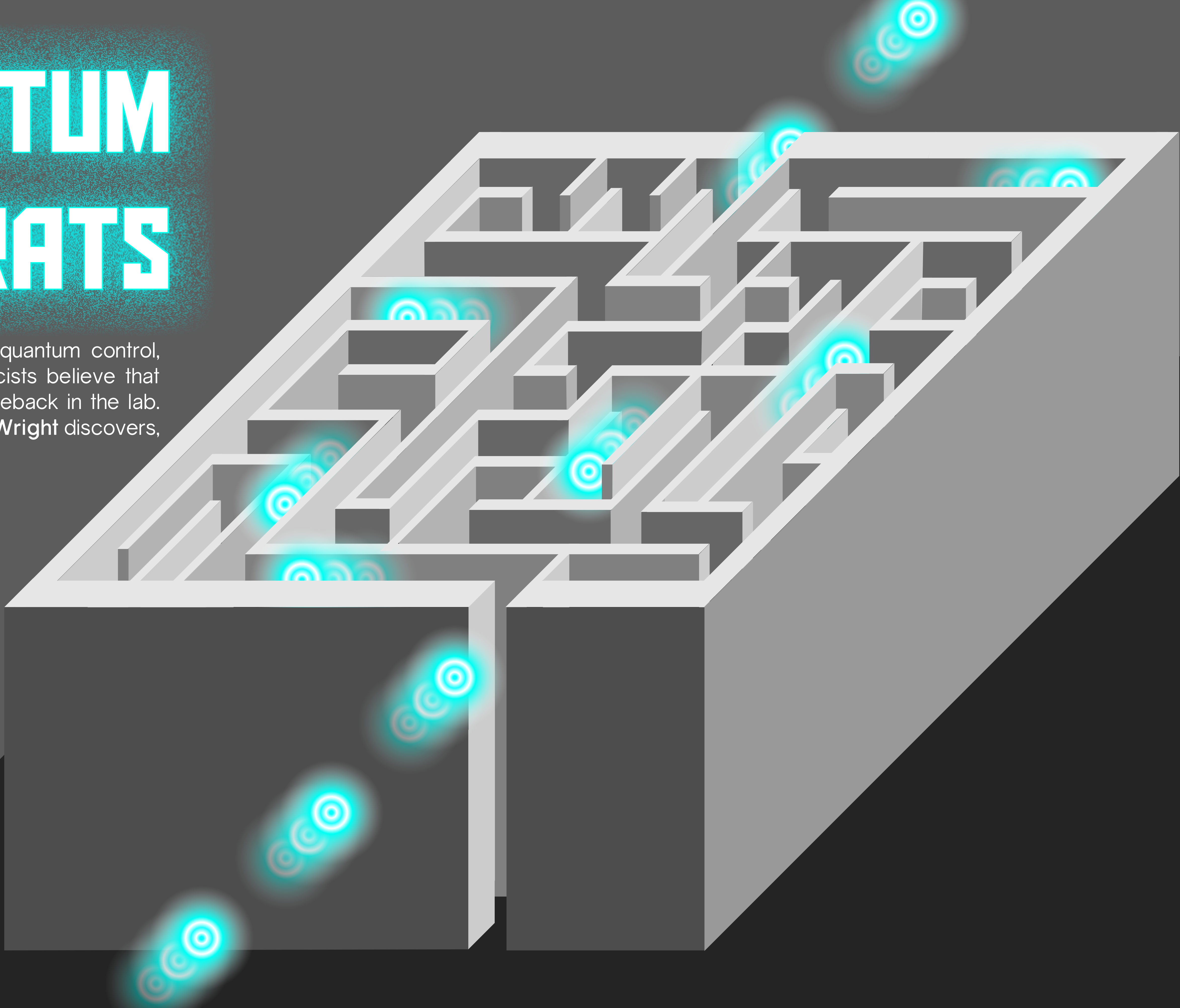
QUANTUM LAB RATS

With new advances in quantum control, one group of UK physicists believe that mazes will make a comeback in the lab. Except this time, **Lewis Wright** discovers, it won't be mice inside...



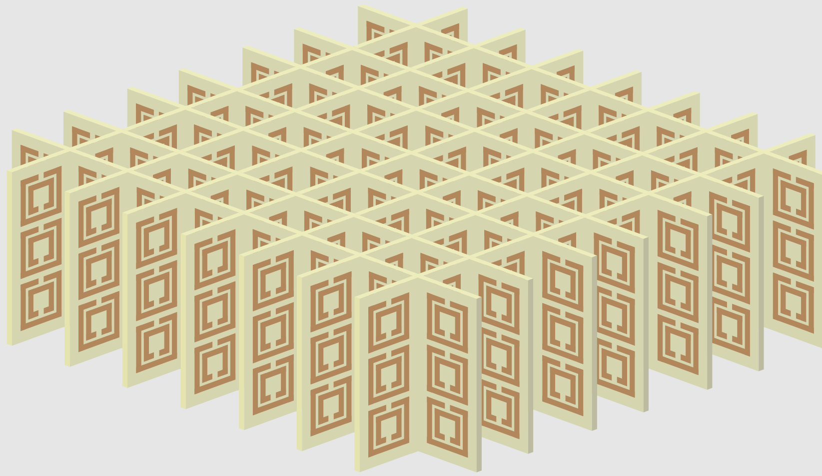
There is little doubt that quantum physics is the great academic achievement of the 20th century. Such intellectual willpower was (and continues to be) needed to overcome the comfortable picture of classical physics that sits in our minds and is so easily observed and understood in the world around us, that even today some still question if it truly is the Holy Grail it is made out to be. It has been put on a pedestal for good reason though; using mathematics so basic that most of it is taught at A-level, predictions of unprecedented accuracy can be made. The astonishing thing is that the predictions are correct.

How do you solve a problem like quantum theory?

Zero-point energy (which prevents negative-charge electrons from falling into the positive-charge nucleus and annihilating each other) and specifically allowed energies for electrons (which correlates with the energy levels of electron shells) are just two of the fundamentals of nature itself that fall out of proofs in an undergraduate quantum course. These incredible predictions are the result of a few basic postulates and some simple number-play - very little physics even comes into it, as it is almost purely mathematical.

It is foolish though of course to assume that its simplicity means that quantum physics is the easiest concept since sliced bread. It is quite the opposite in fact, and everyone researching in the field today would tell you the same thing - no one understands it. Albert Einstein, Niels Bohr, Max Planck, Paul Dirac, Werner Heisenberg, Wolfgang Pauli; some of the greatest names not only of our time but of \emph{all} time, a list of people directly responsible for the development of quantum theory itself, didn't understand it. Erwin Schrödinger, famous for his wave propagation equation, and even more famous for his cat, is quoted as saying "I don't like it, and I'm sorry I ever had anything to do with it". In an ironic (or is it appropriate?) twist, it is simultaneously a superposition of the simplest maths and most complicated concepts known today.

One of the more important and confusing aspects of quantum theory is the measurement problem - the very act of measuring a quantum object changes it, the so-called 'collapse of the wave function'. A measurement is a form of interaction, and so it follows that any interaction will cause some sort of change in a quantum object. To make matters worse, even the mere presence of light on a quantum object can cause the wave function collapse, so how can scientists test the predictions made by this incredibly powerful theory? The answer it seems, may be found through a modernisation of an existing technology.



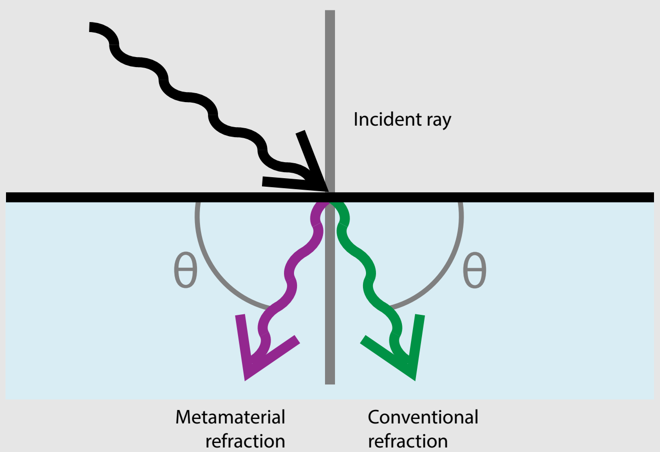
Microscale: Conventional electromagnetic metamaterials are made from sheets of fiberglass slotted together with exactly folded wires embedded to manipulate the wave as desired. Above is an array used on microwaves, with each copper square measuring less than 2mm across.

Man-made

Metamaterials (*meta* meaning *above* or *beyond*) are man-made materials designed with exaggerated properties far beyond those attained in nature. Metamaterials (metamaterial) span a number of disciplines across science and engineering, but find a strong base in optics. Whilst the modern realisation of invisibility cloaks remains firmly in the realms of science-fiction, the ability to deflect light beyond its natural limits is a metamaterial's bread and butter.

Metamaterials grew out of research after World War 1, in which better ways of receiving radio signals were investigated. Modern-day metamaterials deal with the idea of negative refractive indices which would allow light to bend in exotic ways by manipulating the electromagnetic (electromagnetic) wave as it travels through once inside the metamaterial. If light can be bent around an object, and once on the other side continues on its journey as if nothing had happened, you have created an invisibility cloak. If light never falls on the object itself, it may as well not be there. This is achieved by engraving onto or manipulating the shape and geometry of materials used to make your metamaterial. However this must be done on a scale smaller than the wavelength of the electromagnetic wave you are trying to effect - originally metamaterials were proven using microwaves, where wavelengths range from 1m-1mm.

For the team at the Optoelectronics Research Centre (ORC), University of Southampton, they are taking it one step further and moving into the optical region where wavelengths operate at the nanoscale (10^{-9} m). Their work revolves around making fibre-optic information processing more efficient - currently, to decide where to reroute a light signal as it reaches the end of a fibre to continue its journey, it must be converted to an electrical signal, processed, and then converted back again into light to travel along the next fibre. At the ORC, they are working on controlling light with light, and directing signals between fibres using metamaterials. This has a double benefit as it would speed up cometamaterialunication time, and also lower energy usage by removing the need to convert and process signals. To carve the required shapes, the team are nanoengineering using accelerated gallium ions (*J. Opt.*, doi:10.1088/2040-8978/14/11/114009).



Nature improved: The green arrow shows the refracted path of a ray of light as it passes from air into a more dense medium like water or glass. Metamaterials can be specifically produced to give a negative refractive index

Jargon Buster

Scientists live and breathe precision, and it shows in their phrasing. Don't let the language get in the way of your understanding!

Quantum metamaterial ≠ Quantum-state metamaterial

A regular metamaterial of quantum size

A metamaterial that manipulates the state of a quantum object

"I don't like it, and I'm sorry I ever had anything to do with it"

Just because metamaterials are engineered on the nanoscale it by no means limits their uses. Franco Belgiorno and his team at the University of Milan have used metamaterials in their pursuit of confirming Hawking radiation, a key feature that would prove the existence of black holes.

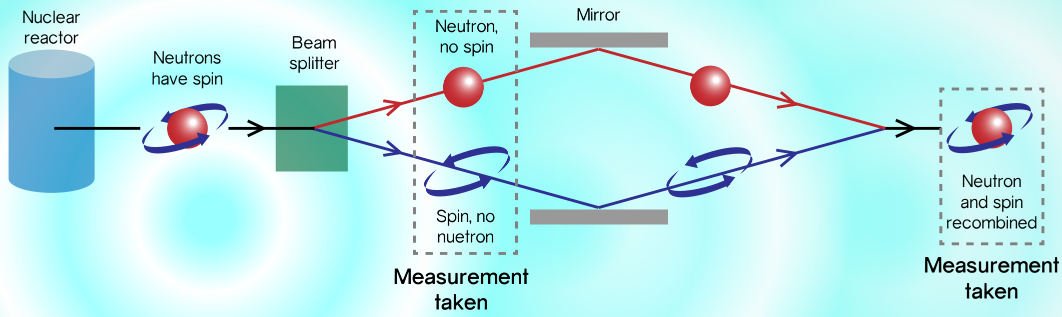
It is known that at the most basic scales, the fabric of space is alive with a continuous bubble of particle-antiparticle pairs being produced from nothing, and almost instantly recombining and annihilating. Stephen Hawking theorised in 1974 that should this creation-annihilation process occur slightly too close to the point of no return of a black hole (called the *event horizon*), one of these particles would fall into the black hole and be forever trapped inside while its partner could escape and be observed as radiation. As metamaterials can distort electromagnetic waves such as light in much the same way as gravity, Belgiorno *et al* fine-tuned the specifications of their metamaterial so as to eventually bring the light waves to a standstill.

If a black hole works by not allowing light to escape, then the opposite (a *white hole*) would not let light in. Extrapolating further, the event horizon of a black hole is the limit at which a particle can be before it cannot escape; a white hole event horizon would be the point at which light cannot pass. If a metamaterial were able to slow light down to the point at which it stops, its would be perfectly analogous to a white whole event horizon. As it has been theorised that black and white holes are essentially the same process, just happening in opposing ways, then to have a perfect analogy would be to prove their existance.

Should a spontaneously produced particle cross this event horizon it would be caught, frozen solid. When they are created particles escape in equal and opposite directions, and so if one moves into the event horizon and is trapped, the other moves away and is free to escape. Belgiorno claims to have ruled out all other possibilities and says the only remaining source of this radiation is as Hawking radiation, however the results are still subject to discussion (*arXiv*:1009.4634).

It is fair to say that the widespread use of metamaterials could never have been predicted, and its far-reaching applications is thanks to the imagination of the scientists that

Quantum Cheshire Cat



Birefringence is an effect well known and studied in optics, where light can take multiple paths through a material. Looking through a glass block would allow you to see what is on the other side, but rotating the block 90 degrees will cause the image to shift as your eyes view the light that took a different path. Staying true to its word though, the world of quantum will always step it up a notch on the weird-o-meter. In quantum birefringence a split beam doesn't produce two half-intensity beams, but rather splits a particle from its properties.

Named after the Alice in Wonderland character who could disappear whilst his smile remained, much the same is happening here. At the point where the beam is split, the cat (particle) goes one way and its smile (properties) go another. Nor is this a crazy interpretation from obscure mathematics - experimentally, a proton has been split from its spin. If this is too hard to comprehend, it may be because it is - a literal interpretation of the experimental results points one way, but a more rational interpretation is still being debated. (*New Scientist*, 26 July 2014, p 32).

use them. The latest use, dreamt up by the Department of Physics at Loughborough University, takes the exact same idea of manipulating a wave that travels through it, but on the smallest scale of them all.

A quantum maze for quantum mice

Mark Everitt, Senior Lecturer in Quantum Control, along with his department peers have devised a way of controlling the wave of a quantum object itself, a step that could have huge benefits for a number of different areas of physics.

There is one main difference between conventional metamaterials and what Everitt is proposing. As previously mentioned, to effect an electromagnetic wave the metamaterial has shapes and patterns on a scale smaller than that of what they are trying to control. The definition of *quantum* is that it is the smallest possible scale and so it is impossible to make anything smaller. Instead, Everitt *et al* propose a quantum-state metamaterial (see 'Jargon Buster'), not a single material but a series of single nodes connected in a net that comprise a system capable of manipulating quantum objects in such a way as to control where it can and cannot exist. The point-like nature of such a setup means that individual nodes can be manually tuned to produce 'walls' which contain the quantum signal that is being tested.

"We've borrowed something from classical electromagnetism and applied it in a totally different and new way, to come up with something remarkably different." says Everitt.

Not only could this be used across a range of disciplines within physics, such as atomic physics, quantum optics and superconducting systems, but it could also be a player in testing to find the elusive quantum-classical transition - the point at which quantum objects become classical in how they act.

It is normal for scientists to start simple and work their way up, however Everitt is already pushing it one step further and working in two dimensions. Whilst it may not seem like a big step, it is a huge leap both mathematically and conceptually, but for good reason. Working in just one dimension is as simple as it gets; working in two dimensions is when the interesting stuff starts to happen. Two dimensions allows for the study of unimaginably strange events such as quantum birefringence (see 'Quantum Cheshire Cat') and other effects that require a change in direction of the wave.

But what about the measurement problem? The team have that licked too - the system they have developed maintains 'global quantum coherence', the official way of saying that the signals act naturally while making their way around the circuit. This means that to an electron inside the system, it wouldn't be able to tell the difference between orbiting an atom or moving around the circuit. This opens the door to a new world of research, as it allows researchers to custom build their environments to test ever-more specific features of the quantum world, and is akin

As the size of the system increases the more likely it is for something to go wrong, and so for now it has only been theorised for 2x2 and 3x3 array systems, but what is next for quantum-state metamaterials?

"The next step is to investigate what happens for larger systems, and maybe different configurations. It would be nice for it to be tested experimentally, but that hasn't been done as of yet. ■