# Principles and Applications of Microcontrollers

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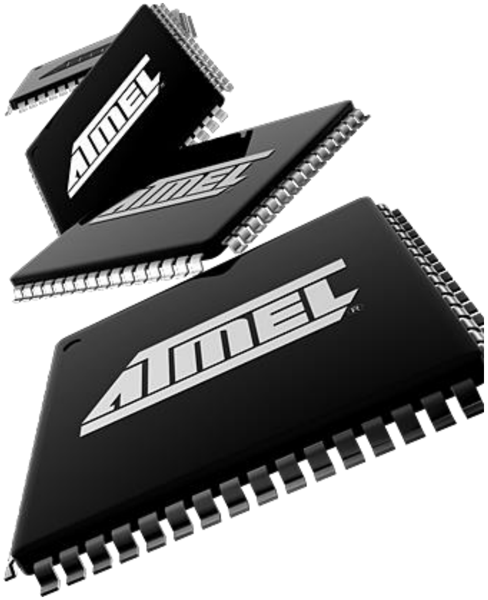
Today:

- Analog-to-digital converter (ADC)



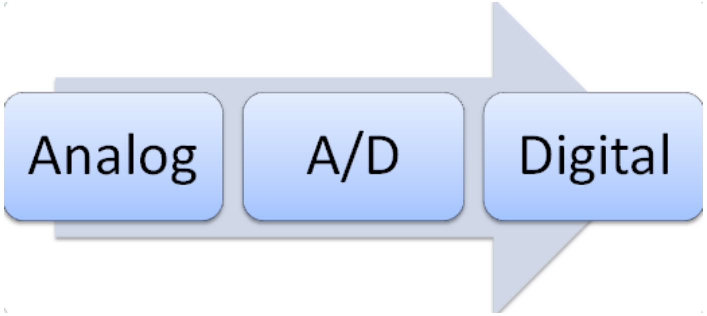
# Review – Bit-wise Operation

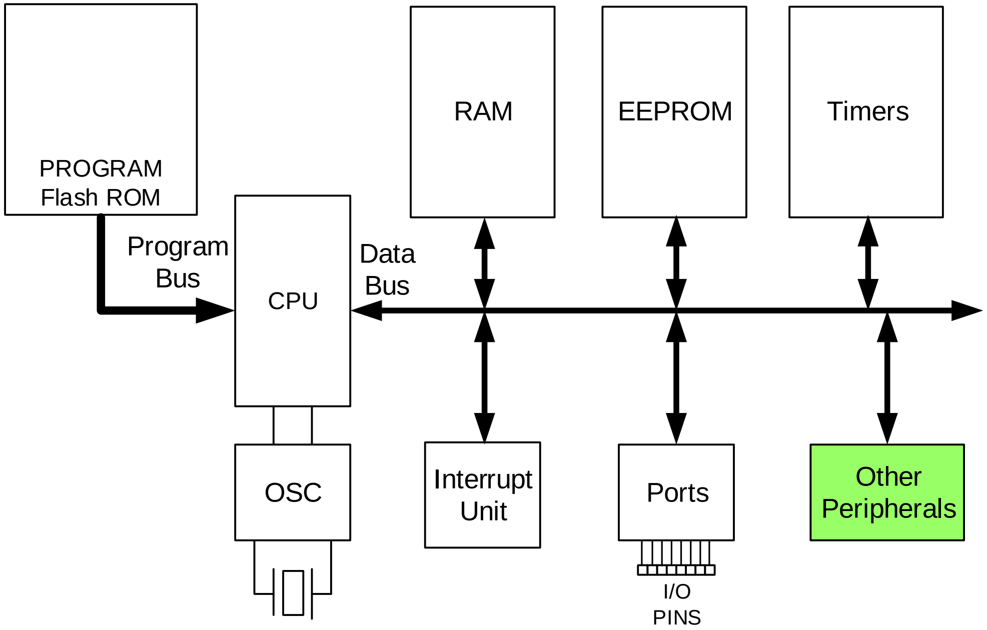
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| TIFR0 | - | - | - | - | - | OCF0B | OCF0A | TOV0 |

- Check a bit in a byte
- Write one to a bit in a byte without changing its content
- Write one to two bits in a byte
- Write zero to a bit in a byte

# Outline

- Analog-to-digital converter (ADC)
  - Analog and digital signals
  - Successive approximation ADC
  - AVR ADC connection
  - ADC registers
  - Single conversion mode
  - Free running mode
- Getting started

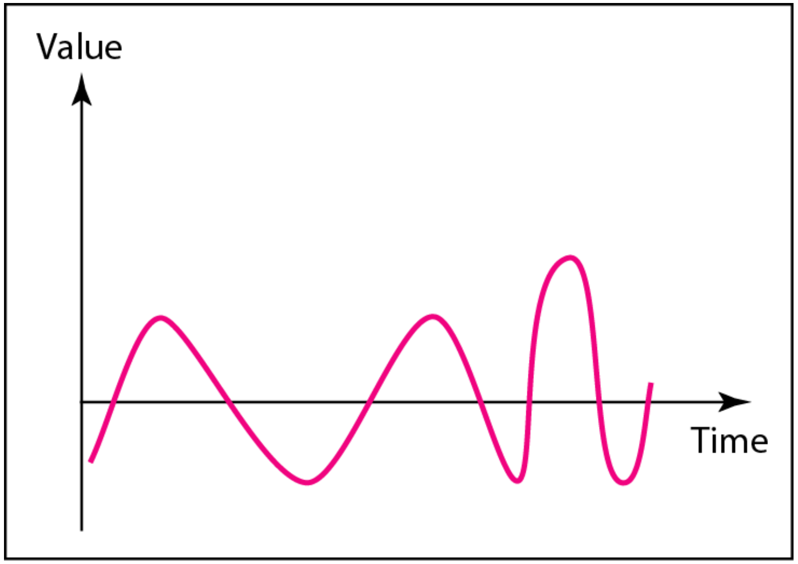




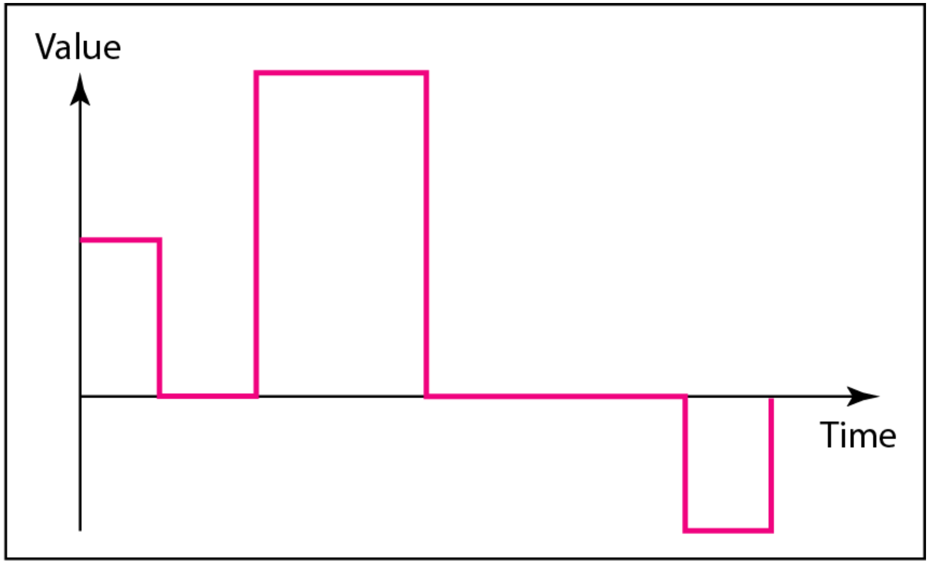
# Analog vs. Digital Signal

# Analog vs. Digital Signal

- Analog signal – directly measurable quantities that are continuous both in magnitude and time
- Digital signal – measurement in states, e.g., binary 0 and 1, that are discrete both in magnitude and time



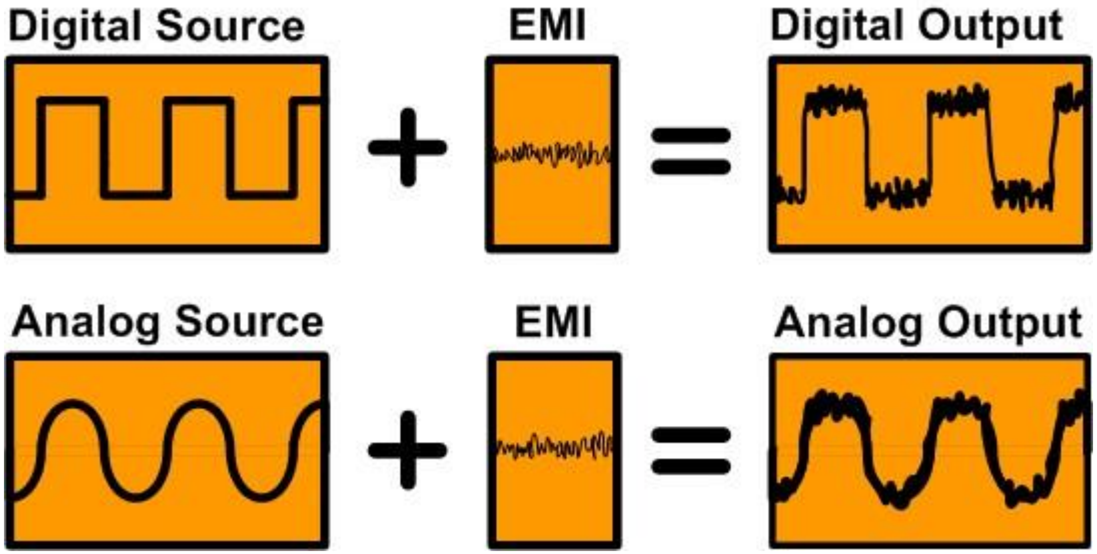
a. Analog signal



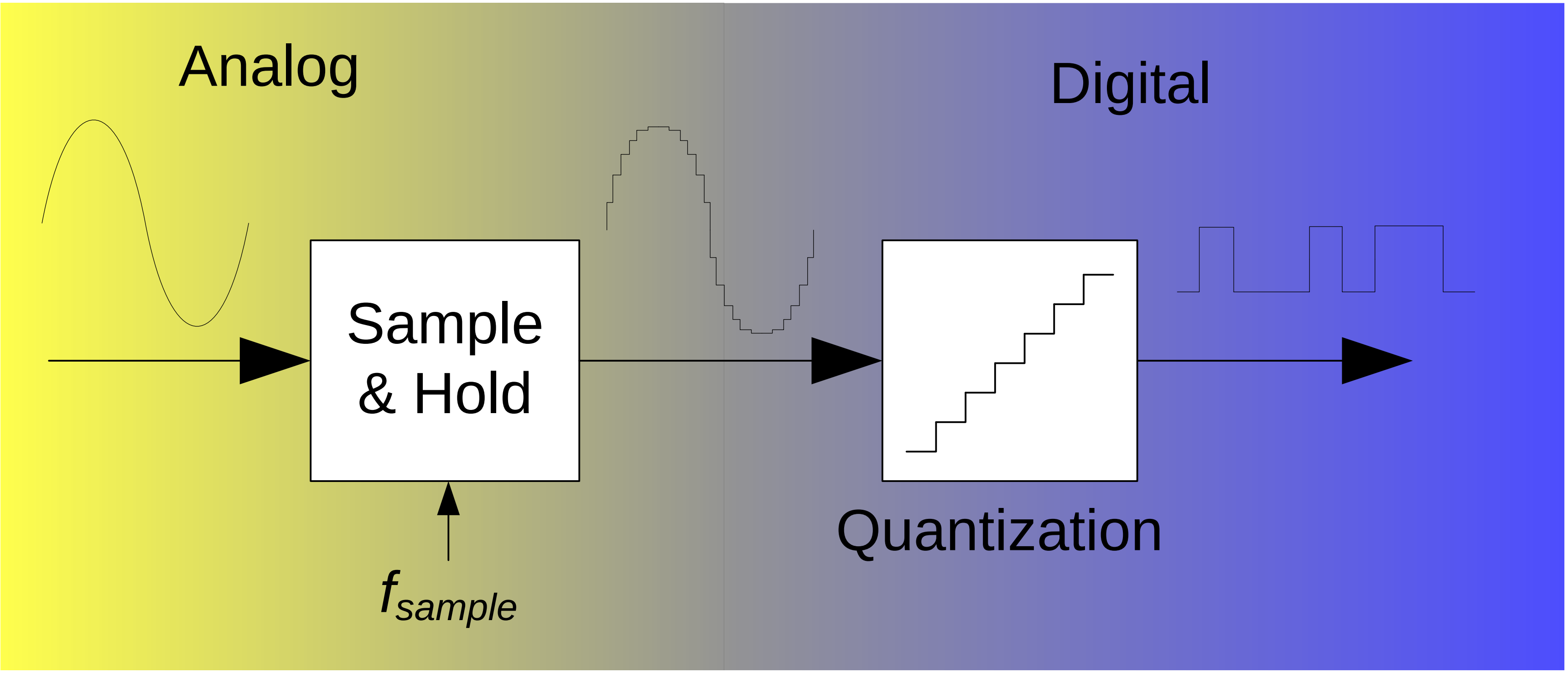
b. Digital signal

# Advantage of Digital Signal

- Increased noise immunity
- Easy to compute nonlinear functions
- Reliable and reproducible



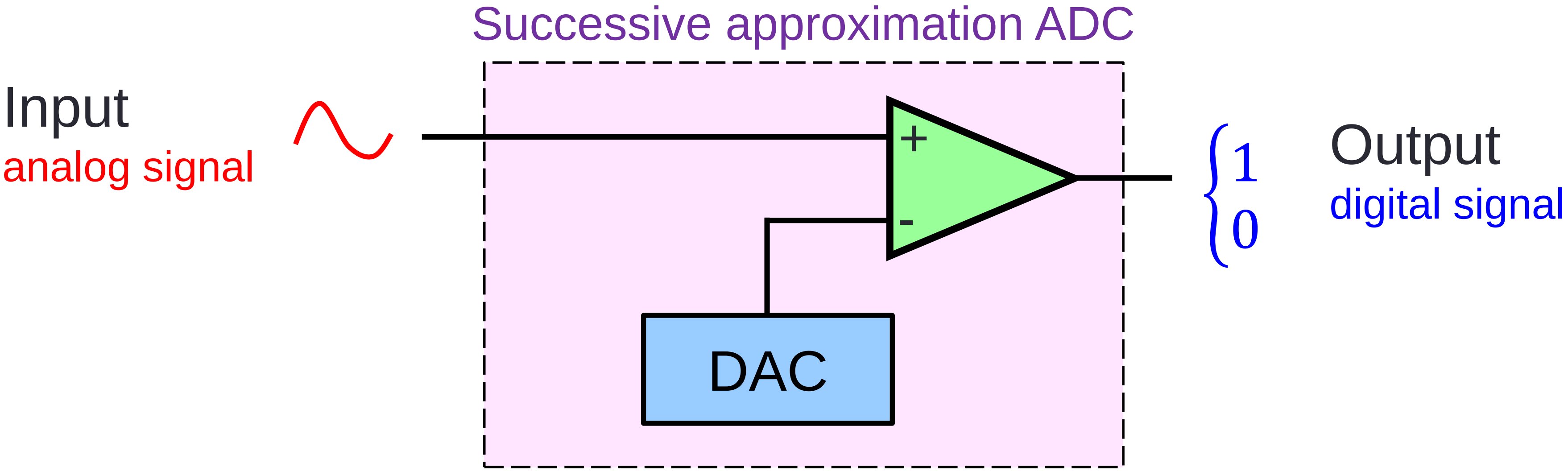
# Scheme of Analog-to-digital Conversion



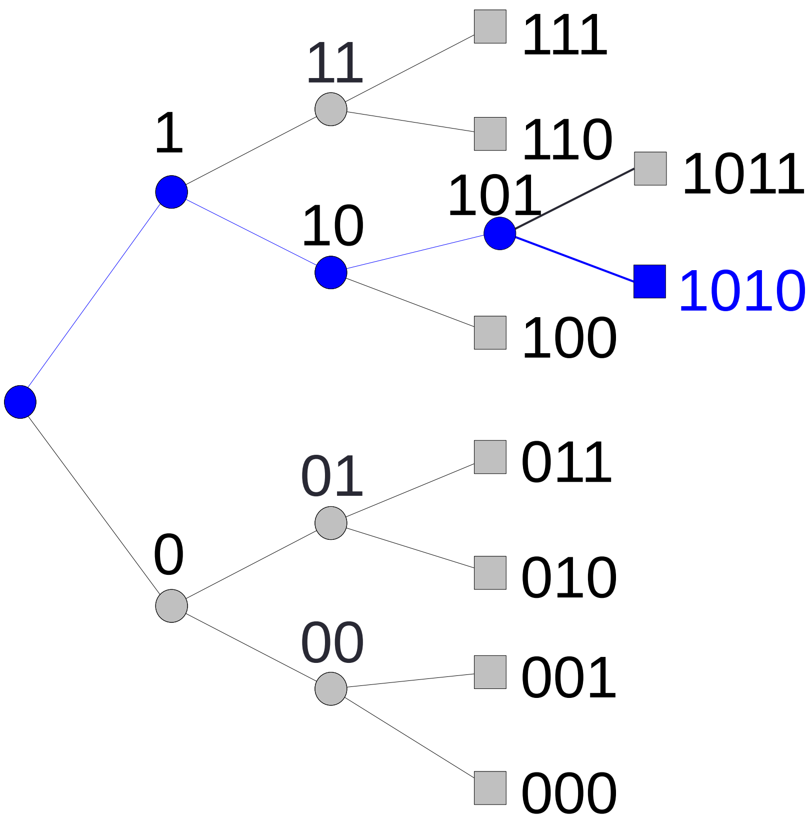
- Quantization – discretizing input magnitude values
- Sampling – reduction of a continuous signal to a discrete signal

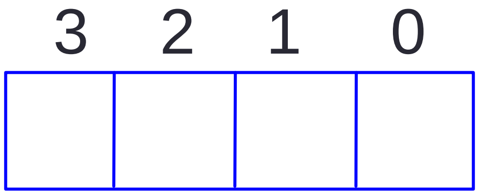
# AVR ADC

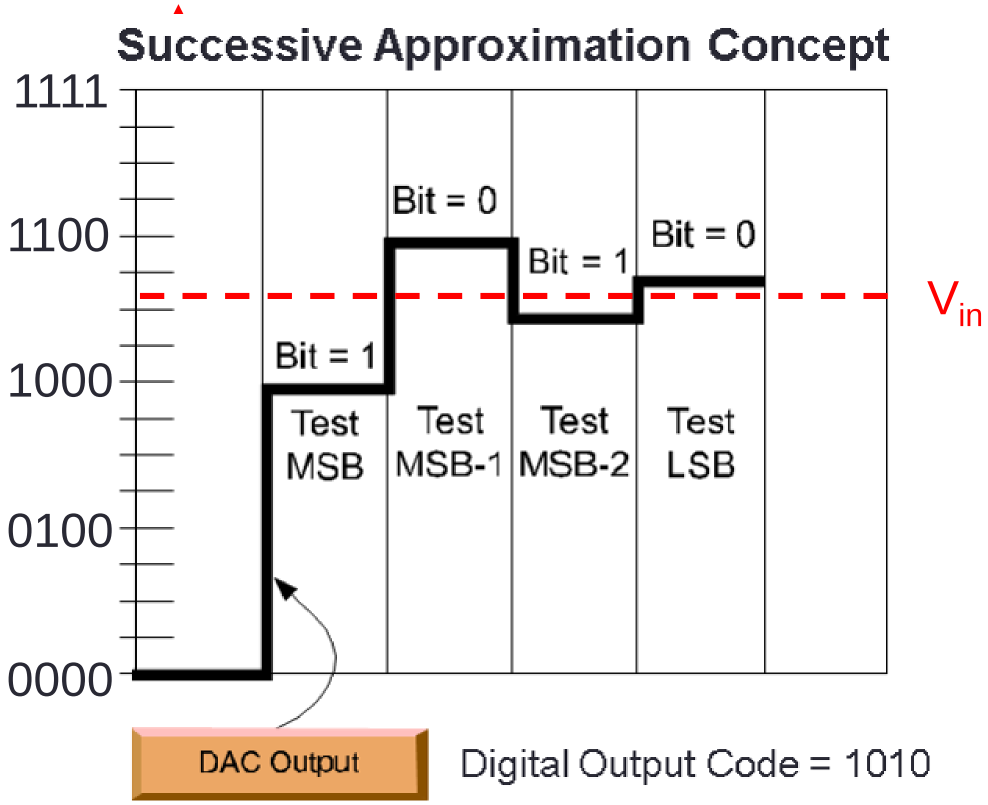
- 6 input channels
- 10-bit resolution
- ±2 LSB absolute accuracy
- Successive approximation ADC
- 13 - 260μs conversion time



# Successive Approximation ADC

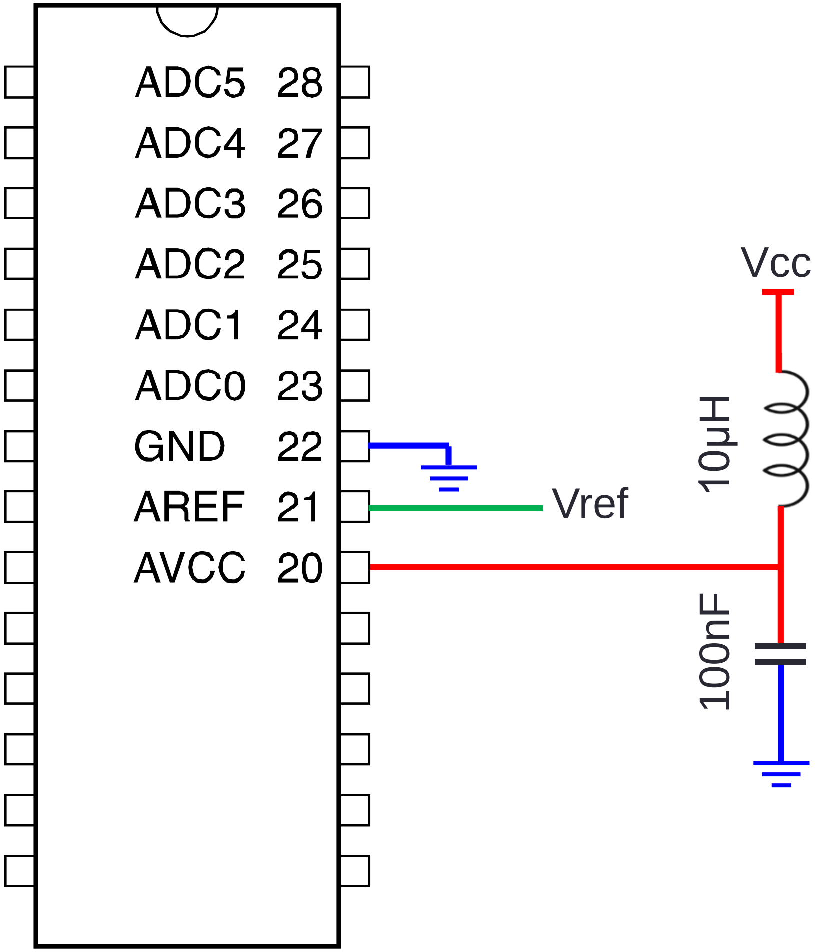






# ADC Connection

- Six analog input pins: PC0 – PC5
- AVcc is the power supply to ADC
- Suggested connection for noise cancelation
- ADC range: 0 – Vref
- Internal Vref available



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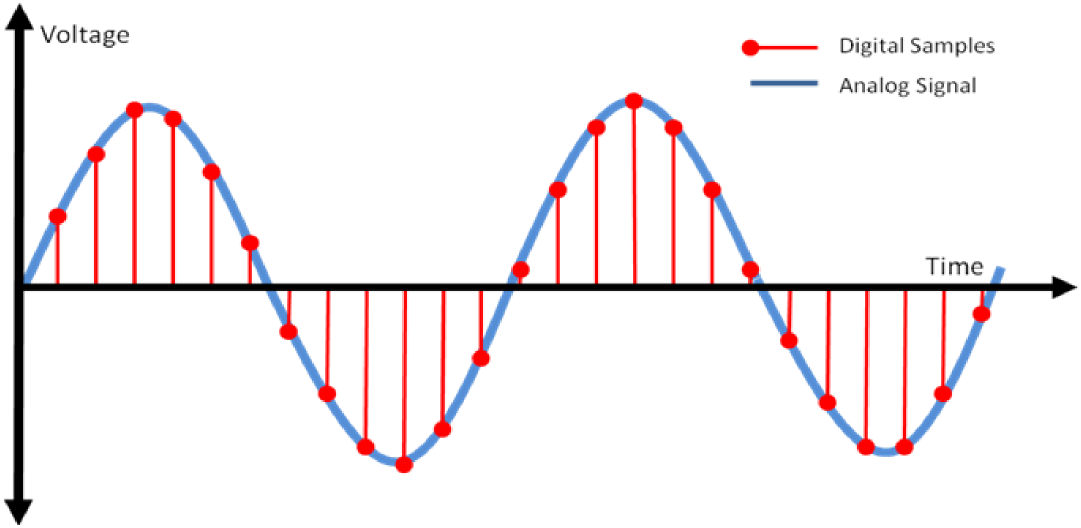
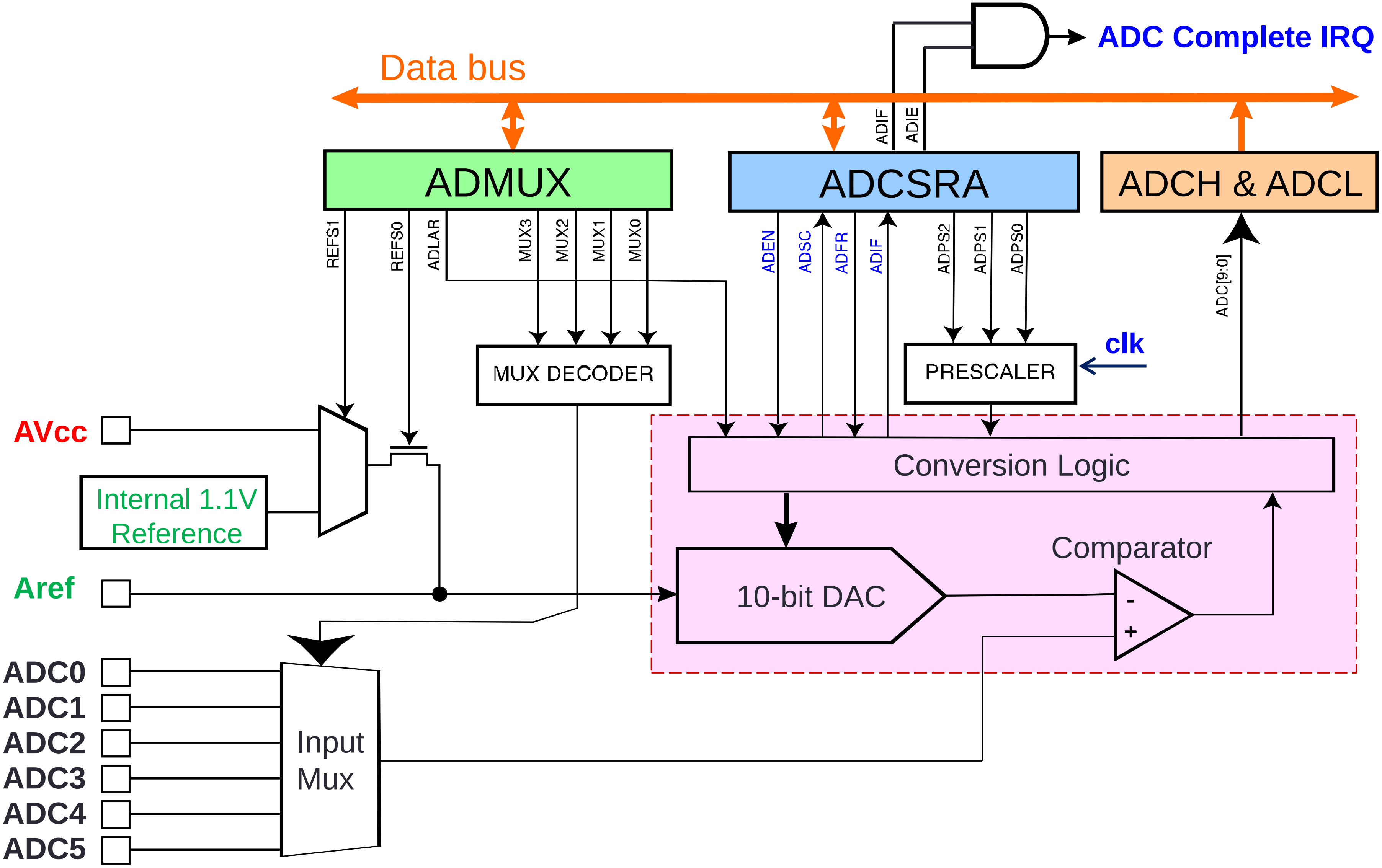


# ADC Schematic Diagram



# ADC Registers

ADMUX

- Input pin and reference voltage control

ADCSRA

- Status and prescalar control

ADCH

ADCL

- ADC data storage
- 10-bit ADC needs 2 bytes for storing

NOTE: read ADCL first!

# Voltage Reference Selection

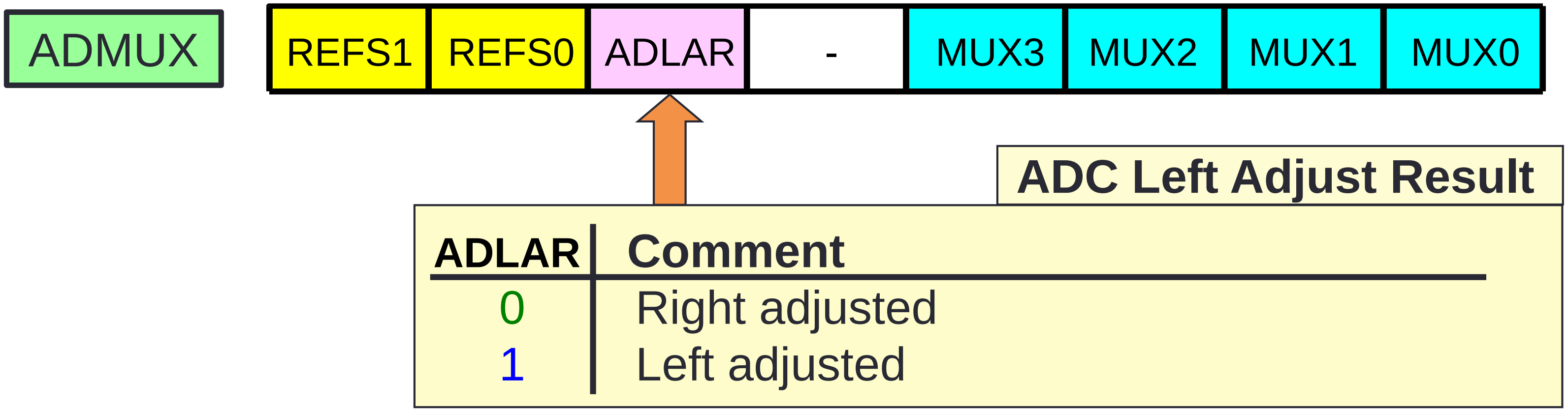
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ADMUX | REFS1 | REFS0 | ADLAR | - | MUX3 | MUX2 | MUX1 | MUX0 |

- ADMUX: ADC multiplexer selection register
  1. Voltage reference selection
  2. ADC result left adjustment
  3. Input channel selection

**Voltage Reference Selection**

| REFS1 | REFS0 | Comment |
|---|---|---|
| 0 | 0 | Aref |
| 0 | 1 | Avcc |
| 1 | 0 | Reserved |
| 1 | 1 | Internal 1.1V |

# ADC Result Left Adjustment



ADMUX

| REFS1 | REFS0 | ADLAR | - | MUX3 | MUX2 | MUX1 | MUX0 |
|---|---|---|---|---|---|---|---|

**ADC Left Adjust Result**

| ADLAR | Comment |
|---|---|
| 0 | Right adjusted |
| 1 | Left adjusted |

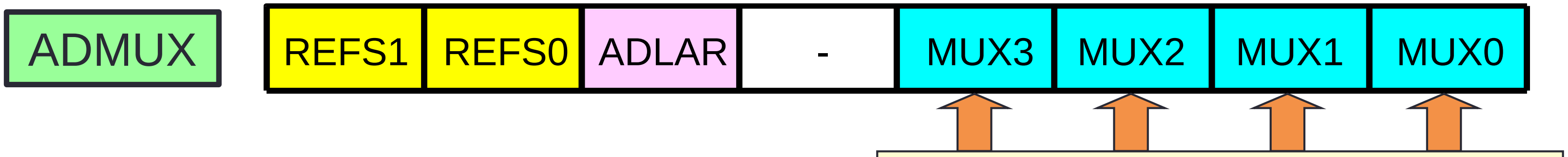
## Right adjusted

| ADCH | | | | | | | | ADCL | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | - | - | - | - | - | ADC9 | ADC8 | ADC7 | ADC6 | ADC5 | ADC4 | ADC3 | ADC2 | ADC1 | ADC0 |

## Left adjusted

| ADCH | | | | | | | | ADCL | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ADC9 | ADC8 | ADC7 | ADC6 | ADC5 | ADC4 | ADC3 | ADC2 | ADC1 | ADC0 | - | - | - | - | - | - |

# Input Channel Selection



ADMUX

| REFS1 | REFS0 | ADLAR | - | MUX3 | MUX2 | MUX1 | MUX0 |
|---|---|---|---|---|---|---|---|

**Input Channel Selection**

| MUX3 | MUX2 | MUX1 | MUX0 | Comment |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | ADC0 |
| 0 | 0 | 0 | 1 | ADC1 |
| 0 | 0 | 1 | 0 | ADC2 |
| 0 | 0 | 1 | 1 | ADC3 |
| 0 | 1 | 0 | 0 | ADC4 |
| 0 | 1 | 0 | 1 | ADC5 |
| 1 | 1 | 1 | 1 | 0V |

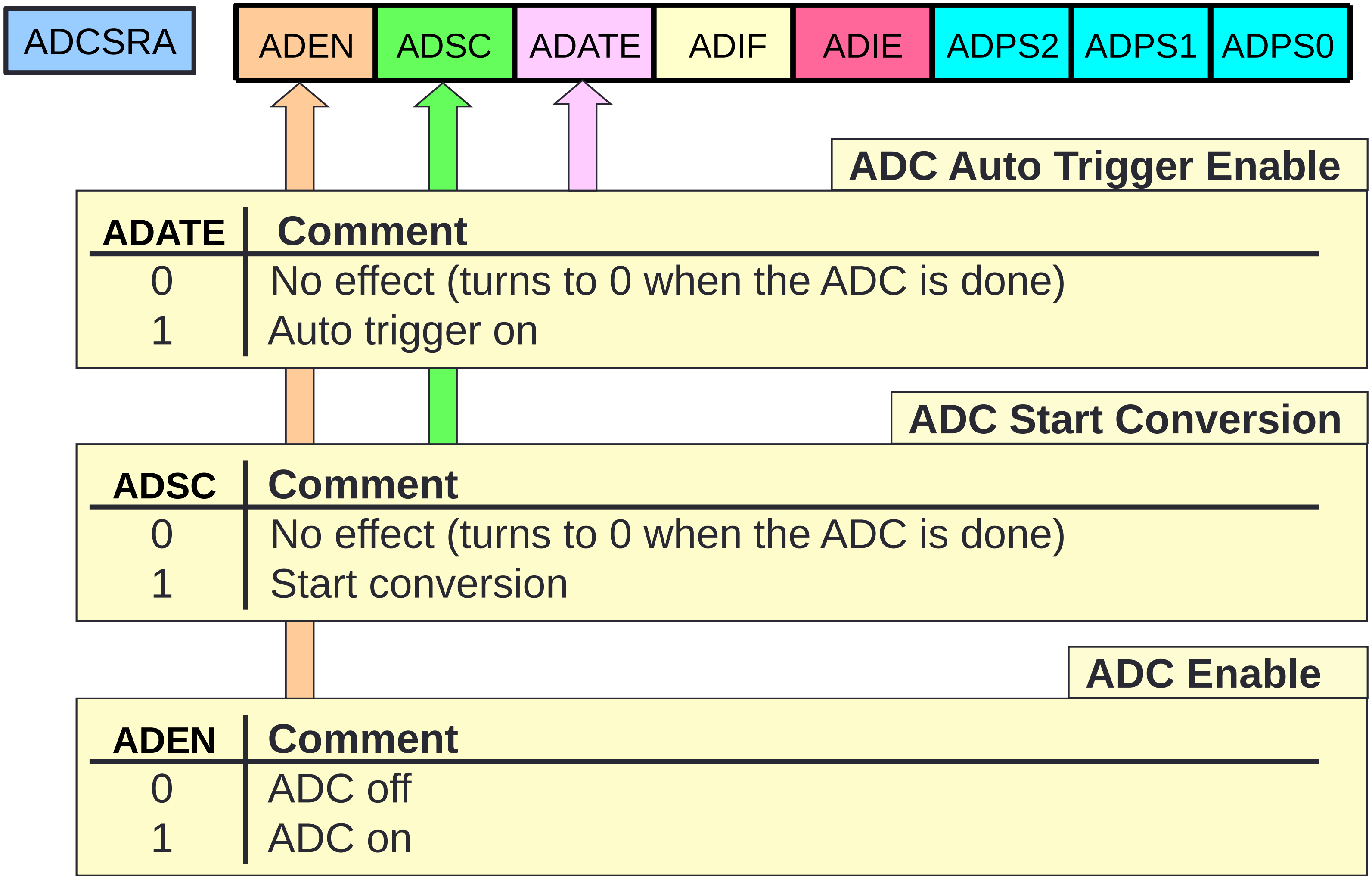
# ADC Control and Status Register A

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ADCSRA | ADEN | ADSC | ADATE | ADIF | ADIE | ADPS2 | ADPS1 | ADPS0 |

- ADCSRA: ADC control and status register A
  1. ADC enable
  2. ADC start conversion
  3. ADC auto trigger enable
  4. ADC interrupt flag
  5. ADC prescaler selection

Note: ADIF is set whenever ADC conversion is done

# ADC Enable, Start Conversion, and Auto Trigger



| ADCSRA | | | | | | | |
|---|---|---|---|---|---|---|---|
| ADEN | ADSC | ADATE | ADIF | ADIE | ADPS2 | ADPS1 | ADPS0 |

**ADC Auto Trigger Enable**

| ADATE | Comment |
|---|---|
| 0 | No effect (turns to 0 when the ADC is done) |
| 1 | Auto trigger on |

**ADC Start Conversion**

| ADSC | Comment |
|---|---|
| 0 | No effect (turns to 0 when the ADC is done) |
| 1 | Start conversion |

**ADC Enable**

| ADEN | Comment |
|---|---|
| 0 | ADC off |
| 1 | ADC on |

# ADC Interrupt Flag and Interrupt Enable

ADCSRA

| ADEN | ADSC | ADATE | ADIF | ADIE | ADPS2 | ADPS1 | ADPS0 |
|---|---|---|---|---|---|---|---|

- Interrupt flag (ADIF) is 1 whenever a conversion is done

**ADC Interrupt Enable**

| ADIE | Comment |
|---|---|
| 0 | Disable interrupt |
| 1 | Enable interrupt |

**ADC Interrupt Flag**

| ADIF | Comment |
|---|---|
| 0 | No effect |
| 1 | Clear the flag |

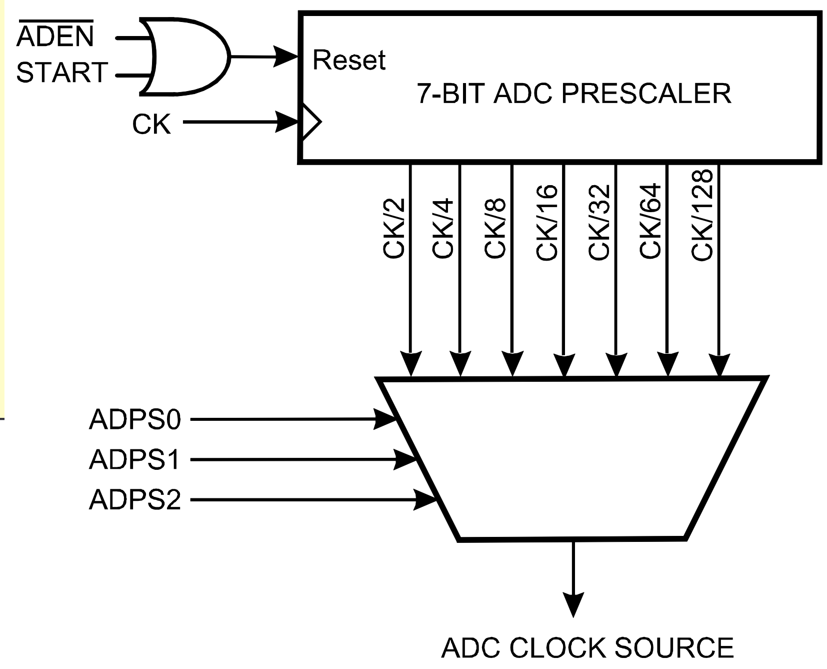
Note: ADIF can be cleared by written 1 into the bit

# ADC Prescaler Selection

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ADCSRA | ADEN | ADSC | ADATE | ADIF | ADIE | ADPS2 | ADPS1 | ADPS0 |

**ADC Prescaler Selection**

| ADPS2 | ADPS1 | ADPS0 | Comment |
|---|---|---|---|
| 0 | 0 | 0 | 2 |
| 0 | 0 | 1 | 2 |
| 0 | 1 | 0 | 4 |
| 0 | 1 | 1 | 8 |
| 1 | 0 | 0 | 16 |
| 1 | 0 | 1 | 32 |
| 1 | 1 | 0 | 64 |
| 1 | 1 | 1 | 128 |



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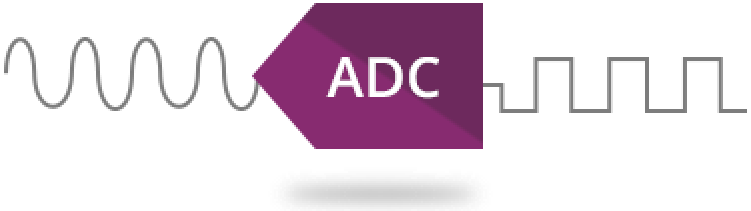
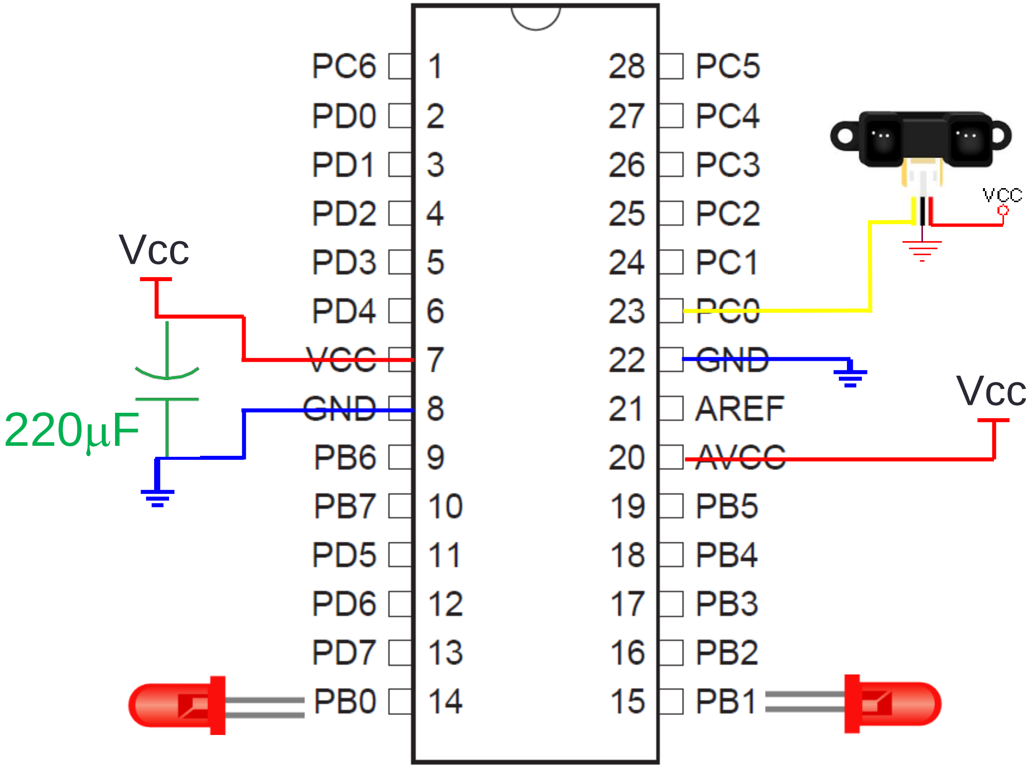


# Example: Read DMS Sensor

- Read from ADC0 (PC0)
- Right adjusted:

  display the result on
  Port B for the high byte
  Port D for the low byte
- ADC prescalar 128
- Vref = internal 1.1V
- Delay for 200ms

| 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|
| PB 1 | PB 0 | PD 7 | PD 6 | PD 5 | PD 4 | PD 3 | PD 2 | PD 1 | PD 0 |



# Flowchart

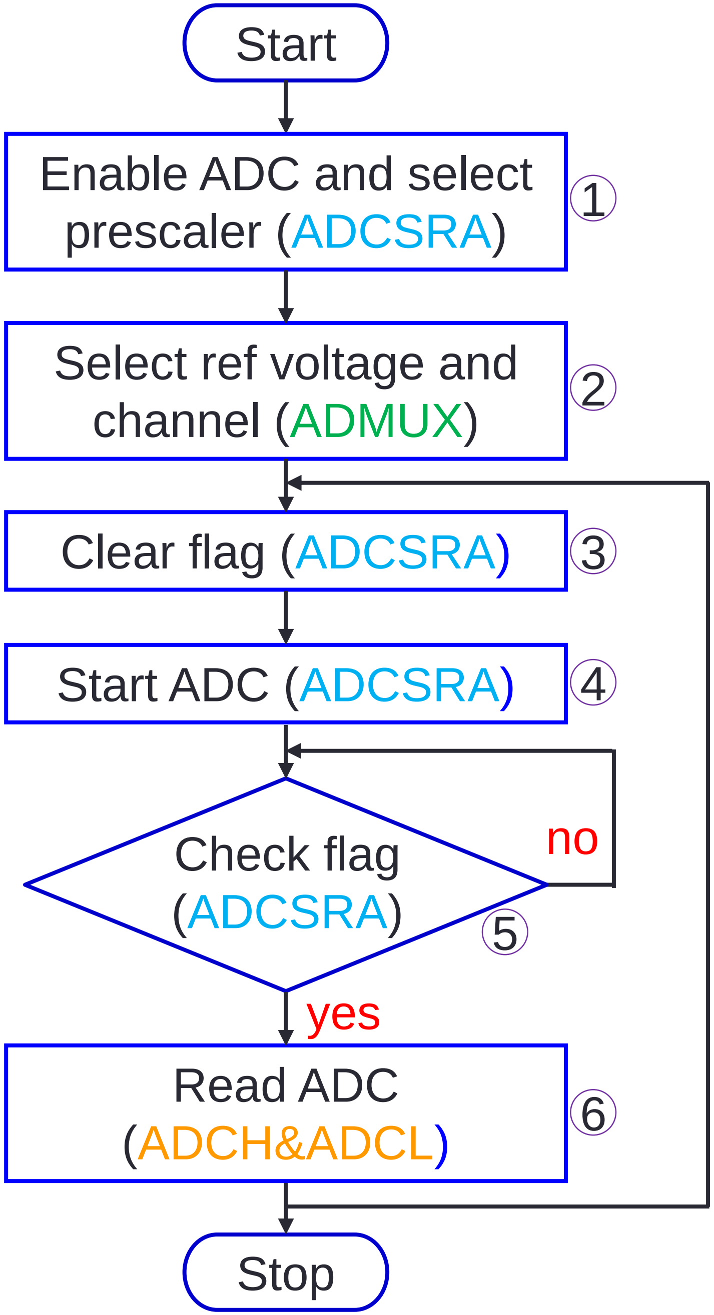
- What value do we set the registers?

ADCSRA

| ADEN | ADSC | ADATE | ADIF | ADIE | ADPS2 | ADPS1 | ADPS0 |
|---|---|---|---|---|---|---|---|
| 1 |  |  |  |  | 1 | 1 | 1 |

| REFS1 | REFS0 | ADLAR | - | MUX3 | MUX2 | MUX1 | MUX0 |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 |  | 0 | 0 | 0 | 0 |

ADMUX



# Read DMS Sensor

```
#define F_CPU 1000000UL
#include <avr/io.h>
#include <util/delay.h>

int main(void)
{
    CLKPR=(1<<CLKPCE);
    CLKPR=0b00000011;                   // set clk to 1Mhz
    DDRB=0xFF;                          // PORTB as output
    DDRD=0xFF;                          // PORTD as output
    DDRC=0;                             // PORTC as input
  ① ADCSRA=0b10000111;                  // enable + prescaler
  ② ADMUX=0b11000000;                   // ref volt + channel
    while (1) {
  ③     ADCSRA|=(1<<ADIF);              // clear ADIF
  ④     ADCSRA|=(1<<ADSC);              // start ADC
  ⑤     while((ADCSRA&(1<<ADIF))==0);   // wait for ADC done
  ⑥     PORTD=ADCL;                     // read low byte first
        PORTB=ADCH;
        _delay_ms(200);
    }
}
```

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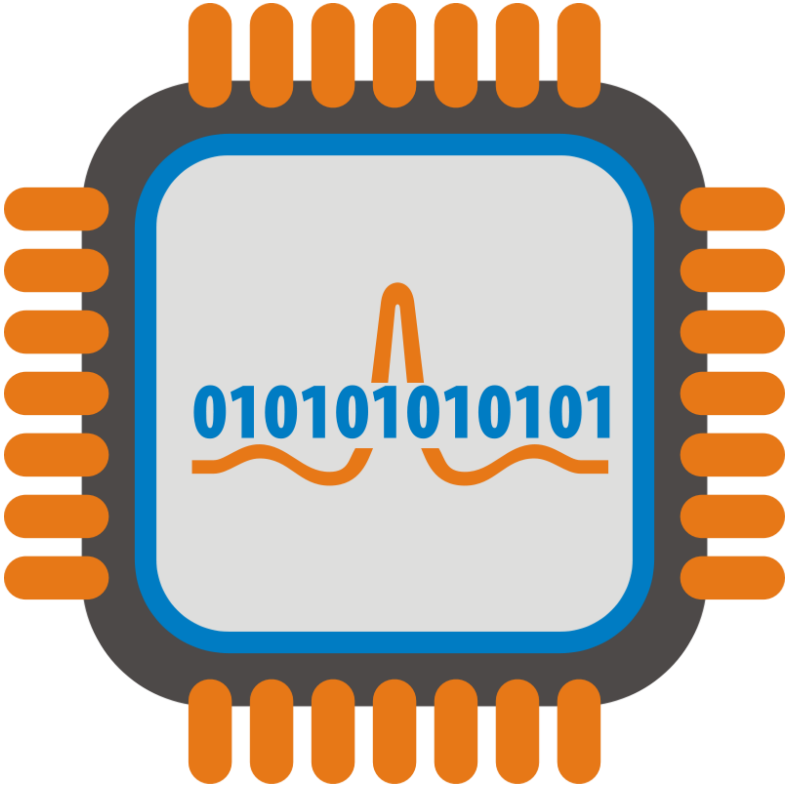


# ADC Running Mode

- Single conversion mode
  - Triggered by your program
  - Write 1 into ADSC in ADCSRA
- Auto trigger mode
  - Triggered automatically or by some events
  - Write 1 into ADATE in ADCSRA
  - Setup the trigger source in ADCSRB
    1. Free running mode
    2. External interrupt request
    3. Timer compare match
    4. Timer overflow

# ADC Control and Status Register B

| ADCSRB | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | - | ACME | - | - | - | ADTS2 | ADTS1 | ADTS0 |

- ADC auto trigger source

**Auto Trigger Source**

| ADTS2 | ADTS1 | ADTS0 | Comment |
|---|---|---|---|
| 0 | 0 | 0 | Free running mode |
| 0 | 0 | 1 | Analog comparator |
| 0 | 1 | 0 | External interrupt request 0 |
| 0 | 1 | 1 | Timer/couter0 compare match A |
| 1 | 0 | 0 | Timer/counter0 overflow |
| 1 | 0 | 1 | Timer/couter1 compare match B |
| 1 | 1 | 0 | Timer/counter1 overflow |
| 1 | 1 | 1 | Timer/counter1 capture event |

# Example: Free Running Mode w/ Interrupt

- Read data from ADC0 and displays the result on Port B and Port D indefinitely
- Enable ADC and select ADC clock to be ck/128

⇒ **ADCSRA** = 0xAF **ADCSRB** = 0x00

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | | 1 | | 1 | 1 | 1 | 1 |
| ADCSRA | ADEN | ADSC | ADATE | ADIF | ADIE | ADPS2 | ADPS1 | ADPS0 |
| ADCSRB | - | ACME | - | - | - | ADTS2 | ADTS1 | ADTS0 |
| | | | | | | 0 | 0 | 0 |

- Select 1.1V internal reference voltage and ADC0

⇒ **ADMUX** = 0xC0

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | | | 0 | 0 | 0 | 0 |
| ADMUX | REFS1 | REFS0 | ADLAR | - | MUX3 | MUX2 | MUX1 | MUX0 |

# Flowchart (Free Running)

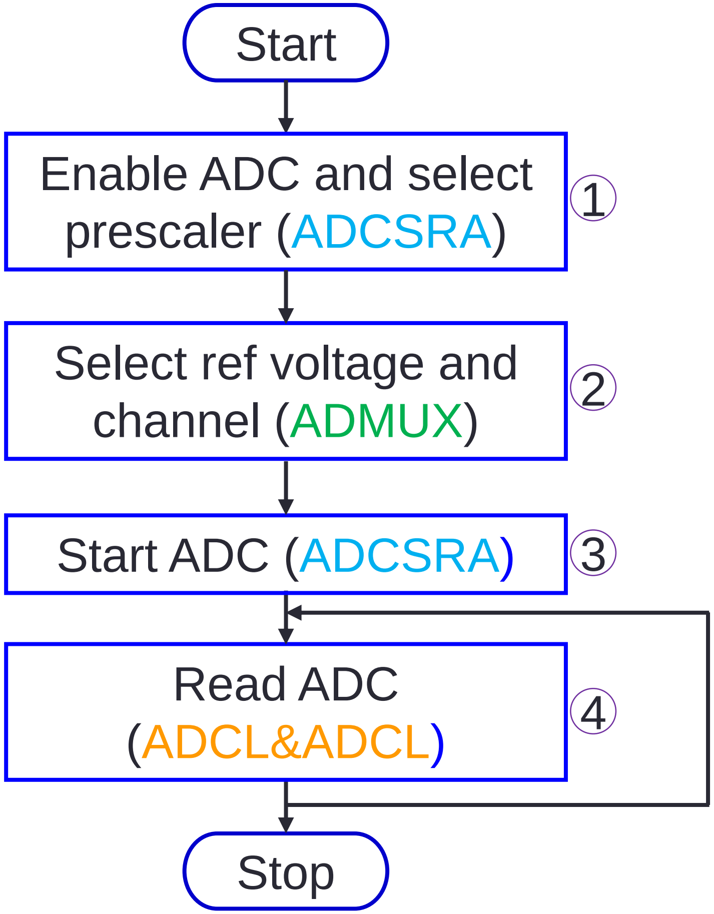
- What value do we set the registers?

ADCSRA

| 1 |  | 1 |  |  | 1 | 1 | 1 |
|---|---|---|---|---|---|---|---|
| ADEN | ADSC | ADATE | ADIF | ADIE | ADPS2 | ADPS1 | ADPS0 |

| REFS1 | REFS0 | ADLAR | - | MUX3 | MUX2 | MUX1 | MUX0 |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 |  | 0 | 0 | 0 | 0 |

ADMUX


Start
Enable ADC and select prescaler (ADCSRA)
1
Select ref voltage and channel (ADMUX)
2
Start ADC (ADCSRA)
3
Read ADC (ADCL&ADCL)
4
Stop

# Read DMS Sensor (Free Running)

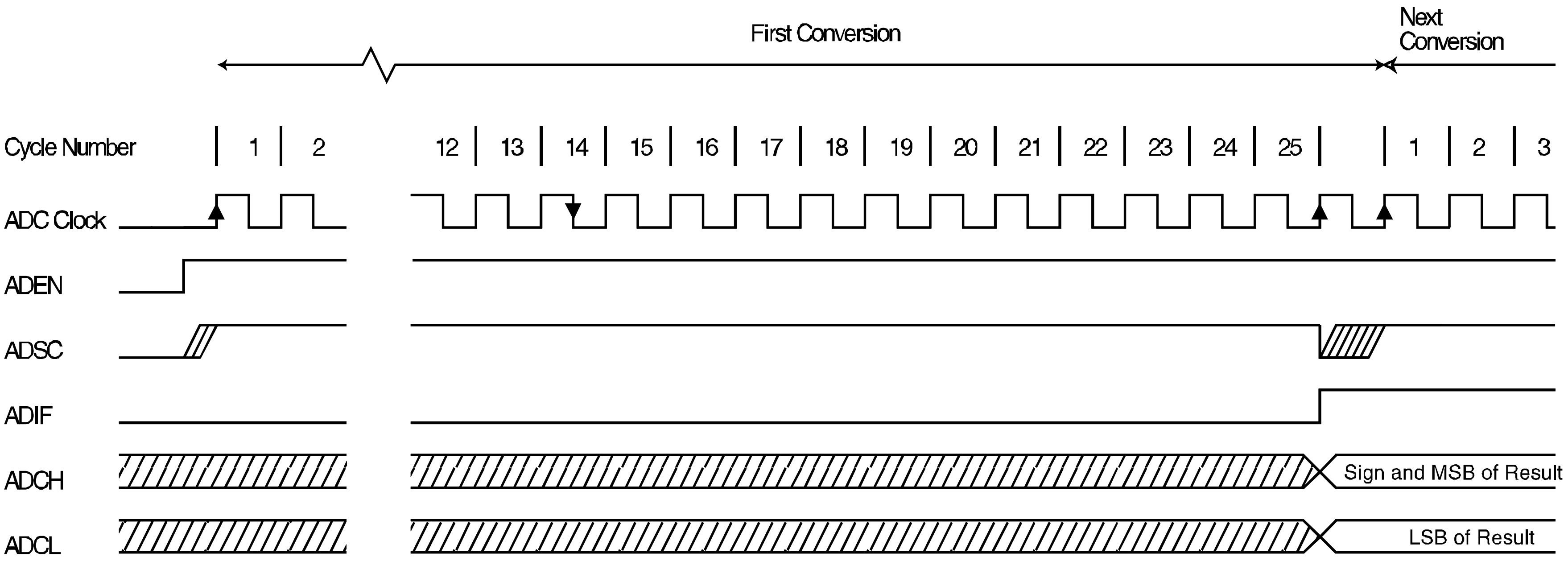
```
#define F_CPU 1000000UL
#include <avr/io.h>
#include <util/delay.h>

int main(void)
{
    CLKPR=(1<<CLKPCE);
    CLKPR=0b00000011;                   // set clk to 1Mhz
    DDRB=0xFF;                          // PORTB as output
    DDRD=0xFF;                          // PORTD as output
    DDRC=0;                             // PORTC as input
    ADCSRA=0b10100111;                  // free running mode
    ADMUX=0b11000000;                   // ref volt + channel
    ADCSRA|=(1<<ADSC);                  // start ADC
    while (1) {
        PORTD=ADCL;                     // read low byte first
        PORTB=ADCH;
        _delay_ms(200);
    }
}
```

Note: Do NOT need to check the flag ADIF

# ADC Conversion Time

- ADC Timing Diagram, First Conversion



| Condition | Sample & Hold (cycle) | Conversion Time (Cycle) |
|---|---|---|
| First conversion | 13.5 | 25 |
| Normal conversions, single ended | 1.5 | 13 |
| Auto triggered conversions | 2 | 13.5 |

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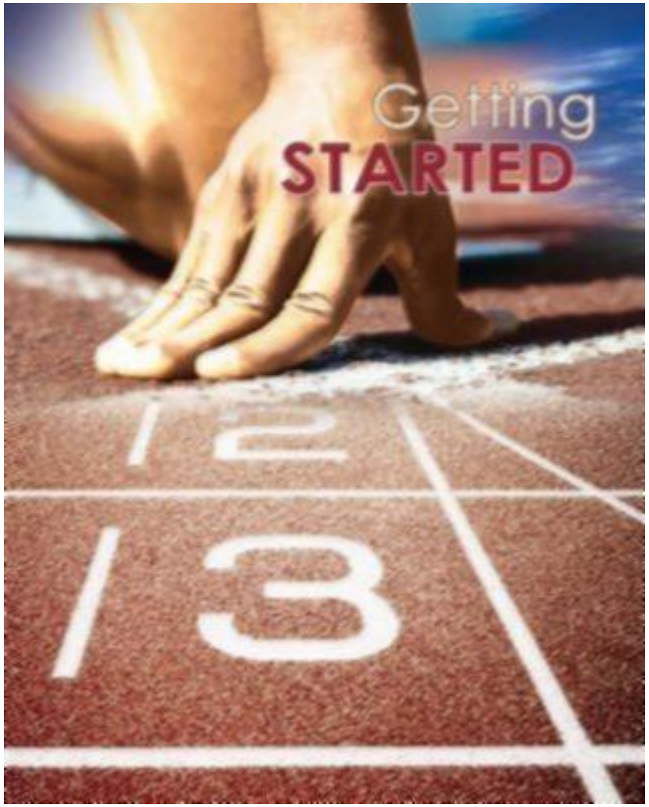

# Reference

- ATmega328P data sheet
- AVR 8-bit instruction set
- Atmel AVR126: ADC of megaAVR in Single Ended Mode
- Atmel AVR127: Understanding ADC parameters
- AVR131: Using the AVR’s High-speed PWM
- M. A. Mazidi, S. Naimi, and S. Naimi, *The AVR Microcontroller and Embedded Systems: Using Assembly and C*, Prentice Hall, 2010
- AVR GCC library help http://nongnu.org/avr-libc/user-manual/modules.html