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Zeno-machines and the metaphysics of time

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ABSTRACT

This paper aims to explore the nature of Zeno-machines by examining their conceptual coherence, from the perspective of contemporary theories on the passage of time. More specifically, it will analyse the following questions: Are Zeno-machines and supertasks coherent if we adopt the eternalist theory of time? What conclusions can be drawn from choosing the eternalist thesis, or the presentist thesis, when examining Zeno-machines? To this end, an overview of the opposing theories of time is provided, alongside the usual objections to Zeno-machines and their theoretical foundations from Zeno's dichotomy paradox.

Keywords: Zeno-machines, philosophy of time, supertasks, Zeno's paradox.

Opposing views about the passage of time

In contemporary philosophy, there is a hot debate on the ontological nature of time and, in particular, on the nature of the *passage* of time. Most of the current literature on this topic derives from McTaggart's initial argument (1908), in which he presents an abstraction of the concept of time's passage and the ontological nature of change and permanence, under two alternative theories, respectively labelled the *A-theory* and the *B-theory* of the passage of time. McTaggart proposes to identify change in the states of affairs of the world by serializing events in accordance with the temporal instant in which they occur. There are two main arrangements for the series: In the A-series, events are ordered by their tense predicate; more specifically, each event index is determined by an intrinsic, monadic property (labelled the A-property), which carries the tenseness of that event in relation to the present instant, indicating whether that particular event occurs in the past, present, or future. In the B-series, events are tenseless, without any hard-coded temporal reference in the events themselves, so the temporal relation between events determines the series sequential order. Thus, the temporal information is inferred from the indexical relation between the series elements, rather than from an intrinsic property. According to the A-theory of time, the present is the instant in which the A-series is arranged, so it has a privileged status, being the reference point used to index all other events in the series. However, in the B-series the temporal relation between events is independent of the moment at which the B-series is arranged; hence, the concept of presentness has no special significance for the B-theory of time.

These theories summarize contemporary approaches to the analysis of ontologies in the passage of time. For the A-theorist, time effectively flows at a constant, inexorable steady pace towards the future as present events unfold and recede away into the past. For the B-theorist, time is conceived as something akin to a spatial dimension and, as such, is static, as space itself is conceived to be.

Most contemporary philosophers of time agree that presentism is the most radical form of A-theory of time, in opposition to eternalism as a B-theory of time. There is con-

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tinuous debate about which theory represents a better ontology for the passage of time, which can be traced back to the pre-Socratic period in Heraclitus's everlasting cycle of creation and destruction, against Parmenides's eternal static permanence (Dainton, 2010). The fundamental aspect of the presentist thesis is that only present states of affairs are considered real and only present statements are true, in opposition to the eternalist thesis that all events, past, present, or future are equally real. So, for an eternalist, present events bear no special, privileged status, and no particular property, nor any other distinction from past or future events.[2]

It is relevant to consider these opposing theories of time in relation to both our intuitions and scientific theories. In particular, Einstein's special relativity and its derived mathematical model in Minkowski's spacetime carry strong philosophical implications for the issue of the passage of time, among which the following:

(a) There is no absolute simultaneity, so there is no absolute flow of time nor a privileged reference frame;
(b) Time and space in distinct reference frames will respectively dilate and contract, depending on the relative velocity or spatio-temporal distance of the reference frames;
(c) Time and space are tied together, effectively being denoted as timespace.[3]

In view of these implications of special relativity theory, it seems difficult to reconcile non-eternalist approaches and other A-theoretical variants with special relativity. Such effort typically involves either reinterpreting or rejecting some of these implications (Mellor, 1974). This topic shall be resumed further below.

In the following section, I will introduce the concept of Zeno-machines, in the context of classical computational limits, tracing their origins back to Zeno's dichotomy paradox. Later, I will examine Zeno's paradox from the perspective of McTaggart's theories of time's passage; in particular, suggesting a B-theoretical approach to illustrate and support Russell's solution to the paradox. Finally, the idea of a Zeno-machine enabled by a relativistic, B-theoretical spacetime will be examined, along with its main objections.

Zeno-machines and supertasks

Zeno-machines are hypothetical machines that belong to the *hypercomputation* subgroup of computability theory and computer science, which encompasses computational models that could supposedly perform beyond the limits set by the Church-Turing thesis[4] (Copeland and Proudfoot, 1999; Copeland and Shagrir, 2011). By definition, Zeno-machines are devices capable of computing infinite steps in finite time (Weyl, 1949). This concept is named after Zeno's dichotomy paradox, since each computational step takes a fraction, usually half, of the computational time elapsed in the previous step. For instance, suppose that the first iteration of the algorithm takes one second to complete, and subsequent iterations will respectively take $\frac{1}{2}$ second, $\frac{1}{4}$ of a second, $\frac{1}{8}$ of a second, and so on, *ad infinitum* on $\mathbb{N}$. The full time required to complete the computation can be expressed as a geometric infinite sum series, whose limit will converge to 2 seconds:

$$computationTime = \sum_{n=0}^{\infty} \frac{1}{2^n} = 2$$

The summation represented in this equation shows that even though there are infinite steps to perform, this is a denumerable, Cantorian infinite (ω). Appropriately, a Zeno-machine is also known as an *accelerating Turing-machine* (Copeland and Proudfoot, 1999). Such a machine apparently has a paradoxical nature, incurring similar problems as those highlighted by Zeno's dichotomy paradox. One interesting property of a Zeno-machine is that it can be clearly distinguished from other non-Turing-machines, like oracle machines or super-π machines, that have been postulated as black boxes of an unknown internal nature, being capable of solving even undecidable problems in just a single operation (Turing, 1939). Moreover, the property that distinguishes Zeno-machines from regular Turing-machines is their accelerated iterative process (Copeland, 2002),[5] thus making them capable of performing supertasks, as defined by Weyl.[6]

[2] There are other, intermediate views regarding the reality of tenseness. The growing block theory states that present and past events are real and true, while future events are not. However, such distinctions about tense realism are not central to the scope of this essay. For an in-depth view about tenseness realism, see Zimmerman (2005) and Boccardi (2013).

[3] For an informative account of Einstein's special relativity theory and Minkowski's mathematical spacetime model, see Russell (1969), Brown (2007), and Dainton (2010).

[4] A capsule, simplified version of the Church-Turing thesis (or conjecture) says that a function on the natural numbers is computable if, and only if, it is computable by a Turing-machine. A full account of the Church-Turing thesis raises controversial and still-debated issues in computability theory, and therefore falls beyond the scope of the present essay. Müller (2011) provides a detailed discussion of the Church-Turing thesis—or theses—in the context of hypercomputation.

[5] In algorithm complexity theory, a strong premise is that every iteration of any algorithm takes the same fixed amount of computational time. This premise is precisely what is distinct in a Zeno-machine.

[6] A supertask is a task that takes infinite steps to be completed, but it *is* somehow completed in a finite amount of time. Thomson (1954) coined this term, inspired by Weyl's concept of an infinity machine (1949).

When Thomson (1954) discussed the concept of supertasks, he coined a philosophical puzzle, ultimately aiming to provide evidence for the unfeasibility of supertasks. Thomson proposed a device that, at each step of its iterative process, toggles a lamp *on* or *off* depending upon its previous state. If the lamp was *off*, it will be turned *on*, and vice-versa. Being a device of supertask capability, *Thomson's Lamp*'s first step will take one second to perform, and each following step will take half the time of the previous step, in the spirit of Zeno's dichotomy. The question that Thomson proposes is the following: What is the lamp's state after two full seconds have elapsed, when all infinite iterations are complete? Thomson then proceeds to conclude that supertasks are impossible, since the lamp's state cannot be determined at the end of the process, even if an *end* could theoretically be reached.

Benacerraf (1962) claims that Thomson's conclusion is erroneous by arguing that it is impossible to determine the lamp's state in its final, transfinite state ($\omega + 1$) by inferring it from the previous state in the series. The transitioning gap between the infinite series to the supertask end state ($\omega + 1$) became known as *Benacerraf's Gap*; bridging this gap is at the core of the discussion about supertasks. It is also relevant to note that the infinite series of Thomson's Lamp actually corresponds to Grandi's series:[7] it is a divergent series and thus its limit towards infinity is mathematically indeterminate. However, indetermination at the infinite limit is not a true condition for every denumerable infinite series. Effectively, Zeno's own dichotomy series converges at its infinite limit. Many philosophers hold Benacerraf's response in high regard, and even Thomson himself acknowledges the failure of his original argument (Shagrir, 2004)—even if he still rejects the viability of supertasks.

Zeno's dichotomy paradox and the metaphysics of time

When discussing Zeno-machines and supertasks, it is important to distinguish the nature of the problem to be solved and the infinite recursion involved, or else one is bound to incur Benacerraf's Gap paradoxes at the transfinite state ($\omega + 1$) of the computation.[8] However, it does not necessarily follow that these paradoxes are evidence or proof of an internal incoherence of supertasks *simpliciter*. The decidability of the supertask problem is very relevant for such analysis, as exemplified by Benacerraf's response to Thomson's challenge.

To analyse Zeno-machines' feasibility, we need first to examine Zeno's original dichotomy paradox, as both scenarios share a similar recursive structure. Russell (1903) provides a sharp argument to dissolve Zeno's motion paradox, colloquially labelled the "at-at theory of motion", built on Aristotle's response to Zeno. Russell claims that the core of the paradox lies in trying to determine kinematic motion as a property of one infinitesimal instant. As Russell argues, motion, by definition, needs a time interval to be defined, or if we abstract time by discrete points, at least two data points are needed to characterize kinematic motion (Boccardi, 2013). Surely, atomizing and individualizing instants, and then trying to identify kinematic motion, is bound to bring us to a paradox.

An interpretation of Russell's argument can be made in the light of McTaggart's temporal series: Zeno is effectively using a temporal B-series to track the history of the runner's spatial positions, recursively bi-partitioning the B-series *ad infinitum*, and finally, trying to identify motion at a discrete, infinitesimal instant *t*. This scenario is equivalent to trying to infer a temporal property from a single element of the B-series. As outlined earlier, however, in the B-series the notion of the passage of time is the relation *between elements* of the series, so a B-element does not contain any intrinsic temporal property. So, in McTaggart's terms, the root of Zeno's contradiction can be interpreted as trying to retrieve an A-property from a single element of the B-series, since Zeno's partitioning process, at its infinite limit, removes the temporal information from the picture.

It is difficult to infer Zeno's true intentions in framing his paradoxes. However, taking into account that Aristotle talks about Zeno as a disciple of Parmenides, perhaps one could speculate that his point is made precisely to subtly emphasize an eternalist, tenseless approach to temporal metaphysics.

The feasibility of Zeno-machines in relativistic spacetimes

In the previous sections, I argued that both Einstein's special relativity and Russell's solution to Zeno's dichotomy paradox align nicely with the B-theory of time and the eternalist view. In this section, I will suggest that Zeno-machines are coherent under the eternalist B-theoretical framework, particularly when Einstein's relativity theories are taken into account. One of the main issues to be addressed is how to bridge the gap between the infinite iterative process and the transfinite end state of the supertask. A sensible choice would be to approach this issue from a relativistic perspective: is it possible to find a reference frame to perform the infinite iterative process, and yet another distinct reference frame to present the computational result? Could this relativistic spacetime configuration enable Zeno-machines?

Relativistic spacetimes have already been suggested as a fruitful framework to hypothetically perform the infinite

[7] $\sum_{n=0}^{\infty} (-1)^n$

[8] For a comprehensive analysis of well-established supertask paradoxes due to heterogeneous indeterminate end-state configurations including Ross's paradox, see Earman and Norton (1996).

iterative process of supertasks, due to the time dilation that occurs as consequence of the difference between reference frames in inertial systems. Pitowsky (1990) has proposed the idea of a bifurcated supertask, defining a spacetime in general relativity, in a scenario similar to the *twin effect* thought experiment of special relativity: a slave machine is placed at a world line γ_1, such as that it can compute its infinite iterative process in its own (infinite) time, while an observer, placed at a different world line γ_2, will acknowledge the result of the computation. Pitowsky invents a tale about verifying Fermat's last theorem:[9]

> *While [the mathematician]* M *[at γ_2] peacefully cruises in orbit, his graduate students [at γ_1] examine Fermat's conjecture one case after the other. […] When they grow old, or become professors, they transmit the holy task to their own disciples, and so on. If a counterexample to Fermat's conjecture is ever encountered, a message is sent to* M*. In this case* M *has a fraction of a second to hit the brakes and return home. If no message arrives,* M *disintegrate with a smile, knowing that Fermat was right after all (cf. Earman and Norton, 1993, p. 25; Pitowsky, 1990, p. 83).*

Earman and Norton (1993) have pointed to some physical inconsistencies in this story, however: *M* at γ_2 is actually accelerating at unbearable magnitudes and subject to *g*-forces, so its cruise is not so peaceful after all, and will certainly collapse. Whatever the case may be regarding these physical qualms, Pitowsky's story also involves a more pervasive, conceptual problem: in case Fermat's conjecture is correct, *M* will never receive a signal from γ_1, and there is no way for *M* to know if the reason for the absence of the signal is actually a confirmation of Fermat's conjecture or not.

Malament-Hogarth spacetime was proposed to circumvent these difficulties, currently consisting of the most notable relativistic spacetime to postulate Zeno-machines, arranged in such a way as to avoid the problems of Pitowsky spacetime. Earman and Norton (1993, 1996) have successfully demonstrated that Malament-Hogarth spacetimes are theoretically consistent in general relativity theory by satisfying Einstein's field equations and energy constraints. This spacetime is defined in such a way that there will be a future-directed timelike curve γ_2 from a point *q* to *p*, where *q* can be located at the causal future of the past endpoint of γ_1, meaning that if no signal ever reaches event *p*, Fermat's conjecture can be confirmed as actually right, as expected in Pitowsky's thought experiment. Several other authors have entered the debate over Zeno-machines in Malament-Hogarth spacetimes, raising new objections or presenting new arguments, but these will not be examined here.[10]

Objections

As briefly discussed earlier, the main problem for supertasks is to find a way to bridge Benacerraf's transfinite gap. Benacerraf suggests that a divergent series is indeterminate in its transfinite state; however, a convergent series may not be so. One approach would be to formulate the supertask in a semi-decidable manner. A classic example of an undecidable supertask would be to expand all decimal digits of π (the postulated, black box super-π machine is an instance of a machine that could perform this supertask). No supertask, bifurcated or otherwise, will be able to provide answers to contradictory end-states, nor iterate through the cardinality of the *continuum*. However, a semi-decidable formulation could be admitted: instead of trying to fully expand the decimal digits of π, one could verify whether there is a sequence of *777* in the decimal expansion of π, as famously questioned by Wittgenstein (Copeland, 2002).

Another point of disagreement is whether Zeno-machines actually compute. The issue here lies in the definition of both computability and Turing-machines. By definition, Zeno-machines compute what Turing-machines cannot compute. Also by definition, anything that computes is a Turing-machine. That makes Zeno-machines Turing-machines that are not Turing-machines. Contradiction looms again. There are some ways to avoid such a deadlock, such as extending the definition of computation or rejecting the idea that Zeno-machines actually compute. Shagrir (2004) proposes classifying Zeno-machines as non-Turing-machines on the same grounds as Benacerraf's response to Thomson's Lamp, namely by defining the transfinite final state ($\omega + 1$) of the computation as a physical state instead of a Turing-machine state, so that the halting task is left to the physical layer of the system. Another alternative would be to extend the definition of a Turing-machine to include the transfinite state in the regular computation, as proposed by Hamkins and Lewis (2000), under the form of infinite-time Turing-machines.

There are other arguments, more conceptual in nature, against the coherence of Zeno-machines or supertasks, which reject the metaphysical premises on which Zeno-machines are based. The first class of arguments stems from the adoption of an A-theoretical approach, rejecting Einstein's special relativity and defining a privileged, absolute spatio-temporal reference frame. Perhaps the most well known instance of this view is the form of neo-Lorentzian relativity put forward by Craig (2000) and Hinchliff (2000), among

[9] Fermat's last theorem, or Fermat's conjecture, states that there are no three natural numbers (*a*, *b*, *c*) such that can satisfy the equation $a^n + b^n = c^n$ for any integer $n > 2$.

[10] For a complete definition of Malament-Hogarth spacetimes and their applicability to Zeno-machines with sufficient mathematical strictness, see Earman and Norton (1993), Etesi and Németi (2002), and Welch (2008).

others. This approach incorporates the empirical findings of relativity into the presentist A-theory, by positing an absolute frame of reference, not unlike Lorentz's æther, and acknowledging relativistic phenomena like time dilation and spatial contraction, always from the perspective of this privileged reference frame.

Since this hypothetical privileged reference frame cannot be detected experimentally, from an empirical standpoint the proposal seems to have no significant consequence for general relativity, so Malament-Hogarth spacetimes could still theoretically be viable even under such assumptions. However, from a metaphysical perspective, this line of reasoning arguably falls victim to Occam's razor, since special relativity is more consistent and surprisingly elegant in its simplicity, in comparison to the neo-Lorentzian approach.

Craig's defence of a privileged frame of reference and the presentist arrow of time seems to be driven by his theological-causal view of metaphysics, and the same can be said of his finitist rejection of Cantorian transfinite arithmetic. But dismissing a highly praised and well-established theory by evoking theological premises makes a weak philosophical argument in itself (Balashov and Janssen, 2003).

Another possible critique comes from finitism, which tends to follow from intuitionism (much like presentism itself); as a consequence, the concept of Zeno-machines would equally be rejected. Ironically, the introduction of the idea of supertasks by Weyl (1949) is elaborated as a finitist argument for the impossibility of supertasks. Nonetheless, finitism is a hot topic in philosophy of mathematics and set theory, and falls beyond the limits of this essay.[11]

Finally, there are a couple of remaining critiques of the standard interpretation of special relativity yet to be addressed. The first, from Markosian (2004), uses an *a priori* argument in order to reduce special relativity to a theory based exclusively on empirical evidence, a *philosophically austere* theory, as he puts it, and thus rejects the existence of relative simultaneity, as implied by relativity theory. The second critique comes from Craig, a presentist himself, and curiously proposes a distinct objection: that special relativity is based on postulates devoid of proper empirical import (Balashov and Janssen, 2003).

Both objections miss important aspects of special relativity theory. As defined by Einstein, special relativity is a theory of principle, with a strong deductive structure. Yet relativity is consistently corroborated by empirical evidence. Markosian dismisses the deductive structure of relativity, basing his argument on empirical verificacionism only, while Craig ignores the empirical evidence for relativity. These points can be taken as evidence of the contingency of both the *philosophical austere* and *empirically devoid* objections; I thus opt to dismiss both of them.

Conclusion

In this essay I have argued that Zeno-machines are coherent, at least in a specific relativistic theoretical setting; that relativity theory is well aligned with McTaggart's B-theory of time; that the B-theory of time is also consistent with Russell's resolution of Zeno's paradox; and thus that Zeno-machines can be seen as integrating the cohesive *B-package* theory of time, as coined by Boccardi (2013).

In the previous section I discussed a few objections to Zeno-machines and concluded that these objections can be circumvented by accepting the *B-theory* of time. However, I also noted that supertasks are still bound by computability limits and so must be formulated at least as semi-decidable problems, bound by denumerable infinity, unlike other hypercomputing black box oracles.

It is also clear that beyond the ontological aspect, there are important physical limits to be considered. Berkenstein bound and Bremermann's limit[12] are probably serious challenges to infinity machines, and there is no viable technology to implement such devices. In addition, epistemic limits in general relativity theory still need to be expanded, and thus Zeno-machines are completely implausible in the actual world, both now and in the foreseeable future.

Besides these physical limits, Aaronson has also proposed a normative argument against Zeno-machines:

> *We should immediately be skeptical that, if Nature was going to give us these vast computational powers, she would do so in a way that's so mundane, so uninteresting (Aaronson, 2013, p. 31).*

This statement resonates with the problem of whether Zeno-machines are computing machines or not. Aaronson's remark is certainly appealing for most computer scientists, since one of the core activities of theoretical computer science consists in finding ingenious algorithms to solve hard computational problems. So, from a normative standpoint, I agree with Aaronson and Shagrir: Zeno-machines are not Turing-machines, as they deviate beyond the core of theoretical computer science; in this sense, I think that *hypercomputation* is a misnomer for this class of para-computational, hypothetical machines.

[11] For a few examples of the finitism/infinitism debate, see Bendegem (1987) and Dummett (1975); in relation to the metaphysics of time, see Dummett (2000).

[12] In physics, *the Berkenstein bound* is a theory that implies an upper limit on the entropy that can be contained within a finite spatial region with a finite amount of energy. In computer science, *the Bremermann's limit* is a theory derived from Berkenstein bound that postulates the upper computational speed of a self-contained computational system. For an in-depth examination on computational physical limits, see Markov (2014).

Nonetheless, there is certainly room for fresh research on all these issues, in both theoretical and practical terms, in philosophy, physics, mathematics and computer science, particularly for general relativists.

In the classical Turing conception of a computing machine, there is no reference to the time elapsed in each operational step, and the common intuition of absolute time in our privileged, earth-bound frame of reference is implicitly assumed, since it conforms to the most common human intuitions about the natural "flow" of time. The same can be said about classical Newtonian physics. Nonetheless, the image of unorthodox models springing from scientific and metaphysical theories is very captivating, as the ontological debate on the nature of time's passage positively enriches both science and philosophy, even if common intuitions are challenged. As Kuhn said:

> *Scientific revolutions are inaugurated by a growing sense, again often restricted to a narrow subdivision of the scientific community, that an existing paradigm has ceased to function adequately in the exploration of an aspect of nature to which that paradigm itself had previously led the way (Kuhn, 1962, p. 92).*

Thinking along these lines, the debate over the metaphysics of time could be seen as a by-product of a clash of scientific paradigms dating back, in terms of its deep conceptual origins, to pre-Socratic times. Last, to deny the possibility of supertasks and Zeno-machines, one has to deny Einsteinian relativity and its contemporary developments both in the sciences and philosophy. It seems to me that to reject such possibilities is a high price to pay, for the sake of preserving one's cherished intuitions.

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