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Communication

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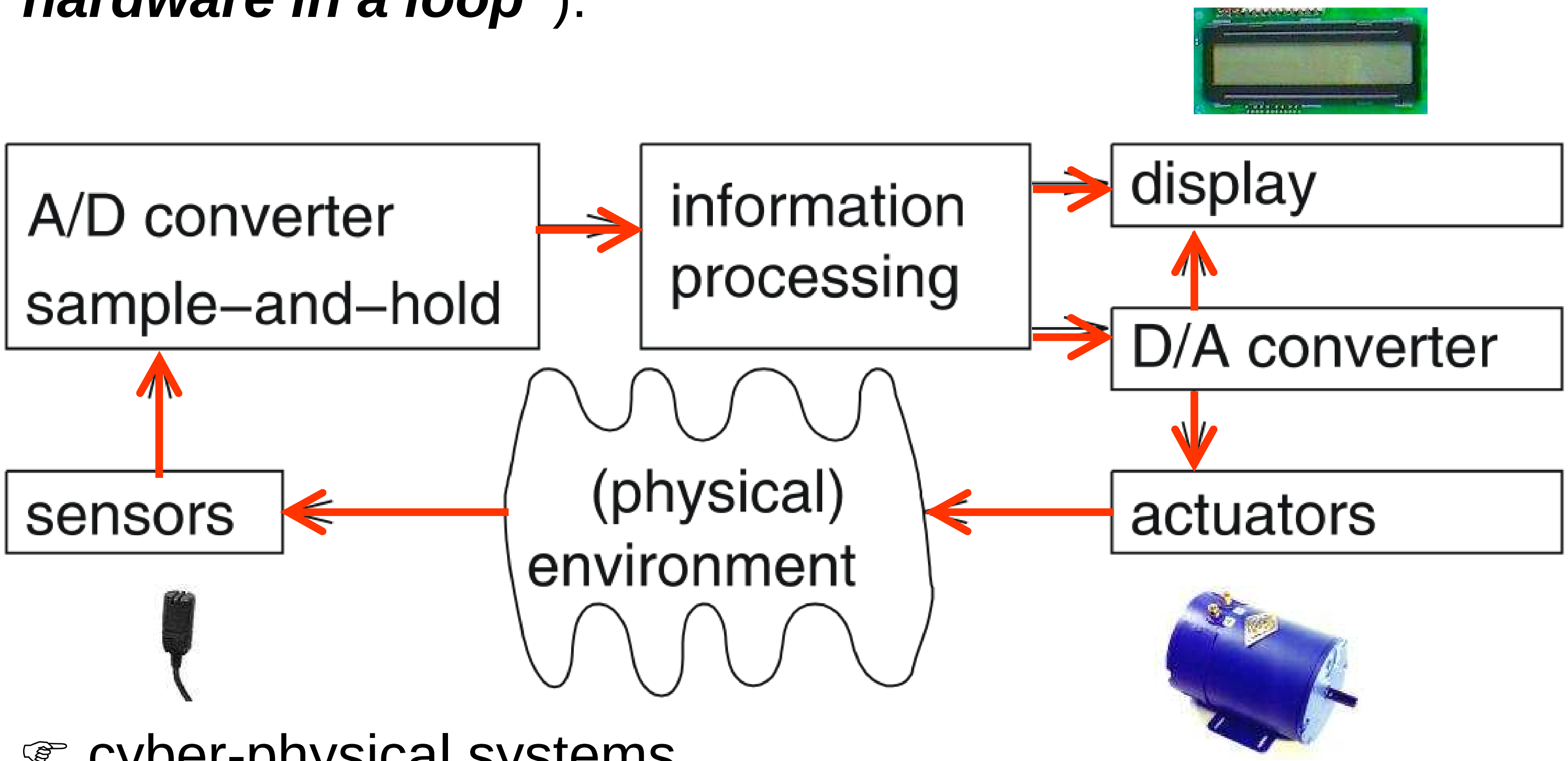
Embedded System Hardware

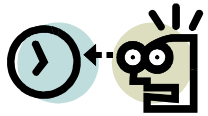
Embedded system hardware is frequently used in a loop (***“hardware in a loop“***):



☞ cyber-physical systems

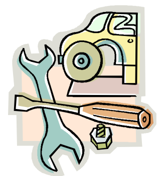
Communication
- Requirements -

- Real-time behavior

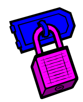


- Efficient, economical
  (e.g. centralized power supply)

- Appropriate bandwidth and communication delay
- Robustness
- Fault tolerance
- Diagnosability
- Maintainability



- Security

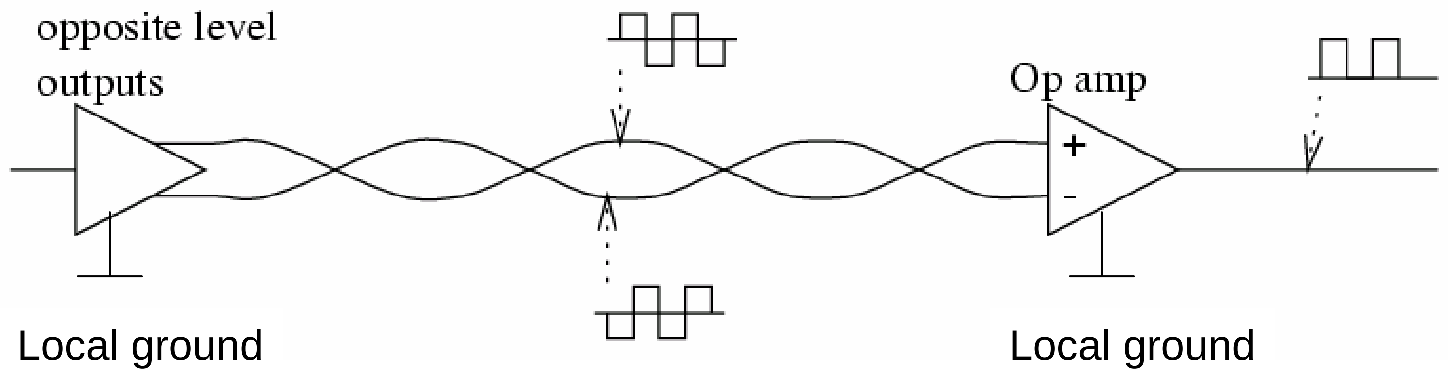


- Safety

Basic techniques: Electrical robustness

Single-ended vs. differential signals

Voltage at input of Op-Amp positive → '1'; otherwise → '0'



Combined with twisted pairs; Most noise added to both wires.

Evaluation

Advantages:

- Subtraction removes most of the noise
- Changes of voltage levels have no effect
- Reduced importance of ground wiring
- Higher speed

Disadvantages:

- Requires negative voltages
- Increased number of wires and connectors

Applications:

- USB, FireWire, ISDN
- Ethernet (STP/UTP CAT 5/6 cables)
- differential SCSI
- High-quality analog audio signals (XLR)

© wikipedia

Communication
- Requirements -

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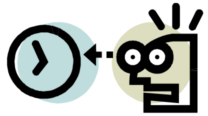

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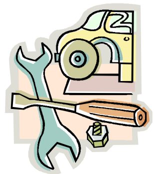

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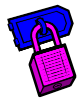
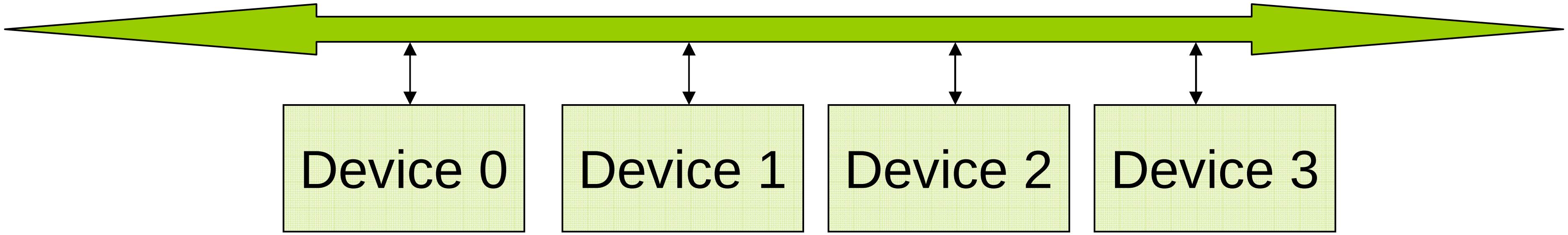


- Safety

Priority-based arbitration of communication media

For example, consider a bus



- Bus arbitration (allocation) is frequently priority-based
- ☞ Communication delay depends on communication traffic of other partherns
- ☞ No tight real-time guarantees, except for highest priority partner

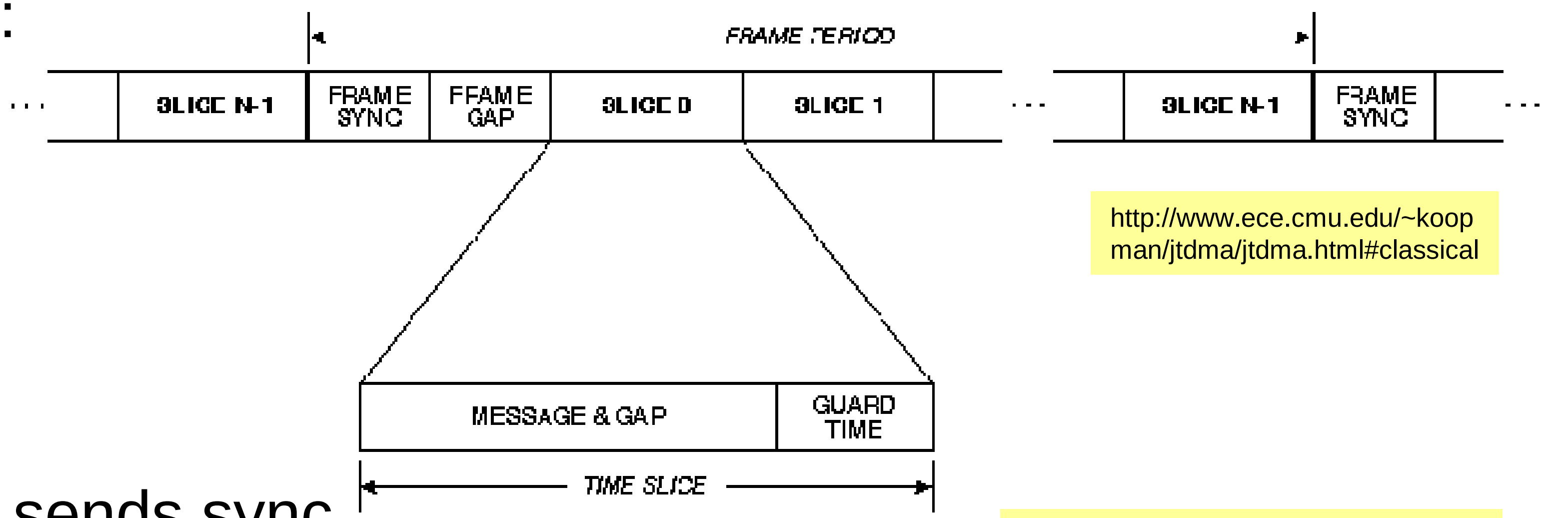
Real-time behavior

Carrier-sense multiple-access/collision-detection (CSMA/CD, Standard Ethernet) no guaranteed response time.
Alternatives:

- token rings, token busses
- Carrier-sense multiple-access/collision-avoidance (CSMA/CA)
  - WLAN techniques with request preceding transmission
  - Each partner gets an ID (priority). After each bus transfer, all partners try setting their ID on the bus; partners detecting higher ID disconnect themselves from the bus. Highest priority partner gets guaranteed response time; others only if they are given a chance.

Time division multiple access (TDMA) busses

Each communication partner is assigned a fixed time slot.
Example:



http://www.ece.cmu.edu/~koopman/jtdma/jtdma.html#classical

[E. Wandeler, L. Thiele: Optimal TDMA Time Slot and Cycle Length Allocation for Hard Real-Time Systems, ASP-DAC, 2006]

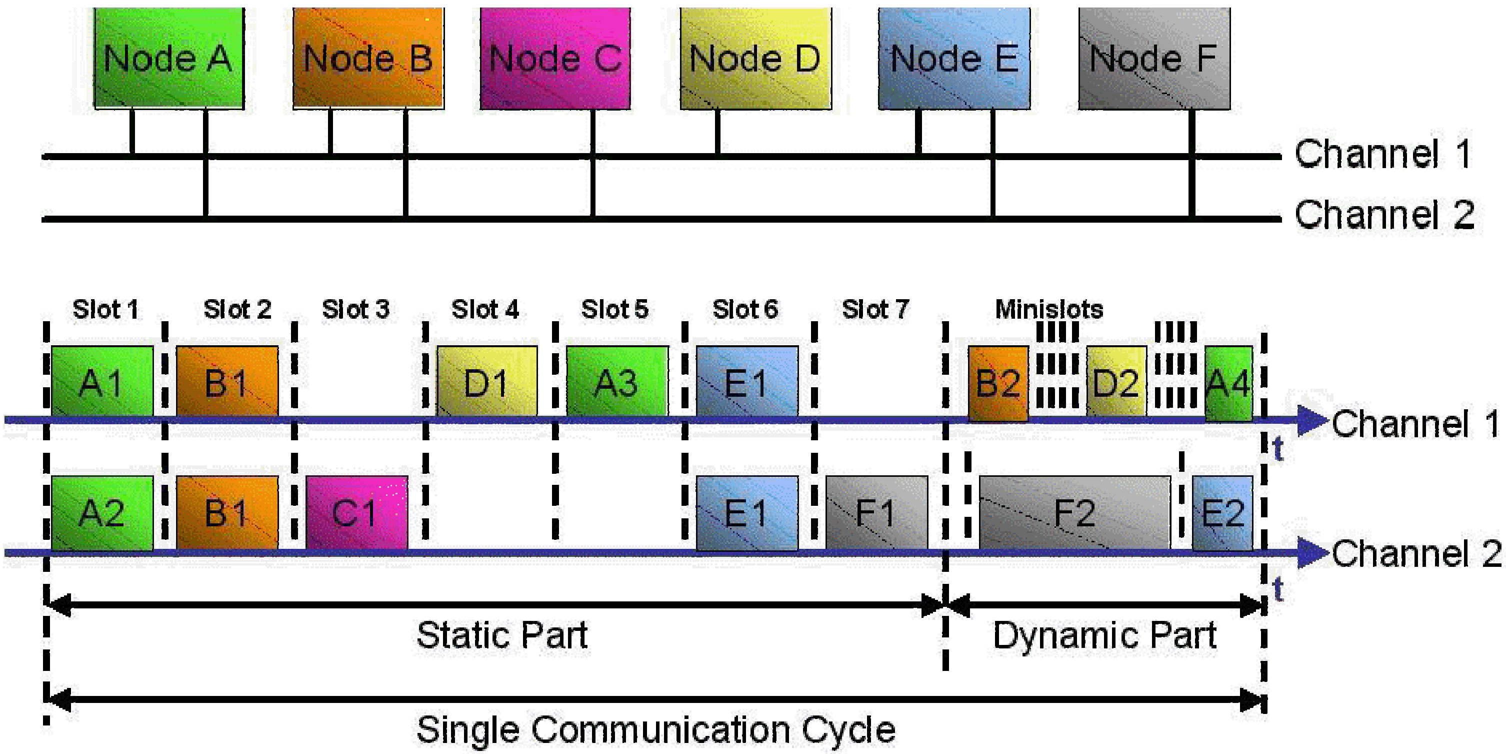
- Master sends sync
- Some waiting time
- Each slave transmits in its time slot
- ∃ variations (truncating unused slots, >1 slots per slave)
- **TDMA resources have a deterministic timing behavior**
- **TDMA provides QoS guarantees in networks on chips**

FlexRay

- Developed by the FlexRay consortium (BMW, Ford, Bosch, DaimlerChrysler, …)
- Specified in SDL
- Improved error tolerance and time-determinism
- Meets requirements with transfer rates >> CAN standard **High data rate can be achieved:**
  - initially targeted for ~ 10Mbit/sec;
  - design allows much higher data rates
- TDMA protocol
- Cycle subdivided into a static and a dynamic segment.

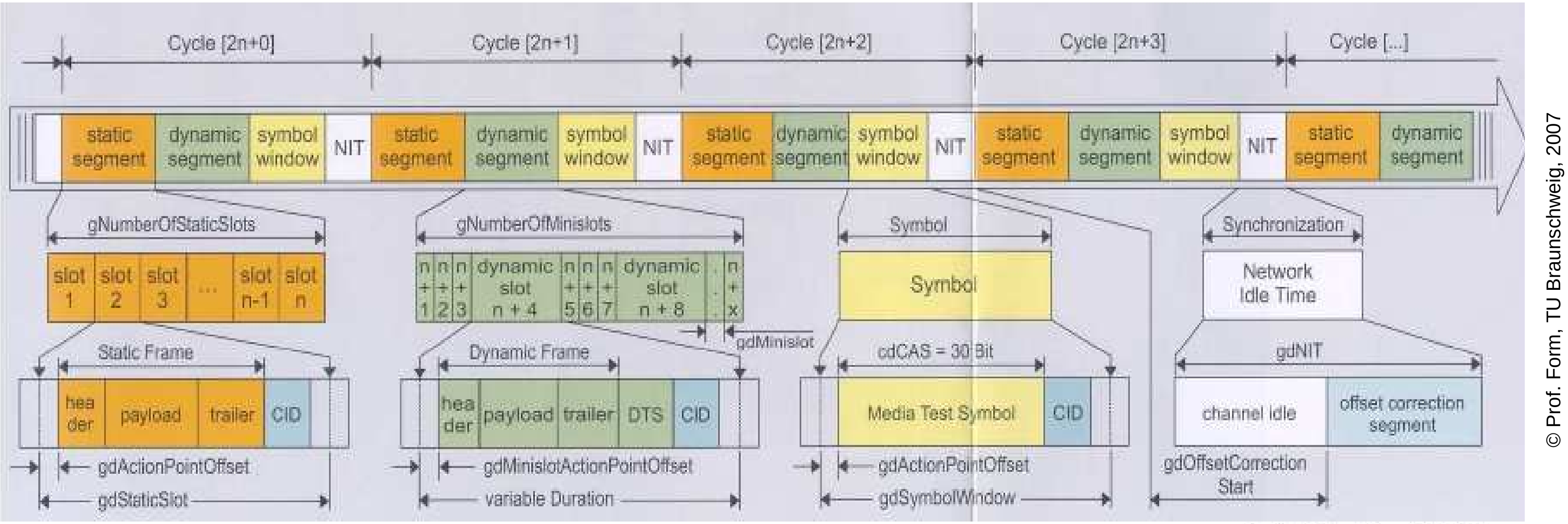
TDMA in FlexRay

Exclusive bus access enabled for short time in each case.
Dynamic segment for transmission of variable length information.
Fixed priorities in dynamic segment: Minislots for each potential sender.
Bandwidth used only when it is actually needed.



http://www.tzm.de/FlexRay/FlexRay_Introduction.html

Time intervals in Flexray

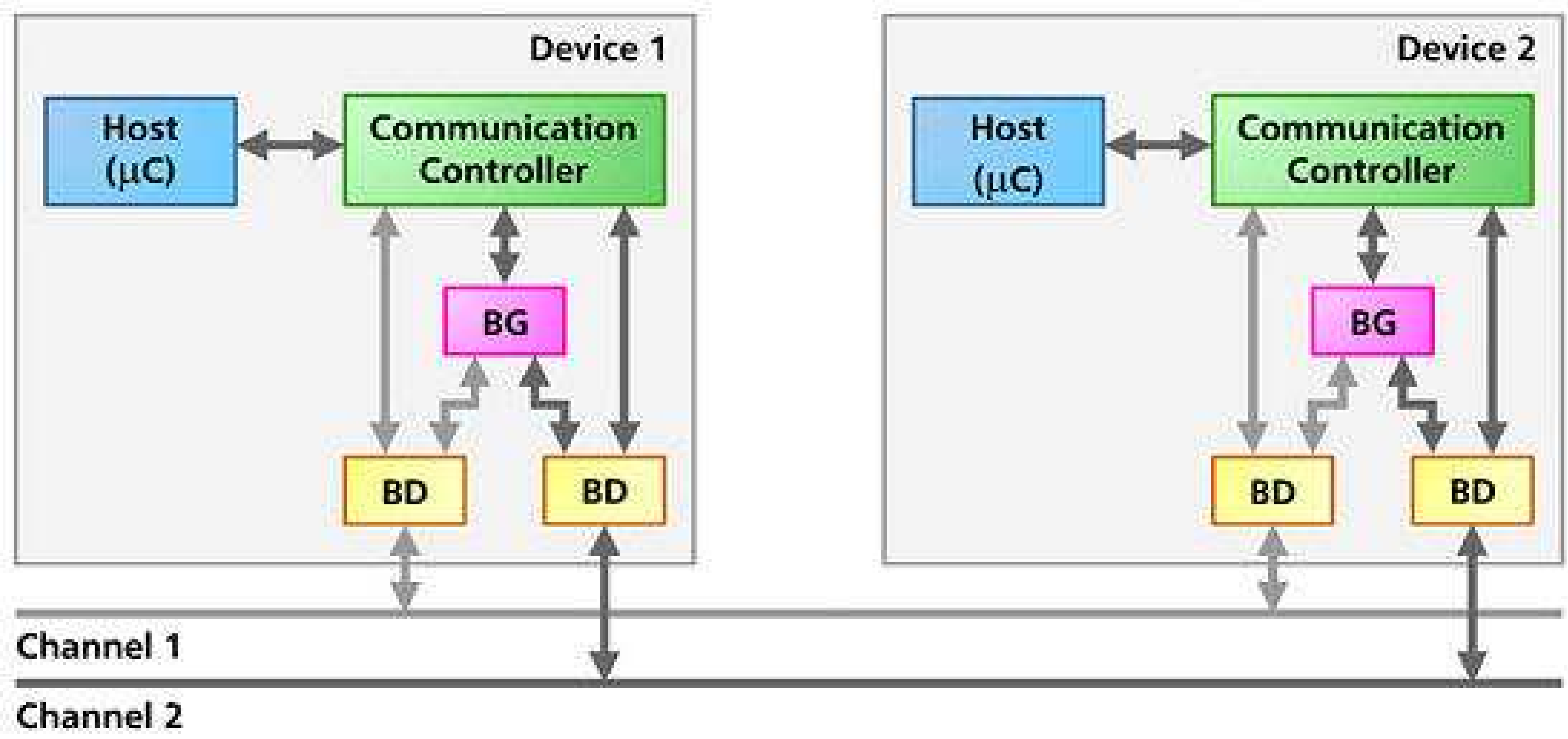


Quelle: Vector Informatik GmbH

- **Microtick (*µt*)** = Clock period in partners, may differ between partners
- **Macrotick (*mt*)** = Basic unit of time, synchronized between partners (=$r_i \times \mu t$, r_i varies between partners *i*)
- **Slot**=Interval allocated per sender in static segment (=$p \times mt$, *p*: fixed (configurable))
- **Minislot** = Interval allocated per sender in dynamic segment (=$q \times mt$, *q*: variable)
  Short minislot if no transmission needed; starts after previous minislot.
- **Cycle** = Static segment + dynamic segment + network idle time

Structure of Flexray networks

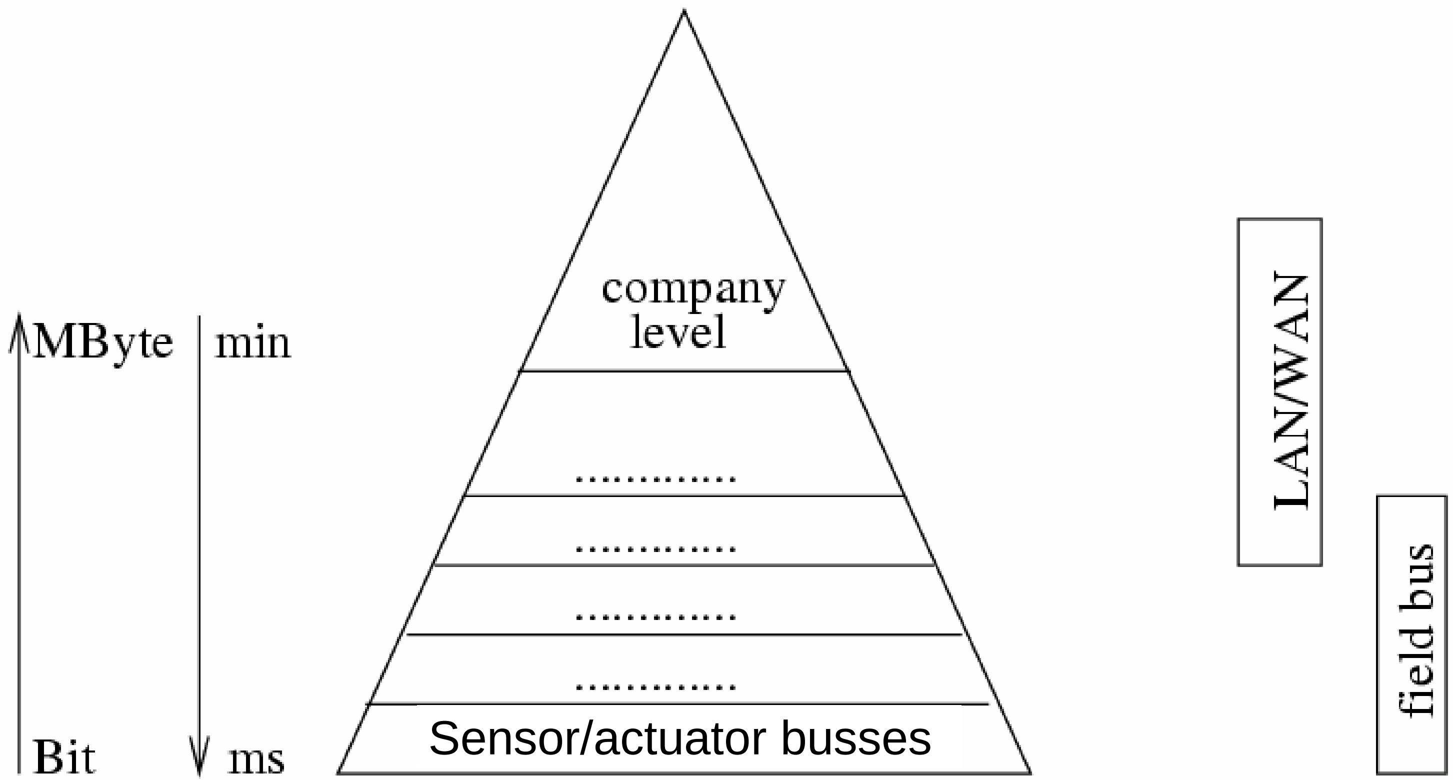
Bus guardian protects the system against failing processors, e.g. so-called “babbling idiots”



http://www.ixxat.de/index.php?seite=introduction_flexray_en&root=5873&system_id=58 75&com=formular_suche_treffer&markierung=flexray

Communication: Hierarchy

Inverse relation between volume and urgency quite common:



Other busses

- **Sensor/actuator busses:** connecting sensors/actuators, low rates
- **Field busses**
- **CAN:** Controller bus for automotive
- **LIN:** low cost bus for interfacing sensors/actuators in the automotive domain
- **MOST:** Multimedia bus for the automotive domain (not a field bus)
- **MAP:** bus designed for car factories.
- **Process Field Bus (Profibus):** used in smart buildings
- **The European Installation Bus (EIB):** bus designed for smart buildings; CSMA/CA; low data rate.
- **IEEE 488:** Designed for laboratory equipment.
- Attempts to use standard Ethernet. Timing predictability an issue.

Wireless communication: Examples

- IEEE 802.11 a/b/g/n
- UMTS; HSPA
- DECT
- Bluetooth
- ZigBee

Timing predictability of wireless communication?

D/A-Converters

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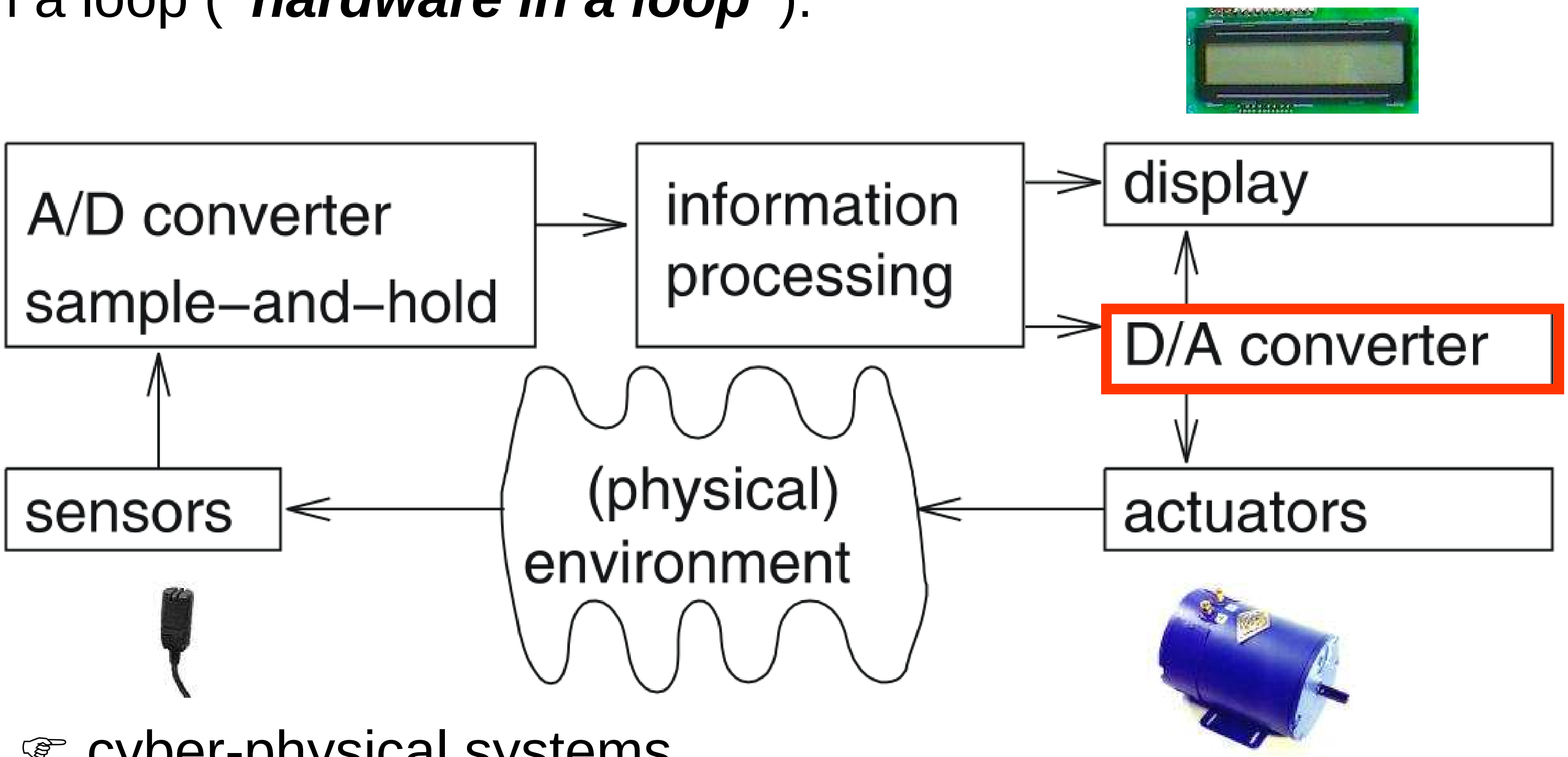
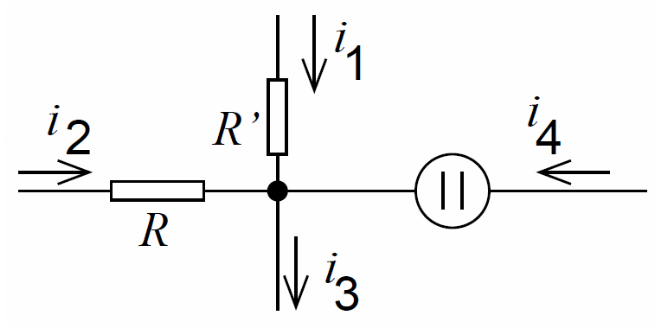


☞ cyber-physical systems

Kirchhoff‘s junction rule
Kirchhoff‘s Current Law, Kirchhoff‘s first rule

Kirchhoff’s Current Law:
At any point in an electrical circuit, the sum of currents flowing towards that point is equal to the sum of currents flowing away from that point.
(Principle of conservation of electric charge)

Example:



$$i_1 + i_2 + i_4 = i_3$$

Formally, for any node in a circuit:

$$i_1+i_2-i_3+i_4=0$$

$$\sum_k i_k = 0$$

Count current flowing away from node as negative.

[Jewett and Serway, 2007].

Kirchhoff's loop rule

Kirchhoff's Voltage Law, Kirchhoff's second rule

The principle of conservation of energy implies that:

The sum of the potential differences (voltages) across all elements around any closed circuit must be zero

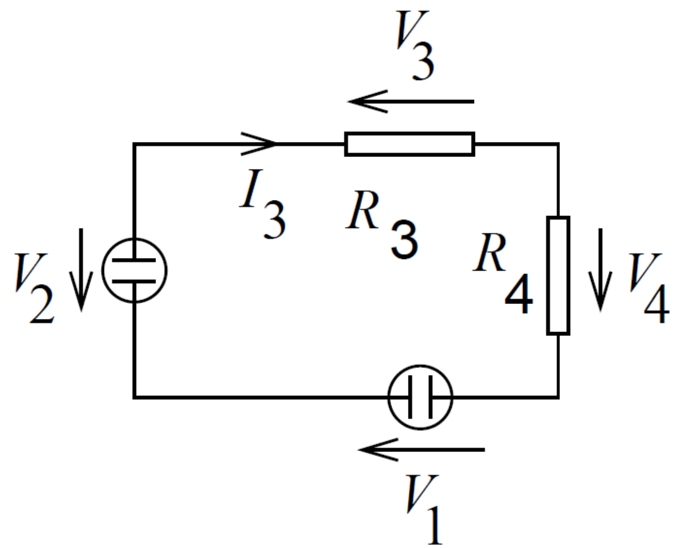
[Jewett and Serway, 2007].

Formally, for any loop in a circuit:

$$\sum_k V_k = 0$$

Count voltages traversed against arrow direction as negative

Example:



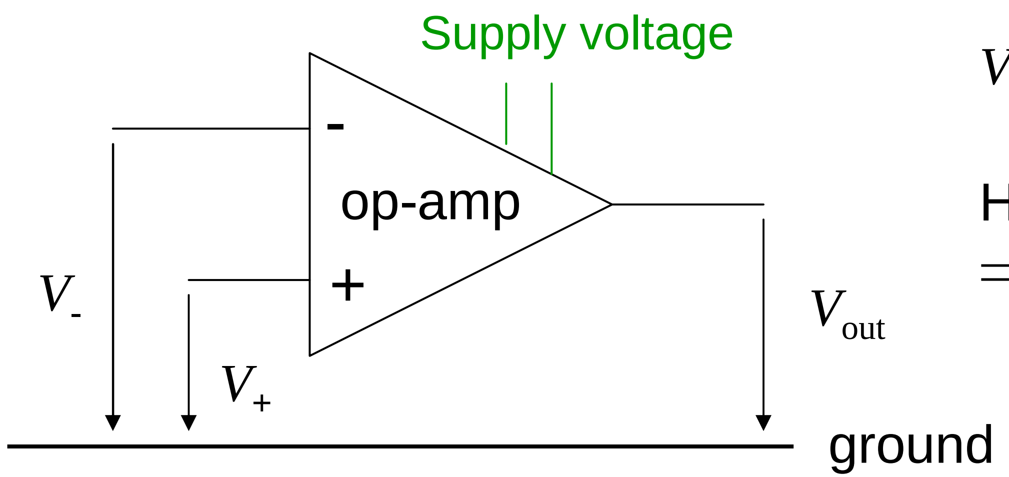
$V_1 - V_2 - V_3 + V_4 = 0$

$V_3 = R_3 \times I_3$ if current counted in the same direction as V_3

$V_3 = -R_3 \times I_3$ if current counted in the opposite direction as V_3

Operational Amplifiers (Op-Amps)

Operational amplifiers (op-amps) are devices amplifying the voltage difference between two input terminals by a large gain factor g



$V_{out}=(V_+ - V_-) \cdot g$

High impedance input terminals
$\Rightarrow$ Currents into inputs $\approx$ 0

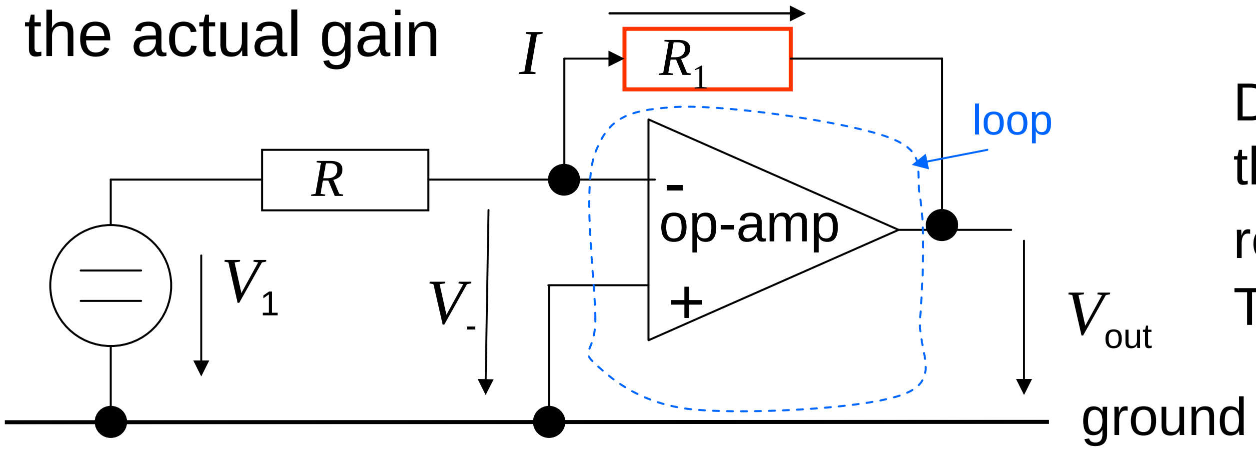
Op-amp in a separate package (TO-5) [wikipedia]

For an **ideal** op-amp: $g \rightarrow \infty$

(In practice: g may be around $10^4..10^6$)

Op-Amps with feedback

In circuits, negative feedback is used to define the actual gain



Due to the feedback to the *inverted* input, R_1 reduces voltage V_-. To which level?

$V_{out} = -g \cdot V_-$ (op-amp feature)

$I \cdot R_1 + V_{out} - V_- = 0$ (loop rule)

$\Rightarrow I \cdot R_1 + -g \cdot V_- - V_- = 0$

$\Rightarrow (1+g) \cdot V_- = I \cdot R_1$

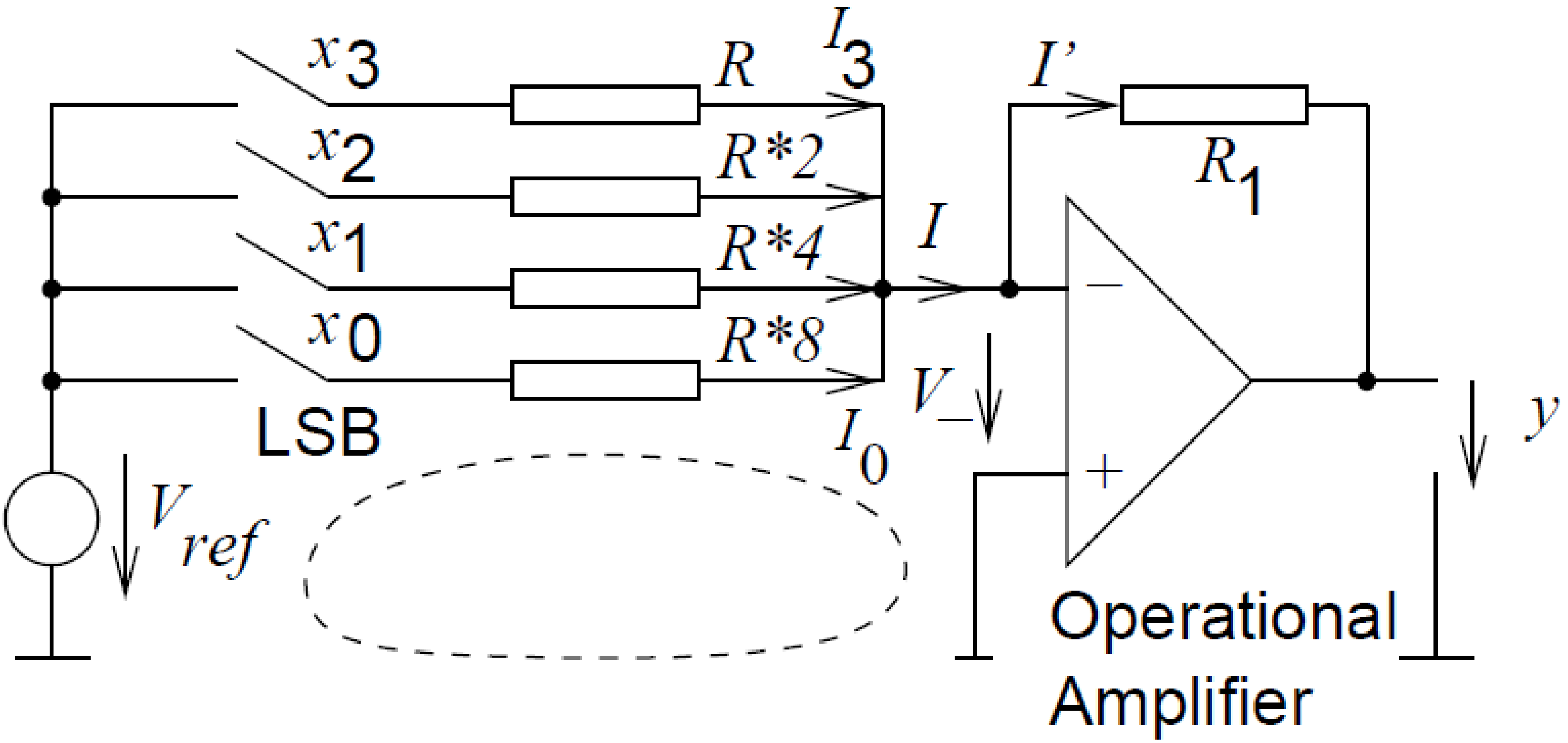
$$\Rightarrow V_- = \frac{I \cdot R_1}{1+g}$$

$$V_{-,ideal} = \lim_{g \to \infty} \frac{I \cdot R_1}{1+g} = 0$$

V_- is called **virtual ground**: the voltage is 0, but the terminal may not be connected to ground

Digital-to-Analog (D/A) Converters

Various types, can be quite simple, e.g.:



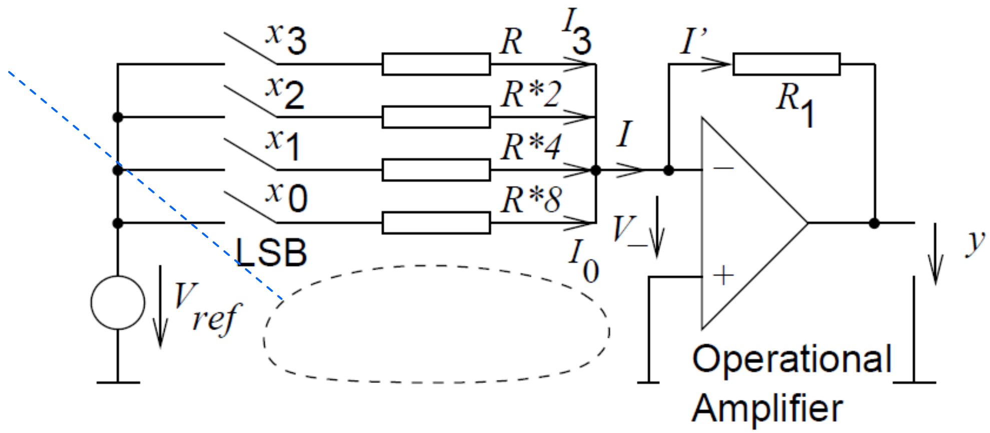
Current ~ no. represented by x

Loop rule:

$$x_0 \cdot I_0 \cdot 8 \cdot R + V_{-} - V_{ref} = 0$$

☞ $$I_0 = x_0 \times \frac{V_{ref}}{8 \times R}$$

In general: $$I_i = x_i \times \frac{V_{ref}}{2^{3-i} \times R}$$



Junction rule: $$I = \sum_i I_i$$

☞ $$I = x_3 \times \frac{V_{ref}}{R} + x_2 \times \frac{V_{ref}}{2 \times R} + x_1 \times \frac{V_{ref}}{4 \times R} + x_0 \times \frac{V_{ref}}{8 \times R} = \frac{V_{ref}}{8 \times R} \times \sum_{i=0}^{3} x_i \times 2^i$$

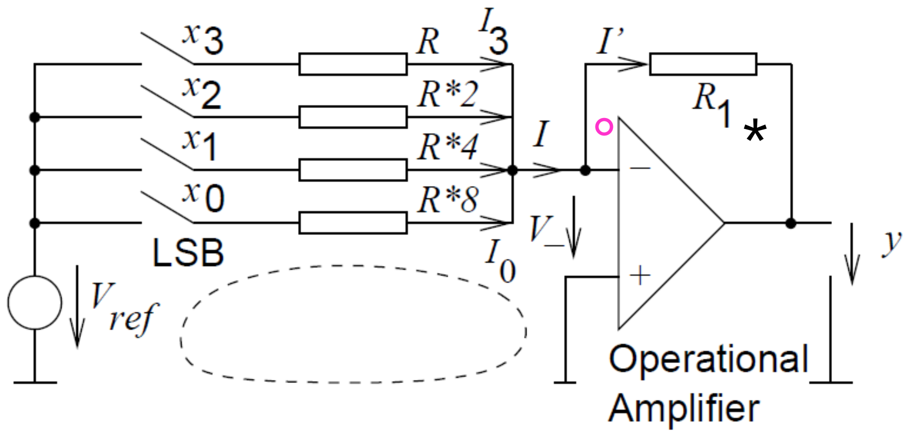
$I \sim nat(x)$, where $nat(x)$: natural number represented by x;

Output voltage ~ no. represented by *x*

Loop rule*: $y + R_1 \times I' = 0$

Junction rule°: $I = I'$

☞ $y + R_1 \times I = 0$



From the previous slide

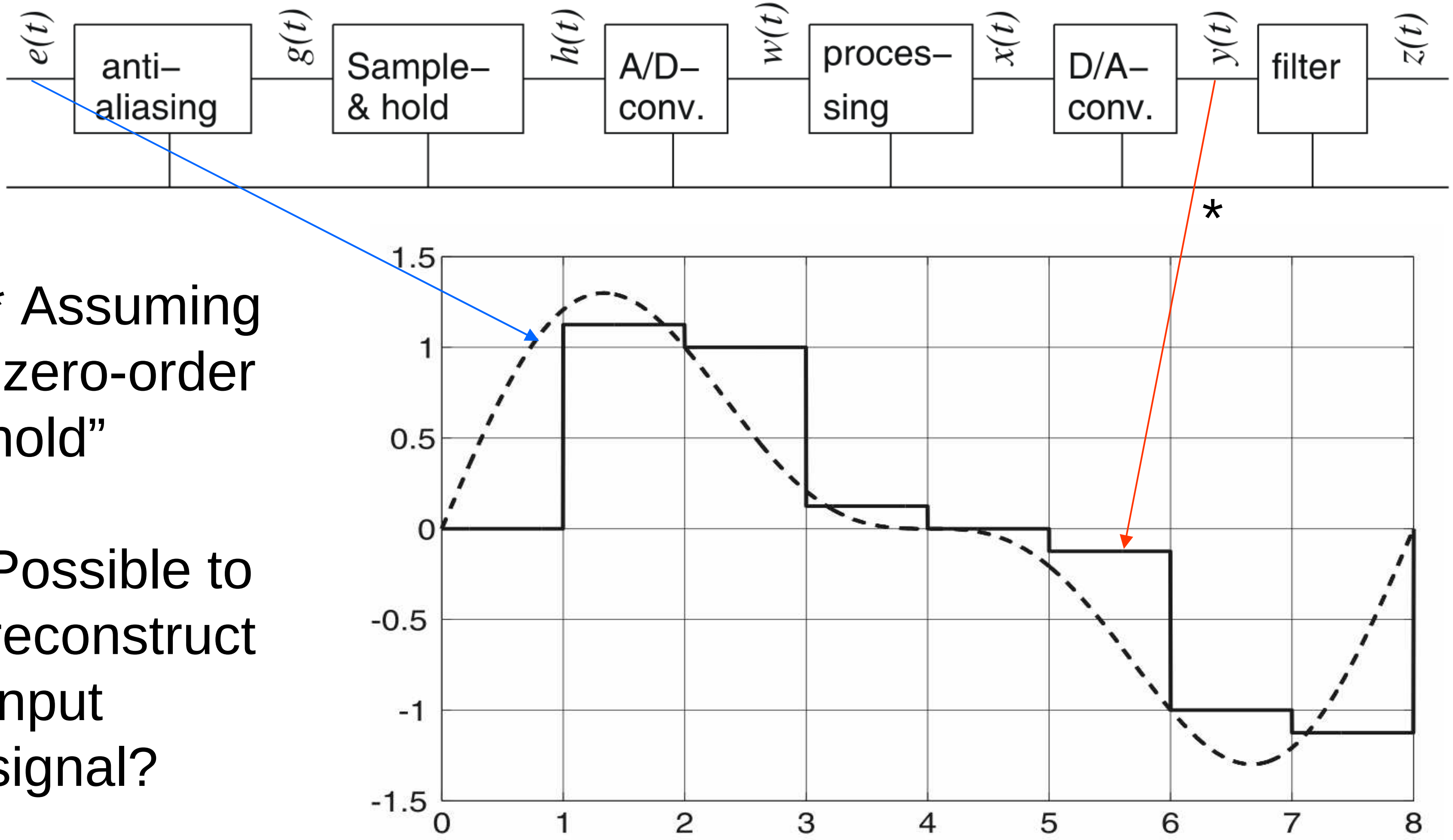
$$I = \frac{V_{ref}}{8 \times R} \times \sum_{i=0}^{3} x_i \times 2^i$$

Hence:

$$y = -V_{ref} \times \frac{R_1}{8 \times R} \sum_{i=0}^{3} x_i \times 2^i = -V_{ref} \times \frac{R_1}{8 \times R} \times nat(x)$$

Op-amp turns current $I \sim nat$ (x) into a voltage $\sim nat\ (x)$

Output generated from signal $e_3(t)$



* Assuming "zero-order hold"

Possible to reconstruct input signal?

Sampling Theorem

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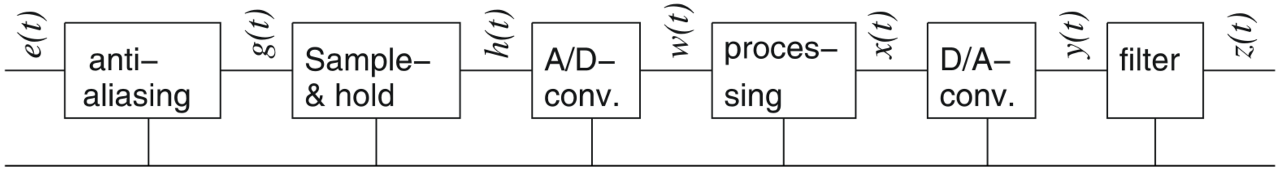
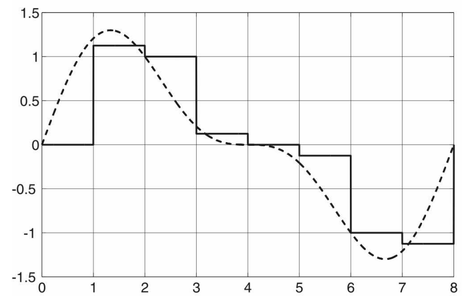
Possible to reconstruct input signal?





- Assuming Nyquist criterion met
- Let $\{t_s\}$, $s = ..., -1,0,1,2, ...$ be times at which we sample $g(t)$
- Assume a constant sampling rate of $1/p_s$ ($\forall s$: $p_s = t_{s+1} - t_s$).
- According sampling theory, we can approximate the input signal as follows:

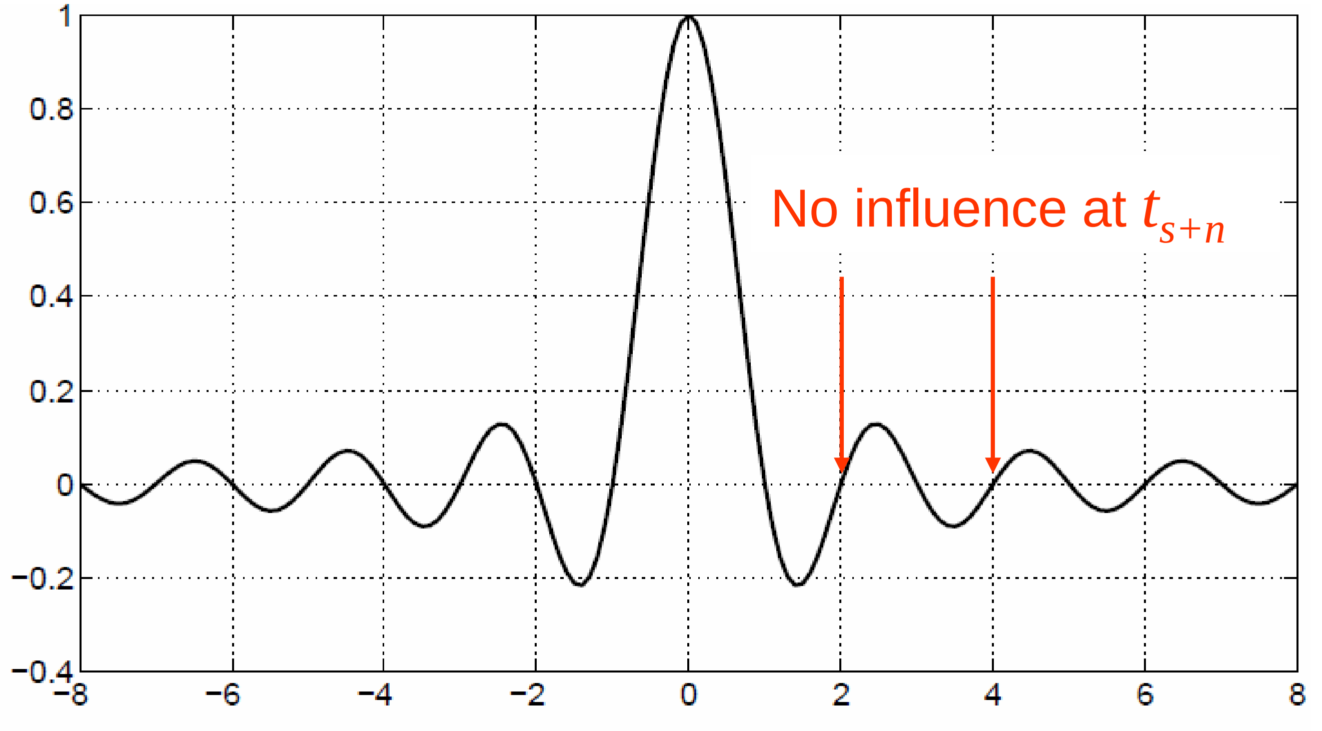
$$z(t) = \sum_{s=-\infty}^{\infty} \frac{y(t_s) sin \frac{\pi}{p_s}(t - t_s)}{\frac{\pi}{p_s}(t - t_s)}$$

Weighting factor for influence of $y(t_s)$ at time t

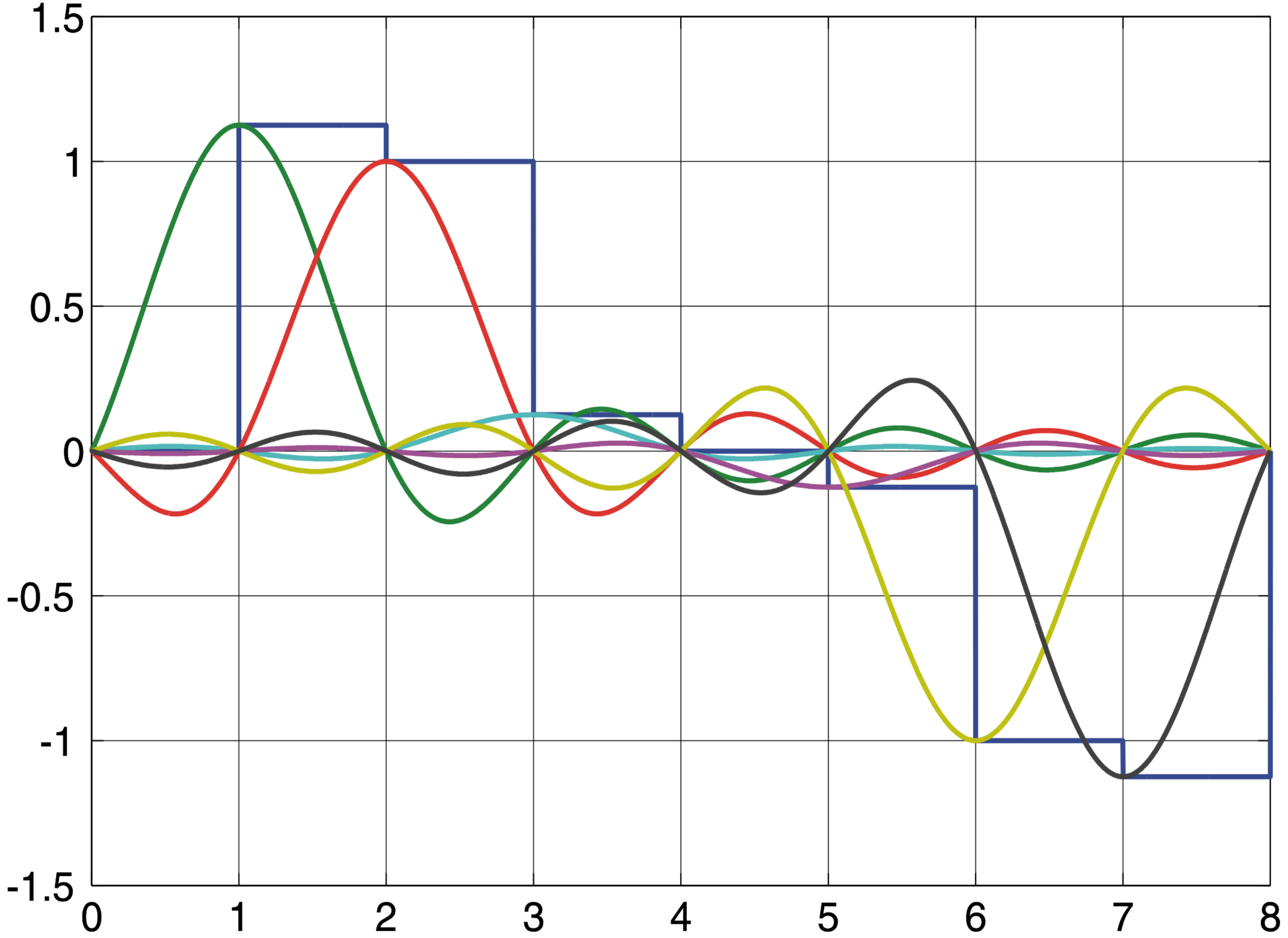
[Oppenheim, Schafer, 2009]

Weighting factor for influence of $y(t_s)$ at time t

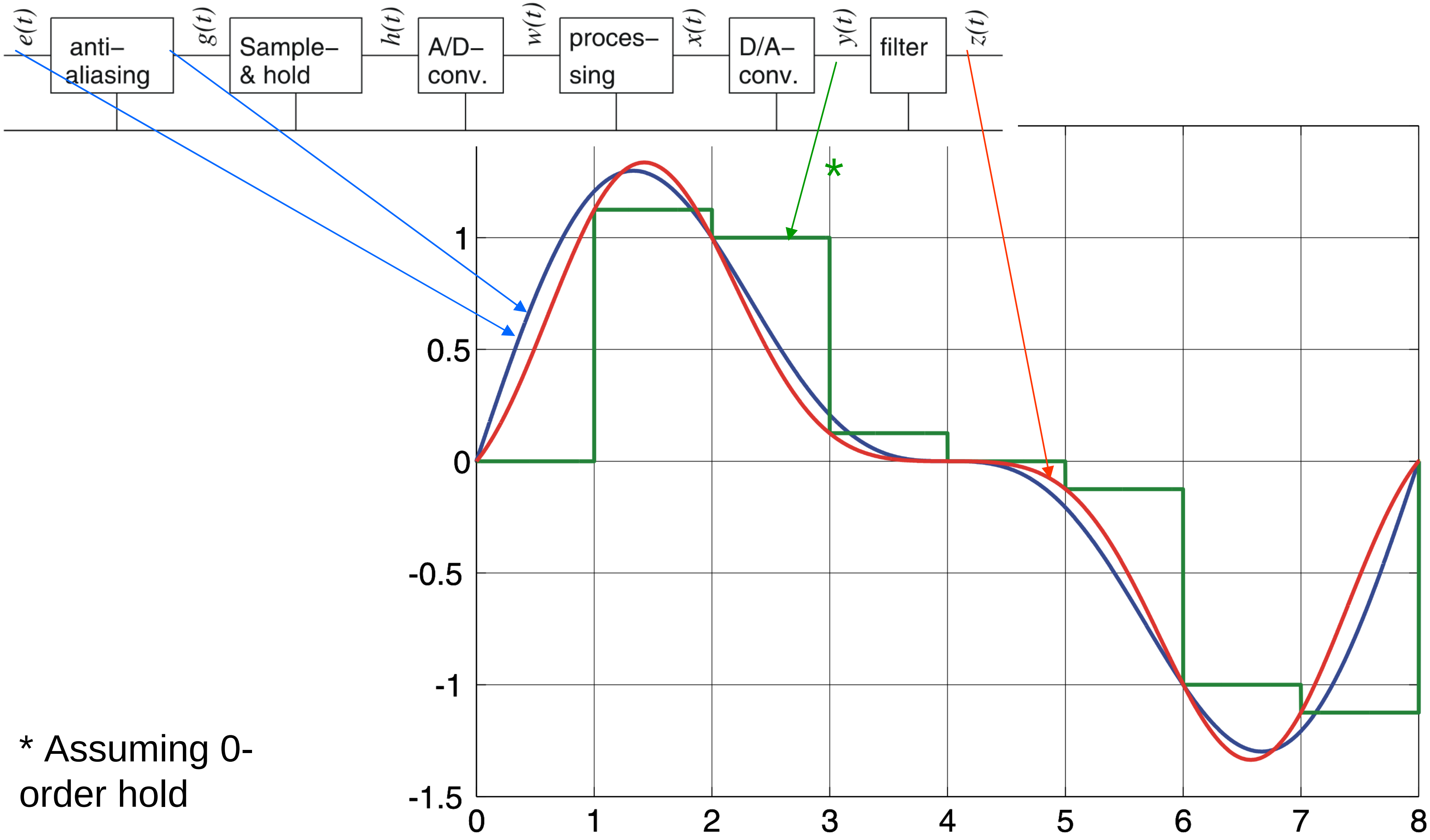
$$sinc(t - t_s) = \frac{sin(\frac{\pi}{p_s}(t - t_s))}{\frac{\pi}{p_s}(t - t_s)}$$



Contributions from the various sampling instances



(Attempted) reconstruction of input signal

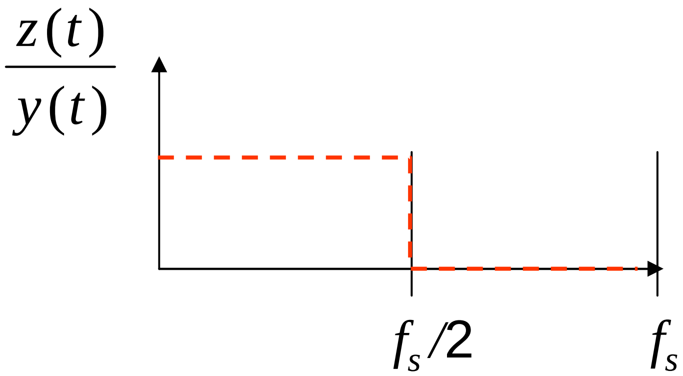


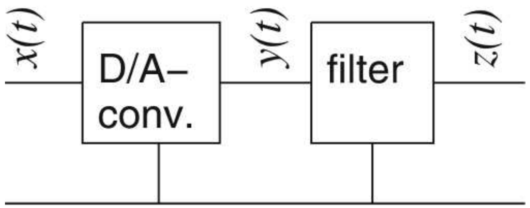
* Assuming 0-order hold

How to compute the *sinc*( ) function?

$$z(t) = \sum_{s=-\infty}^{\infty} \frac{y(t_s) \sin \frac{\pi}{T_s}(t - t_s)}{\frac{\pi}{T_s}(t - t_s)}$$

- **Filter theory:** The required interpolation is performed by an ideal low-pass filter (*sinc* is the Fourier transform of the low-pass filter transfer function)





Filter removes high frequencies present in $y(t)$

How precisely are we reconstructing the input?

$$z(t) = \sum_{s=-\infty}^{\infty} \frac{y(t_s) sin \frac{\pi}{T_s}(t - t_s)}{\frac{\pi}{T_s}(t - t_s)}$$

- **Sampling theory**:
  - **Reconstruction using *sinc* () is precise**
- However, it may be impossible to really compute $z(t)$ as indicated ….

Limitations

$$z(t) = \sum_{s=-\infty}^{\infty} \frac{y(t_s) sin \frac{\pi}{T_s}(t - t_s)}{\frac{\pi}{T_s}(t - t_s)}$$

- Actual filters do not compute *sinc*( )
  In practice, filters are used as an approximation.
  Computing good filters is an art itself!
- All samples must be known to reconstruct $e(t)$ or $g(t)$.
  ☞ Waiting indefinitely before we can generate output!
  In practice, only a finite set of samples is available.
- Actual signals are never perfectly bandwidth limited.
- Quantization noise cannot be removed.

Output

Output devices of embedded systems include

- **Displays:** Display technology is extremely important. Major research and development efforts
- **Electro-mechanical devices:** these influence the environment through motors and other electro-mechanical equipment.
  Frequently require analog output.

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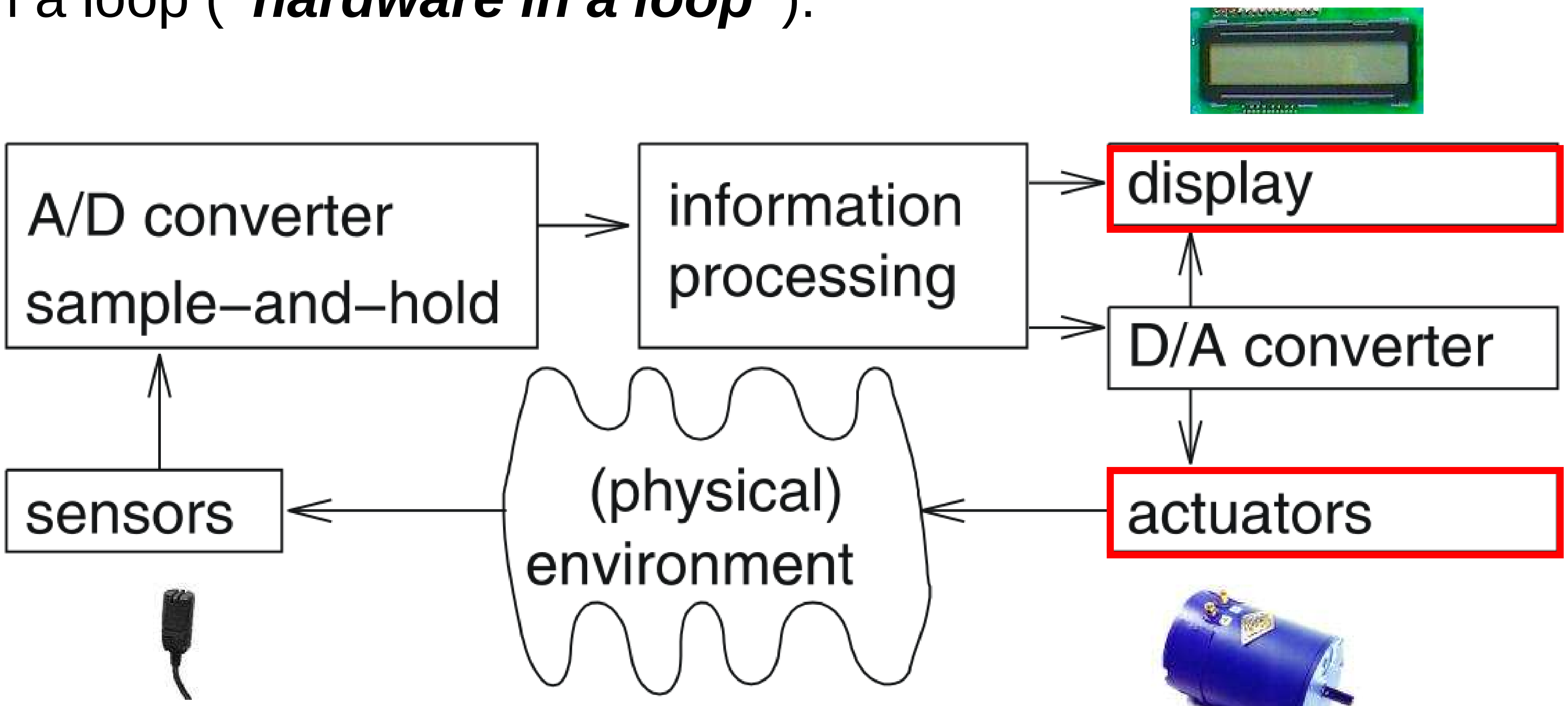

☞ cyber-physical systems

Actuators

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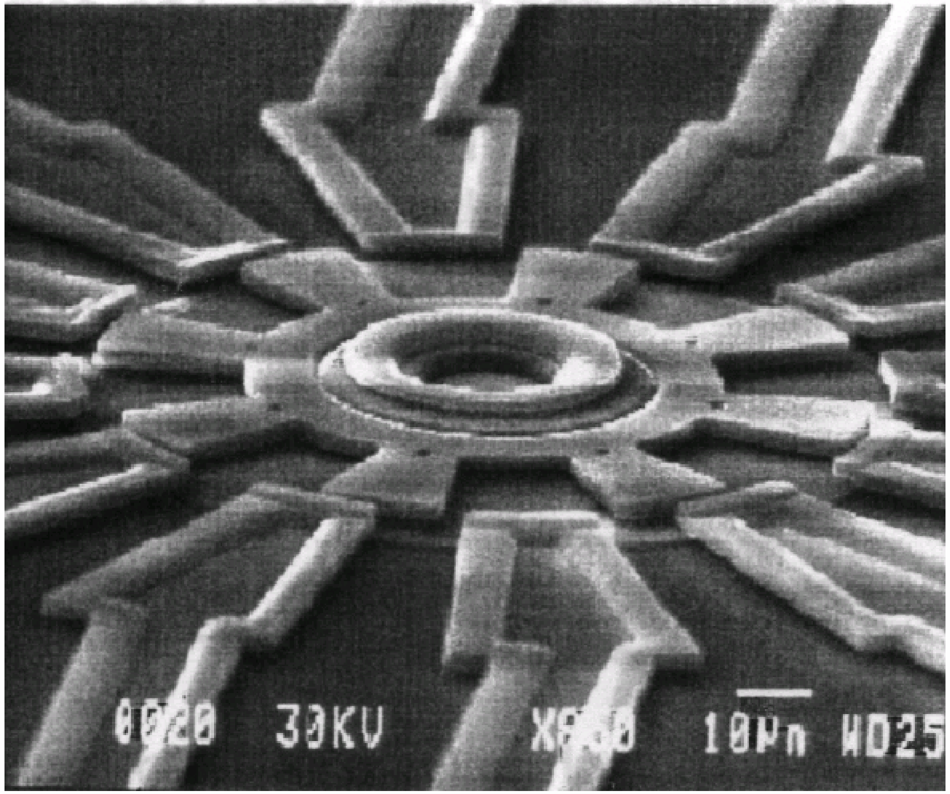
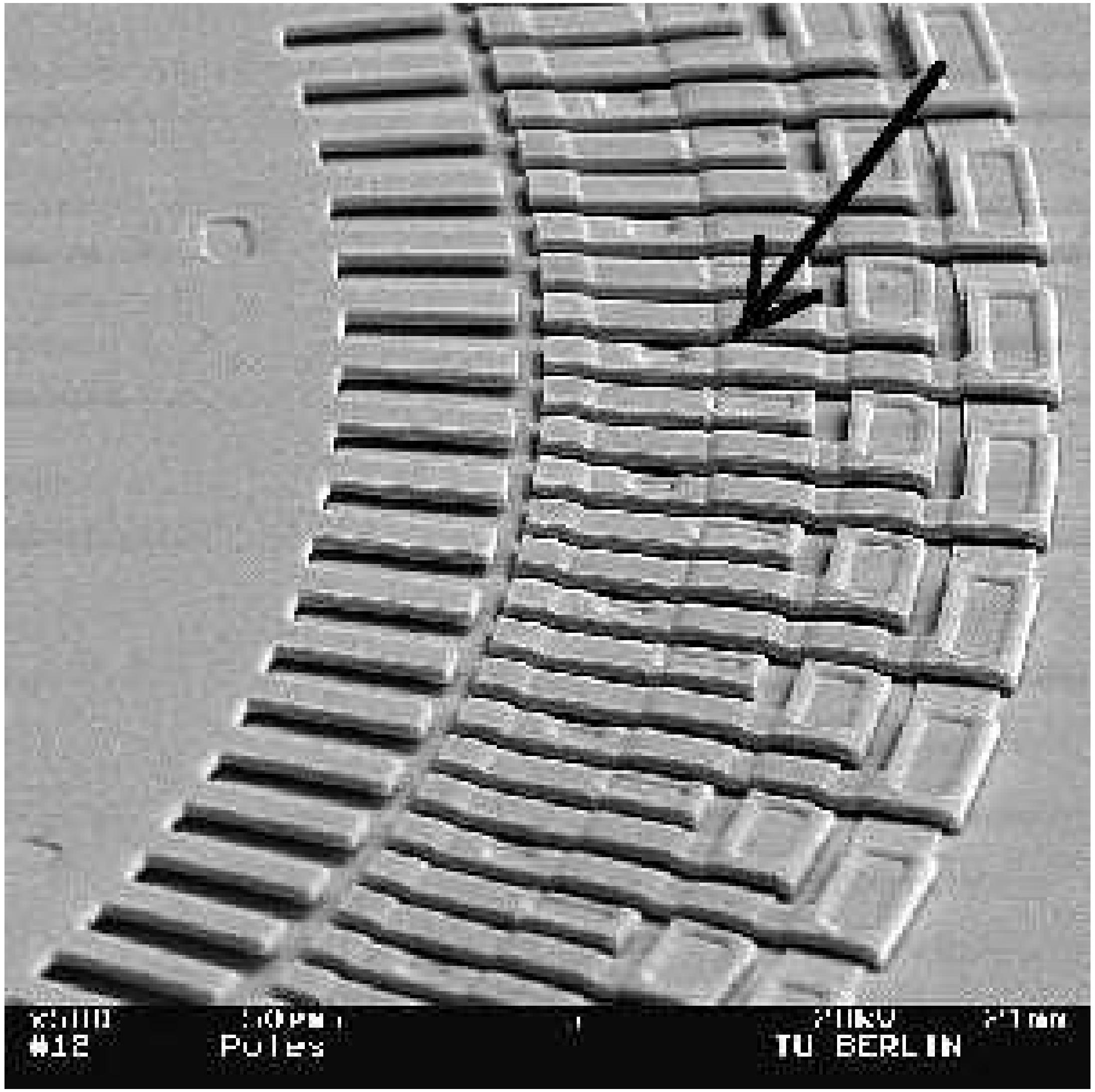
Actuators

Huge variety of actuators and output devices, impossible to present all of them.
Microsystems motors as examples (© MCNC):



(© MCNC)

Actuators (2)



Courtesy and ©: E. Obermeier, MAT, TU Berlin

http://www.piezomotor.se/pages/PWtechnology.html

http://www.elliptec.com/fileadmin/elliptec/User/Produkte/Elliptec_Motor/Elliptecmotor_How_it_works.h

Secure Hardware

- Security needed for communication and storage
- Demand for special equipment for cryptographic keys
- To resist side-channel attacks like
  - measurements of the supply current or
  - Electromagnetic radiation.

  Special mechanisms for physical protection (shielding, sensor detecting tampering with the modules).
- Logical security, using cryptographic methods needed.
- Smart cards: special case of secure hardware
  - Have to run with a very small amount of energy.
- In general, we have to distinguish between different levels of security and knowledge of “adversaries”

Summary

Hardware in a loop

- Sensors
- Discretization
- Information processing
  - Importance of energy efficiency, Special purpose HW very expensive, Energy efficiency of processors, Code size efficiency, Run-time efficiency
  - Reconfigurable Hardware
- Communication
- D/A converters
- Sampling theorem
- Actuators