cal behavior of stability limits reveal themselves geometrically.

One can neither ponder these analogies nor comprehend the universality of Gibbs's methods without standing in awe of the intellect that created them. It is yet another tribute to the genius of the man that he postulated these connections over a century before machines were invented to visualize them.

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Reversible Computing and Physical Law

The work of Rolf Landauer, Charles Bennett and others on reversible computation (as described in Landauer's article "Information Is Physical," May 1991, page 23) is illuminating, and their conclusions are almost definitely correct. However, it is important to realize that as currently formulated, their work does not constitute formal physics. Phrased differently, the field of reversible computation is still very much in its infancy.

The problem lies in the absence of an overarching theoretical framework for dealing with the subject (despite some tentative attempts through the years to create one). At present there is no formal mechanism for reasoning about the restrictions that apply to any and all physical computing systems. This lack is reflected in the fact that not one single broadly applicable physics equation is presented in any of the work on reversible computation. The only mathematics in that body of work either involves abstract computation theory (for example, Turing machine theory) or hopefully illustrative engineering examples. In particular, the crucial conjecture that entropy must increase in any many-to-one mapping is nowhere formally proven. In fact no broadly applicable sequence of equations involving the expression $-\int d\Gamma\, \rho \ln\rho$ is presented anywhere, never mind such a sequence that formalizes the relationship between $-\int d\Gamma\, \rho \ln\rho$ and many-to-one mappings.

This lack of an overarching theoretical framework forces the field of reversible computation to rely heavily on reasonableness arguments and on generalizing from particular examples. Unfortunately, neither kind of argument can *prove* anything. Moreover, these kinds of arguments are extremely fragile and limited in scope. For example, the usual (reasonableness) argument that total entropy must increase in any many-to-one mapping, whether that mapping occurs in a computer or elsewhere, can be summarized as follows: A many-to-one mapping reduces entropy in those degrees of freedom of the system that contract in the mapping. Since total entropy cannot decrease, it follows that such a mapping must be accompanied by an increase in entropy elsewhere. One presumes that this entropy increase more than makes up for the entropy decrease occurring in the contracting degrees of freedom, so total entropy increases. QED. (See, for example, page 24 of Landauer's article.)

However, as has been pointed out by Jorge Berger[1] among others, this argument does not establish that total entropy *must* increase in a many-to-one mapping, only that such an increase is reasonable and that under no circumstances can there be an entropy decrease (both of which statements are true for all mappings, many-to-one or otherwise). Moreover, this kind of word argument cannot meaningfully address the temporal inverse of a process that involves a many-to-one mapping: Would such a temporal inverse of a many-to-one mapping cause a *decrease* in entropy? If so, does that mean that such a mapping is physically impossible? And what if the variable undergoing the many-to-one mapping is the entropy value itself? After all, the second law says that the multitude of possible low-entropy values of a system get mapped through time to a maximal value. As such, the evolution of such a system is essentially a many-to-one mapping over the entropy values. Yet the reasonableness argument recounted above is clearly inapplicable to such an entropic many-to-one mapping. This raises the obvious question, Might there be other situations as well in which that reasonableness argument doesn't apply?

There are a number of other major shortcomings in the (current) theory of reversible computation. For example, nowhere is there even presented a broad yet formal definition of what "many to one" means for a physical system. Does the meaning of "many to one" rely crucially on physical noninvertibility? Or can it instead be defined in terms of logical noninvertibility accompanying partitions of phase space (said partitions being induced whenever one interprets a device as being "digital")? If the meaning of "many to one" relies on physical noninvertibility, is one to conclude that if the coupling between a real-world computer and its external environment is reduced, so that the computer becomes more and more a closed (and therefore invertible) system, then the amount of entropy produced by the operation of the computer shrinks?

One can't resolve these kinds of issues by close examination of the mathematics. This is because there *is* no mathematics. Clearly, then, what is needed is a formal and rigorous mathematical theory of reversible computation.

One expects that Landauer disagrees with this conclusion and has ready replies to at least some of the issues raised above (replies based on yet more reasonableness arguments and engineering examples, no doubt!). After all, in his PHYSICS TODAY article there isn't so much as a hint that Landauer is concerned about lack of rigor. The reluctance of Landauer and Bennett to acknowledge fully the need to get away from reasonableness arguments and create a formal mathematics of reversible computation is quite strange. After all, a formal mathematics might quiet, once and for all, the various doubters of reversible computation. Moreover, in the last decade or so Landauer and Bennett have often pointed out the danger inherent in relying on reasonableness arguments when those arguments have been made by Léon Brillouin and others (see page 26 of Landauer's article, for example); one might have hoped that they would have recognized the danger inherent in their own reliance on exactly the same kinds of arguments. Indeed, it's worth noting that for several decades(!) essentially all researchers, Landauer included, were sure that reversible computation was impossible, a conclusion they reached using informal reasonableness arguments. And as it turned out, as Landauer himself readily acknowledges, this conclusion of theirs was just plain one hundred percent wrong.

Aesop himself couldn't have created a more pointed object lesson on the danger of overreliance on informal reasoning.

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Rolf Landauer's informative and provocative article ends with the suggestion that "information handling is limited by the laws of physics and the number of parts of the universe; the laws of physics are, in turn, limited by the range of information processing available." A theory that fits comfortably into this description has already achieved considerable conceptual clarity and quantitative success.[1]

We start with a finite universe of N bit strings (that is, finite ordered sequences of 0's and 1's) of length S. This universe grows by adding new strings and adding bits to strings in an algorithmic manner. The bit strings model intervals between events; one with N_1 1's and N_0 0's corresponds to a spatial separation of $(N_1 - N_0)(h/mc)$ and a time separation of $(N_1 + N_0)(h/mc^2)$. The velocity of a "particle" traveling between the two events is then given by $v = [(N_1 - N_0)/(N_1 + N_0)]c$.

If we now consider three events, we can model the system by three bit strings of the same length that add to the null string using XOR (addition modulo 2). The number of 1's in the strings satisfies the triangle inequalities and hence can be used to define the angles between the lines connecting the events. If the events lie on one line, it also follows that the velocities as defined above satisfy the usual relativistic velocity addition law, suggesting that our integer theory is "Lorentz invariant." We prove that the model gives us the usual position, momentum and angular momentum commutation relations.

To identify particles within the model we attach labels to the *content* strings that describe the (finite and discrete) space–time structure. Using 16 bits, the labels give us the six quarks, three neutrinos, three charged leptons, $W^{\pm}$, Z^0 and γ of the standard model. Three strings that add to the null string map onto a Feynman diagram vertex. Baryon number, lepton number, the z component of weak isospin and color are conserved; color is necessarily confined. Mapping the (2,4,16) decomposition of the labels onto $2^2 - 1 = 3$, $2^3 - 1 = 7$ and $2^7 - 1 = 127$, we obtain the cumulative cardinals (3,10,137), separating neutrinos from charged leptons and leptons from quarks. We justify the identification of the 137 as a first approximation to $\hbar c/e^2$ by correctly modeling the relativistic Bohr hydrogen atom, and we correct this result by deriving both the Sommerfeld formula and a logically consistent correction factor:[2] $\hbar c/e^2 = 137/[1 - 1/(30\times 127)] = 137.035\,967\,4$. Reference 2 also gives results for other basic parameters of comparable quality. Weak–electromagnetic unification at the "tree level" comes about through using the same geometrical argument to calculate the electron mass in ratio to the proton mass either from the weak or the electromagnetic interaction and equating the two results. A searching test of the theory will be whether we can go beyond order α^2 in QED to get the Lamb shift or calculate the "running coupling constant" at the mass of the Z^0 to be close to $1/_{128}$. Corrections to our first-order cosmology might also cast the whole approach into question if they fail to meet current data.

Extending our label length and mapping from 16 to 256 we get the fourth (terminal) cardinal of the combinatorial hierarchy: $2^{127} + 136 \approx 1.7\times 10^{38} \approx \hbar c/Gm_p{}^2$, suggesting gravitational closure. Since we have baryon number conservation, we can consider an assemblage of nucleons and antinucleons with baryon number $+1$, charge $+e$ and spin $\frac{1}{2}\hbar$ containing $N = \hbar c/Gm_p{}^2$ pairs with average separation $\hbar/m_p c$. Since the escape velocity for a massive particle from this assemblage exceeds c, it is gravitationally stable against particle emission but is unstable to energy loss due to Hawking radiation. Thanks to our baryon number conservation it ends up as a rotating, charged black hole with Beckenstein number (the number of bits of information lost in its formation[3]) $\hbar c/Gm_p{}^2$, which is indistinguishable from a (stable) proton. This result extends John Wheeler's "it from bit" concept[4] (cited by Landauer) to particle physics.

Whether or not our particular way of articulating a fully discrete and finite theory for physics in which the "laws" are directly constructed from the "information content" survives further tests, we concur enthusiastically with Landauer's contention that something along these lines is needed to help us better understand the proposition that information is physical.

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Landauer replies: I am pleased that Pierre Noyes finds a relationship between his views and my paper. In that connection I want to point out that my own, much less specific viewpoint[1] concerning the laws of physics was first published in 1967.

The work of a number of contributors with very differing viewpoints and backgrounds has led to our understanding of reversible computation. David Wolpert sees a need for a more formal approach. I wish him luck, and hope he can generate it. Wolpert accuses us of ignoring Gibbs entropy, $-\int d\Gamma \, \rho \ln \rho$. But it was invoked already in my 1961 paper.[2] Wolpert correctly summarizes the original (but not the most definitive) argument for the energy dissipation required by noninvertible logic functions: The compression in phase space of the information-bearing degrees of freedom must be made up by an expansion in phase space of the "environment." This expansion *is* the dissipation, reflected as an increase in the entropy of the environment. We do not need to go beyond that, and we do not need to invoke a further net increase in phase space, as implied by Wolpert. Resetting bits, or spins, into a standardized state is, after all, the opposite of adiabatic demagnetization, and we can expect the environment to be heated as a result. Wolpert tells us that one cannot use the kind of argument we have invoked to meaningfully address the temporal inverse of a process that involves a many-to-one mapping. But I have done exactly that.[3]

Wolpert invokes the Gibbs entropy, which characterizes an ensemble but not a specific physical configuration such as the state of the computer at hand. Then he goes on to suggest the use of this entropy as an information-bearing variable. He has lost me at this point. From someone who likes formality, this seems a strangely vague proposal. Does he have systems in mind that carry information *only* through their distinction in entropy, without a distinction in other variables used to define the ensemble?

Wolpert tells us that the literature on reversible computation contains no mathematics. That is an inaccurate characterization. The key points, as in thermodynamics, are best stated in simple terms.

Until Charles Bennett came along and expounded reversible computation,[4] admittedly there was confusion, inconsistency and a tendency to assume that information loss was an essential ingredient in computation. Wolpert overstates the case in writing that "all researchers ... were sure that reversible computation was impossible." In 1961, I had already pointed out that logically irreversible operations could be imbedded in larger reversible operations.[2]

Wolpert's reference to Léon Brillouin is misleading. Brillouin's analysis of Maxwell's demon assumed that the information transfer from a molecule to a register inevitably had to be accompanied by an energy dissipation of order kT because the particular method Brillouin invented for that purpose needed this dissipation. That is a far cry from the kind of reasoning used in discussions of reversible computation. A single proposal that shows how computation can be carried out with arbitrarily little dissipation per step is enough to show conclusively that there is no minimal dissipation penalty of order kT per step.

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More on Mind over Measurement

In his reply to my comments (October, page 14) on his Reference Frame column of December 1990 (page 9), Philip Anderson adds a number of new errors to his original misstatements. Most serious is his allusion, via an unidentified third body, to "discarded data" in the work of myself and my colleagues. In point of fact, every shred of data ever acquired in our laboratory has been recorded and preserved with triple redundancy, included in all appropriate analyses and published in proper course. Complete databases of every experiment performed since the laboratory's inception in 1979 remain available to any sincere scholar who would care to sit at our computers. These data entail many "unsuccessful" experiments, and needless to say, we have learned at least as much from those experiments as from those showing anomalous yield. Any implication of data selection, however veiled, is viciously illegitimate.

As to the adequacy of our statistics, I would only note that our analyses are regularly vetted by several senior statisticians here and at other institutions, that they are refereed in due course as part of the publication process and that we have indeed examined in detail, and published, the application of Bayesian statistics to our data. We find that whenever appropriately deployed, such techniques yield essentially the same results as the more canonical methods.[1]

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Safety Assurances for Chinese Conference

In response to a news report on page 62 of the December issue, I would like to tell everyone who is interested in participating in the 21st International Conference on Semiconductor Physics, to be held on 10–14 August 1992 in Beijing, that the Chinese Physical Society and the China International Conference Center for Science and Technology have given assurances that the policies of the International Council of Scientific Unions and the International Union of Pure and Applied Physics will be honored. The executive director of CICCST, Wu Ganmei, made the following statement in a letter to the secretary general of IUPAP, Jan S. Nilsson: "As the executive director of CAST [the China Association for Science and Technology] working with ICSU over 10 years, I would like to confirm to you that CAST and Chinese Society of Physics will fully guarantee the unions' policy on the free circulation of all scientists including the free entry and exit of Chinese students now studying and working abroad. If there is any question concerning the above matter, please contact me." The vice president of the Chinese Physical Society, Yang Guozhen, also wrote to Nilsson, "According to the policy of the Chinese government, we, on behalf of