The Quantum Limit to Moore's Law

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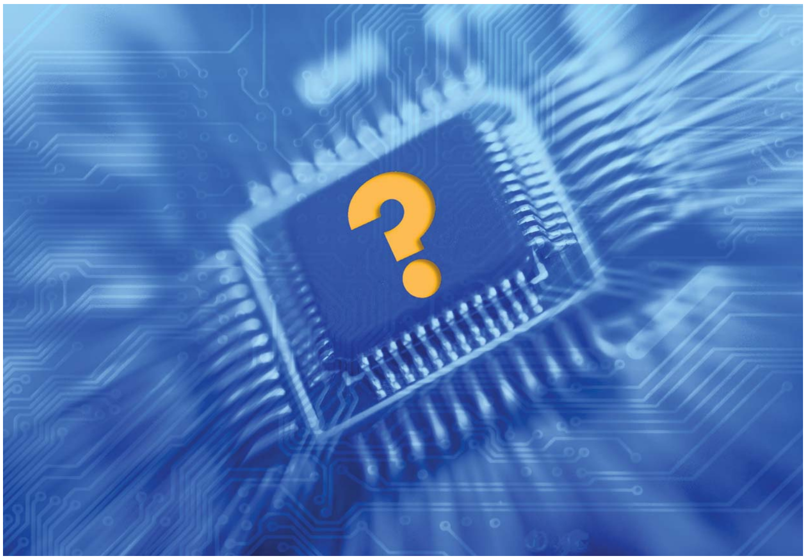

Moore's law has accurately predicted the growth of computing power from the increasing density of transistor devices on integrated circuit (IC) chips since 1965. Many believe this trend will continue indefinitely; however, quantum physics may define a future limit to electronic miniaturization and ever-increasing computing power. Heisenberg uncertainty in terms of the Compton wavelength of particle physics suggests such a boundary, even for anticipated advances in quantum computing.

Moore's law has been a reliable predictor of the pace of electronic technology advancement since 1965 [1]; however, quantum physics may provide the ultimate limit to this mathematical model. Gordon Moore's prediction is that the density of transistors and computing power doubles every two years, which has held since there were fewer than 100 transistors in an integrated circuit until today with many millions of transistors on a single integrated computer chip. This amazing predictive history has emboldened some authors to state that technological evolution often follows a fairly predictable path [2] and that, "Periodically, people predict the death of Moore's law. They state that Moore's law eventually will end because of some future technological or scientific barrier. However, to date, engineers and scientists have found a way around these problems, and Moore's law continues to be an accurate means of predicting the future development of technology" [3].

This assertion, however, contradicts modern physics, which postulates that there is an absolute limit to the resolution that science and engineering can achieve, which is Heisenberg uncertainty based on Planck's constant h. Where do Moore's law and Heisenberg uncertainty converge, and is this a future ceiling to continued doubling of computing power every two years? Gordon Moore himself stated during an interview September 18, 2007, at Intel's twice-annual technical conference that we will soon be bumping against the laws of physics: "Another decade, a decade and a half I think we'll hit something fairly fundamental." Since this involves a physics limit (in his words), he went on to quote Stephen Hawking during his visit to Intel in 2005. "When Stephen Hawking was asked what are the fundamental limits to microelectronics, he said the speed of light and the atomic nature of matter" [4]. Determining an ultimate physics limit to Moore's law would mark out a future boundary to electronics miniaturization.

I. A CALCULATION OF THE QUANTUM LIMIT TO MOORE'S LAW

The power of Moore's law has been the mathematics of doubling, the doubling of the number of transistors on an IC or computer chip every two

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years. This law can be written in equation form as [5]

$$n_2 = n_1 2^{[(y_2 - y_1)/2]}. \tag{1}$$

This equation predicts the number n_2 of transistors or equivalent computing power in any given year y_2 from the number n_1 of transistors in any other earlier year y_1. From the definition of Moore's law, we know that the characteristic dimension or length L of a transistor is inversely proportional to the number of transistors n on an IC. If the measurement of n is in "number per meter" (m^{-1}), then, from dimensional analysis, the measurement of L is in meters (m). Or, equivalently, $1/L$ is the number per meter just as in (1). We can then rewrite (1) as

$$1/L_2 = (1/L_1) 2^{[(y_2 - y_1)/2]}. \tag{2}$$

For L_1, we can choose 45 nm or 0.045×10^{-6} m as the current representative transistor size since both Intel and Advanced Micro Devices are offering 45 nm technology this year [6]–[8]. For L_2, we can look at the current and predicted state-of-the-art in quantum computing research. A recent paper reports a breakthrough in "spintronics" in which electron spin, either up or down, was measured in a semiconductor constructed of aluminum gallium arsenide and gallium arsenide flanked by metal plates [9], [10]. In this experiment, electron spin was manipulated as an electrical gate, which could feasibly become the future transistor. Given the electron as the future limit of this technology, what can we use for the characteristic dimension or "size" of this transistor? The characteristic dimension of an electron from Heisenberg uncertainty is the Compton wavelength [11] $\lambda_c = \text{h}/\text{m}_e\text{c} = 2.4263 \times 10^{-12}$ m based on Planck's constant h, the mass of the electron m_e, and the speed of light c. The Compton wavelength of the electron is the fundamental limit to measuring its position based on quantum mechanics and special relativity, or the length scale where a relativistic quantum field theory (which we do not have) is necessary for an adequate description [12]. The Compton wavelength is therefore the fundamental boundary to determining the position (or spin) of a particle, which satisfies the Stephen Hawking prediction that this limit would be based on the speed of light and the atomic nature of matter since λ_c is determined by c, m_e, and h. Rewriting (2) using the current year, transistor feature size, and Compton wavelength, 2.4263×10^{-12} m or 0.00243 nm

$$(2.4263 \times 10^{-12}\ \text{m})^{-1} = (0.045 \times 10^{-6}\ \text{m})^{-1} 2^{[(y_2 - 2008)/2]}. \tag{3}$$

Solving for the exponent $\Delta y = (y_2 - 2008)$ using the natural log function

$$\ln(0.045 \times 10^{-6}/2.43 \times 10^{-12}) = (\Delta y/2) \ln 2. \tag{4}$$

Therefore

$$y_2 = \Delta y + y_1 = 2(9.827)/0.693 + y_1 = 28.36\text{y} + 2008 = \text{year } 2036. \tag{5}$$

This is the quantum limit year predicted by Moore's law if electrons were implemented as the smallest quantum computing transistor elements.

II. DISCUSSION

Whether there is an ultimate limit to Moore's law is an open question dependent upon future electronic innovation and physics. A persuasive argument from quantum mechanics is that Heisenberg uncertainty defines the eventual limit to the miniaturization we can achieve in physics and engineering. There may be other factors affecting this constraint including thermal or heat dissipation, leakage current, and thermal noise [13], which are probably not issues for successful electron-transistor implementation but only for present-day silicon-based ICs. In personal communication with Dr. Moore, he stated that in the semiconductor world, these and other atomic limitations will prevent even approaching the quantum uncertainty limit [14]. If, however, these engineering barriers continue to be overcome, Heisenberg uncertainty would be the fundamental limit to Moore's law, and if the electron is the smallest possible transistor component, then the year 2036 is a reasonable prediction of when Moore's law and quantum physics will converge. ■

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