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What is Reality?

(Image: Carol & Mike Werner/Visuals Unlimited/Getty)

WHEN you woke up this morning, you found the world largely as you left it. You were still you; the room in which you awoke was the same one you went to sleep in. The outside world had not been rearranged. History was unchanged and the future remained unknowable. In other words, you woke up to reality. But what is reality? The more we probe it, the harder it becomes to comprehend. In the eight articles on this page we take a tour of our fundamental understanding of the world around us, starting with an attempt to define reality and ending with the idea that whatever reality is, it isn't what it seems. Hold on to your hats.

DEFINITION

Even trying to define what we mean by "**reality**" is fraught with difficulty:

What do we actually mean by reality? A straightforward answer is that it means **everything that appears to our five senses** - everything that we can see, smell, touch and so forth. Yet this answer ignores such problematic entities as electrons, the recession and the number 5, which we cannot sense but which are very real. It also ignores phantom limbs and illusory smells.
Both can appear vividly real, but we would like to say that these are not part of reality.
We could tweak the definition by **equating reality with what appears to a sufficiently large group of people**, thereby ruling out subjective hallucinations. Unfortunately there are also hallucinations experienced by large groups, such as a mass delusion known as koro, mainly observed in South-East Asia, which involves the belief that one's genitals are shrinking back into one's body. Just because sufficiently many people believe in something does not make it real.

Another possible **mark of reality we could focus on is the resistance it puts up**: as the science fiction writer Philip K. Dick put it, **reality is that which, if you stop believing in it, does not go away**. Things we just make up yield to our wishes and desires, but reality is stubborn. Just because I believe there is a jam doughnut in front of me doesn't mean there really is one. But again, this definition is problematic. Things that we do not want to regard as real can be stubborn too, as anyone who has ever been trapped in a nightmare knows. And some things that are real, such as stock markets, are not covered by this definition because if everyone stopped believing in them, they would cease to exist.

There are two definitions of reality that are much more successful. **The first equates reality with a world without us, a world untouched by human desires and intentions**. By this definition, a lot of things we usually regard as real - languages, wars, the financial crisis - are nothing of the sort. Still, **it is the most solid one so far because it removes human subjectivity from the picture**.

The second **equates reality with the most fundamental things that everything else depends on**. In the material world, molecules depend on their constituent atoms, atoms on electrons and a nucleus, which in turn depends on protons and neutrons, and so on. In this hierarchy, every level depends on the one below it, so **we might define reality as made up of whatever entities stand at the bottom of the chain of dependence, and thus depend on nothing else**.

This definition is even more restrictive than "the world without us" since things like Mount Everest would not count as part of reality; reality is confined to the unknown foundation on which the entire world depends. Even so, when we investigate whether something is real or not, these final two definitions are what we should have in mind.

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STANDARD MODEL OF PARTICLE PHYSICS
The bedrock of it all

Can we explain reality purely in terms of matter and energy, asks **Valerie Jamieson**

IS ANYTHING real? The question seems to invite only one answer: of course it is. If in doubt, try kicking a rock. Leaving aside the question of whether your senses can be trusted, what are you actually kicking? When it boils down to it, not a lot.

Science needs remarkably few ingredients to account for a rock: **a handful of different particles, the forces that govern their interactions, plus some rules laid down by quantum mechanics**.

This seems like a solid take on reality, but it quickly starts to feel insubstantial. If you take a rock apart, you'll find that its basic constituent is atoms - perhaps 1000 trillion trillion of them, depending on the rock's size. Atoms, of course, are composed of smaller subatomic particles, namely protons and neutrons - themselves built of quarks - and electrons. Otherwise, though, atoms (and hence rocks) are mostly empty space. If an atom were scaled up so that its nucleus was the size of the Earth, the distance to its closest electrons would be 2.5 times the distance between the Earth and the sun. In between is nothing at all. **If so much of reality is built on emptiness, then what gives rocks and other objects their form and bulk?**

Physics has no problem answering this question: **electrons**. Quantum rules dictate that no two electrons can occupy the same quantum state. The upshot of this is that, no matter how hard you try, you cannot cram two atoms together into the same space. "Electrons do all the work when it comes to the structure of matter we see all around us," says physicist Sean Carroll at the California Institute of Technology in Pasadena. That's not to say the nucleus is redundant. Most of the mass of an atom comes from protons and neutrons and the force binding them together, which is carried by particles called gluons. And that, essentially, is that. **Electrons, quarks (mostly of the up and down variety) and gluons account for most of the ordinary stuff around us.**

But not all. Other basic constituents of reality exist too - 17 in total, which together comprise the standard model of particle physics (see illustration). **The model also accounts for the mirror world of antimatter with a complementary set of antiparticles**.
Some pieces of the standard model are commonplace, such as **photons** of light and the various **neutrinos** streaming through us from the sun and other sources. Others, though, do not seem to be part of everyday reality, including the top and bottom **quarks** and the heavy, electron-like **tau particle**. "On the face of it, they don't play a role," says Paul Davies of Arizona State University in Tempe. "Deep down, though, they may all link up." That's because the standard model is more than a roll call of particles. **Its foundations lie in symmetry and group theory, one example of the mysterious connections between reality and mathematics** (see "Reality: Is everything made of numbers?").

The standard model is arguably even stranger for what it doesn't include. It has nothing to say about the invisible **dark matter** than seems to make up most of the matter in the universe. Nor does it account for **dark energy**. These are serious omissions when you consider that dark matter and dark energy together comprise about 96 per cent of the universe. It is also totally unclear how the standard model relates to phenomena that seem to be real, such as time and gravity.

So **the standard model is at best a fuzzy approximation, encompassing some, but not all, of what seems to comprise physical reality, plus bits and pieces that do not**. Most physicists would agree that the standard model is in serious need of an overhaul. It may be the best model we have of reality, but it is far from the whole story.

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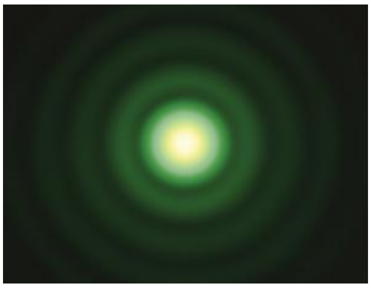
MATTER
Is matter real?



It's relatively easy to demonstrate what physical reality isn't. It is much harder to work out what it is.

NOTHING seems more real than the world of everyday objects, but things are not as they seem. A set of relatively simple experiments reveals **enormous holes is our intuitive understanding of physical reality. Trying to explain what goes on leads to some very peculiar and often highly surprising theories of the world around us**.

Here is a simple example. Take an ordinary desk lamp, a few pieces of cardboard with holes of decreasing sizes, and some sort of projection screen such as a white wall. If you put a piece of cardboard between the lamp and the wall, you will see a bright patch where the light passes through the hole in the cardboard. If you now replace the cardboard with pieces containing smaller and smaller holes, the patch too will diminish in size. Once we get below a certain size, however, the pattern on the wall changes from a small dot to a series of concentric dark and light rings, rather like an archery target.

This is the "**Airy pattern**" - a characteristic sign of a wave being forced through a hole (see image).

In itself, this is not very surprising. After all, we know that light is a wave, so it should display wave-like behaviour.

But now consider what happens if we change the set-up of the experiment a bit. Instead of a lamp, we use a device that shoots out electrons, like that found in old-fashioned TV sets; instead of the wall, we use a plate of glass coated with a phosphor that lights up when an electron strikes it. We can therefore use this screen to track the places where the electrons hit. The results are similar: with sufficiently small holes we get an Airy pattern.

This now seems peculiar: electrons are particles located at precise points and cannot be split. Yet they are behaving like waves that can smear out across space, are divisible, and merge into one another when they meet.

Perhaps it is not that strange after all. Water consists of molecules, yet it behaves like a wave. The Airy pattern may just emerge when enough particles come together, whether they are water molecules or electrons.

A simple variant of the experiments shows, however, that this cannot be right. Suppose we reduce the output of the electron gun to one particle each minute. The Airy pattern is gone, and all we see is a small flash every minute. Let's leave this set-up to run for a while, recording each small flash as it occurs. Afterwards, we map the locations of all the thousands of flashes.

Surprisingly, **we do not end up with a random arrangement of dots, but with the Airy pattern again. This result is extremely strange. No individual electron can know where all the earlier and later electrons are going to hit, so they cannot communicate with each other to create the bullseye pattern**. Rather, each electron must have travelled like a wave through the hole to produce the characteristic pattern, then changed back into a particle to produce the point on the screen. This, of course, is the famous wave-particle duality of quantum mechanics.

This strange behaviour is shared by any sufficiently small piece of matter, including electrons, neutrons, photons and other elementary particles, but not just by these. Similar effects have been observed for objects that are large enough in principle to be seen under a microscope, such as buckyballs.
In order to explain the peculiar behaviour of such objects, physicists associate a **wave function** with each of them. Despite the fact that these waves have the usual properties of more familiar waves such as sound or water waves, including amplitude (how far up or down it deviates from the rest state), phase (at what point in a cycle the wave is), and interference (so that "up" and "down" phases of waves meeting each other cancel out), what they are waves *in* is not at all transparent. Einstein aptly spoke of a "**phantom field**" as their medium.
For a wave in an ordinary medium such as water, we can calculate its energy at any one point by taking the square of its amplitude. **Wave functions, however, carry no energy**. Instead, the square of their amplitude at any given point gives us the probability of observing the particle if a detector such as the phosphor-coated screen is placed there. Clearly, the point where an object switches from being a **probability wave**, **with its potential existence smeared out across space**, and becomes an actual, spatially localised object **is crucially important to understanding whether matter is real**.

What exactly happens when the wave function collapses - when among the countless possibilities where the particle could be at any moment, one is chosen, while all the others are rejected?
First of all, we have to ask ourselves **when this choice is made**. In the example described above, it seems to happen just before the flash on the phosphor screen. At this moment, a measurement of the electron's position was made by a piece of phosphor glowing as the particle struck it, so there must have been an electron there, and not just a probability wave.

But assume we cannot be in the lab to observe the experiment, so we point a camera at the phosphor screen and have the result sent via a satellite link to a computer on our desktop. In this case, the flash of light emitted from the phosphor screen has to travel to the camera recording it, and the process is repeated: like the electrons, light also travels as a wave and arrives as a particle. What reason is there to believe that the switch from probability wave to particle actually occurred on the phosphor screen, and not in the camera?
At first, it seemed as if the phosphor screen was the measuring instrument, and the electron was the thing being measured. But now the measuring device is the camera and the phosphor screen is part of what is measured. **Given that any physical object transmitting the measurement we can add on to this sequence - the camera, the computer, our eyes, our brain - is made up of particles with the same properties as the electron, how can we determine any particular step at which to place the cut between what is measured and what is doing the measuring?**

This ever-expanding chain is called the **von Neumann chain**, after the physicist and mathematician John von Neumann. One of his Princeton University colleagues, **Eugene Wigner**, made a suggestion as to where to make the cut. As we follow the von Neumann chain upwards, the first entity we encounter that is not made up in any straightforward fashion out of pieces of matter is **the consciousness of the observer**. We might therefore want to say that **when consciousness enters the picture, the wave function collapses and the probability wave turns into a particle**.**The idea that consciousness brings everyday reality into existence is, of course, deeply strange; perhaps it is little wonder that it is a minority viewpoint**.
There is another way of interpreting the measurement problem that does not involve consciousness - though it has peculiar ramifications of its own. But for now let's explore Wigner's idea in more depth.

If a conscious observer does not collapse the wave function, curious consequences follow. As more and more objects get sucked into the vortex of von Neumann's chain by changing from being a measuring instrument to being part of what is measured, the "spread-out" structure of the probability wave becomes a property of these objects too. The **"superposed" nature of the electron - its ability to be at various places at once - now also affects the measuring instruments**.
It has been verified experimentally that not just the unobservably small, but objects large enough to be seen under a microscope, such as a 60-micrometre-long metal strip, can exhibit such superposition behaviour. Of course, we can't look through a microscope and see the metal strip being at two places at once, as this would immediately collapse the wave function. Yet it is clear that **the indeterminacy we found at the atomic level can spread to the macro level**.
Yet **if we accept that the wave function must collapse as soon as consciousness enters the measurement, the consequences are even more curious**. If we decide to break off the chain at this point, it follows that, according to one of our definitions of reality, **matter cannot be regarded as real**. If consciousness is required to turn ghostly probability waves into things that are more or less like the objects we meet in everyday life, **how can we say that matter is what would be there anyway, whether or not human minds were around?**
But perhaps this is a bit too hasty. Even if we agree with the idea that consciousness is required to break the chain, all that follows is that **the dynamic attributes of matter such as position, momentum and spin orientation are mind-dependent**. It does not follow that its **static attributes**, including mass and charge, are dependent on in this. The static attributes are there whether we look or not.
Nevertheless, **we have to ask ourselves whether redefining matter as "a set of static attributes" preserves enough of its content to allow us to regard matter as real**.

In a world without minds, there would still be attributes such as mass and charge, but things would not be at any particular location or travel in any particular direction. Such a world has virtually nothing in common with the world as it appears to us. **Werner Heisenberg** observed that: "**the ontology of materialism rested upon the illusion that the kind of existence, the direct 'actuality' of the world around us, can be extrapolated into the atomic range. This extrapolation, however, is impossible... Atoms are not things."**
It seems that the best we are going to get at this point is the claim that some things are there independent of whether we, as human observers, are there, even though they might have very little to do with our ordinary understanding of matter.
Does our understanding of the reality of matter change if we choose the other strong definition of reality - not by what is there anyway, but by what provides the foundation for everything else (see "Reality: The definition")?
In order to answer this question, we have to look at **the key scientific notion of a reductive explanation**. Much of the power of scientific theories derives from the insight that we can use a theory that applies to a certain set of objects to explain the behaviour of a quite different set of objects. We therefore don't need a separate set of laws and principles to explain the second set.
A good example is the **way in which theories from physics and chemistry, dealing with inanimate matter, can be used to explain biological processes**. There is no need to postulate a special physics or a special chemistry to explain an organism's metabolism, how it procreates, how its genetic information is passed on, or how it ages and dies. **The behaviour of the cells that make up the organism can be accounted for in terms of the nucleus, mitochondria and other subcellular entities, which can in turn be explained in terms of chemical reactions based on the behaviour of molecules and the atoms that compose them. For this reason, explanations of biological processes can be said to be reducible to chemical and ultimately to physical ones.**

If we pursue a reductive explanation for the phenomena around us, a first step is to reduce statements about the medium-sized goods that surround us - bricks, brains, bees, bills and bacteria - to **statements about fundamental material objects, such as molecules**.
We then realise everything about these things can be explained in terms of their constituents, namely their **atoms**. Atoms, of course, have parts as well, and we are now well on our way through the realm of ever smaller subatomic particles, perhaps (if string theory is correct) all the way down to **vibrating strings of pure energy**. So far we have not reached the most fundamental objects. In fact, there is not even an agreement that there are any such objects.
Yet this is **no reason to stop our reductionist explanation here, since we can always understand the most basic physical objects in terms of where they are in space and time**. Instead of talking about a certain particle that exists at such-and-such a place for such-and-such a period of time, **we can simply reduce this to talk about a certain region in space that is occupied between two different times**.
We can go even more fundamental. If we take an arbitrary fixed point in space, and a stable unit of spatial distance, we can specify any other point in space by three coordinates. These simply tell us to go so many units up or down, so many units left or right, and so many units back or forth. We can do the same with points in time. We now have a way of expressing points in space-time as sets of four numbers, x, y, z and t, where x, y, and z represent the three spatial dimensions and t the time dimension. In this way, **reality can be boiled down to numbers**.
And this opens the door to something yet more fundamental. Mathematicians have found a way of **reducing numbers to something even more basic: sets**. To do this, they replace the number 0 with the empty set, the number 1 with the set that contains just the empty set, and so on (see "Reality: Is everything made of numbers?"). All the properties of numbers also hold for all these **ersatz numbers** made from sets. It seems as if we have now reduced all of the material world around us to an array of sets.

For this reason, it is important to know what **these mathematical objects called sets really are**. There are two views of mathematical objects that are important in this context. First, there is the view of them as "**Platonic" objects**.
This means that **mathematical objects are unlike all other objects we encounter**. **They are not made of matter, they do not exist in space or time, do not change, cannot be created or destroyed, and could not have failed to exist**. According to the Platonic understanding, **mathematical objects exist in a "third realm", distinct from the world of matter, on the one hand, and the world of mental entities, such as perceptions, thoughts and feelings, on the other.**

Boe: third realm – triton genos (Plato Timaeus)

Second, **we can understand mathematical objects as fundamentally mental** in nature. **They are of the same kind as the other things that pass through our mind: thoughts and plans, concepts and ideas**.
They are not wholly subjective; other people can have the very same mathematical object in their minds as we have in ours, so that when we both talk about the Pythagorean theorem, we are talking about the same thing. **Still, they do not exist except in the minds in which they occur**.

Either of these understandings leads to a curious result. **If the bottom level of the world consists of sets, and if sets are not material but are instead some Platonic entities, material objects have completely disappeared from view and cannot be real in the sense of constituting a fundamental basis of all existence**.

If we follow scientific reductionism all the way down, we end up with stuff that certainly does not look like tiny pebbles or billiard balls, not even like strings vibrating in a multidimensional space, but more like what **pure mathematics** deals with.
Of course, the Platonistic view of mathematical objects is hardly uncontroversial, and **many people find it hard to get any clear idea of how objects could exist outside of space and time**. But if we take mathematical objects to be mental in nature, we end up with an even stranger scenario.
The scientific reductionist sets out to reduce the human mind to the activity of the brain, the brain to an assembly of interacting cells, the cells to molecules, the molecules to atoms, the atoms to subatomic particles, the subatomic particles to collections of space-time points, the collections of space-time points to sets of numbers, and the sets of numbers to pure sets. But at the very end of this reduction, we now seem to loop right back to where we came from: to the **mental entities**.
We encounter a similar curious loop in the most influential way of understanding quantum mechanics, the **Copenhagen interpretation**. Unlike Wigner's consciousness-based interpretation, this does not assume the wave function collapses when a conscious mind observes the outcome of some experiment. Instead, it happens when the system to be measured (the electron) interacts with the measuring device (the phosphor screen). For this reason, it has to be assumed that the phosphor screen will not itself exhibit the peculiar quantum behaviour shown by the electron.
In the Copenhagen interpretation, then, things and processes describable in terms of familiar classical concepts are the foundation of any physical interpretation. And this is where the **circularity** comes in. We analyse the everyday world of medium-sized material things in terms of smaller and smaller constituents until we deal with parts that are so small that quantum effects become relevant for describing them. But when it comes to spelling out what is really going on when a wave function collapses into an electron hitting a phosphor screen, **we don't ground our explanation in some yet more minute micro-level structures; we ground it in terms of readings made by non-quantum material things**.

What this means is that **instead of going further down, we instead jump right back up to the level of concrete phenomena of sensory perception, namely measuring devices such as phosphor screens and cameras**. Once more, we are in a situation where we cannot say that the world of quantum objects is fundamental. Nor can we say that the world of measuring devices is fundamental since these devices are themselves nothing but large conglomerations of quantum objects.

We therefore have **a circle of things depending on each other, even though, unlike in the previous case, mental objects are no longer part of this circle**. As a result, **neither the phosphor screen nor the minute electron can be regarded as real in any fundamental sense, since neither constitutes a class of objects that everything depends on**.

What we thought we should take to be the most fundamental turns out to involve essentially what we regarded as the least fundamental.

In our search for foundations, we have gone round in a circle, from the mind, via various components of matter, back to the mind - or, in the case of the Copenhagen interpretation, from the macroscopic to the microscopic, and then back to the macroscopic. But this just means that **nothing is fundamental**, in the same way there is no first or last stop on London Underground's Circle Line. The moral to draw from the reductionist scenario seems to be that **either what is fundamental is not material, or that nothing at all is fundamental.**

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MATHEMATICS

Is everything made of numbers?

Dig deep enough into the fabric of reality and you eventually hit a seam of pure mathematics, says **Amanda Gefter**

Dig deep enough into the fabric of reality and you eventually hit a seam of pure mathematics:

WHEN Albert Einstein finally completed his general theory of relativity in 1916, he looked down at the equations and discovered an unexpected message: the universe is expanding. Einstein didn't believe the physical universe could shrink or grow, so he ignored what the equations were telling him. Thirteen years later, Edwin Hubble found clear evidence of the universe's expansion. Einstein had missed the opportunity to make the most dramatic scientific prediction in history.
How did Einstein's equations "know" that the universe was expanding when he did not?
If mathematics is nothing more than a language we use to describe the world, an invention of the human brain,
how can it possibly churn out anything beyond what we put in? "It is difficult to avoid the impression that **a miracle confronts us here**," wrote physicist **Eugene Wigner** in his classic 1960 paper "*The unreasonable effectiveness of mathematics in the natural sciences"* (*Communications on Pure and Applied Mathematics*, vol 13, p 1).

The prescience of mathematics seems no less miraculous today. At the Large Hadron Collider at CERN, near Geneva, Switzerland, physicists recently observed the fingerprints of a particle that was arguably discovered 48 years ago lurking in the equations of particle physics.
How is it possible that mathematics "knows" about Higgs particles or any other feature of physical reality? "**Maybe it's because math *is* reality**," says physicist **Brian Greene** of Columbia University, New York. Perhaps **if we dig deep enough, we would find that physical objects like tables and chairs are ultimately not made of particles or strings, but of numbers.**
"These are very difficult issues," says philosopher of science James Ladyman of the University of Bristol, UK, "but it might be less misleading to say that the universe is made of maths than to say it is made of matter."
Difficult indeed. **What does it mean to say that the universe is "made of mathematics"?**

An obvious starting point is to ask what mathematics is made of. The late physicist John Wheeler said that the "**basis of all mathematics is 0 = 0"**. All mathematical structures can be derived from something called "**the empty set**", **the set that contains no elements**. Say this set corresponds to zero; you can then define the number 1 as the set that contains only the empty set, 2 as the set containing the sets corresponding to 0 and 1, and so on. Keep nesting the nothingness like invisible Russian dolls and eventually all of mathematics appears. Mathematician **Ian Stewart** of the University of Warwick, UK, calls this "**the dreadful secret of mathematics: it's all based on nothing**" (*New Scientist*, 19 November 2011, p 44). Reality may come down to mathematics, but **mathematics comes down to nothing at all**.

That may be the ultimate clue to existence - after all, a universe made of nothing doesn't require an explanation. Indeed, mathematical structures don't seem to require a physical origin at all.
"A dodecahedron was never created," says Max Tegmark of the Massachusetts Institute of Technology. "To be created, something first has to not exist in space or time and then exist." A dodecahedron doesn't exist in space or time at all, he says - it exists independently of them. "**Space and time themselves are contained within larger mathematical structures**," he adds. **These structures just exist; they can't be created or destroyed**.

That raises a big question: **why is the universe only made of some of the available mathematics?** "There's a lot of math out there," Greene says. "Today only a tiny sliver of it has a realisation in the physical world. Pull any math book off the shelf and most of the equations in it don't correspond to any physical object or physical process."
It is true that seemingly arcane and unphysical mathematics does, sometimes, turn out to correspond to the real world. **Imaginary numbers**, for instance, were once considered totally deserving of their name, but are now used to describe the behaviour of elementary particles; **non-Euclidean geometry** eventually showed up as gravity. Even so, these phenomena represent a tiny slice of all the mathematics out there.
Not so fast, says **Tegmark. "I believe that physical existence and mathematical existence are the same, so any structure that exists mathematically is also real," he says.**

So what about **the mathematics our universe doesn't use?** "Other mathematical structures **correspond to other universes**," Tegmark says. He calls this the "**level 4 multiverse**", and it is far stranger than the multiverses that cosmologists often discuss. Their common-or-garden multiverses are governed by the same basic mathematical rules as our universe, but Tegmark's **level 4 multiverse operates with completely different mathematics**.
All of this sounds bizarre, but **the hypothesis that physical reality is fundamentally mathematical has passed every test**. "If physics hits a roadblock at which point it turns out that it's impossible to proceed, **we might find that nature can't be captured mathematically,**" Tegmark says. "But it's really remarkable that that hasn't happened. Galileo said that the book of nature was written in the language of mathematics - and that was 400 years ago."
If reality isn't, at bottom, mathematics, what is it? "Maybe someday we'll encounter an alien civilisation and we'll show them what we've discovered about the universe," Greene says. "They'll say, 'Ah, math. We tried that. It only takes you so far. Here's the real thing.' What would that be? It's hard to imagine. **Our understanding of fundamental reality is at an early stage.**"

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INFORMATION THEORY

A universe of information

What we call reality might actually be the output of a program running on a cosmos-sized quantum computer, says **Michael Brooks**

What we call reality might actually be the output of a program running on a cosmos-sized quantum computer:

WHATEVER kind of reality you think you're living in, you're probably wrong. The **universe is a computer**, and **everything that goes on in it can be explained in terms of information processing**.
The connection between reality and computing may not be immediately obvious, but strip away the layers and that is exactly what some researchers think we find. We think of the world as made up of particles held together by forces, for instance, but **quantum theory tells us that these are just a mess of fields we can only properly describe by invoking the mathematics of quantum physics**.
That's where the computer comes in, at least if you think of it in conceptual terms as something that processes information rather than as a boxy machine on your desk. "**Quantum physics is almost phrased in terms of information processing**," says Vlatko Vedral of the University of Oxford. "It's suggestive that **you will find information processing at the root of everything.**"
Information certainly has a special place in quantum theory. The famous uncertainty principle - which states that you can't simultaneously know the momentum and position of a particle - comes down to information. As does entanglement, where quantum objects share properties and exchange information irrespective of the physical distance between them.
In fact, **every process in the universe can be reduced to interactions between particles that produce binary answers**: yes or no, here or there, up or down. That means **nature, at its most fundamental level, is simply the flipping of binary digits or bits, just like a computer**. The result of the myriad bit flips is manifest in **what we perceive as the ongoing arrangement, rearrangement and interaction of atoms - in other words, reality**.

According to **Ed Fredkin** of the Massachusetts Institute of Technology, if we could dig into this process we would find that **the universe follows just one law, a single information-processing rule that is all you need to build a cosmos**. In Fredkin's view, this would be some form of "if - then" procedure; the kind of rule used in traditional computing to manipulate the bits held by transistors on a chip and operate the logic gates, but this time applied to the bits of the universe.
Vedral and others think it's a little more complex than that. Because we can reduce everything in the universe to entities that follow the laws of quantum physics, the universe must be **a quantum computer** rather than the classical type we are familiar with.

One of the attractions of this idea is that it can supply **an answer to the question "why is there something rather than nothing?**". The randomness inherent in quantum mechanics means that **quantum information - and by extension, a universe - can spontaneously come into being**, Vedral says.

Boe: Lawrence M. Krauss a universe from nothing, Simon&Schuster, 2012

For all these theoretical ideas, proving that the universe is a quantum computer is a difficult task. Even so, there is one observation that supports the idea that the universe is fundamentally composed of information. In 2008, the GEO 600 gravitational wave detector in Hannover, Germany, picked up an anomalous signal suggesting that **space-time is pixellated. This is exactly what would be expected in a "holographic" universe**, where **3D reality is actually a projection of information encoded on the two-dimensional surface of the boundary of the universe**
(*New Scientist*, 17 January 2009, p 24).

This bizarre idea arose from an argument over black holes. One of the fundamental tenets of physics is that information cannot be destroyed, but a black hole appears to violate this by swallowing things that contain information then gradually evaporating away. What happens to that information was the subject of a long debate between Stephen Hawking and several of his peers. In the end, Hawking lost the debate, conceding that the information is imprinted on the event horizon that defines the black hole's boundary and escapes as the black hole evaporates. This led theoretical physicists Leonard Susskind and Gerard't Hooft to propose that the entire universe could also hold information at its boundary - with the consequence that our reality could be the projection of that information into the space within the boundary. If this conjecture is true, reality is like the image of Princess Leia projected by R2D2 in *Star Wars*: a hologram.

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CONSCIOUSNESS

How does consciousness fit in?

Some theories hold that reality and consciousness are one and the same.
Is the universe really all inside your head, asks **Michael Brooks**

Some theories hold that reality and consciousness are one and the same. Is the universe really all inside your head:

DESCARTES might have been onto something with "I think therefore I am", **Cogito ergo sum,** but surely "I think therefore you are" is going a bit far? Not for some of the brightest minds of 20th-century physics as they wrestled mightily with the strange implications of the quantum world.

According to prevailing wisdom, **a quantum particle such as an electron or photon can only be properly described as a mathematical entity known as a wave function**. Wave functions can exist as "superpositions" of many states at once.

A photon, for instance, can circulate in two different directions around an optical fibre; or an electron can simultaneously spin clockwise and anticlockwise or be in two positions at once.

When any attempt is made to **observe these simultaneous existences, however, something odd happens: we see only one. How do many possibilities become one physical reality?**

This is the central question in quantum mechanics, and has spawned a plethora of proposals, or interpretations. The most popular is the **Copenhagen interpretation**, which says **nothing is real until it is observed, or measured. Observing a wave function causes the superposition to collapse**.

However, Copenhagen says nothing about **what exactly constitutes an observation**. **John von Neumann** broke this silence and suggested that **observation is the action of a conscious mind**. It's an idea also put forward by **Max Planck**, the founder of quantum theory, who said in 1931, "**I regard consciousness as fundamental. I regard matter as derivative from consciousness**."

That argument relies on the view that **there is something special about consciousness, especially human consciousness**. Von Neumann argued that everything in the universe that is subject to the laws of quantum physics **creates one vast quantum superposition**. **But the conscious mind is somehow different. It is thus able to select out one of the quantum possibilities on offer, making it real - to that mind, at least.**

Henry Stapp of the Lawrence Berkeley National Laboratory in California is one of the few physicists that still subscribe to this notion: we are "**participating observers**" whose minds cause the collapse of superpositions, he says. **Before human consciousness appeared, there existed a multiverse of potential universes**, Stapp says. **The emergence of a conscious mind in one of these potential universes, ours, gives it a special status: reality**.

There are many objectors. One problem is that many of the phenomena involved are poorly understood. "There's a big question in philosophy about whether consciousness actually exists," says Matthew Donald, a philosopher of physics at the University of Cambridge. "When you add on quantum mechanics it all gets a bit confused."

Donald prefers an interpretation that is arguably even more bizarre: "**many minds**". This idea - related to the "many worlds" interpretation of quantum theory, which has each outcome of a quantum decision happen in a different universe - argues that **an individual observing a quantum system sees all the many states, but each in a different mind. These minds all arise from the physical substance of the brain, and share a past and a future, but cannot communicate with each other about the present.**

Though it sounds hard to swallow, this and other approaches to understanding the role of the mind in our perception of reality are all worthy of attention, Donald reckons. "I take them very seriously," he says.

***Michael Brooks** is a consultant forNew Scientist, and author of The Secret Anarchy of Science (Profile/Overlook)*

EPISTEMOLOGY

How can we know reality exists?

Proving whether or not reality is an illusion is surprisingly difficult.

PHILOSOPHERS are not being rude when they describe the approach most of us take as **naive realism**. After all, when they cross the street on the way to work, they **tend to accept implicitly - as we all do - that there is an external reality that exists independently of our observations of it**. But at work, they have to ask: if there is, **how can we know?**
In other words, the question "what exists?" reduces, for what in philosophy passes for practical purposes, to questions such as "**what do we mean by 'know'?**"
Plato had a go at it 2400 years ago, defining "knowledge" as "**justified true belief**". But testing the justification or the truth of beliefs traces back to our perceptions, and we know these can deceive us.
Two millennia later, **René Descartes** decided to work out what he was sure he knew. Legend has it that he climbed into a large stove to do so in warmth and solitude. He emerged declaring that **the only thing he knew was that there was something that was doubting everything**. The logical conclusion of Descartes's doubt is **solipsism**, the conviction that one's own consciousness is all there is. It's an idea that is difficult to refute.
Samuel Johnson's notoriously bluff riposte to the questioning of the reality of objects - "I refute it thus!", kicking a stone - holds no philosophical water. As Descartes pointed out a century earlier, it is impossible to know we are not dreaming.
Nor has anyone had much luck making sense of **dualism** - **the idea that mind and matter are distinct**. One response is that **there is only matter**, making the mind an illusion that arises from neurons doing their thing. The opposite position is "**panpsychism**", which **attributes mental properties to all matter**. As the astrophysicist **Arthur Eddington** expressed it in 1928: "**the stuff of the world is mind-stuff... not altogether foreign to the feelings in our consciousness**".

Boe: my swimming Weltbildhaus

Quite separately, rigorous logicians such as Harvard's Willard Van Orman Quine abandoned the search for a foundation of reality and took "coherentist" positions. **Let go of the notion of a pyramid of knowledge, they argued: think instead of a raft built out of our beliefs, a seaweedy web of statements about perceptions and statements about statements, not "grounded" in anything but hanging together and solid enough to set sail upon. Or even, possibly, to *be* a universe.**

This idea is circular, and it's cheating, say critics of a more foundationist bent. It leads back to the suspicion that there actually is no reality independent of our observations. But if there is - how can we know?

***Mike Holderness** is a writer based in London*

SIMULATION

The future

It's possible that we live in fundamental reality. Future beings almost certainly won't, says **Richard Webb**

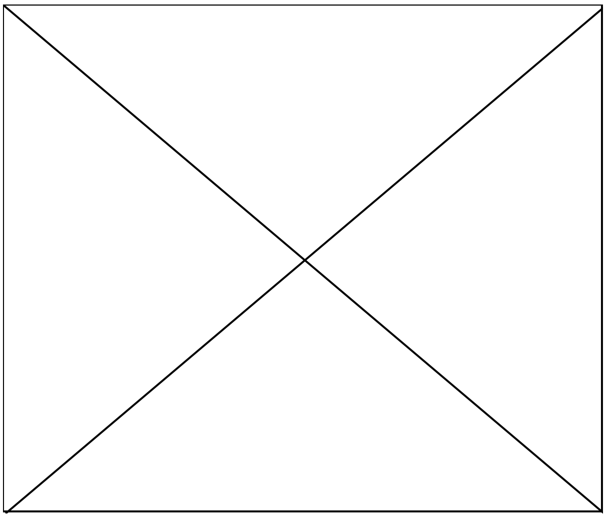
It's possible that we live in fundamental reality. Future beings almost certainly won't:

BEFORE cursing the indolence of today's youth, absorbed in the ever-more intricate **virtual realities** of video games rather than scrumping the ripe fruits of **real reality** outside, consider this: Perhaps they are actually immersing themselves in our future - or even our present.
The story of our recent technological development has been one of ever-increasing computational power. At some future time we are unlikely to be content with constructing tightly circumscribed game worlds. **We will surely begin to simulate everything, including the evolutionary history that led to where we are**.
Flicking the switch on such **a world simulation** could have fundamental ramifications for our concept of reality, according to philosopher Nick Bostrom of the University of Oxford. If we can do it, that makes it likely it has been done before. In fact, given the amount of computing power advanced civilisations are likely to have at their fingertips, it will probably have been done a vast number of times.
So switching on our own simulation will tell us that we are almost undoubtedly in someone else's already. "**We would have to think we are one of the simulated people, rather than one of the rare, exceptional non-simulated people**," says Bostrom.
Probably, anyway. **There has to be a basement level of reality somewhere, in which the "master" simulation exists. It is possible that we live in that reality**. Depending on its laws of physics, **the basement's computing resources are likely to be finite**. And those resources must support not only the master simulation, but any simulations people in that simulation decide to create - perhaps limiting their number, and thus increasing the chances that ours is the base reality.

Either way, **our ability to check our own status, and that of the fundamental physical laws we discover, is limited**.
If we are in the basement, we have nowhere to drill down to, and if we aren't, whether we can depends on the rules put in place by those who built the simulation. **So even if we do end up constructing what could be reality for someone else, we'll probably never know for sure where we ourselves stand. Who's to say video games are the lesser reality?**

***Richard Webb** is a New Scientistfeature editor*

VIDEO



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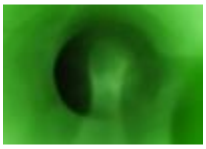

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