Design with Microprocessors

Lecture 1

Year 3 CS
Academic year 2023/2024
1st Semester

Lecturer: Radu Dănescu

Introduction

Objectives

- Know, understand and use concepts like: microprocessor, bus, memory system, I/O system and data transfer methods, interfaces.
- Analyze and design systems with microprocessors

Prerequisites

- Logic Design, Digital System Design, Computer Architecture, Assembly Language Programming, Computer Programming (C/C++)

Discipline structure

- 2C + 1L + 1P / week

Lecture structure

- Part 1 – ATMEL (ATmega2560, Arduino) and applications
- Part 2 – ESP 32 based applications

Topic for lab works

- Hands on work using Arduino boards (ATmega2560 (MEGA2560), ATmega328P(Uno)), ESP 32 boards, and multiple peripheral modules

Bibliography

Lecture slides, available on the website:

http://users.utcluj.ro/~rdanescu/teaching_pmp.html

Microcontrollers overview

G. Grindling, B. Weiss, Introduction to Microcontrollers, Vienna Institute of Technology, 2007.

https://ti.tuwien.ac.at/ecs/teaching/courses/mclu/theory-material/Microcontroller.pdf

Atmel AVR, Arduino

M. A. Mazidi, S. Naimi, S. Naimi, The AVR Microcontroller and Embedded Systems Using Assembly And C, 1-st Edition, Prentice Hall, 2009.

Michael Margolis, Arduino Cookbook, 2-nd Edition, O'Reilly, 2012.

ESP 32

N. Kolban, Kolban's Book on ESP 32, 2017

Additional documents

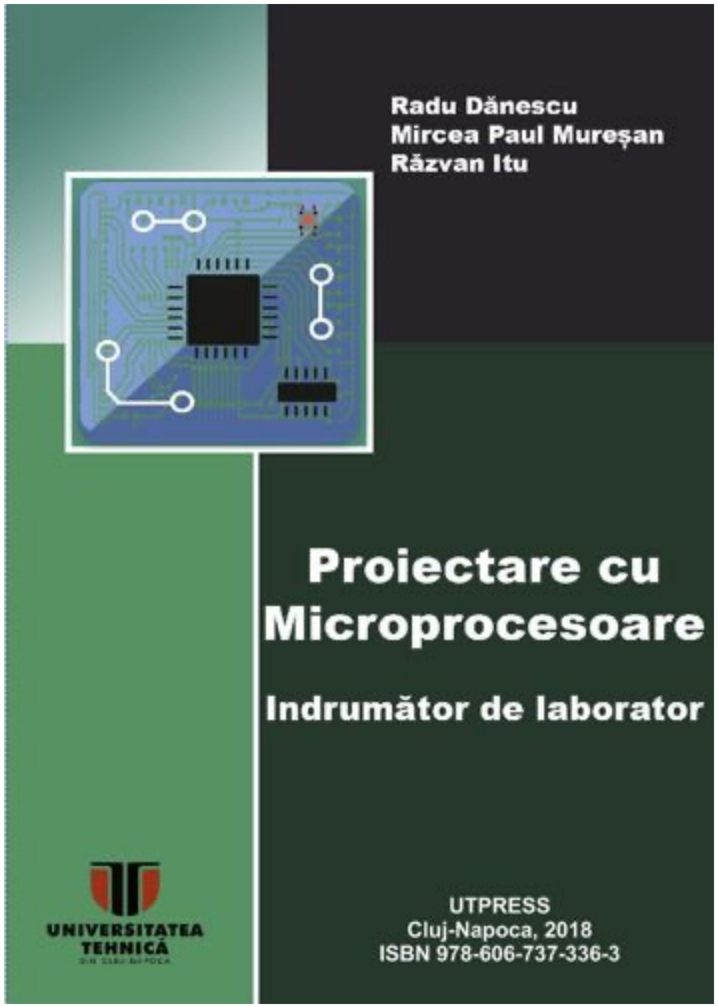
Data sheets Atmel, Intel etc, Arduino tutorials: **http://arduino.cc/en/Tutorial/HomePage**

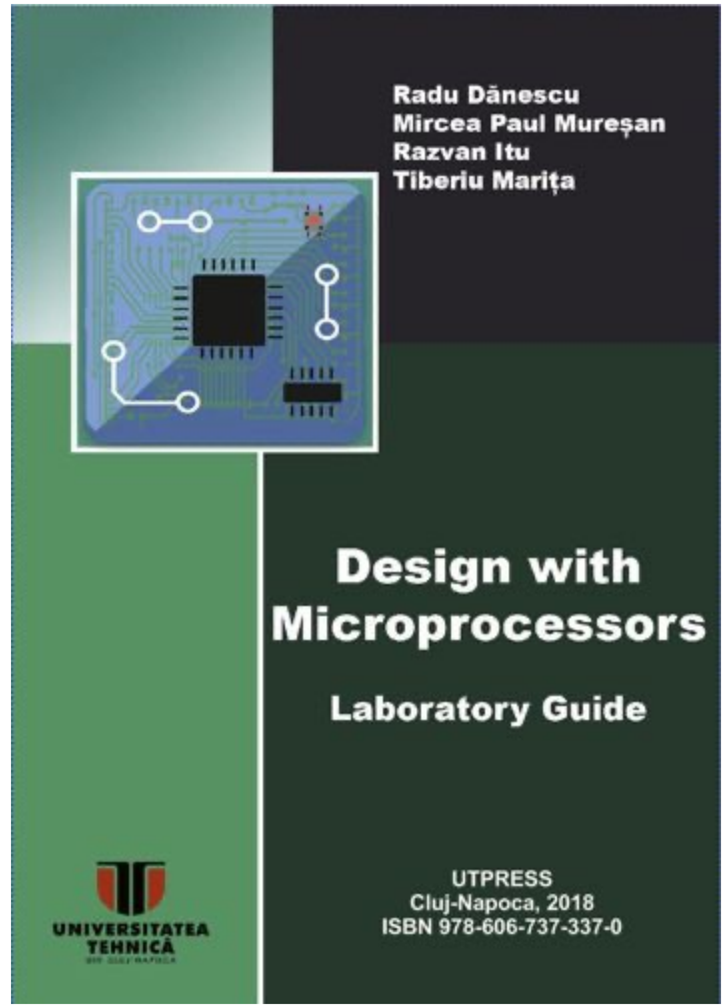
Datasheet ESP 32
https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf

Bibliography

Laboratory guides – some laboratory works will be updated this semester!

https://biblioteca.utcluj.ro/carti-online-cu-coperta.html





Evaluation

Evaluation: exam mark (E) + lab/project mark (LP)

```
if (LP > = 5) AND (E > = 4.5)
     Final_mark = 0.5 *LP + 0.5 * E
else
     Final_mark = 4 OR Absent
```

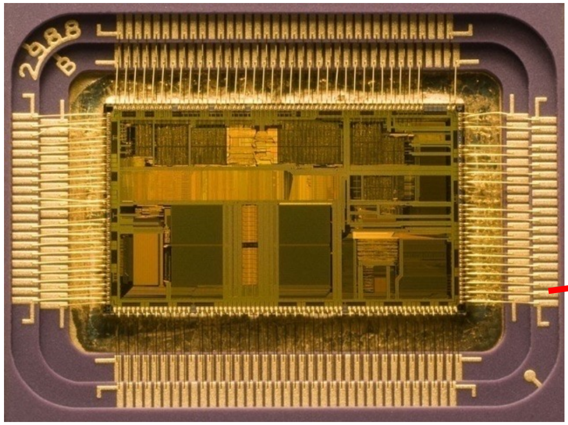
Bonus - can be awarded for exceptional activity during lecture/lab, or for participation in student competitions.

What is a microprocessor

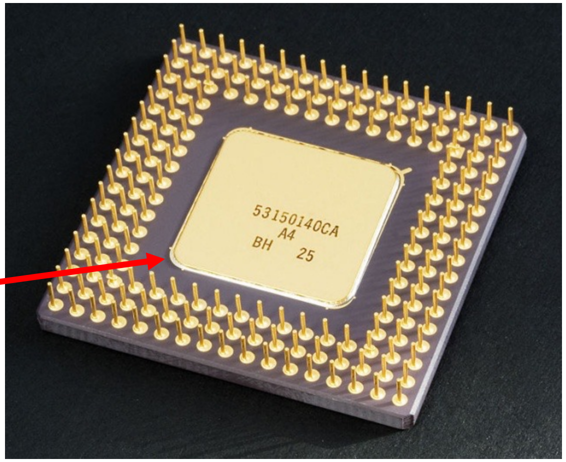
A **microprocessor** is an integrated circuit that includes all or most of the functions of a Central Processing Unit.

A **Central Processing Unit (CPU)** is a logic machine that can execute computer programs.

The program is a **sequence of instructions**, stored in a memory. The instructions are usually executed in four steps: reading the instruction (**fetch**), decoding the instructions (**decode**), executing the instruction (**execute**), and writing the results (**write back**).

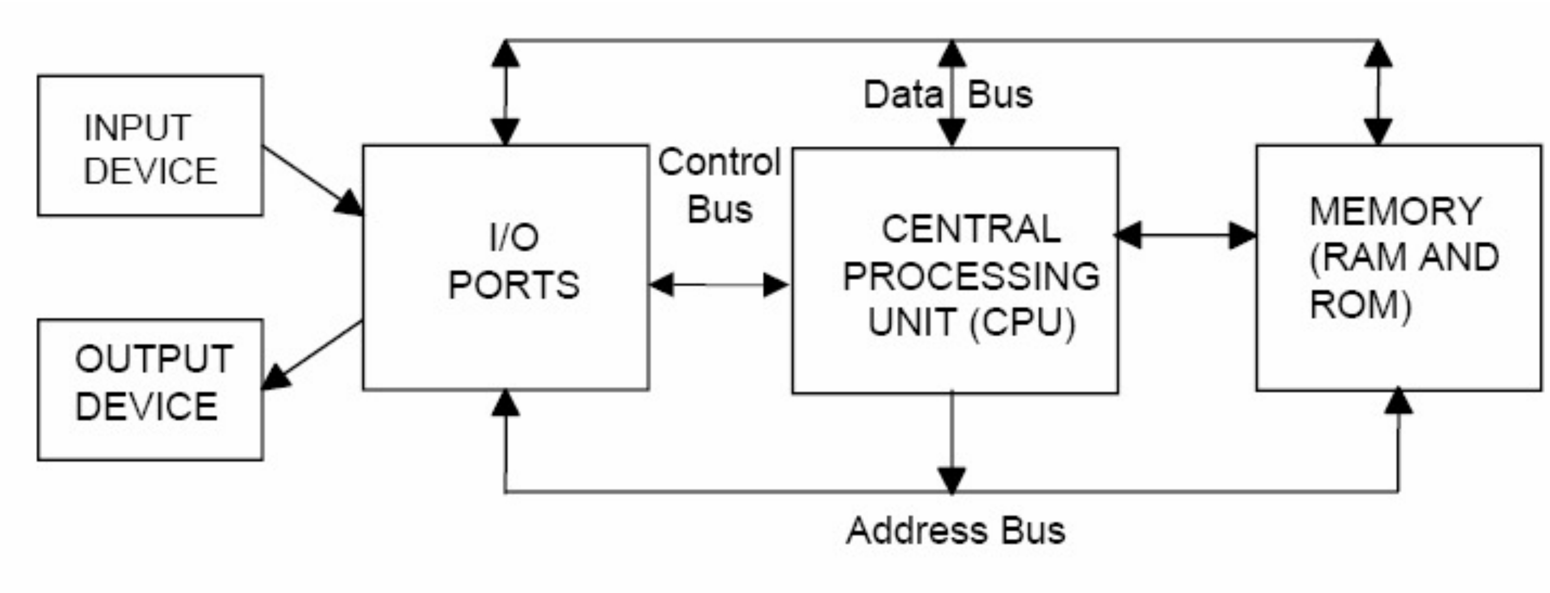


Intel 80486DX2 , interior



Intel 80486DX2 – external view

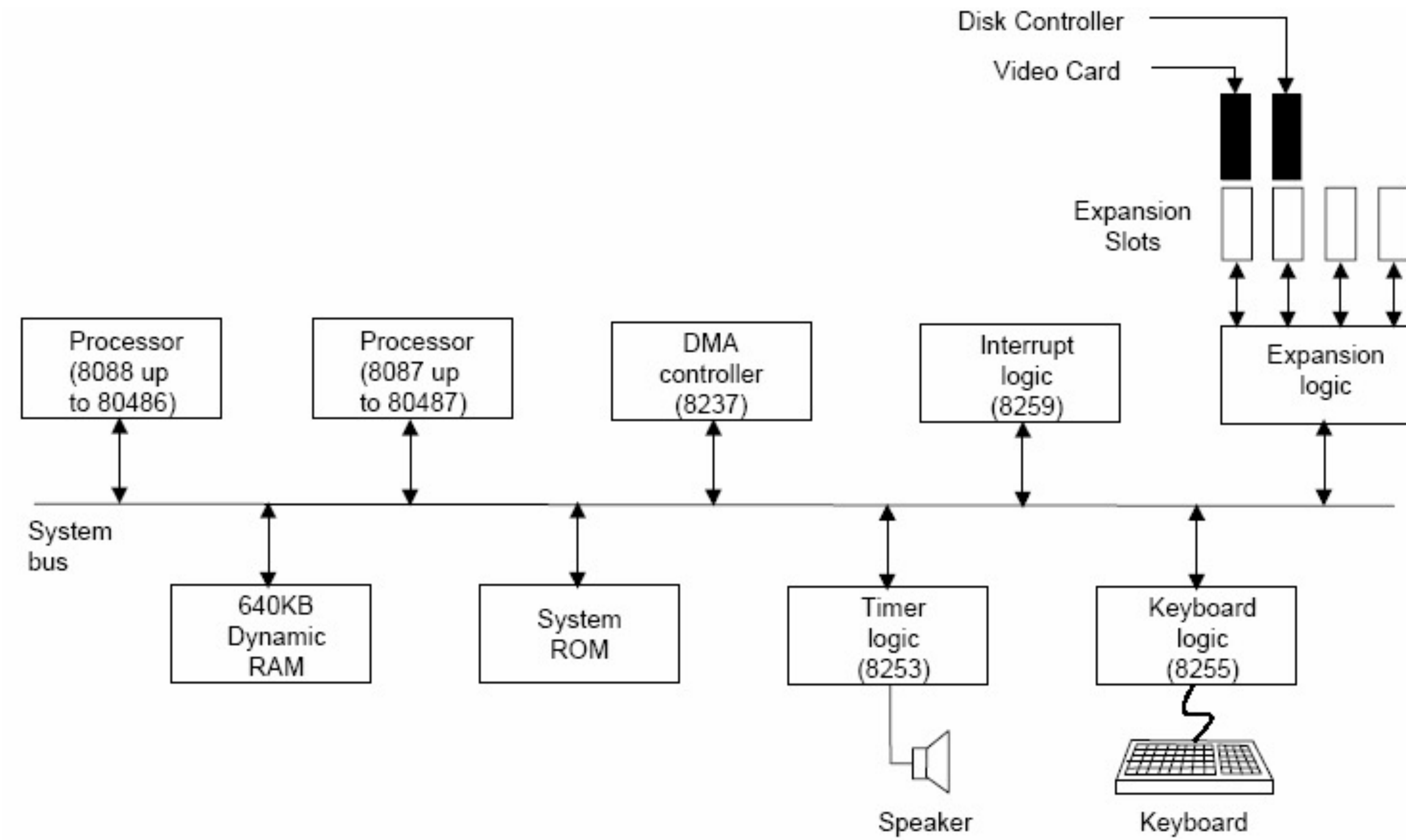
Microprocessor based systems



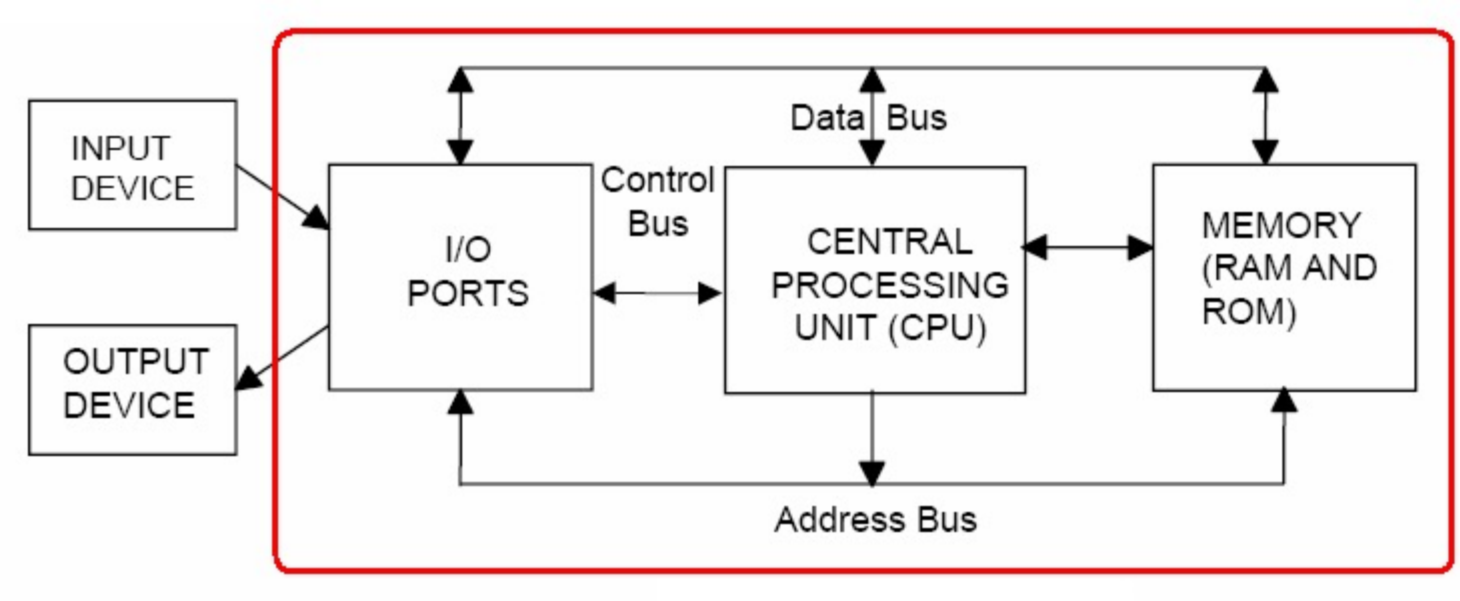
Essential elements: CPU, Memory, I/O

Additional elements: Interrupt controller, DMA controller, coprocessor, etc

Example: PC Motherboard



Microcontroler (MCU)



Multiple components of a microprocessor based system are included on the same integrated circuit - Microcontroller

- RAM and ROM (Flash) memories, for program and data
- Peripherals (Timer/ Counter, Serial/parallel communication interfaces, etc)

Design with Microprocessors

General objective: using the microprocessors (microcontrollers) to develop electronic systems for solving specific problems.

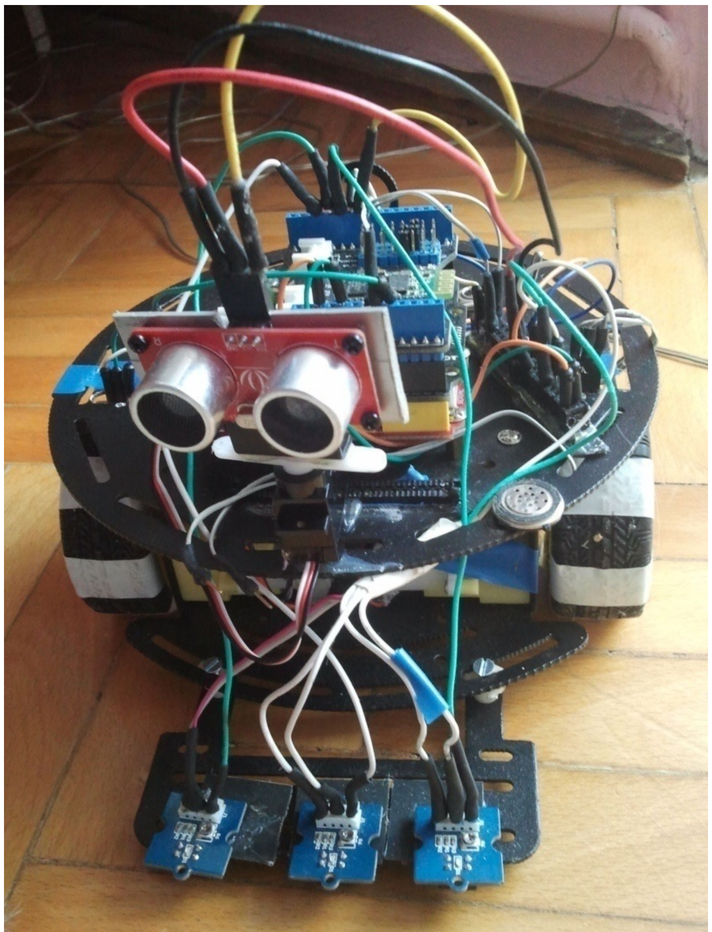
Example applications: autonomous robots, intelligent sensors, mobile sensors, audio or video signal processing, automatic control of processes, etc.

Steps towards the goal:

- Study of the **CPU’s Instruction Set Architecture** (ISA), and learning how to use the **programming tools**;
- Study of the microcontroller’s integrated resources, and the resources of the microcontroller’s development board – **the built in peripherals**;
- Study of the **external devices** required for solving the specific problems;
- Study of the **communication interfaces**, data formats, and timing diagrams, required for connecting the microcontroller to the external devices;
- Setting up the **mechanical and electrical connections** between components;
- Programming the **algorithms** to solve the problem.

Design with Microprocessors

Example: design of a robot capable of autonomous movement with obstacle avoidance, line following, or human guided operation.



Microcontroller: AVR ATMega328, Arduino board, C/C++ programming

Internal resources: I/O ports, interrupts, serial communication interface, timers

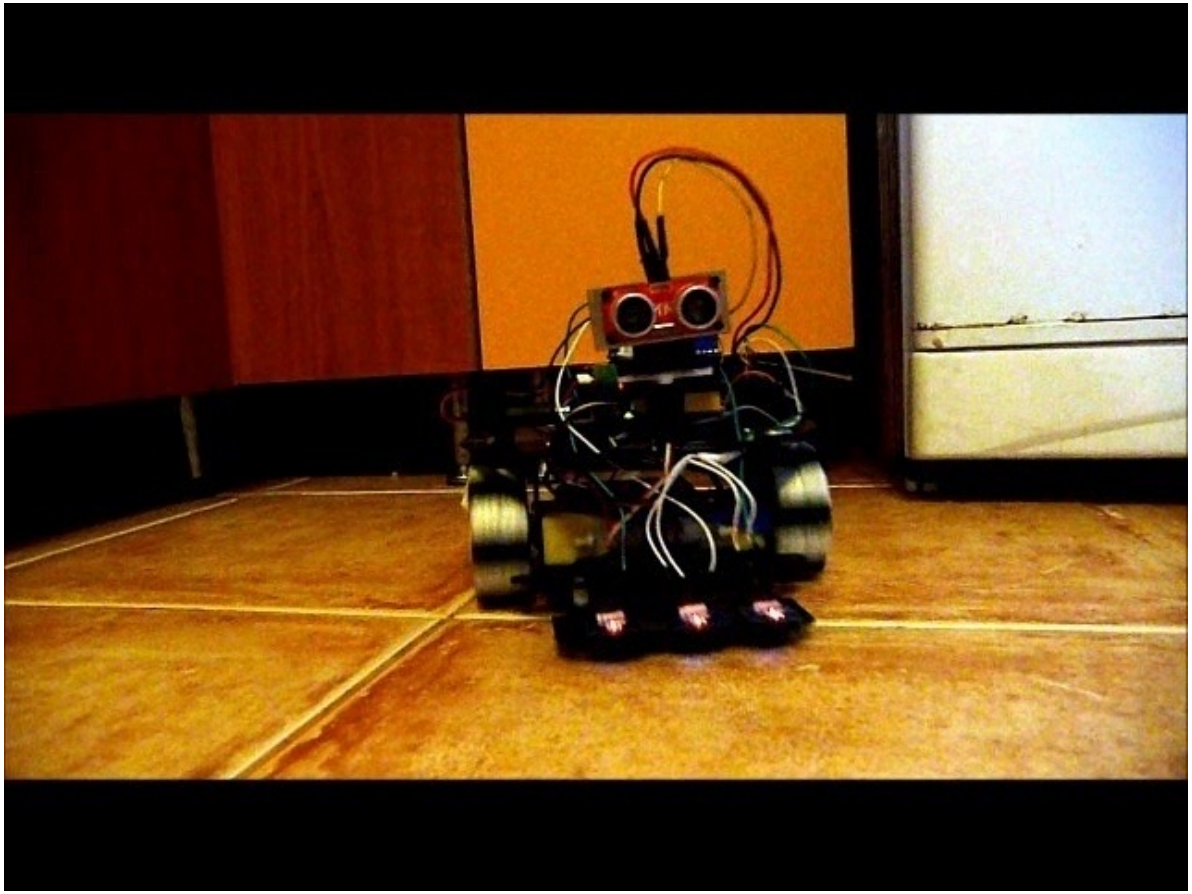
External components: 1 DC motor, 1 servo motor, reflectivity sensors, H bridge, sonar distance sensor, Bluetooth module.

Communication interfaces: UART serial between MCU and the Bluetooth module, PWM between MCU and the motors, analog signal from the reflectivity sensors, digital pulse between sonar and MCU.

Algorithms: scanning the environment for obstacle detection, line following, wheel control for straight line movement, etc.

Design with Microprocessors

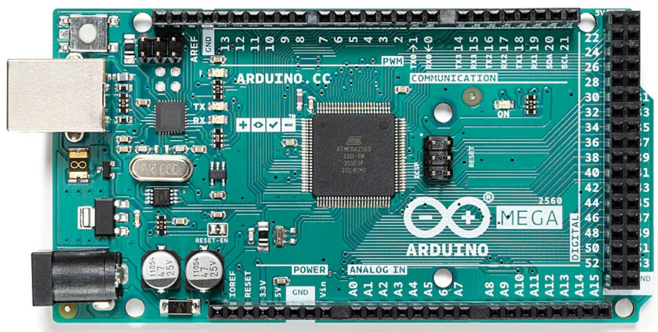
Example: design of a robot capable of autonomous movement with obstacle avoidance, line following, or human guided operation.

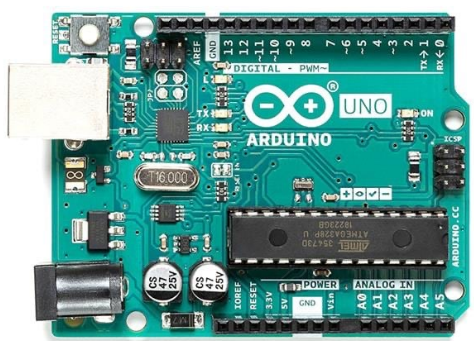


Design with Microprocessors

Example: design of a robot capable of autonomous movement with obstacle avoidance, line following, or human guided operation.

We'll focus on



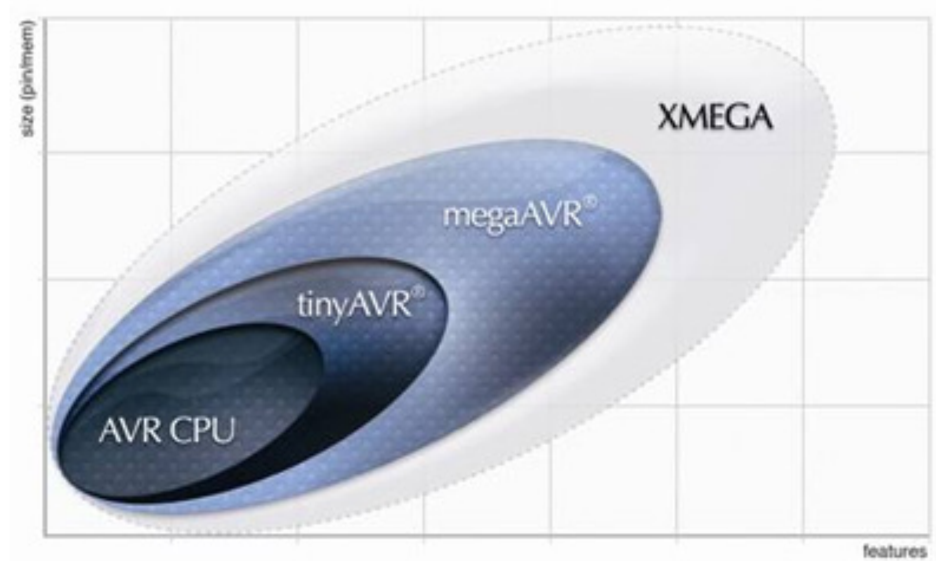


Arduino family: Mega and Uno

ESP32 Family: ESP32 Devkit V1

The (~~Atmel~~) Microchip AVR 8 bit microcontroller family

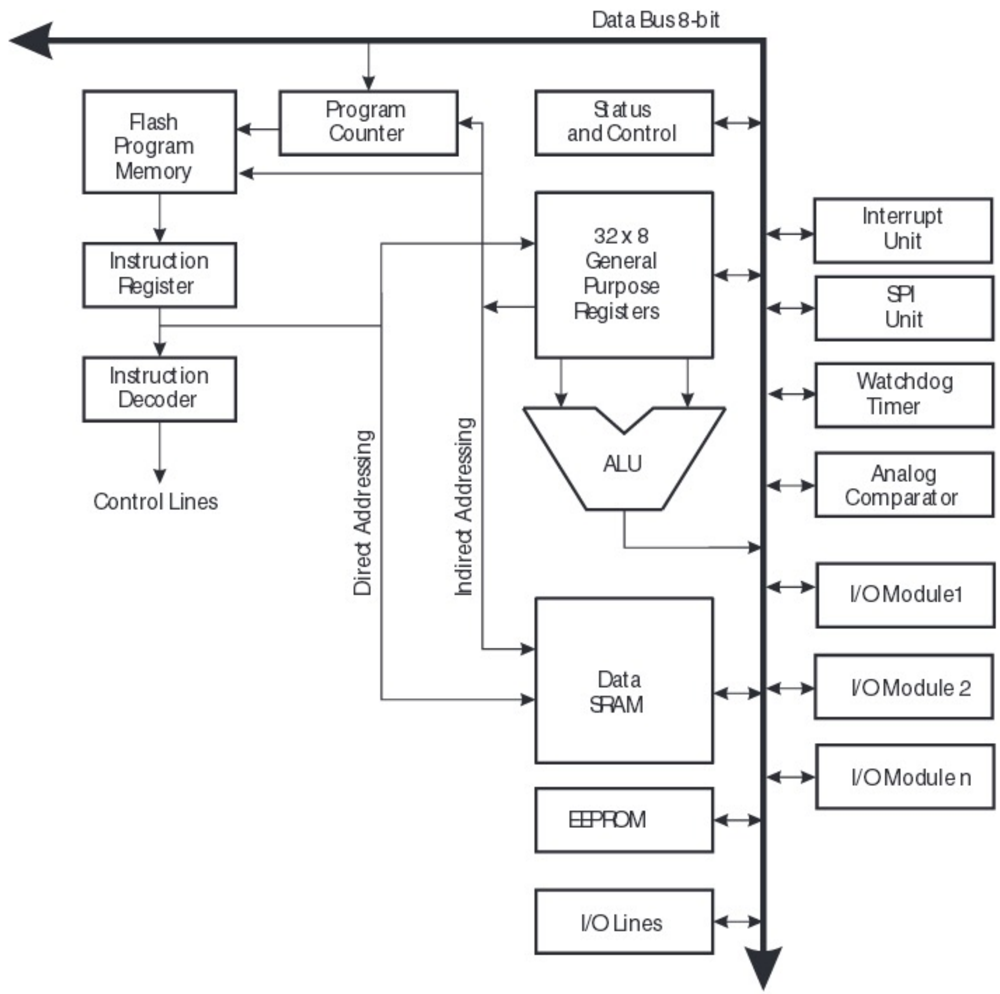
- RISC architecture
- 1 instruction / cycle execution
- 32 general purpose registers
- Harvard architecture
- Voltage range 1.8 - 5.5V
- Software controlled frequency
- High density of code
- Wide range of devices
- Variable number of pins
- Code compatibility between devices
- Compatible families of pins and capabilities
- A single set of development tools for all devices



<u>tinyAVR</u>
1–8 kB program memory
megaAVR
4–256 kB program memory
Extended instruction set (e.g. multiplication)
XMEGA
16–384 kB program memory
Extra: DMA, cryptography support
Application specific AVR
megaAVR with dedicated interfaces: LCD, USB, CAN etc.

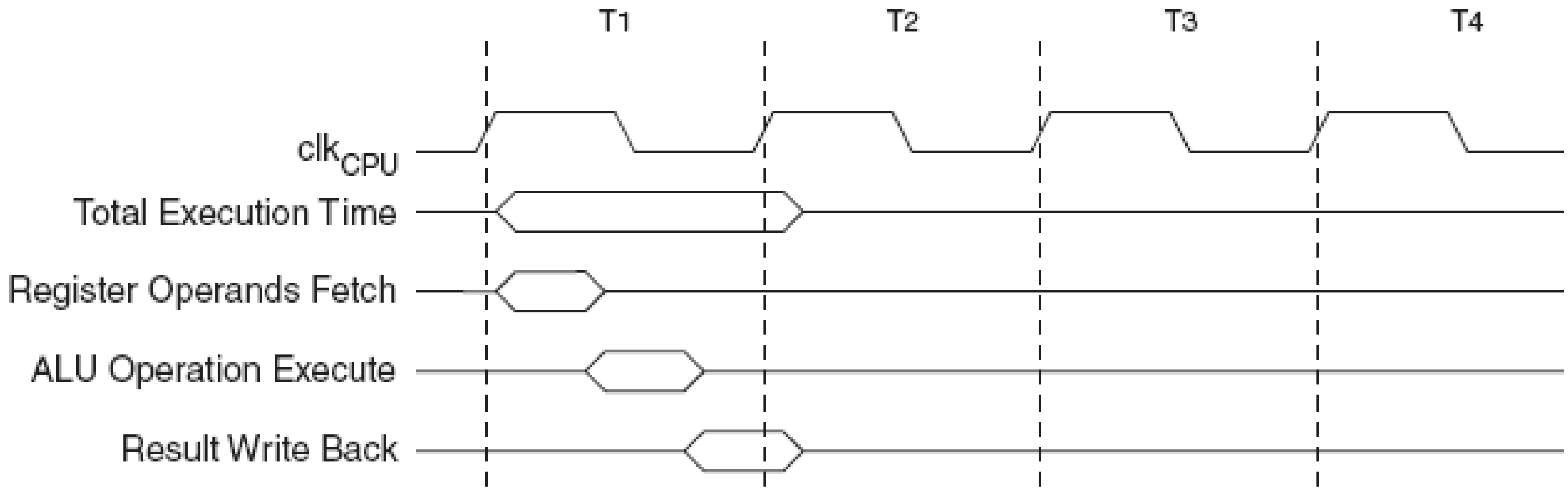
Generic architecture of an AVR microcontroller

- RISC machine (Two address load-store)
- Modified Harvard architecture – special instructions allow reading data from the program memory
- Two stage pipeline: Fetch & Execute

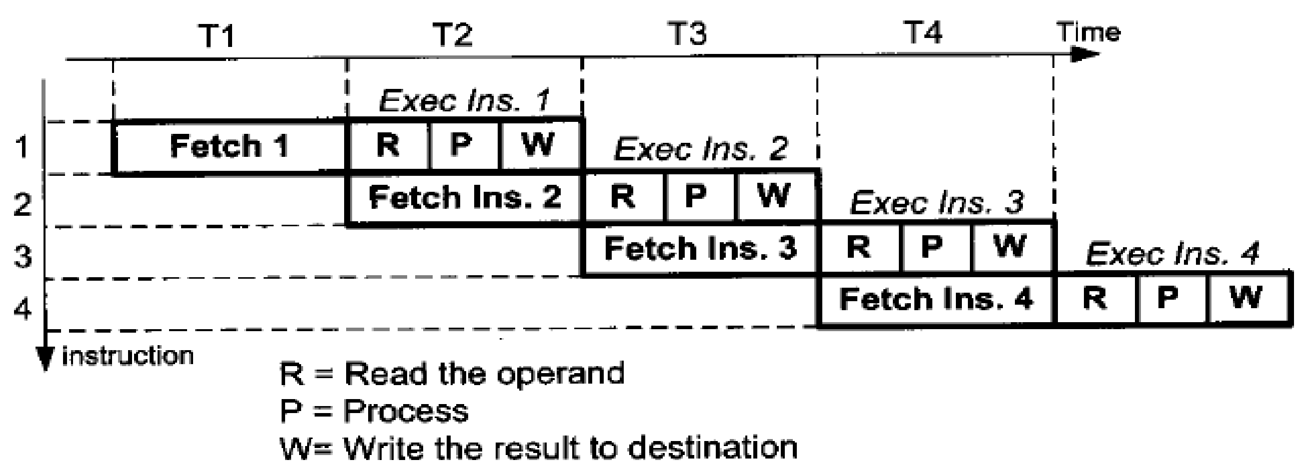


AVR timing diagrams

- Execution of arithmetic-logic instructions: 1 clock cycle/ instruction

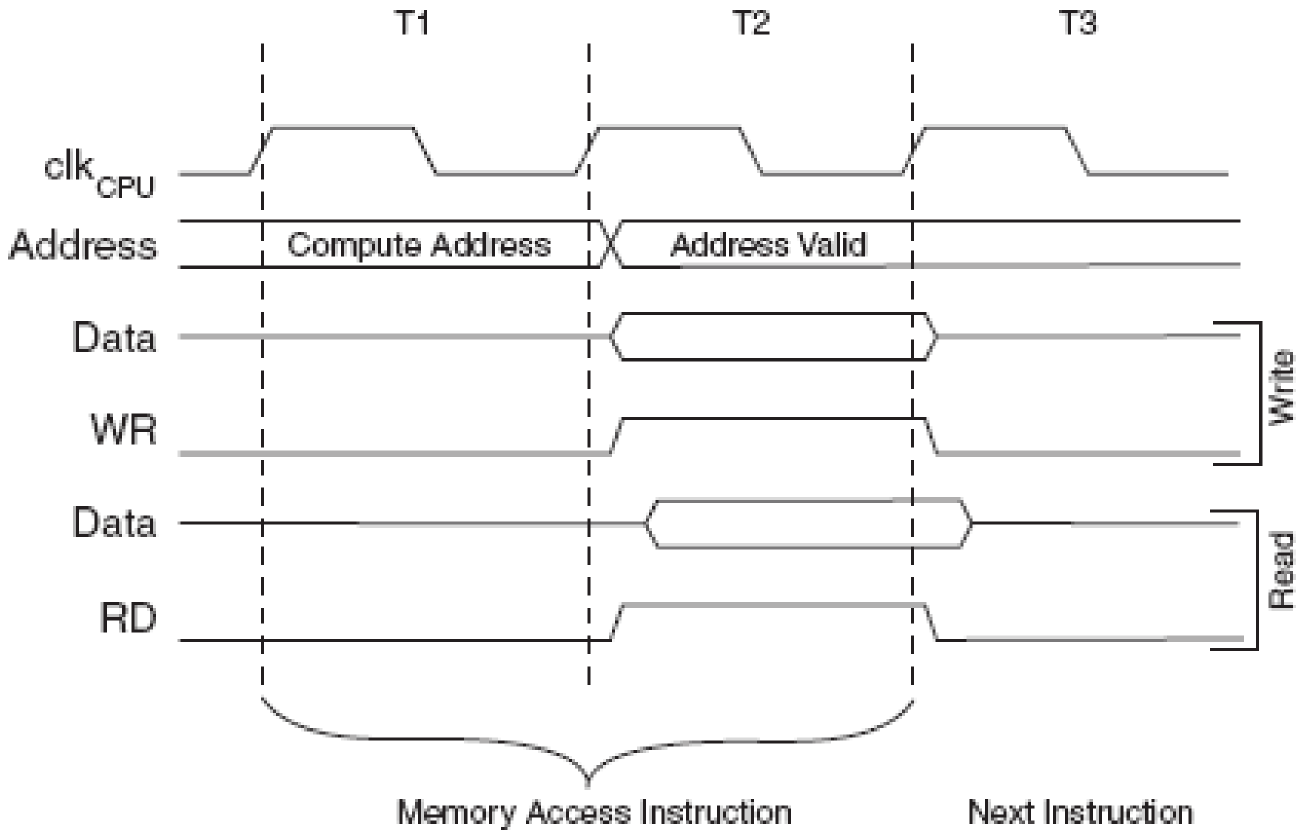


- Pipelining for reading the next instruction while executing the current one



AVR timing diagrams

- Instructions that access the SRAM memory: 2 clock cycles/ instruction



General Purpose Registers – GPR

- Immediate values can be loaded only in registers R16-R31
- The registers R26 – R31 can be used as pointers, in pairs
- Each register is also mapped in the data memory address space – uniform addressing

	7 0	Addr.	
	R0	0x00	
	R1	0x01	
	R2	0x02	
	...		
	R13	0x0D	
General	R14	0x0E	
Purpose	R15	0x0F	
Working	R16	0x10	
Registers	R17	0x11	
	...		
	R26	0x1A	X-register Low Byte
	R27	0x1B	X-register High Byte
	R28	0x1C	Y-register Low Byte
	R29	0x1D	Y-register High Byte
	R30	0x1E	Z-register Low Byte
	R31	0x1F	Z-register High Byte

Register operations

- Data copy

```
mov r4, r7
```

- Working with immediate values – possible only with r16 – r31

```
ldi r16, 5
ori r16, 0xF0
andi r16, 0x80
subi r20, 1
```

- Logic and arithmetic operations between registers

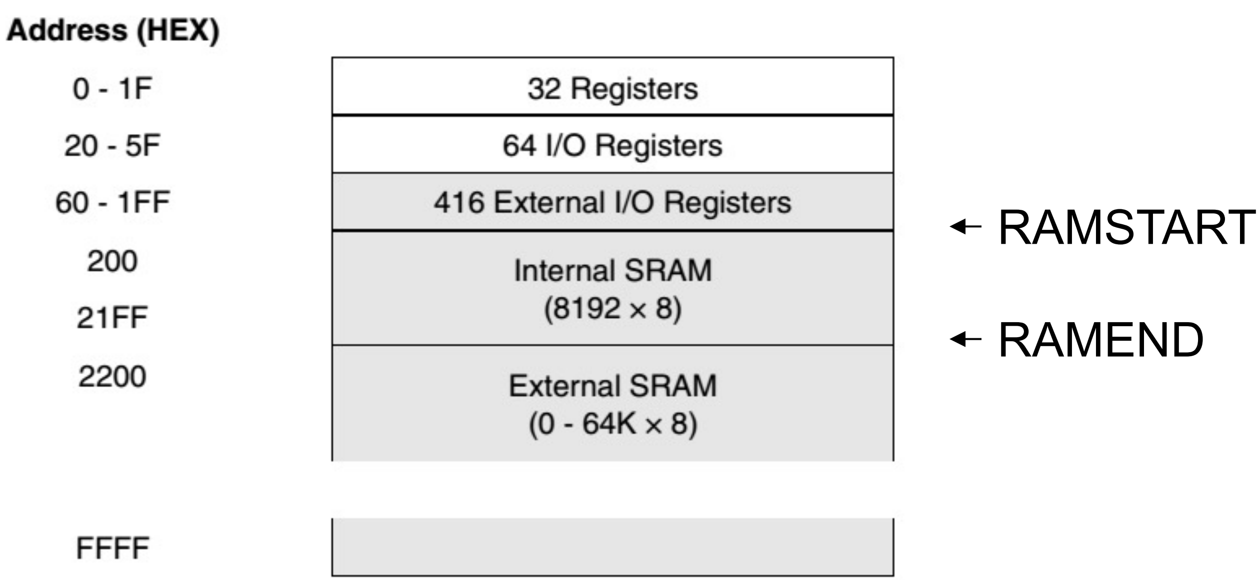
```
add r1, r2
or r3, r4
lsl r5
mul r5, r18        – r1:r0 = r5*r18
rol r7
ror r9
inc r19
dec r17
```

Data memory

- The first 32 byte addresses – the register block
- Next 64 addresses – the I/O registers accessible by special I/O instructions
- Next 100+ addresses – extended I/O space, can be accessed by load/store instructions. This space is dependent on the microcontroller type.
- SRAM, several Kbytes (2, 4, 8 …)
- External SRAM, can be up to 64 KB

The predefined constants RAMSTART and RAMEND mark the beginning and end of the internal SRAM

ATmega 2560 data memory map



Data memory operations

- Direct addressing

```
lds r3, 0x10FE
lsl r3
sts 0x10FE, r3
```

- Indirect addressing, using the pointer registers X, Y, Z

ldi r27, 0x10	The High byte of X is r27
ldi r26, 0xFE	The Low byte of X is r26
ld r0, X	
lsl r0	
st X, r0	

- Auto-increment/decrement indirect addressing

ld r0, X+	access location pointed by X, then increment X
ld r0, +X	increment X, then access location pointed by X
ld r0, X-	
ld r0, -X	

Program memory

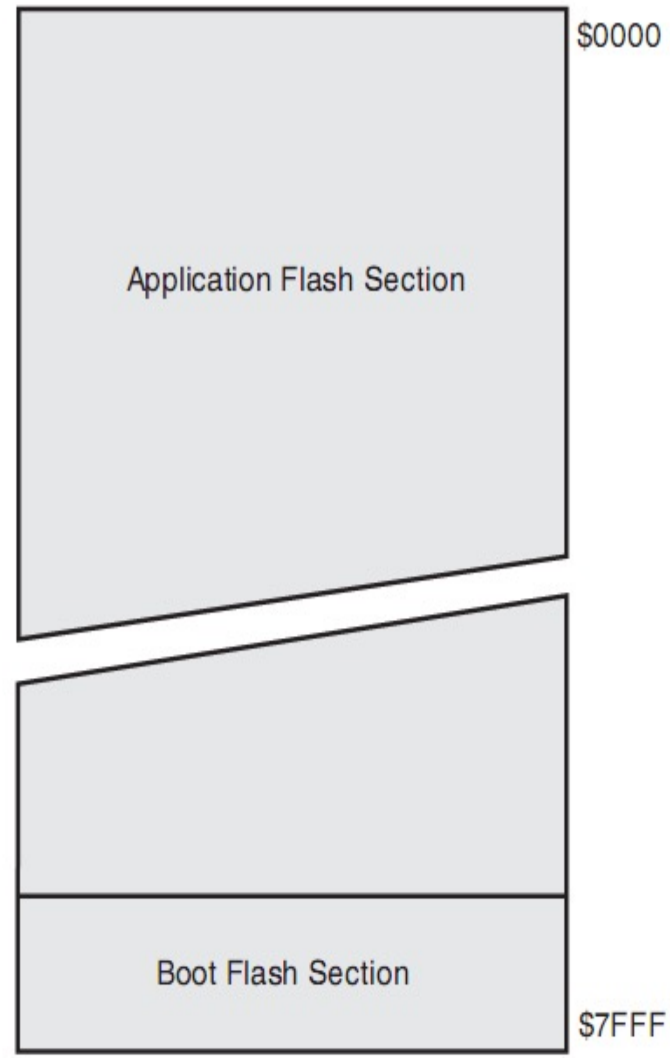
- Flash memory for storing the applications
- Organized in 16 bit words
- Two sections: Boot and Application
- At least 10000 write/erase cycles
- The constants can be declared in the code segment, they will be stored in the program memory
- Accessing the program memory:
  Reading – Byte access, address is specified by the Z pointer only

  LPM r5, Z
  LPM r5, Z+
  LPM r0 is destination, Z address

ELPM uses a larger address: RAMPZ:Z, for accessing the memory above 64 KB.

- **Writing** – word only

  SPM PM(Z) <= R1:R0



State register SREG

- The SREG register (8 bit) contains information about the state of the microcontroller, and about the result of operations
- Used for changing the behavior of the program, or for conditional jumps
- It is not saved automatically at subroutine calls or at interrupt servicing !

Bit	7	6	5	4	3	2	1	0	
0x3F (0x5F)	I	T	H	S	V	N	Z	C	SREG
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- I – global interrupt activation flag
- T – transfer bit, can be copied to and from register bits using the BLD and BST instructions
- H – half carry (carry between half bytes, used for BCD operations)
- S – Sign bit, **N xor V**
- V – overflow flag, indicates if the sign bit is changed due to overflow
- N – indicates a negative result
- Z – indicates a null result
- C - carry

Jump instructions

- Unconditional jumps
  RJMP – relative jump, PC +- 2KB
  JMP – absolute jump
  IJMP – indirect jump, address indicated by the Z pointer
- Conditional jumps (branch)
  CP, **CPI** – compares two registers, or a register with an immediate
  BREQ – branch if the Z flag is set (compared numbers are equal)
  BRNE – branch if the compared numbers are not equal
  BRCS – branch if the carry flag C is set
  SBRS – skips the next instruction is a bit in a register is set
  SBRS r5, 2 – if bit 2 of register r5 is set, skip over the next instruction
  SBRC, SBIS, SBIC
- Procedure call
  RCALL, CALL, ICALL - saves the return address on the stack, then makes the jump
- Return from procedure
  RET – extracts the return address from the stack, then jumps to this address

Examples

- C

```c
char a, b;
...
a = b;
```

- AVR ASM

```asm
lds r24, b
sts a, r24
```

Examples

- C

```
char a;
...
a = 0x10;
```

- AVR ASM

```
ldi     r24, 0x10    ; Load imm 10
sts     a, r24       ; Store to a
```

Examples

- C

```
int a = *pInt;
```

- AVR ASM

```
; Use the Z register (R31:R30)
lds R30, pInt          ; Load from pInt
lds R31, pInt+1        ;
ld  r24, Z             ; load from (*pInt)
ldd r25, Z+1           ;
sts a,   r24           ; store to a
sts a+1, r25           ;
```

Examples

- C

```c
void strcpy (char *dst, char *src)
{
    char ch;

    do {
        ch = *src++;
        *dst++ = ch;
    } while (ch);
}
```

MOVW	Rd, Rr	Copy Register Word	Rd+1:Rd ← Rr+1:Rr

- AVR ASM

```
; dst in R25:R24, src in R23:R22
strcpy:
    movw r30, r24     ; Z<=dst
    movw r26, r22     ; X<=src
loop:
    ld   r20, X+      ; ch=*src++
    st   Z+, r20      ; *dst++=ch
    tst  r20          ; ch==0?
    brne loop         ; loop if not
    ret
```

Examples

- C

```c
int a, b;
...
a = a + b;
```

- AVR ASM

```
lds   r18, a     ; load a
lds   r19, a+1   ;
lds   r24, b     ; load b
lds   r25, b+1   ;
add   r24, r18   ; add lower half
adc   r25, r19   ; add higher half
sts   a+1, r25   ; store a.byte1
sts   a, r24     ; store a.byte0
```

Examples

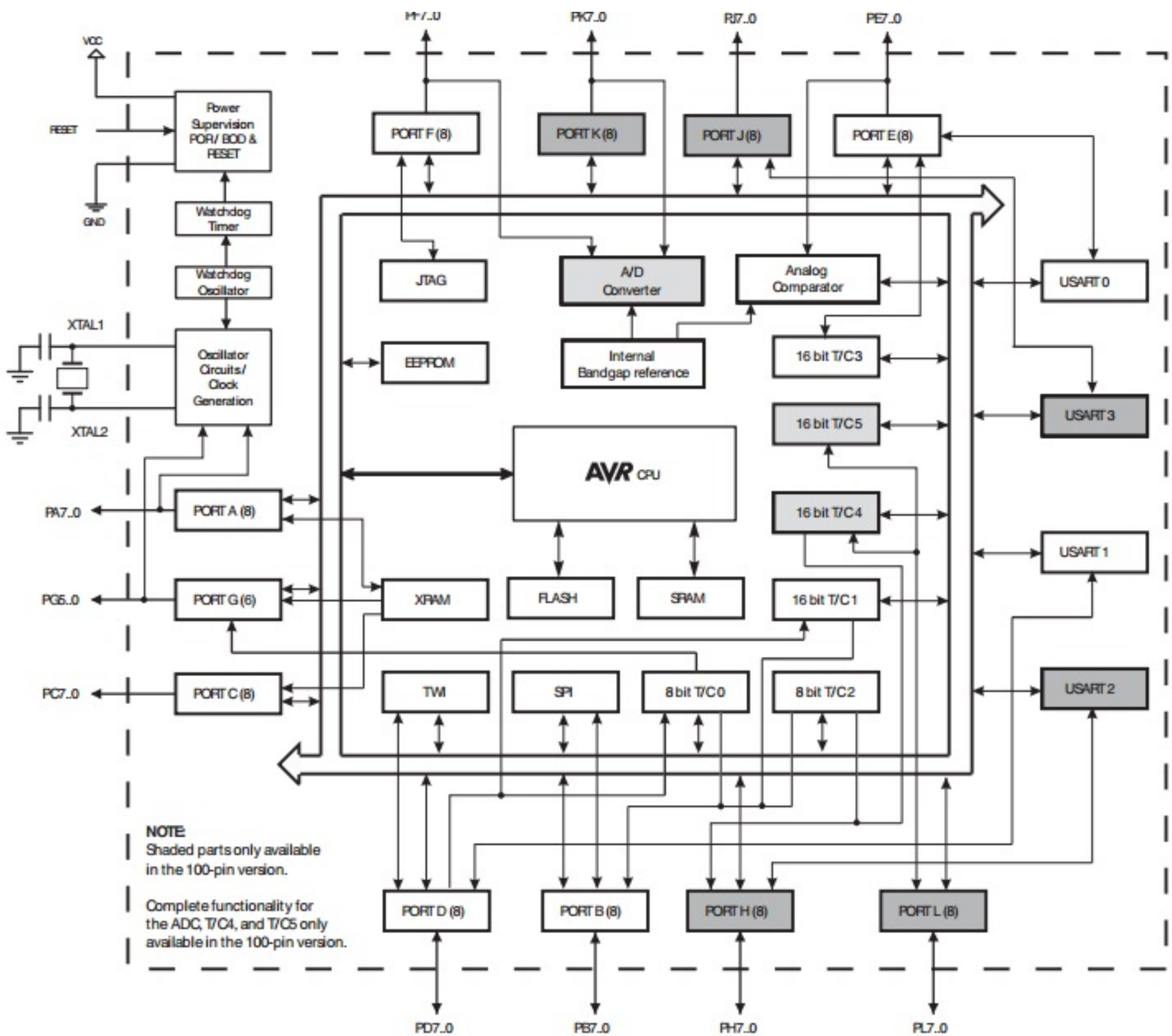
- C

```
char sum, n;
...
for (n = 0; n < 10;
   n++)
   sum += n;
```

- AVR ASM

```
; assume r16=n, r3=sum
        clr     r16         ; n = 0
        rjmp    check
loop:   add     r3, r16     ; sum+= n
        inc     r16         ; n++
check:  cmpi    r16, 10     ; comp n and 10
        brlt    loop        ; br if n<10
```

The AVR AtMega 2560 microcontroller



Atmega 2560 – Technical features

- 135 instructions, most are executed in 1 clock cycle
- 32 general purpose 8 bit registers
- 256 K Bytes re-programmable flash memory
- 4K Bytes EEPROM
- Internal SRAM 8K Bytes
- Read/write cycles: 10,000 Flash/100,000 EEPROM
- Up to 64 KB RAM addressable locations (if external RAM is used)

Integrated peripherals

- Two 8-bit timer/counters
- Four 16 bit timer/counters
- 4 PWM channels (8 bit), 12 PWM channels (16 bit)
- 16 Analog/Digital conversion channels (10 bit)
- 4 programmable USART interfaces
- 1 SPI interface
- Two Wire Interface (TWI), similar to I2C
- Interrupt generation by pin state change detection

Arduino

- Microcontroller boards and open source development tools
- Hides the microcontroller specific details, providing a unified API
- Wide range of boards, shields and accessories
- Vast quantity of documentation, most of it free
- Vast quantity of examples for most problems

Web: **www.arduino.cc**

Distributors in Romania:

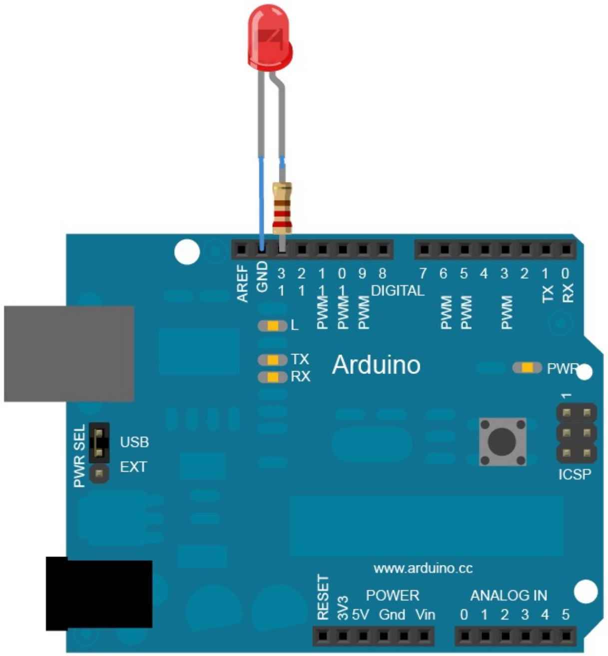
www.robofun.ro – originals, more expensive

www.ardushop.ro – clones, cheaper

Arduino Mega 2560

- Based on the ATMega2560 8 bit microcontroller
- 54 digital I/O pins
- 16 analog input pins
- 4 UART serial communication ports
- Microprocessor frequency: 16 MHz
- USB powering and programming

Sample Arduino program



- Intermittent lighting of a LED, connected to an output pin (digital output)

Sample Arduino program

```
/*
  Blink
  Turns on an LED on for one second, then off for one second, repeatedly.

  This example code is in the public domain.
 */

// Pin 13 has an LED connected on most Arduino boards.
// give it a name:
int led = 13;

// the setup routine runs once when you press reset:
void setup() {
  // initialize the digital pin as an output.
  pinMode(led, OUTPUT);
}

// the loop routine runs over and over again forever:
void loop() {
  digitalWrite(led, HIGH);   // turn the LED on (HIGH is the voltage level)
  delay(1000);               // wait for a second
  digitalWrite(led, LOW);    // turn the LED off by making the voltage LOW
  delay(1000);               // wait for a second
}
```