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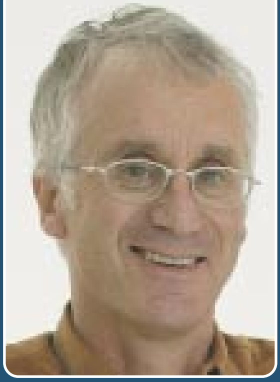
Chapter from "Waves of the Future", the book of lectures from the 33rd Professor Harry Messel International Science School, 3-16 July 2005.

WAVES OF THE FUTURE



PROFESSOR HUW PRICE was born in Oxford, and came to Australia on an Italian liner when he was 13. He attended the ISS in 1969, and went on to study Mathematics, Physics and Philosophy at ANU, Oxford and Cambridge. He has worked at the University of Sydney since 1989, except for a two-year break early this century, when he was Professor of Logic and Metaphysics in the Department of Philosophy at the University of Edinburgh. He is now ARC Federation Fellow and Challis Professor of Philosophy at Sydney, and heads the Centre for Time in the Department of Philosophy.

Huw has written several books including *Facts and the Function of Truth* (Blackwell, 1988), *Time's Arrow and Archimedes' Point* (Oxford University Press, 1996), as well as a range of articles in academic journals such as *The Journal of Philosophy*, *Mind*, *The British Journal for the Philosophy of Science* and *Nature*. he is a Fellow of the Australian Academy of the Humanities, and a Past President of the Australasian Association of Philosophy. He is also a consulting editor for the *Stanford Encyclopedia of Philosophy*, an associate editor of *The Australasian Journal of Philosophy*, and on the editorial board of *The Philosophical Quarterly* and *Logic and Philosophy of Science*.

Huw, what got you interested in science in the first place?

I've always been very interested in anything that starts with "s". "sc" is even better. I was quite good at all my school subjects, starting with home economics (making scones), and by adolescence I was into sports science (Scalectrix, sculling and scuba diving). So when I looked around for career opportunities, science seemed like the go. Physics is a particularly fruitful areas for "sc"s: we have plenty of schisms, for example, several of them involving Schrödinger.

What were you like as a kid? Were you curious, pulling apart stuff to see how it worked?

I often tried to pull other kids apart to see how they worked.

What's the best thing about being a researcher in your field?

I think I'd have to say the adulation. The adulation and the parking spot.

Who inspires you – either in science or in other areas of your life?

I think it's fair to say that most scientists are inspired by fairly ethereal things. Science is not something you plan, like climbing a mountain: it's a field in which you have to be patient, and willing to follow your curiosity wherever it goes. And in both those things, I feel — like most scientists, probably — that reality TV is the best inspiration one could ask for. The way in which perfect strangers form strong attachments and even stronger hatreds within minutes of meeting each other has inspired me, for example, to investigate the mathematical symmetry between waves which converge on a point in space and those which diverge from

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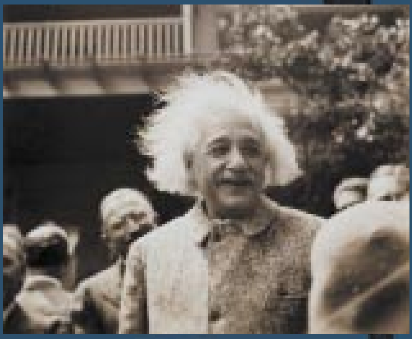
Einstein and the Quantum Spooks

Huw Price

Introduction

THE INTERNATIONAL YEAR OF Physics celebrates the centenary of Einstein's amazing debut: the three groundbreaking papers he published in 1905. The most famous paper introduced the first of the two great revolutions in twentieth century physics, the special theory of relativity. Another paper, studying the statistics of Brownian motion, provided crucial new support for the (then still controversial) hypothesis that matter was made of atoms. And the third, proposing a new understanding of something called the photoelectric effect, was one of the important steps towards the century's second great revolution, the theory of quantum mechanics. So Einstein is not only the father of the theory of relativity. He's also one of the grandparents of quantum theory that, after gestating for about a generation, was born into the world in another remarkable twelve months for physics, between June 1925 and June 1926.



Albert Einstein

We know that grandparents tend to be more indulgent than parents. In the case of Einstein and his famous theoretical offspring, however, it was the other way round. Far from being a doting grandparent to quantum mechanics, Einstein always disliked it, or at least the interpretation of what it meant that became widely accepted in physics during his lifetime. This popular view of the meaning of quantum mechanics was called the Copenhagen Interpretation, because it was developed and championed by the 'Great Dane' of twentieth century physics, Niels Bohr (1885-1962).

Niels Bohr

Bohr was another grandfather of quantum theory, and his disagreement with Einstein about the meaning of the theory was very much like a bitter family feud. It led to a personal rift between these two former friends, two of the giants of twentieth century physics, which persisted until Einstein's death in 1955. Even more like a family feud, perhaps, Einstein's unhappiness with quantum mechanics had a lot to do with tensions between quantum mechanics and his own brainchild, the theory of relativity, although the full extent of that tension didn't become clear until at least a decade after Einstein's death.

This chapter is about why Einstein was unhappy with quantum mechanics, and about the amazing sequel to his objections that later came to light. This sequel, unearthed by an Irish physicist called John Bell (1928-1990) in 1965, is still one of the most puzzling things in contemporary physics. Nobody really knows what it means. Worse still, it reveals a deep tension between quantum mechanics and Einstein's own special theory of relativity. As the special theory reaches its one-hundredth birthday, in other words, we still don't know how to reconcile it with its illustrious eighty-year-old cousin. It is as if these two great theories have lived side by side for eighty years, never properly speaking the same language.

It is true that for many purposes this conflict doesn't matter very much. Working physicists know how to deal with one or the other theory, as necessary. But the tension is still there, and it is one of the deepest mysteries that Einstein's century has bestowed on the one we now call ours. It is impossible to say whether the resolution of this mystery will one day lead to new revolutions in physics, in the way that Einstein himself developed relativity as a solution to tensions in nineteenth century physics. But I think we can be sure that there is something important we don't understand about the physical world, until we find a better understanding of these quantum mysteries.

Fuzzy Pictures versus Fuzzy Reality

Quantum mechanics had several parents and grandparents, but the two with best claim to be fathers of the new theory were young German physicist, Werner Heisenberg (1901-1976), and the Austrian physicist, Erwin Schrödinger (1887-1961). Heisenberg and Schrödinger discovered what turned out to be different but equivalent forms of the new theory in 1925 and 1926, respectively. You've probably come across these names already. You've heard about Heisenberg's Uncertainty Principle, and the idea that quantum mechanics shows that properties often don't have sharp values in the quantum world – that a particle can't have both a sharply defined position and a sharply defined momentum, for example. You may have also heard, at least briefly, about Schrödinger's unlucky cat.

I said earlier that Einstein wasn't at all a doting grandfather to quantum mechanics. And Schrödinger tended to side with Einstein on these important family matters. Certainly, he wasn't at all happy with the interpretation that was soon being placed on quantum mechanics by people such as Bohr. His famous cat first turns up in 1935, as an objection to the Copenhagen view. This is what Schrödinger says:

> *One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device ... In a Geiger counter there is a tiny bit of radioactive substance, so small that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid.*
>
> *If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The* ψ *function for the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.*
>
> *It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality. In itself it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks.* (Schrödinger 1935)

Schrödinger's basic point is if we understand quantum mechanics as saying (in the way that Bohr's Copenhagen school recommended) that reality is 'fuzzy', like a cloud or a fog-bank, then it is easy to think of cases in which large things, like cats, would have to be fuzzy too. And we're not talking about the usual kind of feline fuzziness, of course: in the experiment as described, the cat would have to be in some indeterminate state, neither alive nor dead, for example. If that's really absurd, as Schrödinger thought it was, then it follows that the fuzzy reality interpretation of quantum mechanics must be wrong. The fuzziness of quantum mechanics must be in the *picture*, not in the *world*.

Erwin Schrödinger

Schrödinger's Copenhagen opponents tended to say that in quantum mechanics, reality stopped being fuzzy when we make a measurement – when we decide to measure either the position or the momentum of an electron, for example, and thereby make it the case that it has a definite value for one or the other. However if that's right, what about the poor cat? Does it only stop being neither alive nor dead when we open the box, and make a measurement – when we look to see how it is fairing, inside the 'diabolical device'?

The usual answer was that the cat itself is perfectly capable of making a measurement. Bohr and his supporters said that ordinary classical physics applied to big or 'macroscopic' things, like measuring devices, and that surely included cats. However, this answer just raises a further question. What does 'big' mean here? How big does something have to be to count as a measuring device and to stop the world being fuzzy?

One way to make this problem vivid is to imagine a range of variants on the cat experiment, in which we replace the cat with progressively simpler 'detectors', all the way down to microscopic objects, such as an amoeba, or a virus, or a molecule, or an atom. A few of these possible variations are shown in Figure 1. The notation $\psi_{yes} + \psi_{no}$ is just a way of writing the possibility that quantum mechanics describes, in which it is not yet a determinate matter whether the radioactive atom in the source has decayed ('yes') or not ('no'). The quantum *state* or *wave function* thus contains two components, one corresponding to each possibility.

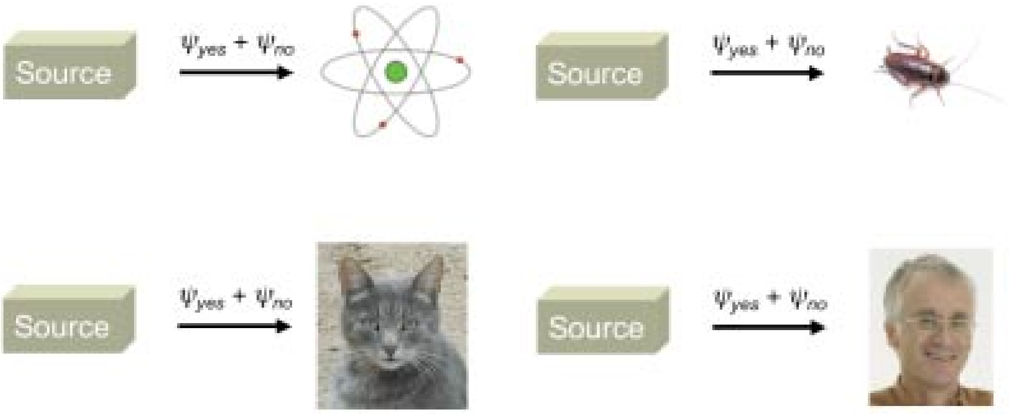
For good measure, I've also included a variant in which the cat is replaced by something a little more complex. This version of the experiment has a name. It is called the 'Wigner's Friend' thought experiment, after the physicist Eugene Wigner, who suggested replacing Schrödinger's cat with a human observer. Wigner thought that only consciousness could stop the world being fuzzy.

Here's the problem, in this new form. In which of these various experiments does a measurement take place, to stop the world being fuzzy, *before the box is opened? 'What counts as a measurement?'* turns out to be one of the hardest problems to answer in quantum mechanics. Today, it is called the Quantum Measurement Problem. Many people think that it still doesn't have a satisfactory solution (although this is a controversial issue). We don't have time to explore this debate here. Before we move on I want to emphasise two points.

First, I want to stress the main reason why this is a problem: according to the Copenhagen view of quantum mechanics that Schrödinger was criticising (which remains popular today), nothing definite happens in the quantum world until a measurement is made. If that's true, then it is a very important matter what counts as a measurement. Until we know that, we haven't understood why the world isn't just 'fuzz', all the way up to the level of our experience.

The second thing I want to emphasise is that it is Schrödinger's famous feline, seventy-years-old this year, which first puts her paw on this crucial issue. That's why she's so important, and that's why, as far as we can tell, she'll have a permanent place in the mythology of physics, along with Archimedes' bath, Galileo's feather and Newton's apple.

Figure 1 - variants on the Schrödinger cat experiment, with different 'detectors'.



Einstein and the Completeness of Quantum Mechanics

As we've just seen, Schrödinger favoured the view that quantum mechanics gives us a fuzzy picture of a sharper reality. In other words, he thought that quantum mechanics is an incomplete description – a description that leaves out some of the details. But Schrödinger isn't the most famous opponent of the view that quantum mechanics is a complete description. That honour goes to Einstein, and his strongest argument is in a famous paper written with two of his Princeton colleagues, Boris Podolsky and Nathan Rosen, that appeared in the same year as Schrödinger's Cat. (In fact, Schrödinger's paper was a response to the Einstein-Podolsky-Rosen paper, in which Schrödinger was offering further arguments for the same conclusion.)

The Einstein-Podolsky-Rosen (EPR) paper introduces a class of experiments that turn out to involve some of the strangest consequences of quantum mechanics. Now known collectively as EPR experiments, the crucial feature of these cases is that they involve a pair of particles that interact and then move apart. Provided the interaction is set up in the right way, quantum mechanics shows that the results of measurements on one particle enable us to predict the results of corresponding measurements on the other particle. For example we might predict the result of measuring the *position* of particle 1 by measuring the *position* of particle 2, or predict the result of measuring the *momentum* of particle 1 by measuring the *momentum* of particle 2 (see Figure 2).

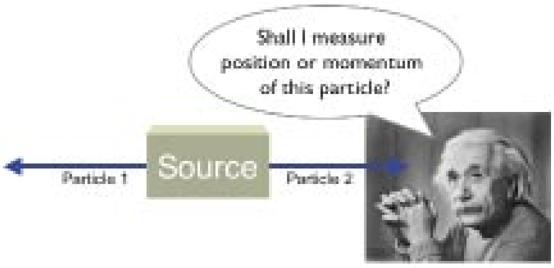
This was the feature of these cases that interested Einstein. In philosophical terms, Einstein was a *realist* – in other words, he believed that the world exists independently of minds and observations. He had no time for Bohr's view that reality depends on what we humans choose to observe. And he thought that the features of quantum mechanics that Bohr and others took as evidence of deep entanglement between observation and reality were really a result of the fact that the theory gives only a fuzzy description of reality. As he saw it, then, the crucial question is therefore whether the quantum mechanical description of reality can be considered to be complete. Does it say all there is to be said about a physical system, or are there further facts about the physical world not captured by quantum mechanics?

The two-particle systems seemed to provide the decisive argument that Einstein was looking for. He argued like so. First of all, he laid down what he called a *criterion of reality* – in other words, a principle that tells us when there is something real, 'out there' in the world. This criterion says that if we can predict with certainty what the result of some measurement would be then there must be an element of reality responsible for that measurement. Let's write this down explicitly.

> **Criterion of Reality**: If we can predict with certainty the result of a measurement of some physical quantity F, then there is something in reality corresponding to F.

This is how Einstein, Podolsky and Rosen express this criterion: 'If, without in any way disturbing a

Figure 2 - An EPR experiment



system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to that quantity.' (Einstein, Podolsky and Rosen, 1935) (You might like to think about whether you agree with this principle. If not, why not?)

The second important ingredient in the EPR argument is an assumption. It says that so long as the two particles are sufficiently far apart, what we do to one of them doesn't affect the other one. Another way to put this is to say that anything we do to one particle only has effects *locally* – and that is why this assumption is called the *assumption of locality*.

> **Assumption of Locality**: There is no action at a distance. Or as EPR put it: 'If at the time of measurement ... two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system.' (Einstein, Podolsky and Rosen, 1935)

At this point it's important to keep in mind Einstein's strongest reason for believing in this locality principle. One of the fundamental principles of his theory of relativity is that nothing – no particle, signal, or causal influence – can travel faster than the speed of light. So if two particles are a long way apart – say, as far apart as the Earth and the Sun – then no change in one particle can affect the other particle for at least eight minutes (the time it takes light to travel this distance). So from the EPR point of view, the locality assumption seemed to be guaranteed by the biggest Swiss bank in town, the theory that Einstein himself had thought up while working in the patent office in Berne, thirty years earlier.

Let's see how the EPR argument goes, given these two principles:

A. If we measure the position of Particle 1, we can infer with certainty the result of a position measurement on Particle 2. (Quantum mechanics tells us this.)
B. So, if we measure the position of Particle 1, then there is an element of reality corresponding to the position of Particle 2. (This follows from A, by the Criterion of Reality).
C. But by the Assumption of Locality, what we do to Particle 1 doesn't affect Particle 2. So it follows from B that there must be an element of reality corresponding to the position of Particle 2, *regardless of whether we measure the position of Particle 1*.
D. Similarly, going through the same three steps for momentum instead of position, that there must be an element of reality corresponding to the *momentum* of Particle 2, regardless of whether we measure the *momentum* of Particle 1.
E. So, even if we don't measure anything on Particle 1, there must be elements of reality corresponding to both the position and the momentum of Particle 2. Or in other words, there is a sharp reality out there after all, and quantum mechanics is just a fuzzy picture of it.

Thus, Einstein believed that he had given a conclusive argument that quantum mechanics only gives us an *incomplete* description of reality. Accordingly, he thought that there must be extra 'hidden variables', of which quantum mechanics didn't provide us with any account. He seems to have thought that quantum mechanics was just a statistical theory, describing the average behaviour of large collections of particles, a bit like the theory of gases provided in statistical mechanics (where properties such as temperature and pressure are just averages, not fundamental properties of the real constituents of gases).

The response to this argument from Bohr and his Copenhagen Interpretation followers isn't easy to describe. In fact, many people say that they simply don't understand it. However, because Einstein's argument is so simple, and obviously correct if you accept the two principles of the Criterion of Reality and the Assumption of Locality, Bohr could only challenge it by rejecting one of these principles, or both. In fact, he seems to have been committed to rejecting both: to rejecting Locality, on the grounds that until a measurement is made, the two particles are not genuinely independent; and to rejecting the Criterion of Reality, on the grounds that there isn't a definite element of reality, until a measurement is actually made.

Einstein was aware that his opponents would try to evade the argument in this way, but he wouldn't have any of it, and for a very good reason: as I noted earlier, his own theory of special relativity provided the strongest argument in favour of Locality. His attitude is nicely summed-up in a famous remark in a letter to his old friend and colleague, Max Born (1882-1970) in 1947. (Max Born was another of the fathers, or grandfathers, of quantum theory. He was also the maternal grandfather of the Australian singer and actress, Olivia Newton-John - which means that she's a kind of second cousin of quantum mechanics!) Einstein writes to Born that he can't accept quantum theory in its current form, because 'the theory cannot be reconciled with the idea that physics should represent a reality in space and time, *free from spooky actions at a distance*.' (Letter to Born, 3 March 1947, my emphasis.)

However, the spooks were going to turn out to be much harder to eradicate than Einstein had thought and, ironically, he himself had got half way to showing why by focusing attention on the kinds of experiments involved in the EPR argument. The Irish physicist John Bell made the next crucial step in 1965, about ten years after Einstein's death. The crucial part of Bell's argument is remarkably straightforward, as we can see by examining a case that has nothing to do with quantum mechanics, at least on the surface.

The Scandinavian Institute of Synchronised Swimming

Imagine it is the year 2021. There's turmoil in the world of sport. Many countries are still reeling from their dismal performance at the Auckland Olympics the previous year where, for the first time in Olympic history, the host nation won every single medal! The three Scandinavian countries – Sweden, Norway and Denmark – decide to join forces, and to concentrate on improving a single sport. They choose synchronised swimming. At great expense, the three governments establish the Scandinavian Institute of Synchronised Swimming (SISS) – demolishing the famous Neils Bohr Institute (NBI) in Copenhagen, founded exactly a century earlier, to make way for several new swimming pools.

From all over Scandinavia, hopeful pairs of swimmers arrive in Copenhagen, hoping to be chosen for the elite training squad. Of course, there's a rigorous selection procedure. Only the most committed and synchronised teams are wanted. Here's how it works. The two candidates are separated, and isolated in different interview rooms. Each of them is then asked just one question, chosen from a list of three:

1. Would you like to swim for Sweden?
2. Would you like to swim for Norway?
3. Would you like to swim for Denmark?

The two questions are chosen at random, independently, in the two rooms, so sometimes they're the same (three times out of nine, in fact, on average) and sometimes they're different. And neither candidate knows what question the other candidate is being asked.

Of course, if the two candidates are asked the same question and give different answers, then that's the end of the matter. They're not sufficiently synchronised, and they're both shown politely to the door. So consistency is absolutely vital in this case. It's better if they both say *No* to the same question than if one says *Yes* and the other says *No*.

But what if they're asked different questions? In this case, it's no use if they both say *Yes*. That would show that they wanted to swim for different countries, and again, they'd be shown the door. And it's not much better if they both say *No*. That reduces their chances of getting picked for any of the national teams, even if they do get into the Institute. So they have to try to give different answers in this case: have one say *Yes* and the other say *No*.

So far, this is just simple sport psychology. Now let's introduce a little bit of mathematics. Let's figure out the maximum possible success rate for the second part of the strategy – the part that applies if they are asked different questions – given that they need to guarantee that they always give the same answer when they're asked the same question. Obviously, the only way to guarantee that they give the same answer if they're asked the same question is for them to agree in advance what they'll say, in response to each of the three possible questions. We can write down their possible policies in this form: YYN, YNY, etc. Thus YYN means that they would answer *Yes* to Questions 1 and 2, and *No* to Question 3. YNY means that they would answer *Yes* to Questions 1 and 3, and *No* to Question 2. And so on.

It is easy to see that there are just eight possible strategies of this kind: YYY, YYN, YNY, NYY, YNN, NYN, NNY and NNN. Of these eight strategies, two (YYY and NNN) ensure that the candidates give the same answer, no matter what two questions they are asked. So these two strategies are bad strategies. Remember, the candidates are trying to maximise their chances of giving different answers when they are asked different questions. That leaves just six possible strategies: YYN, YNY, NYY, YNN, NYN, and NNY. Let's pick one of these, say NYY, as an example, and think about what it implies about the chances of a pair of candidates who chose that strategy giving different answers, when they are asked different questions.

There are six possible ways the two candidates can be asked different questions, as in the following table; this also shows, for each combination of questions, whether the NYY candidates manage to give different answers.

Candidate A	Candidate B	Different answers?
Q1	Q2	Yes
Q1	Q3	Yes
Q2	Q1	Yes
Q2	Q3	No
Q3	Q1	Yes
Q3	Q2	No

So with the strategy NYY, pairs of candidates can expect a success rate of about 66% in their attempt to give different answers when they're asked different questions. Some will be lucky, some won't, but on average, if the questions are chosen at random, there'll still be a failure rate of around 33%.

It's not hard to see that the same applies to any of the other five strategies we just listed: YYN, YNY, YNN, NYN or NNY. In each case, there'll be two out of six possible combinations of questions in the table for which the strategy doesn't give different answers – so still a failure rate of 33%.

Let's summarise these conclusions. We've deduced that there is no strategy for making sure that the two candidates give the same answer when they're asked the same question, which also has a success rate higher than about 66% when they are asked different questions (where 'success' means giving different answers, in these cases). To put it another way, if they make sure they give the same answers to the same questions, then they'll also give the same answers to different questions, at least about 33% of the time. As we've seen, it's just a matter of arithmetic.

Is there any way to cheat the arithmetic? To do better than a 66% success rate, in the different question cases? Notice that it would be easy to do better if the two swimmers could communicate, and tell each other what their own question is – if they were telepathic, for example, and could flash a message such as 'I've got the Sweden question!' to their partner in the other interview room. But we've assumed that they're genuinely isolated. In other words, we've assumed that *the question asked in one room can't make any difference to the answer the other swimmer gives in the other room*.

Does this assumption sound familiar? It should, because effectively it is the Assumption of Locality, as used by Einstein, in his argument that quantum mechanics is incomplete. In other words, we should really put our conclusion like this:

> **SISS Theorem**: If the Assumption of Locality is true for candidates interviewed for the SISS, then the maximum success rate in the different-question cases is 66%.

If the Assumption of Locality is true, in other words, then there's no way for the candidates to cheat the arithmetic.

Quantum Mechanics to the Rescue?

What has this got to do with quantum theory? It's simple. Somehow, quantum mechanics does manage to cheat the arithmetic. In fact, if the founders of SISS hadn't demolished the Niels Bohr Institute so hastily, they would have discovered that there's a way to use quantum mechanics to get a higher success rate than the arithmetic seems to allow. And the bit of quantum mechanics we need is very similar to the kind of experiments discussed by Einstein, in the EPR argument of 1935. Like that argument, it involves physical systems in which we have two particles produced in some common source, which can then be measured in different locations.

In the original EPR experiment, we had a choice of two measurements on each particle, either position or momentum. But there are similar experiments in which we can find three possible measurements we can perform on each particle, each of them mutually exclusive with the other two. In other words, just as we can measure either the position or the momentum but not both in the original experiment (remember, this is Heisenberg's Uncertainty Principle at work), so we can measure just one of these three new properties in the new EPR experiments.

One example is provided by the polarisation of photons, or particles of light. We can measure the polarisation of a photon by putting a polarising lense in front of it, and detecting whether it passes through. And we can rotate the lense, and thus measure the polarisation in different directions. What we can't do is measure the polarisation in more than one direction at the same time.

Thus versions of the EPR experiment with polarisation measurements work just as well as Einstein's original, for the purposes of Einstein's argument. If we choose our pairs of photons in the right way, we can find out the polarisation of one photon, for a particular orientation of the lense, by measuring the polarisation of the other photon in the same orientation. Again, there's a perfect correlation between the two results – or more exactly, an anti-correlation, in the sense that if one photon goes through the polariser, the other one is always blocked, and vice versa. (We can turn it into a perfect correlation by rotating one polariser through 90°.)

Another version of the EPR experiment uses electrons. In this case we measure a property of the electrons called 'spin', which is related to angular momentum. Like polarisation, it is measured in a chosen direction perpendicular to the direction of travel of the particles. Whatever direction we choose, electrons always turn out to have a spin of either +1/2 or -1/2 (don't worry too much about what the numbers mean) in the chosen direction; and if a pair of electrons is produced in the right way, the total spin must be zero, and so there must be one of each. So a spin measurement on one particle enables us to predict the result of a corresponding measurement on the other particle (i.e., a spin measurement at the same angle, perpendicular to the line of flight of the electron), just as in the original EPR case.

In the spin case, the physics gives us a perfect anti-correlation. In other words, if we get a result of +1/2 on one side we get -1/2 on the other. But by making the measurement on one side reveal 'minus-spin' (that is, making the device display +1/2 when it measures -1/2, and vice versa) we easily turn this into a perfect correlation. Better still, we can set things up so that on one side the measurement device shows YES when it records +1/2 and NO when it records -1/2, and on the other side, the same in reverse.

We then have something with exactly the same form as the SISS case, if we let the three different questions in the SISS case correspond to measuring the spin in three directions spaced at 120° with respect to each other, perpendicular to the line of flight. In effect, there are three different 'questions' we can ask each electron, and the measuring device produces either a 'Yes' or a 'No'. And if we ask the same question, we get the same answer, on both sides.

The simple arithmetic we used in the SISS case proves that if the questions are chosen at random on each particle, then when the two particles are asked different questions they will produce the same answer *at least 33% of the time*. As in the

SISS case, the argument depends on the Assumption of Locality – but as long as that holds, it is just arithmetic.

This piece of simple arithmetic now has a name in quantum theory. It's called *Bell's Inequality*, after the physicist who first saw its importance. (It is called an 'inequality' because it says that the correlation has to be at least 33%.) Why is it important? Because, as Bell realised, *quantum mechanics predicts something different*. Depending on how we set up the experiment, quantum mechanics predicts a correlation as low as 25%, in these cases in which the two particles are subject to different measurements.

John Bell

One way to see how surprising this is is to notice that if SISS hadn't demolished the Niels Bohr Institute, they could have used a real-life device, based on quantum mechanics, to cheat the arithmetic we derived above. In principle, it could work like this. Electrons or photons would be produced in the right kind of pairs, and directed into mirrored boxes, where they could be stored until needed. Each candidate would take one box, and a three-setting measurement device. They'd be instructed to base the measurement setting on which of the three possible questions they were asked, and to base the answer to the question on the result of the measurement on the particle in the box. With careful experimental design, they could certainly do better than the theoretical limit of 33% – in principle, according to quantum mechanics, they could reduce the number of occasions on which they gave the same answer to different questions to around 25%.

In other words, quantum mechanics enables our swimmers to do something that is mathematically impossible, if the Assumption of Locality is true. *So quantum mechanics must imply that the Assumption of Locality is false!* That was John Bell's great discovery.

Synchronised Spookiness

Thus Einstein had assumed Locality, and used it, in an ingenious argument based on these two-particle EPR experiments, to argue that quantum mechanics is incomplete – that quantum theory must be a fuzzy picture of a sharper reality. But Bell showed that those same EPR experiments could be used to show that the predictions of quantum mechanics were inconsistent with the Assumption of Locality. If quantum mechanics is right, then the Assumption of Locality is wrong anyway, and Einstein's argument for the fuzzy interpretation collapses.

For this reason John Bell is sometimes called the man who proved Einstein wrong. But it is important to be clear what Bell actually proved Einstein to be wrong about. Bell did show that Einstein must be wrong about the Assumption of Locality (at least if quantum mechanics is true). But he didn't show, as people often wrongly assume, that Einstein was wrong about quantum mechanics being incomplete. It could still be true, as Einstein thought, that there are extra 'hidden variables', not described by quantum mechanics. It is just that they couldn't be *local* hidden variables, satisfying the Assumption of Locality. Somehow, the measurement made on one particle would have to affect the hidden variables of the other. (There are some well-developed extensions of quantum mechanics of this kind. The best-known was invented by the physicist David Bohm (1917-1992), who also invented the version of the EPR experiment described above, on which Bell's analysis was based.)

David Bohm

Where do we stand, then, in the light of Bell's result? First, Einstein's best argument for the fuzzy picture view of quantum mechanics has been seriously undermined. Secondly, and more importantly, Bell has put his finger on a simple and basic fact: *if quantum mechanics is true, then the Assumption of Locality is false, and vice versa*. If quantum mechanics is true, in other words, *there really is spooky action at a distance*.

At the time of Bell's original work, in the 1960s, experiments to test the predictions of quantum mechanics were not technically feasible. But by the 1970s, various experimenters were devising ways to do it, and since then the predictions of quantum mechanics have been confirmed many times. (The best-known results are those of a team led by the French physicist, Alain Aspect.) So very few people doubt that 'Non-locality' is here to stay.

> "...the strongest reason for believing in Locality is Einstein's own special theory of relativity."

As we saw earlier, however, the strongest reason for believing in Locality is Einstein's own special theory of relativity. Accordingly, the real importance of Bell's results is that they expose a very deep tension between the two most important theories in twentieth century physics. Roughly speaking, quantum mechanics does something that simply shouldn't be possible, according to special relativity. Quantum systems can be 'entangled' in some strange way, even when they are very long distances apart. (In principle, we could arrange an EPR experiment in which the two particles had travelled light years apart. Almost everybody in physics now believes that even in this case, the bizarre effects of quantum entanglement would still apply.)

It is true that there are some subtleties here, which soften the blow a little. It looks as if the strange non-local correlations that Bell noticed in EPR experiments can't be used to send faster-than-light messages, for example – there's no prospect of an instantaneous 'Bell telephone', as someone once put it. But the conflict is there all the same, and Bell himself thought that it implied that Einstein's own understanding of the meaning of special relativity was wrong – that we had to go back to the 'pre-revolutionary' ideas that physicists such as Lorentz had developed before Einstein.

Back From the Future?

To end this chapter, I want to describe another curious idea, sometimes suggested as a way of resolving the tension between quantum mechanics and relativity. I'll introduce it by going back to our synchronised swimmers in 2021, trying to ensure that they give different answers when they're asked different questions at the SISS admission interviews. Think how easy it would be for the swimmers if they had precognition – if they could just 'see' in advance what question they were going to be asked. If they knew this before they left each other's company, then it would be easy for them to collaborate, to make sure they gave different answers. (For example, suppose the two swimmers foresee that they are going to be asked questions 1 and 2 from the list of three. They could then adopt a strategy such as YNY, which gives different answers to these two questions).

This possibility reveals another hidden assumption in the mathematical argument we used to show that the maximum possible success rate was around 66%. We were assuming, implicitly, that the swimmers didn't know the questions in advance – that their strategy had to be independent of the choice of question in the future.

In the case of quantum particles, this amounts to the assumption that the properties of the two particles in an EPR experiment cannot be affected by the kind of measurement they're going to encounter in the future. (If they're affected by the future measurement, then they 'know about it', at least metaphorically speaking; and again, there's a possible way of cheating the arithmetic – getting a success rate higher than 66%.)

Of course, this assumption seems uncontroversial. How could photons and electrons possibly know anything about what is going to happen to them in the future? But it's worth examining this issue a little more closely. After all, we don't find anything controversial about the idea that photons and electrons know something about what happened to them in the past; or in other words, less metaphorically, that their properties depend on what happened to them in the past. So why not the future, too?

At this point, we get to a fascinating tug of intuitions. On the one hand, it seems *just obvious* that causation only works one-way, from past to future – the past can affect the future, but the future can't affect the past. On the other hand, however, the basic laws of physics seem to make no distinction between the past and the future. At the fundamental level, physics is almost entirely *time-symmetric*, in the sense that if it allows a process to happen then it also allows the reverse process to happen (roughly, what we would see if we reversed a video of the first process). So where does the past-future bias of causation come from, if it isn't in the fundamental physics?

We don't have time to explore these issues here. They would take us deep into philosophy, as well as physics. But to finish up with, let's think about what it would mean for the conflict between Bell's

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a point, such as when you throw a stone into a still pond or spa bath. These symmetries turn out to be greater than many have previously thought, and from this idea one can get almost a whole theory of backwards-in-time causation ... something which might come in very handy for contestants on Survivor.

If you could go back and specialise in a different field, what would it be and why?

When I was appointed to a Personal Chair at the University of Sydney, I actually had the opportunity to name the chair, and I thought of calling myself Professor of Management Consulting, so that I could make a lot of money on Friday afternoons. So that would be one option. It is possible to make a bit of money in science, but the really big bucks go to the less honest among us. Another thing I might have liked to specialise in would have been philosophy. That might have been fun.

What's the 'next big thing' in science, in your opinion? What's coming up in the next decade or so?

As someone at the very theoretical end of the spectrum it's hard for me to know what will be next. In theoretical science you can never say with much confidence what the next big thing will be, because if you could you'd already have it. But it's fun to guess.

result and relativity, if we allowed 'backward causation'. Suppose the properties of our two electrons are affected by the measurements we choose to perform on them in the future. Then when we choose what measurement to make on Particle 1, we affect its properties, all the way back to the source. However, at the source, Particle 1 interacts with Particle 2. So by affecting the properties of Particle 1, it is possible, at least in theory, that we could affect Particle 2, as well; and Particle 2 could then carry those effects into the future, to the time at which its properties are measured, on the other side of the experiment.

But this means, the choice of measurement on one side of the EPR experiment could affect the results on the other side – and all without any spooky actions at a distance! All the actions are ordinary local actions, and the only novelty is that one of them works backwards in time.

So here's a *possible* resolution of the mystery, a resolution which ought to make Einstein happy, at least in one sense, because it avoids spooky action at a distance. On this account, the 'non-local' effects that look like action at a distance actually turn out to be the result of a combination of two component actions, each of which is thoroughly compatible with relativity. (In other words, the proposal shows how we could have a kind of pseudo-non-locality, that isn't really in tension with relativity. Apparent action at a distance gets resolved into a kind of zig-zag effect, where the 'zig' goes backwards in time.)

I stress that at this stage, this is just an intriguing idea. It hasn't been developed very far, and most physicists and philosophers seem to think that this kind of backward causation is even more spooky than the actions at a distance that Einstein hated so much. But as I mentioned a moment ago, the temporal bias of ordinary forward causation is itself a bit spooky, or at least mysterious, in the light of the apparent time-symmetry of fundamental physics. So it's just possible that this strange idea will turn out to rid physics of two spooks, though admittedly at the cost of some considerable damage to naive ideas of cause and effect. If so, then it will have turned out that Einstein was right after all, in two ways: first, in thinking that there is no genuine action at a distance; and second, in believing that quantum mechanics is incomplete (for if this proposal is right, then ordinary quantum mechanics leaves out the mechanisms responsible for these zig-zag causes).

I'd like to speculate that time-symmetric theories of physics, incorporating backwards causation, will be one big thing in theoretical physics. Also probably esoteric theories of computation: that field's been a bit static since shortly after Turing founded the field in the 1930s, but if quantum computing works then Turing's whole theory will have to be reworked. Turing was an interesting character. He is perhaps most famous for his saying, "It's amazing what people will believe if they read it on the web, even though they wouldn't believe it if they read it anywhere else." Widely recognised as a genius at an early age, he was driven to suicide in the 1950s by the homophobia of his society. I can't predict whether the same thing will happen to the new theoreticians of computing.

The third big thing I predict is something like a cross between old-skool rap and progressive house, only with a bit of an acid jazz backbeat. Either that or yet another blatant Christmas song, perhaps with Rolf Harris.

Q&A with Professor Huw Price (with a little help from Jason Grossman)