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Abstract

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A Revised Attack on Computational Ontology

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Abstract. There has been an ongoing conflict regarding whether reality is fundamentally digital or analogue. Recently, Floridi has argued that this dichotomy is misapplied. For any attempt to analyse noumenal reality independently of any level of abstraction at which the analysis is conducted is mistaken. In the *pars destruens* of this paper, we argue that Floridi does not establish that it is only levels of abstraction that are analogue or digital, rather than noumenal reality. In the *pars construens* of this paper, we reject a classification of noumenal reality as a deterministic discrete computational system. We show, based on considerations from classical physics, why a deterministic computational view of the universe faces problems (e.g., a reversible computational universe cannot be strictly deterministic).

1 Introduction

Recently, Luciano Floridi has argued that the dichotomy between a digital ontology and an analogue one is misapplied, since any attempt to analyse noumenal reality independently of any level of abstraction (LoA) is mistaken. This argument recasts, in a new light, Kant's thesis and antithesis of the second antinomy of pure reason (1996, vv. A 434–5/B 462–3). The thesis claims (roughly) that every composite substance in the world consists of simple parts. The antithesis claims (roughly) that no composite thing in the world consists of simple parts.

Floridi proposes a thought experiment that supposedly shows why a classification of reality as *digital* is wrong. The last part of this thought experiment, so he argues, shows that the digital versus analogue dichotomy may be easily

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misapplied. For reality in itself[1] could be neither digital nor analogue, though it might be *experienced* as either depending on how the epistemic agent is related to it (Floridi, 2011, §14.3). Floridi claims that digitality and analogicity are features of the LoAs adopted to analyse reality, rather than of reality in itself. We find this thought experiment (at least as it stands) and the reasoning behind it to be not compelling. This is the target of the *pars destruens* of our paper.

In the *pars construens*, we argue for a more modest conclusion, namely that the universe is not a deterministic discrete computational system. Tackling head on the question of whether reality is digital or analogue requires treading on a very slippery path. Instead, we show why, based on considerations in classical physics, a deterministic computational view of the universe faces problems. Our critique proceeds in two parts, because the universe may be construed as either a reversible or an irreversible (deterministic) computational system. We first criticise the view that the universe is an irreversible computational system based on considerations of the decline of information in the universe. Subsequently, we criticise the view that the universe is a reversible computational system by examining different implications of this view (e.g., the universe can no longer be strictly deterministic).

The paper is organised as follows. Section 2 briefly gives a preparatory discussion of the differences among analogicity/continuity, digitality/discreteness and computationality/computability. The first part of Section 3 outlines Floridi's main argumentation and thought experiment and the second proceeds to the criticism thereof. In Section 4 we offer an argument that focuses on the intimate relation between discrete irreversible computation and the growth and destruction of

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[1] Some writers, for a variety of reasons some of which may be epistemological, are leery of using the qualifier 'in itself' when discussing reality. For a robust defence of this usage (in an epistemological context) see Galen Strawson's analysis (2008).

information. Section 5 presents various challenges to a deterministic reversible computational view of the universe. Section 6 concludes the paper.

2 Analogicity, Digitality and Computationality

In this section, we briefly discuss some pertinent distinctions between analogicity and continuity, digitality and discreteness as well as between computationality and computability. These sometimes-subtle distinctions matter for the ensuing discussion about digitality and analogicity as features of reality and the computational view of the universe.

Some may find it unfortunate that the question about whether reality is continuous or discrete has been recast in terms of analogue or digital. For one thing, the analogue/digital distinction is sometimes applied to systems of representation, and there seems little reason to view the whole universe as such a system. Second, several authors have argued that the analogue/digital distinction should be kept separate from the continuous/discrete distinction (cf. Blachowicz, 1997; Lewis, 1971; Maley, 2010). This is part of a longstanding debate about modes of representation. Some have also argued that computation is the processing of representations (cf. Pylyshyn, 1984; O'Brien & Opie, 2006). It follows, by their lights, that a computational universe processes representations too. Yet, others, including the first author, have argued against the representational view of computation (cf. Fresco, 2010; Piccinini, 2007). For our purposes here, we remain neutral about the representational character of computation.

We restrict our discussion to *discrete* computation and only adhere to the digital/analogue distinction where Floridi uses it explicitly in criticising digital ontology. Consider the case of conventional digital computers. They operate discretely when considered in some ways and continuously when considered in some others. At one LoA, digital computers, like finite state automata (FSAs) and Turing machines (TMs), clearly move from one distinct state S_1 to another S_2 settling on S_2 without settling on any other "intermediate" states. However, at the electrical LoA, the voltage flowing through an electronic digital computer does not simply "stop" at some voltage level, say, 0.5v and then "jump" to another, say, 1.5v. Rather, it flows continuously between 0.5v to 1.5v. This shows one problem for equating the digital/analogue distinction with the discrete/continuous one. In the *pars construens* we shall resort to using 'discrete' (rather than 'digital') and take it to be the relational property of being separate and distinct.

By way of concluding this section, we make some brief observations about the difference between computation and computability. The intension of a function is its definition that specifies the relationship that holds between inputs and corresponding outputs. A function can also be characterised extensionally as a set of ordered pairs that pair up the arguments and values of the function (i.e., a set of ordered input-output pairs). As a function, this set is such that no two input elements are a part of more than one input-output pair. Using the Church-Turing Thesis, we might say that a function is (Turing-) computable *iff* there exists an algorithm (or a TM) that computes it. The algorithm follows a specific sequence of instructions for converting (legal) input into the corresponding output (Rapaport, 1998: p. 403).

For the present purposes, the assertion that the (evolution of the) universe is compu*table* is equivalent to the assertion that there is an (or a collection of interrelated) algorithm(s) for "computing the evolution of the universe". Note that this assertion is *not* equivalent to "the evolution of the universe *is* computa*tional*". For whilst the evolution of the universe may be computable, it need not result from the *execution* of some algorithm(s) (i.e., it need not be computational). "After all, a computable function need not be given as [an algorithm]: it might just be [given as] a set of input output pairs [… in the form of] a table look-up" (ibid, p. 404).[2]

Consider the case of Kepler's laws of planetary motion. One might argue that the solar system evolves in a way describable by Kepler's laws. It can possibly be argued that these laws are compu*table* and that a description of planetary motion in the solar system in terms of computability has explanatory power. By contrast, it is also possible to argue that the solar system does not *execute* algorithm(s), that is, it is not computa*tional*. There may certainly be some causal process that maps what seems to be "input" to some corresponding "output" (i.e., compu*table* by extension), but it need not be computa*tional*. This last part is further discussed in Sections 4 and 5.

3 Problems with Floridi's Argument and Fourfold Thought Experiment

3.1 An outline of Floridi's argument and thought experiment

In making his case against digital ontology, Floridi argues that two related questions need to be distinguished (2011, p. 320). The first question concerns the *modelling* of the physical universe asking whether the universe might be adequately modelled by digital computation, independently of whether it is actually digitally computational in itself. The second question concerns the *ultimate nature* of the physical universe asking whether the universe might actually be digital and computational in itself, independently of how it can be adequately modelled.

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[2] Of course, if this set of input-output pairs is infinite, it is questionable whether it can be "given" in an effective sense.

Having distinguished these two questions, Floridi turns in the third part of his work (2011, §14.3) to addressing the latter.[3] He follows this in the fourth part by considering objections and replies (Floridi, 2011, §14.4). The main conclusion argued for in the third part is the following.

> "[I]t is not so much that reality in itself is not digital, but rather that, in a metaphysical context, the digital vs. analogue dichotomy is not applicable" (Floridi, 2011, p. 325).

After outlining the argument for this conclusion he attempts to make it more vivid and intuitive by way of a thought experiment using four idealised agents. We begin with his outline.

The starting point of Floridi's argument is the following conditional.

> "If the ultimate nature of reality in itself is digital, this implies that it is either digital or analogue" (Floridi, 2011, p. 325).

He observes (in Floridi, 2011, fn. 11) that the 'or' in this conditional is being treated "for the sake of simplicity" as "logic disjunction", that is, weak or inclusive disjunction, and adds that "[n]othing depends on this simplification". His intention is to show that the consequent of this conditional is false and to conclude (by Modus Tollens) that the antecedent is false, i.e., that the ultimate nature of reality in itself is not digital.

Floridi claims that he can show that the consequent is mistaken in two steps. Step one is to argue that even if it were true, an epistemic agent facing an (at least partly) analogue world of experience would not be able to establish its truth. He raises some objections to this that lead him to put more weight on the second step in which he argues that:

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[3] He focuses on digitality from Section 14.3 on. We bring the computational back in in Sections 4 and 5.

> “[T]he intrinsic nature of reality does not have to be digital or analogue because the dichotomy might well be misapplied. Reality is experienced, conceptualised and known as digital or analogue depending on the [… LoA] assumed by the epistemic agent when interacting with it. Digital and analogue are features of the LoA modelling the system, not of the modelled system in itself” (Floridi, 2011, p. 325).

The term ‘LoA’ used in the above paragraph needs some brief explanation. It is used in modelling to refer both to the modelling process and the resulting model. An LoA taken to be an object of study (a “system”) consists of a finite, non-empty set of observables which are interpreted typed variables. Floridi gives as a simple example traffic lights where abstracting away from other features of the system the single observable, called ‘colour’, has the type {red, amber, green} with the usual interpretation for these three colours of the lights. Thought of as a modelling process, the input to the LoA is the system under study and its output is a model of that system. When an LoA comes with constraints on the possible combinations of values its observables can take it is called a moderated LoA (Floridi, 2009, pp. 165–166). An LoA is called discrete *iff* the types of all its observables have only finitely many possible values and analogue *iff* none of the types of its observables has finitely many possible values (otherwise, it is hybrid). The traffic light example with a single observable with a three-element type is discrete.

Back to Floridi’s argument. He draws both a negative conclusion from this reasoning and a positive conclusion from it when it is supplemented by a further premise. The negative conclusion is that one cannot know whether reality in itself is digital or analogue. We may note that the stronger conclusion that it is neither digital nor analogue is held to follow from the second step and a fortiori so is his intended conclusion that reality in itself is not digital. The positive conclusion is that structural realisms, which treat the intrinsic nature of reality as relational and hence neither digital nor analogue, have rivals eliminated and have room created for their development.

Having outlined his argument Floridi presents a four stage thought experiment "(i)n order to develop the arguments" (2011, p. 326). Our interest is mostly in the fourth stage of this thought experiment but we will very briefly characterise here the first three. At stage one, we are asked to imagine an agent, Michael, who has the capacity to tell whether reality in itself is digital or analogue. There is an interesting discussion of how this might be possible for a superhuman or ideal agent that need not detain us here. At stage two, a second agent, Gabriel, who works as an interface between reality in itself (as determined by Michael) and the world, which is observed by Raphael (a third agent), ensures that whatever way the world *is* Raphael gets an analogue "view" of it. If the world is digital, Gabriel uses a digital to analogue converter (DAC) and if it is analogue, Gabriel "uses it as his input to produce an analogue reality" (Floridi, 2011, pp. 329–330). In the first two stages reality in itself is assumed to be digital or analogue. At stage three, given only this analogue view, Raphael cannot tell whether reality in itself is digital or analogue.

At the fourth stage, it is stipulated that another agent, Uriel, builds a wheel with four nodes "containing" either a DAC or an analogue to digital converter (ADC) alternating around its perimeter (Floridi, 2011, §14.3.4). The diagram representing this has two of each with Uriel at the axle. Floridi writes:

> "Uriel's wheel generates a system—as an output from an analogue or digital ontology—which will be observed by Raphael as being either analogue or digital

depending on the latter's position with respect to the wheel. It is now obvious that it makes no sense to ask whether the system is digital or analogue in itself" (Floridi, 2011, p. 333).[4]

Floridi's argument, though essentially completed here, concludes in part 4 with a discussion of and replies to three objections. We leave aside Floridi's second objection, which concerns the relation between his argument and Kant's. His first objection is that perhaps the argument developed through the thought experiment in stages 1-3 begs the question by stipulating what needs to be proved. The third one is that his argument may illegitimately assume that all LoA are on a par and so no special weight should be given to what emerges from our best fundamental physical theories.

3.2 A criticism of Floridi's argumentation

We begin evaluation of Floridi's argument with a relatively minor point concerning his remarks about the 'or' in his important first premise:

"If the ultimate nature of reality in itself is digital, this implies that it is either digital or analogue" (Floridi, 2011, p. 325).

He says that nothing depends on the simplifying assumption of treating it as weak disjunction. But this is a mistake. If the 'or' were stronger (e.g. exclusive 'or'), then the conditional may not be true[5] and in that case any argument using it as a premise would be unsound. As it happens, on his reading, it is true (even a logical truth) and we can consider the first step in his argument. As Floridi notes himself there is an

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[4] Floridi takes quantum mechanical wave particle duality to be a less metaphysical example.

[5] An example where it might nevertheless be true is if the disjuncts are necessarily mutually exclusive.

epistemological gap in the first step "for it establishes, at best, only the unknowability of the intrinsically digital (or analogue) nature of reality" (ibid). Not knowing that q, of course, is in general not sufficient to establish ~q. The second step is stronger but a key premise for it remains inadequately supported, viz. that digital and analogue are features of some particular LoA modelling the system, *not* of the modelled system in itself. The second clause of this claim is crucial but not well supported.

In a preliminary characterisation of the last step of his argument Floridi writes: "the alternative digital vs. analogue may easily be misapplied, when talking about reality in itself, because the latter could be neither, while it might be experienced as either digital or analogue depending on how the epistemic agent is related to it" (Floridi, 2011, p. 327).

Here the claim is the modally weakened one that reality in itself *could be* neither analogue nor digital. We are not disagreeing with this claim, but as it is it will not feed into his Modus Tollens to support the conclusion that reality in itself is not digital.

Floridi considers the plausibility of an intermediate position in the third objection considered.

"[S]omeone might argue that it is reasonable that, if our best fundamental physical theory is, say, digital, then this gives us good reason to think that the fundamental nature of reality is digital. This is not deductive warrant, but it does appear to provide some degree of justification" (Floridi, 2011, p. 336).

However, he ends up arguing that:

"Once we accept that epistemology is LoA-based and that no ontology can be LoA-free, then a second, but equally crucial move consists in realising that digital and analogue are features of the LoAs adopted to analyse reality, not features of reality in itself, or, to put it differently, that digital and analogue features are internal features of the models made possible by various LoAs, not external features of the systems modelled by LoAs. So the argument is not just that some LoAs show reality to be digital, while others show it to be analogue, and that we cannot decide which LoAs are better, but, far more importantly, that some LoAs are digital and some are analogue and that, depending on which of them we adopt (because of requirements, goals etc., i.e., teleologically), reality will be modelled as digital or analogue" (ibid).

Here again, without sufficient warrant, Floridi says that we realise "that digital and analogue are features of the LoAs adopted to analyse reality, *not* features of reality in itself" (ibid, italics added). But there is a lack of justification. Where is it shown that although purportedly we cannot help but view reality through our LoAs and they will be either analogue or digital[6], reality in itself is neither? A possible objection is that the question itself should not be asked. But even granted that for every LoA there are some questions that cannot be meaningfully asked and which are unanswerable in principle (Floridi, 2009, p. 166), it does not follow that some questions cannot be meaningfully asked and are in principle unanswerable at any LoA.

We are not rejecting the conclusion that reality in itself is neither digital nor analogue, but rather questioning the reasoning involved in this particular path to it. It is our view that the fourth stage of the thought experiment is *no*t "(a) good way of making sense of the conclusion" (Floridi, 2011, p. 332). When considering Uriel's wheel in the fourth stage of the thought experiment it has been asserted as obvious, but has not been established, that it "makes no sense to ask whether the system is

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[6] We follow Floridi here in omitting the third possibility that they be hybrid.

analogue or digital in itself" (Floridi, 2011, p. 333). However, without appealing to merely stipulated extra features of LoAs, this is not obvious and stipulating this arrangement does not provide the needed justification.

4 An Argument Against Irreversible Computational Ontology

Floridi's second question in Section 3.1 about whether the ultimate nature of the physical universe might be actually discrete and *computational* forms the backdrop for the ensuing discussion. Because computation can be either reversible or irreversible, in this section we argue against the view of the universe as a deterministic irreversible discrete computation.

Let us briefly explain what the difference between reversible and irreversible computation is. A logical operation takes a finite number of distinct input states α and maps them to a finite number of output states β. An operation for which each output state, β, has exactly one possible input state, α, is logically reversible. Given any β state, it is always possible to determine the corresponding α state. For this reason, logical reversibility (and reversible computation) implies the conservation of information. For example, the negation operation (NOT) is fully reversible. Logical conjunction has only one reversible path: the one yielding '1' as output. This path preserves information about the history of the computation. There can be only one combination of input bits that yields '1' as output: (1, 1).

Irreversible computation, on the other hand, implies the discarding of information. An operation for which an output state, β, has more than one possible input state, α, is logically irreversible. When a conventional Boolean AND-gate produces the equivalent of a '0', it discards information regarding the original values of its input lines. Logical conjunction is, therefore, an irreversible operation. Since all three input combinations (0, 1), (1, 0) and (0, 0) yield the same output, information regarding the history of the bitwise conjunction operation is discarded, once the ‘0’ output is produced. We now turn to our critique.

Our argument[7] may be summarised as follows.

- (P1) The universe is a deterministic irreversible discrete computational system.
- (P2) Deterministic irreversible discrete computation is an information discarding process.
- Therefore, (IC/P3) the overall amount of information in the universe decreases over time to a lower level.
- However, according to the second law of thermodynamics, (P4) if the universe is a closed system, then it will reach a state of equilibrium with maximal entropy and thus, maximal information.
- Hence, on the assumption that the universe is a closed system, (C) either P3 or P4 is false.

The gist of this argument is that the assertion that the universe, interpreted as a closed system, is a deterministic discrete irreversible computational system implies that the second law of thermodynamics is false. But this is an absurd consequence. Whilst the first premise (P1) is not explicitly endorsed by discrete computational ontologists (as far as we know), it should be tackled before its “reversible” counterpart is challenged. According to Eric Steinhart, for example, “[u]ltimate reality is computational space-time, and that is just the universal metaphysical hardware into which particular physical worlds are programmed” (1998, p. 117). According to Konrad Zuse, “the universe could be conceived as a gigantic computing machine […]

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[7] This argument elaborates on and defends the following observation made by Pieter Adriaans and Peter van Emde Boas. “If deterministic computation is an information discarding process then it implies that the amount of information in the universe rapidly decreases. This contradicts the second law of thermodynamics” (Adriaans & Van Emde Boas, 2011, p. 16).

a relay calculator" (1993, p. 104). Yet, he does not identify this "gigantic computing machine" with a reversible one. John Wheeler adds that "[e]vidently we must have an *irreversible* world if we are to have a world of distinguishability and meaning" (1982, p. 570, italics added).

Computational ontologists typically conceive the universe as a cellular automaton (CA) (cf. Fredkin, 1990; Wolfram, 2002), rather than as a TM (Turing machine). However, the particular type of discrete computational system in question matters little for the purposes of this argument. It does not matter whether we view the universe as, say, a deterministic CA, a TM or an FSA (i.e., a finite state automaton). The main point is whether in the process of computation the overall amount of information either increases or decreases. The same measure can be used for quantifying the growth or destruction of information processed by CAs, TMs or FSAs.

There are two basic ideas underlying discrete computational ontology. The first one is that space, time and every entity and process in the universe are ultimately discrete. The Finite Nature Hypothesis states that "space and time are discrete and that the number of possible states of every finite volume of space-time is finite" (Fredkin, 1992). Accordingly, all measurable quantities of physics arise from some Planck scale substrate for information processing. The second idea is that all these information processes proceed in discrete state-transitions, which are in principle Turing-computable.

The crux of our argument is establishing the plausibility of the second premise (P2). Deterministic irreversible discrete computations have a very limited capacity to produce new information, and over time they discard information. In a similar manner to the conjunction operation that produces a '0', the calculation of $x + y = z$ (for x, y, z

$\in \mathbb{N}^+$) discards information (as in the case of button presses of a simple calculator) unless the input is somehow "saved" temporarily. The input of this calculation contains, roughly, ($\log x + \log y$) bits of information, whereas its output contains, roughly, $\log(x + y)$ bits (i.e., less information). The amount of information lost in the calculation corresponds to the information that is needed to separate z into x and y. In general, for the positive integers, since there are many possible pairs of addends adding up to the output z (for either $z>3$ or, if the input is ordered, $z>2$), an algorithm, which computes the function $F(x, y) = x + y$, discards information about the precise history of the computation.

An irreversible computational system discards information by its very nature. Over time, such a system loses the information that is needed to reverse its computational history (e.g., reversing a logical conjunction operation that yields a '0')[8]. The destruction of information about the history of the computation is conveyed by Landauer's principle of logical irreversibility[9] (1961). If irreversible deterministic computational processes either preserve[10] or discard information, then over time the overall information is very likely to decrease. The more many-to-one input-to-output relations the computation has the more information about its history is lost, for there are increasingly many more paths the computation could have taken whilst producing the same output. An idealised TM may use its infinite tape to record information about the history of the computation performed as it scans symbols and changes its states. However, in a *finite* universe infinite storage is unavailable. The computational process in question discards information (otherwise, it would have been reversible).

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[8] Of course, the destruction of information does not apply to all outputs of deterministic discrete computations, for example, as observed above, logical conjunction that yields a '1'.

[9] This principle states the minimum amount of entropy (released into the environment) that is the cost of erasing one bit of information.

[10] This is consistent with Calude's result that discrete computation can only generate new information upper bounded by a constant (2009, pp. 84–85).

It should now be clear how the intermediate conclusion (IC/P3), which follows from P1 and P2, is inconsistent with the second law of thermodynamics. This is the case provided that the universe is a closed system. Zuse, for example, held that the entire universe could be seen as a closed system where each state is a function of its preceding state (1970). Indeed, if we view the universe (or ultimate reality) as finite, then by implication there is nothing physical outside the universe. By definition, the universe is a unique, individual whole – a closed system – without an external "environment".

If the processes in this universe are deterministic irreversible discrete computations that discard, rather than increase, information, then over time the universe reaches a lower level of information. However, according to the second law of thermodynamics, closed systems converge to equilibrium, at which point they are in a state of maximal entropy and therefore maximal information (see next paragraph). So, even if some regions of the universe (as subsystems) have low entropy (and therefore low information) in some time interval, eventually the universe (and all its subsystems) will converge to equilibrium and reach a state of maximal information. It follows then that either P3 or P4 has to be rejected. It is our contention that P3 has to be rejected, and so should P1.

Since P3 has to be rejected, either P1 or P2 has to be false. There is some plausible evidence for keeping P4. The second law of thermodynamics has a good track record of producing reliable conclusions in many scientific applications.[11] If we keep P4 but reject P3, then either P1 or P2 is false. On the one hand, P1 is highly speculative and impractical, if not impossible, to corroborate. On the other hand, P2 is evidenced by

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[11] Consider, for example, the original formulation of the second law of thermodynamics by Rudolf Clausius. According to his formulation, heat cannot flow spontaneously from a cold reservoir to a hot reservoir without external work being performed on the system. This is easily evident from everyday experience of refrigeration (Bais & Farmer, 2008, pp. 613–614).

simple cases of computation as illustrated above for AND-gates and summation. We conclude that P1 is false.

Some qualifications are called for in relation to premises P3 and P4. P3 does not spell out which conception of information is used. The information referred to in P2 is analysed in terms of *algorithmic information*. For P3 to follow from premises P1 and P2 it has to consistently use the same conception of information. P4, however, makes use of *Shannon information* that is compatible with thermodynamic entropy. So as it stands, our argument equivocates on 'information'. There are certainly conceptual differences between algorithmic information and Shannon information that influence the way the relevant equations are used in the analysis of the phenomenon in question. Thus, some caution has to be exercised.[12]

However, in the present context, the two conceptions may be used interchangeably. Firstly, it has been shown that for any computable probability distribution, the expected value of algorithmic information equals Shannon information, up to a fixed constant term depending only on the distribution (cf. Li & Vitányi, 2008, pp. 602–608; Teixeira et al., 2011). Our argument centres on a universe where everything is supposedly computational, so probability distributions are computable. Hence, the two conceptions may be used interchangeably admitting that there is a quantitative difference that is upper bounded by a fixed constant, which depends on the probability distributions of the information in question. Secondly, it has been recently shown that algorithmic entropy is not just analogous to thermodynamic entropy as a measure of disorder defined in statistical mechanics, rather it is a special case of thermodynamic entropy (Baez & Stay, 2010), which is typically associated with Shannon information. Here algorithmic entropy is defined as the information gained upon learning a

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[12] We thank Ariel Caticha for suggesting this caveat.

number, on the assumption that this number is the output of some randomly chosen program. Again, up to some error bounded by a constant, which depends on the selected programming language, algorithmic information is algorithmic entropy.

P4 raises two interrelated questions regarding the anthropomorphic character of thermodynamic entropy and the universe being a closed system[13]. We start with the second one, 'Is the universe a closed system?' The space of the universe is populated by fields. A field has a finite number of degrees of freedom[14] located at each point in space. It is claimed by some astronomers that the space of the universe is expanding by way of some clusters of galaxies moving away from others (Koupelis 2011, pp. 520–521). Accordingly, the number of degrees of freedom is increasing. This is a signature of an open system (Caticha, personal correspondence).

On the other hand, the universe may be deemed a closed system in the sense that there is nothing outside to interact with, so that its energy/mass is fixed. The assumption that the universe is a closed system seems to be consistent with the Finite Nature Hypothesis and the views of some computational ontologists (cf. Zuse 1970). For the purposes of this argument we adopt this latter view. As we have seen, reference to 'the whole universe' implies that there is nothing outside it. This means that the universe has bounds, though they are very large.

The second question concerns the applicability of theoretical entropy analyses of physical systems. Edwin Jaynes, for one, argued that "the 'entropy of a physical system' is not meaningful without further qualifications" (1965, p. 398). "For it is a property, not of the physical system, but of the particular experiments you or I choose to perform on it" (ibid). By these lights, (thermodynamic) entropy is not a property of

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[13] See footnote 12.

[14] A degree of freedom of a physical system is, roughly, a direction for potential action. A particle, for example, has three degrees of freedom, as it can move in any one of three independent possible directions in space.

the system but of the description of the system. This makes P4 problematic. For P4 applies the second law of thermodynamics to the universe as a whole, rather than to an “isolated” experimental environment whose parameters are (supposedly) known to the experimenter. But then computational ontologists face a similar challenge. It is one thing to analyse a specific isolated physical system computationally where its relevant microstates are spelled out, but not when the computational analysis is extended to apply to the whole universe.

Now that we have rejected the claim that the universe is a deterministic irreversible discrete computational system, we turn to point out the problems that follow from the claim that the universe is a *deterministic* and *reversible* discrete *computational* system.

5 An Attack on Deterministic Reversible Computational Ontology

In the previous section we have argued against irreversible computational ontology, because irreversibility implies the destruction of information. But Charles Bennett showed that logical irreversibility can be avoided in discrete computation in general (1973). In this section we offer a critique of the deterministic reversible computational conception of the universe (DRCU, for short). We argue that proponents of the DRCU view face the following challenges.

CI. The computational universe is the equivalent of an accelerated TM.
CII. Determinism has to be given up.
CIII. The Loschmidt's reversibility paradox.

We conclude Section 5 with three more observations in the context of the DRCU view concerning miscomputation, input and the collection of garbage information.

Let us elaborate on each of the three challenges in order, starting with CI. We begin with an analogy to Karl Popper's Tristram Shandy argument[15]. The universe, on the DRCU view, is a closed system that computes its own behaviour in space and time according to some algorithm. Because the universe performs reversible computation, for every (irreversible) computational step $S_i \rightarrow S_{i+1}$ the inverse step $S_{i+1} \leftarrow S_i$ has to be recorded. Russell's Tristram Shandy paradox applies in consideration of the instantaneous description (ID) of the computational system (i.e., the universe). The ID of a TM, for example, is specified by the state of the controller, the entire tape contents and the position of the read/write head on the tape.

Let us assume that the universe is a reversible TM, *M*, which is a multi-tape, multi-head machine[16]. When M performs a single computational step $S_i \rightarrow S_{i+1}$, the inverse step $S_{i+1} \leftarrow S_i$ is also recorded. In the construction of the reversible TM proposed by Bennett (1973) a history tape is used for that purpose. However, in a similar vein to Tristram Shandy's autobiography, M always falls behind in capturing its precise ID at any given time. In the process of writing $S_{i+1} \leftarrow S_i$ to the history tape, M has already moved to S_{i+2}. Even if M is arbitrarily quick, it must be incapable of bringing this ID completely up to date. Yet, an objection, as Popper remarked, might be raised at this point that there is no paradox here. If M (like Tristram Shandy) continually improves its methods of description or the speed of writing to the history tape, it may bring the ID more nearly up to date without a limit to this procedure (Popper, 1950b, p. 174).

But what is the implication of such a procedure in the case of M? Arguably, it is that M is an *accelerating* machine. There is certainly no reason to assume that the

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[15] See the appendix or (Popper, 1950a, 1950b) for the details of this argument.

[16] This construction is merely meant to remove the constraint imposed on the standard TM of at most changing a single symbol on a scanned square at any given time. Parallel operations on different regions of the tape are disallowed. Strictly, the multi-tape extension is unnecessary. Importantly, neither the extra head(s) nor the extra tape(s) increases the computational power of the machine.

universe is a sequential TM. So, let us further assume that for any process in M performing the "standard" computation (call it *C*) thereby transitioning from S_1 to S_2 to … S_n there is another process (call it *R*) recording these transitions to the history tape. For R to continually improve the speed of writing to the history tape there has to be some value, however small, by which its speed increases. This situation is akin to Zeno's motion paradox of Achilles and the Tortoise. R has to perform the second recording operation in, say, half the time taken to perform the first, the third in half the time taken to perform the second, and so on. We get a convergent series of recording operations, such as:

$$1/2^0 + 1/2^1 + 1/2^2 + 1/2^3 + ... + 1/2^n + \ldots$$

that converges to 2. The result is a computational process that can perform arbitrarily many recording operations before two consecutive moments of running time have elapsed. We do not argue here that accelerated TMs are logically impossible[17], but this does raise problems for the DRCU view, not least because of the finiteness of the universe on this view (cf. Laraudogoitia, 2011).

Moreover, to be able to record the computational history of C, R has to "observe" C and in so doing it participates in and affects C. In a similar manner to Popper's Predictors interfering with each other in predicting future states, by recording C's state transitions, R interferes with C's operations. "In obtaining initial information, the [observing system] must interact with the system in question, and this interaction introduces into the system a disturbance whose magnitude is unpredictable within a certain halo of uncertainty" (Popper, 1950a, p. 127). Checking pressure in a tyre, for example, is achieved by causing a release of air thereby causing a slight change in the

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[17] There are certainly those who argue that accelerating TMs are not logically impossible (e.g., (Copeland, 2002)). But the physical possibility of accelerating TMs in either an atomic universe or a quantum mechanical universe is highly questionable ((Davies, 2001, pp. 677–679)).

tyre’s pressure. The disturbance to C by the measurement of R inevitably renders C indeterministic, for the prediction of some events in C in accordance with the methods of science breaks down (Popper, 1950a, p. 118). If that is right, then due to the reversibility of the computational universe it is no longer strictly deterministic. This leads us to the second challenge, CII.

The challenge is the (im)possibility of an algorithmic prediction in a deterministic computational ontology. Note that CII need not be *specific* to a reversible computational conception of the universe. As observed in Popper’s Predictors and the Oedipus effect arguments (see the appendix for more details), predictive self-information, *I*, about the state of a computer, *C*, is liable to strongly interfere with this state, thereby destroying the predictive value of I (Popper, 1950b, pp. 188–189). What an algorithmic predictor C means here is that C can predict the state of some system (either C in itself, by way of self-prediction, or another system) ahead of time (i.e., before the time of the predicted event has elapsed). As the output of C we expect not only the answer (or the prediction result), but also the event or state in question to eliminate answers that are fortuitously correct.

In the case of self-predictions of C, their character cannot be the same as a complete self-information of C. There will always be predictive questions about C in itself that C will be unable to answer correctly. The reason, as Popper argued, is that for I to be correct and up to date at some time t_i, it would have to contain a physical description of that very self-information (leading to a regressive self-reference), using the same type of description as in the rest of its information (ibid, p. 190). This is clearly impossible in a *finite* universe.

Similar arguments against the possibility of algorithmic predictions have been put forward more recently (Calude et al 1995; Wolpert, 2001). David Wolpert shows that there cannot be a physical computer that can correctly predict any aspect of a future state of some physical system before that future state actually occurs (2001, pp. 016128–1). His results hold for a computer that is infinitely fast, has an infinite amount of time to perform the calculation (either before or after the predicted event occurs), has the correct value of the variable it is trying to predict explicitly contained in its initial input and regardless of whether this computer performs discrete or continuous computation (ibid, p. 016128-2).

To establish such general results, Wolpert casts computation in terms of partitions of the space of possible world lines of the universe. The specification of the input of a particular physical computer at some given time is given by means of specifying a particular subset of all possible world lines of the universe, where different inputs to the computation correspond to different non-overlapping such subsets. The specification of the output is given in a similar manner. The impossibility of the relevant physical predictive computation in the universe is derived by a consideration of the relationship that exists among these types of partitions (ibid).

Wolpert's key theorem is that there cannot be a computer to which one can pose all possible (binary) questions about the universe. The reasoning underlying the proof of this theorem is as follows. Consider two algorithmic predictors, P_1 and P_2, whose answer subpartitions are binary, and whose initialisation time (T_0) equals 0 and question time equals T. P_1 is set to predict the time T output bit of P_2. P_1 produces that prediction as its output and halts by time $T_X < T$. P_2 is set to predict the negation of P_1's time T output bit just before P_2 halts. Since both P_1 and P_2's output calculations must halt by T_X, they will contradict each other when the prediction time T arrives. Hence, they cannot both correctly predict the question time. It is the need to specify both the question and the predictive answer in the output of P_1 and P_2 that ultimately means that there cannot be two such physical predictors capable of being asked arbitrary questions concerning the output of the other. Note that this type of reasoning is applicable to any two discrete computers (ibid, p. 016128-7).

In a similar vein, Cris Calude et al. show by resorting to algorithmic information theory that in a deterministic universe, whose evolution is (possibly) computable (but not necessarily computational), an algorithmic prediction is impossible (1995, §5). The motivation for this result also appears in Wolpert (2001, pp. 016128–1): "[t]he universe cannot support the existence within it of a computer that can process information as fast as it can".

Let us briefly describe their proof. Let *S* be a computational system and x an input to S. T_S (x) is the running time of S on input x. There exists a universal computational system *U*, such that for every S there exists a constant *c* (*U*, *S*), such that if S(x) = y, there exists an input x', such that

1. U(x') = y (that is, U produces the same y as output on input x')
2. $|x'| \leq |x| + c(U, S)$ (where |x| is the length of the string x)

For the sake of a contradiction, it is assumed that an algorithmic prediction is possible. Accordingly, U can simulate the predictor and thereby it can also act as a predictor. This in turn means that U can simulate any other computational systems in a shorter time (that is, T_U (x') < T_S (x)). For every string x in the domain of U, let t(x) be the minimal running time necessary for U to produce U (x). Since U is a predictor, it follows from T_U (x') < T_S (x) that there exists a string x' such that U(x') = U(x), and T_U(x') < t(x), which is false (Calude et al. 1995, §5). Thus, in an analogous manner to Popper's self-predictors, every universal predictor is too "slow" for some tasks, particularly self- predicting time-consuming tasks.

Next we turn to the third challenge, CIII. Loschmidt's reversibility paradox[18] states that, according to classical mechanics, a system of particles interacting with any forces and going through a sequence of states starting from some initial state, will go through the same sequence in reverse (returning to its initial state), if the velocities of all the particles are reversed. But this conflicts with the second law of thermodynamics, according to which for any such sequence of states (of a closed system) the entropy never decreases (i.e., the sequence cannot be reversed back to its initial state) (Modgil, 2009). This paradox poses a challenge to the DRCU view, provided that the computation may proceed in a “backward direction” (i.e., from some intermediate state back toward the initial state). If reversible computation is time-symmetric, rather than unidirectional, then it may also proceed in an entropy-decreasing direction contrary to the second law of thermodynamics.

Several considerations seem to suggest that reversible computational processes may proceed in a “backward direction” as well. For example, Fredkin and Toffoli’s billiard-ball model of a reversible computer uses reversible physical components (Fredkin & Toffoli, 1982). The presence of moving spherical billiard-balls at specified points are defined as 1s and their absence as 0s. Yet, this model relies on the motion of these balls in a friction-free environment. In a physical reality, these computing balls are very unreliable, since instability arises from arbitrarily small perturbations. This model requires a logically irreversible error-correction step. Bennett has shown that it is possible (at least in principle) to perform an unlimited amount of computation without any energy dissipation, thereby giving rise to a more

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[18] Note that this paradox is the result of a thought experiment rather than of some observed phenomena. One approach that provides a quantitative resolution of this paradox is the Fluctuation Theorem (Evans & Searles, 2002). This theorem quantifies the probability of observing violations of the second law in small systems observed for a short time. Still, it applies to small-scale systems, whereas here the whole universe is considered as one closed system.

realistic model of a *physical* reversible computer (1973). However, for the purpose of our discussion, this comes at a cost.

Are physical implementations of reversible computational models time-symmetric? Bennett's reversible model computes functions bi-directionally: once in a "forward direction" to obtain and save the computation result, and then in a "backward direction". Bennett's construction of a reversible TM uses a history tape as discussed above. When the TM halts, its output is copied to a special output tape and the history tape is used to "undo" the computation (Sutner, 2004, p. 319). Using Bennett's technique only the input and the output of the computation are preserved[19]. Other, more recent, attempts propose different reversible models of computation that also assume a time-symmetry of the computation. Lange et al. propose a reversible TM that "periodically restarts its computation (progressively enlarging its allotted space) from an initial configuration which may or may not be *legal* and which may or may not correspond to the *'true' initial configuration* […] on [input] w" (2000, p. 365, italics added). Incidentally, it is not clear what an illegal initial input would be, if we considered the universe to be a reversible TM.

Does a computational process have an intrinsic arrow of time (thereby proceeding in a single direction)? Some have argued that a computational system moves only in a "forward direction" in a manner that is aligned with the increase of entropy in the universe (Schulman, 2005). But, arguably, any computational process that may take place in an entropy-increasing universe, may equally take place in an entropy-decreasing universe (Maroney, 2009). On the basis of statistical mechanical arguments, Owen Maroney shows that whilst computational processes may have an

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[19] Using Lecerf's method instead, once the computation is undone only the input remains, assuming that the TM accepts the input. Otherwise, the simulation process does not terminate (Sutner, 2004, p. 319).

intrinsic arrow of time, there are no grounds for linking any computational arrow to the thermodynamic arrow of time. If that is right, then a reversible computational universe proceeding in an entropy-decreasing direction is at odds with the second law of thermodynamics.

By way of concluding this section, we make three last observations pertaining to miscomputation[20], input and garbage collection. Firstly, if the evolution of the universe is computational (and not merely computable), what does it mean for the universe to miscompute? In accordance with the example of Kepler's laws of motion for planets discussed in Section 2, would a miscomputation in some region of the universe result in a planet being thrown out of orbit? Although some arithmetic/logical operations, such as negate and increment, are invertible, multiplication, for example, allows the possibility of multiplication by zero and losing much of the previous information prior to the multiplication. So, unlike division by zero, which is strictly undefined, multiplication by zero is permitted yet irreversible.

Furthermore, when considering physical realisations of idealised computational systems errors cannot be ignored. The computing billiard-balls in Fredkin and Toffoli's (idealised) model of a reversible computer would be very unreliable in reality. Any instability resulting from arbitrarily small disruptions to the regular path of the balls by some external influence may lead to the proliferation of errors. These errors can be corrected, but the error correction process is irreversible, for it has to erase the erroneous information.

Secondly, there still remains the question of the input to a closed computational system. If the universe is "all that exists", then even assuming the Big Bang as the

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[20] 'Miscomputation' here means a computational error or malfunction, which may occur when a physical computational system fails to correctly follow some step of the algorithm and thereby possibly produce an incorrect output.

initial state of the universe, where did the initial input to the universe come from? That is curious, for by definition there is nothing outside the universe. Incidentally, based on Calude's result regarding the limited capacity of computational processes to produce new information (2009, pp. 84–85), we conjecture that, being a reversible computational closed system, the universe can only produce limited new information. Calude shows that there is no algorithm that produces an infinity of output strings of unbounded information. The universe started in a state of low entropy (though it was in thermal equilibrium for the given constraints, volume, etc.). Provided that new information can be produced algorithmically only in a bounded quantity, it seems implausible that a closed system all of whose processes are algorithmic and deterministic will lead to a state of maximal entropy. If that is right, it is at odds with the second law of thermodynamics.

Thirdly, standard models of *reversible* computation generate "garbage" information that must eventually be discarded due to the finiteness of the universe. Whether we consider reversible algorithms or reversible Boolean gates, "garbage" outputs are added in addition to the "real" outputs. A reversible Boolean AND-gate can be built by adding "garbage" output lines. That is, rather than being a two-input, one-output Boolean gate, it has the same number of input and output lines. This design allows input to always be deducible from the output (Li & Vitányi, 2008, p. 631). Similarly, the limitation of Bennett's reversible TM model is space rather than time. When space is limited, there may not be enough space to store "garbage" information. This inevitably results in the need to *irreversibly* erase some "garbage" information (Vitányi, 2005, p. 440).

It seems that from the point of view of a finite universe changing in an entropy-increasing direction, "garbage" information should be discarded to allow the production of new information. From the point of view of a computational process “a garbage object [… is] inaccessible and cannot influence the future course of the computation” (Baker, 1992, p. 512). Still, for the overall system (the computational universe) “the [garbage] object is still accessible, and will be reclaimed by the [garbage] collector” (ibid). In reversible computational systems “garbage” information does not “influence” the future evolution of the computation. It is redundant information designed to allow the reconstruction of the computational history of the system. Yet, once the “garbage” information is “collected” there is, inevitably, some information loss. The need to record some redundant information, but then destroy it when extra storage space is needed raises some interesting questions about the effectiveness and efficiency of the physical laws of the “computational” universe.

6 Conclusion

Whilst Floridi’s claim that *reality in itself is not digital* may seem plausible, we argue that it is not well justified. He claims that digital and analogue are not features of the modelled system in itself, but of some particular LoA modelling the system. He asserts, but does not establish, that it is only LoAs that are analogue or digital not noumenal reality.

Rather than arguing against *digital* ontology, it has been the burden of this paper to argue against *deterministic* (discrete) *computational* ontology. That has been done in two parts. The first part (Section 4) has argued specifically against an *irreversible* computational view of the universe. The main reason is that irreversible computations discard information, whereas the information in the universe, according to the second law of thermodynamics, increases over time. The second part (Section 5) has argued against a *deterministic reversible computational* view of the universe. Several challenges have been raised against a computational, deterministic and reversibly computational nature of the universe. It is our contention that *even* if the physical laws of the universe are compu*table*, the universe need not be compu*tational*.

Appendix

In order to make our analysis above more self-contained and accessible for readers of different backgrounds, we provide below a brief summary of some of Popper's arguments, which are relevant for our discussion. He argued that most physical systems are indeterministic (Popper, 1950a, 1950b). Popper equated (physical) indeterminism with the doctrine that "not all events are 'determined' in every detail'" (1950a, p. 120). Conversely, determinism was taken to be the doctrine that all events are *determined*, without exception, whether future, present or past. By "determined events" he meant events that are "predictable in accordance with the methods of science" (ibid). The unpredictability of events under consideration is such that it cannot be "mitigated by the predictability of their *frequencies*" (ibid, p. 117, italics added). This account of determinism makes it scientifically refutable.

Moreover, the predictability of events is, according to Popper, a physical impossibility. An unpredictable observable event may still be correctly described fortuitously. So the predictability of such event is not *logically* impossible, but rather *physically* impossible by means of the rational methods of prediction in physics. These methods include the acquisition of initial information by observation (ibid, pp. 117-118). Popper showed that in an important sense all scientific predictions are deficient even from the perspective of classical physics.

Furthermore, Popper suggested that the deterministic character of classical Newtonian mechanics is illustrated by the story of the Laplacean demon, a superhuman omniscient entity (ibid, p. 122). If all the natural laws were in the form of equations, which uniquely determine the future from the present state, then by having a perfect knowledge of the initial state of the world (the *initial information*) and using mathematical deduction this demon would be able to predict every future state of the world. This kind of predictability is arguably deterministic, for it implies that given the foreknowledge of any future state (based on the initial information), all future states must be determined *now*, because past, present and future states are all necessarily connected.

To ground this nonphysical demon in a physical realm, Popper proposed to replace it with a calculating predicting machine – *Predictor* (ibid, p. 118). Predictor (which is in fact a computer) was designed according to the laws of classical physics so as to produce permanent records of some type (say, a write-once TM tape) that can be interpreted as predictions of the positions, velocities, and masses of physical particles. Popper argued that Predictor could never *fully* predict every one of its own future states, and the part of the world with which it interacts. He showed that either no such Predictor could exist in the physical world or its future states could not be predicted by any existing Predictor (ibid, p. 119).

The crux of Popper's Predictor argument is that just as indeterminism in quantum physics is related to the measurement problem, in classical physics the interaction of Predictor with the system it measures (possibly itself) results in a similar indeterminism. If Predictor B measures another Predictor A, then B amplifies the signals from A. When another Predictor C measures the system A+B, C must also interact and amplify the signals from A+B. It is further assumed that B must also measure C and that, Popper argued, leads to the breakdown of the "one way membrane" between B and C and with it the conditions for successful predictions. None of these Predictors can have knowledge of its own state before that state has passed. Each Predictor can obtain information about its own state only either by studying the results obtained by another Predictor or by being given these results (ibid, pp. 129-130). Also, he showed that there could not be an infinite series of Predictors, such that the n^{th} Predictor is superior to its predecessors. Only on the assumption that for every Predictor P there exists some P^+ that is not only superior to P but also undetectable by P does the finite determinist doctrine hold (ibid, pp. 131-133).

Another version of the Predictor argument was based on a variation on Russell's Tristram Shandy paradox. Tristram Shandy attempts to narrate his full autobiography and in so doing he spends more time on the description of the details of every event than the time it took him to live through it. His autobiography, accordingly, rather than reaching a state of being "up to date" with present time, becomes more and more out of date. Even if Tristram Shandy is arbitrarily fast in narrating the full description of his history, he must be incapable of bringing it completely up to date (Popper, 1950b, p. 174).

Popper proposed another Predictor (call it *TP*) that is endowed with a memory in which results of its calculated predictions and the initial information received are stored. TP receives accurate and complete information about its state at time T_0 and is tasked to predict some future state at time T_n. For every physical machine, there is a maximum running speed and as a result a minimum length of time needed for completing even the shortest description of which that machine is capable. Therefore, it cannot be simply assumed that the series of time intervals between T_0 and T_n when

TP attempts to perform its prediction task converges. TP must retain in memory not only records of the final predictions, but also intermediate partial results of its calculations. Any description will take at least as much memory space as the description of the state to be predicted. Since the memory space, which can be used before T_n has elapsed, is finite, the description of TP's memory cannot be completed before T_n regardless of TP's speed (Popper, 1950b, pp. 175–177).

The last argument presented here is Popper's *Oedipus Effect*, according to which prediction can influence the predicted event (ibid: pp. 188-190). The point is that the receipt of complete information about its immediate past by a Predictor C will ultimately change its future state, since C is designed to act upon the informative signals received. This self-information qualifies as a strong interference with the working of C. Still, some very superior C^+ may foresee the future state change caused by C receiving the information, and give C inaccurate information about C's state ingeniously designed to induce C to make correct predictions about itself. However, no finite piece of information can be precise self-information. For the finite self-information must contain a description of itself and this is impossible, as there cannot be a bijection from a finite data set *S* to a smaller subset of S.

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