Physics as Computing

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Abstract

A potentially valuable side effect of the ongoing research into the fundamental physical limits of computing has been the enhancement of our understanding of how we can interpret all physical systems (with their dynamical behavior) as constituting computational systems, construed in a broad sense. As an example of this new understanding, we survey what is known regarding some ways that a variety of *physical* quantities (such as entropy, energy, temperature, momentum, *etc.*) can (validly, and we hope usefully) be reinterpreted and understood in a somewhat new way, using terminology and concepts that are borrowed from information and computation theory.

We begin with entropy, that (originally enigmatic) ratio of heat transfer to temperature which, with many thanks due to Boltzmann's pioneering work, we today can understand as being a measure of the portion of the physical information content of a system which is either *unknown or incompressible*. We discuss how this particular disjunctive conception (also suggested by Zurek) can be justified in light of the arbitrariness of the dividing line that we tend to draw separating the *knower* (that is, any entity described as possessing a probability distribution about the state of another system) from the system in question, and we discuss precisely what "incompressible" means in this context. We also discuss a conjectured connection between the entropy (in this broad definition) and the degree of entanglement of a system.

Next we visit energy, which Margolus & Levitin, Lloyd and others have shown imposes an upper bound on the rate at which computational "operations" (characterized as orthogonalizing unitary transforms) can take place. In fact, we can make the connection between energy and rate of computing even stronger. An easy proof in complex analysis shows that the action of any time-dependent Hamiltonian gives the amount of *area* swept out by a state vector's components (in any basis!) in the complex plane. If we *define* this area as the *amount of computational work* performed, then the value of the Hamiltonian becomes *exactly* the rate of computation, and prior results about the minimum time to perform various unitary transformations in a system of given energy can then be recast as giving the *amount* of computation that those transformations require (minimized over the possible Hamiltonians that could carry them out).

Next we discuss temperature, which Lloyd has provocatively pointed out seems to be related to *clock speed*, or rate of computing per bit. As a simple example, we show that at least for a simple example system of an ideal Fermi gas, the *generalized* temperature (which is defined even for non-equilibrium states) does indeed correspond exactly (apart from a constant of integration) to the average rate of computing (relative to the ground state) per unit of information capacity.

We conclude with momentum, which we analyze by breaking down the relativistic mass-energy Hamiltonian into two parts, which we term *motional* and *internal* energy. The motional energy is not exactly kinetic energy, but is closely related to it. It describes the rate of *motional computation*, that is, of computation that results in an object's being translated in a given reference frame. Meanwhile, the internal energy (which is not exactly the thermodynamic kind) describes the rate of *internal computation*, that is, of an object's updating of its internal state (as opposed to its overall position). We show that this picture is fully consistent with special relativity. In our picture, (relativistic) momentum becomes simply *the amount of motional computation performed per unit of translation through space* in a given frame. As an interesting aside, the ordinary action (the action of the Lagrangian) can be shown to correspond (modulo sign) to the amount of *internal* computation, and so, Hamilton's principle becomes equivalent to the statement that a system tends to follow the trajectory that extremizes its amount of internal computation.