1

Basic and Historical Definitions

This chapter, introduction to the field, presents after the basic definitions, a history. In this context, the key characteristics of the microprocessors representative of these five decades are given.

1.1. Basic definitions

A microprocessor or MPU (MicroProcessor[1] Unit) is the integrated version of the central processing unit[2] (CPU) of computers from the 1960s, the prefix "micro" referring to miniaturization[3]. The central unit was made up of several electronic cards at the time where many integrated circuits in DIP (Dual-In-Line Package; *cf.* § 3.3 of Darche (2004)) were installed. These cards communicated with each other using a backplane bus (*cf.* § V2-4.2.7). The architecture of the microprocessor therefore inherits that of the central processing units of previous computers, themselves resulting from the von Neumann model (*cf.* § V1-3.2.2) for almost all. Of course, all of the current features, such as virtual memory (VM) or cache (this will be covered in a future book), were only gradually integrated due to the integration limitations of the technologies of the time.

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1 The term "microprocessor" was used for the first time by the company Viatron Computer Systems Corporation in 1968 to name its terminal System 21 2140/2150 (Computers and Automation 1968; Bassett 2002) of which the CPU consisted only of discrete logic components of type MSI/LSI.

2 In the sense of Chapter 3 of Volume 1, that is, without integrated primary memory (for now!).

3 It should not be associated with that of microprogramming (this will be covered in a future book by the author on microprocessors) because the control of a microprocessor is not necessarily microprogrammed. It can be wired.

This component is in the form of a single Integrated Circuit (IC) in monolithic version, originally belonging to the LSI category (Large-Scale Integration; *cf.* § V1-1.2) and developed in PMOS technology (positive (channel) metal-oxide semiconductor; *cf.* § 2.1.3 of Darche (2004)). Today, the microprocessor, essentially CMOS technology (Complementary MOS; *cf.* § 2.4 of Darche (2004)), offers parallel hardware execution. Exceptions included where the microprocessor was a set of integrated circuits, an example being the iAPX 432 (Witten and Cleary 1983) of the company Intel made up of three integrated circuits but that remained marginal.

From a logical point of view, a microprocessor is a sequential system (*cf.* Chapter 3 of Darche (2002)) programmable, synchronous[4] most of the time, which executes a program, that is, an ordered sequence of instructions, stored in a so-called central, main or primary memory, volatile or not. We can see it as a complex form of state machine (FSM for Finite-State Machine; *cf.* § 3.7.3 of Darche (2002)).

Its basic instructions make it possible to carry out the logical and arithmetic processing of information and to carry out a transfer of control. To do this, it has three functions, calculation, storage and transfer of information.

When it integrates memory and Input/Output (I/O) controllers, it becomes a microcontroller or MCU (MicroController or MicroComputer Unit; *cf.* § 5.3) including the TMS 1000 from the company Texas Instruments (TI – 1974) was the first representative. The microprocessor can be general purpose (multipurpose or general-purpose MPU, GPP for General-Purpose Processor) or specialized in an application domain (ASP for Application-Specific Processor or ASIP for Application-Specific Instruction set Processor). The Digital Signal Processor (*cf.* 5.2) is a microprocessor specializing in digital signal processing, which is found, for example, in home video amplifiers. A subcategory of ASP is the bespoke processor (Moore 2017), a proposal by Cherupalli (2017) where the custom architecture is automatically generated to meet the needs of applications with high energy constraints such as the Internet of Things (IoT). The fields of use of the microprocessor are obviously IT, micro or classic, but industrial embedded systems are the real market. Since 2000, the trend has always been towards more integration. This has led to the emergence of systems-on-chip (SoCs, *cf.* § V1-1.2 and § V2-4.2.9), which involves the integration of an entire digital system, that is, multiple processors, memory and I/O controllers, into a single chip.

By extension, a processor is a reduction of a microprocessor in the sense that it contains at least one control unit, a calculation unit and registers. Today we also talk of core. The latter term appeared with the integration on the same chip of several cores in

4 The asynchronous version is envisaged for reasons of power consumption and signal propagation time, but it remains marginal industrially.

2001 (multicore approach) with, today (2018), a dozen cores integrated on industrial chips. This trend was a response to the powerwall (*cf.* § V1-1.5), which materializes the physical limit.

1.2. History

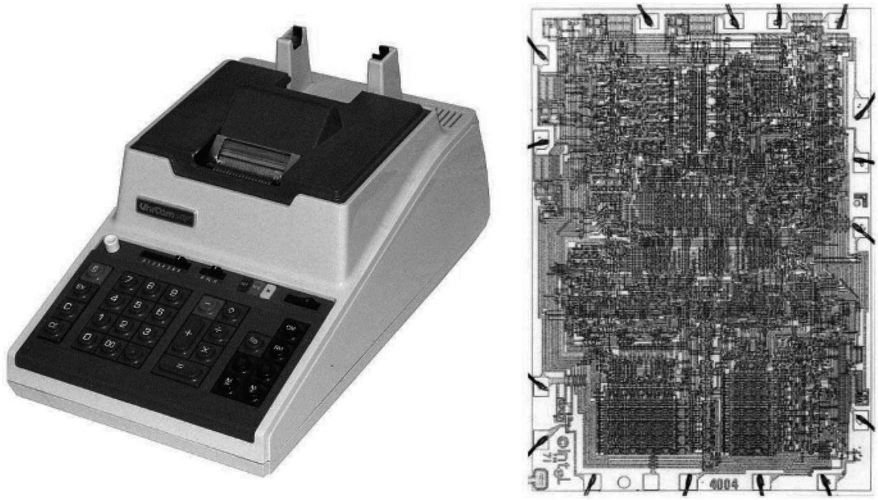
The microprocessor was created in California in Silicon Valley. It was originally designed to meet the needs of a Japanese manufacturer of desktop calculators, the Nippon Calculating Machine Corporation. Intel[5] announced it commercially in an advertisement in the November 15, 1971, issue of Electronic News. In fact, this component was part of a family of four integrated circuits called MCS-4 (Intel 1973), MCS for Micro Computer Set. It consisted of the ROM with I/O port of 2 Kib, the RAM with output port of 320 bits, the SIPO register (Serial-In Parallel-Out) of 10 bits and the CPU referenced respectively 4001, 4002, 4003 and 4004. Originally, this company required the design of 12 integrated circuits for the Busicom 141-P calculating machine (Figure 1.1(a)). Marcian[6] E. Hoff, Jr., engineer in charge of the project at Intel, had the idea of integrating a programmable logic system. Subsequently, the rights were transferred to the company Intel for $60,000 at the time. The MPU included 2,300 transistors (Figure 1.1(b)), and it had a 4-bit architecture with single internal bus (*cf.* § V1-3.4.1). Ironically, the idea of the microprocessor was patented by the company Texas Instruments (Boone 1973). Additional historical information can be found in Noyce and Hoff (1981), Mazor (1995) and Halfhill (2006).

Before the microprocessor, there were several offers for the integration of logical subsets. Let us cite, in 1967, the company Fairchild which introduced a calculation unit in 8-bit format with an accumulator under the reference AL1. In 1969, the company Four Phased founded by Lee Boysel introduced a terminal using this component, perhaps the first bit-slice microprocessor (*cf.* § 5.1). In 1971, the offer revolved around families of components allowing realizing the function of MPU in discrete components. Let us take as an example of the MAPS family (Microprogrammable Arithmetic Processor System) from the company National Semiconductor (NS), which was a family of five components composed among others of an Arithmetic and Logic Unit (ALU) (MM5700), a register unit (MM5701), a control unit with a clock circuit (MM5702) and a control ROM (MM5705). In

5 The company Intel was founded on July 18, 1968, by Robert Noyce, Andy Grove and Gordon Moore, ex-employees of the company Fairchild, the latter not believing in the concept or unwilling to get started. Intel also designed the first RAM (Random Access Memory; *cf.* Chapter 4 of Darche (2012)) and the first EPROM (Erasable Programmable Read-Only Memory; this will be covered in a future book by the author on memories).

6 Nicknamed Ted.

addition, industrialists working for the American military worked on this type of family long before. Let us cite the D200 from Autonetics/North American Aviation (Booher 1968; Shirriff 2016).



a) **b)**

Figure 1.1. *(a) The Busicom 141-P calculator and (b) photomicrograph of the 4004 (respective sources: Wikipedia.org and the Intel company). For a color version of this figure, see www.iste.co.uk/darche/microprocessor3.zip*

The next generation was the 8008, a component originally designed for the Datapoint 2200 terminal from Computer Terminal Corporation. The latter did not use it for performance reasons. It should be noted that the first MPU was the TMX 1795 (X for eXperimental) from the company TI, prototyped but never sold. The reference patent is Boone (1973). It was designed to replace the CPU of the Datapoint 2200 terminal. In 1972, the 8008 was used by the French company R2E to manufacture the first[7] microcomputer (MICRAL N released in 1973). This circuit manufactured in PMOS technology like its predecessor included 3,500 transistors. Its 8-bit architecture was single internal bus. The calculations despite its format were performed in n = 1 bit

7 Americans consider that the first microcomputer is American. It is the Altair 8800 from the American manufacturer MITS (Micro Instrumentation and Telemetry Systems), sold as a kit in 1975 (*cf.* § V1-1.2).

format. It was later followed by PPS-4 from Rockwell, PPS-25 from Fairchild, IMP-16[8] from NS and 5065 from Mostek.

To increase the speed of calculation, one approach has been to increase the format n of calculation. We also speak of bit-level parallelism. Thus, microprocessors can be classified into five generations by taking as a criterion the format of the integers that it handles. The first generation was that of 4 bits, then that of 8 bits, 16 bits and 8 bits improved, 32 bits and the fifth 64 bits. From the 16-bit generation, the components were called (at the time) “super microprocessor” (Vajda 1986) because they become able to execute programs written in High-Level programming Languages (HLL) and to support a multitasking Operating System (OS). Suzuoki *et al*. (1999) proposed a 128-bit version.

Table 1.1 presents two key characteristics of microprocessor development. The microprocessor now processes integers in 64-bit format when their format was originally 4 bits. The number of integrated transistors has increased from a few thousand to 10 billion. It thus doubled approximately every 18 months according to Moore’s “law” allowing the integration of new functional units. Knowing that the acronyms CISC (Complex Instruction Set Computer) and RISC (Reduced Instruction Set Computer; this will be covered in a future book by the author on microprocessors) refer to models of ISA (Instruction Set Architecture, *cf.* § V1-3.5), it should be noted the downward difference in the number of transistors of this second architecture for a higher computing power. The economic aspect of the development of integrated circuits can be found in Moore (2003). In particular, it was found that the price of the transistor went from \$1 in 1968 to $\$10^{-6}$ in 1998, a slope of about 37%/year.

Year of marketing	**Company**	**Reference**	**Type**	**Format n bits of integer processing**	**Number of transistors**
1971	Intel	4004	CISC	4	2,300 (2,238)
1972	Intel	8008	CISC	8	3,500
1974	Intel	4040	CISC	4	3,000
1974	Intel	8080	CISC	8	4,500
1974	Motorola	MC6800	CISC	8	4,100
1975	MOS Technology	MCS6502	CISC	8	4,528
1976	RCA	CDP1802	CISC	8	5,000

8 IMP for Integrated MicroProcessor, bit-slice version (*cf.* § 5.1).

1976	Intel	8085	CISC	8	6,500
1976	Zilog	Z80	CISC	8	8,500
1977	Motorola	MC6802	CISC	8	11,000
1978 (12/77)	Motorola	MC6809	CISC	8	9,000
1978	Intel	8086	CISC	16	29,000
1979	Intel	8088	CISC	16	29,000
1979	Zilog	Z8001	CISC	16	17,500
1979	Motorola	MC68000	CISC	16	68,000
1981	Intel	iAPX 432	CISC	32	97,000
1982	UC Berkeley	RISC I	RISC	32	44,420
1982	Intel	80186	CISC	16	55,000
1982	Intel	80286	CISC	16	134,000
1983	UC Berkeley	RISC II	RISC	32	40,760
1983	Stanford University	MIPS	RISC	32	24,000
1983	Zilog	Z80 000	CISC	32	91,000
1984	NS	NS32032	CISC	32	70,000
1984	Motorola	MC68020	CISC	32	190,000
1985	Intel	80386DX	CISC	32	275,000
1985	MIPS	R2000	RISC	32	110,000
1986	Fairchild Semiconductor	Clipper	RISC	32	300,000
1986	ARM	ARM1	RISC	32	24,800
1987	Motorola	MC68030	CISC	32	273,000
1987	ARM	ARM2	RISC	32	30,000
1988	MIPS	R3000	RISC	32	115,000
1988	Motorola	88100	RISC	32	165,000
1989	Intel	80486DX	CISC	32	1,180,235
1989	Intel	i860	RISC	32/64 (FPU)	$> 1 \times 10^6$

1991	Motorola	MC68040	CISC	32	1,200,000
1991	MIPS	R4000	RISC	64	1,350,000
1992	DEC	Alpha 21064	RISC	64	1,680,000
1993	Intel	Pentium	CISC	32	3,100,000
1993	HP	PA7100	RISC	32	850,000
1994	Motorola	MC68060	CISC	32	2,500,000
1995	Sun	UltraSPARC	RISC	64	5,200,000
1995	Intel	Pentium Pro	CISC	32	5,500,000
1996	AMD	K5	CISC	32	4,300,000
1997	Intel	Pentium II	CISC	32	7,500,000
1997	AMD	K6	CISC	32	8,800,000
1997	IBM-Motorola	PowerPC 750	RISC	32	6,350,000
1997	Sun	UltraSPARC II	RISC	64	5,400,000
1999	Intel	Pentium III	CISC	32	9,500,000
1999	AMD	Athlon	CISC	32	22×10^6
2000	Intel	Pentium 4 (Willamette)	CISC	32	42×10^6
2001	Sun	UltraSPARC III	RISC	64	29×10^6
2001	Intel	Itanium	EPIC[9]	64	25×10^6
2002	Intel	Itanium 2	EPIC	64	220×10^6
2002	Intel	Pentium 4 (Northwood)	CISC	32	55×10^6
2004	Intel	Pentium 4 (Prescott)	CISC	32	55×10^6
2005	Sun	UltraSPARC T1	RISC	64	279×10^6
2006	Intel	Core Duo	CISC	32	151×10^6
2006	Intel	Core 2 Duo	CISC	64	241×10^6

9 For Explicitly Parallel Instruction Computing (*cf.* § 4.7).

2006	Sony/IBM/Toshiba	Cell	RISC	64	234×10^6
2007	IBM	POWER6	RISC	64	790×10^6
2007	Sun	UltraSPARC T2	RISC	64	503×10^6
2008	Intel	Core i7 (4 cores)	CISC	64	731×10^6
2010	Sun/Oracle	SPARC T3 (16 cores)	RISC	64	1×10^9
2010	Intel	Core i7 (6 cores)	CISC	64	$1{,}17 \times 10^9$
2014	IBM	POWER8	RISC	64	$4{,}2 \times 10^9$
2015	Sun/Oracle	SPARC M7 (32 cores)	RISC	64	10×10^9

Table 1.1. *Number of transistors of the first microprocessors (Boland and Dollas (1994) completed)*

Another classification criterion was the complexity of the architecture. Thus, Tredennick (1996) offered the first generation, which was that of the first microprocessors with an operation according to the principles of von Neumann. The second generation introduced the pipeline (this will be covered in a future book by the author on microprocessors), the idea being to increase the bus occupancy rate by a functional division of the microprocessor. The 8088/8086 microprocessor had two functional units, the Execution Unit (EU) and the Bus Interface Unit (BIU). The third generation, in 1984, is that of the second-generation pipeline with the MC68020 (three-stage pipeline depth), which was the first MPU to introduce a cache. The fourth generation introduces the superscalar architecture of the 1990s. The fifth generation is that of current multicore chips with more than a billion transistors.

Since 1971, the year of its commercial announcement, the functionalities and the computing power (*cf.* § V4-3.4) of the microprocessor have not stopped increasing thanks to the progress of micro-electronic technologies. Its clock frequency went from 740 kHz (1971) to more than 3 GHz (2003) for a core, a factor of over 4,000 in 30 years (Table 1.2). Note that this parameter is an indicator of computing power (*cf.* § V4-3.4), but other parameters must be taken into account such as the number of cycles necessary to execute an instruction (*cf.* § 2.4.1) or the type of architecture (*cf.* § V1-3.1.4).

Year of sale	Company	Reference	Reference Internal clock frequency f (MHz) of the first version	Cycle time (ns) (= f^{-1})
1971	Intel	4004	740 kHz	1.35 µs
1972	Intel	8008	500 kHz	1.25 or 2 µs
1974	Intel	4040	740 kHz	1.35 µs
1974	Intel	8080	2	500
1974	Motorola	MC6800	1	1 µs
1975	MOS Technology	MCS6502	1	1 µs
1976	RCA	CDP1802	2.5 @ 5 V	400
1976	Intel	8085	3.125	320
1976	Zilog	Z80	2.5	400
1977	Motorola	MC6802	1	1 µs
1978 (12/77)	Motorola	MC6809	1	1 µs
1978	Intel	8086	5	200
1979	Intel	8088	5	200
1979	Zilog	Z8001	4	250
1979	Motorola	MC68000	8	125
1981	Intel	iAPX 432	5	200
1982	UC Berkeley	RISC I	1	1 µs
1982	Intel	80186	6	166
1982	Intel	80286	10	100
1983	UC Berkeley	RISC II	3	233
1983	Stanford University	MIPS	2	500
1983	Zilog	Z80 000	5	200
1984	NS	NS32032	10	100
1984	Motorola	MC68020	16	62.5
1985	Intel	80386DX	16	62.5
1985	MIPS	R2000	8	125
1986	Fairchild Semiconductor	Clipper	33	30
1986	ARM	ARM1	62	16.1
1987	Motorola	MC68030	20	50

1987	ARM	ARM2	8	125
1988	MIPS	R3000	12	83.3
1988	Motorola	88100	25	40
1989	Intel	80486DX	25	40
1989	Intel	i860	33	30
1991	Motorola	MC68040	25	40
1991	MIPS	R4000	100	10
1992	DEC	Alpha 21064	150	6.66
1993	Intel	Pentium	66	15
1993	HP	PA7100	100	10
1994	Motorola	MC68060	50	20
1995	Sun	UltraSPARC	143	6.99
1995	Intel	Pentium Pro	150	6.66
1996	AMD	K5	75	13.3
1997	Intel	Pentium II	233	4.29
1997	AMD	K6	166	6.02
1997	IBM-Motorola	PowerPC 750	233	4.29
1997	Sun	UltraSPARC II	200	5
1999	Intel	Pentium III	450	2.22
1999	AMD	Athlon	500	2
2000	Intel	Pentium 4 (Willamette)	1,300	0.77
2001	Sun	UltraSPARC III	600	1.66
2001	Intel	Itanium	733	1.36
2002	Intel	Itanium 2	1,000	1
2002	Intel	Pentium 4 (Northwood)	1,300	0.77
2004	Intel	Pentium 4 (Prescott)	3,400	0.29
2005	Sun	UltraSPARC T1	1,200	0.833
2006	Intel	Core Duo	1,100	0.90
2006	Intel	Core 2 Duo	1,860	0.54
2006	Sony/IBM/Toshiba	Cell	3,200	0.313

2007	IBM	POWER6	3,600	0.28
2007	Sun	UltraSPARC T2	1,400	0.71
2008	Intel	Core i7 (4 cores)	2,660	0.38
2010	Sun/Oracle	SPARC T3 (16 cores)	1,600	0.625
2010	Intel	Core i7 (6 cores)	3,200	0.31
2014	IBM	POWER8	3,000	0.33
2015	Sun/Oracle	SPARC M7 (32 cores)	4,130	0.242

Table 1.2. *Frequency of first microprocessors (Boland and Dollas (1994) completed)*

The dotted line in Figure 1.2 indicates the break introduced by the introduction of multicore in order to stop the increase in the operating frequency. By refining, Hennessy and Patterson (2011) calculated three growth rates, 15%/year (1978–1986), then 40% (1986–2003) and, finally, less than 1%/year (2003–2010). The last level does not mean a stagnation in performance, but it corresponds to the transition to multicore architecture, the frequency of a core no longer increasing among other things for reasons of energy dissipation (*cf.* § 6.1.2). In addition, computing power (unit of measurement: MIPS for Million Instructions Per Second; *cf.* § V4-3.4.2) increases by about 40% per year. The red brick wall symbolizes the physical limit to integration and, perhaps, that of computing power.

As illustrated in Figure V1-1.15, microelectronic technology for manufacturing integrated circuits has evolved over time. Initially of the bipolar type, it slowly evolved towards unipolar technologies, MOS then, today, CMOS. The first microprocessors were manufactured in unipolar PMOS technologies and NMOS (negative (channel) MOS) for reasons of switching speed and number of supply voltages. The tables in Chapter 4 indicate the technologies of these first components. In addition, these technological advances will have an impact on the value of the supply voltage (Figure 6.1) and on current consumption. Bipolar technology was only reserved for areas where speed of calculation was essential, such as the military with its real-time and signal processing applications. Let us cite as examples of this component the SBP9989 (Lucas and Sobering 1983) and the F9450, manufactured in the following technologies respectively I^2L (Integrated Injection Logic; *cf.* § 2.3.2 of Darche (2004)) and I^3L (Isoplanar I^2L (Hennig *et al.* (1977)), which were 16-bit models from TI and NS respectively. The bit-slice processors (*cf.* § 5.1) were also mainly manufactured in bipolar technology for the same reason.

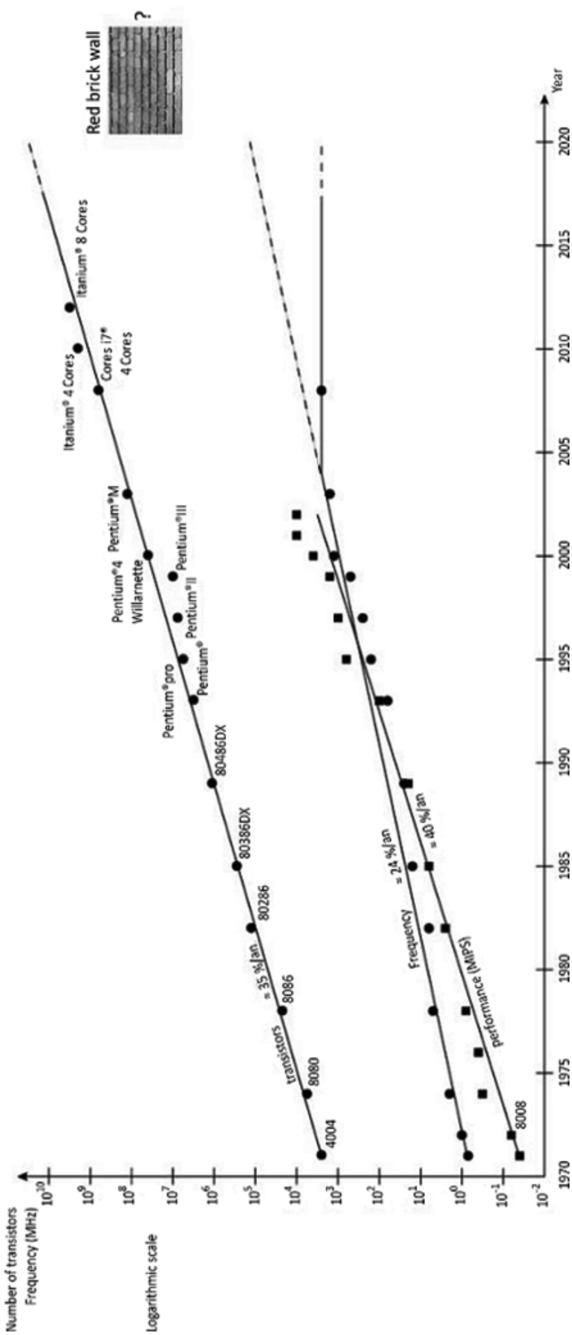


Figure 1.2. *Evolution over time of the internal clock frequency and the number of transistors for the Intel range. For a color version of this figure, see www.iste.co.uk/darche/microprocessor3.zip*

Figure 1.3 shows the classification of the first microprocessors on the market. The dotted line indicates a break in characteristics (set of instructions not compatible; *cf.* § V4-3.3.2). A microprocessor can belong to a family, for example, x86, MIPS or SPARC. This notion was introduced by Stevens (1964) who defined it as a set of processor implementations, each of which, capable of executing programs written for others. As for the classes of Bell (2008a, 2008b) (*cf.* § V1-1.2), these processors belong in the same price and performance category. The interest for the user lies in the fact that he can migrate to a more efficient machine of the family while keeping compatibility. For a microprocessor, this means that it shares a set of characteristics such as a base instruction set (i.e. basic) allowing, for example, a backward compatibility (*cf.* § V4-3.3.3) of the programs. A generation manipulates the same data format. The 8-bit generation (*cf.* § 4.3) can be broken down into three phases, the first with the 8008, the second with the 8080 and the MC6800 and the MCS6502 and the third with the 8085, the MC6802 and the Z80. The representatives of the 16-bit generation microprocessors (*cf.* § 4.5) were the MC68000 from Motorola, the Z8001 from Zilog and, of course, the 8086[10] from Intel. They are compared in Heering (1980). What characterizes the 16-bit generation is the introduction of advanced memory management (i.e. virtual memory; this will be covered in a future book by the author on microprocessors), a set of instructions and advanced addressing modes and parallelism (Whitworth 1980). To this list, we must add the introduction of several execution modes, mainly user and supervisor modes (*cf.* § V4-3.2.2). Virtual memory with its segmentation and paging mechanisms introduces a logical address space (*cf.* § 2.1.1.1) for the more important programmer, protecting memory and relocating code and data. The 1980s saw the emergence of multiprocessor systems. This generation undoubtedly marks the decline of Assembly Language (AL) in favor of High-Level programming Languages (HLL). The 32-bit generation (*cf.* § 4.6) appeared with the MC68020 from Motorola in 1984. The 64-bit generation (*cf.* § 4.7) appeared in 1991 with the R4000, which had a RISC architecture (this will be covered in a future book by the author on microprocessors). IEEE (1996) presents testimonies of the stakeholders of this history. Its new integrated features allow the operating system architecture to evolve and speed up its operation.

In the beginning, the designer and manufacturer of a microprocessor were identical with, possibly, one or more second sources that manufactured the component under license. Take as an example the circuit referenced MC6809 whose designer and manufacturer was Motorola. There were also second sources such as the French EFCIS (company which later became SGS-Thomson Microelectronics, then STMicroelectronics), AMI (American Microsystems, Inc.), Fairchild and Hitachi. Today, they can be separate, as is the case for the Arm® processor (Advanced RISC Machines) that the company of the same name, without factory (fabless), licenses to manufacturers in the form of Intellectual Property (IP) that is, a reusable and

10 It should be noted that the object code of 8085 was not compatible with that of 8088/86.

configurable basic brick. We must thus distinguish three trades, which consist of designing the IP block in itself that which consists of designing a SoC based on IP blocks and that which is in charge of manufacturing (the founder). Thus, companies only design components (MIPS as another example), others manufacture the component like any other integrated circuit and, finally, companies design and manufacture (designers and founders like Intel, for example). There may also be components from competing companies compatible in terms of hardware and/or software (*cf.* § V4-3.3), Table 1.3 showing an example with the x86 family. Competitors in this family at the time included the companies Cyrix, AMD and Nec. As a complement, Hennessy (1984) details the architecture of the VLSI (Very LSI) microprocessors.

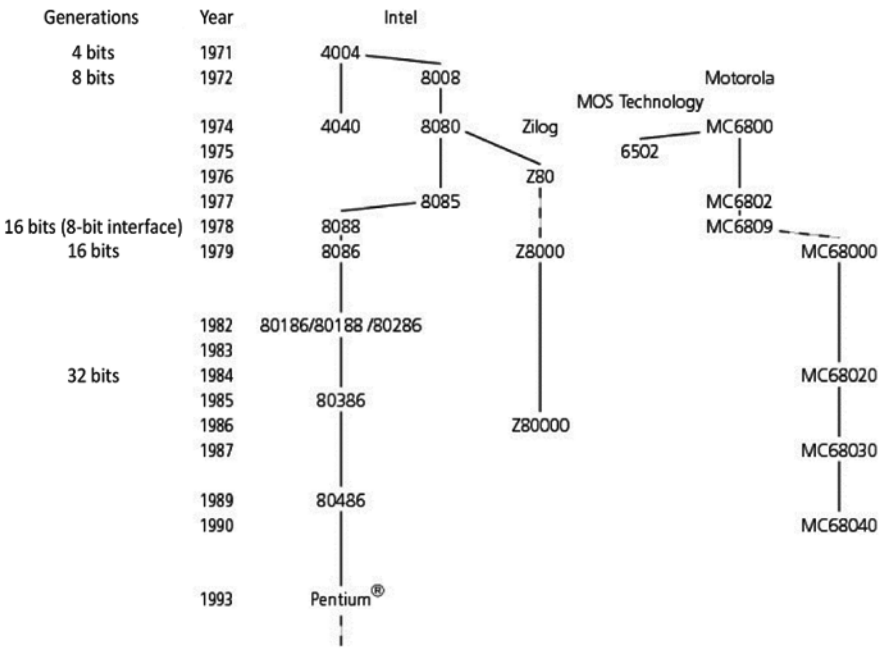


Figure 1.3. *Examples of classification of the first main families of microprocessors (RISC families excluded)*

Alternative source type	Development required	AMD x86 CPU generation
Second source license	Manufacturing only	8086 and 80286
Unlicensed CPU clone	Reverse engineering	386 and 486
CPU-compatible at pin level	Original CPU design (parallel engineering)	K5 (with *chipset* Pentium)
Software-compatible CPU	Original CPU and chipset designs	K6 and K7
Upward-compatible CPU	Original 64-bit CPU and chipset designs	K8

Table 1.3. *Hardware and software compatibilities for the x86 family (Halfhill 2009)*

1.3. Conclusion

This chapter presented a brief history of the development of microprocessors by specifying, in particular the different generations of components.