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Information as a physical quantity

Neal G. Anderson

Department of Electrical and Computer Engineering University of Massachusetts Amherst Amherst, MA 01003-9292, USA

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ABSTRACT

A new physical conception of classical information in quantum mechanical systems is explicated, critically assessed, and formalized in a quantitative measure. Observer-local referential (OLR) information—a shared physical property of entities accessible to a specified observer—is defined on the joint states of composite systems, distinguished from related conceptions of information, and tested against strict criteria that would simultaneously qualify it as a physical state quantity and as a meaningful measure of classical information. It is shown specifically to satisfy these criteria in the technological context of digital computation on quantum-physical substrates, where familiar alternatives—the von Neumann entropy and quantum mutual information (or correlation entropy)— fall short. The OLR conception provides a natural foundation for the fundamental physical description of information processing in digital computing systems, both because it defines information as a physical state quantity—placing it on an equal footing with other physical quantities appearing in such descriptions—and because it captures essential features of information in computational contexts that alternative physical conceptions do not. The OLR information measure enables straightforward and thoroughly physical quantification of digital information in general quantum systems and processes, enabling unambiguous determination of bounds on physical costs of generally noisy digital computation. More generally, OLR information offers a physical foundation for information that does not require the physical to be—ontologically or metaphorically—already informational.

1. Introduction

Information is physical, so the mantra goes [22], but how physical and in what sense? Disparate views prevail. It is widely accepted that information must somehow take form in physical reality, but this leaves room for starkly different perspectives on the *nature* of the relationship between the physical and the informational. One possibility is that there is no distinction; the physical universe is made of information so the physical is informational and the informational is physical. On this view, ontologically bold as it may be, information is physical "by decree", and thus in a tautological sense. Another possibility is that information is physical in the sense that the physical can be *regarded as* being informational for the purposes of gaining new insights. On this view, which imbues physical description with ideas and formal approaches from the information sciences, information is physical in a metaphorical sense. A closely related view takes the assertion that "information is physical" to be a methodological commitment—a commitment to view physical systems through an information-theoretic lens [30].

E-mail address: anderson@ecs.umass.edu

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Yet another possibility—the possibility pursued in this work—is that information is physical in the same sense that, say, the internal energy of a gas is physical; it is a physical quantity defined on a system's physical state. Can information be physical in this strong sense? Put another way, does there exist a physical state quantity that deserves to be called "information"?

In this work, we explicate and critically assess a thoroughly physical conception of information that provides an affirmative answer to this question. Our conception of physical information—specifically of "classical" information in a closed quantum universe—is overtly relational and observer relative: information is defined as a joint property of physical entities belonging to an observer-accessible part of the physical universe. As such, it is quantified by an *observer-local* correlation entropy that counts correlations between observer-accessible entities—and *only* observer-accessible entities—as information. Implicit in this "observer-local referential (OLR)" information is a conceptual picture of information that rings true in the ubiquitous technological context of digital computing contexts and plausibly in broader, non-technical contexts as well. Held to the same standards, conceptions of information supported by familiar physical self-entropy and correlation (mutual information) measures—also physical state quantities—fall short.

Three essential features characterize the OLR conception of information: *aboutness, observer locality, and simultaneity*. These features collectively enable the unambiguous definition and quantification of information and its distinguishability from noise and self entropy; an unambigious definition of information processing that distinguishes physical state transformations that process information from those that do not; an account of information creation and destruction within a closed universe; and formal description of the role that situated observers play in informational settings. As such, OLR information provides a natural foundation for the fundamental physical description of information processing in computing systems, both because it defines information as a physical state quantity—placing it on an equal footing with other physical quantities appearing in such descriptions—and because it more clearly and comprehensively captures essential features of information in computational contexts than do other physical conceptions. More generally, it offers a physical foundation for information that does not require the physical to be—ontologically or metaphorically—already informational.

The paper is organized as follows: In Section 2, we make the notion of a "strong-sense physical conception of information" (SSPCI) precise, proposing a set of physical and conceptual criteria that such a conception should satisfy. In Section 3, we introduce *observer-local referential (OLR) information*—the physical quantity we propose as a basis for a SSPCI—and define this quantity within the framework of non-relativistic quantum theory using the density matrix formalism. We discuss the essential features of OLR information, distinguish it from alternatives that are self-referential and/or that do not include an observer-locality restriction, and demonstrate that OLR information easily satisfies the *physical* SSPCI criteria. Next, we address the question of whether OLR information also satisfies the *conceptual* SSPCI criteria in digital computing contexts. We outline essential aspects of the physical description of information processing by computing artifacts—physical systems that can be used by observers to perform computations—in Section 4, and clarify the connection between information processing and use of a physical system for computation. Then, in Section 5, we demonstrate the importance of satisfying the conceptual criteria for clear, unambiguous, and thoroughly physical conception and quantification of information in digital computing scenarios, and show how each of the conceptual SSPCI criteria are satisfied by OLR information in this ubiquitous technological context. We further demonstrate that these criteria cannot be fully satisfied by quantum-physical generalizations of Shannon's entropy and mutual information [28]—the von Neumann entropy and the correlation entropy (or quantum mutual information)—which are widely used as physical information measures in the literature. We then discuss applications that require a strong physical conception of information, including a key application where the OLR measure has already been deployed: the isolation of irreversible information loss in concrete digital computing scenarios and the unambiguous quantification of its minimal dissipative costs. The paper concludes in Section 6.

2. Information as a physical quantity: criteria

We begin by stating more precisely what we mean by a strong-sense physical conception of information. Any such conception should provide a comprehensive, physically grounded, and defensible account of information, unifying recognized features of information in a given context with rigorous physical description. This implies satisfaction of mutually supporting physical and conceptual criteria that are adequate to the task and are sufficiently specific and distinct from criteria supporting other conceptions of information that appropriate distinctions can be made. We propose the following criteria as adequate for, and appropriately specific to, a SSPCI:

Physical criteria – a strong-sense physical conception of information should:

- P1: be explicitly formalized within a fundamental physical theory.
- P2: include an unambiguous, quantitative information measure that is defined on the state of a physical system at any time.
- P3: clearly distinguish physical states and evolutions that bear and process information from states and evolutions that do not.

Conceptual criteria – in addition to meeting criteria P1–P3, a strong-sense physical conception of information should:

- C1: clearly support a conceptual notion of information that is compelling and defensible in its own right.
- C2: describe familiar information-related processes, such as the creation, destruction, and transfer of information, in ways that are compelling and defensible in their own right.