The physics of now

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The world is four-dimensional according to fundamental physics, governed by basic laws that operate in a spacetime that has no unique division into space and time. Yet our subjective experience is divided into present, past, and future. This paper discusses the origin of this division in terms of simple models of information gathering and utilizing systems (IGUSs). Past, present, and future are not properties of four-dimensional spacetime, but notions describing how individual IGUSs process information. Their origin is to be found in how these IGUSs evolved or were constructed. The past, present, and future of an IGUS is consistent with the four-dimensional laws of physics and can be described in four-dimensional terms. The present, for instance, is not a moment of time in the sense of a spacelike surface in spacetime. Rather, there is a localized notion of present at each point along an IGUS' world line. The common present of many localized IGUSs is an approximate notion appropriate when they are sufficiently close to each other and have relative velocities much less than that of light. But modes of organization that are different from present, past, and future can be imagined that are consistent with the physical laws. We speculate why the present, past, and future organization might be favored by evolution and be therefore, a cognitive universal.
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I. INTRODUCTION

A lesson of the physics of the last century is that on length scales much greater than the Planck length characterizing quantum gravity, the world is four-dimensional with a classical spacetime geometry. There is neither a unique notion of space nor a unique notion of time. Rather, at each point in spacetime there is a family of timelike directions and three times as many spacelike directions. Yet, in this four-dimensional world, we divide our subjective experience into past, present, and future. These seem very different. We experience the present, remember the past, and predict the future. How is our experience organized in this way? Why is it so organized? What is the four-dimensional description of our past, present, and future? Is the division into past, present, and future the only way experience can be organized? This paper is concerned with such questions.

The general laws of physics by themselves provide no answers. Past, present, and future are not properties of four-dimensional spacetime. Rather, they are properties of a specific class of subsystems of the universe that can usefully be called *information gathering and utilizing systems* (IGUSs).[1] The term is broad enough to include both single representatives of biological species that have evolved naturally and mechanical robots that were constructed artificially. It includes human beings both individually and collectively as members of groups, cultures, and civilizations.

To understand past, present, and future, it is necessary to understand how an IGUS employs such notions in the processing of information. To understand why an IGUS might be organized in this way, it is necessary to understand how it is constructed and ultimately how it evolved. Questions about past, present, and future, therefore, are most naturally in the domains of psychology, artificial intelligence, evolutionary biology, and philosophy.[2]

However, questions concerning past, present, and future cannot be completely divorced from physics. For instance, these notions must be describable in four-dimensional terms to be consistent with the fundamental picture of spacetime. Furthermore, as we review, the distinctions between the past, present, and future of an IGUS depend on some of the arrows of time that our universe exhibits, such as that summarized by the second law of thermodynamics. In the tradition of theoretical physics, we illustrate these connections with simple models of an IGUS—achieving clarity at the risk of irrelevance. Our considerations are entirely based on classical physics.[3] One such model IGUS, a robot, is described in Sec. II. It is simple enough to be easily analyzed, but complex enough to suggest how realistic IGUSs can distinguish between past, present, and future. The four-dimensional description of this robot is discussed in Sec. III. There we will see that the robot's present is not a moment in spacetime. Rather, there is a present at *each* instant along the robot's world line consisting of its most recently acquired data about its external environment. The approximate common notion of ''now'' that could be utilized by a collection of nearby robots moving slowly with respect to one another is also described.

Section IV describes the connection of present, past, and future with the thermodynamic arrow of time and the radiation arrow of time. It addresses the question, ''Could we construct a robot that remembers the future?'' Section V describes alternative organizations of a robot's experience that are different from past, present, and future, but equally consistent with the four-dimensional laws of physics. The possibility of these alternative organizations shows that past, present, and future are not consequences of these laws. We speculate, however, that, as a consequence of the locality of the laws of physics, the past, present, and future organization may offer an evolutionary advantage over the other modes of organization for sufficiently localized IGUSs. A past, present, and future organization may then be a cognitive universal.[6]

II. A MODEL IGUS

Imagine constructing a robot that gathers and utilizes information in the following manner (Fig. 1):

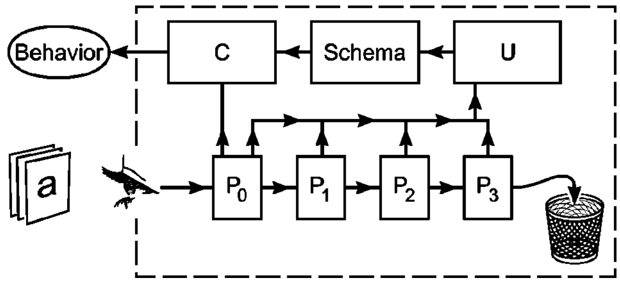

Fig. 1. Information flow in the robot described in the text is represented schematically in this diagram. The internal workings of the robot are within the dotted box; its external environment is without. At every proper time interval τ_*, the robot captures an image of its external environment. In the example illustrated, this is of a stack of cards labeled a, b, c, etc. whose top member changes from time to time. The captured image is stored in register P_0 which constitutes the robot's present. Just before the next capture the image in P_3 is erased and images in P_0, P_1, and P_3 are shifted to the right making room for the new image in P_0. The registers P_1, P_2, and P_3 therefore constitute the robot's memory of the past. At each capture, the robot forgets the image in register P_3. The robot uses the images in P_0, P_1, P_2, and P_3 in two processes of computation: C ("conscious") and U ("unconscious"). The process U uses the data in all registers to update a simplified model or schema of the external environment. That is used by C together with the most recently acquired data in P_0 to make predictions about its environment to the future of the data in P_0, make decisions, and direct behavior accordingly. The robot may therefore be said to experience (through C) the present in P_0, predict the future, and remember the past in P_1, P_2, and P_3.

Information gathering. The robot has $n+1$ memory locations $P_0, P_1, \cdots, P_n$ which we call "registers" for short. These contain a time series of images of its external environment assembled as follows: At times separated by intervals τ_*, the image in register P_n is erased and replaced by the image in P_{n-1}. Then, the image in P_{n-1} is erased and replaced by the image in P_{n-2}, and so on. For the last step, the robot captures a new image of its external environment and stores it in register P_0. Thus, at any one time, the robot possesses a coarse-grained image history of its environment extending over a time $(n+1)\tau_*$. The most recent image is in P_0; the oldest is in P_n.

Information utilization. The robot employs the information in the registers $P_0, P_1, \cdots, P_n$ to compute predictions about its environment at times to the future of the data in P_0 and direct its behavior based on these predictions. It does this computation in two steps employing two different processes of computation:

(1) *Schema:* The robot's memory stores a simplified model of its environment containing not all the information in $P_0, P_1, \cdots, P_n$, but only those parts important for the robot's functioning. This model is called a *schema*.[1] At each time interval τ_*, the robot updates its schema making use of the new information in P_0 and the old information in $P_1 \cdots P_n$ through a process of computation we denote by U.

The schema might contain the locations and trajectories of food, predators, obstacles to locomotion, fellow robots, etc. It might contain hard-wired rules for success (e.g., get food—yes, be food—no) and perhaps even crude approximations to the rules of geometry and the laws of physics, e.g., objects generally fall down. It might contain summaries of regularities of the environment abstracted from the information gathered long before the period covered by registers $P_0, \cdots, P_n$ or explained to it by other robots, etc.[7]

(2) *Decisions and Behavior:* At each time interval τ_*, the robot uses its schema and the fresh image in P_0 to assess its situation, predict the future, and make decisions on what behavior to exhibit next by a process of computation that we denote by C. This process is distinct from U. The important point in the context of this paper is that the robot directly employs only the most recently acquired image in register P_0 in this computation C. The information in $P_1, \cdots, P_n$ is employed only through the schema.

It seems possible that such a robot could be constructed. As a model of sophisticated IGUSs, such as ourselves, it is grossly oversimplified. Yet, it possesses a number of features that are similar to those in sophisticated IGUSs which are relevant for understanding past, present, and future: The robot has a coarse-grained memory of its external environment contained in registers $P_0, P_1, \cdots, P_n$. The robot has two processes of computation, C and U. Without entering into the treacherous issue of whether the robot is conscious, the two processes have a number of similarities with our own processes of conscious and unconscious computation:

(1) U computation provides input to decision-making C computation.
(2) There is direct input to C computation only from the most recently acquired image in the register P_0. The images in $P_1, \cdots, P_n$ affect C only through the schema computed in U.
(3) Information flows into and out from the register P_0 directly used by C.

Equally evident are some significant differences between the robot and ourselves. Our information about the external environment is not exclusively visual, neither is it stored in a linear array of registers, nor is it transferred from one to the other in the simple manner described. Input and records are not separated by sharp time divisions. We can consciously access memories of other than the most recent data, although often imperfectly, and after modification by unconscious computation. This list of differences can easily be extended, but that should not obscure the similarities discussed above.

The analogies between the robot and ourselves can be emphasized by employing everyday subjective terminology to describe the robot. For example, we will call C and U computation "conscious" and "unconscious," secure in the confidence that such terms can be eliminated in favor of the mechanical description that we have employed up to this point if necessary for clarity. In this way, we can say that the robot "observes" its environment. The register P_0 contains a record of the "present," and the registers $P_1, \cdots P_n$ are records of the "past."[8] When the register P_n is erased, the robot has "forgotten" its contents. The present extends[9] over a finite interval[10] τ_*.

The robot has a conscious focus on the present, but only access to the past through the records that are inputs to the unconscious computation of its schema. The robot can thus be said to "experience" the present and "remember" the past. The "flow of time" is the movement of information into the register of conscious focus and out again. Prediction

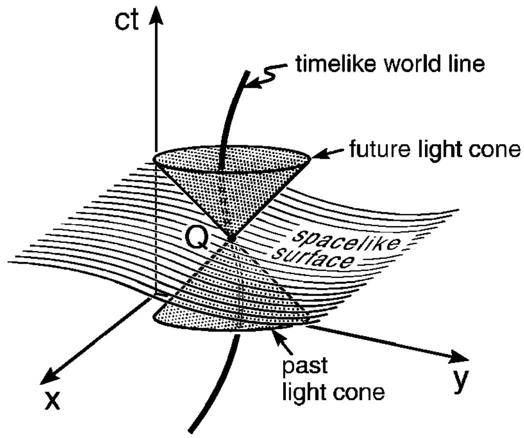

Fig. 2. This spacetime diagram represents a three-dimensional slice of a four-dimensional flat spacetime defined by three axes ct, x, and y of the four specifying an inertial (Lorentz) frame. The ideas of event, light cone, world line, and spacelike surface are illustrated. An event is a point in spacetime like Q. Each point has a future and past light cone. A spacelike surface like the one illustrated defines an instant in time. Each such surface divides spacetime into two regions conventionally called the future of this surface and its past. There are an infinity of such families and thus infinitely many different ways of defining instants in time and their futures and pasts. In the context of cosmology, the past of a spacelike surface is defined to be the region closest to the big bang and the future is the region furthest away.

requires computation—either conscious or unconscious—from memories of the present and past acquired by observation and is thus distinct from remembering.

The subjective past, present, and future, the flow of time, and the distinction between predicting and remembering are represented concretely and physically in the structure and function of the model robot. We now proceed to describe this structure and function in four-dimensional terms.

III. THE PRESENT IS NOT A MOMENT IN TIME

In the following, we describe the robot of Sec. II in the four-dimensional spacetime terms of special relativity.[11] For simplicity, we consider the flat spacetime of special relativity (Minkowski space). But with little change, it could be a curved spacetime of general relativity.

A. Some features of Minkowski space

We begin by recalling a few important features of four-dimensional spacetime that are illustrated in Fig. 2.[12] Events occur at points in spacetime. At each point Q, there is a light cone consisting of two parts. The future light cone is the three-dimensional surface generated by the light rays emerging from Q. The past light cone is similarly defined by the light rays converging on Q. (The labels ''future'' and ''past'' are conventions at this point in the discussion. In Sec. IV, we will define them in the cosmological context.) Points inside the light cone of Q are timelike separated from it; points outside the light cone are spacelike separated. Points inside the future light cone of Q are in its future; points inside the past light cone are in its past. Points outside the light cone are neither.

The center of mass of a localized IGUS, such as the robot of Sec. II, describes a timelike world line in spacetime. At each point along the world line, any tangent to it lies inside the light cone so that the IGUS is moving at less than the speed of light in any inertial frame.

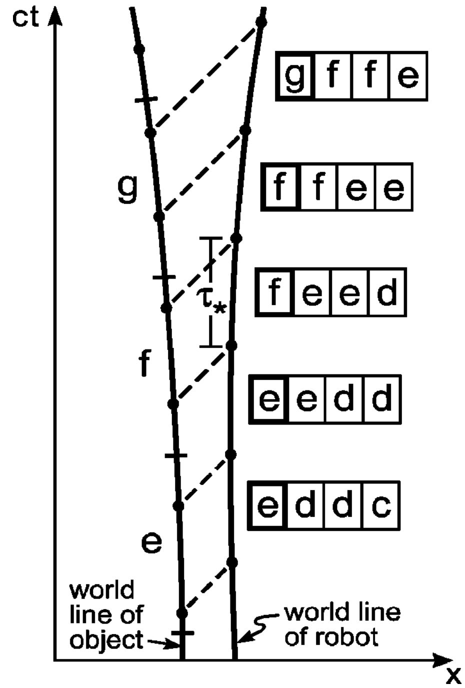

Fig. 3. A spacetime description of the present and past of the robot whose information processing is illustrated in Fig. 1. In addition to the world line of the robot, the figure shows the world line of an external object that is the source of its images such as the stack of cards in Fig. 1. This source changes its shape at discrete instants of time demarcated by ticks, running through configurations $\cdots b,c,d,e,f,g,\cdots$. The configuration in each time interval of the object's world line is labeled to its left. At discrete instants separated by proper time τ_*, the robot captures an image of the object. The light rays conveying the image from object to robot are indicated by dotted lines. The images are stored in the registers P_0, P_1, P_2, and P_3 described in Fig. 1. The contents of these registers in between image captures are displayed in the boxes with P_0 on the left and P_3 on the right. The history of the contents of the register P_0 constitute the four-dimensional notion of present or now for this robot (the heavily outlined boxes). The present is not one instant along the robot's world line, much less a spacelike surface in spacetime. Rather, there is a present for each instant along the robot's world line extending over proper time τ_*. In this way, the evolution of the contents P_0 can be described four dimensionally and is fully consistent with special relativity. In a similar way, the contents of P_1, P_2, and P_3 constitute a four-dimensional notion of past.

A moment in time is a three-dimensional spacelike surface in spacetime—one in which any two nearby points are spacelike separated. Each spacelike surface divides spacetime into two regions—one to its future and one to its past. A family of spacelike surfaces such that each point in spacetime lies on one and only member of the family specifies a division of spacetime into space and time. Surfaces defined by constant values of the time of a particular inertial frame are an example of such a family (for instance, the surfaces of constant ct in Figs. 2–4). Different families of spacelike surfaces define different notions of space and different notions of time, none of which is preferred over the other.

B. The past, present, and future of the robot

Figure 3 shows the world line of the robot introduced in Sec. II together with the world line of an object in its environment that appears in the robot's stored images. The robot illustrated has a short memory with only four registers, P_0, P_1, P_2, and P_3, whose contents in each interval τ_* are

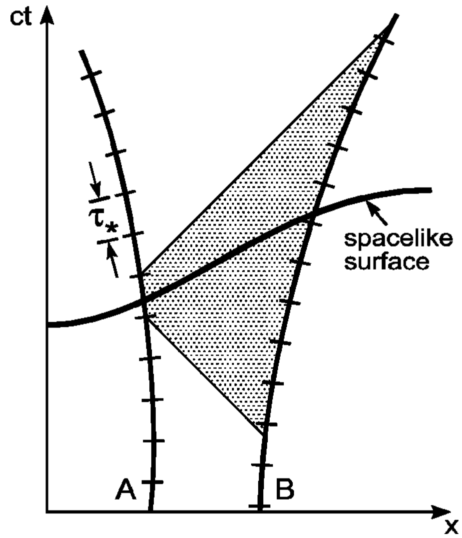

Fig. 4. This spacetime diagram shows the world lines of two similarly constructed robots *A* and *B*. The intervals of proper time of length τ_* over which the contents of the registers defining their individual presents are constant are demarcated by ticks. A common present would be defined by an identification of each interval on one world line with that on the other ''at the same time'' (to the accuracy τ_*). But special relativity allows many different such identifications. Using the constant *t* surfaces of the inertial frame illustrated is one way to define a common present; but any other spacelike surface such as the one shown would do equally well. The range of ambiguity for intervals on *B* that could be said to be ''at the same time'' as one interval on *A* is indicated by the shaded region. The figure shows two robots separated by a distance (for example, as defined in the rest frame of one) over which the light travel time is longer than τ_* In this situation, the ambiguity in the definition of a common present is much larger than τ_*. However, if the distance between the robots is much smaller than $c\tau_*$, and if their relative velocity is much less than *c* so this continues to be the case, then the ambiguity is much smaller than τ_*. An approximate common present can then be defined.

indicated by the content of the boxes to the right of the world line. These contents change at proper time intervals τ_* as described in Sec. II.

The contents of the register P_0 defining the robot's present do not define a spacelike surface representing a moment in time. They do not even define an instant along the robot's world line because the contents of P_0 are constant over proper time intervals τ_*. Rather, there is content defining the present for *every* instant along the world line. For each point along the world line, the most recently acquired image defines the present. That is the four-dimensional description of the present. In a similar way, the data acquired earlier and stored in registers P_1, P_2, and P_3 define the robot's past for each point along the world line.

Thus, there is no conflict between the four-dimensional reality of physics and the subjective past, present, and future of an IGUS. Indeed, as defined above, the subjective past, present, and future *are* four-dimensional notions. They are not properties of spacetime but of the history of a particular IGUS. In Sec. V, we will see that IGUSs constructed differently from our robot could have different notions of past, present, and future. All of these are fully consistent with a four-dimensional physical reality.

However, there is a conflict between ordinary language and the four-dimensional, IGUS—specific notions of past, present, and future. To speak of the ''present moment'' of an IGUS, for instance, risks confusion because it could be construed to refer to a spacelike surface in spacetime stretching over the whole universe. No such surface is defined by physics.[13] In fact, the ''moment'' in the context of this section refers to the most recently acquired data of an IGUS. This is not a notion restricted to one point on the IGUS's world line which somehow moves along it. Rather is a notion present at *every* point along the world line.

C. The common present

The previous discussion has concerned the present, past, and future of individual localized IGUSs. We now turn to the notion of a common present that may be held by collections of IGUSs separated in space.

When someone asked Yogi Berra what time it was, he is reported to have replied ''Do you mean now?'' [14] The laughter usually evoked by this anecdote shows how strongly we hold a common notion of the present. More precisely, different IGUSs agree on ''what is happening now.'' This section is concerned with the limitations on the accuracy of this agreement that arise both from the construction of the IGUSs and the limitations of defining simultaneity in special relativity. We continue to use robot model IGUSs to make the discussion concrete.

Figure 4 shows the world lines of two robots in spacetime together with the intervals on their world lines that define their individual notions of now. There are at least two reasons that there is no unambiguous notion of a common now that can be shared by the two robots. The first is the elementary observation[15] that the present for each individual robot is not defined to an accuracy better than τ_*. The second reason arises from special relativity.

A precise common now would specify a correspondence between events on the two world lines. Such a correspondence would specify a notion of simultaneity between events on the world lines. But there is no unique notion of simultaneity provided by special relativity. Rather, there are many different notions corresponding to the different possible spacelike surfaces that can intersect the two world lines. Figure 4 illustrates the range of ambiguity.

To illustrate the ambiguity of the present more dramatically, imagine you are a newscaster on the capital planet Trantor of a galaxy-wide empire some hundreds of thousands of years in the future. News of events from all over the galaxy pour in constantly via electromagnetic signals. You want to broadcast a program called ''The Galaxy Today'' reviewing important events in the last 24 hours (galactic standard). But what time do you assign to the latest news from the planet Terminus at the edge of the galaxy 60 000 light years away? There is an inertial frame[16] in which those events happened within the last 24 hours. But in the approximate rest frame of the galaxy, they happened 60 000 years ago. There is thus no unambiguous notion of present for the collective IGUSs consisting of the citizens of the galactic empire, because the ambiguities in defining simultaneity are large compared to the time scales on which human events happen. You could, of course, fix on the time of the galactic rest frame as a standard for simultaneity. But in that case, the only comprehensive program you could broadcast would be ''The Galaxy 60 000 Years Ago.'' One imagines the audience for this on Terminus would not be large because the program would be seen 120 000 years after the events there happened.

The satellites comprising the global positioning system are an example of a collective IGUS closer to home that faces a similar problem. The special relativistic ambiguity in defining simultaneity for two satellites is the order of the light travel time between them in the approximate inertial frame in which the Earth is at rest. That is much larger than the light travel time across the few meters accuracy to which the system is designed to locate events. Precise agreement on a definition of simultaneity is therefore needed. Each satellite clock is corrected so that it broadcasts the time of a clock on the Earth's geoid (approximately, the ocean surface).[17]

No such agreement on a definition of simultaneity appears to be a prerequisite for the everyday notion of now employed by human IGUSs. Rather, we seem to be employing an approximate imprecise notion of the common present appropriate in everyday situations and characterized by the following contingencies:

(1) The time scale of perception τ_* is short compared to the time scales on which interesting features of the environment vary.
(2) Individual IGUSs are moving relative to one another at velocities small compared to c.
(3) The light travel time between IGUSs in an inertial frame in which they are nearly at rest is small compared to the time scales τ_*.

Contingency (1) means that the ambiguity in the now of each IGUS is negligible in the construction of a common present. Contingency (3), based on (2), means that the ambiguity arising from the definition of simultaneity is negligible.[18]

Collections of robots satisfying contingencies (1)–(3) can agree on what is happening now. Consider just two robots—Alice and Bob. Alice can send Bob a description of the essential features of the image currently in her register P_0. Bob can check whether these essential features are the same as those of the image in his register P_0 at the time of receipt. He can then signal back agreement or disagreement. As long as the light travel time is much shorter than τ_* [contingency (3)], and as long as the essential features vary on much longer time scales [contingency (1)], Alice and Bob will agree. Contingency (2) ensures that this agreement will persist over an interesting time scale. Thus, Alice and Bob can construct a common present, but it is a present that is local, inherently approximate, and contingent on their relation to each other and their environment. This approximate common now is not a surface in spacetime.

No modification of the laws of physics is needed to understand the common now of a group of IGUSs as has sometimes been suggested.[19] The common nows of IGUSs meeting the above contingencies will coincide approximately with constant time surfaces in any inertial frame in which they are approximately at rest. But these frames are not singled out by the laws of physics. Indeed, the experimental evidence against preferred frames in special relativity is extraordinarily good.[13] Rather the frames are singled out by the particular situations of the IGUSs themselves.

IV. WHY DON'T WE REMEMBER THE FUTURE?

The fundamental dynamical laws of physics are invariant under time reversal to an accuracy adequate for organizing everyday experience.[20] They are *time neutral*. The Einstein equation of general relativity and Maxwell's equations for electrodynamics are examples. But the boundary conditions specifying solutions to these equations describing our universe are not time symmetric. The universe has a smooth (nearly homogeneous and isotropic) big bang at one end of time and a very different condition at the other end. This other end might be the unending expansion driven by a cosmological constant of the simplest cosmological models favored by observation.[21] Or with different assumptions, it could be a highly irregular big crunch. In any event, one end is different from the other.[22]

By convention, this paper refers throughout to the times closer to the big bang as the "past" and times further away as the "future." Asymmetry between past and future boundary conditions is the origin of the various time asymmetries—arrows of time—exhibited by our universe. The arrow of time associated with the second law of thermodynamics is an example.[26]

The operation of Sec. II's robot is not time neutral in at least two respects. First, the robot receives information about external events in its past (closer to the big bang) and not the future.[31] Second, its processing of the received information is not time neutral. The flow of information from recording to erasure defines a direction in time. As mentioned in Sec. II, that direction gives a concrete model for the subjective feeling of inexorable forward progression in time commonly called the "psychological arrow of time." In natural IGUSs, such as ourselves, information flows from past to future. More specifically, the records in registers $P_1, \cdots, P_n$ are of external events to the past of those in P_0 in decreasing order of time from the big bang. This is the reason that Sec. II's robot could be said to experience the present, remember the past, and predict the future.[32]

Could a robot be constructed that receives information from the future? Could one be constructed whose psychological arrow of time runs from future to past with the consequence that it would remember the future? Both of these possibilities are consistent with time neutral dynamical laws. But two familiar time asymmetries of our universe prohibit such constructions as a practical matter. These are the radiation arrow of time and the arrow of time associated with the second law of thermodynamics.

Records of the future are possible as in a table of future lunar eclipses.[33] Indeed, records of the future are the outcome of any useful process of prediction. But, our robot's records of the future are obtained by computation, whereas its records of the past are created by simple, automatic, sensory mechanisms. These are very different processes, both physically and from the point of view of information processing by the robot.[34] By a robot that remembers the future, we mean one constructed[35] as in Sec. II with the records in registers $P_1, \cdots, P_n$ of events to the future of P_0.

First consider the question of whether information from the future could be recorded by the robot. In our universe, electromagnetic radiation is retarded—propagating to the future of its emission event. That time asymmetry is the radiation arrow of time. The electromagnetic signals recorded by the robot propagated to it along the past light cone of the reception event. The images received by the robot, whether of the cosmic background radiation, distant stars and galaxies, or the happenings in its immediate environment, are therefore all from past events. As far as we know, all other carriers, neutrinos for example,[36] are similarly retarded. One reason the robot does not remember the future is that it receives no information about it.

Irrespective of the time its input originates, could a robot like that in Sec. II be constructed whose psychological arrow of time is reversed, so that internally information flows from future to past? In such a robot, the events recorded in registers $P_1, \cdots, P_n$ would lie to the future of that in P_0—further from the big bang. The robot would thus remember the future. Such a construction would run counter to the arrow of time specified by the second law of thermodynamics as we now review.[37]

All isolated subsystems of the universe evolve toward equilibrium. But the preponderance of isolated systems in our universe are evolving toward equilibrium from past to future, defining an arrow of time. That is the second law of thermodynamics that is expressed quantitatively by the inexorable increase of an appropriately defined total entropy.

If the robot processes information irreversibly, then its psychological arrow of time must generally be congruent with the thermodynamic arrow of time. The formation of records are crucial steps. An increase in total entropy accompanies the formation of many realistic records. An impact crater on the moon, an ancient fission track in mica, a darkened photographic grain, or the absorption of a photon by the retina are all examples.

But an increase in total entropy is not a necessary consequence of forming a record. Entropy increase is necessary only for the erasure of a record.[39] For the model robot discussed in Sec. II, the only part of its operation in which entropy must necessarily increase is in the erasure of the contents of the register P_n at each step.[40] However, that is enough. To see that, imagine the process of erasure run backward from future to past. It would be like bits of smashed shell reassembling to form an egg.

To construct a robot with a reversed psychological arrow of time, it would be necessary to reverse the thermodynamic arrow, not only of the robot, but also of the local environment it is observing. That is possible in principle. However, because we have a system of matter coupled to electromagnetic radiation, it would be necessary to deal with every molecule and photon within a radius of 2×10^{10} km to reverse the system for a day. More advanced civilizations may find this amusing. We can have the same fun more cheaply by running the film through the projector in reverse.

The origin of both the thermodynamic and radiation arrows of time are the time-asymmetric boundary conditions that single out our universe from the many allowed by time-reversible dynamical laws. These boundary conditions connect the two arrows. A brief sketch of the relevant physics is given in the Appendix, although it is not necessary for understanding the main argument of this paper. But it is interesting to think that our subjective distinction between future and past can ultimately be traced to the cosmological boundary conditions that distinguish the future and past of the universe.

V. ALTERNATIVES TO PAST, PRESENT, AND FUTURE

The preceding discussion suggests that the laws of physics do not define unambiguous notions of past, present, and future by themselves. Rather, these are features of how specific IGUSs gather and utilize information. What then is the origin of the past, present, and future organization of information in familiar, naturally occurring IGUSs? Is it the only organization compatible with the laws of physics? If not, does it arise uniquely from evolutionary imperatives, or is it a frozen accident that took place in the course of three billion years of biological evolution? This section discusses such questions.

Certainly some features of the laws of physics are essential prerequisites to the functioning of the robot discussed in Sec. II. There would be no past, present, and future at all if spacetime did not have timelike directions. The fact that IGUSs move on timelike rather than spacelike world lines is the main part of the reason they can have an approximate common now rather than an approximate common "here." An IGUS functioning in a spacetime where it moved along a closed timelike curve could not maintain a consistent notion of past and future. Likewise, a local distinction between past and future would be difficult to maintain in the absence of the arrows of time discussed in Sec. II. But the features of the physical laws of dynamics and the initial condition of the universe that are necessary for a past, present, and future organization of temporal information are consistent with other organizations of this information as we now show.

A. Different organizations of temporal information

Perhaps the easiest way of convincing oneself that the notions of past, present, and future do not follow from the laws of physics is to imagine constructing robots that process information differently from the one described in Sec. II. We consider just three examples:

(1) *The Split Screen (SS) Robot*. This robot has input to C computation from both the most recently acquired data in P_0 and from that in a different register P_J that was acquired a proper time $\tau_s \equiv J\tau_*$ earlier along its world line. There is thus input to conscious computation from *two* times.

(2) *The Always Behind (AB) Robot*. This robot has input to C computation only from a particular register $P_K, K > 0$, and the schema. That input is thus always a proper time $\tau_d \equiv K\tau_*$ *behind* the most recently acquired data.

(3) *The No Schema (NS) Robot*. This robot has input to C computation from all the registers $P_0, \cdots, P_n$ equally. It employs no unconscious computation and constructs no schema, but rather makes decisions by conscious computation from all the data it has.

There seems to be no obstacle to constructing robots wired up in these ways, and they process information differently from the present, past, and future organization with which we are familiar.[41]

An *SS* robot would have a tripartite division of recorded information. Its present experience, its now, would consist of two times (P_0, P_J), equally vivid and immediate. It would remember the intermediate times $(P_1, \cdots, P_{J-1})$, and the past $(P_{J+1}, \cdots, P_n)$ through the U process of computation and its influence on the schema.

The *AB* robot also would have a tripartite division of recorded information. Its present experience would be the contents of the the register P_K. It would remember the past stored in registers $P_{K+1}, \cdots, P_n$. But also it would remember its future stored $P_0, \cdots, P_{K-1}$ a time τ_d ahead of its present experience.[42] (Or perhaps we should say that it would have premonitions of the future.)

What would discussions with an *AB* robot be like assuming that our information processing is similar to the robot discussed in Sec. II? Assume for simplicity that we and the *AB* robot are both nearly at rest in one inertial frame and that contingencies (1)–(3) of Sec. III C are satisfied. The *AB* robot would seem a little slow—responding in a time τ_d or longer to questions. Its answers to queries about "What's happening now?" would seem out of date. It would always be behind.

The *NS* robot would just have one category of recorded information. Conversations with an *NS* robot would be impressive because it would recall every detail it has recorded about the past as immediately and vividly as the present.[43]

The laws of physics supply no obstacle of principle to the construction of robots with exotic organizations of information processing such as the *SS*, *AB*, and *NS* robots. But are such organizations a likely outcome of biological evolution? Can we expect to find such IGUSs in nature on this or other planets? We speculate that we will not. It is adaptive for an IGUS of everyday size to focus mainly on the most recently acquired data as input to making decisions. The effective low-energy laws of physics in our universe are local in spacetime and the nearest data in space and time is usually the most relevant for what happens next. A frog predicting the future position of a fly needs the present position and velocity of the fly, not its location 10 s ago. An *AB* frog would be at a great competitive disadvantage by not focusing on the most current information. An *SS* frog would be wasting precious conscious focus on data from the past that is less relevant for immediate prediction than current data.

An *NS* robot would make inefficient use of computing resources by giving equal focus to present data and data from the past whose details may not effect relevant future prediction. Employing a schema to process the data is plausibly adaptive because it is a more efficient and faster way of processing relevant data with limited computing resources. The collective IGUS linked by human culture certainly evolved to make use of schema rather than focus on the individual records that went into them. For instance, prediction of the future of the universe is much simpler from a Friedman–Robertson–Walker model characterized by a few cosmological parameters than directly from the records of the measurements that determined them.[5]

B. Different laws, different scales

Something like the *SS* organization of temporal information might be favored by evolution if the effective laws of physics on accessible scales were not local in time. Suppose, for instance, that the positions of objects to the future of a time t depended,[44] not just on the forces acting and their positions and velocities at that time, but rather on their positions at time t and on earlier times $t-h$ and $t-2h$ for some fundamental fixed time interval h. Then, an organization such as the *SS* robot with conscious focus on both the most recently acquired data and that acquired at times h and $2h$ ago might be favored by evolution.

Similarly different organizations might evolve if the IGUS is not smaller than the scale over which light travels on the characteristic times of relevant change in its environment. The present, past, and future organization is unlikely to serve such an IGUS well because these notions are not well defined in these situations, as was discussed in Sec. III C. As mentioned there, the galactic empires beloved of science fiction would be examples of such IGUSs. Faster-than-light travel inconsistent with special relativity often is posited by authors whose stories feature these empires to make their narratives accessible to IGUSs, like ourselves, that do employ—however, approximately—a present, past, and future organization of information.

VI. CONCLUSION

A subjective past, present, and future are not the only conceivable way an IGUS can organize temporal data in a four-dimensional physical world consistently with the known laws of physics. But it is a way that may be adaptive for localized IGUSs governed by local physical laws. We can conjecture that a subjective past, present, and future is a cognitive universal[6] of such localized IGUSs. That is a statement accessible to observational test, at least in principle.

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APPENDIX A: THE COSMOLOGICAL ORIGIN OF TIME'S ARROWS

The origin of our universe's time asymmetries is not to be found in the fundamental dynamical laws which are essentially time reversible. Rather, both the radiation and the thermodynamic arrows of time arise from special properties of the initial condition of our universe.[45] This appendix gives a simplified discussion of these special features starting, not at the very beginning, but at the time the hot initial plasma had become cool enough to be transparent to electromagnetic radiation. This is the time of "decoupling" in cosmological parlance—about 400 000 years after the big bang or a little over 13 billion years ago.

As Boltzmann put it over a century ago: "The second law of thermodynamics can be proved from the [time-reversible] mechanical theory if one assumes that the present state of the universe... started to evolve from an improbable [special] state."[46] The entropy of matter and radiation usually defined in physics and chemistry is about 10^{80} in the region visible from today at the time of decoupling (in units of Boltzmann's constant). This seems high, but it is in fact vastly smaller than the maximal value of about 10^{120} if all that matter were dumped into a black hole.[28] The entropy of the matter early in the universe is high because most constituents are in approximate thermal equilibrium. However, the gravitational contribution of the smooth early universe to the entropy is near minimal, and entropy can grow by the clumping of the matter arising from gravitational attraction leading to the galaxies, stars, and other inhomogeneities in the universe we see today.

Amplifying Boltzmann's statement, the explanation of why the entropies of isolated subsystems are mostly increasing in the same direction of time is this: The progenitors of these isolated systems were all further out of equilibrium at times closer to the big bang (the past) than they are today. Earlier, the total entropy was low compared to what it could have been. Therefore, it has tended to increase since.

The radiation arrow of time also can be understood as arising from time asymmetric cosmological boundary conditions applied to time-reversible dynamical laws. These are Maxwell's equations for the electromagnetic field in the presence of charged sources. Their time reversal invariance implies that any solution for specified sources at a moment of time can be written in either of two ways: (R) a sum of a free field (no sources) coming from the past plus retarded fields whose sources are charges in the past, or (A) a sum of a free field coming from the future plus advanced fields whose sources are charges in the future. More quantitatively, the four-vector potential $A_\mu(x)$ at a point x in spacetime can be expressed in the presence of four-current sources $j_\mu(x)$ in Lorentz gauge as either

$$A_\mu(x)=A_\mu^{\rm in}(x)+\int d^4x' D_{\rm ret}(x-x') j_\mu(x') \quad (R), \quad \text{(A1)}$$

or

$$A_\mu(x)=A_\mu^{\rm out}(x)+\int d^4x' D_{\rm adv}(x-x') j_\mu(x') \quad (A). \quad \text{(A2)}$$

Here, $D_{\rm ret}$ and $D_{\rm adv}$ are the retarded and advanced Green's functions for the wave equation and $A_\mu^{\rm in}(x)$ and $A_\mu^{\rm out}(x)$ are free fields defined by these decompositions.

Suppose there were no free electromagnetic fields in the distant past so that $A_\mu^{\rm in}(x)\approx 0$. If we use the R description, this time asymmetric boundary condition would imply that present fields can be entirely ascribed to sources in the past. Fields are thus retarded and that retardation is the electromagnetic arrow of time.

This explanation needs to be refined for our universe because, at least if we start at decoupling, there is a significant amount of free electromagnetic radiation in the early universe constituting the cosmic background radiation (CMB). Indeed, at the time of decoupling the energy density in this radiation was approximately equal to that of matter. Even today, approximately 13 billion years later, after being cooled and diluted by the expansion of the universe, the CMB is still the largest contributor to the electromagnetic energy density in the universe by far.

The CMB's spectrum is very well fit by a black-body law.[47] That strongly suggests that the radiation is disordered with maximal entropy for its energy density. There is no evidence for the kind of correlations (sometimes called "conspiracies") that would tend to cancel $A_\mu^{\rm out}(x)$ in the far future and give rise to advanced rather than retarded effects.[48]

The expansion of the universe has redshifted the peak luminosity of the CMB at decoupling to microwave wavelengths today. Thus, there is a negligible amount of energy left over from the big bang in the wavelengths we use for vision, for instance. The radiation used by realistic IGUSs is therefore retarded. A contemporary robot functioning at wavelengths where the CMB is absent will therefore be receiving information about charges in the past. This selection of wavelengths is plausibly not accidental but adaptive. A contemporary robot seeking to function with input from microwave wavelengths would find little emission of interest, and what there was would be overwhelmed by the all-pervasive CMB, nearly equally bright in all directions, and carrying no useful information.

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[1]M. Gell-Mann, *The Quark and the Jaguar* (Freeman, San Francisco, 1994).

[2]See, for example, J. Butterfield, *The Arguments of Time* (British Academy and Oxford University Press, Oxford, 1993) for a collection of philosophical papers on time. This paper does not aim to discuss or resolve any of the philosophical debates on the nature of time.

[3]Arrows of time in the context of quantum mechanics, as well as the quantum mechanical arrow of time, are discussed in Ref. 4 in the framework of a time-neutral generalized formulation of quantum theory. The author knows of no obstacle of principle to extending the present classical discussion to quantum mechanics in that framework. For the special features of history in quantum mechanics, see, for example, Ref. 5.

[4]M. Gell-Mann and J. B. Hartle, "Time symmetry and asymmetry in quantum mechanics and quantum cosmology," in *The Physical Origins of Time Asymmetry*, edited by J. Halliwell, J. Pérez-Mercader, and W. Zurek (Cambridge University Press, Cambridge, UK, 1994); gr-qc/9309012.

[5]J. B. Hartle, "Quantum pasts and the utility of history," Phys. Scr., T **76**, 67–77 (1998); gr-qc/9712001.

[6]R. N. Shepard, "Perceptual-cognitive universals as reflections of the world," Psychonomic Bulletin & Review **1**, 2–28 (1994); "How a cognitive scientist came to seek universal laws," *ibid.* **11**, 1–23 (2004).

[7]A history book is a familiar part of the schema of the collective IGUS linked by human culture. It is a summary and analysis of records gathered at diverse times and places. That is true whether the history is of human actions or the scientific history of the universe. The schema resulting from the reconstruction of present records simplifies the process of future prediction. For more on the utility of history, see Ref. 5.

[8]For the moment we take the records $P_1, \cdots, P_n$ to define the past. Section IV will connect this notion of past with other physical notions of "past," for instance that defined by the the time direction toward the big bang.

[9]As James put it more eloquently: "...the practically cognized present is no knife-edge, but a saddleback, with a certain breadth of its own, on which we sit perched, and from which we look in two directions in time." See, W. James, *Principles of Psychology* (Holt, New York, 1890).

[10]For human IGUSs the time τ_* can be taken to be of order the 0.1 s separation time needed to discriminate between two visual signals. See, for example, G. Westheimer, "Discrimination of short time intervals by the human observer," Exp. Brain Res. **129**, 121–126 (2000); G. Westheimer, "Visual signals used in time interval discrimination," Visual Neuroscience **17**, 551–556 (2000).

[11]An abbreviated version of this discussion was given in Ref. 5.

[12]For a classic text on special relativity from a spacetime point of view, see E. F. Taylor and J. A. Wheeler, *Spacetime Physics* (Freeman, San Francisco, 1963).

[13]There is no evidence for preferred frames in spacetime and modern versions of the Michelson–Morley experiment and other tests of special relativity set stringent limits on their existence. The fractional accuracy of these experiments range down to 10^{-21} making Lorentz invariance at accessible energy scales one of the most accurately tested principles in physics. See for example, M. P. Haugan and C. M. Will, "Modern tests of special relativity," Phys. Today **40**(5), 69–76 (1987) or C. M. Will, "The confrontation between general relativity and experiment," Living Rev. Relativ. **4**, (2001), ⟨http://www.livingreviews.org/lrr-2001-4⟩. For a modern version of the Michelson–Morley experiment see, in particular, A. Brillet and J. L. Hall, "Improved laser test of the isotropy of space," Phys. Rev. Lett. **42**, 549–552 (1979).

[14]Lawrence E. Berra was a catcher for the New York Yankees baseball team in the 1950s. See Y. Berra, *The Yogi Book* (Workman Publishing, New York, 1998).

[15]The ambiguity in the common present arising from the finite time of IGUS operation has been discussed by C. Callender (unpublished) including a review of current neurophysiological data bearing on this question.

[16]For example, there is the inertial frame moving with speed V with respect to the galactic rest frame such that $\Delta t' = \gamma[\Delta t - V(\Delta x/c)]$, where $\gamma = (1-V^2)^{-1/2}$, $\Delta t' = 24$ h, $\Delta t = 6\times 10^4$ year, and $\Delta x = 6\times 10^4$ light years. The required velocity is within a few parts in 10^7 of the velocity of light.

[17]See, for example, N. Ashby, ''Relativity and the global positioning system,'' Phys. Today **55**, 41–47 (2002).

[18]These kinds of contingencies and the synchronization protocols necessary when they are violated have been discussed by J. Butterfield, ''Seeing the present,'' Mind **93**, 161–176 (1984). Reprinted in *Questions of Time and Tense*, edited by R. Le Poidevin (Oxford University Press, Oxford, 1998).

[19]See, for example, the preface to F. Hoyle and G. Hoyle, *The Fifth Planet* (Harper and Row, New York, 1963).

[20]The effective theory of the weak interactions applicable well below the Planck scale is not time-reversal invariant. This lack of invariance is important, for instance, for the synthesis of baryons in the early universe but negligible for the functioning of our robot. See, for example, Ref. 4 for further discussion.

[21]See for example, D. N. Spergel *et al.*, ''First year Wilkinson microwave anisotropy probe (WMAP) observations: Determination of cosmological parameters,'' Ap. J. Suppl. **148**, 175–194 (2003); J. L. Tonry *et al.*, ''Cosmological results from high-z supernovae,'' Ap. J. **594**, 1–24 (2003).

[22]We thus exclude, mainly for simplicity, the kind of cosmological model where initial and final conditions are related by time symmetry that have sometimes been discussed. See for example, Refs. 4 and 23–25.

[23]R. Laflamme, ''Time-symmetric quantum cosmology and our universe,'' Class. Quantum Grav. **10**, L79 (1993), gr-qc/9301005.

[24]D. Craig, ''Observation of the final condition: Extragalactic background radiation and the time symmetry of the universe,'' Ann. Phys. (N.Y.) **251**, 384 (1995), gr-qc/9704031.

[25]H. Price, *Time's Arrow and Archimedes' Point* (Oxford University Press, Oxford, 1996).

[26]For reviews of the physics of time asymmetry from various perspectives, see Refs. 4, 27, 28, 29, 30, and 25. There is also some discussion in the Appendix. These are only a few of the references where these issues are treated.

[27]P. C. W. Davies, *The Physics of Time Asymmetry* (University of California Press, Berkeley, 1976).

[28]R. Penrose, ''Singularities and time asymmetry,'' in *General Relativity: An Einstein Centenary Survey*, edited by S. W. Hawking and W. Israel (Cambridge University Press, Cambridge, UK, 1979).

[29]H. D. Zeh, *The Physical Basis of the Direction of Time* (Springer, Berlin, 1989).

[30]H. Reichenbach, *The Direction of Time* (University of California Press, Berkeley, 1956).

[31]More precisely, registered signals originate from events within the past light cone of their reception event. We use ''future'' and ''past'' in the present discussion understanding that in each case these are defined by an appropriate light cone as described in Sec. III A.

[32]In Sec. II, we defined the robot's past to be the records in the registers $P_1, \ldots, P_n$. If information flows from past to future in the robot, that notion coincides with the physical past defined as the direction in time towards the big bang. From now on, we assume this congruence except where discussing its possible violation, as in this section.

[33]We use the term ''record'' in a time-neutral sense of an alternative at one time correlated with high probability with an alternative at another time—future or past. Thus, there can be records of the future.

[34]Realistic IGUSs, such as human beings, also create records of the past by computation as in differing interpretations of past experience, and as in the collective construction of human history, and the history of the universe. However, we did not explicitly endow our robot with these functions.

[35]In Sec. V, we will describe a different construction of a robot which could be said to remember the future.

[36]See for example, K. Hirata *et al.*, ''Observations of a neutrino burst from the Supernova SN1987A,'' Phys. Rev. Lett. **58**, 1490–1493 (1987).

[37]Many other authors have connected the ''psychological'' arrow of time with that of the second law. See, for example, Refs. 28, 30, and 38.

[38]S. W. Hawking, ''The direction of time,'' New Sci. **115**, 46–49 (1987).

[39]R. Landauer, ''Irreversibility and heat generation in the computing process,'' IBM J. Res. Dev. **5**, 183–191 (1961).

[40]Possibly an isolated robot could be constructed on the principles of reversible computation that would not have an erasure step. However, it seems unlikely that the whole system of robot plus a realistic observed environment could be reversible. See for example, C. Bennett, ''Logical reversibility of computation,'' IBM J. Res. Dev. **17**, 525–532 (1973); E. Fredkin and T. Toffoli, ''Conservative logic,'' Int. J. Theor. Phys. **21**, 219–253 (1982).

[41]Some idea of what the notion of ''present'' would be like for some of these robots could be had by serving time in a virtual reality suit in which the data displayed was delayed as in the AB case, or in which there was an actual split screen as in the SS case. An alternative realization of the SS robot's experience might be produced by electrical stimulation of the cortex that evokes memories of the past which are comparably immediate to the present. See, W. Penfield and L. Roberts, *Speech and Brain Mechanisms* (Princeton University Press, Princeton, N.J., 1959).

[42]That is not in conflict with the discussion in Sec. IV because each record is still of events in the past to the proper time it was recorded.

[43]Perhaps not unlike conversations with Ireneo Funes in the story, ''Funes, the Memorious,'' J. L. Borges, *Ficciones* (Grove Press, New York, 1962).

[44]It is not difficult to write down dynamical difference equations with this property. For instance in a one-dimensional model, we could take $F(t) = m[x(t)-2x(t-h)+x(t-2h)]/2h^2$, where $x(t)$ is the body's position, m its mass, and $F(t)$ the force. However, such equations are not consistent with special relativity and the author is not suggesting a serious investigation of alternatives to Newtonian mechanics.

[45]For example, Hawking's ''no boundary'' wave function of the universe. See S. W. Hawking, ''The quantum state of the universe,'' Nucl. Phys. B **239**, 257–276 (1984).

[46]L. Boltzmann, ''Zu Hrn. Zermelo's Abhandlung Über die mechanische Erklärung irreversibler Vorgange,'' Ann. Phys. (Leipzig) **60**, 392–398 (1897), as translated in S. G. Brush, *Kinetic Theory* (Pergamon, New York, 1965).

[47]D. J. Fixsen *et al.* ''The cosmic microwave background spectrum from the full COBE FIRAS data set,'' Ap. J. **473**, 576–587 (1996).

[48]For an experiment that checked on advanced effects see R. B. Partridge, ''Absorber theory of radiation and the future of the universe,'' Nature (London) **244**, 263–265 (1973).