Miniaturization of electronics and its limits

by R. W. Keyes

The long-continued advance of the performance of information processing technologies has been based on miniaturization of components. The history of miniaturization is presented through examples. They suggest that limits proposed by Landauer in the 1960s will be reached in two or three decades.

The large relay computers developed during the 1940s demonstrated the power and versatility of electronic computation and stimulated a demand for more powerful machines. The high cost and limited reliability of relays limited the size of machines that could be built from them. In addition, the dependence of the relay on mechanical motion led to slow operation. The search for a purely electronic replacement led to the vacuum tube, which was faster.

Inventions of the 1950s showed that electronic computation and storage could be implemented with solid-state devices. It became clear that solid-state devices offered smaller size, lower power, higher speed, and greater reliability than previous components.

The ferrite core was the first solid-state component to find wide use in computers [1]. The advantages of miniaturization of cores were quickly recognized: Smaller cores could be switched faster and with less power, allowing increases in both the speed of access to information and the size of the memory measured in bits.

Magnetic cores were discrete devices, made and handled individually, although by automated machinery. Further miniaturization and lower cost of magnetic storage elements was achieved with the invention of the magnetic disk file [2]. Here too there was a very strong incentive for efforts to reduce the area occupied by each bit, allowing more bits to be placed on a disk; dividing the cost of the file among many more bits drastically reduced the cost per bit of storage.

These trends in devices developed during the late 1950s and early 1960s are illustrated in **Figures 1** and **2**. Figure 1 shows the reduction in the diameter of core memories and Figure 2 the increasing density at which bits could be written on a magnetic disk in a disk file. At any given time plans for future products with even smaller dimensions than current products were being advanced in development laboratories.

The invention of the transistor provided the primary fuel for the solid-state electronic revolution. Again the quest for higher operating speeds and lower power dissipation led to ever-smaller devices. A giant step in this direction was made with the development of planar processing methods around 1960 [3].

This was the environment in which Rolf Landauer and John Swanson recognized at an early date that miniaturization could not persist indefinitely, that the physical nature of the world set limits on the size of electronic devices [4–6]. They thereby inaugurated a new field of endeavor: the study of the physical limitations on information processing technologies.

Their early results were oriented to realistic limits set by the atomistic nature of matter—that is, any device contains only a finite number of atoms and electrons; and thermal noise, the thermal energy of particles, introduces an uncertainty into the response of devices to applied signals. These considerations suggested that some number of the order of one hundred particles is required to represent information reliably [4, 5]. Numbers of this order were also suggested by Landauer's study of the limits of storage in active devices, specifically, in a tunnel diode [6]. Such limits were extremely remote from the structures that could be produced by the technology of 1960.

A further concern of that era was the heat produced in information processing operations. For example, storing and reading information in magnetic cores cycled the magnetic material through a hysteresis loop and converted the $B - H_c$ energy to heat. Transistors controlled the passage of a current through a significant voltage differential and IV power was produced as heat. Miniaturization allowed denser packing of components and increased the density at which heat was produced. Thus another question of interest was that of how much energy must be dissipated to heat during logic operations.

Landauer identified the basic issue here as involving the representation of information by the location of particles in phase space, and thereby established a connection to statistical thermodynamics. Logic operations involve manipulations of the energy barriers that confine systems to limited regions of phase space. If this is done in an irreversible way, so that the course of the operation cannot be retraced in the opposite direction (as in the logical operations of computers), dissipation is inevitable. It was shown that the rate of escape from a metastable region depends on barrier height as $\exp(-E_B/kT)$ [7]. Barriers that retained information for a long time must have a height much larger than kT. However, if the manipulations were carefully carried out and the phase space was that of a single particle, it was possible to show that the dissipation could be reduced to near the thermal energy, kT [5]. Landauer identified the dissipative step as the erasure of information; the creation of entropy $k \ln 2$ is involved in the destruction of the representation of a bit. Subsequently Charles Bennett argued that such irreversibility is not necessary in logic, that systems can be devised that can perform logic operations in a fully reversible fashion, avoiding the erasure of information [8]. While Bennett's idea has great conceptual significance, and idealized systems that implement dissipationless logic in principle have been described, it is unlikely that it will be turned to practical advantage [9].

Miniaturization and the invention of the integrated circuit made possible the production of solid-state electronic circuitry at rapidly decreasing cost after 1960. Miniaturization and integration also led to increases in the speed and reliability of electronics. These striking improvements spawned a major industry based on handling information with solid-state components. The trends suggested in Figures 1 and 2 and the growth of the industry have continued to the present day. We illustrate the progress of miniaturization with **Figure 3**, a plot of the area of an entity that stores one bit of information as a function of time. As shown, the trend spans a variety of technologies.

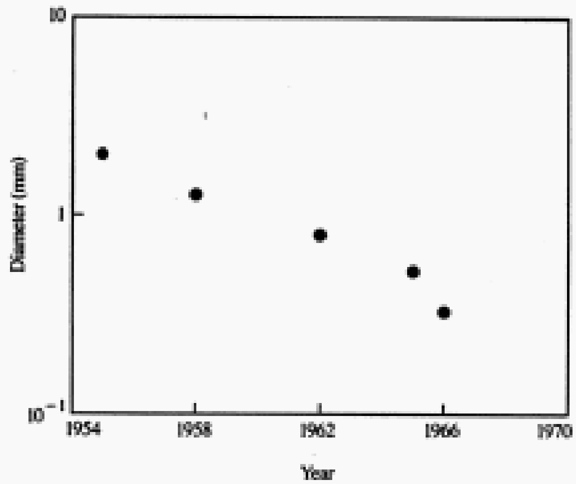

Figure 1

Miniaturization of ferrite cores for computer memories [1].

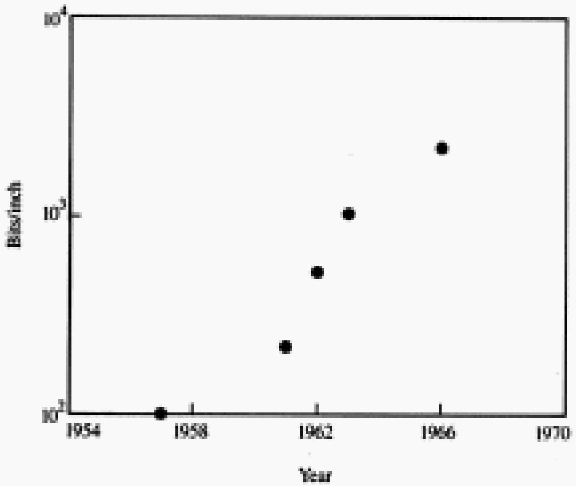

Figure 2

Increases in the number of bits per inch of track during the first decade of disk file development [1].

The density of storage on disk files has continued to increase. The invention of thin-film memories [1] and magnetic bubbles [10] allowed access to magnetically stored information without mechanical motion and with much higher density than cores. However, after 1970

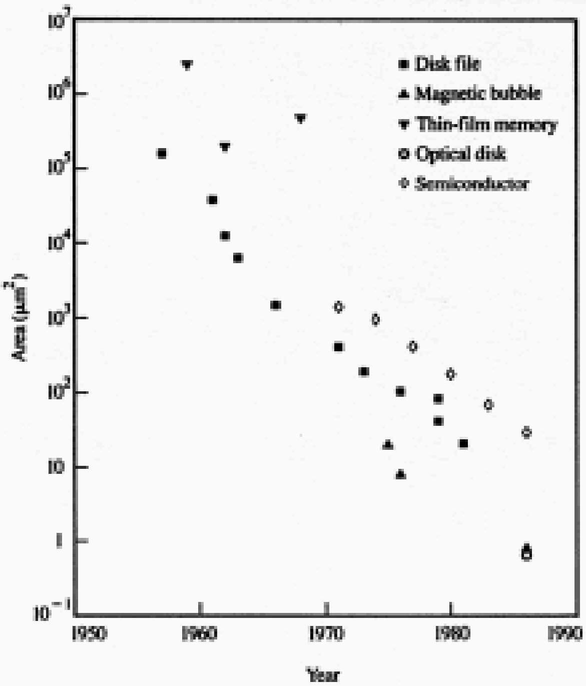

Figure 3

Area of a planar surface used to represent a bit of information.

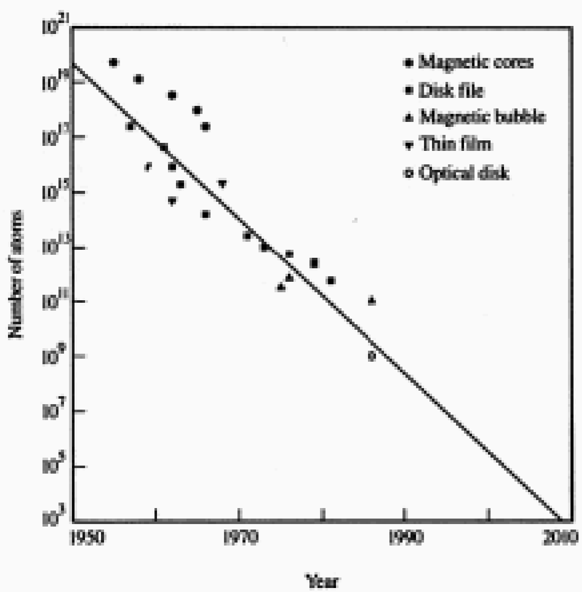

Figure 4

Number of atoms used to store a bit in discrete magnetic entities and in file technologies.

semiconductor memory came to dominate electronically accessible memory and entirely captured the market that was previously supplied by cores.

The limits derived in early work [4–6] are still present, however. We now turn to an examination of the present state of technology and its rate of progress in the light of these limits. For example, **Figure 4** shows the number of atoms used to store a bit in cores and in file technologies as a function of time [1, 2]. The scales are chosen to permit extrapolation to a significant distance into the future. It is seen that the fundamental limit of about 10^2 atoms will be reached early in the next century if present rates of miniaturization continue.

Semiconductor technology relies on patterns of dilute concentrations of impurities to create electronic devices. Miniaturization has already led to small numbers of doping atoms in functionally important regions of transistors. **Figure 5** shows the changes in number of doping atoms in the bases of bipolar transistors intended for logic circuits [11]. An extrapolation shows that the continuation of present trends will reduce this number to 1000 by the year 2000.

Figure 6 addresses the rapidly decreasing amount of energy dissipated in a logic operation. Technologies ranging through relays, vacuum tubes, and various kinds of transistors and transistor circuits, most recently CMOS, are included [12]. Again, a continuation of historical rates of change will lead to the kT limit being reached early in the next century.

Continued miniaturization of solid-state electronic components may be confidently anticipated. For example, the use of synchrotron light sources for lithography promises at least an order-of-magnitude reduction in the resolution with which resists can be exposed by optical means. Molecular beam epitaxy and metal–organic chemical vapor deposition have enabled the preparation of very thin well-controlled layers. Steady refinements of a variety of process technologies allow such advances to be translated into miniaturized devices.

Novel concepts also provide possibilities for storage of information at higher densities. The storage of information in Bloch lines in domain walls has been demonstrated [13]. The technique offers storage in smaller volumes than bubbles in known materials. In another approach to storage, many bits can be optically stored in a given volume by use of the frequency domain [14]. It has been suggested that over 10^3 bits can be stored in a 100-μm spot by spectral hole burning with a tunable laser in an inhomogeneously broadened absorption line, about 10^{13} bits per cm^3 of material.

One number, the number of electrons that are used to store a bit in dynamic random access semiconductor memories, has resisted decrease for several years. The number is limited by the requirement that it must not be overwhelmed by the charge collected from a track produced in the silicon by ionizing radiation, the "soft-error" effect [15]. About 100 fC, or 6×10^5 electrons, are needed. Attacks on this problem are constrained by the extreme cost-sensitivity of memory devices, billions of which may be required for a single system. However, it is probable that modifications of material systems and device structures will eventually permit storage with fewer electrons [16].

The limits recognized by Landauer at the beginning of the development of solid-state electronics were ten to twenty orders of magnitude away from the technology of the time. It seemed inconceivable that they should ever be relevant to the real world of technology. Yet if we date the birth of the microelectronic revolution as 1960, half of the distance to the limits has already been traversed. There is no reason to expect that the rates of change will decrease soon. The remoteness of the early Landauer limits from reality no longer appears so certain.

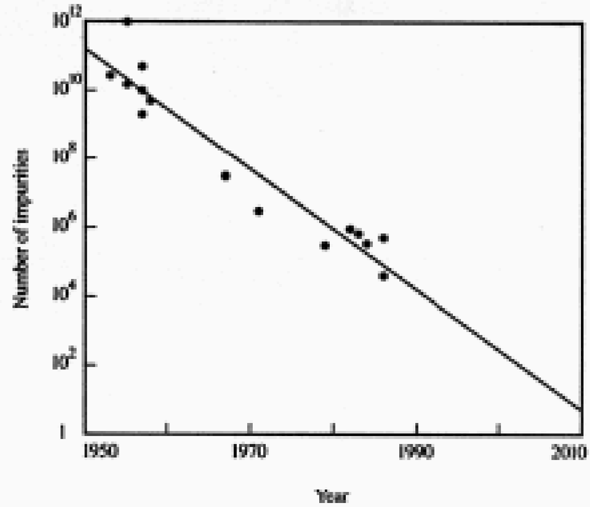

Figure 5

The decreasing number of dopant impurities in the base of bipolar transistors for logic.

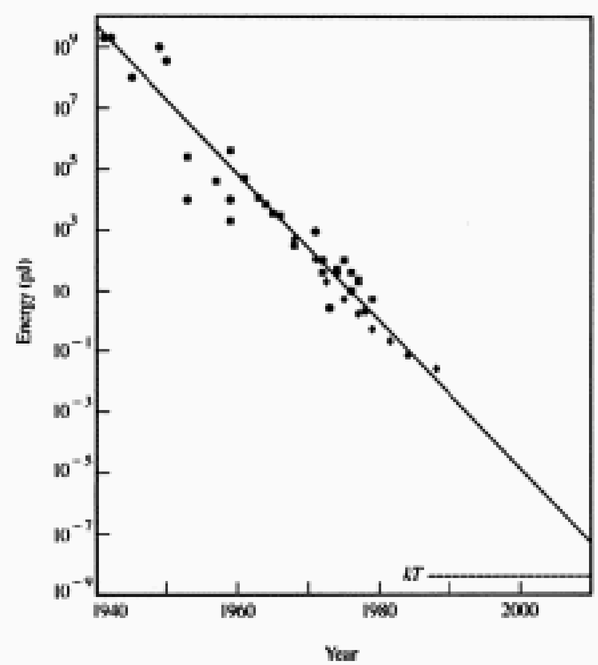

Figure 6

The decreasing energy dissipated per logic operation [12].

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