

Analysis.

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On the Ontological Limitations of Digital Twins

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Abstract

As modern computing prospects move toward high-fidelity modeling of complex physical phenomena, a philosophical tension emerges between the distinction of the independent digital representation and the target global and local systems of reality. Using Landauer's fundamental claim that information is physical, and by using the ontological analytical framework of Gehlert and Esswein, we interrogate the ontological status of equivalence through physical laws and mathematical isomorphism. We determine whether a target system, ontology, in this case a continuum that is reality, can be ever represented equivalently in a digital substrate through digital twins (DTs). There exists a fundamental limitation of digital substrates in their discreteness that posits a construct deficit and excess, and incompleteness according to the Einstein-Podolsky-Rosen criterion for completeness, hence, for all cases, there exists a divergence in the ontological equivalence of its target system and its digital representation. We prove this mathematically by cardinality, by thermodynamics, by

quantum mechanics, by mappings, and by digital physics. We conclude that regardless of increased fidelity, there exists a mathematical, physical, and ontological limitation for equivalence that is contradictory to the laws of nature.

Keywords: digital twins, modeling, information theory, ontology, systems

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1 Introduction

A digital twin (DT) is a mirror image of a target physical process or system that is articulated . As modern computing prospects move toward high-fidelity modeling of complex phenomena, as with the push for artificial general intelligence (AGI), world models, and extensive mappings of the physical world for predictive capacities (Ding et al., 2025; Matsuo et al., 2022; Weingram et al., 2025), there emerges a philosophical question on whether digital twins, and all technologies under its category may ever reach such fidelity that it can accurately simulate real-time phenomena to an absolute accuracy with no ontological residue, which we pertain to as construct excess/deficit, and may even predict future events within the system it represents.

Batty (2018) states that the target system and its DT cannot be equivalent, as they become merged and are identical, hence contradicting its existence as a digital twin and a collapse. In other words, the DT is an identity of the target system. However, should we presuppose that a DT must be independent, there emerges an inquiry on whether such a claim would hold.

In addition, Tomko and Winter (2019) attempt to claim that Batty’s very claims are ”plagued by a variety of misinterpretations”, more precisely arguing for its relevance as Batty initially claims irrelevance, yet states relevance by the end of his work, to which the two critique.

Here, instead of debating such matters, we investigate the very ontology, and its equivalence of DTs toward the physical realities they attempt to capture, predict, and are trained on. By the very basis of Landauer (1991)’s fundamental claim that information is physical, we use physical laws and mathematical logic to prove the non-equivalence of DTs and their target system using the framework of ontological analysis as provided by Gehlert and Esswein. The laws of nature we will discuss as with their physical implications include the limitations of the digital substrate,

thermodynamics, quantum measurement and system disturbance, and completeness theory.

It is also important to consider that the scope of this analysis will focus on global and local systems but not specifically targeting any system by choice. Thus, we will not be delving into the intricacies of artificial neural networks themselves, as such would be a reach into epistemological discussion and would present a stacked overflow of philosophical problems, rather than being focused on the implications of DTs as a whole. Hence, we consider that DTs are inclusive, as mentioned in the first paragraph, of its subcategories: CAD modeling, artificial intelligence (inclusive of deep learning, machine learning architectures), and other simulations of physical phenomena that can be measured empirically, exclusive of the *human* aspect of information as we tackle it in a perspective similar to that of Shannon.

This paper aims to achieve:

1. An improved understanding of the fundamental limitations of computational modeling with the use of discrete, silicon-based computers even in its hypothetically highest fidelity.
2. A concise, physically-grounded means of ontologically analyzing artificial intelligence, digital twins, and computational models.

2 Notation

R	Target physical system (reality / object-in-itself)
δ	Structural divergence of D and R
D	Digital twin / digital representation of R
S_t	True state of system R at time t
\mathbb{Q}	Quantum state $ \psi\rangle$ associated with element $r \in R$
\mathbb{C}	The possibility of cloning an arbitrary unknown quantum state.
L	Landauer cost: minimum thermodynamic cost of bit erasure
k_B	Boltzmann constant: Landauer principle scaling factor
$equiv(D, R)$	Ontological equivalence of states systems D and R
$sim(D, R)$	Ontological similarity of states systems D and R , where certain elements either unrepresented or
$\Delta(D, R)$	D and R exist as separate, different physical entities
$comp(D, R)$	Valid completeness according to the Einstein-Podolsky-Rosen Paradox

3 Axioms

1. Information is physical and tangible; it is a dissipative state of matter that incurs a non-zero thermodynamic cost $L = \Delta S > 0$ (Chattopadhyay et al., 2025; Landauer, 1991)
2. The target system Reality R is a continuous manifold defined by real-valued fields.
3. Information is not the fundamental stuff of the universe. It is a necessary condition that there exists a physical substrate for an *it* from *bit* to manifest.
4. To assimilate information to a DT D , there must be a measurement made on R
5. There exists a changed system R' from observations of R as the act of measurement $M(R) \supset R'$ creates a disturbance in the system in which the initialization of an observation perturbs the system itself.

6. By definition, an entity within a digital substrate d must operate discretely regardless of high-power computing. Therefore, its composite D must be fundamentally limited in discrete operations.
7. Any physical description, theory, or representation of reality is considered ontologically equivalent only if it is considered complete.
8. R and D are independent systems as $D \neq R$ in its definition as a separate representation.

4 Criteria for Ontological Equivalence

Framework for Ontological Analyses : The formalization of March and Allen (2007)'s *Ontological Foundations for Active Information Systems* by Gehlert and Esswein (2007) is one of the foundational frameworks we will utilize in this paper. In particular, Gehlert and Esswein (2007) formalize ontological analysis mathematically, and define four requirements that are used both for evaluating ontological frameworks and ontology-in-itself.

In this regard, we will utilize their requirements in the evaluation of ontological equivalence, and an additional criteria which may also be considered under the requirements, the Einstein-Podolsky-Rosen Paradox.

These requirements are defined as the following:

1. Analysis must be based on the same ontological constructs
2. The analysis must specify the constructs of the modeling grammar that is used.
3. Each pairwise mapping of a system must be represented as equivalent, similar, or different
4. For each similarity mapping type, the criteria must be made explicit.

In the paper, we will use select terminologies interchangeably, particularly the modeling grammar, which may also be *theory*, in the context of EPR, the digital twin itself, the digital substrate, and symbolically, and much more commonly we refer to as D wherein D contains elements of a digital substrate d .

Ontology, as used in the framework, is what we use as the *target system* or the *reality* itself. Note that target systems are not always reality, but we use reality as the target system as measurements must be made in reality to be twinned.

A *construct deficit* refers to a lack in representation of the modeling grammar D to the ontology R . A *construct excess* will mean that there is excess information or element in modeling grammar D that is lacking in R . An *ontological overload* is where an element of modeling grammar D is mapped to represent more than one element of R .

Interpretation mapping refers to a function that relates modeling grammar onto ontology, and representation mapping refers to the converse.

The Einstein-Podolsky-Rosen (EPR) Criterion for Completeness $comp(D, R)$: If a physical element r of the physical reality R can be predicted with certainty in D , without a disturbance in the system, there must exist a counterpart in the physical theory, which in this case is our modeling grammar, D (Einstein et al., 1935). We denote this as:

$$comp(D, R) \equiv \forall r \in R, \exists d \in D$$

such that $f(d) = r$ for a digital substrate be ontologically equivalent to its target system.

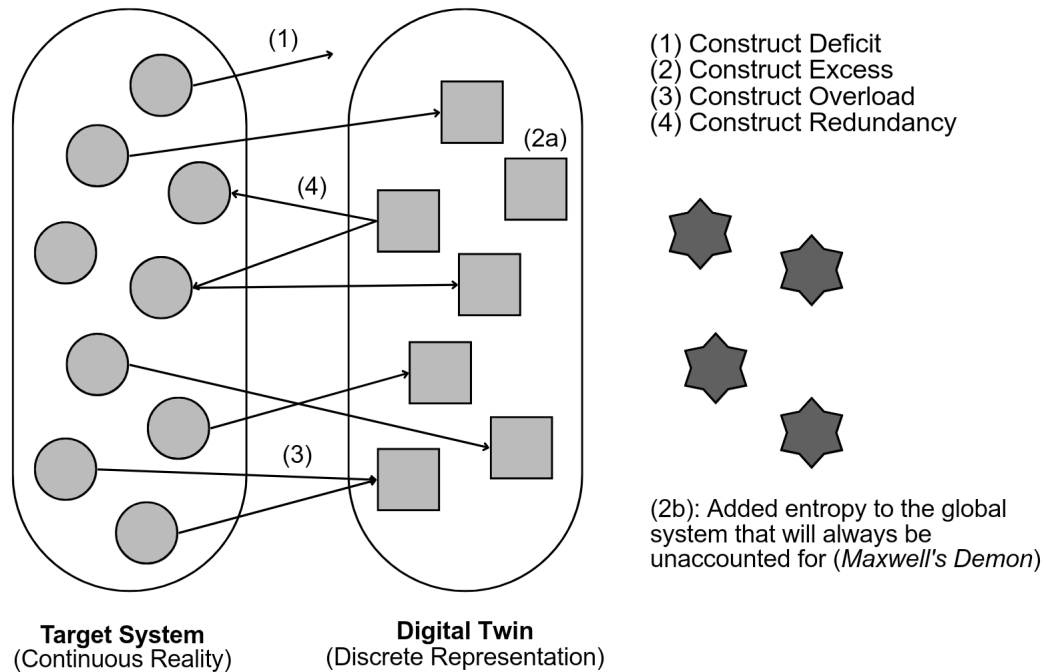


Figure 1. A graphical representation of mapping based on Gehlert and Esswein (2007). A complete, equivalent mapping of a set would posit all elements meet (1). Also representative of cardinality mapping as we will see in section 5.1, using set theory.

5 Proofs

5.1 Proof by Cardinality

Writing in terms of bijective mapping we get:

$$\text{equiv}(D, R) \supset f : |R| \xrightarrow{\sim} |D|$$

In Axiom 2, we have defined R as a continuous manifold in real-valued fields, in set theory of cardinality $|R| = 2^{\aleph_0}$. By Axiom 6, the digital substrate D is defined as limited to discrete operations, thus countably infinite $|D| = \aleph_0$. According to our criterion, we want all elements $r \in R$ to be mapped by a value of $d \in D$ regardless of whether the system is locally or globally defined over its domain.

It is mathematically impossible for a discrete set to be bijectively mapped onto a continuous set and vice versa due to difference in cardinality.

Therefore, a contradiction and a collapse emerges from our conditions of completeness and equivalence, as there exist construct deficits:

$$1 : \sim ((f : |R| \xrightarrow{\sim} |D|))$$

$$2 : equiv(D, R) \supset (f : |R| \xrightarrow{\sim} |D| = \forall r \in R, \exists d \in D)$$

2,1 MT

$$\therefore \sim equiv(D, R)$$

We observe that based on the discrete substrate D , there exists an infinite construct deficit as there are uncountably infinite points in the continuum R that is unaccounted for in D by cardinality. Recall that states in R must be accounted for in D , Therefore, the mapping is only similar by requirement 3.

5.2 Proof by Thermodynamics

By Landauer (1991)'s Principle, any increase in the resolution of D with respect to R leads to a proportional increase in entropy: $\Delta S > 0$. The erasure of one bit, in particular, would posit an exact change of $k_B \ln 2$ (Chattopadhyay et al., 2025).

As we increase the resolution, complexity of D , the amount of information that must be processed increases as we decrease δ .

By Axiom 1, the work that is required for the digital substrate to update its state is limited to the erasure of its bits, because it cannot store infinite information. By Axiom 4, as a requirement of assimilation and initialization, there always exists a continuous change in the states as the model updates and erases the previous states.

Since R is a continuous manifold by Axiom 2, the state of R contains infinite information. For D to achieve $equiv(D, R)$, there must be an infinite erasure rate to keep up with the continuity of

R .

To achieve $equiv(D, R)$ identically $\delta = 0$ and where R is independent by Axiom 5, there would be an infinite number of bit erasures and updates within every infinitesimal moment. Therefore, the total Landauer cost approaches infinity as the resolution/fidelity of the twin approaches the continuous limit of reality $\Delta t \rightarrow 0$. We may represent this as a mathematical limit of the total Landauer cost:

$$L = \lim_{\Delta t \rightarrow 0} \sum \frac{k_B T \ln 2}{\Delta t}$$

By elementary limit calculations,

$$L \rightarrow \infty$$

If we assume that a state of $equiv(D, R)$ can be achieved even without an infinite energy source, then there would be an infinite capacity to process information without an increase in the environment's entropy: which is akin to Maxwell's Demon, which also requires that there exists a construct excess as there is energy unaccounted for by system for there to be equivalence and completeness.

By Axiom 1, a physical substrate cannot support a complete digital twin without violating the Second Law of Thermodynamics. By our framework, there must exist a construct residue that is unaccounted for if we assume a global system.

5.3 Proof by Quantum Mechanics

Here we utilize Wootters and Zurek (1982)'s No-Cloning Theorem which posits that it is impossible to create an identical, independent copy of an arbitrary unknown quantum state. We define \mathbb{Q} as the quantum state of an element $r \in R$, and \mathbb{C} as the boolean possibility of cloning the quantum state.

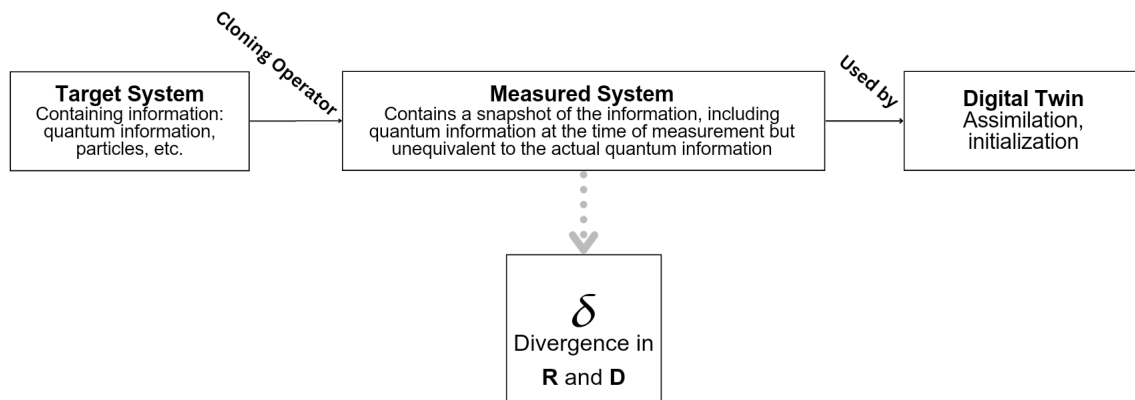


Figure 2. A graphical representation of a measurement in the quantum system upon an initialization of a copy by U , and its outcome wherein the two systems are no longer alike. Hence, a violation of Axiom 1 by quantum mechanics and Axiom 5 on measurement.

Recall that:

$$equiv(D, R) \equiv \forall r \in R, \exists d \in D ||Q_d\rangle = |Q_r\rangle$$

In other words, equivalence must mean that elements, including quantum states and information are equivalent.

Suppose we let the variable s_D represent the blank slate of the digital substrate before its initialization and U as the unitary twinning operator. By the theorem, formally, no unitary operator U can copy an arbitrary quantum state Q . So, if Q is a superposition, then any attempt to copy a state would result in collapse.

$$\nexists U |U(Q_R \otimes s_D) = Q_R \otimes Q_D$$

Any copy equated from the unitary operator in D would be a classical, reduced approximation or a measurement outcome Q_D , and have an unlike quantum state with the real system Q_R .

Recall that such measurements are necessary for either initialization or assimilation by Axiom 4. Hence, if the two are inequivalent by the act of measurement, then there exists a divergence

$\delta \neq 0$.

If we attempt to force a duplication of states, R, D become entangled, in other words, are made inseparable. Entanglement, in which if we measurement on one subsystem constrains the outcomes of another, would posit that the two are no longer independent entities $\Delta(D, R)$. Therefore, to be a twin, $D = R$. By Axiom 8, we know that D and R must be independent $D \neq R$. Therefore, this violates Axiom 8.

And so, it is not the case that all information within a system can be copied, as quantum information cannot be cloned. Thus there exists a construct deficit in which the reality is unmodeled, rather the modified reality. By Axiom 5, this also creates a violation of EPR.

5.4 Proof by Mappings

Here we focus on a much smaller system by looking at intervals than global sets in section 5.1.

By Axioms 2 and 6, we see that the shift from a continuum R to a discrete substrate D fundamentally collapses the causal continuity of reality.

Suppose that in a continuous manifold R for any two elements, in which we will consider points r_1, r_2 , then there exists an infinite number of intermediate states in their interval $I(r_1, r_2)$.

By Axiom 6, there must exist a minimum distance to move from r_1 to r_2 in intervals. Thus, there emerges an ontological residue in $\delta > 0$.

In a way, such a perspective may be likened to that of Zeno's Paradox in reality, and in theory.

Physical laws in R are defined by equations that utilize approximations of infinity and zero. Discrete representations are unable to do such a thing. Take for instance, a Riemann Sum and the formal integral: There always exists intervals in the space. By Axiom 3, each block is a physical state.

If we apply Landauer's Principle, by placing each hypothetical block to approximate a hill's area would require infinite energy, and infinite heat. Recall that such an occurrence, by the Proof of Thermodynamics, would lead to a violation of the Second Law of Thermodynamics, which therefore violates Axiom 1.

Hence, there exists $\delta > 0$ and a construct deficit.

5.5 Proof by Signals

The Nyquist-Shannon theorem (Nyquist, 1928; Shannon, 1949) posits that a continuous time signal can be perfectly reconstructed using its samples if the sampling rate f_s is greater than twice the highest frequency component. This is also known as the minimum required rate *Nyquist rate*.

In a continuous system R , it contains fluctuations at arbitrarily small scales. If R possesses infinite bandwidth, then the highest frequency approaches infinity as well. A requisite to equivalence would be an infinite sampling rate, necessitating infinite memory and processing power, which conclusively violates Axiom 3 and thermodynamics.

Asymptotically, when we scale parameters, computing power, or model complexity, like say, adding more data centers, graphical processing units to measure and process as a DT, as f_s increases, so long as f_s remains discretely finite, and the highest frequency remains infinite in the continuous manifold, then $\delta \rightarrow 0, \delta \neq 0$. For such equivalence to be valid, there must be a construct excess regardless.

Table 1: A tabular representation of axioms, requirements affected and are used by the proofs

	5.1	5.2	5.3	5.4	5.5
A_1		X	X		X
A_2	X	X		X	X
A_3		X			X
A_4			X		X
A_5		X	X		X
A_6	X			X	X
A_7	X	X	X	X	X
A_8		X			X
Requirements of Equivalence					
EPR	X	X	X	X	X
Status	$sim(D, R)$	$sim(D, R)$	$\Delta(D, R)$	$sim(D, R)$	$sim(D, R)$

6 Conclusion

We conclude that the representation mapping of D will always be ontologically barred for equivalence with R , incomplete by the EPR, and similar by the framework. As fidelity increases, there exists a fundamental physical limitation for ontological equivalence by construct excess, and a mathematical limitation of construct deficit. Therefore, there exists information *noise* generated by complexity scaling that contributes to the physical excess.

7 Supplementary Cases

7.1 The Argument of a Binary Universe

We are presented with a reasonable dilemma when a fundamental axiom from our system is challenged. Particularly, suppose that Wheeler (1989)'s postulate of It-From-Bit is correct, thus R is not a continuous manifold. In this case, we will be operating in a world where Axiom 2 is discarded. In this interpretation, reality is fundamentally discrete and informational; wherein the fundamental stuff is *information* and is, by its title, emerges from binary units.

By such perspective, the universe, then, would be an exponentially complex binary composite of operations; that in which our two proofs, particularly the Proofs by Cardinality and Mappings

fall short.

If R is already digital, then a digital substrate of R , D could theoretically achieve ontological equivalence and completeness by satisfactorily mapping bijectively.

However, we must understand that for D to be a twin, it must exist on a substrate within R independently. If the universe were a computer, then D is a simulation within such a computer, sort of like the philosophical equivalent of a *virtual machine*. To represent its target system perfectly, it [the digital substrate] would need more bits than the target system itself by Berkenstein.

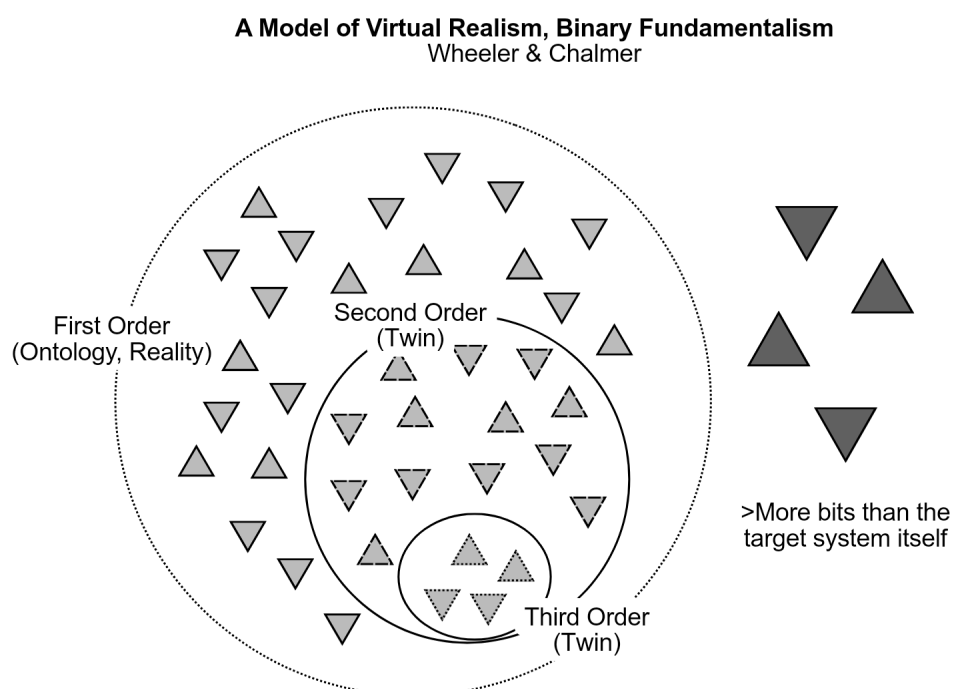


Figure 3. A graphical representation of a binary unit reality as argued in Virtual Realism (Chalmers, 2017) and It-from-Bit (Wheeler, 1989). Here we visualize the incompatibility of a bit-based reality and the hypothetical models that a complete DT aims to achieve. If such were the case, then the target reality itself must be in another digital substrate, hence an infinite regression of substrates.

Additionally, even if R is discrete, performing a copy of its state into D requires energy and generates entropy, in which our Proof of Thermodynamics still holds.

7.2 Floridi's Levels of Abstraction

I had initially considered Floridi (2010)'s Levels of Abstraction (LoA) as a fundamental axiom, but that in itself would create an epistemological *leap* of sorts.

That is, all possible outcomes of twinning would posit an **abstraction**. When a proponent claims that they have achieved formal isomorphism and ontological equivalence, then they are simply making a claim about an abstraction of fundamental reality that is uninterpretable. In addition, such a claim of ontological equivalence would, in fact, be practically impossible as there emerges an immutable perspectival boundary between an observer and the natural world.

7.3 Turing's Argument from Continuity of the Nervous System

In *Computing Machinery and Intelligence*, one of the objections to the question 'Can Machines Think' by Turing (1950) was the continuous nature of the nervous system as an analog system against the possibility of a discrete machine such as both the [analog] computer of his time and the computer of now ever being able to think.

In a way, and largely, in fact, is very similar to the central proofs presented in this paper. However, it is important to acknowledge that this rests under the fundamental assumption of the continuity physical reality, which up to now, is being debated upon in fundamental physics, and a debate that I hope this paper will at the very least contribute to, ever so slightly.

8 Discussion

8.1 On World Models and Functional Equivalence

As we conclude that ontological equivalence is physically impossible and fundamentally limited for digital twins, the contemporary push for world models as a prospect in modern AI remains trivial in its pursuit for accuracy. However, as we also conclude, it is not necessarily a limitation for functional equivalence. In fact, they may be considered *similar*.

It has become apparent that the prospects of digital twinning is widely what the industry wishes

to pursue the next step in this technology, however it must come to their realization that such models may never achieve the absolute minimum of error. It is, however, not really the goal to reach such a threshold of error.

Still, I argue, that even as we increase epochs, nodes, layers, and data centres, that we may never reach the fidelity of the continuum of the universe. It remains unclear whether AGI, world models, or actual copied neurons *are* actual intelligence, actual "realities", and are actual *living* beings. It is only clear to us that they will never become of the same quality as what is ontological.

8.2 On Wheeler's It-From-Bit

As with section 7.1, we observe that there may exist a challenging outcome with the acceptance of a digital reality. However, by Landauer's physicality, although information is physical, a binary unit is not necessarily the fundamental stuff. Instead, it exists as a separate physical manifestation that generates entropy. A perfect "copy" of such a binary world would need more bits than the target system contains.

Reality can not be information alone, and it cannot be the fundamental stuff as there remains a structure of the reality that is unmapped by any hypothetical digital representation as they are both mathematically and physically constrained.

8.3 On Simulation Theory

In the possibility that the plane of existence, our lived system of reality, is not necessarily what our target reality is, and we are incomprehensibly complex simulacra in an incomprehensibly complex simulation, then there exists a reality of a magnitude higher than us that is the true target reality, and we are an imperfect imitation in a substrate.

There are two possibilities in this, in the case that we are living in a digital substrate in highly complex hypothetical computers, then we are fundamentally barred from being *real*. If we are living in a hypothetical continuum, in a hypothetical, infinite complex analog computer, then we may be in a reality that is not fundamentally barred, and that there may exist worlds like ours in the

same fidelity, and we may even be of the same fidelity as the precedence of our world.

8.4 On Temporality

It is important to consider the question of *time* here. Although we can model local systems fairly easily, and so much so as a feat of the ingenuity of physics and engineering where we may model the aerodynamics, thermodynamics, chemical reactions, and so on, a global model, or even so much so as a model that just accounts for more than one physical object at a time, its interactions, its dynamics, remains significantly difficult to both maintain and to create.

Artificial neural networks, with the likes of physics-informed neural networks (PINNs), have managed to solve some of these problems, as with also the example of AlphaFold where millions of proteins were finally given 3D molecular structures, which would have taken centuries to accomplish with manual work.

So, then, will time-series models be able to account for such a vast amount of calculations, information processing as the real world? To this, we say no. It is important to consider the finiteness of both resources and of the universe as we show with thermodynamic limits in section 5.2.

Hypothetically, should a digital twin be able to become independent and equivalent, only will it become able to predict *everything*. As we prove that it is a fundamental limitation, exact phenomena of both global and local systems may never be convergent. At a certain point in time, there will always be divergence. In a global model of a target system, from its inception, it will always be divergent.

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