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Author(s)	John Pendry
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John Pendry

My Life in Science

Yes, as I was saying, I was asked to talk about my early life, so that's what I will do. So, let's just begin at the beginning.

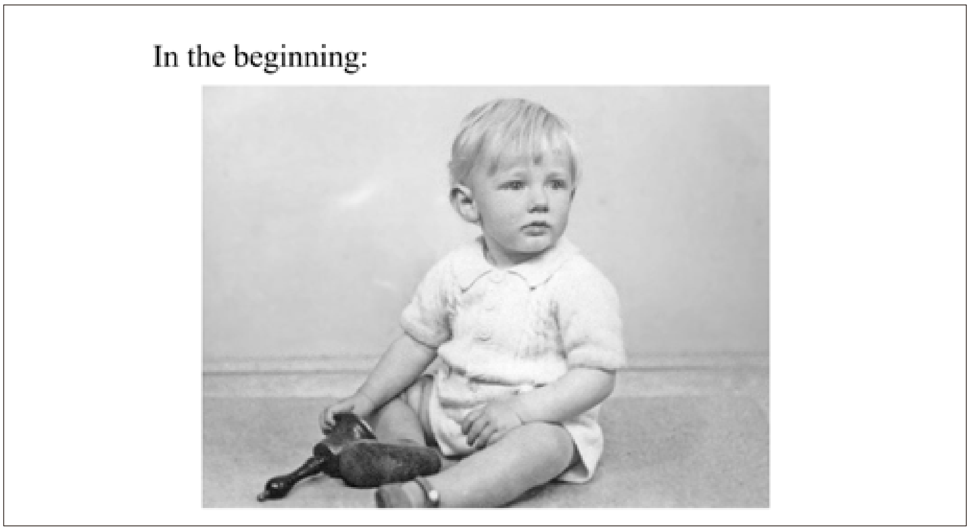

Fig. 1

I was born in Lancashire, in a Lancashire cotton town called Ashton-under-Lyne. That was in 1943, and times were very different in 1943. My father worked in the aircraft industry, and my mother was a clerk in the civil service. It was wartime.

We lived with my grandmother. Little boy heaven, she owned a candy store in a street called Penny Meadow. There wasn't much meadow to it in those days. That meadow was long past. It was one of the main shopping streets of the town, which was close to the very center of the town, the marketplace. The other stores in the street, many of them were occupied by young families, so I had plenty of friends to play with and get up to mischief and so on. The shop was quite a social center, especially on Saturdays when our relatives would do their shopping. When that was done, they'd come to talk with my grandmother and my mother and stop in for a cup of tea.

So we were quite a social center. I had to get used to that, to disturbances to my research at an early age. At that time, the reason my parents lived with my grandmother was that Mr. Hitler had seen to it that there's not a lot of property on the market at that time, but despite this wartime destruction, there was a very positive mood in the population for the future, and particularly, people saw the future benefits that science would provide. So, from an early age, I was hooked on science: I cannot remember a time when I did not want to grow up to be a scientist. They were the best.

Times have changed. This is how we were in the 1940s, as depicted in *Lancashire Street* (1951), a painting by an artist called L. S. Lowry, who recorded scenes from the Lancashire cotton society. This painting probably sold at the time for a few thousand pounds. It's now worth several million, I imagine. That's what his works go for. He originally worked in the next town from us, Oldham, but painted scenes from our town as well. When he got a little bit of money he moved a little further out into Mottram, a small village in the hills. People used to go and interview him from my school.

I'll draw your attention to a few things there. The smoky chimneys, which is a sign that the cotton mill is working. He was famous for what we will call the stick men. These are Lancashire people going about their business. Lancashire people are noted for being very sociable. So that's a picture of a typical environment at the time I grew up.

As I mentioned, cotton was the basis of the 19th century prosperity of my town, and the landscape of my childhood was dominated by the mighty cotton mills. One of them was the Imperial Cotton Mill. I'm not quite sure where it was located, but it was close to us. It had a chimney, and the whole building was driven by a single steam engine powered by coal, which was mined locally. We called coal, black diamond. It has not such a nice reputation these days, but it powered these mills. One steam engine drove a series of belts, operating very, very noisy machinery. Cotton came into the town, imported through Liverpool, from places like Galveston in America, then it was spun, woven and exported around the world. Those cotton mills don't exist anymore. So this is a piece of history.

I was very fortunate. My parents and my grandmother provided a loving and stable environment. It was a somewhat chaotic home because we didn't have much space. We all lived together in a single living room with a kitchen adjoining it, and the things which were going on there: a constant stream of visitors, customers in the store, my father's singing lessons, singing scales—oh dear! Not to mention my messing about with chemicals. The family was very close, particularly on my mother's side. My grandmother was widowed when her children were in their teens, and she was left to bring up my mother and my uncle.

My uncle Sid was a great influence on my development. He worked for the Admiralty in the war, and later, he was a teacher. He never seemed to tire of answering my questions. He was a lovely man. He played the piano, wasn't terribly good at it, but I was listening to him play one time, I happened to be sick in bed, so there was nothing to do but listen to uncle Sid on the piano. Again, I was hooked, and I demanded of my parents that I have piano lessons. Unfortunately, I'm not terribly good at it, but there's an old saying, isn't there, if a thing is worth doing, it's worth doing badly.

The natural world

My mother was a woman of boundless energy some of which I seem to have inherited. This led to her passion for walking. The northern mill towns are small and often surrounded by countryside, particularly to the east where the Pennine hills rise up to moors purple with heather in the late summer. Great walking country.

Further to the north is our Lake District its beauty hailed by the likes of Wordsworth. This was for summer holidays where we stayed at Skelgill, a farmhouse. From there we would climb over 'Cat Bells' ridge to the Derwent Water ferry and more walks.

Fig. 2

My mother was a great walker. She was a woman of tremendous energy. I hope I have a little bit of it in me; I think I have. She had a passion for walking. She loved the countryside.

The northern mill towns were quite small. Ashton was about 50,000 people, I think, so it's easy to escape from them, even by walking. Particularly on the eastern side of Lancashire, where

Ashton was located, you could escape to the Pennines, which were covered in purple heather in the late summer. Further to the north, in the Lake District, we used to go on holidays there, to a little farm called Skelgill. This is a picture of Friar's Crag in Derwentwater, where we went to after we climbed over Catbells to do some more walking (Fig. 2).

So onto school and student days. I see my time ticking by.

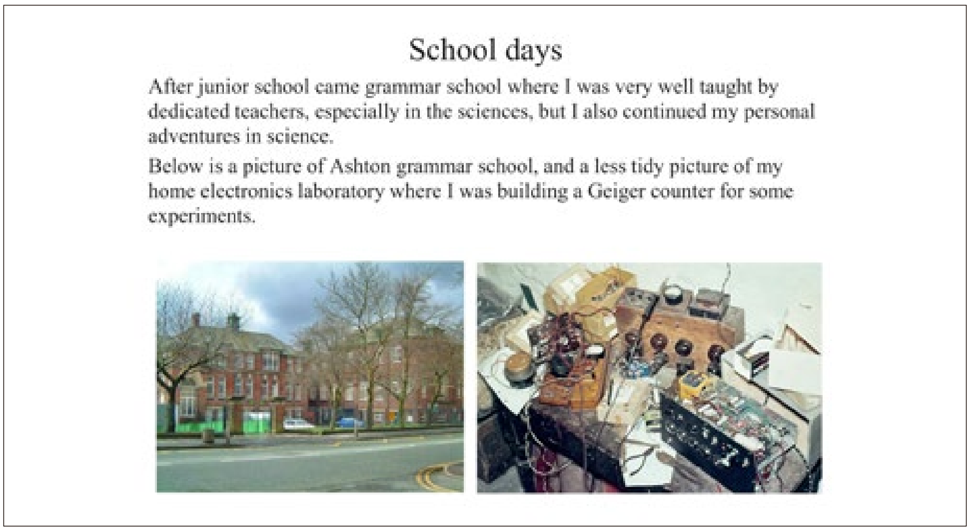

Fig. 3 Left image: Photo provided by Sandra Martin

I was very fortunate in that I had very good teachers at my grammar school. They looked after me extremely well, but in parallel with my schoolwork, I also did my own activities, and here you see the terrible mess that is my worktop, where I was building a Geiger counter (Fig. 3, right). Here is the counter, the Geiger. Its tube is somewhere else. As you can see, I was thoroughly involved in electronics and so on. In those days it was valves. It was only later that transistors came onto the market.

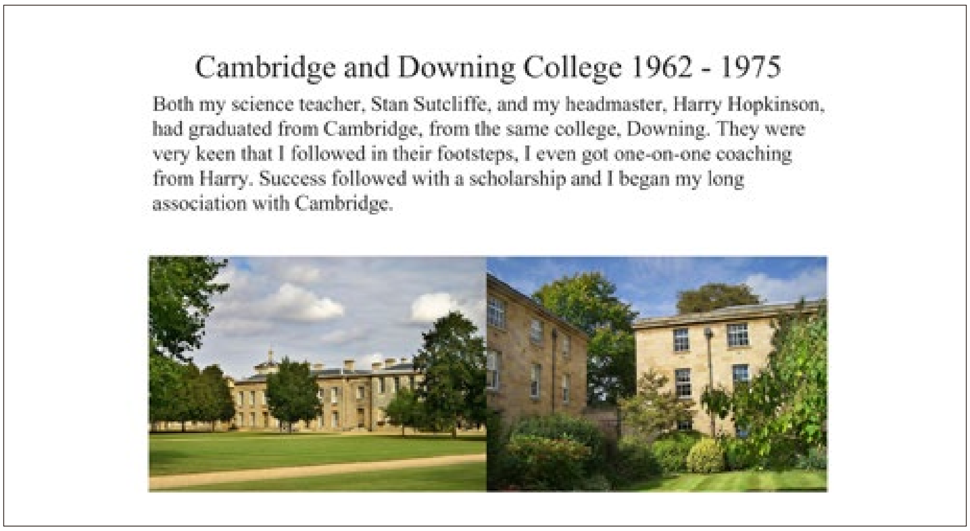

Fig. 4

Then, after school, I got a scholarship to Downing. Both my physics teacher and my headmaster had been to Downing College. They were very, very keen that I should also go to that college, to the point where the headmaster gave me personal tuition, and I was fortunate to get a scholarship to Downing. That was my room in Downing, where I lived for some years (the lower-left window of the building on the right in Fig. 4).

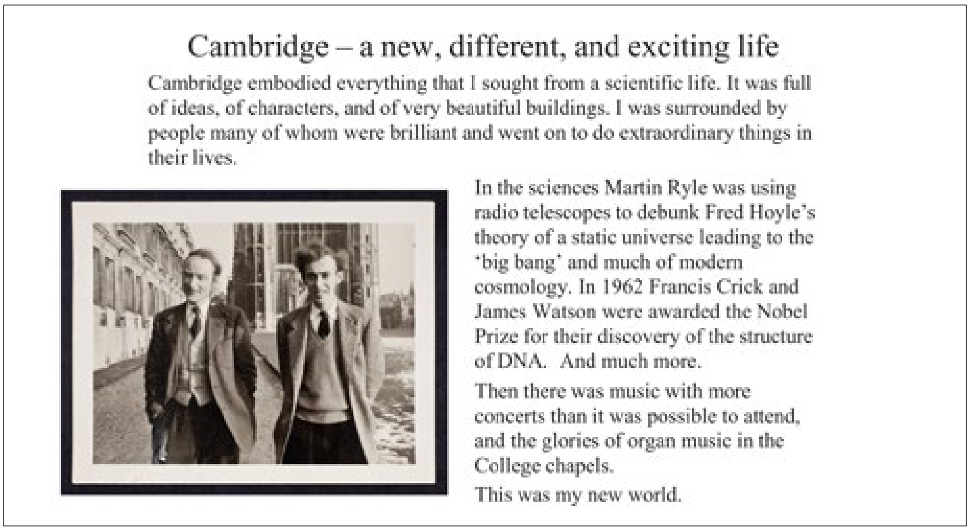

Fig. 5 Courtesy of the BGI Nobel Laureates Archives, Cold Spring Harbor Laboratory, New York

So, I was like a fish in water, a fish that had found water in Cambridge. It embodied everything I'd sought from a scientific life, full of ideas and characters, very beautiful buildings, surrounded by people, many of whom had brilliant minds.

In the sciences, there was Martin Ryle, and he was using some of the early radio telescopes to debunk Fred Hoyle's picture of this static universe. They used to have quite acrimonious debates about who was right. It turned out that Ryle was right: the universe was expanding. Not only that, but there was Crick and Watson (Fig. 5). They did their work in a little shed that looked like a bus shelter, overlooked by the office where I worked for my Ph.D. And much more.

Then on the art side, there was more music in Cambridge than you could possibly attend. I particularly gloried in the organ music, which was provided in the college chapels. This was my new world.

So, with that introduction, which has taken much longer than I intended, let me talk about some of the research which led to my obtaining this wonderful prize. I hope to show that my work has its origins in very fundamental things but that these fundamental things can lead on to practical things, which in turn, can lead on to things which people actually want to buy because they are useful in their everyday lives. It's been a long story because some of this research that I'll show you is quite old.

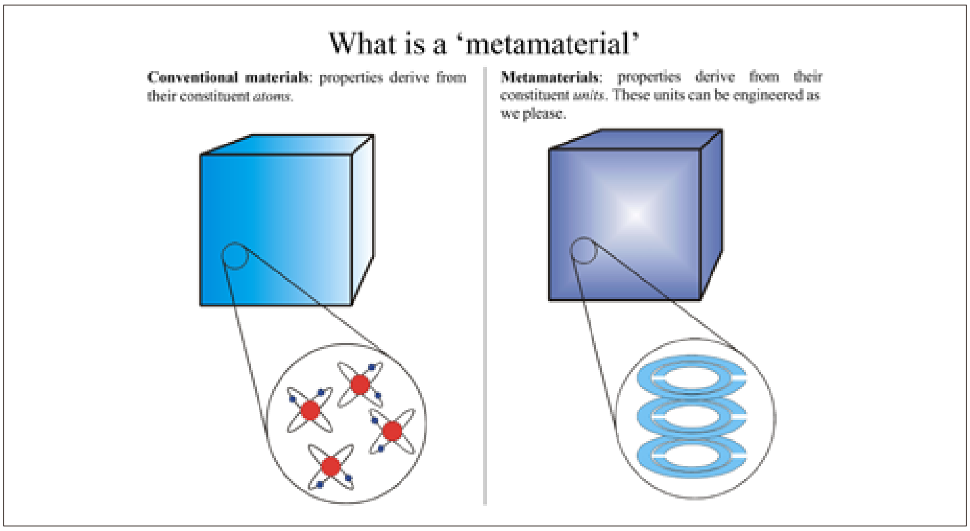

Fig. 6

Negative refraction, JB Pendry, *Contemporary Physics*, 07 Aug 2006, Taylor & Francis, reprinted by permission of the Taylor & Francis

So the first question I guess you would ask of me is, what is this metamaterial that we keep talking about? Quite simple to explain. So an ordinary material consists of atoms (Fig. 6, left), and it's the properties of the atoms that ultimately determine how a piece of glass behaves. You don't see the individual atoms: it's the sort of average of what each atom does. It's a very collective thing that you see in the response of glass.

But the things which respond don't have to be as small as atoms. They just have to be smaller than the wavelength, so there's a lot of space between the size of an atom, which is 10^{-9} meters, a nanometer across or less, much less. There's a factor of 1,000 between that and the wavelength of light. So you can cram into that space objects which are big enough that you can actually manufacture them, particularly if the wavelength is long.

This is what we call a split ring, and its diameter is, in this case, just a few millimeters because it's designed to work with radiation with very long wavelength, typical of radar (Fig. 6, right). Other metamaterials have much smaller structures these days as we get more clever with the engineering, but the basic idea is that the function of a metamaterial comes from engineered meta-atoms.

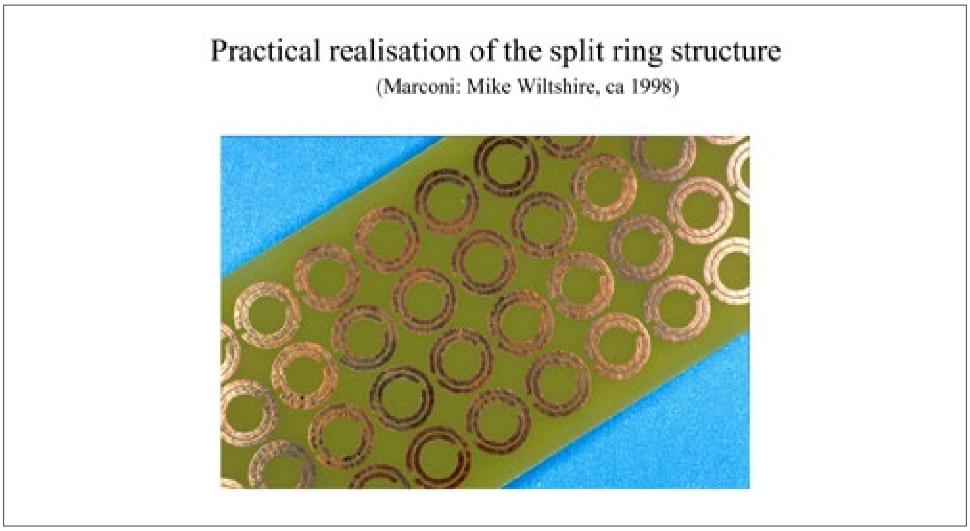

Fig. 7

Here is the first realization of that so-called split ring structure (Fig. 7). One of the reasons that the field took off was they were very, very easy to make. So if you're working at radar frequencies, which this is again designed for, then the whole size of this is maybe about 10 centimeters, and you don't even have to make it yourself. You design on a computer and send it off to a company that manufactures printed circuit boards, and they will etch it for you into any shape or form you want. So anybody could get in on the game if they had a computer and some design software.

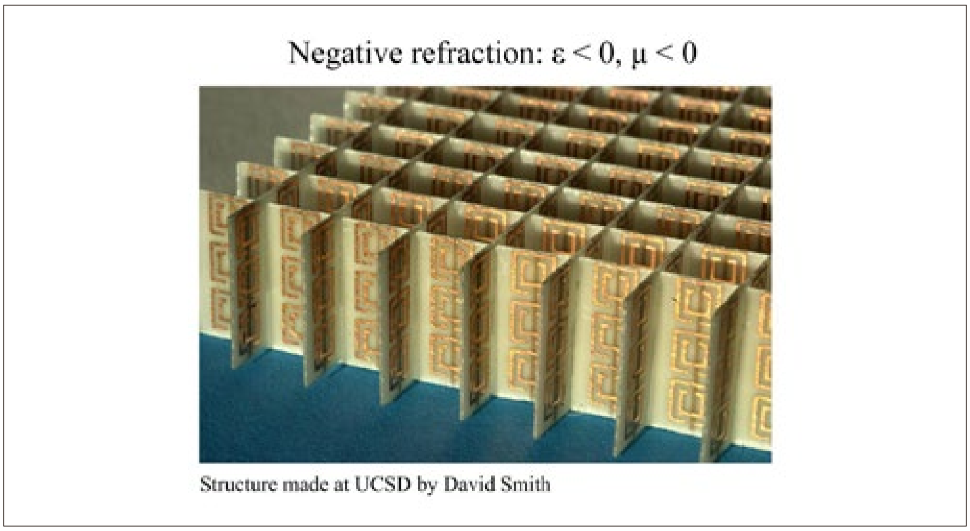

Fig. 8

From D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, *Science*, **305**, 788–792 (2004) "Metamaterials and Negative Refractive Index". Reprinted with permission from AAAS.

Here's another structure that exploited the idea that you could have very, very unusual properties by having a metamaterial. So here's the rings, which you design to have a magnetic response (Fig. 8). There are some wires, which you can only see as a slight shadow in this image as well, and they give an electrical response. This was the first structure that realized a negative response to electricity and a negative response to magnetism. That made something that have been sought for decades. Combined, they make a negative refractive index; in other words, they bend light the wrong way when it goes through the material.

Another example, from much later, is a compound structure designed to do the same thing only now at a much smaller length scale. Instead of being centimeters, this is microns, a submicron structure, and this is designed to work in infrared. It was manufactured by Zhang Xiang's group in California.

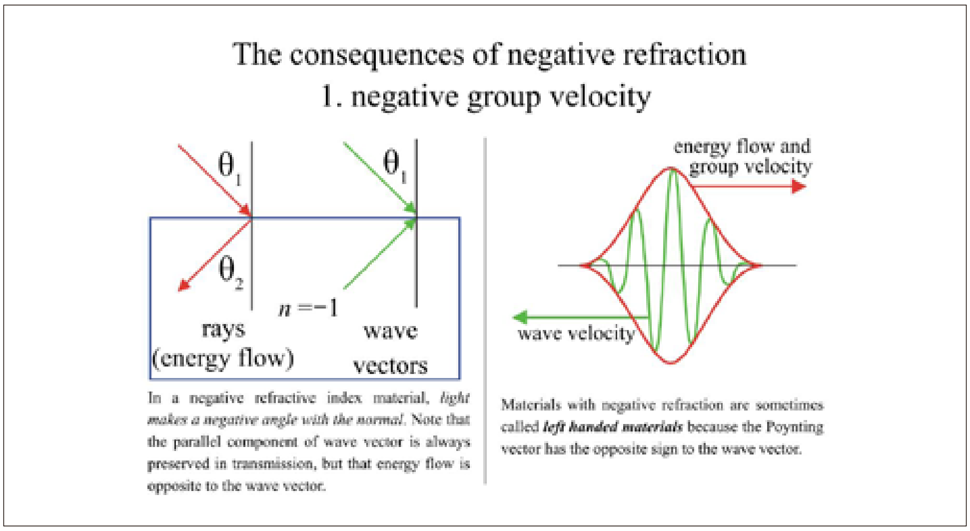

Fig. 9

Negative refraction, JB Pendry, *Contemporary Physics*, 07 Aug 2006, Taylor & Francis, reproduced by permission of the Taylor & Francis

Well, what is this negative refraction? A guy called Veselago, a Russian guy who died only recent actually, published a paper in about 1960 that said that if you could have a material with negative refraction, it would have all sorts of crazy properties.

So if you have normal refraction, then a ray of light would come to the right-hand side of the normal here (Fig. 9, left). There is a formula relating these angles to the index of refraction of a medium. But this negative refraction bends the light back on itself, and for that reason, it creates very strange properties. Without going into too much detail, here's one of them, that if you make a little pulse of light and send it through the medium, then the way the pulse travels is the opposite to the way the wave travels. So imagine that you've got these waves (Fig. 9, right): there's an envelope here (the red line), and the envelope is going this way (the red arrow), and the waves (the green line) are wriggling through like that, trying to get out of the back of the envelope (the green arrow). Very, very strange stuff.

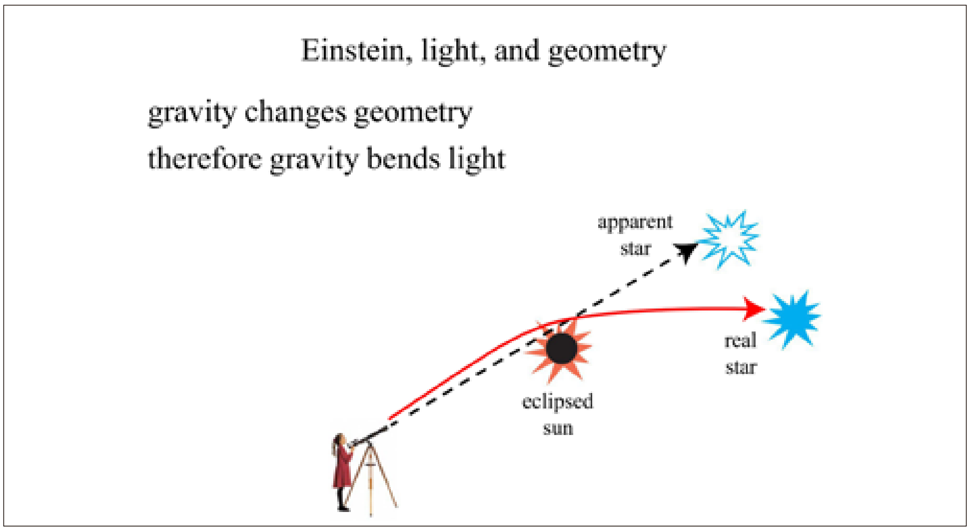

Fig. 10

Now, when you have a metamaterial with countless degrees of freedom, you've got to have some way of controlling them. How do you design things? For this, we turn to this gentleman, Einstein, who is well-known to all of you, I'm sure. He had a theory that light can be bent by a star. Einstein said that space isn't empty. In the 19th century, people, scientists, thought of words for space that were basically saying nothing, vacuum, nothing. But Einstein said, no, it isn't nothing.

It's in many ways just like a material. It has properties like, for example, it's got a metric, which, essentially, as far as light is concerned, describes a refractive index. Space has a refractive index, and you can change it. You can change it by putting something very heavy near it.

One of the first experiments that proved Einstein right was this experiment in which the deflection of starlight by the Sun was observed during an eclipse—otherwise you can't see the star. This deflection agreed with the prediction of Einstein's theory (Fig. 10). We're going to use that idea of Einstein's that space is made of rubber to have a new design paradigm.

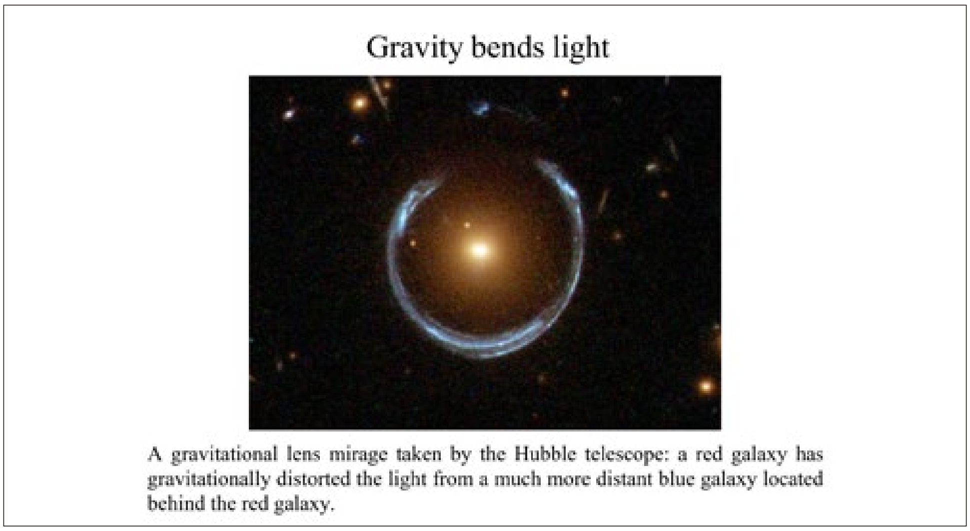

Fig. 11 ESA/Hubble & NASA

This is another illustration from the Hubble telescope (Fig. 11). This shows a red galaxy in the foreground, and behind, this is a blue galaxy. If the red star wasn't there, you'd see a blue dot. But because it is there, it refracts the light around it, just like a lens made of glass would. So space has a refractive index, and Einstein was right.

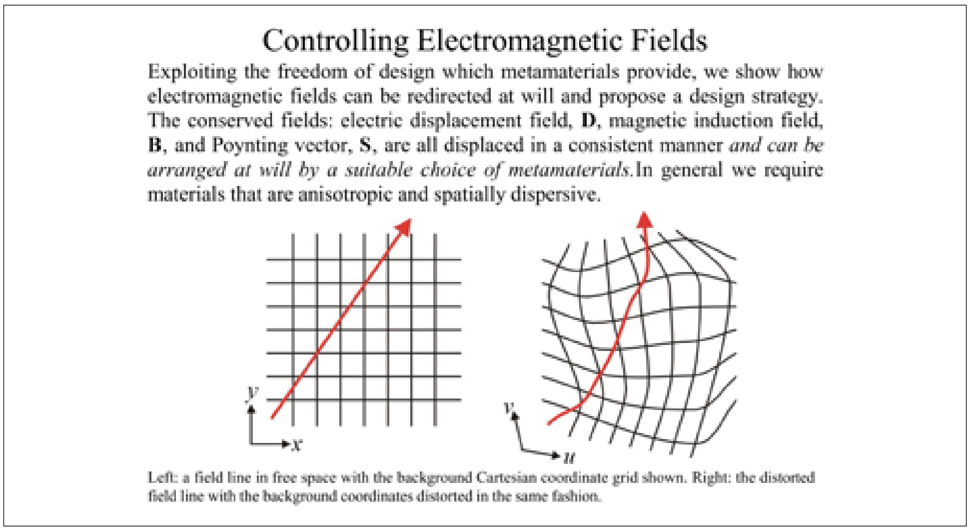

Fig. 12 From J. B. Pendry, D. Schurig, and D. R. Smith, *Science* **312**, 1780–1782 (2006). "Controlling Electromagnetic Fields". Reprinted with permission from AAAS.

That leads on to what we call transformation optics. If we want to control a ray of light, we imagine it's embedded in a rubber sheet, or space which behaves like rubber. Then, to push the ray the way we want it to go, we take hold of space, remembering that you can change it like a piece of rubber, we stretch it and pull it until the ray, which is embedded in the space, moves with the rubber and goes the way you want it to be. So where you pull the rubber, the ray moves. If you don't distort the rubber and its vicinity, the ray stays where they are. That's going to be very important when we come to designing a cloak.

Fig. 13

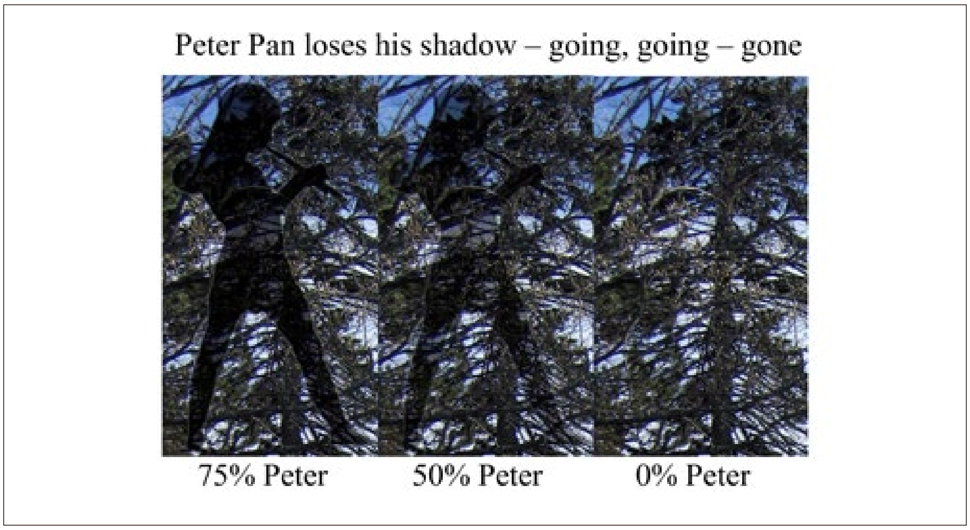

Fig. 14

So one of the things which caused some consternation was when we announced that we could design a cloak of invisibility. This illustrates the challenge of designing a cloak. Most stealth technology relies on the fact that the object doesn't reflect light. That can be quite useful: it's a feature of many modern military aircraft, in fighters and bombers and so on. But black is not enough because even if something's black, it has a shadow.

Some of you will have heard of Peter Pan. Peter Pan was a little boy who lost his shadow. When Peter has lost his shadow, he's not only black, but he is invisible. So how do we make a shadow disappear?

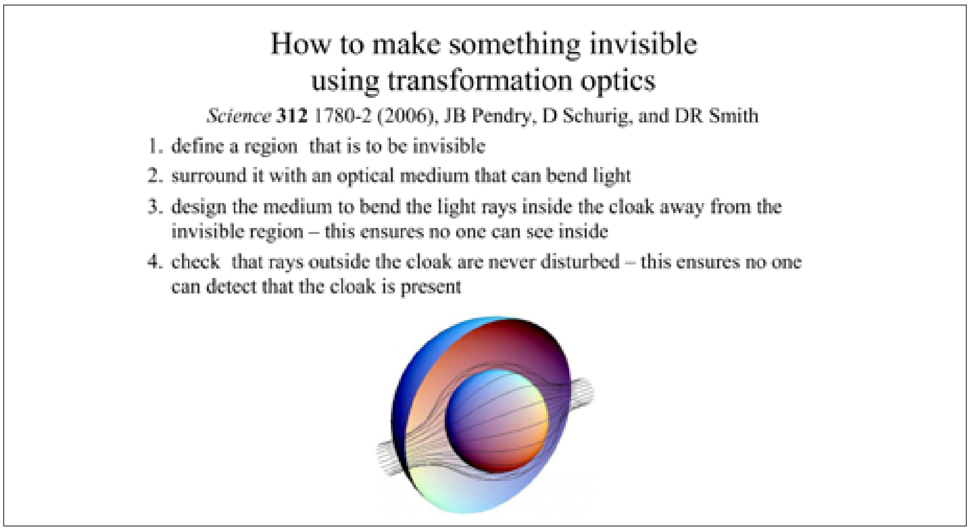

Fig. 15

From J. B. Pendry, D. Schurig, and D. R. Smith, *Science* **312**, 1780–1782 (2006). "Controlling Electromagnetic Fields". Reprinted with permission from AAAS.

Here's the story. You employ transformation optics (Fig. 15). So the idea is that you mustn't touch what happens in this sphere here, so you mustn't distort anything here, and you mustn't distort where the rays go outside the cloak because the rays must go where they would have done if there was nothing there, now there is something there. You are only allowed to mess with this stuff in the graded region surrounding the sphere. So I'm going to take this bit of rubber, which is the cloaked region surrounding the sphere. I'm going to stretch it and pull it until all the rays of light are expelled from the inner region and concentration in the cloak, but I'm not going to do any stretching and pulling inside the inner sphere nor in the space outside the cloak.

You might think that it's a huge challenge to design something which sends these rays on a trajectory that come out exactly as they would have, had nothing been there, and it is unless you have this technology of transformation optics enables us very easily to design a cloak. You could indeed write down the formula for the cloak. It proved a great sales pitch for metamaterials and transformation optics, because people said, if you could solve this apparently very, very difficult problem so simply, maybe these things could solve more simple problems very easily. And so it proved.

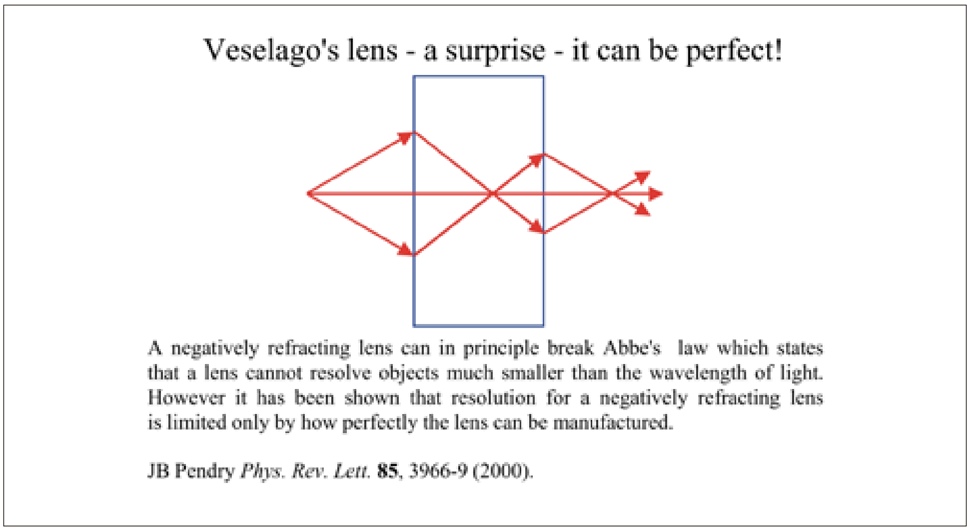

Fig. 16

I'll move on to discuss negative refraction because this is another idea which caused a bit of a storm. Veselago already knew that if you could bend light the wrong way in a negatively refracting medium, inevitably it would come to a focus in that medium.

So here are the rays, they bend the wrong way, and they come to a focus (Fig. 16). By the way, they come to a second focus. He knew that his negative refracting material could make a lens. The only problem was that at the time he wrote the paper, there was no such material, and that situation continued until metamaterials came along.

I alluded to a rainy Sunday morning in my little talk I gave earlier, in the video you saw, and on that rainy Sunday morning, what I was thinking about was this lens. I realized that a very old law, called Abbe's law, wasn't true. The law says that with an ordinary microscope, you can't see anything smaller than the wavelength of light, which is about half a millionth of a meter. Now that may seem very small, but that's just the size at which cells start to be interesting. You can't see inside a cell with an ordinary microscope because it can't resolve what's in there. So this was thought to be an iron-cast law, except that on that rainy Sunday morning, I realized that there was more to Veselago's lens than had been realized, that if you made it in the right way, it was perfect, it could be perfect. But there's the catch: you have to make it in exactly the right way.

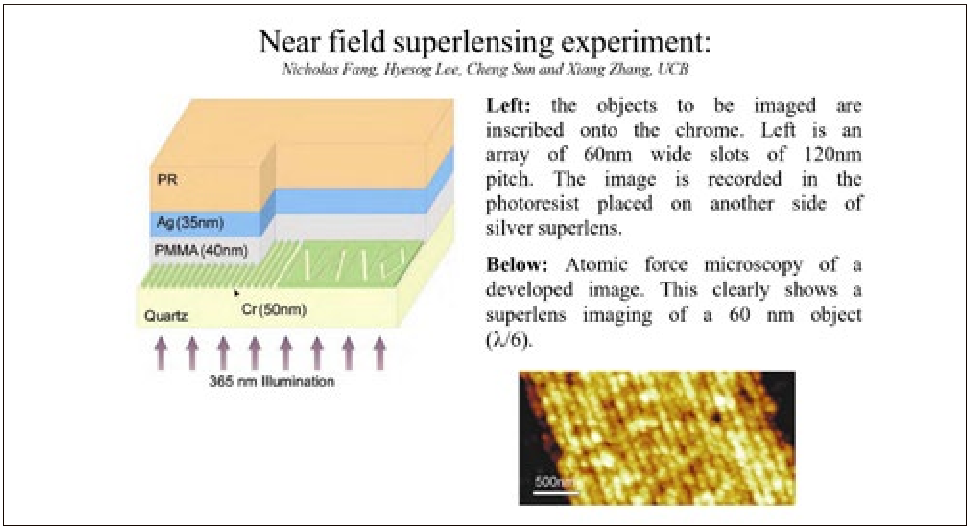

Fig. 17 From Nicholas Fang, Hyesog Lee, Cheng Sun, Xiang Zhang, *Science* **308**, 534–537 (2005). "Sub-Diffraction-Limited Optical Imaging with a Silver Superlens". Reprinted with permission from AAAS.

Here's an approximation to it (Fig. 17, left). This again is in the Zhang laboratory in Berkeley. They made an approximation to the lens out of a piece of silver. So there's a lens (Ag), there's a spacer (PMMA), and there's the thing they're looking at, which is a bit of chromium (Cr). Since things are too small to see with a microscope, you actually have to write them in essentially a bit of material, which we call a photoresist. You send the light in from the direction indicated by the lower arrow. It has 365 nanometers wavelength, and you're trying to see something which is a few tens of nanometers across. How well are you doing? Here's an image of the grating, and you can see that although the structure of the grating is on a scale of 60 nanometers or so, you can resolve it with this technique (Fig. 17, right).

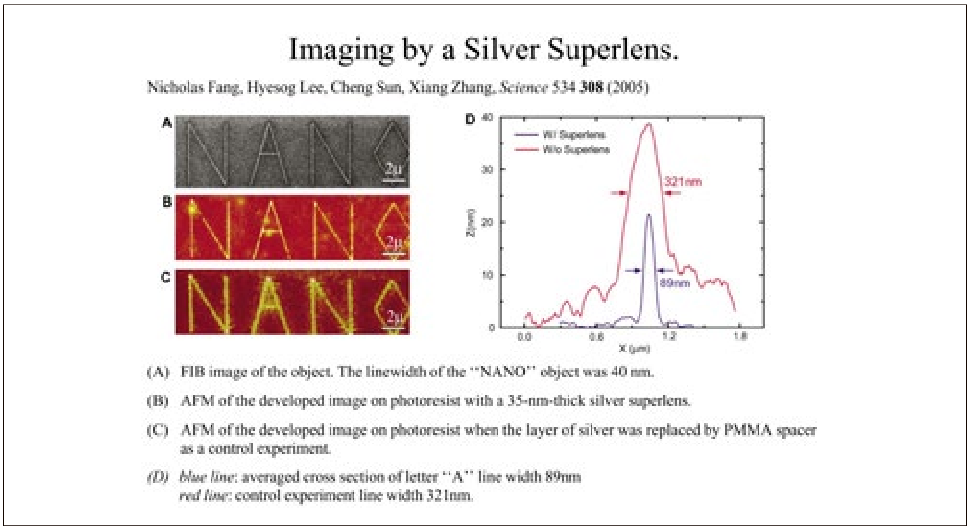

Fig. 18 From Nicholas Fang, Hyesog Lee, Cheng Sun, Xiang Zhang, *Science* **308**, 534–537 (2005). "Sub-Diffraction-Limited Optical Imaging with a Silver Superlens". Reprinted with permission from AAAS.

More impressive is this figure here, where you're looking at the word nano in the chromium, and there's a 2-micron scale (Fig. 18, left). This is what you see if you don't have any lens (C), and if you put the silver lens in place (B), it's like putting your spectacles on. It all comes into focus. This is a scan across which shows that you have in fact improved the resolution from what would have been about 320 nanometers, which you see here, to 90 nanometers (Fig. 18, right). Okay, not perfect, but a lot better.

Now, in the time remaining to me, I want to show you how these ideas, which spring from Einstein and Maxwell's equations from which we've made some playful experiments, really demonstrators of the theory, not designed for practical things at that stage, but which showed that practical things could be done. I just want to spend the remaining time whizzing through some of the many applications which metamaterials have spawned.

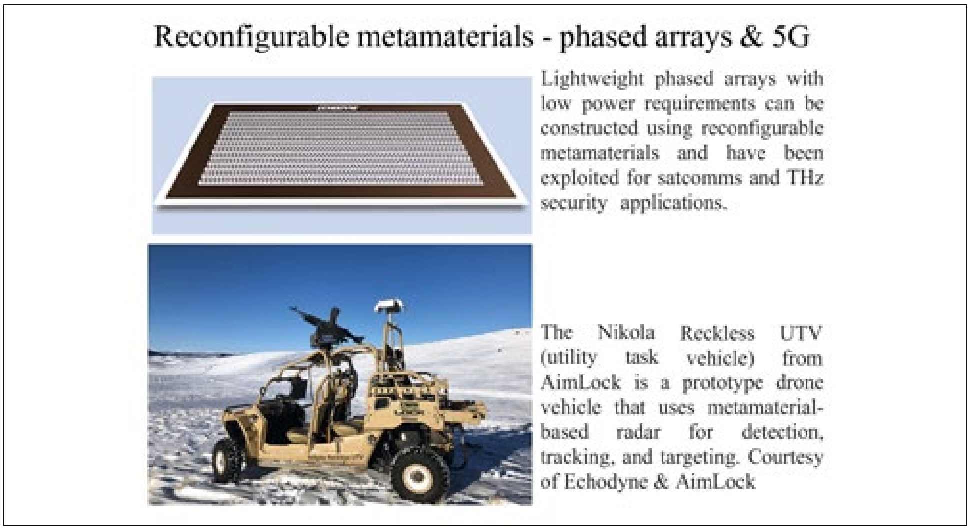

Fig. 19 Image Courtesy of Echodyne

Here's an early one. What you're seeing here is this remote-controlled vehicle (Fig. 19), which has to communicate with a satellite. The conventional way of doing that is to have a satellite dish, which is heavy, and has to be steerable to follow the satellite. Far better to have what's called a phased array, which is normally very expensive because it's full of transistors, but this phased array is made out of a metamaterial. It turns out you can very easily change the properties of metamaterials, without it physically moving, allowing it to point at any part of the sky you want.

Echodyne is also developing this same technology to ease your passage through airports. Now you have to have a terahertz scan: you go in this machine and things whizz around: a complete nuisance. With their technology, you can walk past the machine, and as you walk you'll be scanned, stopped if there's anything wrong, but free to proceed if not.

Fig. 20 Courtesy of Richard Syms

It's also being applied to MRI (Fig. 20). This is my colleague, Richard Syms. He's developing technology to improve the speed of MRI scanning, magnetic resonance imaging. The signal is a magnetic resonance, a beautiful, pure magnetic field, which in present technology, we promptly turn into an electrical signal, which then has to make its way through a very noisy environment. Richard's idea is to keep the magnetism and design not a conventional wire, which conducts electrons, but a wire which conducts magnetism, and that keeps the signal pure. You can have lower noise levels. The scan doesn't take 20 minutes, it takes 2 minutes or so. And you can do more scans. So that's one more useful thing you can do with metamaterials.

Another example is a device that actually generates the terahertz radiation, which you would use in that scanning technology I mentioned. What you're doing here is taking a device which generates terahertz waves, but is not very good at sending them out to you. On top of it, you build a metamaterial structure, which is very good at extracting the power from that device. This is from the Capasso Group in Harvard.

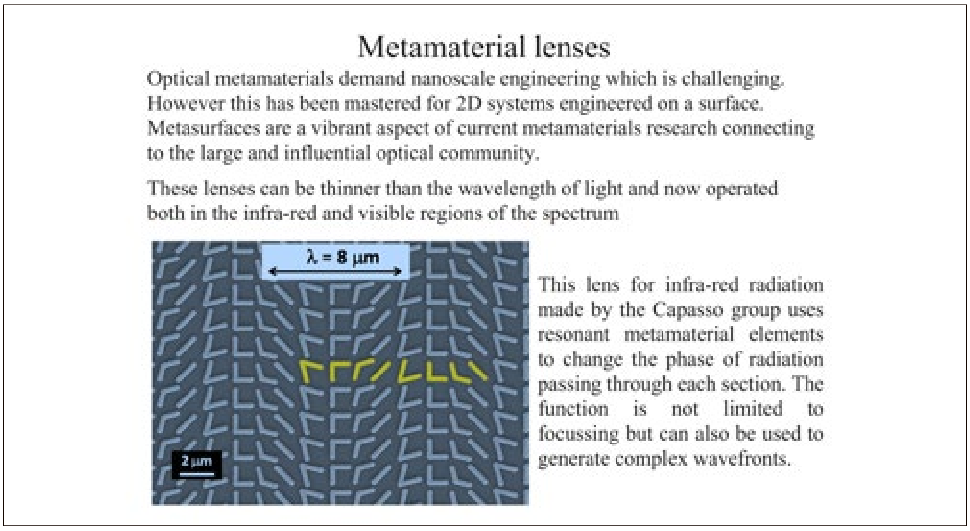

Fig. 21 From N. Yu, *et al.*, *Science*, **334**, 333–337 (2011), "Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction". Reprinted with permission from AAAS.

Another favorite of the Harvard group is making lenses that are extremely thin (Fig. 21). This isn't a split ring, but it's sort of semi-split-ring. These are little resonators, which are very much sub-wavelength, and you can see they change their orientation and the shape. The idea of that is it's like changing the refractive index of a lens. The difference from an ordinary lens is that this lens can be just a few nanometers thick. You can make very, very, very thin lenses using metamaterials.

Fig. 22 Provided by TOYOTA MOTOR CORPORATION

What else? Yes, I thought I'd show you this one. Kymeta, another company that manufactures metamaterials, put satellite communications dishes on top of some of Toyota's cars (Fig. 22). I don't know where that's got to these days, but this car was driven from, I think Los Angeles to Michigan. Toyota headquarters were in contact with it the whole time. The idea is that one day your car will have antennae like this on the top, and will continuously be in contact with whoever. Whether you like that idea or not is a good question.

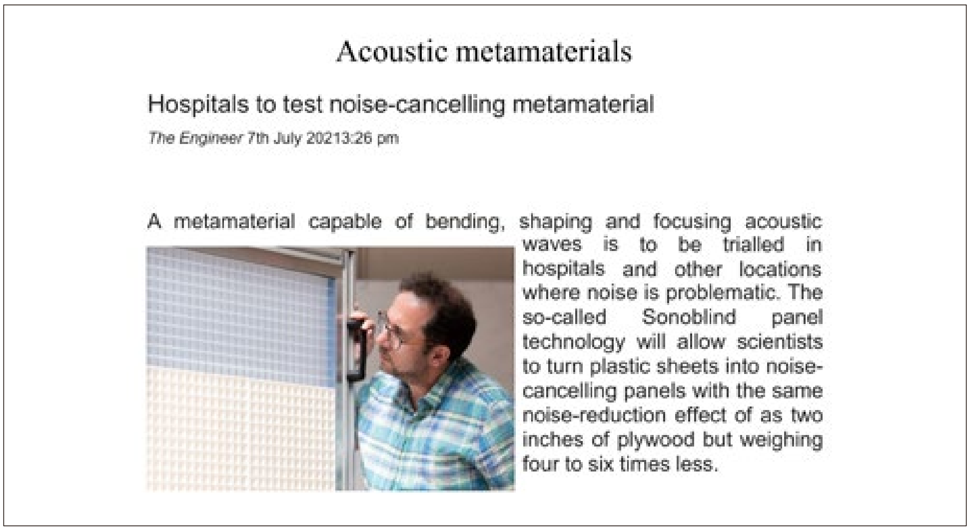

Fig. 23 Courtesy of the University of Sussex

And on and on. This is a panel which is designed to control not electromagnetic waves, not light, but is designed to control sound (Fig. 23). Sound is a wave, so metamaterials control almost any sort of wave you like, and this panel is full of little resonators. You can't see them properly but they are there. The idea is that this panel stops sound. It is sold by Bristol company for use in hospitals to make a silent zone around the bed of a very sick patient.

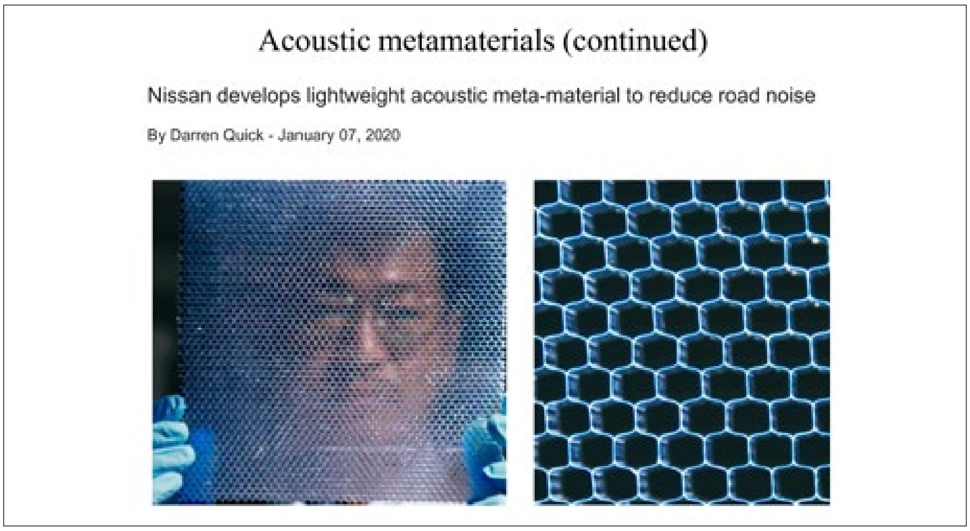

Fig. 24 Provided by Nissan Motor Co., Ltd.

This is also being developed by Nissan, to use metamaterial resonators to control the road noise in a car (Fig. 24). The major source of noise from a car traveling at speed on the motorway is road noise, and metamaterials can help eliminate that.

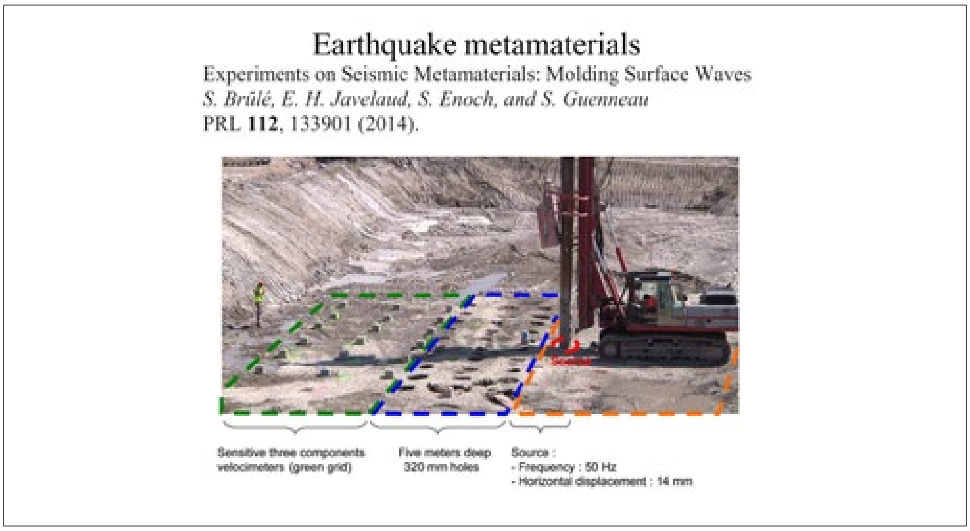

Fig. 25 【Experiments on Seismic Metamaterials: Molding Surface Waves, S. Brûlé, E. H. Javelaud, S. Enoch, and S. Guenneau, *Phys. Rev. Lett.* **112**, 133901 (2014), https://doi.org/10.1103/PhysRevLett.112.133901】CC BY 3.0

Finally, something really way out. One of my former post-docs, Sebastian, had the idea that another sort of wave is an earthquake. It's really a wave, and if you can deflect it away from really sensitive objects, like nuclear power stations, then that might be something useful. This is a very sort of crude metamaterial, made by drilling holes in the ground (Fig. 25). In the blue-outlined area, you can just about see these holes. It's not a cloak at this stage, but the idea is to see if this structure alters the way that waves move through the earth. He has persuaded an oil company to lend him this thumper truck. Here's a heavy weight which is hoisted up and then comes down like that, thump on the ground, and send waves out. Then they ask the question, does this structure send those waves where we're trying to send them? The answer is yes: it has been published here in *Physical Review Letters*.

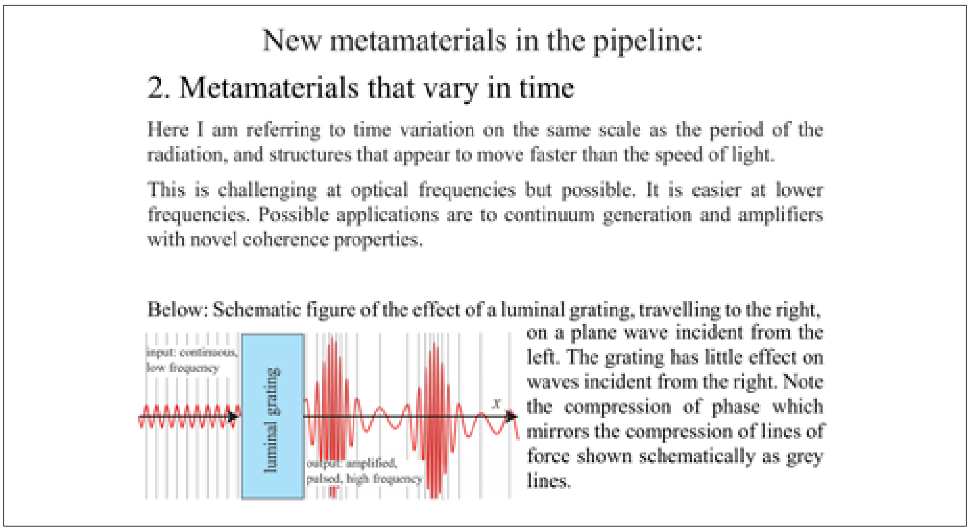

Fig. 26 ©J. B. Pendry, E. Galiffi, and P. A. Huidobro, "Gain mechanism in time-dependent media," *Optica* **8**, 636–637 (2021)

I'm afraid I don't have time to explain this slide in detail (Fig. 26), so let me just talk around it. What next for metamaterials? Metamaterials are structured in space; that's what gives them their unique properties. But there's another dimension, the dimension of time. If you can change a material in time very, very rapidly that will strongly affect radiation moving through it.

Imagine that you have some sort of modulation of, say, the refractive index, that will affect the way light moves. If you can also make that modulation move, that will do something very different.

The key thing about that is if you start mucking about with time, you break a very, very strict law which holds for things that do not vary in time. If things don't vary in time, the equations of physics are reversible in time. So you can send things forward and backwards. That's both an advantage and disadvantage. It implies energy conservation. But if things change in time, that law is broken, there is no longer a law. You may have other laws, but you lack that one of energy conservation. You can make structures like this which will take an ordinary plane wave, squeeze it, put energy into it.

In London, we are exploring the possibilities of these crystals in time, which will do even more extraordinary things than regular metamaterials.

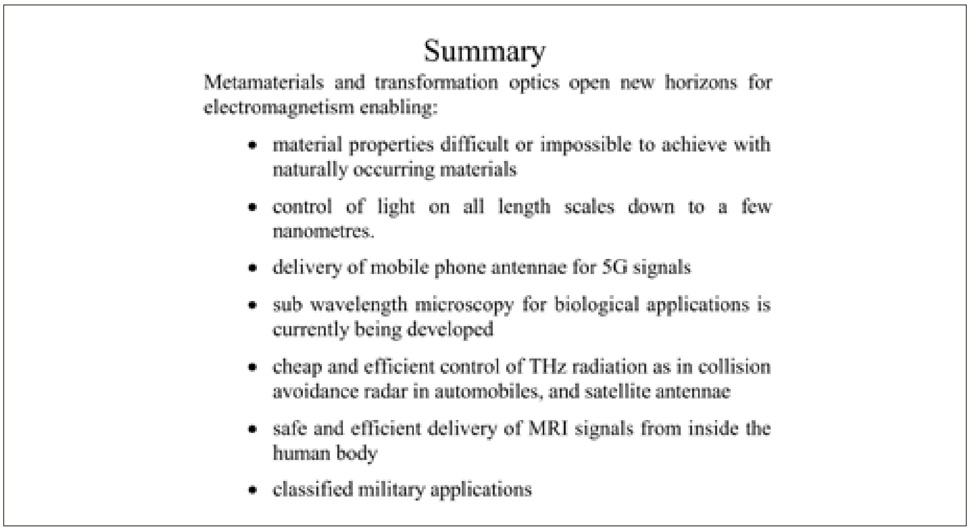

Fig. 27

So with that, I thank you for your attention and I leave you with my conclusions as I'm already over time. So thank you.

You can watch the interview video after the commemorative lecture on the Kyoto Prize YouTube channel.
(https://youtu.be/TgZVxIXQ5-w?si=4dfIU27nhgq3-ToL)