

**THE CUTTING EDGE;**  
**QUANTUM LEAPS;**  
**AS LIMITS ON CHIP SIZE AND PRICE NEAR, AN EXOTIC TECHNOLOGY**  
**OFFERS HOPE**

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**Byline:** MICHAEL A. HILTZIK, TIMES STAFF WRITER

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## **Body**

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You've probably heard about the year-2000 problem, which holds that billions of dollars' worth of business software will crash at the moment of the millennium.

But how about the year-2010 problem?

"Right now I view the year 2010 as a very dark curtain," Stanley Williams says. "And I don't know what's behind it."

It's no accident that Williams sounds slightly apocalyptic.

As principal laboratory scientist of Hewlett-Packard Laboratories here, Williams counts among his chief responsibilities determining exactly what lies behind the dark curtain of 2010. For that's when current technological trends are finally expected to lead to a computer chip too small to work (and too expensive to manufacture).

The fortunes of the \$ 132-billion semiconductor industry--and, by extension, a large chunk of the world's increasingly technology-driven economy--rest on piercing the 2010 curtain and learning how to commercialize whatever lies behind it.

Semiconductors are the materials and devices that power computers and countless other electronic devices in home, office and factory.

Over the last 30 years, the semiconductor industry has relied on the axiom that computing devices would continue shrinking in size and increasing in power at an exponential rate according to what is known as Moore's Law. As articulated by Gordon Moore, one of the founders of semiconductor giant Intel Corp., the law states that computing power will roughly double in scale (or halve in price) every two years.

This is the trend that has led to computers packing hundreds of times more power into a desktop PC than once fit into computers so big they were operated by teams of men walking around their innards.

Most computer professionals have long understood that such an exponential increase in power could not continue indefinitely; at some point the very laws of physics would interfere. Accordingly, most of the debate about Moore's Law has been over when, not if, it would break.

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Today the smart money says that silicon-based computing devices have about four generations left, "with every generation representing a quadrupling of transistors on a chip and a 25% gain in speed," Williams says. That means chips with a basic device size of 0.07 micron, or about three times as detailed as the circuits on today's most advanced chips.

"Most people believe that's basically it," Williams says.

Most, but not all. Some experts argue that many functions of today's chips will continue to improve even as miniaturization passes the 0.07-micron limit. Others say that advances in networking and communications will take up the slack in enhancing computing performance.

Indeed, the demise of Moore's Law has been forecast before, only to be deferred for decades by sudden and unheralded advances in technology.

"There's a lot of punch left in Moore's Law," says S. Atiq Raza, chief technical officer at Advanced Micro Devices and the developer of that company's well-received new K6 microprocessor. He acknowledges, however: "We are hitting a wall of how far we can push silicon technology."

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Two basic trends are coming together to mark the end of "classical" semiconductor design. One is the sheer cost of the extraordinarily precise machines needed to fabricate smaller and more elaborate chips.

The price of chip factories, or "fabs," as they are known in the industry, long ago passed the \$ 1-billion mark. One plant to be opened in Dresden by Advanced Micro Devices in 1999 will cost \$ 1.9 billion.

Industry experts say that at current rates of growth, the price of a fab will hit \$ 10 billion or even \$ 25 billion soon after the turn of the century. At that point, the cost of manufacturing computer chips becomes almost a political issue, for there may be no single company--or perhaps just one--with the money to erect a facility that costly. Overcoming that hurdle may require an unprecedented level of research and development cooperation among chip makers and industry suppliers.

The second limiting factor is more fundamental: the behavior of the electron. Electronic devices such as microprocessors work essentially by sending streams of charged electrons over circuits and through logic "gates" designed to switch "on" or "off" depending on whether a current is present or not.

The configuration of these gates makes up the basic architecture of the integrated circuit and thus of the computer itself, performing the functions of addition, subtraction and other mathematical processes at the heart of digital computing.

Today's chips need several hundred electrons at a time to switch the gates. As the chips become smaller, fewer are needed. That's good, because it means the chips consume less power and generate less heat as they operate.

But it's also bad. The fewer the electrons needed to switch the gate, the more troublesome the background noise.

Think of a water faucet: One can create a pulse of water by turning it on and off. The faster and shorter the bursts, the more they blend together, because one burst may not hit the drain before the next one is sent by the open tap. Eventually it becomes almost impossible to tell where one burst ends and the next begins. Similarly, a circuit gate switched by 10 electrons may not know whether it is reading a deliberate burst of current or simply an irregular but ever-present parade of stray ions.

"When you start getting down to the tens of electrons, you have a problem with statistics," says Williams. "Is five electrons 'on' or 'off'? When you're talking about such small numbers, one in every 100 gates will be in an unknown state, and that's unacceptable."

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Then there's the "quantum effect." At subatomic levels, the deterministic rules of classical physics codified by Sir Isaac Newton break down. At these infinitesimal distances and in isolation, electrons stop acting like marbles being meekly herded through a maze of circuitry. Their behavior becomes unpredictable and at times bizarre.

Electrons subject to quantum forces behave sometimes like particles and sometimes like waves. They can transmute through solid matter, unexpectedly reverse their charge and even seem to be in many places at once. They don't act predictably, but only according to a range of probabilities.

Quantum mechanics is perhaps the most confounding field in science today--as it has been since it was first observed in 1913. Among those who felt left behind was Albert Einstein, who famously objected to its probabilistic nature with the words "I am convinced that God does not throw dice."

But to many scientists, quantum mechanics may yet be the savior of digital computing. Because quantum effects inevitably creep into the behavior of electronic devices when they are sufficiently small, researchers are hard at work on ways to harness, rather than overcome, them.

"Quantum effects are a pain in the butt," says Seth Lloyd, a physicist at the mechanical engineering department of Massachusetts Institute of Technology. "They make impossible things happen. So the reasoning is, if you can't beat them, use them."

This research is following several related paths, all built around the quantum phenomenon known as "superposition."

Stated simply, this seemingly implausible notion means that an electron in a quantum state can represent not only "on" or "off"--the "1" or "0" of digital language--but both positions simultaneously. This, theoretically, allows an electron in effect to perform hundreds of calculations at once.

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That's the theory. The reality is today the subject of vigorous research at Caltech, Stanford, MIT and other top-level laboratories around the world.

"We're fighting on two fronts," says James S. Harris, a professor of electrical engineering and director of the solid-state laboratory at Stanford, whose students have succeeded in isolating individual electrons for quantum computing experiments. "Can you make a device that works on a single electron, and how can you use it?"

Both questions can be answered, at least theoretically. Devices can be made, at least under laboratory conditions, and some uses have already suggested themselves.

One is in factoring large numbers, an important application in the field of cryptology. Factoring is one of a family of mathematical problems that increase exponentially in complexity as the digits at hand increase, meaning they quickly outpace the calculating power of conventional computers--even supercomputers.

Take the factoring of a 100-digit numeral (that is, identifying the whole numbers that are its divisors). As Hewlett-Packard's Williams observes, even a computer much faster than anything built today would need longer to complete this process by the simplest means possible, dividing by consecutive integers, than the age of the universe.

"But a quantum computer could do it instantaneously," Williams says.

Still, the practical obstacles to exploiting these theories are enormous. They include the exotic conditions necessary to isolate electrons and keep them in a quantum state; most manipulation of electrons requires temperatures approaching absolute zero (273 degrees below zero Centigrade), and devices that are only a few atoms deep and wide in size.

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Then there's the issue of error correction, which takes on a whole new meaning in the quantum realm. Quantum computers turn out millions of wrong answers along with the correct answers, and thus require ingenious methods to distinguish right from wrong.

Yet, recent developments have made researchers more confident than ever before that these problems can be solved.

"It's looking better and better in terms of testing the feasibility and coming to a conclusion about whether this is for real or not," says Nabil Amer, who is head of the experimental effort at IBM's Almaden Research Center south of San Jose into fabricating so-called ion traps, which confine single electrons. "Very good people are getting into this business."

Harris' group, for example, has fabricated a single electronic transistor, or "quantum dot," that works at room temperature. Advances in scanning electron microscopes give researchers virtually an atom's-eye view of their own handiwork.

But perhaps the most promising development was announced earlier this year by Neil Gershenfeld, a researcher at MIT, and Isaac Chuang, currently at Los Alamos National Laboratory. Building on earlier research, they showed how nuclear magnetic resonance spectroscopy, a widely available and easy-to-use technology, could be utilized to manipulate atomic nuclei of molecules to produce a computational answer.

The importance of the Chuang-Gershenfeld finding is that it shows that quantum computing does not always require isolated electrons, which are so hard to corral. Instead, it works even better when trillions of molecules are jostling one another all at once as in, say, a cup of room-temperature liquid.

Quickly dubbed "computing in a coffee cup," the theory holds that the error messages of the great mass of molecules in the cup will cancel each other out, leaving just enough molecules to produce an identifiably right answer.

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Each molecule in the computing soup, as it were, has a magnetic "spin" of a plus or a minus--"1" or "0" in digital terms. NMR, which produces a magnetic field, could be used to manipulate those spins by applying pulses of radio waves that can flip the spins of certain molecules from plus to minus or vice versa.

As Lloyd, who has done pioneering research in the field, puts it, flipping a molecular spin by applying a stimulus like a radio frequency is exactly analogous to instructing a digital transistor to switch from "on" to "off" by applying an electrical current--the way classical computers work.

By observing and controlling how different molecules react to different frequencies and to their neighbors, one can construct increasingly complex logic devices, gradually reaching a level that matches or surpasses the complexity of today's computers, but that are smaller and faster.

Refining the techniques of manipulating these quantum bits and reading their answers is still enormously difficult, researchers caution. But many say that Chuang and Gershenfeld have cleared up a problem that confounded the field.

"If you'd asked me three months ago how long it would be before we could do anything with quantum computing, I'd have said 25 years," says Williams. "But now I'd say we can do it now."

As for how to use quantum computing, experts are entranced by the prospect of applications thus far unimagined.

"There are many things we're using today in ways that were not originally intended," says Amer. "Once we have the capacity in hand, we'll see what it's good for."

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Hiltzik writes frequently about technology. He can be reached via e-mail at [michael.hiltzik@latimes.com](mailto:michael.hiltzik@latimes.com).

### Going It Alone

#### TODAY: THE CONVENTIONAL TRANSISTOR

In a classical semiconductor transistor, a current, or flow of electrons, moves from "source" to "drain" along a negatively charged channel surrounded by a positively charged material. Applying voltage to the "gate" widens the channel, allowing more electrons, or current, to flow; reducing or removing the voltage cuts off the flow, thus allowing the drain to register whether the transistor is switched on or off.

#### TOMORROW: THE SINGLE ELECTRON?

A quantum dot, otherwise known as a single electron-transistor, is designed to trap a single electron, whose fluctuations in energy state function roughly the way a current does in classical transistors. In this example, researchers have deposited a tiny rectangle of titanium oxide (yellow) on a base of pure titanium (red). A single electron can be induced to tunnel through the barriers onto the island, where its charge is powerful enough to keep other electrons from joining it. This structure, however, works reliably only at temperatures hundreds of degrees below zero Fahrenheit.

Sources: Stanford University; MITI Electrotechnical Lab, Tsukuba, Japan

### The Shrinking Microprocessor

Advances in chip-making technology are expected to continue to shrink the size of a chip's "features," or transistors, over the next 13 years and allow a corresponding increase in the number of transistors per chip.

#### Minimum Transistors

feature per cubic  
size, centimeter,

Year in microns in millions

1995	0.35	4
1998	0.25	7
2001	0.18	13
2004	0.13	25
2007	0.10	50
2010	0.07	90

\* A micron is one-thousandth of a millimeter.

Source: Semiconductor Industry Assn.

## Graphic

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PHOTO: Nabil Amer heads IBM's effort to fabricate electron "traps." PHOTO: Below, a laser is used to calibrate the trapping device at the company's facility near San Jose. PHOTOGRAPHER: MATT BLACK / For The Times GRAPHIC-DRAWING: Going It Alone, LORENA INIGUEZ / Los Angeles Times GRAPHIC-TABLE: The Shrinking Microprocessor / Los Angeles Times

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