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REPORT

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On To Embedded

AMD's 64-bit x86 microprocessor is the answer to Intel's incompatible IA-64. It will not be cheap or easy for Intel to reassemble its 64-bit x86 development teams to create a rival.

Inside:

Here's the story of computer development that says where microprocessor makers are headed. My story compresses sixty years of development into a few pages that conclude with appraisals of the fate of **Advanced Micro Devices** (AMD), **Arc International** (ARC), **ARM Holdings** (ARM), **Intel** (INTC), **MIPS Technologies** (MIPS), **Tensilica**, **Transmeta** (TMTA), **VIA Technologies** (2388.TW), and others.

When people think of microprocessors, they think of PCs. But PCs are a tiny part of the microprocessor market. There's a much larger market for microprocessors in embedded applications. According to *Silicon Insider's* Jim Turley, the PC market for 2004 will be 170 million units and the market for embedded microprocessors will be 6.5 billion units. The microprocessor is invisible (embedded) in a toaster, blender, or microwave oven because the microprocessor mimics functions of displaced application-specific hardware and doesn't interact in computer-like ways with the user.

The story is divided into history and predictions. To skip to the predictions, start reading at "what will happen."

The history

The computer was a breakthrough in problem-solving methods because it could simulate hardware. Before computers, engineers solved problems with custom (application-specific) hardware. Such computer-based solutions were slower and less efficient than custom hardware, but hardware was expensive. Because computers were general purpose, their hardware costs could be amortized across many problems, making them more cost effective than single-purpose hardware.

MAINFRAMES. Early computers were unique. Even computers from the same manufacturer varied from one generation to the next. Computers were big and expensive and their utility seemed to be in solving large, expensive problems. Between the 1940s and the 1960s, a bunch of computer companies emerged. **IBM** (IBM) dominated a market for computers that supported Burroughs, Univac, **NCR** (NCR), Control Data Corporation, and **Honeywell** (HON), among others.

IBM INVENTS COMPATIBILITY. IBM dominated mainframe computers partly because it invented software compatibility with its System/360 computers. Compatible computers locked in customers for IBM because customers upgraded to larger computers without changing their software.

MINICOMPUTERS. Semiconductors and integrated circuits made computers small, reliable, and cheap. Smaller, cheaper computers solved problems for smaller organizations. As the computer shrunk, the computer business grew. In the 1960s, manufacturers making small computers, called minicomputers, proliferated; and so did their products. Among the manufacturers were Data General, Digital Equipment Corporation /DEC, **Hewlett-Packard** (HPQ), Interdata, Nanodata, Prime, Scientific Data Systems/SDS, **Tektronix** (TEK), Varian Data Systems, and Wang. These computers were small enough and cheap enough for university engineering departments.

The minicomputer invasion in universities spawned generations of graduating computer enthusiasts. For DEC in particular, seeding universities with cheap minicomputers was an effective marketing strategy. Students that became familiar with DEC minicomputers as

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undergraduates wanted DEC computers in engineering work environments. DEC became the standard in minicomputers.

MICROPROCESSORS. About 1970, it became possible to squeeze the elements of the computer's central processing unit onto one chip. The microprocessor was born.

The microprocessor brought the computer's problem-solving methods to engineers designing hardware. Microprocessor-based systems forfeited raw efficiency to improve designers' productivity and to reduce cost. Microprocessors improved designer productivity because they raised the conceptual level needed by the designer from electrical components to logical results. Costs dropped because a few generic components (microprocessor, memory, and peripheral chips) covered a wide range of applications, which meant the chips could be made in high volume, and at low unit cost. Manufacturers designed their microprocessors to be used in "embedded" solutions—where the microprocessor is invisible. That means it is not directly linked to the outside world.

Embedded systems required low absolute cost and just-adequate performance. The microprocessor had to be cheaper than a custom-hardware alternative, it had to meet performance requirements, and it had to work with a variety of memory chips and peripheral chips. The first microprocessors were not designed to be the central processing unit in a computer system. But by 1974, Moore's-law improvements made the microprocessor good enough and cheap enough that a hobbyist market developed for *microprocessor-based* computers.

During the 1970s, enthusiasm for microprocessor design grew and by the end of the decade, students in engineering classes were designing their own microprocessors.

PCS AND WORKSTATIONS. By the late 1970s, the microprocessor was fast enough to be the central processing unit in commercial computer systems. This was the beginning of the workstation market and the beginning of the end for minicomputers. **Sun** (SUNW) introduced a workstation based on **Motorola's** (MOT) MC68000 microprocessor in 1982. Meanwhile, researchers experimented with microprocessor designs.

Unlike commercial microprocessors of the time, research-project microprocessors were designed to be the central processors in computer systems. They were performance-oriented designs, in contrast with their cost-oriented commercial counterparts, which were designed to work with low-cost memory systems and with a variety of peripheral chips.

Research microprocessors were simplified to make their design feasible for students. So-called reduced instruction-set computers (RISCs) let students produce results in an academic year. RISCs threw out complex instructions such as multiply and divide, reducing the instruction set to instructions that could be implemented quickly and easily.

The RISC fad began. Soon, there was a host of workstation companies: Apollo Computer, Daisy Systems, DEC, HP, IBM, **Intergraph** (INGR), MIPS Computer Systems, **Silicon Graphics** (SGI), Sun, and of RISC microprocessors: Alpha, ARC, ARM, MIPS, PA-RISC, PowerPC, SPARC. The number of workstation manufacturers increased through the 1980s, peaked in 1992 at more than seventy-five, then declined.

Apple (AAPL) was the first big success in the hobby computer market. It could have dominated the personal computer market but for two strategic blunders. The first blunder was electing to take higher margins on the Macintosh instead of increasing market share with a lower price. Apple's second blunder was its transition from the Motorola MC68000 microprocessor to the PowerPC.

For the first blunder, Apple forfeited market share to the IBM PC and its clones. The second blunder was more subtle. Apple elected to move its flagship Macintosh computer line from an older-generation microprocessor to a new, but incompatible, RISC microprocessor. Apple made the transition as seamless as possible, but it was still a disruption. Customers considering an upgrade knew they would have adjustments in transition, so many considered moving to IBM-compatible computers. Apple's microprocessor transition weakened its lock on customers. Apple thought that the transition would give its computers a performance advantage over IBM compatibles that would gain market share.

IBM built the personal computer market with its 1981 introduction of the IBM Personal Computer. The IBM PC, in a break with IBM's normal practice, was built from off-the-shelf components. It was built for low cost and for quick delivery. IBM's design team selected Intel's lowly 8088 microprocessor as the central processor for the system. Folklore notwithstanding, the 8088 was probably chosen for its ready availability, for its family of peripheral chips, and for its excellent documentation.

Most important, IBM's reputation made the personal computer *credible* in business environments. IBM sold 15,000 systems the first year.

PC-compatible clones soon appeared and the market for x86-based computers took off. Though there were many competing small computers from companies such as Acorn, Alpha Micro, Apple, Atari, Commodore, DEC, IMSAI, **Radio Shack** (RSH), Scelbi, and **Texas Instruments** (TXN), IBM and its clones once again proved the enormous value of compatibility.

If IBM invented compatibility and if that compatibility was key to dominating the mainframe computer market, then why didn't the IBM System/360 instruction set take over the world? Critical mass. IBM built mainframes for enterprise customers. It moved up market and it moved down market. But its *business model* was incompatible with the mass market of personal computers. IBM charged a premium for hardware and for maintenance and it essentially gave away its software. In desktop markets, the situation reversed. Consumers wouldn't pay a premium for hardware and they wouldn't pay annual maintenance fees, but they expected to pay for software and for software updates.

So, here's the situation in the 1980s. The minicomputer makers began in their own market segment, but soon moved up market to wipe out most of the mainframe makers. Workstation makers began in their own market segment and were in the process of moving up market to wipe out the minicomputer makers. The IBM-compatible PC was working its way into businesses and its use was growing among consumers.

Workstation makers, facing a host of competitors in a relatively small market, looked with envy at a personal computer market that was ten times larger in unit sales. With a performance advantage or with a cost-performance advantage, workstation makers thought they could encroach on the personal computer market. Instead, personal computers encroached on the workstation market.

Workstation makers designed for performance, resulting in high system cost and excellent performance. Some workstations even beat the personal computer in price performance (divide price by performance to compute cost per processing unit). If workstations could beat PCs on absolute performance and on price performance, couldn't workstations displace PCs in the market? No. The PC created its market. It didn't displace minicomputers or workstations (at least initially). PCs competed on performance, but they also competed on price, and there was a limit to the absolute price PC customers would pay. Workstation makers could not meet this *absolute price*, even with their best cost-performance systems.

RISC-based workstations and x86-based PCs fought it out in the 1980s and 1990s. Workstation makers built for performance and hoped to cost reduce to achieve volume (not seeing that it is volume that yields lower cost). PC makers built for volume and grew with the market. Throughout that period, Intel, the dominant producer of x86 microprocessors, worried about competition from RISC microprocessors. Intel invested heavily to keep the performance of its x86 competitive. We should all be grateful that Intel did so, because the stellar performance of today's PCs is the result of Intel's paranoia.

A problem lurked in the background: microprocessor design cost. The cost of designing a computer's microprocessor is amortized across its lifetime sales. By the mid 1990s, when the cost to design a microprocessor passed $100 million, PC shipments were high enough that the amortized design cost amounted to only a dollar per PC. By contrast, the same microprocessor design cost had to be amortized across only tens of thousands of units for even the leading workstation manufacturers. Amortized microprocessor design cost added more than a thousand dollars to the cost of a workstation.

RISC-based workstations are doomed; x86-based computers dominate desktops, laptops, workstations, and servers. The irony is that Intel, whose volume-based strategy trounced the workstation makers' performance-based strategy, got caught in the RISC fad. Intel introduced its new and incompatible IA-64 Itanium microprocessor with a performance-based strategy. Intel probably intended to move the personal computer market to a proprietary microprocessor in order to avoid competition from AMD, Transmeta, and VIA Technologies. Even with an infinite supply of money and engineering effort, it won't succeed. The market cannot be converted from x86.

THE INTERNET AND THE x86. The (x86-based) PC grew up with the Internet. The PC is the universal development platform. The PC has the programmers, the compilers, the applications, the device drivers, the application programming interfaces, the peripheral devices, the protocols…—it has critical mass in everything and the Internet connects it all together to give it even more stability than binary (software) compatibility already offers.

It may seem in these days of the Internet, with browser-based access to everything, that the processor wouldn't matter. Applications are written in high-level languages or they exist in portable software in an intermediate form such as Java or html. So ARM, MIPS, PowerPC, or SPARC would be as good as the x86. It just isn't so. Portable applications and portable code are becoming more common, so it's possible to get access to applications and information using a microprocessor that's not x86, but there's a cost in doing so. Paraphrasing Fred Weber, CTO of AMD's Computation Products Group, from his keynote speech at last October's Microprocessor Forum: "*Portability is good; porting is not.*" Designers move to higher levels of abstraction to raise problem-solving productivity; portability is a byproduct. Portability makes moving between instruction sets possible; porting means that it costs time, money, and engineering effort to do so.

Porting moves the application from an x86 to something else. *Any* porting is 100% overhead relative to the cost of running the application on an x86. Significant costs include adapting the application and the system software to the platform, rewriting programs for different application programming interfaces, and programming device drivers. The largest cost will probably be in verifying that the application works as well as it did on an x86-based computer.

This argument is as valid for operating systems as it is for application software. Windows runs only on x86-based computers (orphan WinCE notwithstanding), so there's no argument about the cost or value of porting to other microprocessors. **Microsoft** (MSFT) has a modularized version of Windows XP for embedded applications, but it's still too large and too expensive for cost-sensitive applications. Linux, however, is portable, it is cheap, and it is already popular in embedded systems. It can be and has been ported to probably any microprocessor you can name. But there's overhead cost in porting to anything other than x86. There are fewer applications, fewer software utilities, fewer device drivers, and fewer developers.

Lessons from computer development

LESSON ONE. Binary compatibility, which locks users to a microprocessor's instruction repertoire, has a compelling market advantage over incompatible instruction sets. IBM proved it with mainframes, the x86 proved it twice more in wiping out its desktop competitors and in its battle with workstations.

LESSON TWO. Instruction-repertoires aren't a performance differentiator. The RISC premise is that new instruction sets offer performance advantages over old instruction sets. It wasn't so. Other factors (binary compatibility and business model) dominate. Features such as cache size, clock rate, pipelining, and other implementation techniques far outweigh the instruction set in determining system performance. And these techniques are available to any microprocessor, not just RISCs. More accurately, being able to spread the cost of the most advanced semiconductor manufacturing process across many units *enables* one to cheaply implement big caches, high clock rates, etc. The much-maligned x86 instruction set was good enough to take on all comers.

LESSON THREE. Volume is its own barrier to entry. The PC built for volume and it grew up with the Internet. The x86 is

TELECOSM TECHNOLOGIES

Advanced Fibre Communications	(AFCI)
Advanced Micro Devices	(AMD)
Agilent	(A)
Altera	(ALTR)
Analog Devices	(ADI)
Avanex	(AVNX)
Broadcom	(BRCM)
Cepheid	(CPHD)
Chartered Semiconductor	(CHRT)
Ciena	(CIEN)
Corvis	(CORV)
Cypress	(CY)
Energy Conversion Devices	(ENER)
Equinix	(EQIX)
Essex	(EYW)
EZchip	(LNOP)
Flextronics	(FLEX)
Intel	(INTC)
JDS Uniphase	(JDSU)
Legend Group Limited	(LGHLY.PK)
McDATA	(MCDTA)
Microvision	(MVIS)
National Semiconductor	(NSM)
Proxim	(PROX)
Qualcomm	(QCOM)
Samsung	(05930.KS)
Sonic Innovations	(SNCI)
Sprint PCS	(PCS)
Synaptics	(SYNA)
Taiwan Semiconductor	(TSM)
Terayon	(TERN)
Transmeta	(TMTA)
United Microelectronics	(UMC)
VIA Technologies	(2388.TW)
Wind River Systems	(WIND)
Xilinx	(XLNX)

Note: The Telecosm Technologies list featured in the *Gilder Technology Report* is not a model portfolio. It is a list of technologies that lead in their respective application. Companies appear on this list based on technical leadership, without consideration of current share price or investment timing. The presence of a company on the list is not a recommendation to buy shares at the current price. George Gilder and *Gilder Technology Report* staff may hold positions in some or all of the stocks listed.

Advance Fibre Communications (AFCI)

LAST MILE OPTICS, FIBER TO THE CURB

JANUARY 21: 23.91, 52-WEEK RANGE: 13.93 - 27.50, MARKET CAP: 2.08B

With recent announcements from Verizon, Bell South, and SBC, envisaging several billions of dollars of investment over the next three years in fiber to the home and curb, this at last is the epoch of last mile fiber. Alas, we find ourselves-after a decade of predicting this paradigm-without a company that plays in that space. Fortunately, AFCI is a profitable pure play in last mile optics, with an array of demonstrated technologies and some $330M of revenues in 2003. At first restricted to digital loop carriers for telco digital backhaul and fiber to the home, it has now purchased Marconi's fiber-to-the-curb assets. In Korea, fiber to the curb or to the apartment basement, enabling up to 54 megabits per second links with VDSL, has prospered more than fiber directly to homes themselves. With the purchase of Marconi, which holds the FTTC contract with Bell South, AFCI becomes an omnibus last mile optics player. With the cable companies increasing its modem speeds to some 2.8 megabits a second and pushing IP telephony, the Bells will have to respond with unusual alacrity. AFCI is ready and willing. Well valued at the moment, it joins our list as a key paradigm player.

Advanced Micro Devices (AMD)

UPWARD-COMPATIBLE X86 MICROPROCESSORS

JANUARY 21: 15.90, 52-WEEK RANGE: 4.78 – 18.50, MARKET CAP: 5.54B

Added to the list this month.

Agilent (A)

CDMA DUPLEXERS AND AMPLIFIERS, FIBER OPTIC TRANSCEIVERS

JANUARY 21: 34.77, 52-WEEK RANGE: 11.33 – 34.36, MARKET CAP: 16.56B

The company's new mobile phone power amplifier (PA) won the "product of the year" award from *Electronic Products* magazine. Agilent claims the power amp, available in both CDMA and GSM variants and already designed into 15 new phones, improves battery efficiency, increasing talk-time up to 30 minutes. The stock is up 23% since we added it to our list in December.

Broadcom (BRCM)

BROADBAND INTEGRATED CIRCUITS

JANUARY 21: 39.87, 52-WEEK RANGE: 11.86 – 42.96, MARKET CAP: 12.07B

The company introduced a series of new chips for digital television applications, including personal video recorders (PVRs), high-definition (HD), direct broadcast satellite (DBS), and chip-sets that combine all three applications. The company also announced it has already sold 11 million "54 G" 802.11g Wi-Fi chips. The stock stands at a two-year high, and the company reports earnings January 27.

Ciena (CIEN)

METRO WDM PLATFORMS

JANUARY 21: 7.65, 52-WEEK RANGE: 4.19 – 8.14, MARKET CAP: 3.62B

The Pentagon finally announced what had been known for some time: that Ciena won the optical transport and switching contract for the GIG-BE (global information grid bandwidth expansion) project, which seeks to connect more than 100 military and intelligence locations.

Corvis (CORV)

WDM SYSTEMS, RAMAN AMPLIFICATION, EDGE SWITCHES

JANUARY 21: 2.78, 52-WEEK RANGE: 0.47 – 3.07, MARKET CAP: 1.32B

Mr. Market is smart. The stock has jumped from $1.60 to $3.00 since we noted the company's substantial undervaluation vis-à-vis rival Level 3 in our December report. "The company hasn't done or said anything to explain the big short-term jump," wrote *The Wall Street Journal.* "'There wasn't any major news on the company at all,' says Andy Backman, Corvis's vice president for investor and public relations.'" Since the spike, network subsidiary Broadwing announced a strategic partnership with DSL provider Covad. Then a judge in the Allegiance Telecom bankruptcy case said Corvis could bid against Qwest and others in the February 12 auction. Once headed by co-location master Royce Holland, Allegiance focused on small and medium-sized businesses and lasted longer than most of its CLEC competitors. But like the vast majority of last-mile telecom players, it finally succumbed to the copper cage maze of regulation. The winner of the auction mainly acquires Allegiance's attractive enterprise customers. Corvis also reports earnings on February 12.

Equinix (EQIX)

SECURE INTERNET BUSINESS EXCHANGES

JANUARY 21: 35.57, 52-WEEK RANGE: 2.00 – 37.54, MARKET CAP: 335.10M

In December the company eliminated any outstanding worries about its debt with a secondary offering of stock and a prepayment of $55 million, or more than 60%, of its credit facility, leaving more cash than debt on the balance sheet. Equinix also added a second Internet Business Exchange in Silicon Valley, bringing its total to 14 worldwide. The company reports earnings February 4.

Intel (INTC)

MICROPROCESSORS, SINGLE-CHIP SYSTEMS

JANUARY 21: 32.20, 52-WEEK RANGE: 14.88 – 34.60, MARKET CAP: 210.33B

Intel reported December quarter sales of $8.74 billion, an increase of 12% sequentially and 22% year-over-year. Net income was $2.2 billion on margins of 63.6%. For 2003, the company repurchased $4 billion worth of stock and paid out $524 million in dividends.

MEAD'S ANALOG REVOLUTION
NATIONAL SEMICONDUCTOR (NSM)
SYNAPTICS (SYNA)
SONIC INNOVATIONS (SNCI)
FOVEON
IMPINJ
AUDIENCE INC.
DIGITALPERSONA

COMPANIES TO WATCH
ATHEROS
ATI TECHNOLOGIES (ATYT)
BLUEARC
COX (COX)
CYRANO SCIENCES
ENDWAVE (ENWV)
ESS TECHNOLOGIES (ESST)
MEMORYLOGIX
NARAD NETWORKS
POWERWAVE (PWAV)
QUICKSILVER TECHNOLOGY
RF MICRO DEVICES (RFMD)
SEMITOOL (SMTL)
SiRF
SOMA NETWORKS
SYNOPSYS (SNPS)
TERABEAM
TENSILICA

JDS Uniphase (JDSU)

ACTIVE AND PASSIVE OPTICAL COMPONENTS

JANUARY 21: 5.378, 52-WEEK RANGE: 2.51 – 5.885, MARKET CAP: 7.66B

After stagnating between $2 and $4 for almost two years, the stock finally broke out in December and January, as optical and telecom stocks rose generally. Now close to $6, JDSU commands an $8 billion market cap on $1.1 billion in cash. Analysts expect the company to break even or earn a small profit in the next year. In the last week, rumors swirled that Alcatel was looking to acquire JDSU, but it seemed unlikely given that Alcatel just last year sold its own optronics division to Avanex.

Qualcomm (QCOM)

CDMA INTEGRATED CIRCUITS, IP, SOFTWARE

JANUARY 21: 58.77, 52-WEEK RANGE: 29.58 – 60.73, MARKET CAP: 47.02B

December quarter sales were $1.2 billion, up 37 percent sequentially and 13 percent year-over-year. Core net income was $419 million, and core earnings were $.51 a share. The company now sees an even better 2004, predicting total worldwide CDMA phone sales of 138-146 million units, yielding GAAP revenue growth of 8-12% and core earnings of between $1.56 and $1.61 a share.

A forthcoming book by Dave Mock makes a powerful case that Qualcomm is the world's best technology company. It is demonstrably the leading fabless semiconductor company during an era when the foundry model is steadily gaining share. It is overwhelmingly the leading wireless player during an era when wireless is becoming dominant. It is the champion manager of intellectual property at a time when share value is increasingly based on IP. It is the most effective broadband player in America at a time when broadband is gaining momentum among customers (later this year courtesy of Qualcomm's EV-DO, Verizon's 36 million wireless customers will enjoy faster Internet access than Verizon's DSL users). It is the worldwide leader in 3G and is expanding its technology portfolio through GSM and TDMA. It is the most successful U.S. company in the ascendant domains of China and it now has over 5 million subscribers in India. It is pervasive in Latin America and gaining in Russia. It will be the pivotal player in the new world of ubiquitous still and motion photography to be unleashed as Foveon breaks through in coming months. It is a leading software vendor with BREW and Eudora. It is a leading satellite player with Omnitracs. It has an ever more resourceful portfolio of new technologies, such as software radio, Q-chat, and digital cinema. And it dominates location based services using GPS and complementary technologies. What more do you want?

Sprint PCS (PCS)

NATIONWIDE CDMA WIRELESS NETWORK

JANUARY 21: 8.00, 52-WEEK RANGE: 3.10 – 8.04, MARKET CAP: 8.28B

PCS shares have gained in the general telecom run-up and also from news that AT&T Wireless is looking for a buyer. Some speculated PCS could be the next to be acquired, but other analysts doubt the Department of Justice would allow two large wireless mergers. This, regardless of the fact that the FCC anti-merger rule was dropped a year ago. The stock stands at an 18-month high.

AT&T's hand was forced, as we always predicted it would be, when wireless gorilla Verizon committed to immediate deployment of Qualcomm's EV-DO high-speed mobile system, yielding 700 kilobit-per-second average user download speeds, at a cost of $1 billion. Verizon reported enthusiasm for the EV-DO services in its test markets of Washington, D.C. and San Diego. AT&T had just done an expensive ($400 million) but dead-end upgrade of its own, deploying the GSM EDGE system, which delivers some 30 kilobits to phones and around 100 kilobits to PC cards. Alas, there is no further upgrade path in the GSM world. Cingular, DoCoMo, and two other companies have expressed interest in what is now to be a formal auction process.

PCS remains on the CDMA high road and plans eventually to move directly past EV-DO to EV-DV, which will deliver average speeds of 1 megabit or more. It's a move that could save capital outlays in the long-run but risks bleeding high-end, data-hungry customers to top-dog Verizon in the meantime.

Xilinx (XLNX)

PROGRAMMABLE LOGIC DEVICES

JANUARY 21: 40.39, 52-WEEK RANGE: 18.50 – 45.40, MARKET CAP: 13.83B

Xilinx shares jumped almost 10% after the company reported a 16% sequential revenue increase in its December quarter. Net income was $69.4 million, compared to a $3.4 million loss last year. The company's high-end Virtex-II FPGA set a record with $100 million in sales for the quarter, accounting for more than 27% of total revenue. Xilinx also announced that NASA is using the Virtex-II in the "main brain" of the Mars rover. The radiation-tolerant chips help control the motors, wheels, arms, cameras, and instrumentation, in addition to assisting the entry/landing phase. Sales to Asia are booming, growing to 27% of total business from 15% a year ago, while sales across applications (communications, data storage, industrial) are mostly stable. Looking forward, the company expects sequential revenue growth to be 7-10% and gross margins to remain high at 63%.

Intel Spurns Tredennick's Law

TREDENNICK'S FIRST LAW: Seek performance first and you lose volume; seek volume first and you gain performance.

TREDENNICK'S SECOND LAW: Volume is the best barrier to entry.

Intel has long been the world's most relentless enforcer of Tredennick's laws. But now it is retreating into an upmarket niche, chasing performance at the expense of volume and opening the way for AMD with its 64-bit Athlon, which unlike Intel's Itanium extends the x86 instruction set.

Thus Intel proudly announces that "In enterprise computing, a number of customers around the world adopted Itanium2-based servers, including CompUSA, Fiat Group, First Trust Corporation, the ING Group, the Koehler Group of Germany and Korean telecommunications provider KT. The Itanium2 processor extended its performance leadership by achieving the industry's first TPC-C benchmark result exceeding 1 million transactions per minute. In high-performance computing, the number of Intel processor-based systems in the TOP500 list grew by nearly 50% over a six month period, with supercomputers based on Intel processors outnumbering those based on RISC processors for the first time." Gee, whiz, sounds just like Sun.

Meanwhile in downmarket volume applications, Intel prospered, building new beachheads for x86 and its licensed StrongARM XScale designs. "Motorola and Samsung announced new cellular phones based on Intel XScale technology-based processors. Motorola announced its new A760 smart phone based on the Intel PXA 262 processor with 256 megabytes of stacked Intel StrataFlash memory. Samsung introduced a variety of new products based on the Intel PXA 255 processor, including its SGH-i700 smart phone. The Linksys division of Cisco Systems featured its wireless digital media adapter based on the Intel PXA 250 processor during the 2003 holiday selling season, allowing consumers to experience PC-based digital photos and music on traditional TV and stereo equipment. Intel announced it is working with Creative Labs, iRiver America and Samsung to help deliver a new category of portable media players based on Intel XScale technology for the high-quality playback of authorized music, photo and movie content."

Intel also entered the flat-panel, high-definition TV market. It plans to design and manufacture displays using liquid-crystal-on-silicon (LCOS) technology, which it believes outperforms simple liquid-crystal displays (LCD) or digital light processors (DLP) in terms of resolution and color. By 2005 the company expects its LCOS components to cost as much or less than competing technologies, enabling TV makers to offer consumers LCOS TVs at competitive prices—under $2000, says COO Paul Otellini. In conjunction, Intel also announced the formation of a $200-million Digital Home Fund that will invest in companies "developing innovative hardware and software technologies for the digital home." The company said it plans to design and make silicon components for the whole range of computer and entertainment systems. One of its first is the Entertainment PC, a "slim" x86 based device that connects to the TV and stores videos, photos, and music.

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entrenched. No matter how much portability is achieved, there's a cost to port to anything and the incumbent is the x86.

On to embedded

If the x86-based PC is the universal development platform, doesn't it follow that x86 microprocessors dominate embedded applications? It sounds reasonable, but that's not how the industry grew. Microprocessor-based hardware developed for ten years before the PC's introduction, so embedded applications used a wide range of non-x86 microprocessors. The emergence of the PC market did nothing to change the situation because of the huge price difference between x86 microprocessors and embedded microprocessors.

While the PC market has consolidated around the x86, the embedded market has done just the opposite; it has fragmented into hundreds of microprocessors and microcontrollers. The embedded market has fragmented for three reasons. First, the microprocessors in embedded systems ave been isolated or *invisible*. The electric toothbrush didn't communicate with other household devices, so there was little incentive to consolidate embedded designs toward standards. Unlike the PC, there's been no incentive for different refrigerator manufacturers, for example, to standardize on a common microprocessor. Second, great diversity and huge volumes among embedded applications encouraged suppliers to tailor microcontrollers for specific market segments. Tailoring the microcontroller for a market segment improves its efficiency and may lower the system cost, but it also fragments production, which increases chip cost. Third, designs for much of the huge range of embedded systems come from small design houses. The engineering teams' decisions are independent, there is neither incentive nor mechanism for standardization.

The major incentive for moving to x86 microprocessors for embedded applications (beyond capitalizing on the PC's hardware and software standardization) is that it leverages engineering expertise developed for PC-based applications. It's cheaper.

The majority of embedded applications are consumer devices, so low cost is the primary design goal. In these applications, general-purpose microprocessors are cheaper than application-specific hardware for two reasons. First, a few standard microprocessors, memory chips, and peripheral chips fit a broad range of applications. Second, microprocessor-based design is cheaper because engineers are more productive writing application software than designing custom hardware.

Because of the low-cost design goal, the huge unit volumes, and the generally modest processing requirements, the average selling price for embedded microprocessors is a few dollars. By contrast, Intel commands average selling prices on the order of $200 for its high-end desktop and laptop microprocessors. Intel's margins are high because it is the dominant producer in a market that is locked into x86 compatibility for PCs. While, secondary producers of x86 microprocessors, AMD, Transmeta, and VIA Technologies, cannot charge as much as Intel, they still command princely sums relative to the prices of embedded microprocessors. With this difference in pricing between x86 microprocessors and embedded microprocessors, there's little incentive for x86 manufacturers to allocate wafers in their production lines for embedded chips.

In addition to the difference in margins making the embedded market unattractive for x86 manufacturers, the x86 microprocessors themselves have been too large ("die size") and, therefore, too expensive and too power-hungry for most embedded applications.

For these reasons, the embedded market and the PC market grew separately. The embedded market is hundreds of different 4-bit, 8-bit, 16-bit, 32-bit, and 64-bit low-cost microprocessors. The PC market is x86.

Semiconductor process improvements have shrunk transistors to the point that a very capable microprocessor fits in a tiny area. Many embedded microprocessors occupy *less area than is needed to accommodate their external connections*. Once the chip's external connections determine the minimum chip size, the chip's production cost cannot decrease. As transistors continue to get smaller, the cost of larger, more-capable microprocessors approaches the cost of the "pad-limited" chips.

Pad-limited microprocessors

As even the cheapest semiconductor processes get better, more and more microprocessors and microcontrollers become "pad limited." Being pad limited means the chip's size is determined by the minimum area for its connections to the outside world. Once pad limited, functions occupying space that would otherwise be wasted are free. The elements of a PC could fit on one chip today. This one-chip PC would be good enough for an ever-growing set of embedded applications.

Also, there's a cost incentive to connect embedded systems to the Internet. It is cheaper and more efficient to have each soft-drink machine monitor its products and its status and to request as-needed deliveries (and maintenance) than it is to send delivery trucks to every vending machine on a regular schedule. This is true for everything from meter reading to trash collection.

As remote monitoring, remote control, and remote access become more common, there's more incentive to implement (at least the external interfaces to) these systems with x86 microprocessors because x86-based systems are cheaper to develop and they are easier to integrate into the Internet.

What will happen

The x86 will take over embedded systems.

As systems become more intelligent, it becomes more of a challenge to present their options to the user. The most familiar interface for users dealing with intelligent systems is Windows running on x86. It makes sense for makers of intelligent systems to build on consumers' general familiarity with Windows rather than to create new user interfaces for their intelligent systems. Anyone who can adjust time on a Windows PC would immediately know how to set the time on a VCR or set-top box with a Windows interface. The simplest way to implement a Windows interface on a set-top box is to base the design on a PC and on an x86 microprocessor. This reasoning extends to other home entertainment systems, to intelligent appliances, and to business systems such as point-of-sale terminals.

There's a similar argument for cell phones and for other untethered systems. Incompatibilities between these systems and the PC are an enormous inconvenience to their users. Just try to transfer phone numbers from Microsoft Outlook to a cell phone. You can buy a program that will translate between the two, but it would be more efficient if they spoke the same language. Some day they will.

Right now, however, there's a problem with the x86 invading set-top boxes and home appliances or cell phones and PDAs. In set-top boxes and in home appliances, low-margin microprocessors own the market and won't give it up without a fight. Up to now, microprocessors for embedded systems have had competition from every microprocessor except the x86. There hasn't been much competition from x86 because there weren't many x86 manufacturers. Until recently, there were AMD, Intel, **National Semiconductor** (NSM), **STMicroelectronics** (STM), Transmeta, and VIA Technologies. National sold its Geode x86 microprocessor line to AMD and STMicroelectronics doesn't have Pentium-class designs, so the main competitors are all producers of desktop, laptop, and server microprocessors. There's little incentive for leading makers of high-margin, performance-oriented microprocessors for computer systems to begin making low-margin, cost-oriented microprocessors for embedded systems. AMD and Intel will likely continue to concentrate on the computer market where margins are high.

Transmeta and VIA Technologies, with small shares of the laptop and desktop markets, have more interest in embedded systems. Transmeta and VIA have microprocessors suitable for some embedded applications, such as set-top boxes and point-of-sale terminals.

The new opportunity

One problem for these manufacturers is that their microprocessor designs are computer-oriented. By the standards of embedded systems, their processors are too large, too expensive, and use too much power. Also, for high-volume embedded systems, the manufacturer may cost-reduce the system to one or two chips. None of the x86 manufacturers offers either a hard or a soft core for licensing. *There's an opportunity in the market for a company to make a Pentium-class x86 microprocessor for embedded applications.* This microprocessor would have small caches, a scalar execution unit, minimal branch prediction, and a plastic package. This design makes the microprocessor small and cheap and yet endows it with enough performance to manage the overhead of a Windows or Linux operating system as its user interface.

There's at least one startup with a plan to do this. **MemoryLogix**, if it can get funding to build its designs, would sell embedded x86 chips and it would license soft-core x86 microprocessors.

These x86 designs will invade consumer appliances, home entertainment electronics, and business systems, and they will eventually invade untethered devices, including the cell phone.

x86 will sweep the field

The x86 will completely dominate computer systems—Sun and its SPARC architecture are doomed. Sun is the last holdout among pure-play workstation companies because it was vertically integrated. It locked in its customers and it will ride them into the ground.

In an unexpected irony, however, Intel is now choosing the imitate Sun. Not content to dominate x86 microprocessors for computer systems, Intel has launched an exotic up market Itanium processor—widely known as the Itanic—that is incompatible with the x86. (see center spread for sordid details). In other words, Intel decided to move the market away from its competitors with a new instruction set. In its effort to move the market, Intel chose a performance-oriented strategy! It probably planned to build high-end Itanium systems and to move them down market over time. Intel's strategy will fail. Fortunately for Intel, it still dominates the x86-microprocessor market. Its design teams will continue building x86 microprocessors.

AMD has an excellent position for the future by virtue of its strategy to build upward-compatible x86 microprocessors. AMD should gain market share in high-end, high-margin systems. AMD extended the x86 instruction set from 32 bits to 64 bits, giving AMD access to markets for high-performance desktops, servers, and workstations. AMD's 64-bit x86 microprocessor is its answer to Intel's incompatible IA-64. It's an easy win for AMD and propels the company onto our list. It will not be cheap or easy for Intel to reassemble its 64-bit x86 development teams for chipsets, peripherals, and software for a rival 64 bit x86 product. In the meantime, AMD gets the chance to enjoy Intel-style first mover margins for the top end of its micro line.

MIPS and PowerPC are failed workstation and desktop microprocessors that have turned to embedded applications in search of a market. They have had some success as embedded systems designers converted from old 4- and 8-bit microprocessors to more modern microprocessors with large, flat address spaces and with enough performance to meet the requirements of more intelligent systems. But their days are numbered in embedded applications as they offer no compelling advantage over either x86 or ARM.

ARC and Tensilica make configurable microprocessors. ARC and Tensilica, though they have smaller market share than MIPS or PowerPC, may not share their fate. Tensilica, for example, has repositioned itself from being primarily a vendor of custom processors to being an implementer of logic blocks. Instead of building a collection of logic functions for a system-on-chip design, Tensilica suggests programming the functions on processors customized for each function. Instead of a collection of unique hardware designs that require individual verification, designers get custom processors that are correct by construction. It's an attractive proposition and a strategy not threatened by an x86 invasion.

Cypress (CY), **Hitachi** (HIT), and **Triscend** offer microcontrollers with a fixed microprocessor core and configurable peripherals. With this strategy, and the fact that so many microcontrollers are pad limited, these companies should have been able to consolidate the microcontroller market. It hasn't happened yet, partly, I think, because they have elected to take higher margins in preference to gaining market share (which may not be as bad in their heterogeneous markets as it was in the computer market). There's still excellent opportunity for these companies, especially if one gets a (not-yet-available) x86 core.

ARM is its own story. It may seem from its huge volumes, exceeding by a wide margin shipments of x86 microprocessors, that the ARM architecture has reached critical mass and that it's as likely that it will displace the x86 as that the reverse will happen. Sorry, ARM is doomed too. But in ARM's case, it will take years for this to happen and ARM's market will grow in the interim. ARM is entrenched in its applications, particularly the cell phone, but compatibility with Windows and the x86 is compelling, so cell phone makers will include an x86 core as the simplest bridge to the Internet. Eventually, the x86 core will displace ARM because two microprocessor cores is one too many in untethered systems. Despite ARM's still-huge momentum, this displacement casts a shadow over its future. As a result, the highly valued ARM leaves our list to make way for AMD.

As embedded processors shed their invisibility and become visible to and from the Internet, ARM will give way to the x86 standard. The x86 is bound into the Internet, into its system software, into its applications, and into the connectivity among computers. Even a non-Microsoft application such as Apache or Linux that runs at as many as 70 percent of the Internet Service Providers was written for the Intel x86 instruction set. When a cell phone connects to the Internet, it doesn't connect to other ARM microprocessors, it connects to x86s, so the value in deployed numbers of ARM microprocessors is not aggregated in the same way that the deployed x86 microprocessors are.

Every time one of those billions of ARM processors must link to one of the millions of x86 applications, whether on Windows or on Linux, the program must be adapted and recompiled for the ARM device. Today, with limited cell phone memory and bandwidth, that may not seem to matter most of the time. I may have to struggle with downloading my Outlook address book into **Palm** (PSRC) but there is software available for such a ubiquitous application. But as cell phone capabilities rise toward broadband levels, increasing numbers of PC functions will become feasible on the device. It won't be merely Outlook. It will be games galore and network security and the latest brand of WiFi connectivity and the newest speech translator and the most up-to-date graphics decoder. At that point, the need and ability to tap into millions of x86-based systems will become a showstopper. At that point, the difference between mere portability and actually porting the application becomes a chasm. Too bad for ARM. And too bad for Palm, Symbian, and all the other cell phone operating systems and applications that chiefly ride on ARM.

In a PC-compatible environment, applications and components are commodities. Some efficiency is forfeited in adopting the PC's standards, but the engineering effort is redirected from recreating the support infrastructure to creating product features and product differentiation.

The shift in embedded systems toward x86 compatibility will necessitate new x86 designs, both in chips and in soft cores. (For a description of soft cores, see *Dynamic Silicon*, July 2002, in the www.gildertech.com archives.) Today, there are no soft-core x86 designs available. The embedded x86 chips that are available are derived from performance-oriented designs, so they only fit some embedded applications. This leaves a huge opportunity for new embedded x86 chips and cores.

Decades of experimenting proved that new microprocessors cannot achieve gains that make forfeiting software compatibility worthwhile. Standardizing on the x86 instruction repertoire won't end innovation in computer design just as standardizing on a steering wheel and accelerator didn't end automotive innovation. Standards provide focus that is missing with open experimentation. Engineers have barely begun to integrate sensors, to co-opt solutions from nature, and to develop reconfigurable systems. The context for these experiments is an x86-compatible software interface.

——Nick Tredennick and Brion Shimamoto
January 20, 2004

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