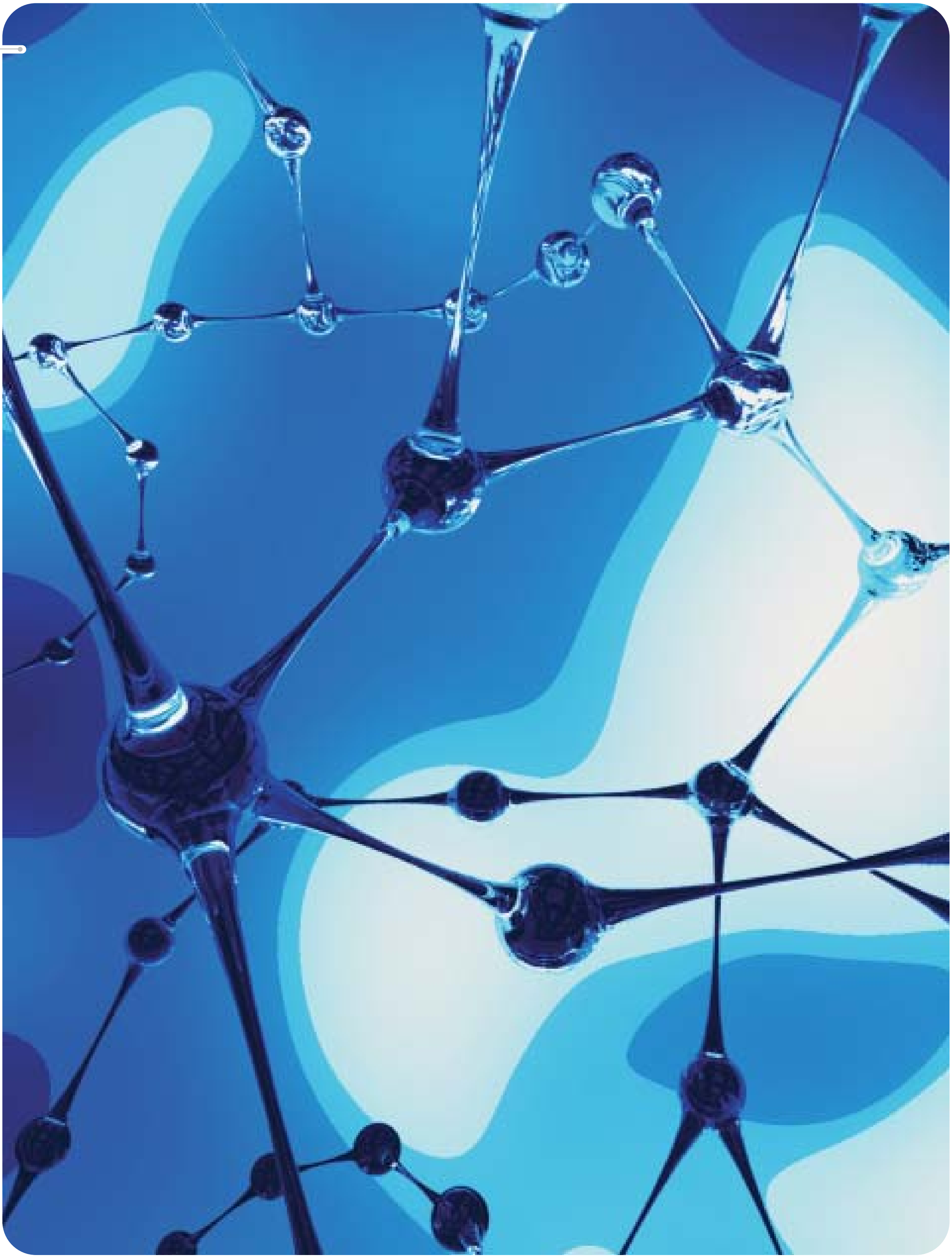
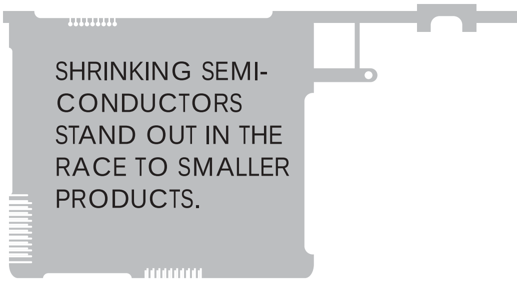


ROB MAGIERA / NOUMENA DIGITAL

BY MAURY WRIGHT, EDITOR IN CHIEF

MINIATURIZATION ENABLES INNOVATION—PAST, PRESENT, AND FUTURE



SHRINKING SEMICONDUCTORS STAND OUT IN THE RACE TO SMALLER PRODUCTS.

Ask someone on the street what miniaturization means to them, and they will most likely indicate a mobile handset or perhaps an MP3 player. Ask an engineer, and you'll probably get a Moore's Law-centric answer. Clearly, those answers are intertwined because one enables the other. And, in fairness, compelling portable consumer devices require smaller everything—speakers, microphones, disk drives, batteries, connectors, and so forth. Complex technologies, such as disk drives, require advancements that rival the innovation in ICs. Still, the big digital IC that lies at the heart of these products has been in the miniaturization spotlight at least since the Intel 4004 debuted, and the SOC (system on chip) promises to continue as the most important enabler of cool things for some time to come.

Over the 50 years of *EDN*'s history, few constants have remained in the tech industry, but there has been a constant march in shrinking end products, driven by the shrinking enabling technologies inside those products. We always hear that everything is smaller, faster, and cheaper, but even that saying is not necessarily true. Early transistors sold for far more than the technologies that they would usurp. Increased integration in ICs always makes for smaller products, albeit not necessarily higher performance ones. Only the smaller angle is almost universally correct.

On miniaturization, Texas Instruments (www.ti.com) Principal Fellow Gene Frantz says, "You can almost say that we are on the path to the vanishing product—where the product will be so small and insignificant in size but so significant in capability that we really don't know where we have it; we just know we have it."

Dean Kamen, founder and head of DEKA (Dean Kamen) Research (www.dekaresearch.com), has leveraged the miniaturization trend in everything from the Segway to computerized medical instruments. "We've come to expect that electronics have gotten so small, computing power has gotten so cheap, memory has gotten so plentiful, and power consumption has gotten so reasonable," says Kamen. "You put all of that together, and, literally, we're now at a point with electronics, which we aren't with any of the other fields of engineering, where it isn't a question of what you can do; it's a question of what should you do because you know it can be done. What was unthinkable 10 years ago is virtually trivial now."

Looking back, as we at *EDN* have done for our Milestones That Mattered series and interactive time line, it's amazing that inventors in our industry often didn't realize the true significance of their work—

HOW MINIATURIZATION BEATS THE HEAT

By Lewis Counts, Analog Devices Inc

Without advances in mixed-signal technology, a cell phone would be too hot to hold; you would need a backpack to carry it. Instead, today's mixed-signal ICs allow cell phones to feature color displays with still cameras and videocameras and even allow for TV broadcasts, especially if you live in Asia. A phone's size might make you forget it is in your pocket while you are on a commuter train, hiking in the mountains, or swooshing down ski slopes. Oh, and by the way, it also lets you make phone calls.

How did technology advancements take us from the op amps of the 1970s that were in dual-in-line packages to the miniature surface-mount ICs in today's cell phones? Moore's Law played a part, yes. But much more was involved than mere reductions in package size. For example, nanometer geometries have resulted in unheard-of digital-performance levels in laptop microprocessors. In addition, process enhancements and clever design also played big roles in improving analog-circuit performance–with a corresponding decrease in power consumption.

GAUGE IT WITH AN OP AMP

Op amps are everywhere, especially in SOCs (systems on chips). Today's op-amp circuit measures less than half the size of a 1970-era bond pad, or between $^1/_{400}$ and $^1/_{1000}$ the die area of one of the industry's first op amps, Texas Instruments' μA741.

The size means there is less capacitance to push around, so a microprocessor can perform more digital functions at higher speeds with the same amount of power. The analog world also benefits from less capacitance. At least two ways exist to view this phenomenon.

First, lower on-chip capacitance translates to less current to achieve the same or more bandwidth and slew rate. You can compensate amplifiers to maintain closed-loop stability at higher frequencies because lower capacitance also raises the frequencies of parasitic poles, the dominant cause of instability.

Second, less current means less heat. The μA741, which Analog released in 1968, typically draws 1.7 mA from ±15V supplies. That amount may not seem like much; it is only 51 mW. Today, that same 1.7-mA figure powers two video-speed op amps with more than 400 times the μA741's gain-bandwidth product. And 1.7 mA are more than enough for one precision op amp with 50 times less offset voltage, seven and a half times less drift, and 36 dB more common-mode rejection.

Because of their output stages, stand-alone op amps draw more current than their integrated cousins. System designers need stand-alone circuits for design flexibility in one-of-a-kind applications, and they provide a valuable gauge of bandwidth per milliamp from a standard function.

MORE BANDWIDTH PER MILLIAMP

Some interesting trends have emerged in the gain-bandwidth-per-supply-current metric (Figure A). Analog Devices built the μA741 using Fairchild's planar-bipolar process, then the granddaddy of all IC manufacturing. Its internal compensation set it apart from earlier competition.

BiFET op amps, such as Linear Technology's LF356 and Analog Devices' AD711, began to appear in 1978. These circuits offered a 1.4 to four times bandwidth increase for each milliamp of supply current. Input-bias currents decreased dramatically, thanks to integrated JFETs: The AD711's 15 pA is more than 5000 times lower than the μA741's.

But the situation for wideband-system applications was even better. Adding true complementary PNPs to go with the NPNs, Analog Devices' AD847 of 1988 had more than 10 times the μA741's bandwidth per milliamp.

A later silicon-on-insulator-process technology resulted in the development in 1995 of the Analog Devices AD8011, with more than 400 times the bandwidth performance per milliamp. The demands of high-definition video would have been impossible with the μA741, and the AD847 would have been hard-pressed to meet the performance requirements. But video op amps such as the AD8011 make it easy.

Bandwidth for the supply current has increased rough-

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at least at the time of their inventions. And third parties, including *EDN* editors, were often no more perceptive. For instance, in our look back at Fairchild's (www.fairchildsemi.com) introduction of Micrologic Elements (see "The planar IC—revolution underestimated" at www.edn.com/article/CA6325586), *EDN* originally discounted the significance of the ICs, reasoning that batteries and other components in aerospace applications would render miniature logic insignificant. Of course, that assumption ignored the multitude of consumer applications that would come to rely on digital logic.

In discussing milestones from the technology industry history, Walden Rhines, chairman and chief executive officer of Mentor (www.mentor.com), states, "In most cases, the actual components were developed initially without knowledge of what the killer application would be." Rhines claims that such lack of foresight is a typical trait of revolutionary developments.

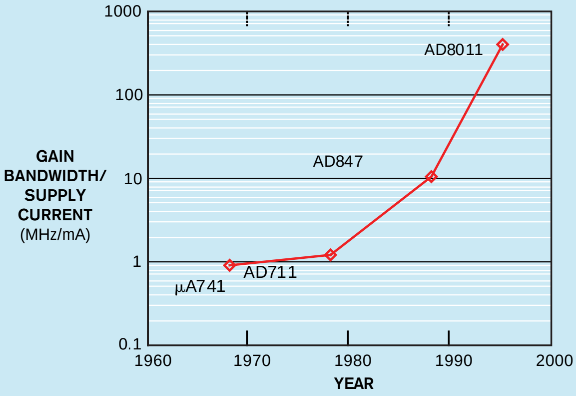

Figure A Some interesting trends have emerged in the gain-bandwidth-per-supply-current metric.

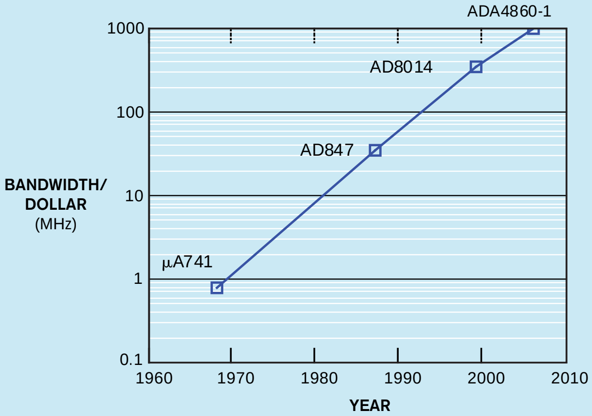

Figure B Bandwidth per dollar has increased about 10 times per decade.

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ly 10 times every decade since 1980. And the AD8011 costs less than the µA741 did when it debuted.

MORE BANDWIDTH PER DOLLAR

Figure B illustrates that bandwidth per dollar has increased about 10 times per decade. Today, you can purchase 1-GHz devices for $1–and that dollar is inflated compared with a 1968 dollar. The µA741 came in an eight-pin TO-99 or mini DIP. For designers requiring high-speed op amps, the ADA4860-1 is available in a six-pin surface-mount package almost nine times smaller than the µA741 with lower parasitics and no holes to drill into a pc board.

Do you need high precision rather than speed in that tiny space? Op amps such as the AD8698 have just 20-µV offset, 50 times less than a µA741. Analog Devices' AD8698 also has 36 dB more power supply and common-mode rejection, making it useful in noisy environments. It also touts 30,000 times more gain and $^{1}/_{100}$ the input-bias current–for lower cost.

The last 35 years have not brought just increasing bandwidth and precision for lower current, cost, and size. Shrinking processes also made possible cool analog- and mixed-signal ICs in small spaces. These ICs in turn made possible cell-phone still cameras and videocameras and wireless headsets. Cell phones are low-power enough to allow several hours of call time on a small battery.

Without advances in signal-processing technology, you would not be able to carry a backpack-sized cell phone far, and it would burn your hand to hold it, even if you could. Instead, you would have to find an ac outlet just to power it. Now, you can transmit video to colleagues, family, or friends as you talk long-distance on your cool-running, pocket-sized gadgets on your commute to work, hike in the mountains, or ski run down the slopes.

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Lewis Counts is vice president of technology and fellow at Analog Devices.

He continues, "If you float a technology out there and make it easy enough to use, someone will discover it and match it up with the end application."

Before working at Mentor, Rhines worked at TI managing the semiconductor group. And both Rhines and Frantz relate similar stories about the birth of the DSP. In the early 1980s when the TMS32010 came to market, TI expected—but didn't find—success in the speech market. The two markets in which they would find early success—PC-graphics acceleration and hard-disk-motor control—weren't on the radar. Later, the DSP would enable the dial-up modem and the digital cellular handset, among other products.

THE ONGOING TECHNICAL REVOLUTION

By Gene Frantz, Texas Instruments

We are in the middle of a technological revolution. Innovation is rampant as a result of advances in IC technology, which has improved end products by bringing us higher performance, lower cost, longer battery life, and decreased size. Each of these aspects has had a part in fueling this technological revolution. Things that you now carry in your pockets used to require large, air-conditioned rooms. This revolution has come in three waves. You have seen one successful wave of innovation in telecommunications. Now, you are in the middle of a second wave, entertainment, and are at the beginning of the third wave.

WAVES OF INNOVATION

Next year will mark the 25th year that Texas Instruments has been in the DSP (digital-signal-processing) business, and, during those years, TI has been a key driver of the first two waves of the revolution. The first wave, telecommunications, digitized the phone system to allow phone lines to transmit data. Modem rates rose from 1.2 to 56 kbps, and DSLs (digital-subscriber lines), cable modems, and Ethernet carried data rates into the megabit-per-second area. Meanwhile, digital cell phones evolved into multimedia appliances that integrate cameras, MP3 players, and more.

The second wave, entertainment, started in 1983 with the introduction of the CD format. Entertainment demands not only performance, but also portability–or, in IC terms, low power dissipation.

Today, products that are not only portable, but also personal define digital entertainment. They record, store, and play back your music play lists, photos, videos, and games.

WHAT'S NEXT?

With the first two waves well under way, what is the next wave? It could be transportation, quality of life, security, or education. In transportation, improving vehicle safety will be a strong technology force over the next 20 years, with imaging, sensing, and in-vehicle safety systems playing important roles. Engineers have worked to make cars safer except for removing the obvious problem: the driver.

Medical applications are among the leaders in improving quality of life. An eye-opening example is an artificial-vision system developed at the University of Southern California (Los Angeles, www.usc.edu). A miniature camera attaches to a wireless receiver behind your ear. The receiver carries signals that travel along a wire under your skin to an electronic electrode array that attaches to the eye's retina. Resolution at this point is minimal–a 4×4-pixel image.

Speech patterns, fingerprints, facial recognition, and retinal scans can all identify people, but security needs 100% accuracy. For this reason, transitions will occur in this area. First, the camera, a source of information for humans, will find use as a second source of opinion, carrying information to the human in charge. In another transition, information from the camera provides the first opinion, and the human acts as the backup. Finally, information from the camera becomes the *only* opinion.

In education, most people accept that technology can improve the learning process. The sticky problems of determining which technologies to deploy and how to measure their effect counter this positive view, however. Much like physicians, educators often believe that their first duty is to do no harm. This conservative approach has allowed students to sprint ahead of their teachers in adopting technology in the classroom. Sometimes, their innovations are unnerving, such as using the SMS (short-messaging service) of mobile phones to cheat on tests. Typically, educators respond to this bright idea by barring cell phones.

Better ways to use this technology should emerge. With all of the computing, communications, and entertainment capabilities available, a revolution in this market is about to happen. Innovation will drive this revolution.

For the next wave, education may well be the sleeper of the four candidates, but transportation, security, and quality of life are not. If you think the last 25 years have been exciting with new innovations, just wait for the next 25 years.

AUTHOR'S BIOGRAPHY

Gene Frantz is technical fellow at Texas Instruments (Houston).

MINIATURIZATION HISTORY IS NOT THE FULL STORY

By Walden C Rhines, Mentor Graphics

At first glance, the progress of electronics seems to have been a steady march toward miniaturization. Certainly, the path along major milestones–from vacuum tubes to transistors to ICs to ASICs to SOCs (systems on chips)–generally tells a tale of more on less. But the cost reduction has been the driving factor toward miniaturization.

Almost all cost reduction for ICs has historically come from shrinking features and increasing wafer diameters. But miniaturization has occurred as a special case of the learning curve, which mandates that the cost per unit of everything produced decreases by a fixed percentage every time total cumulative volume doubles. This law applies to all goods and services produced over the centuries when measured in constant currency. Throughout their history, transistors and ICs have followed a relatively steep learning curve.

Gordon Moore last predicted in 2003 that Moore's Law, which postulates that the number of transistors on the most advanced ICs will double every 18 months, would be good for another decade. But even Moore acknowledges that "no exponential is forever." According to the ITRS (International Technology Roadmap for Semiconductors, www.itrs.net), by 2010 we will have only eight electrons available to switch a transistor. By 2020, only one electron will be available, which, although theoretically possible, stretches the laws of physics. So, it is clear that scaling has physical limits. Shrinking feature sizes and increasing wafer diameters will no longer maintain the learning curve. Miniaturization brings its own set of serious problems. Nevertheless, the learning curve will continue. But the methodologies to stay on the curve are changing. The ongoing drive to achieve reduced cost per function and improved quality will require other innovations besides miniaturization.

These new developments include innovative assembly and packaging of multiple chips. Despite the historical drive toward the single chip as the ultimate approach for any application, it is becoming increasingly apparent that the single chip is not always the lowest cost, most reliable, or highest quality. When vendors integrate semiconductor technologies on a single chip, the final chip favors the lowest cost and takes place in the least expensive technology, rather than a superset of all the technologies. Again, cost reduction is the driving factor, and reduced size matters only in so far as it helps to reduce costs.

As geometries shrink, the fixed costs of design, verification, software, and tooling have increased to the point at which it's common to see companies spend $20 million to design a complex SOC. And the revenue per ASIC is increasing more slowly than the fixed costs of cutting-edge design. The learning curve is seriously out of alignment here, and a change in ASIC methodologies is essential to reducing the fixed costs. Attempts include structured ASICs and richer design libraries, but the most promising approaches include a move to higher levels of abstraction and to new techniques for system verification.

Whenever size decreases, power dissipation and power density increase. Indeed, power issues constitute major challenges for today's designers. To increase gate count without increasing power density, designers need to turn to innovations in advanced process technology, such as high-k dielectric gates; lower channel-leakage structures, such as FinFET and oxide isolation; improvement in circuit-design techniques, such as variable voltage and power-down techniques; and, especially, architectural trade-offs in the system design.

Semiconductor-manufacturing costs have soared with miniaturization. When these two vectors collide, further miniaturization depends on cost containment. For example, resolution-enhancement software is beginning to offset lithography-equipment costs, which were increasing in step with Moore's Law. Techniques such as embedded deterministic test are dramatically reducing test costs, which are sometimes more than half the manufacturing cost.

The number of RET (resolution-enhancement-technology) layers increases every process generation, and physical features dramatically impact yield, which has major cost ramifications. DFM (design-for-manufacturing) and design-for-yield tools are addressing the problem at the design stage, with DFM guidelines to avoid feature-limited yield problems and lithography-friendly tools that allow designers to analyze the effects of manufacturing variability.

Long after Moore's Law becomes invalid, we will continue to reduce the cost of logic gates, just as we did before the development of solid-state electronics. However, we won't achieve this indefinitely by miniaturization, because miniaturization must have a physical limit. We will continue to develop other techniques to reduce costs, as the learning curve ensures that innovation continues.

AUTHOR'S BIOGRAPHY

Walden C Rhines is chairman and chief executive officer of Mentor Graphics Corp.

You might wonder about recent examples of technology's success in unforeseen ways, because developers are increasingly designing products for target applications. "As an industry matures, you have less of that," Rhines admits.

Rhines is enthusiastic in looking back at his experience, both at Mentor and at TI, and offering opinions on key milestones in the miniaturization march. He points out the significance of the first germanium and then the first silicon transistors. He claims that the silicon version was especially significant because it was stable over temperature changes and therefore suitable for consumer products such as transistor radios.

Rhines also credits Intel (www.intel.com) for commercializing microprocessors and memory and especially for moving to NMOS technology, thereby enabling denser memories. And he believes the industry's move to CMOS was ultimately even more significant. Rhines relates that TI had to use low-power CMOS for its work with battery-powered devices, such as watches and calculators. But the challenge was immense. "Fundamentally, you were saying, 'I'm going to put two transistors down everywhere there is one today, and I'm somehow going to make the die smaller, faster, and lower power,'" he says. Rhines credits the Japanese conglomerates for wading through the CMOS challenge and delivering on its promise. And CMOS was clearly the best technology choice for digital ICs and even increasingly for analog ICs.

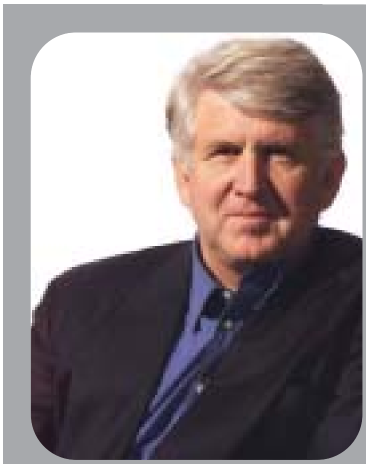
At the same time that microprocessors and memory were matriculating at Intel and elsewhere, Bob Metcalfe was already thinking about the value in connecting discrete computers. The miniaturization trend would make Ethernet possible. Metcalfe developed the LAN while working at Xerox PARC (Palo Alto Research Center) in the early to mid-1970s and went on to found 3Com and make Ethernet a commercial success.

Metcalfe recounts that the first version of Ethernet in Xerox's labs operated at 2.94 Mbps. After five years of work with Ethernet in a laboratory-type environment, his team evaluated the 2.94-Mbps network and found it to be nearly optimally loaded. The group foolishly thought that it had arrived at the exactly correct speed choice. Looking back, Metcalfe admits, "The fact was that any application that couldn't run at 2.94 Mbps didn't catch on. All the applications that could squeeze through 2.94 Mbps did." Soon, the first standardized version of Ethernet would emerge at 10-Mbps rates. "We settled on 10 Mbps for the first standard because that's how fast the Intel chips could run," he says. And Metcalfe garnered the credit for Metcalfe's Law, which suggests that the value of a network is proportional to the square of the number of users on the network.

Although silicon advancements are fairly easy to chart along Moore's Law and to apply in computers, real-world products require motors, valves, and the like. Disk drives are some of the few electromechanical products to truly ride the miniaturization curve. "Those of us in the semiconductor industry tend to try not to pay attention to the fact that the density of bits on a hard disk have increased at a slightly greater or at least at the same rate as the density of bits on an IC," says Mentor's Rhines.

Even in the real world, though, it's tough to move a miniaturization discussion away from semiconductors. Kamen of DEKA has worked on everything from tiny, implantable medical devices to his iBot, which is somewhat akin to a Segway but can also climb stairs and helps the disabled regain mobility. "The big things for us were DSPs, but high-power control stuff was also important," he says, noting that a device such as the iBot needs both powerful motors and power semiconductors and control devices that can drive kilowatt-sized loads in small packages.

The meaning of "miniaturization" also depends on the context. For a disabled person, an iBot is a miniature transportation device. For dialysis patients, the portable Homechoice dialysis machine, which DEKA designed and Baxter International (www.baxter.com) sells, frees patients to travel and receive needed medical care. Kamen also notes that the lowering of the quiescent power in semiconductors is key to small medical devices, such as implantable products, which must run for extended periods.



"ANY APPLICATION THAT COULDN'T RUN AT 2.94 MBPS DIDN'T CATCH ON. ALL THE APPLICATIONS THAT COULD SQUEEZE THROUGH 2.94 MBPS DID."

Regarding electromechanical products, such as motors, Kamen says that performance is improving but that cost has also increased, compared with the costs in the IC market. Kamen makes the same generalization about batteries. He advocates moving mechanical functions into the electronics whenever possible.

Battery and power issues seem to resonate with everyone from users facing frustratingly short handset-battery life to design engineers managing expectations and capability. The road map of process technology for years has guaranteed power savings. These days, however, leakage current means that savings come less freely. Designers have had to get serious about power management.

"We have just figured out that power dissipation is important," says TI's Frantz, who points out that you must attack the problem both by using better batteries and by increasing the power efficiency of the circuits. "If I reduce the power dissipation of my electronics by half, I can either, with the same battery, double the battery life or, with a battery half the volume, keep the same battery life,” he says. The factor of two that Frantz mentions can be significant, but he also suggests that a reduction in power requirements by an order of magnitude could make plausible a battery that is one-tenth the size of today’s batteries.

You can save power by increasing the number of transistors on a chip, he points out. The savings can come not only through better power management, but also through more basic chip operation. A dual-processor chip with each processor running at 0.5 GHz from a 1V supply, he claims, offers significantly lower power dissipation than a single-processor chip running at 1 GHz from a 1.5V supply.

Even Intel has low-power-system fever. When the company launched the Intel Core 2 Duo in August, President and Chief Executive Officer Paul Otellini claimed that the company began to focus more heavily on performance per watt when it launched the Centrino in March 2003. Intel still pushes performance. On the newest, second-generation, 65-nm strained-silicon process, Otellini says, “ We’ve seen stunning improvement in the transistor-level performance from generation to generation.” The Yonah core that Intel announced in January of this year reduces leakage current by a factor of 25 and boosts performance by 40%, he says.

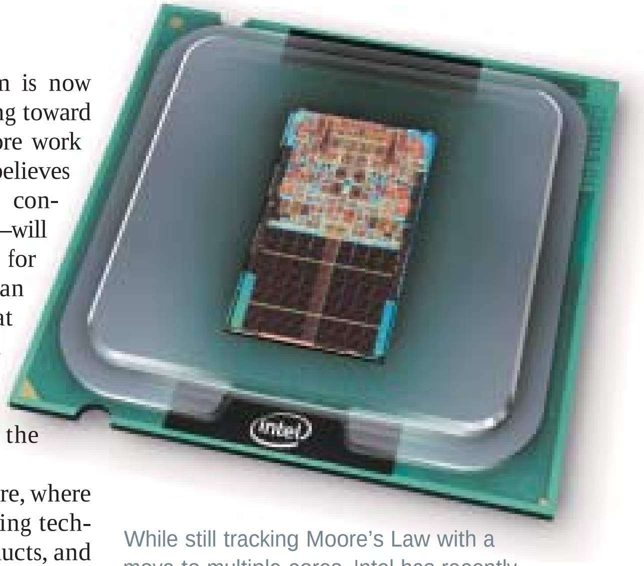
The jury is still out on how much progress the industry has made on low power. Luis Pineda, senior vice president of Qualcomm Chip Technology’s (www.qualcomm.com) marketing and product-management group, is more bullish than TI’s Frantz, and both work at companies with a major handset focus in which battery life matters. “We’re very advanced with our power-management techniques,” says Pineda. Referring to a CDMA-chip set, he says, “One of the chips is a dedicated power-management IC.” The power manager can shut down portions of the chip set when necessary and controls the power amplifier, he says. Moreover, it integrates many discrete functions, such as low-voltage regulators and peripheral drivers, from earlier designs.

Pineda also claims that process technology is still helping to reduce power. He points out that Qualcomm is now shipping 65-nm ICs and working toward 45-nm ICs. “There is a lot more work than we can do,” he says. He believes that the demands from the consumer—especially to play video—will escalate. Pineda claims, for instance, that the iPod Video can play at most 90 minutes and that consumers will demand more. Referring to power management, he states, “We’re probably three-quarters to where the industry can be.”

Turning to today and the future, where do we stand overall with enabling technologies for miniature end products, and what are the future trends? Some of the relatively new enablers are amazing. For instance, Knowles Acoustics (www.knowlesacoustics.com) approximately two years ago announced tiny MEMS (microelectromechanical-system)-based microphones for use in handsets and other small products. The company just followed with the MEMS-based Digital SiSonic microphone, which outputs a pulse-density-modulated bit stream. The company also offers miniature balanced-armature speakers that fit into headsets that rival the best noise-canceling headphones on the market.

THE JURY IS STILL OUT ON HOW MUCH PROGRESS THE INDUSTRY HAS MADE ON LOW POWER.

Even cabling and connectors may surprise you. Molex (www.molex.com), for instance, is shipping coaxial connectors with 0.4-mm pitch. The 40-pin connectors find use in connecting through hinges in clamshell handsets.



While still tracking Moore’s Law with a move to multiple cores, Intel has recently shown an increased emphasis on power efficiency. Both trends are evident in the recent Core 2 Duo launch.

Grand surprises are still to come. These days, Ethernet inventor Metcalfe works as an entrepreneur and a venture capitalist at Polaris Venture Partners (www.polarisventures.com). He also serves as chairman of Ember Corp (www.ember.com), which focuses on the ZigBee wireless standard. Other investments connect Metcalfe to the miniaturization angle. For example, Metcalfe invests in Unison Products (www.thinfilmaudio.com/), which plans to integrate speaker technology on the surface of a display. The scheme relies on tiny piezoelectric elements along the edges of a display that move a membrane stretched across the screen. Presumably, the scheme will conserve space, and the sound comes from the best possible location facing the user.

Perhaps the biggest advancement might be in energy “harvesting,” or gathering energy to power a device from the immediate environment. Researchers are working on converting body heat, vibrations, stray RF energy, and light of all types into energy that could keep a relatively small battery charged. Remember Frantz’s comment about a vanishing product? He finished by saying, “As much as possible, it would be good to run a product off body heat or to have no power or battery at all.” But is energy harvesting feasible, and, if so, when? “If you think solar power is one of those solutions, it’s here,” he says, pointing out that TI has long built solar-powered calculators that use a relatively small battery that charges sporadically in lighted environments.

It’s probably no surprise that Metcalfe has an energy investment and an interest in harvesting. He states, “Batteries are a big venture-capitalist kind of thing; there are a million battery deals going around." His investment, Infinite Power Solutions (www.infinitepowersolutions), focuses on tiny batteries that generate tiny amounts of power at a low duty cycle. The batteries might find use in applications such as implantable medical devices. A patient might sporadically—say, once a year—visit a doctor to receive an inductive battery charge through the skin, for example. Someday, energy harvesting might continuously charge that battery. Infinite Power is building a semiconductorlike fab to build the flat batteries using vapor deposition on a flexible substrate and is offering a 1-in.^{2} battery for sampling. You can solder the battery onto a pc board or build it into the board and ultimately perhaps into an IC substrate.

The discussion returns to semiconductor processes even when a battery is front and center. After all, process technology has been the constant enabler of technology. "All new fields lead off with innovations in material science," says Mentor's Rhines, pointing out that mastering silicon-purification techniques was the obstacle that TI, Fairchild, Intel, and others cleared in launching the IC industry, and material scientists drove the innovation.

Meanwhile, other engineering disciplines await such a breakthrough. "We're starting to enter an age now in which electronics might have been a couple of decades ago, when material science, surface finishes, nanostructures, building compounds, materials, and surfaces are getting so extraordinary that we are going to see some big changes in everything from electrical properties to thermal properties to strength and structural properties of materials that are going to be pretty exciting," says Kamen.

He still counsels that you should leverage the maturity of electronics in every way possible. "There are opportunities to move some of the issues out of the world of the mechanical into the world of the electronic and take advantage of the high-performance electronics," he says, citing the transition from the phonograph to the CD to the MP3 player as an example. The CD eliminated contact with the media, and a flash-based MP3 player eliminates the mechanics.

Metcalfe is also a staunch believer in the IC as the key enabler. "Moore's Law is the fundamental; all of the rest comes along," he says. His biggest interest these days is in embedded microcontrollers and especially connecting those microcontrollers, again exploiting Metcalfe's Law. He defines a layer of embedded networking below Wi-Fi, Bluetooth, or cellular in which machines communicate with machines.

Ember, with ZigBee, is a player in embedded networking, and Metcalfe believes that wireless is the key. "You can't run cable very well among lots of embedded micros; you had better do it wireless; hence, the development of CMOS radios," he says, claiming that vendors annually ship approximately 10 billion microcontrollers. "That number is going to go up thanks to the arrival of embedded networking," he says.

Not surprisingly, with his semiconductor and EDA background, Rhines believes the future of innovation is in chip design and the number of design engineers that have access to chip-design technology. He points out that, when ASICs debuted, custom-IC folks laughed off the upstart technology because ASICs would offer lower performance and be bigger than custom ICs. During the custom-IC era, however, only a few thousand IC designers existed, he points out. ASIC technology allowed tens of thousands of engineers to design ICs. Rhines claims that FPGAs or another disruptive technology will result in the emergence of 5 million chip designers by 2010 to 2020. "In itself, that should generate more innovation," he says. EDN


You can reach
Editor in Chief
Maury Wright
at 1-858-748-6785,
and mgwright
@edn.com.