Quantum shadows: The mystery of matter deepens

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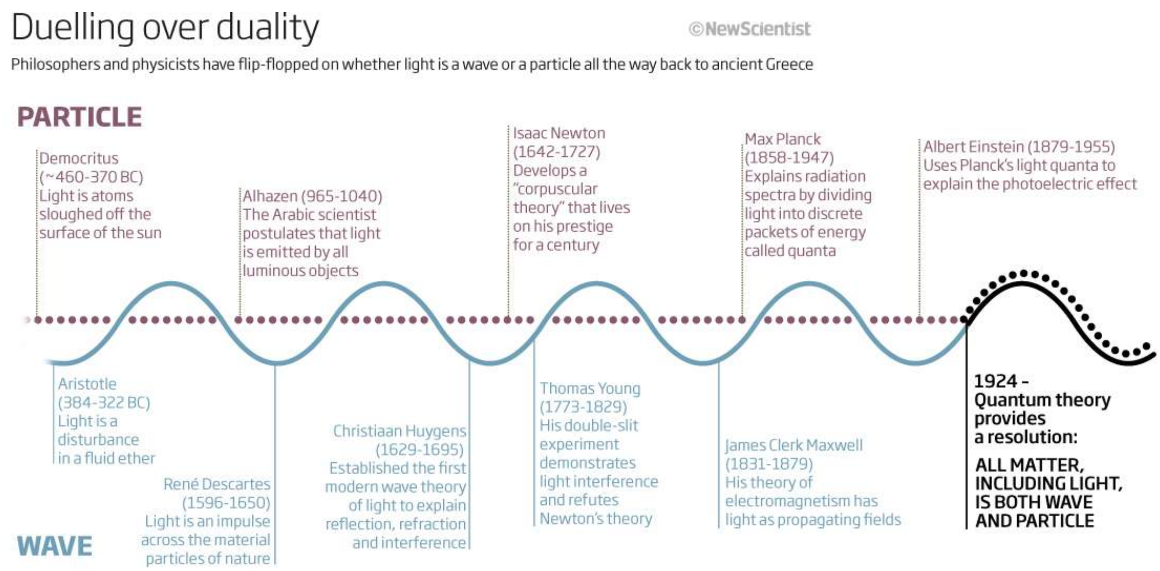
Forget particles and waves. When it comes to the true guise of material reality, what's out there is beyond our grasp

"IF YOU haven't found something strange during the day," John Archibald Wheeler is said to have remarked, "It hasn't been much of a day." But then, strangeness was Wheeler's stock in trade. As one of the 20th century's leading theoretical physicists, the things he dealt with every day - the space- and time-bending warpings of Einstein's relativity, the fuzzy uncertainties and improbabilities of quantum physics - were the sort to boggle the minds of most mere mortals.

Even so, one day in 1978 must have been quite something for Wheeler. That was when he first lit on a very strange idea to test how photons might be expected to behave. Half a century earlier, quantum physics had produced the startling insight that light - everything in the quantum world, in fact - has a dual character. Sometimes it acts as if made of discrete chunks of stuff that follows well-defined paths - particles. At other times, it adopts the more amorphous, space-filling guise of a wave. That led to a question that exercised Wheeler: what makes it show which side, and when?

It took a while for the test Wheeler devised to become experimental reality. When it finally did, the answer that came was strange enough. Now, though, the experiment has been redone with a further quantum twist. And it's probably time to abandon any pretence of understanding the outcome. Forget waves, forget particles, forget anything that's one or the other. Reality is far more inscrutable than that.

For centuries, light has illuminated our ideas of the material world. The debate about its nature, wave or particle, goes back to the philosophers of ancient Greece, and has featured luminaries such as Newton, Descartes and Einstein on one side or the other. By the dawn of the 20th century, the result was best described as a scoring draw, with both sides having gathered significant support (see diagram).



The central mystery

Quantum physics broke the deadlock essentially by saying that everyone was right. The apparent proof comes with a quantum version of an experiment first performed by the English physicist Thomas Young in 1803, ironically to support the wave theory of light. Young shone light on a screen with two tiny, parallel slits in it. On another screen a distance behind the first, he saw alternating vertical fringes of light and dark that seemed incontrovertible proof of light's wave character. Water waves passing through two narrow openings in a sea wall diffract and interfere in a similar way, sometimes constructively amplifying and sometimes destructively reducing each other beyond.

The strangeness starts when you lower the light intensity to the point at which only a single photon enters the experimental setup at any one time. In 1905, Einstein had strongly suggested that a single photon is a particle, and indeed, place a detector at one or other of the slits and you hear the beep, beep of single particles hitting it. But remove the particle detector and place a light-collecting screen - a kind of long-exposure camera - a distance behind the slits, and the same pattern of light and shade that Young had observed slowly builds up. It is as if each photon is an interfering wave that passes simultaneously through both slits. The same happens with other quantum particles: electrons, neutrons, atoms and even 60-carbon-atom buckyballs.

For Niels Bohr, the great Danish pioneer of quantum physics, this "central mystery" was nothing less than a principle of the new theory, one he called the complementarity principle. Quantum objects such as photons simply have complementary properties - being a wave, being a particle - that can be observed singly, but never together. And what determines which guise an object adopts? Bohr laid out a first outline of an answer at a grand gathering of physicists at the Istituto Carducci on the shores of Lake Como in Italy in September 1927: we do. Look for a particle and you'll see a particle. Look for a wave and that's what you'll see.

The idea that physical reality depends on an observer's whim bothered the likes of Einstein no end. "No reasonable definition of reality could be expected to permit this," he huffed in a famous paper he co-authored in 1935 with Boris Podolsky and Nathan Rosen (*Physical Review*, vol 47, p 777). Einstein favoured an alternative idea of an underlying but as-yet inaccessible layer of reality containing hidden influences that "told" the photon about the nature of the experiment to be performed on it, changing its behaviour accordingly.

There is more to this than wild conspiracy theory. Imagine an explosion that sends two pieces of shrapnel in opposite directions. The explosion obeys the law of conservation of momentum, and so the mass and velocity of the pieces are correlated. But if you know nothing of momentum conservation, you could easily think that measuring the properties of one fragment determines the properties of the other, rather than both being set at the point of explosion. Was a similar hidden reality responsible for goings on in the quantum world?

This is where Wheeler's thought experiment came in. Its aim was to settle the issue of what told the photon how to behave, using an updated version of the double-slit experiment. Photons would be given a choice of two paths to travel in a device known as an interferometer. At the far end of the interferometer, the two paths would either be recombined or not. If the photons were measured without this recombination - an "open" interferometer - that was the equivalent of putting a detector at one or other of the slits. You would expect to see single particles travelling down one path or the other, all things being equal, splitting 50:50 between the two (see "Neither one nor the other").

Alternatively, the photons could be measured after recombination - a "closed" setting. In this case, what you expect to see depends on the lengths of the two paths through the interferometer. If both are exactly the same length, the peaks of the waves arrive at the same time at one of the detectors and interfere constructively there: 100 per cent of the hits appear on that detector and none on the other. By altering one path length, however, you can bring the wave fronts out of sync and vary the interference at the first detector from completely constructive to totally destructive, so that it receives no hits. This is equivalent to scanning across from a bright fringe to a dark one on the interference screen of the double slit experiment.

Wheeler's twist to the experiment was to delay choosing how to measure the photon - whether in an open or a closed setting - until after it had entered the interferometer. That way, the photon couldn't possibly "know" whether to take one or both paths, and so if it was supposed to act as a particle or a wave.

Or could it?

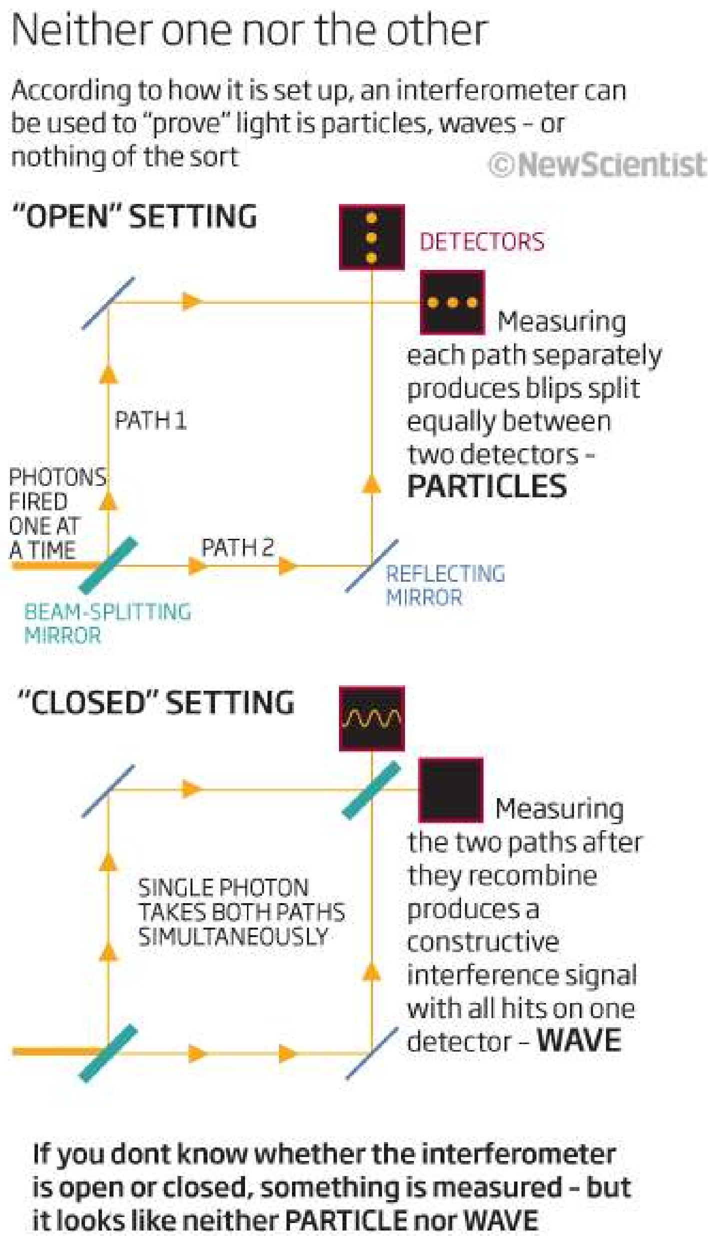
It was almost three decades before the experiment could actually be done. To make sure there was no hidden influence of the kind favoured by Einstein, you needed a very large interferometer, so that no word of the choice of measurement could reach the photon, even if the information travelled at light speed (anything faster was expressly forbidden by Einstein's own theory of relativity). In 2007, Alain Aspect and his team at the Institute of Optics in Palaiseau, France, built an interferometer with arms 48 metres long. The result? Whenever they chose at the last instant to measure the photons with a closed interferometer, they saw wave interference. Whenever they chose an open interferometer, they saw particles (*Science*, vol 315, p 966).

There was no getting round it. Wave and particle behaviours really do seem to be two sides of one coin representing material reality. As to which way it flips - well, you decide. "Isn't that beautiful?" said Aspect in a public lecture *at the Physics@FOM conference* in Veldhoven, the Netherlands, last year. "I think there is no other conclusion to draw from this experiment."

Unless, of course, you make things even stranger. In December 2011, Radu Ionicioiu of the Institute for Quantum Computing in Waterloo, Canada, and Daniel Terno of Macquarie University in Sydney, Australia, proposed extending Wheeler's thought experiment (*Physical Review Letters*, vol 107, p 230406). Their new twist was that the decision of how to measure the photon, as a particle or as a wave, should itself be a quantum-mechanical one - not a definite yes or no, but an indeterminate, fuzzy yes-and-no.

Infinite shades of grey

There is a way to do that: you use light to control the detector designed to probe the light. First you prepare a "control" photon in a quantum superposition of two states. One of these states switches the interferometer to an open, particle-measuring state, and the other to a closed, wave-measuring state. Crucially, you only measure the state of the control photon after you have measured the experimental "system" photon passing through the interferometer. As far as you are concerned, the system photon is passing through an interferometer that is both open and closed; you don't know whether you are setting out to measure wave or particle behaviour (see diagram). So what do you measure?



This time, it took only a few months for the experimentalists to catch up with the theorists. But when three independent groups, led by Chuan-Feng Li at the University of Science and Technology of China in Hefei, Jeremy O'Brien at the University of Bristol, UK, and Sébastien Tanzilli at the University of Nice, France, performed different versions of the experiment last year, the results were unnerving - even to those who consider themselves inured to the weirdnesses of quantum physics (*Nature Photonics*, vol 6, p 600; *Science*, vol 338, p 634 and p 637).

The answer is, what you see depends on the control photon. If you look at the measurements of the system photons without ever checking the corresponding measurements of the control photons - so never knowing what measurement you made - you see a distribution of hits on the two detectors that is the signature neither of particles or waves, but some ambiguous mixture of the two. If particle is black and wave is white, this is some shade of grey.

Do the same, but this time looking at the control photon measurements as well, and it is like putting on a pair of magic specs. Grey separates clearly into black and white. You can pick out the system photons that passed through an open interferometer, and they are clearly particles. Those that passed through a closed interferometer look like waves. The photons reveal their colours in accordance with the kind of measurement the control photon said you made.

It gets yet stranger. Quantum mechanics allows you to put the control photon not just in an equal mix of two states, but in varying proportions. That is equivalent to an interferometer setting that is, say, open 70 per cent of the time and closed 30 per cent of the time. If we measure a bunch of system photons in this configuration, and look at the data before putting on our magic specs, we see an ambiguous signature once again - but this time, its shade of grey has shifted closer to particle black than wave white. Put on the specs, though, and we see system photons 70 per cent of which have seemingly - but clearly - behaved as particles, while the remaining 30 per cent acted as waves.

In one sense, the results leave Bohr's side of the argument about quantum reality stronger. There is a tight correlation between the state of the control photon, representing the nature of the measurement, and the system photon, representing the state of reality. Make for more of a particle measurement, and you'll measure something more like a particle, and vice versa. As in earlier experiments, a hidden-reality theory *à la* Einstein cannot explain the results.

But in another sense, we are left grappling for words. "Our experiment defies the conventional boundaries set by the complementarity principle," says Li. Ionicioiu agrees. "Complementarity shows only the two ends, black and white, of a spectrum between particle and wave," he says. "This experiment allows us to see the shades of grey in between."

So, has Bohr been proved wrong too? Johannes Kofler of the Max Planck Institute of Quantum Optics in Garching, Germany, doesn't think so. "I'm really very, very sure that he would be perfectly fine with all these experiments," he says. The complementarity principle is at the heart of the "Copenhagen interpretation" of quantum mechanics, named after Bohr's home city, which essentially argues that we see a conflict in such results only because our minds, attuned as they are to a macroscopic, classically functioning cosmos, are not equipped to deal with the quantum world. "The Copenhagen interpretation, from the very beginning, didn't demand any 'realistic' world view of the quantum system," says Kofler.

The outcomes of the latest experiments simply bear that out. "Particle" and "wave" are concepts we latch on to because they seem to correspond to guises of matter in our familiar, classical world. But attempting to describe true quantum reality with these or any other black-or-white concepts is an enterprise doomed to failure.

It's a notion that takes us straight back into Plato's cave, says Ionicioiu. In the ancient Greek philosopher's allegory, prisoners shackled in a cave see only shadows of objects cast onto a cave wall, never the object itself. A cylinder, for example, might be seen as a rectangle or a circle, or anything in between. Something similar is happening with the basic building blocks of reality. "Sometimes the photon looks like a wave, sometimes like a particle, or like anything in between," says Ionicioiu. In reality, though, it is none of these things. What it is, though, we do not have the words or the concepts to express.

Now that is strange. And for quantum physicists, all in a day's work.

***Anil Ananthaswamy** is a consultant for New Scientist*

This comment breached our terms of use and has been removed.

No, Einstein & Co Will Be Proved Right Eventually

Fri Jan 04 14:32:40 GMT 2013 by **Julian Mann**

Photons are actually particles, not waves. As I have said before, when we see waves, it is because we see a particle travelling in "Backward Time" This was hinted to by Richard Feynman, when he said that a Positron was merely an electron travelling backwards in time. Also this must be obvious from the numerous double-slit type of experiments, when waves always resolve into particles, when detectors are strategically placed at critical points in the apparatus. THERE IS NO WAVE-PARTICLE DUALITY, that was a fudge to try and explain results scientists didn't really understand. We cannot be living in a reality in which the Observer determines fundamental properties of the world. The World existed long before we or any other observer set foot on the planet. I cannot see how the universe in which we live could retain it's Physical Integrity, if it were subject to the whim of random observers and experimenters

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No, Einstein & Co Will Be Proved Right Eventually

Sat Jan 05 03:11:03 GMT 2013 by **Damir Ibrisimovic**
http://home.pacific.net.au/~damir-dsl/

Dear Julian,

The issue of observer is trickier than a simple: "We cannot be living in a reality in which the Observer determines fundamental properties of the world." While there are fundamental properties of the world, the question is: Are these properties exactly as we say there are?

In simple terms, if we do not know the potential perceptual and other biases we may have --- we are in danger of projecting our own biases as "fundamental properties of the world". That is why I have raised here a legitimate concern (now deleted). While it might be irritable to some, an open debate is long overdue...

The simple fact is: All physicists were and are humans. It is useless and counterproductive to pretend otherwise. This might take some cherished gloss from the abstract observer --- but only a better understanding of ourselves can bring us closer to the ideal...

I will illustrate this with 17th century picture of cause and effect driven universe. Back then, everything seemed to be governed by the principle --- everything seemed to have been predetermined = determinism. However, the closer we looked the principle seemed more elusive. So, we added probabilistic to the picture = probabilistic/deterministic universe. In essence, we have added a little devil that spoils otherwise perfectly predictable outcomes...

Nowadays we are simulating orbital resonances (many-body problem) and one would expect causality (as principle) to be revisited. Instead, we still have maintenance of this habitual thought expressed in the ridiculous contradiction in terms: Deterministic Chaos. Now, I do not claim that similar phenomena are not followed by other kinds of similar phenomena --- I only claim that we need a fresh look at the causality phenomenon...

Have a nice day,

Damir Ibrisimovic

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No, Einstein & Co Will Be Proved Right Eventually

Sat Jan 05 18:13:56 GMT 2013 by **Joe Bloggs**

"In simple terms, if we do not know the potential perceptual and other biases we may have --- we are in danger of projecting our own biases as "fundamental properties of the world".

Yes, that is a real danger. Because of the way conceptuality grows, it is not part of the remit of physics to consider the nature of the system of understanding that it employs, and whose rationale it endorses. Such a consideration has to be meditative, and of course meditation isn`t science; meditative awareness is where science starts from, in the immediate reality, which is progressively hidden by the increasing status of process. Democritus had something to say about that, a few thousand years ago.

Hey, you weren`t selling Swiss watches, were you ?

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No, Einstein & Co Will Be Proved Right Eventually

Sat Jan 05 22:34:17 GMT 2013 by **Damir Ibrisimovic**
http://home.pacific.net.au/~damir-dsl/

Dear Joe,

Two and a half thousand years ago, Democritus did not have what we have now. In short, cognitive psychology now maps subjective experiences with scans of brain activity. Together with other methods, we can now discern how "mere" humans see and think about world. Perceptual and other biases are also exposed. Epigenetics and anthropology are also offering their insights...

In my opinion, replacing the idealised picture of observer with a more realistic one --- might help to resolve many quandaries about which physicists are now wasting their time...

And no, I was not selling watches. Neither was I rude. The only reason I can think of is that this issue was irritable to someone...

Have a nice day,

Damir Ibrisimovic

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No, Einstein & Co Will Be Proved Right Eventually

Mon Jan 07 15:50:27 GMT 2013 by **Markjb**

The observer means anything else that exists - or is 'observed' by things that are observed / exist. Relativism is the only thing we can be sure of..

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No, Einstein & Co Will Be Proved Right Eventually

Mon Jan 07 17:39:36 GMT 2013 by **Lee Borrell**
http://leebor2.100webspace.net/Zymic/index.html

Anyone who thinks photos are JUST particles obviously has little understanding of physics and is failing to follow the duplicity involved. I agree that the odds are the observer is not altering reality - we are just failing to understand it in terms of WAVES and PARTICLES,both of which are features man has given TO the universe. The actual property that defies measurement is probably some other process that we have not got to.But to say "just particles" is absurd.

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There Is Another Natural Explanation

Sun Jan 06 08:20:03 GMT 2013 by **Dirk Pons**
http://cordus.wordpress.com/

To say that there is no other conclusion to draw from this experiment is simply an uncritical acceptance of QMs founding premise that particles are zero dimensional points. Instead we have to allow the possibility that particles may have internal structure. This means being open to a non-local hidden-variable (NLHV) design, which by-the-way is not precluded by the Bell inequalities.

This is an unorthodox approach, but we think we have found a workable solution with one particular NLHV structure. This gives very exciting results and interesting new possibilities. It gives natural explanations to many problematic phenomena in fundamental physics, including wave-particle duality, entanglement, and contextual measurement (which is the problem explored in this New Scientist article). It offers explanations for many other effects too, such as asymmetrical baryogenesis (i.e. why the universe is made of matter rather than antimatter). You can read our paper on the resolution of wave-particle duality here http://physicsessays.org/doi/abs/10.4006/0836-1398-25.1.132, or the preprint here http://vixra.org/abs/1106.0027. We call this unorthodox idea the Cordus conjecture. See our blog or the physics archive http://www.vixra.org for more explanations.

Coming back to the NS article, if the cordus explanation is correct, then indeed the photon is neither a particle nor a wave, but rather a specific structure with discrete fields. We can explain why its behaviour depends on how it is observed, which is also fascinating. When looked at from the Cordus perspective, the behaviour of the photon is perfectly natural. The weirdness is not because reality is weird, but only because quantum mechanics is not a true description of reality: it simply does not have the necessary concepts. We now think we have both the words and the concepts to express what the photon really is. At least at the next deeper level of physics below QM.

Read the paper and tell us whether you think we have got this right or wrong.

Thank you

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There Is Another Natural Explanation

Sun Jan 06 21:53:55 GMT 2013 by **David Allen**

I like that you are looking for better ways to describe reality, but it isn't clear to me that the Cordus conjecture improves upon the existing theories.

Specifically the conjecture doesn't seem to lead to any new predictions that allow it to be verified and other possible models excluded (including existing theories of physics); instead of solving mysteries like the wave-particle duality, and wave-function collapse, it appears to transform them into new mysteries like 'Why would each reactive end "choose" to always go through different slits instead of both going through the same slit sometimes?'; and it doesn't seem to provide a perspective that makes existing problems easier to solve.

So, while I would encourage this kind of exploration, it does not appear to me that the Cordus conjecture provides any benefit over current theory or pragmatics.

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Can Objectivity Be A Man-made Concept?

Sun Jan 06 23:57:09 GMT 2013 by **Anonymyx**

How can objective reality exist if our perception of the world is through a subjective scope?

I don't think us as human beings can realistically experience objective reality, or ever determine whether or not it exists.

I believe the only true path, or existence of objective reality is death, nothingness.

Perhaps the subjective experience is under-estimated?

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Can Objectivity Be A Man-made Concept?

Mon Jan 07 02:09:53 GMT 2013 by **David Allen**

"How can objective reality exist if our perception of the world is through a subjective scope?"

Objective reality can perhaps exist in terms of itself. This is just another way of saying that the universe generates its own existence, or that it is a thing-in-itself.

If you insist on a universal status for objectivity then the only universally valid perspective is the universe itself. Any subset of the universe therefore can only provide a subjective perspective--so yes, human beings can only experience subjective reality and only guess at objective reality, but never identify it conclusively.

However, the concept of objectivity in science does not refer to true universal objectivity, but objectivity from the perspective of a standard scientific model. Valid claims made within that model may appear to be universally valid (hence objective), but these claims inherently depend upon the model itself and so are actually subjective.

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