research that they and the postdocs and graduate students working with them have done in the past . . . ," but I thought the sentence was long enough already, and that most readers would understand the shorter version. I knew the PHYSICS TODAY editor would pressure me to shorten it anyway!

I did not write that I am "concerned about foreign competition." American astronomers welcome it. But I *do* question whether the citizens of this country want to give up the leadership in studying the universe that we have had for the last century. Astronomical research should not be cut back compared with other disciplines. Research is hard. It is expensive. But it is worth doing, and worth paying for.

There have been a few very encouraging developments since I wrote the column last fall, and I continue to hope that Congress and the President are going to begin turning around the funding crisis in astronomy.

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7/90

Controversy *re* Reversible Computers

In his Opinion column "Can We Switch by Control of Quantum Mechanical Transmission?" (October 1989, page 119) Rolf Landauer rightly strikes "a note of caution" with respect to the all-too-enthusiastic optimism with which a series of recent switching proposals has been popularized. Landauer's most prominent argument is that in "good switches . . . a sufficiently large applied force gives the desired open or closed state." Certainly, this force has to do work against the static friction by which every "good switch" has to be prevented from unintentional changing between "on" and "off" due to thermal fluctuations, and so this force has to dissipate an energy of at least some $10kT$ at every switching operation to assure sufficient reliability.

On the other hand, Landauer is one of the most prominent advocates of "reversible computers," which "dissipate arbitrarily small amounts of energy per step" if run "sufficiently slowly."[1] In a recent debate, I discussed in detail at which steps in the strongly advocated "billiard ball" and "Fredkin gate" machines amounts of at least several kT of energy have unavoidably to be dissipated,[2] yet Landauer insisted on the feasibility of frictionless devices—"We are not far from devices with atomic precision and with perfectly periodic surfaces"—and dissipationless "information transfer at input and output" as well as the advantages of "computation reversal."[3] Now, quite surprisingly, we read in Landauer's Opinion column: "Dissipationless computation is, in fact, not desirable, even if it were achievable. It requires perfect machinery to work properly." But up to now we were told that all the "Brownian motion" machines (for measurement, copying, information transfer and computation!) do not depend on perfectly precise machinery, nor is it evident why the "time-dependent potential well" model should depend on such precision.

In this situation it appears appropriate to present several more arguments that may eventually call the whole concept of "reversible computation" into question:

▷ Landauer has discussed a "Brownian motion machine" that "moves back and forth in a diffusive fashion if watched over a short period, but with a predictable velocity over a long period."[3] The most simple calculation demonstrates the need for a minimum of many kT of dissipated energy: Let L be the distance from input to output of the "machine" (be it an individual gate, a computer, a measuring setup, a copier or something else), $D = kT/6\pi\eta r$ be the diffusion constant of the information-bearing "particle" (where r is the particle radius), F be the driving force and $v = F/6\pi\eta r$ be the "predictable" velocity. To justify the claim that such a system "carries out a computation" we have to assure that after the "predictable" passage time $t = L/v$ the particle is (with high probability!) much closer to the output than to the input. This leads to the plausible requirement that $L = vt \gtrsim 10\sqrt{Dt}$, which is equivalent to $Lv \gtrsim 100D$. So any reduction in v (and, respectively, in the driving force F) requires a proportional increase in L to maintain constant reliability. All this results in a minimum dissipated energy per logic step of $LF \gtrsim 100kT$.

▷ Leaving aside all questions of what kind of dissipationless machinery might be used to achieve a time-dependent potential well, one unavoidably energy-dissipating process step in that scheme is the switching from the coupled to the decoupled state of the information-bearing particles in two adjacent potential wells. This switching must require some $10kT$ of dissipated energy; otherwise it could occur unintentionally through thermal disturbance, and no controlled computing steps could be performed.

▷ The following arguments are generally adduced in favor of "unwinding the program": Unavoidable energy dissipation occurs only where information is discarded, that is, when resetting the output register (or the measuring apparatus) to the standardized state; "after a long computation the final state of a reversible computer has many more balls [the information-bearing particles in the Fredkin–Toffoli billiard-ball model] whose state depends on the computation"[3]; and after unwinding the program, the input register can be "uncopied," without dissipation, against a copy of the input information preserved there for just this purpose. However, if the second argument were correct (even though every reversible computing step is a 1:1 imaging process!) this computation would reduce entropy (or generate negentropy), evidently by taking heat from the environment. The computer would get colder the longer it ran. During unwinding, this negentropy certainly would get lost again. But with Landauer's dissipationless copying process we can do much better by providing a resetting store at the output (with all bits in the 0 position). Copying this "information" into the output register after computation is completed involves precisely the same, presumedly dissipationless copying steps Landauer described in reference 3. Evidently, his copying process makes it possible to discard information without dissipating energy. (Unwinding the program then is just a waste of time and energy, and there is no need for extra hardware to store all the input information.)

In conclusion, the question arises of whether "reversible computation" is another of those "many episodes" Landauer so correctly describes in his Opinion column, where "the advocates are . . . carried away by their enthusiasm" and the skeptic will not be "invited to the conferences, which the proponents . . . dominate." In all generality, the skeptics are simply those who take the trouble to think a few steps further than the enthusiasts, who try to ignore everything that does not fit into their (frictionless) dreams.

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LANDAUER REPLIES: My Opinion column provided a conservative assessment of some logic technology proposals and undoubtedly appears controversial to their respective advocates. Eginhart Biedermann uses this as an opportunity to return to a different and earlier debate already published in *Nature*. The earlier debate concerned a much more fundamental and conceptual question: What is the minimal energy dissipation requirement imposed on computation by the laws of physics? Biedermann takes issue with Charles Bennett's notion of reversible computation, first published in 1973. Bennett demonstrated that computation can be carried out with an energy dissipation *per step* that can be reduced to any desired extent, if we are willing to compute sufficiently slowly. This concept has been confirmed and elaborated by a great many subsequent investigators with different backgrounds and viewpoints, including the late Richard Feynman.[1] Bennett's work has been labeled "epoch-making."[2] I do not believe that reversible computation requires a detailed defense against *all* of Biedermann's critique, and cite below three recent items to lead to the citation trail.[3]

I do suggest that the reader of Biedermann's critique keep two items in mind. First of all, reversible computation as viewed by Bennett and by me is not *totally* without dissipation, as was claimed for one of the proposals that my Opinion item analyzed. Additionally, Biedermann states that for computation with a roughly predictable execution time, a limited total energy expenditure, say, $100kT$, is required. I do not consider the exact energy expenditure significant; the key point is that the expenditure is not proportional to the number of elementary logic functions carried out during a long computation. But why should we even require a computation to be characterized by a "predictable passage time"? Even for today's practical computers, which have a well-defined execution time per step, the number of successive logic steps required to carry out a program is, in general, not predictable. Finally, Biedermann ignores the fact that some reversible computer proposals, such as that of Konstantin Likharev using Josephson junction circuits,[4] are clocked just as actual current computers are.

The occasional published dissent that, like Biedermann's, still considers reversible computation to be excessively optimistic is balanced on the other side by the proposal of Eiichi Goto and his colleagues asserting that the special precautions invoked in reversible computation are not needed.[5] Reversible computation uses logic functions at every step that are one-to-one and do not discard any information. Goto and his colleagues claim that this is not essential. In a fashion typical of critics of reversible computation, Biedermann analyzes the energy requirements of his own notion of minimally dissipative computation. Once again he tells us that static friction is essential, but does not tell us what is wrong with Likharev's scheme, which clearly avoids static friction.

In his final paragraph, Biedermann suggests that the exponents of reversible computation have been carried along by uncritical enthusiasm. Actually, reversible computation is a somewhat counterintuitive notion on first exposure, as demonstrated by Biedermann's repeated objections. Feynman, at a 1981 workshop, was the only one I have ever seen who caught on immediately. My own history was very different. When I first heard from Bennett about his evolving ideas, in 1971, I was totally skeptical. After all, this was a major departure from my own earlier publications. It took me six months to become convinced. It is now, however, almost two decades and many papers later, and it should no longer be that difficult!

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Wigner Distribution Malfunction

I am writing to point out some minor mathematical inconsistencies in the otherwise interesting and informative article on squeezed and antibunched light by Malvin C. Teich and