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What does the “arrow of time” stand for?

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ABSTRACT

One hundred and thirty years after the work of Ludwig Boltzmann on the interpretation of the irreversibility of physical phenomena, and one century after Einstein's formulation of Special Relativity, we are still not sure what we mean when we talk of “time” or “arrow of time”. We shall try to show that one source of this difficulty is our tendency to confuse, at least verbally, time and becoming, *i.e.* the course of time and the arrow of time, two concepts that the formalisms of modern physics are careful to distinguish. The course of time is represented by a time line that leads us to define time as the producer of duration. It is customary to place on this time line 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, has a well-defined direction, even if this direction is arbitrary. The arrow of time, on the other hand, 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. We think that it is worthwhile to emphasize the difference between several issues traditionally subsumed under the label “the problem of the direction of time”. If the expressions “course of time”, “direction of time” and “arrow of time” 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.

Keywords: Time, Time'S Arrow; Temporal Asymmetry; Principle of Causality; Irreversibility

1. INTRODUCTION

Each one of us can make the following observation: we often talk about time as if it corresponded only to a “becoming”, to the stream of changes affecting a thing, a person, an institution, a physical system. Certainly, change is truly the phenomenon that best suggests the idea of time, and one can easily understand why: 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, as our natural language does, that *time* and *becoming* are the same is a step that is too easily made: without proceeding to further investigation, time is mostly referred to as if it resembled what it holds. It is said to stop or disappear when nothing seems to be happening as if all its dynamics depended not upon time itself but upon its contents.

Such short-cuts serve to answer, before it is even formulated, the question of the relationship between time and events, as well as the question of its dynamics: is time an abstract structure into which events are inserted, that is to say a reality in itself preceding all possible events, or is it composed of the stream of events itself? In other words, is it legitimate to differentiate time from the concrete succession of events? If the answer is yes, then what makes time go forward? If the answer is no, do events determine its flow?

Those questions are neither purely academic nor purely theoretical. They deserve to be thoroughly examined since concealing them creates a confusion between time and becoming, which leads to a kind of intellectual vagueness through repetition: concepts get lost, clouded and confused with one another. Moreover, this confusion constantly exposes our conception of temporality to metaphors that ultimately discourage us from thinking about time for what it is. By willing too much to harmonize the representation of time with the experience of becoming, common thinking in fact engenders confusion

between time and irreversible physical phenomena. At least for the sake of hypothesis, and without going back to a Newtonian conception of time, why not conceive of time as a more fundamental entity than temporal phenomena? A kind of skeletal being whose flesh would be made of events? The discreet background of any concrete becoming? Those are the questions we would like to discuss by examining the kind of answers physics provide...

For this purpose, we have studied the theoretical constructions specific to conventional physics (classical physics, quantum mechanics, special or general relativity). As we will see, this study shows that through its operational formalisms, physics distinguishes time from becoming. It even distinguishes them completely; 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 of the majority of phenomena taking place in time, specifically irreversible temporal phenomena.

The course of time establishes an asymmetry between past and future: if two events are not simultaneous, then one of them is earlier than the other one. It also establishes a difference of position (but not of nature) between past and future moments: on a timeline, tomorrow isn't set where yesterday is – a certain amount of time separates them definitely. *So defined, the course of time expresses the irreversibility of time itself.* 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.* It is the concrete manifestation of becoming.

Today, physics has become so spectacularly effective 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. Especially because physics not only distinguishes them but almost opposes them. In a way, it considers the course of time as that which never becomes, in the sense that it never changes its way of renewing the present moment or, to put it differently, its way of being time. Therefore, almost ignoring the meaning of words and going against how we normally think of time when we don't really think about it, physics conceives of the existence, within the course of time itself, of a principle that remains and never changes: within passing time, there is something that doesn't pass, something that time doesn't affect.

2. TIME AND TEMPORAL PHENOMENA: DON'T JUDGE BY APPEARANCES

Because of a transference process between concepts, we don't distinguish between time and what happens within it: we automatically mistake the contents for its container.

Because we notice that cyclical phenomena exist around us, we pretend that the course of time is cyclical. Or, if our schedules get crammed, if we manufactured objects at a frantic pace, we declare that it is time itself that's speeding up. Our notion of time is always of a time marked by events, by the phenomena it contains, a full time excluding any notion of emptiness or abstraction.

It is of course possible to pretend that those are only figures of speech, frequently used expressions that don't hinder our understanding of time in any way. But this would be to ignore that this shift, this simplification of language doesn't exclusively happen in daily life. Some philosophers have repeated it: as soon as they learned that scientists have discovered a new category of phenomena, they declare that time itself has therefore been modified even that it has just been the object of an ontological revolution.

On the subject of chaos theory, which shows that a system defined by deterministic equations doesn't necessarily have a predictable evolution, the French philosopher Michel Serres wrote: "Time does not always flow according to a line nor according to a plan but, rather, according to an extraordinarily complex mixture, as though it reflected stopping points, ruptures, deep wells, chimneys of thunderous acceleration, rending, gaps – all sown at random, at least in a visible disorder. Thus, the development of history truly resembles what chaos theory describes."

What does this mean? That the existence of chaotic phenomena necessarily implies that the course of time itself is chaotic? But chaos theory, as revolutionary as it first appears, can be explained through classical Newtonian mechanics. It even belongs to it completely. Neither the status nor the representation of time have been modified by this theory or even questioned by it: time in chaos theory is the same as Newtonian time. The discovery of a new typology of phenomena doesn't necessarily require a new conception of time in order to be characterized.

Similar remarks could be made about a book from 1979 that has had a lasting influence: *The New Alliance* by Ilya Prigogine and Isabelle Stengers, which is often presented as the manifesto for "*temps retrouvé*" (the rediscovery of time) supposedly because its authors conclude that: "Today's physics no longer denies time. It acknowledges the irreversible time of evolutions toward equilibrium, the rhythmical time of structures whose impulse feeds on the world that runs through them, the zigzagging time of evolutions through instabilities and amplifications of fluctuations, and even the microscopic time that reflects the indeterminacy of macroscopic physical evolutions.²" But has physics ever "denied" time? And what is "rhythmical time"? What about "zig-

¹*Conversations on Science, Culture and Time*, Michel Serres with Bruno Latour, University of Michigan Press, 1995, p. 57.

²Ilya Prigogine, Isabelle Stengers, *La Nouvelle Alliance*, Paris, Gallimard, 1979, p. 275.

zagging time”? And what kind of time would not be “irreversible”?

To postulate that time is equivalent to what it contains, or even that it is generated by phenomena is to concede explicitly that a multiplicity of time exists: there would then be the same number of times than the number of temporalities. In this sense, time is labelled with several adjectives that specify the type of phenomena associated with it: there is a psychological time, a geological time, a astrophysical time, a subjective time, one or several historical times, even a “rhythmical time” or a “zigzagging time”, because those phenomena inhabit time in a way that varies according to each... Such posture makes believe that multiple kinds of time can coexist. But could there seriously be a time for rocks and one for atoms, a time for stars and one for galaxies?

Ilya Prigogine found it useful to add another element to the list: the “entropic time”, which is supposed to reflect the irreversible evolution of a system by quantifying the scope of changes that have affected it. This “time” is proportional to the variation of a system’s entropy during a given irreversible process.³ What does this mean?

As we know, the entropy of a system is a quantity that characterizes the system’s ability to experience spontaneous changes: the bigger the entropy, the smaller the system’s ability to transform itself. The second law of thermodynamics states that a closed system’s entropy can only increase throughout time. This means that by changing, the system necessarily loses some of its ability to change even more. A closed system spontaneously tends toward a state of maximum entropy, in which any spontaneous transformation will become impossible. Let’s take an example: the total entropy of a sugar cube and of a cup of coffee being inferior to the entropy of a cup of coffee with sugar, a sugar cube dropped into a cup of coffee has no choice but to be dissolved into the coffee. This phenomenon is irreversible: the sugar cube dissolved in the coffee cup will never return to its original square shape, nor will it recover its whiteness, and the coffee won’t ever get its bitterness back. As such, the second law of thermodynamics is in accordance with the fact that physical phenomena seem to go in a truly specific direction.

Another way of defining entropy is to say that it measures the energy quality available within a system. The energy is conserved and can therefore only be transformed. But during this transformation, its quality lessens and it becomes less and less usable. Good quality energy is organized energy with little entropy, like the

³If dS is the variation of entropy for a system and $P(t)$ the production of entropy per unit of physical time, then of course: $dS = P(t)dt$. The idea on which the concept of entropic time is based consists in building a “time” t^* for the variation of entropy during the time interval dt to be proportionnal to dt^* : $dS = P(t)dt = a \cdot dt^*$, where a is a constant. We therefore have: $\int dt^* = (1/a) \int P(t)dt$.

entropy of a waterfall whose overall falling movement can activate a water turbine. At the bottom of the fall, water molecules have lost the vertical organization they had during the fall due to the action of gravity. Their energy is now of lower quality: it can’t be used so easily.

That being said, let’s go back to Ilya Prigogine who, by using the entropic variation, links the course of physical time to processes that happen within it. In fact, he creates a kind of time that resembles the phenomena it contains and clearly depends on the system. Somehow, he “mixes up” the length of time during which the system changes and the intensity of these changes: if the system doesn’t change, its entropic time doesn’t increase; if it changes, its entropic time shifts from physical time and this shift depends on the production of entropy. The specificity of entropic time is that it stops as soon as the system’s entropy becomes constant while physical time keeps on passing. Entropic time is similar to Bergsonian time: it only passes when it creates novelty. This time is only valid for the changes it brings and stops as soon as the system can’t evolve anymore⁴. Besides, the course of entropic time has a clearly defined motor: it is “pulled” or “pushed” by the irreversibility of temporal processes that occur within it.

But Prigogine is far from having created a new time since his definition of entropic time explicitly relies on physical time. Entropy variation being the manifestation of any irreversible change, it can certainly be used to characterize a system’s inner dynamics through its relationship to the duration of that system’s change. But is it therefore judicious to measure a system’s irreversible evolution using a variable called “time” if this variable has actually been set to proceed outside of...time? “Entropic time” appears as a misleading expression in the sense that it implies that entropy could be generated by time even though it is a quantity linked to *what is happening* throughout time.

This kind of confusion between time and temporal phenomena seems implicit, evident, but is it even relevant or justified? Can such assimilation of time with temporal developments be found among the formalisms of physics?

3. TIME AND BECOMING: PHYSICS SEES DOUBLE

Physics formalisms are mostly composed of equations, which condense fundamental relationships, reflect essential properties, and reveal things more profound than our human discourse can express however subtle it might be. But equations don’t speak, at least in the common sense of the verb. So what can we say about time and becoming that the equations would say if they

⁴« Time is invention or it is nothing at all », Henri Bergson, *Creative Evolution*, Courier Dover Publication, 1998, p. 341.

could speak?

Here is the short answer to this question: modern physics has been constructed through formalisms that make a distinction between time and becoming, or more precisely between the *course of time* and the *arrow of time*. Since its birth, that is since the apparition of Newtonian mechanics, physics has conceived a time that doesn't need something to happen somewhere to pass. Physics' operational effectiveness, its experimental successes have become so impressive that it seems right to believe that the distinction it establishes between time and becoming represents a "negative philosophical discovery" of the highest importance since it alters the terms in which the philosophical question of becoming is stated.

We are now going to explain the comment above. What does *course of time* and *arrow of time* mean?

The course of time only reflects the passing of time. In a way, it is time itself. It is represented by a line, a timeline on which a little arrow is usually drawn, *an arrow that is not the arrow known in physics as the arrow of time*. It is there to indicate that time has a single direction, and that time travel is indeed impossible; our presence on the timeline at a specific moment conditions our subsequent positions on that line. It is also impossible to come back, nor to go through the same moment twice.

We have to notice that this depiction of time as a line is fundamentally incomplete because it omits indicating how this line is built. Since 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 is responsible of the course of time, in the sense that it continuously renews the present: without it, the newness of each instant could not arise. 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 that we have to consider that the mystery of time exists less in the line through which we represent it than in the hidden dynamic that builds this line.

The course of time has a structure, which by itself guarantees that each event is necessarily definitive. As soon as the event occurs, this fact can't be erased by anything. If the imprint that the event might have left can be erased, this erasure will change the close or distant future, but not the past. More generally, any present action can only have consequences in the future, never in the past. The course of time thus maintains a constant possibility of distinguishing the past from the future.

As for the arrow of time, what is it if not the little arrow placed on a timeline? 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 can't return to its original state. The dynamics of those physical phenomena is then marked with an arrow, wrongly called the "arrow of time" (since this arrow is linked to the dynamics, not to the time itself).

The problem of the arrow of time is often 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. But in fact, the question asked doesn't concern the arrow of time since 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) that 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 subsumed under the label "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 (as we see, this problem is conceptually different from the explanation of the origin of the course of time, and also from the description of the engine of time).

To better grasp this distinction between the course of time, the arrow of time and the engine of time, we should remember that since Newton, the principle of causality has always constrained *from the outside* the representation of the course of time in physics. This principle is generally summarized by saying that every event has a cause that precedes it, but a point should be clarified here.

Even if it might not seem so, the notion of cause, in the strict sense of the term, gave a lot of trouble to physicists who ended up abandoning it. After playing an essential role in 17th and 18th century physics, its importance declined with the emergence of probabilities in statistical physics. In the 20th century, quantum physics definitely wiped it out. Indeed, quantum physics uses probabilities in a way that precludes referring to a cause, in the strict sense of the term, when talking about quantum processes. Therefore, the notion of cause slowly disappeared from scientific theories in favour of the notion of physical laws, or was absorbed by the dynamics of systems.

The fact remains that the principle of causality, even freed of the notion of cause, has enabled the development of modern physics' theories, and deeply structures those currently being elaborated, such as superstring theory. It sets an absolute and compulsory order between several types of phenomena, even if none can be presented as the cause of another, and thus imposes a direction to time. In short, the principle is reduced to a classification method for events that fall under its influence, a rule that organizes them according to a systematically constraining order.

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 can't influence its cause retroactively). In special relativity, it posits that a particle can't 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 equation⁵. In particle physics, causality made it possible to predict the existence of antimatter, and it is now formally expressed by CPT invariance to which the dynamics of physical phenomena must respond. What does CPT invariance represent? The fact that physical laws ruling our universe are perfectly identical to the rules of a universe in which matter and antimatter would interchange their roles, observed in a mirror, and where time would go backward (CPT invariance imposes that the mass and lifetime of particles must be strictly equal to the mass and lifetime of their antiparticles).

Putting aside their most technical aspects, these declinations and implications of the principle of causality are quite clear, so clear that they tend to hide a fundamental conceptual problem. In fact, the notion of causality can't be thought of, or even defined, outside of events that embody it. How it relates to the course of time then becomes partly ambiguous: if the principle of causality constrains the course of time, this means that the latter is indirectly "contaminated" by causally related phenomena that occur within it. In other words, the principle of causality (partly) aggregates the course of time and temporal phenomena despite the distinction established between them.

But we would like to emphasize one thing: in every physical theory, once the course of time is dependent upon the principle of causality, it then becomes completely irreversible, in the sense that an instant can't occur twice. This irreversibility can never be compensated or erased by the reversibility of any movement or dy-

namical process; as fast as one can possibly return from Paris after being to Genève, time has irreversibly passed during the trip and one is therefore a bit older. More generally, the absence of the arrow of time doesn't stop the hours from passing.

The course of time possesses a direction that is quite different from the arrow of time. When it exists, the arrow of time appears *in addition*, "filling up" the irreversible course of time with irreversible phenomena. We shall later see that physicists have identified possible explanations for the irreversibility of phenomena. All of them presuppose the existence of a set course of time within which time-oriented phenomena take place.

While time passes, the course of time in itself doesn't change (all successive instants are equal in the sense that they have the same status with respect to physical laws). It doesn't change throughout time its way of being time. Thus it escapes becoming (the variable t , designing the time, doesn't vary according to time). It is the arrow of time that constitutes the true expression of becoming. It manifests itself within the course of time, which it doesn't affect in any way but which it overruns with mostly irreversible phenomena. In some respects, the notion of "the course of time" therefore precedes the notion of becoming.

This is also what the second law of thermodynamics suggests: the assertion that the entropy of isolated systems going through a spontaneous transformation only increases with time implicitly presupposes that the transformation in question follows the direction of a time that leads us from our "past" toward our "future", and not in the opposite direction. It presupposes that the course of time has first been defined.

It is possible to illustrate the distinction between time and becoming, to make it visible. Let's 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, which happens even if nothing happens; if each number drawn is new (and each moment is completely new), it is always obtained by adding a unit to the preceding number. As for the photographs the artist takes of himself regularly under unchanging conditions (on a white background, with a white shirt, under a white light, with the same facial expression), 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 and the accumulation of canvases; on the other, becoming is represented by a series of photographs of the same being changing. This dual representation is enough to prove, if not to demonstrate, that these two kinds of irreversibility, which always appear entangled to the point that they seem whole, can in fact be separated. But since they're so often combined and have simultaneous effects, it is

⁵In 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 respected.

hard for us not to confuse them even though they are always just superposed.

4. WHERE DOES THE ARROW OF TIME COME FROM?

Why are some temporal phenomena irreversible or others not? When a phenomena is irreversible, that is to say when an arrow of time appears, what is its origin?

The arrow of time wasn't part of physics fundamental formalisms from the start, neither in classical mechanics, nor in quantum physics and the theory of relativity. Therefore how do we understand it? Where could it have come from?

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 that they would be the same if the course of time was going in the opposition direction. If they allow a certain process to occur when time goes into one direction, they allow it to happen when it goes into the opposite direction: the initial and final states could be interchanged. 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 isn't 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.

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. We will present them briefly:

- *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, don't behave exactly like their anti-particles. More specifically, they don't disintegrate into other particles at the same pace than 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 can appear contradictory since 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 and Roger Penrose, think that this arrow of time could be the arrow mastering all the others, but not all physicists share this position.

We've gone far enough to be able to make two remarks.

The first one is that the 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. (We 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 even demonstrates – that the course of time and the arrow of time are two distinct things in contemporary physics; *the irreversibility of phenomena doesn't 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 such or such physical theories, but are not *incorporated* into any formalism. There is indeed no operating physical theory that integrates becoming from the start (through the use

of irreversible fundamental equations). Consequently, becoming can only be accounted for in physics through the reading of theories that don't 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. These disagreements are not without similarities to the debate between supporters of Parmenides and supporters of Heraclitus. Some physicists think this is only a fake problem: on the pretext that no arrow of time appears in physics' fundamental equations, they believe, like Parmenides, that becoming is only pure appearance and is closely related to how our limited senses make us perceive the world. Others, following the Heraclitian tradition, consider that because actual physics can't 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 don't include the arrow of time. For if becoming wasn't integrated directly into its principles, physics has always referred to the course of time. One can regret that physics hasn't integrated becoming from the start – or better suggest how physics could make room for becoming in its formalisms -, but it can't be blamed for forgetting to integrate the course of time.

Although, *on paper*, it is possible to change the sign of time in a physical equation, this doesn't imply that the course of time can be physically reversed. Only the direction of phenomena can be physically reversed, not the direction of the course of time.

However let us be clear: it is not excluded that the flow of time and the arrow of time come from the same source, more profound than they both; that they are by-products of underlying phenomena that a "new physics" might reveal. Moreover, some progress has recently been made in that direction, in characterizing causality independently of any concept of time and deriving both time and becoming from an ordering relation on sets of events taken as primitives. It may thus appear that causality cannot be understood as a feature of the world that would exist independently of any phenomenon. Causality would be intrinsically shaped by the phenomena. As the principle of causality underlies our representation of time in physics, this would give some formal foundation to a close connection between time and becoming. But for the time being, it would be wiser to formally distinguish them in order to make the arguments clearer.

This is not always the case. For example, in the cosmological context, it is often told that the problem of the arrow of time owes its origin to the intuitive asymmetry between past and future. According to what we have shown, the expression "course of time" would be there more appropriate. Because of this confusion, many authors argue that the direction past-to-future is related to

the direction of the gradient of the entropy function of the universe, forgetting that the definition of the entropy of the universe is a very controversial matter: entropy is a thermodynamic magnitude that is typically associated with subsystems of the universe, and not with the universe as a whole. To evade this difficulty, some authors⁶ have tried to define a course of time for the universe only on the basis of the geometrical properties of space-time, independently of any entropic consideration. Unfortunately, they have called this direction past-to-future the "global arrow of time". The expression "global course of time" would have suited better.

5. WHAT MAKES THE TIME FLOW?

The nature of the "engine of time" that makes us feel the flow of time has not been elucidated but a lot 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, and most popular among physicists, 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 scientific laws, or, if it has been missed there, then in future scientific 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, have the same degree of existence along 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, 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 the 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.

The third theory 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

⁶See for example: Mario Castagnino, Olimpia Lombardi, Luis Lara, *The Global Arrow of Time as a Geometrical Property of the Universe*, Foundations of Physics, Vol. 33, N° 6, June 2003; G. Matthews, "Time's arrow and the structure of space-time", *Philosophy of Science* 46, 82-97 (1979).

non-existent, to be created later as the now advances. Thus physics should grant time's flow a well defined place in its formalisms⁷.

It is not our purpose here to discuss these theories in detail or to argue for or against any one of them. We 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. CONCLUSIONS

What can these considerations 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. It would allow us to better think about the question of time.

Therefore, the principle of causality could benefit from being renamed "antecedence principle" or "principle of chronological protection", as Stephen Hawking proposed it. Similarly, when referring to a physical process, the quite awkward expression "time reversal" could be replaced by the expression "movement reversal", since the intention is not to create a time machine but to reverse the speed of the physical entities concerned. When a phenomenon's dynamics are reversible, the course of time (or the direction of time) is indeed arbitrary, but once it has been chosen, it can't simply be reverted.

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

results from a convention. To change this convention and declare that an electron's charge is positive and a proton's negative wouldn't change anything to the laws of physics or the universe. Beginning with a conventional choice, it is therefore possible to design physical laws that are unconventional.

To claim that the course of time doesn't exist according to physics under the pretence 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 don't change if each charge's sign is reversed.

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⁷See for example "Becoming as a bridge between quantum physics and relativity", A. C. Elitzur, S. Dolev, in *Endophysics, Time, Quantum and the Subjective*, 589-606, R. Buccheri *et al* (eds), World Scientific Publishing Co., 2005.