PROLOGUE: UNDERNEATH THE DANUBE

Every January 1, the New Year's Concert of the Vienna Philharmonic ushers in a new year. This concert is held in the great Golden Hall of the Musikverein, the home of the traditional music society of Vienna, and is transmitted worldwide to literally hundreds of millions of people eager to listen to the beautiful waltzes, polkas, overtures, and other pieces by the Strauss family and their contemporaries. Once the official program ends, we join the audience in applauding, but everyone is still waiting for the encore. Then the very low sounds of the strings start, and everyone applauds again, recognizing the expected piece. The orchestra stops, and the conductor wishes everyone in the concert hall and around the world a happy new year. Again, the strings start and the orchestra plays what is often called the unofficial Austrian anthem, the famous "Blue Danube" waltz by Johann Strauss the Younger. There are not many pieces of music that are able to convey both the pleasure and the intrinsic melancholy of human existence as well as this music, written for the grand balls in Vienna's imperial and courtly ballrooms and still performed today during the ball season every year.

Little do those present and those at their TV sets know that not far from the Golden Hall, within the city limits of Vienna, an experiment is being conducted at the cutting edge of modern technology, challenging the imagination with ideas previously found only in science fiction and with the implications of those ideas for how we can understand the world around us.

The concert ends with its final encore, Johann Strauss the Elder's "Radetzky March," one of the most vibrant and jolly pieces ever written. We leave the concert hall and drive to the river Danube. It is a beautiful winter day with not many people about, as January 1 is a national holiday. The Danube passes through the city of Vienna in two branches, forming a long island in between. We cross from one of the riverbanks onto the island over a bridge that not even our car's GPS knows, as it is not open to the public. The island is off limits to cars except for those on official business.

On the island, we head for a building hidden behind high trees. This is the location of the pumping station of Vienna's sewage system. There is a huge sewer passing under the river, connecting the two sides. Its purpose is to convey all the sewage collected on the eastern side of the river, a part of the city the Viennese lovingly call Transdanubien ("the place across the Danube"), to a huge waste-treatment plant on the other side. In this way, the Viennese, who are very environmentally conscious, make sure that sewage is not deposited directly into the Danube.

We enter the building and take the elevator two levels down, below the river. After a short walk, we reach two large tunnels opening to the left and the right, connecting both banks of the river, Transdanubien and Vienna proper. Through this huge tunnel, tubes run in parallel, carrying sewage, and there are many cables. Tucked away, near the entrance to one of the tunnels, a different scene greets us.

We see a small room off in a corner, with glass walls. Coming closer, we see laser light inside, with lots of high-tech equipment including modern electronics, computers, and the like, and we meet Rupert. He tells us that he is a student at the University of Vienna working on his Ph.D. dissertation, which he hopes to finish soon in order to earn his doctorate. The title of his dissertation is "Long-Distance Quantum Teleportation." We ask Rupert to briefly explain what it is that we see here. He tells us that the point of the experiment is to teleport a particle of light—a photon—from the Danube Island side of the riverbank over to the Vienna side.

Noticing that we don't understand much, he tells us that teleportation is a little bit like "beaming" in science fiction, "but not quite." He smiles broadly and starts to explain. While we still don't understand much, we listen with increasing fascination. He promises to give us a more detailed explanation later. At the moment, we just want to gain a small degree of familiarity with the language used, to get accustomed to the setup and the general concepts being studied, and to acquaint ourselves with the strange surroundings.

The lasers, we learn, are mainly here to produce a very special kind of light. Light consists of particles called photons, and this laser produces peculiar pairs of photons that are "entangled" with each other. This entanglement, as we shall learn in more detail later on, means that the two photons are intimately connected with each other. When one is measured, the state of the other one is instantly influenced, no matter how far apart they are separated.

The notion of *entanglement* was identified by the Austrian physicist Erwin Schrödinger in 1935. He wanted to characterize a very interesting state of affairs. Shortly before, Albert Einstein had hinted at an interesting new situation emerging in quantum mechanics in a paper he published together with his young colleagues Boris Podolsky and Nathan Rosen.

For us to understand a little of what entanglement is about, let's consider two particles that have had some interaction with each other. For example, they could have hit each other just as billiard balls do and could now be moving apart. In classical—that is, traditional—physics, if one billiard ball moves, say, to the right, the other one moves to the left. Furthermore, if we know the speed of the hitting ball and how it hit the ball at rest, and if we also know how fast and in which direction the ball that was at rest moves away, we can figure out exactly where the other ball goes. This is what a good billiard player actually does when he is figuring out how to hit a ball with his cue.

Quantum "billiard balls" are much stranger. They will also move away from each other after the collision, but with these interesting and very strange differences. Neither of the two balls has a well-defined speed, nor does it move in a specific direction. Actually, neither of the balls has a speed or direction after the collision. They just move apart from each other.

The crucial point is this: as soon as we observe one of the quantum billiard balls, the ball instantly assumes a certain speed and moves along a certain direction away from the collision. At that very moment—but not before—the other ball assumes the corresponding speed and direction. And this happens no matter how far apart the two balls are.

So, quantum billiard balls are entangled. Of course, this kind of phenomenon has not been seen for real billiard balls yet, but for elementary particles, it is standard fare. Two particles that collide with each other are still intimately connected over a large distance. The actual act of *observation* of one of the two particles influences the other one instantly, no matter how far away the other one is.

Einstein did not like this strange feature, and he called it “spooky action at a distance.” He was hoping that physicists might find a way to get rid of the spookiness. In contrast to Einstein, Schrödinger accepted this feature as something completely new, and he coined the term “entanglement” for it. Entanglement is *the* feature of the quantum world that forces us to say farewell to all our cherished views of how the world is built up.

When we ask Rupert about the purpose of his entangled photons, he smiles and tells us, “That’s the magic trick.” He keeps one of the two photons at his mini-laboratory down below the level of the water and sends the other photon along a glass fiber to the receiver at the other side of the river.

Rupert talks about “Alice” and “Bob” sending photons to each other and talking to each other as if they were humans. But it turns out that they are imaginary experimentalists, Alice sitting in her laboratory here and Bob on the other side of the river.

When we ask Rupert why he calls these two Alice and Bob, he tells us that this is not his invention. The names come from the cryptography community, in which it is important to make sure that messages sent between two people cannot be read or heard by unauthorized third parties. We immediately think of spies in an exciting setting, but Rupert calms us down. Cryptography, he explains, is broadly used these days. Even if you log on to the Internet and transmit, say, your credit card number, it is usually encrypted so nobody else can read it. He continues: “Initially, people called the sender of the message ‘A’ and the receiver ‘B,’ and then someone thought it better to simply call them ‘Alice’ and ‘Bob,’ to make it easier to talk about them.”

Rupert shows us the thin glass fiber where Bob’s photon enters, apparently no different from those widely used in telecommunication these days.

We let our eyes follow the glass fiber cable from Rupert’s laser through the wall of his small laboratory up to a place where it joins all the other cables running through the large tunnels under the Danube. Rupert follows our eyes and asks, “Want to see where it goes?” We eagerly say yes, and our small excursion to the underground of Vienna begins.

First, we enter a tube of about four meters (thirteen feet) in diameter that goes steeply downward. Below us are two pipes, each about a meter in diameter, which carry the sewage. As they are tightly sealed, this does not influence our comfort very much, though a little bit of a strange smell hangs in the air. We are easily able to walk upright, but the space is not very wide. To our right and left are cable trays. Somewhere on one of these cable trays is our small optical fiber. One of us remarks, "Just like *The Third Man*," reminded us of one of the greatest movies of all time, set in Vienna after World War II. Some of the movie's best scenes are wild chases in the city's underground sewage system. We expect Orson Welles to pop around the corner at any moment, and the Harry Lime theme played by Anton Karas on his zither seems to ring in our ears.

After some time, we reach the deepest point of our travels, and Rupert tells us that the river is just above us. It is difficult to avoid imagining what would happen if somehow a crack were to appear and the water of the river started to flood in. Which direction would we run in? Fortunately, nothing happens, and we continue trotting along. The path starts to climb slightly upward. After a while, we emerge into a small room, and looking out, we see we have passed under not only the river but also a little adjacent park, a railroad, and a major road.

In the room, the glass fiber leaves its plastic housing and ends up in a setup similar to the one on the island, but much smaller. Again, a computer is nearby, as are a few optical elements such as mirrors and prisms and lots of electronics. Rupert explains that what happens here is the measurement of the teleported photon and in particular the verification of whether it has all its properties and features intact. Of the cables leading to Rupert's small table, we see one running upward; it ends on the roof of the building we are in. Rupert proudly tells us that this is the "classical" channel connecting Alice and Bob—a standard radio connection between the two players. At this point, we are slightly confused. What is this classical channel for? What was Rupert talking about when he mentioned entangled photons? What is teleportation?

Before exploring these questions, we climb to the roof of the building and are rewarded with a great view. On the other side of the river is the building where Alice is located. The river flows rather swiftly in between. Ships pass by, making their own slow and steady progress. A few ducks and swans enjoy the clean water. On our side of the river, next to the building where we are, we see a little pagoda built by Vienna's Buddhist community, and immediately our minds drift off into philosophical questions like what might all this mean, what is our role in the universe, what are we doing when we observe the world, and what the heck does quantum physics have to do with all of this?

To the west, we see the hills of the Vienna Woods, which are actually the easternmost reaches of the Alps, and to the east, the edge of the great Hungarian plains. History drifts into our thoughts; we remember the fact that the Turks, coming from the east, twice tried unsuccessfully to conquer Vienna. We can imagine how a successful conquering of Vienna would have changed history. We also consider how the kinds of questions we ask, the very deep questions, those about the meaning of our existence, might depend on our culture—Buddhist, Islamic, Christian. It is getting cold, and we allow ourselves to return slowly back to the life of modern Vienna.

SPACE TRAVEL

When we hear of teleportation, we often think it would be an ideal means of traveling. We would simply disappear from wherever we happened to be and reappear immediately at our destination. The tantalizing part is that this would be the fastest possible way of traveling. Yet, a warning might be in order here: teleportation as a means of travel is still science fiction rather than science.

Thus far, people have only been able to travel to the Moon, which on a cosmic scale is extremely close, the equivalent of our backyard. Within our solar system, the closest planets, Venus and Mars, are already roughly a thousand times more distant than the Moon, to say nothing of the planets farther out in the solar system.

It is interesting to consider how long it would take to go to other stars. As we all remember from the Apollo program, which put the first men on the Moon, it takes about four days to go from Earth to the Moon. Traveling by spaceship from Earth to the planet Mars would take on the order of 260 days, one way. It is evident that our space travelers would get quite bored during that time, so they might make good use of their time by performing experiments involving quantum teleportation.

In order to get even farther out, we might use the accelerating force of other planets or even of Earth itself, as has been done with some of the unmanned spacecraft exploring outer planets. The idea is simply to have the spaceship pass close by a planet so that, by means of a sort of slingshot action, it can be accelerated into a new orbit that carries it much farther outward. For example, using these methods, the spacecraft *Pioneer 10* took about eleven years to travel past the outermost planets of the solar system on its probably unending journey into the space between the stars. We can thus estimate that it will, for example, take *Pioneer 10* about 100,000 years to get to Proxima Centauri, the closest star except for the Sun, at its current speed.

Perhaps, therefore, it would be good to have some other way to get around, to cover large distances. What we want is to travel anywhere instantly, without any limitation on how far we can go. Is that possible, at least in principle? This is why science-fiction writers invented teleportation. Magically, you disappear from one place, and, magically, you reappear at another place, just an instant later.

THE STUFF CALLED LIGHT

The first teleportation experiments were done with light, but what is light? Humans have always been fascinated by light. Probably long before we learned to write things down, people must have discussed how it is possible that through light, we experience objects close by or even at large distances. There are two basic concepts physicists use to explain how something travels from a light source—say, the Sun, or even a tiny candle—all the way to our eyes so we can recognize the object that emits the light. One concept assumes that light travels to us as *particles*, pieces of something, just like chunks of matter. The other assumes that light travels to us in the form of *waves*.

The simplest analog for the particle concept is that light travels just as a bullet or a small marble does. For the wave concept, the simplest pattern we can think of is the pattern of waves spreading out on the surface of water, for example, in a small pond. These two simple images convey the essential features of the particle and the wave concepts.

In the case of the marble, we have something localized—restricted in space—that moves. Similarly, the particle of light moves from place to place—from the light source, to the object we see, to our eye—by following some trajectory. Furthermore, just as marbles or bullets come one by one, the light source, for example the Sun, emits many tiny particles of light that travel toward us. They hit, for example, the tree across the road, some of them are reflected and scattered off that tree, and a few finally are collected by our eyes.

In contrast, the wave on the surface of a pond is not localized at all. If we throw a stone into a quiet pond, we see a wave that eventually spreads out all over the pond (Figure 1). Furthermore, waves do not

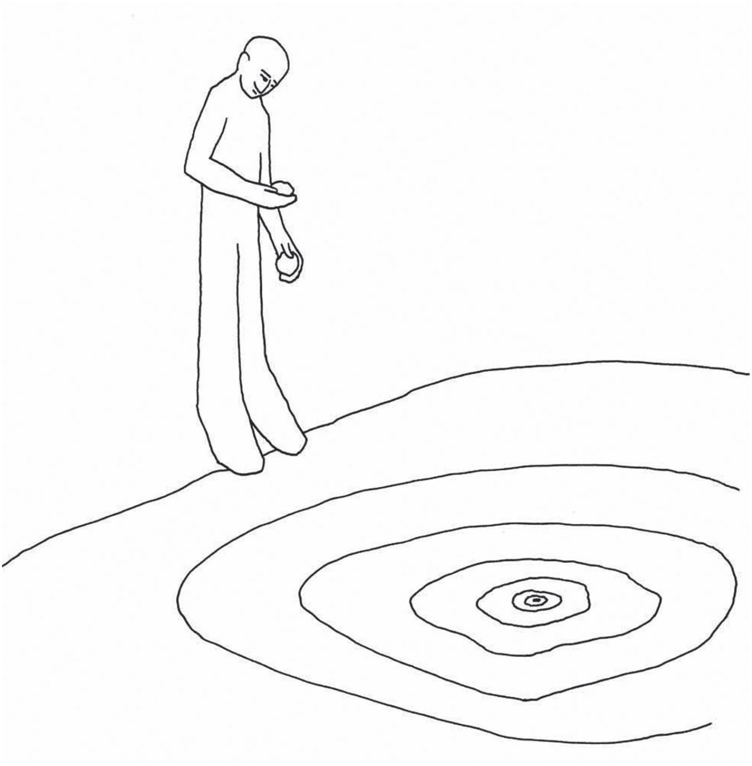

Figure 1. The nature of waves. Waves spread on a pond from the point where a stone was thrown into the water.

come in pieces, in chunks, but, rather, a wave can come in any size. There are very tiny waves caused, for example, by the legs of a small insect gliding across the quiet pond, or huge waves created by large stones thrown into the water. So there is continuity to the size of water waves.

So the big question is, What is light? Which concept applies to the phenomenon of light—the wave concept or the particle concept? Which of the features we just listed are actually features of light?

Much of the history of physics can be written as a history of the nature of light. Very early on, people started to carefully investigate which of the criteria for particles or for waves apply to light. In the early 1700s, there was a large battle between adherents of the particle picture, led by Isaac Newton, and followers of the wave picture, led by Robert Hooke. Back at that time, the particle picture triumphed. Many say that the weight and authority of Newton tipped the scales.

LIGHT IS A WAVE

In 1802, the English medical doctor Thomas Young performed an experiment that turned out to be crucial for our understanding of the nature of light. The experiment itself—actually one of the great experiments in the history of science—is extremely simple. Thomas Young just let light pass through two pinholes in a screen.

Behind the pinholes, he observed light and dark stripes (top sketch in Figure 2), called "interference fringes" today.

What happens if we cover one of the two slits? Then we do not see any fringes, but rather a broad patch of light (middle sketch in Figure 2). If we cover the other slit, we get a similar broad patch of light slightly shifted (bottom sketch). There is a large region where the two patches overlap.

From a particle-picture point of view, when we open both slits, we would expect that the light on the screen would be the sum of the two. But this assumption turns out to be wrong. Instead, in the overlap region, Young observed bright and dark stripes—the fringes. So there are positions, the dark fringes, where no light at all arrives when both slits are open. But when either slit is open alone, we have light there. Careful measurement shows that at the bright fringes, the amount of light is more than the sum of the two intensities that we would get with just either slit open. How can that be explained?

Figure 2. Thomas Young's double-slit experiment in a modern version. The light emitted by a laser passes through two slit openings in a diaphragm. Finally, it hits an observation screen. When both slits are open (*top*), we see a series of dark and bright stripes, called "interference fringes." If only one of the two slits is open (*middle* and *bottom*), we observe a broad illuminated area without any stripes. It is clear that the striped pattern in the top picture, when both slits are open, is not the sum of the two others. Rather, at the dark locations, the two waves coming there from the two slits extinguish each other. At the bright locations, they reinforce each other. The extinction at the dark stripes and the amplification in the bright stripes are a clear confirmation of the wave nature of light.

The wave picture provides an explanation of the fringes. Let's assume that a light wave comes from a certain direction, say, from the left, as shown in the figure. It hits the two-slit opening. On the other side of each slit a new wave starts. The two waves reach the observation screen. At the center line on that screen, the two paths leading from the slits will be of equal length. In that case, the two waves will oscillate in sync and they will mutually reinforce each other, and a bright stripe results. If we move our observation point, right or left in the figure, one of the paths gets a little shorter while the other one gets longer. The two paths leading from the two slits to any given point on the observation screen are no longer of equal length. There is a difference in path length.

So, depending on where exactly the new observation point is, the two waves will get more and more out of step. At some point, the two waves will be completely out of step. Where one wave is at its maximum, the other one is at its minimum. Where this happens, the two waves cancel each other out. Just consider the same situation for water waves. If two waves meet so that the crest of one meets the trough of the other one, they cancel each other out.

If we move even farther out, the path length difference will keep getting larger. At some point, the path length difference will be exactly one wavelength. In that case, crest meets crest again: the two waves reinforce each other and a bright stripe will be seen.

If we move the observation point even farther out, the pattern repeats. There will again be positions where crest meets trough: the waves cancel each other out, there is no light, and it will be completely dark, and so on. The interference fringes appear because in those places where we have mutual reinforcement, we get more light resulting in the bright fringes, and in those places where crests meet troughs we have the complete extinction of light—the dark fringes, destructive interference. So we see a striped pattern.

After Thomas Young's experiment, physicists no longer doubted that light consists of waves and not particles.

LIGHT IS PARTICLES

Then, in 1905, a completely unknown clerk at the Swiss patent office in Bern published a series of papers that changed the nature of physics. At that time, Albert Einstein was only twenty-six years old. In one of the papers, he proposed his relativity theory. But it is the first paper published in that year on which we focus now. It is the only one of his works that Einstein himself, in a letter to his friend Conrad Habicht, called "very revolutionary." In that paper, Einstein suddenly suggested that light is made of particles.

These particles of light, also called light *quanta*, later were named *photons* by the American chemist Gilbert Newton Lewis in 1926. In the face of all the evidence for the wave nature of light existing in Einstein's time, with the double-slit experiment being only one proof, how did this young clerk at the Swiss patent office in Bern dare to come up with the idea that light might be composed of particles, just the opposite concept? To discuss this question in detail, we have to learn something about the way physicists describe order and disorder.

SHEEPDOGS AND EINSTEIN'S PARTICLES OF LIGHT

There are many competitions worldwide every year to find out which sheepdog is the best. One of the jobs such dogs must perform is to gather a flock of sheep and move them to one specific place, say, into one corner of a field. From a physicist's point of view, what the sheepdog does is increase the order of the system. Before, the sheep might be scattered all over the field, particularly if they feel safe and no enemy is around. The sheepdog has something in its genes that tells it how to gather the sheep all together into one pack. In sheepdog competitions, that dog wins who herds the flock together in the shortest time, who gathers all the sheep in an orderly way at some place its master specifies.

Actually, the situation is very similar to clearing off the stuff—books, pieces of paper, and brochures—cluttering a desk. Most desks after some time look completely messy, a piece of paper lying here, a newspaper over there, a coffee cup on top of the newspaper, some other piece of paper in another corner, and so on.

Just as the sheepdog puts all the sheep into one corner of the field, one way to increase the order on the desk is simply to make, say, three stacks, one for notes, one for newspapers and journals, and one for books (Figure 3). Suddenly, all these items are in place and the rest of the desk is free. But unless we take care, the stuff will spread all over the desk again after some time. So, in both the case of the sheep and the case of the desk, we have a natural tendency for stuff to spread out evenly over the available space, and we also see that it takes a special effort to gather the stuff together again. The situation where the stuff is gathered together is one of higher order than the situation where it is evenly spread out.

Interestingly, a gas in a container behaves in the same way. Suppose

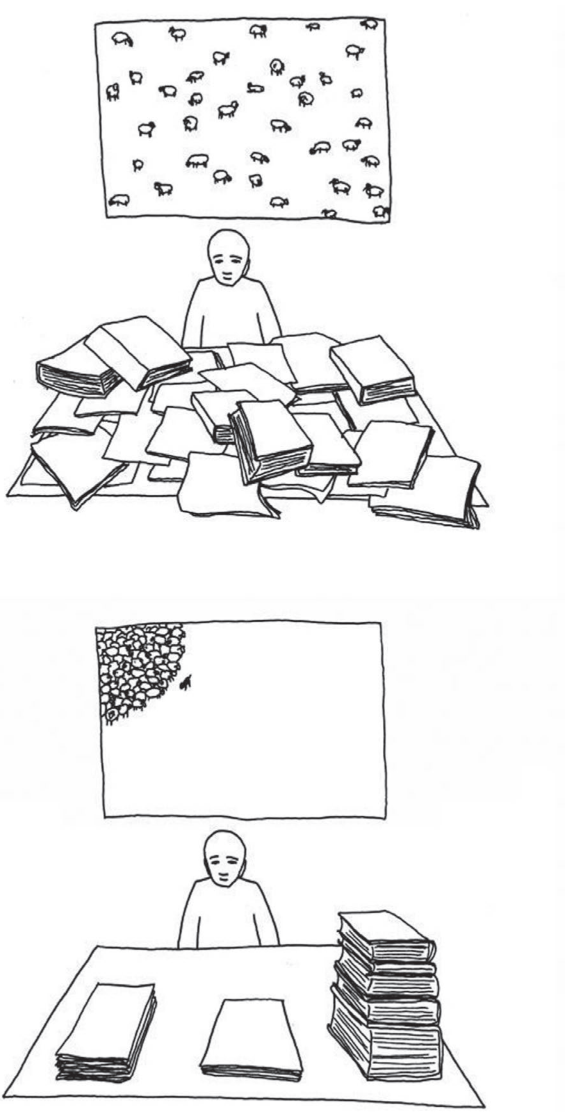

Figure 3. It always requires an effort to create order (*bottom*) out of disorder (*top*). In the case of sheep on the field, as shown in the picture on the wall, it is the effort of the sheepdog that provides the order. In the case of the mess on the desk, it's the effort of the person. Unfortunately, all systems in general have a natural tendency toward increasing their disorder.

we have a vessel separated into two parts by a wall with an opening that can be shut or not (Figure 4). We start with the valve closed, and all the gas particles are in one half, while the other half is empty. Then, we open the shutter. It's obvious what will happen. The gas will spread out evenly over the whole vessel. There will be a lower density then, since the gas has to thin out. Gas really consists of atoms and molecules. So the situation is just like two fields, one of them full of sheep. If we open a gate to the other, empty field, after some time, the sheep will spread out over both fields. We assume that there is an equal amount of food available on both sides and that there is no danger—and no sheepdog—pushing them either way.

Now, let us assume the opposite. Let's assume we start with the gas filling both sides. Will it ever happen that all the atoms will, of their own accord, move to one half of the vessel, leaving the other half empty? Probably not. Why not? In principle, such behavior is not impossible. If we look closely, we will observe atoms going through the opening in both directions, some from the right to the left, and some from the left to the right. It could happen by sheer coincidence that at some time, all the atoms are assembled on one side and none on the other. But apparently that is very unlikely.

Likewise, it is very unlikely that within one container, all the atoms will move into one corner together, leaving the rest of the container empty. In principle, this is not impossible; since every molecule moves around in its own zigzag fashion, it could simply happen by chance that they, at some instant, end up in one place. But this is extremely unlikely. The contrary obviously happens easily. If we have all the atoms in one corner and let them fly freely, they will immediately fill the available space in a homogeneous way.

This leads us to the observation that the universe tends to increase its disorder. All the atoms in one corner together means a highly ordered situation; all the atoms filling the available volume is a less ordered one. Also, we can see a clear connection between probability and order. The more orderly a situation is, the less probable it becomes.

Physicists like to describe disorder using the notion of *entropy*. Entropy is just a measure of disorder. More precisely, entropy reflects in how many ways a given situation can be realized. The larger the entropy, the more disordered a situation is, and the larger the entropy, the higher the probability for that situation to exist. For the case of gas filling a certain volume, it turns out that entropy increases with the in-

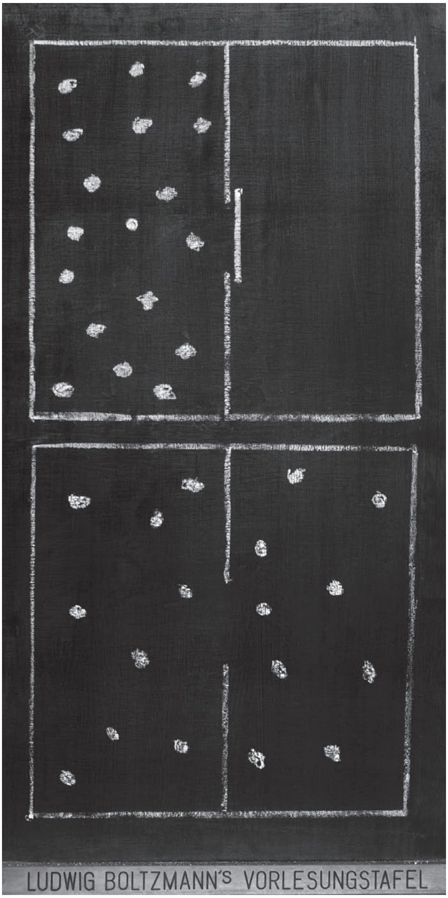

Figure 4. Gas, limited initially to one side of a container (*top*), immediately spreads out all over the place when the shutter is open (*bottom*). This condition will remain so, with the individual gas particles going back and forth between both sides. The reverse procedure, where all evenly dispersed particles of a gas (*bottom*) assemble on their own on one side only (*top*), never happens. The reason is that this latter procedure is, statistically, highly improbable. It would mean that all molecules happen by chance to move the same way across the opening. Albert Einstein observed that light inside a cavity behaves in a similar way and therefore assumed that light, like gas, must also consist of particles. The connection between probability and order was discovered by the Austrian physicist Ludwig Boltzmann. His blackboard ("Vorlesungstafel") was used to draw the sketches for this book.

crease in volume. In a sense, putting all the atoms in the smaller volume is like putting them all together in a corner.

In 1905 the young Albert Einstein made an important discovery. He studied the entropy of a gas filling a certain volume and compared it with the entropy of light filling the same kind of volume. What Einstein discovered was an interesting coincidence. He read and compared scientific papers that had already been around for more than five years, so anyone else could have made the same discovery. But Einstein discovered that the entropy—remember, this is the measure for disorder—of radiation in general, or light more specifically, filling a certain volume is very similar to the entropy of gas filling that same volume. Indeed, he found out that the mathematical expression derived by the German physicist Wilhelm Wien for the entropy of radiation filling some volume is the same as the mathematical expression derived earlier by the Austrian physicist Ludwig Boltzmann for a gas filling a container. More precisely, the two mathematical expressions for entropy vary in the same way if one changes the available volume.

Einstein, seeing this analogy, made a very bold conjecture. He knew that the expression for the entropy of gas filling a volume can easily be understood on the basis of how the individual molecules move around, and how improbable it is that they fill only a part of the available space. Because of the analogy of the two mathematical expressions for light and for particles, Einstein assumed that light is also made up of particles, which move around just like molecules and which also don't like to end up in some corner if a large volume is available to them.

Einstein was very careful. He called his idea just a heuristic aspect in the title of the paper: "On a Heuristic Point of View about the Creation and Conversion of Light." We talk of *heuristics* when we talk about an idea that helps us to find out, to make guesses, to get a feeling for a situation. We do not necessarily imply that we are able to prove our point. Maybe Einstein did not want to offend the adherents of the wave theory of light too much. But in the paper, Einstein himself is very explicit. In his 1905 paper, he takes the particles of light quite literally, as localized points moving around in space, just like atoms.

Einstein was not content with just making this bold guess. He thought about where else in nature the idea of light being particles would also have interesting consequences. He suggested that his explanation, if correct, would also help to explain a phenomenon not understood by physicists at his time—the *photoelectric effect*.

The German physicist Wilhelm Hallwachs had discovered this effect in 1888. He saw that something interesting happens when we shine light on a metal plate. The light can actually free electrons out of the metal, and these electrons can easily be detected as an electrical current. People had tried to explain that effect using the wave concept of light, which was, at that time, the accepted one. But the wave idea ran into serious problems when it came to explaining what experimentalists saw.

One of the unaccountable features is that the electrons start to appear instantly when we start to shine light on the metal plate.

Why is that a problem for the wave concept? Well, a wave is an oscillation back and forth. In the case of light, it is an oscillation of an electric and a magnetic field. When light hits a metal plate, it will make the electrons inside the metal plate start to oscillate. The electrons would oscillate initially just a little bit, and they would oscillate more and more as they absorbed more and more light, until finally they would break loose from the surface of the metal and be free. Imagine a person on roller skates who oscillates back and forth in a half tube. By pumping with his feet, he pumps more and more energy into the oscillation until he is able to jump above the tube. Evidently, it takes a while to accumulate enough energy to do this. So, for our photoelectric effect, it would not be so surprising if the electrons started coming out right away when we illuminated our metal surface with a strong light beam, because then the electrons could be brought to large oscillations in a very short time. But people did experiments with very weak light and found out that the electrons start coming out immediately anyway. According to the wave concept, it should take some time until the electrons have accumulated enough energy. This was just one problem with the wave concept of light.

However, if light consists of particles, this problem is resolved. What happens, as Einstein remarked, is simply that an individual light particle, an individual photon, just might, by chance, kick out an individual electron (Figure 5). This explains why the electrons start coming out immediately after we turn on the light beam, and it also explains why the amount of electrons observed is strictly proportional to the amount of light shining on the surface. Double the light intensity means double the photons hitting the surface, which again means double the electrons set free.

Einstein made another bold prediction based on this model, and this is where physicists always prove their worth. The final test of a the-

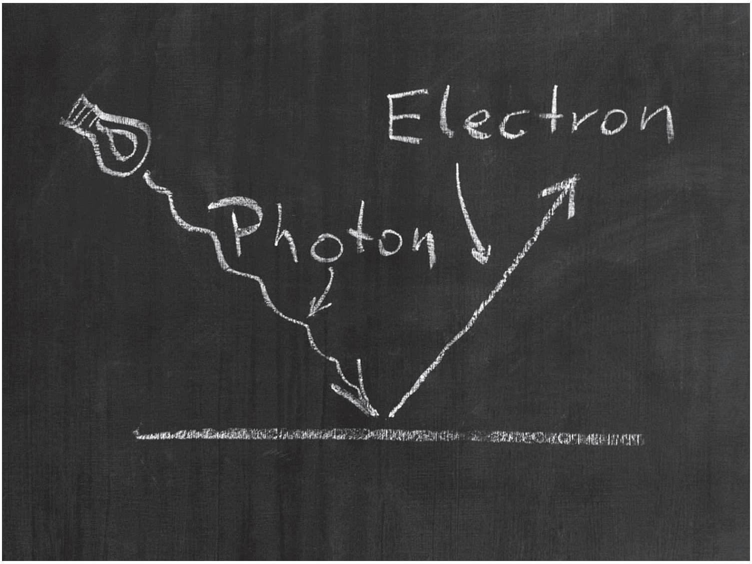

Figure 5. Light hitting a metal surface can kick out electrons, which then move away. This is the photoelectric effect. Einstein explained it by saying that light consists of individual particles, called photons.

ory is not just that it explains some phenomena already observed in the laboratory or in nature. The most convincing argument for a new theory is that it is able to predict something no one had been able to calculate so far and something that had not been observed until then. What Einstein predicted for the photoelectric effect is a connection between the frequency of the light shining on the metal plate and the energy of the electrons coming out.

Suppose a photon with some energy hits the metal plate. It might kick out an electron or it might not. Suppose it does. So, how fast will the electron move after it has left the metal plate? What will its energy be? There are many things that can happen. The photon might hit the electron such that it cannot convey all its energy to the electron, just as a billiard ball might hit another one and still keep moving. But it could happen that the photon would hit the electron such that it transfers all its energy to the electron. Then, the electron would move quite fast. But it might lose some of its energy inside the metal plate before it gets out. But it could also happen that the electron would be hit by the photon right on the surface of the metal such that the electron would not lose any energy before it got free. But it still would have to get out. Every surface has some attraction to electrons. This amount of attraction depends on the material of the surface, but the electron always needs some energy to overcome this attraction.

So, what this all boils down to is the following. If we get lucky and the photon hits the electron in the right way, and if we get luckier still and the electron somehow does not lose all its energy inside the metal, the electron comes out with the original energy of the photon, reduced by the energy required to get out of the metal. Now we have to ask ourselves, What is the original energy of the photon? And there, Einstein took an idea suggested by Max Planck five years before, that is, that the energy is quantized. It comes in chunks, in multiples of quanta such that the energy of a photon E is given by its frequency v multiplied by a constant, Planck's quantum of action h: $E = hv$. The most important point now is this: if Einstein is right, then the maximum energy with which the electrons come out of a metal must be increasing in proportion to the frequency of the light shining on the metal plate. This prediction of Einstein's was confirmed in a very beautiful experiment by the American physicist R. A. Millikan in 1916. For his work on the photoelectric effect, Einstein was awarded the Nobel Prize in Physics in 1921.

EINSTEIN AND HIS NOBEL PRIZE

Actually, the story of Einstein's Nobel Prize is quite interesting. In general, in order to be awarded a Nobel Prize, a person has to be nominated. The Royal Swedish Academy of Sciences, which chooses the prize recipient every year, has a small selection committee. Many physicists all over the world are invited to make nominations, and the academy then selects out of these nominations the laureate, or up to at most three joint laureates. For the final decision, the academy draws upon recognized experts in the respective fields and asks them to provide their opinion about the nominations. In Einstein's time, this expert work was done mostly by the members of the Nobel committee themselves.

Einstein had been nominated many times, for the first time in 1910, only five years after his annus mirabilis. In that notable year of 1905, Einstein wrote five scientific papers. In one of them he proposes his relativity theory. In another one, the most famous equation in physics, $E = mc^2$, appears for the first time. In the third one, in the field of atomic physics, he gives a very good estimate of the size of atoms. But the first paper that was published in 1905 is the one where he proposed the concept of photons.

Nearly all the nominations that Einstein received were for his relativity theory. The problem was that there were two members of the Nobel committee who either did not like the theory of relativity or even thought it was wrong. The fact that Einstein had not received the prize started to become a strange situation in the scientific community. The breakthrough came when the theoretical physicist Carl Wilhelm Oseen became a member of the academy and realized why Einstein had not received the Nobel Prize. Oseen suggested giving the prize to Einstein