The Quantum Physics of Time Travel

Common sense may rule out such excursions—but the laws of physics do not

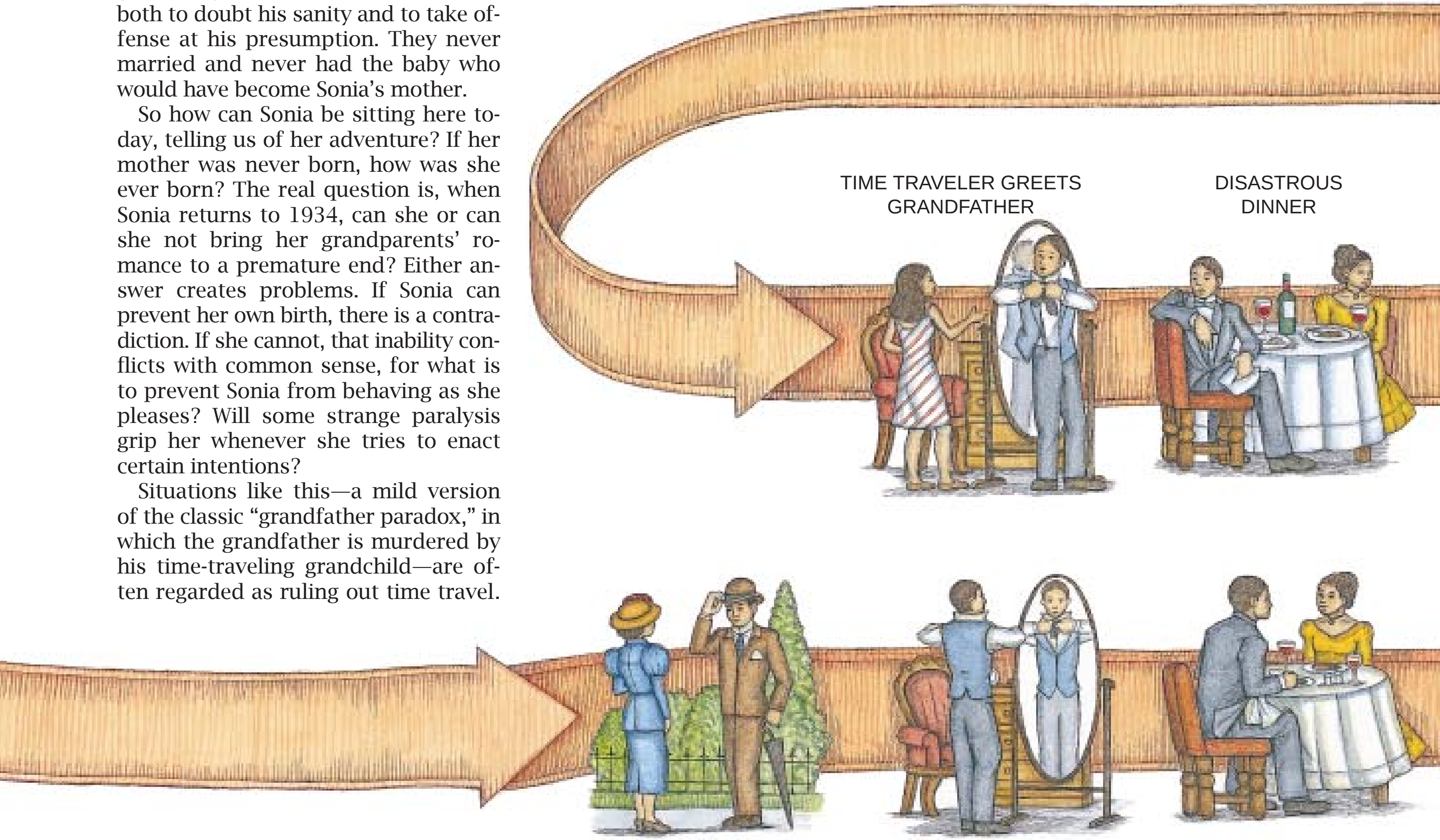
by David Deutsch and Michael Lockwood

Imagine, if you will, that our friend Sonia keeps a time machine in her garage. Last night she used it to visit her grandfather in 1934, when he was still courting her grandmother. Sonia convinced him of her identity by referring to family secrets that he had not yet revealed to anyone. This left him stunned, but worse was to follow. When he told his sweetheart over dinner that he had just met their future granddaughter, the lady's response was both to doubt his sanity and to take offense at his presumption. They never married and never had the baby who would have become Sonia's mother.

So how can Sonia be sitting here today, telling us of her adventure? If her mother was never born, how was she ever born? The real question is, when Sonia returns to 1934, can she or can she not bring her grandparents' romance to a premature end? Either answer creates problems. If Sonia can prevent her own birth, there is a contradiction. If she cannot, that inability conflicts with common sense, for what is to prevent Sonia from behaving as she pleases? Will some strange paralysis grip her whenever she tries to enact certain intentions?

Situations like this—a mild version of the classic "grandfather paradox," in which the grandfather is murdered by his time-traveling grandchild—are often regarded as ruling out time travel. Yet, surprisingly, the laws of physics do not forbid such adventures.

Another paradox, which often appears in science fiction, has been discussed by the Oxford philosopher Michael Dummett. An art critic from the future visits a 20th-century painter, who is regarded in the critic's own century as a great artist. Seeing the painter's current work, the critic finds it mediocre and concludes that the artist has yet to produce those inspired paintings that so impressed future generations. The critic shows the painter a book of reproductions of these later works. The painter contrives to hide this book, forcing the critic to leave without it, and then sets about meticulously copying the reproductions onto canvas. Thus, the reproductions exist because



GRANDFATHER PARADOX, in which a time traveler prevents his or her own birth, is a stock objection to time travel.

they are copied from the paintings, and the paintings exist because they are copied from the reproductions. Although this story threatens no contradiction, there is something very wrong with it. It purports to give us the paintings without anyone's having to expend artistic effort in creating them—a kind of artistic "free lunch."

Persuaded by such objections, physicists have traditionally invoked a chronology principle that, by fiat, rules out travel into the past. One-way travel into the future raises no such problems. Einstein's special theory of relativity predicts that, with sufficient acceleration, astronauts could go on a journey and return to the earth decades into the future, while physically aging only a year or two. It is important to distinguish between predictions such as this, which are merely surprising, and processes that would violate physical laws or independently justifiable philosophical principles.

We shall shortly explain why traveling into the past would not violate any such principle. To do so, we must first explore the concept of time itself, as physicists understand it. In Einstein's special and general theories of relativity, three-dimensional space is combined with time to form four-dimensional space-time. Whereas space consists of spatial points, space-time consists of spatiotemporal points, or events, each of which represents a particular place at a particular time. Your life forms a kind of four-dimensional "worm" in space-time: the tip of the worm's tail corresponds to the event of your birth, and the front of its head to the event of your death. An object, seen at any one instant, is a three-dimensional cross section of this long, thin, intricately curved worm. The line along which the worm lies (ignoring its thickness) is called that object's worldline.

At any point on your worldline, the angle it makes with the time axis is a measure of your speed. The worldline of a ray of light is typically drawn as making an angle of 45 degrees; a flash of light spreading out in all directions forms a cone in space-time, called a lightcone [*see illustration on next page*]. An important difference between space and space-time is that a worldline—unlike, say, a line drawn on paper—cannot be any arbitrary squiggle. Because nothing can travel faster than light, the worldline of a physical object can never stray outside the lightcone emanating from any event in its past. Worldlines that meet this criterion are called

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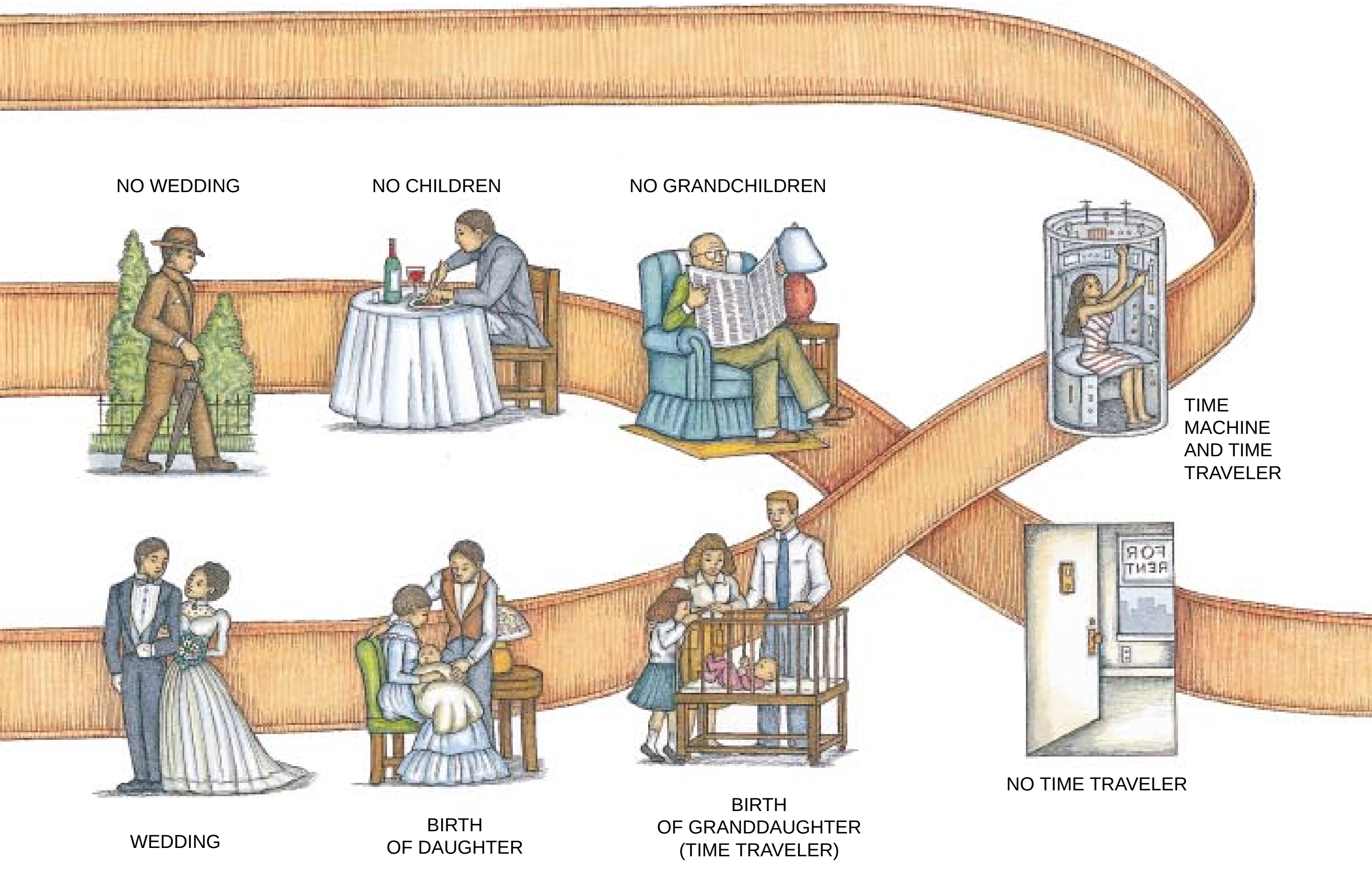
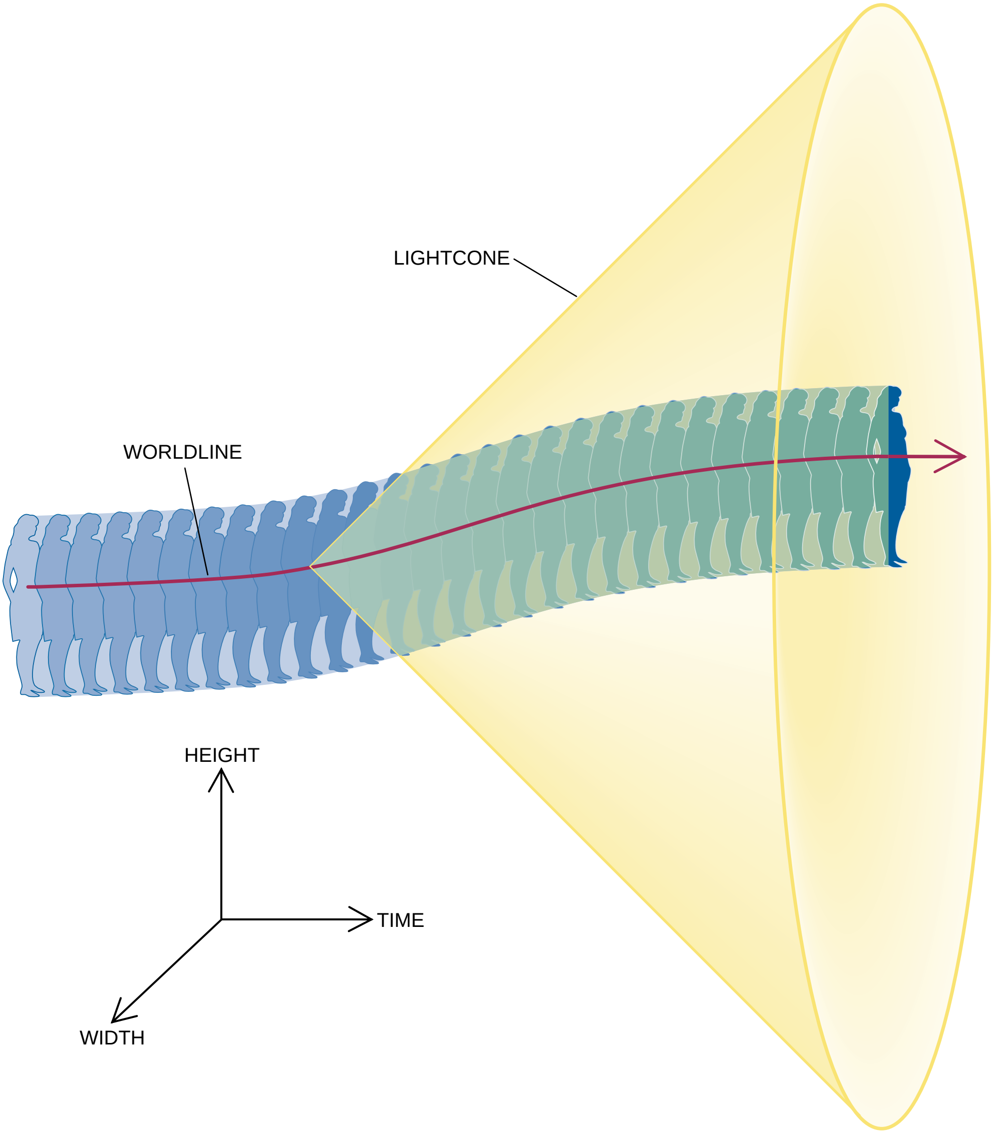




SPACE AND TIME are combined into one four-dimensional entity, space-time. Here we show two space dimensions and time. A worldline connects all events in our life in space-time; since we have some size, a person's worldline is more like a worm extending from birth to death than a line. The worldlines of light rays emanating in all space directions from an event trace out a cone in space-time, called a lightcone. The worldline of any object, such as the navel of this figure, cannot stray outside a lightcone emanating from any point in its past.

timelike. Time, as measured by a watch, increases in one direction along a worldline.

Einstein's special theory of relativity requires worldlines of physical objects to be timelike; the field equations of his general theory of relativity predict that massive bodies such as stars and black holes distort space-time and bend worldlines. This is the origin of gravity: the earth's worldline spirals around the sun's, which spirals around that of the center of our galaxy.

Suppose space-time becomes so distorted that some worldlines form closed loops [*see illustration on opposite page*]. Such worldlines would be timelike all the way around. Locally they would conform to all the familiar properties of space and time, yet they would be corridors to the past. If we tried to follow such a closed timelike curve (or CTC) exactly, all the way around, we would bump into our former selves and get pushed aside. But by following part of a CTC, we could return to the past and participate in events there. We could shake hands with our younger selves or, if the loop were large enough, visit our ancestors.

To do this, we should either have to harness naturally occurring CTCs or create CTCs by distorting and tearing the fabric of space-time. So a time machine, rather than being a special kind of vehicle, would provide a route to the past, along which an ordinary vehicle, such as a spacecraft, could travel. But unlike a spatial route, a CTC (or rather, the surrounding closed timelike tube) gets used up if repeatedly traversed; just so many worldline worms can fit into it, and no more. If one travels on it to a particular event, one will meet everyone who has ever traveled, or will ever travel, to that event.

Does our universe now, or will it ever, contain CTCs? We do not know, but there are various theoretical conjectures about how they might be formed. The mathematician Kurt Gödel found a solution to Einstein's equations that describes CTCs. In that solution, the whole universe rotates (according to current evidence, the actual universe does not). CTCs also appear in solutions of Einstein's equations describing rotating black holes. But these solutions neglect infalling matter, and how far they apply to realistic black holes is a matter of controversy. Also, a time traveler would be trapped inside the black hole after reaching the past, unless its rotation rate exceeded a critical threshold. Astrophysicists think it unlikely that any naturally occurring black holes are spinning that fast. Perhaps a civilization far more advanced than ours could shoot matter into them, increasing their rotation rate until safe CTCs appeared, but many physicists doubt that this would be possible.

A kind of shortcut through space-time, called a wormhole, has been mooted by Princeton University physicist John A. Wheeler. Kip S. Thorne of the California Institute of Technology and others have shown how two ends of a wormhole could be moved so as to form a CTC. According to a recent calculation by J. Richard Gott of Princeton, a cosmic string (another theoretical construct that may or may not exist in nature) passing rapidly by another would generate CTCs.

We are at present a very long way from finding any of these CTCs. They may, however, become accessible to future civilizations, which might well attempt to enact time-travel paradoxes. Let us therefore take a closer look at the paradoxes to see what principles, if any, time travel would violate, according to classical and quantum physics.

Classical physics says, unequivocally, that on arriving in the past Sonia must do the things that history records her doing. Some philosophers find this an unacceptable restriction of her "free will." But as an argument against time travel within classical physics, that objection is unpersuasive. For classical physics in the absence of CTCs is deterministic: what happens at any instant is wholly determined by what happens at any earlier (or later) instant. Accordingly, everything we ever do is an inevitable consequence of what happened before we were even conceived. This determinism alone is often held to be incompatible with free will. So time travel poses no more of a threat to free will than does classical physics itself.

The real core of the grandfather paradox is not the violation of free will but of a fundamental principle that underlies both science and everyday reasoning; we call this the autonomy principle. According to this principle, it is possible to create in our immediate environment any configuration of matter that the laws of physics permit locally, without reference to what the rest of the universe may be doing. When we strike a match, we do not have to worry that we might be thwarted because the configuration of the planets, say, might be inconsistent with the match being lit. Autonomy is a logical property that is highly desirable for the laws of physics to possess. For it underpins all experimental science: we typically take for granted that we can set up our apparatus in any configuration allowed by physical law and that the rest of the universe will take care of itself.

In the absence of CTCs, both classical and quantum physics conform to the autonomy principle. But in their presence, classical physics does not, because of what John L. Friedman of the University of Wisconsin and others call the consistency principle. This states that the only configurations of matter that can occur locally are those that are self-consistent globally. Under this principle, the world outside the laboratory can physically constrain our actions inside, even if everything we do is consistent, locally, with the laws of physics. Ordinarily we are unaware of this constraint, because the autonomy and consistency principles never come into conflict. But classically, in the presence of CTCs, they do.

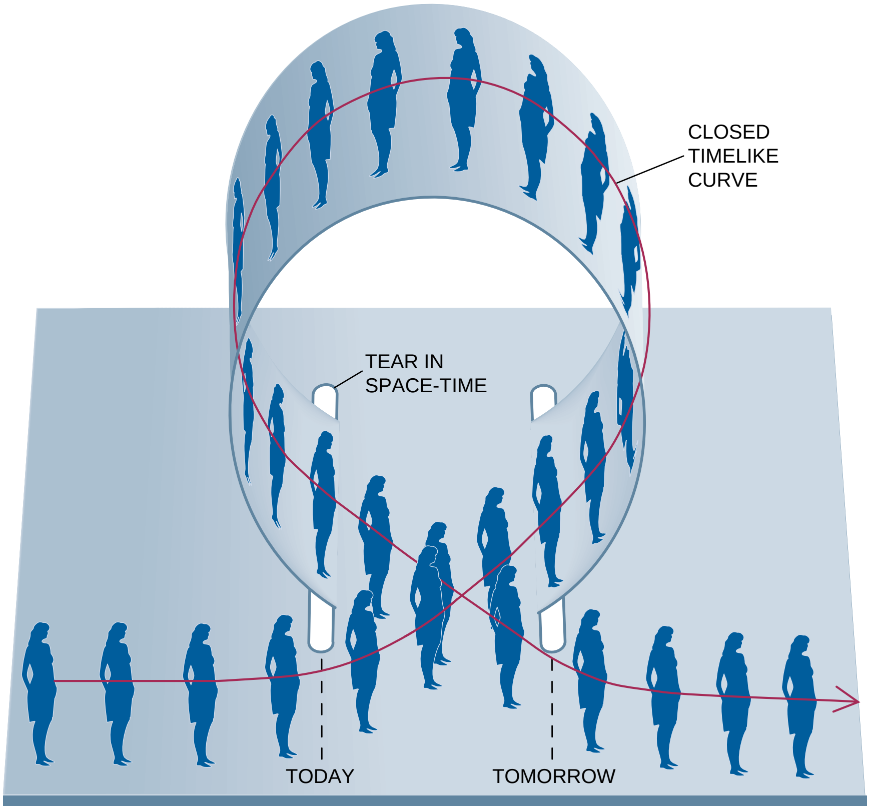
Classical physics says there is only one history, so try as she might to do other than what history dictates, consistency requires Sonia to act out her part in it. She may visit her grandfather. But perhaps when he tells Sonia's grandmother-to-be what happened, she becomes worried about his state of health. He is very touched and proposes to her; she accepts. Not only could this happen—under classical physics something like it must happen. Sonia, far from altering the past, becomes part of it.

What if Sonia is determined to rebel against history? Suppose she travels back to meet her earlier self. At this meeting, her younger self records what her older self says and, in due course, having become that older self, deliberately tries to say something different. Must we suppose, absurdly, that she is gripped by an irresistible compulsion to utter the original words, contrary to her prior intentions to do otherwise? Sonia could even program a robot to speak for her: Would it somehow be forced to disobey its program?

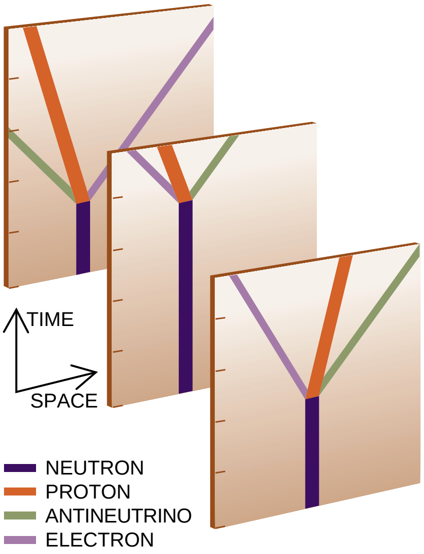
Within classical physics, the answer is yes. Something must prevent Sonia or the robot from deviating from what has already happened. It need not be anything dramatic, however. Any commonplace hitch will suffice. Sonia's vehicle breaks down, or the robot's program turns out to contain a bug. But one way or another, according to classical physics, consistency requires the autonomy principle to fail.

Now let us return to the story of the time-traveling art critic. We call this violation of common sense a knowledge paradox (the grandfather paradox is an inconsistency paradox). We use the term "knowledge" here in an extended sense, according to which a painting, a scientific article, a piece of machinery and a living organism all embody knowledge. Knowledge paradoxes violate the principle that knowledge can come into existence only as a result of problem-solving processes, such as biological evolution or human thought. Time travel appears to allow knowledge to flow from the future to the past and back, in a self-consistent loop, without anyone or anything ever having to grapple with the corresponding problems. What is philosophically objectionable here is not that knowledge-bearing artifacts are carried into the past—it is the "free lunch" element. The knowledge required to invent the artifacts must not be supplied by the artifacts themselves.

In an inconsistency paradox, physical events seem to be more tightly constrained than we are used to. In a knowledge paradox, they are less tightly constrained. For instance, the state of the universe before the art critic arrives does not determine who, if anyone, will arrive from the future or what he or she will bring along: the generally deterministic laws of classical physics allow the critic to bring back great pictures, poor pictures or no pictures at all. This indeterminacy is not what we



CLOSED TIMELIKE CURVE can be formed if space-time loops around. Entering such a curve tomorrow and moving forward in time, we can end up at today.



NEUTRON DECAY can occur at any time, though some times are more likely than others. For each instant in which the neutron might decay, there is a universe in which it decays at that instant, according to Everett's multiverse interpretation of quantum mechanics.

usually expect from classical physics, but it constitutes no fundamental impediment to time travel. Indeed, the indeterminacy would allow the classical laws to be supplemented with an additional principle, stating that knowledge can arise only as a result of problem-solving processes.

Yet that principle would land us in the same problem regarding autonomy as we encountered in the grandfather paradox. For what is to prevent Sonia from carrying new inventions into the past and showing them to their supposed originators? So although classical physics can, after all, accommodate the kind of time travel that is usually considered paradoxical, it does this at the cost of violating the autonomy principle. Hence, no classical analysis can wholly eliminate the paradox.

All this, however, is in our view academic. For classical physics is false. There are many situations in which it is an excellent approximation to the truth. But when closed timelike curves are involved, it does not even come close.

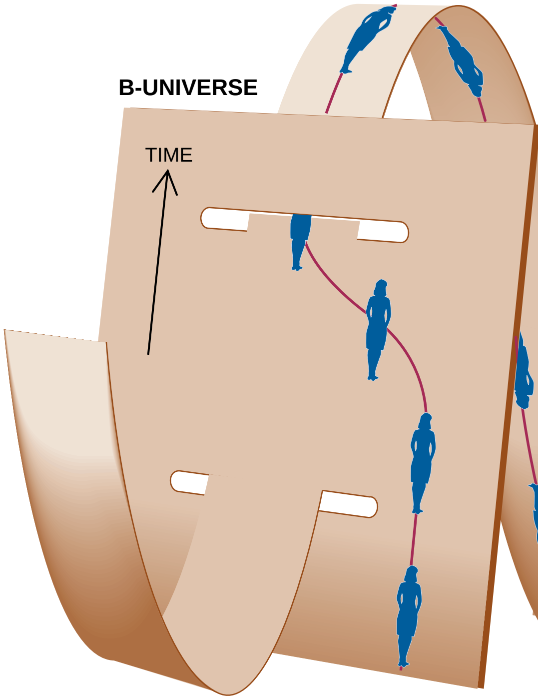
One thing we already know about CTCs is that if they exist, we need quantum mechanics to understand them. Indeed, Stephen W. Hawking of the University of Cambridge has argued that quantum-mechanical effects would either prevent CTCs from forming or would destroy any would-be time traveler approaching one. According to Hawking's calculations, which use an approximation that ignores the gravitational effects of quantum fields, fluctuations in such fields would approach infinity near the CTC. Approximations are inevitable until we discover how to apply quantum theory fully to gravity; but space-times containing CTCs push current techniques beyond the limits where they can be confidently applied. We believe that Hawking's calculations reveal only the shortcomings of those techniques. The quantum-mechanical effects that we shall be describing, far from preventing time travel, would actually facilitate it.

Quantum mechanics may necessitate the presence of closed timelike curves. CTCs, while hard to find on large scales, may well be plentiful at submicroscopic scales, where the effects of quantum mechanics predominate. There is as yet no fully satisfactory theory of quantum gravity. But according to many versions that have been proposed, space-time, though it appears smooth at large scales, has a foamlike submicroscopic structure containing many wormholes as well as CTCs reaching about 10^{-42} second into the past. For all we know, time travel by subatomic particles may be going on all around us.

More important, quantum mechanics can resolve the paradoxes of time travel. It is our most basic physical theory and constitutes a radical departure from the classical worldview. Rather than predicting with certainty what we shall observe, it predicts all possible outcomes of an observation and the probability of each. If we wait for a neutron to decay (into a proton, an electron and an antineutrino), we are most likely to observe this in about 20 minutes. But we might observe it immediately or be kept waiting indefinitely. How are we to understand this randomness? Is there something about the internal state of neutrons, currently unknown, that differs from one neutron to another and explains why each neutron breaks up when it does? This superficially attractive idea turns out to conflict with predictions of quantum mechanics that have been experimentally corroborated.

Other attempts have been made to preserve our classical intuitions by modifying quantum mechanics. None are generally deemed to have succeeded. So we prefer to take quantum mechanics at face value and to adopt a conception of reality that straightforwardly mirrors the structure of the theory itself. When we refer to quantum mechanics, we mean its so-called many-universes interpretation, first proposed by Hugh Everett III in 1957. According to Everett, if something physically can happen, it does—in some universe. Physical reality consists of a collection of universes, sometimes called a multiverse. Each universe in the multiverse contains its own copy of the neutron whose decay we wish to observe. For each instant at which the neutron might decay, there is a universe in which it decays at that instant. Since we observe it decaying at a specific instant, we too must exist in many copies, one for each universe. In one universe we see the neutron break up at 10:30, in another at 10:31 and so on. As applied to the multiverse, quantum theory is deterministic—it predicts the subjective probability of each outcome by prescribing the proportion of universes in which that outcome occurs.

Everett's interpretation of quantum mechanics is still controversial among physicists. Quantum mechanics is commonly used as a calculational tool that, given an input—information about a physical process—yields the probability of each possible output. Most of the time we do not need to interpret the mathematics describing that process. But there are two branches of physics—quantum cosmology and the quantum theory of computation—in which this is not good enough. These branches have as their entire subject matter the inner workings of the physical systems under study. Among researchers in these two fields, Everett's interpretation prevails.



MULTIVERSE PICTURE OF REALITY unravels the time travel paradoxes. Sonia plans to enter the time machine tomor-

What, then, does quantum mechanics, by Everett's interpretation, say about time travel paradoxes? Well, the grandfather paradox, for one, simply does not arise. Suppose that Sonia embarks on a "paradoxical" project that, if completed, would prevent her own conception. What happens? If the classical space-time contains CTCs, then, according to quantum mechanics, the universes in the multiverse must be linked up in an unusual way. Instead of having many disjoint, parallel universes, each containing CTCs, we have in effect a single, convoluted space-time consisting of many connected universes. The links force Sonia to travel to a universe that is identical, up to the instant of her arrival, with the one she left, but that is thereafter different because of her presence.

So does Sonia prevent her own birth or not? That depends on which universe one is referring to. In the universe she leaves, the one she was born in, her grandfather did marry her grandmother because, in that universe, he received no visit from Sonia. In the other universe, the one whose past Sonia travels to, her grandfather does not marry that particular woman, and Sonia is never born.

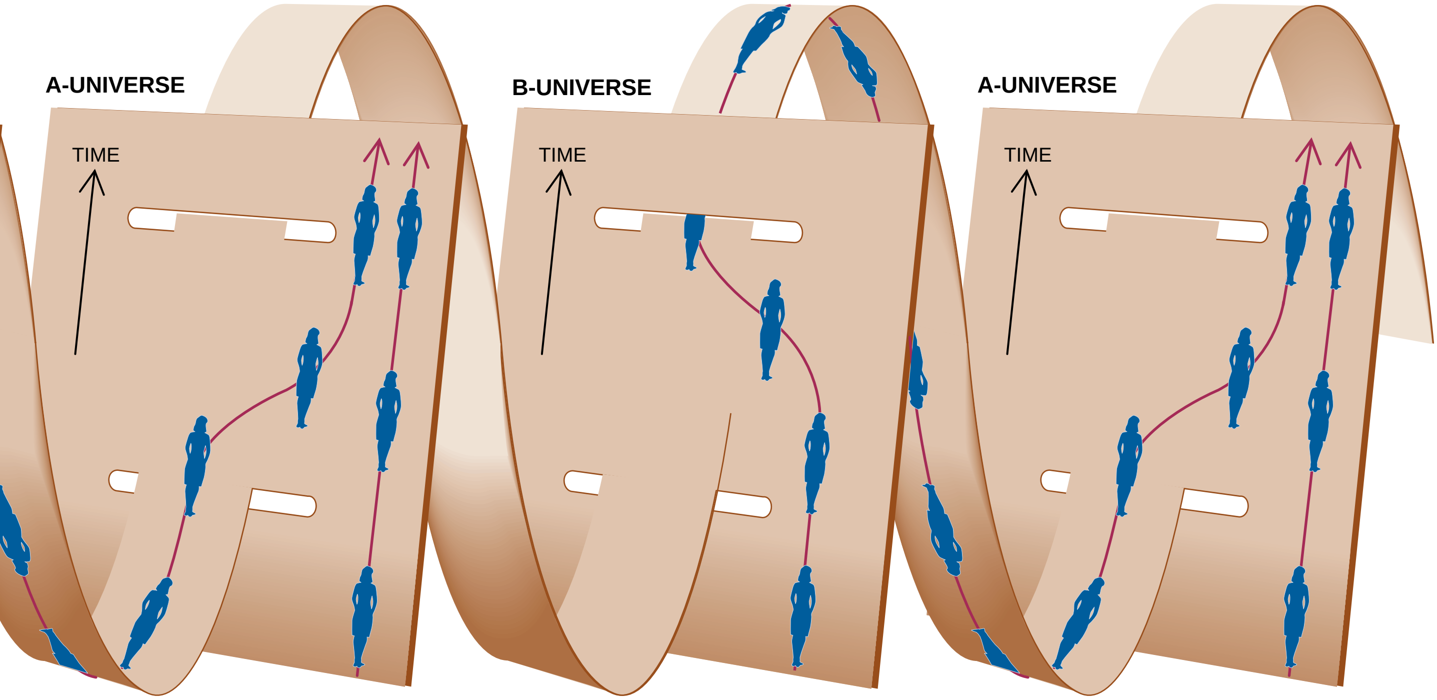
Thus, the fact that Sonia is traveling in time does not constrain her actions. And it turns out, according to quantum mechanics, that it never would. Quantum mechanics, even in the presence of CTCs, conforms to the autonomy principle.

Suppose Sonia tries her best to enact a paradox. She resolves that tomorrow she will enter the time machine and emerge today, unless a version of her first emerges today, having set out from tomorrow; and that if a version of her does emerge today, she will not enter the time machine tomorrow. Within classical physics, that resolution is self-contradictory. But not under quantum physics. In half the universes—call them A—an older Sonia steps out of the time machine. Consequently, just as she resolved, Sonia does not enter the time machine tomorrow, and each A-universe thereafter contains two Sonias of slightly different ages. In the other (B) universes, no one emerges from the time machine. So Sonia sets out and arrives in an A-universe where she meets a younger version of herself. Once again, she can behave as she likes in the past, doing things that depart from her (accurate) recollections.

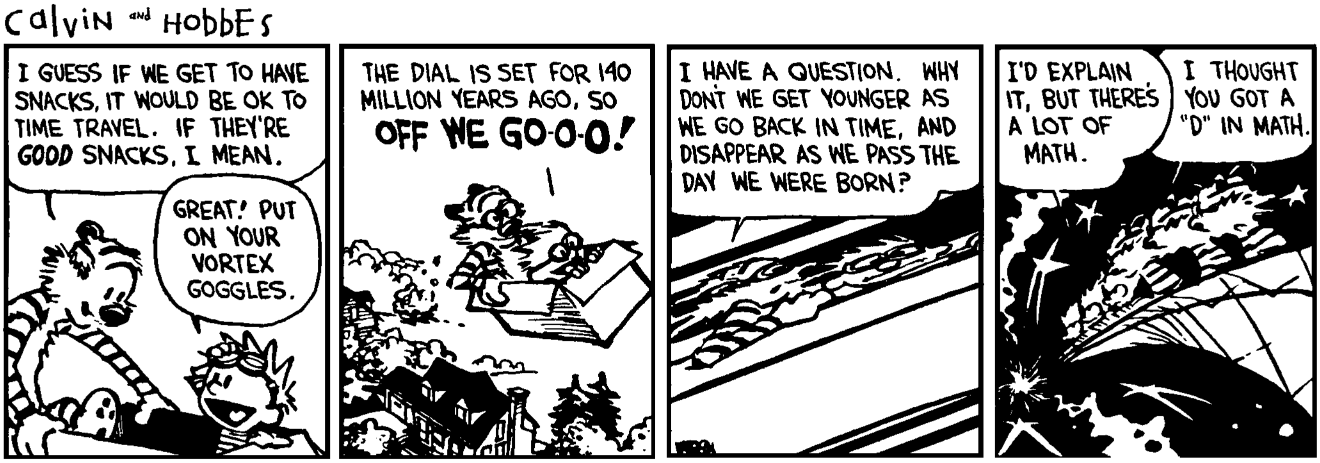
So in half the universes there is a meeting between two Sonias, and in half there is not. In the A-universes an older Sonia appears "from nowhere," and in the B-universes she disappears "into nowhere." Each A-universe then contains two Sonias, the older one having started life in a B-universe. Sonia has gone missing from each B-universe, having emigrated to an A-universe.

However convoluted Sonia's plans might be, quantum mechanics says the universes link up in such a way that she can carry them out consistently. Suppose Sonia tries to cause a paradox by traveling around the link twice. She wants to reappear in the universe she started from and join her previous self for a spaghetti dinner instead of the stir-fry she remembers having. She can behave as she likes, and in particular eat whatever she likes, in company with her younger self; however, the multiverse, by being linked up in a way different from that of the previous paradox, prevents her from doing so in her original universe. Sonia can succeed in sharing spaghetti with a version of herself only in another universe, while in the original universe she is still alone, eating stir-fry.

Time travel would make possible another curious phenomenon, which we call asymmetric separation. Suppose that Sonia's boyfriend, Stephen, stays behind while she uses her time machine in one of the ways we have described. In half the universes, she enters it and never returns. Thus, from Stephen's point of view, there is a possibility that he will be separated from her. Half the versions of him will see Sonia departing, never to return. (The other half will be joined by a second Sonia.) But from Sonia's point of view, there is no possibility of her being separated from Stephen, because every version of her



row and travel back to today but resolves that if she emerges from the time machine today, she will not enter tomorrow. She is able to carry out this plan, without paradox. In a B-universe she does not emerge today and so enters the time machine tomorrow. She then emerges today, but in an A-universe, and meets her copy—who does not enter the time machine.



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will end up in a universe containing a version of him—whom she will have to share with another version of herself.

If Stephen and Sonia follow a similar plan—entering the time machine if and only if the other does not first emerge—they can separate completely, ending up in different universes. If they carry out more complex intentions, each of them could end up in the company of any number of versions of the other. If time travel were achievable on a grand scale, competing galactic civilizations could use these asymmetric separation effects to have the whole galaxy to themselves. Also, an entire civilization could "clone" itself into any number of copies, just as Sonia did. The more often it did this, the likelier it would be that an observer would see it disappear from his universe, just as Stephen sees Sonia disappear from the A-universe when her "clone" appears in the B-universe. (Perhaps this explains why we have not yet encountered any extraterrestrials!)

In the art critic story, quantum mechanics allows events, from the participants' perspective, to occur much as Dummett describes. The universe that the critic comes from must have been one in which the artist did, eventually, learn to paint well. In that universe, the pictures were produced by creative effort, and reproductions were later taken to the past of another universe. There the paintings were indeed plagiarized—if one can be said to plagiarize the work of another version of oneself—and the painter did get "something for nothing." But there is no paradox, because now the existence of the pictures was caused by genuine creative effort, albeit in another universe.

The idea that time travel paradoxes could be resolved by "parallel universes" has been anticipated in science fiction and by some philosophers. What we have presented here is not so much a new resolution as a new way of arriving at it, by deducing it from existing physical theory. All the claims we have made about time travel are consequences of using standard quantum mechanics to calculate the behavior of logic circuits—just like those that are used in computers, except for the additional supposition that information can travel into the past along CTCs. The time travelers in this computer model are packets of information. Similar results have been obtained using other models.

These calculations definitively dispose of the inconsistency paradoxes, which turn out to be merely artifacts of an obsolete, classical worldview. We have argued that the knowledge paradoxes would likewise present no obstacle to time travel. But one cannot make that argument airtight until concepts like knowledge and creativity have been successfully translated into the language of physics. Only then can one tell if the "no-free-lunch" principle we require—that it takes problem-solving processes to create knowledge—is consistent, in the presence of CTCs, with quantum mechanics and the rest of physics.

There is a final argument that is often raised against time travel. As Hawking puts it, "The best evidence that time travel never will be possible is that we have not been invaded by hordes of tourists from the future." But this is a mistake. For a CTC reaches only as far back as the moment it was created. If the earth's first navigable CTC is constructed in 2054, subsequent time travelers could use it to travel to 2054 or later, but no earlier. Navigable CTCs might already exist elsewhere in the galaxy. But even then we should not expect "hordes of tourists from the future." Given the limited capacity of CTCs and that our stock of them at any given time cannot be replenished in this universe, a CTC is a nonrenewable resource. Extraterrestrial civilizations or our descendants will have their own priorities for its use, and there is no reason to assume that visiting the earth in the 20th century would be high on their list. Even if it were, they would arrive only in some universes, of which this, presumably, is not one.

We conclude that if time travel is impossible, then the reason has yet to be discovered. We may or may not one day locate or create navigable CTCs. But if anything like the many-universes picture is true—and in quantum cosmology and the quantum theory of computation no viable alternative is known—then all the standard objections to time travel depend on false models of physical reality. So it is incumbent on anyone who still wants to reject the idea of time travel to come up with some new scientific or philosophical argument.

FURTHER READING

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