The Impact of Quantum Information Science: 45 Years Later and Still "Plenty of Room"

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In 1965, Gordon Moore noted that integrated circuit complexity scaled exponentially in time **[1]**. Less than a decade after the invention of the integrated circuit, Mr. Moore recognized the enormous potential for its miniaturization. Since then, circuit complexity has continued to double roughly every two years. Today the central processor inside a typical desktop computer contains as many as 40 million transistors within an area of about 1cm^2. Assuming this trend continues, within 60 years a typical microchip will have in excess of $4\text{x}10^{16}$ transistors. The width of a transistor on such a chip would be about 50pm, roughly the radius of a hydrogen atom. Of course this trend cannot hold indefinitely. It predicts transistor dimensions on order of the Planck length (clearly a theoretical impossibility) by the year 2400. If the current rate of progress is to be maintained for more than even a few short decades, humans will need to begin building computers on molecular and atomic scales.

The task of building truly nano-scale devices was put forward by Richard Feynman in his famous 1959 talk, "There's Plenty of Room at the Bottom" **[2]**. Forty-five years later, much progress has been made in the way of achieving those goals, but there is still a long way to go. While computers today would not be possible without knowledge of quantum theory, they remain founded on a classical theory of computation. It seems unlikely that this classical theory will remain applicable for the molecular and sub-molecular computing machines one may expect to see by the middle of this century.

Strangely enough, increasing miniaturization is rarely touted as one of the driving reasons for developments in quantum information science. More often, excitement revolves around such topics as algorithmic speed-ups, cryptography, and even quantum "teleportation." Quantum resources have been shown to allow significant speed-ups for a few specific computational tasks, but they have yet to show any *general* computational advantage **[3]**. Quantum cryptography is inherently more secure than its classical counterpart, but classical cryptographic systems will remain more than adequate until quantum computers can be built to break them. And while quantum "teleportation" is a most fascinating phenomenon, its title remains a misnomer and its applicability uncertain. Intriguing as these results may be, their potential to impact our daily lives is debatable. Miniaturization, on the other hand, has long since demonstrated a profound effect on the way humans live. In the not-too-distant future, the semiconductor components of today will seem as bulky, unreliable, and inefficient as the vacuum tubes that preceded them.

So what will these new quantum computing machines be like? Their implementations will likely be quite different from the current prototypes, which all too often require large and expensive apparatus to operate. Instead, in addition to being very, *very* small, these computers will have to be cheap, plentiful, reasonably durable, functional at room temperature, and (unlike today's computers) environmentally sustainable. These are demanding requirements! Yet there can be little doubt that such devices will come into common use, as computing systems of similar description already exist.

Deoxyribonucleic acid (DNA) provides the medium for what may be the smallest, fastest, and most efficient computational devices on the planet **[4]**. They are certainly better than anything humans can build. In scale, DNA exists just at the border between the so-called quantum and classical worlds. And though information stored in DNA seems essentially classical (i.e., it can be copied without being destroyed), quantum mechanics no doubt plays a heavy role in its processes. Studying such marvelous computational systems as these—where the bits are not qubits, but perhaps not *entirely* classical bits either—could provide great insight into developing practical quantum computers and the classical interfaces with which to control them.

It is an understatement to say that quantum information science will impact further developments in miniaturization. Rather, increasing knowledge in quantum information science will be necessary in order to *allow* these developments. This science, along with related fields, will herald in a new era of computation. Such an era has been described by some as that of "ubiquitous computing" **[5]**. Computers will soon be the size of motes of dust. And as microfabrication gives way to nanofabrication, the cost of these computers will continue to drastically decline.

Even in today's age of ever-present computation, one can hardly fathom such a reality. Imagine a world where computers are *literally* everywhere: in the air we breathe, in the food we eat, in the blood running through our very veins. Consider the applications! Surely the greatest impact of quantum information science will be through increasing developments in miniaturization. Furthermore, these revolutions are not those of the distant future. Many will be revolutions of the coming decades, the first of which are already happening today.

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1 Moore, Gordon E. "Cramming more components onto integrated circuits." *Electronics* **38**, no. 8, April 19, 1965.

2 Feynman, Richard. "There's Plenty of Room at the Bottom." Delivered to the American Physical Society at Caltech, December 19th, 1959. E-print available at http://www.zyvex.com/nanotech/feynman.html.

3 Neilsen, Michael A. & Isaac L. Chuang. *Quantum Computation and Quantum Information*. Cambridge University Press, Cambridge 2000.

4 Adleman, Leonard M. "Molecular computation of solutions to combinatorial problems." *Science* **266**, 1021 (1994).

5 For further reading on this fascinating topic, the author suggests beginning here: http://www.ubiq.com/hypertext/weiser/UbiHome.html.