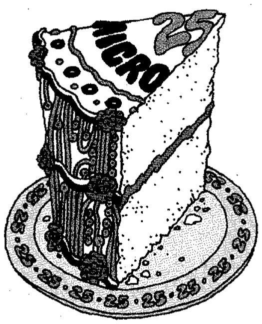
A PARTICIPANT'S PERSPECTIVE

R. Gary Daniels

Motorola



The "father" of the 6805 MCU relates his role in the history of the microprocessor.

My agreement to write this article on the microprocessor (in a moment of weakness) came out of respect for Federico Faggin and his contributions to our society and profession.

Here is the story, as told by an active participant. Briefly, in the space allowed. Accurately, as best my memory permits. Interestingly, as my writing talent allows. But admittedly, from my viewpoint.

Before the beginning (1946-1970)

The willing marriage of two revolutionary industries set the stage for the microprocessor.

The first was the computer industry. In 1946 at the University of Pennsylvania, J. Presper Eckert and John Mauchly demonstrated the world's first electronic computer. It was the size of a boxcar, weighed 30 tons, and used 150,000 watts of power. Its 18,000 vacuum tubes could compute gunnery coordinates 100 times faster than a human. ENIAC started the computer revolution.

The second industry began in 1948 with the invention of the transistor at Bell Labs by William Shockley, John Bardeen, and Walter Brattain. The first transistor was also, by today's standards, big (about the size of a BB pellet) and crude (two sharpened points that probed a piece of germanium). But this point-contact structure promised future electronic devices that would be smaller and lighter and have much longer life. It launched the semiconductor revolution.

These revolutions started slowly, gained momentum in the 1950s, and began to exhibit real utility in the 1960s—mostly for military and space applications.

The integrated circuit invention in the late 1950s (jointly credited to Jack Kilby of Texas Instruments and Robert Noyce of Fairchild Semiconductor) was a key milestone for the fledgling semiconductor industry.

By 1970, both of these industries had matured and prospered. Both were accepted as viable technologies (and businesses), and both were relatively well understood—certainly by the engineering community. Computer architectures were no longer mysteries, and most engineering schools' curricula offered the concepts of software programming.

The IBM System/360, one of the first IC-based computers, was the most popular mainframe in 1970. It featured software compatibility over several models. Minicomputers had appeared that offered lower cost and smaller size while maintaining substantial performance.

Similarly, semiconductor technology had progressed from discrete to integrated circuits (used predominantly in computers in 1970) to the leading edge of the VLSI era. MOS technology in 1970 offered the capability of integrating several hundred transistors—perhaps a few thousand—on a single piece of silicon. For the first time, we could monolithically integrate a complete electronic system!

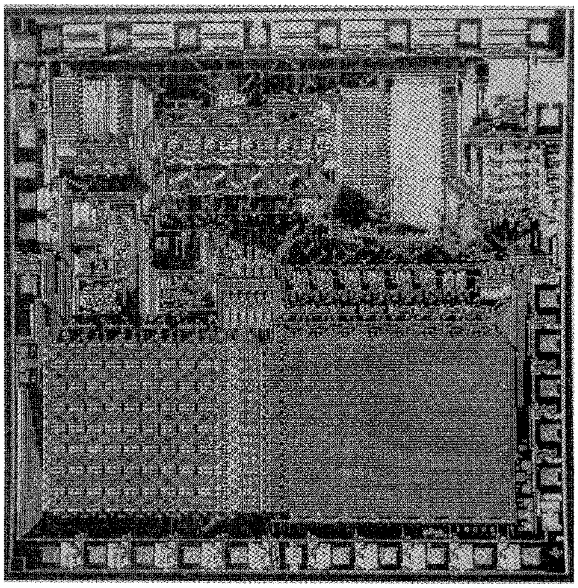
The most popular choices for system integration in 1970 were the calculator and the electronic timepiece.

My project in 1970? The design of an electronic wristwatch chip (in 10-micron silicon-gate CMOS at 1.5 volts). My career with Motorola Semiconductor had started in 1966 as an engineer in the Applied Science Department in Phoenix, Arizona.

The 1970s were a time of high engineering achievement and excitement. We had put a man on the moon in 1969! It was also a period of high economic growth—in the country, and especially, in the computer and semiconductor industries.

Microprocessor design methodology in the late 1970s

Design specifications were books of many hundred pages. We used pencil and paper to generate flow charts and logic diagrams. To verify the functional description, we constructed breadboards (with MSI components) that we also used to develop and debug diagnostic software. We used logic and circuit computer simulation programs extensively, and these were reasonably accurate—if we could obtain process parameters. We laid out ICs by hand and used computer digitizing to get a computer database for mask preparation and for checking (manually). Computer programs could verify IC layout rules—but they were slow and rudimentary by today's standards. High-level simulation was still in the future, as was logic-to-layout verification.



Texas Instruments TMS-1000 (1973)

The beginning (1971-1973)

In this exciting period, the marriage of the computer industry and the semiconductor industry happened—thereafter forever altering the paths of these two industries.

The idea of a general-purpose programmable calculator was Ted Hoff's at one-year-old Intel. The implementation by a young engineer, Federico Faggin, is certainly the most pivotal story of this time.

The preceding article in this series tells the whole story. Suffice it to say here that Intel introduced the world's first microprocessor, the 4004, in 1971. The 4-bit machine contained 2,300 transistors in P-channel silicon-gate (8-micron) technology. It was fabricated on two-inch wafers and assembled in a 16-pin package. The 4004 operated with a –15-V power supply at 750-kHz clock speed and could address up to 8 Kbytes of ROM and 640 bytes of RAM. Its performance was roughly comparable to the ENIAC.

Intel followed the 4004 with the 8-bit 8008 in 1972. The 8008 (a Faggin-Feeney design) contained 3,500 transistors and could address 16 Kbytes of memory. However, it was still an invention in search of a market, as the technical world was just beginning to view the microprocessor seriously.

Fortunately, interest was sparked at several semiconductor firms.

Motorola initiated a custom microprocessor project in 1972 that never made it to silicon. The design team led by Tom Bennett went on to design our first microprocessor, the 6800.

Texas Instruments laid the groundwork for future microcontrollers in 1973 with the metal-gate PMOS TMS-1000. This monolithic IC contained a 1-Kbyte ROM, 32-byte RAM, 4-bit CPU, 300-kHz clock oscillator, and on-chip input/output pins. TI designed the TMS-1000 to span a range of handheld calculator products.

Other early entrants in the microprocessor race included Rockwell's PPS-4 in 1972 and PPS-8 in 1974; National's 8-bit, PMOS IMP 8 (perhaps the first to address 64 Kbytes of memory) in 1973; and RCA's COSMAC (the first 8-bit, CMOS entry) in 1974.

The early years (1974-1979)

My career took an abrupt turn in late 1974. Bob Galvin decided to close down our Timepiece Electronics Unit (a wise business decision in retrospect, but it left me looking for a job). An opportunity occurred in the new Microprocessor Design Department working for Tom Bennett in Gary Tooker's MOS Operation. However, this assignment meant a move to Austin, Texas.

The 6800 had just been introduced. The semiconductor industry was entering a recession.

My first assignment was to lead a small team to redesign the 6800 MPU to make it more manufacturable and so that higher speed versions could be selected. This product, known internally as the 6800A, contained about 5,000 transistors in 6-micron silicon-gate NMOS technology.

The 6800 operated from a single 5-V power supply (unique at the time) at up to 2-MHz clock and bus speeds and addressed 64 Kbytes of memory. It was fabricated on three-inch wafers and assembled in a 40-pin ceramic dual-in-line package (DIP).

A typical 6800 system configuration included the 6800 MPU, a 6810 128-byte RAM, a 6830 1-Kbyte ROM, a 6820 peripheral interface adapter (PIA), and possibly a 6850 asynchronous communications interface adapter (ACIA).

The company billed the 6800 as a "modern architecture": two 8-bit accumulators, two 16-bit registers (index and stack pointer), a 16-bit program counter, and a condition code register. It had a 16-bit address bus and an 8-bit bidirectional data bus (therefore, to us, it was an 8-bit machine). Memory-mapped I/O allowed a sophisticated interrupt structure.

As were other microprocessors of its day, the 6800 was seen as a replacement for random logic on several printed circuit boards. Use in an automobile or for desktop com-

The personal computer

Richard A. Shaffer, Technologic Partners

This is the 20th anniversary of the personal computer, give or take a year or so, and in its two decades the PC has transformed the way we work and play and learn.

In roughly one human generation, this most widely recognized embodiment of microprocessor technology has evolved from a crude device controlled through panel switches to a marvel that can read handwriting and understand speech. Often smuggled into companies in its early days because those in charge of corporate computing viewed it as a toy, the PC has replaced the mainframe as the dominant form of information processor. The PC, which was the instrument of an information rebellion, has become the establishment.

The early PCs were difficult to use, but enough progress has been made in two decades that the machines now appeal to a broad audience. These days, Americans buy more PCs every year than TVs. Two households in every five own a PC. This year's college graduates will never have known a world without PCs. When their parents graduated, only nerds used computers; now computers are cool.

For the most part, PCs are still doing the five basic jobs they have done since the beginning: spreadsheets, word processing, databases, communications, and graphics. Communications, however, is becoming increasingly important. Indeed, in some ways the PC is becoming more like the telephone. Originally valued for the work it could do by itself, the PC increasingly is valued for the work it can do when connected to other PCs. The calculation tool is becoming a communications tool.

The benefits of the PC are sometimes difficult to measure. In business and education, the billions spent on PCs have yet to improve productivity or standardized test scores. Yet most executives and educators believe their companies and schools could not operate without PCs.

Clearly, the PC has changed the way many jobs are done. Draftsmen, for example, now have disappeared from architectural firms; PC-based design systems have taken their place. Typesetters will soon be gone from newspapers. In the time it used to take just to check the data entries on a calculator tape, a corporate analyst now can run a spreadsheet to examine dozens of business possibilities. Memos that once had to be dictated, typed, revised, and retyped now are turned out on PCs perfectly spelled, grammatically correct, and may even be sent electronically, bypassing paper completely.

In many classrooms, PCs act as patient tutors, taking the place of the teacher for drill, practice, and much more, opening new worlds through multimedia education. In homes, the PC with a CD-ROM or Internet connection replaces the encyclopedia. For fast action and compelling graphics, PC games are beginning to rival those in video arcades. More cerebral entertainment is popular too. A computer isn't yet chess champion of the world, as used to be predicted regularly, but ordinary PCs are good enough to beat most players most of the time.

Originally, the central idea of personal computing was that one person was in total control of all the machine's resources. If the mainframe and minicomputer eras were ones in which the motto was "One computer, many people," the slogan of the PC age is "One person, one computer." Now, for some, the PC has become almost too personal; a device they cannot seem to do without. They use a desktop model at work, take a notebook model on travels (even on vacation), and carry around a handheld model as a constant digital companion. Who would have imagined it 20 years ago?

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puting was beyond our wildest dreams. The first volume customer for the 6800 made video games.

Programmers used assembly language for early microprocessors. An assembler converted this to the 1s and 0s (object code) that the MPU could understand.

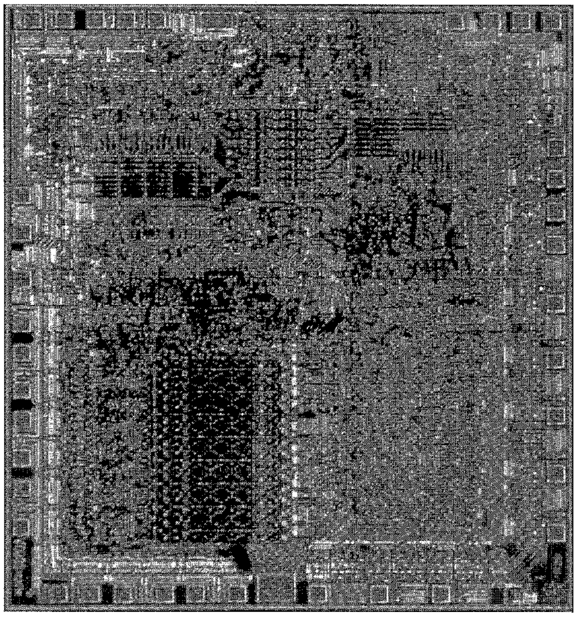
Motorola's major competitor was clearly Intel. The 8080, introduced a few months before the 6800, had similar features and performance. In the first of many "religious debates," we would argue the 6800 architecture was "cleaner and simpler." The 8080 became the brain of what many consider the first personal computer, the Altair.

The Z80, an upgraded but compatible product from Faggin (then at Zilog) introduced in 1975, made it essentially a three-horse race. However, by the end of 1975 there were many microprocessors on the market (see Table 1, next page).

In 1976, we had a very important customer visit: Delco Electronics. Delco had accepted the task of designing an engine control module to meet the new government regulations for emissions for all General Motors vehicles. It needed a semiconductor supplier and partner, and we won the program against stiff competition. Here was the high-volume application and industry-leading partner we had been looking for!

The system became known as GMCM (General Motors Custom Microprocessor), and it built much of Motorola Austin. Delco engineers J.D. Richardson, Phil Motz, and others, working with the Motorola design team led by Stan Groves and Gene Schriber, defined a system based on an enhanced 6800 plus a half-dozen companion chips.

The upward-compatible enhancements to the 6800 included new 16-bit instructions, additional index register instructions, an 8×8 multiply, and faster execution cycles on key store and branch instructions. And, of course, we had to meet the hostile automotive temperature and voltage require-



Intel 8080 (1974)

ments. We were to learn the quality expectations later (painfully but very beneficially).

In 1977, the semiconductor industry was still recovering from the recession, and although we were hiring again, the GMCM program was understaffed. As my experience on the 6800 redesign was fresh, Motorola decided that I should lead the CPU design; Gene Schriber took charge of the companion chips.

By then, my title was design manager for microprocessors. Since management duties required much of my at-work time, a large part of the GMCM CPU design work took place at home (on my pool table).

The GMCM technology was pretty much the same as the 6800, except that we moved up to 4-inch wafers and into high-pin-count plastic DIPs to satisfy the automotive environment (and cost) requirements. Delco's quality demands led us to test grade (fault validate) all the test programs.

GMCM was a very successful program—for both Motorola and Delco Electronics. It cemented a partnership that remains a model for our industry. Production volumes for this program dwarfed most other microprocessor applications at the time. And, it was just the beginning. The number of microprocessors/microcontrollers in an automobile would steadily increase for another 15 years!

Meanwhile, Intel announced the 8-bit 8048 microcontroller

Table 1. Major microprocessor and microcontroller merchant suppliers, rank ordered by sales. *(Sources: Dataquest; ICE, Phoenix, Ariz.; In-Stat, Scottsdale, Ariz.; Motorola)*

Chip	1975	1980	1985	1990	1995
Microprocessors	Intel	Motorola	Intel	Intel	Intel
	Motorola	Zilog	Motorola	Motorola	AMD
	AMD	Intel	AMD	AMD	Motorola
	Signetics	Synertek	AT&T Technologies	NEC	IBM
	National	NEC	DEC	Inmos	Texas Instruments
	NEC	National	Fairchild	Siemens	Cyrix
	Gould	Rockwell	Hitachi	Hitachi	Hitachi
	Texas Instruments	RCA	Inmos	Zilog	NEC
		Mostek	National	LSI Logic	IDT
		AMD	NCR	National	National
		Commodore	NEC	Performance	Toshiba
		Fairchild	Zilog	Toshiba	SGS-Thomson
		Signetics	Data General	Cypress/Ross	Fujitsu
		Gould	Hewlett-Packard	IDT	GEC Plessey
Microcontrollers	Rockwell	Texas Instruments	NEC	NEC	Motorola
	Texas Instruments	NEC	Motorola	Motorola	NEC
	Fairchild	National	Mitsubishi	Hitachi	Mitsubishi
	Mostek	Matsushita	Intel	Mitsubishi	Hitachi
		Intel	Toshiba	Intel	Intel
		General Instrument	Hitachi	Matsushita	Philips
		Rockwell	Philips	Toshiba	Matsushita
		Sharp	General Instrument	Fujitsu	Toshiba
		Fairchild	Siemens	Philips	SGS-Thomson
		Mostek	Texas Instruments	National	Fujitsu
		Motorola	Signetics	Sharp	Siemens
		Hitachi	National	Oki	Microchip Tech
		Gould	Matsushita	Texas Instruments	Texas Instruments

unit and an EPROM version, the 8748. The 8048 contained a 1-Kbyte ROM, a 64-byte RAM, an 8-bit timer, 27 I/O pins, and an on-chip clock oscillator. The 40-pin MCU operated from a 5-V supply. Other 8-bit MCU competitive products included the F8 from Fairchild, the 3870 from Mostek, and the 1650 from General Instruments. It was decreed that Motorola must have a single-chip microcontroller.

The product became known as the 6801. It contained a 128-byte RAM, 2-Kbyte ROM, sophisticated 16-bit timer (à la automotive), 4-MHz on-chip clock oscillator, programmable digital I/O, serial port and, of course, the CPU.

We originally intended to use the 6800 for the CPU, but the GMCM CPU fit the IC layout better and offered enhanced features. We explained to Delco engineers that since they would likely use the 6801, it would be in Delco's best interest to grant our request to use the GMCM CPU. Delco agreed.

We introduced the 6801, our first microcontroller, in 1978. The design team included Pern Shaw, Fuad Musa, Wayne Busfield, and Mike Wiles. This was our first system on a chip. The 5-micron NMOS 6801 contained 35,000 transistors in a 40-pin DIP. We were all very proud of it—except for our marketing manager, Gary Summers, who complained at an operations review that it was too expensive.

That was tantamount to calling my baby ugly! At home that night my anger turned (after a few glasses of wine) to a challenge. I had a logic diagram of the 6800 at home, and I began to study it. What if we eliminated one accumulator? I red-marked that logic. How about the decimal-adjust instruction that was seldom used but took a lot of silicon area? More red marks. How about an 8-bit index register and stack pointer? More red.

By the wee hours of the morning my logic diagram was bloody red. The next morning I handed the marked-up document to a young engineer, Jim Thomas, to pursue further. Jim worked with Joel Boney and others removing even more features for a few days. Then they began to carefully add a few back—including powerful (I/O) bit manipulation and conditional branches.

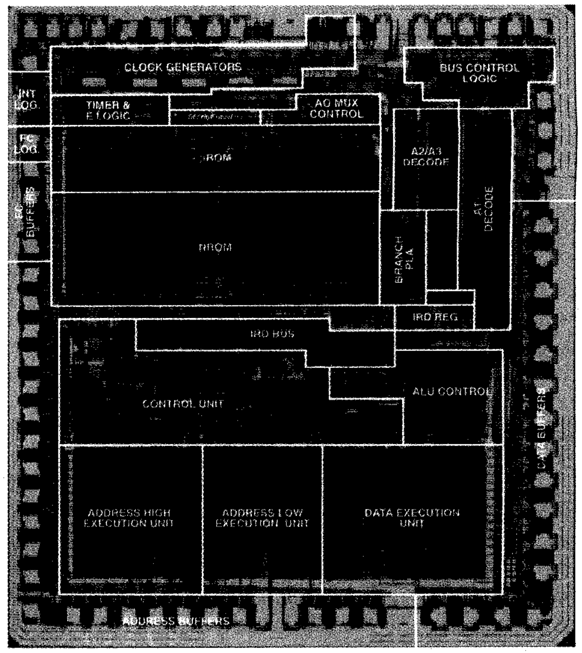
We named this new 8-bit architecture the 6805. The 6805 line, introduced in 1979, is, we believe at this writing, the largest selling microprocessor architecture in the world (over two billion units shipped of the 6805, 146805, and 68HC05 lines).

In 1979, we received inquiries from a sister division about a microcontroller for pagers. This was the brainchild of technical wizard Walt Davis—and he brought designers to help do it! The architecture selected was the 6805, but to meet the low-power requirements of a pager, the technology had to be CMOS.

This design team included Phil Smith and Raghu Raghunathan. The product was the 146805. We were suddenly in the CMOS MCU business! We also had started our first long-lasting partnership with a sister division.

In 1977, our operations manager, Colin Crook, envisioned the need for a step-function increase in microprocessor performance. He established a "skunk-works" activity with Tom Gunter as the leader.

Tom and his team made the assumption that memory would be readily available and cheap (little did they know!)



Motorola 68000 (1979)

and that future software would be written in high-level languages. To increase bandwidth, they called for a 16-bit data bus and a 32-bit address bus (package limitations reduced this to 24 bits on the first product). They made the registers general purpose and 32 bits wide—and there were plenty of them (16). The implementation used microcode (for the first time—at Motorola anyway).

The product was the 68000.

Introduced in 1979, the 68000 was fabricated on 5-inch wafers in 4-micron HMOS technology. Coincidentally, the transistor count was about 68,000. The 68000 used a special package: a 64-pin DIP (ceramic first, plastic later).

The 68000 operated at 5 V and at 8-MHz clock speed. It performed at about 1 MIPS (million instructions per second).

Apple Computer selected the 68000 for its Macintosh personal computer line, and we formed another long-lasting partnership.

The 68000 in 1979 was in a class by itself, and we were proud of it. If any competitor was of serious concern, it was Zilog with its Z8000, also introduced in 1979. The Z8000 was assembled in a 48-pin DIP and contained close to 18,000 transistors. Other early 16-bit microprocessors were the National PACE and the General Instruments CP1600.

But in our industry, the competition, it seems, never sleeps.

Intel had introduced a 16-bit microprocessor, the 8086, in 1978 and an 8-bit pin-out version in a 40-pin package, the 8088, in 1979. With 29,000 transistors, an address range of only 1 Mbyte, and an 8-MHz clock speed (in 3-micron HMOS technology), we felt it was no match for our 68000.

Nonetheless, the 8088 won the most important design socket of the decade—for the IBM personal computer.

Intel's 8061 won the Ford engine control socket, while

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