CAN WE SWITCH BY CONTROL OF QUANTUM MECHANICAL TRANSMISSION?

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All switches, whether in a computer circuit or for turning on the light in a room, control electron transmission. Relays, vacuum tubes and transistors all are switches in this sense. Typically, however, the electron in its transit through the switch suffers many inelastic collisions; the electron transmission is not a quantum mechanically coherent process. Recent years have seen rapid advances in the study of very small samples that an electron has a good chance of traversing without undergoing inelastic collisions. The quantum mechanical phase of the electron when it emerges from such a sample has a well-defined relationship to the incident phase.[1] These advances have led to a number of proposals for computer logic devices. Optimistic assessments about the performance of such devices, as in the case of many a new technological proposal, have already appeared in popular and semipopular magazines.[2,3]

The most well-established of the proposals invokes resonant tunneling through two successive barriers in III–V compound heterostructures, such as GaAs–AlGaAs, made by molecular-beam epitaxy.[2] The transmission peaks when the energy of the incident electron coincides with that of a quantized level in the well between the two barriers. The behavior of such a structure can be controlled in a number of ways through a third electrode. Other proposals include use of an interferometer that offers the electron two paths, as in an Aharonov–Bohm geometry, and in which the relative phase delay between the two paths is most likely controlled through applied electrostatic fields. Alternatively, one might control the transmission through the top of a T-shaped structure by varying the effective length of the vertical, open-ended lead. This latter scheme is an adaptation of a well-known technique used in electrical transmission lines. Several of these proposals are discussed in the proceedings of a recent conference.[4]

Attempts to improve computer devices have used a very simple recipe: Make them smaller.[5] Smaller devices have shorter electron transit times, and reducing the device size also reduces the capacitances that need to be charged and discharged when operating the device. Furthermore, one can put many more smaller devices on a chip of a given size, making each circuit cheaper.

Thus the attempt to move toward utilization of the exciting recent advances in the physics of small conductors, often called mesoscopic physics, would seem most welcome. Much of the physics underlying both resonant tunneling and mesoscopic physics has emerged from work by my colleagues at IBM. I have long had a concern with the ultimate limitations imposed on computers by the laws of physics. I have also advocated an approach to computing conductances from the transmissive properties of the sample that can easily be applied to mesoscopic systems. So I might be expected to be particularly responsive to the new proposals. Instead, I want to strike a note of caution.

Some of the problems I will list may be overcome, but it seems unlikely to me that they will all disappear. The most fundamental problem arises from the fact that in all of the new proposals high transmission occurs only for particular values of the input signal and for particular values of the parameters describing the structure. Good switches are not at all like that. Rather, they are like a door, a faucet or a wall switch, where a sufficiently large applied force gives the desired open or closed state. The dimensions of the handle on a wall switch and its coefficient of friction, for example, do not require critical adjustment. Similarly, we must not let the performance of our computers depend on perfect devices or on perfectly adjusted signals arriving at each stage.

Another problem arises from the fact that mesoscopic samples, which act in a quantum mechanically coherent way, exhibit phenomena described by the slogans "universal fluctuations" and "fingerprint of the sample."[1] These relate to the delicate dependence of electron transmission through a mesoscopic system on its particular set of elastic scatterers. By contrast, ordinary macroscopic resistors and devices have a self-averaging feature: Their measured behavior is an average over many independently acting volumes. This makes it much easier to achieve reproducibility. A number of the existing proposals do not even tell us how the desired voltage swing at the output terminal affects the intended transmission. Nor do they discuss the electrons that, after leaving the device and undergoing subsequent scattering in another circuit element, return to the device.

Furthermore, mesoscopic devices that are small in all three dimensions (resonant tunneling structures, by contrast, need to have only one very small dimension) have impedances that are very large compared with the impedances of the typical electromagnetic transmission lines used for connecting circuits. But the impedances should be comparable.

Finally, of course, the typical laboratory mesoscopic device is delicate. That, perhaps, is the least of the difficulties: After all, any attempt to move toward smaller structures takes us toward devices that are more likely to suffer from deterioration. On the other hand, we will want to use the smaller devices in greater numbers. Therefore the smaller devices must be more reliable than their larger forebears, not just equally reliable. Indeed, this need to make the smaller devices more rugged is the central challenge of microelectronics. The introduction of new device kinetics is the easy part.

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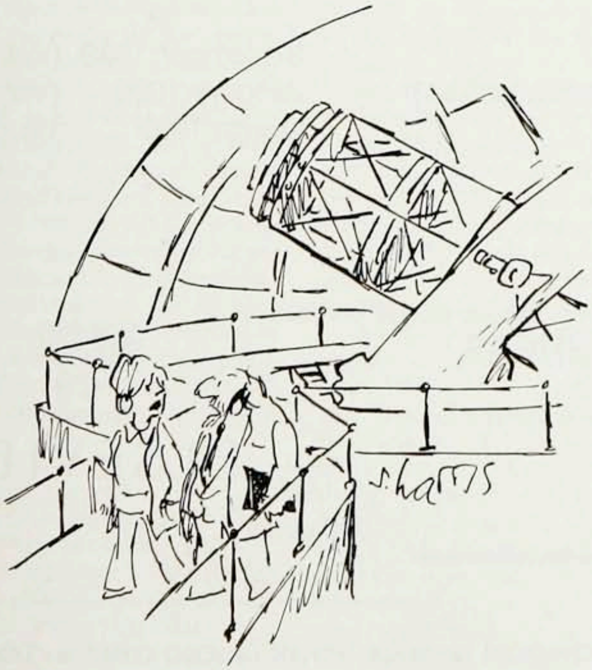
I do not want to suggest that mesoscopic physics is irrelevant for devices. As we continue toward ever smaller devices, mesoscopic phenomena are bound to turn up as adverse or beneficial complications. My note of caution is intended only for proposals that try to eliminate too much of the traditional transistor. The transistor continues to advance: 0.1-micron silicon field-effect devices are here and show[6] a raw inverter delay of 13 psec.

Logic devices that use oscillating, or radiative, degrees of freedom, instead of simple voltage or current swings, have been advocated off and on for decades. The earliest version, using parametric excitation of subharmonics, stems from independent inventions in the 1950s by Eiichi Goto in Tokyo and John von Neumann. In contrast to later versions, the Goto–von Neumann version was clearly a workable proposal; as a matter of fact, it was used in functioning computers in Japan. The most recent proposal, celebrated by a semipopular magazine,[7] depends on the controlled interference of coherent electromagnetic waves. In this case nonlinear optical effects are used to adjust the relative delay along the two branches of an interferometer. I will not attempt to analyze the detailed kinetics of this proposal, but only its central claim that it provides *dissipationless* computation. Dissipationless computation is, in fact, not desirable, even if it were achievable. It requires perfect machinery to work properly. If the machinery has imperfections, then we must continually restandardize our signals to bring them back to their intended values. That means we must compress the phase space of the information-bearing degrees of freedom. But we cannot compress the phase space of a conservative system; so compression in the important degrees of freedom must result in an expansion of the unimportant degrees of freedom. That means heating of the environment, and dissipation.

Proposals based on mesoscopic devices and on control of interference are examples of the new ways of accomplishing computer logic that physicists interested in basic research have advocated. The more widely advocated proposals include the use of optical bistability, neural networks that attempt to copy the functional coupling between neurons,[8] and attempts to imitate biological hardware via control at the molecular level. A recent popular volume views all these proposals with great approval.[9] Unfortunately, the advocates are sometimes carried away by their enthusiasm before they have learned the full set of functional requirements for their intended purposes. As a result a premature public relations campaign gets under way. A successful technological climate must reward risk-taking and must allow failures. But there have been many episodes where everyone eventually sheepishly realized that the flaws or disadvantages were understood at an early stage, but that the voices of dissent were not heeded. Of course, in some cases the proposal does eventually find a limited niche of real utility, and that may well happen for some of the proposals I have cited. Among the many supposedly broadly applicable logic schemes we have seen come and go, we may count Gunn-effect logic, tunnel diodes, ferrite-core logic, schemes using combinations of electroluminescent devices and photoconductors, fluid logic, parametric microwave excitation and Josephson junctions. Of course, some innovative proposals, such as Josephson-junction logic, magnetic bubble storage and the battery-powered automobile, did deserve serious examination. And when they were discarded, it was with some trepidation and the awareness that the decision might not last forever.

Our system is organized to give the enthusiasts the advantage. Those in need of funding put forth the positive view, write papers and organize workshops. Even funding agencies, after a first hard and sincere decision, may get locked into renewing grants. The contract supervisor wants to demonstrate that the original decision was sound.

In contrast, the skeptic does not have the same motivation to speak up. Nor will the skeptic be cited in the literature or invited to the conferences, which the proponents often dominate. We do not celebrate whistle blowing, except perhaps in public-safety matters. Then why bother? Furthermore, once a "thrust area" in advanced technology is abandoned, there is no incentive for a technical obituary. Those who do not know technical history are condemned to reinvent it.



"I'VE SEEN OUT TO THE LIMIT OF THE OBSERVABLE UNIVERSE, AND BELIEVE ME, IT'S NO BETTER OUT THERE THAN IT IS HERE."

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