Why Does Time "Flow" but Space Is? Answers in Evolution and Cognition

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Abstract

In physics, the following puzzle exists: there appears to be a physical device, the human brain, which manages to detect properties absent from the formulas of physics; namely, the one-way direction of time and its "flowing" quality. So, either (a) these two properties are physical and physics is an incomplete theory, or (b) they are cognitive (reducible to quantum physics after several levels of reduction, i.e., the neurobiological and chemical levels) and physics is complete as far as our knowledge of time is concerned. This essay claims that (b) is true: both the directionality and the flowing quality of time emerged as evolutionary adaptations in cognitively complex animal species. The main contribution of this essay is to explain *why* these adaptations emerged in such species, and thus to help disengage discussions on the directionality and flowing quality of time from physics proper.

Illusions We Live by

Let us start with a factual observation: the speeds of objects in our terrestrial environment are extremely slow with respect to c, the speed of light. A consequence of this is that we fail to perceive the world with its relativistic geometry and physics (as it really is). Instead, we perceive it as having a Euclidean geometry and obeying Galilean-Newtonian physics — let us call this "the EGN worldview". An example will help explain why the EGN worldview emerged as the best solution for biological organisms with speeds $<< c$.

Suppose I run with speed v_1 and throw (while running) a stone with speed v_2 relative to me. Then our Newtonian physics says that the overall speed v of the stone relative to the ground will be the sum of the two speeds: $v = v_1 + v_2$. But, *in reality,* the world is not EGN, but relativistic, so the speed v of the stone is not the simple sum of the component speeds, but the slightly more complex $v = (v_1 + v_2) / (1 + v_1 \cdot v_2/c^2)$. However, because the speeds v_1 and v_2 are too small compared to c, the factor $v_1 \cdot v_2/c^2$ is negligible. As a result, the estimate $v_1 + v_2$ is *excellent* as an approximation of the real speed v.

Of course, the previous discussion does not mean to suggest that our prehistoric ancestors computed speed sums, such as $v_1 + v_2$, while throwing stones. But they had a rough idea of how hard the stone would hit its target if thrown while in motion. This rough idea is "good enough" for solving problems of survival, rendering the relativistic solution a luxury, a needlessly accurate solution for a problem that can be adequately solved otherwise. So, our EGN worldview causes us the *illusion* that speeds add up as $v_1 + v_2$.

• Similarly, our EGN worldview causes the *illusion* that the sum of the angles of a triangle is always 2π, whereas in reality (if the triangle is moving relative to the observer, or if it is within a gravitational field) the sum can be less than 2π.

• We have the *illusion* that exactly one straight line parallel to a given one can be drawn passing through a point outside of the given straight line (a version of the 5th Euclidean postulate), but in reality an infinity of such lines can be drawn (in a gravitational field).

- We have the *illusion* that mass is so very different from energy, whereas in reality the two are exchangeable, related by the formula $E = m \cdot c^2$.

- We have the *illusion* that space is so very different from time, whereas in reality the two are exchangeable, related by the formula $s = c \cdot t$.

- Last, but not least, we have the *illusion* that our clocks tick in synchrony, whereas in reality they can go out of synch, if we only move relative to each other.

Living in an environment with speeds << *c*, animals evolved with the EGN worldview. Simply, perceiving the world relativistically would confer to them no significant evolutionary advantage.

Now, an EGN worldview implies the perception of four dimensions: three for space and one for time. But why do we perceive three of the dimensions as so much different from the fourth one? Why can we move about in any direction in space, but we can't do so in time? Why do we attach some extra properties to the fourth dimension, such as that it "flows", and in one direction only? Before answering these questions, we must first note a large-scale property of time that is objectively missing from space.

Large-scale (Macroworld) Temporal Asymmetry: a Purely Mathematical Result

Although the laws of physics do not distinguish between past and future, that is, they are *symmetric* with respect to time, we know plenty of events in which we can distinguish between the "before" and the "after". For example, if an ice cube melts, we know it was solid *earlier,* and turned to liquid *later*. Today physicists agree that the laws of physics describe a world *locally symmetric* with respect to time (nearly always [4, p. 495]), which means that if we look at a movie showing quantum particles interacting, we have no way of knowing whether the movie is run in the forward or backward direction. But the large-scale temporal asymmetry of the macroworld is a result of the Second Law of Thermodynamics (2ndLoT), which states that, over time, matter disperses in space. What is not made clear often is what *causes* the 2ndLoT.
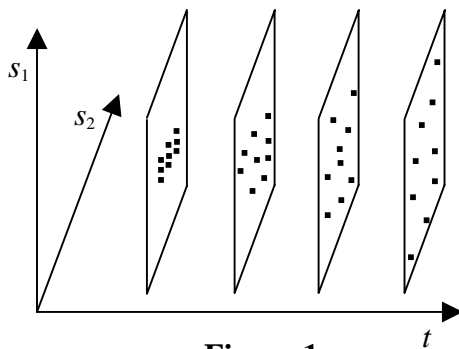

Figure 1

The full justification of the 2ndLoT is beyond the scope of this essay. However, a mathematical derivation of it has been presented in [2], where it is proven that a set of particles that are set free to perform *random walks* will disperse in space over time (see Fig. 1), and thus give rise to the 2ndLoT. In the proof, the average speed of such particles is computed under certain assumptions, and is found to be equal to $\sqrt{t}$ (where *t* is the elapsed time), a result that agrees with Einstein's 1906 paper on Brownian motion. [1]

But there is an easier way to see why the 2ndLoT holds, which doesn't use much math. In Fig. 2, point p is one of the dots of Fig. 1, and the s_1s_2-plane is one of the four planes shown in Fig. 1. Suppose p started at the origin O, and is now about to jump a distance r in space, in a random direction. Therefore, it will end up anywhere on the circumference of the circle centered at p that has a radius of r. Now, it turns out that the arc of the circle marked in bold is slightly longer than the rest of the circumference, because the bold part is those points that are *farther from the origin* O. Therefore, p has higher probability to end up on the bold part (farther from the origin) than on the rest (closer to the origin). And since the direction of p is random, p will distance itself from the origin O *on average*. This is the intuitive geometric and statistical justification of the 2ndLoT, but the reader is referred to [2] for a fuller explanation.
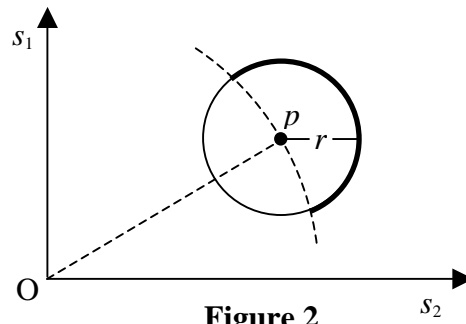
Thus, the 2ndLoT turns out to be a purely mathematical result, a *theorem* of statistics and geometry. Because it was first noted in the context of thermodynamics, it acquired its name and was thought to be derivable from the rest of the laws of physics. But it is not a physical law, strictly speaking. As another example where statistics can cause a particular structure to be formed in the world, consider Fig. 3: a number of balls that drop from the top-center take binary "decisions" at each ∧-obstacle, falling left or right with equal probability. The result is the Gaussian-like shape of the ball distribution at the bottom. This is a real shape of a real-world object, but no physical law suffices to explain it, only the math of statistics.
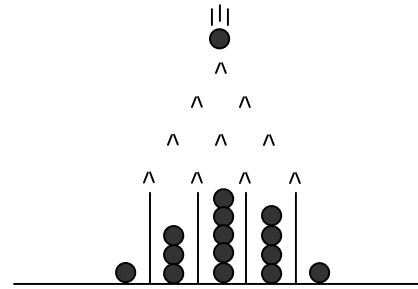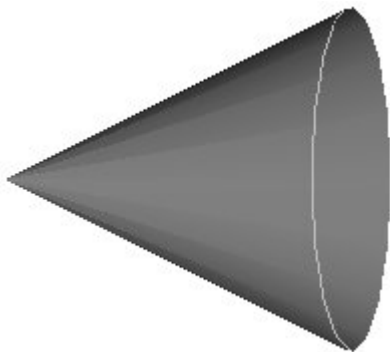
Figure 3

In summary, temporal asymmetry in the macroworld is a result of the 2ndLoT, which in turn is a result of mathematics. However, this asymmetry still does not explain its perceived one-way direction by us. Think, for example, of a cone (Fig. 4): it is an asymmetric object, but with no inherent directionality, since it can be scanned either from tip to base, or vice versa.

Figure 4

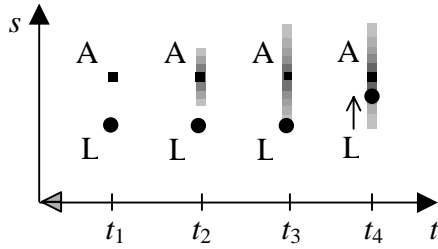## Directionality of Time: a Cognitive "Add-on" to Physical Reality

Figure 5

Consider a typical biological situation, as abstracted in Fig. 5. At time t_1, an antelope (A) comes to the vicinity of a lion (L), but remaining invisible to the lion. The smell of A starts spreading in the environment (time t_2), and at a later time (t_3) the smell reaches L. Subsequently (t_4), L moves toward A, with the "intention" to fill an empty stomach. (For our purposes, it makes no difference if we assume a Euclidean space-time.)

More abstractly, information (the odor-particles, in our example) from a source (A) spreads in the environment due to the 2ndLoT, and reaches a receiver (L), who processes the information and proceeds according to rules dictated by survival. What was just described was the "orthodox (forward-going) movie" of time.

Now let us run the "movie" backwards in time: At time t_4, a lion L moves away from an antelope A. L reaches a maximum distance at t_3 where it stops, and we see the smell of A *miraculously* shrinking back into A. "Miraculously", because there would be no explanation for the marching of particles that form the "olfactory extension" of A toward a common point in space-time, since the 2ndLoT predicts a spreading, *even when time runs backwards* — see the proof of the "dispersion theorem" in [2], which is independent of the direction of the temporal dimension. That is, for the particles to end up all at A simultaneously, they would need to perform not random walks, but *biased* walks, and the bias that would run against probabilities and direct them to space-time event A at t_1 would be *inexplicable*. Alas, the universe would be full of such inexplicable events:

- seeds of a plant would be all swept by the wind (and also moved in other ways, e.g., carried by insects) and magically be directed toward the plant;
- molecules of $CaCO_3$ and other substances forming debris on the bottom of the oceans would miraculously gather up and form the shells of fully shaped bivalves;
- photons would be emitted from the chloroplasts of plants and magically be all sent to a single nearby star, the Sun, as if the photons "knew" which direction to go. (The Sun would thus be an "advanced [backward-in-time] wave source".)

Thus, an astronomical number of such miraculous events would imply that *causality* would break down in such a universe. It would not be possible to say: "The seeds of a plant march back toward the plant, because…" — there would be no "because". To a cognitive observer, it would all appear as an act of magic.

However, one might counter-argue that an often missing causality would not be a lethal blow to cognition as we know it: we might have to accept it as an axiom that, in our universe, there is an unexplained "force" that moves bits and pieces together, which form whole structures. It would be a world unfriendly to physicists and philosophers, but not so to lay people. Yet there is a more serious problem in a universe with a backward-running time in which the 2ndLoT does not hold: it is that *memories would vanish*. Here is why:

Consider Fig. 5 again. Moving backwards from time t_3 toward t_2, L *loses* the memory of a smell (which, in the forward temporal direction, caused L to move toward A). Similarly, every memory of every cognitive being *disintegrates* and vanishes in the backward time direction. This happens because memories *form* in the forward direction.

Normally (time-wise forwardly), memories are *concentrations of information,* working against the 2ndLoT. They do not violate the 2ndLoT of course, because brains are not closed systems. But they somehow become more complex as time goes by, reflecting the corresponding complexity of material structures, such as a rock, a tree, a village, a nation, an enterprise, etc., which also form in the forward direction as time goes by. There is no mystery in this structure-formation in the world: material structures form because the forces of nature put material bits and pieces together. For instance, gravity causes matter to accumulate and collapse, but the other forces of nature "resist" the collapsing and cause stars and planetary systems to form. Then, on our planet, once evolution (an emergent, biological "force") was set in motion with the first self-replicating molecules, biological structures started emerging, of ever-increasing complexity. A memory simply reflects this complexity in "software", i.e., in mental structures. And, just as world structures are formed in the forward direction, so do memories, in spite of the 2ndLoT, which leads structures to deterioration, *if left to their own devices*. The forces of nature do not leave things to their own devices, that's why structures and memories form. But in the backward temporal direction exactly the opposite happens: not only does matter un-spread miraculously, but also memories disintegrate. Thus, cognition vanishes.

Now, one might counter-argue that, in the backward direction, "backward memories" (remembering our future in the normal, forward direction) might still form: simply, since the mysterious matter-accumulating force creates structures, memories could evolve to reflect these structure-building events. But this is unsupportable by evidence: we are talking about *our* universe, our world as we know it, not some different, hypothetical one, so the onus of pointing to something that could be interpreted as an existing "backward memory" in our world is on the shoulders of those who would bring forth this objection.

In conclusion, the asymmetry of the 2ndLoT results in causally connected memories that yield cognition in only one direction. Cognition is inconceivable in the opposite direction.

Why Time Flows

A cognition with a one-way direction still does not explain our sense of a "flowing" time.
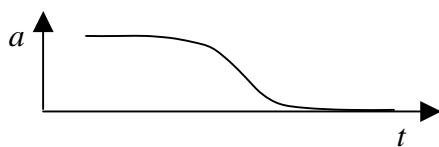

Figure 6

The sense of flow can be understood as an artifact of a *densely populated short-term memory* (STM) the structures of which are activated (or "primed" in psychological terms), and fade quickly in the forward direction (see Fig. 6).

Fig. 6 shows the graph of the activation (*a,* vertical axis) of some primed STM structure as it fades in time (*t,* horizontal axis). Activations in neurons start at some high value, stay near that value for some time, then drop precipitously and stay near zero for some more time, and are finally zeroed [5]. The shape of this curve is called a "sigmoid". Activations fade following sigmoid curves, unless reinforced within a short time. As

activations fade, memory structures ("ideas") become inaccessible and are lost from the STM [3]. But as long as a cognitive system stays alert it receives new input, and so new ideas form, causing the activation of new structures before the old ones fade completely away. This continual activation and formation of new and overlapping structures in STM, combined with the fact that each one can refer only to those that are causally connected with it unidirectionally, is what gives rise to the sense of temporal flow. An analogy is a commercial sign with a row of light bulbs that turn on and off in succession, yielding the illusion of motion.

The flow appears smooth to us, because activations in STM appear and fade away very quickly, producing a dense sequence of successive, overlapping structures. There is no physical sense of "speed" in this flow, because physical speed is defined as space over time, and there is nothing like motion in space in STM. But we are capable of *comparing the number* of successive mental structures that form and fade against the number of real-world events that occur in a given interval of time. The comparison is rough and inaccurate, but it gives us a sense of "how fast we think". So we end up with the illusion that our thought has a "speed" which, since it is comparable with true speeds in the world that happen in time, we conflate with real time and identify as the passage of time itself.

In contrast, long-term memory (LTM) does not work like that. LTM resembles a storage of episodes arranged *roughly* in chronological order. That is, we have a rough sense of which episode preceded which one in remote past time (though we are not always right), but there is no rapid succession of overlapping events that come-and-go as in our STM (except in rare instances of very vivid memories). So, LTM does not give us the sense of a flow, but rather one of chronologically ordered episodes, retrievable at will.

Why We Feel We Can't Move in Time, but We Can Do so in Space

All the previous discussion, although pertaining to features of time such as its large-scale asymmetry (a provable mathematical theorem) and its one-way directionality and sense of "flow" (cognitive add-ons), still does not answer directly a deep conundrum: If time is as similar to space as modern physics assures us that it is, why do we feel "stuck at present" in time, unable to move at will toward the past or the future, but we get a very different feeling about space, in which we can move about in any direction — up, down, back, forth, left, or right?

To answer this conundrum, we first need to make some additional factual observations. Observe that space and time are not identical, but are related through the relation $s = c \cdot t$. This relation tells us how *stretched* time is with respect to space; that is, by what factor (c) we must multiply the dimension t in order to obtain an interval of equal measure along the dimension s.

At this point I need to make a brief parenthetical remark. It might be argued that all the above is true only in special relativity, which assumes a universe without mass — better yet, a universe with no gravitational fields — whereas the true geometry of the universe is not Minkowskian: general relativity corrects the special one, rendering the latter an approximation only of the former. This claim is formally correct, but inconsequential for the purposes of this discussion, which concerns the cognition of animals that evolved in our familiar terrestrial environment. We did not evolve on the surface of a neutron star,

on which applying general relativity would be nearly obligatory. In a world of extremely weak gravitation, such as our own, special relativity is an excellent approximation of reality, so excellent that it renders the introduction of general relativity redundant for this argument. The reader should keep in mind that any corrections that general relativity would introduce in what follows would not be worth the effort of making them.

Returning to the previous discussion, we might note that the relation $s = c \cdot t$ implies that time appears *very* stretched to us, because c is a large constant if expressed in units suitable for humans, such as meters and seconds ($c = 299,792,458$ m/s). In other words, the equivalent of a second of time in space is nearly 300,000 km, a very long distance by human standards. Of course, one might note that *if* we used the light-year and the year as units of space and time, respectively, then c would be equal to 1 (light-year per year) — a small constant. But it's not a mystery why we don't use such units for our everyday experience on Earth: they would be entirely inappropriate, and the reason is that *our speeds are too slow* compared to c. Therefore, from our human perspective, time indeed appears *very* stretched with respect to space.
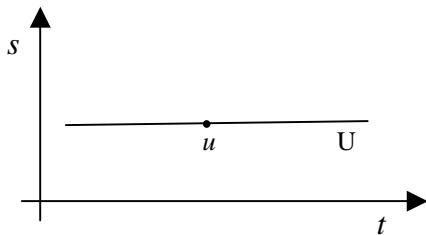

Figure 7

If one second is the equivalent of nearly 300,000 km (186,000 mi), then the 80 years that the average life of a modern human lasts would be equivalent to 80 light-years of space. The diagram in Fig. 7 attempts to show schematically what an enormously stretched temporal dimension with respect to the spatial one means for our lives: an individual's "time-line" (U) is depicted as a long line with a very slight (nonzero) slope.

What we perceive as our "selves" is depicted with a dot on line U, marked by the letter u in the figure: a tiny region in space-time, because our spatial extension is the mere familiar volume of our bodies, and our temporal extension is the fuzzy interval of time that it takes for our STM mental structures to fade and be replaced by others — a few milliseconds in duration. (The notion that each "now" lasts exactly zero time, i.e., that it is a mathematical point in time, is a Western notion, not necessarily a human cognitive universal.) The entire line U consists of such overlapping "dots" like u, but only one of them is shown, to avoid cluttering the drawing. In Fig. 7, U depicts only a part of an individual's existence, and has a slight nonzero slope because u moved in space during that part of U's lifetime. But because the speeds in our environment are too slow compared to c, no matter how far u went, U's temporal extension is by far longer. For example, if u were in a car moving at a speed of 100 km/h (62 mi/h) then in a single second u moved by less than 30 m; but one second is equivalent to about 300,000,000 m of space, which explains why the slope of the line for any object in our environment must be nearly horizontal. Note that terrestrial speeds do not increase much relative to c even if we consider objects as following Earth in space and thus as moving relative to the faraway stars.

A possible objection regarding Fig. 7 is that special relativity concerns *relative* speeds, so what could the interpretation of space-time in that figure be? What is depicted in Fig. 7 is *absolute space-time* [4, p. 59]; specifically, a region of it without strong gravitational fields, as the environment in which we evolved is. Accordingly, the space-time geometry

in Fig. 7 is not Euclidean but Minkowskian. (This means that lengths are not preserved when rotated by some angle $< 90°$; but this need not concern us here.)

The purpose of this exercise is to predict how *u* would perceive space and time; namely, why *u* would feel that motion in space is possible, but that motion in time is impossible; and further, why space *feels* entirely different from time. But before answering these questions it is necessary to see what a *photon* looks like in Fig. 7. That's because photons are, for us, the primary carriers of information (since we can neither hear, nor smell, nor touch, etc., objects beyond some short distances), and we saw the central role that information plays in the formation of memories, and hence, of cognition. So let's populate Fig. 7 with some more entities: a photon *φ,* and an individual W who exchanges information with U (see Fig. 8).
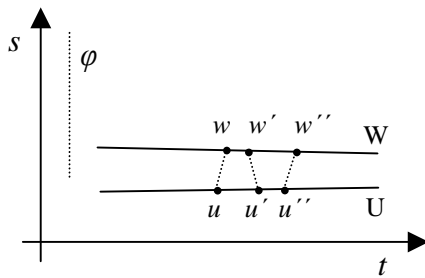

Figure 8

Another individual's time-line W has been added to Fig. 7 in Fig. 8, together with a few more instances, or "time slices", of U's and W's existence. Initially, *u* sends a signal toward W's way (dotted line that connects *u* and *w*). The signal travels very fast, but not at the speed of light (suppose it's an e-mail message), hence its not-exactly-vertical slope. At the left we see a photon *φ,* with an exactly vertical slope: *φ* is extended in space, but stays at the same coordinate in time. Then W's instances process the message for some time, and instance *w′* sends a reply toward U's way (dotted line that connects *w′* and *u′*); later, instance *u′′* sends a reply that reaches *w′′*; and so on.

Such is the description *from the point of view of individual instances* of U and W, such as *u, w,* etc. But from a global perspective *nothing moves* in figures 7 and 8. There are only lines and dots on a plane with a not-so-familiar geometry. This is the "block world" view.

However, each individual instance *u, w,* etc., feels fully cognitive. For example, *u′′* might have a memory of instances *u′* and *u*. (But *u* cannot have a memory of *u′,* nor of *u′′*.) The crucial question is: how would *u* perceive space and time?

The answer is that *u* would feel that motion in space is possible. That's because *u* evolved with perceptual detectors, such as eyes, that are capable of detecting even the tiniest change in spatial coordinates, for reasons of survival, since motion in space might signify "predator" or "food". Sensory receptors compare the small spatial displacements against zero (the immobility in surrounding space), find that they differ from zero, and conclude that motion took place. In contrast, no biological receptors evolved for detecting changes in coordinates along dimension *t*. This happened for at least a couple of reasons:

- First, it is most probably *biologically impossible* for such detectors to evolve. For *u* to perceive a change in *t*-coordinates within a line like U, it would be like trying to perceive a whisper near the roaring engine of a jetliner. Our *t*-coordinates do change when we move in space (e.g., synchronized clocks go out of synch), but their change is akin to a whisper. In this analogy, the analogue of the jetliner is the ever-changing *t*-coordinates of individual instances along U, and the ultimate cause of the jetliner's roaring is the magnitude of *c*.

- And second, it is *not even necessary* to develop such detectors. As mentioned, perceiving the addition of speeds by the formula $v_1 + v_2$ is an excellent approximation of the real $(v_1 + v_2) / (1 + v_1 \cdot v_2/c^2)$. No animal would be conferred an evolutionary advantage by being able to perceive the relativistic sum of speeds, since the difference is negligible. And this observation applies not just to sums of speeds, but to everything perceivable, including changes in t-coordinates. So, the EGN worldview is excellent as far as survival is concerned. Why bother to evolve a relativistic worldview if the EGN one suffices?

Hence, the *whisper near the jetliner engine effect,* as well as *biological utilitarianism,* are possible explanations for why we possess detectors of change in s-coordinates, but not detectors of change in t-coordinates. But there is something more:

Note that photons have only spatial extension, thus φ appears vertical in Fig. 8. This implies that we receive information about space, since photons come to us from any spatial direction: we *see* objects out there. On the contrary, we receive no information from objects along time, neither from the past, nor from the future. Why is that so? What would be analogous to a photon φ along the t dimension? The answer is it would be an *object with mass,* appearing as an exactly horizontal line if drawn in the earlier diagrams. But such an entity would not carry information. Pure information is pure, massless energy, and the latter travels at speed $c,$ drawn vertically in our diagrams. The farther from the vertical direction a line in such diagrams is, the smaller the percent of its kinetic energy, and the greater the percent of mass in its [mass + energy] material existence. An exactly horizontal line has no kinetic energy at all, hence it transmits no information; it is pure mass, an *object* out there, staying relatively immobile with respect to u and to faraway stars (i.e., with respect to absolute space-time). Since the temporal extensions of objects do not provide us with information, we have no way of knowing what is out there in time; hence our ignorance of the future. As for the past, again we receive no information about it directly; we only possess long-term memories that *represent* past events, and act as repositories of stored information.

Conclusion

The contribution of this essay is to *explain* why, if there are cognitive beings at all in the block-world view of the universe, they are bound to perceive time (the fourth dimension of their 4D space-time) as "flowing", and in one direction only. It was noted that time-wise our macroworld is asymmetric, although the microworld (locally) is symmetric, and that the 2ndLoT, responsible for the asymmetry, can be proven mathematically. It was then shown that if cognitive beings exist with memories that form, "opposing" the 2ndLoT, they are bound to perceive one direction (the one toward their causally-connected past memories) as different from the opposite direction. They will also develop a sense of "flow" in time, due to properties of their short-term memories. They will feel unable to move in time, having not evolved with biological detectors of temporal change, because of the sluggish speeds (relative to c) in their environment. Finally, they will also be unable to receive information along the temporal dimension, which — contrary to space, which they *see* out there — adds to their sense of an unknown future and a forever bygone past.

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