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Spooky action and beyond

Viennese physicist Anton Zeilinger talks about teleportation, the information stored in a human being and freedom in physics.

***Die Weltwoche**: Professor Zeilinger, the media calls you "Mister Beam". You personally were absolutely against the association with beaming. Why?*

Anton Zeilinger. Photo: Jacqueline Godany

Anton Zeilinger: Because it gives the wrong impression of my work. "Beaming" exists only in science fiction films, where it was invented as a money-saving device. Actually having to land on all those planets runs up huge production costs. Beaming is cheaper: 1,2,3 and you're somewhere else. But that's a long way from anything we're doing here.

What are you doing?

Transferring the properties of light particles over certain distances onto other light particles, with no time delay. The procedure is based on phenomena which exist only in the quantum world, and is known as "**quantum teleportation**."

It sounds almost as exciting as "beaming".

Yes, but there are two major differences. Firstly, we **transfer properties**, not matter. And secondly, until now we have had more success with light particles and occasionally with atoms, not with larger objects.

In 1997 your team successfully performed the first quantum teleportation. What distances can be crossed with this technique today?

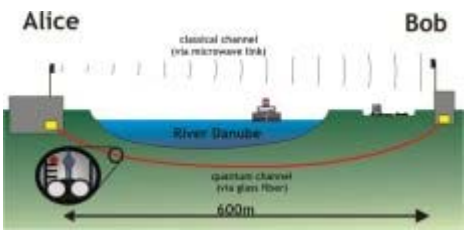

illustration of the teleportation of light particles under the Danube

Last year we teleported light particles across a distance of 600 metres under the Danube – that's the current world record. In theory the range is limitless. I always say that when the Americans really start their Mars mission, the 280-day journey will be deadly boring for the astronauts. They might be interested in taking part in a few teleportation experiments on the way, and increase the record by a hundred million kilometres or so.

You said that you only transfer properties, not particles. Would "copying" not be a more accurate expression than "teleportation"?

No. Firstly it differs from simple copying in that the original **loses all its properties**. That is something so crazy that it could only exist in the quantum world. You can actually remove all the properties of a particle and give them to another particle.

But both particles remain where they are.

Yes, but the question is: how do I recognise an original? I maintain: solely through its properties. Matter itself is completely irrelevant. If swap all my carbon atoms for other carbon atoms, I am still Anton Zeilinger.

This happens over the course of our lives. We are continually changing our cells.

Exactly. The only important thing are my properties, and they are based on the order of the atoms – that what makes me who I am. The atoms are unimportant in themselves. So when we transfer characteristics during teleportation, in this sense we are actually **transferring the originals**.

Some teams of physicists are already teleporting single atoms. So what really stands in the way of beaming humans?

We are talking about quantum phenomena here – we have no idea how we could produce these with larger objects. And even if it was possible, the problems involved would be huge. Firstly: for physical reasons, the original has to be **completely isolated** from its environment for the transfer to work. There has to be a total vacuum for it to work. And it is a well-known fact that this is **not particularly healthy** for human beings. Secondly, you would take all the properties from a person and transfer them onto another. This means producing a being who no longer has any hair colour, no eye colour, nix. A man without qualities! This is not only unethical – it's so crazy that it's impossible to imagine.

Well, in Vienna perhaps... But you said that another problem was the mass of information. You once calculated that if you burnt all the information in one human being onto CDs there would be enough of them to make a tower that reached from here to the centre of the milky way.

That was a few years ago – with today's technology the tower would not be quite so tall. But we can do a rough calculation. The atoms in a human being are the equivalent to the information mass of about a **thousand billion billion billion bits**. Even with today's top technology, this means it would take about 30 billion years to transfer this mass of data. That's twice the age of the universe. So we'll need a number of major breakthroughs in technology first.

What do think are the limits of teleportation?

Who knows, perhaps in a thousand years we really will be able to **teleport a coffee cup**. But beware: even the tiniest interference can mean that the cup arrives without its handle. This method of transport would be far too dangerous for humans.

Why is the procedure so sensitive to disturbance?

Because any disturbance – and this goes for a measurement or observation – alters the state of the particles which are involved in the teleportation. The rules of quantum physics are completely different from those of the world we live in. For quantum teleportation we use methods of entanglement. This is a particular state which can connect two or more particles, but which disappears as soon as it is observed from outside.

Entanglement – we should imagine this as...

...there is no way of imagining it. The Austrian physicist Erwin Schrödinger coined the term in 1935 and also said that the twist in the phenomenon of quantum physics is that it forces us to **bid farewell** to all our dearly held ideas about the world.

Help us do this!

When two particles collide like billiard balls at a quantum level, then they are immediately linked or "entangled". Neither of the two particles has a clearly defined position or a clearly-defined momentum: location and speed are uncertain, as we say.

Heisenberg's famous uncertainty principle.

Exactly. But then I can go and measure, say, the momentum of one of the entangled particles. By way of this measurement, the momentum which was previously uncertain can now be determined. The peculiar thing is that in the same instant, the second particle also gains a clearly-defined momentum. No matter how far away it is.

Albert Einstein called this effect "spooky action at a distance"

Right. But the truly strange is yet to come.

I can't wait.

The result of my measurement of the first particle is **completely random**. There is no way of predicting it, on principle. But as soon as I have the result, I can deduct the momentum of the second participle.

So I can accurately measure the momentum of the second particle, even if it is hundreds of billions of kilometres away.


illustration of a non-local four-proton entangled state

Theoretically yes. The effect has so far been proved across a distance of a hundred kilometres. The amazing thing is that there can be **no exchange of information** between the two particles. They react absolutely in synch, although they could could never know anything of each other's existence. You can think of it as two dice far away from each other that always land on the same number, without there being any kind of mechanism which connects them. Absurd!

Uncertainty, coincidence, spooky effects – doesn't it make you dizzy sometimes?

It's all pretty crazy. The spooky effect at a distance is a process outside time and space that even I can't really imagine. But I believe that quantum physics tells us something very profound about the world. And that is that the world is not the way it is independently of us. That the characteristics of the world are to a certain extent **dependent on us**.

That almost has a New Age ring.

You have to be careful not to be cubby-holed. I mean it's like this: an experimenter can determine through his choice of measuring equipment which physical size becomes reality. Take a particle with an uncertain location and an uncertain velocity. When you look at it through a microscope and locate it, the particle gives you an answer: "Here I am." That means, the location becomes reality at that moment. Beforehand, the particle had no location at all. With the choice of the measuring equipment we've had a major impact on reality. But the answer that nature gives is completely random.

I choose the measuring equipment, and nature chooses the result?

That's right. I call that the **two freedoms**: first the freedom of the experimenter in choosing the measuring equipment - that depends on my freedom of will; and then the freedom of nature in giving me the answer it pleases. The one freedom conditions the other, so to speak. This is a very fine property. It's too bad the philosophers don't spend more time thinking about it.

I'd like to come back to these freedoms. First, if you assumed there were no freedom of the will – and there are said to be people who take this position – then you could do away with all the craziness of quantum mechanics in one go.

True – but only if you assume a completely determined world where everything that happened, absolutely everything, were fixed in a vast network of cause and effect. Then

sometime in the past there would be an event that determined both my choice of the measuring instrument and the particle's behaviour. Then my choice would no longer be a choice, the random accident would be no accident and the action at a distance would not be action at a distance.

Could you get used to such an idea?

I can't rule out that the world is in fact like that. But for me the freedom to ask questions to nature is one of the most essential achievements of natural science. It's a discovery of the Renaissance. For the philosophers and theologians of the time, it must have seemed **incredibly presumptuousness** that people suddenly started carrying out experiments and asking questions of nature and deducing laws of nature, which are in fact the business of God. For me every experiment stands or falls with the fact that I'm free to ask the questions and carry out the measurements I want. If that were all determined, then the laws of nature would only appear to be laws, and the entire natural sciences would collapse.

Are there physicists who advocate complete determinism?

I've met one. At the time I was a lot younger and cheekier than I am today, and I intentionally insulted him publicly at a conference. He was incensed. I said to him: "Why are you getting so upset? Neither you nor I are free in what we do."

I'd like to come to the second freedom: the freedom of nature. You said that for example the velocity or the location of a particle are only determined at the moment of the measurement, and entirely at random.

I maintain: it is so random that **not even God** knows the answer.

Ultimately that implies something monstrous: namely that the particle had absolutely no characteristics before it was measured. The great Danish physicist Niels Bohr once said: no one has ever seen a chair. There is no objective reality. Only that which is measured exists. We construct reality, and only in the moment of measurement or observation.

I think you have to make a distinction: in my view there is something that exists independently of us – in physics we call that **the singular event**. For example the activity of a particle detector. Or the activity of a certain cell in my eye, which registers a certain number of light particles and then provokes a chemical reaction that is then registered in the brain. The images that we form on the basis of this are our constructs. Bohr's chair or on a much more abstract level, the quantum mechanics equation of states, are our **concepts of an object**. Of course they are very purpose-oriented, because they've been corroborated with repeated use.

So there is in fact something that exists independently of us. And the moon is also there when I'm not looking at it.

Something exists, but it is not directly accessible to us. Only indirectly. And whether this thing must really be called the "moon" is another question. That is also **a construct**.

But there is something up there...

... the word "there" is yet another construct. Space and time are concepts aimed at giving meaning to our world of appearances. So they are entirely reasonable constructs. By no means do I want to give the impression that I believe everything is just our imagination.

The world as a huge theatre that only plays in our heads.

That is certainly not my view of things.

Then what would you call it, this something that you can't call moon or space or time – this something that exists independently of us?

Wouldn't I be making another qualification if I tried to **give it a name**? Isn't it enough if I just say it exists? As soon as you use words like "world" or "universe", you start lugging about all that **conceptual ballast** again.

But you defend the thesis that there is an "original matter of the universe": information.

Yes. For me the concept of "**information**" is at the basis of everything we call "nature". The moon, the chair, the equation of states, anything and everything, because we can't talk about anything without de facto speaking about the information we have of these things. In this sense the information is the basic building block of our world.

But just now you spoke of a world that exists independently of us.

That's right. But this world is not directly ascertainable or describable. Because every description must be done in terms of the information, and so you inevitably get into circular reasoning. There's a **limit we can't cross**. And even a civilisation on Alpha Centauri can't cross it. For me that's something almost mystical.

In your last book you wrote: "Laws of nature should make no distinction between reality and information." Why?

We've learnt in the natural sciences that the key to understanding can often be found if we **lift certain dividing lines in our minds**. Newton showed that the apple falls to the ground according to the same laws that govern the Moon's orbit of the Earth. And with this he made the old differentiation between earthly and heavenly phenomena obsolete. Darwin showed that there is no dividing line between man and animal. And Einstein lifted the line dividing space and time. But in our heads, we still draw a dividing line between "reality" and "knowledge about reality", in other words between reality and information. And you **cannot draw this line**. There is no recipe, no process for distinguishing between reality and information. All this thinking and talking about reality is about information, which is why one should not make a distinction in the formulation of laws of nature. Quantum theory, correctly interpreted, is **information theory**.

And can you explain all these strange quantum phenomena conclusively with your information concept?

Not all of them yet, but we're working on it. With **limitation** it works excellently.

How?

I imagine that a quantum system can carry only a limited amount of information, which is sufficient only for a single measurement. Let's come back to the situation of two particles colliding like billiard balls, and in so doing entering a **state of limitation**. In terms of information theory that means that after the collision the entire information is smeared over both particles, rather than the individual particles carrying the information. And that means the entire information we have pertains to the relationship between both particles. For that reason, by measuring the first particle I can anticipate the speed of the second. But the speed of the first particle is entirely random.

Because the information isn't sufficient.

Exactly. Its randomness is ultimately a consequence of the finiteness of the information.

Dr. Zeilinger, you belong to the rare species of philosophising physicists. Earlier there were more, especially in Austria: Wolfgang Pauli, Schrödinger, Ludwig Boltzmann, Ernst Mach...

Not only in Austria. It may be that Vienna is a special city, but there was and still is a tradition in Europe of philosophical thinking among physicists. I saw that in 1977 when I went to America for the first time. Already after a couple of weeks I started to miss philosophical discussion. Here we're more ready to ask really fundamental questions. In Europe it's important to question things. In America it's important to be able to build something. I don't mean that at all negatively.

That's probably what accounts for American superiority, especially in technology.

Certainly. And it also has to do with the American **pioneer spirit** and the "success" of natural sciences in World War II. But I think the European approach is more successful in the long run. Precisely in terms of the major problems facing physics. We've now been working on the unification of gravitation and quantum physics for almost eighty years – there must be something **wrong with our concepts**. I'm convinced we can only succeed with an entirely new philosophical approach.

But in recent times you've also proceeded with a very American-like idea: an elite university for Austria.

Yes, we've been looking for a good name for some time. It's now called "Austrian Institute of Advanced Science and Technology". The idea is to create a scientific institution with an absolutely world-class status, one that attracts the very best people. Something like the ETH in Zurich but...

... a little better?

Well, in some areas the ETH is very, very good, but not in all. That's the major disadvantage of European universities, this mix of **excellence and mediocrity**. You find it in almost every university in Europe. In America, by contrast, differences of quality exist more between the various institutions. There are some absolutely first rate ones, but there are also many mediocre, and even poor ones. My idea is a university solely for doctoral and post-doctoral work. 500 people at the most, a campus where people are constantly discussing and exchanging ideas. In my experience the best results are achieved where there's a high degree of interdisciplinary cooperation.

How far along is the Austrian Institute?

The project is ready, the government has expressed its approval, all that's missing is the money.

It's probably not cheap.

The cost is no higher than a **few kilometres of motorway**: fifty to eighty million euros in initial capital and roughly the same amount again every year in operating costs. I'm convinced Austria needs it. And I'm convinced that in ten or twenty years our region will have such a top-class university. The question is only where. Here, in Bratislava, or in Warsaw?

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*Here a list of books by **Anton Zeilinger**. His most recent work, "Einsteins Spuk. Die neue Welt der Quantenphysik." (Einstein's Veil. The New World of Quantum Physics) is published by Bertelsmann.*

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Anton Zeilinger *is a professor of physics at Vienna University.*

Translation: lp, jab.

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