machine that will go, will operate in a closed cycle and run your wheels and so on for your car. If you have a little piece of negative mass matter, can you use that to generate,

To sort of generate energy from nothing. I'm not sure, actually. I don't know. I have not worked that out.

But as far as things like, sort of, pushing the expansion of the universe, yes, the negative mass matter can make the expansion of the universe accelerate.

Let's see… There's a question here from RBS about Our theory of physics.

Asking, if you imagine that, sort of, everything in the universe is this giant graph.

that sort of relates atoms of space, where atoms of space are just discrete elements that have no structure. In that picture.

Are particles, like electrons and so on, just pockets of computational reducibility in an otherwise irreducible vacuum? Or does… and the question here was, does undecidability limit quantum field theory?

Well, so yes, in our model, kind of particles are organized pieces of the vacuum, or the structure of space. Particles are sort of larger-scale organization in the structure of space.

Same with black holes.

There are things, places where, yes, there's a lot of sort of random reconnection and rearrangement of the structure of space at a very microscopic scale. When you have a black hole, it says, well, there's this whole big area of space that has the form of this black hole and that has the gravity corresponding to a black hole. That is kind of a piece of computational reducibility

In an otherwise computationally irreducible and unpredictable universe.

So… This question of sort of… what…

What is the effect when you have this kind of reducible thing that has recognizable features, and it is moving through this irreducible, random sort of background? What does that do?

My guess is the number one thing that that does is it gives mass to particles.

That, that, as the particle, when we say moving, we have the idea

that we can take an object and just move it in space, and it's just we can pick it up and we can just move the thing. But actually, in our models of physics, what's really happening when you're moving the thing

Is that the pieces of this graph that represent the thing are being sort of rearranged and reconnected to be, to be at a different place.

So to speak. So it's not that the thing… in some sense, the thing is… as you move it, it's a different thing. It's not the same thing anymore. It… but it is… it is something which, to us, we perceive as being the same thing, even though, sort of, at a very microscopic scale, it isn't the same thing. So, for example, if you have a little eddy in water, that eddy can move, the thing that you perceive of the thing swirling around.

that can absolutely move around, and you say the eddy moved, but the fact is, it's not the same molecules that made up the eddy when you first saw it and when it moved. They're different molecules.

But you still say that the thing had some sort of identity that moved, yet that what makes it up is changing all the time. And that's what I think is going on with particles like electrons in our universe, and with every piece of what makes us up.

That we are not made of the atoms of space at successive moments in time, but kind of the way that the things we are made of are arranged stays consistent through time, and then we have this memory, you know, we have this belief

that we're really the same us at successive moments in time in these models. We're not really, at some microscopic scale, the same us, although the arrangement of those atoms of space is the same at successive moments of time.

Lewis is asking, if perpetual motion is impossible, why do pendulum clocks work for so long?

well, you say so long, but the fact is, a pendulum clock eventually swings down. So eventually, there is friction in the kind of the pivot for the pendulum, eventually will take that systematic motion of the pendulum, and eventually it will sort of turn that systematic motion into heat.

Why do they keep going so long?

Well, they keep going so long because the kind of mechanical momentum is kind of… the amount of that that is being sort of siphoned off to turn into heat is quite small, and there's enough momentum that you kind of keep going with it for a long time, and it only kind of degrades into heat at a slow rate, so it keeps running for a while. I mean, there are other things which can run even longer.

Like, if you have a superconductor, you can have an electric current that will just keep going around this loop, for example, for months or years.

It's a case, as a result of quantum mechanics, where electrons can kind of move in a metal, or in a superconducting material. They can move without, without any kind of… they never… the electrons are kind of moving in a very coherent way.

And an individual electron moving in a material, like a metal, the electron will go a tiny distance, and then it will kind of hit, sort of an atom, and it will be thrown off track, and that will keep going.

In a superconductor, the electrons are kind of all going together, and sort of the collective effect of them all going together is they don't really care about there being a little atom in the way, because they're sort of making a big, sort of a big cohort of electrons that are all moving together, and that's why, sort of, you can end up with a superconductor where electrons will kind of keep moving, they'll keep going, and they won't

Get sort of randomized, and they can keep going for months at a time, and so on.

So there are certain cases where you can avoid, sort of, things turning into heat for a while,

But the, you could kind of see that eventually, even the superconductors and so on, eventually things will happen that will kind of get them to… to kind of slow down and so on.

jimmy is asking, what's the best classroom experiment to demonstrate why perpetual motion fails?

I don't know, it's hard to show that something is impossible.

I mean, you could say, well, I've got this particular thing.

and I kind of roll it for a while, and it'll stop rolling. Or I've got this particular thing, and I'm trying to, you know, make… I'm kind of cutting out a whole big discussion about perpetual motion, which has to do with things like steam engines, where you are taking the effects of heat, and you're saying, let me make a hot.

steam push out a piston and make that do mechanical work. So you've got, kind of, the randomness of the steam is doing that. It turns out that to really make use of that, you… if you want to make it in a closed cycle, where you're actually turning wheel around or something like this, or having a piston go back and forth, you have to use the heat.

Then you have to kind of, you have to have something which is cold, where you're sort of extracting the heat.

And then putting the heat back in again, and you're kind of going around a cycle. And that… that… the story of that turns out to be a story where you can't get

above a certain efficiency, which depends on the sort of difference of amount of heat from what's in the system to what's in the sort of reservoir outside. So there's a formula, it's called the Carnot efficiency of a heat engine.

Which essentially says that if you have, sort of the… the hot part of the thing at a certain temperature, the cold part of the thing at another temperature, there's just a formula that says it's the difference of the temperatures divided by the… the,

higher temperature, right, that, that, gives the efficiency of the,

of the device. You can't,

So… but it's hard to… it's hard to really demonstrate an impossibility, I think, in an experiment.

Mario's asking, if you had a superconductor that worked at room temperature, would a persistent current really be able to flow forever? If so, wouldn't that allow us to build a true perpetual motion machine? We'd have a current that's going around forever, but anytime you tried to use that current for something, like, let's say you've got that current going, and you're trying to induce some current and some other thing outside of that superconductor, then that process of that interaction with the outside thing would slow down what's inside the superconductor. So anytime you try and make use of what's in the superconductor, other than for just there's a current there and it's keeping going, like, you might use that, perhaps, to store a bit of information for a long time.

That would be a, a, that, that wouldn't, that wouldn't work. If you're trying to use it for something, you would kind of run down

The, the supercurrent that's circulating in the superconductor.

Lull asks, why did the universe have low entropy at the Big Bang? Chance or not? Oh, people have been so confused about this question.

So… entropy, is… This kind of slightly slippery concept.

That is, you have a system, let's say it has a bunch of molecules in it.

and you say, I know certain things about the system. Like, I know all my molecules are inside this particular size of box. And the question is, how many different microscopic configurations of that system could exist with those molecules in all sorts of different places, and speeds, and all that kind of thing?

Well, the entropy is the log of the number of possible configurations of the system. So, for example, if we had a bigger box, there'd be more places we could put the molecules and so on, so the entropy would be bigger, if we… if we… because there are just more different possibilities for what's in the box.

So, at all times, kind of, you can ask the question, if you… for example, let's say you start all the molecules over in one corner of the box, and you know they're all in one corner of the box. You say, well, the entropy is quite low, because the number of possible configurations consistent with them being all in that corner of the box is quite small.

But then, over time, it's a feature of the second order of thermodynamics, something that I think I can explain in terms of this phenomenon of computational irreducibility. It will tend to be the case that those molecules are sort of bouncing around all over the box, and the

We will just say… if we could tell there's great regularity, like all the molecules just bouncing together from one side to the other and so on, if they were all kind of bouncing together, then we'd say, oh yeah, it's all very organized still.

But it's, but the fact is that, for… what happens is, there's enough, sort of, that the… we…

that process of the molecules bouncing around did sort of so much irreducible computation, it sort of encoded what happened at the beginning to the point where, with any reasonable effort that we could make, we can't decode that. So we just have to say, looks to us like

It's just a bunch of particles in a box.

Not looks to us like it's a bunch of particles that are in this very organized way that are going back and forth, but we could say how they go back and forth.

And so the, quote, entropy increases because what we can say about the system is something that allows many possibilities for the microscopic configurations of molecules. We allow a lot less if we'd say it's this big blob of molecules bouncing back and forth.

So, I think that's, so, okay, that's what we mean by entropy, is the number of states of the system consistent with what we know about the system.

How do we apply that to the whole universe? Well, it's complicated, because if we think the universe is following a definite rule, there's kind of only one of it. The whole universe has no entropy, there's only one possible configuration the universe can have.

Now, it's trickier when we deal with quantum mechanics, and where in our models, there are many different sort of paths of history. The whole object, the whole rulliad, as we call it, that encodes all possible paths of history, that's something that has no entropy, there's just one of it. It's completely determined how it works.

But for us.

we are… we don't know where we are in that whole giant set of possibilities. So, for us, it's like we are… the whole thing has zero entropy, but sort of what we know about where we are, it's kind of a different story, but it's not entropy in the traditional sense.

Now, people… have… I mean, in our models of physics, what happens is there's a certain structure of space.

And the network that represents the structure of space gets bigger over time, and that means there are more possibilities for what can happen in it. And I suppose you could call that an increase of entropy, although the traditional way that entropy is thought about in physics, that wouldn't really… wouldn't have anything to say about that.

But…

you know, one of the things that's sort of been mysterious is it seemed like the universe started in this very, sort of this hot big bang, where everything was kind of random, and then it steadily got to the point where what we see looks less random, because there are galaxies and things like that.

But we don't really…

We can't really make that comparison, because it's certain large-scale features that we identify, but at a microscopic scale, it's still doing all that random stuff.

And when you combine that with the idea that the actual structure of space is expanding, the number of atoms of space is increasing and so on, the picture of sort of how you kind of do the accounting for entropy in the beginning of the universe to now kind of falls apart.

we'd like to figure out more about how this really works, but I think the idea that,

sort of the entropy of the universe started low, and then everything's kind of running down since then. It just doesn't really make sense. And it's not really what you need to talk about, because sort of, you can still have a completely deterministic universe with a single rule, and still it can be the case that a particular part of the universe that you're looking at can be such where that you can either say, oh, I know exactly what's happening to all the particles in it, or it can be such that you can say, I can't decode what's happening, I have to say that it has higher entropy.

Let's see… June is asking, is there such a thing as negative Kelvin temperatures?

Okay, so What is temperature?

Temperature… is… well, heat.

is…

the microscopic motion of molecules, temperature is kind of how much microscopic motion is happening. Temperature is something where if you look at the average kinetic energy of those individual molecules, then the average kinetic energy is proportional to the temperature.

So, as things… as you increase the temperature, the atoms in your gas, or whatever else, molecules in your gas are running around faster and faster. That's what temperature corresponds to, is kind of its… depends on the energy of each individual molecule.

So…

There's a question of what people wondered for a long time, is there kind of a… so that's a sort of modern understanding of what temperature is.

There was a question for a while about, sort of, how you measure temperature, and whether there is an absolute scale of temperature, because when, like, Galileo, for example, back in the early

1600s, had made a thermometer. How did he make a thermometer? Well, he had, I think, alcohol, and he had it in a glass

Tube, and he noticed that when you heat it up, the alcohol expands on the glass tube.

And, later on, Mercury was also… has this feature that it expands when you heat it up.

And, like, when I was a kid, the way you would take your temperature is you would have this glass thing which had mercury inside it, and it was in a very thin, thin sort of tube inside the piece of glass. There would be some mercury, there would be a sort of bulb at the end of it which had mercury in it, you stick the thing under your tongue, and then, depending on the temperature under your tongue.

the mercury would expand a certain amount. You just look at how far did the mercury get pushed in this tube.

Of course, it was important, don't bite down on the glass tube, because if you do, you get mercury in your mouth, and mercury is poisonous, and that would be a really bad thing.

And so, it's probably just as well that mercury thermometers have kind of gone… gone out. But the basic idea is, you're measuring temperature by measuring the expansion of alcohol, mercury, whatever else.

The,

So people wondered, is there sort of an absolute scale of temperature? We could say, well, this is the temperature, this is the amount that

On this day of the year, you know, the temperature is higher, and it expands the mercury in our thermometer by this much, or it expands the alcohol in our thermometer by this much.

The question is, is there sort of some… some way of talking about temperature that doesn't depend on what material is being operated on?

And a chap, called, well, originally William Thompson, later Lord Kelvin, came up with the idea that, yes, there is an absolute scale of temperature that is associated with… well, he didn't know… at the beginning, he didn't know it was associated with microscopic motion of molecules, but that's what turned out to be the case.

So…

temperature, microscopic motion of molecules. When, so you might say, well, how could you possibly have anything other than… how could you have a negative temperature? Here's how.

So… oh, by the way, in the Kelvin scale of temperature, the absolute scale of temperature, there's an absolute zero of temperature. That wasn't obvious before this was figured out, where, you know, you can keep

having the molecules have less and less energy, but you can't have them have less than zero energy. They end up having the… there's an absolute zero of temperature, about minus 273 degrees centigrade, at which

kind of…

There is, in a first approximation, no motion in the molecules in a material. They've just stopped. There is no heat that's adding this sort of microscopic energy, they've just stopped.

Now, of course, there's a footnote to that. Quantum mechanics and these, in fact, these very vacuum fluctuations that I was talking to you about earlier mean that things don't precisely stop.

And usually when things stop, like most materials, when all the atoms have stopped jiggling around, the material will be a solid, because those atoms are also locked in place by being pulled by other atoms, and so on. There's one exception to that, which is helium at standard pressure.

does not become a solid at absolute zero, it's still a liquid, and that's a consequence of vacuum fluctuations that are still jiggling the molecules around enough to prevent the helium from forming into a solid. The forces of attraction between helium atoms are small enough that the quantum fluctuations can jiggle it enough that it never locks into place to be a solid.

But anyway, so… The, the temperature is proportional to the average
energy of the molecules. Average energy.

But actually, there's a distribution of energies of molecules. It's a thing called the Boltzmann distribution, and it turns out that when you have molecules kind of bumping into each other, like, you'll have the two molecules, one of them has a big energy, one of them has a smaller energy, they run into each other, they'll eventually… the energies will maybe be more equalized when the total energy will be the same.

But the energy will be more equally distributed between the two molecules after their collision than before, let's say.

Well, you can work out that you have a bunch of colliding molecules, and so on, and eventually they are in equilibrium, in the sense that the, sort of, on average, the way that energy is distributed going forwards in time and backwards in time is the same. Then it turns out

That there's a sort of mathematical result.

That the distribution of energies of those molecules will be an exponential.

Actually, it's not too hard to see this, okay, it's a little math moment. So if the energies of the, of the particles that are coming in to a collision are E1 and E2, and the ones going out are E3 and E4, then energy conservation means that E1 plus E2 is equal to E3 plus E4.

But if you then say, well, these molecules have a certain distribution of energies, there's some function, F of E, that tells us how many molecules there'll be at energy roughly E.

Then what better be the case, if you're in equilibrium, is that F1… F of E1 times F of E2 equals F of E3 times F of E4.

And it turns out that the only form for F, the only mathematical form for F that satisfies that equation is F as an exponential.

And so, that's kind of the… that's sort of the math derivation of the fact that after all these molecules are bounced around a lot, they will… they will come to equilibrium, and obviously they would do that, but they do, then you will have an exponential distribution of energies. They'll be exponentially damp. There are more lower energies than higher ones. Slight trickiness, if you look at… well, let's just say that, that's…

That's basically the way it works.

So…

Distribution of energies from the lower… the lower energy molecules, there are more of those than the higher energy molecules.

it's, you know, if you're trying to make, like, a nuclear weapon, for example, you really want very high energy particles, because they've got to be able to overcome… you're trying to ram two nuclei together, and they've got to be able to overcome the force of repulsion from electricity… from electric forces, and so you really want the highest energy possible molecules. And if you… if you heat things up.

Then most molecules, let's say you're, you know, you heat something up to 10 million degrees, and then most of the molecules, the average, that temperature of 10 million degrees, means the average energy of the nuclei is whatever it is.

But there's still a tale of ones that are of higher energy, and those are important, because those are the ones that sort of first get to overcome the sort of barrier and do nuclear fusion or whatever else it is that you want.

The, so in any case, the,

But… so there's distribution of energies that tends to be exponentially damped, dies off very quickly. Okay, so if you're just showing

a bunch of molecules, and they have a certain distribution of energies, then you can say, oh, they're falling off. The ones of lower energy, there are more of those. The ones of higher energy, there are lower of those. So we can sort of fit that to saying it's a temperature of, that corresponds to some value of temperature. I should have said the exponential gets broader and broader the lower the temperature. So the formula is exponential minus energy divided

by temperature.

So, that's the distribution of chances to find a molecule of a certain temperature. Okay, so here's a hack you can do. Imagine that you have a system which has a few, just a few energy levels, and imagine that you've somehow managed to get it so that there are more molecules, or more atoms, for example, that are in the higher energy state than there are in the lower energy state.

If you then try and fit this temperature curve, this curve of energies to that, you say, whoops, I can't fit, there's no positive value of temperature, which makes there be more particles of higher energy than of lower energy. So you can say, well, we can think of that as being a negative temperature.

It's not really quite sort of an equilibrium the same way that things in a gas would be, but still, it's a… it's a first cut to say, let's describe what we're seeing as being a negative temperature. We've got,

We've got this inversion of the… there are more higher energy things than lower energy things, and that's like having a negative temperature.

So, does this ever happen?

Well, yes, there are places where it happens. The most notable is in lasers.

Lasers actually work by having, sort of, pumped atoms into lots of atoms into a higher energy state.

And, lasers work using… using the fact that

Photons kind of like to be in the same state, and once you start pumping them there, you can pump more there. But anyway, the end result is that lasers have the property that there are more higher energy states than lower energy ones, so you can say that that corresponds to a negative temperature.

You can do the same thing with other kinds of particularly microscopic experiments.

that will generate, quotes, negative temperature by having this inversion of more high-energy things than low-energy things, although not quite the same thing as the traditional temperature where you have this full exponential distribution. But that's, that's how, that's how negative temperatures work.

Alright.

I should probably wrap up here and go back to my…

Day job, but thank you,

I see lots of interesting questions here, which I look forward to answering another time.

But, thanks for joining me today, and, bye for now.