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Computer Engineering 1

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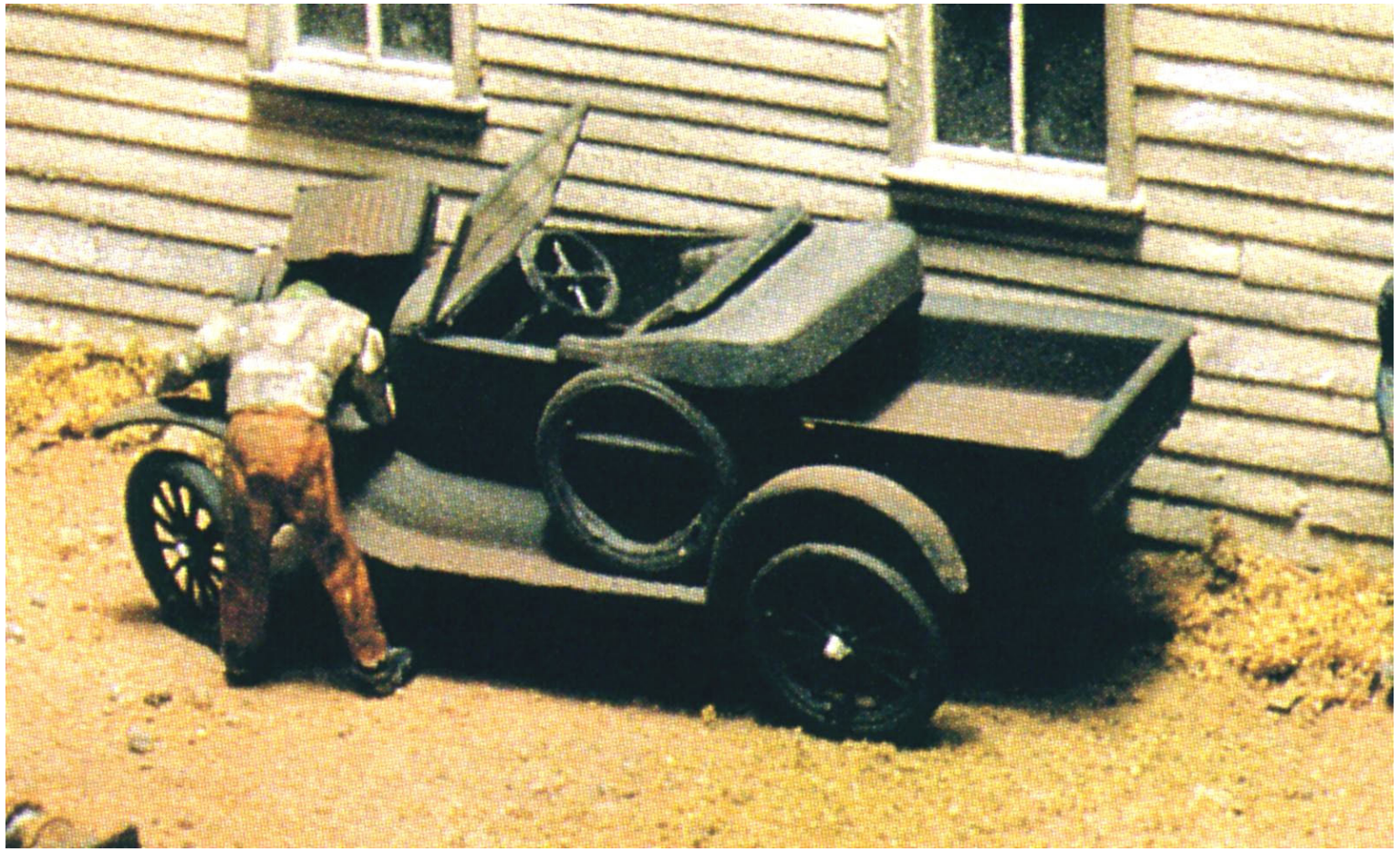
Motivation

- **See what's inside**



Todays Agenda

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- What is Computer Engineering?
- Course Content and Organization
- Computer History
- Properties of a Computer System
- von Neumann Architecture
- Hardware Components
  - CPU, Memory, Input/Output, System Bus
- Software Aspects
  - from C to executable
- Interaction of Hardware and Software

What is Computer Engineering?

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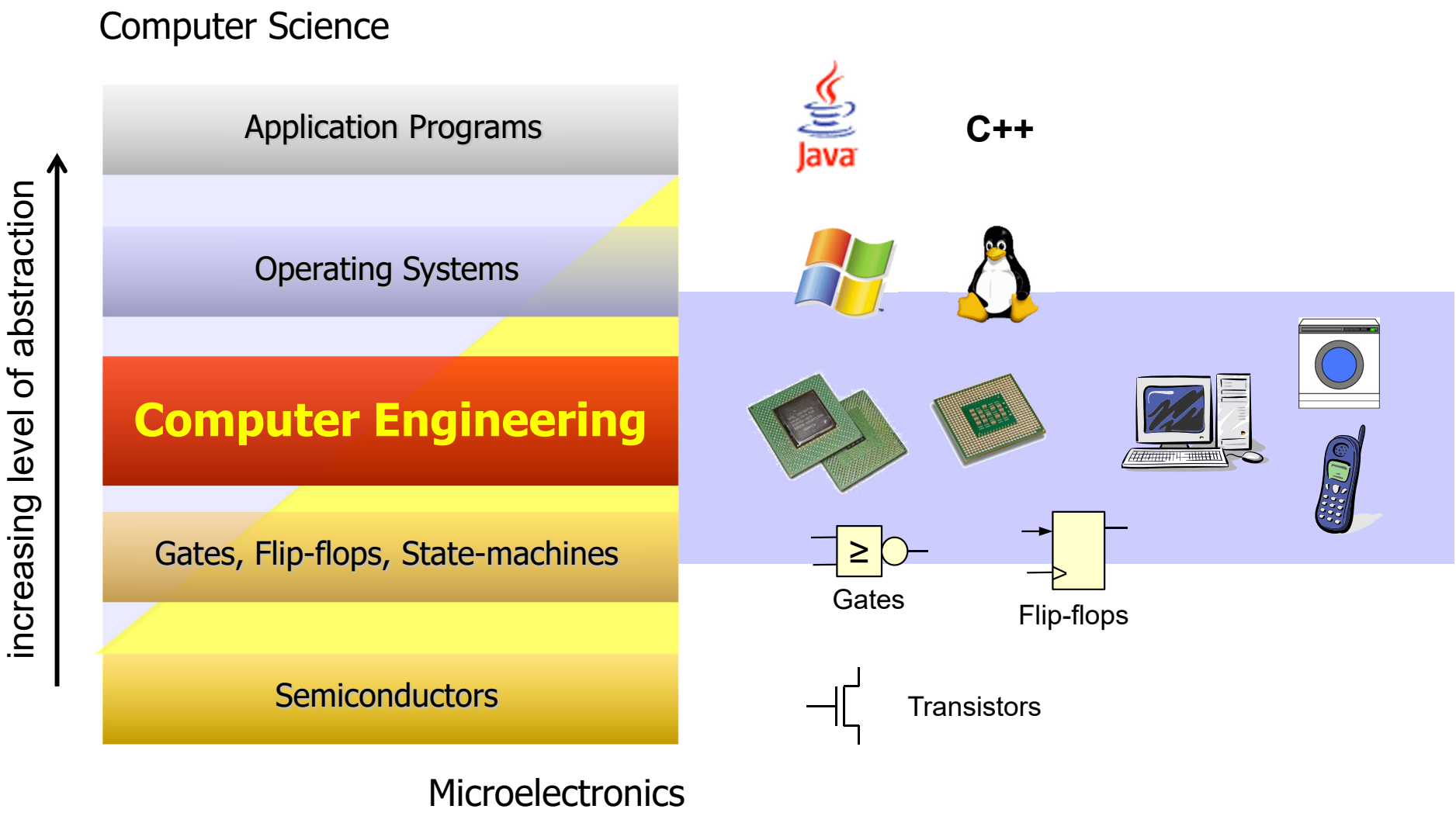
- **Computer Engineering** (Technische Informatik)
  - architecture and organization of computer systems
  - combines hardware and software to implement a computer
- Where **Microelectronics** and **Software** meet
  - 70 years of computer hardware
    - 1940s relay / vacuum tubes
    - 1950s transistors
    - 1970s integrated circuits (CMOS[1)])
  - 40 years of software → Computer Science
    - Assembly Language ("Assembler")
    - High Level Language (e.g. C, ...)
    - Object Oriented Programming (C++, Java, ...)
    - Visual Programming (Model Driven Design)

[1)] Complementary metal–oxide–semiconductor

What is Computer Engineering?



Applications

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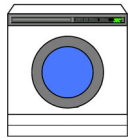
- **Embedded Systems**
  - often part of a larger system
  - control of devices, facilities, processes
  - wireless sensor networks (WSN)
- **Information Technology**
  - communication networks
  - processing of data
  - multimedia
- **Tools**
  - support of technical and scientific activities
  - simulation and modeling
  - logging and analysis of measurement data



Objectives CT 1

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After the course you will be able to

- describe the architecture and the operation of a basic computer system and a processor
- to explain how instructions are executed
- to describe the main architectures and performance features of processors as well as the concept of pipelining
- to comprehend how structures in C are compiled into executable object code and to use this knowledge to eliminate programming errors and to optimize program performance
- to develop, debug and verify basic hardware-oriented programs in C and in assembly language
- to explain the concept of interrupts and exceptions and to implement basic interrupt applications
- to find their way in other microprocessor systems

Course Content CT 1

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- **Organization of computer systems**
  - Representation of information
  - Program translation
  - Architecture: CPU, Memory, I/O, Bus
- **CPU: Principle of Operation**
  - Instruction set
  - Program execution
  - Memory map, little endian vs. big endian
- **Data transfer**
  - Addressing modes
  - Integer data types, arrays, pointers
- **Arithmetic and logic operations**
  - Computing with the ALU
  - Integer casting
- **Control flow**
  - Compare and jump instructions
  - Structured programming
- **Machine code**
  - Encoding of instructions and operands
- **Subroutines/functions**
  - Parameter passing
- **Exceptional Control Flow**
  - Hardware interrupts, interrupt service routine, vector table
  - Exceptions (Traps)
- **Linking**
  - Address Resolution and Relocation
  - Linker Map and Symbol Table
  - Static Linking vs. Dynamic Linking
- **Processor architectures**
  - von Neumann vs. Harvard, Pipelining
- **Hardware-oriented programming labs**
  - Working with cross-compiler, assembler, linker, loader and debugger

Objectives for Today's Lesson

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You will be able to

- outline and explain the function of a simple computer system
- name the four main hardware components of a computer system and to describe their functions
- describe different forms of memory and storage
- recall and explain the four translation steps from source code in C to an executable program
- comprehend the use of target and host during development
- explain why knowledge of assembly language is important

Computer History

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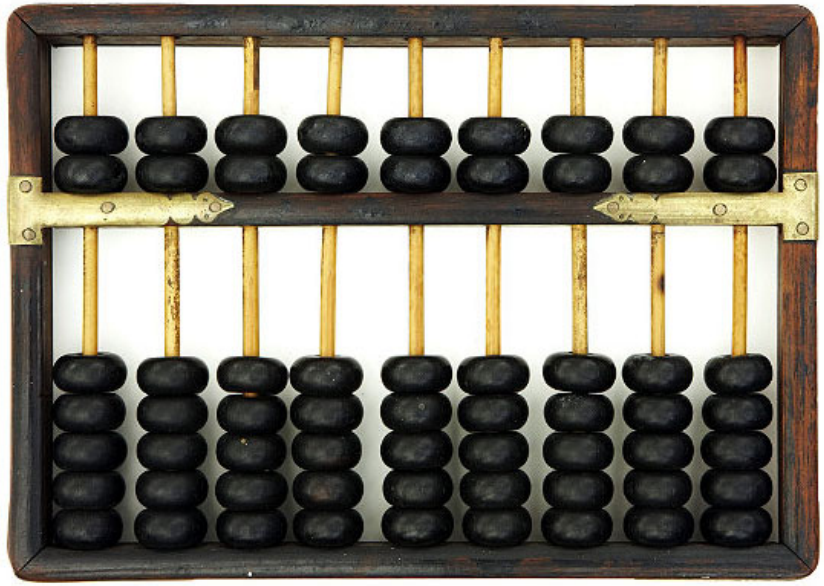
- **Support for calculations**
  - Babylonian / Chinese — between 1000 und 500 BC: Abacus
  - John Napier — beginning AD 1600: tables for multiplications and logarithms



Abacus from *www.computerhistory.org*

Napier's Bones from *www.computerhistory.org*

Computer History

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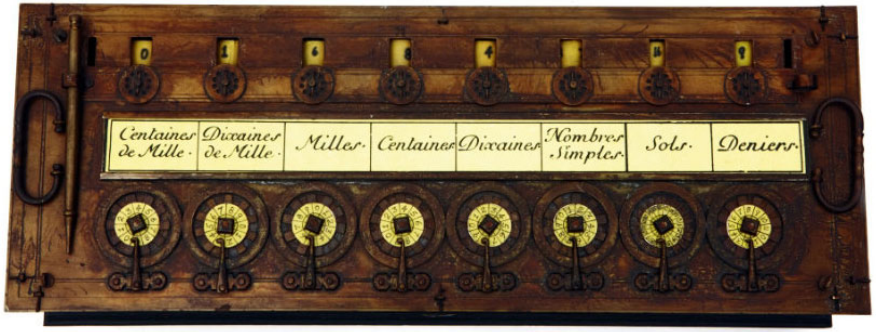
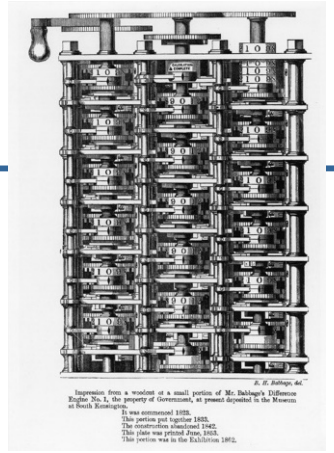
- **First mechanical computers: + - (* /)**
  - Leonardo da Vinci (1452 - 1519)
    - around 1500 → rebuilt successfully in 1967
  - Wilhelm Schickard (1592 - 1635)
    - around1625 → no preserved originals, rebuilt
  - **Blaise Pascal (1623 - 1662)**
    - around 1640 → arithmetic machine (Pascaline)
  - Gottfried von Leibnitz (1646 -1716)
    - → enhancement of arithmetic machine



replica of a Pascaline from *www.computerhistory.org*

Computer History



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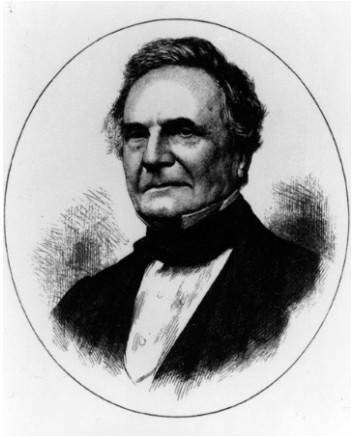
- **First mechanical computer in today's sense**
  - Charles Babbage
    - around 1822 "Difference Engine", not completed
    - replaced by "Analytical Machine"
  - Ada Lovelace
    - Mathematician
    - wrote programs for the Analytical Machine
    - Daughter of Lord Byron



Computer History

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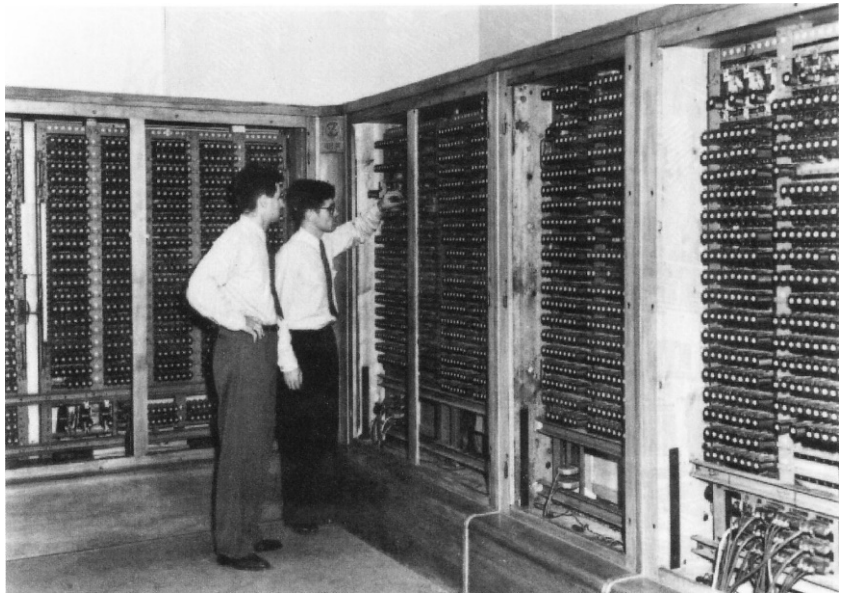
- **First electromechanical computers**
  - Howard H. Aiken
    - Harvard Mark 1, between 1939 and 1944
    - consisting of switches, relays
    - around 750'000 components:
    - 15m x 2.4m x 0.6m, 4500 kg
  - Konrad Zuse, Germany
    - Z3, built in 1941 in Berlin
    - 1944 destroyed by bombing
    - work on Z4 started around 1943
    - used at the ETH from 1950 on



Computer History

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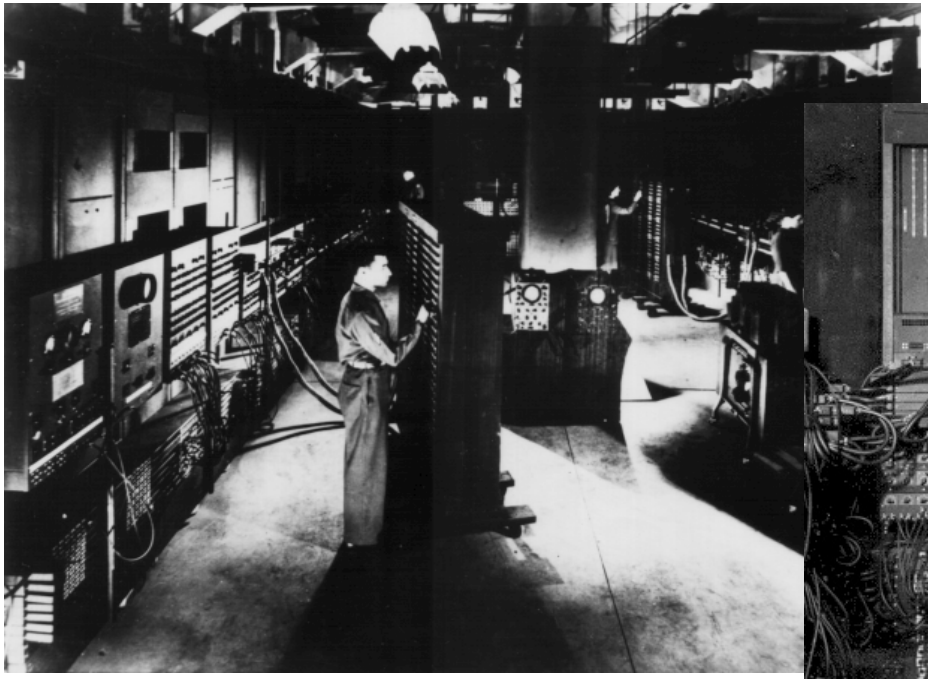
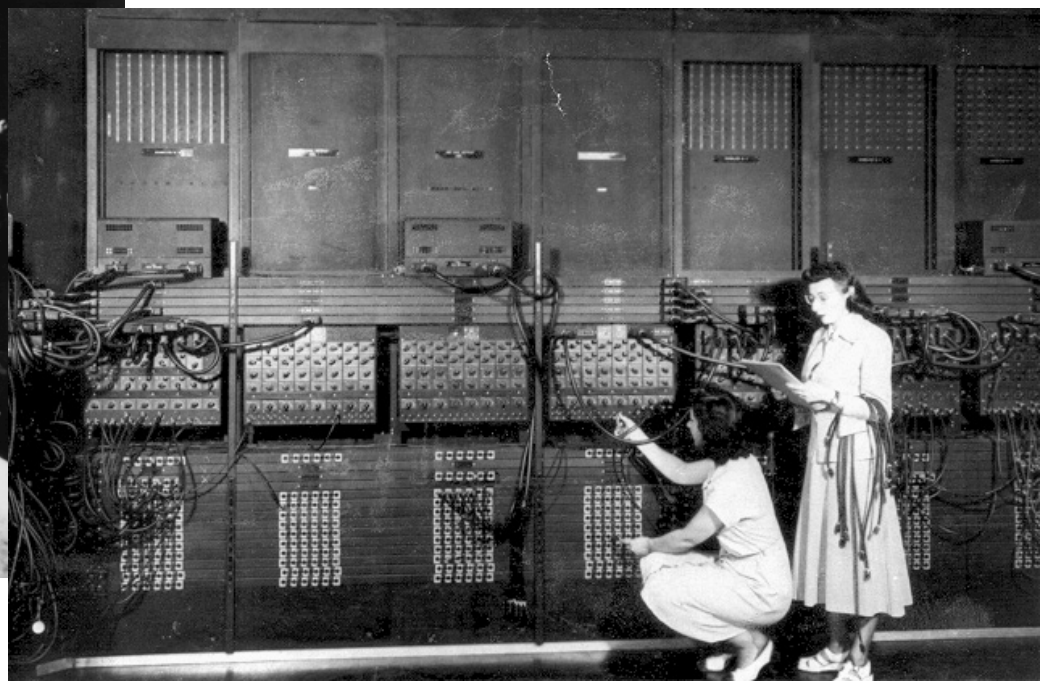
- **First electronic "general purpose" computer**
  - J. Presper Eckert and John Mauchly, Univ. of Pensylvenia
    - ENIAC, 1944 → Electronic Numerical Integrator And Calculator
    - around 18'000 tubes, 30 tons, 140 kW, 5'000 additions / s, 1400 m^2





Computer History

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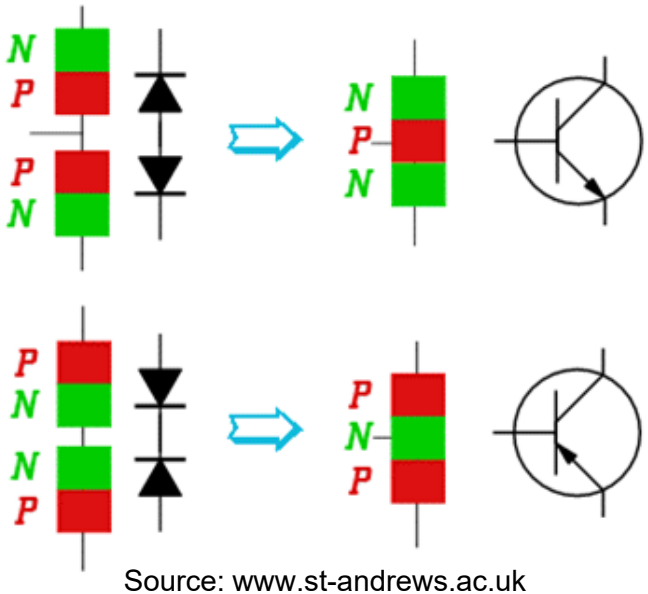
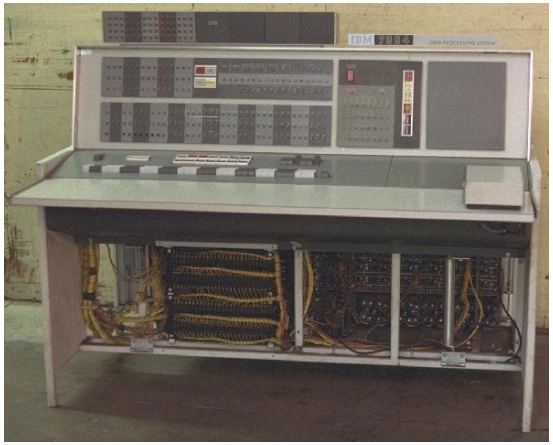
- **First transistors**
  - 1926, patent by Julius Edgar Lilienfeld
  - 1947, Germanium transistor
    - W. Shockley, W. Brattain, J. Bardeen
  - 1950, Bipolar Transistor
    - William Shockley



Source: www.st-andrews.ac.uk

- **Early transistor-based computers**
  - around 1957
    - DEC PDP-1
    - IBM 7000
    - NCR & RCA



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- **Early integrated circuits (IC)**
  - 1958, Jack Kilby at Texas Instruments (TI)
    - based on an idea from 1952
    - several components on the same substrate
  - 1963, Fairchild, "the 907 device"
    - 2 logic gates
  - 1967, Fairchild, "Micromosaic"
    - several 100 transistors
  - 1970, Fairchild
    - first 256-bit static RAM

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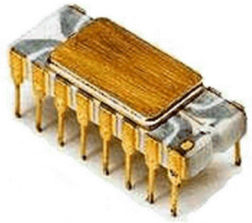
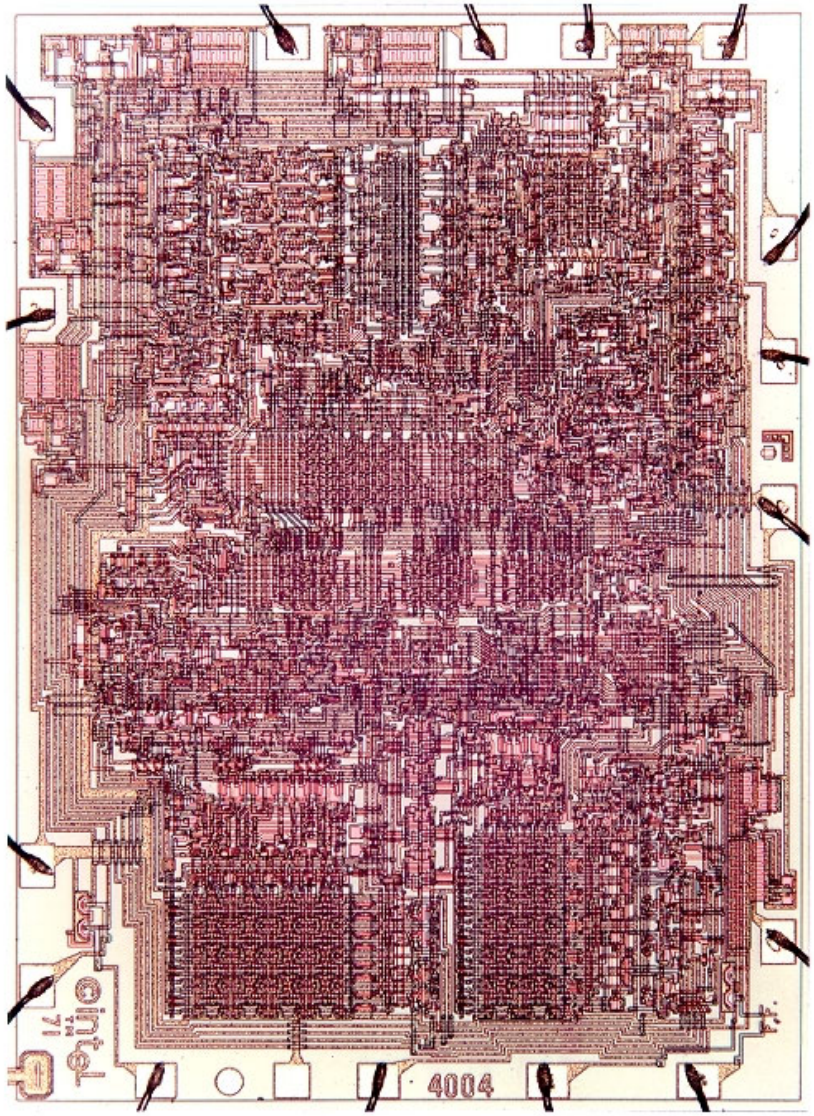
- **Early microprocessors**
  - 1971, Intel 4004
    - all CPU components on a single chip
    - 4 Bit, 2300 transistors
    - 12mm^2 (3x4 mm)
  - 1972, Intel 8008
    - 8-bit version of the 4004





Where are we today?

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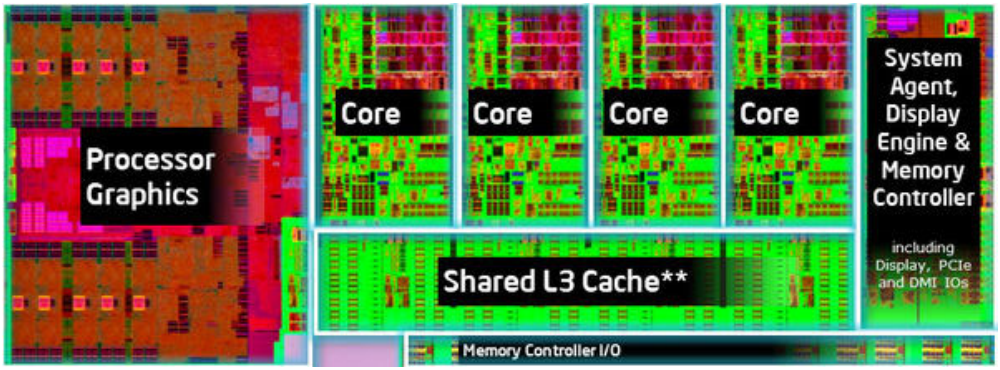
- **Intel Core i7 quad core**
  - Name Haswell
  - ~1600 Mio. transistors
  - ~177 mm^2
  - 3.5 GHz
  - 22nm gate length



- **Area**
  - $A_{i7} = \sim 15 \cdot A_{4004}$

- **Transistors**
  - $T_{i7} = \sim 695'000 \cdot T_{4004}$

Moore's Law

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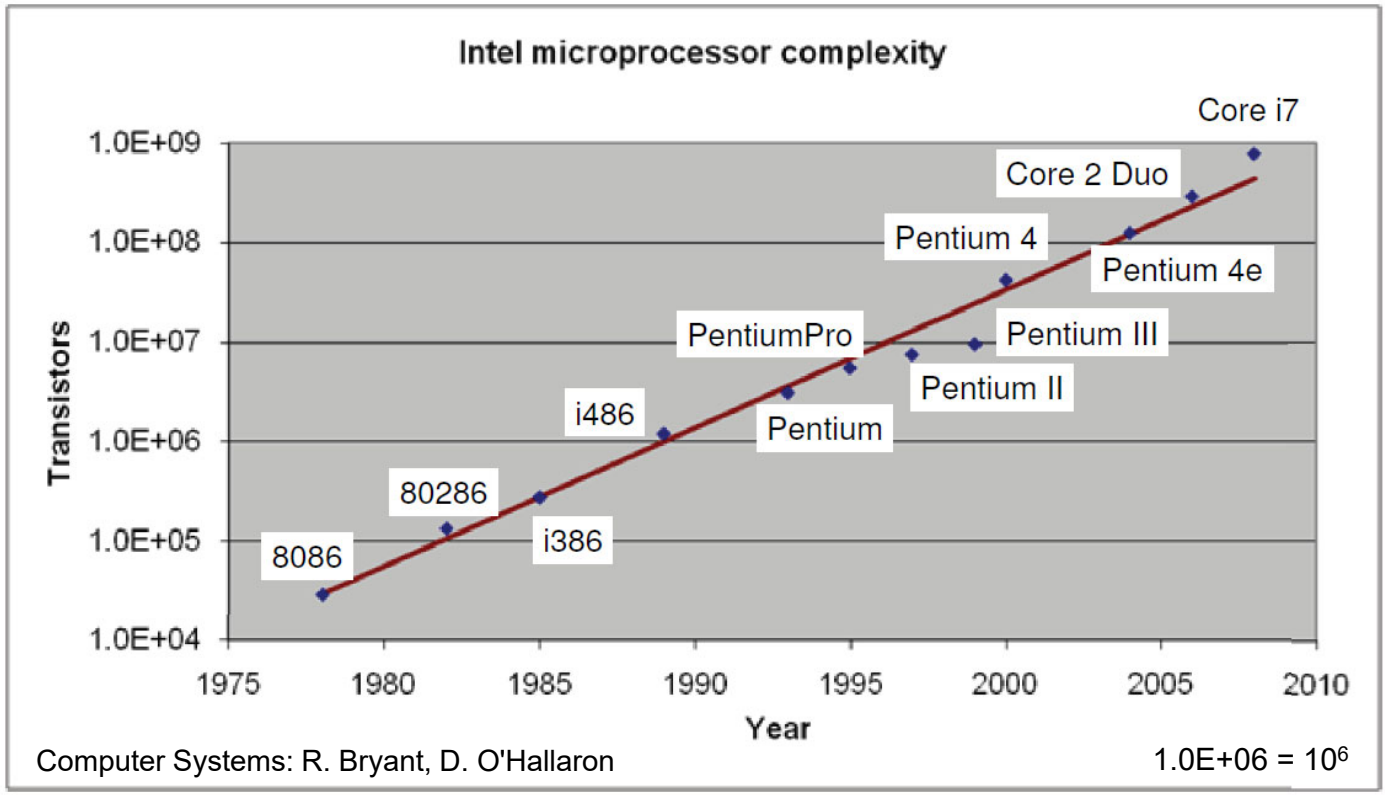
- **Gordon Moore, Intel**
  - 1965: "The number of transistors per IC doubles every year"
  - somewhat slower since 1975 → doubles every 18 months
  - i.e. exponential growth



Properties of a Computer System

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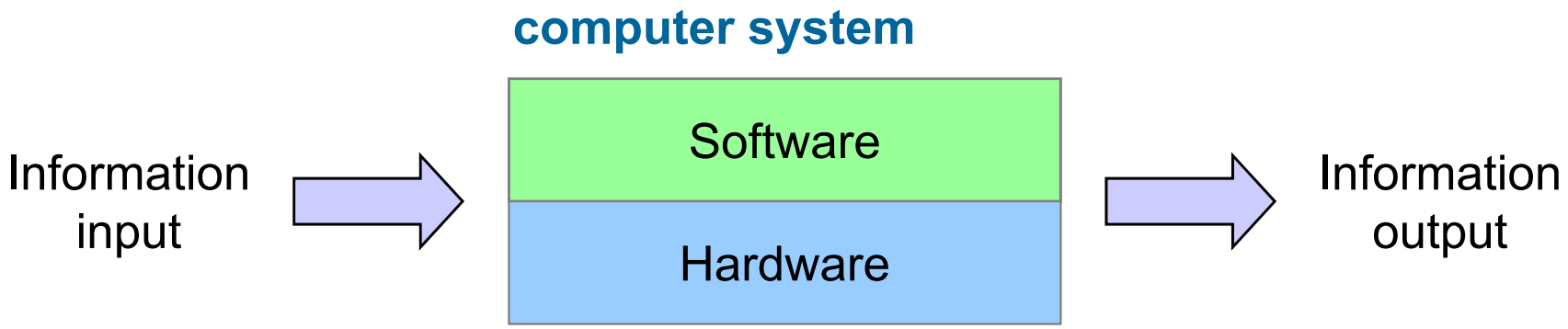
- **A computer system is a device that**
  - processes input
  - takes decisions based on the outcome
  - and outputs the processed information
- **Hardware and software work together → application**
  - often a common hardware is used for many different applications
  - application is defined by the software
    - e.g. controls for washing machines, vending machines, ….



Properties of a Computer System

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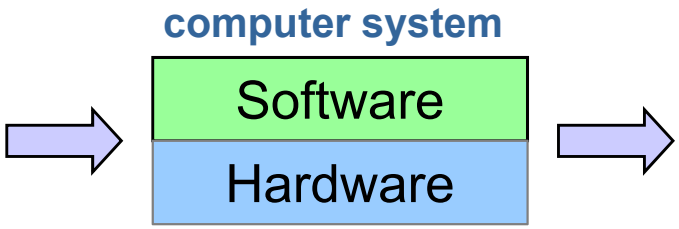
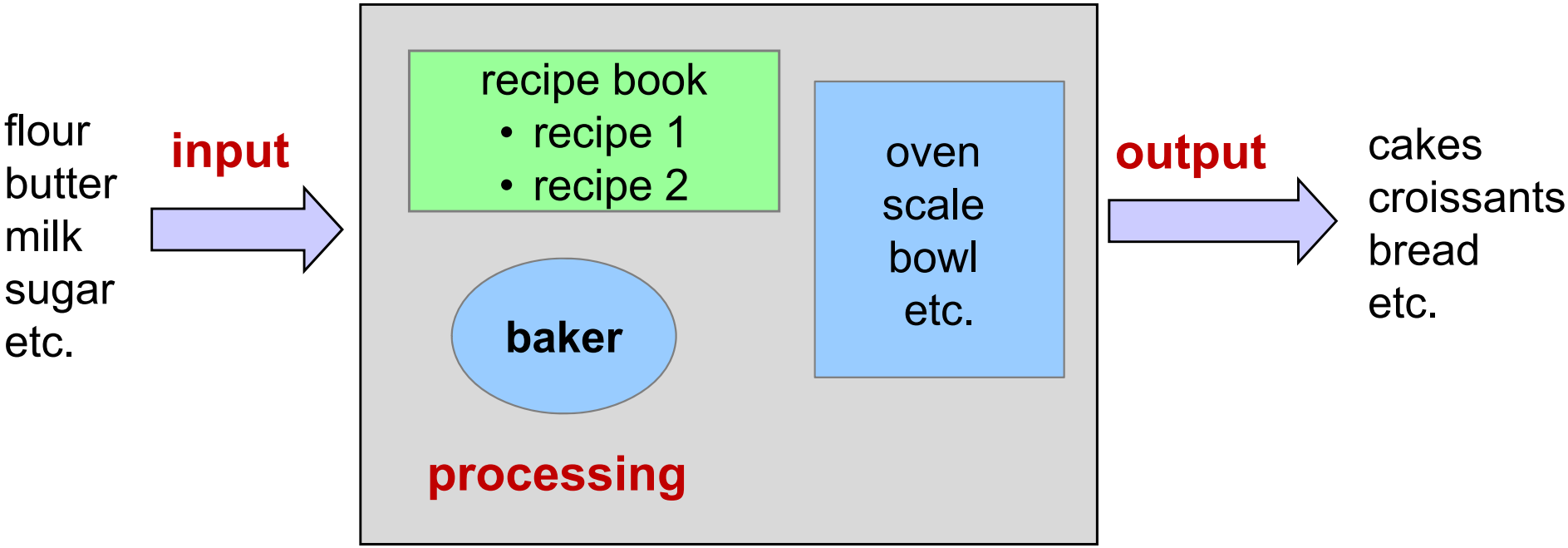
- **Analogy → bakery**
  - baker ↔ processor
  - recipe book ↔ software
  - tools ↔ HW-resources





von Neumann Architecture

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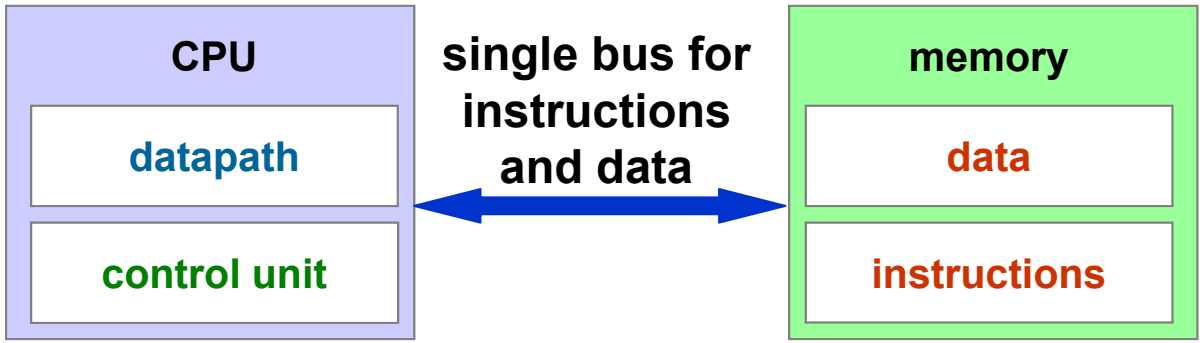
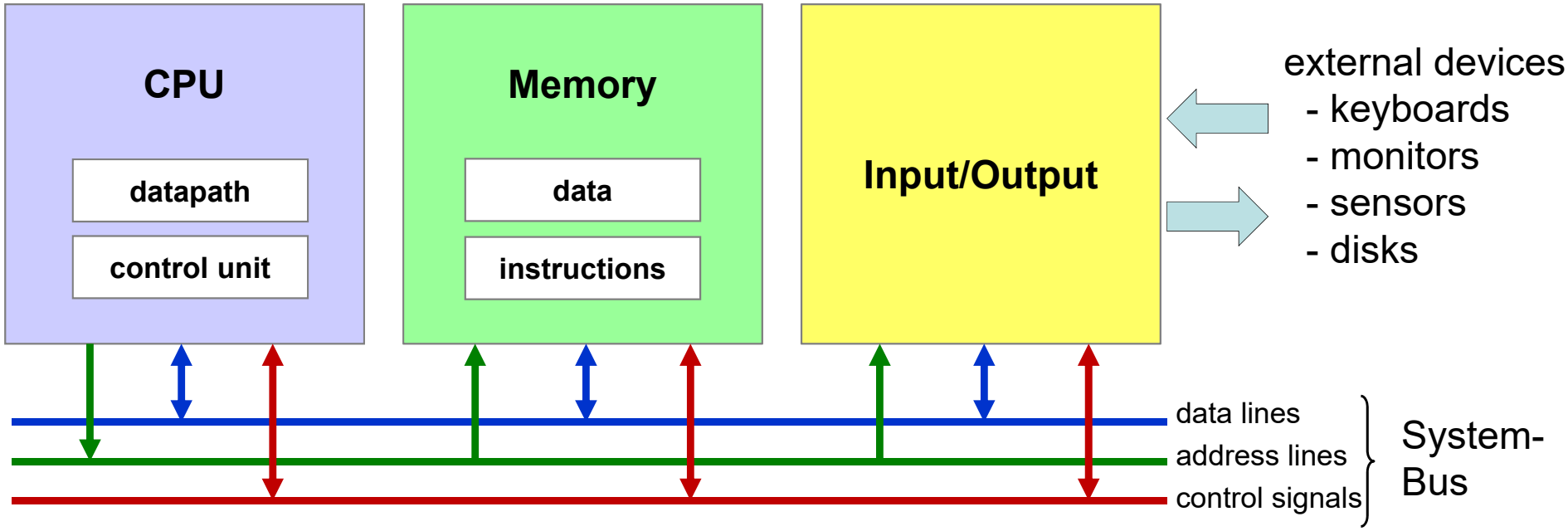
- **Many of today's computers are based on ideas of John von Neumann in the year 1945**
- **Properties**
  - **instructions** and **data** are stored in the same memory
  - **datapath** executes arithmetic and logic operations and holds intermediate results
  - **control unit** reads and interprets instructions and controls their execution

Von Neumann in the 1940s
en.wikipedia.org

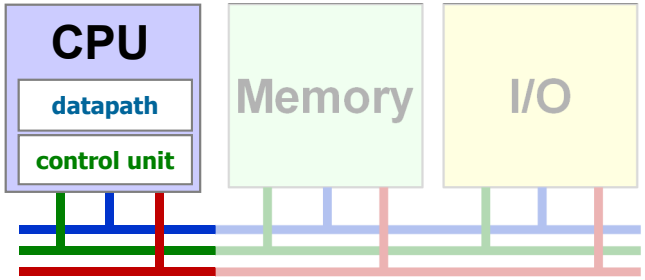


Hardware Components

- **CPU** — **Central Processing Unit or processor**
- **Memory** — **stores instructions and data**
- **Input / Output** — **interface to external devices**
- **System-Bus** — **electrical connection of blocks**



HW Components: CPU



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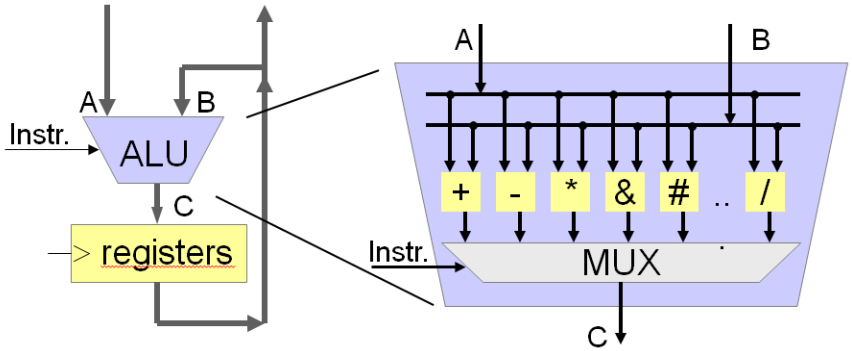
Datapath

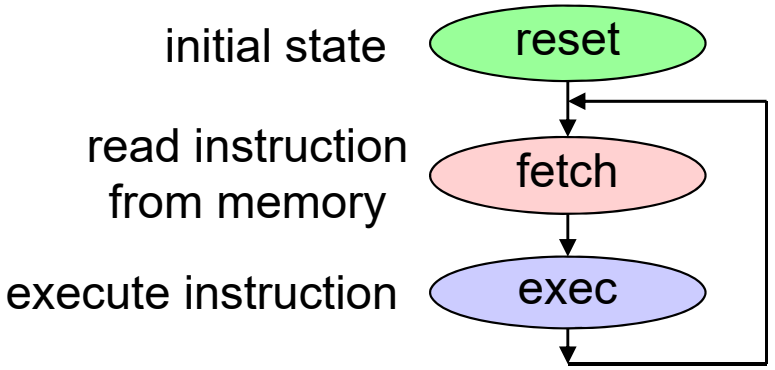
- ALU: Arithmetic and Logic Unit
  - performs arithmetic/logic operations



- registers
  - fast but limited storage inside CPU
  - hold intermediate results
- 4 / 8 / 16 / 32 / 64 bits wide

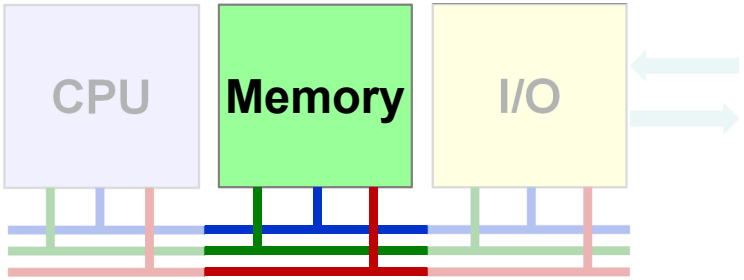
Control Unit

- Finite State Machine (FSM)
  - reads and executes instructions



- types of operations
  - data transfer: registers ←→ memory
  - arithmetic and logic operations
  - jumps

HW Components



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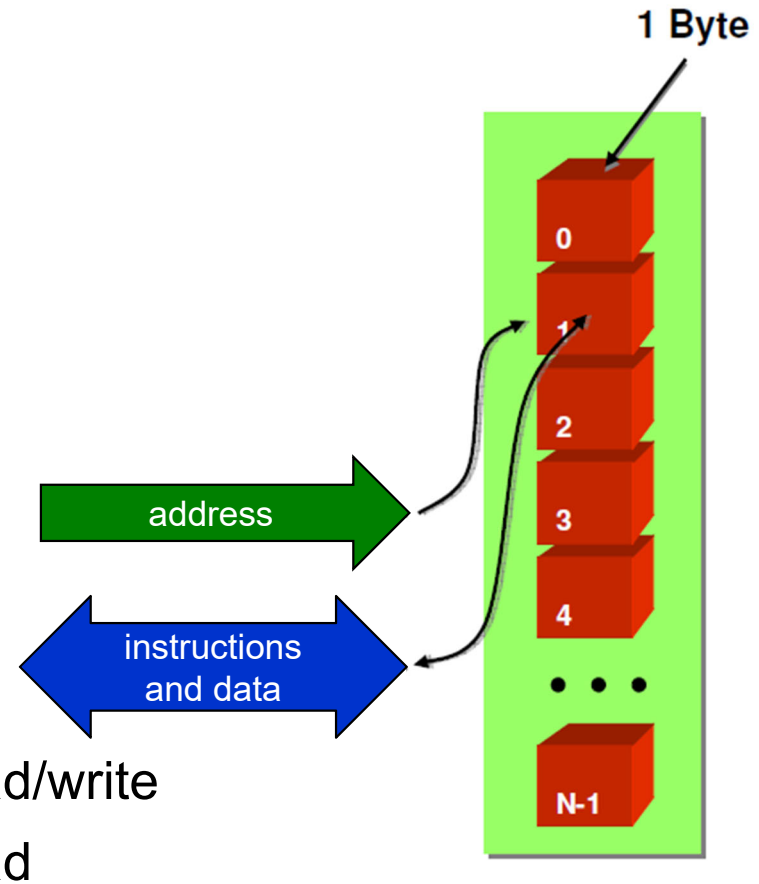
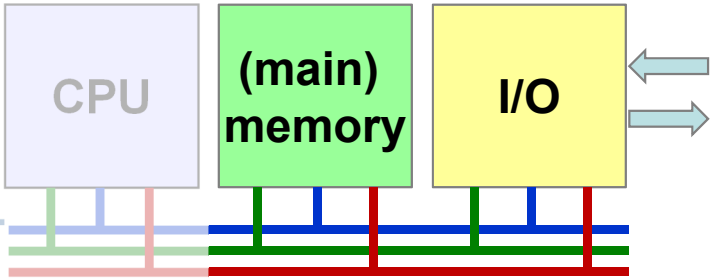
- **Memory**
  - a set of storage cells
    - 8 bit → 1 byte
  - smallest addressable unit
    - one byte
    - one address per byte
  - 2^N addresses
    - from 0 to 2^N-1
    - can be read and sometimes written
    - RAM Random Access Memory read/write
    - ROM Read Only Memory read



HW Components



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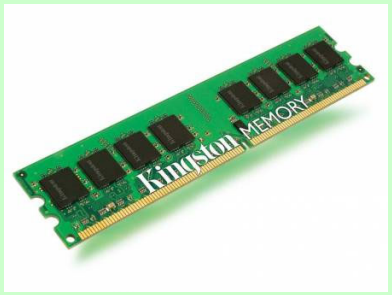
Main memory - Arbeitsspeicher

- central memory
- connected through System-Bus
- access to individual bytes
- volatile (flüchtig)
  - SRAM – Static RAM
  - DRAM – Dynamic RAM
- non-volatile (nicht-flüchtig)
  - ROM factory programmed
  - flash in system programmable



Secondary storage

- long term or peripheral storage
- connected through I/O-Ports
- access to blocks of data
- non-volatile
- slower but lower cost
  - magnetic hard disk, tape, floppy
  - semiconductor solid state disk
  - optical CD, DVD
  - mechanical punched tape/card

HW Components

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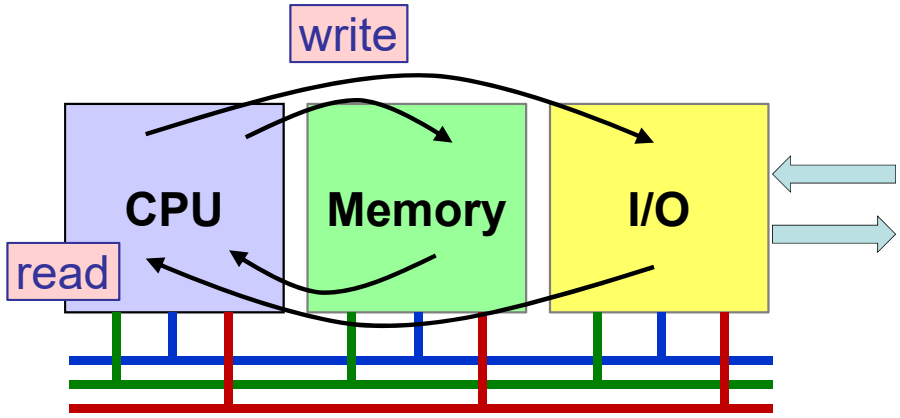
- **System-Bus**
  - CPU writes or reads data from/to memory or I/O



  - **address lines**
    - CPU drives the desired address onto the address lines
      - ▶ to which address does the CPU write?
      - ▶ from which address does the CPU read?
      - ▶ analogy → address on an envelope of a letter
    - number of addresses = 2^n → n = number of address lines
      - ▶ n = 16 → 2^{16} = 65'536 addresses → 64 KBytes
      - ▶ n = 20 → 2^{20} = 1'048'576 addresses → 1 MBytes

HW Components

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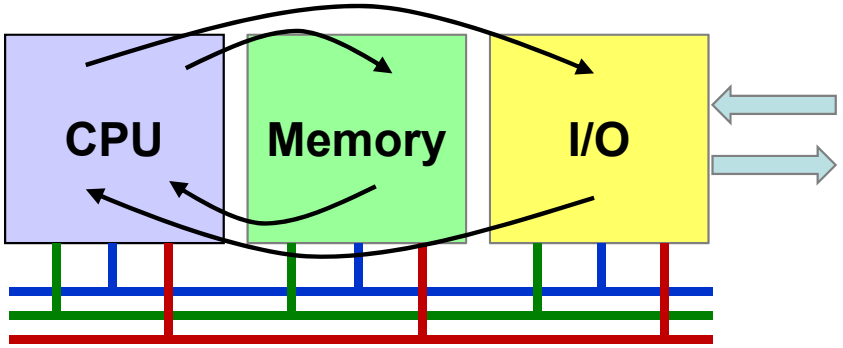
… System-Bus



- **control signals**
  - CPU tells whether the access is read or write
  - CPU tells when address and data lines are valid → bus timing
- **data lines**
  - transfer of data
    - ▶ analogy the letter that's inside the envelope
    - ▶ write CPU provides data → memory receives data
    - ▶ read CPU receives data ← memory provides data
  - 4/8/16/32/64 data lines

HW Components

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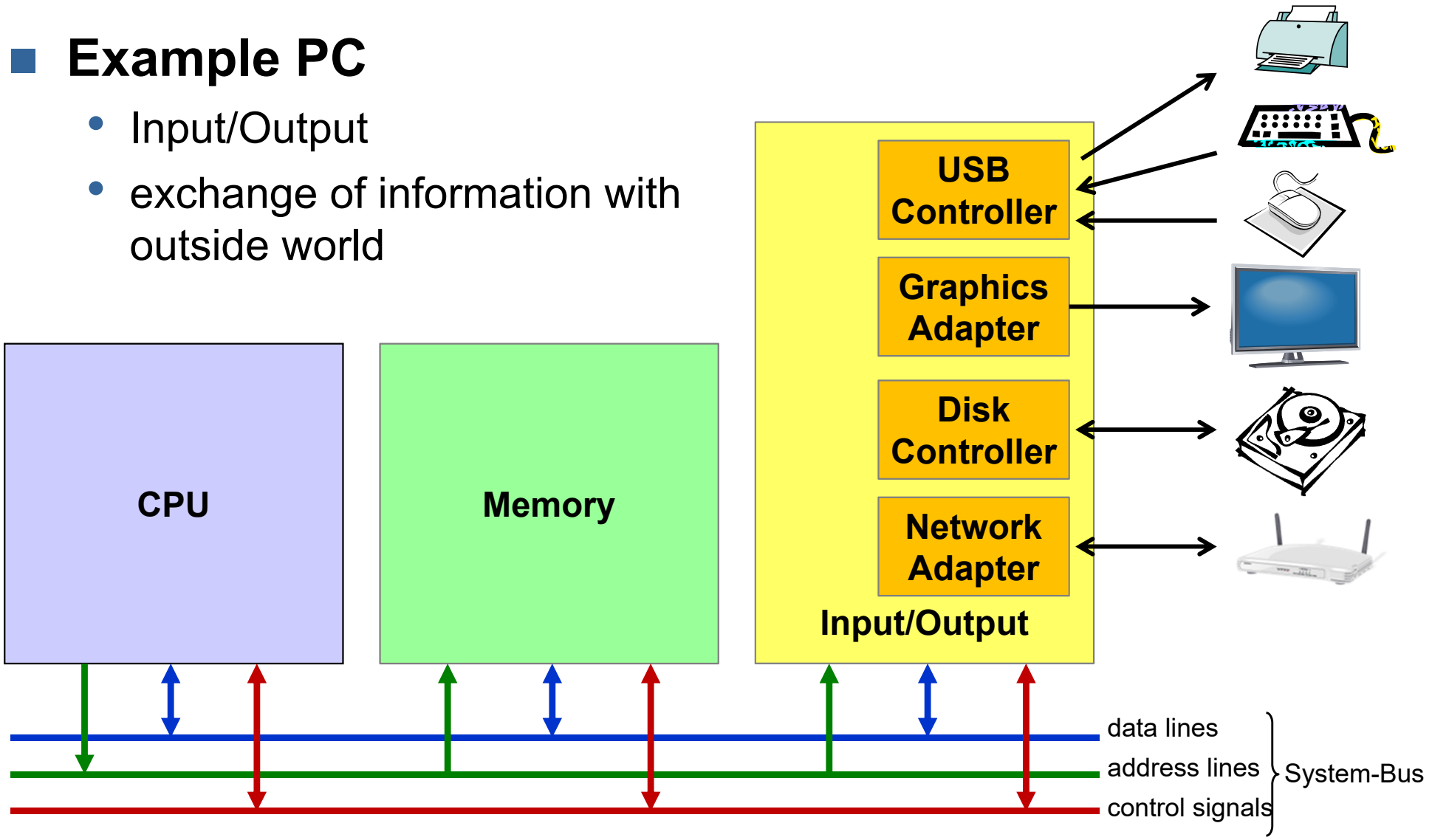
- **Example PC**
  - Input/Output
  - exchange of information with outside world



HW Components

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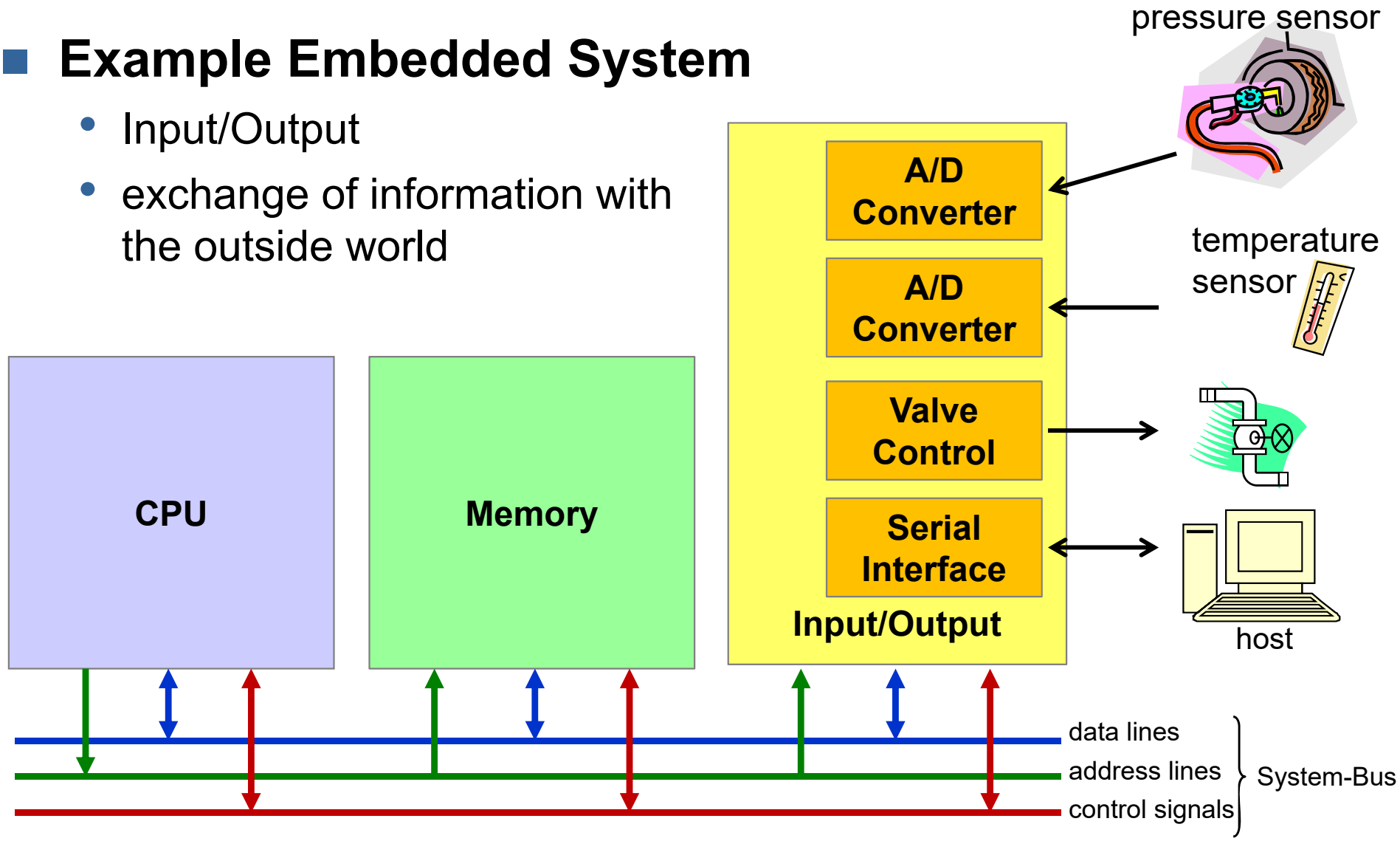
- **Example Embedded System**
  - Input/Output
  - exchange of information with the outside world



Software Aspects

So far

- CPU reads instructions from memory and executes them

But

- How to process a program in a high level language like C so that a CPU can interpret the instructions?
- What is needed for a program in C to allow execution on a CPU?
- What does the path from the C source code to the executable object file look like?

Software Aspects

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- **Programmer writes `main.c` in text editor**

`main.c`

```
#include "utils_ctboard.h"

#define LED_ADDR    0x60000100
#define LED_VALUE   0x12

int main(void)
{
    while (1) {
        write_byte(LED_ADDR, LED_VALUE);
    }
}
```

calls function **`write_byte()`** from module *utils_ctboard*

Software Aspects

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- **`main.c` is stored in ASCII / Unicode format on disk**

```
#include "utils_ctboard.h"

#define LED_ADDR     0x60000100
#define LED_VALUE    0x12

int main(void)
{
    while (1) {
        write_byte(LED_ADDR, LED_VALUE);
    }
}
```

23696E636C756465202275746 96C735F
6374626F6172642E68220D0A0D0A2364
6566696E65204C45445F414444522020
.....

Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char
0	00	Null	32	20	Space	64	40	@	96	60	`
1	01	Start of heading	33	21	!	65	41	A	97	61	a
2	02	Start of text	34	22	"	66	42	B	98	62	b
3	03	End of text	35	23	#	67	43	C	99	63	c
4	04	End of transmit	36	24	$	68	44	D	100	64	d
5	05	Enquiry	37	25	%	69	45	E	101	65	e
6	06	Acknowledge	38	26	&	70	46	F	102	66	f
7	07	Audible bell	39	27	'	71	47	G	103	67	g
8	08	Backspace	40	28	(	72	48	H	104	68	h
9	09	Horizontal tab	41	29	)	73	49	I	105	69	i
10	0A	Line feed	42	2A	*	74	4A	J	106	6A	j
11	0B	Vertical tab	43	2B	+	75	4B	K	107	6B	k
12	0C	Form feed	44	2C	,	76	4C	L	108	6C	l
13	0D	Carriage return	45	2D	-	77	4D	M	109	6D	m
14	0E	Shift out	46	2E	.	78	4E	N	110	6E	n
15	0F	Shift in	47	2F	/	79	4F	O	111	6F	o
16	10	Data link escape	48	30	0	80	50	P	112	70	p
17	11	Device control 1	49	31	1	81	51	Q	113	71	q
18	12	Device control 2	50	32	2	82	52	R	114	72	r
19	13	Device control 3	51	33	3	83	53	S	115	73	s
20	14	Device control 4	52	34	4	84	54	T	116	74	t
21	15	Neg. acknowledge	53	35	5	85	55	U	117	75	u
22	16	Synchronous idle	54	36	6	86	56	V	118	76	v
23	17	End trans. block	55	37	7	87	57	W	119	77	w
24	18	Cancel	56	38	8	88	58	X	120	78	x
25	19	End of medium	57	39	9	89	59	Y	121	79	y
26	1A	Substitution	58	3A	:	90	5A	Z	122	7A	z
27	1B	Escape	59	3B	;	91	5B	[	123	7B	{
28	1C	File separator	60	3C	<	92	5C	\	124	7C	|
29	1D	Group separator	61	3D	=	93	5D	]	125	7D	}
30	1E	Record separator	62	3E	>	94	5E	^	126	7E	~
31	1F	Unit separator	63	3F	?	95	5F	_	127	7F	□

→ 0x23
i → 0x69
n → 0x6E
c → 0x63
....

Software Aspects

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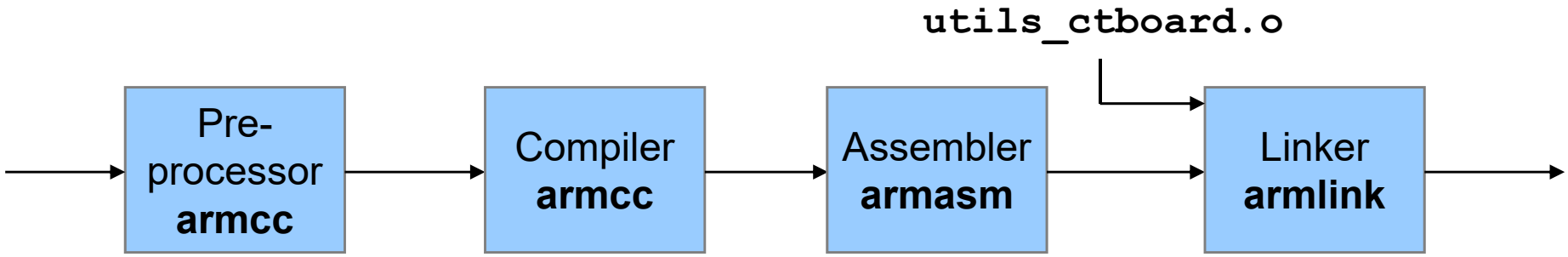
From C to executable

- Translation of **`main.c`** into machine language



`main.c`	`main.i`	`main.s`	`main.o`	`main.axf`
Source program (text)	*Modified source program (text)*	*Assembly program (text) human-readable, CPU specific*	*Relocatable object program (binary)*	*Executable object program (binary)*

Software Aspects

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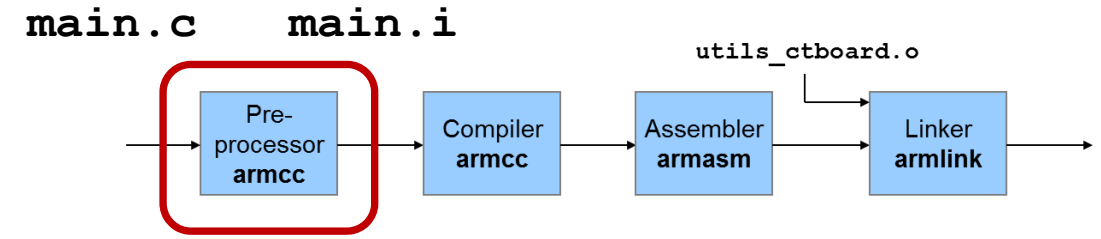
- **Preprocessor**
  - Text processing
  - Pasting of #include files
  - Replacing macros (#define)



pasting included content of included files

main.c

```
#include "utils_ctboard.h"

#define LED_ADDR    0x60000100
#define LED_VALUE   0x12

int main(void)
{
    while (1) {
        write_byte(LED_ADDR, LED_VALUE);
    }
}
```

main.i

```
void write_byte(uint32_t address,
                uint8_t data);

int main(void)
{
    while (1) {
        write_byte(0x60000100, 0x12);
    }
}
```

replacing macros

Software Aspects

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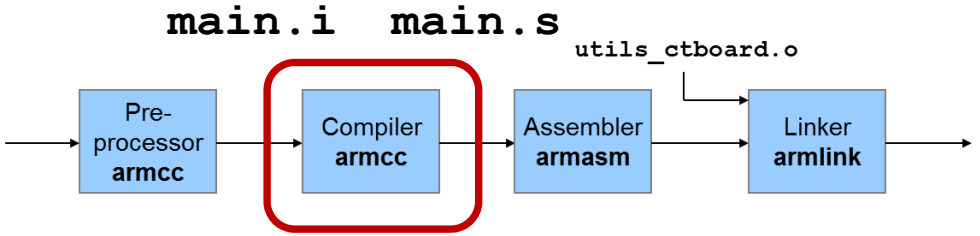
- **Compiler**
  - Translate CPU-independent C-code into CPU-specific assembly code



main.c

```
void write_byte(uint32_t address,
                uint8_t data);

int main(void)
{
    while (1) {
        write_byte(0x60000100, 0x12);
    }
}
```

main.s

```
 AREA .text, CODE, READONLY

main      PROC
          B         endloop

mloop     MOVS      r1,#0x12
          LDR       r0,L112
          BL        write_byte

endloop   B         mloop
          ENDP

L112      DCD       0x60000100
```

human readable

Software Aspects

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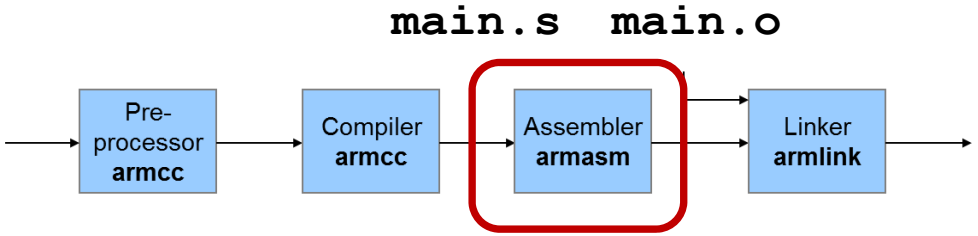
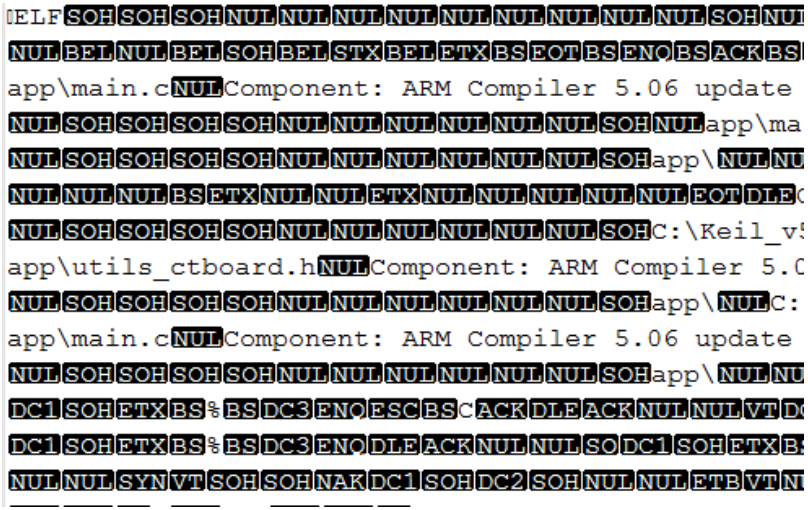
- **Assembler**
  - Translate to machine instructions
  - Result: Relocatable object file
  - Binary file → not readable with text editor, use Hex Dump



main.s

```
 AREA .text, CODE, READONLY

main      PROC
          B         endloop

mloop     MOVS      r1,#0x12
          LDR       r0,L112
          BL        write_byte

endloop   B         mloop
          ENDP

L112      DCD       0x60000100
```

main.o



Software Aspects

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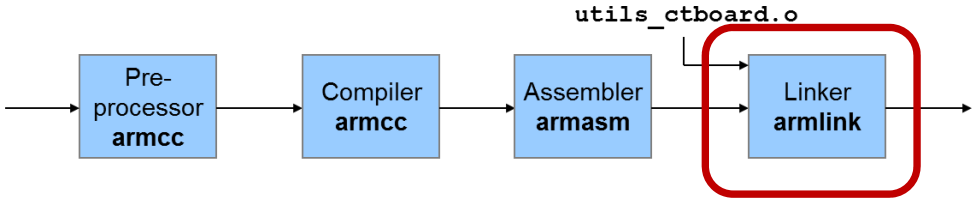
- **Linker**
  - Merge object files
  - Resolve dependencies and cross-references
  - Create executable



utils_ctboard.o

main.o

main.axf

remember: **`main()`** calls function **`write_byte()`** from module *utils_ctboard*

Software Aspects

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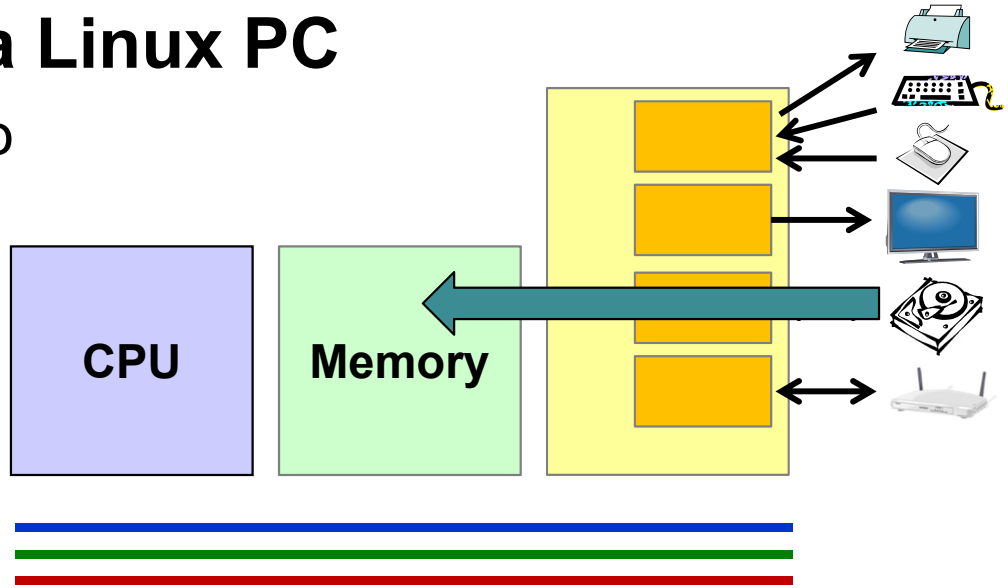
- **Program execution on a Linux PC**
  - load executable **`hello`** into memory and execute it



  - typing **`./hello`** in a shell
    - transfers the executable from disk to memory (RAM)
  - operating system
    - creates a new process
    - jumps to start of **`main()`** function and begins execution

Software Aspects

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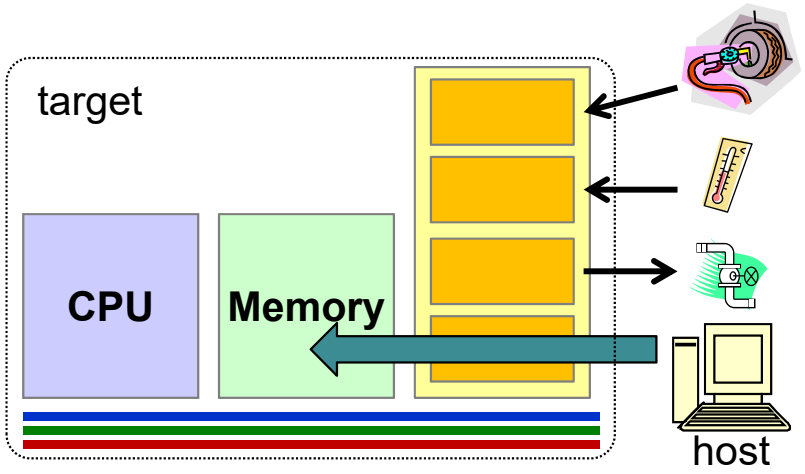
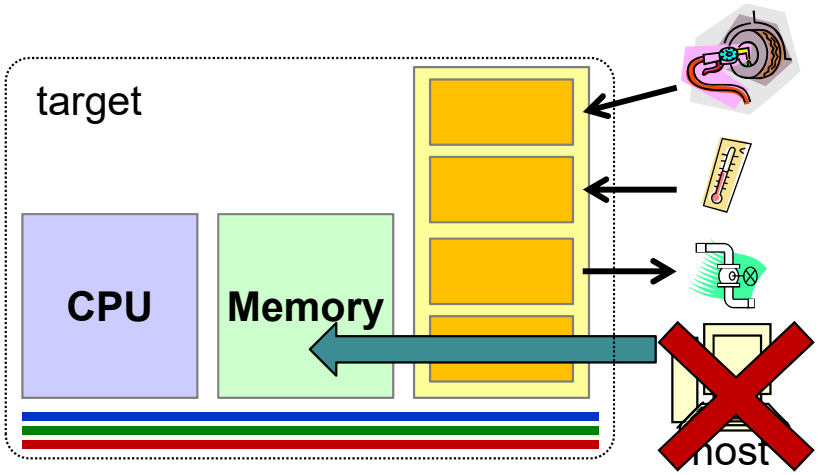
Program execution on Small Scale Embedded System

- Host vs. Target





Software development on host

- Compiler/Assembler/Linker on host
- Loader on target loads executable (e.g. *.axf) from host to RAM
- Loader copies executable from RAM into non-volatile memory (FLASH)
  → Firmware Update

System operation without host

- Loader jumps to `main()` and starts execution
- Instruction fetch often takes place directly from FLASH

Software Aspects

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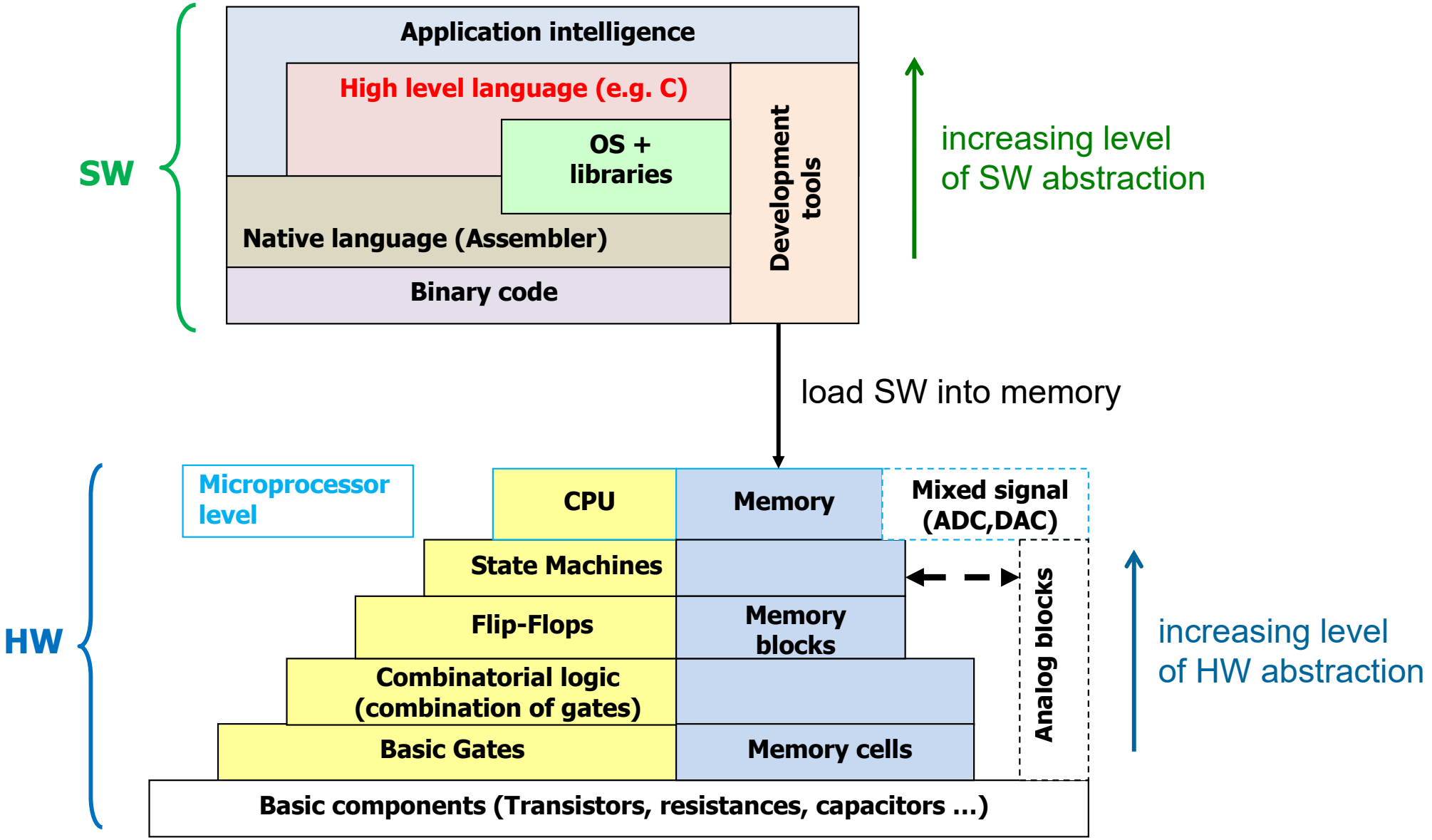
- **Why learn assembly language?**
  - few engineers write assembly code
    - use of High Level Languages (HLL) and compilers more efficient
- **But**
  - assembly language yields understanding on machine level
    - understanding helps to avoid programming errors in HLL
  - increase performance
    - understand compiler optimizations
    - find causes for inefficient code
  - implement system software
    - boot Loader, operating systems, interrupt service routines
  - localize and avoid security flaws
    - e.g. buffer overflow

Interaction of HW and SW



Conclusion

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- **Computer system → hardware and software**
- **Hardware**
  - CPU — Central Processing Unit or microprocessor (µP)
  - memory — stores instructions and data
  - I/O — input and output devices
  - system bus — electrical connection of blocks
- **Software**
  - source code in high level language (C)
  - assembly code → machine-oriented, human readable
  - object code → machine instructions in binary without libraries
  - executable → executable object file including libraries
- **Target vs. Host**