Physical Measures of Computation

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The Problem: As technology progresses, we get more and more storage and processing out of given resources of matter and energy. Someday we may be able to build computers in which an appreciable fraction of the computing power inherent in a piece of matter has been harnessed. In such a computer, how will macroscopic physical parameters such as volume and energy be related to computing capability?

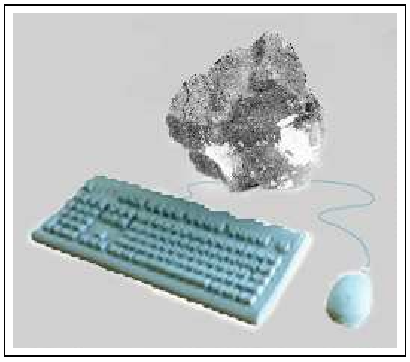

Figure 1: How much computation can be squeezed out of a rock?

Motivation: Information, in the guise of *entropy*, was a fundamental quantity in physics long before Shannon introduced it into computer science. Initially, entropy was a formal parameter that arose in the mathematics of thermodynamics. It was not until the late 1800's that Boltzmann and Gibbs realized that this abstruse parameter was just a logarithmic count of distinct physical states. This insight was further clarified by the advent of quantum mechanics, which made the notion of distinct states precise. In quantum statistical mechanics, counting states reveals which large-scale configurations of a physical system can be realized in the greatest number of ways, and are therefor the most probable configurations. Exactly the same counting can also be used to determine how many bits of information can potentially be stored in a given finite physical system.

Physical entropy is now recognized as a combinatorial quantity with a simple informational interpretation, and other basic physical quantities can also be looked upon in this manner. This leads us to expect that, as computing hardware is matched more and more closely to the constraints of microscopic physics, quantities originally formalized in the context of physics will provide useful measures and parameters governing computation.

Previous Work: Conventional computation involves operations which erase information—a kind of operation which does not exist in the reversible world of microscopic physics. Thus when a physical computer clears a register, the "erased" information does not actually disappear from the universe; microscopically this information still exists, normally in the form of heat. Eliminating the use of irreversible operations in computations can, in principle, eliminate the need for heat dissipation[1].

Computations in which every operation is invertible have been studied, and the behavior of information (and entropy) in these computations is like that of microscopic physics. When other realistic constraints such as locality of interaction and conservation of energy are also incorporated into computational models, their behavior becomes still more physics-like[2, 3]. Concepts such as locally additive conservation laws and the local flow of heat-energy apply directly to algorithms.

Approach: We study both physics-like computing models (such as reversible cellular automata) and computer-like physical systems (such as gases of billiard balls) in order to establish a correspondence between quantities in the computing and the physics domains[2, 4]. We also investigate the macroscopic informational properties of general physical systems, which become evident in a quantum mechanical analysis[5]. Here we'll focus on this last approach.

Finite quantum systems are in many ways similar to classical combinatorial systems. For example, given a set of constraints (volume, energy, materials, etc.) we can calculate how many distinct states the system can be put into. This involves determining how large a set of mutually orthogonal quantum state vectors are compatible with the given constraints. This is a finite number. The log of this number is the maximum amount of information that can possibly be stored in the given system. From statistical mechanics, we know that the number of distinct quantum states is well approximated by the volume of position/momentum space that is accessible to the system—expressed in appropriate units. Thus we know how to count states in terms of macroscopic classical parameters of the system, and so we can actually give a precise physical answer to a question such as, How many bits can we store in a rock (Fig. 1)?

Once we know how much memory our rock has, the next obvious computational question to ask is, How fast can it run? By this we mean, How quickly can the system pass from distinct state to distinct state? The answer to this question can also be given in terms of macroscopic classical parameters—we were the first to calculate this[5]. In appropriate units, the maximum achievable number of state-changes per second is simply equal to the classical energy of the system—taking the zero of energy at the system's ground state.

Difficulty: Quantities in macroscopic physics are related to statistical properties of systems, and so computational quantities derived from them may be relevant to limited domains with the right statistical properties, such as the computational simulation of physics. Additionally, it is hard to construct simple models to study, which incorporate multiple microscopic physical constraints and which capture desired large-scale behavior.

Impact: We know that information (entropy) and peak computing rate (energy) are interesting parameters of *any* computer. Thus we may hope that as our investigation of the computational meaning of macroscopic physical parameters becomes more refined, it may reveal novel computing quantities of immediate interest. Moreover, the simple digital models developed to make contact between physics and computation are of pedagogical interest—they provide clear illustrations of basic concepts in physics. In this context, quantum models—because of their finite-information character—make attractive starting points for trying to develop classical digital models. Developing such digital models would add to the store of semi-classical models that have proven so useful for understanding quantum behavior. Simple digital models of physical systems may also be of practical use for massively parallel computer simulations[2]. Informational models of physical dynamics may also have impact in clarifying the foundations of classical mechanics[4].

Future Work: Simple computer models which incorporate many realistic microscopic physical constraints also inherit some of the richness of physical dynamics, and so may provide useful models in areas such as evolution[2, 4]. Physical parameters which govern the speed of Darwinian evolution in such systems might be of great interest for evolutionary approaches to solving computational problems. It would also be interesting to develop canonical methods for going from macroscopic physical dynamics to microscopic computational models, perhaps via a least-action principle. Finally, the present discussion of energy should be extended to deal with free energy, so that it becomes directly relevant to extractable computation.

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