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Time in Physics

No one conception of time emerges from a study of physics. As science changes—over time or through varying interpretations at a time—our conception of physical time changes. Each of these changes and resulting theories of time has been the subject of philosophical scrutiny, so there are many philosophical controversies internal to particular physical theories. For instance, the move to special relativity radically transformed our understanding of time, but it also gave rise to debates about the nature of simultaneity within the theory itself. Nevertheless, there are some philosophical puzzles that appear at every stage of the development of physics. Perhaps most generally, there is the perennial question, Is there a 'gap' between the conception of time as found in physics and the conception of time as found in philosophy?

One can understand all of these changes and controversies as debates over what properties we should attribute to time. The history of the concept of time in physics can then be understood as the history of addition and subtraction of these properties; and the philosophical controversies can then be understood as debates about particular additions and subtractions. Just as we can take a set of numbers and impose structure on this set to form the real number line, we can take the set of moments or events (which we'll use interchangeably) and impose various types of structure on this set. Each property attributed to time corresponds to the imposition of a kind of structure upon our set of events, making sense of different claims about time. Let us begin with a bare set of

events and successively add structure to this set. In particular, it helps to differentiate *ordering* properties, *topological* properties and *metrical* properties of time.

Order

It seems clear that different times are ordered to some extent. Intuitively, we can give a set an order by making sense of what times are between what other times. The time the cake baked is between the time of mixing the ingredients and the time of eating the cake; eating the cake is between the baking and the feeling full, and so on. Let us therefore impose an ordering on our set of events by adding a ternary "between-ness" relation of the form: "x is between y and z" defined for some or all moments in the set. If betweenness is defined for some but not all distinct triples of moments, then we say that we have a *partially ordered* set; if betweenness is defined for every triple of the set, then we say we have a *totally ordered* set. Newtonian physics, as we shall see, totally orders classes of simultaneous events. Relativistic physics, by contrast, will only partially order the set of all events.

It is interesting to note that between-ness as defined above is not always sufficiently powerful to order topologically non-trivial sets. To see this, consider a circle with four members of the set on it: '1' at 12 o'clock, '2' at 3 o'clock, '3' at 6 o'clock, and '4' at 9 o'clock. Because the set is closed, 2 is between 1 and 3, between 3 and 4, and between 1 and 4. Consequently, the between-ness relation is blind to the difference between this

layout and the same but with '3' at 3 o'clock and '2' at 6 o'clock. For such sets more machinery is needed to order the set.

An ordering does not tell us much about our set of moments, $\{t_1, t_2, t_3\ldots\}$. It does not imply whether t_2 is as far from t_1 as from t_3. Nor does it imply a direction, whether times goes from t_1 to t_3 or t_3 to t_1. Although the baking example suggests a natural direction to our set of times, an ordering is strictly independent of a direction. Nor does the ordering specify the dimensionality of the set or most other properties one normally attributes to time. To make sense of some of these attributions to time, let us move to the next level of structure, topology.

Topology

Topological properties are those that are invariant under 'smooth' transformations. Technically, these transformations are one-to-one and bicontinuous; and what they leave invariant is the so-called neighborhood structure that is given by picking out a family of open subsets closed under the operations of union and finite intersection. Intuitively, the transformations that leave this structure unchanged correspond to operations like stretching or shrinking, as opposed to operations like ripping and gluing. A coffee cup and a donut are, topologically speaking, the same shape; if made out of an infinitely pliable rubber, one could be smoothly transformed into the other. Being closed like a circle, having an edge, and being one-dimensional are examples of topological properties.

No amount of stretching and shrinking can (for instance) make the circle into a line, make an edge disappear, or make a one-dimensional set two-dimensional.

Many issues in the philosophy of time are in fact questions about the topology of time: is time closed or open? discrete? branching? two-dimensional? oriented (directed)? Formally, the answers to these questions are determined by the topological structure of time.

Metric

Once we add topological structure to our set of times, most temporal properties are determined. However, there is still a major one remaining: duration. Of our set $\{t_1, t_2, t_3 \ldots\}$ we still do not know whether t_2 is as far from t_1 as it is from t_3—even after all topological properties are specified. The temporal distance between two moments is not a topological invariant, for it can be smoothly stretched or shrunk. To capture the idea of temporal distance, we must put what is called a *metric* on our topological structure. The temporal metric is a function that gives one a number, the temporal distance or duration, between any pair of times. (In relativity we will instead impose a *spacetime* metric; see below.)

In principle, an infinite number of possible metrics are mathematically possible. One might choose a metric that makes the duration between 1980 and 1990 twice the duration

between 1990 and 2000. However, such a choice would make a mess of almost all of science. It would entail, for instance, that the earth went twice as fast around the sun in the 1990's as it did in the 1980's. One would then have to adjust the rest of physics so as to be compatible with this result. As Hans Reichenbach stresses, there are simpler and more complex choices of temporal metric.

Time in Classical Physics

Time in classical physics is normally assumed to have the ordering, topological and metrical structure of the real number line. That is, it is one-dimensional, continuous, infinite in both directions, and so on. The temporal metric is just the one used for the real line: between any two times, a and b, the duration is b – a. Time in classical physics does have a number of remarkable properties, of which we will mention three. The first two concern the metrical properties of time, whereas the third is more a property of the dynamics than of time itself.

First, the metric of time is independent of the metric of space. This feature implies that the amount of time between any two events is path-independent: if persons A and B leave an event e_1 and then meet at a later event e_2, the amount of time that has elapsed for A is equal to the amount of time that has elapsed for B. The distinct spatial distances traveled by A and B are irrelevant to how much time has passed between e_1 and e_2.

Second, simultaneity is absolute. Before explaining 'absolute', consider the 'simultaneous with' relation. For any event e, there is a whole class of events that are simultaneous with e. Indeed, the 'simultaneous with' relation is an equivalence relation in classical physics. Equivalence relations are reflexive, symmetric and transitive; for us what is important is that they partition a set into disjoint subsets. Hence the 'simultaneous with' relation partitions the set of all events into proper subsets, all of whose members are simultaneous with one another. It is these classes of simultaneous events, rather that the events themselves, that are totally ordered. What is interesting about this partition in classical physics is that it is unique. Classical physics states that every observer, no matter their state of motion, in principle agrees on whether any two events are simultaneous. This observation translates into only one partition (or foliation) being the right one. In this sense simultaneity is absolute – it does not depend on one's frame of reference but is an observer-independent fact of the Newtonian world.

Third, classical physics is time reversal invariant. Consider a sequence of particle positions over time, (x_1, t_1), (x_2,t_2), (x_3,t_3)….(x_n, t_n). The fundamental classical laws of evolution are such that if this sequence is a solution of the laws, then so is the time-reversed sequence (x_n, t_n)…(x_3,t_3), (x_2,t_2), (x_1, t_1). The classical laws are invariant under the transformation of –t for t. This is true also of arbitrarily large multi-particle systems and even of classical fields. If a bull entering a china shop and subsequently breaking vases is a lawful history, then so is a bunch of scattered vase shards

spontaneously jumping from the ground and forming perfect vases while a bull backs out of a china shop.

Time in Special Relativity

In classical physics material processes take place on a background arena of space and time, described above. The move from classical physics to special relativity is usually taken as a change in the background arena from classical space and time to the "spacetime" of Minkowski. This new entity, spacetime, is fundamental, and space and time only exist in a derivative fashion. On this conception, there is not one metric for time and another for space; rather, there is one spacetime metric supplying spatiotemporal distances between four-dimensional events. These spacetime distances are invariant properties of the spacetime. Time can be decoupled from space only in an observer-dependent way; each distinct possible inertial observer (one who feels no forces) carves up spacetime into space and time in a different way. In a sense, there is no such thing as time in Minkowski spacetime, if by 'time' one conceives of something fundamental.

There are, however, two "times" in Minkowski spacetime that correspond to different aspects of classical time, namely, 'coordinate' time and 'proper' time. Let's take coordinate time first. Think of an arrow in three-dimensional Euclidean space. One can decompose this arrow relative to an arbitrary basis {x,y,z} by measuring how far the

arrow extends in the x-direction, how far in the y-direction, and how far in the z-direction, where x, y and z are perpendicular, and the arrow's base lies at the origin. The same arrow would decompose differently in a different basis {x',y', z'}. As one can decompose a vector in Euclidean space along indefinitely many different bases, so too can one decompose a four-dimensional spacetime vector along many different bases in Minkowski spacetime. Mathematically, coordinate time in special relativity is just one component of an invariant spacetime four-vector, just as y' is one component of a Euclidean spatial vector. In the Euclidean case, the value of the arrow along the first component of the decomposition varies with basis; so too in spacetime, the value of the first component--here, coordinate time--varies with frame of reference.

The second bit of residue of the classical time is the so-called proper time. The proper time is a kind of parameter associated with individual trajectories in spacetime. It is often thought of as a kind of clock tied to an object through its motion. This time is a scalar—that is, just a number—and as such is an invariant of the spacetime. All observers will agree on the value of proper time for A as he travels from e_1 to e_2; all will agree on the value of proper time for B as she travels from e_1 to e_2; and all will agree that these values will not be the same if they take different paths. Unlike with classical time, the temporal distance in Minkowski space is not independent of spatial distance. The amount of time between any two events is path-dependent: if persons A and B leave an event e_1 and then meet at a later event e_2, the amount of time that has elapsed for A is in

general not equal to the amount of time that has elapsed for B. Spatial distances can only be completely disentangled from temporal distance in a given inertial frame of reference.

Time in classical physics plays the role of coordinate time and the role of proper time. A little reflection reveals that it can accomplish this task because in classical physics the amount of time between any two events is path-independent.

Three consequences of the shift to special relativity ought to be highlighted. First, simultaneity is not absolute in Minkowski spacetime. Simultaneity is a temporal feature, yet the temporal does not disentangle from the spatial except within an inertial reference frame. What events are simultaneous with one another is observer-dependent. Given spacelike-related events e_1 and e_2, inertial observer A may (rightly) say they are simultaneous whereas inertial observer B, traveling at a constant velocity with respect to A, may (rightly) say e_1 is earlier than e_2. In Minkowski spacetime, they do not disagree over any observer-independent fact of the matter. In terms of our earlier discussion, we can say that the "simultaneous with" relation partitions Minkowski spacetime, but only within a frame of reference.

Second, the temporal ordering in Minkowski spacetime is partial, not total. The only temporal ordering that all observers agree on is the ordering among "timelike" events. Timelike related events are those that are in principle connectible by any particle going slower than the speed of light in a vacuum. Think of all the events that can be reached

from any given event that way. Consider the event of your elementary school graduation (e_1) and the event of your high school graduation (e_2). Obviously sub-luminal particles could make it from one to the other; for instance, you are a set of such particles. Due to the finite speed of light, however, there are many events that such particles could not reach, e.g., whatever was going on at Alpha Centuri simultaneous with (in your reference frame) e_2. What happened on Alpha Centuri simultaneous with e_2 is not an observer-independent fact. But that e_2 follows e_1 is an observer-independent fact. Only the timelike related events are invariantly ordered.

Third, and perhaps most famously, in a sense time passes more slowly for a moving observer than for one at rest. Consider two inertial observers, A and B, traveling at a constant velocity relative to one another, and let a clock be at rest in A's frame. Looking at the ticks of the clock, the special relativistic metric entails that B will conclude that the clock in A's frame is running slow. This effect, known as time dilation, is entirely symmetrical: A would find a clock at rest in B's frame to be running slow, too. Time dilation has many experimentally confirmed predictions, such as that atomic clocks on planes tick slowly relative to clocks on land and that mesons have longer lifetimes than they 'should' from the earth's frame of reference.

Time in General Relativity

General relativity, unlike special relativity, treats the phenomenon of gravitation. It famously does away with Newton's gravitational force, understanding gravitational phenomena as instead a manifestation of spacetime curvature. Loosely put, the idea is that matter curves spacetime and spacetime curvature explains the gravitational aspects of matter in motion. Hence the largest conceptual difference between special and general relativity is that Minkowski spacetime is flat whereas general relativistic spacetimes may be curved in an indefinite number of ways. Otherwise, as regards time, we again have a division between coordinate time and proper time, no privileged foliation of spacetime, only a partial temporal ordering, and the possibility of time dilation.

In terms of our previous division, curvature is a metrical property, so the primary difference between special and general relativity is that the former's metric is merely one of the many possible metrics allowed by the latter. General relativity places various constraints between the spacetime metric, or geometry, and the distribution of matter-energy. Thinking of these constraints as the laws of general relativity, general relativity claims a variety of spacetime geometries are physically possible. Because these different metrics allow and sometimes demand different topologies and even orderings, time may have dramatically different ordering, topological and metrical properties depending on the spacetime model. Some consequences of this fact are especially worthy of note.

First, there are spacetimes without a single global moment. In special relativity, we saw that simultaneity was observer-dependent. Minkowski spacetime could be carved up, or foliated, into a succession of three-dimensional spaces evolving along a one-dimensional time an indefinite number of ways—a distinct foliation for every possible inertial observer. Though this may also be the case in general relativity, there are spacetime models that prohibit even one foliation of spacetime into space and time. The famous Gödel spacetime, named after the great logician Kurt Gödel, is an example of such a spacetime. Due to the effects of curvature, in such spacetimes it is impossible to find even a single global always-spatial three-dimensional surface. There is no global moment of time in such spacetimes. There is no way to conceive of world history, in such a spacetime, as the successive marching of three-dimensional surfaces through time.

Second, perhaps most famously, general relativity has models that permit interesting time travel. In these models a traveler can start off at event e, and by traveling always to the local future (that is, into e's future lightcone), eventually come back to events that are to e's past (that is, in e's past lightcone). Indeed, these models will allow one to travel back to an earlier event: an observer's worldline may intersect e, and then after some proper time has elapsed, intersect e again. These 'causal loops' are called closed timelike curves. Of the many models that allow time travel, the Gödel model is again remarkable for it allows the time traveler the fullest menu of possibilities: in the model, it is possible (given enough time and energy) to get from any event e_1 to any other event e_2 on the entire spacetime, including the case where $e_1=e_2$.

Third, whether time is infinite or finite can be an observer-dependent fact. When discussing Minkowski spacetime we saw that there are different ways to decompose spacetime into space and time; alternatively, there are generally many ways to foliate a spacetime. When non-trivial topologies are considered, there are spacetimes consistent with general relativity that make whether time is infinite or finite a foliation-dependent matter. That is, there are foliations of one and the same spacetime that make time finite and foliations that make time infinite. In spacetimes admitting two such foliations, the age-old question of whether time is finite or infinite would be answered with a convention. In such a world there is no coordinate-independent fact of the matter regarding how long time persists. The universe might last an infinite amount of time according to one coordinization, or language, and a finite amount of time according to another coordinization, or language.

Time in Future Physical Theories

As mentioned, because physical theories are always changing, there is no one conception of time emerging from a study of physics. On the horizon of research are the various programs of 'quantum gravity,' the would-be theory that unifies or at least makes consistent our best theory of matter, quantum field theory, and our best theory of spacetime, general relativity. Though very speculative, virtually all of these programs are entertaining dramatic changes for our conception of spacetime, ranging from the idea that

spacetime is discrete to the idea that time is an emergent property arising from some more fundamental stuff.

Philosophical Controversies

There are many philosophical problems concerning time in physics. Philosophers have debated the physical possibility of time travel in general relativity, the possibility of discrete time, the nature of time reversal invariance, the possibility of backward causation in physics, such as in the Wheeler-Feynman time–symmetric version of electromagnetism, the possibility of time emerging from something more fundamental in quantum gravity, and more. In addition, it will not be surprising that many topics typically dealt with in the context of space also have temporal counter-parts. The absolute-versus-relational debate, famously discussed by Leibniz and Clarke and more than a hundred authors thereafter, is often discussed in the classical context of space; but those arguments apply equally well to the case of time, and in the modern version of the debate, to spacetime. And the many discussions surrounding the conventionality of the metric apply just as well to the temporal metric as the spatial metric (and of course the spacetime metric). Here we will concentrate on the question of whether physical time captures all the fundamental properties of time and the so-called problem of the direction of time.

Tense

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In the famous terminology of J.E. McTaggart, the temporal relations of earlier than, later than and simultaneous with are called "B-properties" and the monadic properties of past-ness, present-ness and futurity are called "A-properties." Those who argue that the B-properties are the fundamental features of time are dubbed advocates of the "tenseless" theory of time; those who argue that instead the A-properties are fundamental are dubbed advocates of the "tensed" theory of time. Much of the work in philosophy of time, especially throughout the twentieth century, can be described as a debate between tensers and detensers.

Because the categories "tensed" and "tenseless" are broad umbrellas covering many different doctrines, it is probably best not to think of this as one debate. A better way to frame the debate is to conceive it on the model of the debate between mind-body dualists and materialists. Dualists find the description of the mind by the natural sciences to be either incomplete or simply wrong. Various features of mental states, e.g., consciousness, are said to be either left out or indescribable by these natural sciences. Materialists counter by either denying the reality of these features or by explaining why the natural sciences do manage to explain such features.

We can conceive the debate regarding time in the same mold. Though the features attributed to time vary with physical theory, some philosophers feel that physical theory has consistently missed out on one or more essential properties of time. Physical theory

orders some or all of the events in time, just as the relations of right and left order events in space. In classical (relativistic) physics, for any (some) pair of events, e_1,e_2, physical theory states whether e_1 is earlier, later or simultaneous with e_2. The theories use relational temporal properties and not monadic ones. One can of course say e_1 is to the past of e_2, but that is just to say that e_1 is earlier than e_2. Physical theory seems to require only tenseless temporal relations. Broadly speaking, the debate is between those who would add some "metaphysical" feature to time as it is found in science and those who would not. Various arguments are adduced to show that such features are needed or not needed, compatible with science or incompatible, and so on. Let us consider three features often felt to be left out by physical time.

The Present. Physical theory does not tell us which time is Now. That is, it tells us which events are earlier, later and simultaneous with which other events, but it fails to mention which among all sets of events are the present ones. Some philosophers argue, based on experience, analysis of ordinary language or study of puzzles surrounding change, that physical theory misses out on a genuine property of time, Now-ness. Others reply that the idea of a metaphysically special present is wrong-headed. Linguistic features of the now are explained via the properties of indexicals in general. As we don't reify the here, we should not reify the now. Attempts are then made to show that the language, thought and behavior attributing objectivity to the present can be explained by facts about human beings and our typical physical environments.

Flow or Becoming. Physical theory also does not describe a property corresponding to the flow of time or to a process of becoming. Again, the different events are ordered, have a certain distance from one another, etc., but there does not seem to be anything that flows (such as the Now). Nor is there a distinction made among events, such that it makes sense to talk about the Now turning an unreal future real. Again, some philosophers argue, based on experience or the study of various puzzles, that there is genuine becoming in the world. C.D. Broad, for example, proposed a model wherein the past and present are real and the future successively becomes present and hence real.

Time's arrow. If physical time is time-reversal invariant, then no where does it distinguish one direction of time. But there are many asymmetric processes: physical ones, such as the radiation and thermodynamic asymmetries, metaphysical ones, such as the asymmetry of causation and of counterfactual dependence, epistemological ones, such as the fact that one typically knows more about the past than the future, and emotional ones, such as that we usually care more about the future than the past. To explain one or more of these asymmetries, some philosophers have posited a directionality to physical time. Others answer that that the physical asymmetries don't themselves need explanation and that they in turn can explain the other asymmetries. To mention one possible sequence of moves, one might try to show that the thermodynamic and radiative temporal asymmetries explain the memory asymmetry (we have memories of the past, not the future), the memory asymmetry explains the knowledge asymmetry, and the knowledge asymmetry explains the psychological asymmetry.

There are also two famous conceptual arguments against the idea that time itself flows (and depending on the model of becoming, against becoming). One, McTaggart's Paradox, claims that the idea of time flowing leads to a logical contradiction. Essential to the idea that time flows, says McTaggart, is the idea that events change their A-properties: for instance, the event of Socrates' death was future, then present, and then past. So every event has all three monadic properties. But this is in straightforward conflict with the claim if an event is future it is not past. McTaggart and his supporters claim that any way of discharging the contradiction by insisting that events are not at the same time past, present and future leads to infinite regress.

Another argument, by the philosophers C.D. Broad and J.J.C. Smart, begins by noting that change is always the change of some property with respect to time. Movement, for example, is having different locations at different times. So if time flows, if, say, the Present moves, then Broad and Smart suggest that it must be that the Present moves with respect to time. But this time, Smart claims, must be a hyper-time; and if this hyper-time is a kind of time, it must flow with respect to a hyper-hyper-time, and so on. There are too many responses to this argument to consider them all here.

It should not be surprising that considerations from physics enter these debates.

Special Relativity and Tense

Some also argue that a metaphysically distinguished present is inconsistent with special relativity. The reason is obvious: since simultaneity is relative, how can a monadic feature of events such as presentness be frame-dependent? In Minkowski spacetime, there will be cases where for observer O_1, e_1 is present and e_2 is later, whereas for observer O_2, e_2 is present and e_1 is later. Assuming presentness is not frame-dependent, we appear to have a contradiction. This argument, originally made by Hilary Putnam and C. Rietjydk, also would affect positions claiming time flows, if the flowing is done by a unique present. Even if correct, by itself this argument does not tell us how to arrange the conflict into premises and conclusion. Does relativity disprove the present or does the present disprove relativity? Naturalistically inclined philosophers are loathe to consider the latter reading; but strictly speaking, if there were enough prior reason to believe in a privileged present, then alternatives to Minkowski spacetime would be forced upon us—such as embedding relativistic phenomena in classical space and time in the manner H.A. Lorentz favored.

General Relativity and Tense

From the perspective of general relativity, the attack on tenses from special relativity seems rather limited. Minkowski spacetime may locally be a good approximation to whatever the true global spacetime is, but strictly speaking special relativity is only valid on planes that are tangent to mere points of the general relativistic geometry. There

appears no particular reason to think that general relativity's impact on the tenses debate will mirror special relativity's impact.

As mentioned, general relativity takes from special relativity a division between coordinate time and proper time and only a partial temporal ordering. The question is whether it banishes a privileged foliation of spacetime into space and time. The answer depends on the particular spacetime model and what one means by 'privileged.' In some models, ones with realistic distributions of matter and energy, one can define a global cosmic time. Cosmic time is defined with respect to the mean motion of matter. The possibility exists of a tenser using cosmic time, which mimics some features of classical time, as the time of becoming, passage, and so on. Challenges to this use include the fact that cosmic time can only be defined in some subset of the solutions to Einstein's field equations, and questions of arbitrariness in the choice of a cosmic time function.

With the possibility of cosmic tiem in mind, Kurt Godel argued that general relativity, far from rescueing tenses, in fact showed that time is 'ideal,' or not fundamental. Reflecting on the odd eponymous spacetime mentioned above, Godel states that it is obvious that time doesn't flow in the spacetime he discovered. But that means, Godel says, that time doesn't flow in our spacetime either. Why? In brief, his idea is that time flow shouldn't be contingent, yet because Godel spacetime enjoys the same laws of nature as our own, it differs from ours in only the contingent distribution of matter and energy. Indeed, Godel

goes so far as to presume time's flow is essential to time, and hence concludes that Godel spacetime shows that there is no such thing as time in our world.

The Problem of the Direction of Time

So far this entry has described issues concerning time in fundamental or near-fundamental physics. There also exists a philosophical problem arising from an apparent conflict between the way microphysics seems to treat time and the way macroscopic physics treats time. While microphysics may be time reversal invariant, the physics describing macroscopic behavior such as the warming or cooling of bodies to room temperature, the expansion of gases, and so on, is not time reversal invariant. Consider the volume of an initially localized sample of a light gas released in the corner of a room. As time goes on, it will spreadthrough its available volume: (v_1,t_1) (v_2, t_2) (v_3, t_3)…, where $v_3 > v_2 > v_1$ and $t_3 > t_2 > t_1$, and so on. While classical mechanics implies that the opposite shrinking process from v_3 to v_1 is lawful, thermodynamics states that it is not.

The science of statistical mechanics seems to reconcile the two by introducing probabilistic considerations: the process from v_3 to v_1 is possible, says statistical mechanics, but highly unlikely, whereas the process from v_1 to v_3 is highly likely. However, statistical mechanics itself is time reversal invariant. It manages to state that evolution from v_3 to v_1 is unlikely and v_1 to v_3 likely. Looked at more closely, however, it implies that *given* v_1, v_3 is more likely in *either time direction*. In other words, it rightly states that v_3 is a likely state to evolve to, but it also implies that it is a likely state *to have evolved from*. The second implication is obviously wrong. This problem and

related ones occupied many of the founders of statistical physics, including Ludwig Stephan Boltzmann, J. C. Maxwell, Joseph Loschmidt, and Ernest Zermelo. Solutions to the problem seem to require inserting a temporal asymmetry somewhere in the physics, either by assuming temporally asymmetric boundary conditions or by introducing new laws of nature.

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