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Abstract

One hundred and fifty years after the work of Ludwig Boltzmann on the interpretation of the irreversibility of physical phenomena, we are still not sure what we mean when we talk of "time" or the "arrow of time." One source of this difficulty is our tendency to confuse time and becoming: that is, the course of time and the arrow of time, two concepts that the formalisms of physics do distinguish clearly. The course of time is represented by a line on which it is customary to place a small arrow that, ironically, must not be confused with the "arrow of time." On the one hand, this small arrow indicates that the course of time is oriented. On the other hand, the arrow of time indicates the possibility for physical systems to experience, over the course of time, changes or transformations that prevent them from returning to their initial state forever.

Keywords

Time – time's arrow – temporal asymmetry – principle of causality – irreversibility

Throughout its history, physics has overturned prejudices, shattered supposed certainties, and opened up whole new horizons. It has even been known to make such radical breakthroughs that, fueled by its own momentum, it has reached far beyond the confines of the discipline itself. This is the case, for example, when it achieves a result that throws existing schools of thought into mayhem or changes the very terms used to formulate certain philosophical questions, which is what we mean when we talk of physicists making "negative philosophical discoveries." For example, who today would dare talk of the nature or the accessibility of the "real" without referring to quantum physics and the revolutionary lessons it has taught us? Or of the structure of space and time without mentioning Einstein's theory of relativity? The most important

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advances in physics have forced certain schools of philosophical thought to rethink themselves and have opened up new avenues of thought.

Physics happens to produce theoretical or experimental results that illuminate or even modify the philosophical answers that we bring to philosophical questions. One of these philosophical questions that collide with physics is the following: Is time identical to becoming? Physics does tell us something about that. I say "does tell us," which is a strange way of talking about physics since physics does not speak. But what I would like to do in this article is try to express what the equations of physics would say about time if they could speak.

1 Is Time Identical to Change? Roman Opalka's Lesson

We notice time because of change, and, in most situations, time and change appear entangled to the point that they seem the same thing. But that entanglement does not imply that time is change. In fact, situations exist in which they can be explicitly separated. Let us look at the work of Roman Opalka, who, every day since 1965, has been painting a series of integers on canvases then photographing himself after each work session. The succession of numbers materializes the irreversible course of time; each number drawn is new (and each moment is completely new), but it is always obtained in the same way—that is, by adding a unit to the preceding number. As for the photographs that the artist takes of himself periodically, they show a series of physical changes over time, that is to say, the irreversibility of his own becoming. On the one hand, the course of time is represented by the succession of numbers; on the other, becoming is represented by a series of photographs of the same being (Opalka himself) changing and becoming older.[1] This dual representation is enough to demonstrate that these two kinds of irreversibility can be distinguished and that their difference can even be made visible.

The question is: Does physics also distinguish between time and becoming?

The first point is to notice that physical time—let us say Newtonian time to begin with—does not have the properties that our way of speaking about time attributes implicitly to it. Let us take an example. We often say that time flows like a river, which suggests that time has a certain speed, because the flow of a river does have a speed. (By the way, in everyday language, time is constantly granted the property of speed.) But speed is the derivative of a

1 Opalka's paintings and photographs may be accessed at his official website: http://www.opalka1965.com/fr/index_fr.php.

certain quantity in relationship to time. The speed of time is then obtained by our determining the rate of the variation of time in relation to itself, and this operation has of course no meaning. If one really wants to define the speed of time, one still can say that it is equal to one hour per hour and that won't help you very much. The metaphor of the river turns the simplest arguments into traps.[2]

The second point is an observation. We talk about time as if it corresponded only to a "becoming," in other words to the stream of changes affecting an object, a person, an institution, a physical system. Change is truly the phenomenon that best suggests the idea of time, and one can easily understand why: In life, we never encounter a specific and directly perceptible reality that would be the time. We only see around us *changing* things, things *becoming* others, and it is therefore through the concrete effect of change that the course of time first appears to us. But to conclude from this argument that *time* and *becoming* are the same is a step that is too easily made without further investigation. We should be careful before saying that, for the following reason: time is mostly referred to as if it looked like what it holds, in the sense that common thinking engenders confusion between time and temporal phenomena. For example, time is said to stop or disappear when nothing seems to be happening, as if its dynamics only depended upon its contents. But are we right when we say such a thing? We should not answer too quickly, because a crucial question has to be first examined: Is time an abstract structure into which events are inserted, that is to say a reality in itself preceding all possible events and as such different from becoming? Or is it composed of the stream of events itself?

These are the questions I would like to discuss by examining the kind of answers physics provides.

2 Time and Becoming: Physics Sees Double

Physical theories are mostly composed of equations. What would the equations say about time and becoming if they could speak? For this purpose, we have to study the structure of physical theories (that is, classical physics, quantum mechanics, special or general relativity). This study shows that the formalisms of physics do distinguish time from becoming. On one side, there is *the course of time*, a primitive entity; on the other side there is the *arrow of time*, which is not a property of time but a property of the majority of phenomena taking place in time, specifically irreversible phenomena.

2 On this point, see Klein (2005).

The course of time does establish an asymmetry between earlier and later. If two events are not simultaneous, then one of them is earlier than the other one. *So defined, the course of time expresses the irreversibility of time itself*; it is not possible to reverse the earlier/later order of the events.[3] As for the arrow of time, it represents the fact that some physical systems evolve in an irreversible way throughout time: They won't go back to their previous states. *So defined, the arrow of time expresses the irreversibility of phenomena within the course of time* and not the irreversibility of time itself.

Today, physics has become so effective (and the discovery of the Higgs boson in 2012 is a new demonstration of that) that it is possible to imagine that the distinction it makes between time and becoming could be transferred to philosophy, which often aggregates the two notions. In other words, the distinction it establishes between time and becoming represents a "negative philosophical discovery" because it modifies the terms in which the philosophical question of becoming is stated.

The course of time is usually represented by a line, a timeline on which a little arrow is usually drawn, an arrow that is not the arrow of time in the sense introduced above: it is there to indicate that time has a dynamics oriented in a single direction, and that time travel is indeed impossible. It is impossible to come back or to go through the same instant twice.

By the way, we have to notice that the depiction of time as a line is incomplete because it omits indicating how this line is built. Because the present does not bring another present by itself, there has to be something, an "engine" of time, to do this "work." This little engine does build the course of time, in the sense that it continuously renews the present. Where does this engine come from? Is it a property of time itself or a property of the arrangement of things in time? Is it linked to a global property of the Universe or to our consciousness? The answers to these questions have still to be elucidated, so we have to consider that the true mystery of time exists in the hidden dynamic that builds the timeline.

As for the arrow of time, contrary to what the expression might suggest, it is not related to time itself but to what happens within it. It is not an attribute of time but a potential property of physical phenomena; most of what exists at our scale is transformed irreversibly throughout time and cannot return to its original state. The dynamics of those physical phenomena is then marked with an arrow, wrongly called the "arrow *of time*."

3 This issue is more complicated in the Special Theory of Relativity, but this irreversibility holds for events that are time-like separated. See Klein (2005).

The problem of the arrow of time can be summarized by the following question: Why do we remember the past and not the future? The answer usually given is that the only way of distinguishing between past and future is by means of the second law of thermodynamics: the future is the direction toward which the entropy of the system increases. But in fact, the question asked does not concern the arrow of time because the invocation of the course of time is enough to answer it. If we do not remember the future, it is because we have not yet been present in . . . the future! Asking "Why are we in a different state in the future than in the past?" is quite another question (whose answer can be, this time, the second law of thermodynamics), which has to be distinguished from the first one.

This example of confusion shows that it is worthwhile to emphasize the difference between several issues traditionally labelled "the problem of the direction of time." The most invoked concepts are the concepts of irreversibility and of time-reversal invariance. *Time-reversal invariance* is a property of physical laws: a law is time-reversal invariant when it is expressed by a differential equation which is invariant under the transformation $t \rightarrow -t$. By contrast, irreversibility is a property of processes: a process is irreversible if it is always observed in the same temporal order and never in the inverse one. The problem of the arrow of time consists in finding out how irreversible processes can be explained by means of time-reversal invariant laws.

Since Newton, the principle of causality has always constrained from the outside the representation of the course of time in physics. This principle has generally been summarized by our saying that every event has a cause that precedes it, but this formulation has to be refined because the concept of cause appears to be unclear in quantum physics. The principle of causality now has a statement that does not refer to the idea of cause: it says that recorded history cannot be changed, in the sense that any event that has occurred cannot be eliminated from the past.

The principle of causality sets an absolute temporal order between several types of events, even if none can be presented as the cause of another, and it thus imposes a "directionality" to time.

In practice, the different formalisms of physics adapt the principle of causality to themselves by giving it a form that depends on how events and phenomena are represented. Its consequences are always constraining. In Newtonian physics, causality implies that time is linear and non-cyclical (which is enough to guarantee that an effect cannot influence its cause retroactively). In special relativity, causality posits that a particle cannot travel faster than the speed of light (which is enough to render travelling to the past impossible). In non-relativistic quantum physics, causality is guaranteed by the structure of Schrödinger's equation.[4] In particle physics, causality made it possible to predict the existence of antimatter, and it is now formally expressed by CPT (charge conjugation, parity transformation, time reversal) invariance to which the dynamics of physical phenomena must respond. What does CPT invariance represent? It represents the fact that physical laws ruling our universe are perfectly identical to the rules of a universe where matter and antimatter would interchange their roles, if observed in a mirror, and where time would go backward.

But one thing has to be emphasized: In every physical theory, once the principle of causality is taken into account, the course of time then becomes irreversible in the sense that an instant cannot occur twice. This argument leads to the question of knowing whether the course of time is irreversible by itself or whether it is due to the fact that it contains events causally linked to each other. But the key point is that this irreversibility of time can never be compensated for or erased by the reversibility of any movement or dynamical process; as fast as one can possibly return from Paris after being to London, time has irreversibly passed during the trip, and one is therefore a bit older (which would not necessarily make you look any different). More generally, the absence of any arrow of time does not stop time from passing. When it exists, the arrow of time appears *in addition*: it "fills up" the irreversible course of time with irreversible phenomena. We shall later see that physicists have identified possible explanations for the arrow of time: all of them presuppose the existence of a set course of time within which time-oriented phenomena take place.

While time passes, it does not change its way of being time. Thus it escapes becoming. It is the arrow of time that constitutes the true expression of becoming. It manifests itself within the course of time, which it does not affect in any way. The notion of "the course of time" therefore precedes the notion of becoming, as in the work of Roman Opalka.

3 Where Does the Arrow of Time Come From?

When a phenomenon is irreversible, that is to say when an arrow of time appears, what is its origin?

4 In quantum physics, the Hamiltonian is the mathematical operator that describes a physical system's evolution throughout time. Schrödinger's equation makes this operator into the infinitesimal generator of time translations. The principle of causality is therefore automatically respected.

The arrow of time was not part of the fundamental formalisms of physics from the start, neither in classical mechanics, nor in quantum physics, nor the theory of relativity. Therefore how do we understand it?

The question appeared only a century and half ago, when physicists started to ask themselves if physical phenomena could "go in both directions." Can a dynamic process capable of changing a system from a state A to a state B make it change from a state B to a state A? This question was born of the conjunction of two apparently contradictory observations:

1. Daily, we can observe around us many physical processes for which corresponding reverse processes have never been observed or are exceptional. Therefore these are, by definition, irreversible phenomena.
2. Yet none of the dynamics laws that govern these processes contain temporal asymmetries—that is to say, they would be the same if the course of time were going in the opposite direction. If they allow a certain process to occur when time goes in one direction, they allow it to happen when it goes in the opposite direction; the initial and final states could be interchanged. (For example, according to the Newtonian equations for gravitation, planets could rotate around the Sun in directions opposite to what they are.) Such equations are called "T-invariant equations": if a system can go from state A to state B, it should be able to go from state B to state A (in that case, the system is not concerned with the arrow of time).

Therefore, why are there some irreversible phenomena? Why is there an arrow of time, that is to say, an asymmetry in the dynamics of certain phenomena that we observe, even though the equations of physics have no room for it?

In view of what we have stated above, these questions can't be answered by explaining "the direction of time," by setting out the reasons why it flows in one direction rather than another, or even less by explaining why we don't remember the future. The issue is solely related to the *asymmetry of physical processes* within time and not to the asymmetry of time itself. It is an asymmetry of the "contents" of time, not an asymmetry of the container itself (see Price 2002).

To try to solve this riddle, physicists advance four categories of argument that can delimit the origins of the arrow of time, and they also study their possible inter-relations. I will just mention them briefly (see Zeh 1989 and Savitt 1995):

- *The second law of thermodynamics*, or the increase of the entropy of isolated systems. In Boltzmann's interpretation, which underlies this principle, there is no arrow of time at the microscopic level, but on a macroscopic level, one can get the impression that one exists.

- *The process of measurement in quantum physics*, which has been the subject of intense debate for eighty years. Generally, it is understood as a temporally asymmetrical process.
- *The violation of CP symmetry during certain phenomena governed by the weak interaction*. Some unstable particles—for example, neutral kaons—do not behave exactly like their anti-particles. More specifically, they don't disintegrate into other particles at the same pace as their antiparticles. This means that they disintegrate according to a temporally asymmetrical law. The fundamental reason for this temporal asymmetry, which remains hard to interpret, is not completely understood. It raises the question of the existence of an "arrow of time" at the microscopic level;
- *The expansion of the universe*, which would make it impossible for any system to return to its initial state because the universe itself is evolving. This argument can appear contradictory because the equations of general relativity are temporally symmetrical, but in reality their cosmological solutions, which are supposed to govern the evolution of the universe, are not. The universe they describe is either expanding or contracting, as represented by the existence of an arrow of cosmic time related to the conditions at the limits of the universe. Some theorists, including Stephen Hawking (1994) and Roger Penrose (1989), think that this arrow of time could be the arrow mastering all the others, but not all physicists share this position.

We have gone far enough to be able to make two remarks.

The first one is that attempts to explain the arrow of time resort to arguments that all differ from the restrictions imposed on the course of time by the principle of causality. (I mentioned them earlier: linear time, the impossibility of going beyond the speed of light, the existence of anti-matter, CPT invariance). *In conclusion, the course of time is accounted for in ways that never coincide with ways in which the arrow of time is justified*. This indicates—or shows or even demonstrates—that the course of time and the arrow of time are two distinct things in contemporary physics; *the irreversibility of phenomena does not come from the irreversibility of time and vice versa*.

The second remark is that none of the explanations given for the arrow of time is likely to constitute a real theory. They are closer to an *interpretation* of this or that physical theory, but they are not *incorporated* into any formalism. There is indeed no operating physical theory that integrates becoming from the start (for example through the use of irreversible fundamental equations). We cannot exclude the fact that this conclusion may change in the future thanks to the building of a new kind of physical formalism, but for the moment, it seems that becoming can only be accounted for in physics through the interpretation of theories that do not include it among their principles. So interpretations of the arrow of time's origins end up mixing physics and philosophy. Thus, they can be subject to disagreement and are indeed very ardently disputed. Some physicists think this is only a fake problem: on the pretext that no arrow of time appears in physics' fundamental equations, they believe that becoming is only pure appearance and is closely related to how our limited senses make us perceive the world. Others conclude that because actual physics cannot explicitly account for becoming, it is either wrong or incomplete.

These two positions can be defended as long as there is agreement on the meaning of words. And also as long as no one is claiming that physics has negated time just because its formalisms do not include the arrow of time. Becoming was not integrated directly into its principles, but physics has always referred to the course of time. One can regret that physics has not integrated becoming from the start—or, better, suggest how physics could make room for becoming in its formalisms—but it cannot be blamed for forgetting to integrate the course of time because it did not forget it.

Although "on paper" it is possible to change the sign of time in a physical equation, this does not imply that the course of time can be "physically" reversed.

4 Should We Adapt Our Vocabulary to What We Know?

What can these considerations teach us? They teach us that a more carefully chosen vocabulary and a more rigorous conceptualization would give us a chance to show how the different theories formalize the course of time, interpret the arrow of time, and relate time and becoming. They allow us to better think about the question of time in general.

The principle of causality, for example, could benefit from being renamed "antecedence principle" or "principle of chronological protection," as Stephen Hawking (1975) proposed. Similarly, when we refer to a physical process, the quite awkward expression "time reversal" could be replaced by the expression "movement reversal" because the intention is not to create a time machine but to reverse the speed of the physical entities concerned. When a phenomenon's dynamics is reversible, the direction of time is indeed arbitrary, but, once it has been chosen, it cannot simply be reversed.

Finally, the situation is the same with the course of time as with electrical charges. Saying that the electron carries a negative charge and the proton a positive one derives from a convention. To change this convention and declare that an electron's charge is positive and a proton's negative would not change anything in the laws of physics or the universe. Beginning with a conventional choice makes it possible to design physical laws that are unconventional.

To claim that the course of time does not exist according to physics under the pretence that the laws of physics are time-reversal invariant (so that the direction of time is arbitrary) is equivalent to saying that electrical charges have no reality because physical laws do not change if each charge's sign is reversed.

5 An Open Question: What Makes Time Flow?

The nature of the "engine of time" that makes us feel the flow of time has not yet been elucidated, but a great deal of theoretical work is now being devoted to this problem. Different avenues are being explored. In fact, there have been three major theories of time's flow. The first is that the flow is an illusion, the product of the faulty river metaphor. The second is that it is not an illusion but rather is subjective, being deeply ingrained due to the nature of our minds. The third is that it is objective, a feature of the mind-independent reality that is to be found in, say, today's physical laws, or, if it has been missed there, then in future physical laws.

The first theory, rooted in the theory of relativity, represents space-time as a fixed whole and suggests that the flow of time is a pure illusion: The entire universe just is, with no special meaning attached to the present time. All past and future times are equally present and have the same degree of existence within time, just as different locations coexist along space. According to this view, there is nothing special about the "now." Incidentally, in the special theory of relativity, there is an uncountable infinity of nows, and the standard symmetries assure that none of them can have special significance.

In the second theory, which can be considered as a variation of the previous one, time would only be a psychological feature linked to the very complex structure of our brain; in the space-time region we are observing, we have the feeling that time passes "from the bottom to the top" of space-time, but in reality space-time is a rigid block without any internal dynamics. We observers would unfold the thread of time ourselves. In other words, we would be the "engine" of time.

Contrary to the first and the second theories, the third one considers that time's apparent flow is real, that it corresponds to a true physical reality. At any moment in time, an observer perceives a "now"; future events are not only unknown but objectively non-existent, to be created later as the now advances. Thus physics should grant time's flow a well-defined place in its formalisms. (See, for example, Elitzur and Dolev 2005).

It is not my purpose here to discuss these theories in detail or to argue for or against any one of them. I merely wished to stress that the common semantic carelessness when it comes to the expressions "course of time," "direction of time," and "arrow of time" makes the arguments of all parties more confusing than they really should be. If these expressions were better defined, systematically distinguished from one another and always used in their strictest sense, the debate about time, irreversibility, and becoming in physics would become clearer.

6 Conclusion

I have shown that the formalisms of modern physics do clearly distinguish the course of time and the arrow of time. The course of time is represented by a timeline that leads us to define time as the producer of duration. As I have pointed out, it is customary to place on this timeline a small arrow that, ironically, must not be confused with the "arrow of time." This small arrow is only there to indicate that the course of time is oriented and has a well-defined direction, even if this direction is arbitrary.

The arrow of time, however, indicates the possibility for physical systems to experience, over the course of time, changes or transformations that prevent them from returning to their initial state forever. Contrary to what the expression "arrow of time" suggests, it is therefore not a property of time itself but a property of certain physical phenomena whose dynamic is irreversible. By its very definition, the arrow of time presupposes the existence of a well-established course of time within which—in addition—certain phenomena have their own temporal orientation.

Today, physics has become so effective that the distinction it establishes between time and becoming could be transferred to philosophy, which often aggregates the two notions. We could even state that it represents a "negative philosophical discovery" because it modifies the terms in which the philosophical question of becoming is stated.

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