

To study the IBM PC, it is easiest to first break it down to small parts. Five sub-systems form a pipeline: Inputs, CPU, RAM, Video, and Audio.

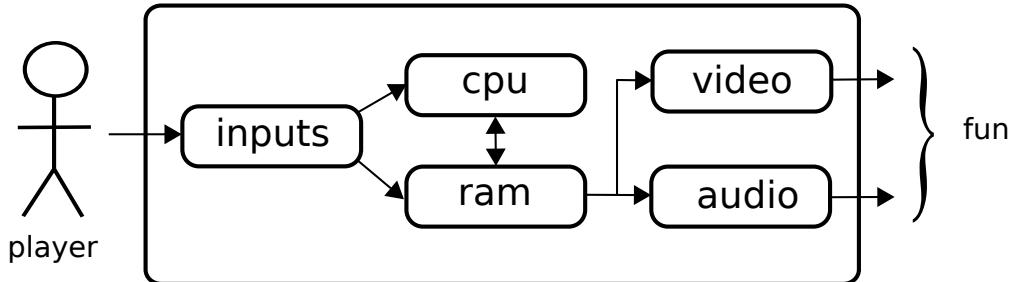


Figure 1: Hardware pipeline.

A lot of friction was present since manufacturers had not embraced the gaming industry yet. Parts quality varied from bad, terrible, to downright impossible to deal with.

Stage	Quality
RAM	Bearable
Video	Impossible
Audio	Very Poor
Inputs	Ok
CPU	Very Poor

Figure 2: Component quality for a game engine.

0.1 CPU: Central Processing Unit

In 1989 around 15% of the households owned a computer¹. The performance of these machines was so overwhelmingly determined by the CPU that a PC was referred to not by its brand or GPU², but by the main chip inside. If a PC had an Intel 8088 or equivalent, it was called a "XT". If it had an Intel 80286, it was a "286" or "AT".

¹<https://www.statista.com/statistics/184685/percentage-of-households-with-computer-in-the-united-states-since-1984/>

²There was no GPU yet. The term was coined by Nvidia in 1999, who marketed the GeForce 256 as "the world's first GPU", or Graphics Processing Unit.

0.1.1 Overview

Intel released the 8086 in 1979, which was the first microchip of the successful x86 family line. One year later, in 1979, it released the 8088 which was a variant of the 8086. The main difference between the two is that there are only eight data lines for the external data bus in the 8088 instead of the 8086's 16 lines. However, because it retained the full 16-bit internal registers and the 20-bit address bus, the 8088 ran 16-bit software and was capable of addressing a full 1MB of RAM. IBM chose the 8088 over the 8086 for its original PC/XT, because Intel offered a better price for the former and could supply more units.

In 1982 Intel released the 80286 microchip. A typical 8088 chip was running at 4.77MHz, while the 80286 was running at 8MHz and later versions at 12.5-16MHz. The 80286 was employed for the IBM PC/AT, introduced in 1984, and then widely used in most PC/AT compatible computers until the early 1990s. Commander Keen could run on a 8088, but an Intel 286 was recommended.

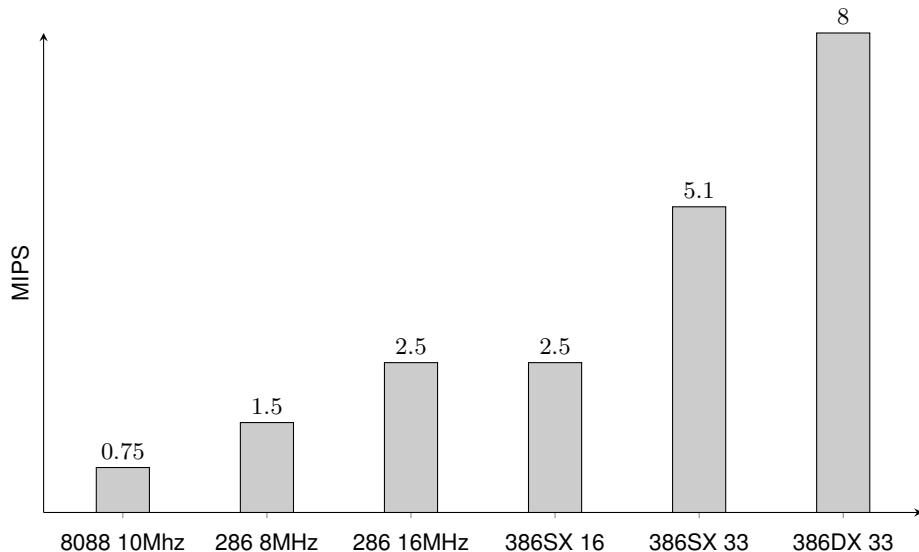


Figure 3: Comparison³ of CPUs with MIPS

Trivia : A modern processor such as the Intel Core i7 3.33 GHz operates at close to 180,000 MIPS.

³Roy Longbottom's PC Benchmark Collection: <http://www.roylongbottom.org.uk/mips.htm#anchorIntel2>.

0.1.2 The Intel 80286

The Intel 80286 chip, first introduced in 1982, is the CPU behind the original IBM PC AT (Advanced Technology). Other computer makers manufactured what came to be known as IBM clones, with many of these manufacturers calling their systems AT-compatible or AT-class computers.

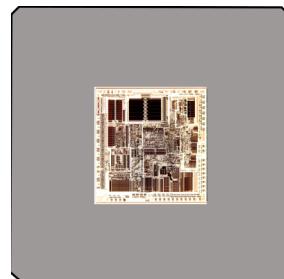
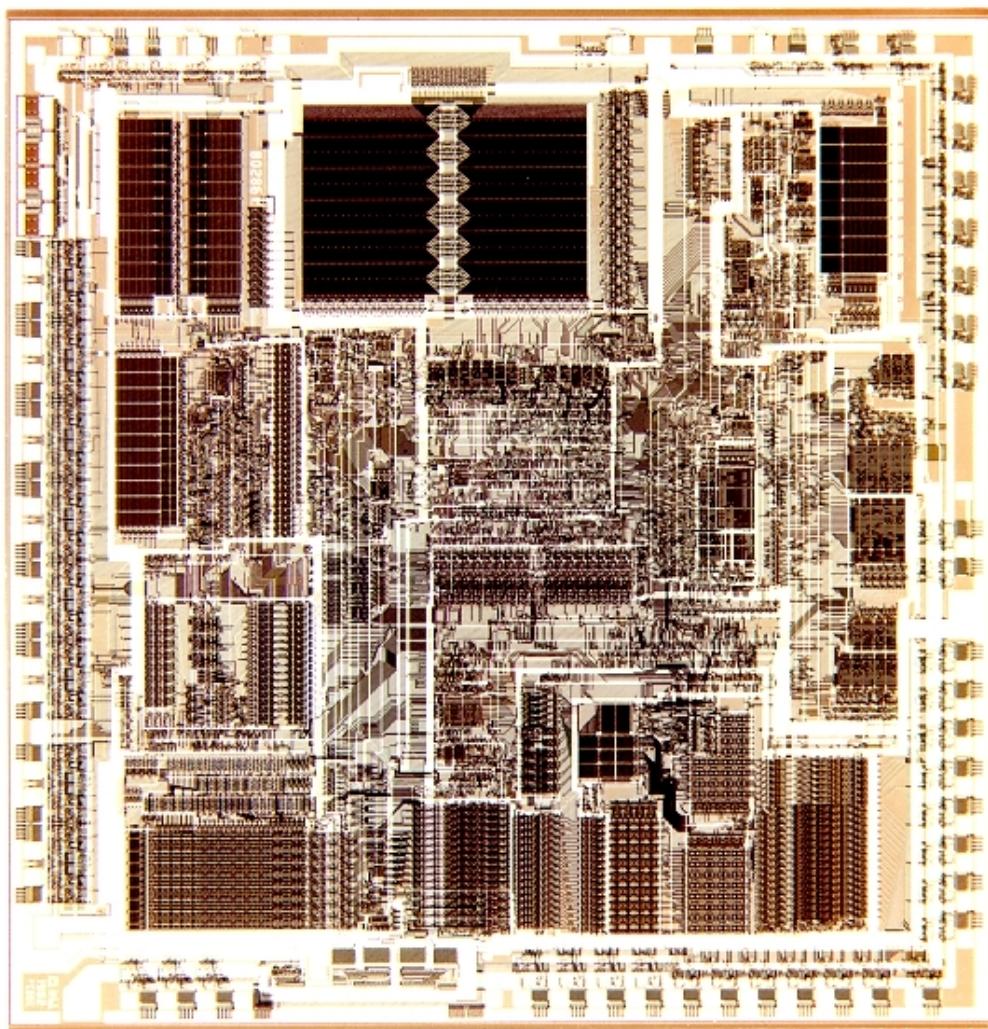


When IBM developed the AT, it selected the 286 as the basis for the new system because the chip provided compatibility with the 8088 used in the PC and the XT. Therefore, software written for those chips should run on the 286. The 286 chip is many times faster than the 8088 used in the XT, and at the time it offered a major performance boost to PCs used in businesses. The processing speed, or throughput, of the original AT (which ran at 6MHz) is five times greater than that of the PC running at 4.77MHz. 286 systems are faster than their predecessors for several reasons. The main reason is that 286 processors are much more efficient in executing instructions. An average instruction takes 12 clock cycles on the 8086 or 8088, but takes an average of only 4.5 cycles on the 286 processor. Additionally, the 286 chip can handle up to 16 bits of data at a time through an external data bus twice the size of the 8088.

The 286 chip has two modes of operation: real mode and protected mode. The two modes are distinct enough to make the 286 resemble two chips in one. In real mode, a 286 acts essentially the same as an 8086 chip and is fully compatible with the 8086 and 8088. In the protected mode of operation, the 286 was truly something new. In this mode, a program designed to take advantage of the chip's capabilities believes that it has access to 1GB of memory (including virtual memory). The 286 chip, however, can address only 16MB of hardware memory. A significant failing of the 286 chip is that it cannot switch from protected mode to real mode without a hardware reset (a warm reboot) of the system. (It can, however, switch from real mode to protected mode without a reset.)

While the 8088 used a $3.0\mu\text{m}$ process, the 20286 used a $1.5\mu\text{m}$ process. The smaller process and increased surface (from 33mm^2 to 49mm^2) allowed Intel to pack 134,000 on a 286 chip versus 29,000 on a 8088 chip.

0.1. CPU: CENTRAL PROCESSING UNIT



Despite the apparent complexity, the 80286 can be summarized by functional units and a three-stage instruction pipeline.

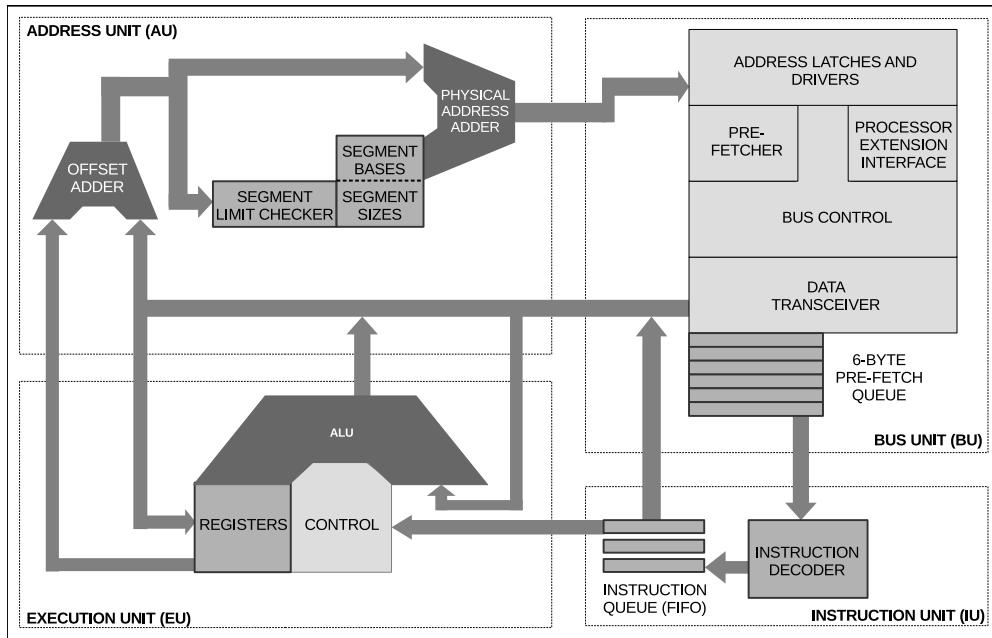


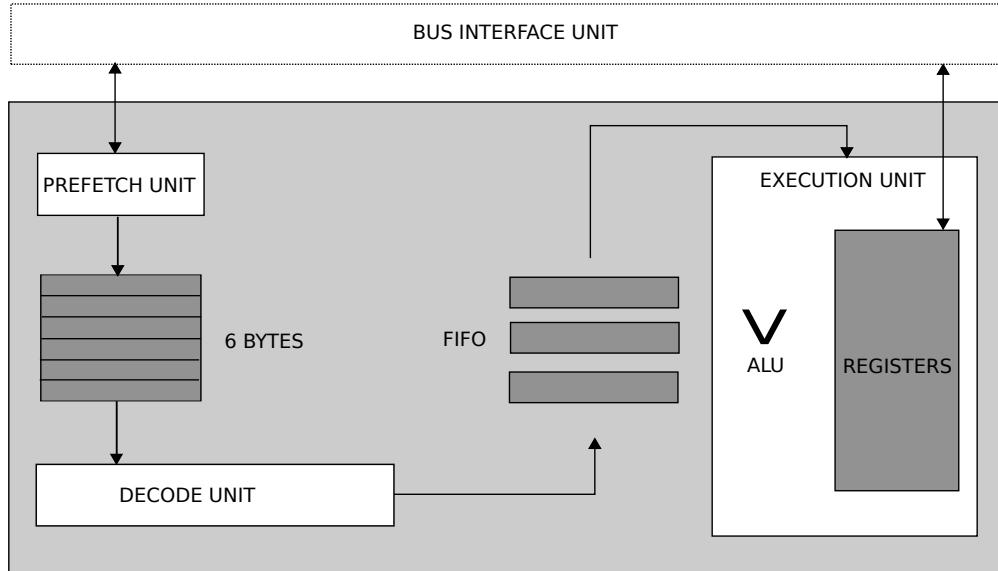
Figure 4: Internal block diagram of the 80286 processor

The four functional units can be described by

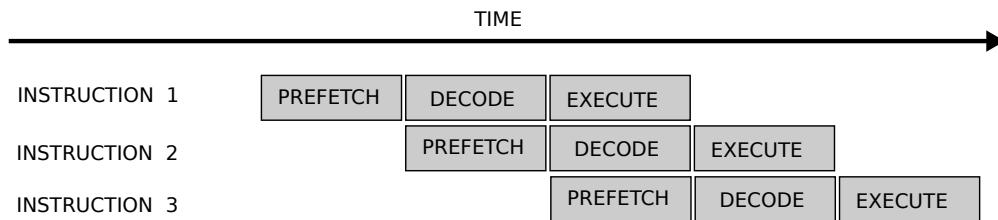
- **address unit (AU)** is used to determine the physical addresses of instructions and operands which are stored in memory. The address lines derived by AU can be used to address different peripheral devices such as memory and I/O devices.
- **bus unit (BU)** interfaces the 80286 with memory and I/O devices. The bus unit is used to fetch instruction bytes from the memory and stores them in the prefetch queue.
- **instruction unit (UI)** receives instructions from the prefetch queue and an instruction decoder decodes them one by one. The decoded instructions are latched onto a decoded instruction queue.
- **execution unit (EU)** is responsible for executing the instructions received from the decoded instruction queue. The execution unit consists of the register bank, arith-

0.1. CPU: CENTRAL PROCESSING UNIT

metic and logic unit (ALU) and control block. The ALU is the core of the EU and perform all the arithmetic and logical operations.



The three units in the execution group form a three stage pipeline: Prefetch, Decode, and Execute. The Prefetch Unit wakes up when the Execution unit is performing but not using the bus and fetches instructions in a 6-byte queue. The prefetcher is linear and cannot predict the result of a branch. As a result, a jump (JMP) instruction triggers a flush of the entire pipeline. Instructions go down the pipeline and are decoded by the Decode Unit: the result of the decode operation is stored in a three-element FIFO where it is picked up by the Execution Unit.



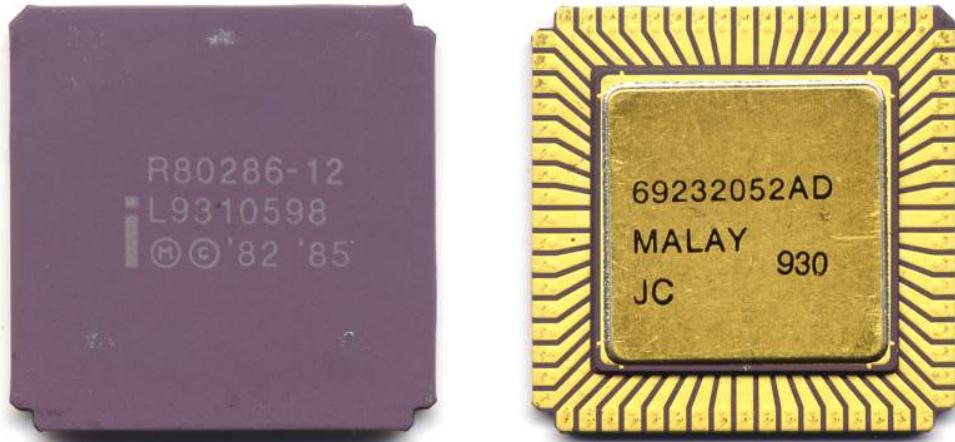


Figure 5: The Intel 286, 10mm by 10mm packing 134,000 transistors

From a programming perspective, a 286 CPU can be summarized by the following elements:

- Arithmetic Logic Unit performing add, sub, mul et cetera.
- 14 registers:
 - 16-bit General Purpose Registers: AX, BX, CX, DX
 - 16-bit Index Registers: SI, DI, BP, SP
 - 16-bit Segment Registers: CS, DS, ES, SS
 - 16-bit Status and Control Register
 - 16-bit Program Counter: IP
- A 24-bit address bus for up to 16MB of flat addressable RAM
- Memory Management Unit

Despite its pipeline design, the 286 cannot do an operation in less than two cycles. Even a simple ADD reg, reg or INC reg takes two clocks. This is due to the absence of a SRAM on-chip cache and a slow decoding unit. Also have a look at multiplications which cost 24 cycles. So as a game developer you really want to avoid many multiplications during game runtime.

Instruction type	Clocks
ADD reg8, reg8	2
INC reg8	2
IMUL reg16, reg16	24
IDIV reg16, reg16	28
MOV [reg16], reg16	5
OUT [reg16], reg16	3
IN [reg16], reg16	5

Figure 6: 286 instruction costs⁴

0.2 RAM

The first CPUs in the Intel x86 family were designed in 1976. At a time when RAM was very expensive, the 8086 and 8088 had 16-bit registers with a 20-bit-wide address bus capable of addressing 1MiB⁵ of RAM. It is difficult to stress how big 1MiB of RAM was in the 70's but as an example the Apple II and the Commodore 64 both shipped with 64KiB⁶ which was enough to write and run amazing things. Sixteen-bit registers and a 20-bit address bus were plenty even though programming was difficult and required combining two registers to build a pointer.

By 1986, hardware had gotten cheaper and Intel made a departure from the old architecture with its 286. This new CPU could be put in what is called "protected mode" featuring a 24-bit-wide address bus for up to 16 MiB of flat RAM protectable with a MMU⁷. To make sure old programs could still run, the 286 processor could be put in "real mode" which replicates how the Intel 8086 and 8088 operated: 16-bit registers, 20-bit address bus giving 1MiB addressable RAM with segmented addressing.

For compatibility reasons all PCs have to start in real mode. You may assume that programmers of the late 80s promptly switched the CPU to protected mode to unleash the full potential of the machines and ditch the 20-year-old real mode. Unfortunately, there was a major obstacle: the operating system MS-DOS by Microsoft Corporation.

⁴Intel 80286 programmer's reference manual - 1987.

⁵This book uses IEC notation where MiB is 2^{20} and MB is 10^6 .

⁶This book uses IEC notation where KiB is 2^{10} and KB is 10^3 .

⁷Memory Management Unit

0.2.1 DOS Limitations

Microsoft Corporation highly valued the applications running on their operating systems. As a business priority, they were adamant to never break anything with a new system⁸. Since many applications were written during the 80s on machines having only real mode, DOS 4.01⁹ and even the later release DOS 5.0¹⁰ kept running that way and as a result its routines and system calls were incompatible with protected mode. This created an awkward situation where the de-facto operating system delivered with every machine sold prevented programmers from using the machine at its full potential. Developers were forced to ignore all the features of a 1984 CPU and instead use it like a very fast Intel 8086 CPU from 1976. They were thus limited to the following characteristics:

- ALU
- 14 registers:
 - 16-bit General Purpose Registers: AX, BX, CX, DX
 - 16-bit Index Registers: SI, DI, BP, SP
 - 16-bit Program Counter: IP
 - 16-bit Segment Registers: CS, DS, ES, SS
 - 16-bit Status Register
- Up to 1MiB of RAM

Trivia : Only a small amount of software that took advantage of the 286 chip was sold until Windows 3.0 offered standard mode for 286 compatibility; by that time, the hottest-selling chip was the 386. Still, the 286 was Intel's first attempt to produce a CPU chip that supported multitasking, in which multiple programs run at the same time.

0.2.2 The Infamous Real Mode: 1MiB RAM limit

With protected mode unavailable, 1990 developers programmed like it was 1976: with a 20-bit-wide address bus offering only 1MiB of addressable RAM. Regardless how much memory was installed on the machine, only 1MiB could be addressed. To top it all off, addressing had to be done by combining two 16-bit registers. One was the segment, the other an offset within that segment. Hence the name: '16-bit segmented programming'.

⁸"Tales of Application Compatibility", Old New Thing by Raymond Chen.

⁹Released in July 1989.

¹⁰Released in June 1991

0.2. RAM

The memory layout is as follows:

- From 00000h to 003FFh : the Interrupt Vector Table.
- From 00400h to 004FFh : BIOS data.
- From 00500h to 005FFh : command.com+io.sys.
- From 00600h to 9FFFFh : Usable by a program (about 620KiB in the best case).
- From A0000h to FFFFFh : UMA (Upper Memory Area): Reserved to BIOS ROM, video card and sound card mapped I/O.

Out of the original 1024KiB, only 640KiB (called Conventional Memory) was accessible to a program. 384KiB was reserved for the UMA and every single driver installed (.SYS and .COM) took away from the remaining 640KiB.

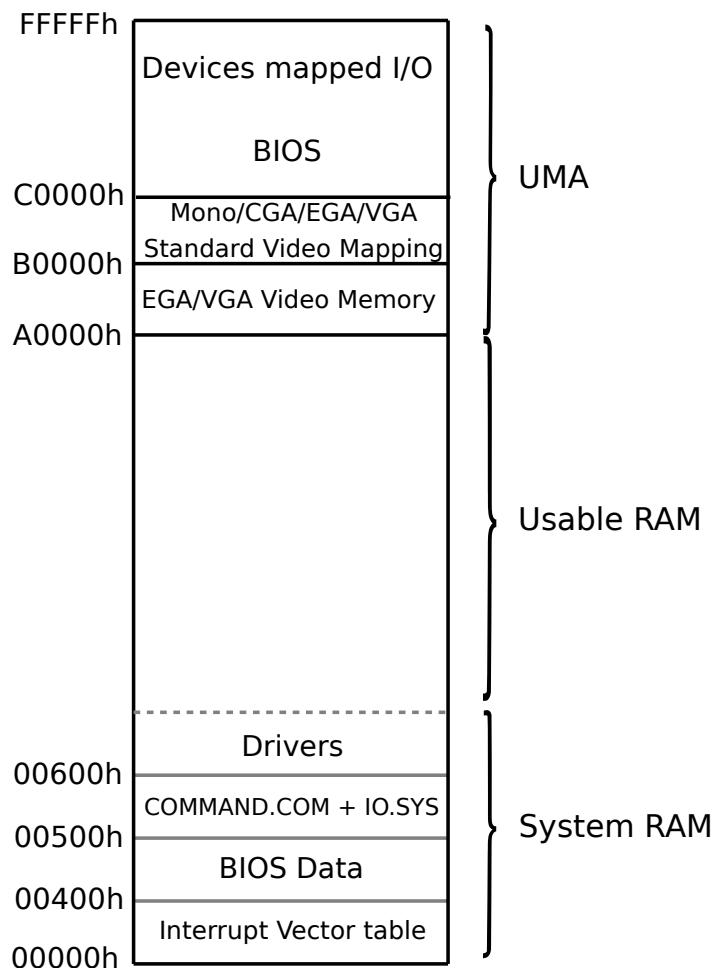


Figure 7: First 1MiB of RAM layout.

0.2.3 The Infamous Real Mode: 16-bit Segmented addressing

With a 20-bit address bus and registers too small to contain a whole address (16-bit wide), Intel had to come up with an addressing system. Their solution was to combine two 16-bit registers, one designating a segment and the other an offset within that segment.

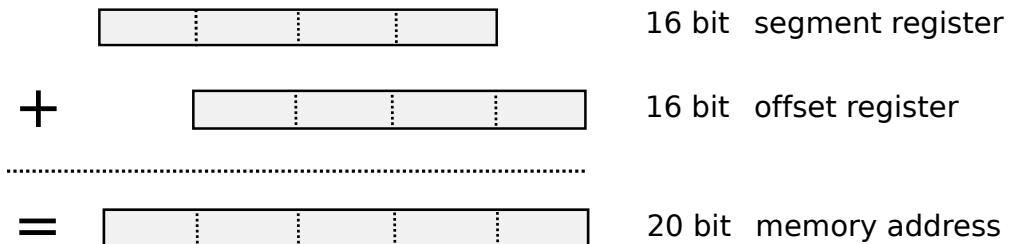


Figure 8: How registers are combined to address memory.

There are two kinds of pointers: `near` and `far`. A `near` pointer is 16 bits and considered *fast* because it can be used as is (but it only allows a `jmp` in the current code segment). A `far` pointer can access anything and allows a `jmp` anywhere but is slower since a 16-bit segment register has to be shifted left 4 bits and combined with the other 16-bit-offset register to form a 20-bit address.

That may not sound too bad, but in practice this segmented addressing leads to many issues. The least problematic is about the language. Since C was invented on a flat memory machine, it had to be augmented by PC compiler manufacturers. That is how the `near` and `far` keywords came into existence. Macro `MK_FP` built them and `FP_SEG/FP_OFF` accessed individual components. `libc` is also "different": `malloc` returns a `near` pointer and therefore can only allocate up to 64KiB. To get more than 64KiB, `farmalloc` is needed.

The larger issue is that two pointers referring to the same address can fail an equality test. In this model, the 1MiB of RAM is divided in 65536 paragraphs by the segment pointer. A paragraph is 16 bytes but an offset can be up to 65536 bytes which results in many overlaps. This can be explained with the following examples.

Pointer A defined as:

0000 0000 0000 0000	Segment	16 bits
+ 0000 0001 0010 0000	Offset	16 bits
<hr/>		
0000 0000 0001 0010 0000	Address	20 bits

Pointer B defined as:

0000 0000 0001 0000	Segment 16 bits
+ 0000 0000 0010 0000	Offset 16 bits
=====	
0000 0000 0001 0010 0000	Address 20 bits

Pointer C defined as:

0000 0000 0001 0010	Segment 16 bits
+ 0000 0000 0000 0000	Offset 16 bits
=====	
0000 0000 0001 0010 0000	Address 20 bits

As defined, A, B, and C all point to the same memory location however they will fail a comparison test.

```
#include <stdio.h>
#include <dos.h>

int main(int argc, char** argv){

    void far *a = MK_FP(0x0000, 0x0120);
    void far *b = MK_FP(0x0010, 0x0020);
    void far *c = MK_FP(0x0012, 0x0000);

    printf("%d\n", a==b);
    printf("%d\n", a==c);
    printf("%d\n", b==c);
}
```

Will output:

```
0
0
0
```

With this system, pointer arithmetic must also receive careful consideration. A **far** pointer increment only increments the offset, not the segment. If you iterate on an array larger than 64KiB you will end up wrapping around. You could use yet another type of pointer **int huge*** to make pointer arithmetic work beyond 64KiB but really, nobody wants to go there.

Trivia : As of 2017, more than thirty five years after the introduction of the 8086, in the name of backward compatibility, all PCs in the world still start in real mode. A bootloader

switches them to protected mode, loads the kernel, and then actual startup can begin.

0.3 Video

PCs were connected to CRT monitors: big, heavy, small diagonal, cathode ray-based, curved-surface screens. Most had a 14" diagonal with a 4:3 aspect ratio.

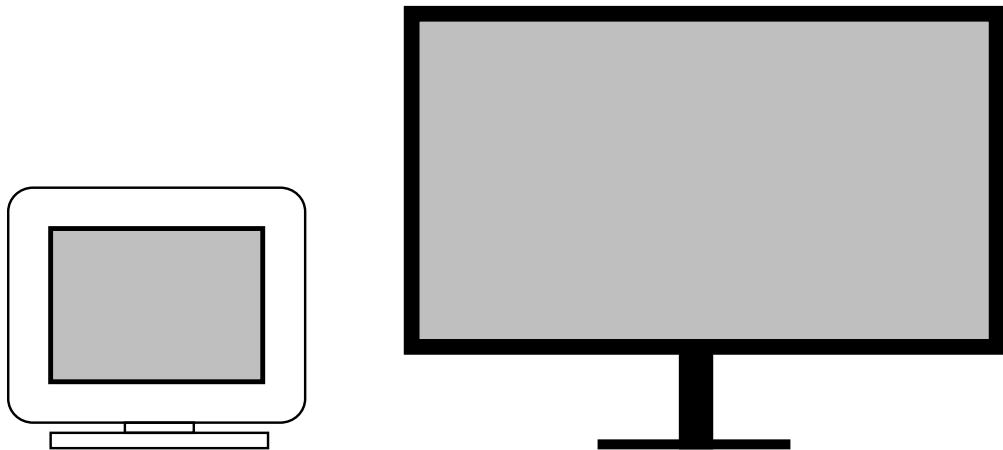


Figure 9: CRT (left) vs LCD (right)

To give you an idea of the size and resolution, figure 9 shows a comparison between a 14" CRT from 1990 (capable of a resolution of 640x200) and a 30" Apple Cinema Display from 2014 (capable of a resolution of 2560x1600).

Trivia : Despite their difference of capabilities, both monitors are the same weight: 27.5 pounds (12 kg).

0.3.1 CRT Monitor

All standard PC monitors use a raster-scan display to create the image. In a raster-scan display, the position of the electron beam is continually sweeping across the surface of the tube. The tube's surface is coated with phosphors that glow when struck by electrons (and for a short time thereafter), and, of course, the beam may be turned on in order to light a phosphor or off to leave it black.

The electron beam scans the phosphor-coated screen from left to right and top to bottom. The period during which the beams return to the left is known as the horizontal retrace. During most of the retrace, the guns must be turned off to prevent writing in the active display area (the area which contains the actual character and/or graphics data); this is known as horizontal blanking. The area immediately surrounding the display area, in which the beam may be turned on during the retrace interval, is called the overscan (or border). The active display area is the portion of the screen that contains characters and/or graphics. These components of the scan are shown in simplified form in Figure 10.

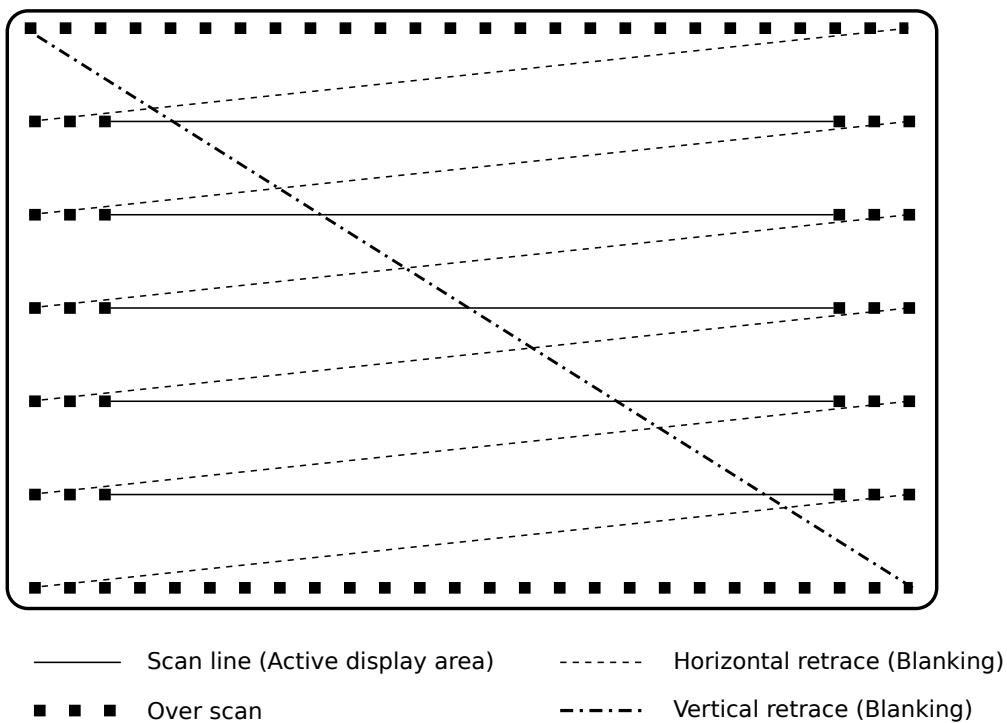


Figure 10: Simplified CRT monitor scan.

After a horizontal scan has been completed, the beam is moved to the next line during the horizontal retrace. This sequence continues until the last line, at which point the vertical retrace begins. The vertical retrace is similar to the horizontal retrace; the electron beam may be enabled through a small overscan area and then turned off (vertical blanking) as the beam returns to the top left corner of the screen. If the vertical refresh is too slow, the display will flicker. Most people can detect flicker when the refresh rate drops below 60 Hz, and thus most displays use vertical refresh frequencies of about 60Hz (EGA) to 70Hz (VGA).

0.3.2 History of Video Adapters

The Monochrome Display Adapter (MDA) was released in 1981 with the IBM PC 5150. It offered two colors, allowing 80 columns by 25 lines of text. While not great, it was standard on every PC. Many other systems followed over the years, each of them preserving backward compatibility.

Name	Year Released	Memory	Max Resolution
MDA (Monochrome Display Adapter)	1981	4KiB	80x25 ¹¹
Hercules	1982	64KiB	720x348
CGA (Color Graphics Adapter)	1981	16KiB	640x200
EGA (Enhanced Graphics Adapter)	1985	64KiB	640x350
VGA (Video Graphics Array)	1987	256KiB	640x480

Figure 11: Video interface history.

Each iteration added new features and by 1990 the predominant graphic system was EGA, although the VGA system was rapidly becoming the new standard. All video cards installed on PCs had to follow the standard set by IBM. The universality of that system was a double-edged sword. While developers had to program for only one graphic system, there was no escaping its shortcomings.

The EGA palette allows 16 colors to be used simultaneously, and it allows substitution of each of these colors with any one from a total of 64 colors, at a resolution of 640 x 350.

Below an ATI EGA Wonder 800 (8-bit ISA). The eight chips on the left of the card form the VRAM where the framebuffers are stored¹².

¹¹Text mode only.



¹²Each VRAM chip from this ATI EGA cards can store 32KiB, accounting for a total of 256KiB VRAM.

0.3.3 EGA Architecture

EGA can be summarized as three major systems made of input, storage, and output:

- The Graphic Controller and Sequence Controller controlling how EGA RAM is accessed (the CPU-VRAM interface)
- The framebuffer (the VRAM) made of four memory banks with a minimum of 16KiB (rather than one bank of 64KiB). Via memory expansion each memory bank could be upgraded to 32KiB or 64KiB (resulting in 128KiB or 256KiB total VRAM). The original model from IBM came with 16KiB per plane, but almost all other EGA cards were equipped with the full 64KiB per plane. For the remainder of this book we will discuss only 256KiB EGA operations.
- The CRT Controller and the Attribute Controller taking care of converting the palette-indexed framebuffer to RGB and then to digital TTL¹³ signal for display

Trivia : In the 1980's integrated video DACs¹⁴ were expensive and difficult to embed into custom chips. Most home computers with RGB output used TTL for digital output. With the introduction of VGA the DAC became the standard.

The most surprising part of the architecture is obviously the framebuffer. Why have four small fragmented banks instead of one big linear one?

The main reason was RAM latency and the need for minimum bandwidth. A CRT running at 60Hz and displaying 640x350 in 16 colors needs a pixel every $\frac{1}{640*350*60} = 74$ nanosecond. At this resolution, one pixel is encoded with 4 bits. Each nibble is translated to a RGB color via the TTL. So that means it requires one byte every 148 nano-seconds.

Unfortunately, RAM access latency was 200ns - not nearly fast enough¹⁵ to refresh the screen at 60hz, so the TTL would starve. If latency could not be reduced, the throughput could still be improved by reading from four banks at a time. Reading in parallel gave an amortized RAM latency of $200/4 = 50$ ns, which was fast enough.

Keep in mind that this architecture reduced the penalty of read operations, but plotting a pixel in the framebuffer with a write operation was still slow. Writing to the VRAM as little as possible was crucial to maintaining a decent framerate.

¹³Transistor Transistor Logic

¹⁴Digital to Analog Converter

¹⁵Computer Graphics: Principles and Practice 2nd Edition, page 168.

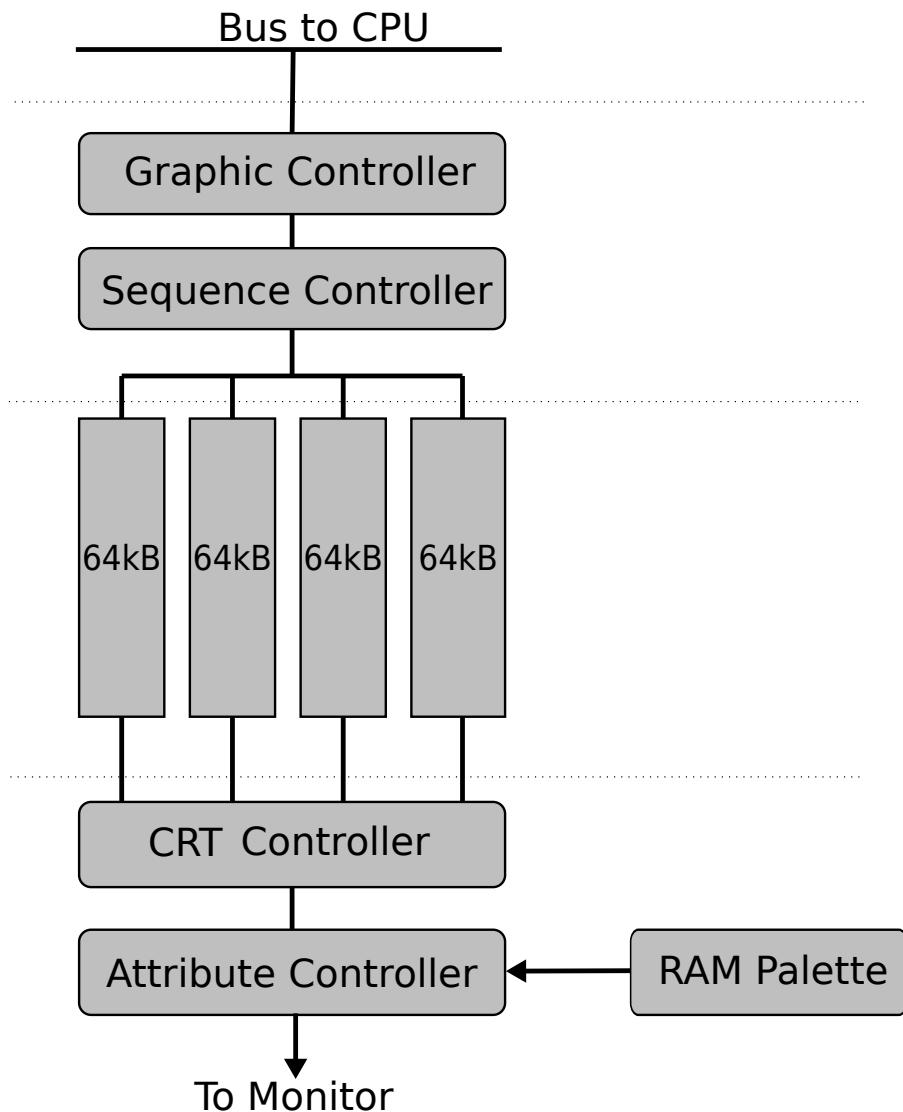


Figure 12: EGA Architecture.

0.3.4 EGA Planar Madness

Four memory banks grant enough throughput to reach high resolutions at 60Hz. However, the price for this solution is complexity of programming.

The first problem with this design is that it is unintuitive. There is no linear framebuffer and figuring out which byte corresponds to which pixel on screen is difficult.

This type of architecture is called "planar". Each plane is like a black-and-white image that stores information about a single colour. For EGA there are 4 planes: Red, Green, Blue and Intensity (RGBI). For example, if a bit is set in the blue plane as well as the red plane, that pixel will appear purple on-screen. In total this results in $2^4=16$ colors. Each of these banks is mapped to the same UMA memory address. This layout is better explained with a drawing.

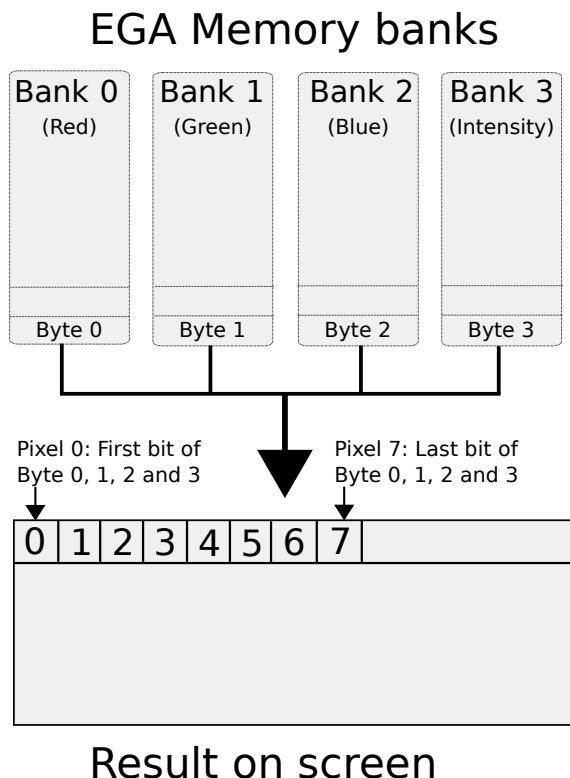


Figure 13: EGA mode 0Dh, How bank layout appears on screen.

In order to configure this mess of planes and the controllers, 50 poorly documented internal registers must be set. Needless to say few programmers dove into the internals of the EGA.

Figure 12, which described the architecture, was actually deceptively simplified. Figure 14

shows how IBM's reference documentation explained the EGA. The maze of wire showcases well the actual complexity of the system.

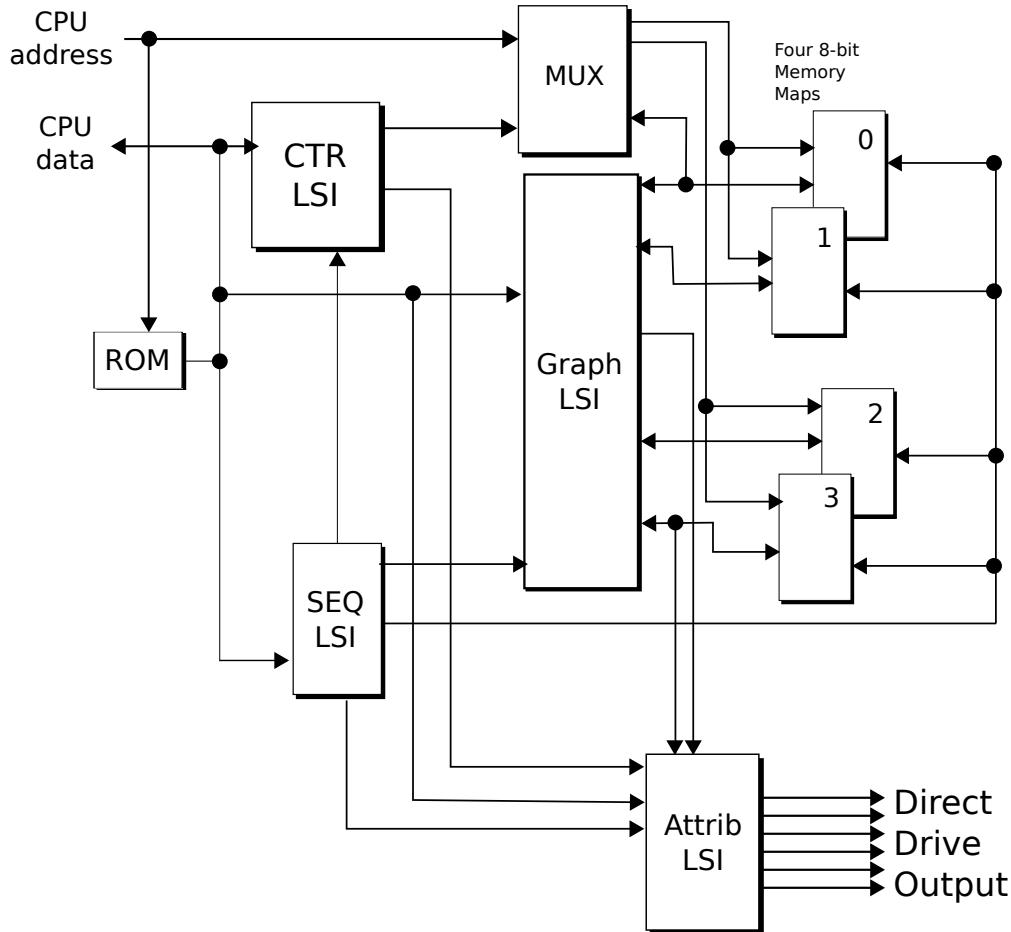


Figure 14: IBM's EGA Documentation.

To compensate for the complexity, IBM provided a routine to initialize all the registers via one BIOS call. One mode can be selected out of 12 available with an associated resolution, number of colors, and memory layout.

0.3.5 EGA Modes

The BIOS can be called to configure the EGA as follows.

Mode	Type	Format	Colors	RAM Mapping	Hz
0	text	40x25	16 (monochrome)	B8000h	60
1	text	40x25	16	B8000h	60
2	text	80x25	16 (monochrome)	B8000h	60
3	text	80x25	16	B8000h	60
4	CGA Graphics	320x200	4	B8000h	60
5	CGA Graphics	320x200	4 (monochrome)	B8000h	60
6	CGA Graphics	640x200	2	B8000h	60
7	MDA text	9x14	3 (monochrome)	B0000h	60
0Dh	EGA graphic	320x200	16	A0000h	60
0Eh	EGA graphic	640x200	16	A0000h	60
0Fh	EGA graphic	640x350	3	A0000h	60
10h	EGA graphic	640x350	16	A0000h	60

Figure 15: EGA Modes available.

0.3.6 EGA compatibility with 200-line CGA modes

The EGA uses a female nine-pin D-subminiature (DE-9) connector for output, identical to the CGA connector, and the signal standard and pinout is backwards-compatible with CGA, allowing EGA monitors to be used on CGA cards and vice versa. When operating in 200-line CGA modes, the EGA card is fully backwards compatible with a standard CGA monitor. Thereby it was able to show all 16 CGA colors simultaneously, instead of only 4 colors when using a CGA card.

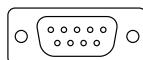


Figure 16: EGA Port

Although EGA supported high resolutions like 640x350 pixels, it required an expensive high resolution EGA monitor. For reasons of the compatibility with CGA and avoid acquiring an expensive EGA monitor most game programmers used mode 0Dh, using the 320x200 resolution with 16 colors.

0.3.7 EGA Color Palette

For each pixel a number index is derived from the 4 planes, representing a color number. The default color palette are all 16 CGA colors, but it allows substitution of each of these colors with any one from a total of 64 colors.

When selecting a color from the EGA palette, two bits are used for the red, green and blue channels. This allows each channel a value of 0, 1, 2 or 3. To select the color magenta, the red and blue values would be medium intensity (2, or 10 in binary) and the green value would be off (0). When calculating the intended value in the 64-color EGA palette, the binary number of the intended entry is of the form "rgbRGB" where a lowercase letter is the least significant bit of the channel intensity and an uppercase letter is the most significant bit. For magenta, the most significant bit in the red and blue values is a 1, so the uppercase R and B placeholders would become 1. All other digits are zeros, giving the binary number 000101 for the color magenta. This is 5 in decimal, so setting a palette entry to 5 would result in it being set to magenta. All the color values for the default colors are listed in the table below.

However, standard EGA monitors do not support use of the extended color palette in 200-line modes. The monitor cannot distinguish between being connected to a CGA card or being connected to an EGA card in a 200-line mode. Compared to CGA, EGA redefines some pins of the connector to carry the extended color information. If the monitor were connected to a CGA card, these pins would not carry valid color information, and the screen might be garbled if the monitor were to interpret them as such. For this reason, standard EGA monitors will use the CGA pin assignment in 200-line modes so the monitor can also be used with a CGA card. To keep CGA compatibility most video games did not take advantage of the color palette and kept the 16 standard CGA colors.

Index Number	Color	rgbRGB	Decimal
0	Black	000000	0
1	Blue	000001	1
2	Green	000010	2
3	Cyan	000011	3
4	Red	000100	4
5	Magenta	000101	5
6	Brown	010100	20
7	Ligh grey	000111	7
8	Dark grey	111000	56
9	Bright blue	111001	57
10	Bright green	111010	58
11	Bright cyan	111011	59
12	Bright red	111100	60
13	Bright magenta	111101	61
14	Bright yellow	111101	62
15	White	111101	63

Figure 17: Default EGA 16-color palette

0.3.8 EGA Programming: Memory Mapping

To write to the VRAM, the RAM's 1MiB address space maps 64KiB starting as indicated in table 15. In mode 0Dh for example, the VRAM is mapped from 0xA0000 to 0xAFFFF. One of the first questions to come to mind is "How can I access 256KiB of RAM with only 64KiB of address space?" The answer is "bank switching" as summarized in figure 18. Write and Read operations are routed based on a mask register indicating which bank should be read or written to.

The most commonly considered mode for game programming is mode 0Dh. It offers a resolution of 320x200 at 60hz with 16 colors. Each pixel is encoded in 4 bits (a nibble) spread across the four banks.

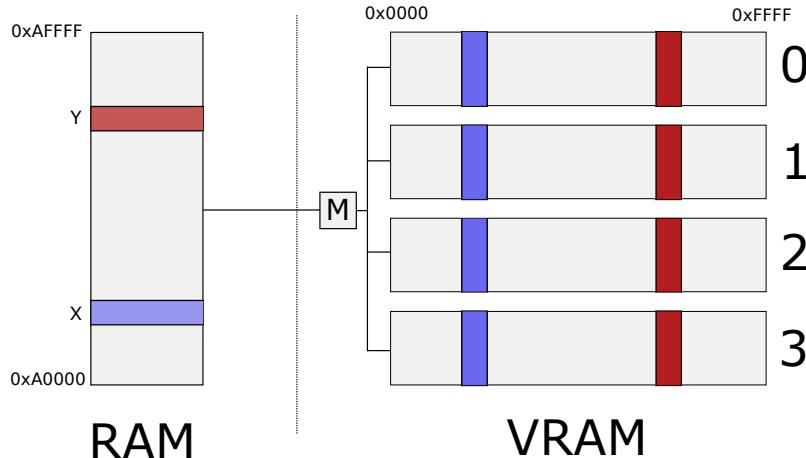


Figure 18: Mapping PC RAM to EGA VRAM banks.

To write the color of the first pixel, a developer has to write the first bit of the nibble in plane 0 (R), the second in plane 1 (G), the third in plane 2 (B) and the fourth in plane 3 (I). The CRT Controller then reads 4 bytes at a time (one from each plane) resulting in 8 pixels on screen. So in figure 19 the first pixel has color magenta(05h), second pixel dark grey (08h) and third pixel bright yellow(0Eh).

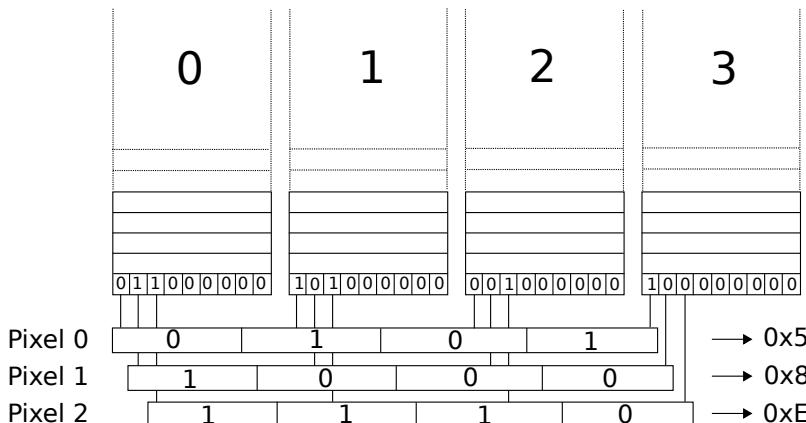


Figure 19: EGA bank layout

Setup

To setup the EGA in Mode 0Dh using the BIOS is incredibly easy. It can be done with only two instructions:

```
_AX = 0xd ; AH=0 (Change video mode), AL=0Dh (Mode)
geninterrupt (0x10) ; Generate Video BIOS interrupt
```

The geninterrupt (0x10) instruction is a software interrupt caught by the BIOS routine in charge of graphic setup. It looks up the ax register, which can be set in the Borland Compiler by _AX, to setup all EGA registers with the corresponding mode.

After the EGA is initialized one can write to the mapped memory at 0xA0000. This can be demonstrated with a code sample; here is some code to clear the screen to black.

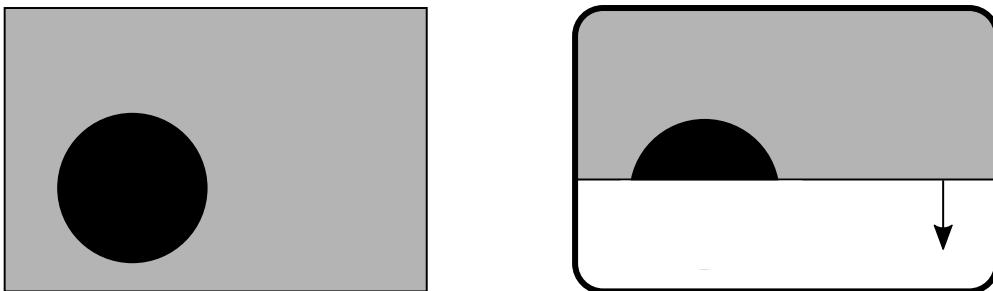
```
char far *EGA = (unsigned char far*)0xA0000000L;

void ClearScreen(void){
    int i;
    _AX = 0xd;
    geninterrupt (0x10);

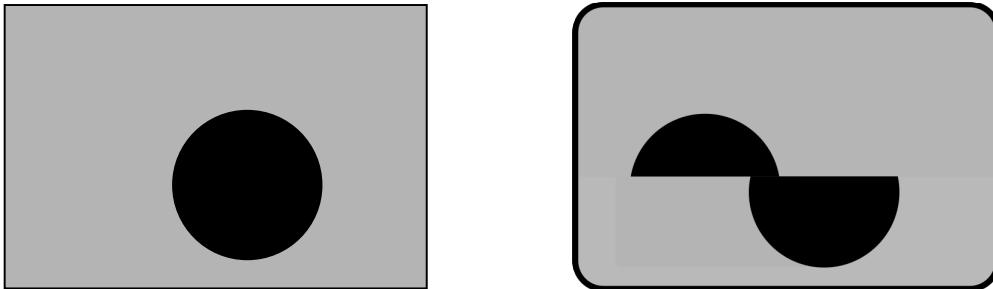
    for (i=0 ; i < 320*200 ; i++)
        EGA[i] = 0x00;
}
```

0.3.9 The Importance of Double-Buffering

Double buffering has been mentioned often while describing the hardware, but so far we have not reviewed why it is paramount to achieving smooth animation. With only one buffer the software has to work at exactly the frequency of the CRT (60Hz). Otherwise a phenomenon known as "tearing" appears. Let's take the example of an animation rendering a circle moving from the left to the right:



In this example the CPU has finished writing the framebuffer (on the left) and the CRT's (on the right) electron beam has started to scan it onto the screen. At this point in time the electron beam has scanned half the framebuffer, so the circle has been partially drawn on the screen.



If the CPU is faster than the frequency of the CRT (60Hz), it can write the framebuffer again, before the scan is completed. This is what happened here. The next frame was drawn with the circle moved to the right. The electron beam did not know that and kept on scanning the framebuffer. The result on screen is now a composite of two frames. It looks like two frames were torn and taped back together. Hence the name "tearing".

With two buffers (a.k.a double buffering) the CPU can start writing in the second framebuffer without messing with the framebuffer being scanned to the screen¹⁶. No more tearing!

Note that creating 320x200 picture with 16 colors on the screen requires 8KiB of VRAM (4 planes, each 2KiB).

¹⁶Now the CPU speed is capped by the CRT refresh rate. Triple buffering can solve this at the price of frame latency.

0.4 Audio

PCs came equipped with a silver-dollar-sized beeper commonly known as a "PC Speaker", capable of generating a square wave via 2 levels of output.

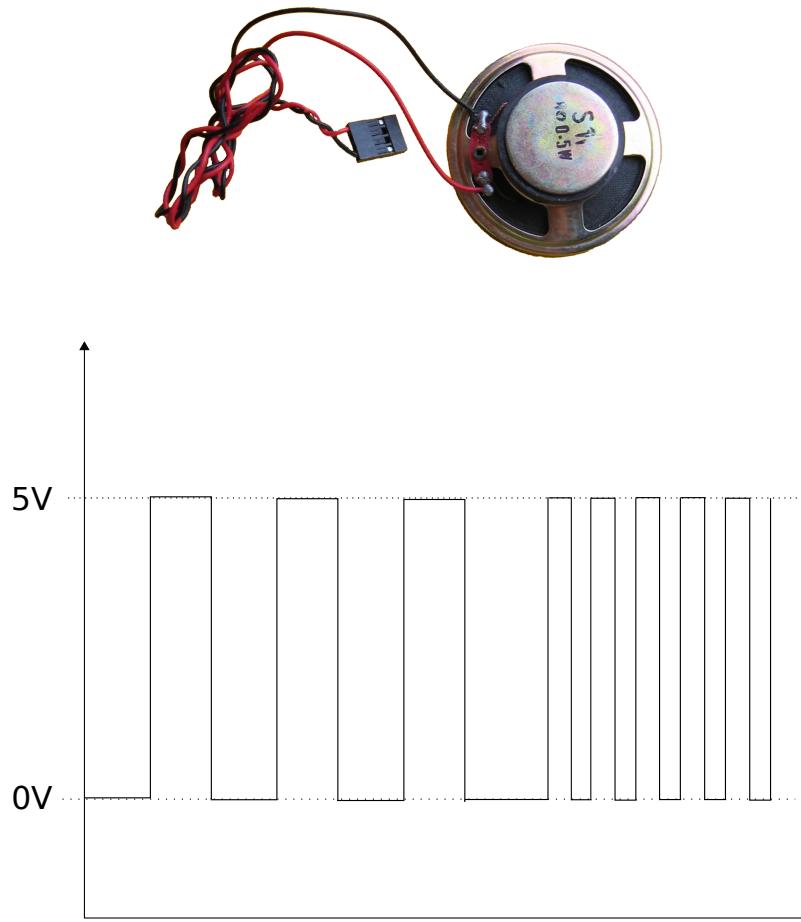


Figure 20: Two beeps of different frequencies generated via PC Speaker.

To this day, the PC speaker is the first output device to be activated during the boot process. The purpose of this primitive loudspeaker is to signal hardware problems with beep codes. It was intended to remain silent after a successful boot.

Beep Code	Meaning
No Beeps	Short, Bad CPU/MB, Loose Peripherals
One Beep	Everything is normal
Two Beeps	POST/CMOS Error
One Long Beep, One Short Beep	Motherboard Problem
One Long Beep, Two Short Beeps	Video Problem
One Long Beep, Three Short Beeps	Video Problem
Three Long Beeps	Keyboard Error
Repeated Long Beeps	Memory Error
Continuous Hi-Lo Beeps	CPU Overheating

However, square waves are not useful for producing anything pleasant. Some people saw a potential market and companies began manufacturing what were known as "sound cards". Users could buy these separately and insert them into one of the machine's ISA slots. These cards could be connected to real audio speakers via 3.5mm jacks and tremendously improved sound capabilities. In 1990, there were three cards on the market:

- AdLib music card
- SoundBlaster 1.0
- Disney Sound Source

Although adoption was growing (Creative would go on to sell one million SoundBlaster cards in 1991), the majority of PCs had no sound card which once again presented a huge problem for game developers. Commander Keen 1-3 did only support the PC speaker, only after introduction of Keen Dreams soundcards were supported.

0.4.1 AdLib

AdLib's music card was first on the market. The company was founded in 1988 by Martin Prevel, a former professor of music from Quebec. After an initial struggle to get game developers to use their card (the SDK was \$300), AdLib managed to convince Taito, Velocity, and Sierra On-Line to support their hardware. Sierra in particular did much to increase adoption with King's Quest IV selling close to 3 million copies. Soon after, all games supported the "music card".

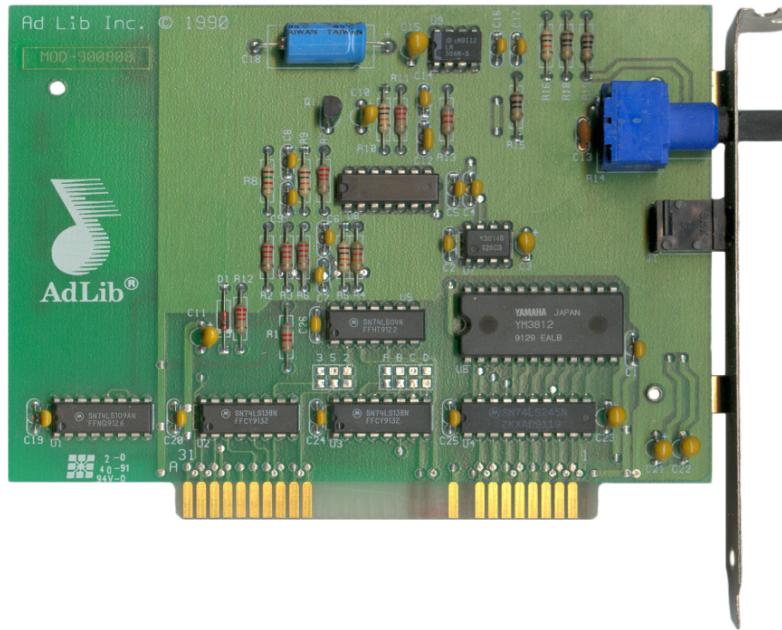


Figure 21: An AdLib sound card. Notice the big YM3812 chip and the 8-bit ISA connector.

Equipped with a Yamaha YM3812, also known as the OPL2, the card can produce 9 channels of sound, each capable of simulating an instrument. Based on FM synthesis, the channels were limited but allowed for pleasant music.

Trivia : Canadian companies, and especially those from Quebec, were prevalent in the early 90s due to their technological prowess. AdLib manufactured Sound Cards, Matrox made a killing with its Millennium Graphics Card, and Watcom sold the best DOS C compiler¹⁷. ATI¹⁸ would later emerge as a major GPU innovator in the 2000s.

0.4.2 Sound Blaster

The Sound Blaster 1.0 (code named "Killer Kard"), was released in 1989 by Creative. It was a smart product which was clearly targeting AdLib's dominant position.

¹⁷Watcom's compiler was so good id would use it to compile Doom.

¹⁸History would repeat itself in the late 90s in the field of graphic cards: Nvidia vs ATI.

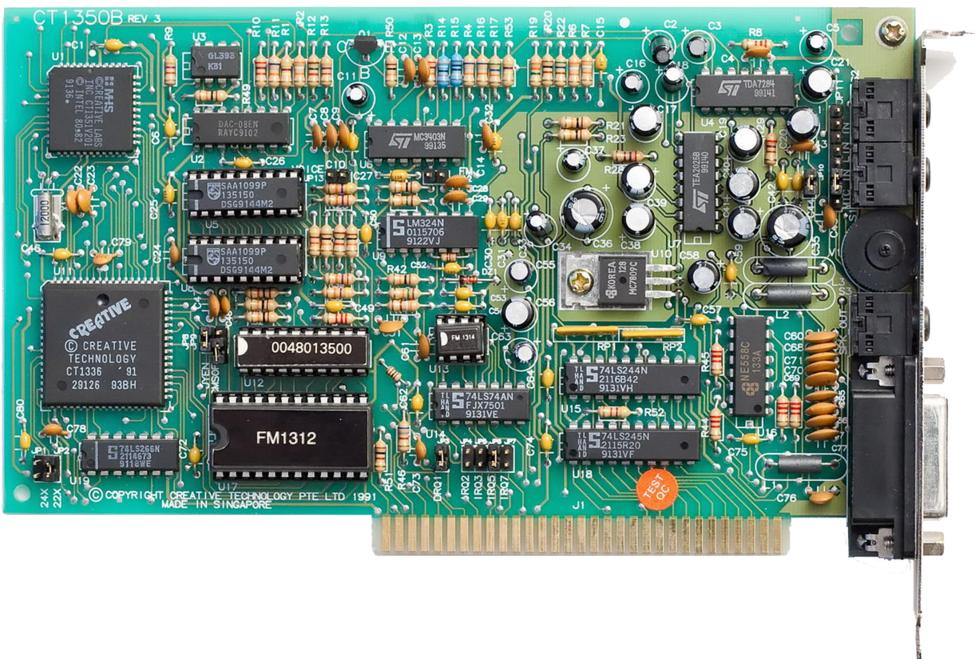


Figure 22: A SoundBlaster (v1.2).

Not only was it equipped with the same OPL2 chip, providing 100% compatibility with AdLib music playback, but it was also technologically superior with a DSP¹⁹ allowing PCM playback (digitized sounds) at 8 bits per sample and up to 22.05kHz sampling rate. The card also came with a DA-15 port allowing joystick connection. Most importantly, the SoundBlaster was \$90 cheaper than the AdLib.

Figure 22 is the Sound Blaster model CT1350B. Notice the OPL2 chip (labeled FM1312), the big CT1336 bus interface (labeled "CREATIVE") on the center left, the CT1351 DSP on the upper left, and the 8-bit ISA bus connector.

Trivia : The numerous advantages of the Sound Blaster card over the AdLib made it the de-facto standard shortly after its release and eventually brought AdLib to bankruptcy²⁰.

¹⁹An Intel MCS-51 "Digital Sound Processor", not "Digital Signal Processor".

²⁰The reign of the Sound Blaster came to an end with Windows 95, which standardized the programming interface at application level and eliminated the importance of compatibility with Sound Blaster

0.4.3 Disney Sound Source

In 1990, Disney began selling the Disney Sound Source (DSS). Plugged into the printer port (parallel port) of the PC, an 8-bit DAC similar to the "Covox Speech Thing" was connected to a speaker box.



Figure 23: The speaker box (DAC not shown).

It was incredibly easy to set up, simple to program (it could only play one type of PCM and had no FM synthesizer), and very cheap compared to the other audio solutions (\$14). It would have made programmers and customers happy if not for one serious limitation. The parallel port bandwidth²¹ allowed a sampling rate up to 18,750 Hz but the design of the DSS limited the PCM sampling rate to 7,000Hz. This was still enough to produce pleasant sounds, but fell short when compared to the 22kHz of a Sound Blaster.

0.5 Floppy Disk Drive

In the time before the internet, a floppy disk was the best medium to share and distribute software and data. The original XT systems were equipped with 5 1/4-inch floppy disk with

²¹The parallel port maximum bandwidth was 150 kbytes/s at the time. Enhanced Parallel Port and later Enhanced Capability Port significantly increased the transfer rate necessary to scanner and laser printers.

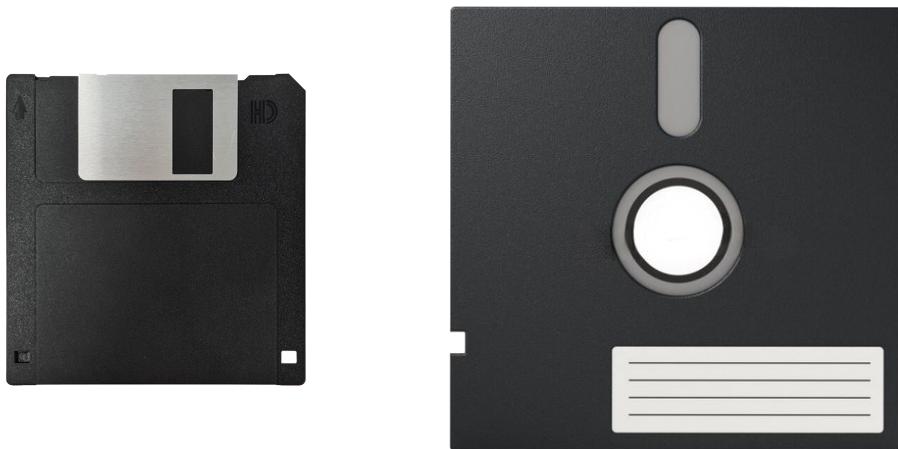


Figure 24: 3½-inch and 5¼-inch floppy disk.

a capacity of 360Kb. In 1984, IBM introduced with its PC AT the 1.2 MB dual-sided 5¼-inch floppy disk, but it never became very popular. IBM started using the 720 KB double density 3½-inch floppy disk in 1986 and the 1.44 MB high-density version in 1987. The advantages of the 3½-inch disk were its higher capacity, its smaller physical size, and its rigid case which provided better protection from dirt and other environmental risks. By the mid-1990s, 5¼-inch drives had virtually disappeared, as the 3½-inch disk became the predominant floppy disk.

Trivia : An USB stick of 128GB contains 91.000 high-density 3½-inch (1.44MB) floppy disks.

A floppy disk is essentially a very flexible piece (hence the term floppy disk) of plastic coated on both sides in a magnetic material. This 'disk' of plastic is contained within a protective envelope or hard plastic case, which is then inserted into the drive and automatically locked onto a spindle. It is then rotated at a constant speed, 360 rpm for standard PC floppy drives. A head assembly consisting of two magnetic read/write heads, one in contact with the upper surface and one in contact with the lower surface of the disk, may be moved in discrete steps across the disk and read the data from the disk.

The floppy disk is controlled via the Floppy Disk Controller (FDC), a typical read operation from the floppy disk contains the following steps:

- Turn the disk motor on. When you turn a floppy drive motor on, it takes quite a few milliseconds to "spin up", to reach the (stabilized) speed needed for data transfer.
- Perform seek operation, which moves the head to the correct location for reading the

data.

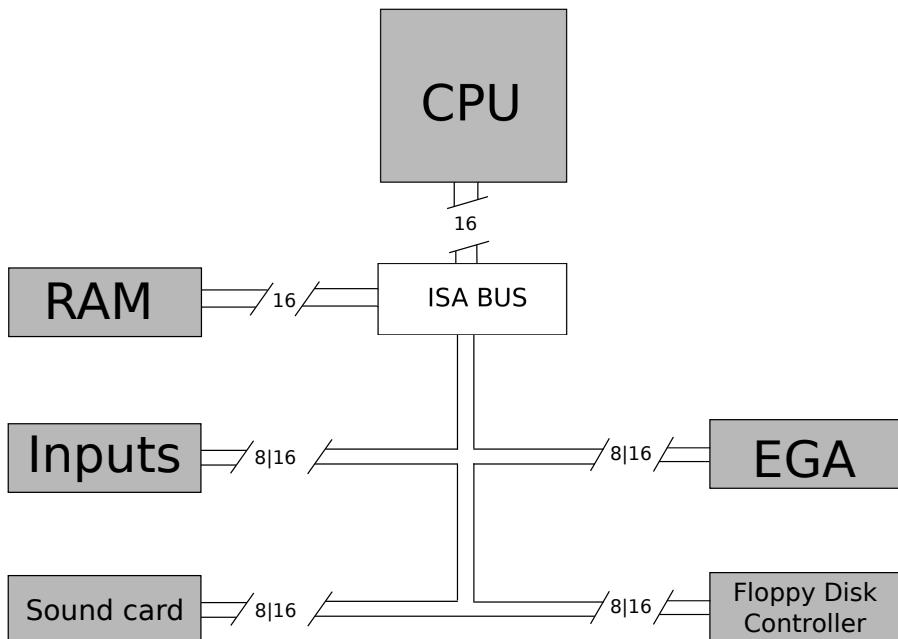
- Read the data from the floppy disk and store the data via the FDC to RAM memory.
- Turn the disk motor off.

You typically should wait a few seconds before turning the motor off. The reason to leave the motor on for a few seconds is that your driver may not know if there is a queue of sector reads or writes that are going to be executed next. If there are going to be more drive accesses immediately, they won't need to wait for the motor to spin up again.

0.6 Bus

Although developers had no control over them, it is still worth mentioning how these components were connected to each other.

The ISA²² bus connects the CPU to all devices, including RAM. It was almost 10 years old in 1990 but still used universally in PCs. The data path to the RAM is 16 bits wide for 286 machines. It runs at the same frequency as the CPU.



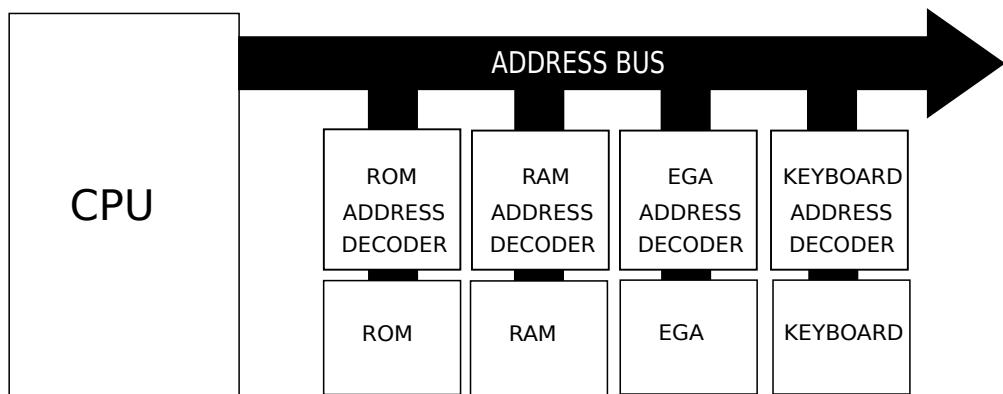
²²Industry Standard Architecture.

The rest of the bus connecting to everything that is not the RAM can be either:

- 8 bits wide at 4.77 MHz for 19.1 Mbit/s
- 16 bits wide at 8.33MHz for 66.7 Mbit/s²³.

It is also backward compatible and an 8-bit ISA card can be plugged into a 16-bit ISA bus.

Trivia : On ISA all devices are connected to the bus at all times and listen on the bus address lane. Each device features an "address decoder" to detect if it should reply to a bus request. This is how the EGA RAM is "mapped" in RAM. The EGA card "address decoder" filters out everything that is not within A0000h and AFFFFh. Accordingly, the RAM disregards any request that is within the range [A0000h - AFFFFh].



In practice the effective bandwidth of the bus is divided by two due to packet overhead and interrupts. As a result, a PC equipped with an 8 bit ISA EGA card can push $19.1\text{Mbit/s}/2/8 = 1.1\text{MB/s}$. In mode 0Dh, since a frame is $320 \times 200 / 8 = 8,000$ bytes, the theoretical maximum framerate with a CPU taking 0ms to render a frame is $1,100,000 / 8,000 = 138$ frames per second. So the good part is that most likely the address bus is not the bottleneck in the entire process.

0.7 Inputs

At a time before the ubiquitous USB, inputs were a mess with no less than four ports, all programmed differently.

²³https://en.wikipedia.org/wiki/List_of_device_bit_rates .

The parallel port (DB-25) was on every computer and usually used to connect dot-matrix printers (loud things that printed with needles). The parallel port was multi-purpose and the Disney Sound Source could be plugged into it.

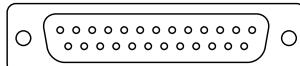


Figure 25: Parallel Port

The serial port (DE9) was used to connect the mouse.

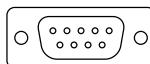


Figure 26: Serial Port

The PS/2 port was used to connect a keyboard.



Figure 27: PS/2 Port

Finally, a SoundBlaster sound card connected via the ISA bus provided a Game Port (DA-15) allowing for connection to a joystick²⁴.

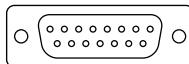


Figure 28: Game Port

0.8 Summary

To say a PC was difficult to program for games would be an understatement. It was a nightmare. The CPU was good at doing the wrong thing, the best graphic interface didn't allow double buffering, the memory model only allowed 1 standard MiB with an address composed of two separate 16-bit registers, and the `near/far` pointers forbade using standard C. Last, but not least, the default sound system could only produce square waves.

²⁴In 1981, the very first IBM PC could be purchased with a DA-15 "Game Port" extension card at the cost of \$55 (\$159 in 2018).

Yet despite all these unfavorable conditions, teams of developers gathered to tame the beast and unleash its power to gamers. One of these called themselves Ideas From the Deep²⁵.

²⁵They originally called themselves Ideas From the Deep but then decided to shorten it to simply id, which stands for "in demand", and is pronounced as in "did" or "kid." The name also refers to id, the part of the brain that behaves by the pleasure principle in Freudian psychology.

