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Introduction to Physics & Nanotechnology:
part 4

Учебное пособие

Саратов

2016

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INTRODUCTION TO PHYSICS & NANOTECHNOLOGY: part 4: Учебное пособие по физике и нанотехнологиям для студентов неязыкового вуза /Сост. А.И. Матяшевская, Е.В. Тиден. — Саратов, 2016. — 54 с.

Предлагаемое учебное пособие представляет собой тексты по данной специальности с системой упражнений, направленных на развитие навыков устной и письменной речи. Аутентичный учебный материал позволяет решать учебно-методические проблемы на современном уровне.

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Работа издана в авторской редакции

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PREFACE

Настоящее пособие включает тексты по актуальной на сегодняшний день проблемам физики и нанотехнологий.

Пособие предназначено для студентов факультета нано- и биомедицинских технологий.

Целью данного пособия является формирование навыка чтения и перевода научной литературы, а также развитие устной речи.

Данное пособие помогает подготовить студентов к самостоятельной работе со специальной литературой, обучить устным формам общения по научной тематике на материале предложенных специальных текстов.

Пособие состоит из разделов, посвященных нанотехнологиям, механике, каждый из которых содержит тексты и упражнения. Раздел “Supplementary reading“ служит материалом для расширения словарного запаса и дальнейшего закрепления навыков работы с текстами по специальности.

Пособие предназначено как для аудиторных занятий, так и для внеаудиторной практики.

Where Traditional Physics Stops

Part 1

Exercise I .

Say what Russian words help to guess the meaning of the following words: physics, examine, idea, mechanics, extreme, galaxies, original, classic, discussions, formula

Exercise II

Make sure you know the following words and word combinations.

fusion reactions (6), fission reactions (6),antimatter (6), positrons (6), quantum physics (7), subatomic particles (7), wavelength (7), orbit (7), uncertainty principle (8), momentum (8)

Where Traditional Physics Stops

We're about to move into the modern age of physics. In the early 1800's, scientists began examining the basis of matter, space, and time. Sometimes it gets very confusing, but the big idea is that Newton's physics describe about 90% of the way things work in the universe (mechanics). His ideas start to break down when you talk about ideas such as objects moving at the speed of light, the inside of atoms, extreme temperatures, and when the objects are huge (like galaxies interacting with each other). (1)

Into the Atom

The original idea of atoms developed by Niels Bohr showed a structure based on various shells and a center area called the nucleus. The electrons were found in those shells while the protons and neutrons were found in the nucleus. There are other ways to look at the structure of atoms (you may have heard of "spdf"), but we're going to stick with the classic view for many of our discussions. This view of the structure of an atom was one of the foundations for modern physics. (2)

Into the Universe

Albert Einstein also played a large part in modern physics. He developed formulas that described the way matter and energy were related. Just about everyone has heard of the formula E=mc^2. That formula explains how energy is related to mass. The idea found its way into the study of fission reactions, and it was proved that enormous amounts of energy were stored in even one atom of a substance. (3)

Current Studies

Even now, scientists are still testing the boundaries of physics and the laws of physics. Only a few years ago a new state of matter was created. The Bose-Einstein condensate was theorized decades ago, but scientists have only recently been able to create it in a lab. Every day astronomers are studying space and learning how black holes and galaxies interact. Stephen Hawking is one of the more famous scientists working in that field. Our point is, there is still much to discover. (4)

Looking at the Nucleus

While atomic physics deals with atoms as a whole, nuclear physics deals specifically with the nucleus of the atom. Physicists still need to understand the area around the nucleus, but they are more concerned with the forces at work keeping that nucleus together. Once they understand those forces, they often try to create new types of fusion and fission reactions. Nuclear energy is the energy released when the nuclei of atoms split or are fused. The nucleus is made up of protons and neutrons. Nuclear forces hold all of the pieces together. Fusion is when two nuclei come together. Fission is when one nucleus is split into two or more parts. Huge amounts of energy are released when either of these reactions occurs. Fusion reactions create much of the energy given off by the Sun. There are even smaller particles that make up the protons and neutrons that physicists are studying every day. (5)

Antimatter

Since we are talking a little about atomic and nuclear physics, we wanted to tell you about antimatter. It is not just found in television shows. Scientists have discovered evidence that it is real. While a regular atom has positive and neutral pieces (protons/neutrons) in the nucleus and negative pieces in orbiting clouds (electrons), antimatter is just the opposite. Antimatter has a nucleus with a negative charge and little positive pieces in the orbits. Those positively charged pieces are called positrons. (6)

Looking into Atoms

Quantum physics is a branch of physics that works with the activities going on inside of atoms. They talk about subatomic particles interacting with each other. We're starting to talk about Albert Einstein and Max Planck's ideas here. In the early 1900's, scientists were beginning to examine the inside of atoms. They were wondering what was going on inside those things that were once thought to be solid. One big idea they came up with was that the energy of an electron depends on the frequency, or wavelength, of the EM Radiation. Another interesting idea they discovered was that energy didn't depend on the intensity, or amount, of radiation. If you apply this idea to the structure of an atom, in the older, Bohr model, there is a nucleus and there are rings (levels) of energy around the nucleus. The length of each orbit was related to a wavelength. No two electrons can have all the same wave characteristics. Scientists now say that electrons behave like waves, and fill areas of the atom like sound waves might fill a room. The electrons, then, exist in something scientists call "electron clouds". The size of the shells now relates to the size of the cloud. This is where the spdf stuff comes in, as these describe the shape of the clouds. (7)

The Uncertainty Principle

A German scientist named Werner Heisenberg came up with this idea called the uncertainty principle. He figured that the position and momentum of an atomic particle cannot both be observed accurately at the same moment in time. The idea shows that because these pieces are so small, whatever device you use to measure the particles will affect them. Think about it. If you use light to examine a piece of light, won't you knock it around? Well now you just lost the idea of position. What if you freeze it in place? That's all very well, but now you don't know where it was going, or how much momentum it had. When you increase the precision of one measurement, the other measurement will suffer. Look at the Heisenberg uncertainty principle in a more general way using the observer effect. While Heisenberg looks at measurements, you can see parallels in larger observations. You can not observe something naturally without affecting it in some way. The light and photons used to watch an electron would move the electron. When you go out in a field in Africa and the animals see you, they will act differently. If you are a psychiatrist asking a patient some questions, you are affecting him, so the answers may be changed by the way the questions are worded. Field scientists work very hard to try and observe while interfering as little as possible.(8)

Exercise III.

Find paragraphs, dealing with the following:

formula, condensate, astronomers, rings, parallels

Exercise IV.

1. How does the quantum mechanical model describe electrons?

2. In the Heisenberg uncertainty principle, which two measurable properties of a particle cannot be observed precisely at the same time?

3. What is a wave function? The square of a particle’s wave function describes the probability of what about the particle?

4. What was the first antiparticle to be discovered? What does the Dirac equation show?

5. What do we call the angular momentum of a particle in quantum mechanics?

6. Max Planck’s great discovery was that radiation energy is emitted in packets. What are they called?

7. Why are electrons assigned quantum numbers?

8. When two particles are entangled and it is observed that one has its spin up, how long does it take for the other's spin to be down?

9. Which of these is not one of the four basic forces: momentum or strong nuclear force or gravity or electromagnetism?

10. Fundamental or elementary particles are particles that aren't made up of smaller particles. What is the most common type of fundamental particle in the universe?

11. Why do positrons have a very short-term existence in our universe?

12. At the present time, what particles are considered to be the elementary ones?

13. How much of our universe is made of matter or energy, which we do not know about?

14. Many scientists believe that time travel to the future could be achieved. What is a way in which a person could hypothetically travel to the future?

15. Traveling to the past poses more problems than traveling to the future. Many complex obstacles could arise in past time travel, leading physicists to believe that it is impossible. One of the major objections to the possibility of time travel is the "Grandfather Paradox". What does this paradox state?

16. The "Twins Paradox" is another example used by physicists to deny hypothetical time travel. What does it state?

Exercise V.

Fill in the gaps according to the text.

1. The original idea of atoms developed by Niels Bohr showed a structure based on various shells and a center area called the…………
2. …………also played a large part in modern physics.
3. Every day astronomers are studying space and learning how black holes and …………interact.
4. While atomic physics deals with ………..as a whole, nuclear physics deals specifically with the nucleus of the atom.
5. The……… is made up of protons and neutrons.
6. ……….is when two nuclei come together.
7. ……….is when one nucleus is split into two or more parts.
8. Fusion reactions create much of the energy given off by the.
9. Those positively charged pieces are called …………
10. Quantum physics is a branch of physics that works with the activities going on inside of …………

Exercise VI .

Make up sentences of your own with the following word combinations:

be about to, break down, at the speed of light, extreme temperatures, come up with, to stick with the classic view for, be concerned with, be made up of, hold something together, discover evidence

Exercise VII.

Determine whether the statements are true or false. Correct the false statements:

1. In the early 2000's, scientists began examining the basis of matter, space, and time.
2. The electrons were found in the nucleus while the protons and neutrons were found in those shells.
3. Albert Einstein developed formulas that described the way matter and energy were related.
4. Many years ago a new state of matter was created.
5. Nuclear energy is the energy released when the nuclei of atoms split.
6. Nuclear forces hold all of the pieces together.
7. Antimatter has a nucleus with a positive charge and little negative pieces in the orbits.
8. In the early 1900's, scientists were beginning to examine the inside of atoms.
9. No two electrons can have all the same wave characteristics.
10. Scientists now say that electrons behave like waves, and fill areas of the atom like sound waves might fill a room.

Exercise VIII .

Match the words to the definitions in the column on the right:

uncertainty principle	an extremely small piece of matter that is smaller than an atom or found inside an atom, such as a proton, neutron, or electron
antimatter	the process or result of joining two or more things together to form a single entity
fission	the branch of physics concerned with quantum theory
wavelength	an extremely small piece of matter with a positive electrical charge, having the same mass as an electron
subatomic particles	the path of an electron round an atomic nucleus
momentum	division or splitting into two or more parts
fusion	the distance between successive crests of a wave, especially points in a sound wave or electromagnetic wave
quantum physics	the quantity of motion of a moving body, measured as a product of its mass and velocity
positron	matter that consists of particles that

	have the opposite electrical characteristics of the particles in regular matter
orbit	the principle that the momentum and position of a particle cannot both be precisely determined at the same time

Exercise IX.

Summarize the article “Where Traditional Physics Stops.”

Part 2

Exercise I.

Identify the part of speech the words belong to.

modern, scientist, universe, extreme, huge, galaxy, discussion, foundation, fission, reaction

Exercise II .

Form nouns from the following words:

original (2), describe (3), relate (3), create (4), interact (4), discover (4), atomic (5), real (6), opposite (6), examine (7)

Exercise III.

Find synonyms to the following words. Translate them into Russian: explore (1), substance (1), maximum (1), discourse (2), base (2), evolve (2), keep (2), border (4), lately (4), popular (4)

Exercise IV .

Find antonyms to the following words. Translate them into Russian:

clear (1), lost (2), atypical (2), fusion (2), disprove (2), performance (6), imaginary (6), irregular (6), boring (8), indifference (8)

Exercise V .

Match the words to make word combinations:

fission	effect
black	particles
uncertainty	reactions
extreme	physics
subatomic	holes
observer	principle
nuclear	temperatures
orbiting	pieces
negative	clouds

Exercise VI.

QUIZ:

1. What must we do to make time travel possible?

A. We have to reach a speed of 100,000 km/h

B. We have to crook the space-time

C. We have to reach a speed of 200,000 km/h

D. We have to reach a speed of 300,000 km/h

E. We have to twist the space-time

2. What cannot we measure in a particle at the same time?

A. The position and the size.

B. The volume and the size

C. The speed and the surface area

D. The position and the speed

E. All of the above

3. Which particle does not have the particle wave duality?

A. All of the Particles.

B. The proton.

C. The electron.

D. The tau neutrino.

4. Which of these things does the neutrino apply to?

A. Dark mass

B. The equation E=mc(cubed)

C. The make-up of waves

D. The make-up of leptons.

E. Dark matter

5. Which is the weakest power of the fundamental powers?

A. The electromagnetic power.

B. The strong power.

C. The weak power.

D. The gravity.

E. The centripical force.

6. What is the consequence of Einstein's formula, E=mc (squared)?

A. How the universe was born.

B. The conversion of mass into energy

C. The Big Bang

D. How we can travel faster than the speed of light

E. How we can travel the speed of light

7. Where can we find lines?

A. In space-time-diagrams

B. In speed-time-diagrams

C. In speed-room-diagrams

D. In pressure-time-diagrams

E. Nowhere, there is nothing symmetrical.

8. Which of these graphs cannot be the line of a human being when the space-time is not crooked?

A. From top left to bottom right .

B. From bottom left to top right .

C. From top right to bottom left

D. From bottom right to top left.

E. None of these.

9. Between which particles does the weak power act?

A. Between all neutrons.

B. Between all photons.

C. Between all leptons.

D. Between all neutrinos

E. Between none of these, there is no weak power

10. How does the energy form in which a star emits?

A. Through fission.

B. Through decay.

C. Throught fusion .

D. Through electrons.

E. Through nuclear decay.

11. For what does the strongest fundamental force usually hold together?

A. Mass and the center.

B. The neucleons

C. Matter and the center of the universe.

D. The nucleus and the world

E. The nucleus and the element of hydrogen

12. What is the densest thing on earth?

A. The proton.

B. The neutrino.

C. The neutron.

D. The electron

E. The suns core

13.The concepts of a "particle" and a "wave"

A. are clear and completely distinct from one another in both classical and modern physics.

B. can both be applied to electromagnetic radiation.

C. have found little use in quantum physics

D. all of the above are true

14. Concerning the photoelectric effect, which of the following is not true?

A. For most metals, ultraviolet light is needed for the photoelectric effect to occur.

B. Because a faint light contains very little energy, it takes a few minutes before electrons are emitted from the metal it is shining upon.

C. A bright light causes more electrons to be emitted than a faint light.

D. Higher frequency light emits electrons with higher kinetic energies.

15. Max Planck

A. proposed that light consists of photons.

B. developed a theory to explain the absorption of light by so-called black bodies.

C. suggested that to explain the spectrum emitted by a hot object, the energy could be viewed as given off in quanta, or units of energy.

D. linked the energy of a photon with its amplitude using Maxwell's equations.

16. Photons

A. possess small but significant mass

B. move at speeds proportional to their frequencies

C. lack momentum

D. are localized in small regions of space

17. Planck's constant

A. remains unknown to this day

B. is the inverse of Einstein's constant

C. is used to find the quantum energy associated with a certain frequency of light

D. is not really constant since it varies from one part of the universe to another

18. X-rays

A. were first discovered in 1895 prior to Planck's concept of quanta

B. demonstrate that phenomena of electron kinetic energy being transformed into photon energy

C. are an extremely penetrating form of radiation

D. all of the above are true

19. The wave theory of light and the quantum theory of light

A. are in direct contradiction to one another

B. together show that X-rays really are an unknown (hence the "X") phenomenon

C. complement each other

D. are both necessary to explain the interference patterns of light

20. According to our best observations, light

A. is exclusively a wave phenomenon.

B. is exclusively a particle phenomenon

C. in any particular event, exhibits either a wave nature or a particle nature, never both at the same time

D. has neither wave nor particle properties

21. The de Broglie wavelength of an object

A. is equal to Planck's constant divided by the momentum of the object.

B. is significant only if the object is moving at 1% of the speed of light or faster.

C. cannot be determined accurately for any subatomic particles.

D. increases as the velocity of the particle increases.

22. Matter waves

A. only make good common sense, as de Broglie demonstrated.

B. contradict the concept of photons as proposed by Einstein

C. are always associated with particles and photons in any state

D. are most significant at the atomic and subatomic level

24. The wave function (psi)

A. represents the particle function associated with a wave.

B. a large value of psi squared indicates the strong possibility of the particle's presence

C. a small value of psi squared indicates the strong possibility of the particle's presence

D. is unrelated to quantum theory and de Broglie waves

25. An important implication of the uncertainty principle discovered by Werner Heisenberg is

A. very small particles moving at slow speeds contain vast quantities of energy, the basis of the atomic bomb

B. if we can gather enough data, then it may be possible to predict the future based on present boundary conditions

C. above a certain particle size the de Broglie waves are so insignificant that they drop to zero

D. we can never predict the future with absolute certainty because it is impossible to know the present with certainty

26. Emission spectra and absorption spectra

A. for a single element complement one another

B. can be used to identify elements in unknown samples, but only if the element is already known by classical chemical means

C. when combined together form a series of bright lines

D. for certain pairs of closely-related elements are identical

27. When the sun's spectrum was first studied in detail

A. it was discovered that the sun's interior is cooler than the exterior

B. very few elements are found in the sun, and all of them were well known from earth samples

C. an apparently new element was discovered, subsequently named helium

D. spectral series were found to be lacking in pure sunlight

28. According to the Bohr model of the atom

A. electrons in orbit around nuclei lose energy so slowly that the universe should exist for at least another five billion years.

B. quantum theory is not applicable to the ultra-structure of an atom

C. electrons around a nucleus can have only certain particular energies and can only occupy certain specific orbits at particular distances from the nucleus

D. all of the above are true.

29. An electron can.................. revolve in a stable orbit around an atomic nucleus while continuously radiating energy without moving to a smaller orbit.

A. often

B. sometimes is less than a de Broglie wavelength in circumference

C. never

D. the answer depends on whether or not the atom is radioactive

30. An atom is said to be in an excited state when it has one or more electrons

at rest.

A. inside the nucleus.

B. in its lower energy level.

C. in a larger orbit than the smallest possible orbits.

31. When an atom absorbs a photon, one of its orbital electrons

A. jumps from a higher to a lower energy level

B. gains energy

C. is absorbed by the nucleus

D. turns into gamma radiation

32. An electron can circle a nucleus only in orbits that contain a whole number of de Broglie wavelengths. This statement

A. has a few exceptions, but they are not important at a quantum level.

B. implies that the quantum number, n, is the sum of all the orbits minus the length of the de Broglie wave.

C. combines both the particle and wave characters of the electron into a single statement

D. suggests that the uncertainty principle is not correct after all.

33. Which of the following types of radiation is emitted directly by the electronic structures of atoms?

A. beta radiation

B. visible light

C. alpha radiation

D. gamma rays

34. In coherent light,

A. the light waves are emitted randomly

B. the light waves are in step with one another

C. the light is said to carry information

D. many different frequencies interact with one another to form a multi-dimensional picture

35. Which of the following properties is a characteristic of the light waves from a laser?

A. The waves all have the same frequency

B. The waves are all in step with one another

C. The waves form a narrow beam

D. All of the above are true

36. Comparing newtonian mechanics to quantum mechanics,

A. it is obvious that if one is true then the other must be absolutely false.

B. most scientists today believe that quantum mechanics was a false side track in physics.

C. quantum mechanics includes newtonian mechanics as a special case.

D. neither actually agrees with fact as we know it, although newtonian mechanics is a little closer

37. Of the four quantum numbers for an atomic electron

A. two determine the electron's mass.

B. two determine the electron's spin.

C. one determines the size and shape of the electron's orbit.

D. three determine the size and shape of the probability cloud of an electron's

38. Wolfgang Pauli concluded that..................

A. in any single atom, no more than three electrons can occupy a particular orbit.

B. the quantum numbers for a particular electron in an atom can never be changed.

C. only one electron in an atom can exist in a given quantum state

D. there is a unique set of quantum numbers for every single atom in the universe

SUPPLEMENTARY READING

1. How Quantum Suicide Works

A man sits down before a gun, which is pointed at his head. This is no ordinary gun; it's rigged to a machine that measures the spin of a quantum particle. Each time the trigger is pulled, the spin of the quantum particle is measured. Depending on the measurement, the gun will either fire, or it won't. If the quantum particle is measured as spinning in a clockwise motion, the gun will fire. If the quark is spinning counterclockwise, the gun won't go off. There'll only be a click.

Nervously, the man takes a breath and pulls the trigger. The gun clicks. He pulls the trigger again. Click. And again: click. The man will continue to pull the trigger again and again with the same result: The gun won't fire. Although it's functioning properly and loaded with bullets, no matter how many times he pulls the trigger, the gun will never fire. He'll continue this process for eternity, becoming immortal.

Go back in time to the beginning of the experiment. The man pulls the trigger for the very first time, and the quark is now measured as spinning clockwise. The gun fires. The man is dead.

But, wait. The man already pulled the trigger the first time - and an infinite amount of times following that - and we already know the gun didn't fire. How can the man be dead? The man is both alive and dead. Each time he pulls the trigger, the universe is split in two. It will continue to split, again and again, each time the trigger is pulled. This thought experiment is called quantum suicide. It was first posed by then-Princeton University theorist Max Tegmark in 1997 . A thought experiment is an experiment that takes place only in the mind. The quantum level is the smallest level of matter we've detected so far in the universe. Matter at this level is infinitesimal, and it's virtually impossible for scientists to research it in a practical manner using traditional methods of scientific inquiry. Instead of using the scientific method - investigating empirical evidence - to study the quantum level, physicists must use thought experiments. Although these experiments are only carried out hypothetically, they're rooted in the data observed in quantum physics.

What science has observed at the quantum level has raised more questions than it has answered. The behavior of quantum particles is erratic, and our understanding of probability becomes questionable. For example, photons - the smallest measure of light - have been shown to exist in both particle and wave states. And the direction of particles is thought to travel in both directions at the same time, rather than in only one direction at different times. So when we examine the quantum world, we are outsiders to the knowledge it holds. As a result, our understanding of the universe as we know it is challenged. This has led some to believe that our grasp of quantum physics is as basic as the understanding of ancient Egyptian astronomers centuries ago, who claimed that the sun was a god. A few scientists believe further investigation into quantum systems will reveal order and predictability within what we currently see as chaos. But is it possible that quantum systems can't be understood within the traditional models of science?

In this article, we'll look at what quantum suicide reveals about our universe, as well as other theories that either support or contradict it. But first, why can't a physicist simply measure the particles he's attempting to study?

2. Heisenberg's Uncertainty Principle

One of the biggest problems with quantum experiments is the seemingly unavoidable tendency of humans to influence the situation and velocity of small particles. This happens just by our observing the particles, and it has quantum physicists frustrated. The mixed results quantum physicists find when examining the same particle indicate that we just can't help but affect the behavior of quantum particles. Even the light physicists use to help them better see the objects they're observing can influence the behavior of quanta. Photons, for example - the smallest measure of light, which have no mass or electrical charge - can still bounce a particle around, changing its velocity. This is called Heisenberg's Uncertainty Principle. Werner Heisenberg, a German physicist, determined that our observations have an effect on the behavior of quanta. Heisenberg's Uncertainty Principle sounds difficult to understand - even the name is kind of intimidating. But it's actually easy to comprehend, and once you do, you'll understand the fundamental principle of quantum mechanics.

Imagine that you're blind and over time you've developed a technique for determining how far away an object is by throwing a ball at it. If you throw your ball at a nearby stool, the ball will return quickly, and you'll know that it's close. If you throw the ball at something across the street from you, it'll take longer to return, and you'll know that the object is far away. The problem is that when you throw a ball - especially a heavy one - at something like a stool, the ball will knock the stool across the room and may even have enough momentum to bounce back. You can say where the stool was, but not where it is now. What's more, you could calculate the velocity of the stool after you hit it with the ball, but you have no idea what its velocity was before you hit it. This is the problem revealed by Heisenberg's Uncertainty Principle. To know the velocity of a quark we must measure it, and to measure it, we are forced to affect it. The same goes for observing an object's position. Uncertainty about an object's position and velocity makes it difficult for a physicist to determine much about the object. Of course, physicists aren't exactly throwing balls at quanta to measure them, but even the slightest interference can cause the incredibly small particles to behave differently.

This is why quantum physicists are forced to create thought experiments based on the observations from the real experiments conducted at the quantum level. These thought experiments are meant to prove or disprove interpretations - explanations for the whole of quantum theory. In the next section, we'll look at the basis for quantum suicide - the Many-Worlds interpretation of quantum mechanics.

3. The Many-Worlds Theory

The quantum suicide thought experiment is based on and seeks to prove what has become an increasingly accepted interpretation of quantum physics, the Many-Worlds theory. According to the Many-Worlds theory, for each possible outcome to an action, the world splits into a copy of itself. One vital aspect of the Many-Worlds theory is that when the universe splits, the person is unaware of himself in the other version of the universe. When the man pulls the trigger, there are two possible outcomes: the gun either fires or it doesn't. In this case, the man either lives or he dies. Each time the trigger is pulled, the universe splits to accommodate each possible outcome. When the man dies, the universe is no longer able to split based on the pulling of the trigger. The possible outcome for death is reduced to one: continued death. But with life there are still two chances that remain: The man continues living or the man dies. When the man pulls the trigger and the universe is split in two, however, the version of the man who lived will be unaware that in the other version of the split universe, he has died. Instead he will continue to live and will again have the chance to pull the trigger. And each time he does pull the trigger, the universe will again split, with the version of the man who lives continuing on, and being unaware of all of his deaths in parallel universes. In this sense, he will be able to exist indefinitely. This is called quantum immortality.

So why aren't all of the people who have ever attempted to kill themselves immortal? What's interesting about the Many-Worlds interpretation is that according to the theory, in some parallel universe, they are. This doesn't appear to be the case to us, because the splitting of the universe isn't dependent on our own life or death. We are observers in the case of another person's suicide, and as observers we're subject to probability. When the gun finally went off in the universe - or version - we inhabit, we were stuck with that result. Even if we pick up the gun and continue shooting the man, the universe will remain in a single state.

After all, once a person is dead, the number of possible outcomes for shooting a dead person is reduced to one. But the Many-Worlds theory stands in contradiction to another quantum theory, the Copenhagen interpretation. In the next section, we'll look at this theory and see why it changes the rules of quantum suicide.

4. The Copenhagen Interpretation

The Many-Worlds theory of quantum mechanics supposes that for each possible outcome of any given action, the universe splits to accommodate each one. This theory takes the observer out of the equation. No longer are we able to influence the outcome of an event simply by observing it, as is stated by the Heisenberg Uncertainty Principle.

For the better part of the last century, the most accepted explanation for why the same quantum particle may behave in different ways was the Copenhagen interpretation Many quantum physicists still assume the Copenhagen interpretation is correct. The Copenhagen interpretation was first posed by physicist Niels Bohr in 1920. It says that a quantum particle doesn't exist in one state or another, but in all of its possible states at once. It's only when we observe its state that a quantum particle is essentially forced to choose one probability, and that's the state that we observe. Since it may be forced into a different observable state each time, this explains why a quantum particle behaves erratically. This state of existing in all possible states at once is called an object's coherent superposition. The total of all possible states in which an object can exist - for example, in a wave or particle form for photons that travel in both directions at once - makes up the object's wave function. When we observe an object, the superposition collapses and the object is forced into one of the states of its wave function.

Bohr's Copenhagen interpretation of quantum mechanics was theoretically proven by what has become a famous thought experiment involving a cat and a box. It's called Schrödinger's cat, and it was first introduced by Erwin Schrödinger in 1935. In his theoretical experiment Schrödinger put his cat in a box, along with a bit of radioactive material and a device for detecting radiation. The Geiger counter was designed so that when it sensed the decay of the radioactive material, it triggered a hammer which was poised to break a flask containing hydrocyanic acid, which, when released, would kill the cat. To eliminate any certainty regarding the cat's fate, the experiment was to take place within an hour, long enough so that some of the radioactive material could possibly decay, but short enough so that it was also possible none would. In Schrödinger's experiment, the cat was sealed in the box. During its stay there, the cat came to exist in an unknowable state. Since it could not be observed, it could not be said whether the cat was alive or dead.

Since the Copenhagen interpretation says that, when observed, an object is forced to take one state or another, the quantum suicide experiment doesn't work according to this theory. Since the direction of the quark measured by the trigger can be observed, eventually the quark will be forced to take the clockwise direction that will fire the gun and kill the man. But isn't all of this just silly? Do these thought experiments and quantum interpretations really teach us anything? In the next section, we'll look at some of the possible implications of these ideas.

5. The Implications of Quantum Physics

When compared to classical science and Newtonian physics, the theories proposed to explain quantum physics seem insane. Erwin Schrödinger himself called his cat experiment "quite ridiculous". But from what science has been able to observe, the laws that govern the world we see every day don't hold true on the quantum level.

Quantum physics is a relatively new discipline, dating back only to 1900. There are competing theories that give different explanations for the peculiar happenings that take place on the quantum level. Perhaps the theory that proves to be the true explanation for quantum physics hasn't been posed yet. But given the logic that this field of study has established, is it possible that all theories explaining quantum physics are all equally true at the same time - even the ones that contradict each other?

Niels Bohr's Copenhagen interpretation of quantum physics is perhaps the most comforting theory put forth. By explaining that particles exist in all states at once - in coherent superposition - our understanding of the universe is put slightly askew, but still remains somewhat comprehensible. Although scientists find a particle's ability to exist in more than one state frustrating, our observations affect the particle. At least it doesn't continue to exist in all states while we're looking at it.

Much less comforting is Everett's Many-Worlds interpretation. This theory takes out of our hands any power over the quantum universe. Under the Many-Worlds theory, our idea of cause and effect goes out the window. Time doesn't exist in a coherent, linear motion.

Instead, it moves in jumps and starts, existing not as a line, but as branches. These branches are as numerous as the number of consequences to all of the actions that have ever been taken. Although he had his own interpretation of the quantum world, Bohr may have accepted the later theory that Hugh Everett introduced concerning the Many Worlds. After all, it was Bohr who said, "Anyone who is not shocked by quantum theory has not understood it.”

6. Taming the Quantum Spooks

Reconciling Einstein with quantum mechanics may require abandoning the notion that cause always precedes effect

Isaac Newton had a problem with the concept of action-at-a-distance. On one hand, like other 17th-century mechanist philosophers, he was deeply suspicious of the idea. As he wrote to the theologian Richard Bentley in 1693: That one body may act upon another at a distance through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to the other, is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it.

On the other hand, there’s his own theory of gravity, published in hisPrincipia several years earlier. It says that one body can exert a force on another, at arbitrary distance, without the need for any intermediary. What was a poor genius to do?

How Newton dealt with this dilemma in his own mind is still a matter for debate. Privately, his letter to Bentley continues: ‘Gravity must be caused by an agent acting constantly according to certain laws; but whether this agent be material or immaterial, I have left open to the consideration of my readers.' In public, he seems to express disdain for the question: 'I have not as yet been able to deduce from phenomena the reason for these properties of gravity, and I do not feign hypotheses.'

Two centuries later, Albert Einstein got Newton off the hook – though not before he'd made the problem even worse. Einstein's 1905 theory of special relativity raised a new difficulty for Newton's theory of gravity. Instantaneous action-at-a-distance requires that the distant effect issimultaneous with the local cause. According to special relativity, however, simultaneity is relative to the observer. Different observers disagree about which pairs of events are simultaneous, and there's simply no fact of the matter about who is right.

Without simultaneity at a distance, the notion of instantaneous action-at-a-distance doesn't make sense. By making Newton's theory of gravity even more problematic, special relativity gave Einstein an extra motivation for developing his own theory. He succeeded in his theory of general relativity (GR) 10 years later. GR explains gravity in terms of the curvature of spacetime, and abandons the idea that it acts instantaneously. In GR, gravitational effects propagate at the speed of light. If the Sun suddenly vanished, it would be eight minutes before the Earth reacted.

Unfortunately for Einstein, the physics of action-at-a-distance turned out to be Whack-a-Mole. He had knocked it on the head in one place, but it popped up in another – and he deserves some of the credit for that, too. Another of Einstein's great discoveries in 1905 – the one he thought most important – was that light can behave like individual particles, now called photons. This became one of the foundations of the new theory of quantum mechanics, developed by Erwin Schrödinger, Werner Heisenberg and others in the 1920s.

Einstein was never happy with quantum mechanics. As he complained later to Max Born, another quantum pioneer: 'The theory cannot be reconciled with the idea that physics should represent reality in time and space, free from spooky actions at a distance.'

Einstein's objections to quantum mechanics began very early. Schrödinger's version of the theory introduced a new mathematical entity, the wave function, which seemed to allow the position of an unmeasured particle to be spread out across an arbitrarily large region of space. When the particle's position was measured, the wave function was said to 'collapse', suddenly becoming localised where the particle was detected. Einstein objected that if this collapse was a real physical process, it would reintroduce action-at-a-distance, and so be incompatible with special relativity.

Einstein wanted to regard collapse of the wave function as a change in our information about the particle, not a change in the particle itself. Seen in this way, there is nothing surprising about it. If you know that your friend is somewhere in London and then spot her in Covent Garden, there's a change in your knowledge but not in your friend herself. But for Einstein's opponents – Niels Bohr and Heisenberg, among others – this view of quantum mechanics was unacceptable. They maintained that the quantum particle simply didn't have a precise location until it was observed.

Einstein thought he had a decisive objection to Bohr and Heisenberg. He published it with two Princeton colleagues, Boris Podolsky and Nathan Rosen, in 1935. The core of the Einstein-Podolsky-Rosen (EPR) argument is the assumption of no action-at-a-distance – ie, as Einstein expressed it later, the principle that 'the real states of spatially separate objects are independent of each other'.

Given this assumption, the EPR argument is very simple. It notes that there are cases in which, because two quantum particles have interacted in the past, a measurement on one makes a difference to the wave function of the other. The two particles concerned can be a long distance apart at this point, so the assumption of no action-at-a-distance implies that the choice of measurement on one doesn't affect the 'real state' of the other. The difference it makes to the wave function of the distant particle must be a difference in our information about that particle. As with our friend who is in Covent Garden, when all we know is that she is in London, quantum particles must have properties not captured by the wave function – the quantum description must be incomplete.

The EPR argument depends on the fact that quantum mechanics allows a new kind of connection between widely separated particles. This connection is now called entanglement, a term coined by Schrödinger in 1935, who also thought it obvious that entanglement cannot allow action-at-a-distance, and that the quantum description must be incomplete: 'Measurements on separated systems cannot directly influence each other – that would be magic.'

Schrödinger and Einstein's view got little traction, even though – cynics might say because – the response of Bohr and his Copenhagen school to the EPR argument is famously obscure. But there are elements that remind us of Newton's response 'I do not feign hypotheses.' The contemporary 'shut-up-and-calculate' interpretation of quantum mechanics (as the physicist David Mermin called it) denies that physics is in the business of describing a real world, in order to avoid any literal commitment to Schrödinger's 'magic'.

The really bad news for Einstein came not from Copenhagen but from Belfast, from the ingenious brain of John Stewart Bell. Bell was no fan of the Copenhagen view – he saw the appeal and power of the EPR argument – but by pressing further on the same kind of two-particle experiments, he derived what seemed an insuperable difficulty for Einstein. Einstein's argument took for granted that there is no action-at-a-distance, but Bell's Theorem (1965) seemed to show that quantum theory requires it.

The theorem turns on Einstein's own discovery that many phenomena in the quantum world show a kind of 'discreteness' not present in classical physics. Bell considered the correlations between such discrete, either/or events in two-particle experiments like those of EPR. A typical EPR-Bell experiment, as they are now called, is performed with pairs of photons produced at a common source. The photons fly in opposite directions into measurement boxes controlled by everybody's favourite thought-experimenters, Alice and Bob. Alice and Bob can choose one of several setting angles for their measurement boxes, and each box produces one of two outputs for each, ie, a detection of the photon on one of two possible channels.

Quantum mechanics predicts that, if the experiment is repeated many times, there will be correlations between the results on Alice's side and on Bob's side. These correlations depend on whether Alice and Bob choose the same or different angles – more precisely, they depend on the difference between the two angles. Bell's brilliance was to see that these correlations are deeply puzzling. They imply that Bob's photon must somehow know what Alice chooses, and vice versa, even though the two experiments can be far apart. This seems to be action-at-a-distance – the very option that Einstein had assumed he could ignore in simpler versions of the experiment.

The core of Bell's argument can be explained using analogies. Consider what we'll call the 'Gemini game'. Pairs of twins are separated, and each is randomly offered one of three coloured cards: red, yellow or blue. Each twin has to accept or decline the card. If they choose differently when offered the same coloured card, they are immediately disqualified. Otherwise, their objective is just to choose differently when offered different coloured cards, as often as possible.

The twins don't know in advance what cards each of them will be offered, nor what card the other is being offered, in any particular instance. So, to avoid disqualification, they need a policy – eg, 'Accept red, decline yellow and blue.' Because there are three cards and only two options (accept or decline), any such policy recommends the same action for at least two different cards – in this case, for yellow and for blue.

There are six ways in which the twins can be shown different cards (three possibilities for Twin 1, and for each of those, two different possibilities for Twin 2). Because any policy recommends the same option for at least two cards, it will tell the twins to do the same thing in at least two of these six situations; in our example, when Twin 1 gets yellow and Twin 2 gets blue, and vice versa. This means that the best the twins can do in their attempt to choose different options when shown different cards is four out of six, or about 67 per cent, on average. This result is what's now known as Bell's Inequality.

Bell's insight was to notice that somehow the quantum world manages to escape this inequality. Quantum particles can do something that even the most intelligent human twins cannot. Playing an equivalent game, for example, photons can get a success rate of 75 per cent. In the Gemini game, we assumed that neither twin knows what colour card the other is offered. Bell reasoned that for quantum particles to do better – to violate Bell's Inequality – the equivalent assumption must fail in quantum mechanics. In some sense, each particle must 'know' what measurement is being made on the other. That 'knowledge' is the action-at-a-distance.

The implications of Bell's result remain disputed. Some claim that it shows quantum mechanics implies action-at-a-distance, period. Others maintain that we can still avoid action-at-a-distance by denying that quantum mechanics is a theory about a reality in space and time. Either way, the consensus is that Einstein can't have what he wanted – a real world in space and time, without action-at-a-distance. And many theorists, including Bell, conclude that the inequality reveals a deep tension between quantum mechanics and special relativity, the two pillars of 20th-century physics.

Over the past forty years, a lot of ingenuity has gone into designing experiments to test the quantum predictions on which Bell's result depends. Quantum mechanics has passed them all with flying colours. Just last year, 3 new experiments claimed to close almost all the remaining loopholes. 'The most rigorous test of quantum theory ever carried out has confirmed that the "spooky action-at-a-distance" that [Einstein] famously hated… is an inherent part of the quantum world,' as Nature put it.

Newton once remarked that if he'd seen further than his predecessors, it was because he stood on the shoulders of giants. For the would-be Newtons of the present century, replicating that feat has become newly challenging. It is not just that you need to be a genius to scale such heights. With Newton, Einstein and Schrödinger huddled on one side, and Bell on the other, the shoulders of the giants now seem seriously out of line.

The surprising news is that there's a simple and elegant solution to the problem – an option that Bell himself missed, apparently, because he confused it for something else. With Bell's authority behind it, the confusion persists to this day, and the solution goes almost unnoticed. Yet if it works, it explains Bell's correlations without Schrödinger's 'magic' and it gets our giants back in line. Quantum mechanics no longer seems in tension with special relativity, and Bell can agree with Newton, Einstein and Schrödinger that there is no action at a distance.

This reconciliation begins with a suggestion first made by a young Parisian graduate student, Olivier Costa de Beauregard, in the late 1940s. He was a student of Louis de Broglie, a pioneer of quantum mechanics who, like Einstein and Schrödinger, was attracted to the idea that the theory is incomplete. Initially, Costa de Beauregard thought he had an objection to the EPR argument. Einstein had assumed that Alice's measurement couldn't affect the result of Bob's experiment, because that would be action-at-a-distance. Costa de Beauregard pointed out that Alice could affect Bob's particle without action-at-a-distance, if the influence followed an indirect, zigzag path through space and time, via the point in the past where the two particles intersect. But there are no zigzags like that in standard quantum mechanics, so if we put them in we are actually agreeing with Einstein that the theory is incomplete.

Later, when Bell's work appeared, Costa de Beauregard recognised the deeper significance of the zigzag: it offers a potential reconciliation between Bell and Einstein. Bell's argument depends on the assumption that the choice of measurement settings at the two sides of the experiment is independent of any earlier properties, or 'hidden variables', of the particles. This assumption is called statistical independence, but the Parisian zigzag gives us a reason to reject it.

Following the setup shown in the EPR diagram above, Costa de Beauregard proposes that Alice's choice of a measurement setting makes a difference to her particle before it arrives at the measuring device – it causes her particle to have one hidden variable rather than another at that stage. This in turn makes a difference to Bob's particle as well as to where the particles meet, and so explains how Alice's choice can affect

Bob’s side of the experiment, even without action-at-a-distance. It is easy to explain the correlations that Bell took to imply action-at-a-distance if we allow such ‘retro’ causality.

Bell himself knew that we don’t need action-at-a-distance if statistical independence fails. So why are we all told that Bell’s Theorem shows Einstein was wrong about spooky action-at-a-distance? Why is Costa de Beauregard’s alternative simply overlooked?

There’s a clue in a letter that Bell wrote to one of us in 1988. Huw Price was a young philosopher in Sydney at the time, and plucked up the courage to send Bell two of his early papers about this retrocausal idea. Bell kindly wrote back, saying: ‘When I try to think of backward causation I lapse quickly into fatalism’ and referred to a published discussion for ‘what little I can say’ about the matter. However, the published discussion is about an entirely different way of rejecting Bell’s statistical independence assumption, an idea that Bell called superdeterminism. In fact, he had good reasons to reject superdeterminism. But he didn’t see the difference between the two proposals, apparently, and threw out the retrocausal baby with the superdeterminist bathwater.

To clear up this decades-old confusion, let’s begin with the familiar point that correlation need not imply causation. Furry tongues are often correlated with headaches, but neither is a cause of the other. They are correlated because they are both effects of the same cause in the past – excessive drinking. An important rule, known to philosophers as Reichenbach’s Common Cause Principle, tells us that where we find correlation without direct causation, we should look for a common cause. The qualification is crucial. Excessive drinking is correlated with headaches, but drinking causes headaches, so we don't need to look for some third thing that causes both.

What does this rule tell us if we apply it to the hypothesis that there is a correlation between Alice's choice of measurement settings and the properties of a particle that is making its way towards her measuring device? Superdeterminism assumes that it tells us to look for something in the past to be a common cause of Alice's choice of measurement settings and of the relevant hidden variables of the particle. But now we have two problems.

First, what kind of common cause could have this strange combination of effects? We could replace Alice with many other ways of choosing measurement settings; for instance, as Bell suggests, we could let the Swiss lottery machine do it. The common cause would need to control that, too, according to this proposal. Second, and in Bell's view even worse, this common cause would be deeply in tension with the belief that we (or Alice) are free to choose whatever setting we like. This is how Bell put it in 1985:

> One of the ways of understanding this business is to say that the world is super-deterministic. That not only is inanimate nature deterministic, but we, the experimenters who imagine we can choose to do one experiment rather than another, are also determined. … In the analysis it is assumed that free will is genuine, and as a result of that one finds that the intervention of the experimenter at one point has to have consequences at a remote point in a way that influences restricted by the finite velocity of light would not permit. If the experimenter is not free

to make this intervention, if that also is determined in advance, the difficulty disappears.

Bell’s concern about fatalism survives to this day. The option of rejecting statistical independence is commonly called the freedom-of-choice loophole. In a recent paper, Anton Zeilinger – one of the giants of experimental quantum theory – and his coauthors write that ‘the freedom-of-choice loophole refers to the requirement, formulated by Bell, that the setting choices are “free or random”.

However, this issue about free will stems from the superdeterminist’s assumption that a correlation between measurement settings and pre-measurement hidden variables of the particle needs a common cause – and that’s simply a mistake. We need common causes in the case of furry tongues and headaches, where neither of two correlated events is a cause of the other. But according to the Parisian zigzag, the choice of measurement settings is a cause of the pre-measurement hidden variables. We don’t need a common cause, and three decades of worrying about free will turn out to have been a complete red herring.

In his paper, Zeilinger mentions a proposal to restrict the freedom-of-choice loophole by letting measurement decisions be determined by chance events in distant galaxies, making it even more unlikely that there could be a common cause. This proposal, and the elaborate experimental programme now based on it, rest on the same mistake: we don’t need a common cause, and won’t learn anything by going to all this trouble to rule one out.

With superdeterminism filed for posterity where it belongs – under ‘Even giants make mistakes’ – it is easy to read Bell’s Theorem as an argument forretrocausality. The argument shows that quantum mechanics implies that the alternative to retrocausality is action-at-a-distance. But ‘that would be magic’, as Schrödinger put it, and it conflicts with special relativity. So retrocausality it should be.

At this point, some readers may feel that, while action-at-a-distance is peculiar, it’s not half as odd as the present affecting the past. Retrocausality suggests the kind of paradoxes familiar from time-travel stories. If we could affect the past, couldn’t we signal to our ancestors in some way that would prevent our own existence? Luckily for the Paris option, it turns out that the kind of subtle retrocausality needed to explain Bell’s correlations doesn’t have to have such consequences. In simple cases, we can see that it couldn’t be used to signal, for the same reason that entanglement itself can’t be used to signal. But first, let’s consider a couple of other objections that critics raise at this point.

Physicists sometimes object that if retrocausality can’t be used to signal then it doesn’t have any experimental consequences. We physicists are interested in testable hypotheses, everything else is mere philosophy, they proclaim (using ‘philosophy’ in its pejorative sense!). But retrocausality offers an explanation of the results of all the standard experimental tests of the Bell correlations. If it works, it is confirmed by these experiments just as much as action-at-a-distance is confirmed. Experiments alone won’t distinguish between the two proposals, but this is no more a reason for ignoring retrocausality than it is for ignoring action-at-a-distance. The choice between the two needs to be made on other grounds – eg, on the basis that retrocausality is easier to reconcile with special relativity.

Some readers may raise a more global objection to retrocausality. Ordinarily, we think that the past is fixed while the future is open, or partly so. Doesn't our freedom to affect the future depend on this openness? How could we affect what was already fixed? These are deep philosophical waters, but we don't have to paddle out very far to see that we have some options. We can say that, according to the retrocausal proposal, quantum theory shows that the division between what is fixed and what is open doesn't line up neatly with the distinction between past and future. Some of the past turns out to be open, too, in whatever sense the future is open.

To understand what sense that is, we'd need to swim out a lot further. Is the openness 'out there in the world', or is it a matter of our own viewpoint as agents, making up our minds how to act? Fortunately, we don't really need an answer: whatever works for the future will work for the past, too. Either way, the result will be that our naive picture of time needs to be revised in the light of a new understanding of physics – a surprising conclusion, perhaps, but hardly a revolutionary one, more than a century after special relativity wrought its own changes on our understanding of space and time.

Still, we want to explain why the kind of retrocausality involved in the Parisian zigzag needn't allow us to send signals to the past. We are going to do this by examining an experiment in which standard quantum mechanics predicts the mirror-image: the same subtle causality directed to the future, achieved without signalling to the future.

We begin with the earlier EPR-Bell experiment. Let’s put it in a mirror, as shown below. The mirror flips Alice’s half of the experiment in time, so that it now looks like an experiment in which a photon enters through one of the two channels at the bottom and leaves through the channel on the top right, heading in the direction of Bob’s measuring device. If we combine the mirror image of Alice’s side with the original version of Bob’s side, we get a diagram of an experiment done with one photon, travelling left to right, from the reflection of Alice’s device to Bob’s device. Let’s call the reflection of Alice ‘Ecila’, to remind us that she is Alice in reverse. This use of the mirror isn’t a trick. Throwing out Alice’s upper-left corner, the remaining experiment is one we can actually perform, using only a single photon. The underlying physics of the original experiment ensures that using the mirror is completely kosher. It ensures that the correlations between Ecila and Bob in the new experiment are exactly the same as the Bell correlations between Alice and Bob in the original experiment.

In the original experiment, each output corresponds to one type of polarisation – the orientation of the vibration of the photon, analogous to the angle at which a guitar string is vibrating. The outcomes on each side are discrete: after passing through the box that represents a ‘polariser’ (which admits only one type of vibration) and being measured, the photon is always found on one channel or the other. The outputs are also completely random from the point of view of Alice or Bob individually. There are correlations when they compare notes but, until they do that, they might as well just be tossing a coin.

To make the new experiment a faithful mirror image on the left, Ecila's inputs need to be discrete and random in the same way. In other words, we need to assume that there's a photon arriving on one channel or the other, but which channel is completely unpredictable. For simplicity, let's give this job to a demon – a random-acting agent. The demon does exactly what 'Nature' does at both ends of the experiment except in reverse, so let's call her 'Erutan'. Alice doesn't know Nature's choice in advance, so we stipulate that Ecila doesn't know Erutan's choice either.

Standard quantum mechanics tells us that, despite Erutan, Ecila has a lot of control over the photon as it leaves her side of the experiment. Ecila controls the polarisation of the photon almost completely by choosing the setting of her polariser. To be precise, she can fix the polarisation to one of two values, differing by 90 degrees. Erutan gets the final choice between those two values by choosing which way the photon enters the box.

We stress two things about Ecila's control of the photon's polarisation. First, it's a consequence of the discreteness condition, the stipulation that Erutan has to supply a photon on one channel or the other. If we do the same experiment in classical physics, Erutan can produce whatever polarisation she likes, taking away Ecila's ability to control anything. Second, Ecila can't signal to Bob, despite her control of the photon's polarisation. It's as though Erutan is tossing a series of coins, and Ecila – without looking – is deciding whether each one should be turned over before it's sent to Bob. Ecila's choices make a difference to the sequence of heads and tails that Bob receives, but the sequence looks completely random (ie, message-free) from his point of view.

We’ve learnt two things from Ecila and Erutan. First, the discreteness condition gives Ecila a new kind of forward control in standard quantum mechanics. Second, this new control can’t be used to signal, even though it surely counts as causation. With these points in mind, we can emerge from the looking glass and apply the same lessons to the Parisian zigzag. Costa de Beauregard’s proposal is that Alice has the same control over the photon before it reaches her polariseras Ecila has over the photon after it leaves her polariser, according to standard quantum mechanics. This control will be enough to explain the correlations in the two-photon experiment, just as in the one-photon experiment; the physics behind the mirror will guarantee that. And because nature behaves just like Erutan, this control will be real enough to count as causation – Alice is making a genuine difference to the photon – but not strong enough to let Alice signal Bob.

In the two-photon case, no one would give this control to Alice without giving it to Bob too. That would be a ridiculous left/right asymmetry, not to mention female/male asymmetry! So the Paris proposal is that Bob, too, has a degree of control over his photon before it reaches his polariser. If we add this to the one-photon experiment, it has a similar benefit: it gets rid of a time-asymmetry between Ecila and Bob.

Now at last we get to the heart of the new argument for retrocausality in the quantum world. It turns on the fact that physics doesn’t seem to care about the direction of time. If the laws allow a physical process, they also allow the same process running in reverse. This isn't true of many everyday processes – eggs turn into omelettes, but not the reverse! – but that seems to be a result of large-scale statistical effects associated with the second law of thermodynamics. At the fundamental level, there is no way to tell whether a video of physical processes is being played forwards or backwards.

Let's apply this time symmetry to our one-photon experiment with Erutan and Ecila at one end, Bob and Nature at the other. We chose Erutan so that she behaves like Nature in reverse. If we reverse a video of the experiment, nothing changes at the two ends; Nature in reverse looks like Erutan, and Erutan in reverse looks like Nature. But if Ecila is affecting the photon between the polarisers and Bob isn't, then reversing the video does make a difference there. In the reverse video, the photon seems controlled from the future, not from the past. If we want our theory to pass the test for time-symmetry, we'll have to allow that Bob controls the photon too. In other words, we need retrocausality.

Notice the role of quantum discreteness. Without it, Ecila has no control over the photon, and so we can pass the test for time-symmetry without giving Bob any control either. Classical theory can be time-symmetric without retrocausality. But the quantum discreteness discovered by Einstein – and at the heart of Bell's Theorem – makes a big difference. In combination with a commitment to time-symmetry, it gives a new reason to think that there's a subtle kind of retrocausality built into the quantum world.

We now have two reasons for taking retrocausality seriously. First, it offers an elegant explanation of the Bell correlations, one that avoids action-at-a-distance and that allows quantum mechanics to play nicely with special relativity. Second, retrocausality preserves time-symmetry in the one-photon experiment. Both reasons turn on discreteness. It is not much of an exaggeration to say that the two experiments are really the same experiment, just differently arranged in space and time. Arranged with two photons, the cost of ignoring retrocausality is action-at-a-distance. Arranged with one photon, the cost of ignoring it is time-asymmetry. Two different 'bads' with the same take-home message: we should all be doing the Parisian zigzag!

At this point, defenders of other views of quantum mechanics will point out, rightly, that the zigzag idea is just a proposal; there isn't yet a well-developed model of how to implement it. They will also insist that Parisian elegance is not compulsory. If you wish, you can choose to live with action-at-a-distance, or time-asymmetry, or shut-up-and-calculate-and-don't-think-about-reality.

To this we say: of course, elegance is no more compulsory in science than it is in everyday life. We don't claim that retrocausality is the only option, just that no one can insist that Bell has shown that Newton, Einstein and Schrödinger were wrong about action-at-a-distance until they explain why the Paris solution won't work.

So, dear reader, the next time you read that Einstein has been refuted, or that action-at-a-distance has been experimentally proven, check to see whether the authors have considered the Parisian zigzag. Probably not, since it hasn't been touched at all by the clever recent physics experiments. In that case, they have more work to do. They need some arguments against Costa de Beauregard's proposal. On our side, we need some well-developed models of how to provide retrocausal foundations for quantum mechanics. And on both sides of the fence, surely, we owe it to all those giants to try to sort this out.