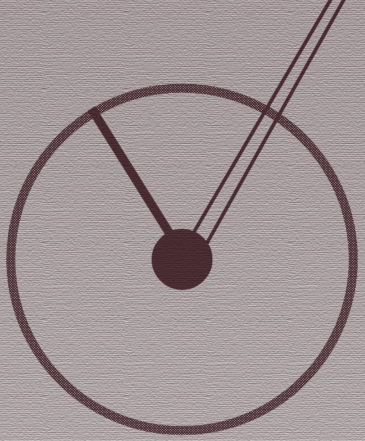
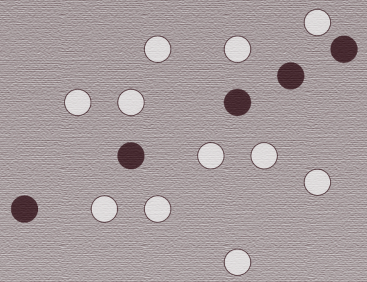




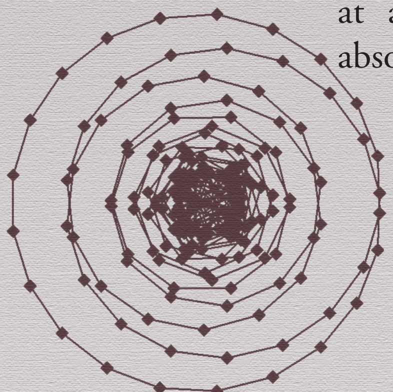
Why Quantum Mechanics Is Not So Weird after All

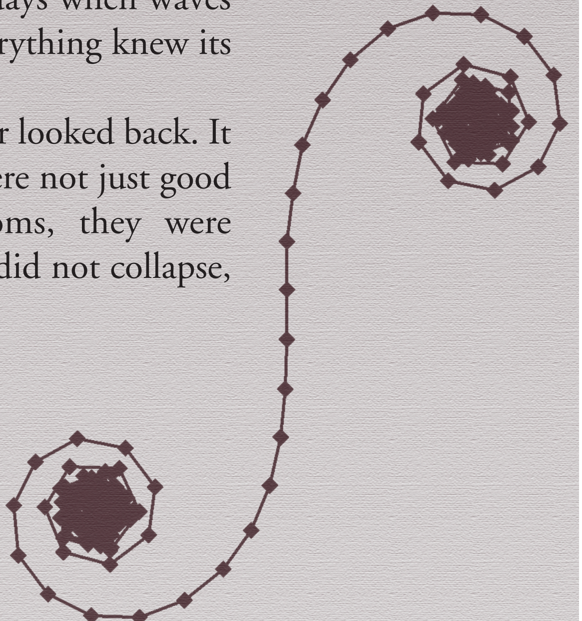
Richard Feynman's "least-action" approach to quantum physics in effect shows that it is just classical physics constrained by a simple mechanism. When the complicated mathematics is left aside, valuable insights are gained.

PAUL QUINCEY

The birth of quantum mechanics can be dated to 1925, when physicists such as Werner Heisenberg and Erwin Schrödinger invented mathematical procedures that accurately replicated many of the observed properties of atoms. The change from earlier types of physics was dramatic, and pre-quantum physics was soon called classical physics in a kind of nostalgia for the days when waves were waves, particles were particles, and everything knew its place in the world.

Since 1925, quantum mechanics has never looked back. It soon became clear that the new methods were not just good at accounting for the properties of atoms, they were absolutely central to explaining why atoms did not collapse,





how solids can be rigid, and how different atoms combine together in what we call chemistry and biology. The rules of classical physics, far from being a reliable description of the everyday world that breaks down at the scale of the atom, turned out to be incapable of explaining anything much more complicated than how planets orbit the sun, unless they used either the results of quantum mechanics or a lot of ad hoc assumptions.

But this triumph of quantum mechanics came with an unexpected problem—when you stepped outside of the mathematics and tried to explain what was going on, it didn't seem to make any sense. Elementary particles such as electrons behave like waves, apparently moving like ripples on a pond; they also seem to be instantaneously aware of distant objects and to be in different places at the same time. It seemed that any weird idea could gain respectability by finding similarities with some of the weird features of quantum mechanics. It has become almost obligatory to declare that quantum physics, in contrast to classical physics, cannot be understood, and that we should admire its ability to give the right answers without thinking about it too hard.

And yet, eighty years and unprecedented numbers of physicists later, naked quantum weirdness remains elusive. There are plenty of quantum phenomena, from the magnetism of iron and the superconductivity of lead to lasers and electronics, but none of them really qualifies as truly bizarre in the way we might expect. The greatest mystery of quantum mechanics is how its ideas have remained so weird while it explained more and more about the world around us.

Perhaps it is time to revisit the ideas with the benefit of hindsight, to see if either quantum mechanics is less weird than we usually think it is or the world around us is more so.

Classical Mechanics in Action

When we think of planets orbiting the sun, we usually adopt Newton's view that they are constantly accelerating—in this case changing direction—in response to gravitational forces. From this, we can calculate the motions precisely, and the impressive accuracy of predictions for total solar eclipses shows how well it works.

There is, however, another way of thinking about what is happening that gives exactly the same results. Instead of the Principle of Acceleration by Forces, as we might call it, there is an alternative called the Principle of Least Action, or more correctly, Hamilton's Principle.

It is a principle that was first put forward about fifty years after Newton's, in its earliest form by the Frenchman Pierre Maupertuis, and in its ultimate form by the Irishman William Rowan Hamilton.

The general idea is that when a planet travels through space, or a ball travels through the air, the path that is followed is the one that minimizes something called the *action* between the start and end points. Action, for our purposes here, is just something that can be measured out for some particular object moving along a particular path. It is exactly defined and is measured in units of energy multiplied by time. The details are not important unless you need to make calculations.

We therefore have two quite different ways of describing situations in classical physics that are equally good in terms of giving the right answer. To give the simplest possible example, we can think of a golf ball travelling across an idealized, frictionless, flat green. In Newton's view (figure 1), the ball moves in a straight line at constant speed, because that is what Newton's Law says it must do. In Maupertuis' view (figure 2), the ball does this because this path is the one that has the least action between the start and end points. This trivial example can be made more interesting by making the green have humps and dips, which are like having forces acting on the ball, but the principles stay the same.

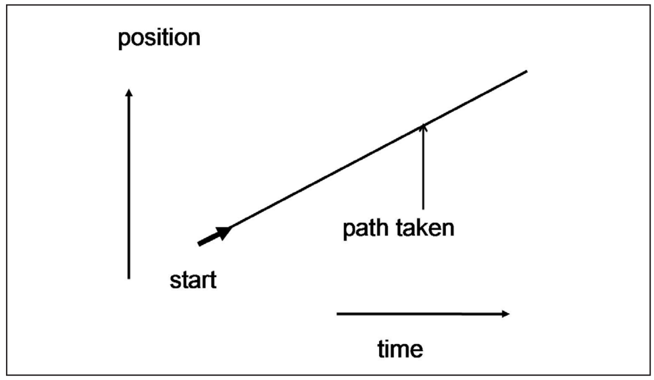


Figure 1: Classical mechanics—Newton's view: the ball moves in a straight line at a constant speed, because that is what things do when there are no forces acting on them.

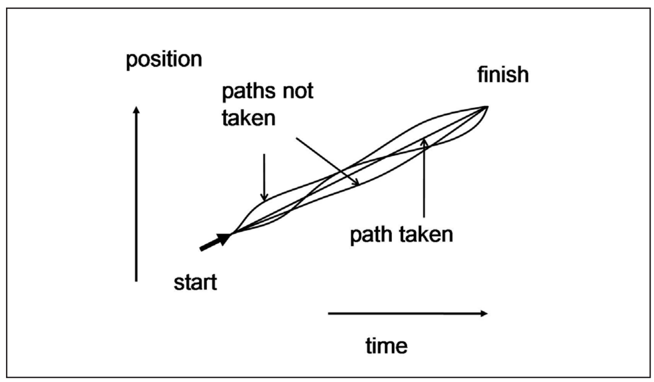


Figure 2: Classical mechanics—Maupertuis' view: the ball moves in a straight line at a constant speed to any given point on its travels, because that is the path of least action between the start and finish.

Hamilton's Principle is fundamentally equivalent to Newton's Laws, and comes into its own when solving more advanced types of classical problems. But as an explanation, it has a major flaw—it seems to mean that things need to know where they are going before they work out how to get there.

Actually, this is where classical mechanics makes its first big step toward quantum mechanics, if only we look at it another way. The mathematics of Hamilton's Principle can be described in words alternatively like this: given its starting

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points and motion, an object will end up at locations that are connected to its starting point by a path whose action is a minimum compared to neighboring paths. If locations away from the classical path are considered, no such paths exist—there will always be a path with the *least* action, but this is not a *minimum*.

It is an unfamiliar idea, but well worth a little effort to try and digest. One vital change to note is that, while still being classical physics, the emphasis has moved away from knowing the path that is followed to having a test to check whether possible destinations are on the right track. And the crucial factor is being able to compare the actions of different paths.

It leads to a third picture for our moving golf ball, central to the later move to quantum physics, which we can call Feynman's view of classical physics (figure 3).

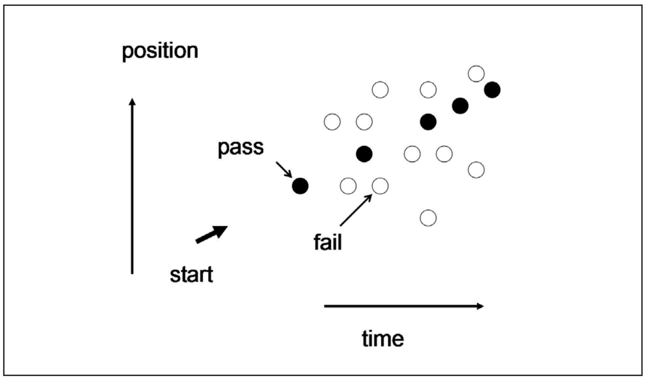

Figure 3: Classical mechanics—Feynman's view: the ball is found at the black points, which happen to lie on a straight line, and not the white points, because only the black points pass the "action test." This means that there is a path from the start to the black points whose action is a minimum compared to neighboring paths, but there is no such path from the start to the white spots.

If we stay within the world of classical physics, we can choose to ignore this strange new description and stick with the more comfortable idea that things are accelerated along paths by forces, but this would be a personal preference rather than a rational one. The new view prompts the question: "How do things work out whether possible destinations are linked to the start by a path of minimal action?" We should appreciate, however, that the old Newtonian view prompts equally difficult questions like: "How do things respond to forces by accelerating just the required amount, instant by instant?" Moreover, as we will see, the action version is the one that the world around us seems to use.

Roll on, Quantum Mechanics

Suppose we take the action question seriously and give it a rather simple answer: Nature has to check out all possible destinations to see if they are on the right track. It must do this by trying to find out if there is a path of minimal action to each destination. It uses a device that can measure the action along all possible paths to each destination.

The device is a simple surveyor's wheel for measuring action—just a wheel with a mark on the rim (figure 4). There isn't literally a type of wheel that measures action, but we can imagine that there is. The mechanism assigns probabilities to each destination according to whether, with just this simple measuring tool, it can find a path of minimal action.

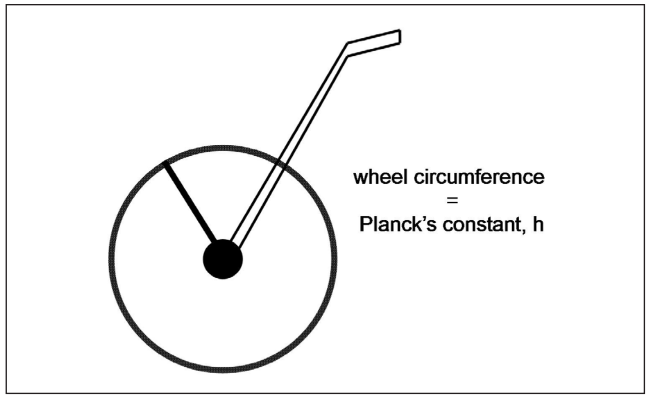

Figure 4: The single most potent image of quantum mechanics—a surveyor's wheel for measuring action

When the actions it is trying to measure are large compared to the size of the wheel, the system typically works just as classical physics requires. But in some situations the mechanism fails to produce classical mechanics and gives us quantum mechanics instead. We call the circumference of the wheel "Planck's constant," after Max Planck, who discovered its importance by an indirect route in 1900.

You may be wondering how exactly the wheel can tell us what we need to know, but we don't need to go into the details here—those interested should read Richard Feynman's book, *QED: The Strange Theory of Light and Matter*, or see the summary given in the box on page 43.

Differences from Classical Physics

As we might expect, the introduction of a mechanism for carrying out classical mechanics only makes a difference when the mechanism can't do its job properly. Specifically, if we want to check out destinations that are too close to the start, as gauged by the size of the wheel, the mechanism doesn't work. It cannot say where the object should be going, and there is an intrinsic fuzziness associated with it, with a scale set by the amount of action known as Planck's constant. This is otherwise known as the Uncertainty Principle.

A second feature arises from the simple circular nature of the measuring device. It cannot tell the difference between paths that differ by an amount of action that is an exact whole number of Planck's constants. This can lead to patterns of probabilities that look just like classical waves, because the mathematics of waves is very similar to the mathematics of circular motion.

The most important change comes when we consider objects in very small orbits, like electrons around nuclei. The mechanism gives zero probability unless the orbit (or more correctly the state) has an action that is an exact multiple of Planck's constant. This crude mechanism explains why atoms can only shrink to a certain point, to a state with an action of Planck's constant, where they become stable.

With one extra idea, which we will mention later, the mechanism seems to explain the workings of chemistry, biology, and all the other successes of quantum mechanics, without ever really stopping being classical mechanics.

Three Conceptual Problems with Quantum Mechanics

The way it is normally introduced, quantum mechanics is something quite baffling, and certainly stranger than just classical mechanics with a mechanism. It is worth addressing the three most obvious difficulties directly:

1) *Quantum mechanics gives answers that are a set of probabilities all existing at the same time. This is totally unreal.* As Schrödinger pointed out, quantum mechanics seems to say that you could create a situation where a cat was both alive and dead at the same time, and we never see this. But this is in fact a very curious piece of ammunition to use against quantum mechanics.

We already have a very good nontechnical word for a mixture of possibilities coexisting at the same time—we call it the future. Unless we believe that all events are predetermined, which would be a very dismal view of the world, this is what the future must be like. Of course, we never experience it until it becomes the present, when only one of the possibilities takes place, but the actual future—as opposed to our prediction of one version of it—must be something much like what quantum mechanics describes. This is a great triumph for quantum mechanics over classical mechanics, which by describing all events as inevitable, effectively deprived us of a future.

Of course, there is now a new big question of how one of the possibilities in the future is selected to form what we see as the present and what becomes the past, but we should not see the lack of a ready answer as a fault of quantum mechanics. This is a question that is large enough, encompassing such ideas as fate and free will, to be set aside for another time. The headline "Physics Cannot Predict the Future in Detail" should be no great embarrassment.

2) *Quantum mechanics means that there is a kind of instant awareness between everything.* This is quite true, but by introducing quantum mechanics in the way that we have, the "awareness" is of a very limited kind—limited to the awareness gained through the action-measuring mechanism as it checks all possible destinations. It is very hard to see how the only result of this—a probability associated with each destination—could be used to send a signal faster than light or violate any other cherished principle. It is rather revealing that one of the few novel quantum phenomena is a means of cryptography—a way of concealing a signal rather than sending one.

3) *Quantum mechanics doesn't allow us to say where everything is, every instant of the time.* This is the most interesting "fault" of quantum mechanics, and it can be expressed in many ways: particles need to be in more than one place at a time; their positions are not defined until they are "observed"; they behave like waves. We will summarize this as an inability to say exactly where particles are all the time.

The "classic" illustration of this is the experiment of passing a steady stream of electrons through two slits (figure 5). Instead of the simple shadows we would expect if the particles were just particles, we see an interference pattern, as if the electrons have dematerialized into a wave and passed through both slits at the same time.

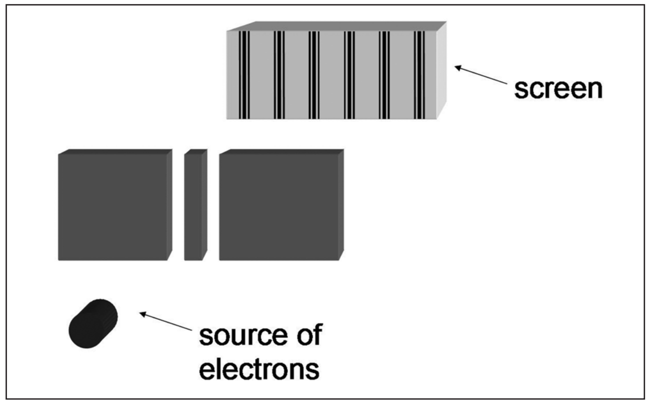

Figure 5: A schematic diagram of the two-slits experiment

There are several ways of coming to terms with this. The first thing to note is that the lack of complete information is not really a problem that arose in quantum mechanics—it originates in the third version of classical mechanics. In the Feynman version, the essence of motion is a process of determining if a destination is on or off the right track. Before the move to quantum mechanics, we can do this as often as we like, so that we can fill in the gaps as closely as we like, but the precedent has been set: physics is about testing discrete locations rather than calculating continuous trajectories. If it is inherent in old-fashioned classical physics, not just "weird" quantum physics, perhaps we can relax a little.

The second point is to clarify what the problem is. To take the two-slit example, we never see electrons dematerialize, or rippling through something, we just find it necessary to think that they do to explain the pattern that we see on the screen. If we deliberately try to observe where the electrons go, we see them as particles somewhere else, but the interference pattern disappears. In effect, the problem is that we cannot say what the particles look like only *when they cannot be seen.*

Now this is an uncomfortable thought, because all our instincts tell us that particles must be somewhere, even when we cannot see them. But if quantum mechanics can accurately describe all the information we can ever obtain about the outside world, perhaps we are simply being greedy to ask for anything more. The headline "Physics Fails to Describe Events That Cannot Be Observed" is, again, rather lacking in impact.

The final point is a little vague but more fundamental. If we accept that the future is not fixed, we expect it to contain surprises. Crudely speaking, this is not very plausible in a world where particles have continuous trajectories and an infinite amount of information is freely available. It is much more plausible in a world that is in some way discontinuous, where the available information is limited. Even though we have set aside the question of how a future full of possibilities turns into an unchanging past, it must involve something that seems pretty weird compared to our normal experience. Perhaps this example of physics not conforming to our expectations is weirdness of the right sort.

The Addition of Spin

It was mentioned earlier that another new idea is needed before the classical physics of electrons and nuclei properly turns into chemistry. That idea is *spin*, a third property of electrons and nuclei alongside mass and electrical charge. Paul Dirac showed that spin is a natural property of charged particles within quantum mechanics. Wolfgang Pauli showed that the spin of the electron prevents more than one electron occupying the same state at the same time—the Exclusion Principle—a fact responsible for the whole of chemistry. The details are not important here, but quantum mechanics with spin seems to account for pretty much all the world we see around us.

Quantum Mechanics—Bringer of Stability

One of the benefits of viewing the quantum world as not fundamentally different from the classical world is that we can imagine how one changes into the other. With a few simple assumptions, a classical world of point-like electrons and nuclei is blindingly chaotic. Atoms are continually trying to collapse, but are prevented from doing so by the huge amount of electromagnetic radiation that is released in the process. It is not the comfortable place that the word *classical* implies.

As we imagine moving to the quantum realm by increasing the size of Planck's constant from zero, something remarkable happens. At some point, the blinding light disappears to reveal stable atoms, capable of forming molecules. Far from making everything go weird, quantum mechanics makes it go normal. To be sure, if Planck's constant increases too far, the atoms fall apart and a different form of chaos takes over, but that just makes the story even more interesting.

So it seems that quantum physics is not weird and incomprehensible because it describes something completely different from everyday reality. It is weird and incomprehensible precisely because it describes the world we see around us—past, present, and future.

Reference

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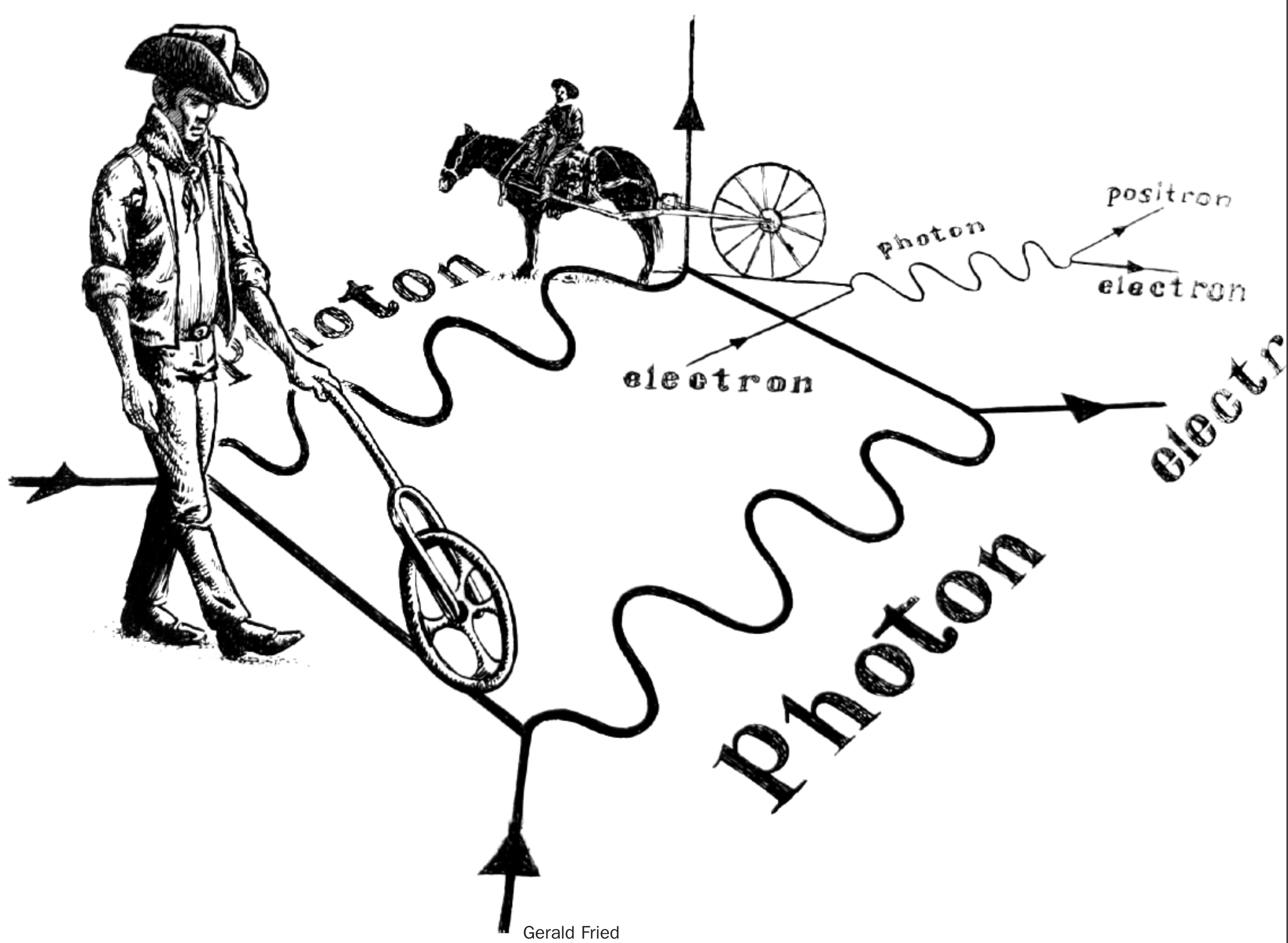

Gerald Fried

Mapping Out the Future with a Surveyor's Wheel

To understand how the quantum mechanism works, it is easiest to describe an analogous situation. Instead of finding out whether there is a path with minimal action to a possible destination, using a "surveyor's wheel" to measure action, we can find out whether there is a path of minimal distance to a possible destination, using an ordinary surveyor's wheel. For reasons that will become clear, we will assume that the wheel has a single spoke connecting the hub to the rim, like the diagram in figure 4.

To use the simple example of a flat plane (analogous to the golf ball example of figures 1 to 3), we start with a particular place and direction and want to find out if another point on the plane is connected to the start by a path with minimal distance. It is obvious to us that this will be true for points directly in line with the starting direction, but we pretend that we don't know this, and have to work it out using our wheel. How is this done?

We suppose that for each possible destination, large numbers of surveyor's wheels roll out to it along every conceivable path, starting with their spokes vertical. They each end up at the destination with their spoke in whatever position the length of the path dictates, but with no record of the path they have taken.

Can we learn from just all these spoke positions if the destination is connected to the starting point by a path of minimal distance? Indeed, we can. Consider that all the possible paths have been tried in some systematic fashion, with the path changing a little bit each time. We don't *need* the paths to have been tested systematically in that order, but if all possible paths have been tried randomly, we can pretend that we have rearranged them systematically.

As we change the path a little at a time, the final position of the spoke, the angle it makes to the vertical, will change smoothly, moving around and around. It will continue to move around and around as we change the path bit by bit in all circumstances *except one*—if the series of paths passes through a path of minimal distance, then a whole bunch of the paths will provide spokes in a similar position.

How can we tell whether our vast collection of spoke positions contains a bunch pointing in roughly the same direction? We can do this simply by putting all the spokes end to end. If there is no path of minimal distance to the destination, the spokes tend to end up in each direction equally often—spiralling around and around—and the end of the "spoke chain" is very near where it started, as in figure 6.

If there *is* a path of minimal distance, on the other hand, the spokes from all the paths close to this path will line up, while everything else cancels out as before, so that the end of the "spoke chain" is much further from where it started, as in figure 7.

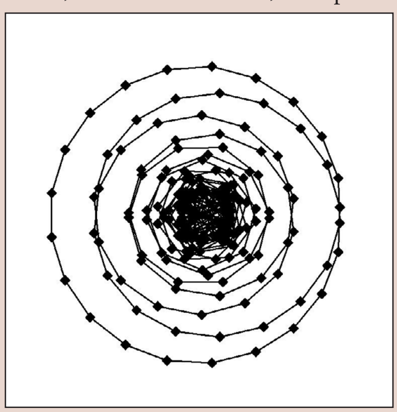

Figure 6: A "spoke chain" for all the paths between the start and a destination where there is no path of minimal distance between them.

We don't need to know which path has led to which spoke position. Putting the spokes end to end is all we need to find out what we want to know—whether there is a path of minimal distance to the destination.

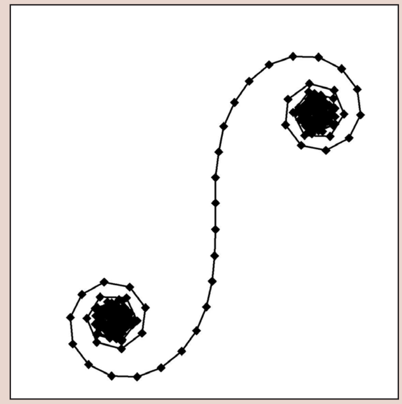

Figure 7: A "spoke chain" for all the paths between a start and a destination where there is a path of minimal distance between them.

This doesn't give us a hard and fast rule for knowing whether there is a minimal path between two places, but it is the best we can do. What we can say is that the *probability* of there being a minimal path is related to the distance between the start and end of the "spoke chain"—the longer the distance, the higher the probability. (The relative probability is actually given by the square of this distance.) In the context of figure 3, the black spots are very dark, and the white spots are very light, but they are all just shades of grey.

Incidentally, the diagrams have been drawn with the spokes from neighboring paths placed next to each other, so that they appear to spiral smoothly around, but this is not necessary. Whatever order the spokes are joined up in, the two ends will be the same distance apart.

It would be fair to say that this is a clumsy, if not ludicrous, mechanism for finding out if there is a path of minimal distance between the start and the destination. But it is a mechanism that uses the simplest of measuring devices, has genuinely no preconceived view of the outcome, and which, in the action version, seems to match what we see around us. □