

# EEM 489

## Microprocessors II Lecture Notes

# History (Intel 4004)

- The Intel 4004 (1971) was the first microprocessor:
  - originally developed for a desktop calculator product
  - contained 2300 transistors
  - occupied a silicon area of 12 mm<sup>2</sup>
  - implemented in 10 mm PMOS semiconductor technology
  - data bus was 4 bits wide
  - 640 bytes of data could be addressed
  - system clock ran at a frequency of 108 KHz
  - could perform roughly 60000 operations per second

# History of Microprocessors

Year	Processor	MIPS
1969	4004	0.06
1970	808x	0.64
1982	80286	1
1985	80386	5
1989	80486	20
1993	Pentium	100
1996	Pentium II	250
1999	Pentium III	500
2000	Pentium 4	1,500

# History (Itanium)

- The Intel Itanium entered mass production in 2001:
  - intended for high-end servers and workstations
  - contains 25.4 million transistors
  - silicon chip area exceeds 300 mm<sup>2</sup>
  - implemented in 180 nm CMOS semiconductor technology
  - 6 layers of metal interconnections
  - 1012 chip pad connections
  - 64-bit data bus; 64-bit address bus; 64-bit registers
  - memory space of over 18 terabytes (264 = 18.45 x 1018).
  - system clock frequency of at least 800 MHz
  - peak performance of 3.2 billion instructions per second
  - The pace of technological progress shows no signs of slowing down in the immediate years ahead . . .

## Technology Directions (Future?)

Year	1999	2002	2005	2008	2011	2014
Feature Size (nm)	180	130	100	70	50	35
logic transistor/cm <sup>2</sup>	6.2	18	39	84	180	390
(M) cost per transistor	1.735	0.580	0.255	0.110	0.049	0.022
number of pads per chip	1867	2553	3492	4776	6532	8935
Clock (Mhz)	1250	2100	3500	6000	10000	16900
Chip size (mm <sup>2</sup> )	340	430	520	620	750	900
Wiring Levels	6-7	7	7-8	8-9	9	10
Power Supply (V)	1.8	1.5	1.2	0.9	0.6	0.5
High Perf. Power (W)	90	130	160	170	175	183

## Computer History - 1940s-1960s



**ENIAC - 1940s  
(Vacuum Tubes)**



**IBM 360 - 1960s  
(Transistors)**

## A Brief History of Computer Technology

- 1940s-50s - Vacuum Tubes
- 1950s-60s - Discrete Transistors
- 1960s-70s - Discrete ICs (e.g., TTL)
- 1970s-present - LSI and VLSI microprocessors

## Computer History - 1970s

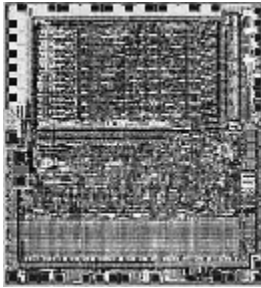


**Intel 4004 - 1970s  
(First Microprocessor)**



**DEC VAX 11/780 - 1970s  
(Discrete IC's)**

## Computer History - 1970s



**MOS Technology 6502**

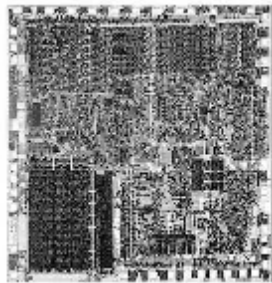


**Apple II Computer**

## Outline - Technology Trends

- Brief History of Computer Technology
- Today's Technology: VLSI .:
- VLSI Technology Trends

## Computer History - 1980s



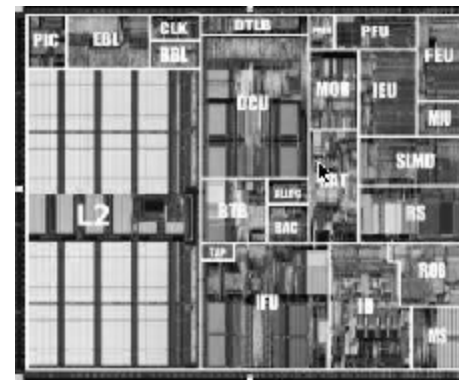
**Intel 8088  
(LSI Microprocessor)**



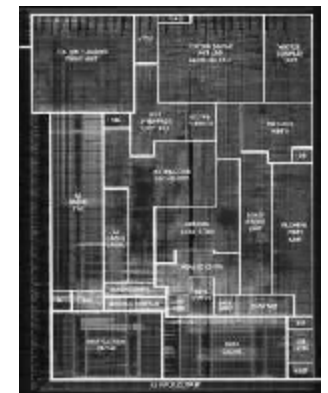
**Original IBM PC**

Images:  
Intel Corporation [www.intel.com](http://www.intel.com)  
pcbiography members.tripod.com/pcmuseum

## Today: VLSI Microprocessors

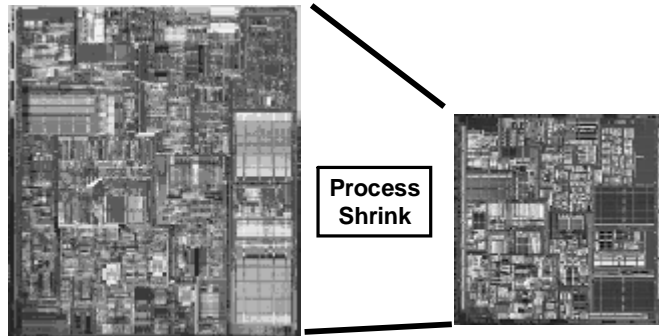


**Pentium® III**  
28M transistors / 733MHz-1Gz / 13-26W  
L=0.25µm shrunk to L=0.18µm



**PowerPC 7400 (G4)**  
6.5M transistors / 450MHz / 8-10W  
L=0.15µm

# Today: VLSI Microprocessors



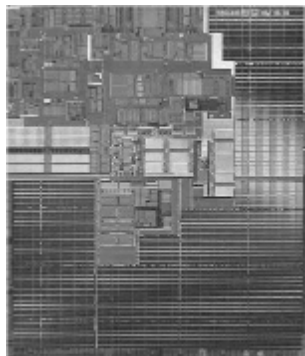
**Pentium® 4**  
42M transistors / 1.3-1.8GHz / 49-55W  
L=0.18µm

**Pentium® 4 "Northwood"**  
55M transistors / 2-2.5GHz  
L=0.13µm Area=131mm<sup>2</sup>

# VLSI Technology Overview

- Fabrication of multiple transistors on a chip
- Dominant technology: CMOS
- Other technologies:
  - Bipolar (e.g., TTL)
  - Bi-CMOS - hybrid Bipolar, CMOS
  - GaAs - Gallium Arsenide (for high speed)
  - Si-Ge - Silicon Germanium (for high speed, RF)

# Today: VLSI Microprocessors



**Intel Itanium® 2**  
410M transistors / 1.3GHz / 130W  
L=0.13µm Area=374mm<sup>2</sup>

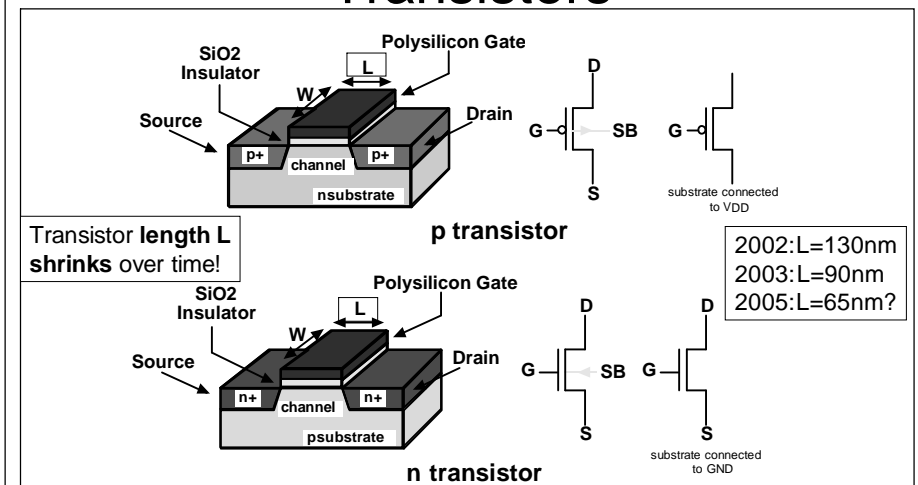
Image source: Intel Corporation [www.intel.com](http://www.intel.com)



**PowerPC® 940 (G5)**  
58M transistors / 2GHz / 97W  
L=0.13µm Area=118mm<sup>2</sup>

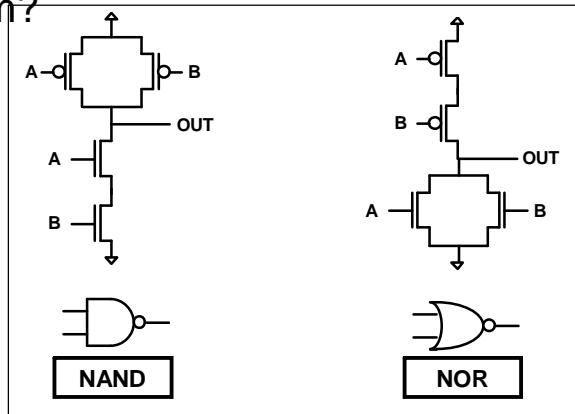
Image courtesy International Business Machines  
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# VLSI Technology - CMOS Transistors



## VLSI Technology - CMOS Logic Gates

- What logic functions do these gates perform?



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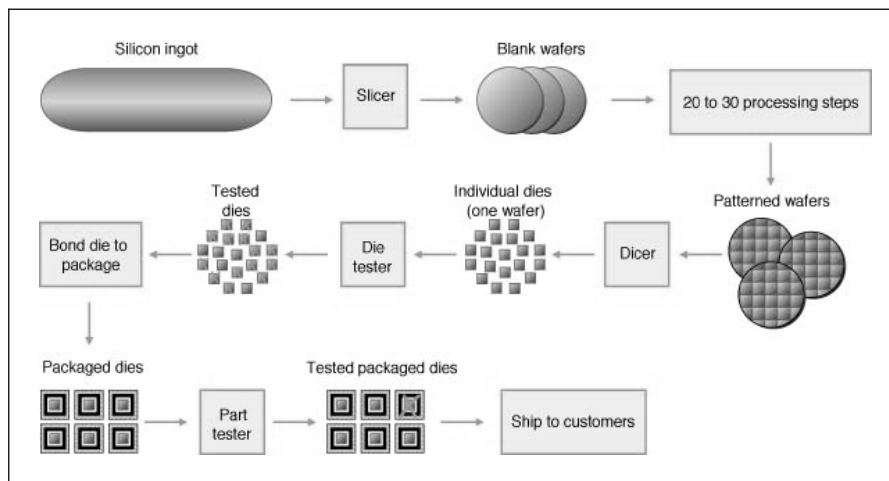
## VLSI Design Tradeoffs

- Cost - related to chip size
  - Amount of logic
  - Current technology
  - Non recurring engineering (NRE) cost vs. unit cost
- Performance
  - Clock speed
  - Implementation
  - Application
- Power consumption
  - Power supply voltage
  - Clock speed

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## VLSI Processing



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## Outline - Technology Trends

- Brief History of Computer Technology
- Today's Technology: VLSI
- VLSI Technology Trends ∴

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# VLSI Trends: Moore's Law

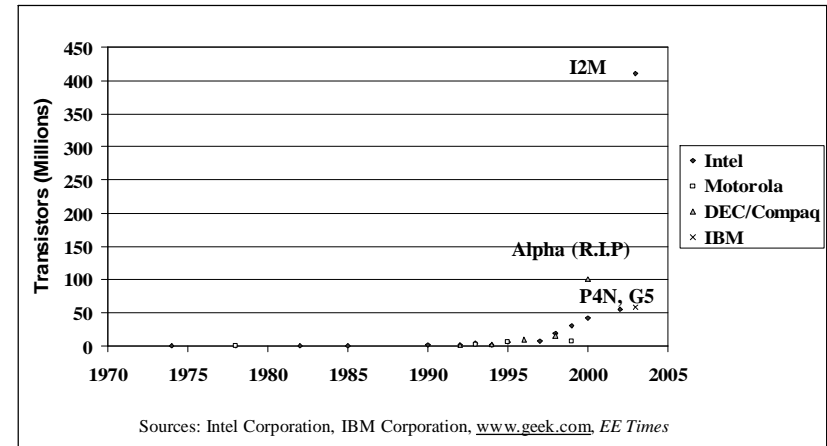
- In 1965, Gordon Moore predicted that transistors would continue to shrink, allowing:
  - Doubled transistor density every 24 months
  - Doubled performance every 18 months
- History has proven Moore right
- But, is the end in sight?
  - Physical limitations
  - Economic limitations

BUT...  
No exponential is forever!



Gordon Moore  
Intel Co-Founder and Chairman Emeritus

# Microprocessor Trends

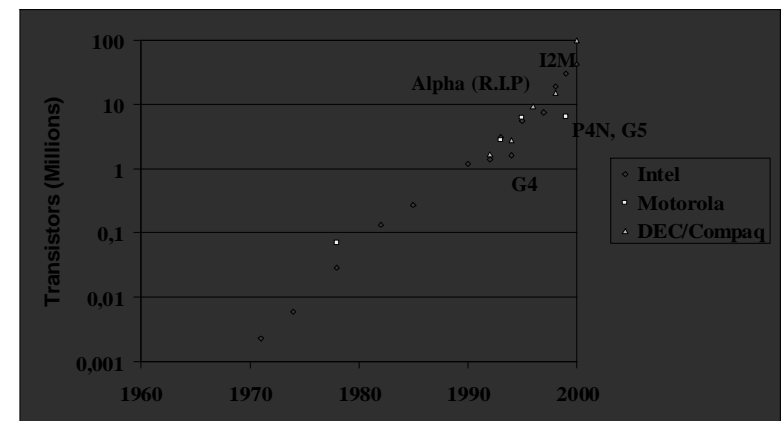


# Microprocessor Trends (Intel)

Year	Chip	L	transistors
1971	4004	10µm	2.3K
1974	8080	6µm	6.0K
1976	8088	3µm	29K
1982	80286	1.5µm	134K
1985	80386	1.5µm	275K
1989	80486	0.8µm	1.2M
1993	Pentium®	0.8µm	3.1M
1995	Pentium® Pro	0.6µm	15.5M
1999	Mobile PII	0.25µm	27.4
2000	Pentium® 4	0.18µm	42M
2002	Pentium® 4 (N)	0.13µm	55M
2003	Itanium® 2 (M)	0.13µm	410M

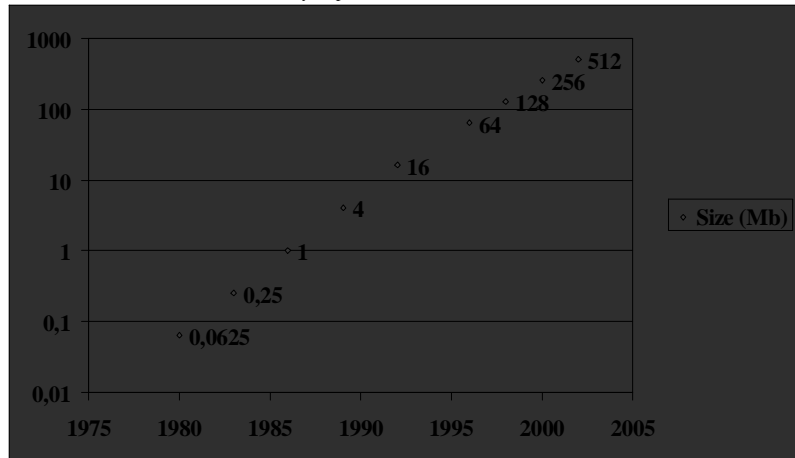
Source: <http://www.intel.com/pressroom/kits/quickreffam.htm>, *EE Times*

# Microprocessor Trends (Log Scale)



# DRAM Memory Trends (Log Scale)

Source: Textbook, Industry Reports



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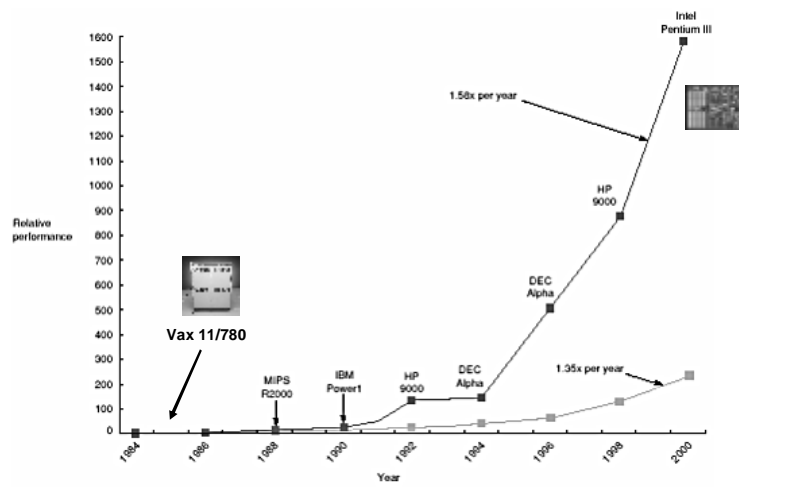
# Summary - Technology Trends

- Processor
  - Logic capacity increases ~ 30% per year
  - Clock frequency increases ~ 20% per year
  - Cost per function decreases ~20% per year
- Memory
  - DRAM capacity: increases ~ 60% per year (4x every 3 years)
  - Speed: increases ~ 10% per year
  - Cost per bit: decreases ~25% per year
- Disk
  - Storage capacity increases ~60% per year

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# Performance Trends



Source: Hennesy & Patterson Computer Architecture: A Quantitative Approach, 3rd Ed., Morgan-Kaufmann, 2002.

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# Microprocessor Revolution

- The appearance of the microprocessor revolutionized digital system design starting in the 1970s, and continuing on until the present day.
- The main advantages of the microprocessor:
  - Programmability. Sophisticated functions can be provided relatively easily in software.
  - Performance. Advances in integrated circuit technology are leading to faster and more powerful microprocessors.
  - Cost-effectiveness. Microprocessors, because they are multi-purpose, are manufactured in large quantities, which tends to minimize their unit cost.
  - Reliability. Integrated circuits are highly-reliable, solid state devices. Microprocessors have no moving parts.
  - Compactness. More and more functionality can be packed onto a single microprocessor/microcontroller chip.

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## Disadvantages of Microprocessors

- The learning curve for designing using microprocessors can be steep. Why is this so?
- Microprocessors have many complex features. The specification “sheets” can often fill entire books. Numerous features are provided to satisfy a wide variety of users.
- Microprocessors are completely unforgiving when program errors are made. They will execute exactly what is in the program, and have no “common sense” or “intuition” about what the designer intended the program to do.
- Debugging tools for microprocessor assembly language programs are usually primitive compared to the tools available for programs in high-level languages.

## Microprocessor Families (Motorola)

- Microprocessor manufacturers tend to release microprocessors in families of increasing complexity and performance.
- Motorola, Inc.:
  - 6800 family
    - 6800 (1974), 6809 ('79), 68HC11 ('84)
  - M68000 family:
    - 68000 (1979), 68010 ('82), 68020 ('84), 68030 ('87), 68040 ('89), 68332 ('89)

## Related Terms

- A “microcomputer” is a computer system that has been built around a microprocessor chip.
- A “microcontroller” is an integrated circuit that contains a microprocessor as well as other useful support circuits, such as timers, memory, input/output interface circuits, etc.
- A “digital signal processor” (DSP) is a specialized microprocessor that has features (e.g. instructions, registers, internal signal paths, arithmetic circuits) that make it particularly efficient at performing the kinds of numerically-intensive calculations that are required in digital signal processing (e.g. in modems and cell phones).

## Microprocessor Families (Intel)

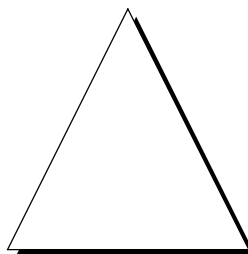
- Intel Corporation:
  - 4004 (1971), 8008 ('72), 8080 ('74)
  - x86 family: 8086 ('78), 8088 ('79), 80186 ('82), 80286 ('82), 80386 ('85), 80486 ('89), Pentium ('93), Pentium II ('97), Pentium III ('99), Pentium 4 (2000)
  - IA-64 family: Itanium (2000)
- Microprocessor families make it easier to carry software over from an older mP to the latest mP. “Upward compatibility” is an important strategy for building customer loyalty.

## Motorola 68300 Microcontroller Family

- Microcontrollers are widely used to implement embedded programmable controllers.
- The MC68300 family includes several 32-bit microcontrollers MC68331, MC68332, MC68340, etc.
- Each microcontroller contains a modified 32-bit MC68020 mP (called a CPU32) plus several other modules for performing parallel and serial input/output, timing, motor control, on-chip memory, system expansion, etc.
- MC68332 = CPU32 + Queued Serial Module (QSM) + 2048 bytes of on-chip RAM + Time Processor Unit (TPU) + System Integration Module (SIM)

## Storage

	speed	Capacity
Registers	1 ns	~KB
Cache	10 ns	~MB
Main memory	100 ns	~100MB
Hard disk	10 ms	~10GB
Archive	>100ms	~TB



## Storage

- Divergence between memory capacity and speed more pronounced
  - Capacity increased by 1000x from 1980-95, speed only 2x
  - Gigabit DRAM by c. 2000, but gap with processor speed much greater
- Larger memories are slower, while processors get faster
  - Need to transfer more data in parallel
  - Need deeper cache hierarchies
  - How to organize caches?

## Instruction Sets (CICS)

- Software costs growing faster than hardware costs (1970s)
  - Machine language v.s. HLL (High Level Lang.)
  - Support for high-level languages
  - Gap between high level languages and computer hardware - semantic gap
- CISC - Complex Instruction Set Architecture
  - Variety of instructions and addressing modes
  - e.g. 68000
- HLLCA - High Level Language Computer Architecture

## Instruction Sets (RISC)

- Resolve problems using simpler architecture. "The case for the reduced instruction set computers" Patterson & Ditzel [1980]
  - Stanford MIPS (Hennessy, 1981)
  - Commercial processors: MIPS R2000 (1986),
  - IBM RS6000, SPARC, PowerPC, etc.
- Good design methodology
- Efficient pipelining and compiler-assisted scheduling of pipeline
- Make the Common Case Fast
  - favor the frequent case

## What is a microprocessor?

- Informally, a microprocessor (mP) is the brain of a computer that has been implemented on one semiconductor chip.
- More precisely, a microprocessor is a single-chip central processing unit (CPU) for a programmable computer.
- A CPU may be considered to be the "brain" of a computer because it "understands" and "executes" the sequence of binary instructions in a compiled computer program.
- Compared to the CPU, the other parts of a computer are relatively "dumb" and require detailed attention from the CPU in order to function properly in the computer system.

## 80x86 Instruction Mix

Instruction Type	Frequency (percentage)
load from memory	22
conditional branch	20
compare	16
store to memory	12
add	8
and	6
sub	5
move register to register	4
or	1
logic operations (xor, not, etc)	1
unconditional branch	1
subroutine call	1
return, jmp indirect	1
shift	1

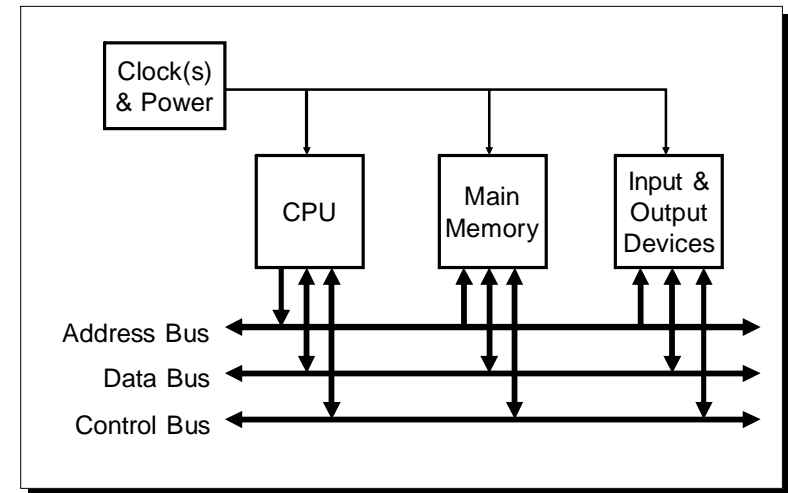
## Applications

- Microprocessors can be found just about everywhere:
  - In general-purpose computers, like mainframes, personal computers (PCs), and single-board computers (SBCs).
  - In special-purpose computers, like calculators, personal data assistants (PDAs), and game computers.
  - In embedded computers that control automobiles, appliances, instruments, communication systems, cell phones, factories, assembly lines, lumber mills, refineries, etc.

## Applications

- Example: In a car, microprocessors are used in the ignition system, emission control system, anti-lock brakes, dashboard display, entertainment system, navigation system, etc.
- Modern cars often contain 20 or more microprocessors.

## Single Bus Microcomputer Architecture



## Computer Architectures

### Bus Operations

## System Clock

- Most computers contain a clock circuit that produces one (or more) frequency-stable square-wave clock signal(s).
- The clock signal is used throughout the computer as a timing reference. It is the “heartbeat” of the system.
- If the clock is slowed down, the number of instructions executed per second will go down proportionally.

## System Clock

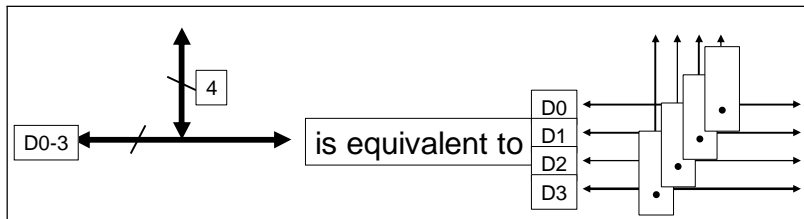
- If the clock is sped up by a small amount, the mP will probably still work, at the faster rate. (Manufacturers sell their chips with a small safety margin.)
- If the clock is sped up by a larger amount, the mP will start to make errors. Instructions will not be executed correctly. The software system will eventually crash.

## System Buses

- The arrows on connecting sub-busses indicate the signal directions.
- The system bus is usually composed of three busses:
  - Address Bus
  - Data Bus
  - Control Bus

## System Buses

- A “bus” is a group of wires that carry related signals and that are routed together inside a computer system.



- In bus notation, the main bus is shown with arrows at either end to indicate that signals flow in either direction.

## System Buses

- The “address bus” is used by the CPU to tell the rest of the microcomputer system which address it is using for the present read, write, or read-modify-write bus operation.
- The “data bus” is used to communicate information between different parts of the microcomputer.
  - During reads, data travels from the addressed location (in either the memory or the input/output devices) to the CPU.
  - During writes, data travels from the CPU to the addressed location (in either the memory or the input/output devices).
  - The data bus “width” (in bits) determines the data size of the microcomputer system.
- The “control bus” contains various signals used to control and synchronize events in the microcomputer.

## Bus Operations

- Signal activity on the system bus is organized in time as sequences of bus operations. Typical bus operations are read cycles, write cycles, read-modify-write cycles, interrupt acknowledge cycles, etc.
- The processing of one microprocessor instruction may require several bus operations.
- The same kind of bus operation (e.g. a read cycle) may take a different number of clock cycles, depending on the devices on the bus that are involved in the operation.
- Memory devices and interface chips may vary widely in their response times, and the microprocessor has to have the flexibility to accommodate these differences.

## Optional CPU Elements

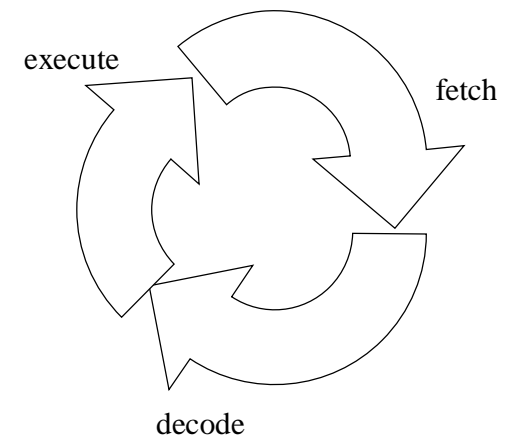
- Exception and asynchronous interrupt handling logic.
- Cache memory for storing data and instructions that were recently used by the CPU, and are likely to be re-used again relatively soon. Locally stored copies of data and instructions can be accessed faster than information stored over the system bus in the main memory.
- A floating point unit (FPU) for speeding up arithmetic operations on floating point numbers.
- A memory management unit (MMU) for controlling two or more levels of a memory hierarchy.
- Branch prediction logic; instruction re-ordering logic.

## Mandatory CPU Elements

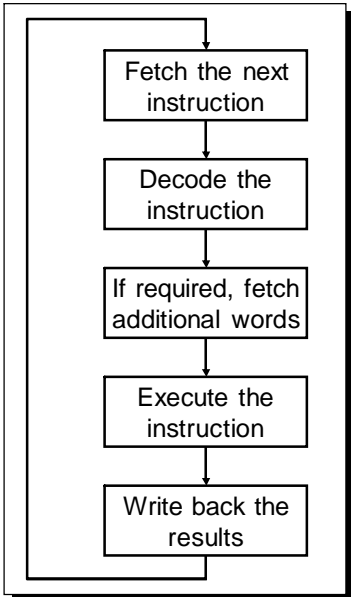
- Fast “registers” for storing frequently used data:
- Data registers, for storing intermediate data results.
- Program counter (PC) for storing the address of the current (or the next) instruction.
- Address registers, for other useful memory addresses.
- Status registers, for storing CPU status bits.
- Control registers, for storing CPU mode control bits.
- Logic for decoding binary instructions read from memory.
- Logic for manipulating data and addresses according to the definitions of the CPU's set of available instructions.
- Logic for interacting with the electrical signals on the address, data, and control busses.

## Basic Instruction Cycle

```
do forever
begin
    fetch instruction
    advance PC
    decode
    execute
end
```



# Fetch – Decode - Execute



- Place contents of PC on the address bus.
- Read first word of the present instruction from the data bus (using a read bus cycle).
- Inspect the “operation code” in the first word of the instruction, decide which kind of instruction is being performed.
- Update the PC, place PC contents on the address bus, and read additional data words (if necessary) using read bus cycles.
- Update all CPU registers (including the PC) according to the present register contents and the present instruction type.
- If necessary, update words in memory and I/O devices using write bus cycles.

# Memory

- A memory holds binary information, which consists of both program instructions and data. (In memory, everything just looks like 0’s and 1’s.)
- Information “words” are identified in a memory using an address, which is just a binary number. The size of a word is usually determined by the number of wires in the data bus (i.e. the data bus size).
- A random-access memory (RAM) allows the words stored in the RAM to be both read and written.
- A read-only memory (ROM) allows the words to be read, but not changed. The contents of a ROM are fixed.

# Instruction Execution

for each instruction:

fetch

read the instruction from the memory

decode

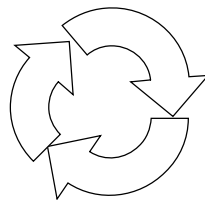
find out what the instruction is

encode

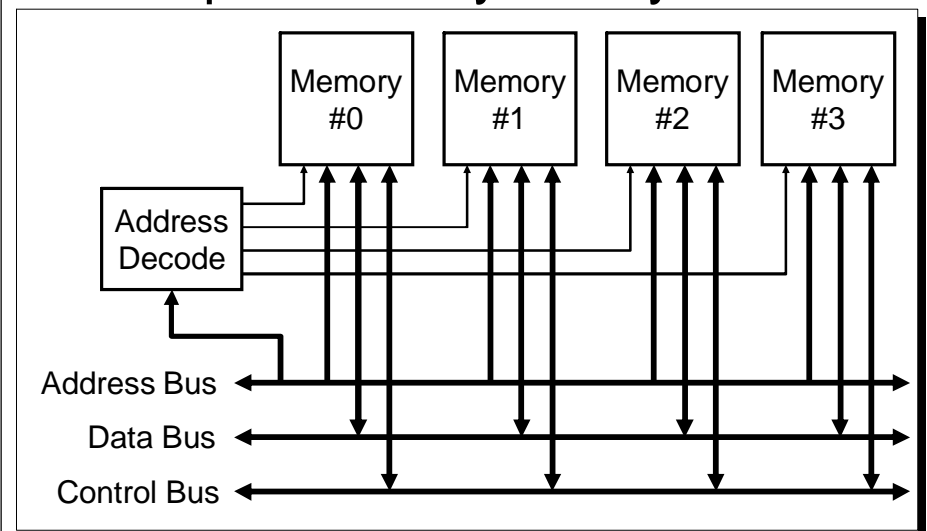
find the sub instructions out and put in a queue. (determine micro-codes)

sequence

at each time step execute the next sub-instruction in the queue



# Simple Memory Subsystems



## Memory Types

- A static RAM (SRAM) is a RAM which retains the stored information indefinitely as long as power is provided, regardless of whether the SRAM is accessed. The bits of stored information are stored in flip-flop like circuits.
- A dynamic RAM (DRAM) is a RAM in which every word location needs to be read periodically to prevent the stored information from disappearing. The bits of information are stored as charges on very small capacitors.
- DRAMs can store more information than SRAMs of the same chip size. DRAMs are cheaper per bit than SRAMs. However, SRAMs are faster to access than DRAMs.

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## Input/Output (IO) Systems

- To be able to do useful work, a microcomputer needs to exchange information with its environment.
- Input devices allow information to be transferred from the environment into the microcomputer.
  - Keyboard, for inputting ASCII-encoded symbols.
  - Mouse, for inputting positions and command selections.
  - Analogue-to-digital converters (ADCs), for converting measurements of analogue signals into digital quantities.
- Output devices allow information to be transferred from the microcomputer out to the environment.
  - Terminal Monitor (CRT), for displaying graphical data and ASCII-encoded symbols.
  - Printers, for producing hardcopy text and graphical output.
  - Digital-to-analogue converters (DACs), for producing controlled analogue signals.

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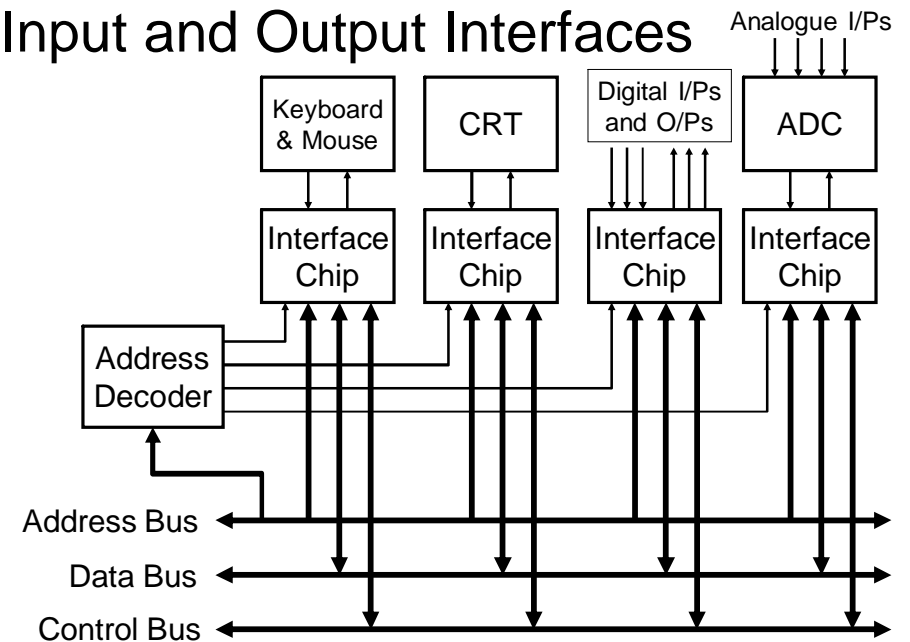
## Memory Types

- A ROM chip is a read-only memory that is programmed permanently at the factory by the manufacturer.
- A programmable ROM (PROM) is a read-only memory that can be programmed once using a chip programmer.
- An erasable PROM (EPROM) is a PROM that can be programmed using a chip programmer, and then erased through exposure to an ultraviolet light (UV) light source.
- Electrically erasable PROM (EEPROM) and flash memory are “read-only” memories that can actually be reprogrammed electrically (using a relatively slow procedure).

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## Input and Output Interfaces



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# Motorola Interface Chips

- MC6800 Family (8-bit data, synchronous system bus):
  - MC6821 Peripheral Interface Adaptor (PIA)
  - MC6840 Programmable Timer Module (PTM)
  - MC6843 Floppy Disk Controller (FDC)
  - MC6845 Cathode Ray Tube Controller (CRTC)
  - MC6850 Asynchronous Communications Interface Controller (ACIA)
- M68000 Family (8/16/32-bit data, semi-synchronous system bus):
  - MC68120 Intelligent Peripheral Controller
  - MC68175 VME Bus Controller
  - MC68454 Intelligent Multiple Bus Controller
  - MC68488 General Purpose Interface Adaptor
  - MC68681 Dual Asynchronous Receiver/Transmitter(DUART)
  - MC68590/802 Ethernet Controller chip set

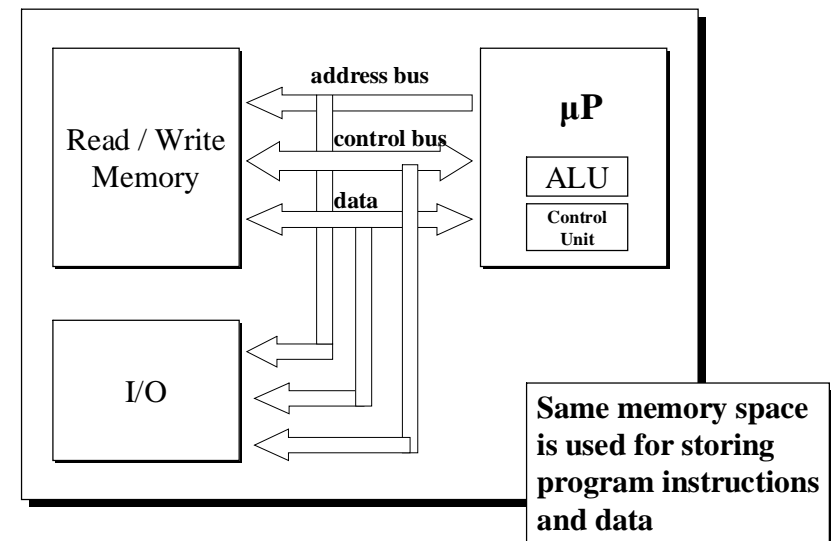
# The Von Neumann Bottleneck

- John von Neumann was an early pioneer in the study of programmability and the architecture of computers.
- Von Neumann was an advocate of the advantages of storing both programs and data in the same memory unit.
  - This simplifies the architecture.
  - Makes it possible to process programs as data.
  - Simplifies the design of compilers, assemblers, etc.
  - Allows for self-modifying programs.
- One disadvantage of the “single bus” or “von Neumann” architecture is that computer performance is limited by the necessity to pass all program and data over restricted number of wires on the bus.
- In modern integrated circuits, the system bus operates at much slower data rates than the logic inside the chips.

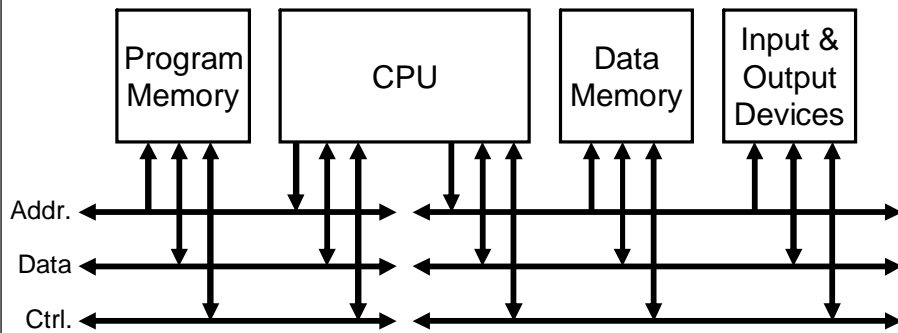
# Computer Architectures

## Von Neumann and Harvard Architectures

# Von Neumann Architecture



## Two Bus Harvard Architecture



- Two busses are used for increased execution speed.
- The von Neumann bottleneck is widened.
- Program instructions and data can be fetched in parallel.

## Von Neumann - Harvard Architectures

