12.24196

Introduction to Embedded Systems

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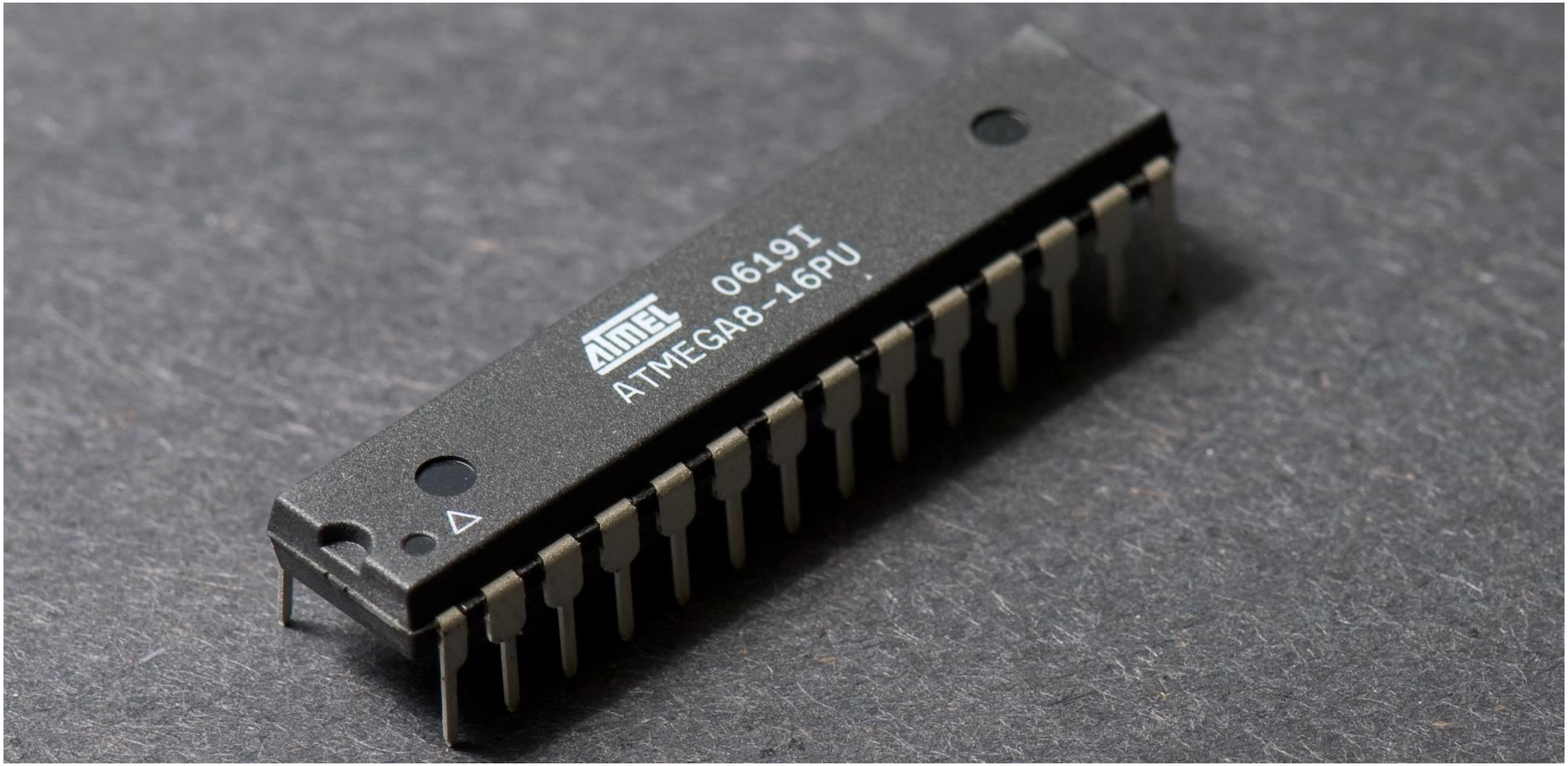
Part 1

Microcontrollers

Microcontrollers



ATMega 8

Content

Microcontrollers

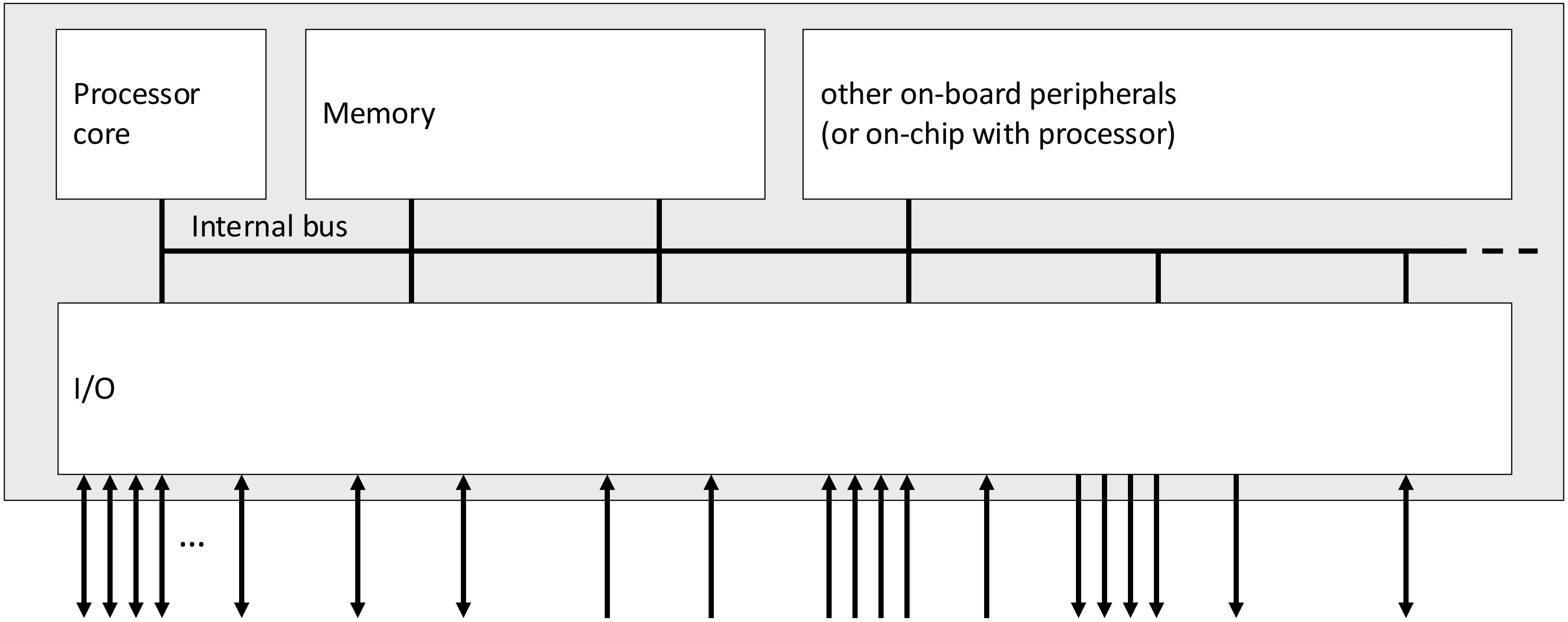
1. Basics
2. Structure/elements
3. Digital I/O
4. Interrupts
5. Timers/Counters
6. Analog I/O

Microprocessors vs. microcontrollers?

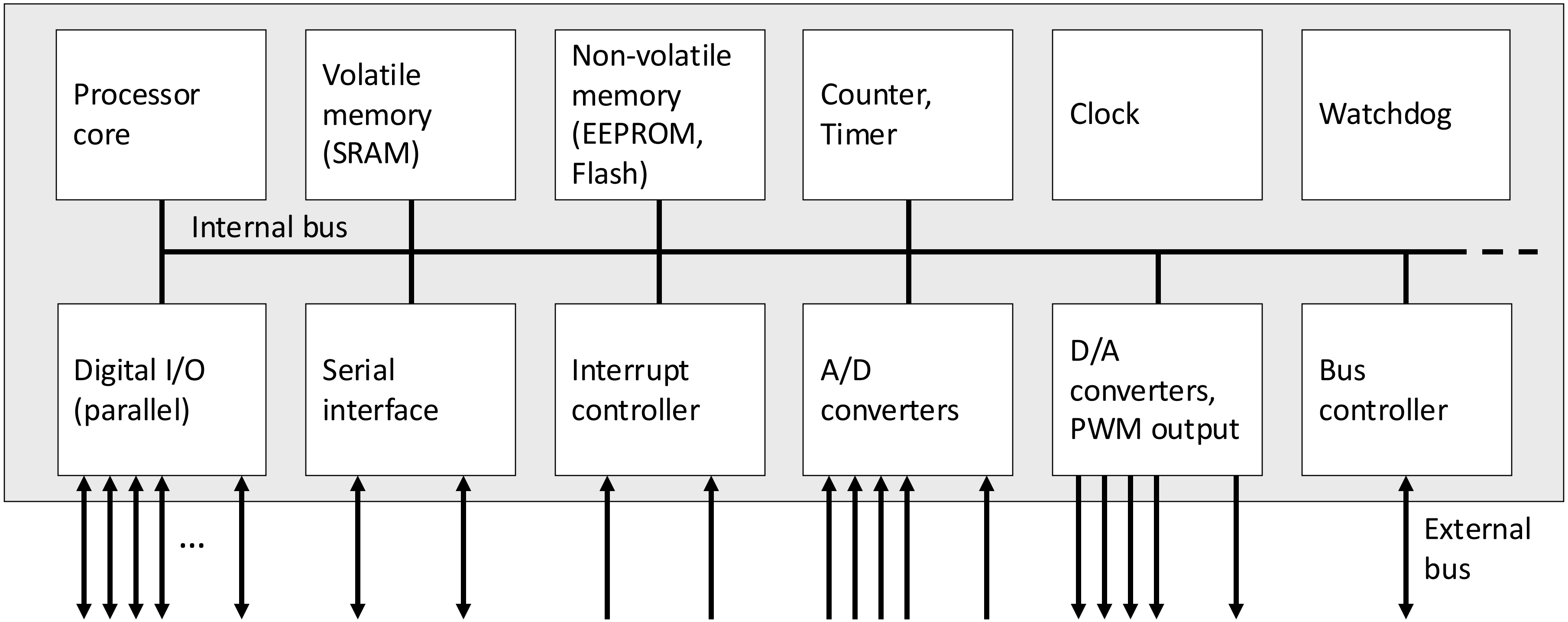
- Microcontroller (often abbrev. “µC”):
  - stand-alone device for embedded applications
  - ≈ low-end microprocessor + memory + I/O + additional peripherals
  - not a general-purpose device
  - cost-optimized control unit for particular application area
  - (but more general than Application Specific Instruction Set Processors (ASIPs) and Systems-on-Chip (SoCs)

- Microcontroller family:
  - Same microprocessor
  - Scalability w.r.t. memory, I/O capabilities, on-chip peripherals, etc.

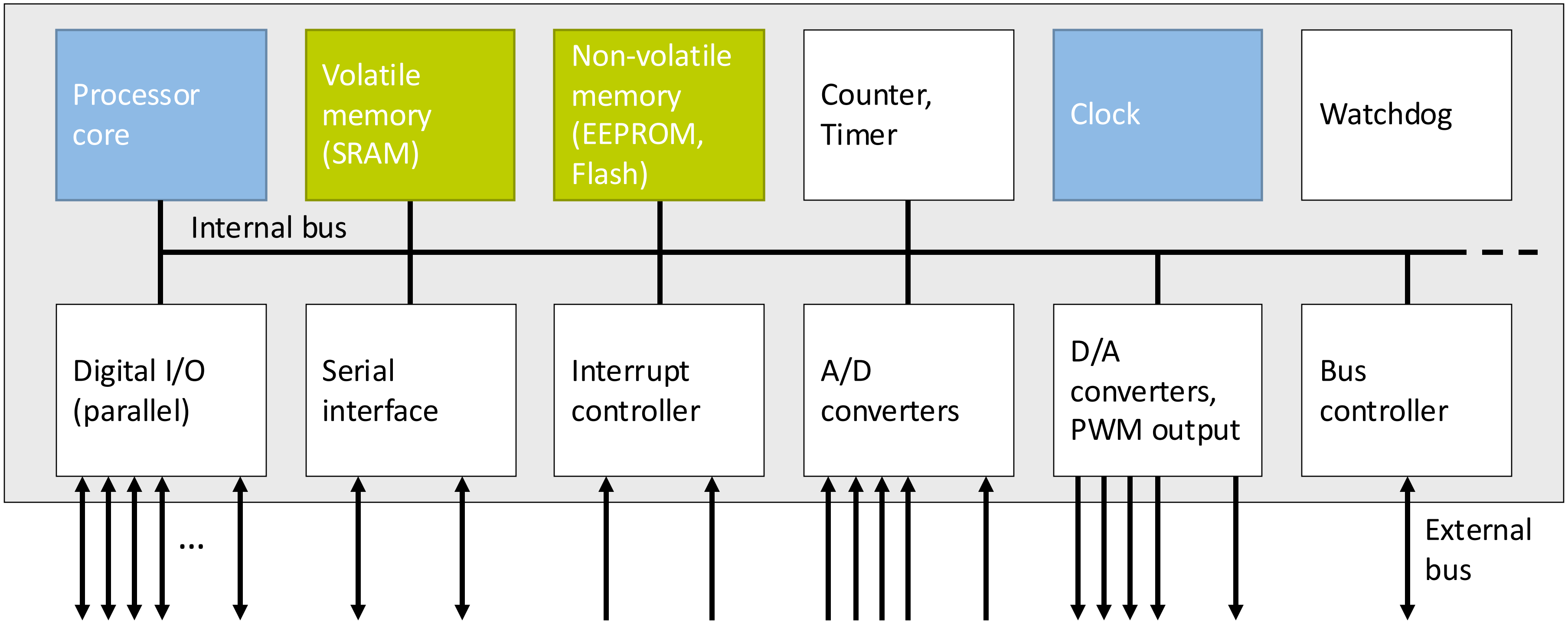
Basic structure of a microcontroller



Basic structure of a microcontroller - refined

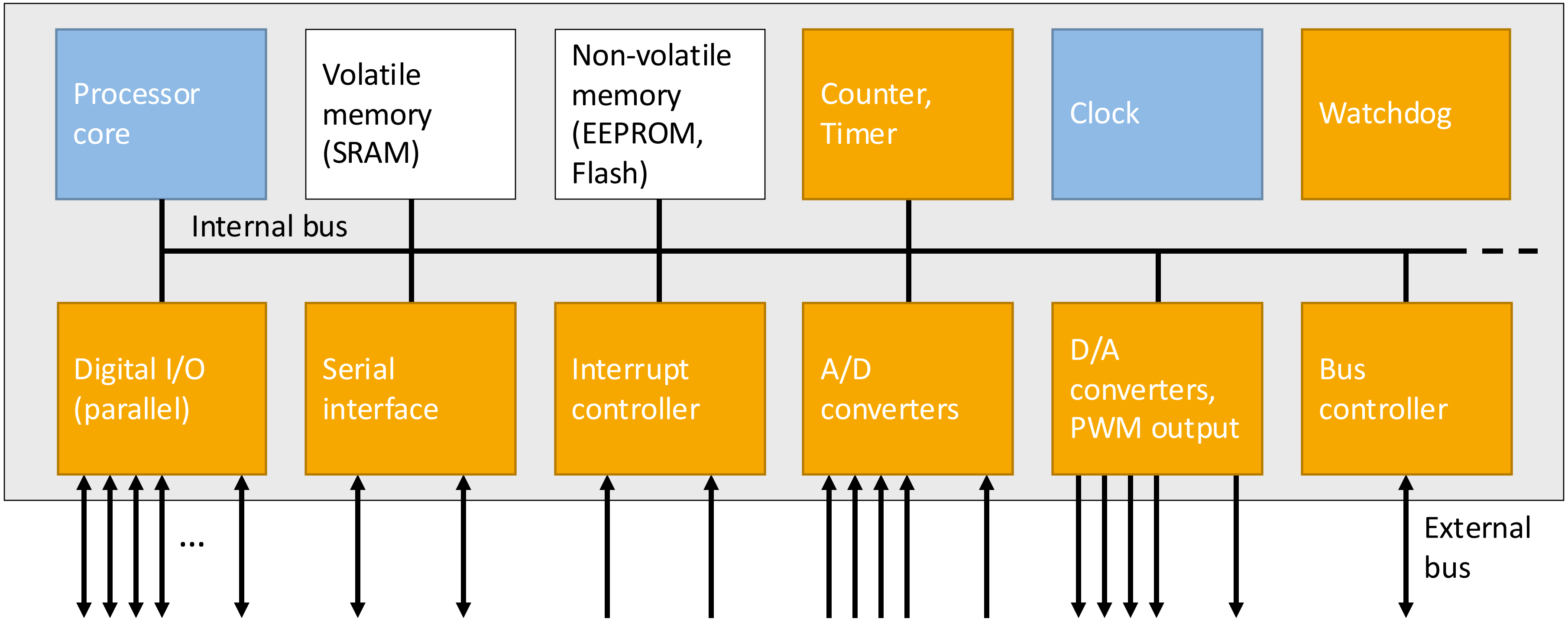


How to access internal blocks? - memory



Memory: - all memory types share a common address range or
- different memory types are mapped into one address range
(if you use C the compiler handles most of it)

How to access internal blocks? - digital I/O & on-chip peripherals



Digital I/O and on-chip peripherals are accessed by dedicated registers.

Content

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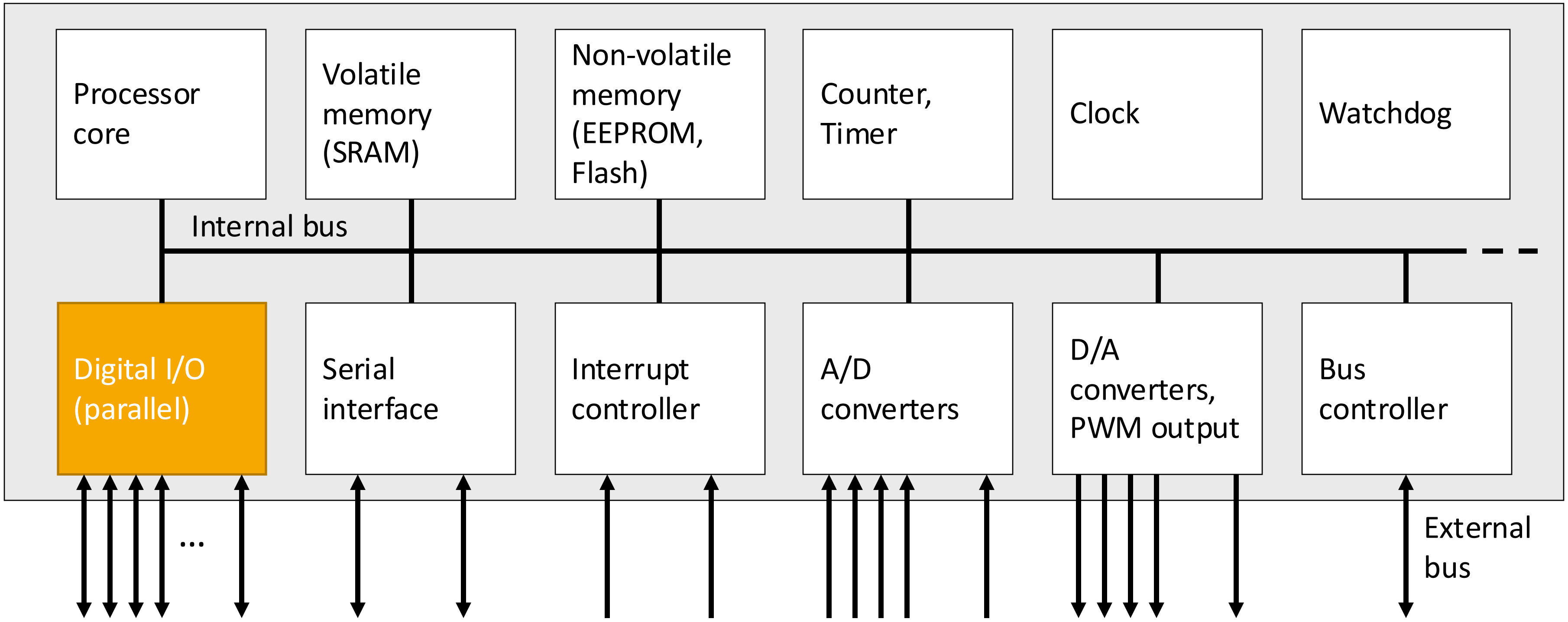
Basic structure of a microcontroller - refined



Digital I/O pins

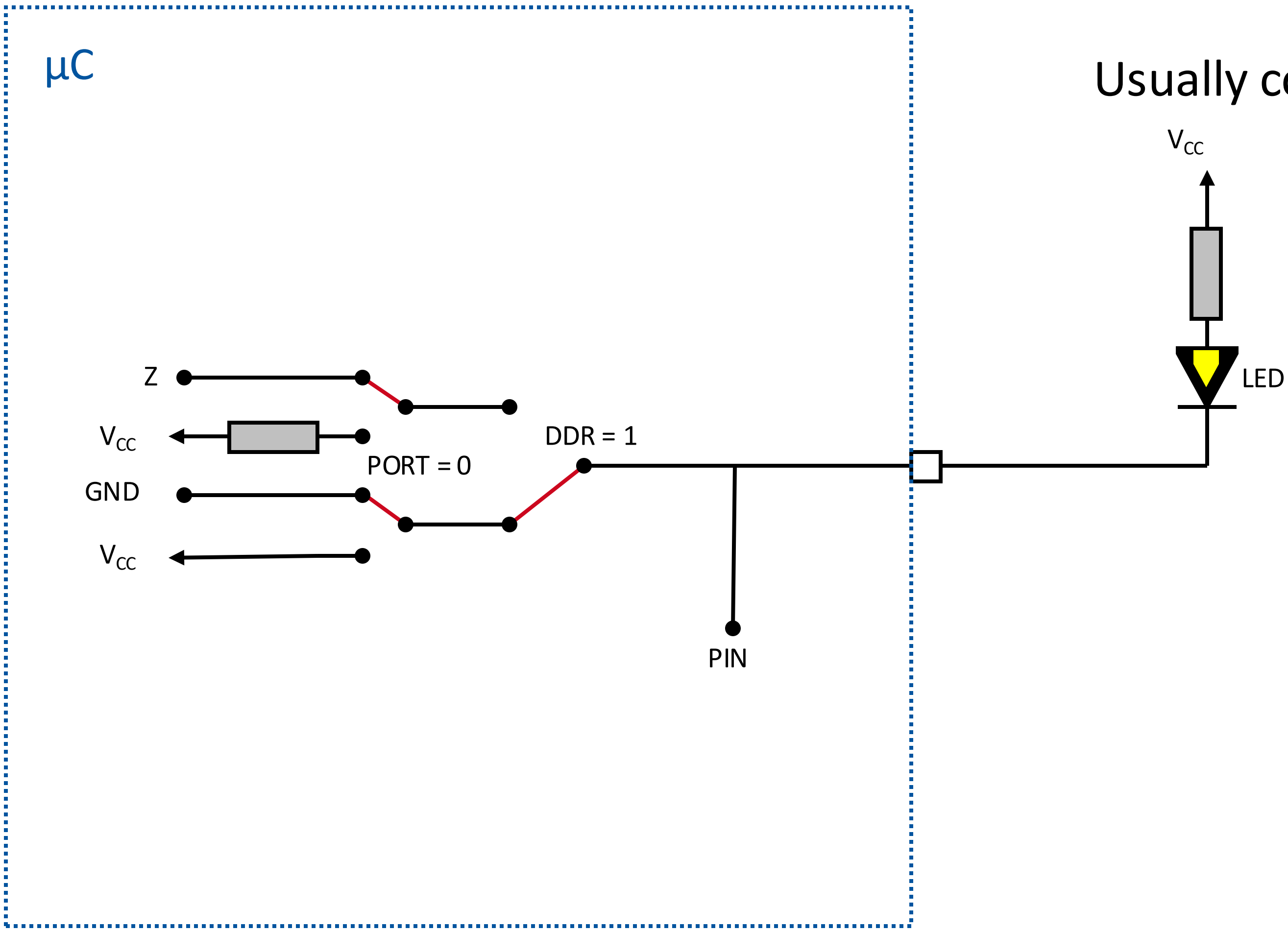
- Basic means to monitor and control external hardware.
- Usually, digital I/O pins
  - are grouped into ports of 8 pins (on 8-bit architecture).
  - are bidirectional (i.e., can be used as input or output pins)
  - can have alternate functions (i.e., can be used for purposes different than digital I/O, e.g., as analog I/O pins)
- Monitoring, access and control of digital I/O pins is done via three special registers for each port:
  - Data Direction Register (DDR)
  - Port Register (PORT)
  - Port Input Register (PIN)

Control of digital I/O pins via registers

- Data Direction Register (DDR):
  - read/write
  - specifies for each bit of the corresponding port whether it is an input or an output bit
- Port Register (PORT):
  - read/write
  - specifies for the output pins whether the output value is high or low
  - ATmega16: also used for controlling pull-up resistors for input pins (see next slides)
- Port Input Register (PIN):
  - read only (writing has no effect or unintuitive semantics)
  - contains the current value (high or low) of all pins (input and output)
  - usual purpose: reading values of input pins

Example: LED control

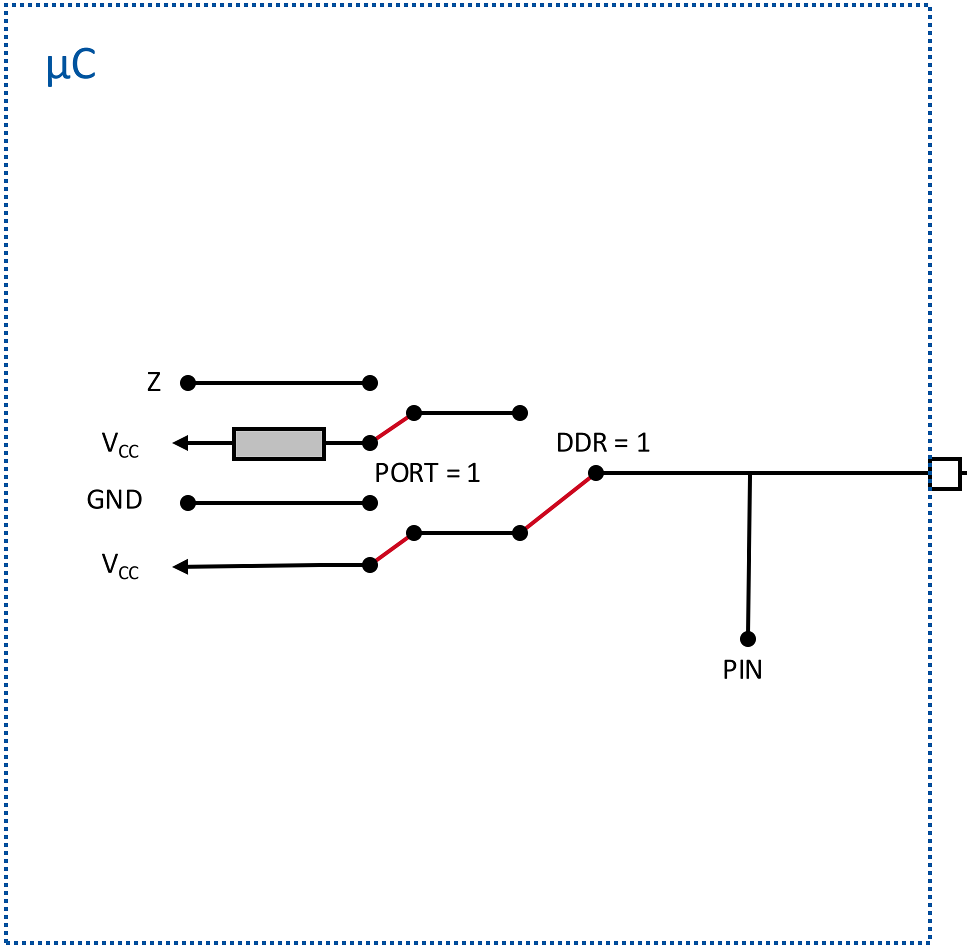
Usually connected to V_{CC}!



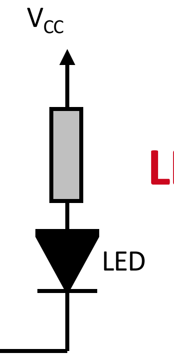
LED is on!

DDR	PORT	Signal on PIN
0	0	1
0	1	1
1	0	0
1	1	1

Example: LED control



Usually connected to V_{CC}!



LED is off!

DDR	PORT	Signal on PIN
0	0	1
0	1	1
1	0	0
1	1	1

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Digital Output

- When a pin is configured as output, the controller drives the pin according to the PORT value of that pin.
- Usually: logic 1 → VCC and logic 0 → GND
- The electric current depends on the connected circuits:
  - Short circuit fault is possible
  - External current limiter might be needed

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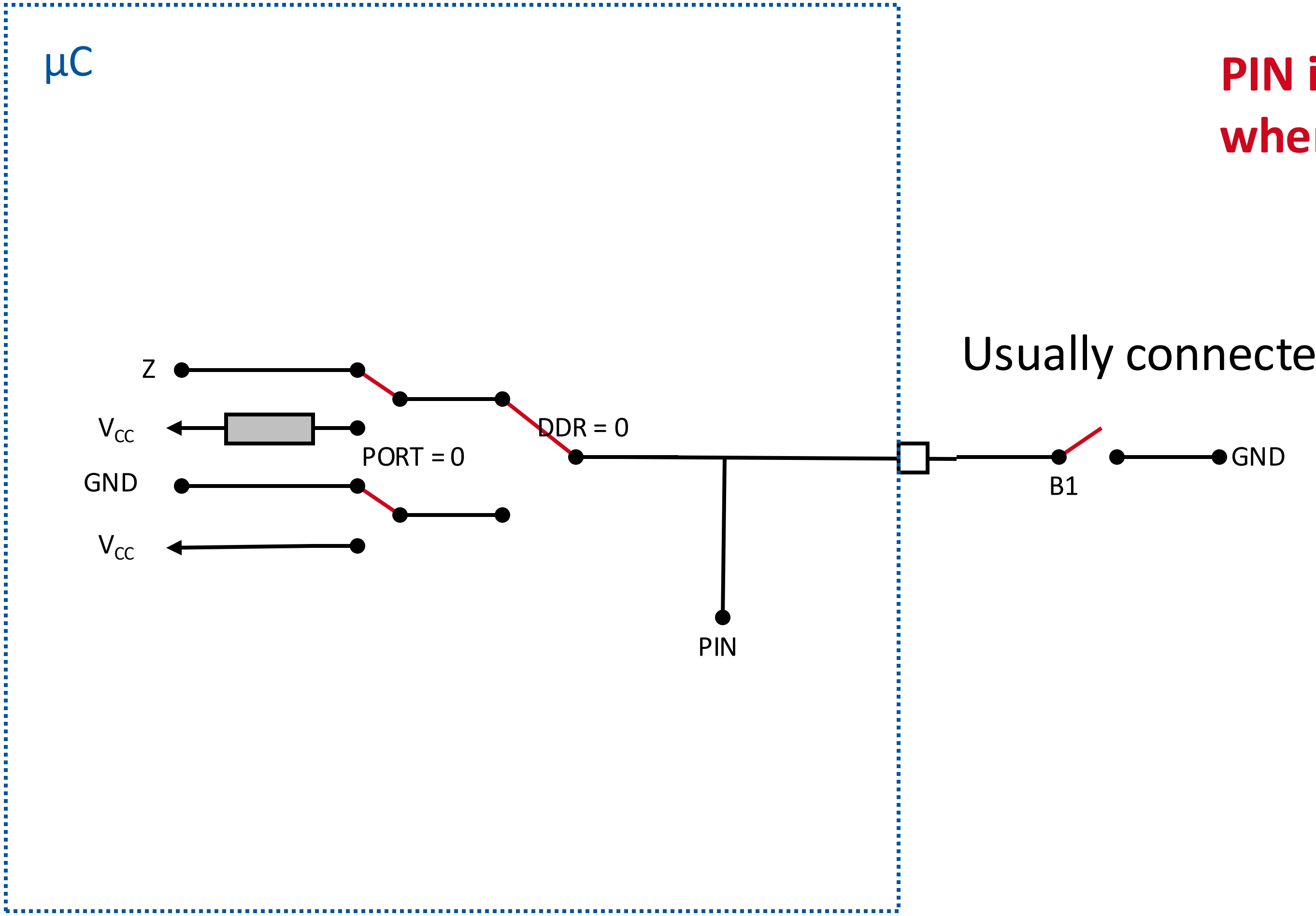
Example: Reading a button

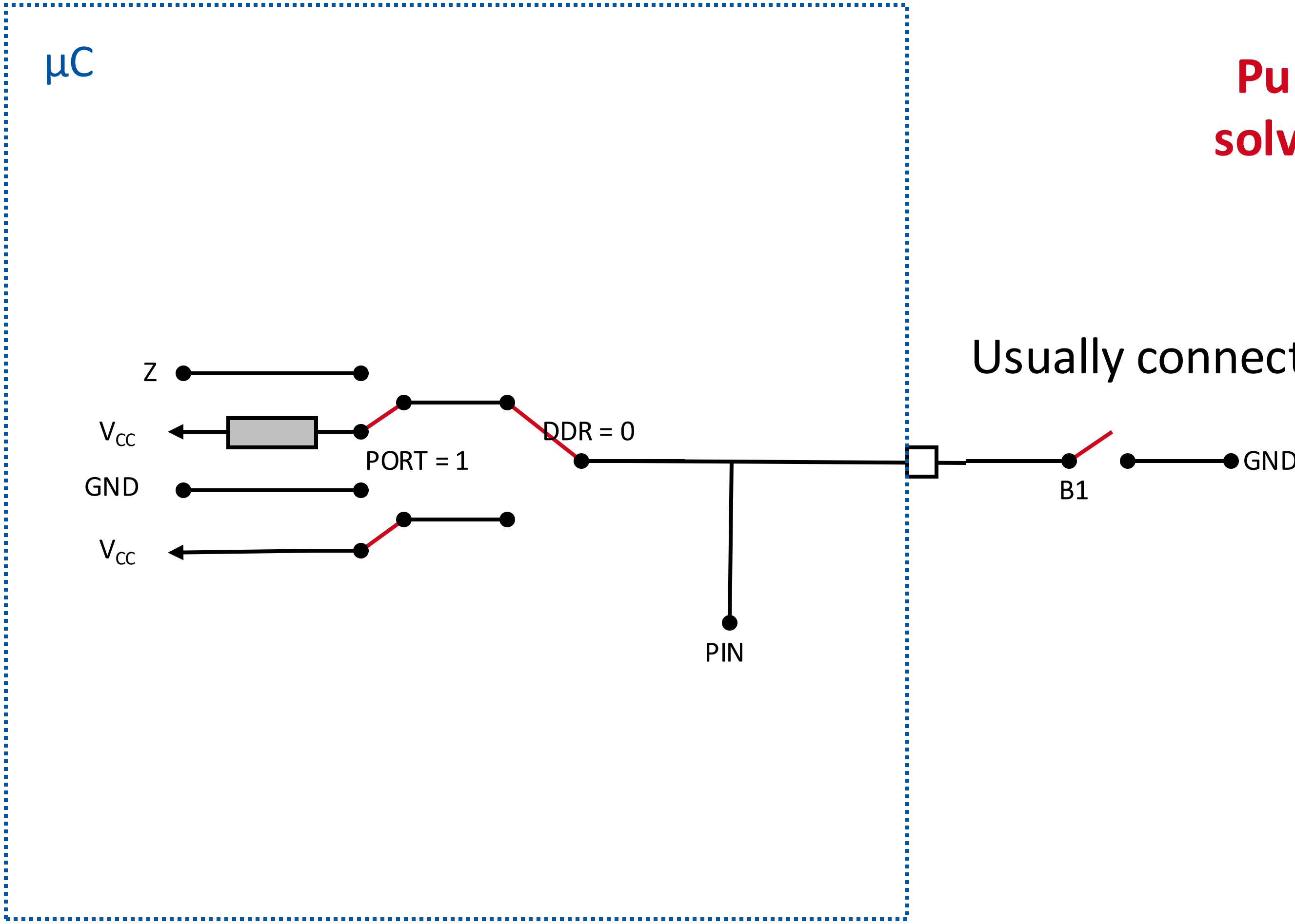


PIN is undefined when B1 is open

Usually connected to GND!

DDR	PORT	Signal on PIN
0	0	?
0	1	1
1	0	0
1	1	1

Example: Reading a button

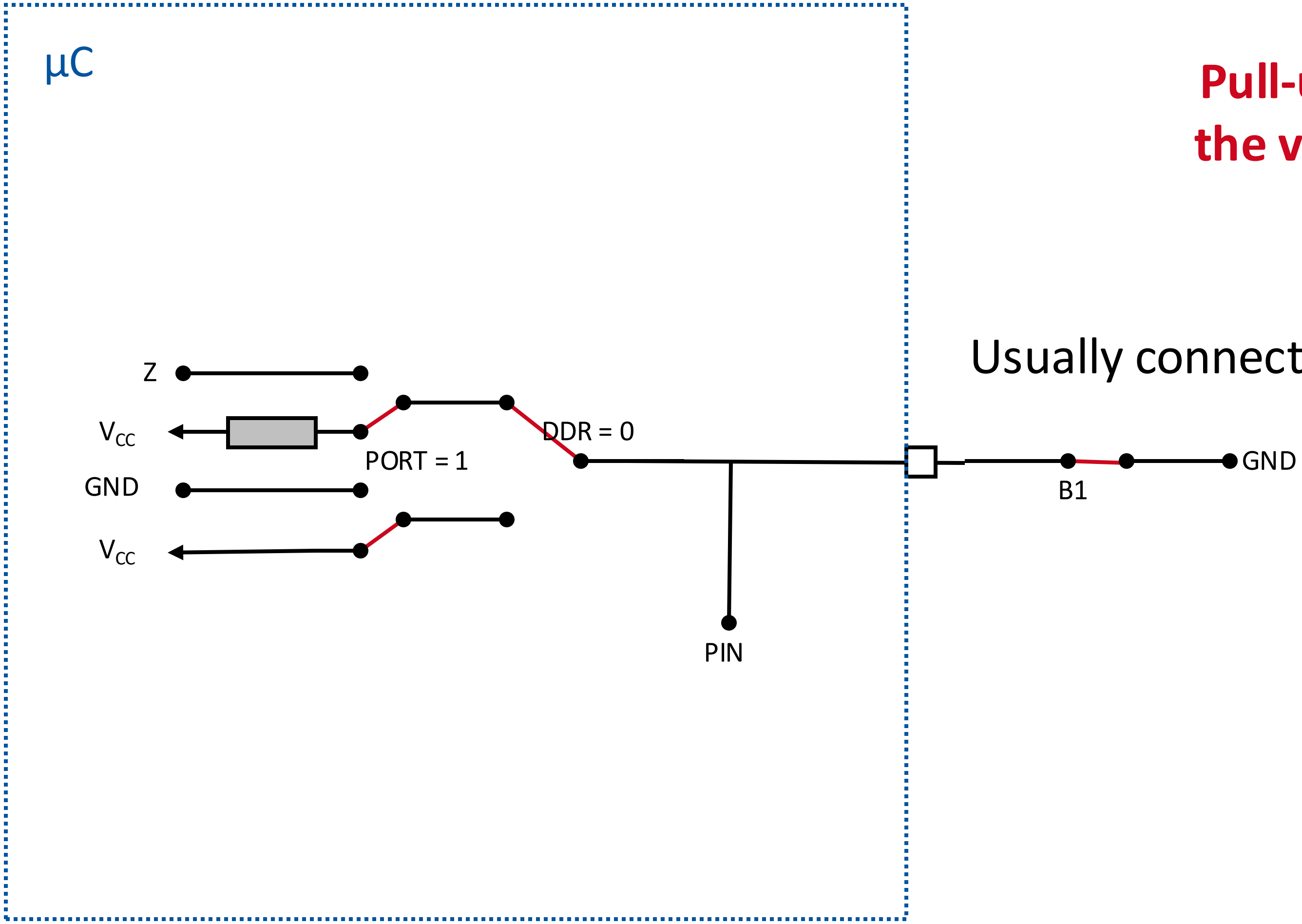


Pull-up resistors solve the problem

Usually connected to GND!

DDR	PORT	Signal on PIN
0	0	?
0	1	1
1	0	0
1	1	1

Example: Reading a button



Pull-up resistors allow the voltage to collapse

Usually connected to GND!

DDR	PORT	Signal on PIN
0	0	0
0	1	0
1	0	0
1	1	⚡

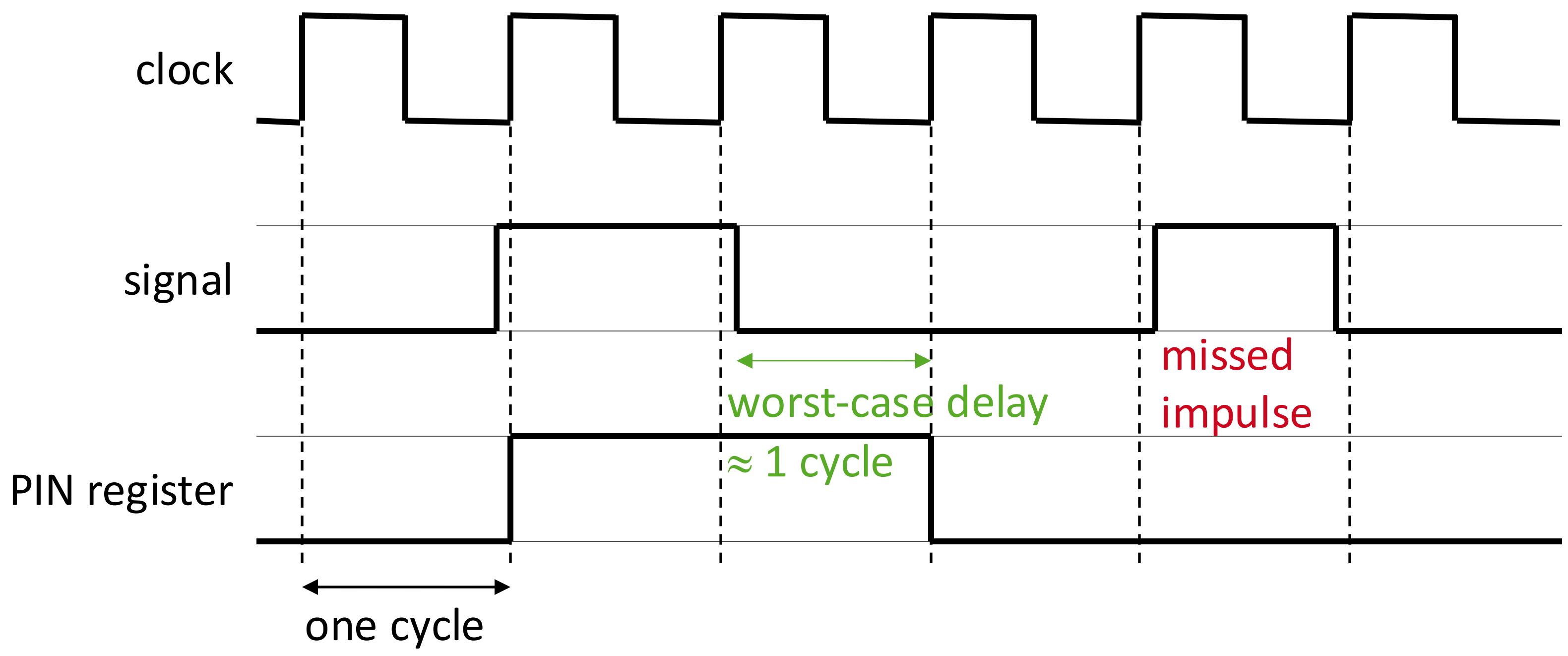
Digital I/O Summary

DDR	PORT	I	II	III	IV	V
0	0	0	1	?	0	1
0	1	0	1	1	0	1
1	0	0	⚡	0	0	0
1	1	⚡	1	1	1	1

- I: direct connection to GND
- II: direct connection to VCC
- III: open switch / button
- IV: resistor connected to GND
- V: resistor connected to VCC

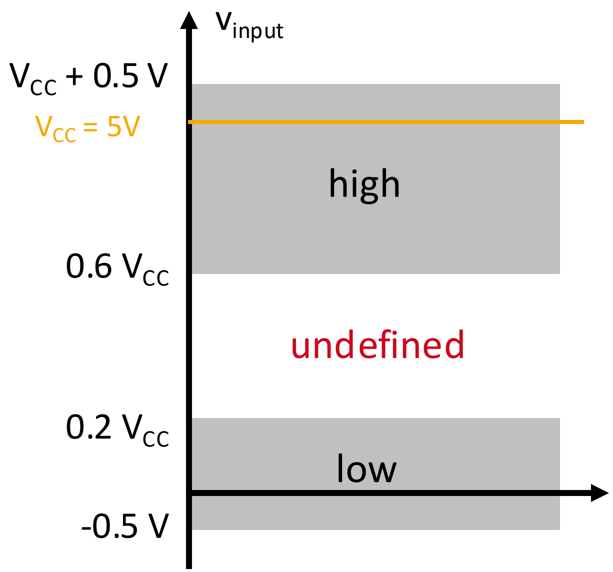
Digital input: Sampling

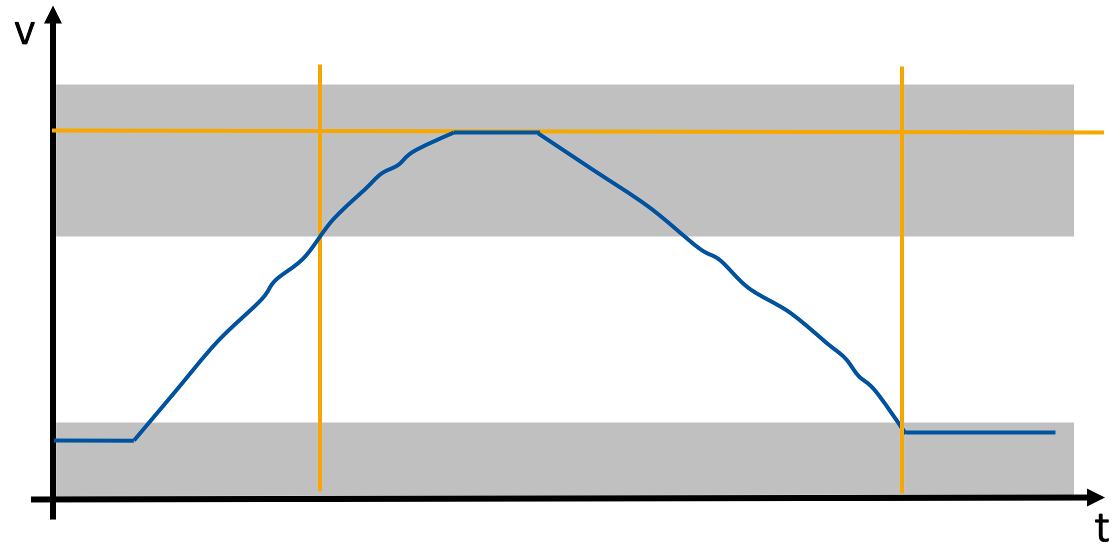
- Sampling with every clock cycle causes a worst-case delay of ~1 clock cycle.
- Impulses shorter than a clock cycle may be undetected.



Digital input: Sampling (2)

- Problem: Signal does not always have a well-defined level.

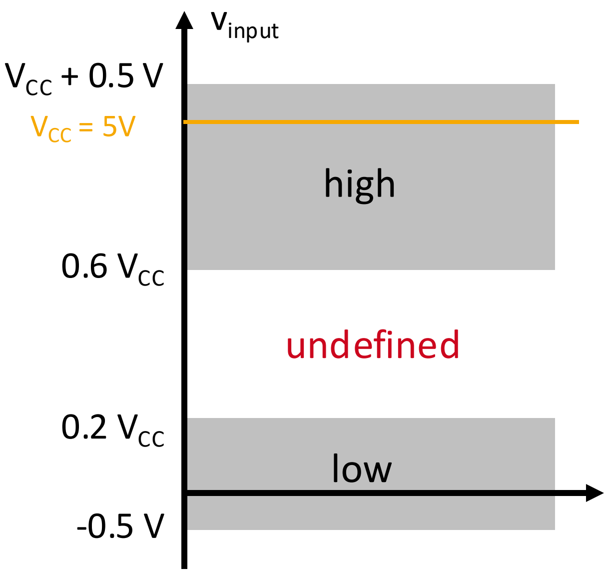


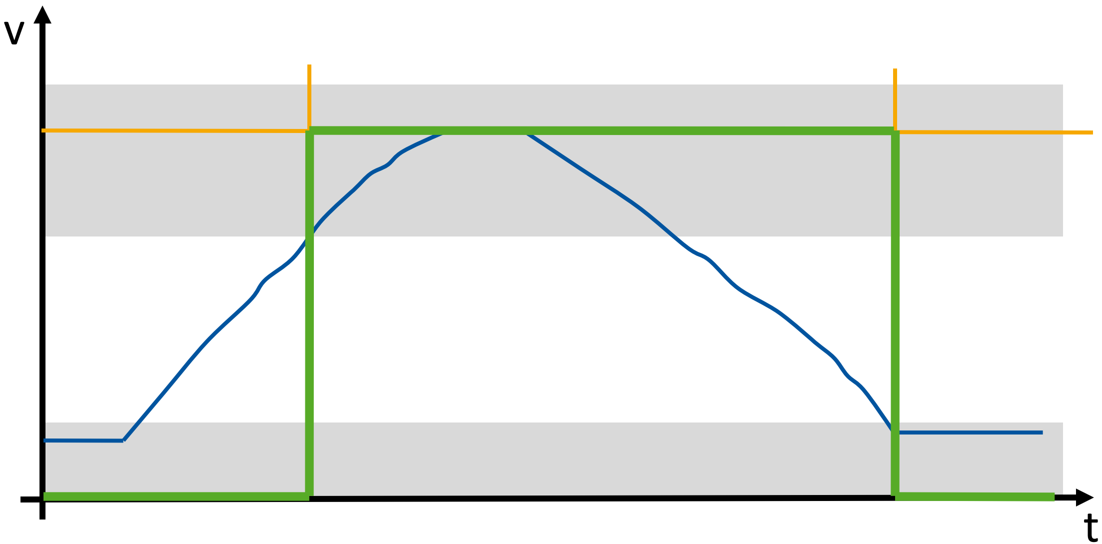


- Remedy:Schmitt trigger

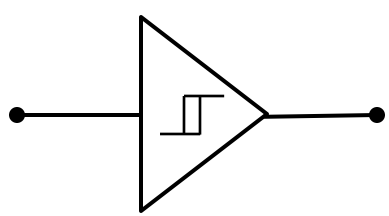
Digital input: Sampling (2) Schmitt Trigger

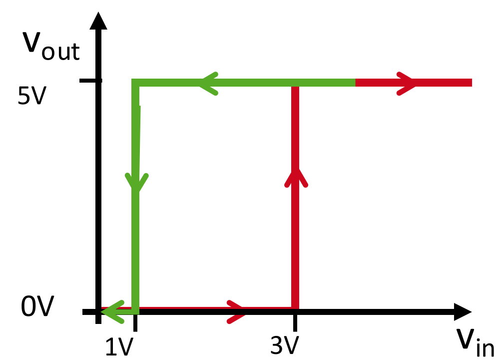
- Problem: Signal does not always have a well-defined level.





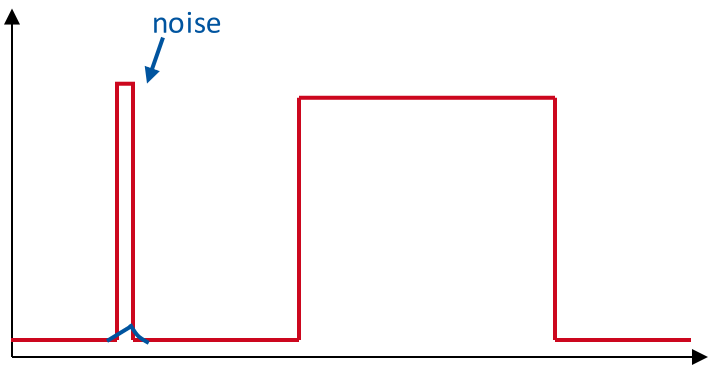
- Remedy:Schmitt trigger



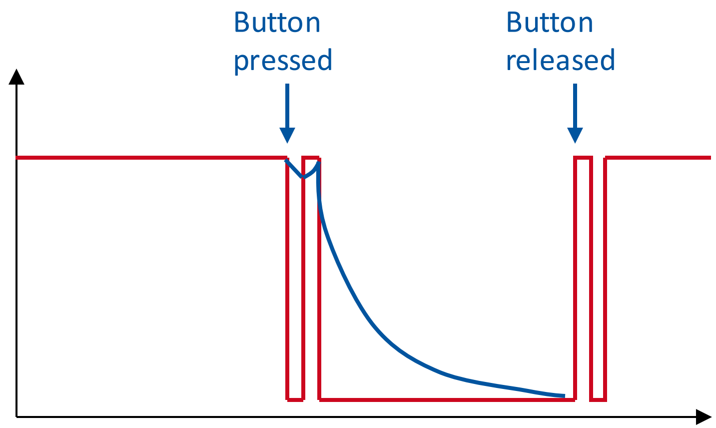


Digital input: Sampling (3)

Noisy signals

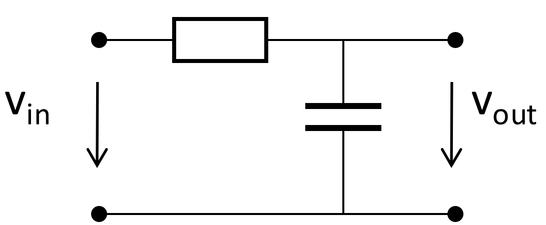


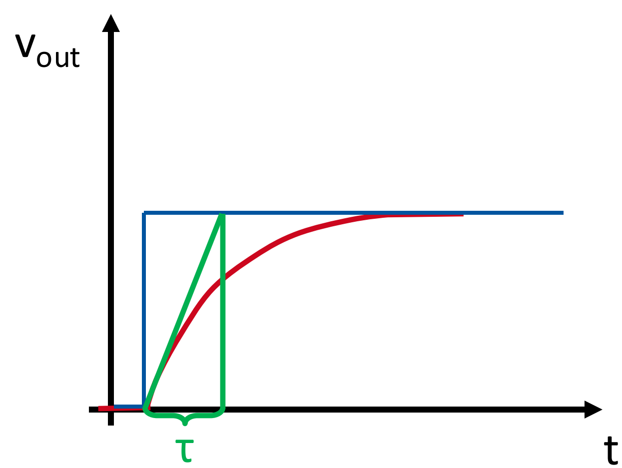
Bouncing



Solutions by Hardware:

- a) Low pass filter



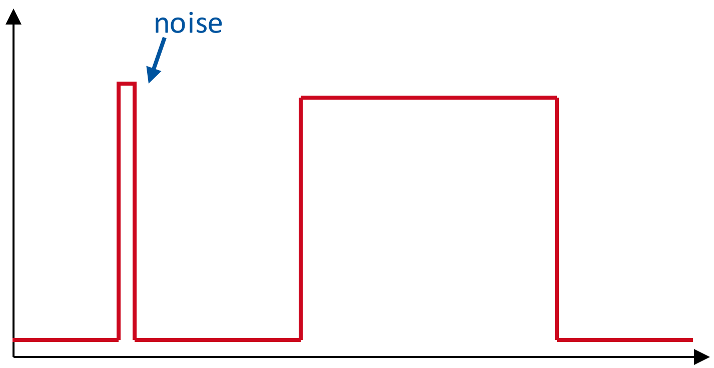


$$V_{out}(t) = K(1 - e^{-\frac{t}{\tau}})$$

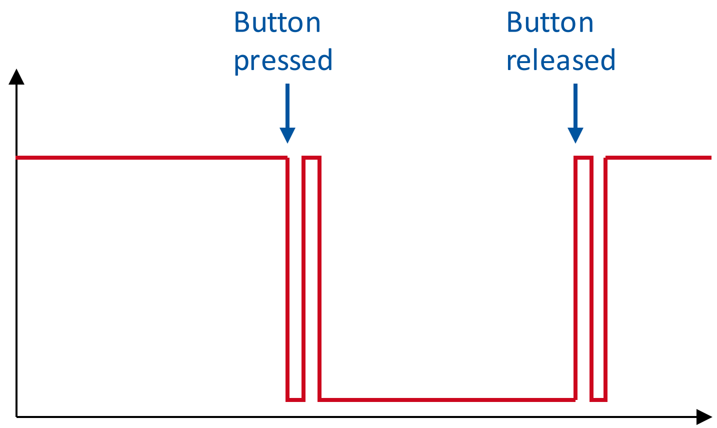
$$\tau = RC$$

Digital input: Sampling (3)

Noisy signals



Bouncing



- Solutions:
- By Hardware:
  - Low pass filter
  - Built in noise cancelation
- By Software:
  - Read Signal twice or more.

Content

Why Interrupts?

- Microcontrollers have to react to events (internal ⇔ external)
- How to ensure proper and timely reaction?

1. **Polling**
   - Periodically check for event
   - Disadvantages:
     - Waste of CPU time if the event occurs infrequently
     - Polling sequence has to fit in the rest of the code (hard to modify or extend)
2. **Interrupts** (IRs)
   - MCU polls the signal and interrupts the main program if a state change is detected.
   - MCU calls an interrupt service routine (ISR) which handles the event

Interrupt Control

- To use Interrupts they have to be activated by modifying the according registers.
- Usually there is a
  - global bit for all interrupts (global interrupt enable) and
  - an individual bit for each interrupt (<name> interrupt enable).
- ATmega family: Mapping of interrupts on the according ISR is done by an Interrupt Vector Table. Example:

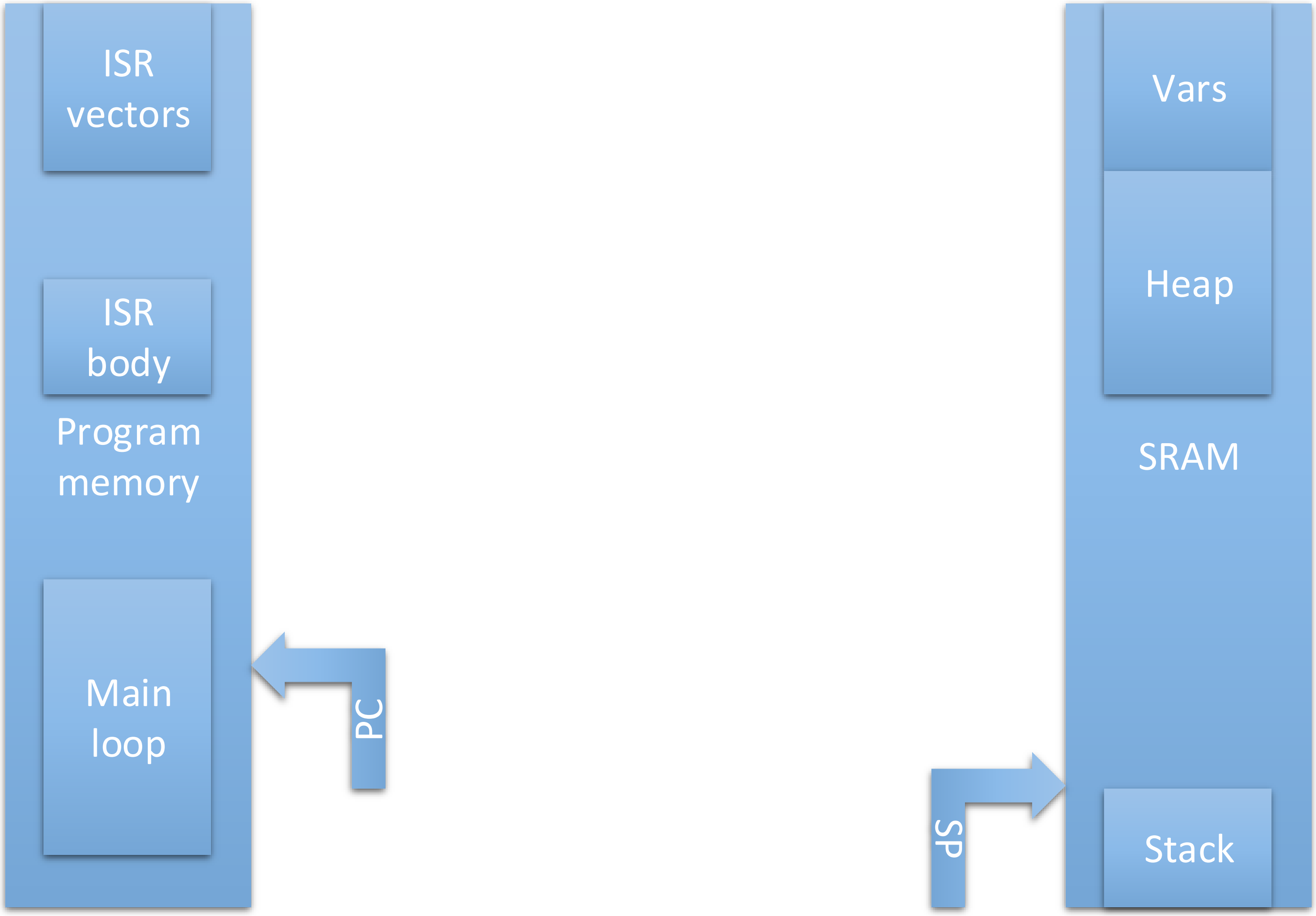
Vector No.	Source	Prg. Addr.	MNEMONICS
1	Reset	$0000	JMP $0312
2	External Interrupt 0	$0002	JMP $1302
3	External Interrupt 1	$0004	JMP $0004
…	…	…	…

- A jump instruction to the according ISR body must be placed at each address
- Empty vectors should point to an infinite loop (trap)

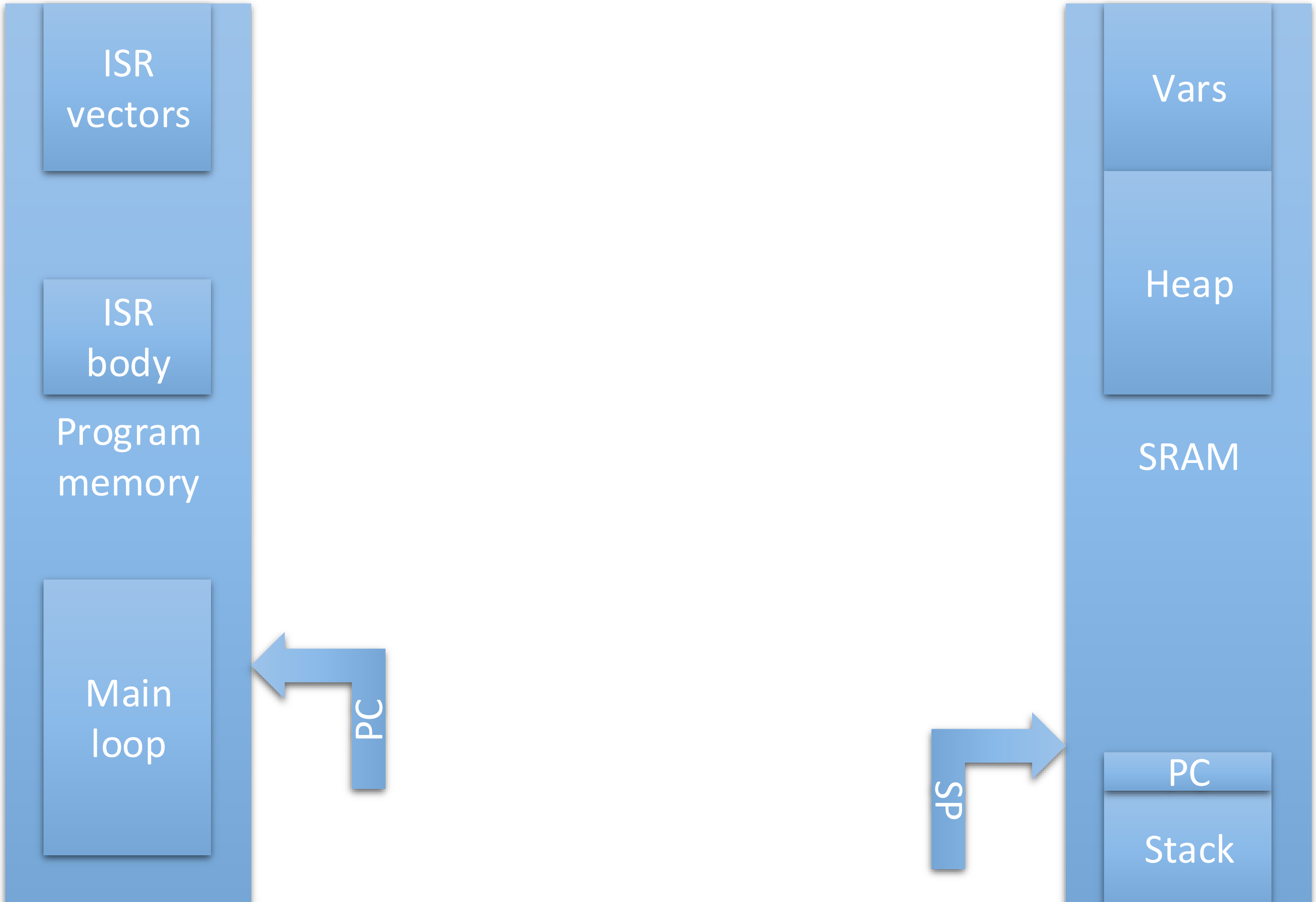
Interrupt Handling

- MCU monitors certain events (e.g., timer overflow)
- When an event takes place, a flag is set by hardware
- MCU calls ISR, if three bits are set:
  - Global interrupt enable bit (I bit)
  - Individual interrupt enable bit (e.g., timer overflow enable bit)
  - Interrupt flag (e.g., timer overflow flag)
- Conflicts are resolved by priorities
  - Static priorities (e.g., ATMEL ATmega family)
  - Dynamic priorities (e.g., Renesas R8C family)

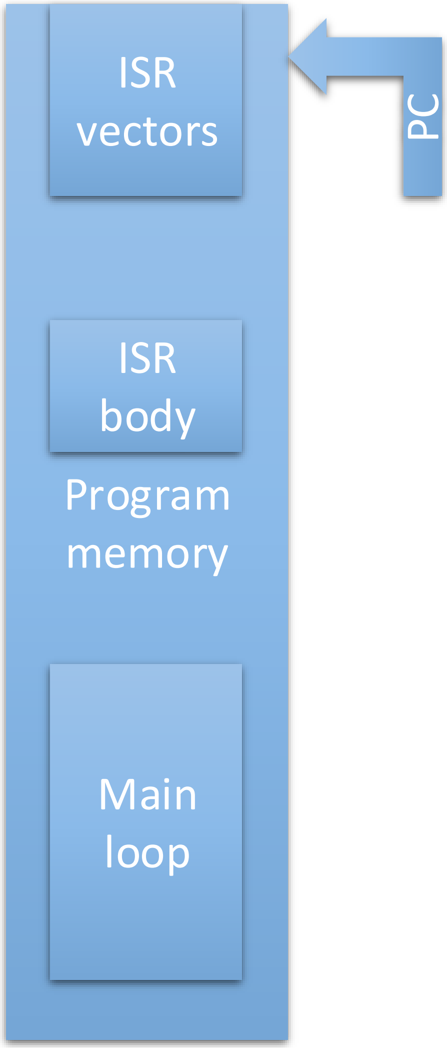
Interrupt Service Routine - Before Call



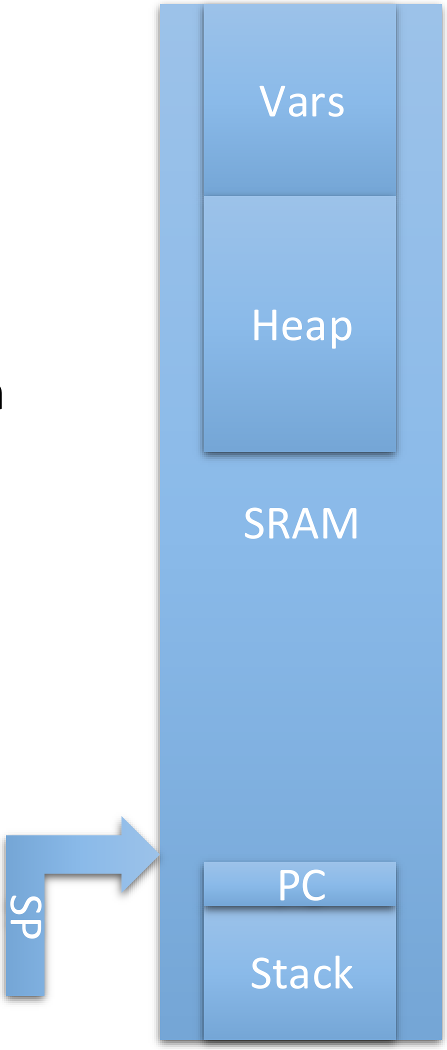
Interrupt Service Routine - Save Return Address



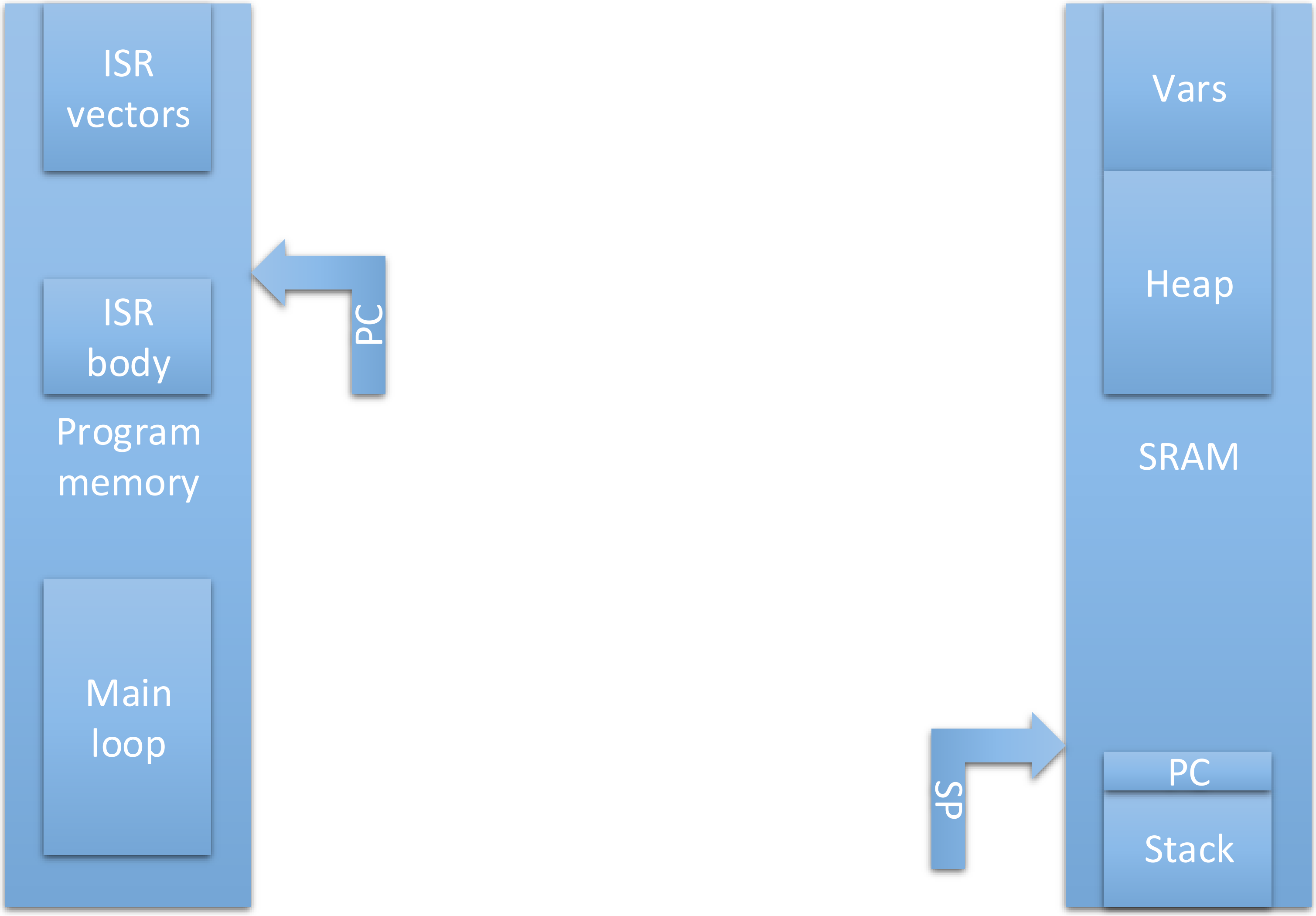
Interrupt Service Routine - Jump to Interrupt Vector



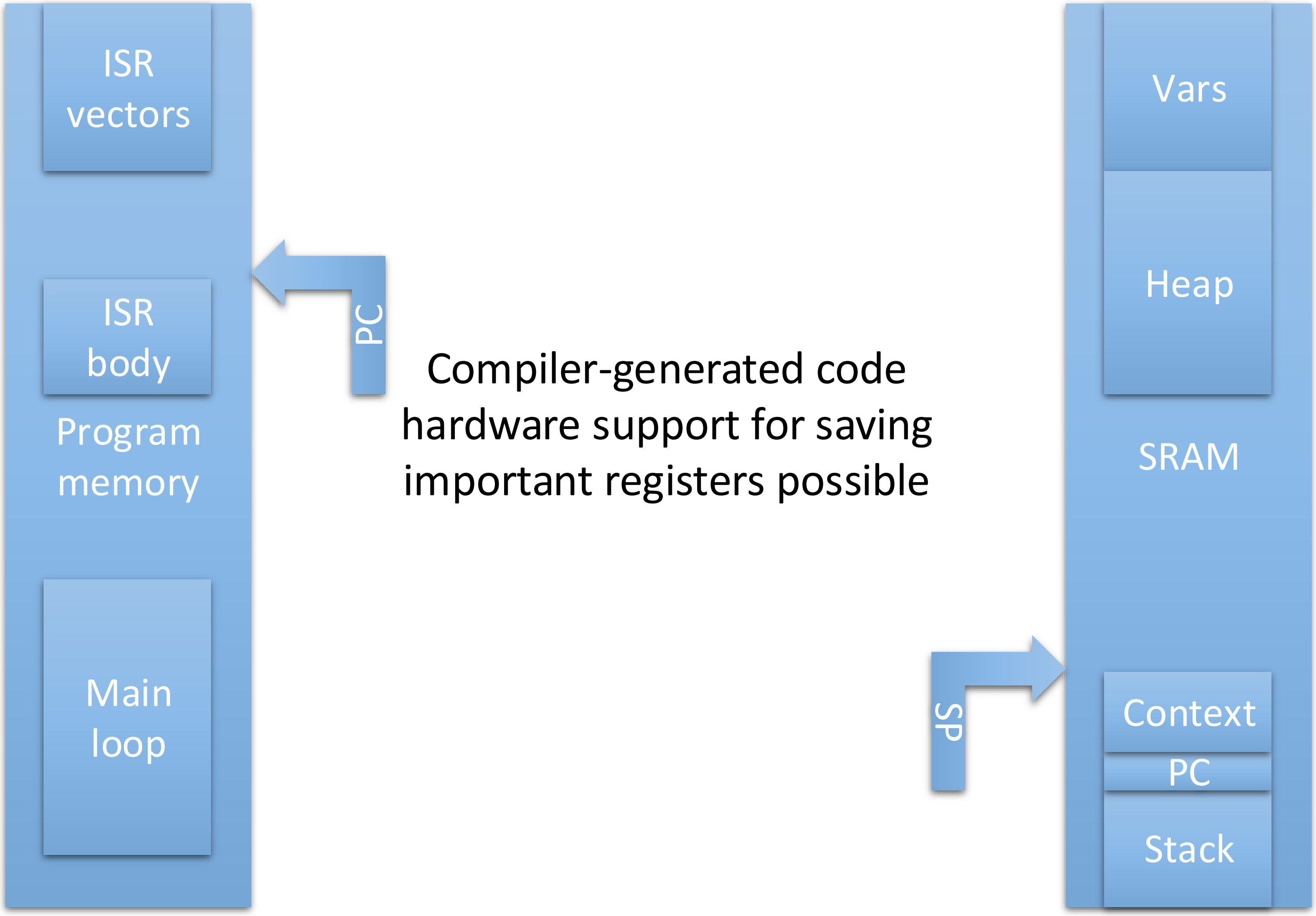
Usually simultaneously with previous step
Clear I bit
Clear flag bit (usually)



Interrupt Service Routine - Jump to ISR body

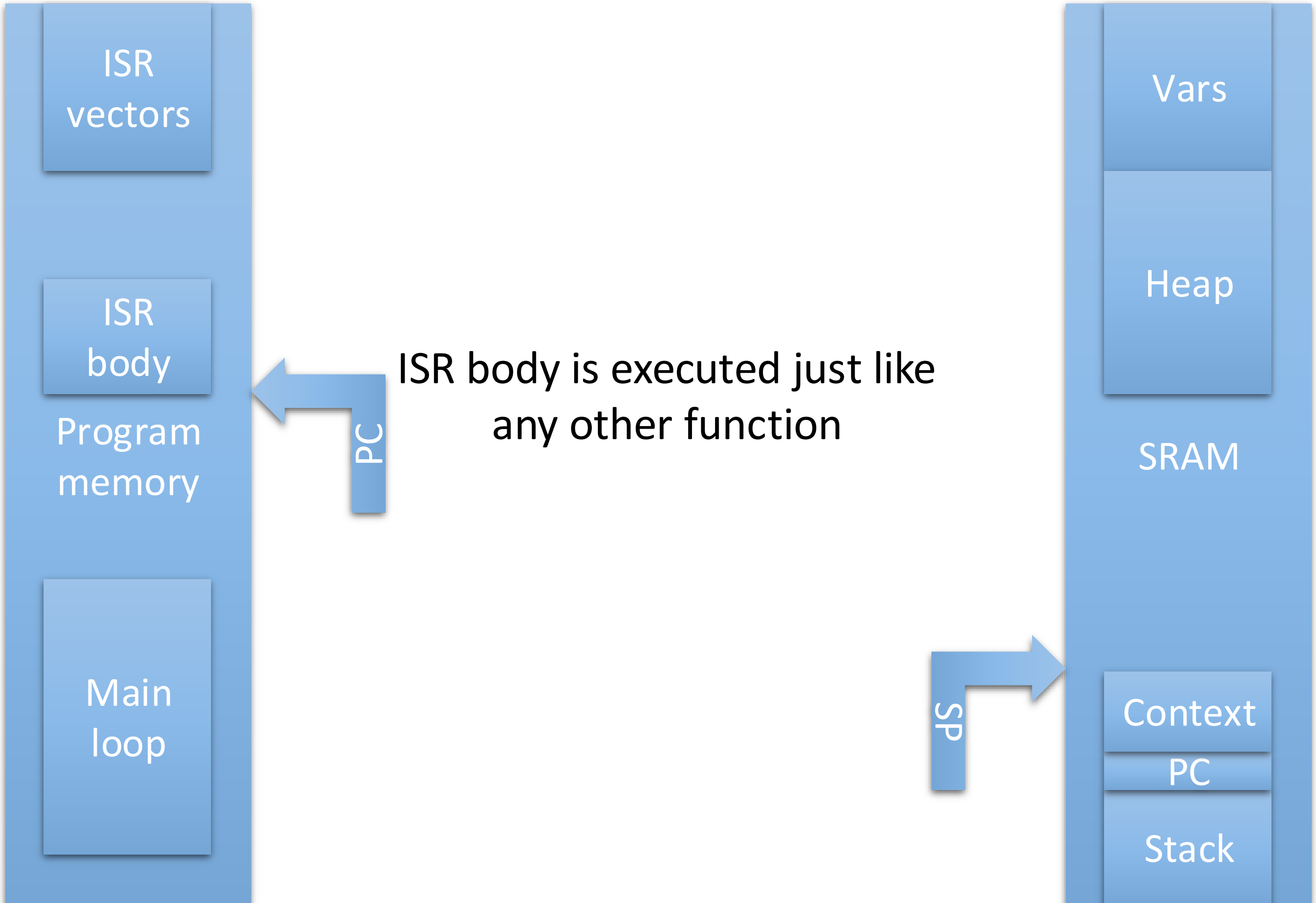


Interrupt Service Routine - Save context



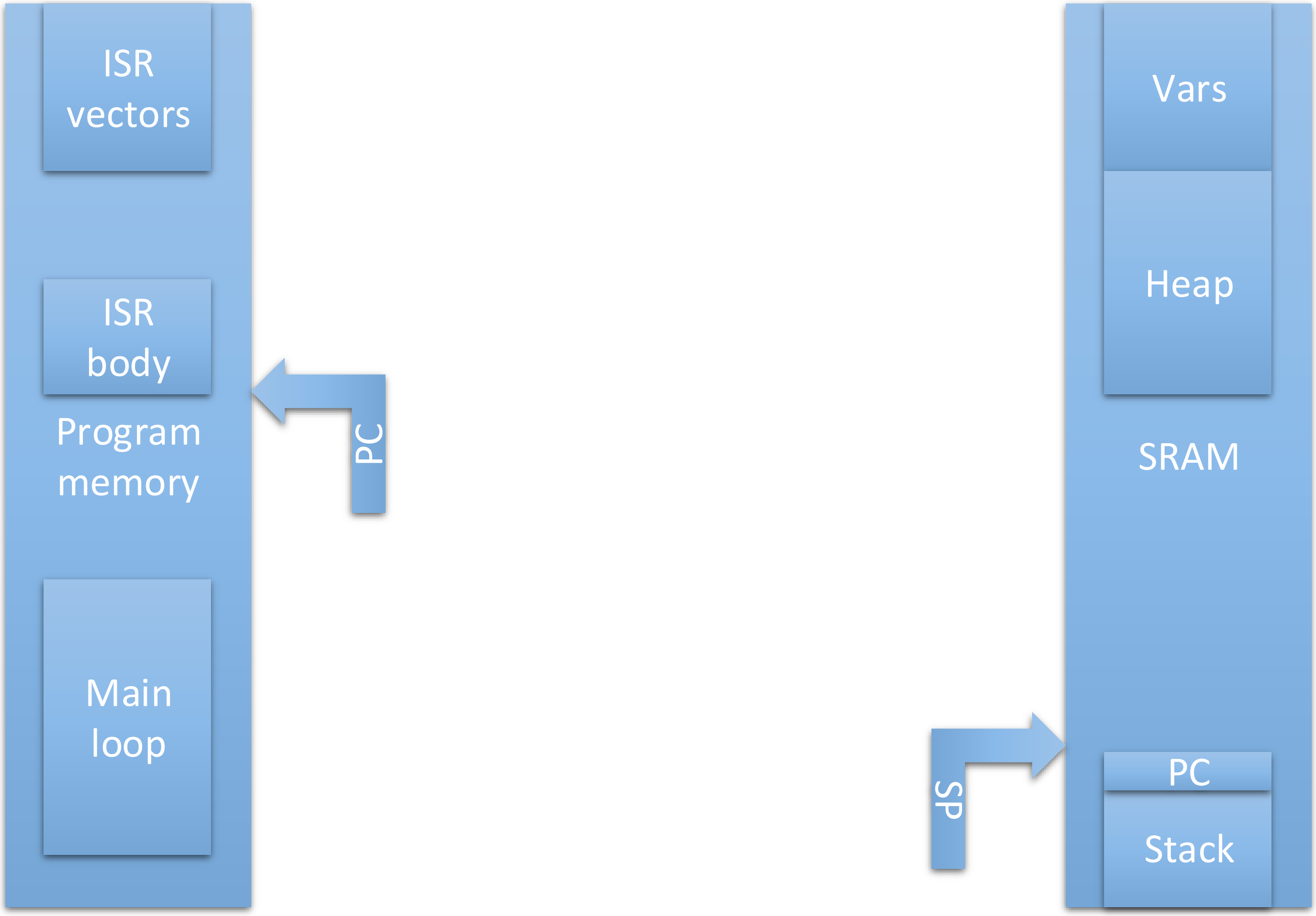
Compiler-generated code
hardware support for saving
important registers possible

Interrupt Service Routine - Execute ISR body

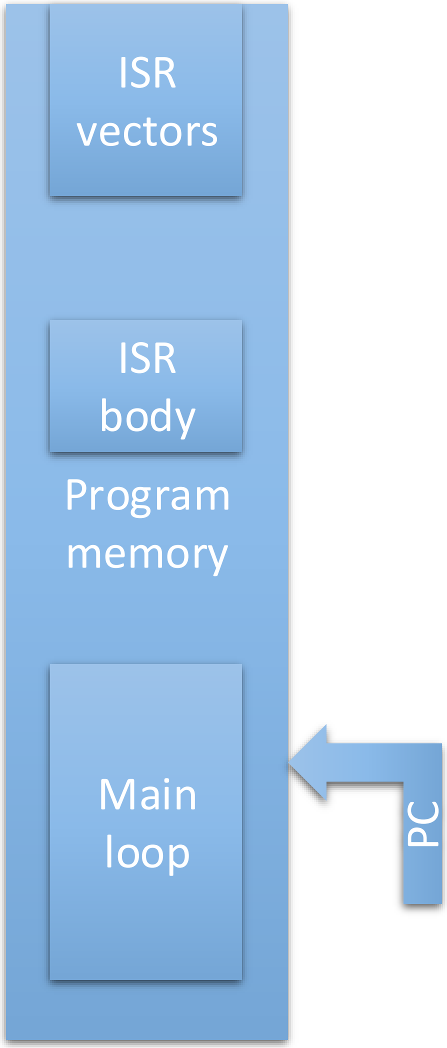


ISR body is executed just like any other function

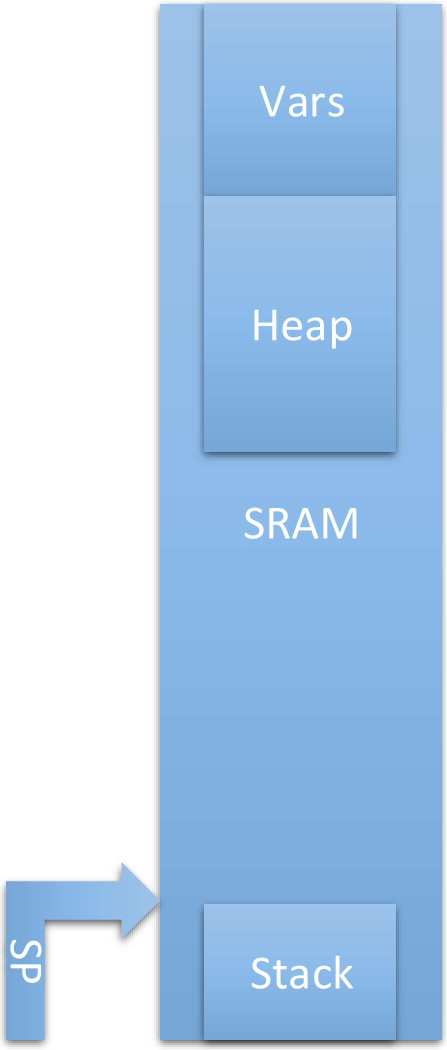
Interrupt Service Routine - Restore context



Interrupt Service Routine - Return to main program



Restore PC
Set I bit (delayed)
Flag bit is NOT set



Interrupt Service Routine - Summary

- ISR is triggered by event
  - Save return address (PC) to stack
  - Clear global interrupt enable bit (I bit)
  - Clear interrupt flag bit (usually)
  - Jump to corresponding interrupt vector table entry (interrupt vector)
- Execute jump instruction at interrupt vector
- Save additional context (anything not automatically saved by hardware)
- Execute ISR body
- Restore context
- Leave ISR by assembly instruction RETI
  - Return to PC popped from stack
  - Set global interrupt enable bit (maybe delayed)

Interrupt vs. Polling

- Hard to decide, but the following should give some hints:
- **Interrupts** should be favored if
  - Event occurs infrequently
  - Long intervals between two events
  - The exact time of the state change is important
  - Short impulses, polling might miss them
  - Nothing else to do in main, could enter sleep mode
- **Polling** might be a better choice if
  - No precise timing is necessary
  - The state is important
  - Impulses are long
  - The signal is noisy (Interrupts would be triggered very often)

Interrupts – final remarks

- A long ISR delays the main program for a long time!
  - Sometimes it is useful to move some of the ISR code to the main routine.
- If more than one IR is used the side effects have to be considered.
  - The execution of an ISR delays the reaction on all other IRs.
  - The order of IR events may have influence on the behavior.
  - Results in complex timing (cf. lectures on real time)
- If IRs are enabled the main program can be interrupted everywhere.
  - For some (short!) parts of the program it might be necessary to disable IRs.
  - Race conditions (e.g., increment from 255 to 256)

Content

Timer/Counter

- On chip peripherals (dedicated hardware)
- Counter:
  - counts external events
  - e.g. number of rising edges at PINB2
- Timer:
  - counts clock cycles (with or without prescaler)

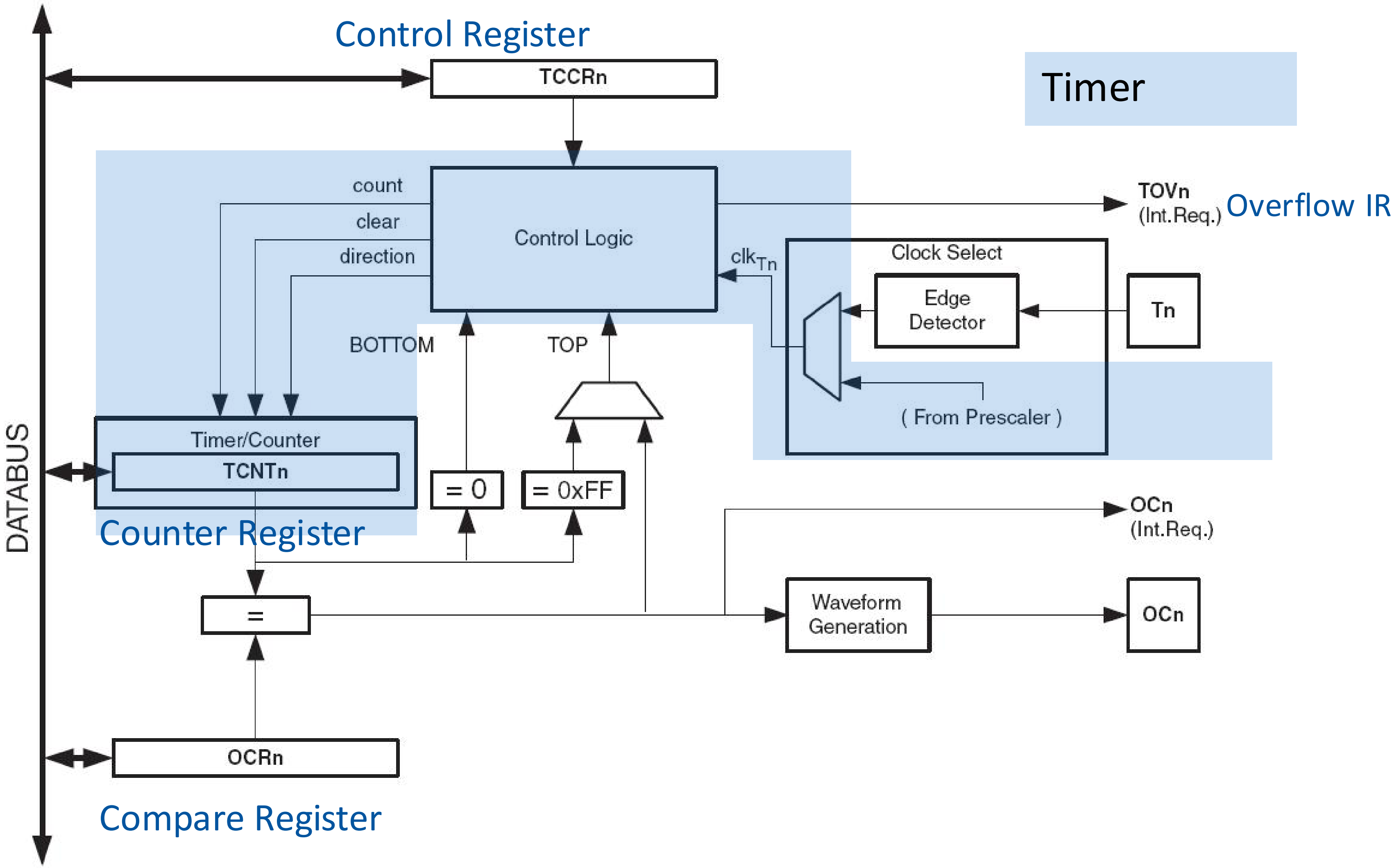
  - Each timer is basically a counter

- Most controllers provide one or more timer/counter with 8 and/or 16 bit resolution.

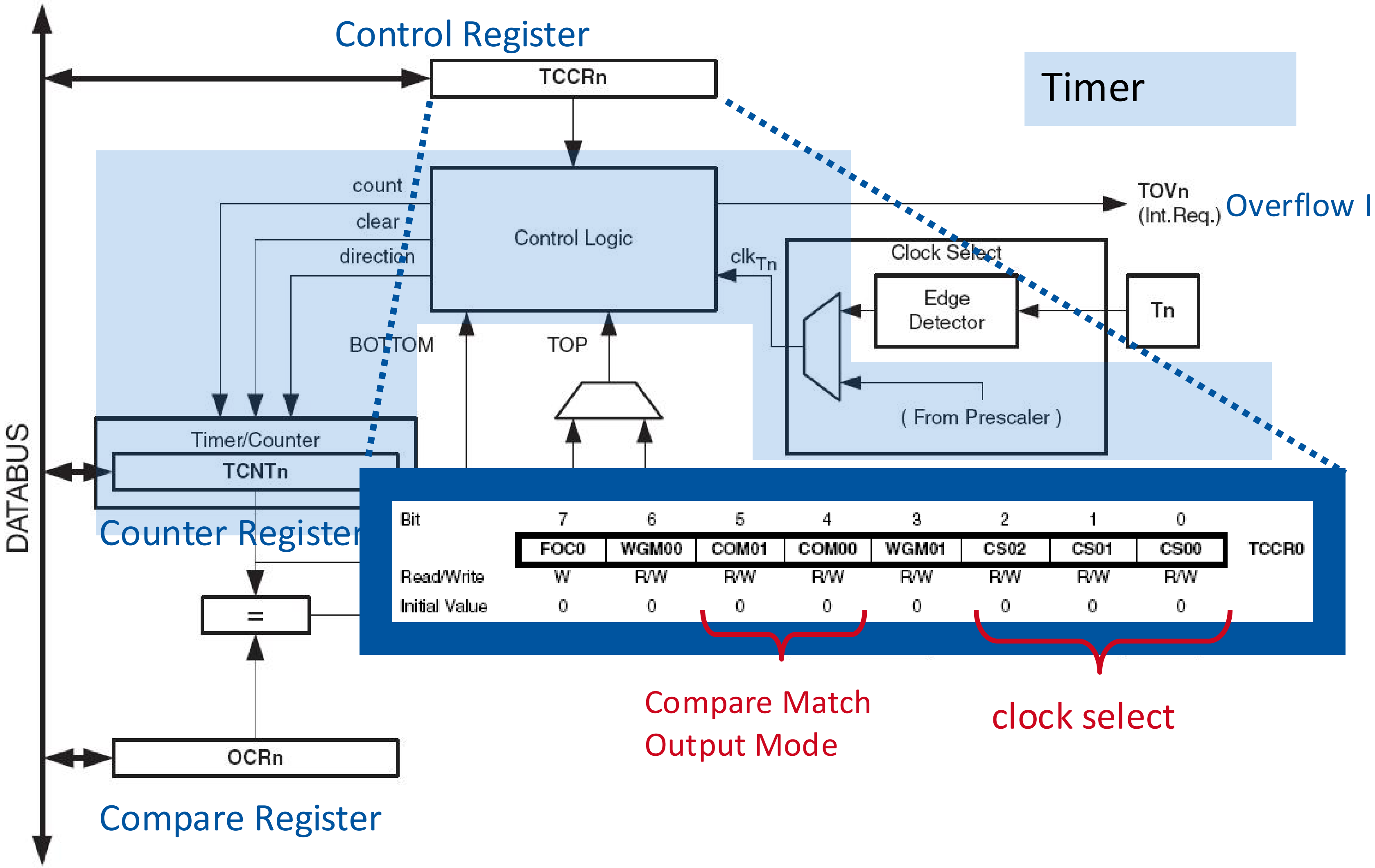
Timer/Counter

- Each Timer/Counter unit is based on a counter register, which can be incremented or decremented.
- Important for the behavior of the Timer/Counter is (are) the according control register(s)
  - mode of operation
  - which prescaler to use (timer)
  - start & stop counting
  - enable/disable interrupts
- Often there is also a compare register, which can be used to generate an interrupt if its content is equal to the counter register.

Timer/Counter (ATmega16)



Timer/Counter (ATmega16)



Bit	7	6	5	4	3	2	1	0	
	FOC0	WGM00	COM01	COM00	WGM01	CS02	CS01	CS00	TCCR0
Read/Write	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	

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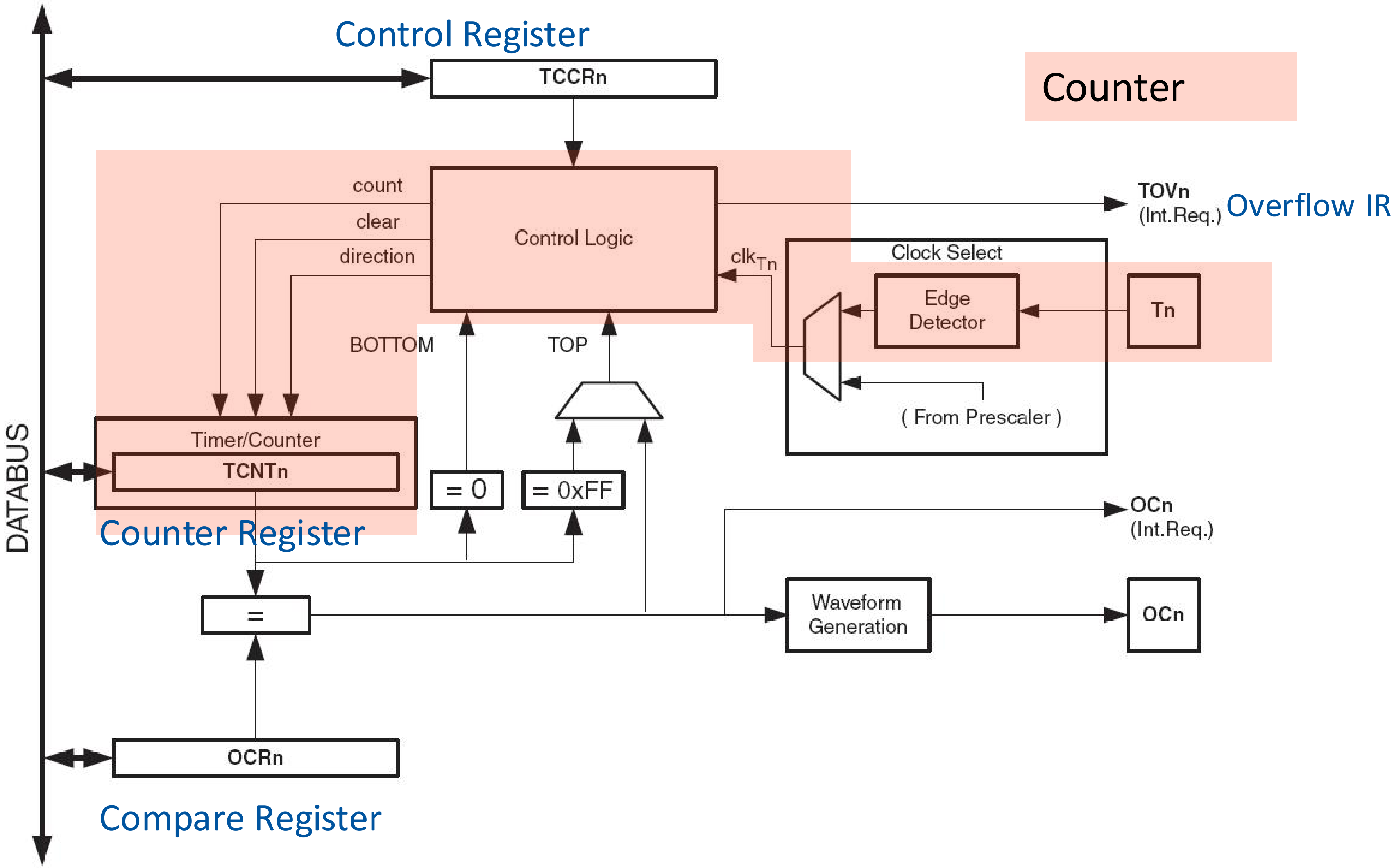
Timer/Counter (ATmega16)



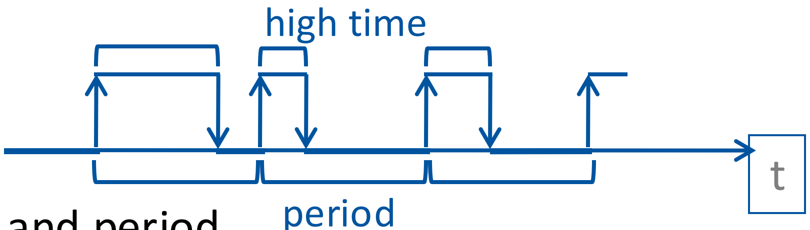
Timer/Counter

- More than just counting events and measuring time.

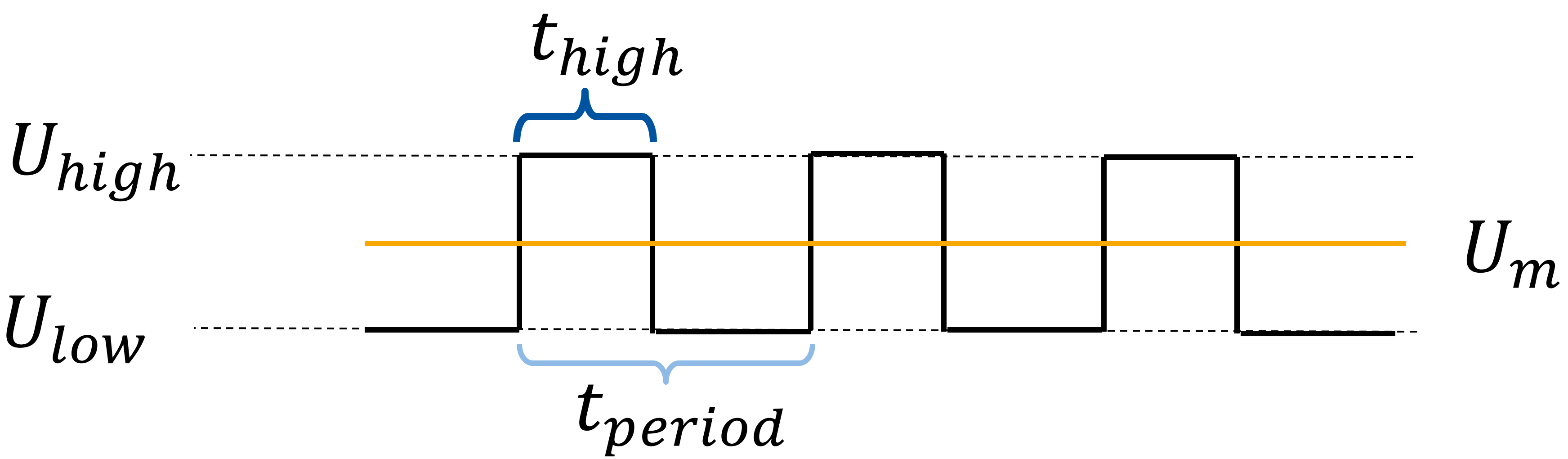
- Other features
  - Input capture
    - Used to timestamp (mostly external) events
    - Whenever the event occurs, the timer automatically copies its current count value to an input capture register

  - Output compare
    - Used to generate signals
    - Whenever a certain timer value is reached, the output compare event is triggered (can automatically set or clear an output line).

  - Pulse Width Modulation (PWM)
    - Special case of output compare
    - Timer generates a periodic digital output signal with configurable high-time and period.



Pulse Width Modulation (PWM)



$$U_m = U_{low} + \left(U_{high} - U_{low}\right) \cdot \frac{t_{high}}{t_{period}}$$

Watchdog Timer (WD)

- Special Timer; used to monitor software execution
- If enabled it counts down and resets the controller as soon as the count value zero is reached.
- During SW execution the WD has to be reset to its initial value before it reaches zero. If this fails the WD resets the controller.
- Useful if the program execution hangs and a restart solves the problem.
- However the WD can also be the source of problems (see Pathfinder problem)

More information…

- …about Interrupts and Timer / Counter can be found in any microcontroller data sheet like the one used in the exercise.

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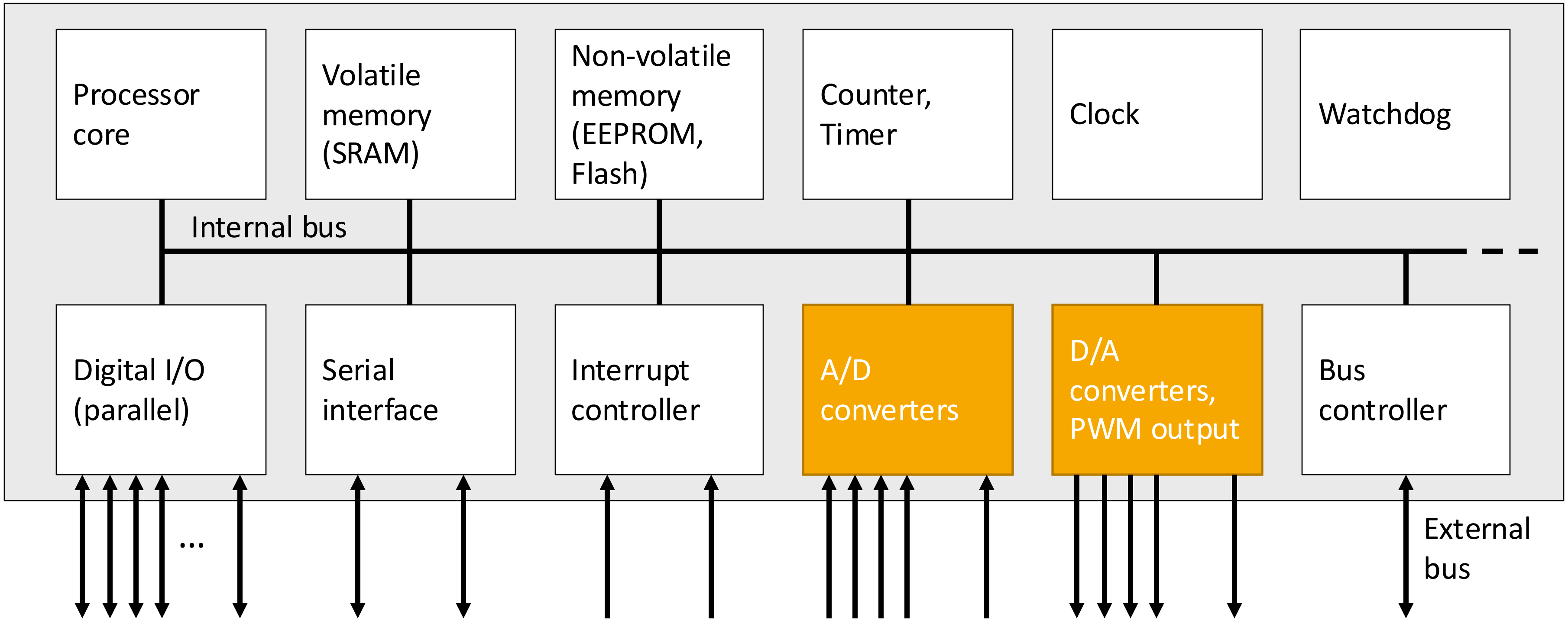
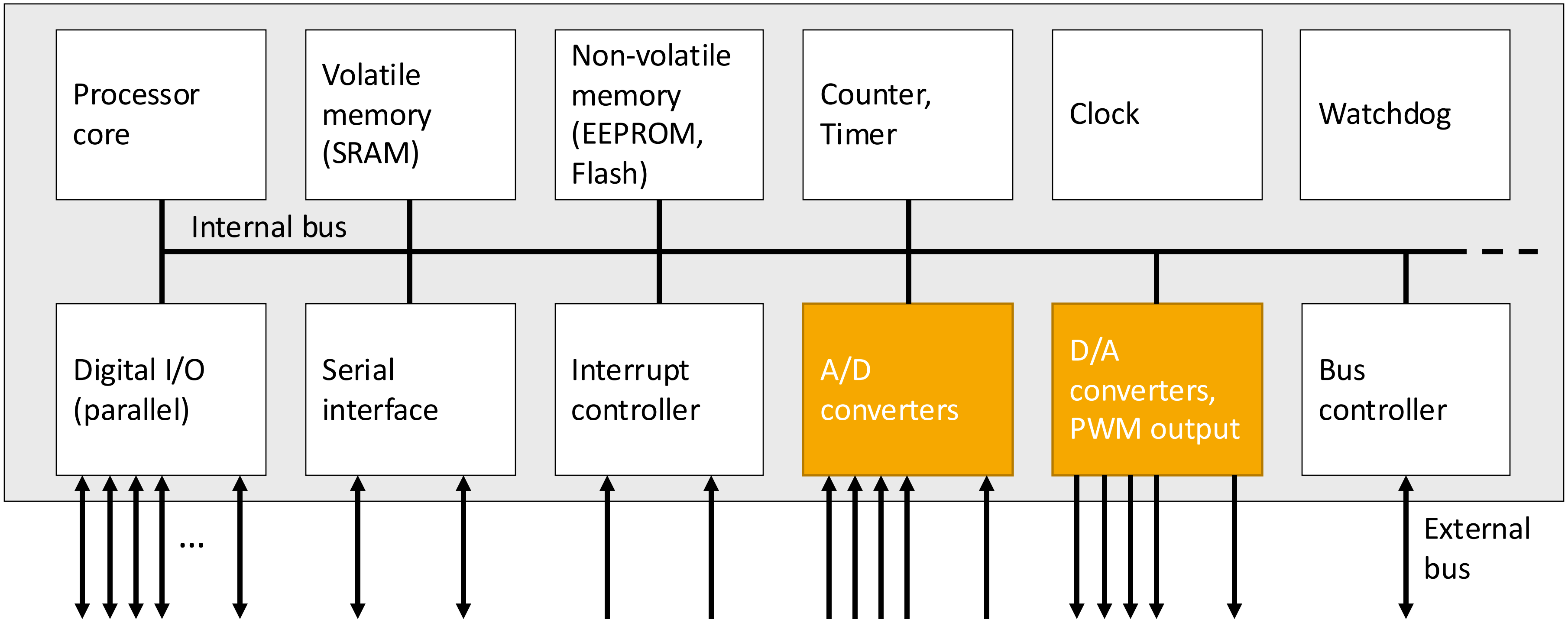
Reminder: Basic structure of a microcontroller - refined



Analog I/O Overview

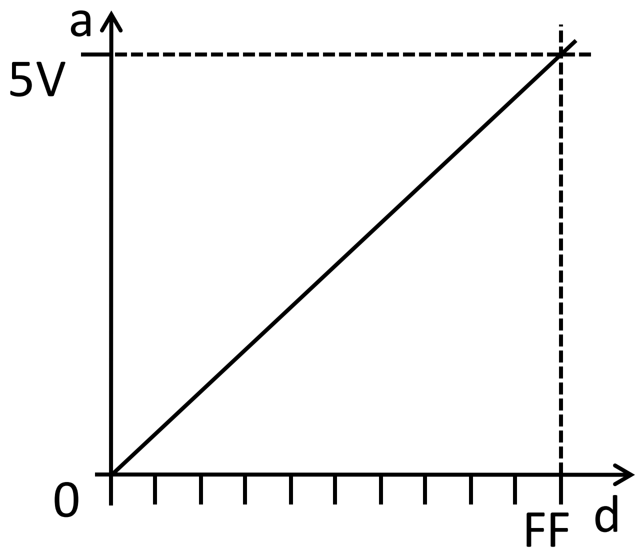
- Two directions: DAC and ADC
- DAC:
  - RC low-pass filter
  - Binary weighted resistor circuit
  - R-2R ladder
- ADC:
  - Simple: Analog Comparator
  - Flash Converter
  - Tracking Converter
  - Successive Approximation Converter
- Errors
- ATMega16 ADC

Reminder: Basic structure of a microcontroller - refined



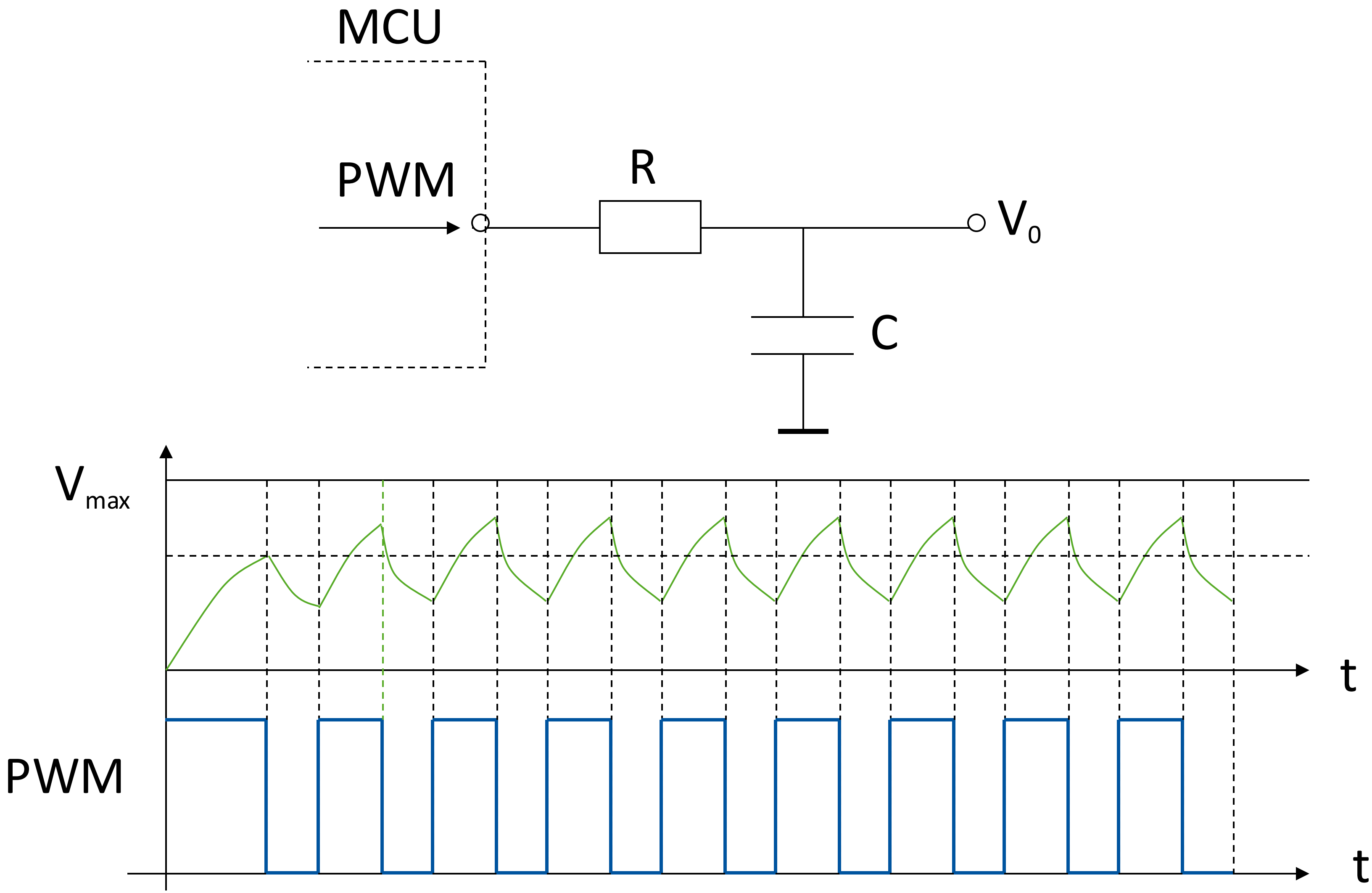
Digital to Analog Conversion

- Transform a digital value $B=(b_{r-1} \ldots b_0)$
- Range of values: $[0, 2^r-1]$
- Aim: proportional analog value V0



a=DAC(d)

RC low-pass Filter Function

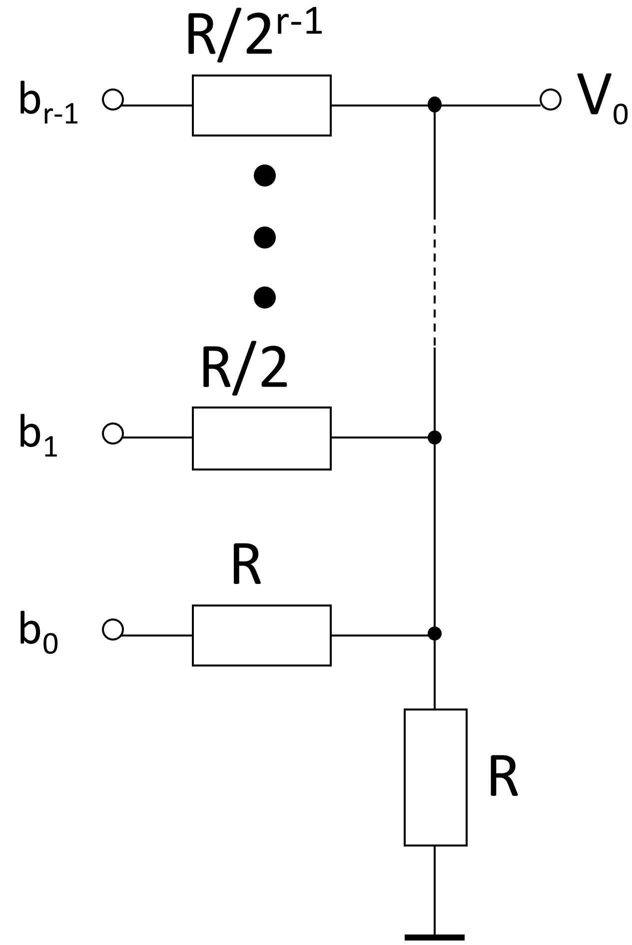


RC low-pass Filter Properties

- Simple and cheap
- 1-PIN
- Uses PWM
- Proportional to PWM (high-time/period)
- Low quality
- Initially delayed (by charging time)

Binary Weighted Resistor Circuit

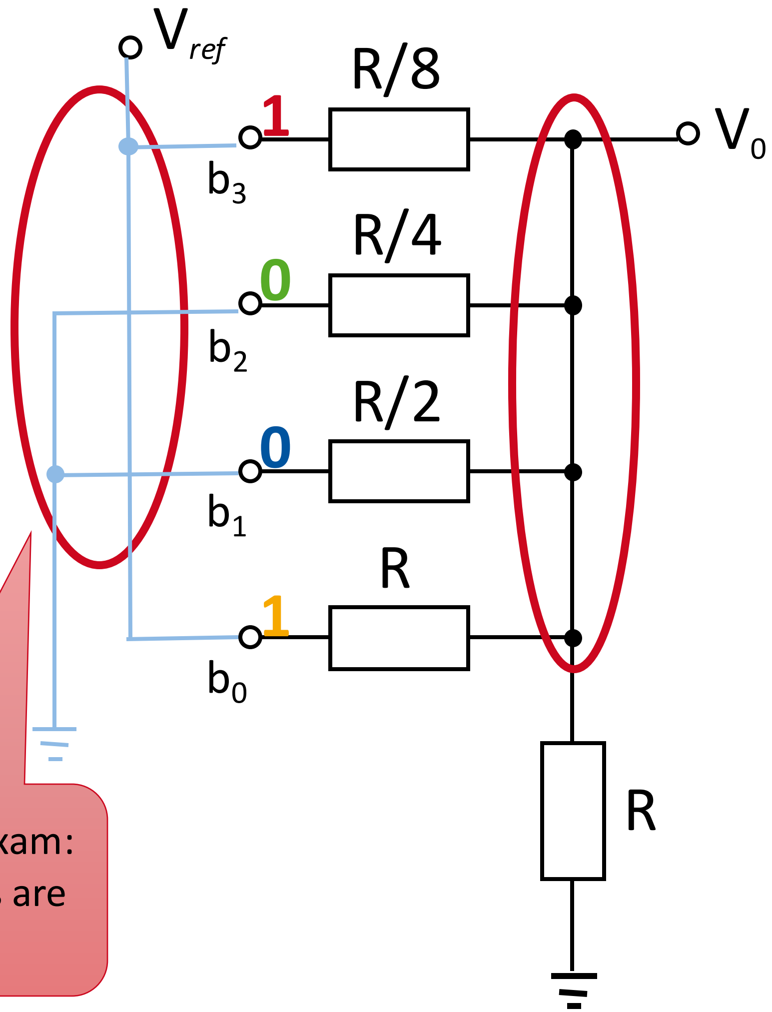
- r-bit input
- Each bit adds to analog output voltage
- Voltage added based on position of bit
- Problems: high precision resistors



$$V_0 = V_{ref} \cdot \sum_{i=1}^{r} \frac{1}{2^i} b_{r-i}$$

Binary Weighted Resistor Circuit

- Example:
  1001

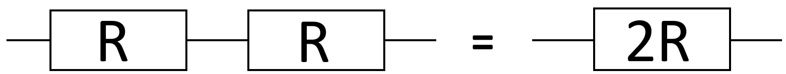


Remember for the exam: The connection dots are important!

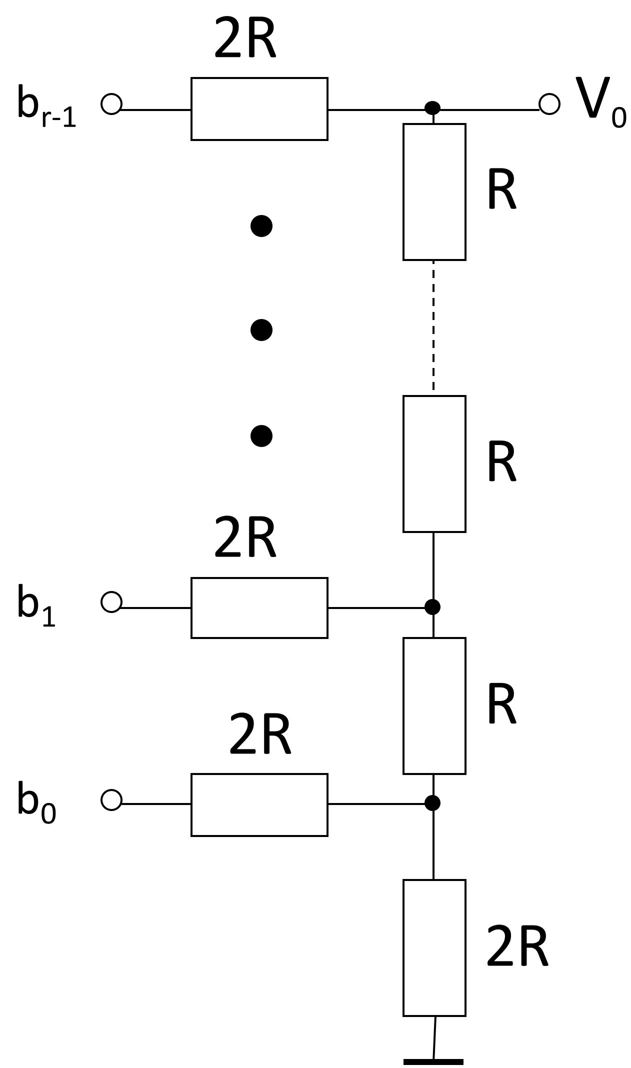
$V_0 = 9/16 * V_{ref}$

R-2R Ladder

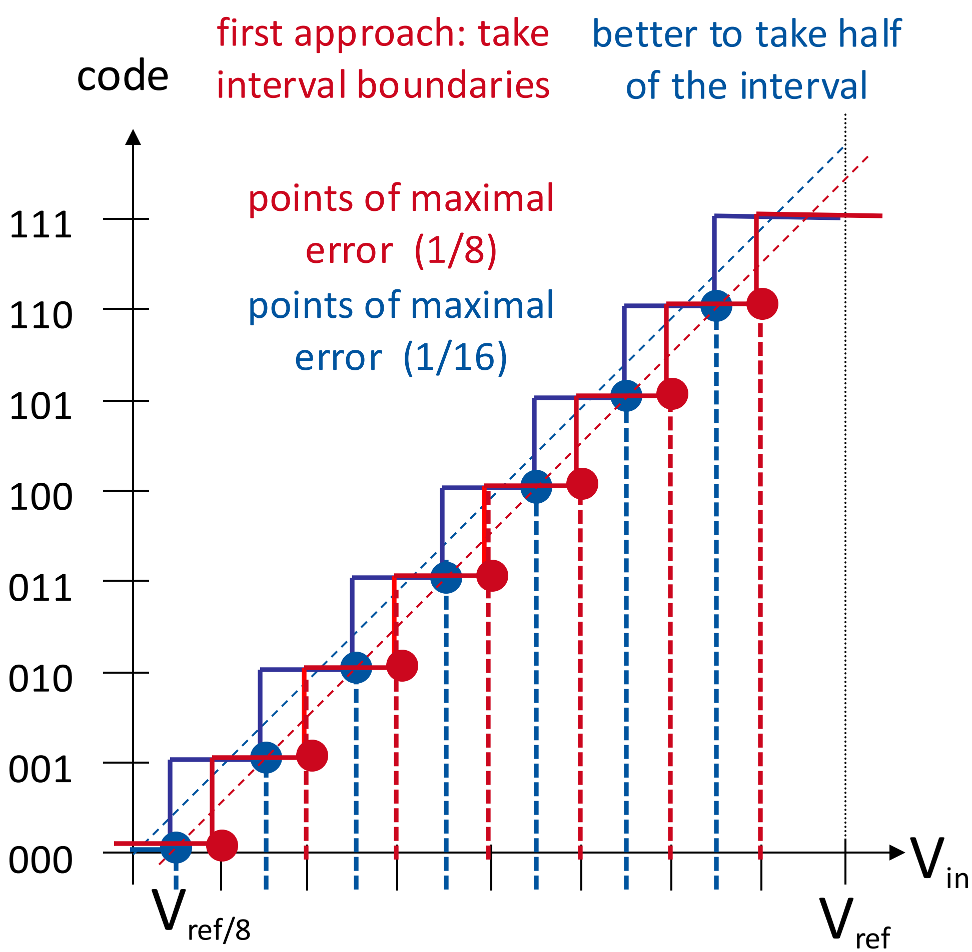
- Two types of resistors
- Can even be done with one type:



- Simpler than solution before
  - Much more precise
  - Less cost
- Many resistors needed
- Same formula
  - Kirchhoff's circuit laws



Analog to Digital Conversion

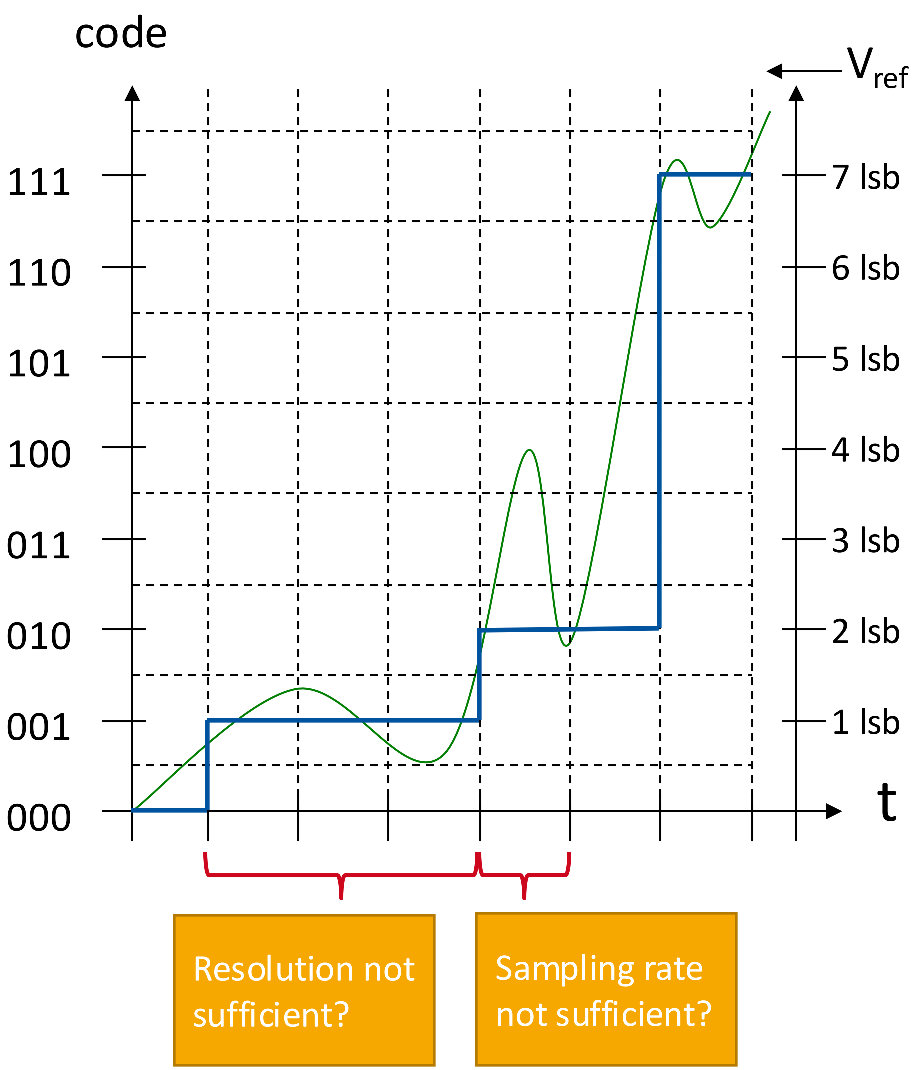


= 1 lsb (least significant bit)

- Transfer function
- Resolution: r bits
- → 2^r classes
- lsb is smallest voltage difference $V_{ref}/2^r$
- lsb is used as unit
- Digitization error of 0.5 lsb
- Class width asymmetry

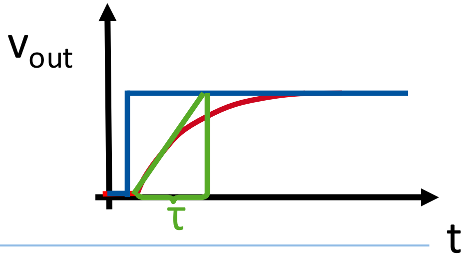
$$rel.error = \frac{abs.\ error}{curr.\ value}$$

Example with Inaccuracies

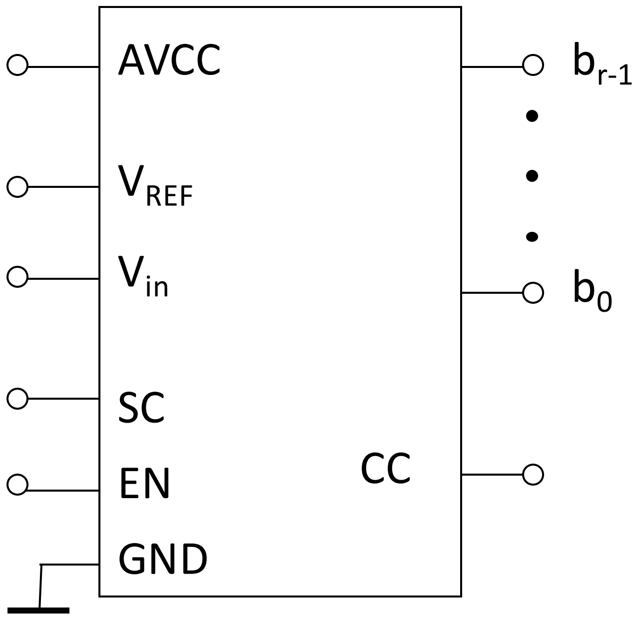


- Information loss
- Work around y-axis
  - Improve granularity
  - E.g. reduce V_{ref} or
  - increase r
- Work around x-axis: conversion time
- Shannon's sampling theorem

Based upon the time constant of the signal



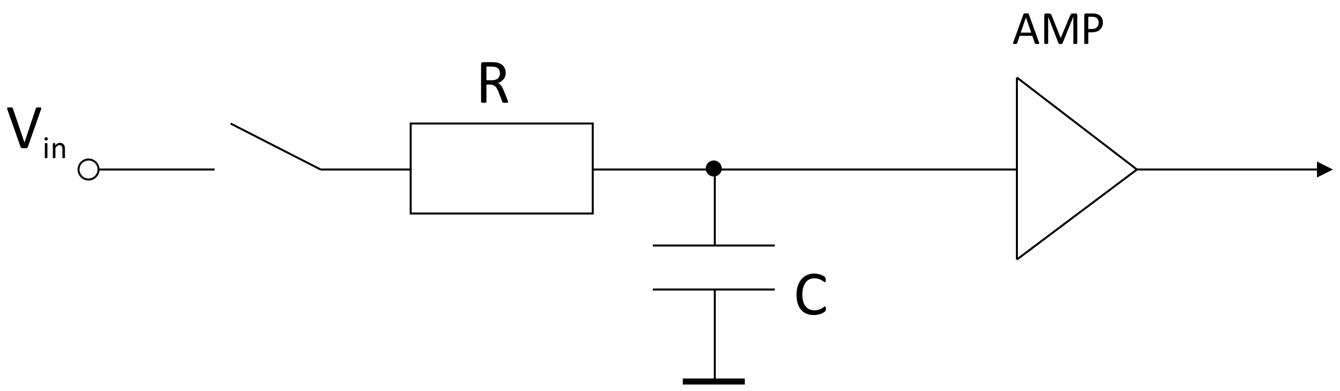
ADC as a Black Box



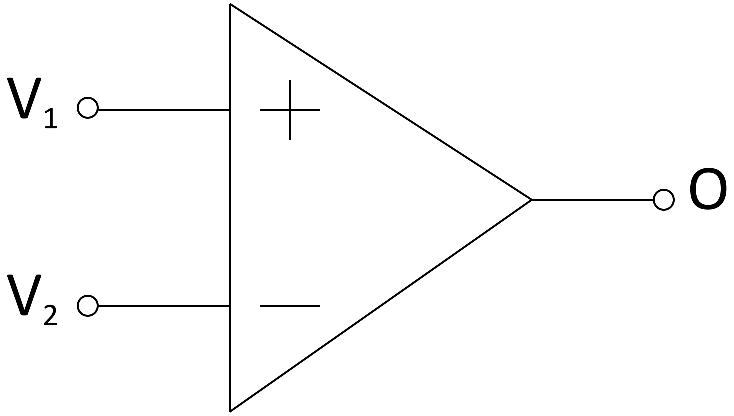
- AVCC, GND: Power supply
- V_{ref} : Maximum voltage to compare too
- V_{in} : Signal to measure
- SC, EN: Trigger input and enable input
- $b_0 – b_{r-1}$: Digital output pins
- CC: Comparison complete

Sample and Hold

- Problem: Current may change during measurement (fluctuate)
- Solution: Create “trap” for voltage
- Capacitor is charged and disconnected

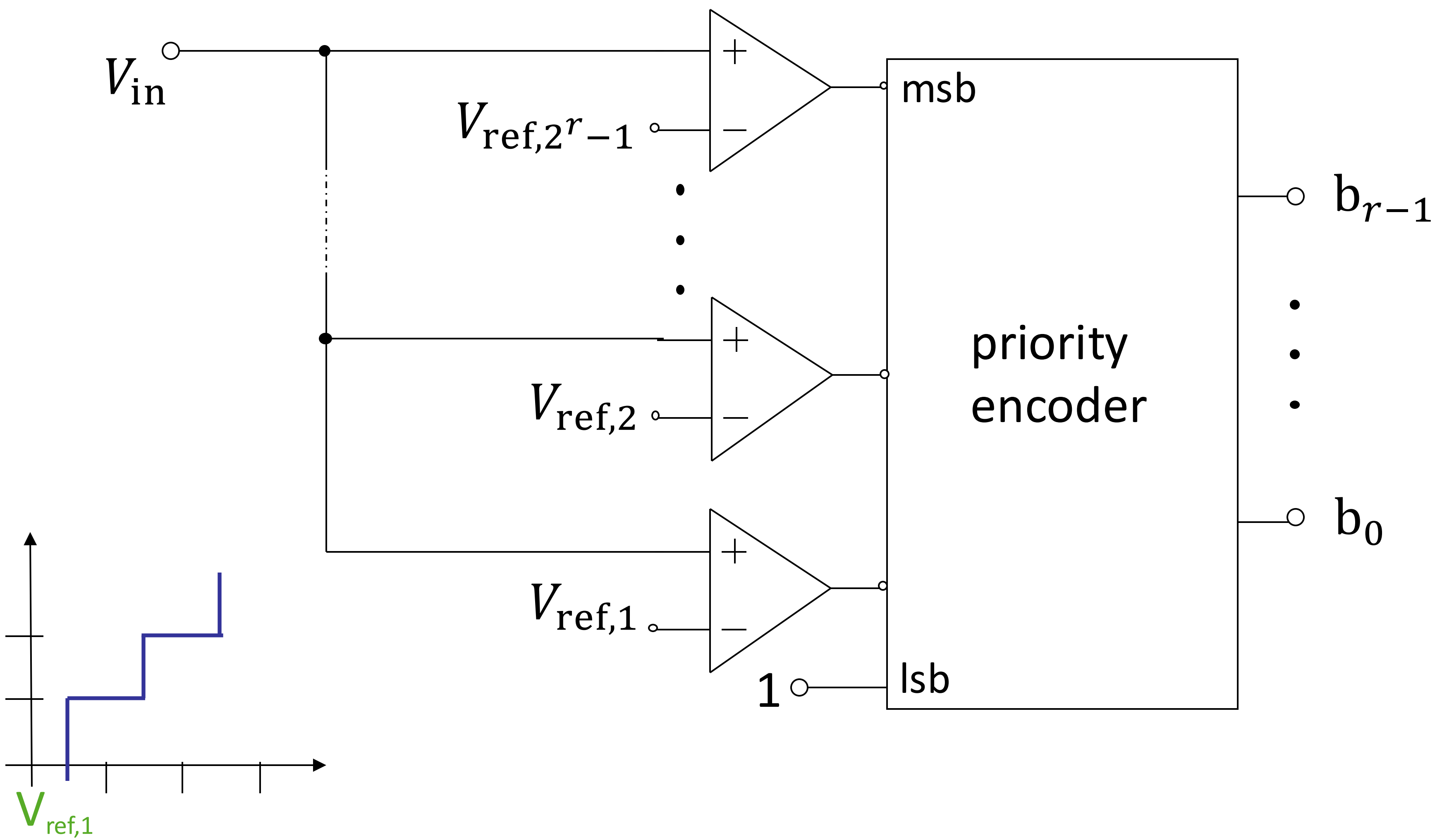


Simple solution: Analog Comparator



- Compares simply V1 and V2
- Output 1 when V1 > V2
- Else 0
- Suffers from meta-stability
- Obviously 1 bit
- Basis for more complex solution

Flash Converter



Properties of a Flash Converter

- Direct application of DAC principle
- Flash means fast: Simultaneous check
- Complexity of converter: 2^r-1 comparators needed for encoding
- Thus expensive

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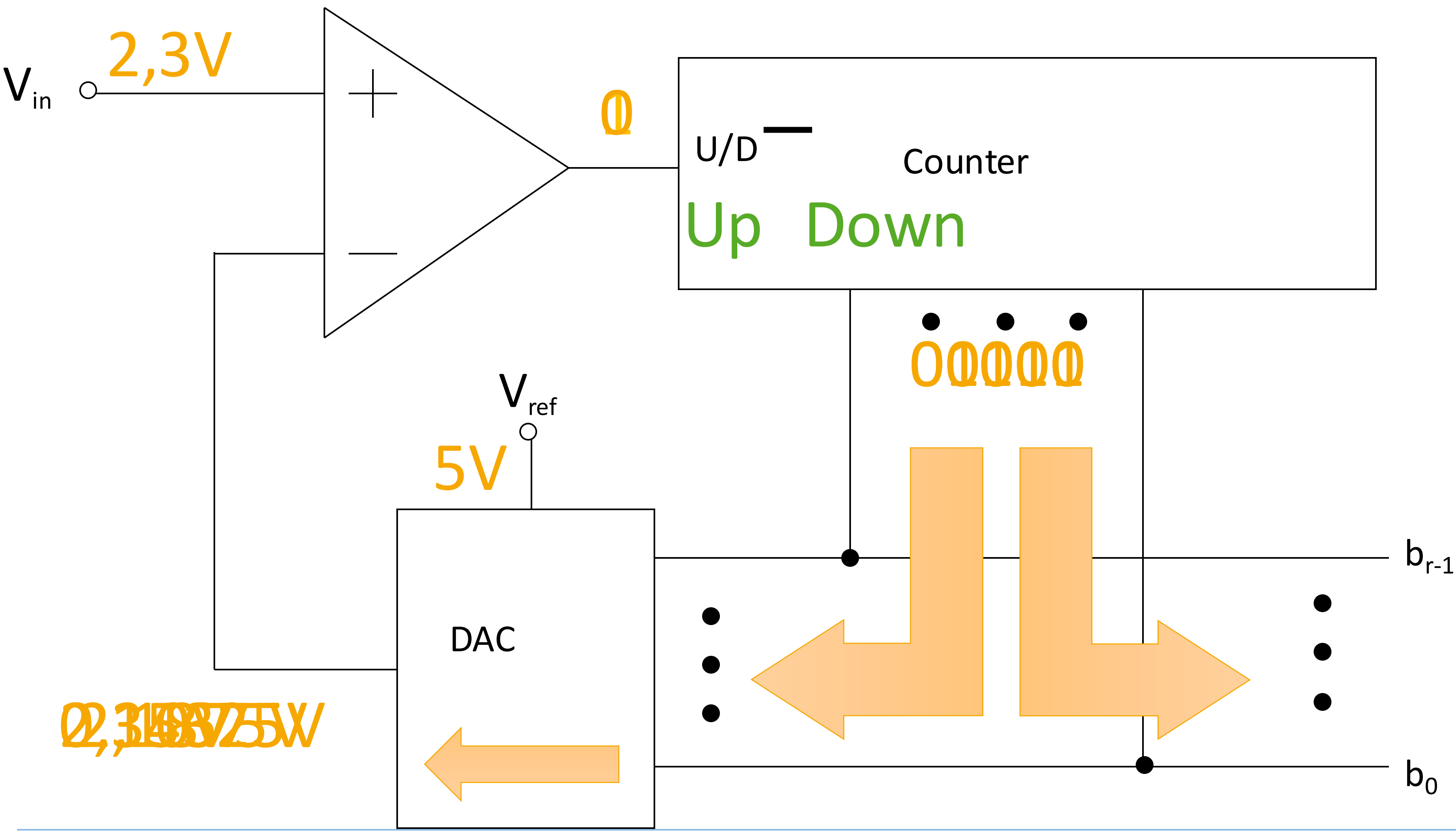
Tracking Converter



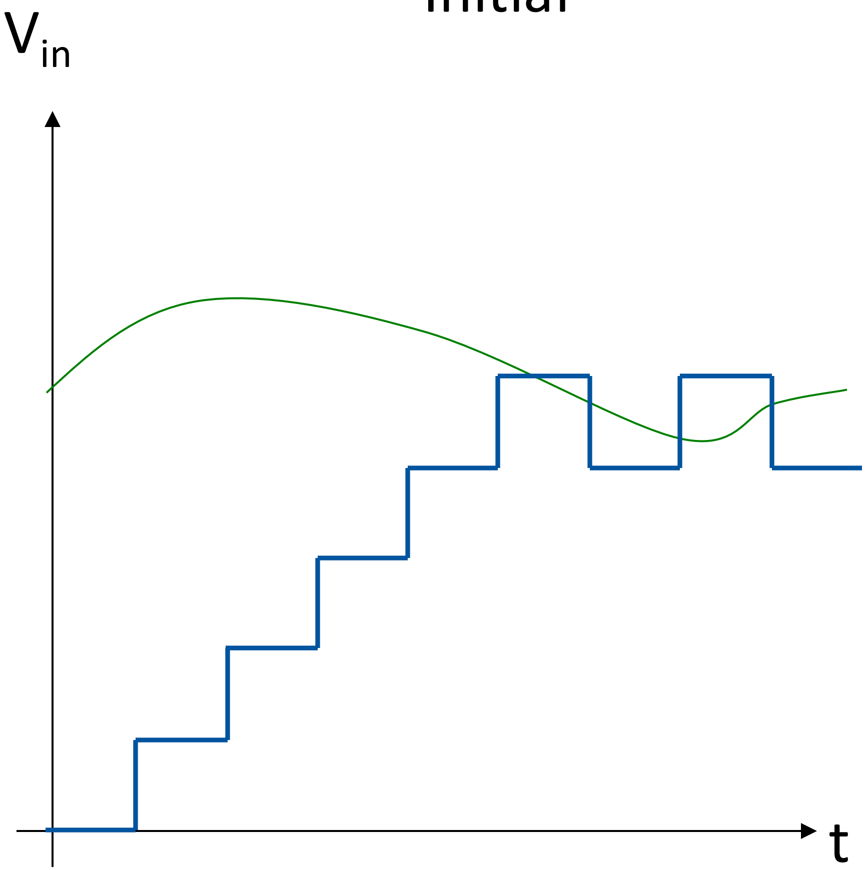
Tracking Converter Principle

- DAC used to do ADC
- Counter holds digital estimate of value
- Counter changed linearly according to outcome of comparator
- Sample and hold
- Disadvantage: Tracking takes some time, worst case $\mathcal{O}(2^r)$
  - 00000 → 00001 → 00010 → … → 01110 → 01111 → 01110 → …
- In the beginning not precise

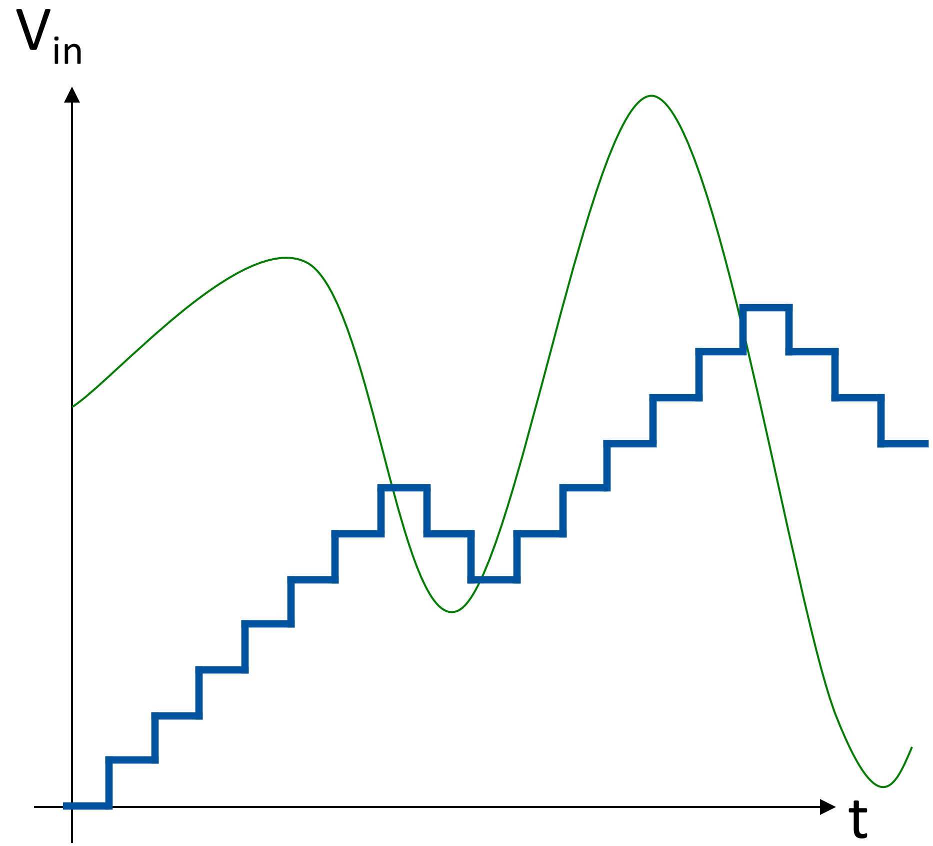
Oscillation

Examples of Tracking Problems

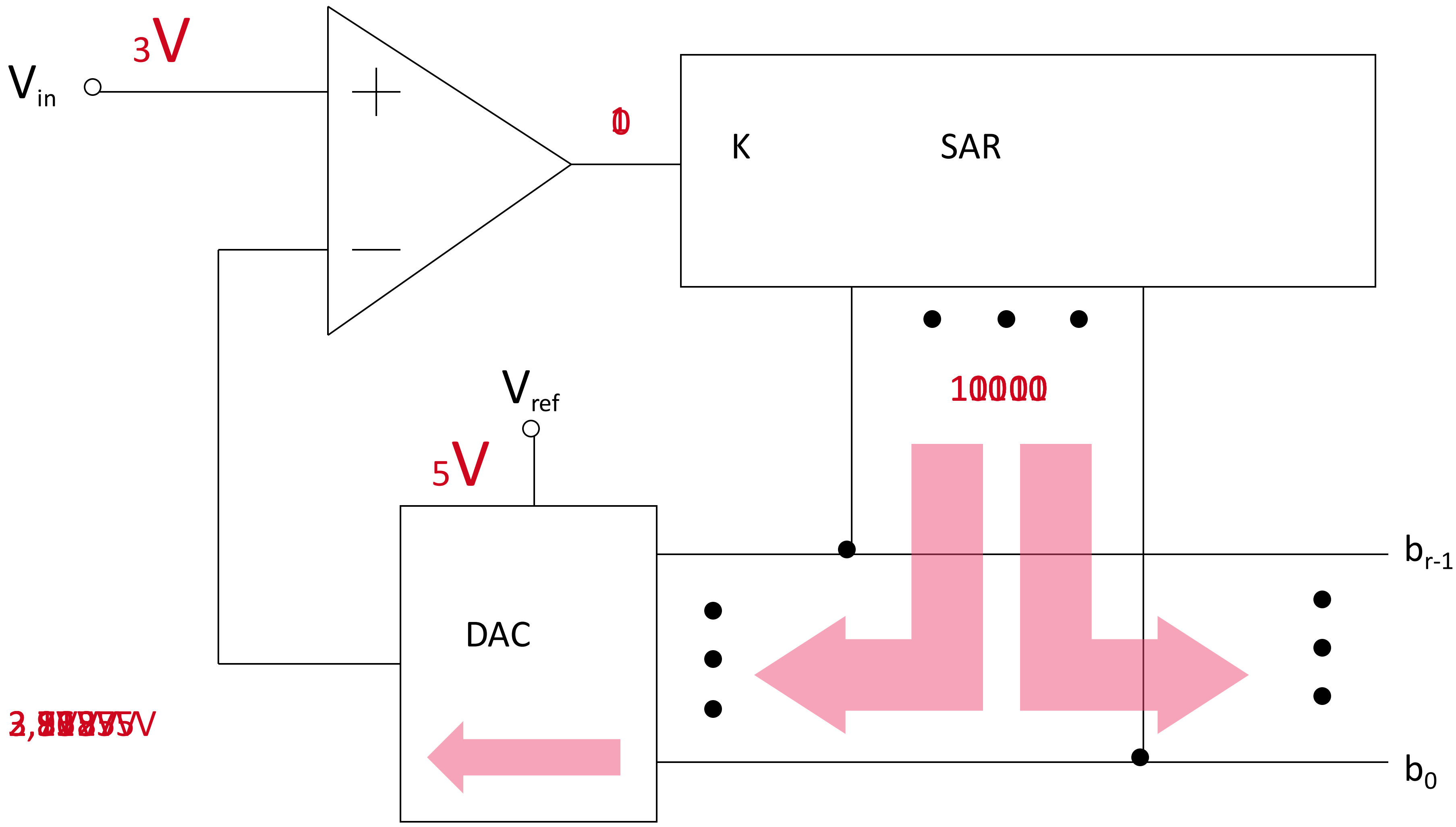
Initial



Time complexity

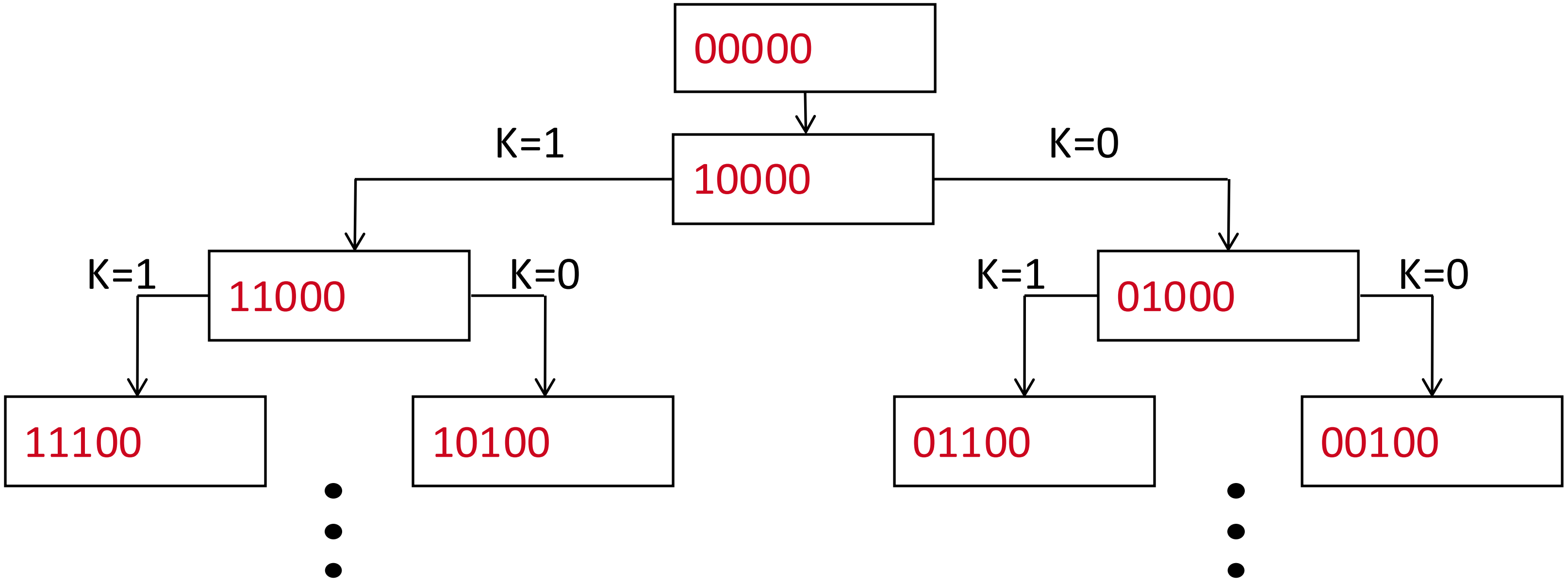


Successive Approximation Converter



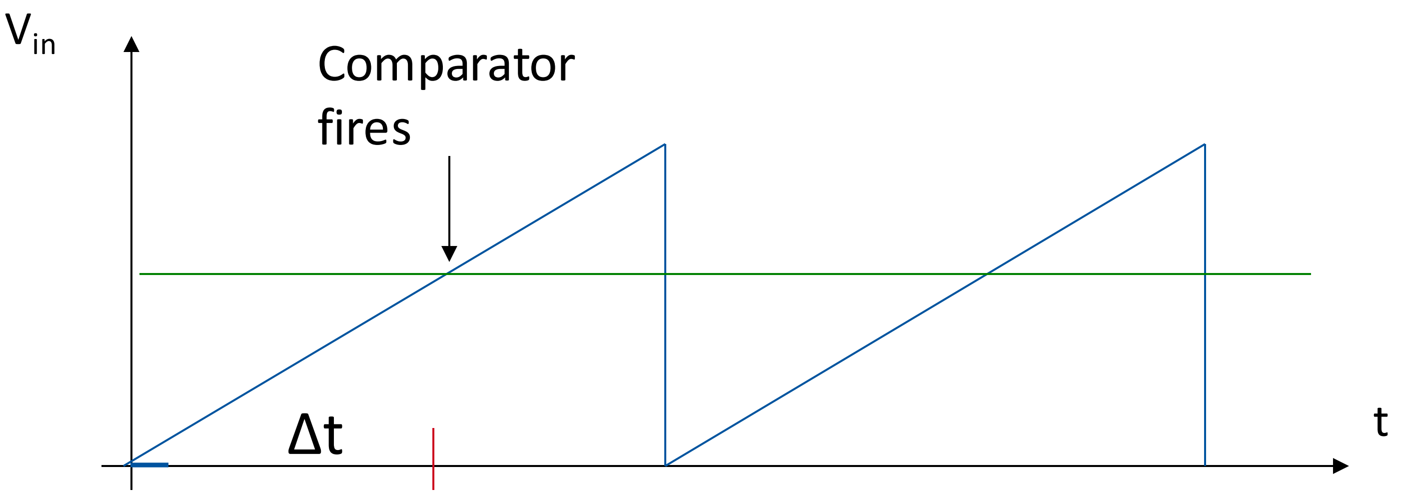
Properties of a Successive Approximation Converter

- Has a successive approximation register (SAR)
- More sophisticated algorithm for approximation used:
  - Starts with $b_{2^{r-1}}$
  - Changes are made in exponential steps
  - Only r comparisons needed, $\mathcal{O}(r)$

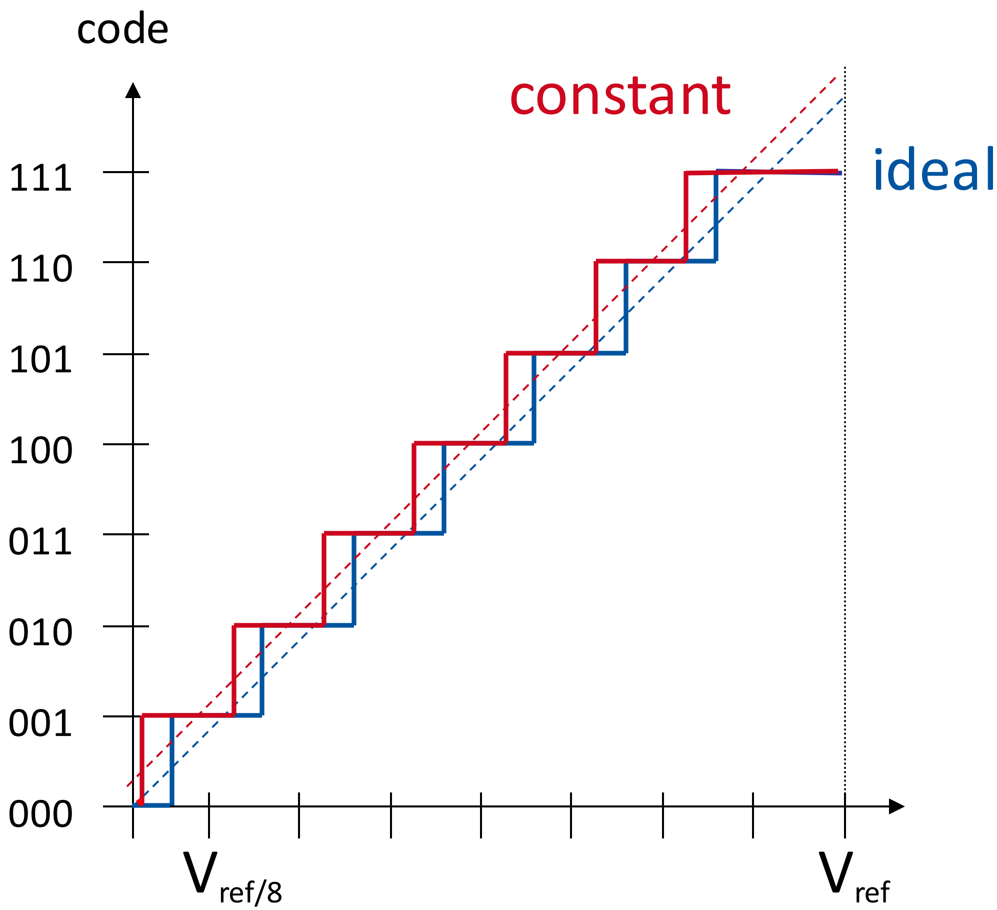


Ramp-Compare Conversion

- Saw signal is generated
- Signal is then compared to measured signal
- When ramp voltage is reached, a comparator fires
- Value can be calculated by measuring the time until it fires
- Ramp signal may be reused for additional conversions

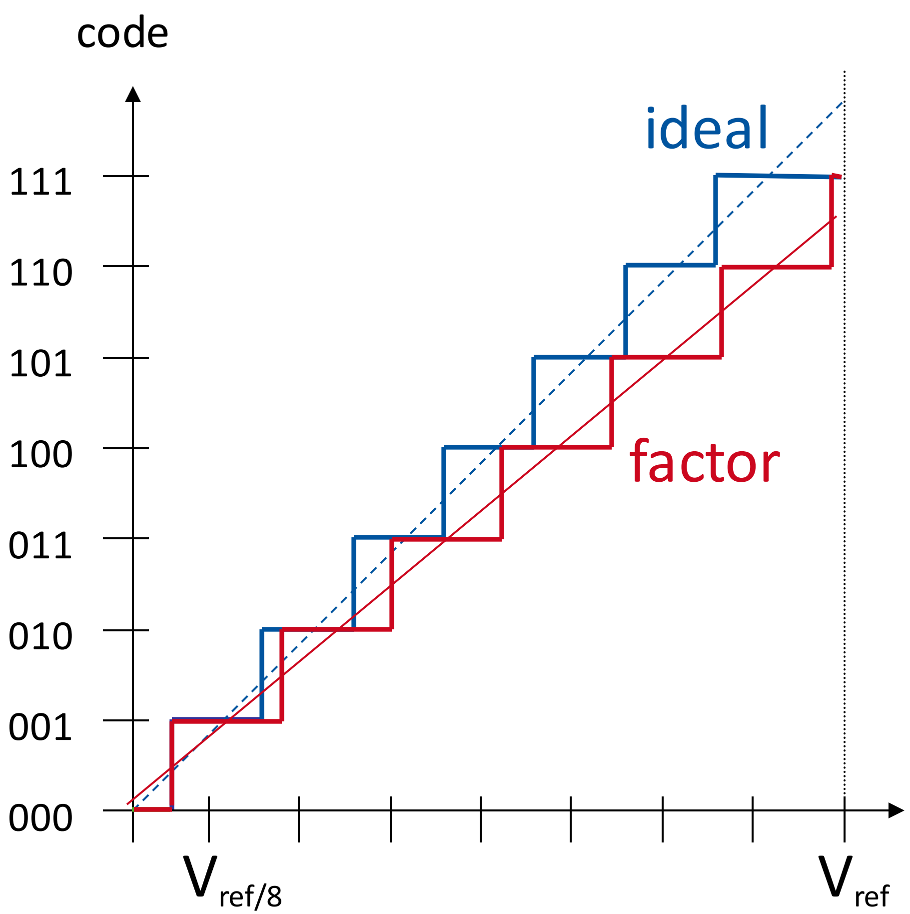


Offset Error



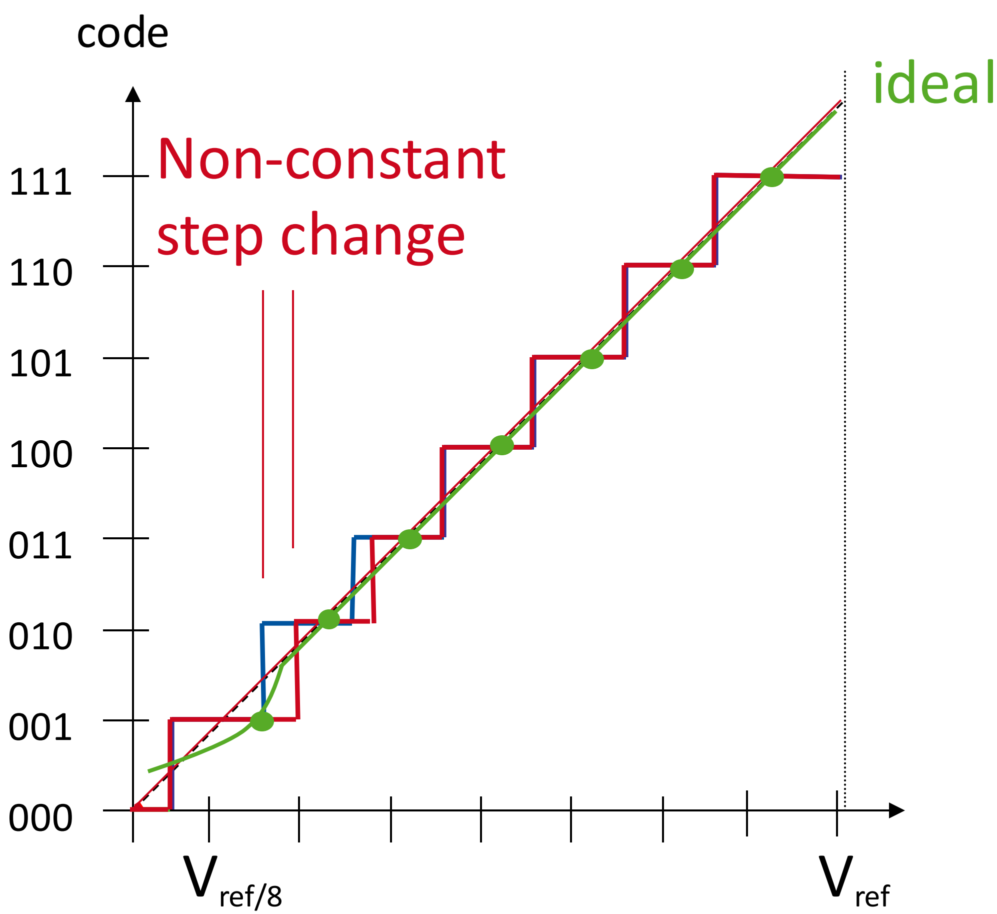
- Constant value added to function
- Step size is the same
- Simple to fix
- Often build-in offset correction

Gain Error



- Step size differs by a constant value
- Gradient diverges
- Build-in gain adjustment

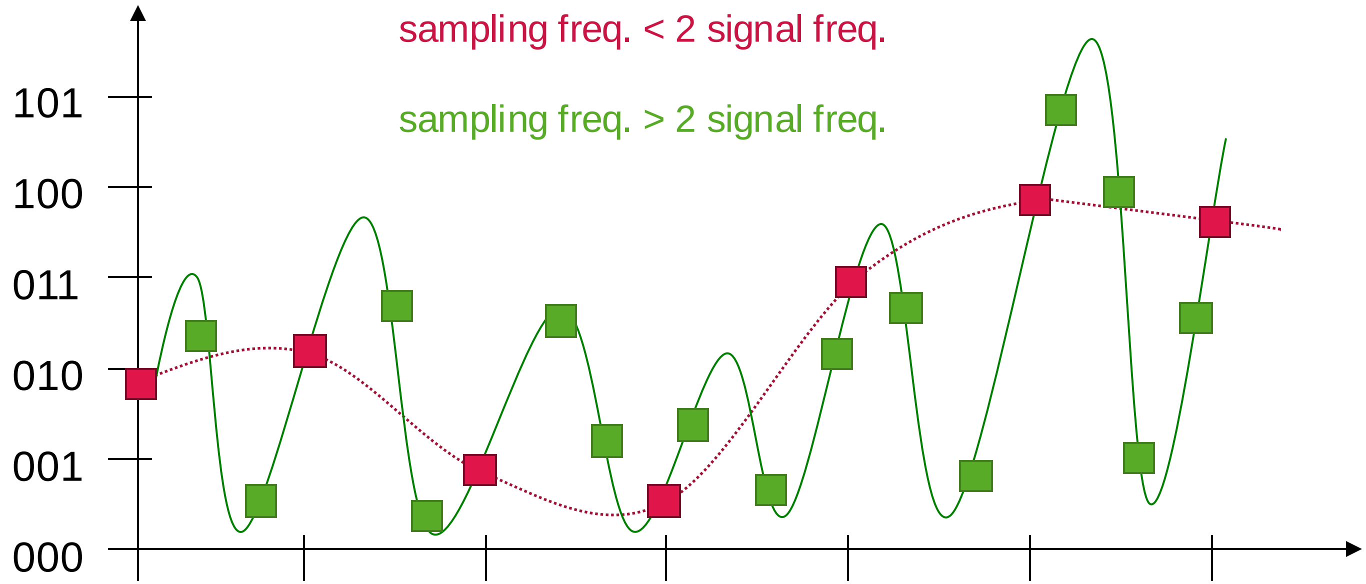
Differential Non-Linearity



- Difference between code transition not 1 lsb
- "Step size" different
- DNL Error is worst case deviation

Conversion Effect: Aliasing

- Signal has a higher frequency than conversion
- Nyquist criterion not met
- Converted signal is only an “alias” of original signal
- Anti-aliasing filters are low-pass filter



ATMega16 ADC Description

- 10-bit Resolution (with atomic read)
- 0.5 LSB Integral Non-linearity
- ±2 LSB Absolute Accuracy
- 13 - 260 µs Conversion Time
- Up to 15 kSPS (kilo samples per second) at Maximum Resolution
- 8 Multiplexed Single Ended Input Channels (single means uses GND)
- 7 Differential Input Channels (compare 2 signals; not necessarily GND)
- 2 Differential Input Channels with Optional Gain of 10x and 200x(1)

ATMega16 ADC Description (cont.)

- 0 - VCC ADC Input Voltage Range
- Free Running or Single Conversion Mode (continuous vs. once)
- ADC Start Conversion by Auto Triggering on Interrupt Sources
- Interrupt on ADC Conversion Complete

Summary

- Digital to analog: PWM + low-pass filter, binary weighted resistor circuit, R-2R Ladder
- ADC: a transfer function
- Analog to digital conversion: comparator, flash converter, tracking converter, successive approximation converter, ramp-compare
- Sample and hold
- 4 error types with seriousness und ways to deal with them
- ATMega16 has very sophisticated control possibilities
- Note: there are more converters like single/dual slope converter, pipeline converter…
- Main source by TU Vienna