1994

Evolution in the Microprocessor Industry for Personal Computers: The Shift from CISC Chips to RISC Chips

James Lamm
College of Saint Benedict/Saint John's University

Evolution in the Microprocessor Industry for Personal Computers: The Shift from CISC Chips to RISC Chips

A THESIS
The Honors Program
College of St. Benedict/St. John's University

In Partial Fulfillment
of the Requirements for the Distinction "All College Honors"
and the Degree Bachelor of Arts
In the Department of Management

by
James D. Lamm
May, 1994

Project Title:

Evolution in the Microprocessor Industry for Personal Computers: The Shift from CISC Chips to RISC Chips

Approved by:

Assistant Professor of Management

Associate Professor of Classics

Associate Professor of Management

Chair, Department of Management

Director, Honors Thesis Program

Director, Honors Program

Table of Contents

Evolution in the Microprocessor Industry for Personal Computers: The Shift from CISC Chips to RISC Chips

John F. Kennedy once said, “Change is the law of life. And those who look only to the past or the present are certain to miss the future.” This is true of the microprocessor industry for personal computers, now more than ever. The industry is at the threshold of major changes in microprocessor standards and performance levels. Essentially, the microprocessor industry for personal computers is shifting from CISC microprocessors to RISC microprocessors to provide the speed demanded at the lowest possible price, while still offering software compatibility. Based on the evidence in the following pages, I believe Intel will lose its dominance of the microprocessor industry for personal computers if they cannot fend off challenges from competitors. First, one must understand the basics of microprocessors and the two personal computer standards. Second, a look at the history of the microprocessor industry for personal computers will reveal the two giants, Intel and Motorola, and the new, small entrants into the industry. Third, one must understand the current developments in microprocessors for personal computers. Fourth, a focus on RISC microprocessors and new hybrid microprocessors will indicate the successes of the past and the direction of the industry for the future. Finally, several conclusions about the industry and its keys to success will show which companies are leading, which are following, and which are positioned to take over the profitable microprocessor industry for personal computers.

Basics of the Computer Industry

Before examining the microprocessor industry for personal computers, one must understand the basic concepts of microprocessors and personal computers. For specific definitions, Appendix A explains many of the critical terms used. There are two main types of microprocessors that are important in the industry: Intel–standard 80X86 series and the Motorola 680X0 series. For personal computers, there are two main standards that are available based upon the two main types of microprocessors: IBM–compatible personal computers based on Intel–standard microprocessors and Apple Macintosh personal computers based on Motorola microprocessors.

Microprocessors

A microprocessor is the "brain" of a computer, placed onto a single microchip. The microprocessor receives information from areas of the computer, manipulates and processes the information using instructions in the microprocessor, and then sends the new information to other areas of the computer. In a microprocessor, an instruction is an action that the microprocessor performs on data. For example, addition and subtraction are simple instructions that microprocessors perform on inputs to achieve a desired output.

The speed of a microprocessor, or clock speed, is expressed in megahertz (MHz), that is, the millions of oscillations per second by the quartz timing crystal in the computer. The clock synchronizes all of the operations in the computer. Clock speeds of microprocessors usually range from 16 MHz to over 100 MHz. The clock speed dictates how rapidly the instructions inside a microprocessor are executed. An instruction, no matter how small, cannot take less than one clock cycle, forcing the microprocessor to wait until the next clock cycle to begin the next instruction (Poole, "Your Computer Revealed" 143). Instructions often take more than one clock cycle. For example, Motorola's 68040 microprocessor averages 1.25 clock cycles per instruction, and it is one of the faster microprocessors for personal computers.

The goal of microprocessor manufacturers is to make the fastest microprocessors possible at the lowest cost. The first way to increase speed is to increase the clock speed with the same circuitry, forcing the microprocessor to run through instructions faster. The drawback is that the increased speed heats up the fragile chip, causing computer manufacturers to install heat sinks and fans to reduce or prevent damage. A second alternative is to make the microprocessor more efficient in the instruction code or make one instruction do several tasks, requiring fewer clock cycles per instruction. The drawback is that more instructions built into the microchip increase the size and heat output of the chip, as well as increasing the time the computer must search for the correct instruction to execute. In the third method of increasing speed, the microprocessor can distribute the instructions to different independent units. These units can operate concurrently, handling more than one instruction per clock cycle. A microprocessor using this process to execute two or more instructions per clock cycle is called superscalar (Woodcock 377).

Superscalar microprocessors generally have between two and five independent units specializing in different categories of instructions (Geppert 20–22).

There are two main types of microprocessors important to the personal computer industry: complex instruction–set computer (CISC) and reduced instruction–set computer (RISC). Traditionally, personal computers have used CISC microprocessors. Until very recently, RISC microprocessors were only used in workstations, high priced computers that are built for raw power such as graphic–intensive tasks. The following introduction of CISC and RISC microprocessors is brief; the details and comparisons between the two technologies will be made later.

CISC

The CISC microprocessors have many different kinds of instructions, the tasks the microprocessor does, built into the chip (Apple Computer, Inc., *PowerPC Technology* 2). These instructions are the building blocks from which computer programs are written. Depending on what needs to be done, the microprocessor directs the information to the proper instruction to handle the task. Examples of CISC chips for personal computers are Intel's and other manufacturers' 80386 (or 386) and 80486 (or 486), Intel's Pentium chips, and Motorola's 68030 and 68040 chips.

RISC

A RISC microprocessor has a small number of instructions, and its performance is optimized for these instructions (Apple Computer, Inc., *PowerPC Technology* 2). The only RISC chips currently available for personal computers are Motorola's new PowerPC line of microprocessors. Workstation computers have been using RISC chips for several years to accommodate the vast power demands of graphic–intensive applications.

Personal Computer Standards

Microprocessors provide the power to make repetitive tasks easier, and personal computers provide the means to harness their power. A personal computer, generally referred to as a PC, is designed so that one person at a time may use it, whether it is for business, home, recreational, or personal uses (Woodcock 298). The percentage of sales by the major personal computer manufacturers is shown in Figure 1.

U.S. Personal Computer Manufacturers as a Percent of 1991 Sales

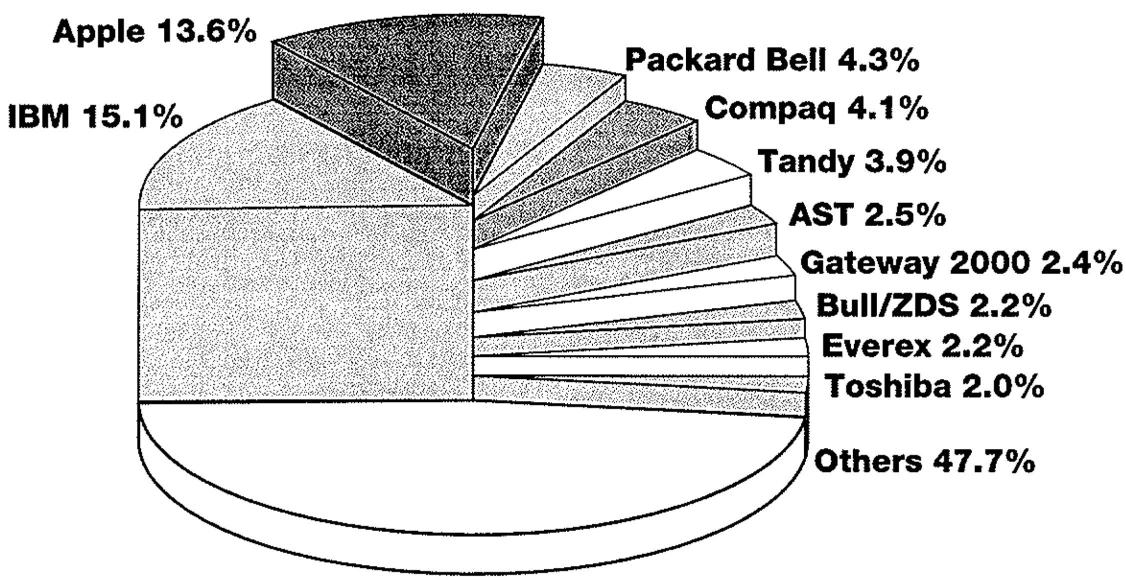

Figure 1
Source: *Standard & Poor's Industry Surveys* C80.

There are two main types of standards for personal computers: IBM–compatible computers and Apple Macintosh computers. There are several other personal computers available, but the two standards make up the majority of the market for personal computers. Research indicates that consumers look at performance first, and brand name second when choosing a personal computer (Pope, "Computers: They're No Commodity").

Because personal computers are designed for one user at a time, they are purchased mainly for home and small business use. Large businesses and government agencies have the funds required to purchase multi–user computers because they can spread out the cost over a great number of users. Even so, there is still a need for personal computers in large business and government. Figure 2 shows the breakdown of the market for personal computer in the United States.

U.S. Personal Computer Purchases in 1991

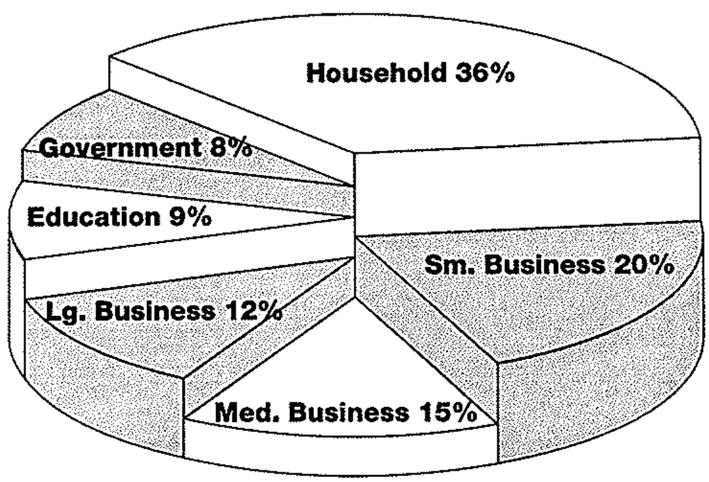

Figure 2
Source: *Standard & Poor's Industry Surveys* C81.

IBM–Compatible Computers

The majority of personal computers sold are based on a standard set by International Business Machines, or IBM. Over the years, the microprocessor powering the computer has become faster and a variety of options and changes have been made. IBM–compatibles have established themselves as the computer of choice for businesses, which has spread into home use as well.

There are a large number of manufacturers of IBM–compatible computers. A survey of personal computer shoppers determined the amount of premium a name brand would bring over an average computer brand, as shown in Figure 1 (Pope, "Computers: They're No Commodity"). There are so many

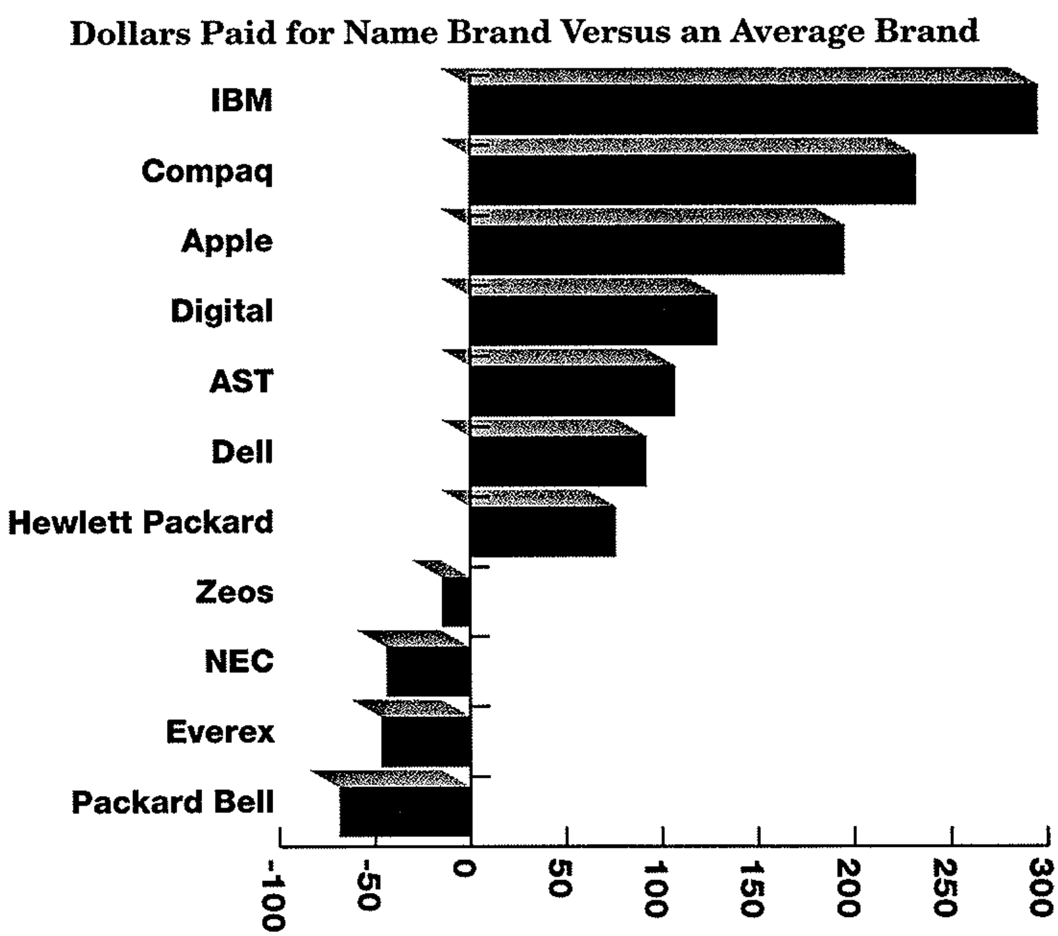

Figure 3
Source: Pope, "Computers: They're No Commodity"

different brands that IBM–compatibles have nearly become a commodity item, that is, they are essentially interchangeable products differentiated only by price, performance, and options. Many of the manufacturers come and go rapidly, and there are even kits for people to build their own computers. Several businesses have built enough of a reputation in the industry to get a premium on their computers.

The majority of IBM–compatibles are powered by Intel Corporation microprocessors, but Advanced Micro Devices, Incorporated, or AMD, and Cyrix Corporation are offering clones of Intel's microprocessors. Intel has the brand recognition to continue to dominate the market for microprocessors for IBM–compatibles, but AMD and Cyrix are gaining fast (Bertrand, "Chip Wars 16; Mitchell and Rebella, "Suddenly, AMD is in the Chips" 32). In 1992, AMD had net sales of $1.51 billion, up from $1.22 billion in 1991 (Willett, "AMD's Record Revenues" 28; Advanced Micro Devices, Inc., *1992 Annual Report* 17). Cyrix had 1992 sales of $72.9 million, up significantly from 1991 sales of $55.3 million (Cyrix Corporation, *Prospectus* 22). Intel still dwarfs them both in comparison, with net sales of $5.84 billion, up from 1991 sales of $4.78 billion (Intel Corporation, *IntelAnnual* 14).

The number of IBM–compatible personal computers sold worldwide each year has gone from about 200,000 units in 1982 to a staggering 22 million in 1992 (Cyrix Corporation, *Prospectus* 31). In total, from its introduction in 1981, until 1992, it is estimated that 113 million IBM–compatible personal computers have been sold worldwide (Cyrix Corporation, *Prospectus* 31).

Apple Macintosh

Apple Computer, Incorporated, brought computers to the homes and schools of the world. Its current line of computers, the Macintosh, has proven to be a strong competitor to the IBM–compatibles. The Macintosh introduced a graphical user interface, or GUI, to personal computers. The graphical interface is easier for users to learn, leading IBM–compatibles to also adopt a graphical user interface as an option to its command–line, text interface. The Macintosh line was designed to be easy to set up, easy to use, and compatible with all the peripherals available for it. Apple was able to accomplish this task by being the only producer of Macintosh computers, regulating the development of software, and designing a standard for its peripherals.

Until recently, Macintosh computers were more expensive than comparable IBM–compatible computers. Apple has reduced its prices to be more competitive, and, as a result, it has raised its market share. The number of computers it is selling has gone up significantly, jumping 36% for the quarter ending September 24, 1993 (Carlton, "Apple Reports a $2.7 Million Profit" B8).

Microprocessor Industry for Personal Computers

Personal computers require microprocessors to operate, and the faster the microprocessor the better. The industry that supplies microprocessors to computer manufacturers is the semiconductor industry. This industry supplies a variety of electronic components made with silicon, which is a semiconductor, that is, it normally stops the flow of electricity but sometimes can be forced to allow the current to pass through. The process of halting and then allowing electric current is what makes transistors work—they either stop or send electricity, resulting in an on or off state (Poole, "Your Computer Revealed" 136). Combine these transistors in certain patterns and they form a circuit, which transforms the electrical patterns flowing into the transistors at one end into a desired pattern at the other end (Poole, "Your Computer Revealed" 136–8). By creating different patterns of transistors, the circuits become the tools a microprocessor uses to carry out instructions (Poole, "Your Computer Revealed" 136–143).

The manufacturing of microprocessors is one portion of the semiconductor industry. Although microprocessors play a central role in the industry, it is not the only product in the industry. Other products in the industry include various forms of Random Access Memory (RAM) chips and specialized microchips for use in electronic products.

Industry in General

The semiconductor industry is very profitable, both in recent history and at present ("Semiconductor Industry" 1058). In 1992, the operating margin for the semiconductor industry was 16.8%, with a 6.5% net profit margin ("Semiconductor Industry" 1058). The average price to earnings ratio for the industry was 15.8 in 1992 ("Semiconductor Industry" 1058). In 1993, sales increased by 29% and semiconductor companies expanded by 35% (Hof, "Semiconductors" 83).

The strong growth and high profits are disappearing with the increased competition in supplying microprocessors for personal computers. The industry is moving into a mature stage in the business cycle, with growth leveling off and earnings following suit ("Semiconductor Industry" 1058). Although the businesses in the industry averaged 20% to 100% or more earnings growth each year in the 1990's, predictions for 1994 include revenue growth of only 14% ("Semiconductor Industry" 1058; Hof, "Semiconductors" 83). Shortages of microprocessors and time–consuming manufacturing processes pushed profits high in the past, but increased competition, new factories, and increased production are eliminating both the shortages and the high profits ("Semiconductor Industry" 1058). Productivity has been climbing steadily in the industry, with the output per employee rising from $84.7 thousand in 1989 to $144.7 thousand in early 1994 (Hof, "Semiconductors" 83).

The main indicator for the semiconductor industry is the book–to–bill ratio, which is the number of products ordered divided by the number of products shipped ("Semiconductor Industry" 1058). In the past, the book–to–bill ratio has been greater than 1.00, indicating greater demand than supply—explaining why the industry has been so profitable. The book–to–bill ratio has fallen from 1.20 in January of 1993 to 1.01 in September, 1.00 in October, and 0.99 in November of 1993 ("Semiconductor Industry" 1058; "Chief Indicator Drops for the Chip Industry" B8). The ratio has fallen under 1.00, which means the producers are shipping more chips than they receive orders for. With supply exceeding demand, either prices will fall or production will slow—either way cutting into the profitability of the manufacturers.

Focus on Key Players

The manufacturing of microprocessors is very complicated, with many years of research and development, testing, and etching complex wiring and circuit patterns on tiny squares of silicon. These factors have allowed a handful of companies to dominate the production and supply of microprocessors for personal computers. Intel and Motorola are the reigning kings of microprocessors for personal computers. Advanced Micro Devices and Cyrix have entered the industry and have started to take market share away from the big two. Focusing on four mainstream personal computer microprocessor manufacturers, Intel, Motorola, Advanced Micro Devices, and Cyrix, one can see how dominant Intel and Motorola are in the industry.

Four Microprocessor Suppliers for Personal Computers

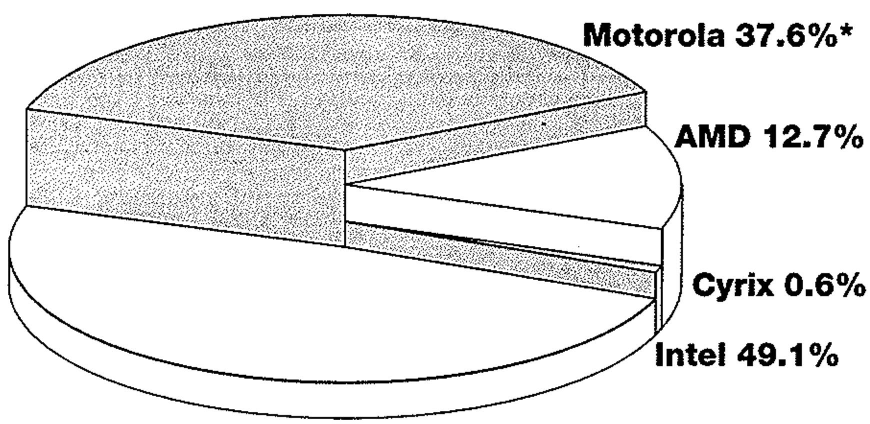

Figure 4
Source: 1992 Annual Reports of Intel, Motorola, AMD, and Cyrix

Intel

Intel is the third largest supplier of semiconductors in the United States, with over $5.8 billion in net sales in 1992 (*Hoover's Handbook* 315; Intel

Corporation, *IntelAnnual* 14). Intel developed the first true microprocessor, the 4004, in 1971. Before that time, microchips were custom made to serve a single application. The 4004 was developed to be a general purpose microchip that could be used in many applications—the microprocessor was born. Intel continued to develop faster and more powerful microprocessors until their big break in 1980, when IBM chose the 8088 microprocessor for its new personal computers (Intel Corporation, *Intel: Architect of the Microcomputer Revolution* 6). The IBM personal computers became popular in businesses, and Intel developed new microprocessors to keep up with increasing demands for speed. Each new microprocessor Intel introduced maintained compatibility with its predecessor, but also made the predecessor obsolete in comparison. The 80286, or 286, was developed in 1982, the 80386, or 386, in 1985, and the 80486, or 486, in 1989 (Intel Corporation, *Intel: Architect of the Microcomputer Revolution* 6–22; *Hoover's Handbook* 315). Currently, Intel's flagship microprocessor is the Pentium chip, a superscalar CISC chip with a 64–bit data bus (Intel Corporation, *Intel Technology Briefing*).

Advanced Micro Devices

In March of 1991, Advanced Micro Devices, or AMD, attacked Intel's dominance of the microprocessor industry for IBM–compatible personal computers, introducing a version of Intel's 386 microprocessor (Bertrand, "Chip Wars" 16; Mitchell and Rebella, "Suddenly, AMD is in the Chips" 32). Until then, Intel was the sole supplier of IBM–compatible microprocessors, having a tight hold on the market (Sprackland, "Comeback Company" 40). Since then, several competitors have decided to cash in on the profits Intel has been enjoying. The new competition forced Intel to lower its microprocessor prices by 35% to stay in the market (Bertrand, "Chip Wars" 16). The AMD versions of Intel's 386 and now Intel's 486 chips have turned AMD's past losses into huge profits. The $53.5 million loss in 1990 turned into a $245 million profit by 1992 as its microprocessors slowly take market share away from Intel (Advanced Micro Devices, Inc., *1992 Annual Report* 17). Most of AMD's 1992 sales were from 386 microprocessors, capturing over 60% of the market for 386 microprocessors, but the falling cost of 486 microprocessors will virtually eliminate the 386 business (Willett 28; "Advanced Micro," *Value Line* 1059). There are continuing legal battles with Intel over the rights to the code in the 486 microprocessors and other claims against the manufacture of clone chips (Yamada, "Advanced Micro" B6; "Advanced Micro," *Value Line* 1059). Profits should continue as AMD's production of 486 microprocessors has reached viable levels, cutting into Intel's 486 sales ("Advanced Micro," *Value Line* 1059).

Cyrix

Another rising competitor to Intel's dominance in the IBM–compatible microprocessor market is Cyrix Corporation. Cyrix produces math coprocessors, which enhance the "number crunching" ability of a computer, and also clones of Intel's 486 microprocessors. The company started manufacturing math coprocessors in 1989, but its focus has shifted to microprocessors (Cyrix Corporation, *Prospectus* 32–3). Increased microprocessor sales generated net sales of $92.3 million in the first nine months of 1993, compared with $45.9 million at the same time in 1992. (Cyrix Corporation, *Third Quarter Report* 2). Microprocessor sales made up 68% of their revenue in the first quarter of 1993, showing their success in the industry (Cyrix Corporation, *Prospectus* 34).

Motorola

Motorola, the communications giant, is also the leading supplier of semiconductors in the United States (*Hoover's Handbook* 392). In 1992, Motorola had net sales of over $13.3 billion (Motorola, Inc., *1992 Annual Report* 25). Motorola has provided Apple Computer, Inc., with the microprocessors for its Macintosh line of personal computers. The 68000, 68020, 68030, and 68040 are examples of microprocessors used in Apple's Macintoshes and other electronic devices such as laser printers and automobiles (*Hoover's Handbook* 392). The 68040 is one of the faster CISC microprocessors in wide use (Poole, "Your Computer Revealed" 143). Motorola has teamed up with IBM and Apple to develop the PowerPC microprocessor. The PowerPC is a RISC microprocessor that promises to shatter the limitations of CISC microprocessors.

Current Developments in Microprocessors for PCs

As with any technology industry, constant research and development is vital to stay ahead of the competition, or even to keep pace with the competition. The microprocessor industry is extremely aggressive with its research and development, with customers demanding twice the performance of microprocessors at the same cost every 18–24 months ("Intel Aims to Double

Its Chip Performance" B6). To keep this pace, the industry average spending for research and development is ten percent of net revenues (Sprackland, "Comeback Company" 41).

Industry in General

The microprocessor manufacturers for personal computers are continually seeking higher performance at a lower cost. The way to increase performance is to pack more transistors onto the chip, but that increases power consumption, cost, and heat. Heat may be the Achilles heel of microprocessors—the electricity flowing through the transistors causes the chip to heat up, possibly damaging or destroying the chip. The faster the clock speed of the microprocessor, the more heat is produced. Manufacturers use heat sinks and fans to dissipate the heat, but the effects are limited and add cost to the production.

Focus on Major Producers

In order to maintain stability in the personal computer industry, standards of compatibility are followed by microprocessor manufacturers. The code in new microprocessors is usually backward–compatible with previous microprocessors to ensure that users upgrading from older computers can still use their software. New microprocessors also offer new features, generally enhancing performance, that software uses for improved performance. Intel sets the standards for IBM–compatible microprocessors, and companies such as AMD, Cyrix, and other competitors scramble to duplicate the standard. Motorola manufactures the only microprocessors used by Apple's Macintosh personal computers, as well as manufacturing microprocessors for IBM and, in the future, IBM–compatibles.

Intel

From the very first microprocessor made, Intel has led the way in developing, producing, and supplying microprocessors for personal computers. The strong sales of IBM–compatibles have bolstered Intel's profits since 1980. Intel now has competition from AMD, Cyrix, and several other new companies, but Intel leads development of new microprocessors and the others must create clones of it or be left out of the profits. Intel spent $780 million on research and development in 1992, which amounts to about 13% of net revenues (Intel Corporation, *IntelAnnual* 14, 29). Experts predict 44 million 486 microprocessors will be sold in 1994, and Intel's share of the supply is 40% (Hof, "Semiconductors" 83). Intel also expects to ship 6 million of its new Pentium microprocessors in 1994 (Hof, "Semiconductors" 83).

Intel has had great success with its 486 microprocessors, but its new microprocessor, the Pentium, promises to make the 486 obsolete, much as the 486 made the 386 chip obsolete. The 486 is a CISC microprocessor with a 32–bit data bus, 32–bit address bus, built–in cache, and a built–in math coprocessor (Woodcock 204). The Pentium chip is a CISC microprocessor boasting a 64–bit data bus, 32–bit address bus, two 8K caches, and over 3.1 million transistors (Woodcock 297; Intel Corporation, *Intel Technology Briefing* 2). It is also a superscalar microprocessor and able to execute two instructions concurrently (Intel Corporation, *Intel Technology Briefing* 1–2).

The Pentium also attempts to eliminate the bottleneck of selecting instructions with branch prediction technology (Intel Corporation, *Intel Technology Briefing* 2). These features simply mean that the Pentium chip is the fastest CISC microprocessor produced for IBM–compatible personal computers. In the future, Intel will release 486 and Pentium microprocessors with faster clock speeds, and Intel also plans to introduce a new microprocessor currently referred to as p54c or Pentium II in mid–1994, rumored to be either a faster version of the Pentium or a CRISC chip, a hybrid of CISC and RISC technologies. The next microprocessor planned, the P6, is planned for 1995 and will be a CRISC microprocessor to help ease the transition to the P7, a RISC microprocessor planned for late 1995 or early 1996. The P7 will be incompatible directly with the 80X86 line of microprocessors, but compatibility is planned through software emulators.

Motorola

Motorola produces more microprocessors than Intel, but not all of their microprocessors are destined for personal computers. Motorola supplies more microprocessors to automotive industries and other electronic industries than Intel. Motorola supplies the only microprocessors for Apple's personal computers, the 680X0 series and the PowerPC series. Recently, Motorola began to supply PowerPC microprocessors to IBM, and IBM–compatible manufacturers will soon begin producing PowerPC–based IBM–compatibles. Motorola spent over $1.3 billion or about 10% of net revenues on research and development in 1992, including communications devices and other products (Motorola, *1992 Annual Report* 25, 30). Motorola's new PowerPC microprocessors could start taking a share of Intel's market away, although only about 1 million are expected to be produced in 1994 (Hof, "Semiconductors" 83; Arnst 81).

Motorola produces the 68030, 68040, and PowerPC series microprocessors used in Apple's Macintosh personal computers. The 68040 is a CISC microprocessor with a 32–bit data bus, 32–bit address bus, two 4K caches, and a built–in math coprocessor (Woodcock 4). Motorola jointly developed the new PowerPC line of microprocessors with Apple and IBM. The PowerPC 601, the first of the PowerPC microprocessors, is a RISC microprocessor. The PowerPC 601 features a 64–bit data bus, 32–bit address bus, built–in math processors, a 32K cache, and over 2.8 million transistors (Motorola, Inc., *PowerPC 601* 2–7). It is superscalar, capable of executing three instructions concurrently per clock cycle (Motorola, Inc., *PowerPC 601* 2). Future PowerPC microprocessors promise much greater speed even than the 601 delivers, offering full 64–bit addressing and four instructions per cycle among other features (Motorola, Inc., *PowerPC 601* 2; Woodcock 312–3). Apple and IBM use the PowerPC line of microprocessors in their highest power personal computers. In the future, Motorola will continue its 680X0 line with the 68060. The new PowerPC microprocessors are currently shipping or planned out soon: the 601 is shipping, the 603 (for portables) is shipping, the 604 (a high–end 601) will ship in the middle of 1994, and the 620 (for multi–processor computers) in late 1994.

The Future: RISC microprocessors

The CISC microprocessors are approaching the limits of their price versus performance ratio, and RISC microprocessors are moving to shatter that barrier (Seiter 97). The alliance of the two largest personal computer suppliers and the largest semiconductor manufacturer in the United States is developing the next generation of microprocessors for personal computers. Apple, IBM, and Motorola have joined forces to develop the PowerPC line of RISC microprocessors that promise to deliver several technological advantages, lower cost, and increased compatibility. Workstation computers, usually high–end graphics machines, have already switched over to RISC microprocessors for these reasons.

Microprocessor Comparison

Name	68040 (25 MHz)	80486 (50 MHz)	Pentium (66 MHz)	PowerPC 601 (80 MHz)
Manufacturer	Motorola	Intel	Intel	IBM / Motorola
Type	CISC	CISC	CISC	RISC
Cache	4 kB instruction 4 kB data	8 kB unified	8 kB instruction 8 kB data	32 kB unified
Instructions issued per clock cycle	1	1	2	3
Chip size	10.8 x 11.7 mm	varies	17.2 x 17.2 mm	11 x 11 mm
Transistors	1.2 million	1.2 million	3.1 million	2.8 million
Operating voltage	5 V	5 V	5 V	3.6 V
SPECint 92*	21	27.9	67.4	85
SPECfp 92*	15	13.1	63.6	105
Peak power use	6 W	5 W	16 W	9.1 W
Price per 1000	$233	$432	$898	$557

* The SPECint 92 and SPECfp 92 are benchmarks of integer and floating point math computer power, respectively. The scale shows the number of times the speed of a VAX 11/780 mini–computer.

Figure 5

Source: Geppert, 21.

Figure 5 is a comparison of the major microprocessors used in current personal computers. The number of instructions issued per clock cycle illustrates the advantage that the PowerPC has over the other microprocessors. A key concern of microprocessor manufacturers is heat. The lower the power and the smaller the chip surface area, the less heat is generated, as in the PowerPC. The processing power of the chips is shown by the SPECint 92 and SPECfp 92 benchmarks. Although the benchmarks measure computing power, the actual performance depends on the implementation in a computer configuration. For example, the benchmarks for the Pentium assume a 256-bit data bus, while the actual implementation has been a 64-bit data bus.

Apple Macintosh personal computers are currently shipping Motorola's 68040 and PowerPC 601 microprocessors. IBM–compatible personal computers are currently shipping with Intel and other manufacturers' 80486 chips, Intel's Pentium, and IBM and Motorola's PowerPC 601 chips.

Technological Advantages

The recent turn to RISC microprocessor in the personal computer industry is a result of the advantages of RISC architecture over CISC architecture. Specifically, the PowerPC microprocessor is the first RISC microprocessor to enter the personal computer market. The RISC microprocessors have been used in computers for the past ten years, but their power has not been available to personal computer users until recently.

CISC

The advantage of CISC microprocessors is that they include many instructions in the microprocessor itself instead of combining more basic instructions to accomplish the task. The problem is that the great number of instructions limits the performance—the microprocessor must choose the correct instruction for the task at hand. To get more computing power, manufacturers add more instructions, but the decision process itself becomes a bottleneck (Thompson, “PowerPC Performs for Less” 74). Picture the large number of instructions as destinations on a road map. This road map is special; one can only choose from two options at a time. One can proceed to either A or B; from A one can chose G or H; from G one can choose Y or Z. This decision process continues until the proper destination is reached. On the road map, points B, H, Y, and Z are all instructions with A and G two decisions along the way. Now imagine an enormous road map of many instructions and decisions. The more decisions that need to be made before the final instruction is reached wastes time that the microprocessor could use to work. Also, more instructions increase the surface area of the chip, causing heat and power problems (Poole, “PowerPC Preview” 106–7).

RISC

The RISC microprocessors were developed to get around the bottleneck of sorting through the exhaustive number of instructions, slowing CISC microprocessors down (Thompson, “PowerPC Performs for Less” 74). The advantage of RISC microprocessors is that they quickly execute the basic instructions, removing the speed limitations of CISC microprocessors—they do not need to search through lists of complex instructions (Ryan, "RISC Drives PowerPC" 79). The problem is that the complex instructions must be created by combining the basic instructions instead of being built in (Poole, "PowerPC Preview" 106–7). Although they must create the complex instructions, RISC microprocessors can be significantly faster than CISC microprocessors because the instructions are located faster and therefore more instructions can be processed in the same amount of time compared with CISC microprocessors.

From a design aspect, the layout and division of labor in a RISC microprocessor is a significant advantage over CISC microprocessors. Instructions are processed more efficiently, and more instructions are executed concurrently during each clock cycle (Poole, "PowerPC Preview" 106).

Comparison

To illustrate RISC and CISC microprocessors' strengths and weaknesses, imagine using a calculator to figure out several types of math problems. A basic, ten dollar calculator will do the basic functions—addition, subtraction, multiplication, division, square roots, and exponents. A more complex calculator has many keys with specialized functions to figure out specific problems, such as trigonometric functions, statistical functions, and financial functions. The basic calculator can solve the same math problems the complex calculator can, but it takes more time to combine the functions to get the desired result and may require some extra knowledge and instruction on the user's part. Assuming a person wants to tackle a wide variety of calculations, ranging from extremely basic to very complex, which calculator is better? In the advanced calculations, the complex calculator has many functions already there so there are fewer formulas the user must know, which speed up operations. The problem with the complex calculator is that there are so many keys for all those functions, making it time–consuming to search through them all, and it is difficult to find the right one for the task. The basic calculator is simple, with few keys, making it fast to use. The problem with the basic calculator is that there are not as many functions, so the user must supply additional information in order to combine several basic functions to accomplish an advanced calculation.

How does this relate to microprocessors? The calculators are types of microprocessors, and the keys are the instructions the microprocessor knows. The basic calculator is a RISC microprocessor, with several basic instructions and fast execution. The complex calculator is a CISC microprocessor, with advanced instructions but slower searching through the number of instructions as a result. With human limitations, mainly data entry speed into the calculator, the illustration puts the complex calculator, or CISC microprocessor, at an advantage. However, with modern personal computers, the information is transferred so rapidly that execution speed is essential to instructions, and RISC microprocessors have a large advantage in this area.

PowerPC RISC

The PowerPC has three separate processing units: a branch–processing unit, an integer (whole numbers) math unit, and a floating–point (with decimal places) math unit, allowing it to process several pieces of data simultaneously (Poole, "PowerPC Preview" 106–7; Geppert 22). The PowerPC line of microprocessors has several other advantages in the way it handles information. Many CISC microprocessors read and write information that it is working with to the computer's RAM, or memory. The PowerPC keeps the information in the chip for the most part until the operations on the data are complete, saving the access times of reading and writing to RAM (Poole, "PowerPC Preview" 106–8). The memory access routines are also faster and more efficient than CISC chips, and there are more registers for storing the information it is processing (Poole, "PowerPC Preview" 106–8).

Cost

Although cost varies by processor and manufacturer, the cost of RISC microprocessors promises to be lower than CISC microprocessors. The RISC microprocessors do not have the vast number of complex instructions built into them, sometimes taking up half of the area of the CISC microprocessors (Poole, "PowerPC Preview" 106–7). In general, the smaller the chip, the lower the cost can be. This holds true for Motorola's PowerPC microprocessors. The PowerPC 601 has a surface area of 121 square millimeters and costs as low as $450 in quantity (Thompson 64). In comparison, Intel's Pentium has a surface area of 262 square millimeters and costs about $965 in quantity (Thompson 64).

Compatibility

In the past, microprocessor manufacturers have developed faster CISC microprocessors designed around a core set of instructions to maintain compatibility. One of the biggest drawbacks of RISC microprocessors in the workstation computer market is that there are so many manufacturers that no standard exists. The lack of a standard architecture forces software developers to rewrite their programs for each microprocessor. As RISC microprocessors begin to invade the personal computer market, this is a critical concern because they are not backward compatible with existing software, at least directly. In IBM's PowerPC line of personal computers, they are not compatible directly with the 386 or 486 microprocessors. Apple's PowerPC line of personal computers are not compatible directly with the 68030 or 68040 microprocessors.

To achieve compatibility and make their computers marketable to present personal computer owners, PowerPC–based computers ship with emulator software allowing the PowerPC chip to translate and handle instructions designed for other microchips. Emulation is a transition piece of software until the software developers rewrite their programs for the PowerPC microprocessor. Although emulation gives compatibility, it slows operations. For example, Apple's PowerPC–based Macintosh is 2–5 times faster than the fastest 68040 microprocessor when it runs native software, or software rewritten for the microprocessor. With emulation, the extra speed is used up in the translation process, bringing the PowerPC to 68040 speeds. The Apple PowerPC–based Macintosh emulates Apple Macintosh software and IBM–compatible software. This offers current speeds to consumers while offering potential growth of 2–5 times the computing power when native software is used.

Apple and IBM are using the PowerPC line of microprocessors to establish a single standard microprocessor architecture for software developers. The major software developers for Macintosh and IBM–compatible personal computers have already announced their support of the PowerPC. In addition, many software developers for workstation computers have decided to support the PowerPC microprocessor with software and operating systems, such as Microsoft's Windows NT and several varieties of the Unix operating system, bringing workstation software to personal computer users. Dave Flack, Editor–in–Chief of *Open Computing* magazine, said about the PowerPC chip, "Never will so many competitive advanced operating systems be ported to a single RISC processor" (Flack 11). Although the user interface and the rest of the computer will be distinctly IBM–compatible or Apple Macintosh, they will use the same microprocessor.

Other RISC Microprocessor Successes

The RISC microprocessors are not new; they have been used in workstation computers, laser printers, and other products before. Workstation computers need the high performance that RISC chips deliver, usually for high–level graphic design or scientific applications. The personal computers are now at the low end of workstation power, and workstation computer costs are falling to the high end of personal computers. Because of this, experts predict the two paths will cross in 1994, with business users targeted for the new personal workstation class of computers (Arnst 81).

Midrange computer systems handle up to 32 users at a time (*Standard & Poor's Industry Surveys* C86). The midrange computer systems have switched to RISC microprocessors, but the industry has not agreed upon a standard architecture (*Standard & Poor's Industry Surveys* C86; Sprackland, "RISC Chips Head for the Mainstream" 43–46). The lack of a standard microprocessor keeps software developers busy writing separate code for each architecture. The benefits of RISC technology for midrange computer systems are lower costs, increased speed, and the ability to have several different software packages running concurrently for several different users without significant delays (*Standard & Poor's Industry Surveys* C86–7). The RISC microprocessors can be combined in a single midrange computer and linked to provide increased computational power. Eventually, personal computers may use several RISC microprocessors to provide the power users demand (*Standard & Poor's Industry Surveys* C86–7; Thompson 56–66).

Conclusions

In the personal computer industry, one must look at the market share leaders for direction. Intel and Motorola are the two microprocessor trendsetters that have enjoyed successes in the personal computer market. Focusing on the key success factors will provide insight to the direction the industry is headed in the future.

Key Success Factors

There are three key success factors in producing microprocessors for personal computers: price to performance leadership, software compatibility, and support of personal computer manufacturers. Intel has traditionally dominated the industry, particularly in IBM–compatible personal computers, the most successful personal computer in the market in terms of sales. Direct competition from AMD and Cyrix cloning Intel's microprocessors and Motorola's alliance with IBM and Apple to produce PowerPC microprocessors is changing the face of the industry. Motorola's new PowerPC microprocessors have the support and the performance necessary to challenge Intel's dominance of the personal computer market.

Price to Performance

As consumers demand more power from personal computers, microprocessor manufacturers are scrambling to meet their needs. The CISC microprocessors have neared the price to performance limit. The RISC microprocessors are early in their growth cycle. To compare the price to performance of current microprocessors, weigh the dollars paid per microprocessor in quantity against the computing power benchmarks of the SPECint 92 and SPECfp 92 combined. This ratio reveals that Intel's 486, at 50 MHz, is $10.54 per power benchmark (Geppert 21). Motorola's 68040, at 25 MHz, is cheaper, at $6.47 per power benchmark (Geppert 21). Intel's Pentium, at 66 MHz, their latest generation CISC microprocessor, costs $6.86 compared to Motorola's new RISC microprocessor, the PowerPC, at 80 MHz, costing only $2.93 per power benchmark (Geppert 21). This price difference is important to both personal computer manufacturers and consumers, putting the PowerPC at a definite advantage over Intel's Pentium.

Software Compatibility

In the past, microchip producers were able to maintain backward compatibility while offering new levels of performance. With the RISC microprocessors, this is not possible. Software emulation can satisfy consumers until they upgrade or purchase new software native for the new microprocessor. Microchip manufacturers must carefully work with the software suppliers or risk losing support. Intel has 80% of the world personal computer market because software developers have written over 30,000 software programs for its line of microprocessors (Dodge 37). Creating a microprocessor that is incompatible with the previous microprocessor would lock out that software and also prevent people who own computers from upgrading to a faster personal computer.

Intel is developing a microprocessor that combines the speed benefits of RISC with the backward compatibility to its CISC microprocessors. The result will be a hybrid microprocessor, classified as a complex reduced instruction–set computer (CRISC). Although it will not have all the speed benefits of a true RISC, it will have the compatibility that Motorola's PowerPC lacks. Marc Dodge, in an article in *Open Computing* magazine, argues that Intel's dominance of the microprocessor market will continue for at least three years until Motorola's PowerPC and other RISC manufacturers can amass the same quantity of software for its microprocessors (Dodge 37). The PowerPC is the largest threat to Intel's dominance because of its backing by IBM and Apple, and the number of software developers that are producing software for it (Dodge 37).

While the PowerPC is still a recent entrant to the market, software developers are producing the software and operating systems necessary to make it successful. Gary Poole commented on the PowerPC's software, "It will eventually run an unprecedented seven operating systems" (Poole, "Presenting PowerPC" 51). A computer is nothing without software, and both Intel and Motorola have the support of software developers for continued success. Intel has the immediate edge with true compatibility built into its microprocessors, but the PowerPC from Motorola can emulate the same software that runs on microprocessors Intel produces while offering 2–5 times any other personal computer's performance when running native PowerPC software.

Manufacturer Support

In the production of personal computers, the dominant company supplying microprocessors is Intel. A majority of personal computer manufacturers use Intel's microprocessors for IBM–compatible computer, but AMD and Cyrix are beginning to take market share away from Intel. Motorola supplies microprocessors to Apple and IBM for personal computers, but plans to begin supplying PowerPC chips to IBM–compatible manufacturers in the near future. Intel has the advantage of established distribution lines and hardware and software compatibility.

To be successful, Motorola must compete directly with Intel for the IBM–compatible manufacturers. Motorola is off to a good start, offering the PowerPC 601 at a lower price and higher performance than Intel's Pentium. Manufacturers are also watching Motorola's PowerPC 603 for portable personal computers because of its low power consumption and high performance. The efforts of Apple, IBM, and Motorola are aimed at reducing Intel's dominance of the microprocessor industry (Poole, "Presenting PowerPC" 51). The three manufacturers predict sales of over one million PowerPC–based personal computers and 200,000 IBM PowerPC–based workstations by the end of 1994 (Poole, "Presenting PowerPC" 51). Major IBM–compatible manufacturers may offer PowerPC–based computers by the end of 1994 (Poole, "Presenting PowerPC" 54).

Final Conclusions

Based on the evidence presented, I believe Intel's dominance and control over the microprocessor industry for personal computers is declining. Intel currently controls the market for IBM–compatible computers. Clone microprocessor manufacturers are challenging Intel's position. Intel has set the standard for personal computing power in the past, but Motorola is challenging that position.

The first indication of the end of Intel's dominance is the success of the clone microprocessor manufacturers. AMD, Cyrix, and a few other new entrants into the microprocessor industry have focused on taking market share away from Intel. These clone microprocessor manufacturers are growing rapidly and are posing a serious threat to Intel's IBM–compatible personal computer market. In the same way that IBM personal computers eventually became indistinguishable from IBM–compatible clones, I believe Intel microprocessors may become indistinguishable from Intel–compatible clone microprocessors. If Intel–compatible microprocessors become a commodity item, the lower prices of AMD, Cyrix, and others will take the IBM–compatible personal computer manufacturing market away from Intel. AMD, Cyrix, and others avoid much of the high research and development costs Intel has because they follow Intel's lead. Through reverse engineering and other techniques, the clone microprocessor makers have lower costs. Lower costs translate into lower prices, higher profits, or a combination of the two. By beating Intel at its own game, AMD, Cyrix, and others are taking away market share from Intel.

The second indication of the end of Intel's dominance is the threat of a new microprocessor standard for personal computers. Intel still leads development of new microprocessors for IBM–compatibles, but Motorola, IBM, and Apple are trying to put an end to that. Motorola's PowerPC microprocessor is changing the face of the industry with high performance, low–cost microprocessors with strong support from hardware and software producers. Although the future is uncertain, the stage is set for a major battle between the microprocessor superpowers. The PowerPC is the first attempt at a standard RISC microprocessor—something the workstation computers could not accomplish. A new microprocessor standard based on the PowerPC would greatly damage Intel's market share, possibly even eliminating Intel from the market of high performance personal computer microprocessors.

Intel is working to combat the attacks from competitors. Intel must price its microprocessors competitively to compete with AMD, Cyrix, and the other clone microprocessor manufacturers. To defend against the PowerPC, Intel must introduce similarly powerful microprocessors at a comparable price. The products Intel is developing may arrive too late. The P6, expected in 1995, will offer backward compatibility with some RISC performance—the CRISC hybrid microprocessor. The P7, expected in late 1995 or early 1996, will complete the transition from CISC to CRISC to RISC—it is a full RISC microprocessor. Although a transition strategy provides an upgrade path for existing customers, the final microprocessor, the P7, is completely incompatible with existing software. Also, by 1996, the PowerPC will be on the market for two years with software already written for it. Although Intel recognizes the shift from CISC to RISC in the microprocessor industry for personal computers, its timing may pass the leadership in the industry to the Apple–IBM–Motorola alliance and the PowerPC microprocessor.

No matter what the experts say about the future, in the present, Intel dominates. Motorola, AMD, Cyrix, and a few other microprocessor producers are challenging Intel's grip on the personal computer industry, but Intel is not willing to let go of the industry. All is not lost for Intel, but they must act now or risk losing control of the industry. New brand names and new technologies take time to gain acceptance. Because of this, I believe that Intel will stay dominant for at least the next two years. Unless Intel can fend off the clone makers and prevent Motorola from defining a new personal computer standard, Intel may be left behind as the microprocessor industry for personal computers evolves.

Appendix A—Definitions

bit - A computer's lowest form of information, either a one or a zero. Eight bits equal one byte, which is a standard size of information in a computer.

bus - The communication lines inside a computer that connect the CPU, RAM, input ports, output ports, and other parts. Similar to a highway, the wider the bus, the more information can pass through it in a given time. There is a data bus sending information, and an address bus sending the location to which the data should travel. Measured in bits, many current microcomputers have a data bus of 8–bits or 16–bits. Both Intel's Pentium microprocessor and Motorola's PowerPC microprocessor have a 64–bit data bus and a 32–bit address bus.

byte - A standard size of information, consisting of eight bits. Other common sizes are kilobyte (K), which is 1024 bytes, and megabyte (M), or 1024 kilobytes (1,048,576 bytes).

cache - A cache is a part of a computer that stores recently used information for fast access if needed again (Woodcock 60). Some microprocessors have built in caches for recently executed instructions to speed repetitive tasks. Some computers also have disk caches for repetitive disk access.

circuit - A pattern of transistors arranged to yield a result. Depending on the pattern of transistors, the electric current entering the circuit can be transformed into a different current. Many circuits make up a microprocessor, which uses the circuits to perform tasks and computations (Poole, "Your Computer Revealed" 136–8).

CISC - Complex instruction–set computer. A microprocessor with an extensive set of instructions built into the chip. Manufacturers increase the number of instructions included on the chip to increase speed. The disadvantage is that the chip must select the correct instruction, so the greater the number of instructions, the slower the selection process becomes.

clock rate - The number of oscillations per second of the clock in a computer. Microprocessors execute instructions and process data at every clock cycle. Superscalar microprocessors can execute more than one instruction per clock cycle. The clock rate for microprocessors is usually measured in megahertz (MHz), or a million cycles per second.

CPU - Central Processing Unit. The part of a computer that executes instructions and does computations. If it is contained on one chip, it is referred to as a microprocessor.

emulation - Software (or hardware) that translates the instructions from software designed for one microprocessor into code usable by another microprocessor. Although it add processing time, it allows more software to be used on one microprocessor. See also native software.

instruction - A single action a microprocessor performs on data. An instruction consumes a minimum of one clock cycle to execute. If it finishes before the next clock cycle, the microprocessor cannot begin another instruction until the next cycle (Poole, "Your Computer Revealed" 143). Often, an instruction takes more than one clock cycle. In superscalar microprocessors, several instructions can be executed concurrently in independent units.

microprocessor - The brain of the computer, what allows it to think. Instructions are passed from the user or a software program and the microprocessor carries out these instructions. A microprocessor is an entire CPU on one chip.

native software - A software program written and optimized specifically for one microprocessor. It runs much faster than emulated software because the software makes direct calls to the microprocessor's instructions instead of translating instructions that are designed for another microprocessor.

Pentium - Intel's latest CISC microprocessor, successor to their 80486 microprocessor. It is superscalar, able to execute more than one instruction per clock cycle. It has a 64–bit data bus, 32–bit address bus, and over 3.1 million transistors.

peripherals - Accessories that are attached to a computer. Examples include keyboards, monitors, and printers.

PowerPC - A RISC microprocessor that is jointly developed by Apple Computer, Inc., International Business Machines, Inc., and Motorola Corp. It is superscalar, with a 64–bit data bus, 32–bit address bus, and over 2.8 million transistors.

RAM - Random Access Memory. The area where the CPU reads and writes information it is thinking about.

RISC - Reduced instruction–set computer. A microprocessor with several basic instructions that execute quickly, translating into high performance. It must combine basic instructions to execute complex instructions, but it still ends up faster than most CISC microprocessors.

semiconductor - The industry that supplies transistors, circuits, and microprocessors made from silicon wafers. Silicon is a semiconductor, meaning it can be manipulated to stop or send electric current.

superscalar - A microprocessor that can do several instructions concurrently during one clock cycle. The instructions are performed in independent specialized units of the microprocessor. It processes several instructions that require similar treatment or use similar resources at the same time (Woodcock 377).

transistor - The basic building block of microprocessors. It either stops or sends an electric current. Combine several transistors and the electric current can manipulate information. The pattern of transistors is called a circuit (Poole, "Your Computer Revealed" 136).

References

"Advanced Micro." *Value Line*. 1993 ed.

"Computers: They're No Commodity." *Wall Street Journal* 15 October 1993: B1.

"Intel Aims to Double Its Chip Performance." *Wall Street Journal* 15 December 1993: B6.

"Intel Corporation." *Hoover's Handbook of American Business*. 1992 ed.

"Motorola, Inc." *Hoover's Handbook of American Business*. 1992 ed.

"Semiconductor Industry." *Value Line*. 1993 ed.

Advanced Micro Devices, Inc. *1992 Annual Report*. 1992 ed.

Apple Computer, Inc. *PowerPC Technology: The Power Behind the Next Generation of Macintosh Systems*. August 1993.

Arnst, Catherine. "Computers: The End of the End for 'Big Iron.' " *Business Week*. 10 January 1994. 81.

Bertrand, Kate. "Chip Wars: Pricing Battle Erupting as Feisty Rivals Challenge Intel's Dominance of the 386 Microprocessor Market." *Business Marketing* February 1992: 16–18.

Burton, Thomas M. "Chief Indicator Drops For the Chip Industry." *Wall Street Journal* 10 December 1993: B8.

Carlton, Jim. "Apple Reports a $2.7 Million Profit And Record Sales for Its 4th Quarter." *Wall Street Journal* 15 October 1993: B8.

Cyrix Corporation. *Prospectus*. 15 August 1993.

Cyrix Corporation. *Third Quarter Report*. 21 October 1993.

Dodge, Marc. "RISC Will Prosper. . .But Intel's King." *Open Computing*. March 1994. 37.

Flack, Dave. "Openness in Power and Usability." *Open Computing*. March 1994. 11.

Geppert, Linda. “Not Your Father’s CPU.” *IEEE Spectrum.* December 1993. 20–23.

Hof, Robert D. “Semiconductors: The Party’s Not Over Yet.” *Business Week.* 10 January 1994. 83.

Intel Corporation. *Intel Technology Briefing.* 1993 ed.

Intel Corporation. *Intel: Architect of the Microcomputer Revolution.* 1989 ed.

Intel Corporation. *IntelAnnual: Intel Corporation’s Annual Report.* 1992 ed.

Mitchell, Russell. “Suddenly, AMD is in the Chips.” *Business Week* 9 December 1991: 32.

Motorola, Inc. *1992 Annual Report.* 1992 ed.

Motorola, Inc. *PowerPC 601 RISC Microprocessor Technical Summary.* 1993 ed.

Poole, Gary. “Presenting PowerPC.” *Open Computing.* March 1994. 50–58.

Poole, Lon. “PowerPC Preview.” *Macworld.* February 1994. 102–8.

Poole, Lon. “Your Computer Revealed: Inside the Processor.” *Macworld.* October 1992. 136–143.

Ryan, Bob. “RISC Drives PowerPC.” *Byte* August 1993: 79–90.

Seiter, Charles. “The Evolving Mac System.” *Macworld.* February 1994. 97.

Sprackland, Teri. “Comeback Company of the Year—Make No Mistake: AMD is Back!” *Electronic Business* 18 November 1991: 40–48.

Sprackland, Teri. “RISC Chips Head for the Mainstream.” *Electronic Business* 8 July 1991: 43–46.

Standard & Poor’s Industry Surveys. July 1993 ed.

Thompson, Tom. “PowerPC Performs For Less.” *Byte* August 1993: 56–74.

Willett, Shawn. “AMD’s Record Revenues Tied to Outdated Chip.” *InfoWorld* 18 January 1993: 28.

Woodcock, JoAnne. *Microsoft Press Computer Dictionary*. 2nd ed. Redmond, Washington: Microsoft Press, 1994.

Yamada, Ken. "Advanced Micro, With Legal Barriers Gone, Begins Shipping Intel Chip Clones." *Wall Street Journal* 20 April, 1993: B6.