Quantum Mechanics_digital physics

In physics and cosmology, **digital physics** is a collection of theoretical perspectives based on the premise that the universe is, at heart, describable byinformation, and is therefore computable. Therefore, according to this theory, the universe can be conceived of as either the output of a deterministic or probabilistic computer program, a vast, digital computation device, or mathematically isomorphic to such a device.

Digital physics is grounded in one or more of the following hypotheses; listed in order of decreasing strength. The universe, or reality:

- is essentially informational (although not every informational ontology needs to be digital)
- is essentially computable (the pancomputationalist position)
- can be described digitally
- is in essence digital
- is itself a computer (pancomputationalism)
- is the output of a simulated reality exercise

History

Every computer must be compatible with the principles of information theory,statistical thermodynamics, and quantum mechanics. A fundamental link among these fields was proposed by Edwin Jaynes in two seminal 1957 papers.[1]Moreover, Jaynes elaborated an interpretation of probability theory as generalized Aristotelian logic, a view very convenient for linking fundamental physics withdigital computers, because these are designed to implement the operations ofclassical logic and, equivalently, of Boolean algebra.[2]

The hypothesis that the universe is a digital computer was pioneered by Konrad Zuse in his book *Rechnender Raum* (translated into English as *Calculating Space*). The term *digital physics* was first employed by Edward Fredkin, who later came to prefer the term *digital philosophy*.[3] Others who have modeled the universe as a giant computer include Stephen Wolfram,[4] Juergen Schmidhuber,[5] and Nobel laureate Gerard 't Hooft.[6] These authors hold that the apparentlyprobabilistic nature of quantum physics is not necessarily incompatible with the notion of computability.

Quantum versions of digital physics have recently been proposed by Seth Lloyd,[7] David Deutsch, and Paola Zizzi.[8]

Related ideas include Carl Friedrich von Weizsäcker's binary theory of ur-alternatives, pancomputationalism, computational universe theory, John Archibald Wheeler's "It from bit", and Max Tegmark's ultimate ensemble.

Overview

Digital physics suggests that there exists, at least in principle, a program for auniversal computer which computes the evolution of the universe. The computer could be, for example, a huge cellular automaton (Zuse 1967[9]), or a universalTuring machine, as suggested by Schmidhuber (1997[*citation needed*]), who pointed out that there exists a very short program that can compute all possible computable universes in an asymptotically optimal way.

Some try to identify single physical particles with simple bits. For example, if oneparticle, such as an electron, is switching from one quantum state to another, it may be the same as if a bit is changed from one value (0, say) to the other (1). A single bit suffices to describe a single quantum switch of a given particle. As the universe appears to be composed of elementary particles whose behavior can be completely described by the quantum switches they undergo, that implies that the universe as a whole can be described by bits. Every state is information, and every change of state is a change in information (requiring the manipulation of one or more bits). Setting aside dark matter and dark energy, which are poorly understood at present, the known universe consists of about 10^{80} protons and the same number of electrons. Hence, the universe could be simulated by a computer capable of storing and manipulating about 10^{90} bits. If such a simulation is indeed the case, then hypercomputation would be impossible.

Loop quantum gravity could lend support to digital physics, in that it assumes space-time is quantized. Paola Zizzi has formulated a realization of this concept in what has come to be called "computational loop quantum gravity", or CLQG.[10][11] Other theories that combine aspects of digital physics with loop quantum gravity are those of Marzuoli and Rasetti[12][13] and Girelli and Livine.[14]

Weizsäcker's ur-alternatives

Physicist Carl Friedrich von Weizsäcker's theory of ur-alternatives (archetypal objects), first publicized in his book *The Unity of Nature* (1980),[15] further developed through the 1990s,[16][17] is a kind of digital physics as it axiomaticallyconstructs quantum physics from the distinction between empirically observable, binary alternatives. Weizsäcker used his theory to derive the 3-dimensionality of space and to estimate the entropy of a proton falling into a black hole.

Pancomputationalism or the computational universe theory

Pancomputationalism (also known as pan-computationalism, naturalist computationalism) is a view that the universe is a huge computational machine, or rather a network of computational processes which, following fundamental physical laws, computes (dynamically develops) its own next state from the current one.[18]

A computational universe is proposed by Jürgen Schmidhuber in a paper based on Konrad Zuse's assumption (1967) that the history of the universe is computable. He pointed out that the simplest explanation of the universe would be a very simple Turing machine programmed to systematically execute all possible programs computing all possible histories for all types of computable physical laws. He also pointed out that there is an optimally efficient way of computing all computable universes based on Leonid Levin's universal search algorithm (1973). In 2000, he expanded this work by combining Ray Solomonoff's theory of inductive inference with the assumption that quickly computable universes are more likely than others. This work on digital physics also led to limit-computable generalizations of algorithmic information or Kolmogorov complexity and the concept of Super Omegas, which are limit-computable numbers that are even more random (in a certain sense) than Gregory Chaitin's number of wisdomOmega.

Wheeler's "it from bit"

Following Jaynes and Weizsäcker, the physicist John Archibald Wheeler wrote the following:

[...] it is not unreasonable to imagine that information sits at the core of physics, just as it sits at the core of a computer. (John Archibald Wheeler1998: 340)

It from bit. Otherwise put, every 'it'—every particle, every field of force, even the space-time continuum itself—derives its function, its meaning, its very existence entirely—even if in some contexts indirectly—from the apparatus-elicited answers to yes-or-no questions, binary choices, bits. 'It from bit' symbolizes the idea that every item of the physical world has at bottom—a very deep bottom, in most instances—an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes-no questions and the registering of equipment-evoked responses; in short, that all things physical areinformation-theoretic in origin and that this is a participatory universe. (John Archibald Wheeler 1990: 5)

David Chalmers of the Australian National University summarised Wheeler's views as follows:

Wheeler (1990) has suggested that information is fundamental to the physics of the universe. According to this 'it from bit' doctrine, the laws of physics can be cast in terms of information, postulating different states that give rise to different effects without actually saying what those states are. It is only their position in an information space that counts. If so, then information is a natural candidate to also play a role in a fundamental theory of consciousness. We are led to a conception of the world on which information is truly fundamental, and on which it has two basic aspects, corresponding to the physical and the phenomenal features of the world.[19]

Chris Langan also builds upon Wheeler's views in his epistemological metatheory:

The Future of Reality Theory According to John Wheeler:

In 1979, the celebrated physicist John Wheeler, having coined the phrase "black hole", put it to good philosophical use in the title of an exploratory paper, Beyond the Black Hole, in which he describes the universe as a self-excited circuit. The paper includes an illustration in which one side of an uppercase U, ostensibly standing for Universe, is endowed with a large and rather intelligent-looking eye intently regarding the other side, which it ostensibly acquires through observation as sensory information. By dint of placement, the eye stands for the sensory or cognitive aspect of reality, perhaps even a human spectator within the universe, while the eye's perceptual target represents the informational aspect of reality. By virtue of these complementary aspects, it seems that the universe can in some sense, but not necessarily that of common usage, be described as "conscious" and "introspective"…perhaps even "infocognitive".[20]

The first formal presentation of the idea that information might be the fundamental quantity at the core of physics seems to be due to Frederick W. Kantor (a physicist from Columbia University). Kantor's book *Information Mechanics* (Wiley-Interscience, 1977) developed this idea in detail, but without mathematical rigor.

The toughest nut to crack in Wheeler's research program of a digital dissolution of physical being in a unified physics, Wheeler himself says, is time. In a 1986 eulogy to the mathematician, Hermann Weyl, he proclaimed: "Time, among all concepts in the world of physics, puts up the greatest resistance to being dethroned from ideal continuum to the world of the discrete, of information, of bits. ... Of all obstacles to a thoroughly penetrating account of existence, none looms up more dismayingly than 'time.' Explain time? Not without explaining existence. Explain existence? Not without explaining time. To uncover the deep and hidden connection between time and existence ... is a task for the future."[21] The Australian phenomenologist, Michael Eldred, comments:

The antinomy of the continuum, time, in connection with the question of being ... is said by Wheeler to be a cause for dismay which challenges future quantum physics, fired as it is by a will to power over moving reality, to "achieve four victories" (*ibid.*)... And so we return to the challenge to "[u]nderstand the quantum as based on an utterly simple and—when we see it—completely obvious idea" (*ibid.*) from which the continuum of time could be derived. Only thus could the will to mathematically calculable power over the dynamics, i.e., the movement in time, of beings as a whole be satisfied.[22][23]

Digital vs. informational physics

Not every informational approach to physics (or ontology) is necessarily digital. According to Luciano Floridi,[24] "informational structural realism" is a variant ofstructural realism that supports an ontological commitment to a world consisting of the totality of informational objects dynamically interacting with each other. Such informational objects are to be understood as constraining affordances.

Digital ontology and pancomputationalism are also independent positions. In particular, John Wheeler advocated the former but was silent about the latter; see the quote in the preceding section.

On the other hand, pancomputationalists like Lloyd (2006), who models the universe as a quantum computer, can still maintain an analogue or hybrid ontology; and informational ontologists like Sayre and Floridi embrace neither a digital ontology nor a pancomputationalist position.[25]

Computational foundations

Turing machines

Theoretical computer science is founded on the Turing machine, an imaginary computing machine first described by Alan Turing in 1936. While mechanically simple, the Church–Turing thesis implies that a Turing machine can solve any "reasonable" problem. (In theoretical computer science, a problem is considered "solvable" if it can be solved in principle, namely in finite time, which is not necessarily a finite time that is of any value to humans.) A Turing machine therefore sets the practical "upper bound" on computational power, apart from the possibilities afforded by hypothetical hypercomputers.

Wolfram's principle of computational equivalence powerfully motivates the digital approach. This principle, if correct, means that everything can be computed by one essentially simple machine, the realization of a cellular automaton. This is one way of fulfilling a traditional goal of physics: finding simple laws and mechanisms for all of nature.

Digital physics is falsifiable in that a less powerful class of computers cannot simulate a more powerful class. Therefore, if our universe is a gigantic simulation, that simulation is being run on a computer at least as powerful as a Turing machine. If humans succeed in building a hypercomputer, then a Turing machine cannot have the power required to simulate the universe.

The Church–Turing (Deutsch) thesis

The classic Church–Turing thesis claims that any computer as powerful as aTuring machine can, in principle, calculate anything that a human can calculate, given enough time. Turing moreover showed that there exist universal Turing machines which can compute anything any other Turing machine can compute—that they are generalizable Turing machines. But the limits of practical computation are set by physics, not by theoretical computer science:

"Turing did not show that his machines can solve any problem that can be solved 'by instructions, explicitly stated rules, or procedures', nor did he prove that the universal Turing machine 'can compute any function that any computer, with any architecture, can compute'. He proved that his universal machine can compute any function that any Turing machine can compute; and he put forward, and advanced philosophical arguments in support of, the thesis here called Turing's thesis. But a thesis concerning the extent of effective methods—which is to say, concerning the extent of procedures of a certain sort that a human being unaided by machinery is capable of carrying out—carries no implication concerning the extent of the procedures that machines are capable of carrying out, even machines acting in accordance with 'explicitly stated rules.' For among a machine's repertoire of atomic operations there may be those that no human being unaided by machinery can perform." [26]

On the other hand, a modification of Turing's assumptions *does* bring practical computation within Turing's limits; as David Deutsch puts it:

"I can now state the physical version of the Church–Turing principle: 'Every *finitely* realizable physical system can be perfectly simulated by a universal model computing machine operating by *finite* means.' This formulation is both better defined and more physical than Turing's own way of expressing it."[27] (Emphasis added)

This compound conjecture is sometimes called the "strong Church–Turing thesis" or the Church–Turing–Deutsch principle. It is stronger because a human or Turing machine computing with pencil and paper (under Turing's conditions) is a finitely realizable physical system.

Criticism

The critics of digital physics—including physicists[*citation needed*] who work inquantum mechanics—object to it on several grounds.

Physical symmetries are continuous

One objection is that extant models of digital physics are incompatible[*citation needed*] with the existence of several continuous characters of physical symmetries, e.g., rotational symmetry, translational symmetry,Lorentz symmetry, and electroweak symmetry, all central to current physical theory.

Proponents of digital physics claim that such continuous symmetries are only convenient (and very good) approximations of a discrete reality. For example, the reasoning leading to systems of natural units and the conclusion that the Planck length is a minimum meaningful unit of distance suggests that at some level space itself is quantized.[28]

Moreover, computers can manipulate and solve formulas describing real numbers using symbolic computation, thus avoiding the need to approximate real numbers by using an infinite number of digits.

A number—in particular a real number, one with an infinite number of digits—was defined by Turing to be computable if a Turing machine will continue to spit out digits endlessly. In other words, there is no "last digit". But this sits uncomfortably with any proposal that the universe is the output of a virtual-reality exercise carried out in real time (or any plausible kind of time). Known physical laws (including quantum mechanics and its continuous spectra) are very much infused with real numbers and the mathematics of the continuum.

"So ordinary computational descriptions do not have a cardinality of states and state space trajectories that is sufficient for them to map onto ordinary mathematical descriptions of natural systems. Thus, from the point of view of strict mathematical description, the thesis that everything is a computing system in this second sense cannot be supported".[29]

For his part, David Deutsch generally takes a "multiverse" view to the question of continuous vs. discrete. In short, he thinks that "within each universe all observable quantities are discrete, but the multiverse as a whole is a continuum. When the equations of quantum theory describe a continuous but not-directly-observable transition between two values of a discrete quantity, what they are telling us is that the transition does not take place entirely within one universe. So perhaps the price of continuous motion is not an infinity of consecutive actions, but an infinity of concurrent actions taking place across the multiverse." January, 2001 The Discrete and the Continuous, an abridged version of which appeared in The Times Higher Education Supplement.

Locality

Some argue that extant models of digital physics violate various postulates ofquantum physics (as in [30]). For example, if these models are not grounded inHilbert spaces and probabilities, they belong to the class of theories with localhidden variables that some deem ruled out experimentally using Bell's theorem. This criticism has two possible answers. First, any notion of locality in the digital model does not necessarily have to correspond to locality formulated in the usual way in the emergent spacetime. A concrete example of this case was recently given by Lee Smolin.[31][*specify*] Another possibility is a well-known loophole inBell's theorem known as superdeterminism (sometimes referred to as predeterminism).[32][*clarification needed*] In a completely deterministic model, the experimenter's decision to measure certain components of the spins is predetermined. Thus, the assumption that the experimenter could have decided to measure different components of the spins than he actually did is, strictly speaking, not true.

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