THE UNIVERSITY *of* EDINBURGH
informatics

Embedded Systems
Lecture 2: Interfacing with the Environment

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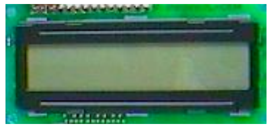
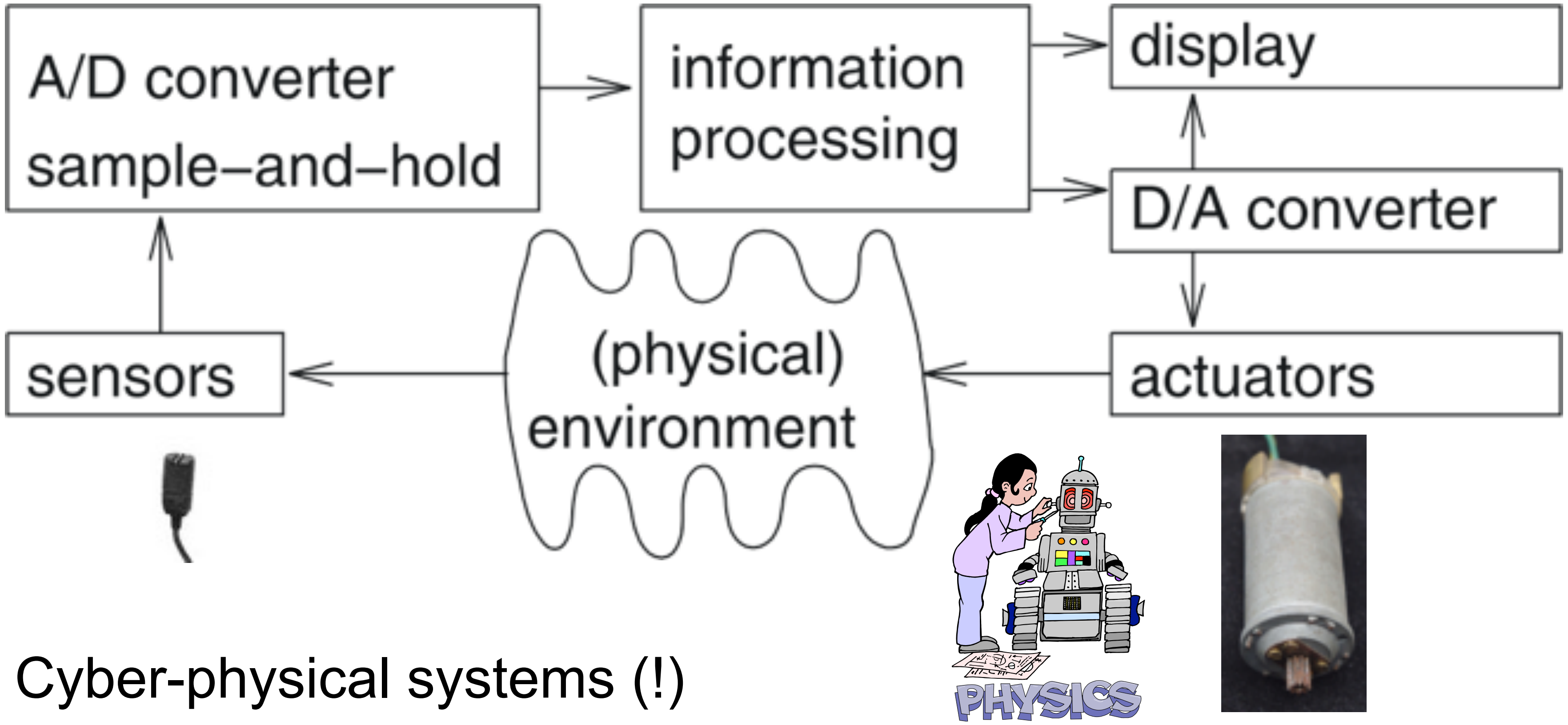
Overview

- Interfacing with the Physical Environment
- Signals, Discretisation
- Input (Sensors)
- Output (Actuators)
- Analog/Digital Conversion, Digital/Analog Conversion

Interfacing with the Physical Environment

CPS & ES hardware is frequently used in a loop
(***“hardware in a loop“***):





Cyber-physical systems (!)

Sensors

- Capture physical/chemical quantity and convert to electrical quantity
- Sensors for many physical and chemical quantities, including
  - weight, velocity, acceleration, electrical current, voltage, temperatures, and chemical compounds.
- Many physical effects used for constructing sensors.
  - law of induction (generation of voltages in a magnetic field),
  - light-electric effects, ...
- Huge amount of sensors designed in recent years.

Sensors - Examples

- Acceleration Sensor
- Temperature Sensor, Pressure Sensor
- Image Sensor
- Rain sensors for wiper control, Proximity sensors, Engine control sensors (“Sensors multiply like rabbits“ [ITT automotive])
- Hall effect sensors, ...
- Deliver electrical representation of original physical/chemical quantity

Signals

Sensors generate *signals*

Definition: a **signal** s is a mapping
from the time domain D_T to a value domain D_V:

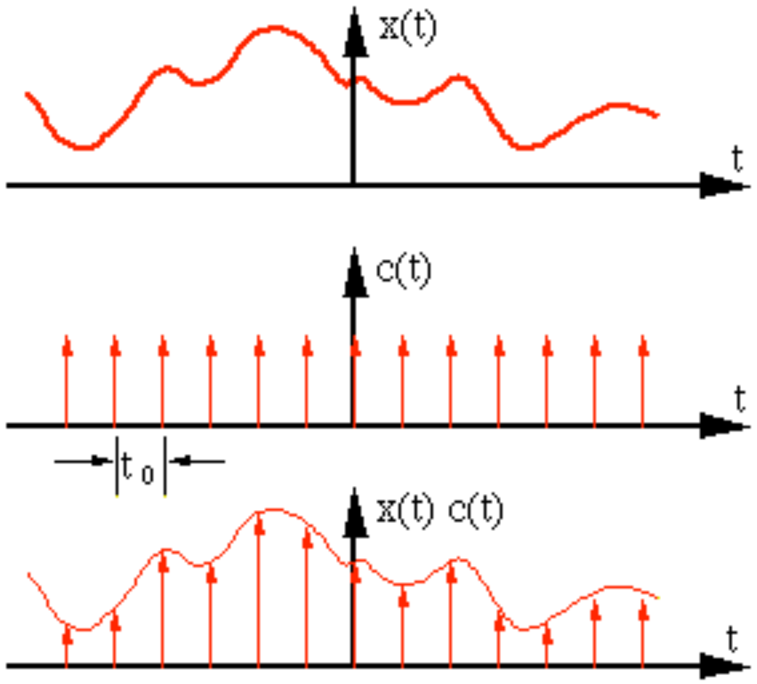
$$s : D_T \rightarrow D_V$$

D_T: continuous or discrete time domain

D_V : continuous or discrete value domain.

Discretisation of Time

Digital computers require discrete sequences of physical values



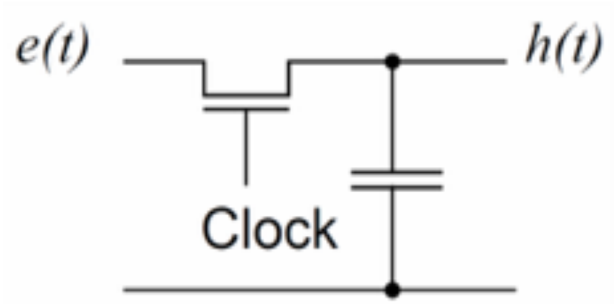
$$s : \underset{\uparrow}{D_T} \to D_V$$

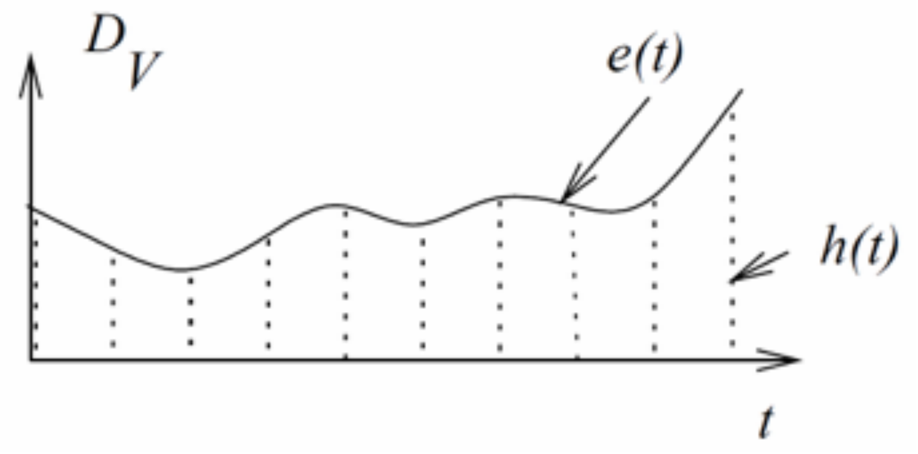
Discrete time domain

☞ Sample-and-hold circuits

Sample and Hold

Clocked transistor + capacitor;
Capacitor stores sequence values

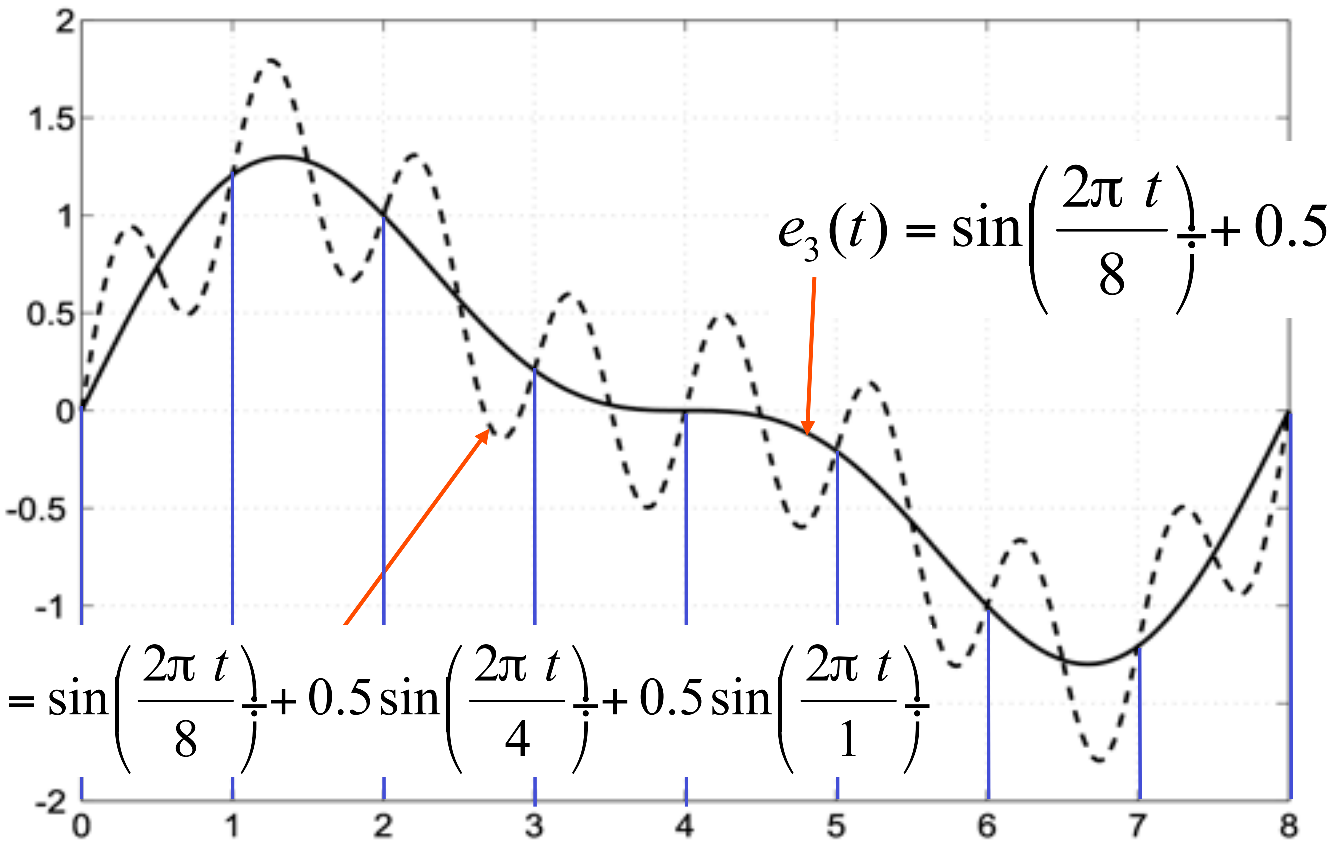




$e(t)$ is a mapping $\mathbb{R} \to \mathbb{R}$

$h(t)$ is a **sequence** of values or a mapping $\mathbb{Z} \to \mathbb{R}$

Aliasing



$$e_3(t) = \sin\left(\frac{2\pi\, t}{8}\right) + 0.5\sin\left(\frac{2\pi\, t}{4}\right)$$

$$e_4(t) = \sin\left(\frac{2\pi\, t}{8}\right) + 0.5\sin\left(\frac{2\pi\, t}{4}\right) + 0.5\sin\left(\frac{2\pi\, t}{1}\right)$$

Periods of p=8,4,1
Indistinguishable if sampled at integer times, p_s=1

Sampling Theorem

☞ Reconstruction impossible, if not sampling frequently enough

How frequently do we have to sample?

Nyquist criterion (sampling theory):

Aliasing can be avoided if we restrict the frequencies of the incoming signal to less than half of the sampling rate.

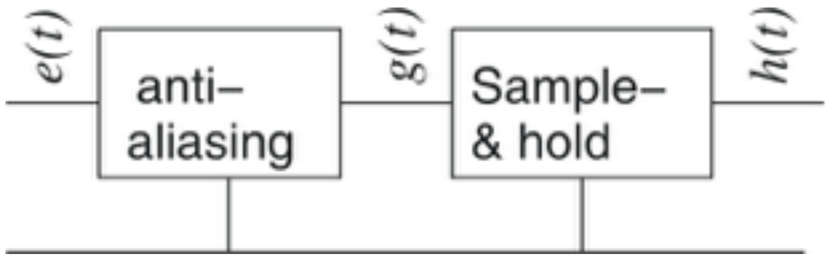
$p_s < ½\, p_N$ where p_N is the period of the "fastest" sine wave

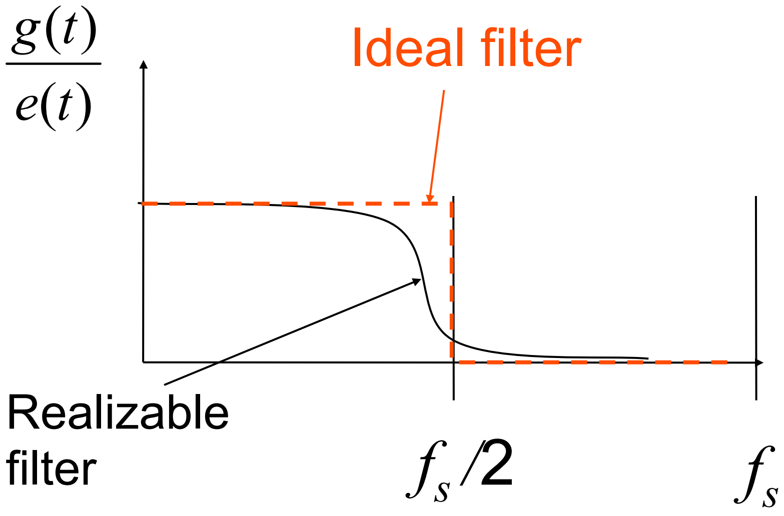
or $f_s > 2\, f_N$ where f_N is the frequency of the "fastest" sine wave

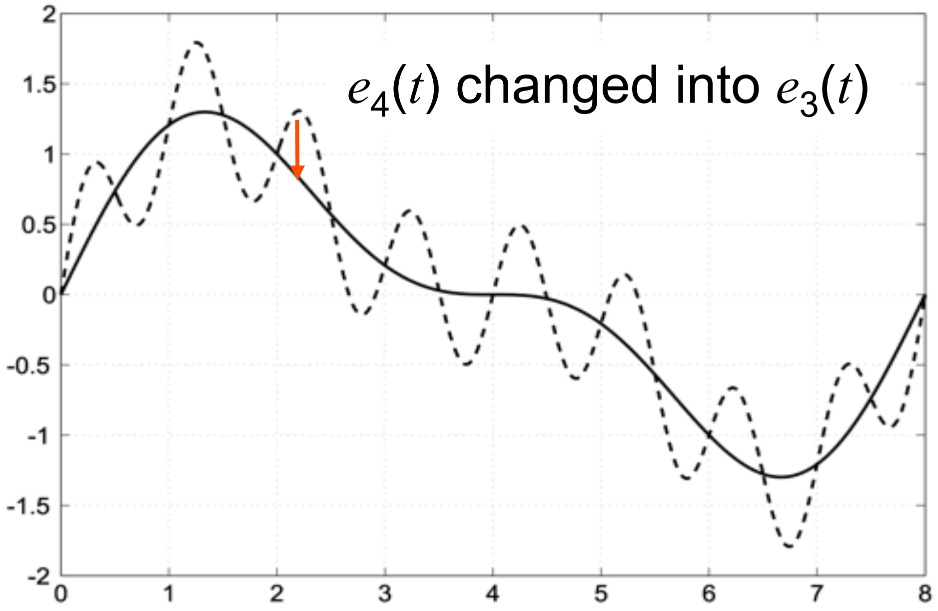
f_N is called the **Nyquist frequency**, f_s is the **sampling rate**.

Anti-Aliasing Filter

A filter is needed to remove high frequencies







Discretisation of Values

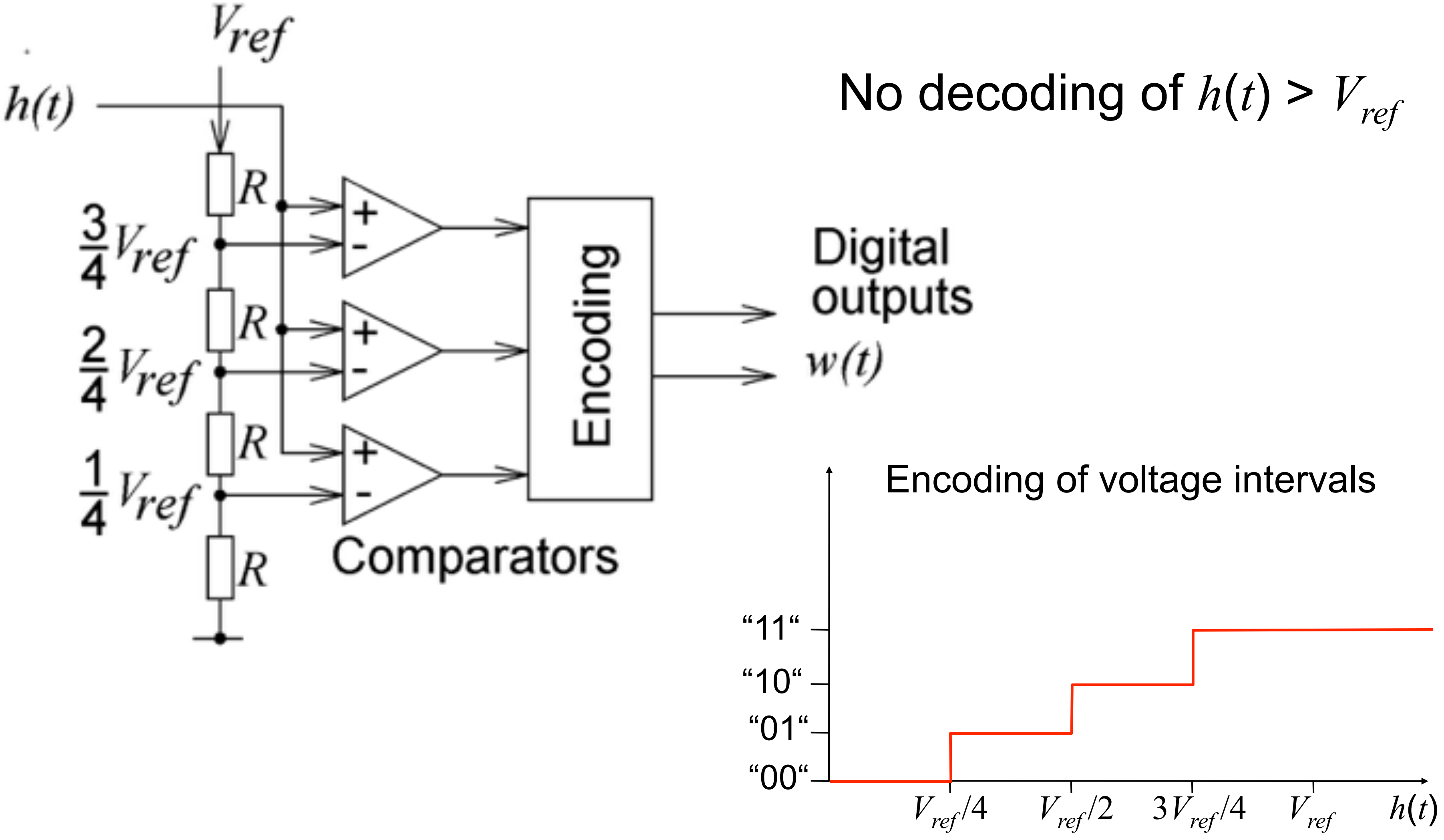
Digital computers require digital form of physical values

$$s\colon D_T \to \underset{\uparrow}{D_V}$$

Discrete value domain

☞A/D-conversion; many methods with different speeds.

Flash A/D Converter



No decoding of $h(t) > V_{ref}$

Encoding of voltage intervals

Resolution

- Resolution (in bits): number of bits produced
- Resolution Q (in volts): difference between two input voltages causing the output to be incremented by 1

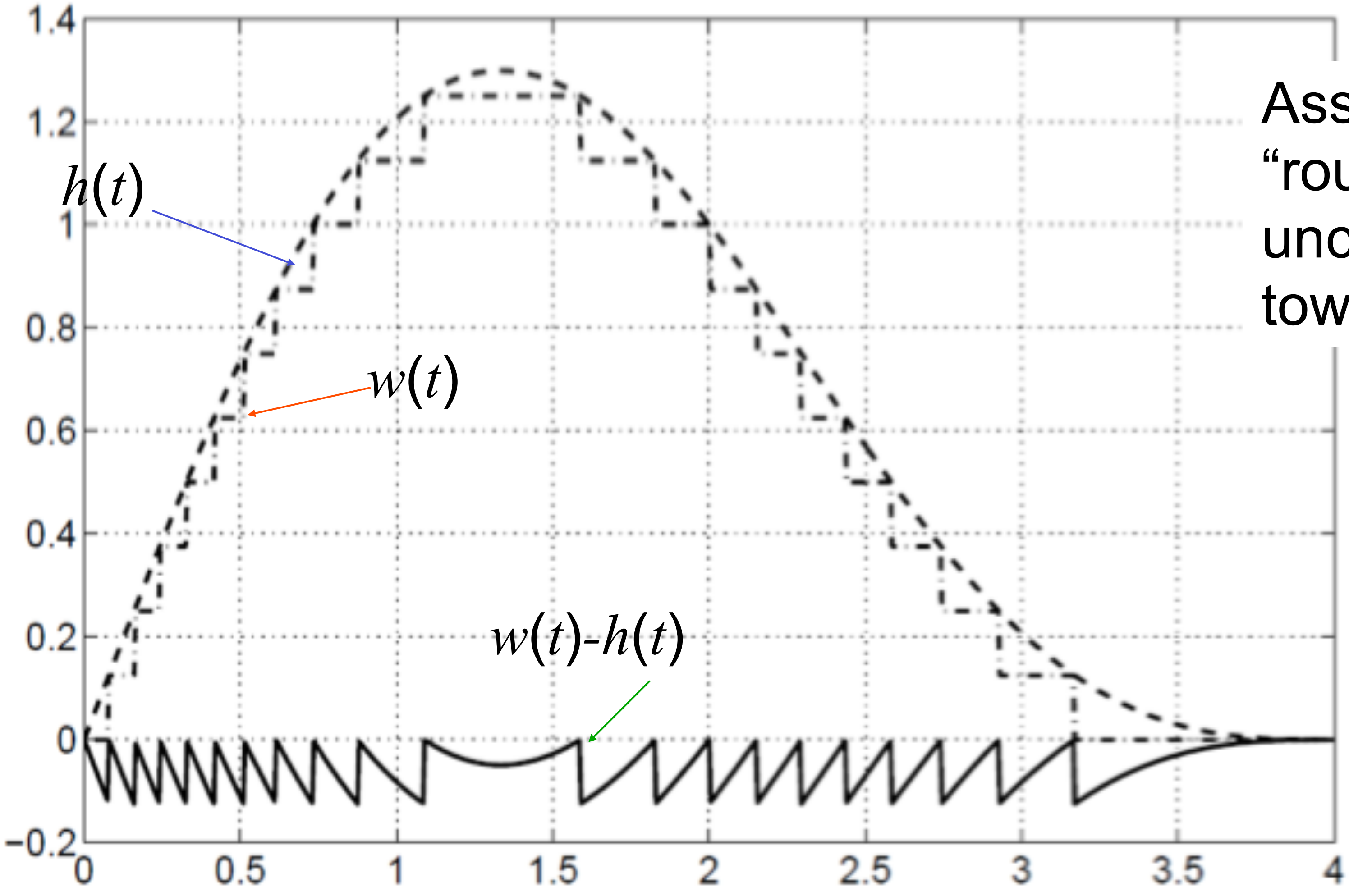
Q: resolution in volts per step

V_{FSR}: difference between largest and smallest voltage

n: number of voltage intervals

Example:
$Q = V_{ref}/4$ for the previous slide

Quantisation Noise



Assuming "rounding" (truncating) towards 0

Signal to Noise Ratio

$$\text{signal to noise ratio (SNR) [db]} = 20 \log_{10}\left(\frac{\text{effective signal voltage}}{\text{effective noise voltage}}\right)$$

e.g.: $20 \log_{10}(2)=6.02$ decibels

Signal to noise for ideal n-bit converter : $n * 6.02 + 1.76$ [dB]
e.g. 98.1 db for 16-bit converter, ~ 160 db for 24-bit converter

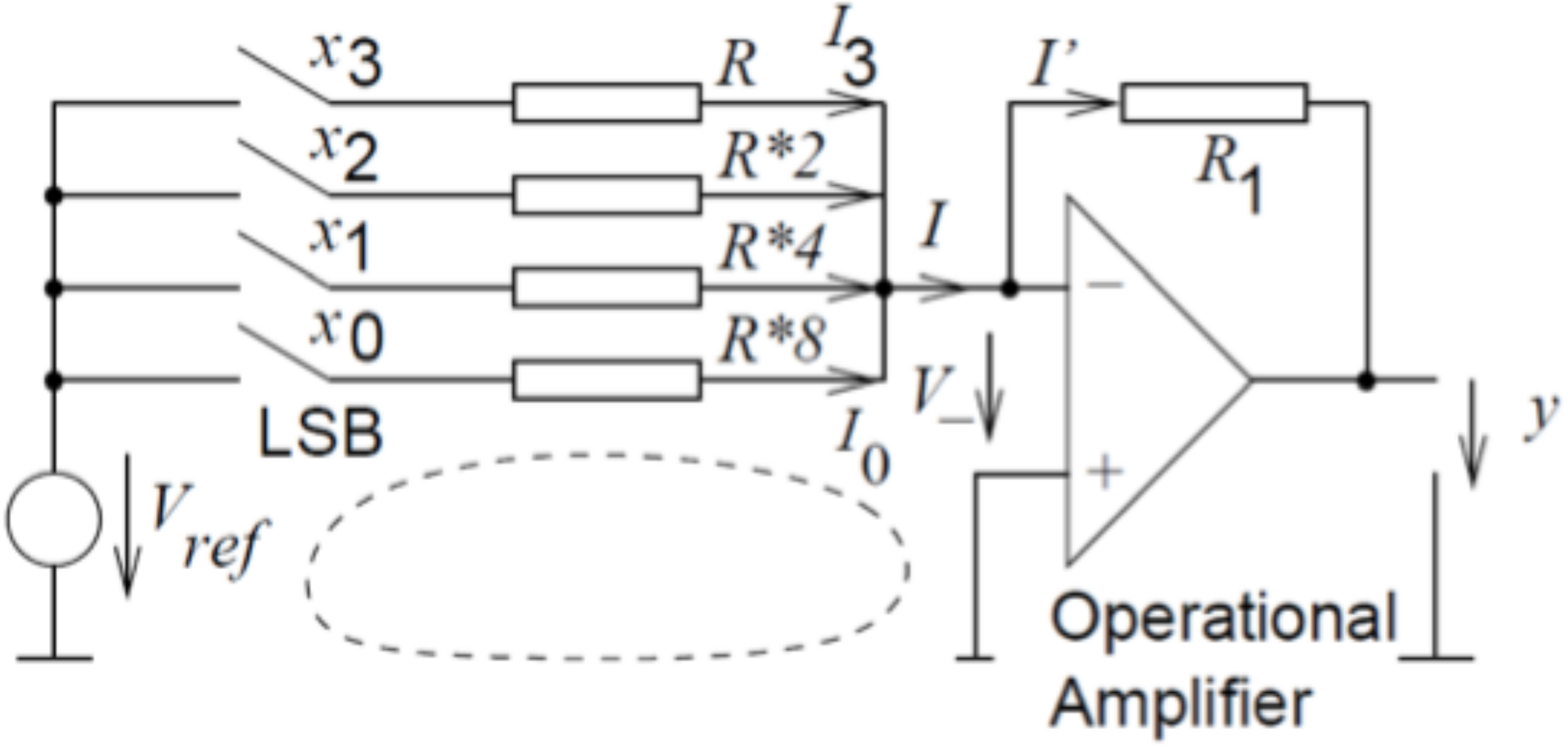
Additional noise for non-ideal converters

Actuators

- Huge variety of actuators and output devices.
- Indicator lights (LED), LCD screen, ...
- Relais, Optocouplers, ...
- Motor, motorised valves, heaters, ...
- Speakers, Buzzers, ...
- Analog output: Digital-Analog-Converters

Digital/Analog Conversion

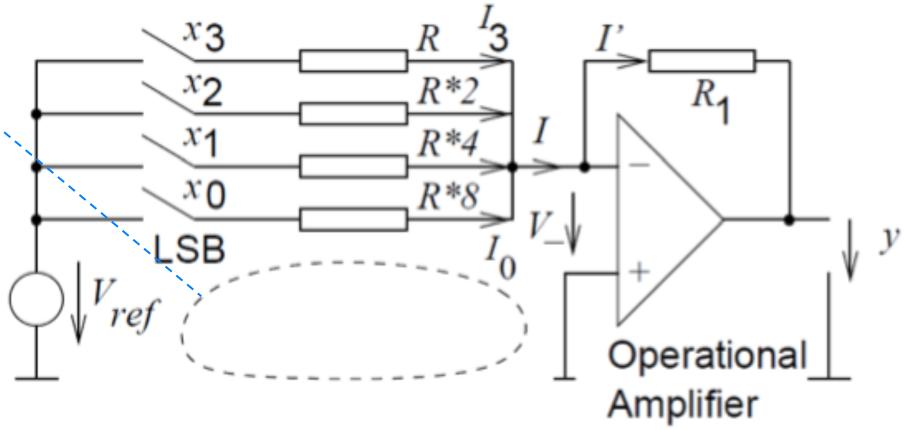
Various types, can be quite simple,
or more advanced.



Digital/Analog Conversion

Loop rule:

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



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

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

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

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

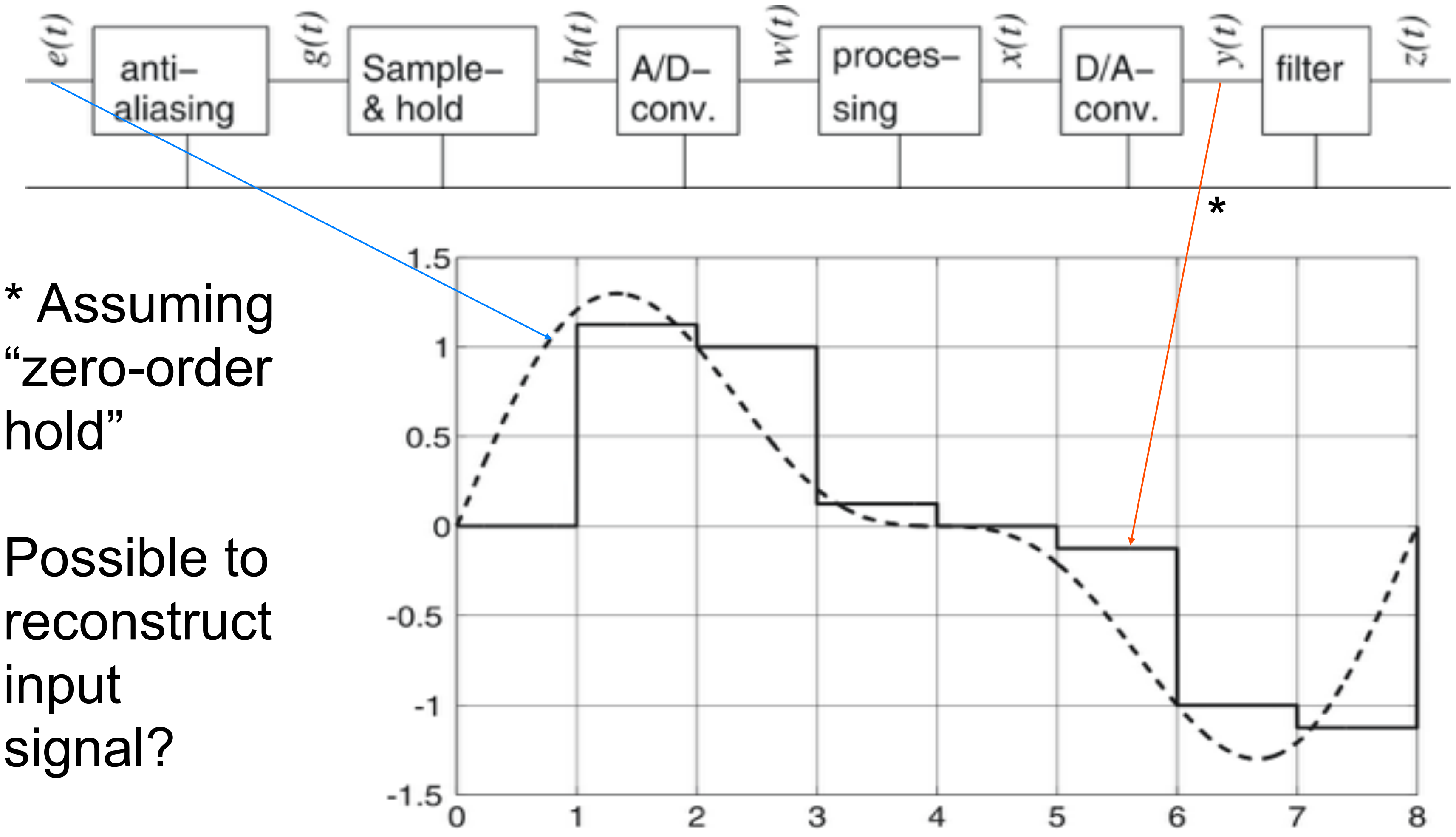
$I \sim nat(x)$, where $nat(x)$: natural number represented by x;

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 $\sim nat(x)$

Processing Chain



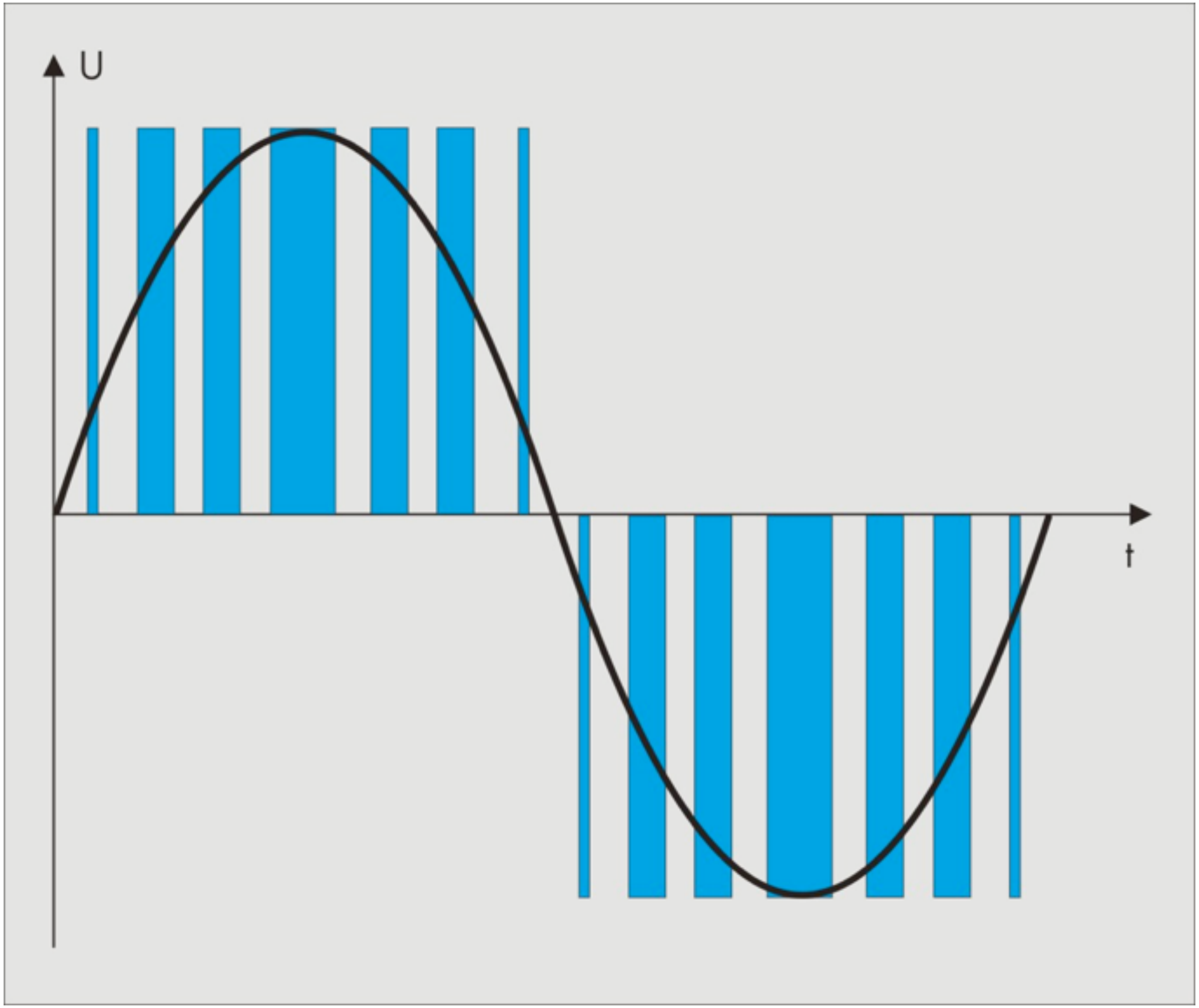
* Assuming “zero-order hold”

Possible to reconstruct input signal?

Pulse Width Modulation

- Commonly used technique for controlling power to inertial electrical devices
- Average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast pace
  - The longer the switch is on compared to the off periods, the higher the power supplied to the load is
- Made practical by modern electronic power switches
- Greater efficiency
  - Switching mode voltage regulation - lower losses.
    - Near lossless when off. $R_{DS,On}$ is typically low in MOSFET.
  - Linear voltage regulation - higher losses
    - “Waste” excess voltage in control element (transistor) as heat

Pulse Width Modulation



Summary

- Embedded System operates in physical environment: interfacing
- Discretisation: Time/Values
- Sensors: A/D Conversion
- Actuators: D/A Conversion, PWM

Preview

- Models of Computation