New Scientist

WEEKLY 16 July 2016

ROBO FLOP
The AI bubble could be about to burst

THE STONED AGE
Civilisation was born in a haze of smoke

EVERYDAY CHEMO
Cancer drugs in your bathroom cabinet?

INSTANT EXPERT EVOLUTION Part one of our new series

DOES REALITY EXIST WITHOUT US?

Solving the greatest quantum mystery of all

No3082 £3.95 US/CAN$5.95

9 770262 407268 28

DOES ANYTHING EAT JELLYFISH? Fighting off the slime invaders

Quantum of solitude

Our best theory says reality only materialises when we look at it. Can we remove ourselves from the picture, asks Jon Cartwright

WHERE, when you aren't looking at it, is a subatomic particle? A quantum physicist would probably answer: sort of all over the place. An unobserved particle is a wisp of reality, a shimmer of existence – there isn't a good metaphor for it, because it is vague both by definition and by nature. Until you do have a peek. Then it becomes a particle proper, it can be put into words, it is a thing with a place.

That picture seems utterly absurd. Yet many, many experiments exploring the microscopic realm over the best part of a century have reinforced the conclusion that when we're not paying attention, the world is fuzzy and undecided. Only by looking at things, observing them, measuring them, do we make them recognisably "real".

Einstein was unimpressed, pointedly asking whether the moon is not there if no one is looking at it. But then Einstein was always raising pesky objections to quantum theory. For many physicists since it has been a case of swallowing any philosophical qualms. The maths works, there's no real alternative, so get on with it. Shut up and calculate.

Except that, just maybe, there is now an alternative. A new twist on standard quantum theory promises not only to rid reality of its observer problem, but also to answer a host of unresolved issues in cosmology, from the workings of black holes to the nature of dark energy to why time flows in only one direction. "It has the potential of providing a very plausible way out of the problems at stake," says quantum physicist Angelo Bassi at the University of Trieste in Italy. Is it for real?

Quantum theory is the most successful, peerlessly predictive theory of basic reality ever devised. Its current formulation dates from the mid-1920s, when experiments had revealed that things such as electrons could perform diffraction and other feats suggesting they were in many places at the same time, like a wave. If you observed them directly, however, they had a single, definite position like a particle (see "A central mystery", page 33).

The Austrian physicist Erwin Schrödinger devised an equation describing this equivocal behaviour, showing it could be represented by a mathematical entity later known as the wave function. The wave function can't tell you for sure what you will find out about a quantum object when you observe it – whether it's over here, over there, spinning this way, spinning that way. Instead it gives you up-to-date, thoroughly reliable odds on which of many possibilities you will see if you take many measurements of identical objects.

> "The act of observation jolts the shadowy quantum world into definite reality"

So much for the maths. But which of those possible states is a particle actually in, pre-measurement? The most popular answer, formulated around the time Schrödinger produced his equation, is known as the Copenhagen interpretation. Named after the home city of one of its pioneers, Niels Bohr, it says that a particle's state before observation is fundamentally, intrinsically, insurmountably uncertain. If the wave function says a particle could be here and there, then it really is here and there, however hard that is to fathom in terms of everyday experience. Only the act of looking at a quantum object "collapses" its wave function, jolting it from a shadowy netherworld into definite reality.

That was hard to stomach, not least for Schrödinger. To illustrate his concern, he famously imagined a cat sealed inside a box along with a radioactive substance. The quantum wave function for the substance gives you a 50-50 chance an atom will decay within a certain time, in the process detonating a canister of lethal poison.

So, asked Schrödinger, before you look in the box, is the cat alive and dead at the same time? Copenhagen says yes: until you look, there both has and hasn't been a radioactive decay, and the cat's fate is similarly undefined. The Hungarian physicist Eugene Wigner later posed an even more profound question. What finally crystallises the cat's alive or dead state – human consciousness? Did you kill the cat?

Surely that can't be right. Yet in 2011, an informal poll of 33 physicists attending a conference on "Quantum physics and the nature of reality" found that over 40 per cent accepted the Copenhagen view, while the ›

DAVIDE PARERE

"Believe the most popular variant of quantum theory, and our universe could never have existed"

others could not agree on an alternative. Theorist Sean Carroll called it perhaps the "most embarrassing" poll in physics.

For Daniel Sudarsky, a physicist at the National Autonomous University of Mexico (UNAM) in Mexico City, it is all the more embarrassing when you start thinking outside the cat's box and consider the universe at large. According to cosmologists, the early universe was a featureless blob, into which particles began to materialise at random. Particles that just happened to materialise closer together began to clump together through gravity – forming the seeds of today's stars and galaxies.

All well and good, except that there were no primordial observers to collapse the wave functions of those initial particles and create their uneven distributions in the first place. Believe the most popular interpretation of quantum theory, and the star-filled universe that we live in could never have existed.

It was this conundrum that spurred Sudarsky into action in the early 2000s. "I wanted to describe the universe 13 billion years ago, when there certainly weren't any sentient beings, unless you want to invoke God," he says. "Which we don't."

Alternatives to the Copenhagen picture fall broadly into three categories. One is that the wave function picture is not a complete description of reality. Decades of rigorous experiments have shown, however, that any additional bells and whistles would have to operate faster than light, breaking perhaps the most fundamental law of physics. A second possibility is that wave function collapse doesn't happen at all; every possible outcome of an observation actually comes to pass in its own separate universe. This is the "many worlds" interpretation (see "Who killed Schrödinger's cat?", page 34).

The many worlds theory also creates almost as many philosophical problems as it solves, so Sudarsky began with a third option: that wave functions are real things and do indeed collapse – but randomly, by themselves. "Something like a measurement occurs, but without anybody actually measuring," says Sudarsky. It doesn't need a human observer, so this process is known as an objective collapse.

Tweaking Schrödinger

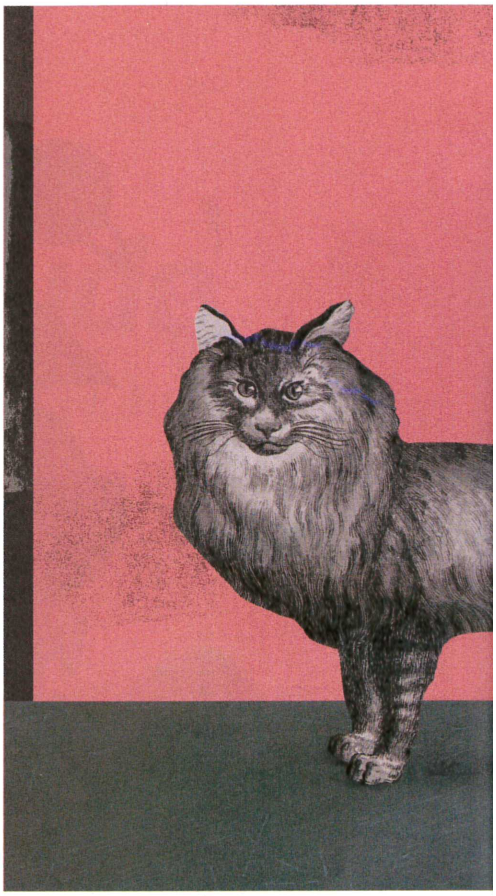
Objective collapse would be rare, but catching. Wait for a single particle's wave function to collapse and you could be waiting longer than the age of the universe. Group many particles together, however, and the chance swiftly escalates. With a few billion particles, you might only have to wait a few seconds for one wave function to collapse – and for that to set the rest off.

Objective collapse theory was first put forward in the 1970s by Philip Pearle at Hamilton College in New York, and later refined by Giancarlo Ghirardi and Tulio Weber at the University of Trieste and Alberto Rimini at the University of Pavia, Italy. Their goal was to tweak Schrödinger's equation so that the wave function evolves naturally, without an observer, from a mix of states into a single, well-defined state. To do so, they added a couple of extra mathematical terms: a non-linear term, which rapidly promotes one state at the expense of others, and a stochastic term, which makes that happen at random.

At least superficially, these tweaks can explain quite a lot that's inexplicable about quantum theory. We never see ghostly quantum effects in large objects such as cats or the moon because, with so many interacting particles, their wave functions readily collapse or else never form. And in the early universe, as Sudarsky and physicist-philosopher Elias Okon, also at UNAM, showed a decade ago, it was only a matter of time before the wave functions of matter collapsed into an uneven distribution from which stars and galaxies could form, God or no God (see "How did it all begin?", left).

Objective collapse theory has an intuitive explanation for the observer problem, too. The human body has upwards of one billion billion billion atoms, all of which contain yet more constituent particles. An observer meddling with even a carefully isolated quantum apparatus will inevitably become quantum-entangled with it, and their collapsed wave function then causes any uncollapsed wave function in the vicinity to collapse too.

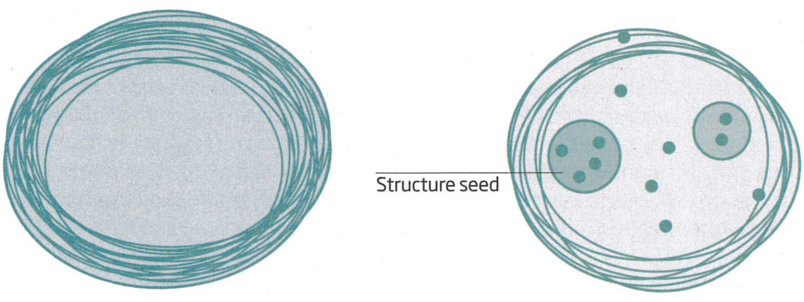
Yet the idea didn't catch on. For a start, it's only an "effective" theory. It states that wave functions collapse randomly and provides a mathematical description, but doesn't explain



How did it all begin?

In our standard cosmological picture, the seeds of stars and galaxies were sown in the early universe by tiny quantum fluctuations in the density of matter. But standard quantum theory doesn't allow this

Standard quantum picture | **Objective collapse picture**

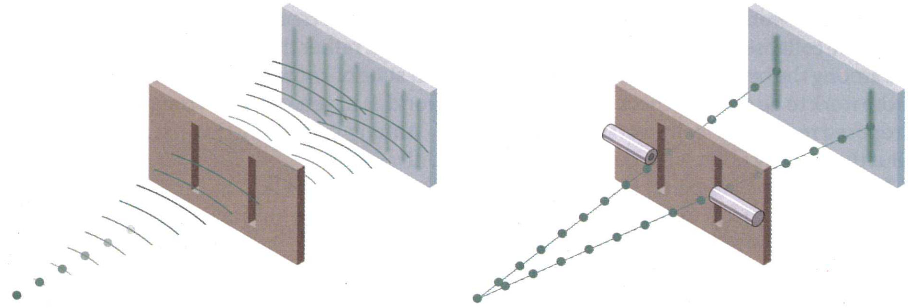


The locations of individual particles are uncertain. There's no observer to localise them to any one place - **no structures form**

Particles localise spontaneously, forming clusters that ultimately give rise to large-scale structures

A central mystery

The classic double slit experiment seems to suggest quantum objects such as electrons are sometimes **particles**, sometimes **waves** – and we decide which guise they take



A stream of single electrons is fired at two slits and measured on a screen behind. An interference pattern forms, as if each electron were a **wave** that passed through both slits at once

Measure the electrons first at the slits, however, and you see individual **particles** passing through one slit or the other – and the interference pattern on the screen disappears

why. There are possible explanations – theorist Roger Penrose at the University of Oxford has suggested that gravity drives the process, for instance – but no consensus. The tweaked Schrödinger equation was also not relativistic; it did not work for particles moving at close to the speed of light, a basic requirement of any modern theory.

That began to change around five years ago, when theorists including Daniel Bedingham of the University of Oxford and Roderich Tumulka of Rutgers University in New Jersey formulated the first relativistic objective collapse models. Still the idea had few takers. For Tumulka, that's because persuading physicists to go for any option besides the Copenhagen interpretation is like Copernicus trying to persuade people in the 16th century to give up Ptolemy's Earth-centric view of the universe. "The difference is that Ptolemy's theory made perfect sense. It just happened not to be right," he says. "But Copenhagen quantum mechanics is incoherent, and thus is not even a reasonable theory to begin with."

Work that Sudarsky and his collaborators have been doing recently might begin to turn the tide. It shows that objective collapse might explain not only how structure began to appear in the universe, but a host of other cosmological problems, too.

Take black holes. These monsters, created by Einstein's theory of gravity, general relativity, crush everything that comes their way – light, matter, information. For nigh on 40 years, physicists have been especially perplexed by the information bit. If all the information about a particle is contained within its wave function, and the only thing that can collapse a wave function is – according to the Copenhagen school, at least – an observer, who is that observer inside a black hole?

No problem in objective collapse theory: no observer is required. Last year, Sudarsky and Okon calculated that the rate of random wave function collapse given by their theory agrees with the information loss rate predicted for black holes (*Foundations of Physics*, vol 44, p 114).

"Perhaps it might solve the biggest cosmic conundrum of all: dark energy"

Spontaneous wave function collapse makes stuff, too. When a wave function disappears, something new appears in its place – a definite position, a piece of information, a tick of energy. Each collapse can only generate a minuscule amount of energy, so we wouldn't notice it on any everyday scale. But in the universe as a whole, this energy creation could be rather significant – and perhaps solve the biggest cosmological conundrum of all.

That conundrum is dark energy, the unknown entity that observations since the 1990s have indicated is accelerating the expansion of the universe. Standard quantum theory supplies what seems at first glance a ready source of dark energy. Quantum uncertainty means that even the nothing of free space has a small chance of containing something, in the form of energy. But work out how much of this energy there should be, and you come up with way too much. About 10^{120} times too much.

Together with theorists Thibaut Josset and Alejandro Perez at the University of Marseille in France, Sudarsky showed earlier this year that energy creation through objective collapse might provide a closer fit. A big caveat is that the process would be compatible only with a slightly modified form of general relativity; accept that, and you're in business. Or not quite. "Our rough calculations came surprisingly close," says Sudarsky. "But with the wrong sign." Their dark energy was pulling the universe together, not causing it to fly apart (arxiv.org/abs/1604.04183).

A big detail, you might say. But the work deliberately ignored the collapse effects of myriad energetic particles whizzing about at near light speed in the early universe, as theories of relativistic objective collapse simply aren't refined enough yet. Take those into account, says Sudarsky, and "things could come out all right". In a more speculative paper this year, he and Okon also claim that objective collapse can explain why the universe started in a state of exceptionally low disorder, or entropy, that has been › increasing ever since. This continuous entropy increase matters to us – it is intimately connected to what we perceive as the one-way flow of time (arxiv.org/abs/1602.07006).

Bassi, who works independently on objective collapse models, thinks these ideas are among the best out there. "There is much more work to be done, to check whether the proposed resolution really works," he says. "But the starting point is encouraging."

But what of the doubters? Matt Leifer, a quantum theorist at Chapman University in Orange, California, acknowledges that objective collapse might untie some philosophical knots in quantum theory, but is sceptical. "I am glad there are people working on the models seriously, but they have always seemed a little ad hoc to me," he says. He believes that treating wave functions as real entities, rather than just things that represent our state of knowledge about the quantum world, is in general "the wrong place to start".

Antony Valentini, a theorist at Clemson University in South Carolina, is more positive. "Too much work in quantum foundations is cut off from the big questions facing physics and cosmology," he says. "This work is still at an exploratory stage, but the ideas are interesting and plausible. I wish more people were looking at this sort of thing."

The test of any good theory is, of course, experiment. The reason we believe standard quantum theory is its ability to explain, at least mathematically, experiments showing quantum objects behaving like waves in one situation and particles in another. These effects have now been observed with objects far larger than single particles – the record, set in 2013 at the University of Vienna in Austria, involves complex molecules some 20 million times the mass of the electron.

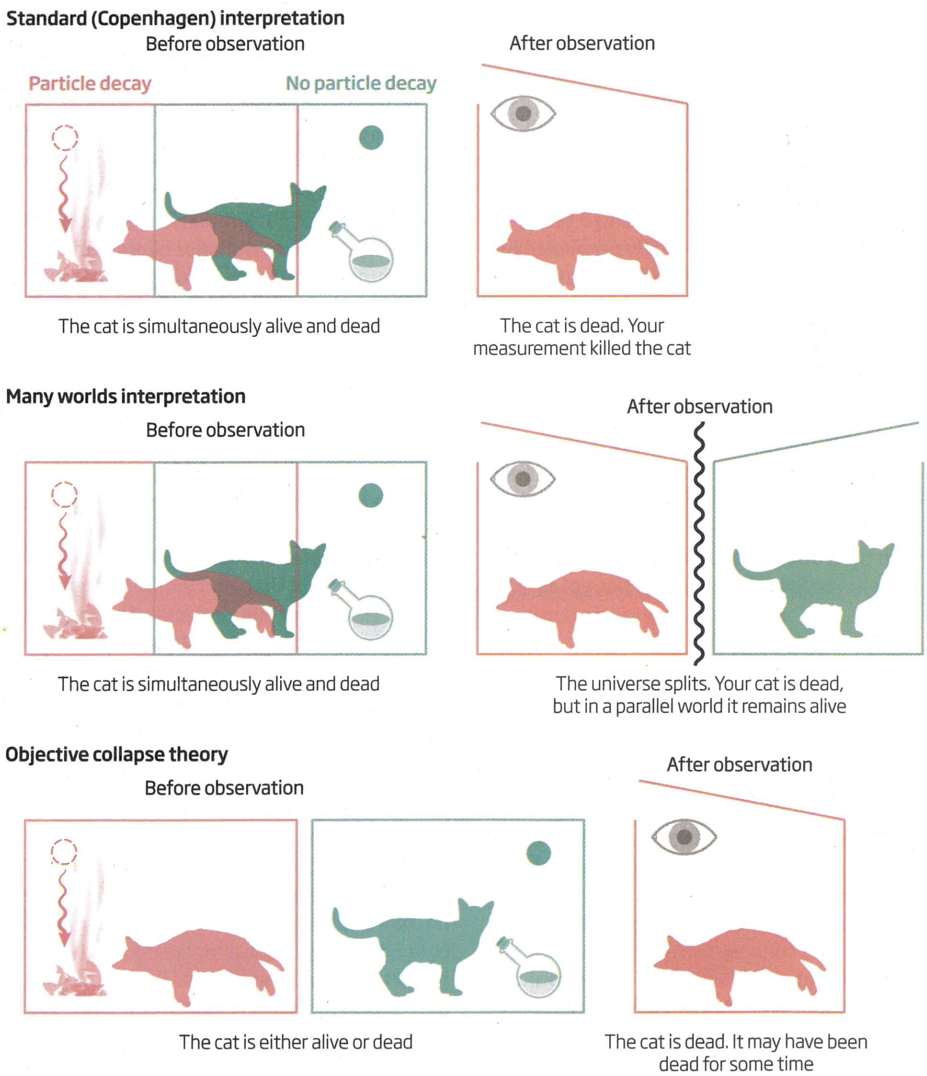
If Sudarsky is right, there is a natural size limit, after which objects begin to collapse spontaneously, removing the wave-like behaviour. Common sense tells us this threshold must be far smaller than that of everyday observations. "It should occur much before I send a cat through the apparatus," says Sudarsky. More exact experiments should be able to test the predictions of various objective collapse models. Hendrik Ulbricht at the University of Southampton in the UK thinks such tests could be performed within a decade, by making silica beads as massive as 20 billion electrons pass through and interfere at "slits" made of laser light.

An alternative test is to look for the excess energy that objective collapse theories predict should arise from spontaneous wave function collapse. Though near infinitesimal here on Earth, this should still be present as an all-pervading background noise that would disrupt the most sensitive experiments, like static muddying an analogue radio broadcast. In March this year, a team in Italy, including Bassi, cooled a vibrating cantilever to within a whisker of absolute zero and found deviations in its regular to-ing and fro-ing only from the tiny remaining thermal energy, nothing more. That established an upper bound on objective collapse noise, ruling out one particular incarnation, but leaving most intact (*Physical Review Letters*, vol 116, p 090402).

For Sudarsky, this newfound testability provides an impetus to make objective collapse theory even more persuasive. It's an uphill battle to win hearts and minds in the face of one of the most successful theories ever devised. But then, understanding why the simple act of looking appears to create the world around us would be a big prize, says Sudarsky. "It's pushing us to solve one of the biggest mysteries we've had for a long time," he says. ■

Who killed Schrödinger's cat?

This thought experiment illustrates the supposed absurdity of quantum theory, with objects existing in uncertain states before they are observed. Within a box, a random radioactive particle decay may break a vial of poison gas that kills a cat. If the cat is dead when you open the box, what has happened?



Jon Cartwright is a freelance journalist based in Bristol, UK