THE ORDER OF TIME

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Translated by Erica Segre and Simon Carnell

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The verses that open each chapter, unless otherwise indicated, are from versions of Horace's *Odes* translated by Giulio Galetto and published in a charming small volume titled *In questo breve cerchio* (Verona: Edizioni del Paniere, 1980); English translations are by Erica Segre and Simon Carnell.

PERHAPS TIME IS THE GREATEST MYSTERY

Even the words that we are speaking now
thieving time
has stolen away,
and nothing can return. (I, 11)

I stop and do nothing. Nothing happens. I am thinking about nothing. I listen to the passing of time.

This is time, familiar and intimate. We are taken by it. The rush of seconds, hours, years that hurls us toward life then drags us toward nothingness. . . . We inhabit time as fish live in water. Our being is being in time. Its solemn music nurtures us, opens the world to us, troubles us, frightens and lulls us. The universe unfolds into the future, dragged by time, and exists according to the order of time.

In Hindu mythology, the river of the cosmos is portrayed with the sacred image of Shiva dancing: his dance supports the coursing of the universe; it is itself the flowing of time. What could be more universal and obvious than this *flowing*?

And yet things are somewhat more complicated than this. Reality is often very different from what it seems. The Earth appears to be flat but is in fact spherical. The sun seems to revolve in the sky when it is really we who are spinning. Neither is the structure of time what it seems to be: it is different from this uniform, universal flowing. I discovered this, to my utter astonishment, in the physics books I read as a university student: time works quite differently from the way it seems to.

In those same books I also discovered that we still don't know how time actually works. The nature of time is perhaps the greatest remaining mystery. Curious threads connect it to those other great open mysteries: the nature of mind, the origin of the universe, the fate of black holes, the very functioning of life on Earth. Something essential continues to draw us back to the nature of time.

Wonder is the source of our desire for knowledge,[1] and the discovery that time is not what we thought it was opens up a thousand questions. The nature of time has been at the center of my life's work in theoretical physics. In the following pages, I give an account of what we have understood about time and the paths that are being followed in our search to understand it better, as well as an account of what we have yet to understand and what it seems to me that we are just beginning to glimpse.

Why do we remember the past and not the future? Do we exist in time, or does time exist in us? What does it really mean to say that time "passes"? What ties time to our nature as persons, to our subjectivity?

What am I listening to when I listen to the passing of time?

This book is divided into three unequal parts. In the first, I summarize what modern physics has understood about time. It is like holding a snowflake in your hands: gradually, as you study it, it melts between your fingers and vanishes. We conventionally think of time as something simple and fundamental that flows uniformly, independently from everything else, from the past to the future, measured by clocks and watches. In the course of time, the events of the universe succeed each other in an orderly way: pasts, presents, futures. The past is fixed, the future open. . . . And yet all of this has turned out to be false.

One after another, the characteristic features of time have proved to be approximations, mistakes determined by our perspective, just like the flatness of the Earth or the revolving of the sun. The growth of our knowledge has led to a slow disintegration of our notion of time. What we call "time" is a complex collection of structures,[2] of layers. Under increasing scrutiny, in ever greater depth, time has lost layers one after another, piece by piece. The first part of this book gives an account of this crumbling of time.

The second part describes what we have been left with: an empty, windswept landscape almost devoid of all trace of temporality. A strange, alien world that is nevertheless still the one to which we belong. It is like arriving in the high mountains, where there is nothing but snow, rocks, and sky. Or like it must have been for Armstrong and Aldrin when venturing onto the motionless sand of the moon. A world stripped to its essence, glittering with an arid and troubling beauty. The physics on which I work—quantum gravity—is an attempt to understand and lend coherent meaning to this extreme and beautiful landscape. To the world without time.

The third part of the book is the most difficult, but also the most vital and the one that most closely involves us. In a world without time, there must still be something that gives rise to the time that we are accustomed to, with its order, with its past that is different from the future, with its smooth flowing. Somehow, our time must emerge around us, at least *for* us and at our scale.[3]

This is the return journey, back toward the time lost in the first part of the book when pursuing the elementary grammar of the world. As in a crime novel, we are now going in search of a guilty party: the culprit who has created time. One by one, we discover the constituent parts of the time that is familiar to us—not, now, as elementary structures of reality, but rather as useful approximations for the clumsy and bungling mortal creatures we are: aspects of our perspective, and aspects, too, perhaps, that are decisive in determining what we are. Because the mystery of time is ultimately, perhaps, more about ourselves than about the cosmos. Perhaps, as in the first and greatest of all detective novels, Sophocles' *Oedipus Rex*, the culprit turns out to be the detective.

Here, the book becomes a fiery magma of ideas, sometimes illuminating, sometimes confusing. If you decide to follow me, I will take you to where I believe our knowledge of time has reached: up to the brink of that vast nocturnal and star-studded ocean of all that we still don't know.

PART 1

THE CRUMBLING OF TIME

1 LOSS OF UNITY

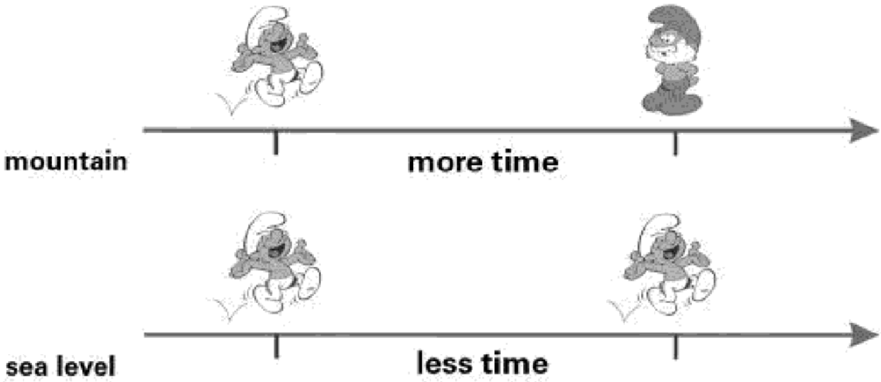
Dances of love intertwine
such graceful girls
lit by the moon
on these clear nights. (I, 4)

THE SLOWING DOWN OF TIME

Let's begin with a simple fact: time passes faster in the mountains than it does at sea level.

The difference is small but can be measured with precision timepieces that can be bought today on the internet for a few thousand dollars. With practice, anyone can witness the slowing down of time. With the timepieces of specialized laboratories, this slowing down of time can be detected between levels just a few centimeters apart: a clock placed on the floor runs a little more slowly than one on a table.

It is not just the clocks that slow down: lower down, all processes are slower. Two friends separate, with one of them living in the plains and the other going to live in the mountains. They meet up again years later: the one who has stayed down has lived less, aged less, the mechanism of his cuckoo clock has oscillated fewer times. He has had less time to do things, his plants have grown less, his thoughts have had less time to unfold. . . . Lower down, there is simply less time than at altitude.



Is this surprising? Perhaps it is. But this is how the world works. Time passes more slowly in some places, more rapidly in others.

The surprising thing, perhaps, is that someone understood this slowing down of time a century before we had clocks precise enough to measure it. His name, of course, was Albert Einstein.

The ability to understand something before it's observed is at the heart of scientific thinking. In antiquity, Anaximander understood that the sky continues beneath our feet long before ships had circumnavigated the Earth. At the beginning of the modern era, Copernicus understood that the Earth turns long before astronauts had seen it do so from the moon. In a similar way, Einstein understood that time does not pass uniformly everywhere *before* the development of clocks accurate enough to measure the different speeds at which it passes.

In the course of making such strides, we learn that the things that seemed self-evident to us were really no more than prejudices. It seemed obvious that the sky was above us and not below; otherwise, the Earth would fall down. It seemed self-evident that the Earth did not move; otherwise, it would cause everything to crash. That time passed at the same speed everywhere seemed equally *obvious* to us. . . . Children grow up and discover that the world is not as it seemed from within the four walls of their homes. Humankind as a whole does the same.

Einstein asked himself a question that has perhaps puzzled many of us when studying the force of gravity: how can the sun and the Earth "attract" each other without touching and without utilizing anything between them?

He looked for a plausible explanation and found one by imagining that the sun and the Earth do not attract each other directly but that each of the two gradually acts on that which is between them. And since what lies between them is only space and time, he imagined that the sun and the Earth each modified the space and time that surrounded them, just as a body immersed in water displaces the water around it. This modification of the structure of time influences in turn the movement of bodies, causing them to "fall" toward each other.[4]

What does it mean, this "modification of the structure of time"? It means precisely the slowing down of time described above: a mass slows down time around itself. The Earth is a large mass and slows down time in its vicinity. It does so more in the plains and less in the mountains, because the plains are closer to it. This is why the friend who stays at sea level ages more slowly.

If things fall, it is due to this slowing down of time. Where time passes uniformly, in interplanetary space, things do not fall. They float, without falling. Here on the surface of our planet, on the other hand, the movement of things inclines naturally toward where time passes more slowly, as when we run down the beach into the sea and the resistance of the water on our legs makes us fall headfirst into the waves. Things fall downward because, down there, time is slowed by the Earth.[5]

Hence, even though we cannot easily observe it, the slowing down of time nevertheless has crucial effects: things fall because of it, and it allows us to keep our feet firmly on the ground. If our feet adhere to the pavement, it is because our whole body inclines naturally to where time runs more slowly—and time passes more slowly for your feet than it does for your head.

Does this seem strange? It is like when, watching the sun going down gloriously at sunset, disappearing slowly behind distant clouds, we suddenly remember that it's not the sun that's moving but the Earth that's spinning, and we see with the unhinged eye of the mind our entire planet—and ourselves with it—rotating backward, away from the sun. We are seeing with "mad" eyes, like those of Paul McCartney's Fool on the Hill: the crazed vision that sometimes sees further than our bleary, customary eyesight.

TEN THOUSAND DANCING SHIVAS

I have an enduring passion for Anaximander, the Greek philosopher who lived twenty-six centuries ago and understood that the Earth floats in space, supported by nothing.[6] We know of Anaximander's thought from other writers. Only one small original fragment of his writings has survived—just one:

> Things are transformed one into another according to necessity,
> and render justice to one another
> according to the order of time.

"According to the order of time" (κατὰ τὴν τοῦ χρόνου τάξιν). From one of the crucial, initial moments of natural science there remains nothing but these obscure, arcanely resonant words, this appeal to the "order of time."

Astronomy and physics have since developed by following this seminal lead given by Anaximander: by understanding how phenomena occur *according to the order of time*. In antiquity, astronomy described the movements of stars *in time*. The equations of physics describe how things change *in time*. From the equations of Newton, which establish the foundations of mechanics, to those of Maxwell for electromagnetic phenomena; from Schrödinger's equation describing how quantum phenomena evolve, to those of quantum field theory for the dynamics of subatomic particles: the whole of our physics, and science in general, is about how things develop "according to the order of time."

It has long been the convention to indicate this time in equations with the letter *t* (the word for "time" begins with *t* in Italian, French, and Spanish, but not in German, Arabic, Russian, or Mandarin). What does this *t* stand for? It stands for the number measured by a clock. The equations tell us how things change as the time measured by a clock passes.

But if different clocks mark different times, as we have seen above, what does *t* indicate? When the two friends meet up again after one has lived in the mountains and the other at sea level, the watches on their wrists will show different times. Which of the two is *t*? In a physics laboratory, a clock on a table and another on the ground run at different speeds. Which of the two tells the time? How do we describe the difference between them? Should we say that the clock on the ground has slowed relative to the real time recorded on the table? Or that the clock on the table runs faster than the real time measured on the ground?

The question is meaningless. We might just as well ask what is *most* real—the value of sterling in dollars or the value of dollars in sterling. There is no "truer" value; they are two currencies that have value *relative to each other*. There is no "truer" time; there are two times and they change *relative to each other*. Neither is truer than the other.

But there are not just *two* times. Times are legion: a different one for every point in space. There is not one single time; there is a vast multitude of them.

The time indicated by a particular clock measuring a particular phenomenon is called "proper time" in physics. Every clock has its proper time. Every phenomenon that occurs has its proper time, its own rhythm.

Einstein has given us the equations that describe how proper times develop *relative to each other*. He has shown us how to calculate the difference between two times.[7]

The single quantity "time" melts into a spiderweb of times. We do not describe how the world evolves in time: we describe how things evolve in local time, and how local times evolve *relative to each other*.

The world is not like a platoon advancing at the pace of a single commander. It's a network of events affecting each other.

This is how time is depicted in Einstein's general theory of relativity. His equations do not have a single "time"; they have innumerable times. Between two events, just as between the two clocks that are separated and then brought together again, the duration is not a single one.[8] Physics does not describe how things evolve "in time" but how things evolve in their own times, and how "times" evolve relative to each other.*

Time has lost its first aspect or layer: its unity. It has a different rhythm in every different place and passes here differently from there. The things of this world interweave dances made to different rhythms. If the world is upheld by the dancing Shiva, there must be ten thousand such dancing Shivas, like the dancing figures painted by Matisse. . . .

2 LOSS OF DIRECTION

If more gently than Orpheus
who moved even the trees
you were to pluck the zither
the life-blood would not return
to the vain shadow . . .
Harsh fate,
but its burden becomes lighter
to bear, since everything
that attempts to turn back
is impossible. (I, 24)

WHERE DOES THE ETERNAL CURRENT COME FROM?

Clocks may well run at different speeds in the mountains and in the plains, but is this really what concerns us, ultimately, about time? In a river, the water flows more slowly near its banks, faster in the middle—but it is still flowing. . . . Is time not also something that always flows—from the past to the future? Let's leave aside the precise measurement of *how much* time passes that we wrestled with in the preceding chapter: the *numbers* by which time is measured. There's another, more essential aspect to time: its passage, its flow, the *eternal current* of the first of Rilke's *Duino Elegies*:

The eternal current
Draws all the ages along with it
Through both realms,
Overwhelming them in both.[9]

Past and future are different from each other. Cause precedes effect. Pain comes after a wound, not before it. The glass shatters into a thousand pieces, and the pieces do not re-form into a glass. We cannot change the past; we can have regrets, remorse, memories. The future instead is uncertainty, desire, anxiety, open space, destiny, perhaps. We can live toward it, shape it, because it does not yet exist. Everything is still possible. . . . Time is not a line with two equal directions: it is an arrow with different extremities.

And it is this, rather than the speed of its passing, that matters most to us about time. This is the fundamental thing about time. The secret of time lies in this slippage that we feel on our pulse, viscerally, in the enigma of memory, in anxiety about the future. This is what it means to think about time. What exactly is this *flowing*? Where is it nestled in the grammar of the world? What distinguishes the past, its having been, from the future, its not having been yet, in the folds of the mechanism of the world? Why, to us, is the past so different from the future?

Nineteenth- and twentieth-century physics engaged with these questions and ran into something unexpected and disconcerting—much more so than the relatively marginal fact that time passes at different speeds in different places. The difference between past and future, between cause and effect, between memory and hope, between regret and intention . . . in the elementary laws that describe the mechanisms of the world, there is no such difference.

HEAT

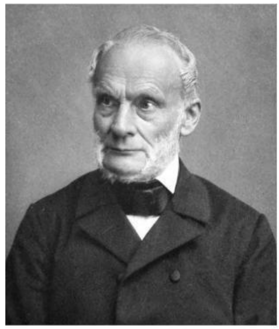
It all began with a regicide. On January 16, 1793, the National Convention in Paris sentenced Louis XVI to death. Rebellion is perhaps among the deepest roots of science: the refusal to accept the present order of things.[10] Among those who took the fatal decision was a friend of Robespierre called Lazare Carnot. Carnot had a passion for the great Persian poet Saadi Shirazi. Captured and enslaved at Acre by the Crusaders, Shirazi is the author of those luminous verses that now stand at the entrance of the headquarters of the United Nations:

All of the sons of Adam are part of one single body,
They are of the same essence.
When time afflicts us with pain
In one part of that body
All the other parts feel it too.
If you fail to feel the pain of others
You do not deserve the name of man.

Perhaps poetry is another of science's deepest roots: the capacity to see beyond the visible. Carnot names his first son after Saadi. Sadi Carnot is thus born out of poetry and rebellion.

As a young man, he develops a passion for those steam engines that at the start of the nineteenth century are beginning to transform the world by using fire to make things turn. In 1824, he writes a pamphlet with the alluring title "Reflections on the Motive Power of Fire," in which he seeks to understand the theoretical basis of the functioning of these machines. The little treatise is packed with mistaken assumptions: he imagines that heat is a concrete entity—a kind of fluid that produces energy by "falling" from hot things to cold, just as the water in a waterfall produces energy by falling from above to below. But it contains a key idea: that steam engines function, in the final analysis, because the heat passes from hot to cold.

Sadi's pamphlet finds its way into the hands of a fierce-eyed, austere Prussian professor called Rudolf Clausius. It is he who grasps the fundamental issue at stake, formulating a law that was destined to become famous: If nothing else around it changes, heat *cannot* pass from a cold body to a hot one.



The crucial point here is the difference from what happens with falling bodies: a ball may fall, but it can also come back up, by rebounding, for instance. Heat cannot.

This is the *only* basic law of physics that distinguishes the past from the future.

None of the others do so. Not Newton's laws governing the mechanics of the world; not the equations for electricity and magnetism formulated by Maxwell. Not Einstein's on relativistic gravity, nor those of quantum mechanics devised by Heisenberg, Schrödinger, and Dirac. Not those for elementary particles formulated by twentieth-century physicists. . . . *Not one* of these equations distinguishes the past from the future.[11] If a sequence of events is allowed by these equations, so is the same sequence run backward in time.[12] In the elementary equations of the world,[13] the arrow of time appears *only* where there is heat.* The link between time and heat is therefore fundamental: every time a difference is manifested between the past and the future, heat is involved. In every sequence of events that becomes absurd if projected backward, there is something that is heating up.

If I watch a film that shows a ball rolling, I cannot tell if the film is being projected correctly or in reverse. But if the ball stops, I know that it is being run properly; run backward, it would show an implausible event: a ball starting to move by itself. The ball's slowing down and coming to rest are due to friction, and friction produces heat. Only where there is heat is there a distinction between past and future. Thoughts, for instance, unfold from the past to the future, not vice versa—and, in fact, thinking produces heat in our heads. . . .

Clausius introduces a quantity that measures this irreversible progress of heat in only one direction and, since he was a cultivated German, he gives it a name taken from ancient Greek—*entropy*:

Sadi Carnot thought that heat was a substance, a fluid. He was wrong. Heat is the microscopic agitation of molecules. Hot tea is tea in which the molecules are very agitated. Cold tea is tea in which the molecules are only a little agitated. In an ice cube, warming up and melting molecules become increasingly agitated and lose their strict connections.

At the end of the nineteenth century, there were many who still did not believe in the existence of molecules and atoms: Ludwig was convinced of their reality and entered the fray on behalf of his belief. His diatribes against those who doubted the reality of atoms became legendary. “Our generation were at heart all on his side,” remarked one of the young lions of quantum mechanics years later.[16] In one of these fiery polemics, at a conference in Vienna, a noted scientist[17] maintained against him that scientific materialism was dead because the laws of matter are not subject to the directionality of time. Scientists are not immune from talking nonsense.

Looking at the sun going down, the eyes of Copernicus had seen the world turning. Looking at a glass of still water, the eyes of Boltzmann saw atoms and molecules frenziedly *moving*.

We see the water in a glass like the astronauts saw the Earth from the moon: calm, gleaming, blue. From the moon, they could see nothing of the exuberant agitation of life on Earth, its plants and animals, desires and despairs. Only a veined blue ball. Within the reflections in a glass of water, there is an analogous tumultuous life, made up of the activities of myriads of molecules—many more than there are living beings on Earth.

This tumult *stirs up* everything. If one section of the molecules is still, it becomes stirred up by the frenzy of neighboring ones that set them in motion, too: the agitation spreads, the molecules bump into and shove each other. In this way, cold things are heated in contact with hot ones: their molecules become jostled by hot ones and pushed into ferment. That is, they heat up.

Thermal agitation is like a continual shuffling of a pack of cards: if the cards are in order, the shuffling disorders them. In this way, heat passes from hot to cold, and not vice versa: by shuffling, by the natural disordering of everything. The growth of entropy is nothing other than the ubiquitous and familiar natural increase of disorder.

This is what Boltzmann understood. The difference between past and future does not lie in the elementary laws of motion; it does not reside in the deep grammar of nature. It is the natural disordering that leads to gradually less particular, less special situations.

It was a brilliant intuition, and a correct one. But does it clarify the difference between past and future? It does not. It just shifts the question. The question now becomes: Why, in one of the two directions of time—the one we call past—were things more ordered? Why was the great pack of cards of the universe in order in the past? Why, in the past, was entropy lower?

If we observe a phenomenon that *begins* in a state of lower entropy, it is clear why entropy increases—because in the process of reshuffling, everything becomes disordered. But why do the phenomena that we observe around us in the cosmos *begin* in a state of lower entropy in the first place?

Here we get to the key point. If the first twenty-six cards in a pack are all red and the next twenty-six are all black, we say that the configuration of the cards is "particular," that it is "ordered." This order is lost when the pack is shuffled. The initial ordered configuration is a configuration "of low entropy." But notice that it is particular if we look at the *color* of the cards—red or black. It is particular because I am looking at the color. Another configuration will be particular if the first twenty-six cards consist of only hearts and spades. Or if they are all odd numbers, or the twenty-six most creased cards in the pack, or exactly the same twenty-six of three days ago. . . . Or if they share any other characteristic. If we think about it carefully, *every configuration is particular*, every configuration is singular, if we look at *all* of its details, since every configuration always has something about it that characterizes it in a unique way. Just as, to its mother, every child is particular and unique.

It follows that the notion of certain configurations being more particular than others (twenty-six red cards followed by twenty-six black, for example) makes sense only if I limit myself to noticing only certain aspects of the cards (in this case, the colors). If I distinguish between all the cards, the configurations are all equivalent: none of them is more or less particular than others.[18] The notion of "particularity" is born only at the moment we begin to see the universe in a blurred and approximate way.

Boltzmann has shown that entropy exists because we describe the world in a blurred fashion. He has demonstrated that entropy is precisely the quantity that counts *how many* are the different configurations that our blurred vision does *not* distinguish between. Heat, entropy, and the lower entropy of the past are notions that belong to an approximate, statistical description of nature.

The difference between past and future is deeply linked to this blurring. . . . So if I could take into account all the details of the exact, microscopic state of the world, would the characteristic aspects of the flowing of time disappear?

Yes. If I observe the microscopic state of things, then the difference between past and future vanishes. The future of the world, for instance, is determined by its present state—though neither more nor less than is the past.[19] We often say that causes precede effects and yet, in the elementary grammar of things, there is no distinction between "cause" and "effect."* There are regularities, represented by what we call physical laws, that link events of different times, but they are symmetric between future and past. In a microscopic description, there can be no sense in which the past is different from the future.*

This is the disconcerting conclusion that emerges from Boltzmann's work: the difference between the past and the future refers only to *our own* blurred vision of the world. It's a conclusion that leaves us flabbergasted: Is it really possible that a perception so vivid, basic, existential—my perception of the passage of time—depends on the fact that I cannot apprehend the world in all of its minute detail? On a kind of distortion that's produced by myopia? Is it true that, if I could see exactly and take into consideration the actual dance of millions of molecules, then the future would be "just like" the past? Is it possible that I have as much knowledge of the past —or ignorance of it—as I do of the future? Even allowing for the fact