Measurement and data processing in material science

Měření a zpracování dat v materiálovém výzkumu

EVF 112

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Experimental data acquisition and processing I

Introduction

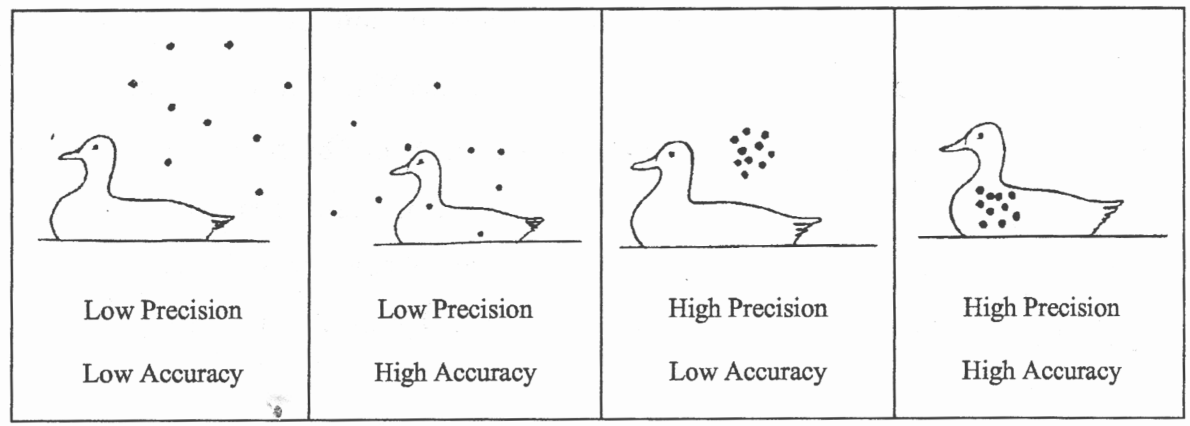
* Physical experiment and its automation
* Computer controlled experiment
* Physical quantities and their conversion
* Sensors and transducers

Measurements in physics

Precision and accuracy

Precision (přesnost)
= agreement among repetitive measurements (scatter), reproducibility

Accuracy (správnost)
= measure of statistical bias (systematic errors)



"It's better to be roughly right than precisely wrong"

– Allan Greenspan, U.S. Federal Reserve Chairman (retired)

Instrument precision limit: ½ the smallest division (analog) or one least significant digit (digital)

Random variations

- data scattered around a mean value (statistical deviations from a normalized value)
- caused by slight changes in pressure, room temperature, supply voltage, friction or pulling force over a distance, etc.

Human interpretation is also a source of random or systematic error (e.g. instrument scale reading)

Model of physical experiment

General relation between physical quantity (*measurand*) and measured value

Experimental data – usually of an indirect character
=> conversion needed

$$Y(t) = M \cdot X(t)$$

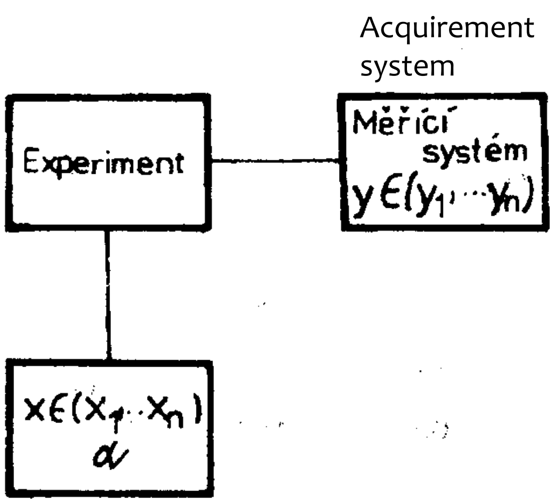
Y … experimentally obtained data

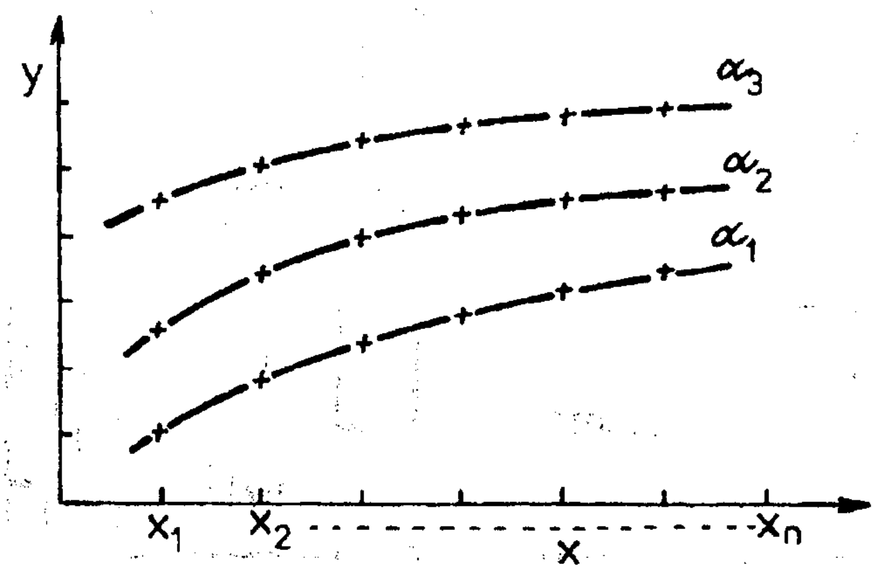
X … functions describing investigated object

M … operator (method determined) → calibration curve

Model of physical experiment

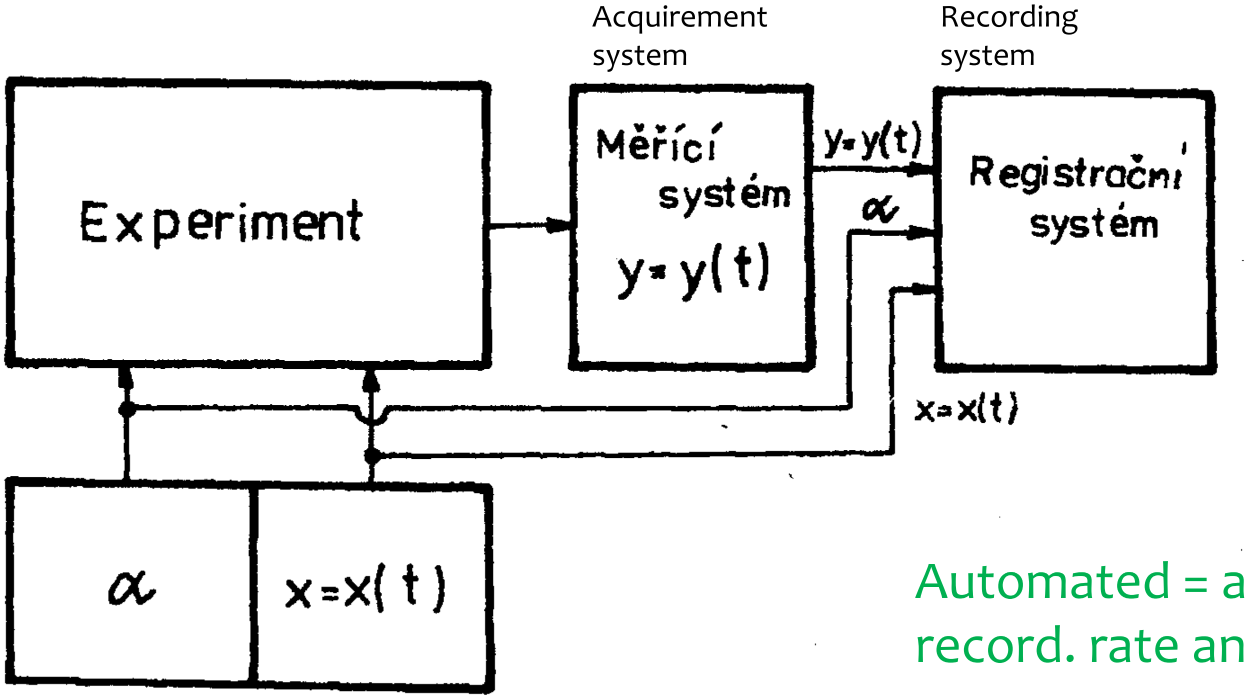
- Determination of dependence of ***y*** on ***x*** at given conditions (for a given parameter α) (e.g., dependence of current through sample on voltage at given temperature)
- Usually repeated measurements for discrete sets of x_i, α_j & determination of mean value and error estimate
- x, α regulated or implicitly time-dependent $x(t)$, $\alpha(t)$





Automated data acquirement

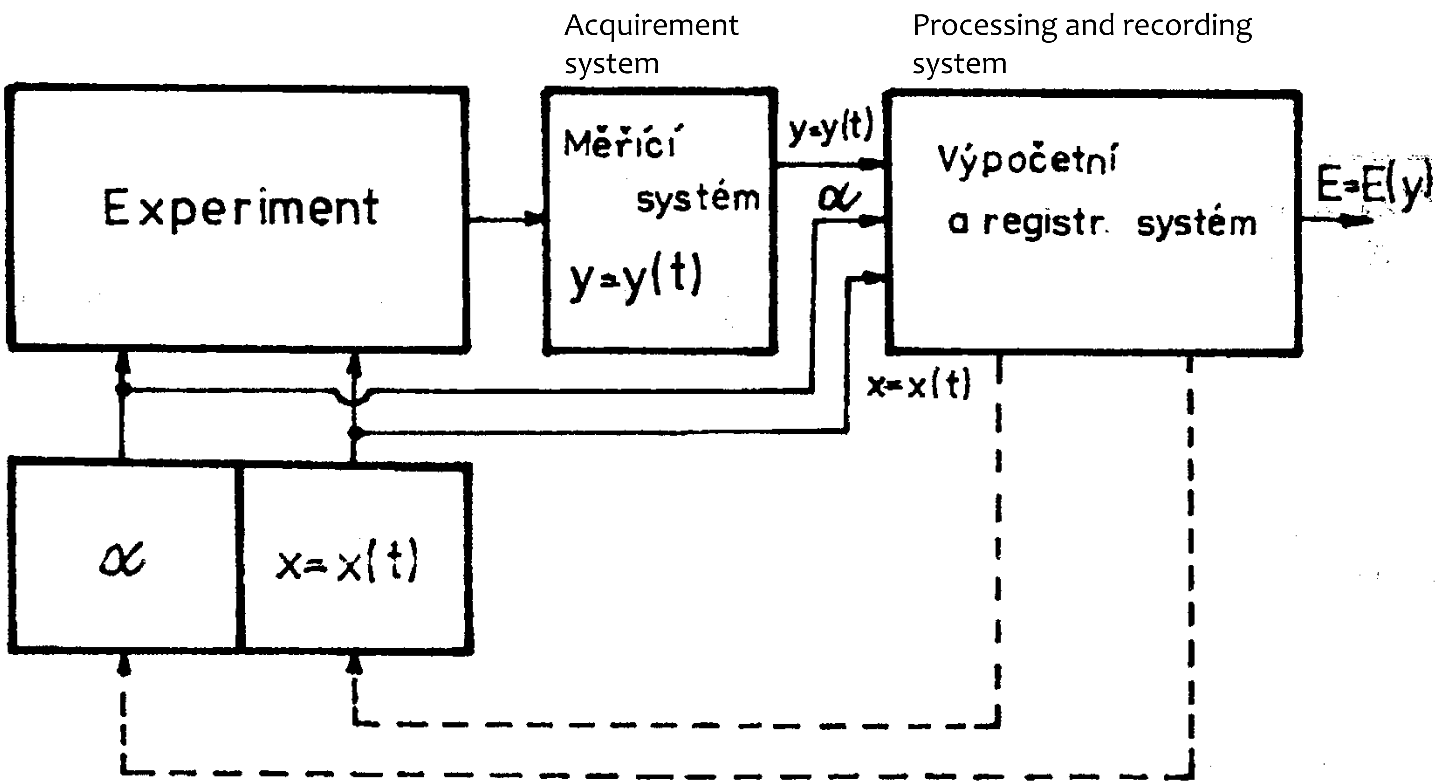
- Manually set ***x***, α resp. ***x(t)***, α***(t)***
- Automatic data recording α***(t)***, ***y(t)***
- Processing and evaluation – typically **after** the experiment



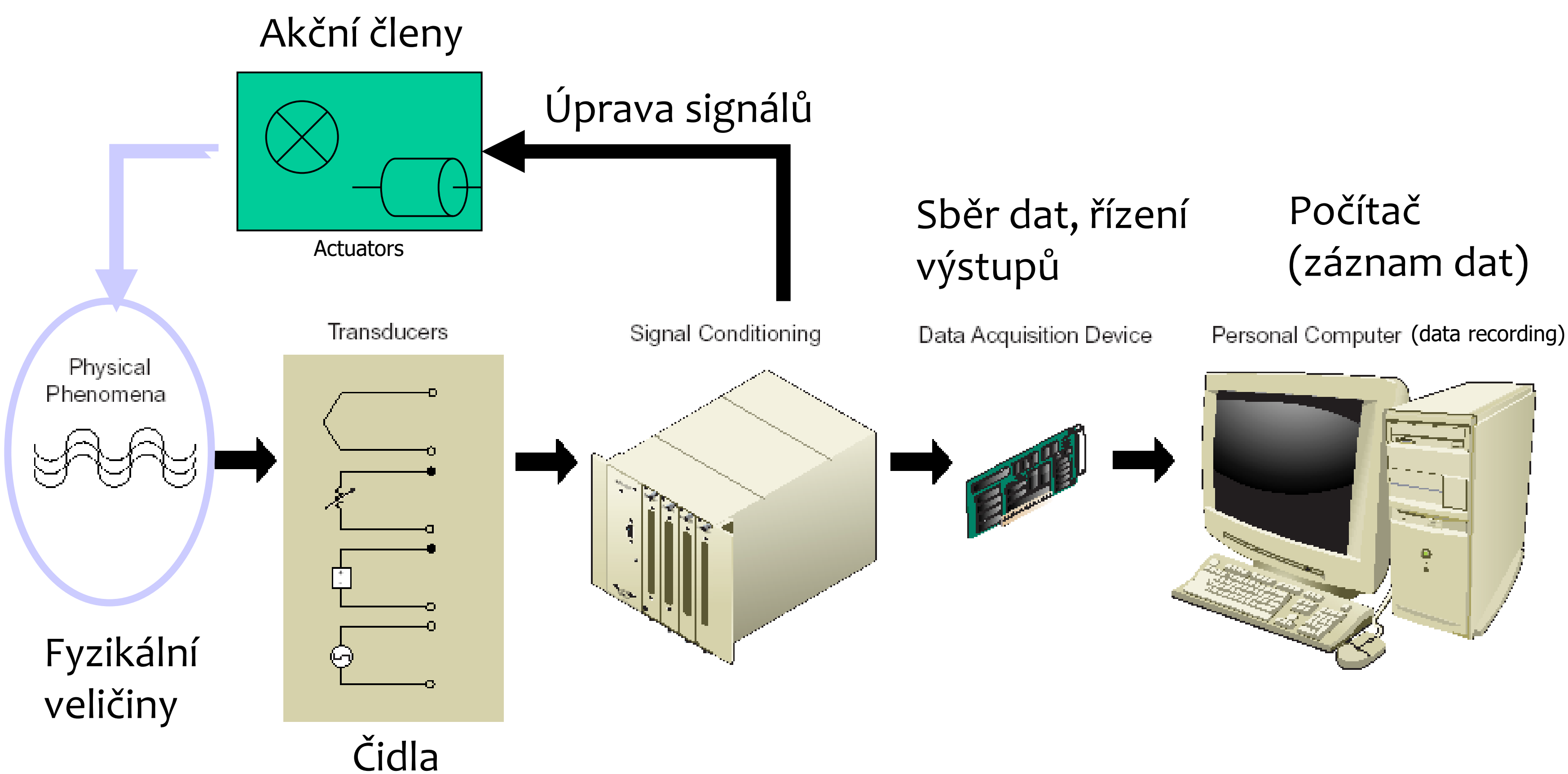
Automated = advantage of record. rate and accuracy

Computer controlled experiment

- Automatically set ***x, α*** resp. ***x(t), α(t)***
  - pre-programmed – automated measurement
  - aimed to stabilize or control ***y*** or ***α*** – regulation
- Automatic data recording ***x(t), α(t), y(t)***
- Processing and evaluation – typically **during** the experiment



Basic scheme of data acquirement and experiment control



Physical quantities

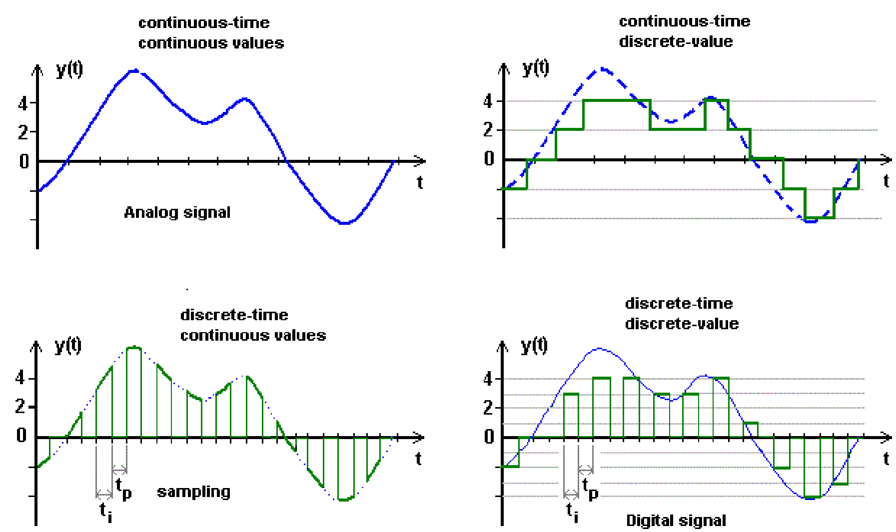
Basic classification

- **Electrical**
  - voltage
  - current
  - resistance, conductivity, inductance, capacitance
  - frequency, phase
  - period, duty cycle
  - impulses, events
  - ....

Expressed by time-dependent value of an electrical quantity (frequency, phase; period, duty cycle; impulses, events)

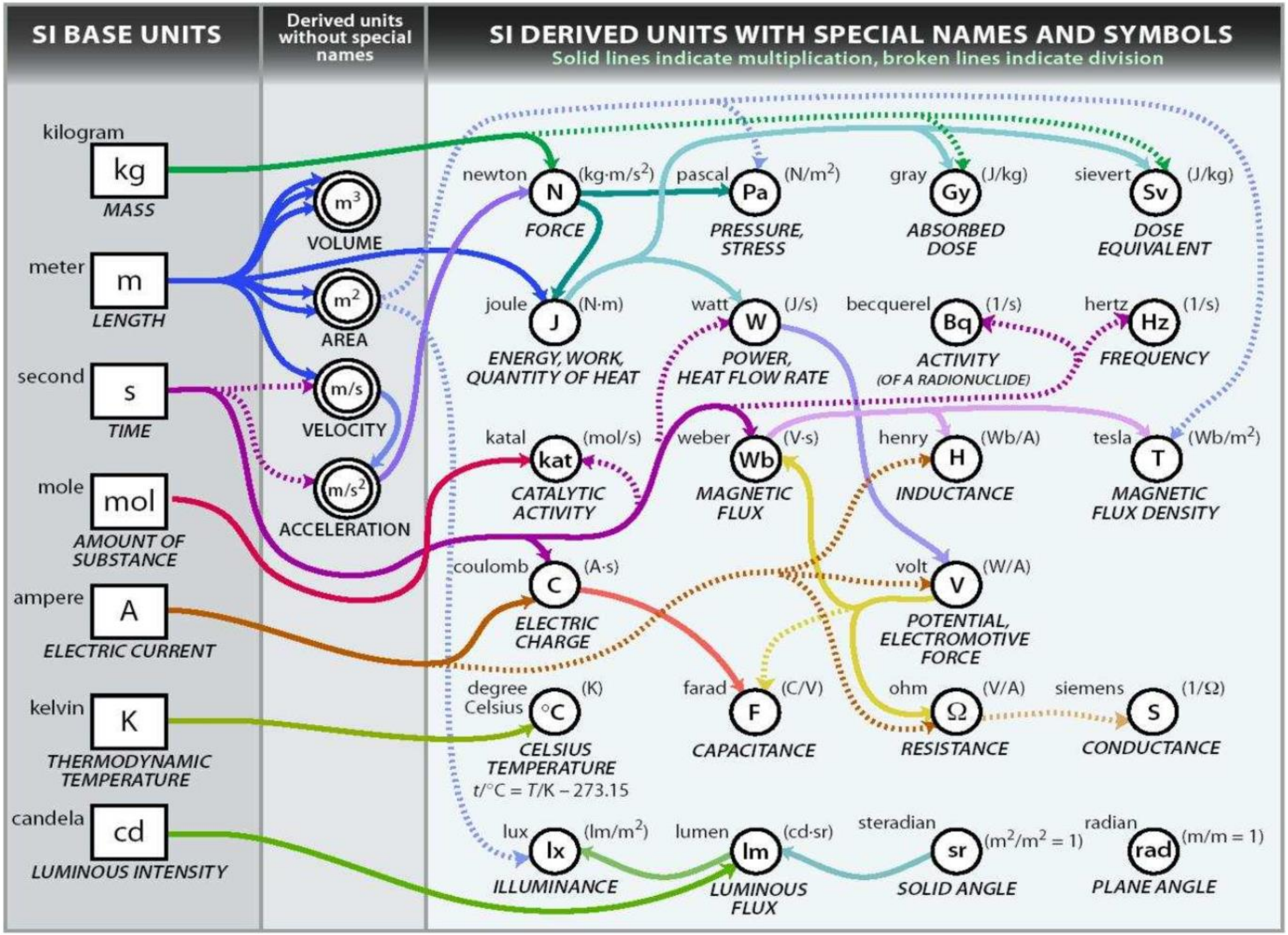
- **Non-electrical**
  - temperature
  - mass
  - position, velocity, acceleration
  - pressure, humidity
  - illumination
  - magnetic field
  - chemical composition
  - …

- Continuous or discrete (in value and/or time)



Physical quantities

Units



Conversion between electrical and non-electrical quantities

Transducer (in general)
= device that converts energy (or a signal in the form of energy) from one form to another

- **Actuators** (Action devices)

  information → action
  - heating element
  - light source
  - valve
  - motor
  - elmg. coil
  - pneumatic device
  - hydraulics
  - ….

- **Sensors** ("Transducers")

  signal → information
  - thermocouple, thermistor
  - photodiode
  - flow meter, pressure gauge
  - position and motion sensor, tensometer, accelerometer
  - Hall probe
  - humidity sensor
  - particle detector
  - ….

Classification of transducers

- **Active („self generating“)** – intrinsic source of electromotive force
  - electromagnetic, thermoelectric, photoelectric (photovoltaic), piezoelectric, Hall effect, electrochemical, …
- **Passive** – require an external power source to operate (*excitation signal*)
  - based on dependence of an electric property of sensor on measured quantity: magnetoresistivity, el. resistance on temperature (thermistor), inductance or capacity on core position, resistance on position or angle (potentiometer type), …
- **Feedback (passive) transducer** – feedback loop establishes equilibrium between input (measured) signal and output (exciting) electric signal
  - temperature controller, flow contr., automatic leak valve, STM tip controller, …

- **According to transduction principle:** resistive, capacitive, inductive, piezoelectric, photovoltaic, photoconductive, …

- **Analog** (continuous output) vs. **Digital** (digital output, pulses, …)

- **Inverse transducer** – converts electrical quantity to non-electrical
  - piezoelectric crystal, loudspeaker, ...

Characteristics of transducers

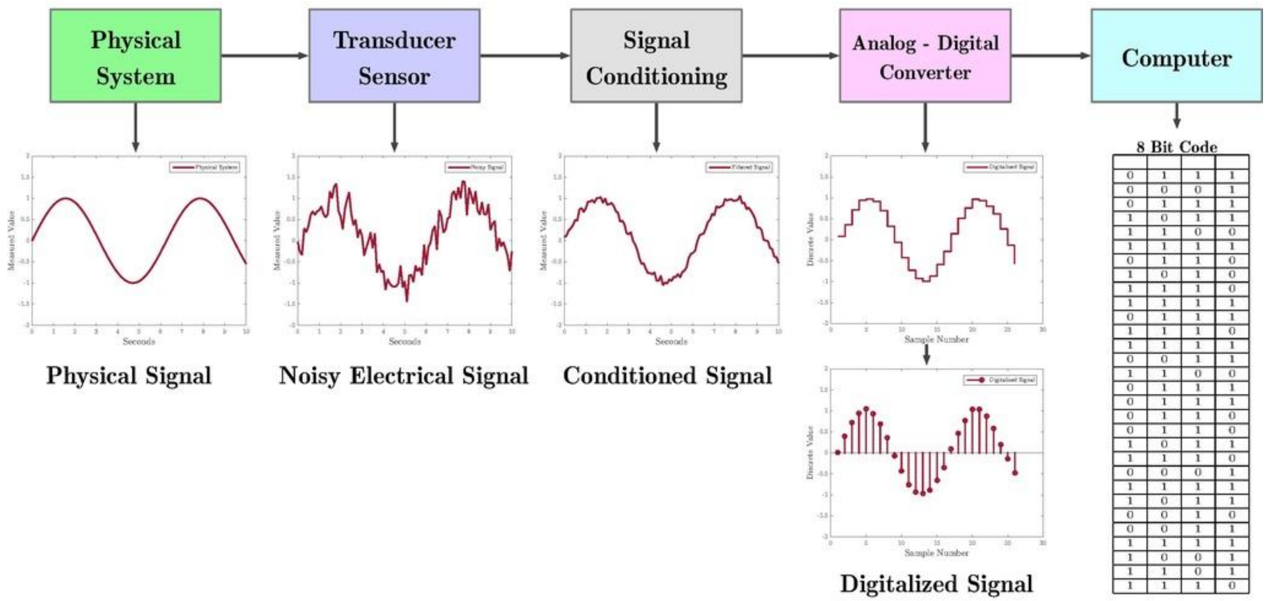
- **Accuracy** – accordance with true value of measured quantity
- **Ruggedness** – tolerance to overloads, overload protection
- **Repeatability** – equal response to equal input (under identical conditions)
- **Stability and reliability** – minimized measurement error, unaffected by environmental conditions
- **Linearity** – linear proportionality of output and input
- **Output strength** – reasonably high to be processed and measured
- **Sensitivity** – output change per unit change in measured parameter
- **Noise level** – noise-to-signal ratio minimized
- **Dynamic range** – operating range of measurement conditions
- **Speed of response** – rapidity of device response to parameter change
- **Size** – compactness (and form-factor) of the system; can be related to other properties (response, sensitivity, noise, ruggedness, stability, …)

Continuous vs. discrete world

Digital computer => discrete information

Concerns both sensors and actuators

Digital Data Acquisition System (**DAQ, DAS**)



Analog signals

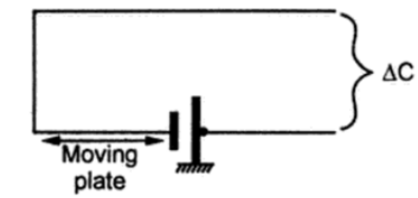
- Direct – conversion A/D and D/A
  - voltage (current)
- Indirect – conversion to time-based quantity or voltage (current)
  - typ. for other electrical quantities:
    - resistivity/conductance, capacitance, inductance, ...

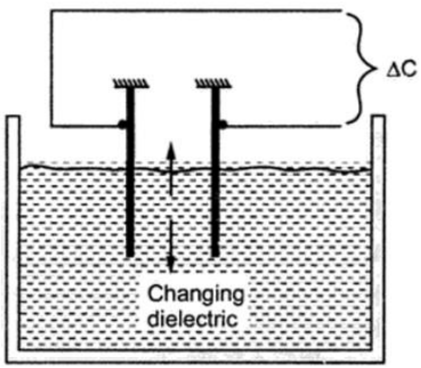
Digital signals

- Direct acquirement/control
  - digital inputs/outputs (logical signals)
  - time-based – frequency, period, pulse duration, duty cycle, phase

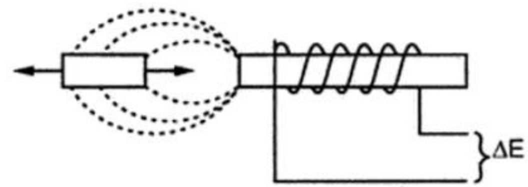
Transducer examples - overview

Capacitive transduction

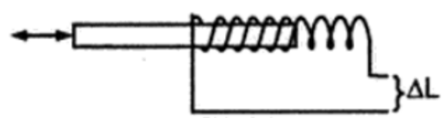




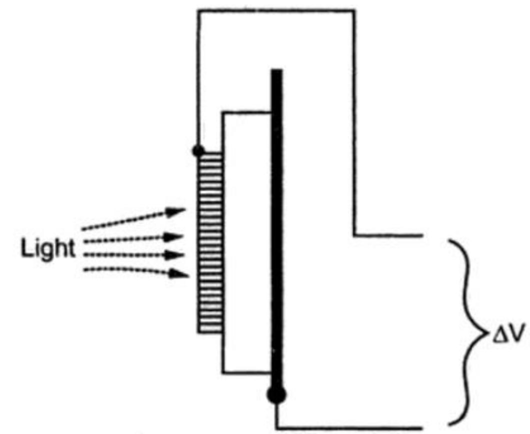
Electromagnetic transduction



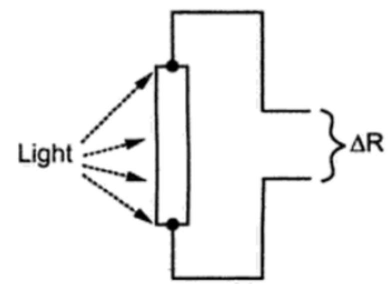
Inductive transduction



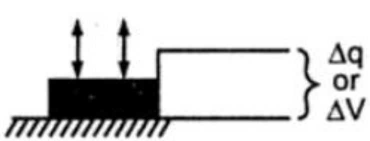
Photovoltaic transduction



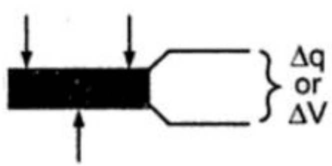
Photoconductive transduction



Piezoelectric transduction



(a) Compression



(b) Bending

Active transducer example

Thermocouple

- Direct energy conversion
  - thermoelectric potential

$$U_o = U_1(T_{ref}) + U_2(T) - U_3(T_{ref})$$

known value

Sensitivity 7 – 50 µV/°C

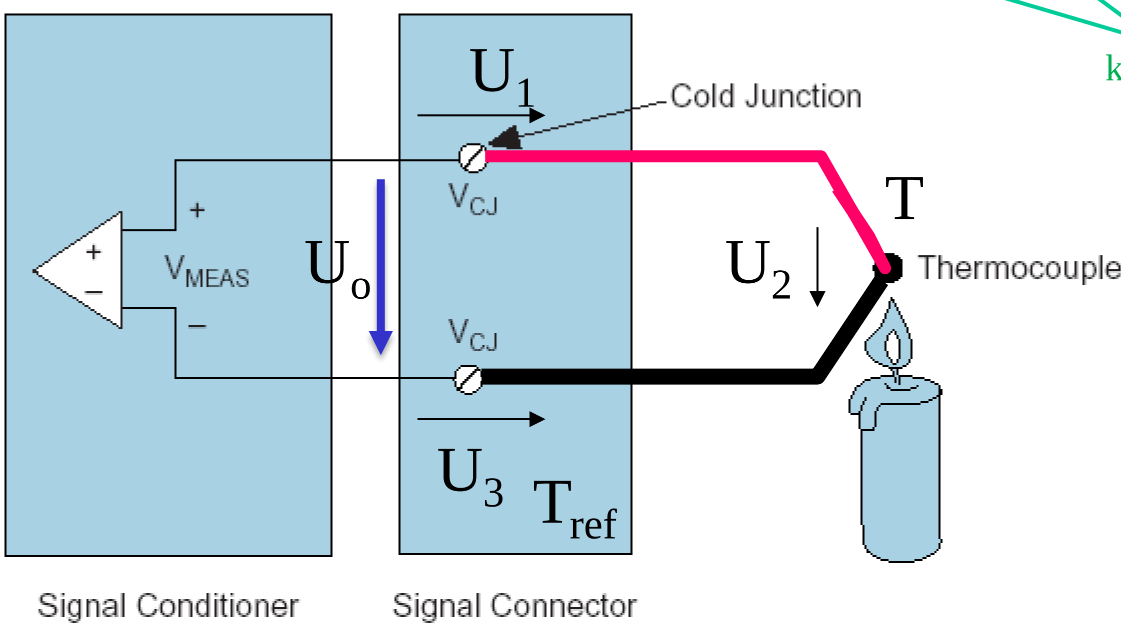
=> digital resolution

$$\frac{10\ \text{V}}{(2^{12}) \cdot 100} = 24.4\ \mu\text{V/bit}$$

voltmeter range

amplification or
1st stage amplifier

bit resolution



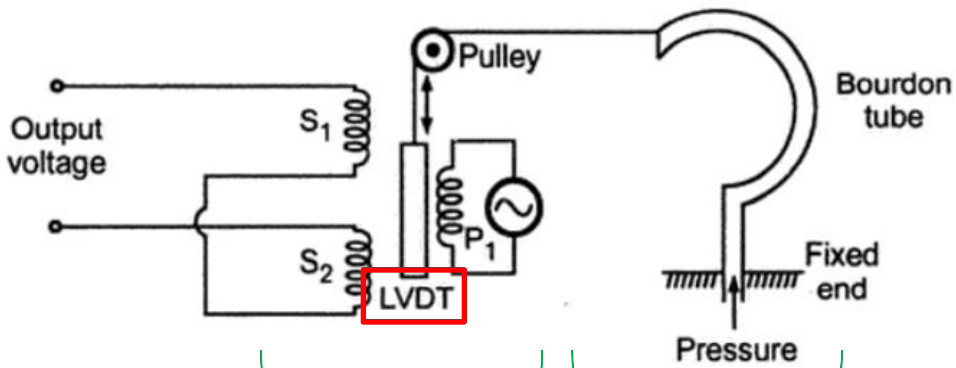
Signal conditioning:

- offset compensation
- amplification
- linearization
- averaging

Passive transducer example

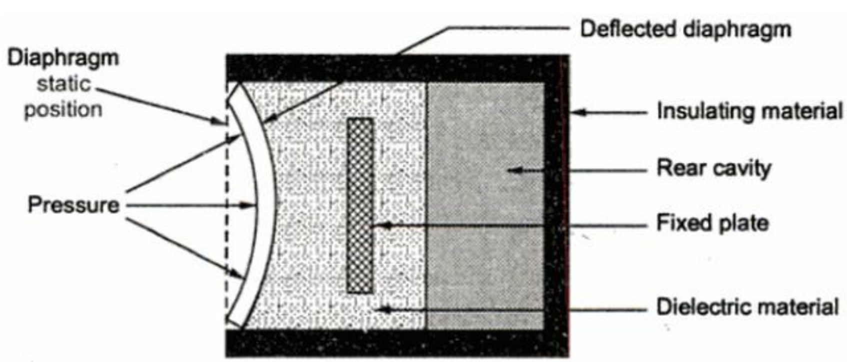
Pressure gauge

Bourdon tube gauge



secondary transducer **primary** transducer

Baratron (capacitive pressure transducer)

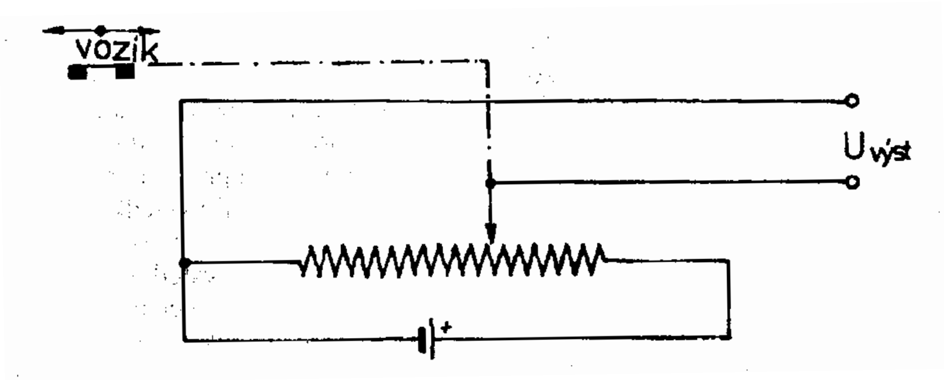


Passive transducer examples

Position (angle) transducer

potentiometer – linear or rotational

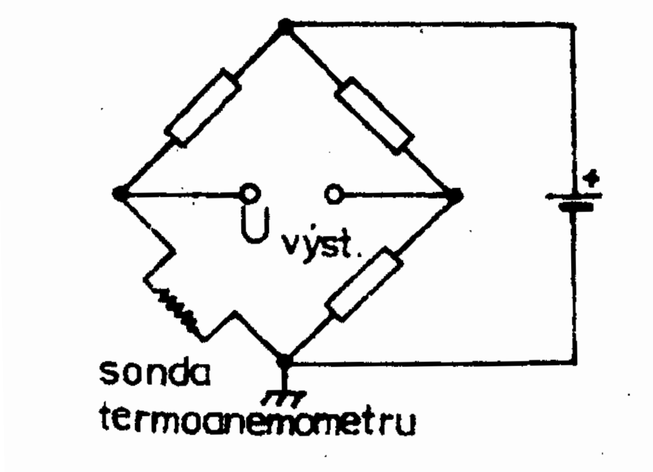
`wiper position → resistance → voltage`



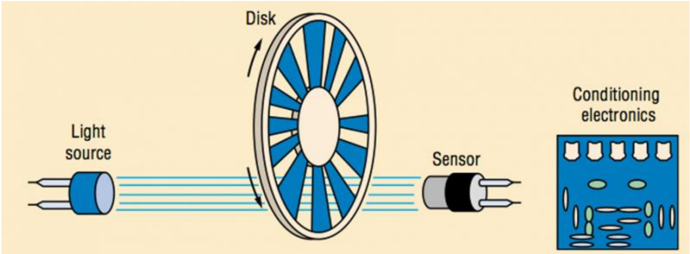
Wire thermo-anemometer

`flow velocity → heat loss on probe → probe temperature → resistivity → output voltage`

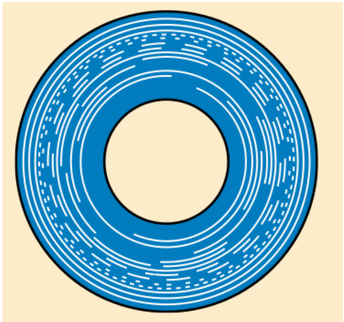
Wheatstone bridge



Digital version: incremental optical encoder



or… absolute-encoder disc pattern

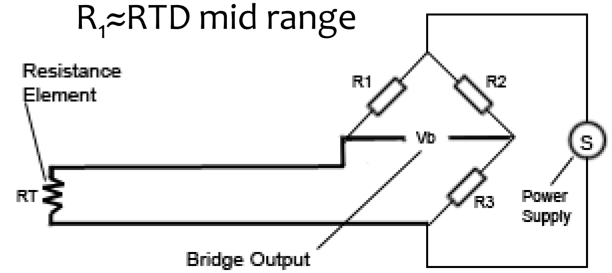


Passive transducer examples

Resistance thermometer (RTD)

- small resistance (typ. 100 Ω)
- small sensitivity (~0.4 Ω/°C)

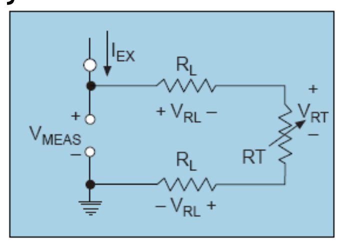
Typical setup:
$R_2=R_3$
$R_1 \approx$RTD mid range



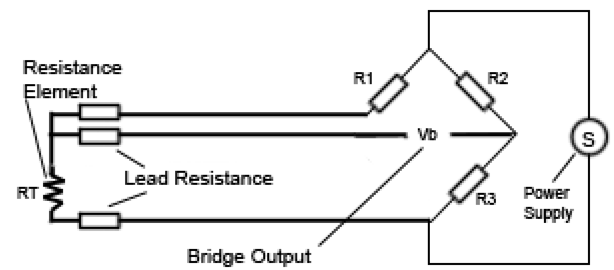
2-wire configuration

– simplest but most inaccurate – mainly due to voltage drop on measuring leads

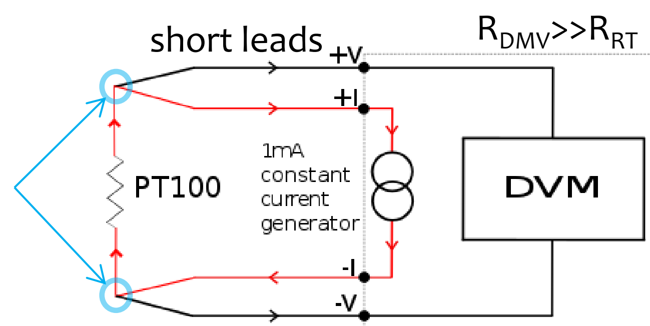
– direct measurement or via bridge



3-wire configuration
– suitable for bridges (Wheatstone)
– lead resistances cancelled out if the same in each arm



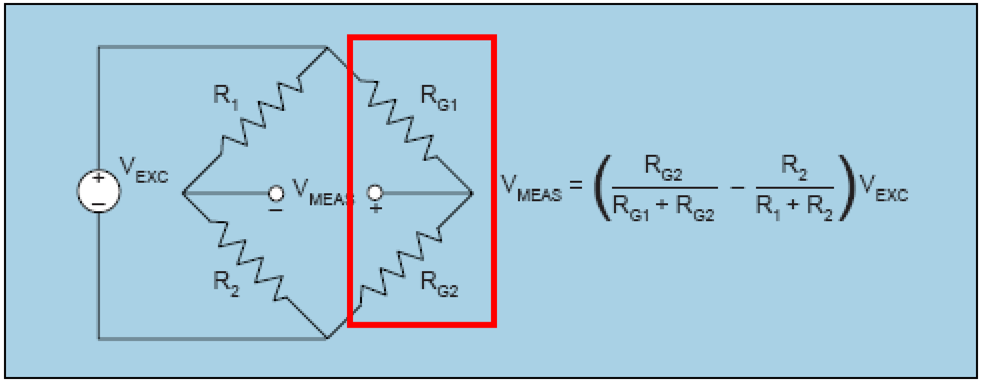
4-wire configuration
– better – lead resistances eliminated
– possible thermoelectric potentials can be cancelled out by averaging with measurement at reverted current



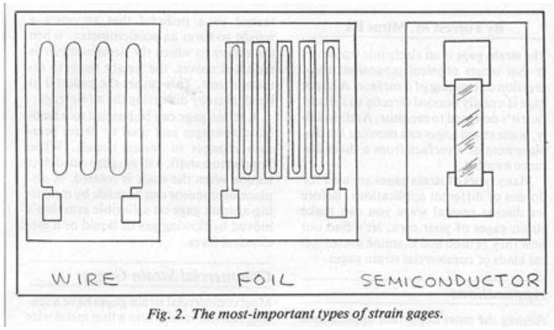
Bridge configurations

RTDs, tensometers, …

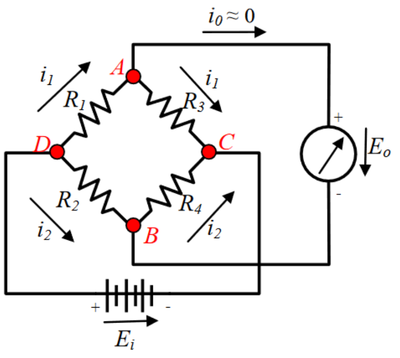
- 3-wire configuration with Wheatstone bridge
  – adjoining arms R_{G1}, R_{G2} compensate resistances of leads

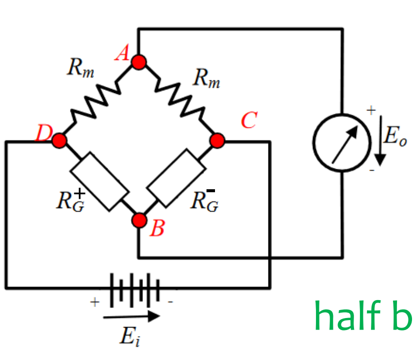


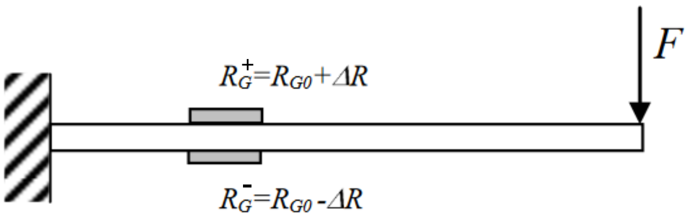
- **Tensometer** (strain sensor)
  - resistivity dependent on mechanic strain/stress
  - bridge connection – complete or half bridge (→ higher sensitivity)
  - can also be used as converter of other force sources – acceleration, pressure, vibrations, …



types of strain sensors



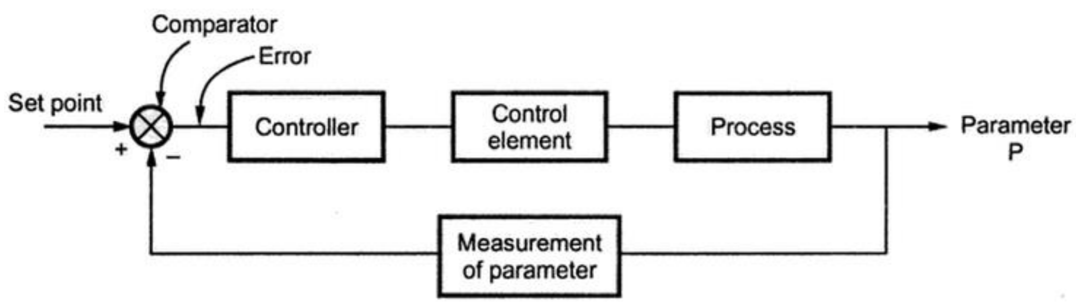




half bridge configuration

Feedback transducer example

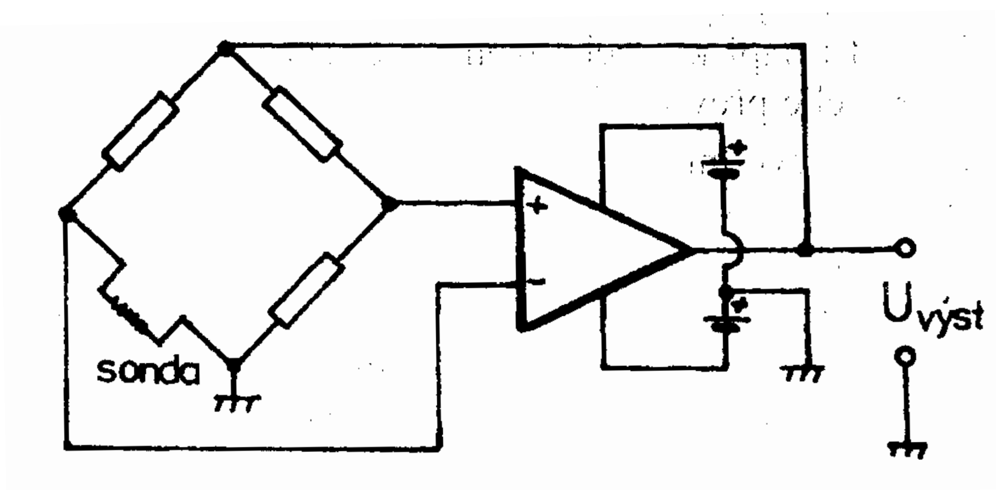
Wire thermo-anemometer



general arrangement of the process control loop

Feedback maintains the bridge balanced → stabilization of probe resistivity (hence temperature)

`(output voltage)² ~ heat loss on probe ~ flow velocity`



⇒

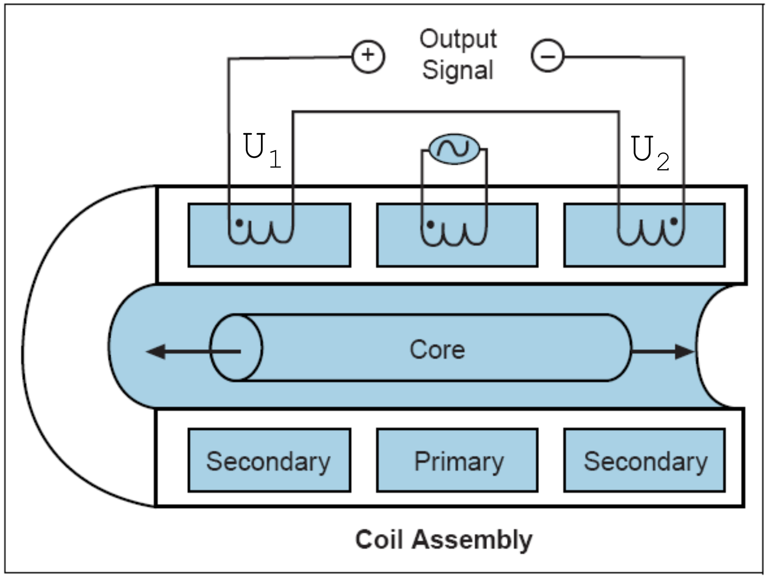
quantity measured **indirectly** via control variable

Other examples

LVDT

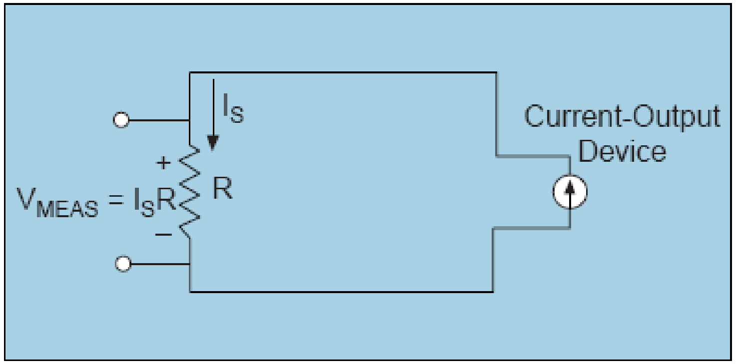
(Linear Variable Differential Transformer)

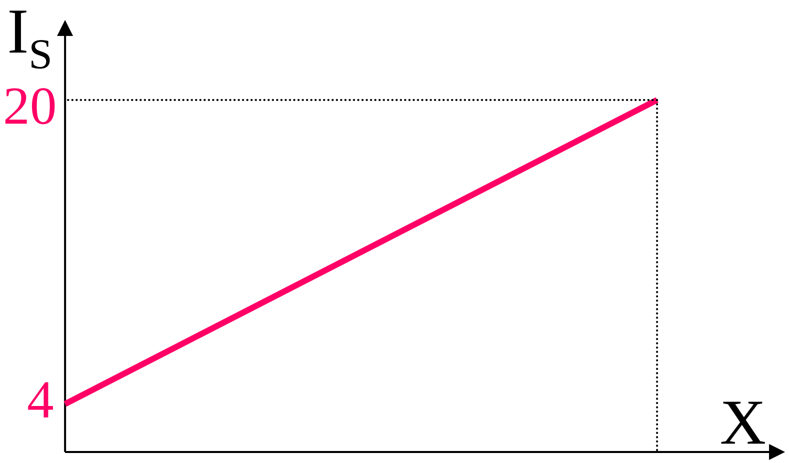
- measurement of linear displacement – different induction in secondary windings
- null position: $U_1 - U_2 = 0$
- good linearity, high sensitivity, wide range
- no amplifier necessary
- low hysteresis



Current loop sensor

- Sensor with internal converter to current loop 0-20 or 4-20 mA
- often electrically insulated





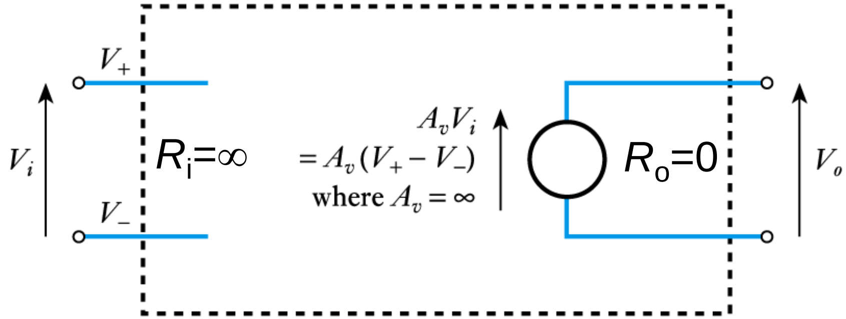
Srovnání vybraných čidel

Čidlo	Elektrické vlastnosti	Požadavky na úpravu signálu
termočlánek	Malé výstupní napětí, nízká citlivost, nelineární výstup	Referenční teplotní čidlo pro kompenzaci studeného konce, velké zesílení, linearizace
odporový teploměr	Malý odpor (typ. 100 Ω), nízká citlivost, nelineární výstup	Proudové buzení, 3-, 4-drátové zapojení, linearizace
integrované teplotní čidlo	Vysokoúrovňový výstup (~V), linearita	Zdroj napájení, malé zesílení
tenzometr	Malý odpor, nízká citlivost, nelineární výstup	Napěťové n. proudové buzení, vysoké zesílení, můstkové zapojení, linearizace, kalibrace bočníků
čidlo s proudovým výstupem	Proudová smyčka (4 – 20 mA typ.)	Přesný rezistor
termistor	Odporové čidlo, vysoký odpor a citlivost, velmi nelineární	Napěťové n. prodové buzení s referenčním rezistorem, linearizace
aktivní akcelerometr	Vysokoúrovňový výstup (~V), linearita	Zdroj napájení, malé zesílení
kapacitní manometr	Kapacita závislá na tlaku (malé hodnoty)	Buzení střídavým proudem, můstkové zapojení nebo oscilátor
LVDT	Střídavé napětí	Buzení střídavým proudem, demodulace, linearizace

Operational amplifiers

Basics

Equivalent circuit of ideal op. amp.



+ unlimited bandwidth

Differential Amplifier

⇒ Amplifies difference between inputs (comparator)

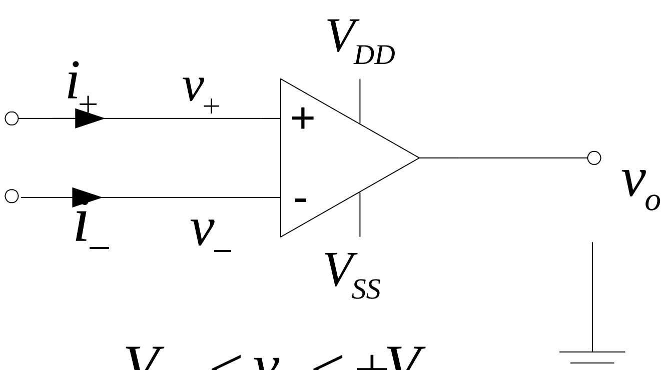
Typical real op. amp.:

$A_V \sim 10^5\text{-}10^6$

$R_i \sim$ MΩ (FET: $\sim 10^{12}$Ω)

$R_o \sim 10$Ω

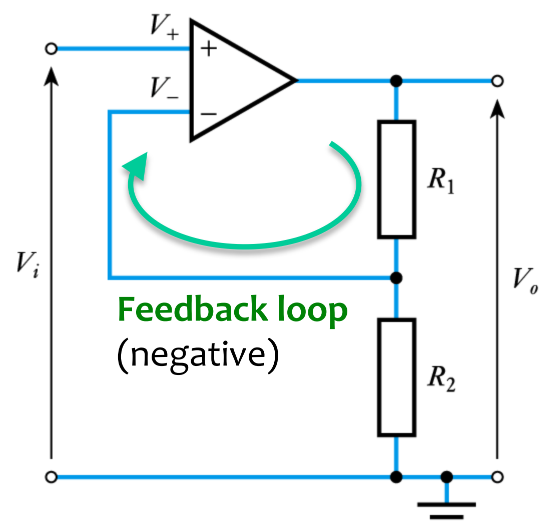
$I_{o(max)} \sim$ 10-100 mA



$$V_{SS} < v_0 < +V_{DD}$$

neinvertující zesilovač

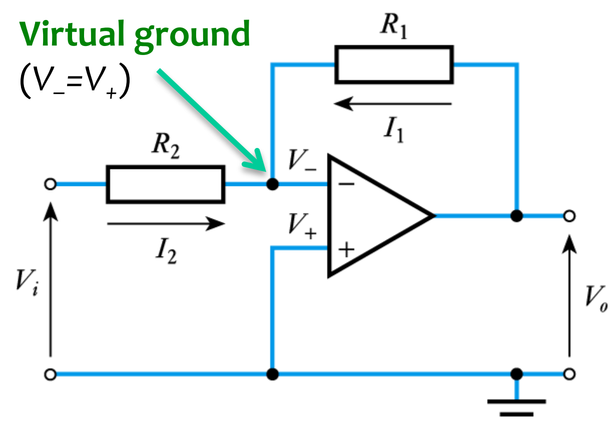
Non-inverting amplifier



$$G = \frac{V_o}{V_i} = \frac{R_1 + R_2}{R_2}$$

invertující zesilovač

Inverting amplifier



"virtual ground circuit"

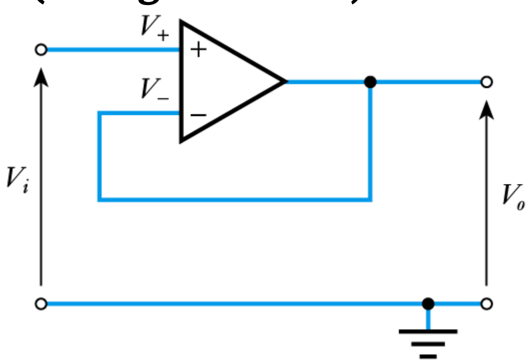
$$G = \frac{V_o}{V_i} = -\frac{R_1}{R_2}$$

Operational amplifiers

Examples of special OA circuits

sledovač napětí

Unity-gain buffer amplifier (voltage follower)

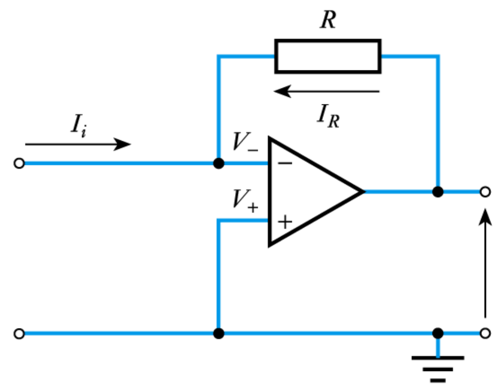


Special case of the non-inverting OA

R_1=0, R_2=∞
G=1

konvertor proudu na napětí

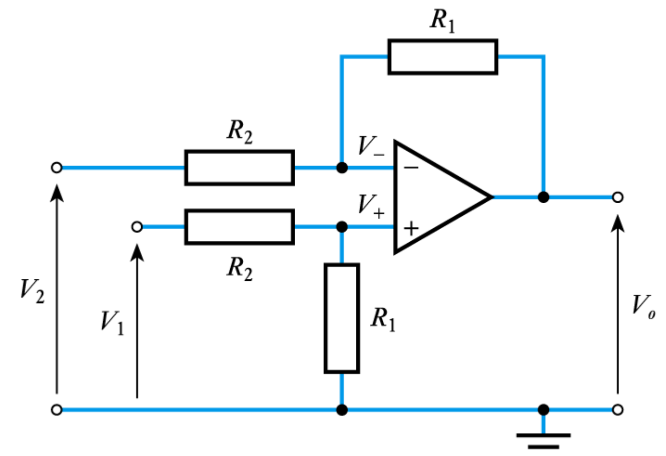
Current to voltage converter



$$V_o = -I_i R$$

rozdílový zesilovač

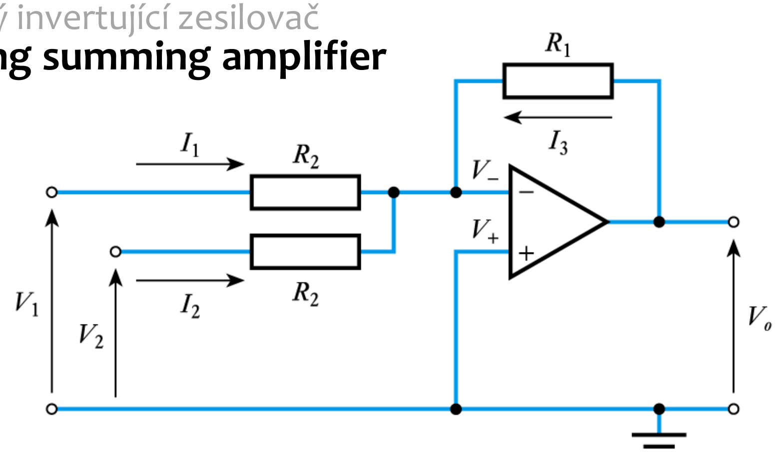
Differential amplifier (or subtractor)



$$V_o = (V_1 - V_2)\frac{R_1}{R_2}$$

součtový invertující zesilovač

Inverting summing amplifier



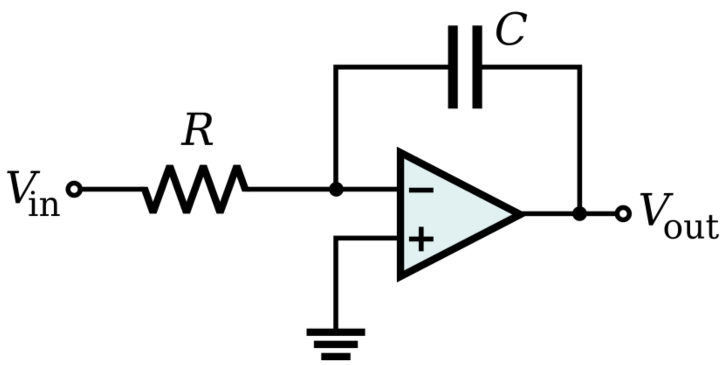
$$V_o = -(V_1 + V_2)\frac{R_1}{R_2}$$

Operational amplifiers

Examples of special OA circuits

integrační zesilovač

Integrating op. amplifier

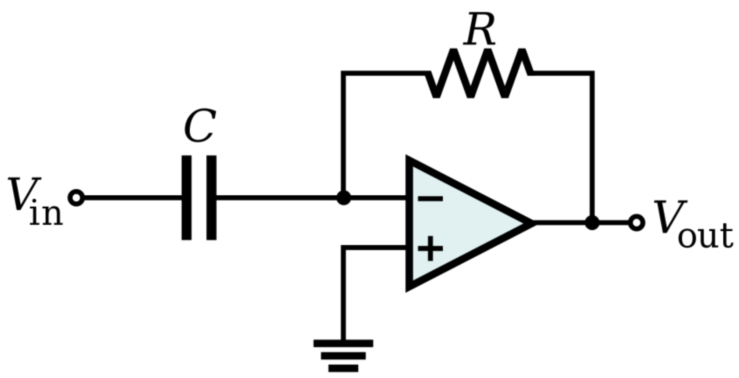


$$V_{out} = -\frac{1}{RC}\int_0^t V_{in}dt + V_{init}$$

Used in PID controllers

derivační zesilovač

Differentiating op. amplifier



$$V_{out} = -RC\frac{dV_{in}}{dt}$$

Used as high-pass filter

PID controllers

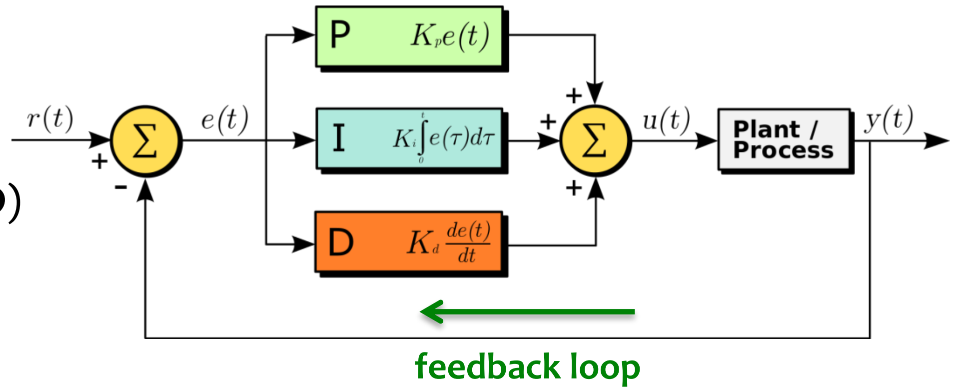
Basics

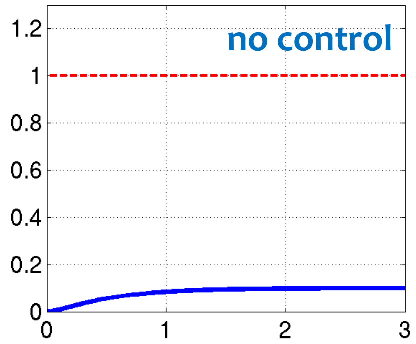
PID controller

= A closed-loop (feedback) control system, generally with Single Input-Single Output (SISO)

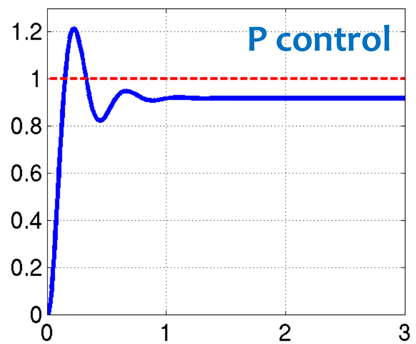
Signal being fed back is:

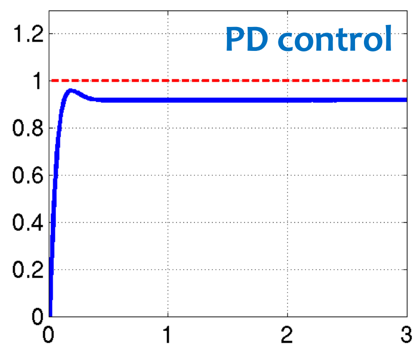
- Proportional to the error signal (**P**)
- Proportional to integral of the e.s. (**I**)
- Proportional to the derivative of the e.s. (**D**)

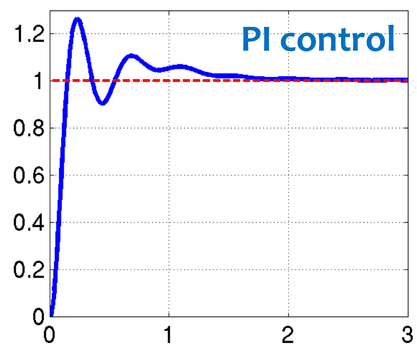


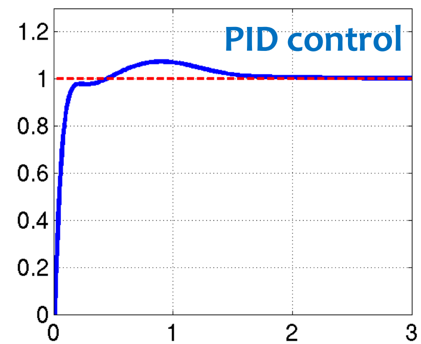


Tuning	Rise Time	Overshoot	SS Error
Proportional	Decrease	Increase	Decrease
Integral	Decrease	Increase	Eliminate
Derivative	~	Decrease	~









Experimental data acquisition and processing II

Analog signals

* Standards and calibration
* Reference and background
* Conditioning of analog (and digital) signals, synchronous detection
* Types of signal sources and measurement systems
* Noise in measurements

Standards

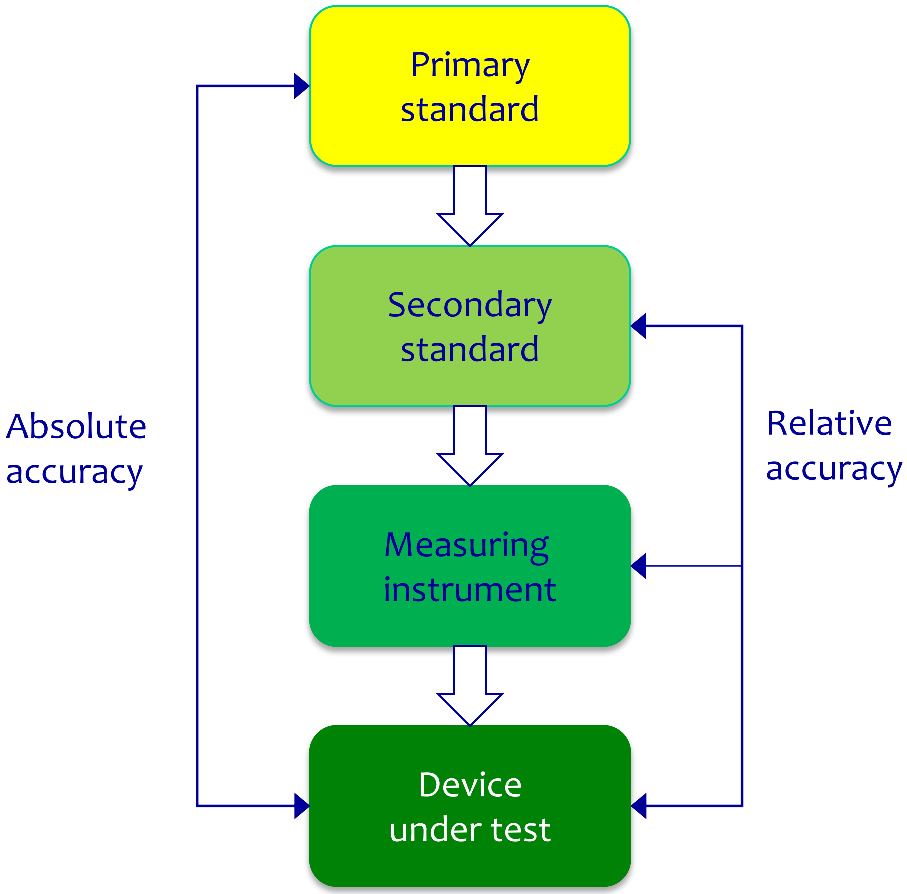
Physical **quantity** & **unit** - abstract concepts
In order to use a unit as a measure – a realization of the unit available
→ **physical standard**:

- an artifact (prototype)
- a natural phenomenon (e.g. atomic processes)
- a standardized procedure of measurement using standardized measurement methods and equipment

Hierarchy of standards

- **Primary** standards – preserved in a special institute (National Institute of Standards and Technology, International Committee for Weights and Measures, ...).
- Measurements are usually based on **secondary** or lower order (**working**) standards (calibrated to higher level standards)
- Lowest order standard (**reference**) – present in every instrument that can perform an absolute quantitative measurement

The hierarchy of standards

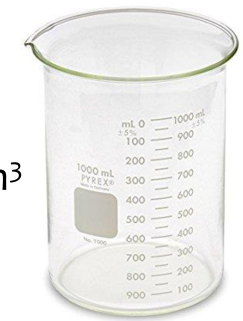


Definitions of primary standards can change over time…

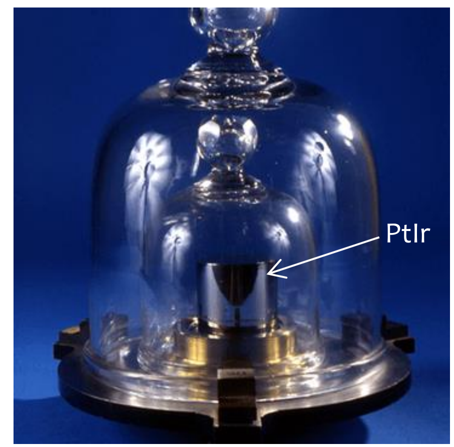
Standard kilogram

18th cent.

Water 1 dm^3



1889



variation over time ~10ppm

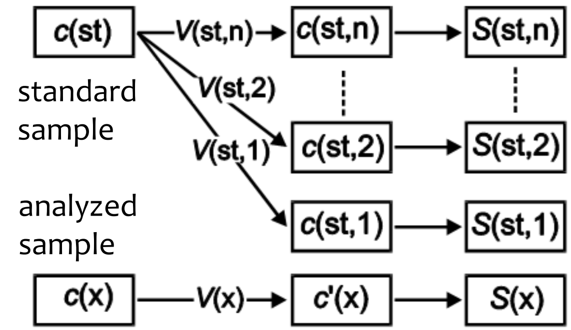
2019

Redefinition: based on Planck constant measurement

Uncertainity <20ppb

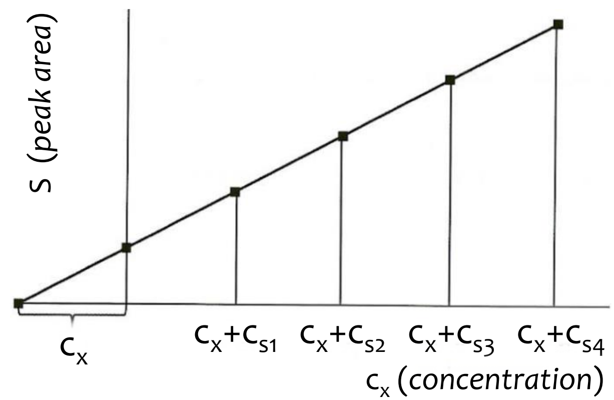
Calibration

- Relation between 2 different quantities: measured value (instrument response) and physical quantity, $S=f(c)$
- Any instruments (capable of absolute measurements) should be calibrated regularly: aging, drift, wear, etc.
- Calibration accuracy: closeness of the value of the reference to the primary standard value



- **External reference method**

– Calibration curve – from measurements of set of known quantities (calibrated externally or created with a well-defined procedure)

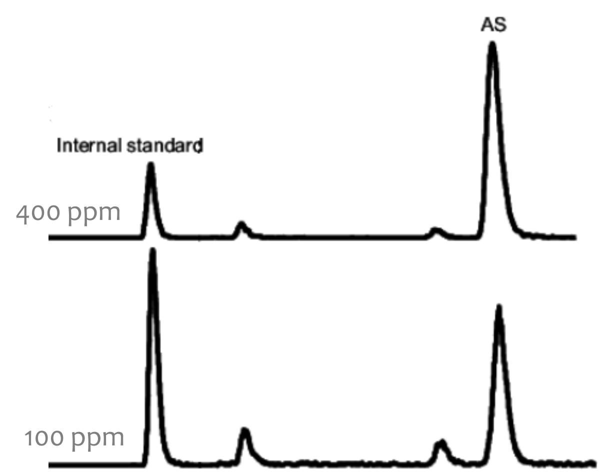


- **Standard addition method**

– requires linear f

- **Internal reference method**

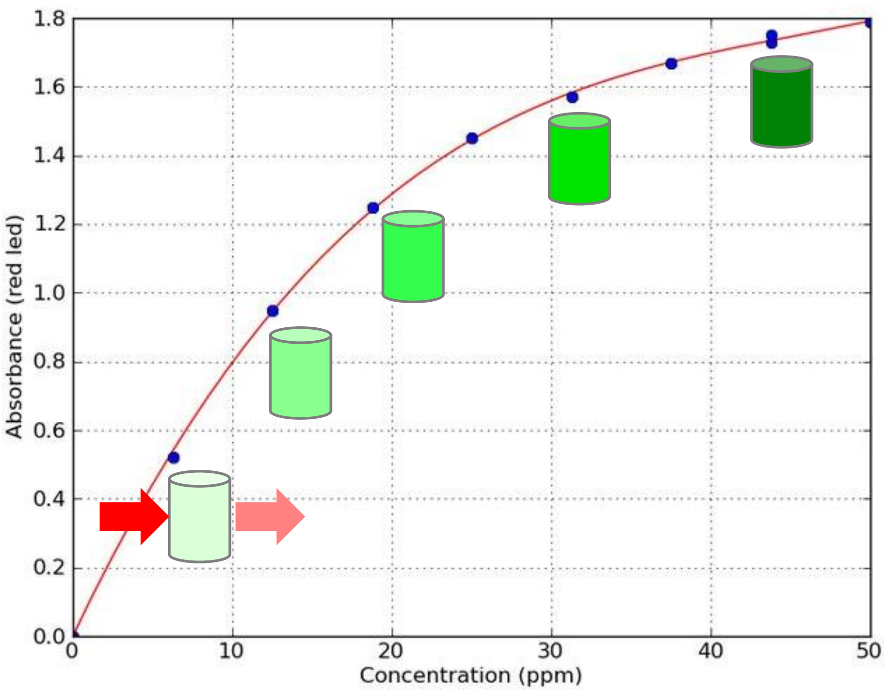
– Direct comparison – standard added directly to all measured samples; normalization often used



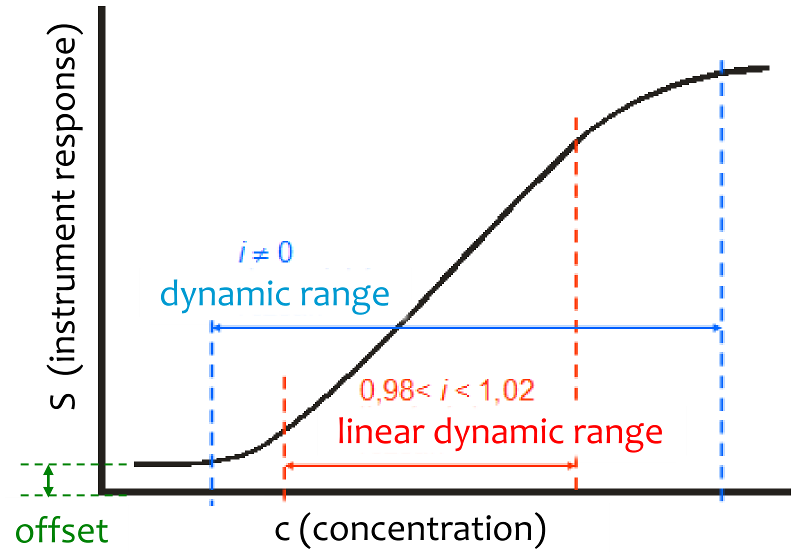
Calibration curve

Calibration curve = Sample response function – ideally linear

Example: optical measurement of solution concentration

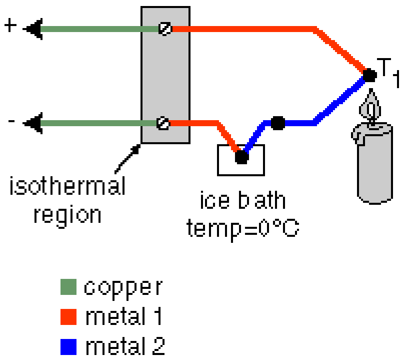


(linear) dynamic range

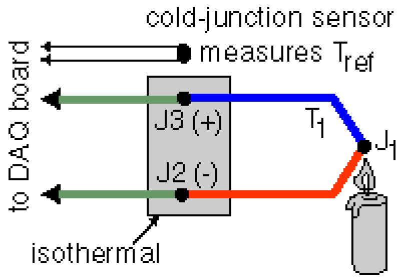


Calibration example – thermocouple

external reference junction



internal reference junction



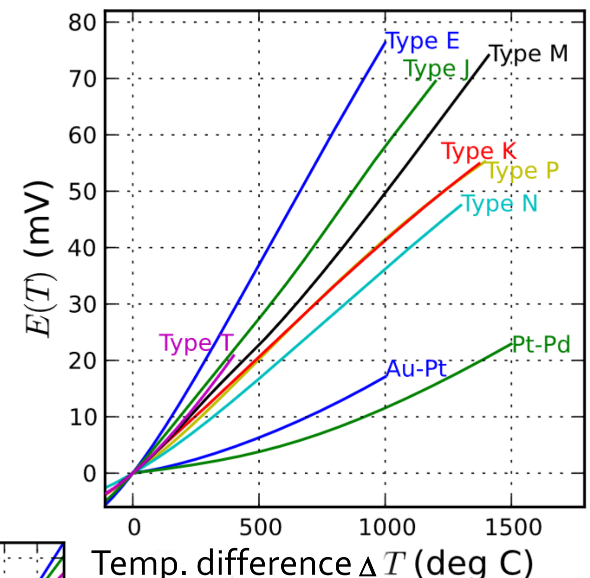
- Thermocouple output is non-linear (especially in negative range)
  => linearization element can be used

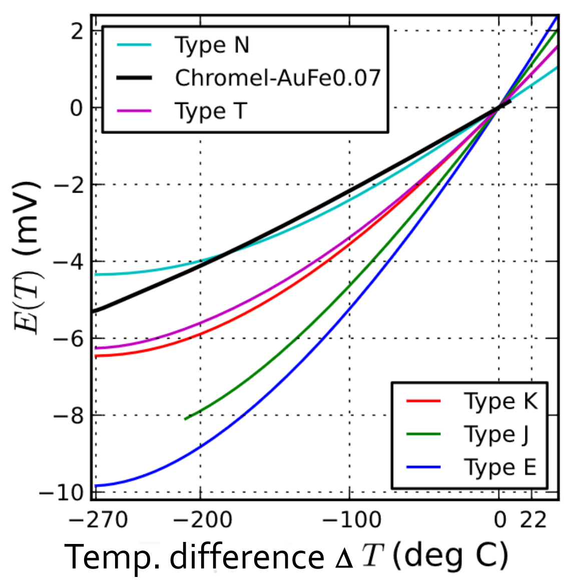
E(T)~ΔT

=> T_{ref} needed, or set to zero

Calibration with

- reference T measurement (thermistor, pyrometer, …)
  – regards also secondary sources of error
- known **E(T)** dependence





Type ANSI Symbol	Materials	Temp. Range (°C)	Error +/– (°C)	Application Notes
T	Copper-Constantan	0-350	1.0	When moisture is present.
J	Iron-Constantan	0-750	2.2	For reducing atmosphere.
E	Chromel-Constantan	0-900	1.0	When corrosion possibility.
K	Chromel-Alumel	0-1250	2.2	For clean oxidizing atmosphere.
R	Platinum-13% Rhodium/Platinum	0-1450	1.5	High resistance to oxidation and corrosion.
S	Platinum-10% Rhodium/Platinum	0-1450	1.5	High resistance to oxidation and corrosion.

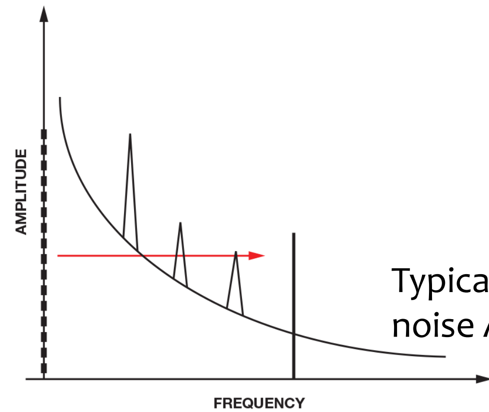
General functions of devices for signal conditioning

- Amplification of analog signal
  - variations of signal match the dynamic range of ADC – better resolution, higher sensivity, higher S/N ratio
- Attenuation
  - reduction of strong signals (high voltage, receiver saturation, ...)
- Filtration
  - noise reduction in selected spectral region (e.g. 50, 60 Hz)
  - aliasing prevention (Nyquist theorem)
- Linearization
  - often coupled with (pre)amplifier
- Isolation (optics, transformers)
  - elimination of ground loops, reduction of noise, device protection, separation of circuits with lethal voltages, …
- Multiplex
  - ADC cyclic switching between multiple channels, selection of signal source
- Parallel sampling of multiple channels
  - high throughput acquirement
- Excitation of (passive) sensors
  - bridge circuits, 3- and 4-wire measurements, …
- Cold junction compensation
  - thermocouples

Synchronous detection

- allows separation of very **weak signals** in high noise
- requires **reference signal** with well-defined **frequency** and **phase** (carrier)
  - can be already available in the signal (e.g. from experiment excitation source)
  - can be added to signal (modulation) before processing (e.g. modulation amplifier)

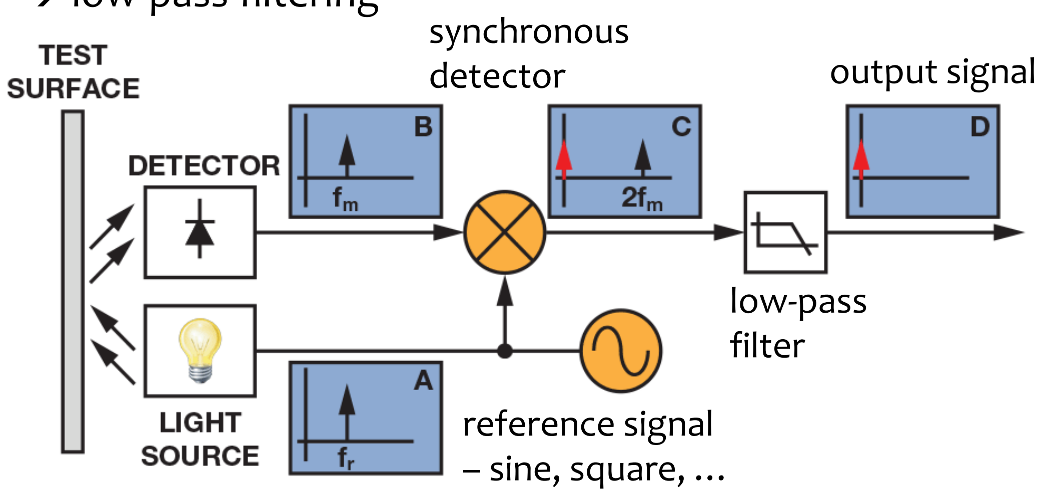
Signal modulation only
(modulation amplifier)
– moves signal away
from noise sources
→ band-pass filtering

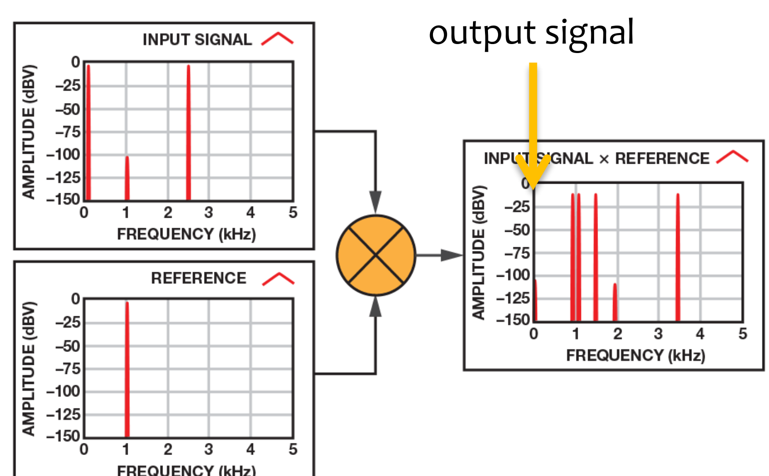


Typical op.amp.
noise A ~ 1/f

Synchronous detection
(lock-in amplifier)
– moves signal to DC level
→ low-pass filtering

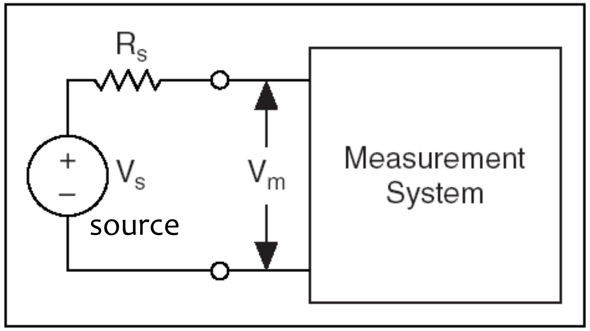
multiplication => only the
signal at modulation
frequency moving to DC





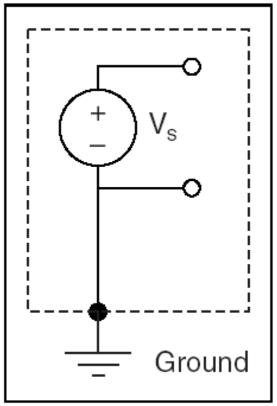
Types of signal sources and measurement systems

- Sensor output – in most cases voltage source (directly or after processing)
- Basic types of sources and meas. devices:
  1. grounded
  2. floating



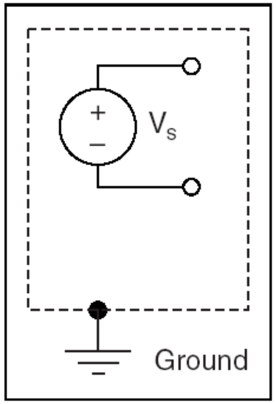
Grounded (ground-referenced)

- typically sources powered from electrical network
- no single ground: grounds of different sources may be at different potentials!



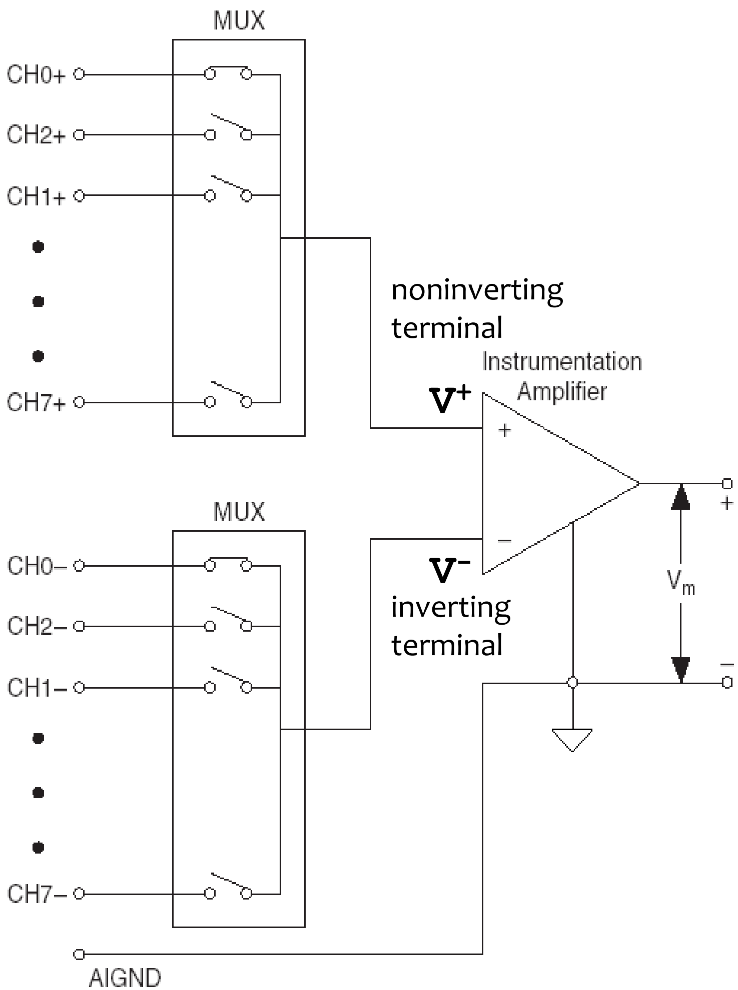
Floating (Non-grounded)

- typically sources powered from batteries, active sensors (e.g. TC), transformers, isolation amplifiers etc.



Differential (non-referenced) meas. system

- None of the inputs connected to ground-ref. potential
  - battery-powered devices
  - systems with instrumentation amplifier (diff. amp. with high input impedance)
  - etc.



Common-mode voltage součtové napětí

= voltage present on both inputs

$V_{cm} = (V^+ + V^-)/2$

Non-ideal amplifier:

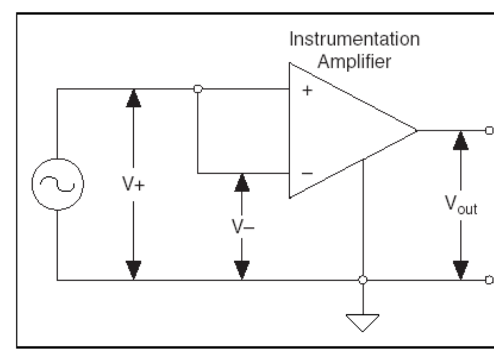
$V_{out} = A_{diff}(V^+ - V^-) + A_{cm}(V^+ + V^-)/2$

=> range limitation

→ **Common-mode rejection ratio** (CMRR)

$K_{CMRR} = A_{diff} / |A_{cm}|$ činitel potlačení součtového napětí

- typ. decreases with frequency
- expressed in dB



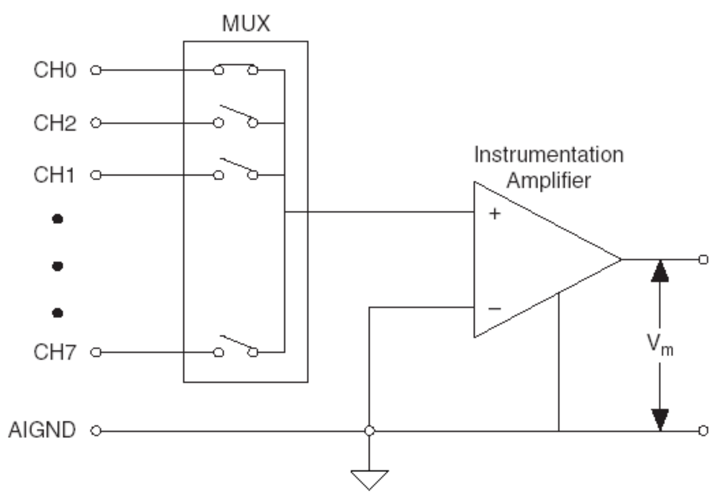
CMRR measurement circuit

Grounded (ground-referenced) meas. system

- Measurement is made with respect to a reference

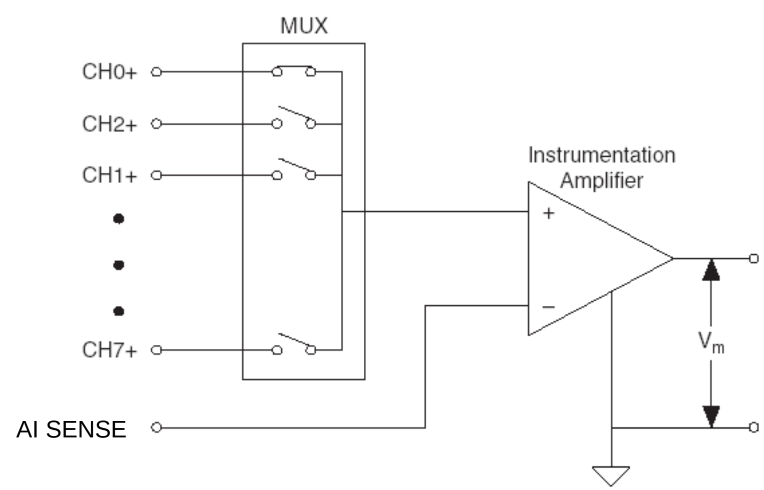
Ground-Referenced Single-Ended ((G)RSE) measurement system

measurements made with respect to the measurement system ground (AI GND)



Non-Referenced Single-Ended (NRSE) (pseudodifferential) measurement system

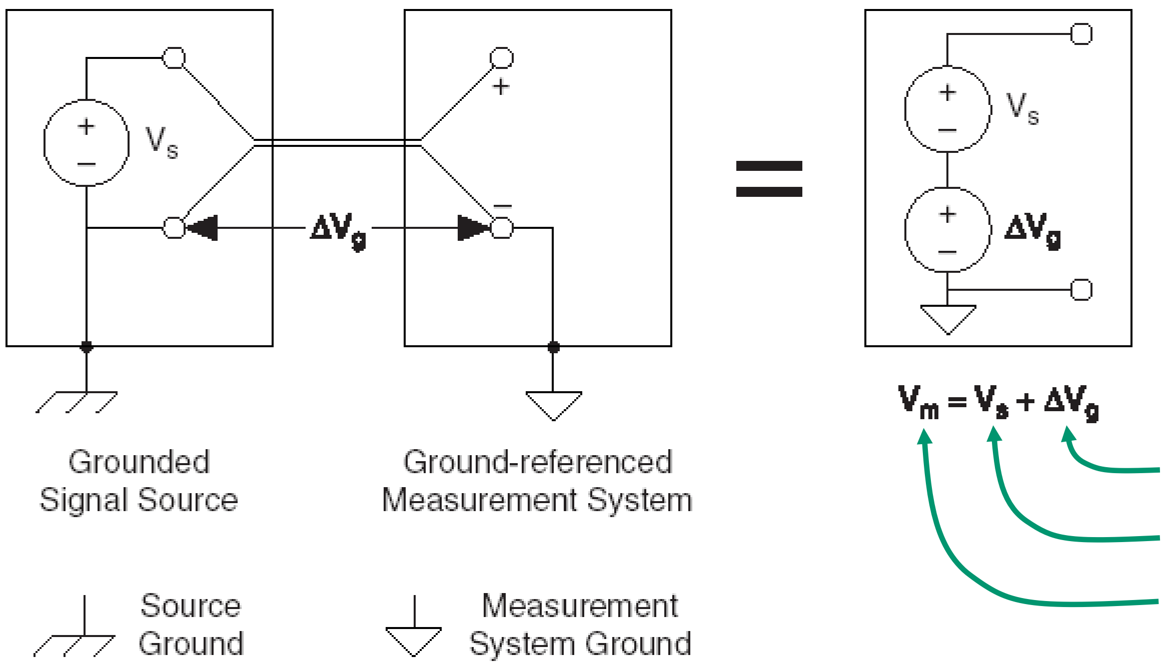
measurements with respect to a single-node (common) AI Sense, but the potential at this node can vary with respect to system ground



Different signal source types and measurement systems
➔ proper choice of measurement system for each type of signal source

Measuring grounded signal sources

- Grounded signal source measured by ground-referenced system



ΔV_g … both DC (offset) & AC (typ. 50/60Hz) component

potential difference

signal voltage

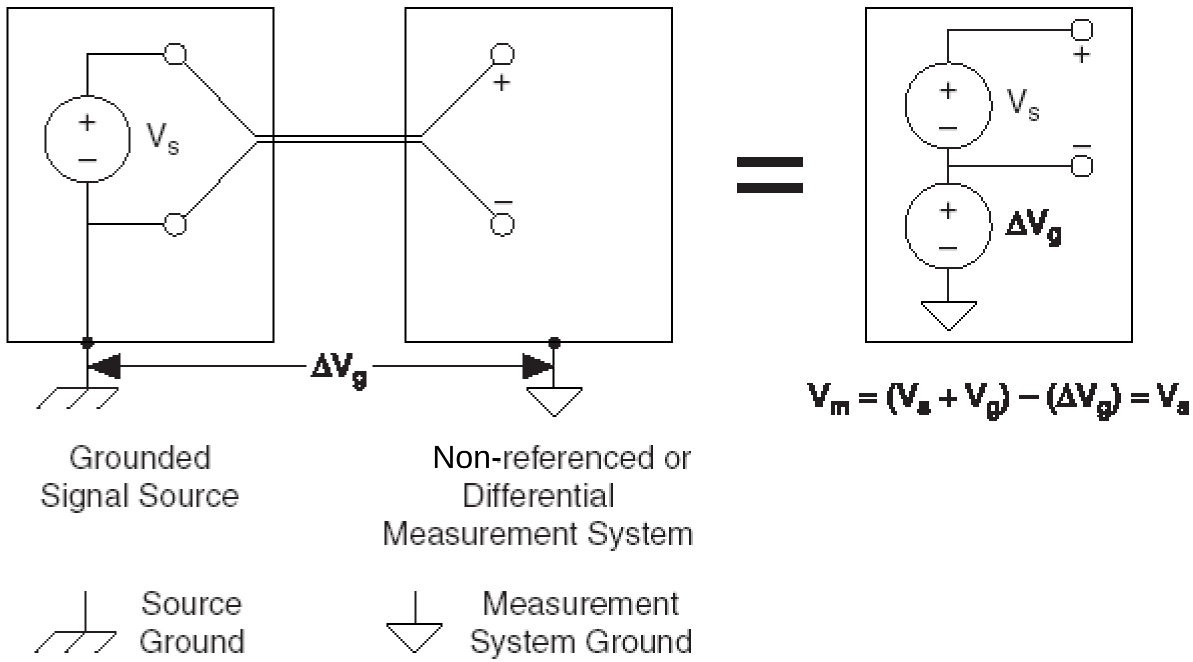
measured voltage

- Generally not recommended
- Can be tolerated for high-amplitude sources with low interconnection impedance

Check polarity of signal source before connecting it to a ground-referenced measurement system to prevent shorting to ground!

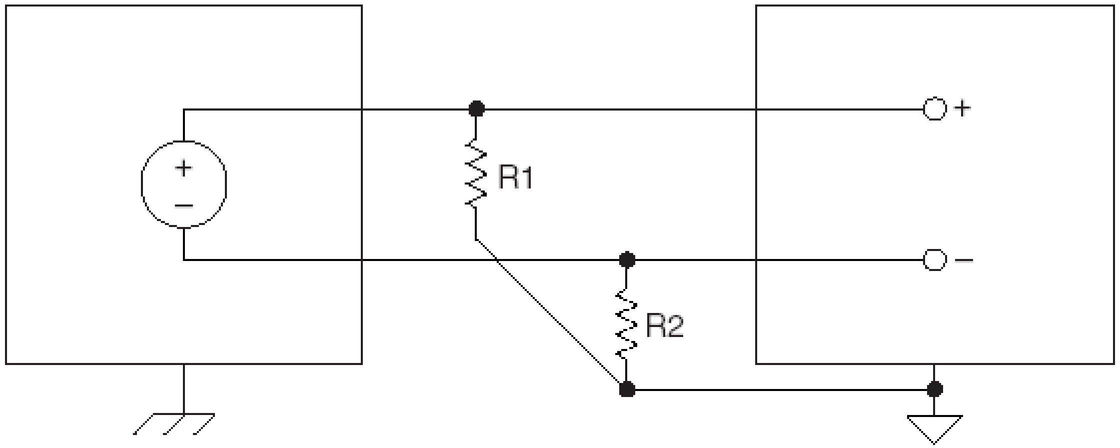
Measuring grounded signal sources

- Grounded signal source is best measured with a differential or non-referenced measurement system: any potential difference between references of source measuring not included in the measured signal



Measuring floating (non-referenced) sources

- Floating signal sources can be measured with both differential and single-ended measurement systems
- **Differential input systems:** common-mode voltage level of the signal (with respect to measurement system ground) should remain in the common-mode input range of the measurement device



Without bias resistors: saturation or erratic behavior can occur!

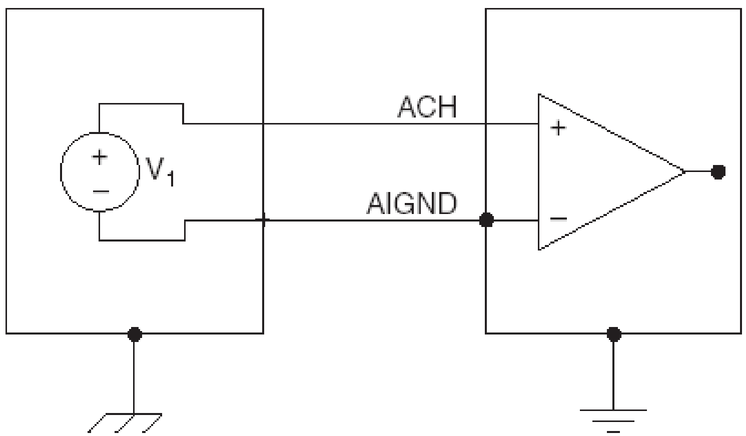
- Bias resistors: voltage level of floating source can move out of the valid range (e.g. due to instrumentation amplifier input bias currents)
  => has to be **anchored** to some **reference**
  - large enough to allow the source to float with respect to AI GND, but small enough to keep voltage in the range (typ. 10-100 kΩ)
  - DC-coupled signal sources: only R2 required (but unbalanced inputs => higher noise, OK for low impedance sources)
  - AC-coupled sources: R1=R2

Measuring floating (non-referenced) sources

Single-ended measurement systems

- No ground loop is created

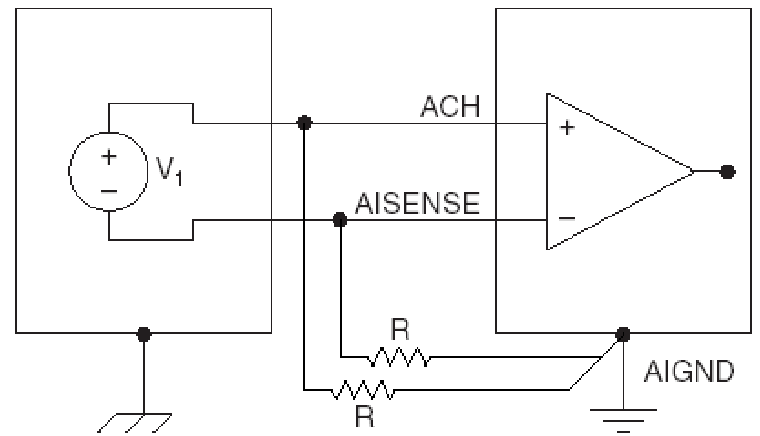
Ground-referenced single-ended



a. GRSE Input Configuration

- No additional resistor(s) needed

Non-referenced single-ended

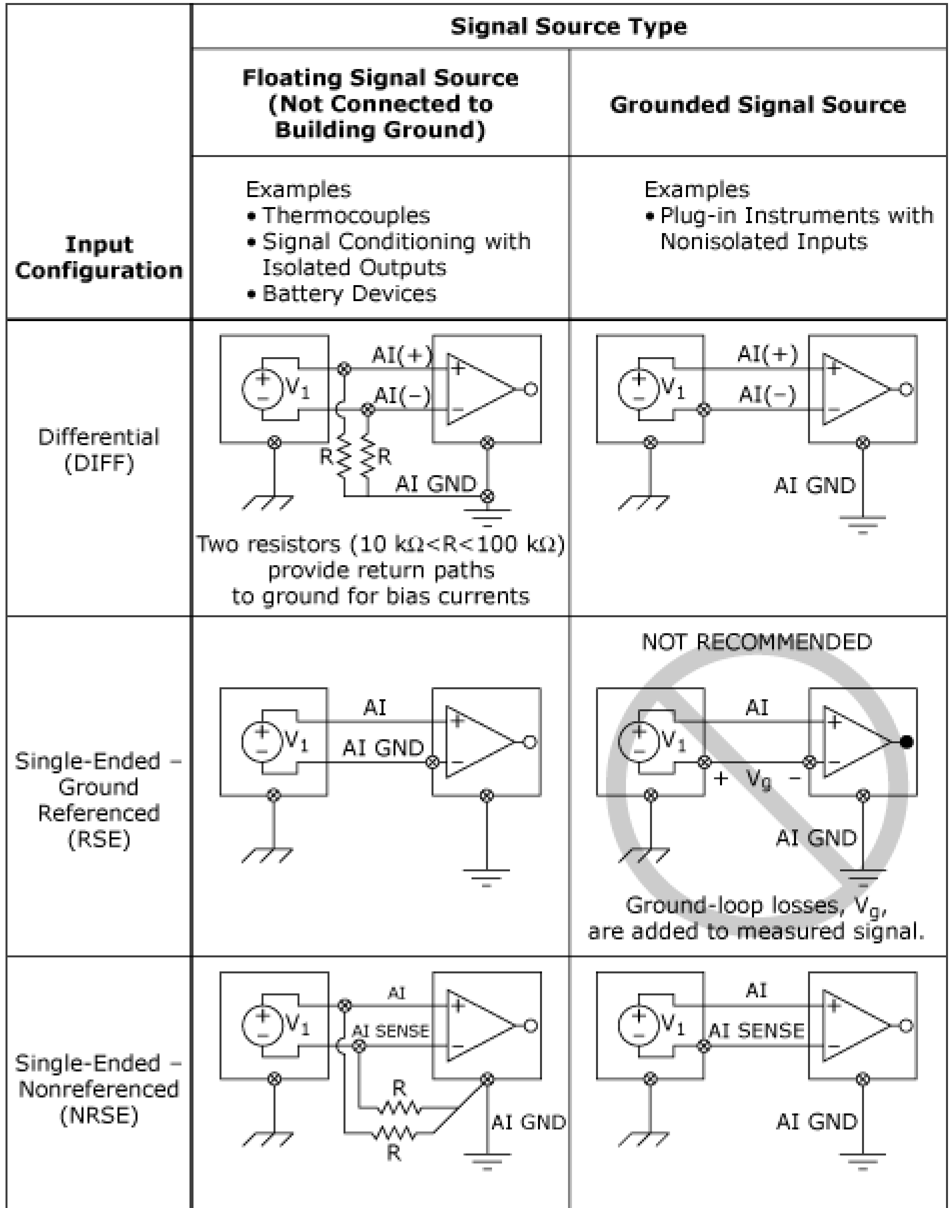


b. NRSE Input Configuration

- Pseudodifferential inputs more immune to noise

- Be aware of common-mode voltage

Connection schemes of analog sources and measurement systems – overview



Differential (DIFF), floating signal source:

+ common-mode voltage independent
- ½ of channels
- bias resistors needed

BEST

Differential (DIFF), grounded signal source:

+ common-mode voltage independent
- ½ of channels

BETTER

Single-Ended – Ground Referenced (RSE), floating signal source:

+ full number of channels
+ no bias resistors
- common-mode voltage dependent

GOOD

Single-Ended – Ground Referenced (RSE), grounded signal source:

+ ground loop voltage
- can destroy the system

NOT RECOMMENDED

Single-Ended – Nonreferenced (NRSE), floating signal source:

+ full number of channels
- common-mode voltage dependent

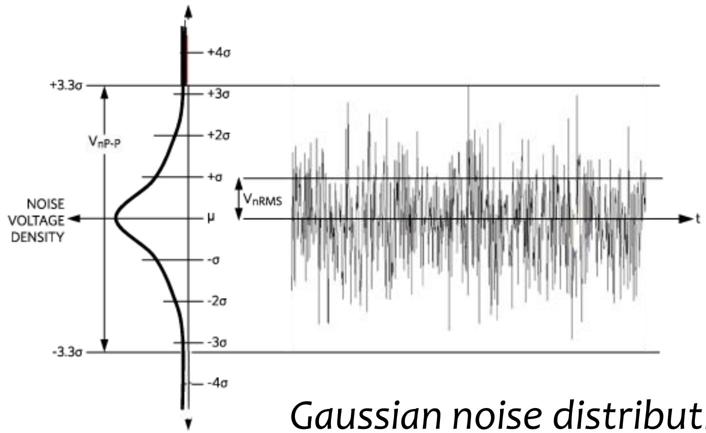
BETTER

Single-Ended – Nonreferenced (NRSE), grounded signal source:

+ full number of channels
- common-mode voltage dependent

GOOD

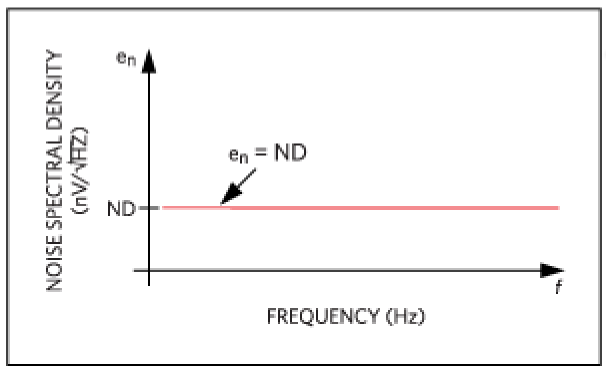
Noise density function



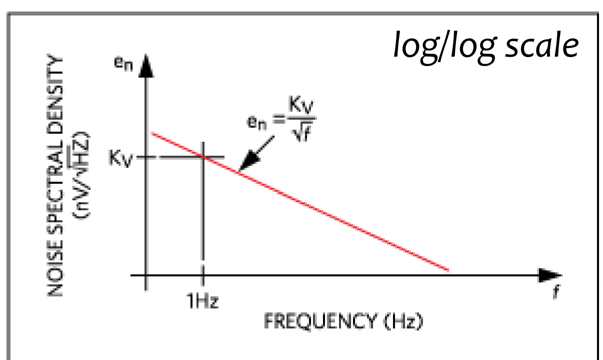
Gaussian noise distribution

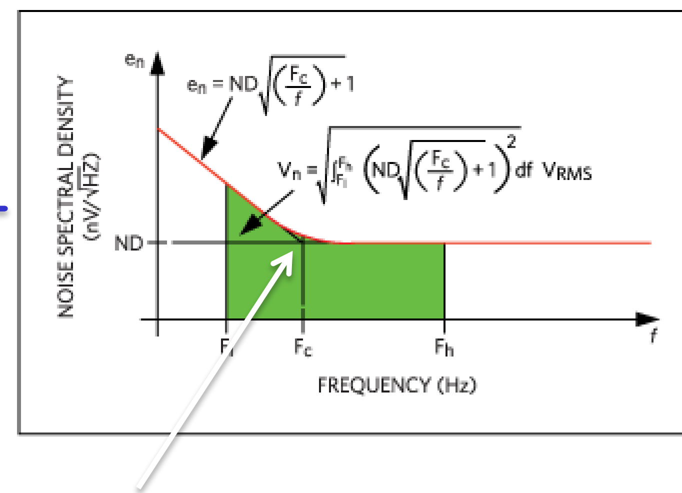
Noise floor of a measurement device
= measured noise level with its inputs grounded
– usually expressed in $\mathbf{V/\sqrt{Hz}}$ – value integrated over the bandwidth of interest

White noise (wideband)
– equal energy at any f



Pink noise ("1/f" noise)
– contains equal amount of energy in each decade

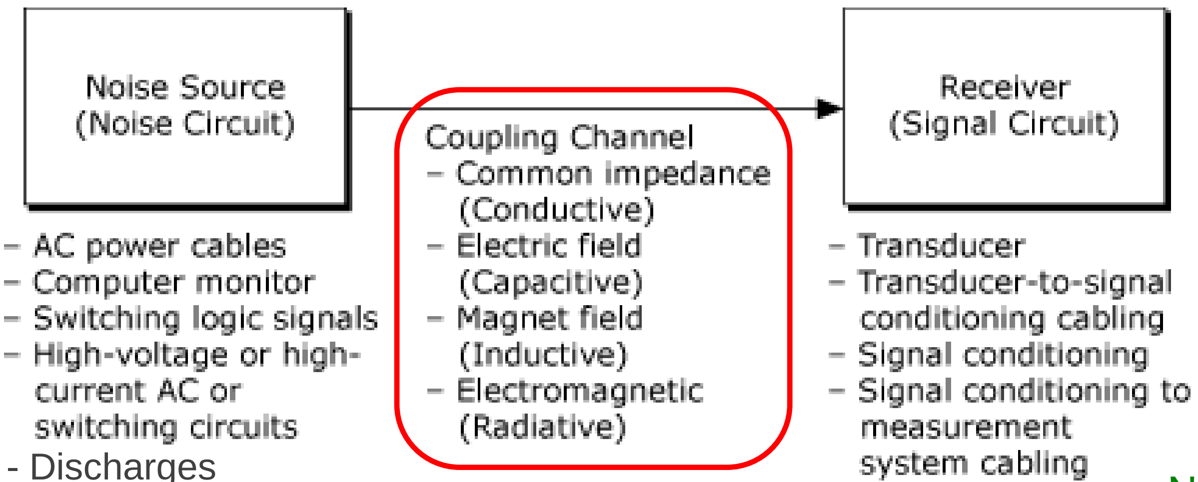




1/f corner

Noise coupling (interference) in the interconnects

Noise – unwanted signal contribution even when ground loops avoided
– should be minimized

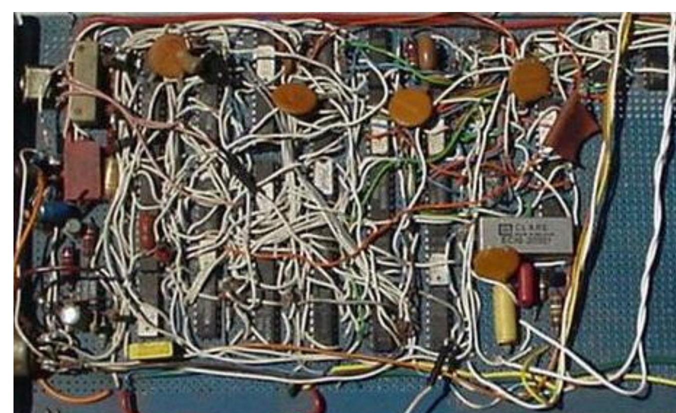


noise coupling ("pick-up") mechanisms

No single solution exists
(in fact, inappropriate solution can make the problem worse!)

Suppresssion – separation of power and signal grounds, shileding, larger separations, balanced differential circuits, …

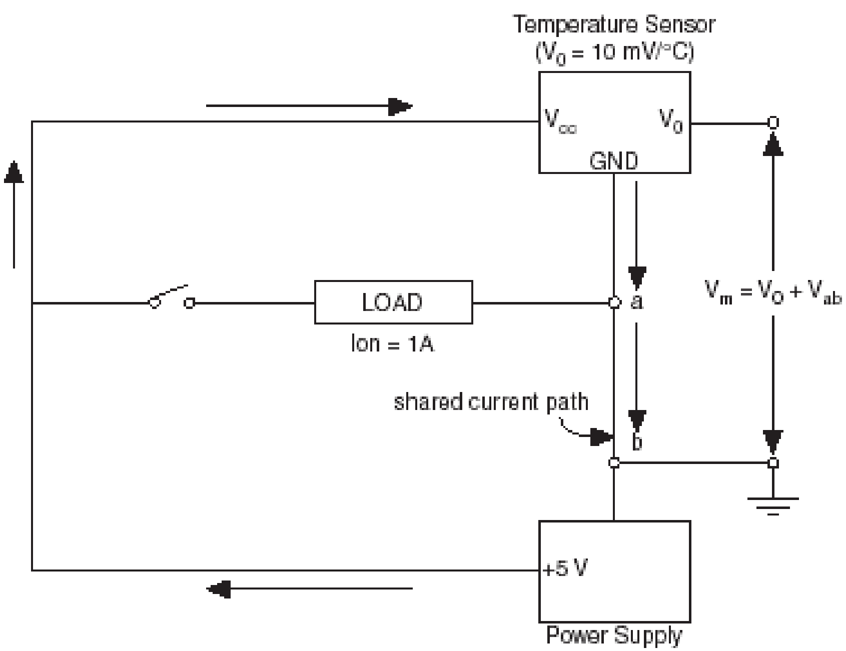
Digital noise reduction – better to minimize noise as much as possible in analog signal, before conversion to digital



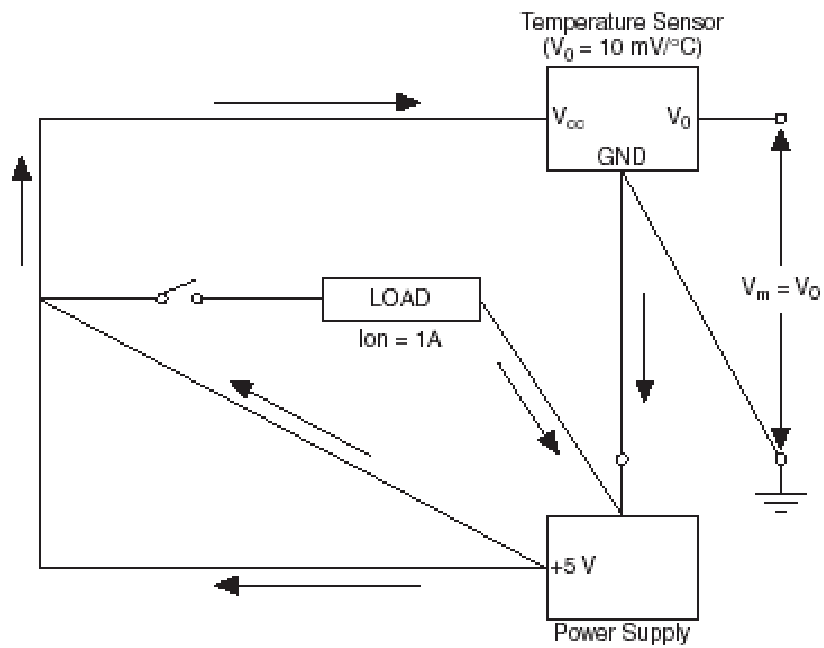
Conductively coupled noise

Conductive (direct, DC) coupling

- Due to finite impedance of wiring
- **Elimination** (minimization):
  - break ground loops
  - separate ground returns for low-level and high-level (high-power) signals



a. Series Ground Connections Resulting in Conductive Coupling

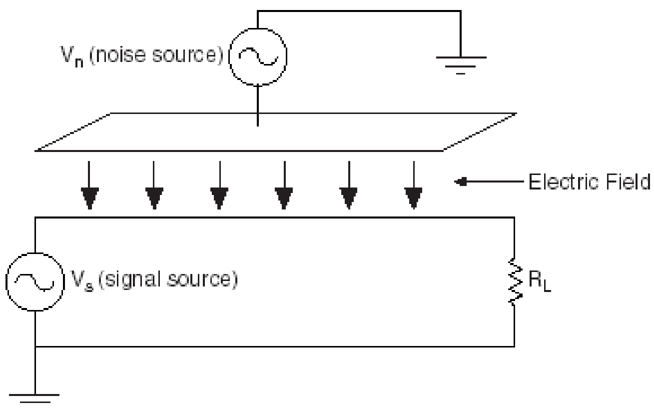


b. Separate Power and Ground Returns to Avoid Conductive Coupling

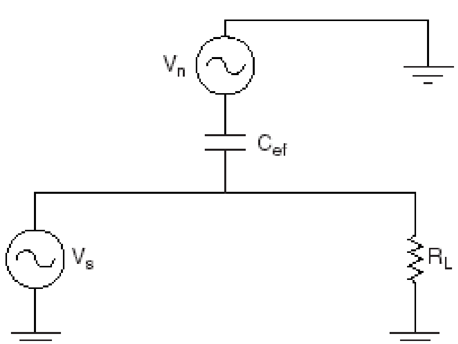
Capacitive and inductive coupling

- Capacitive coupling – results from time-varying electric fields
- Inductive (magnetic) coupling – results from time-varying magnetic fields
- Electromagnetic (radiative) coupling – combined interference considered when electromagnetic field source is far from signal circuit

Capacitive coupling

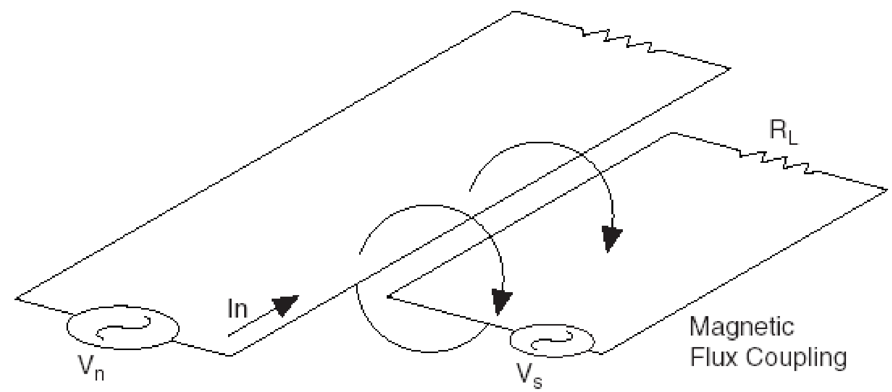


a. Physical Representation

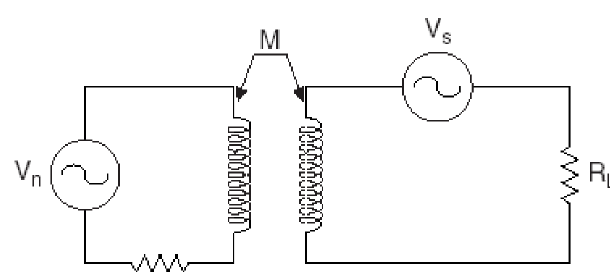


b. Equivalent Circuit

Inductive coupling

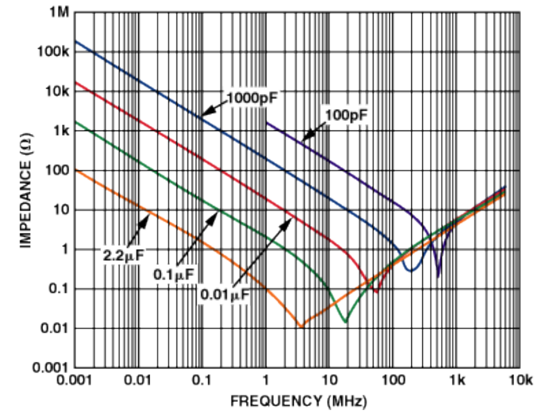


a. Physical Representation



b. Equivalent Circuit

Capacitive coupling

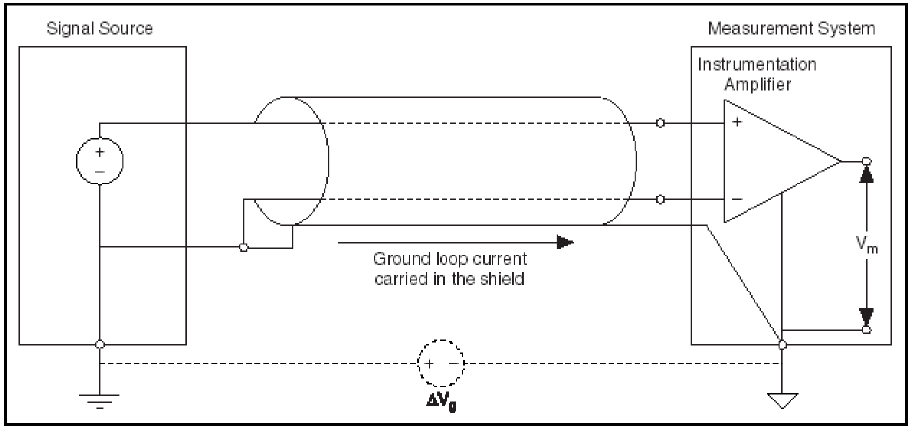


Capacitive (AC) coupling elimination

– frequency dependent => can be reduced by reducing noise source voltage or frequency

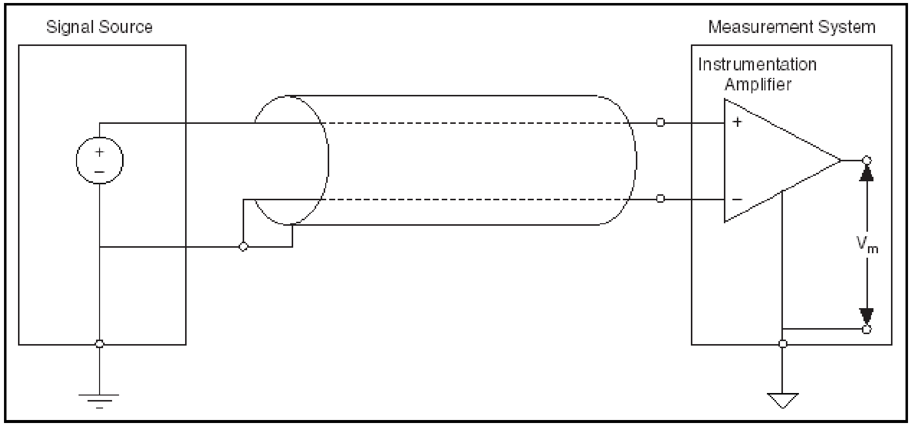
– reduce signal circuit impedance

– employ capacitive shielding (with equivalent capacitance C_{ef})



Both shield **location** and **connection** are important

Improper shield termination
– ground loop currents carried in the shield



Proper shield termination
– no ground or signal current flows through the shield

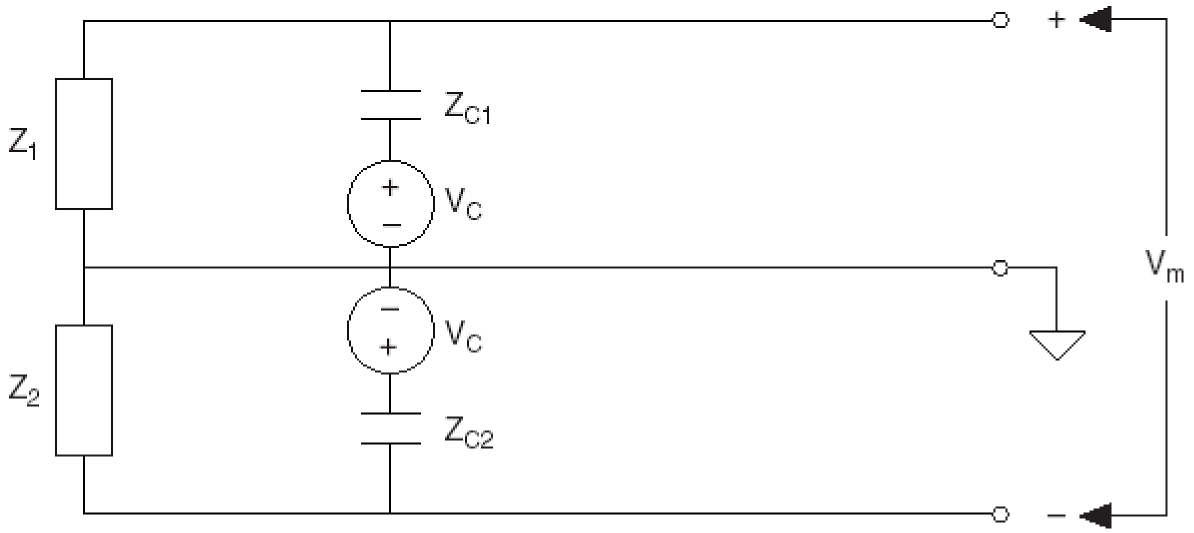
No conductive material in the vicinity of the signal path should be left electrically floating !

Balanced systems

Balanced circuit = meets the following criteria:

1. **source is balanced** – both terminals of the source (signal high and signal common) have equal impedance to ground
2. **cable is balanced** – both conductors have equal impedance to ground
3. **receiver is balanced** – both terminals of the measurement end have equal impedance to ground

$Z_1 = Z_2$ & $Z_{c1} = Z_{c2}$



unbalanced
=> V_c = differential signal

Event. capacitive noise coupling → common-mode voltage

Experimental data acquisition and processing III

Digital signals

* Conversion of analog signal to digital and backwards
* Signal sampling, Nyquist theorem and aliasing
* Quantization and coding
* Examples of D/A and A/D converters

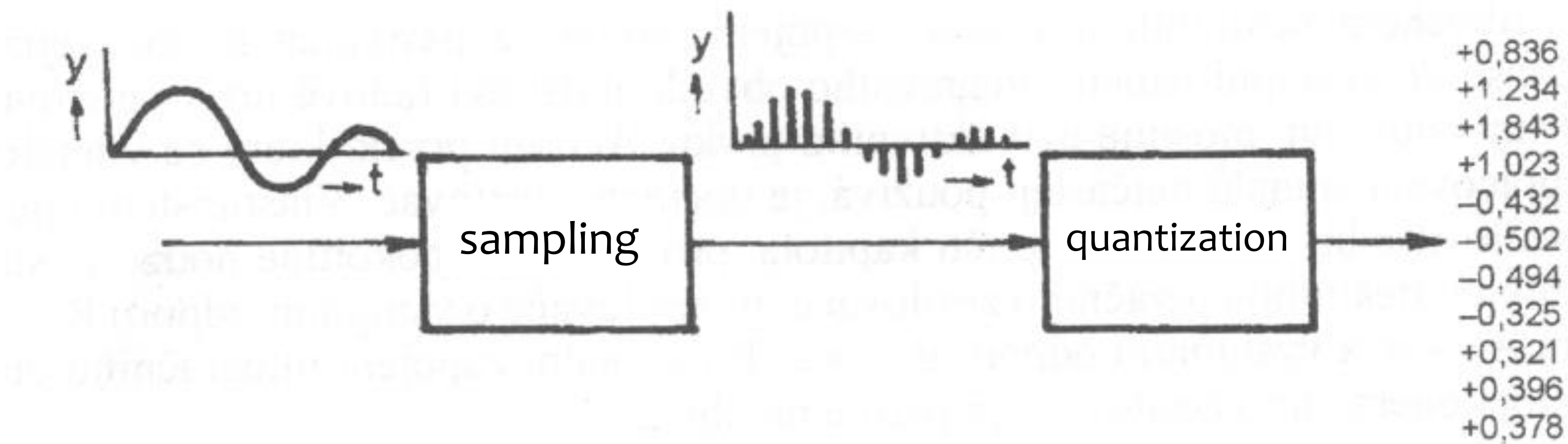
Digital processing of analog signals

Digitization

= conversion of analog signal to digital

3 stages:

1. **sampling** } **Sampling circuit**
2. **quantization** } **A/D converter**
3. **coding**



Sampling strategies

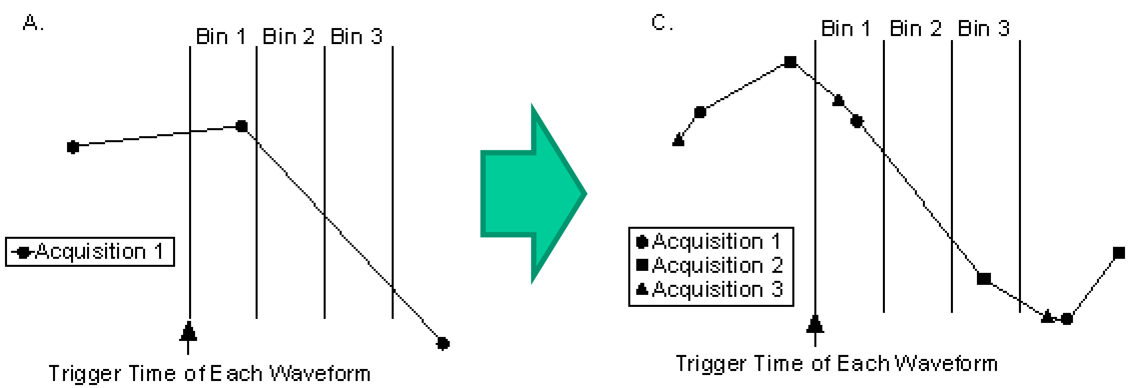
Real-Time Sampling (RTS)

– digitizer gathers all the samples using an internal or external sample clock
– the only option for non-repetitive signals

Equivalent Time Sampling (ETS)

– waveform is created over time from series of samples taken from repetitive waveforms
– synchronized triggering required
– **Random Interleaved Sampling** (**RIS**) – type of ETS; trigger time occurs randomly between two samples

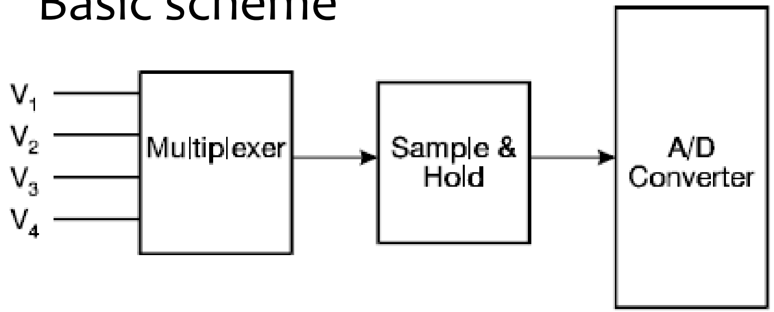
trigger timing meas. accuracy >> sampling rate => oversampling



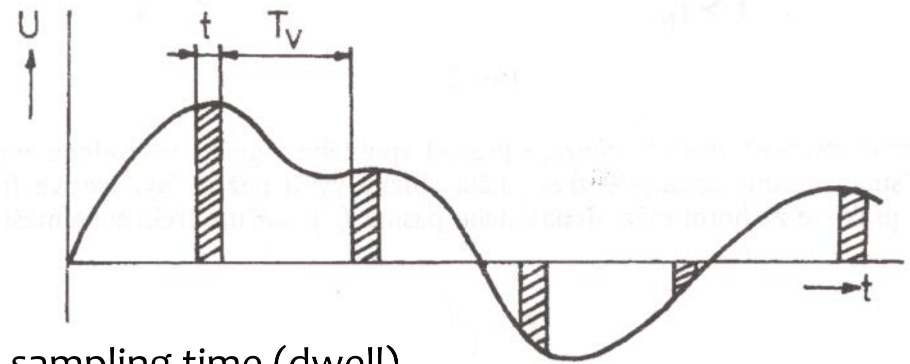
averaging (binning)
→ noise reduction

Sampling circuits

Basic scheme



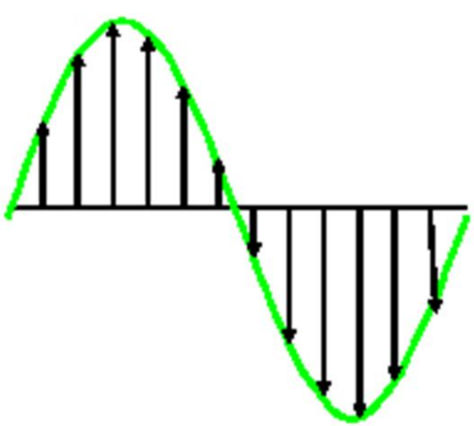
Multiplexer - S/H - A/D



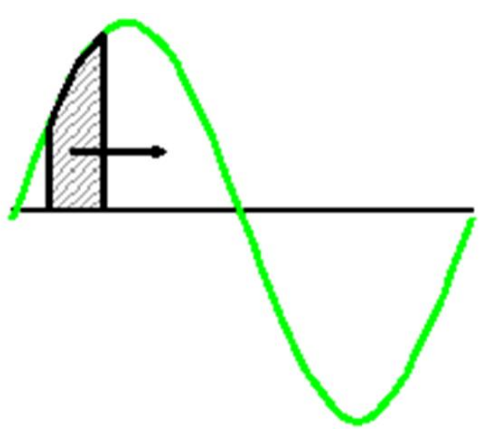
t … sampling time (dwell)
T_v … sampling interval (rate)

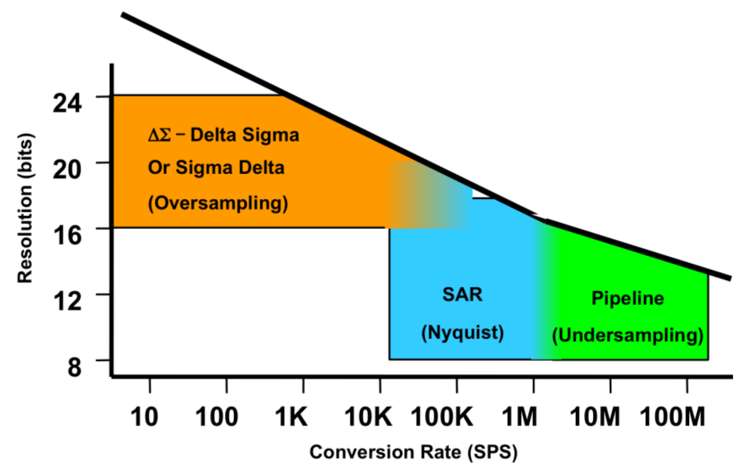
ADC technologies (architectures)

successive-approximation-register (SAR)
– takes "snapshots"

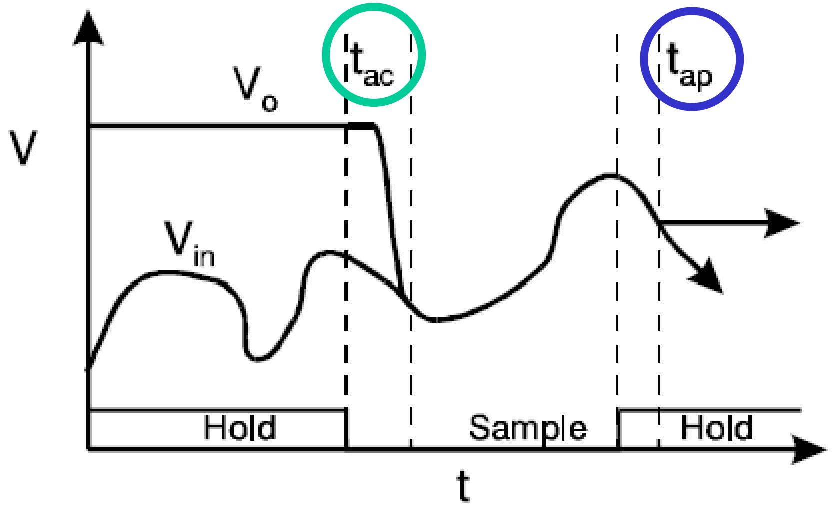


delta-sigma converter
– takes an average





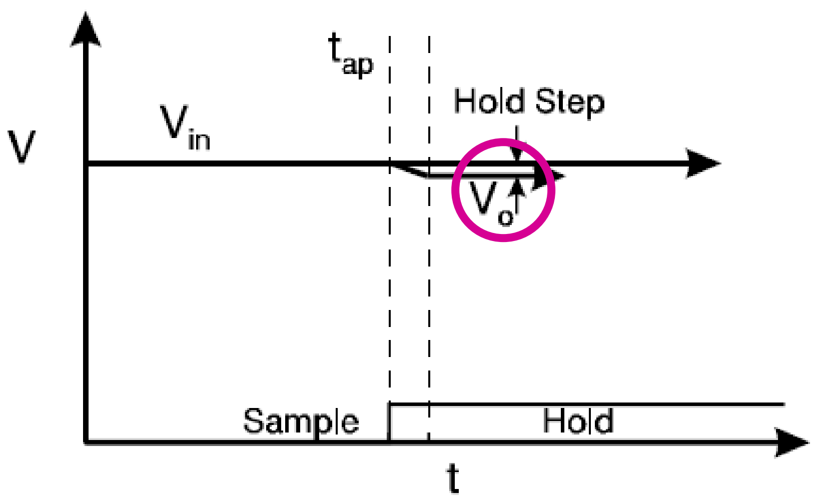
Sampling circuit characteristics



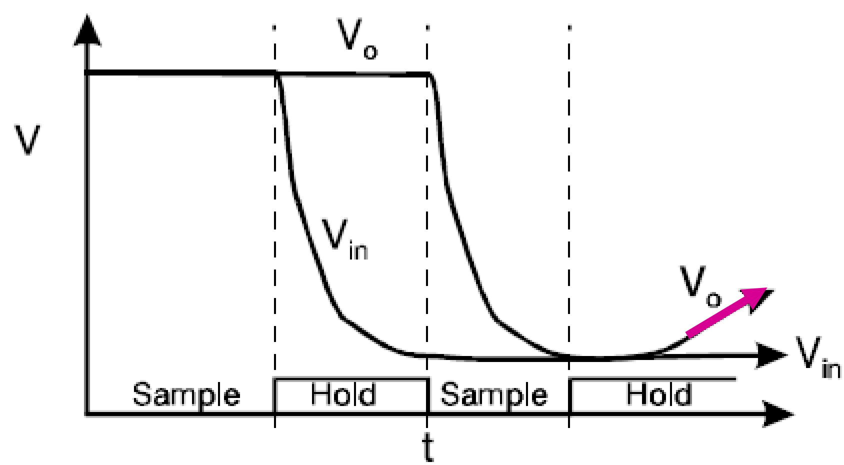
Sample and Hold - Acquisition Time

t_{ac} … acquisition time (req'd by holding capacitor to charge to correct level)
t_{ap} … aperture time (delay of actual hold from hold signal)

doba odběru vzorku

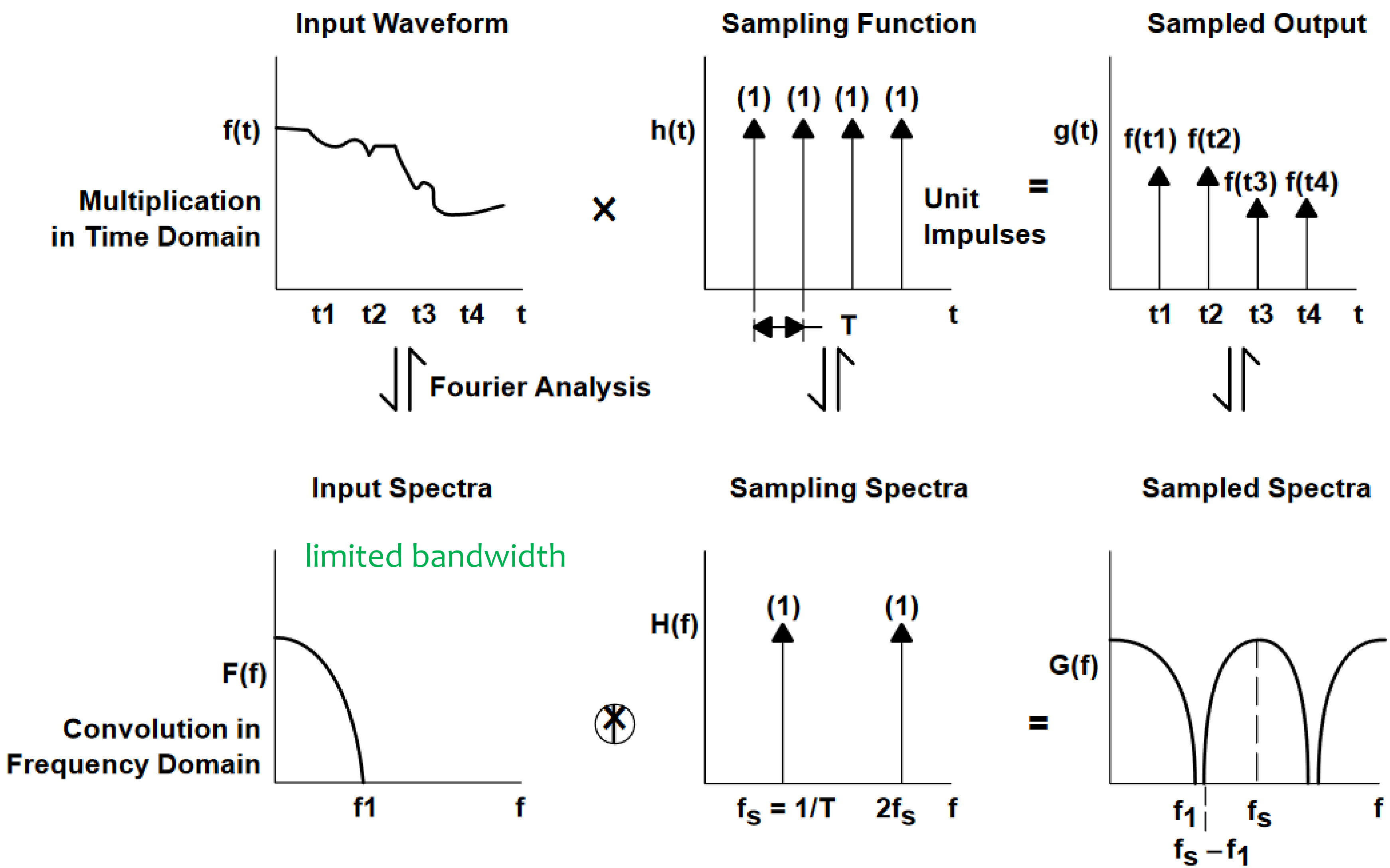


Sample and Hold - Charge Injection



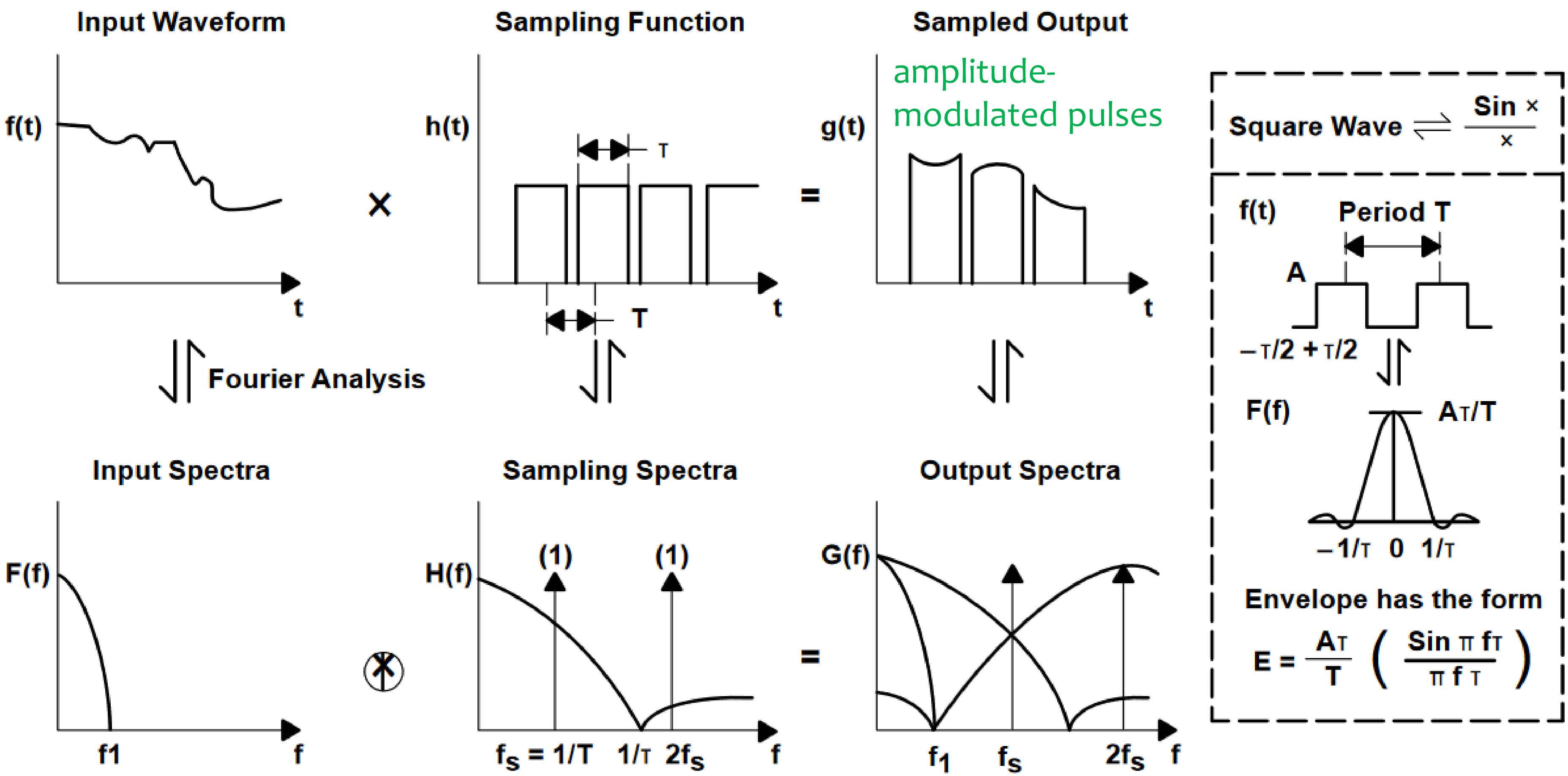
Sample and Hold - Memory Effects

Ideal sampling



NYQUIST'S THEOREM: $f_s - f_1 > f_1 \Rightarrow f_s > 2f_1$ => aliasing doesn't occur

Real sampling



Input signals are not truly band limited

$f(s) \not> 2f_1$

Sampling cannot be done with impulses so, amplitude of signal is modulated by $\frac{\sin x}{x}$ envelope $(x=\pi/f_s)$

Because of input spectra and sampling there is aliasing and distortion

Aliasing effects

Aliasing

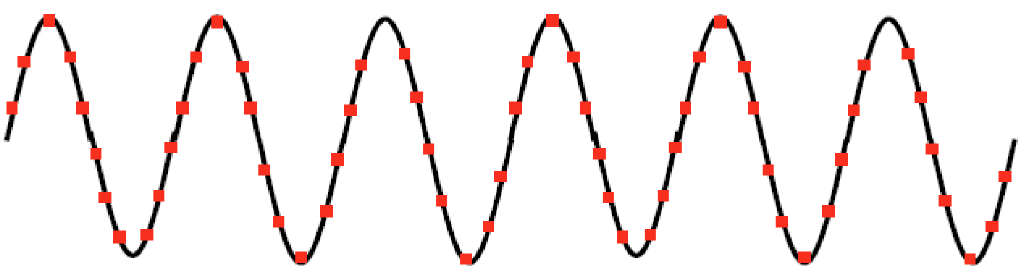
– artefact due to signal undersampling – too low frequency used

Alias = false representation of signal waveform

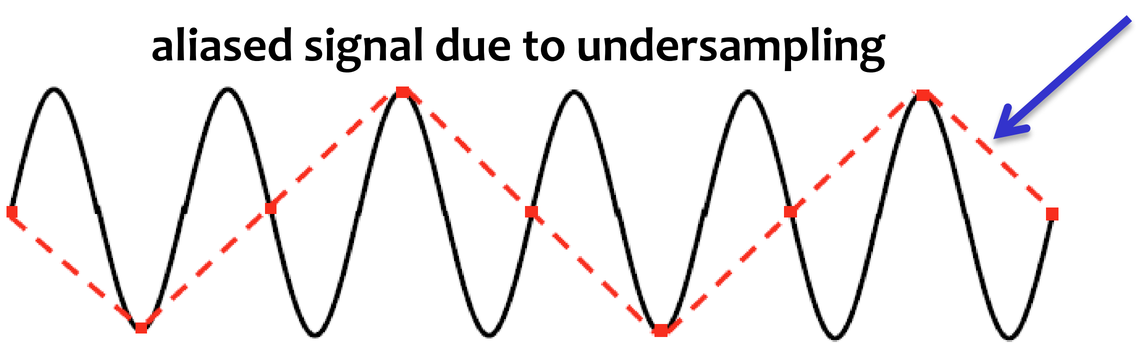
Choice of frequency upper limit:

1. intrinsic limitation of circuitry
2. real signals have infinite bandwidth, but energy of higher frequency components becomes increasingly smaller => useful signal cut-off

adequately sampled signal



aliased signal due to undersampling

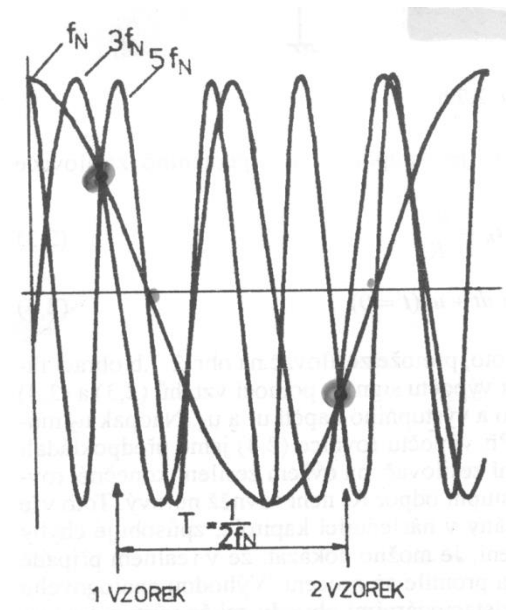


Output of sampling circuit does not reflect the original signal unambiguously

Nyquist theorem

Nyquist–Shannon sampling theorem

– for accurate signal reconstruction, a signal must be sampled at a rate greater than 2 times the bandwidth of the signal



→ **Nyquist (folding) frequency**

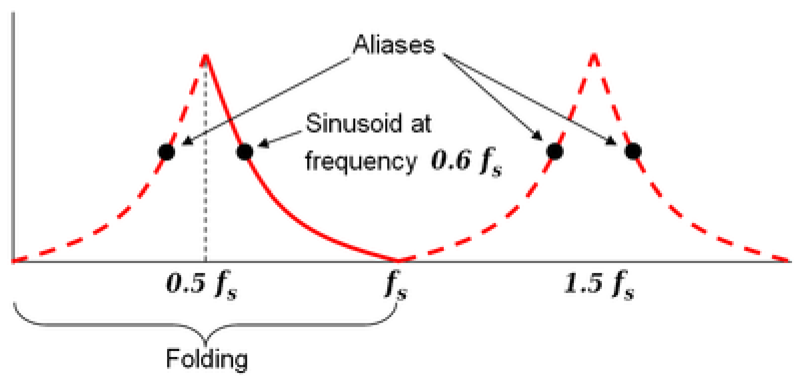
$$f_{Ny} = 0.5\ f_{smp}$$

Shannon:

If a function x(t) contains no frequencies higher than F hertz, it is completely determined by giving its ordinates at a series of points spaced 1/(2F) seconds apart.

Aliasing prevention

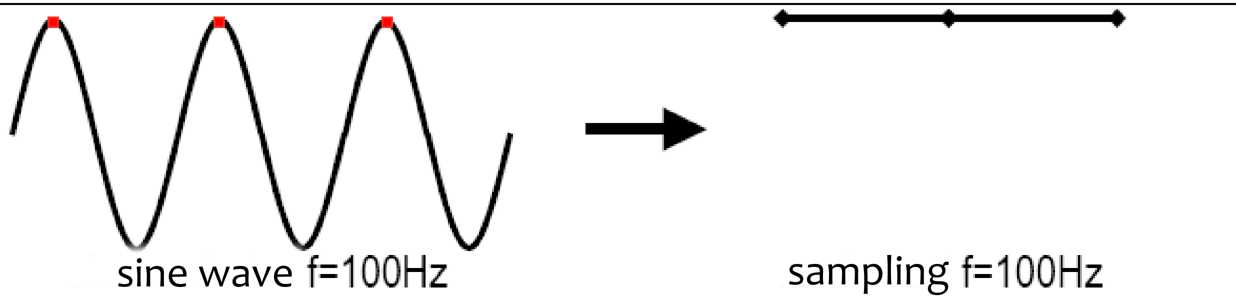
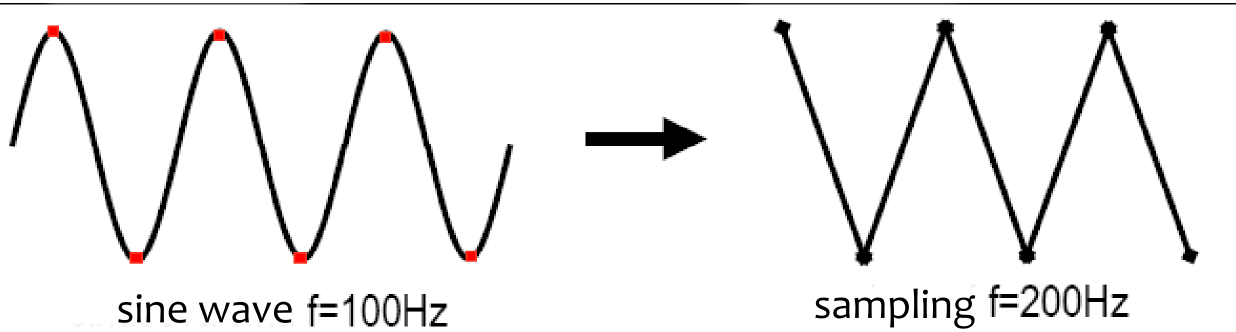
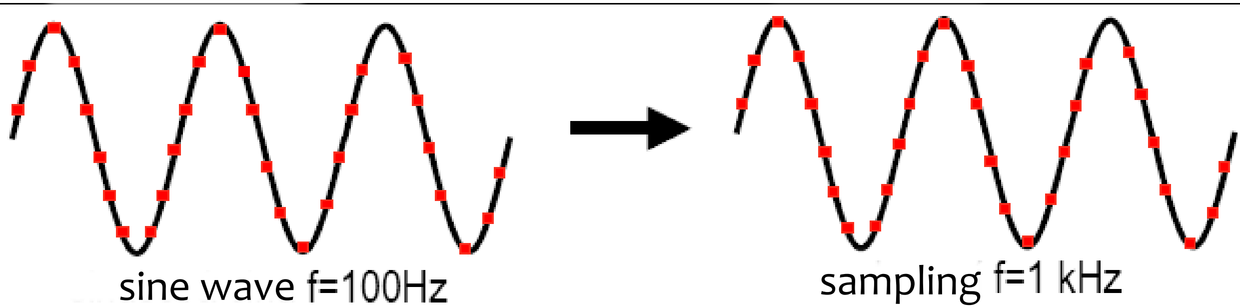
- sampling rate increase
- use of analog filters



Nyquist theorem – examples

Sine wave

– the simplest example: single (fundamental) frequency, no higher harmonics

	distorted signal
	Sampling meets exactly Niquist criterion – amplitude and frequency preserved
	Sufficient sampling frequency – amplitude, frequency, and shape preserved

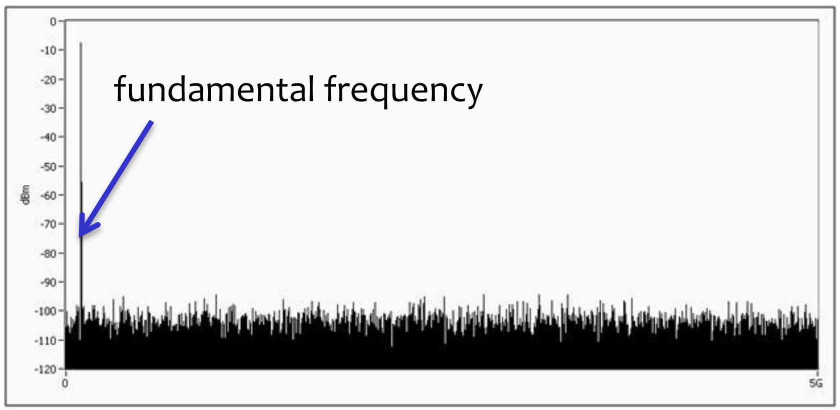
Nyquist theorem – examples

Square wave

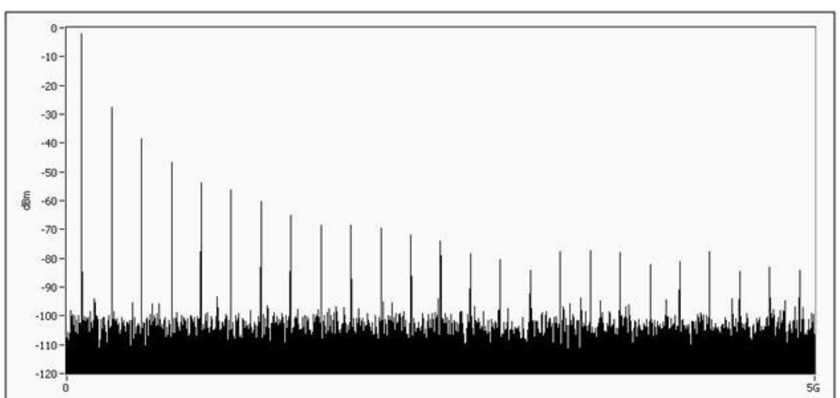
- typical signal with considerable high-frequency components (e.g. digital signals)
- required bandwidth

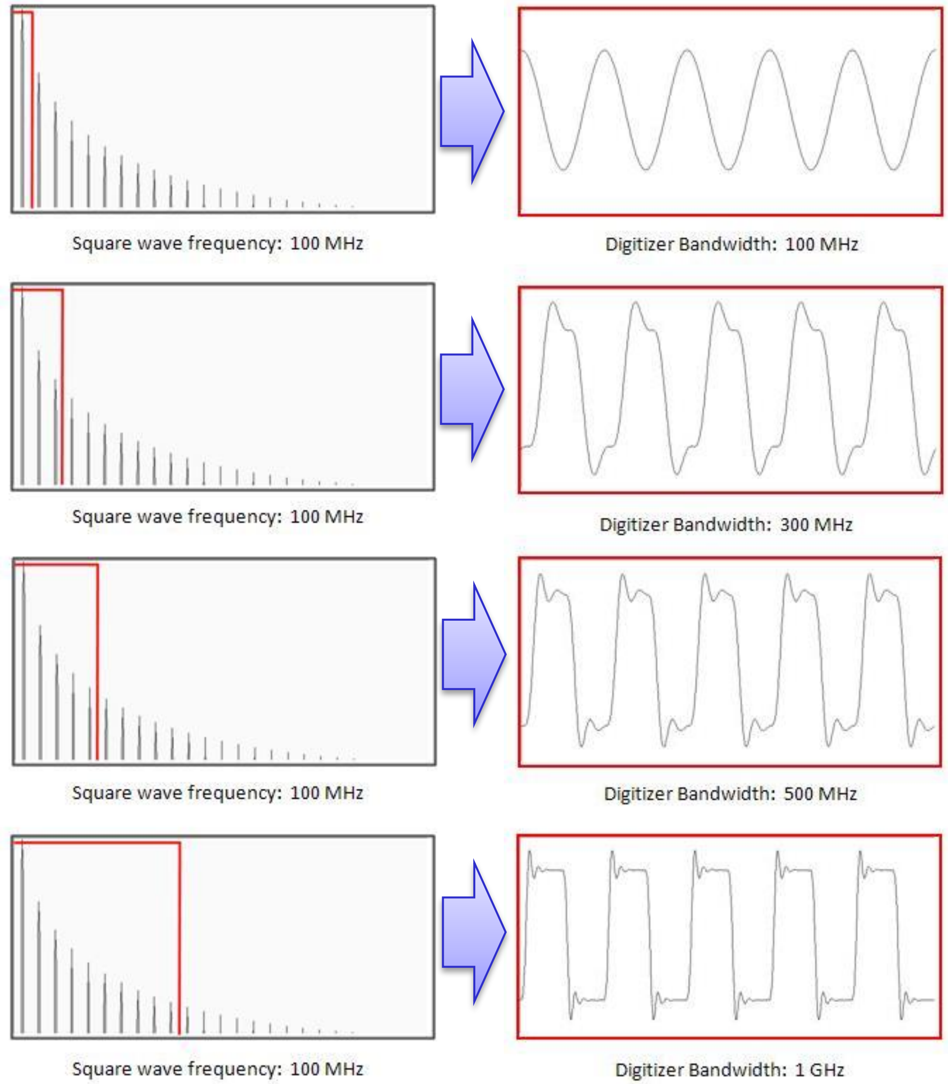
  ≈ 0.35/(rise time of the signal)

sine wave



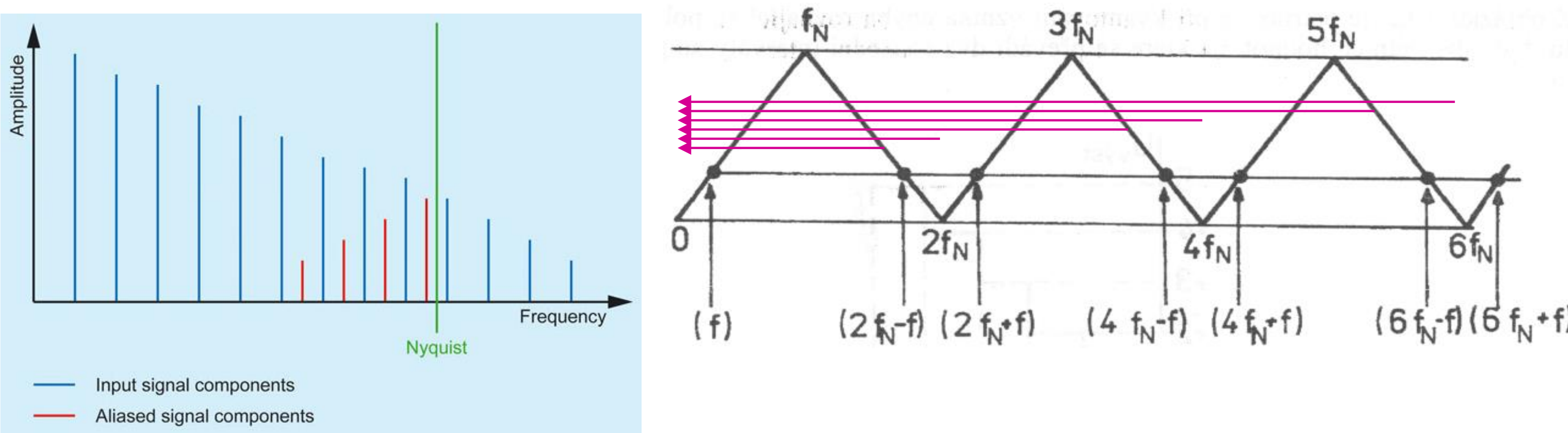
square wave



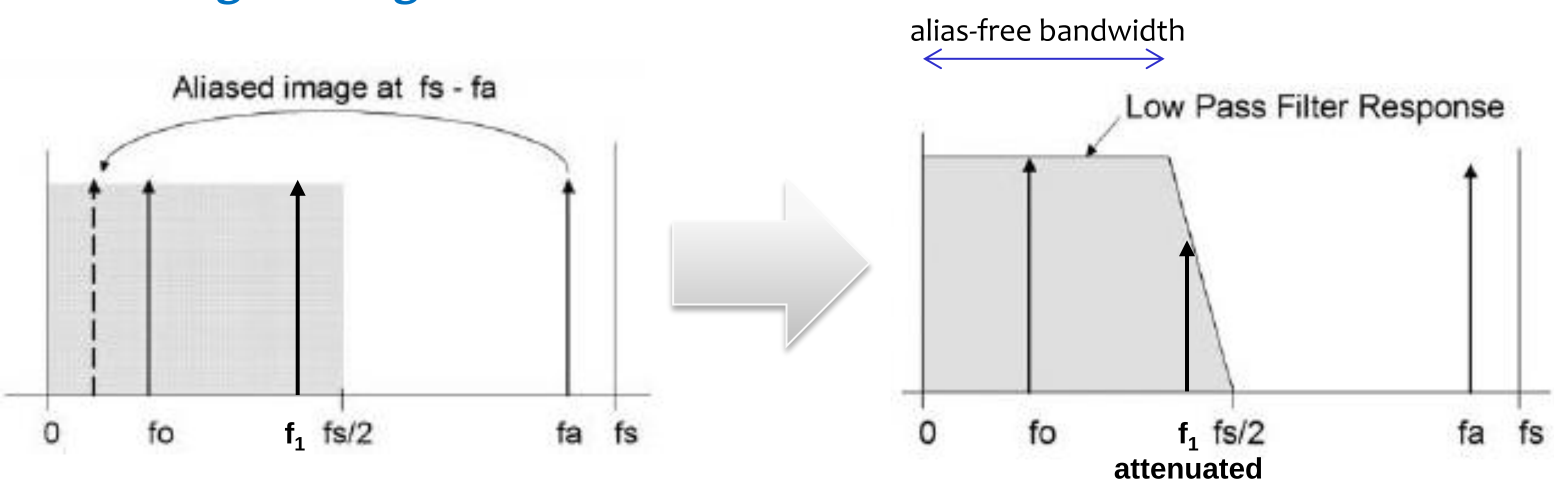


Aliasing

Discrete spectrum

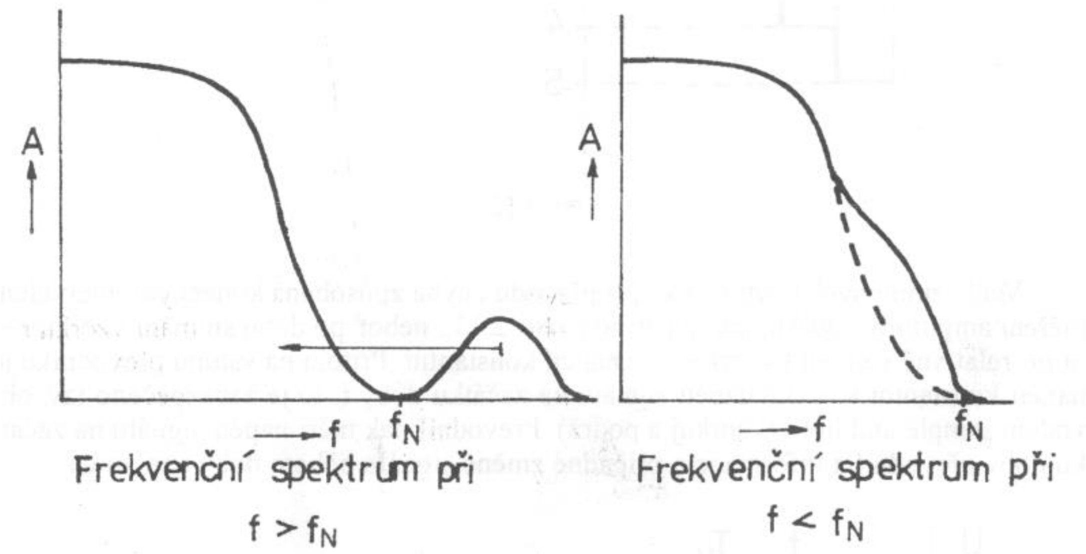


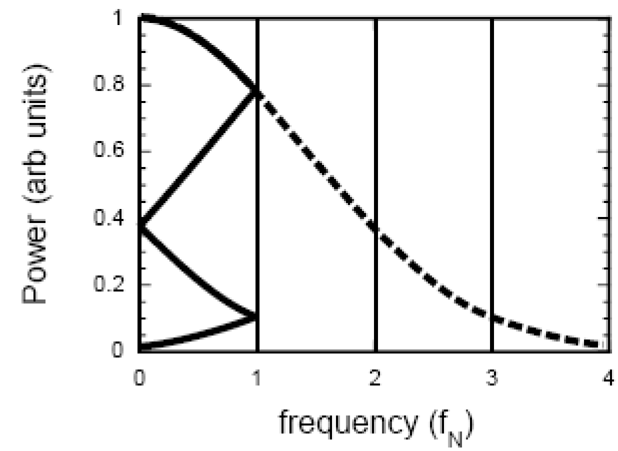
Anti-aliasing filtering



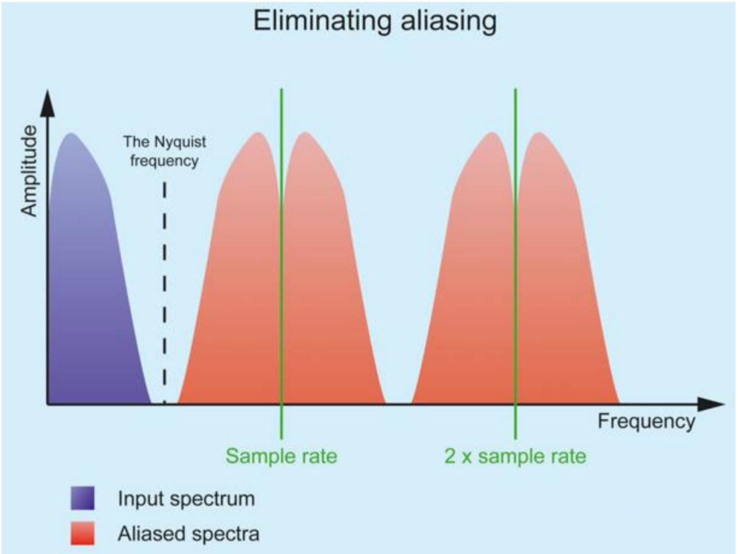
Aliasing

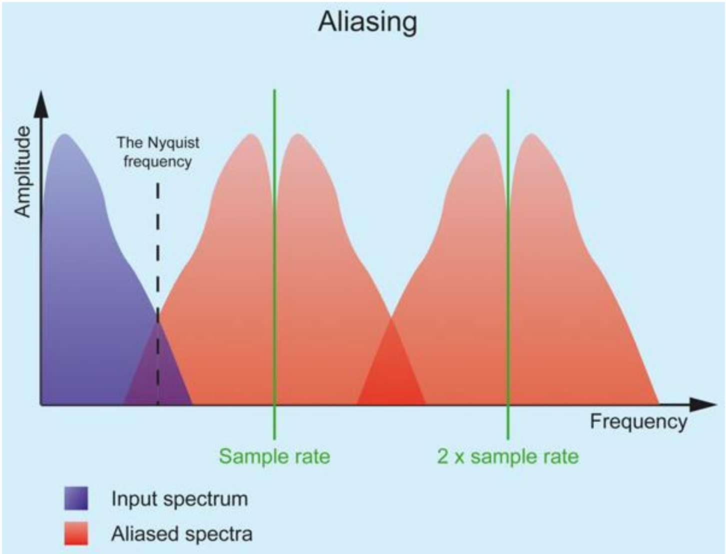
Continuous spectrum





Alias pattern repeats for every integer multiple of the sampling frequency

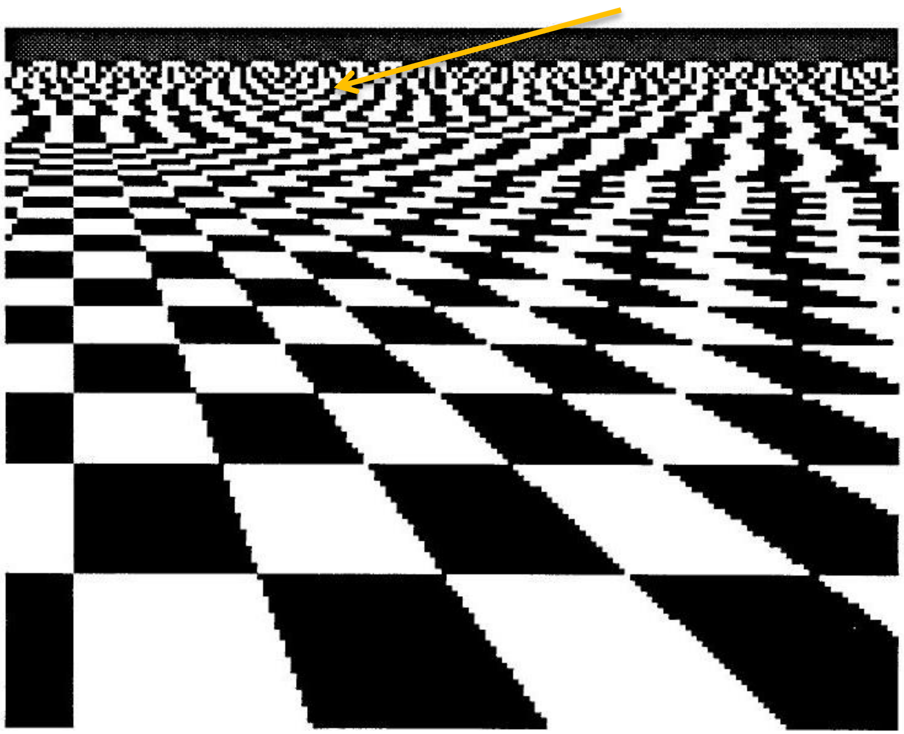


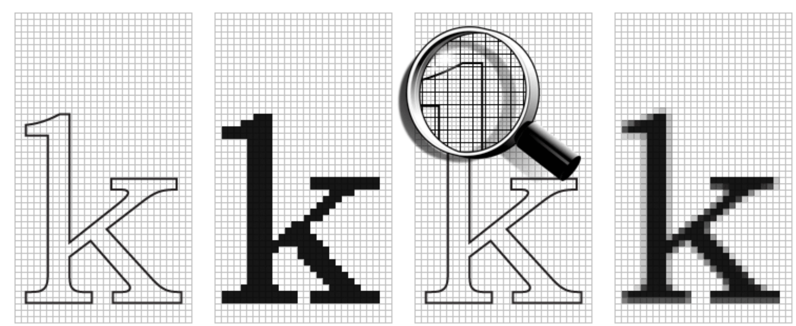


Aliasing

Analogue in pixel graphics (time <-> space sampling)

Texture creates moire near horizon



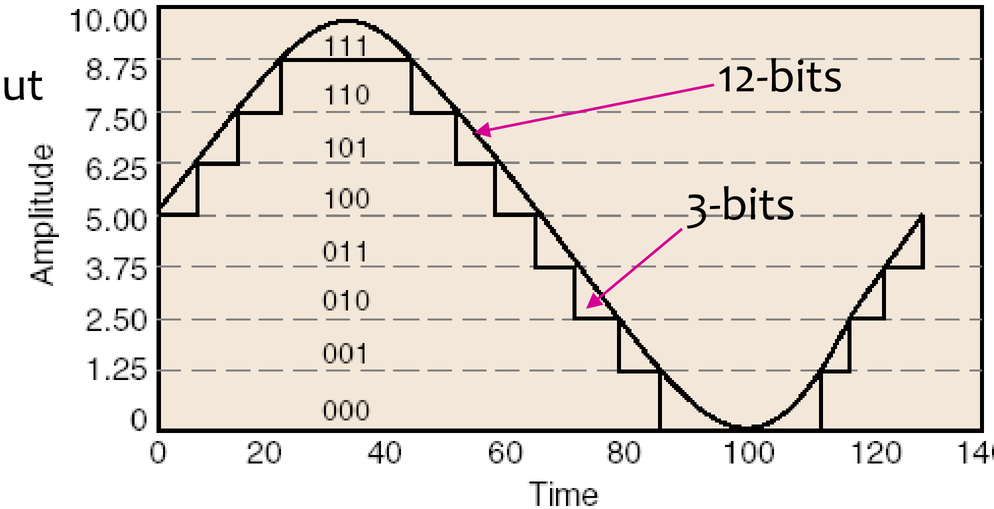


→ related to Dithering

Characteristics of A/D converters

Specifications

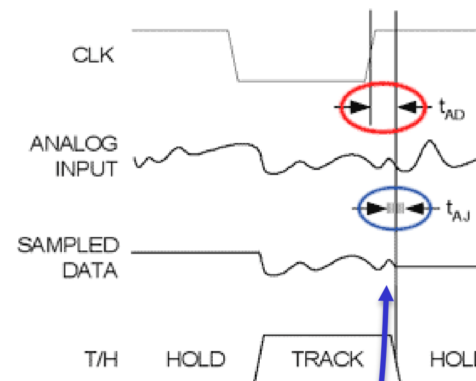
- **(Dyn.) Range** – operating range of input
- **Resolution** – output resolution in bits
- **Sampling rate** – limited mainly by OA response (settling) time
- **Number of channels**
- **Multiplexing capability**
- **Sample size limit**



Accuracy factors

- **Quantization error** – depends on bit resolution
- **Linearity** – linear proportionality of analog and digital signal → differential and integral non-linearity error
- **Jitter** – inaccuracy of sampling clock

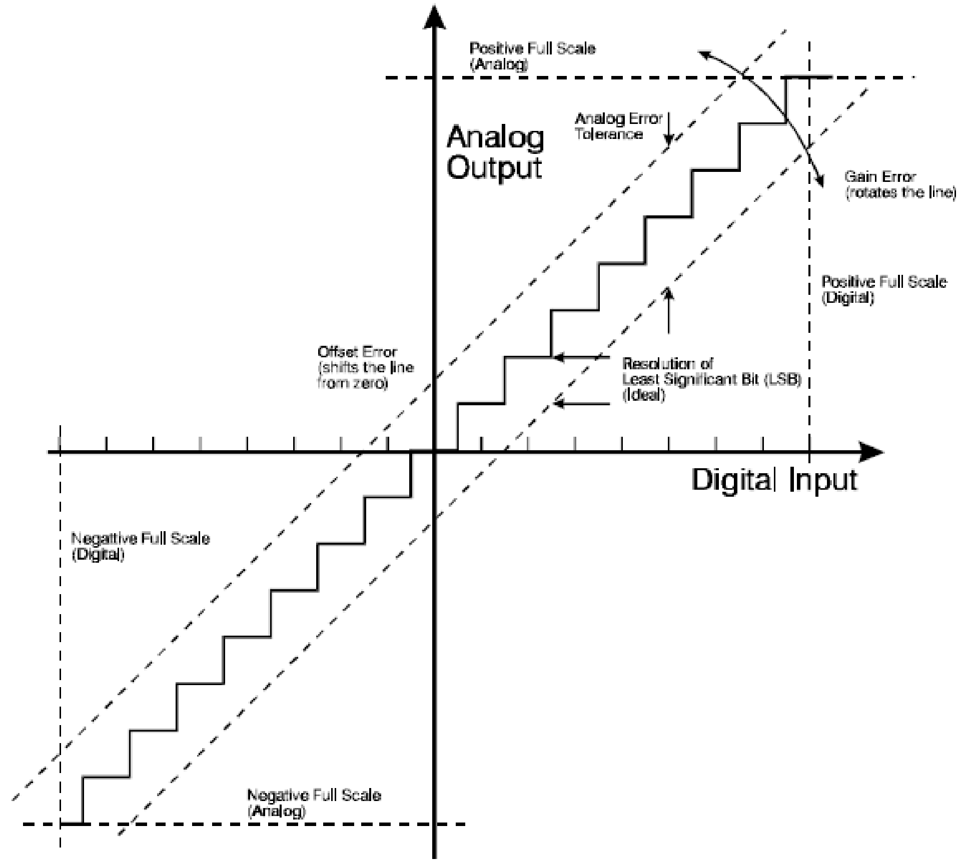
fázová nestabilita
- **Aperture error (jitter)** – hold signal delay and uncertainty in sample/hold time
- **Noise level** – intrinsic noise of ADC circuit
- **Offset** – additive static error
- **Gain error** – multiplicative static error



Characteristics of D/A converters

Specifications

- **Range** – range (and polarity) of output voltages
- **Resolution** – effective output resolution in voltage levels (determ. by ENOB – eff. number of bits)
- **Conversion rate** – output change time upon input change (OA slew rate)
  rychlost přeběhu OZ
- **Number of channels**
- **Reference type** – fixed or multiplying D/A (variable ref. – current output ∝ A×U_{ref})

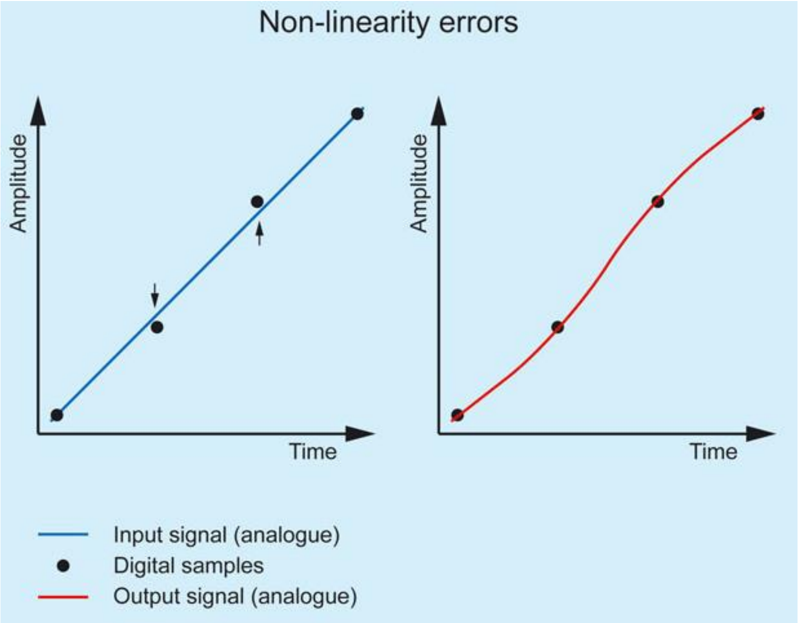


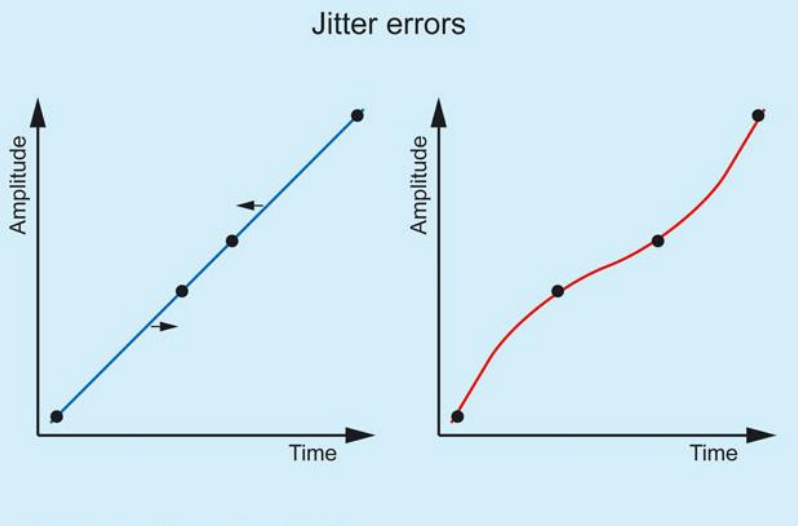
Specifications of a Digital-to-Analog Converter

Accuracy factors

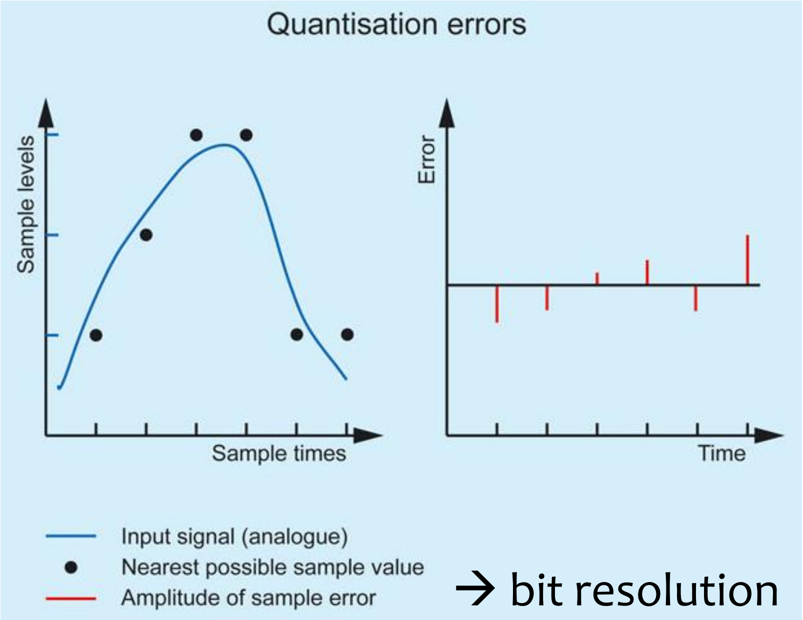
- **Linearity** – linear proportionality of digital and analog signal
- **Stabilization time** – response time
- **Offset** – additive static error
- **Gain error** – multiplicative static error
- **Noise level** (analog error) – intrinsic noise of DAC circuit

A/D converter errors





→ clock accuracy



→ bit resolution

Quantization

Quantization

= process of mapping input values from a large set (often continuous) to output values in a smaller (countable) set

Quantization error

= noise created by limited resolution of ADC board (adds ~0.5 LSB_{rms} Gaussian white noise)

– determined by **quantization resolution**

$Q = E_{FSR} / 2^m$

$E_{FSR} = V_{hi} - V_{low}$ (full scale voltage range)

→ quant. signal/noise ratio odstup signálu od kvantizačního šumu

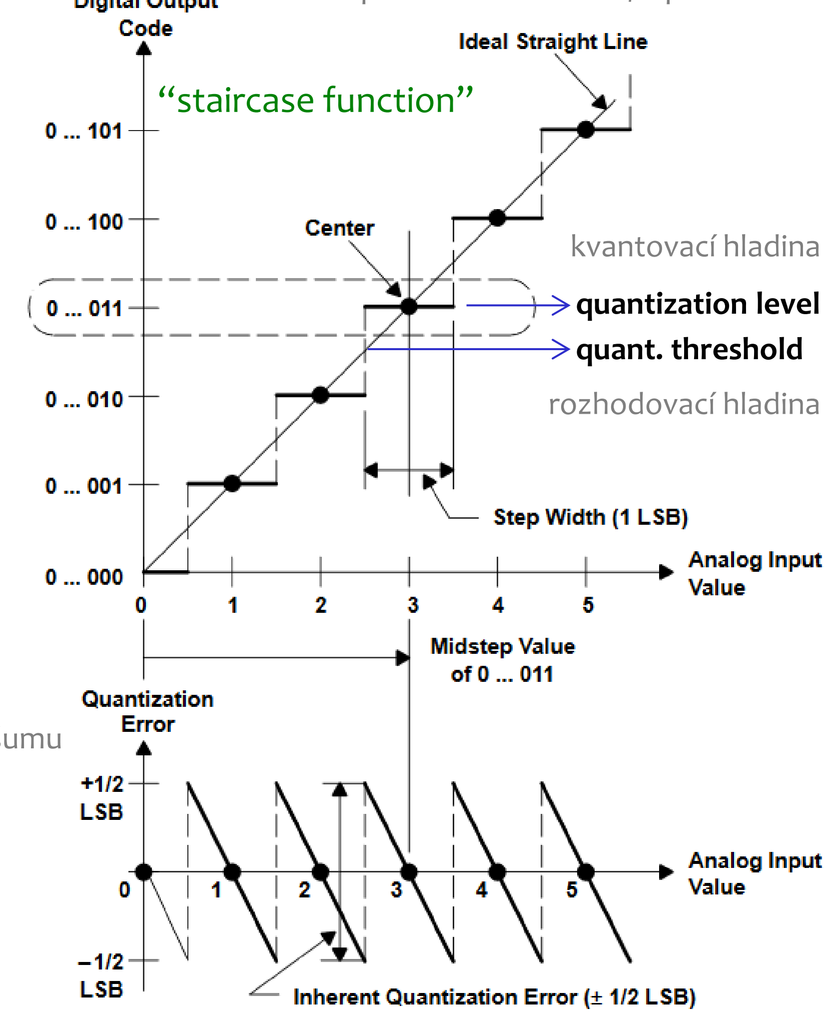
$$SQNR = 20 \log_{10}(2^m) \approx 6.02\ m\ [dB]$$

(for ideal ADC: uniform noise distribution between ±1/2LSB)

– can be reduced by higher quant. resolution, oversampling, or dithering

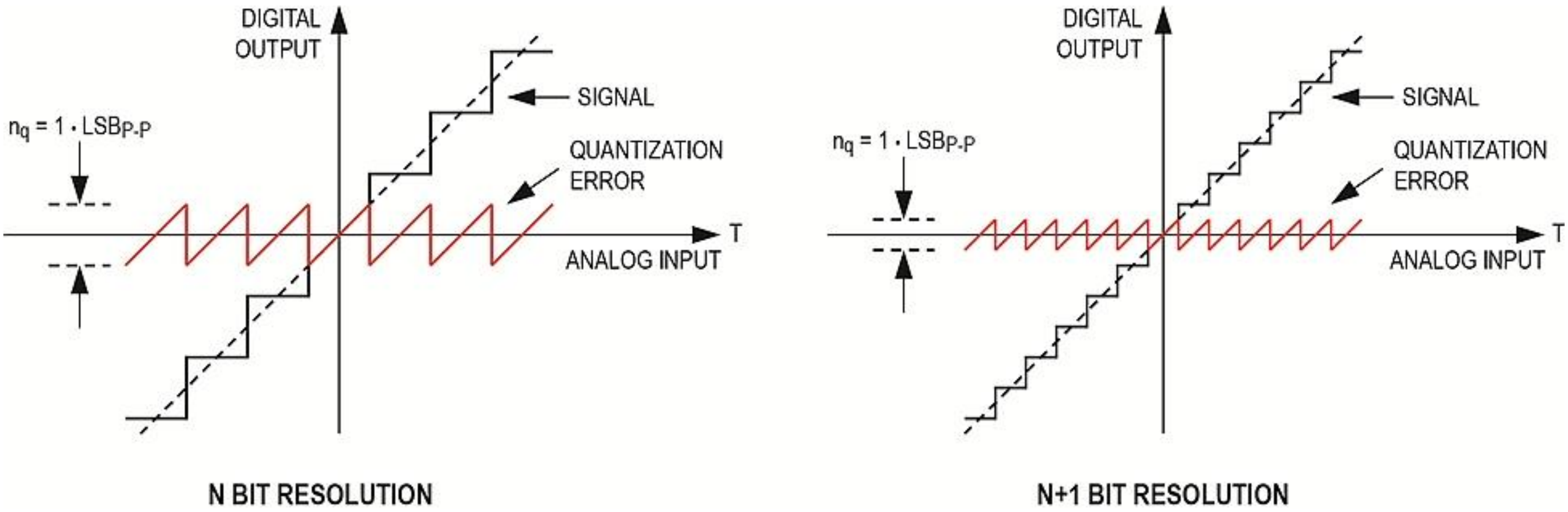
Ideal (linear) transfer function (ADC)

přenosová funkce A/D převodníku

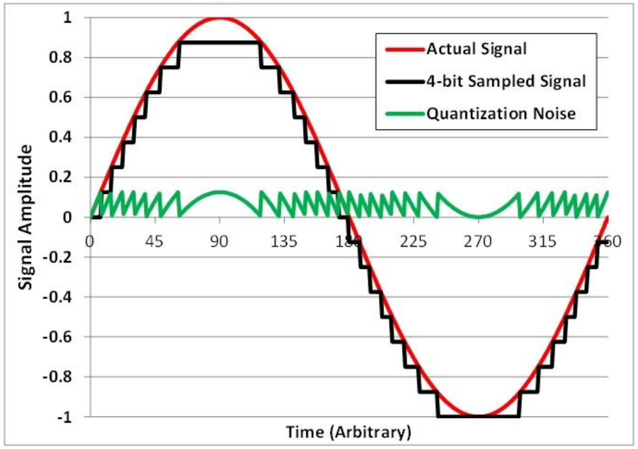


Quantization

Quantization (transfer, A/D conversion) function



Quantization error example



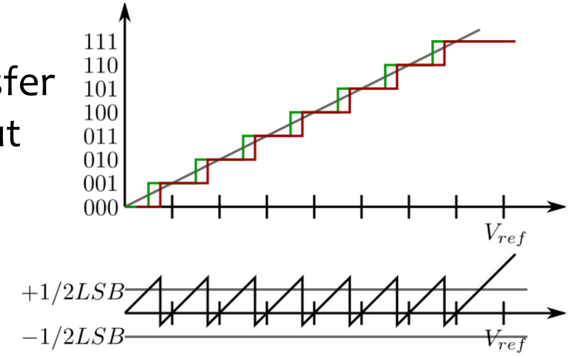
Non-linear quantization

– quantization levels more dense for lower signals => quantization quality (S/N) independent of signal level

Quantization errors

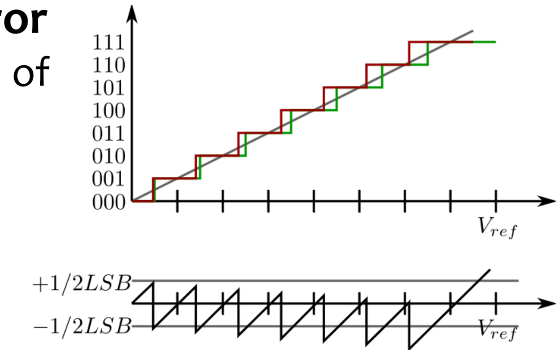
Offset

= deviation of transfer function in the input axis



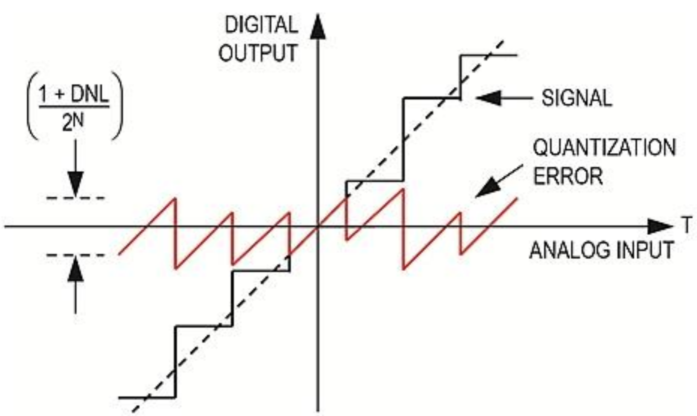
Relative (gain) error

=change in the slope of transfer function



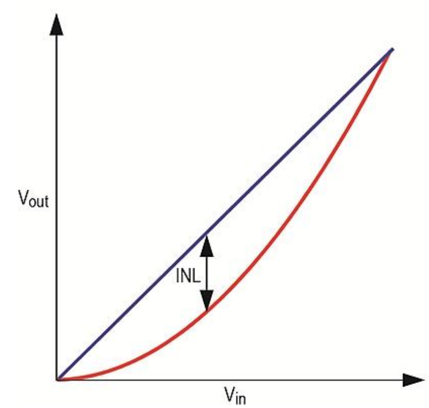
Differential non-linearity (DNL)

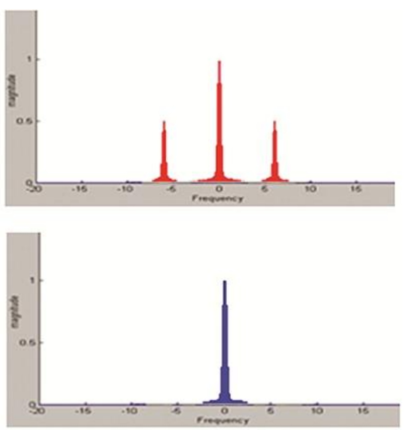
= deviation of any code width from an ideal 1 LSB step (i.e. **from previous level**)



Integral non-linearity (INL)

= maximum deviation of the output **from the ideal transfer function** after gain and offset errors have been removed





quant. signal/noise ratio including DNL

$$SQNR = 20 \log_{10}(2^m/(1+DNL)) \quad [dB]$$

Harmonic distortion

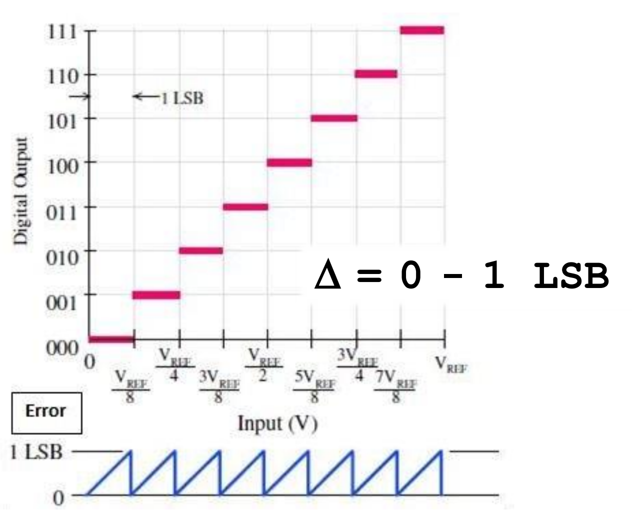
harmonické zkreslení

= error caused by presence of unwanted harmonics

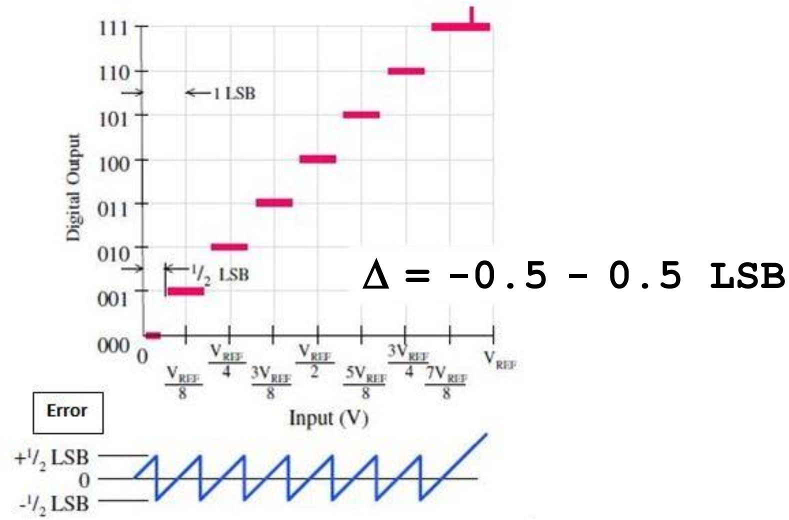
– correlated with INL

Conversion errors – misc.

Uncompensated quantization



Compensated quantization



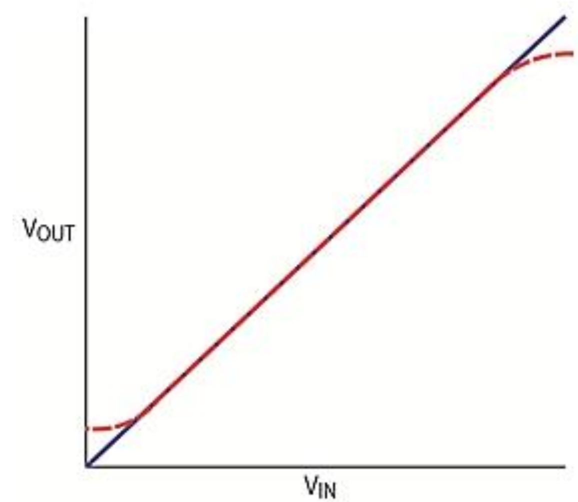
Output buffer distortion

= transfer function distortion near power and ground rails of output buffer OA

→ leads to compression and clipping near extremities

– V_{out} can get within ~20-30 mV of OA rails

– increases with current load at output



Non-monotonicity

– may cause stability problems

D/A conversion errors

Impact of D/A convertor non-linearities on transfer function

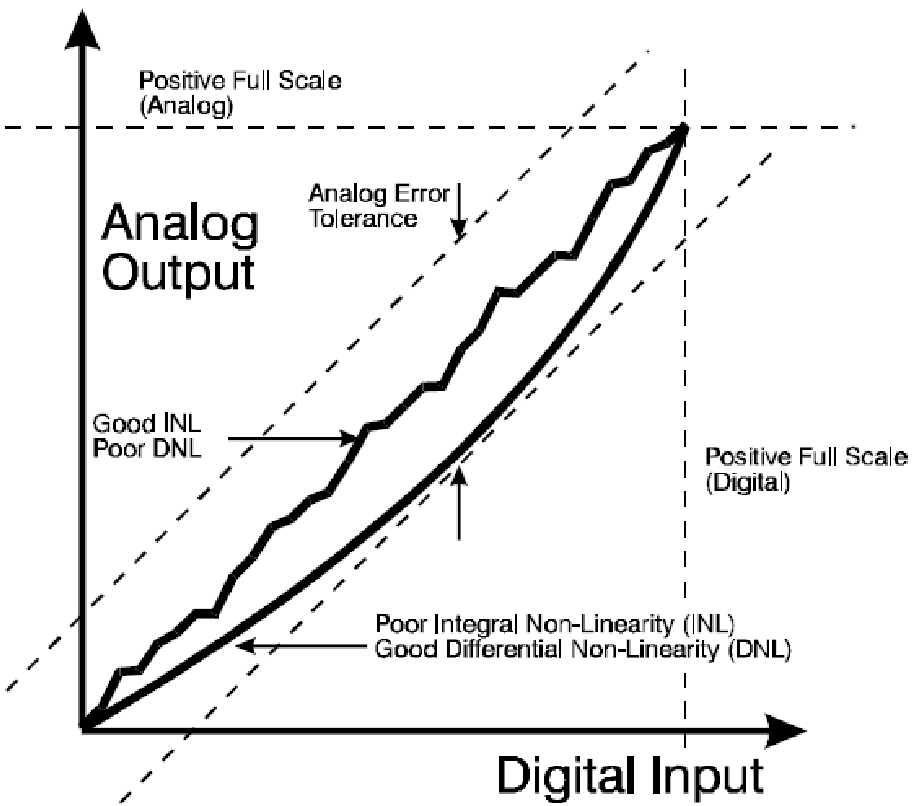
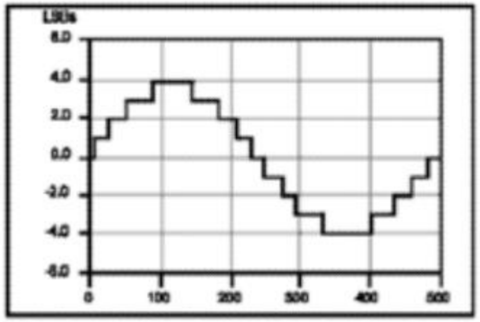


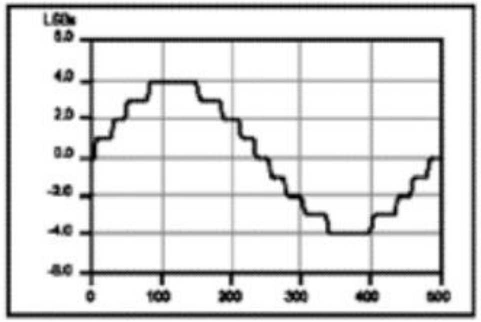
Illustration of Integral Non-Linearity and Differential Non-Linearity in a Digital-to-Analog converter

Dithering

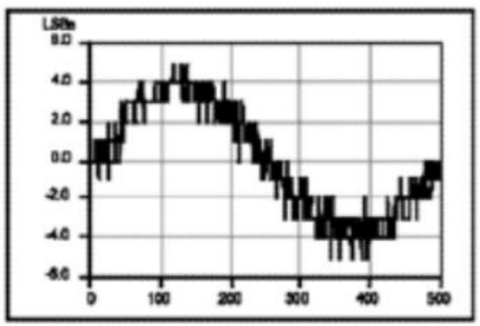
Dithering = resolution improvement beyond ADC specification by adding small Gaussian white noise to the input signal, digitization, and averaging



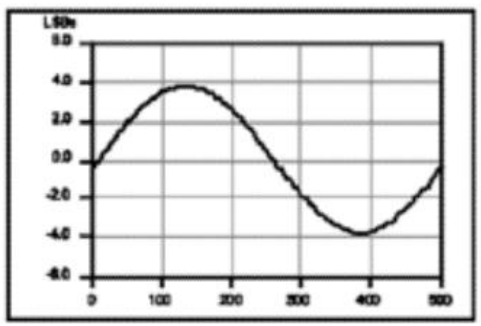
dither disabled, no averaging



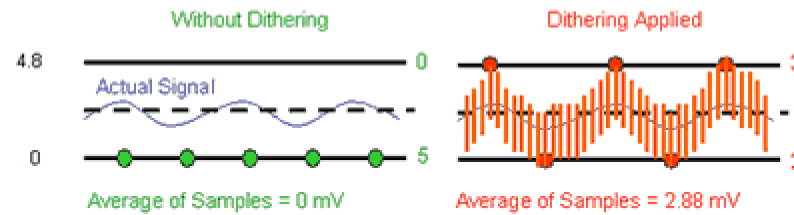
dither disabled, average of 50 acq.



dither enabled, no averaging

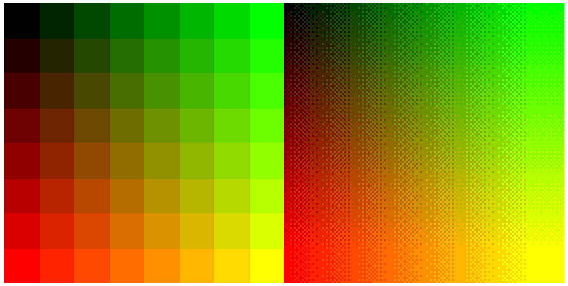


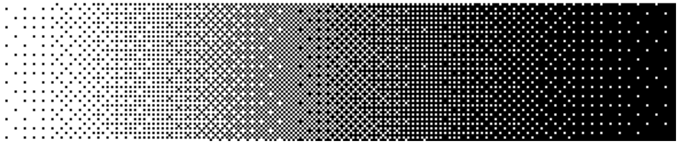
dither enabled, average of 50 acq.



12-bit → "14-bit"

Analogue in pixel graphics



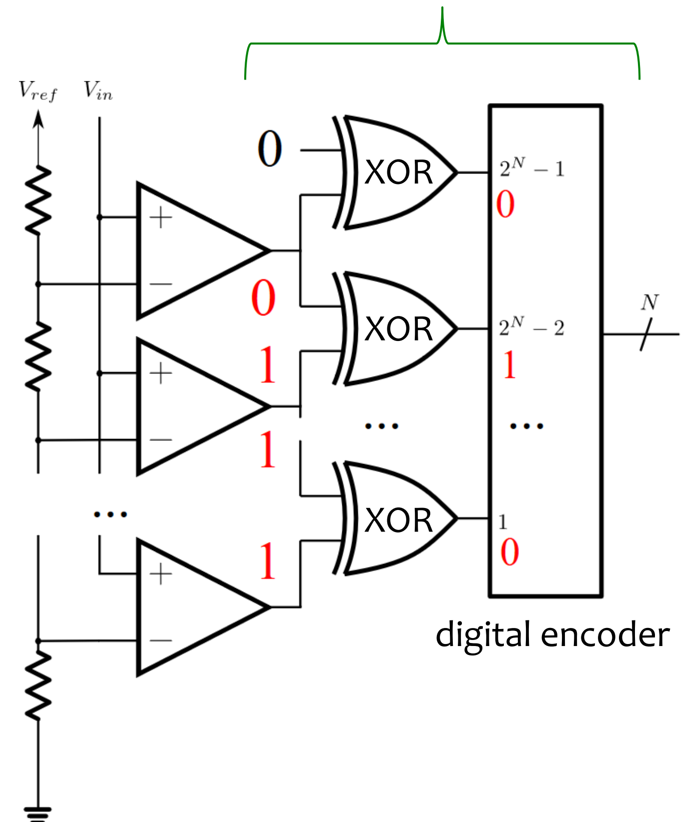


A/D converter architectures

Flash ADC (direct-conversion ADC) Paralelní ADC

– resistive ladder divides $\mathbf{V_{in}}$ to $\mathbf{2^N}$ equal parts
=> **N** bits <--> $\mathbf{2^N-1}$ comparators

Priority encoder
– translation of "gauge signal" into a binary code

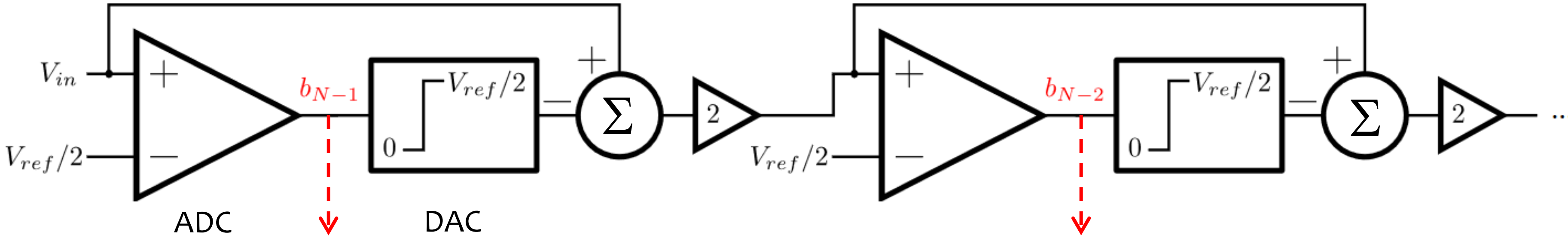


+ very fast (instant)
- doubles in size for each bit added => expensive
- high input capacitance ($\mathbf{2^N-1 * C_{comparator}}$)
- consumes a lot of power

A/D converter architectures

Pipelined ADC (subranging quantizer)

– step-wise conversion: at each step, the input signal is compared to half the reference value
– number of steps ~ number of bits (if 1bit ADCs used)
– high bit-resolution ADC can be built from more low-res ADCs (often flash ADCs)



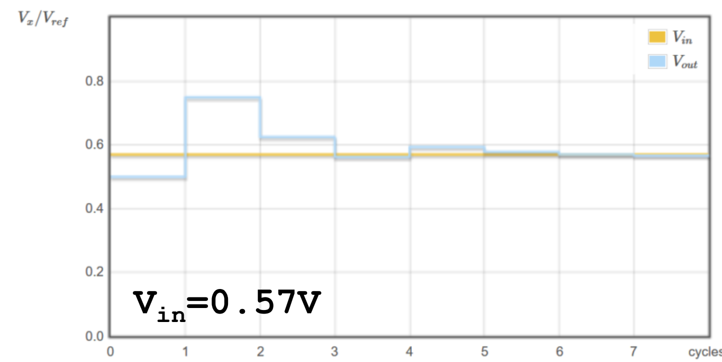
+ very fast (high throughput; almost as flash ADC) - each stage can process a new bit as soon as the previous residue is passed
+ number of stages up to ~ **N** (1bit ADCs)
+ inexpensive
- high latency (up to **N** cycles)
- error accumulation (errors passed to next stage)

A/D converter architectures

Successive Approximation Register (SAR) ADC

ADC s postupnou aproximací (metoda vážení)

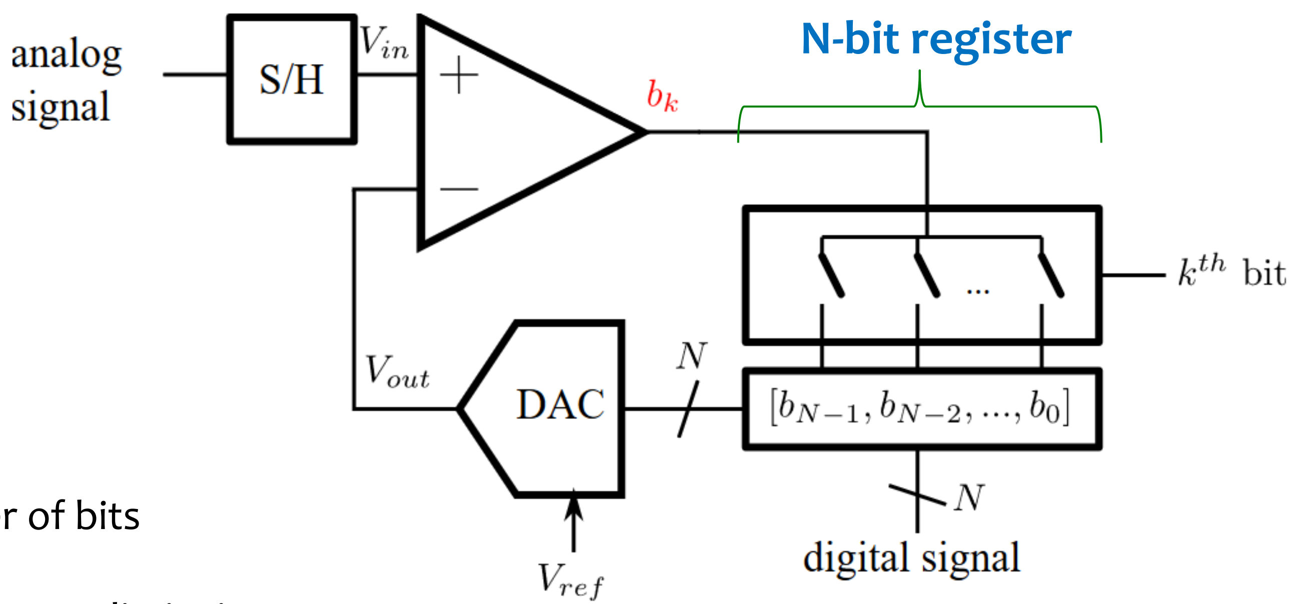
– evaluates each bit at a time – from the most to the least significant



2 steps:

1. **Comparison**: Set bit to 1 and compare the output of the DAC with the input voltage
2. **Latching**: Latch the result of the comparator to the same bit in the register

=> analogue of a balance scale

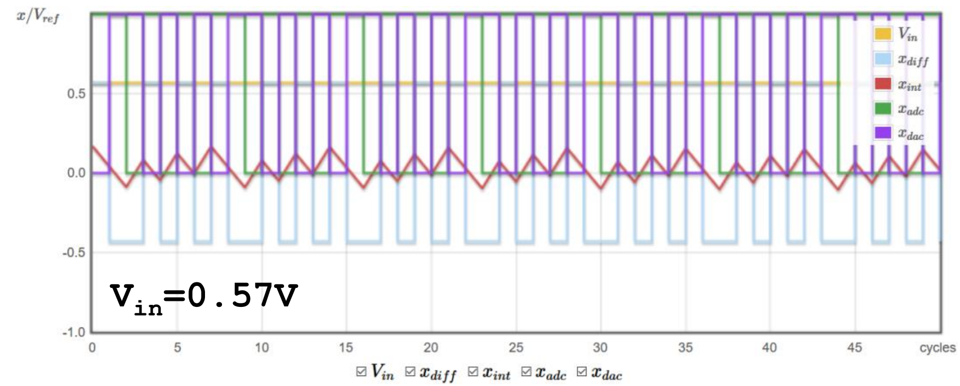


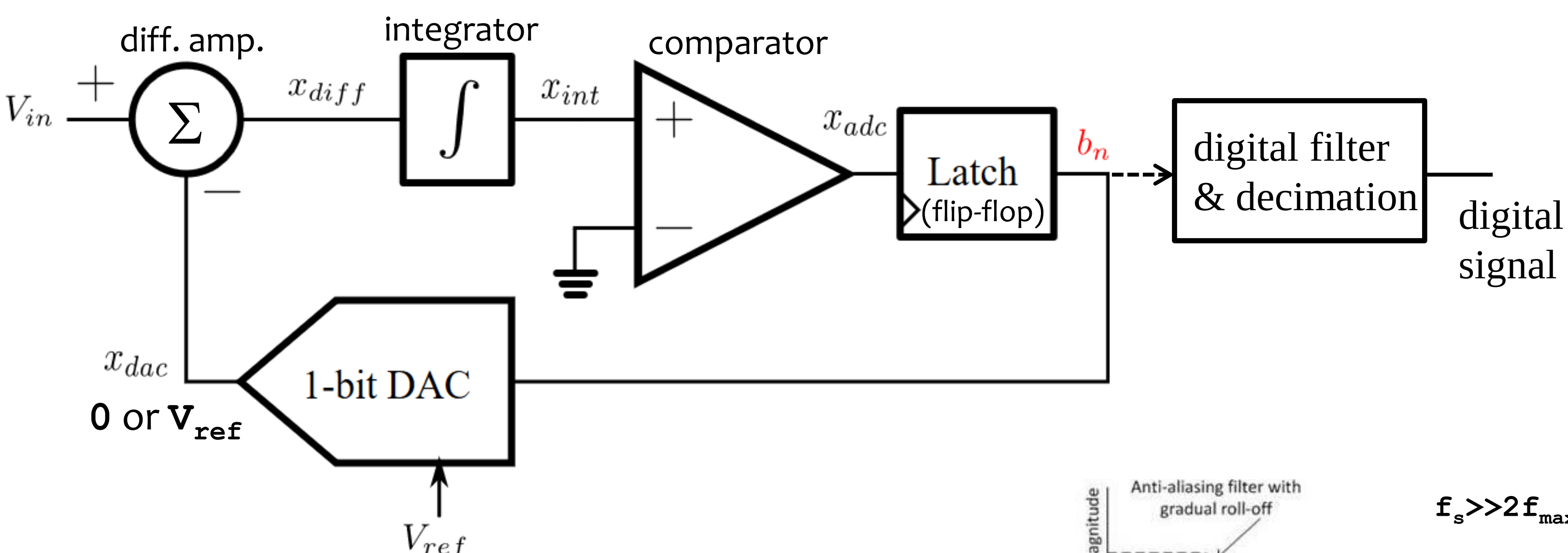
+ only one comparator
+ low power consumption
- DAC grows with the number of bits
- number of cycles = N
- component mismatch in the DAC limits its linearity (and therefore of the ADC) to ~ 12bit

A/D converter architectures

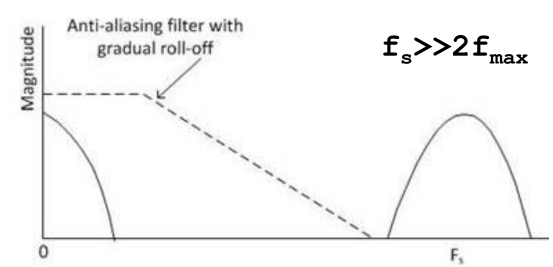
Sigma-Delta ADC
("oversampling converter")

– large oversampling (up to hundreds ×)
– integrates error between reference signal and input signal
– stream of 1s and 0s → conversion to binary code by **decimation filter**





+ inherent antialiasing filtering
+ higher resolution (SQNR): f_s x 4 => equiv. of adding a bit
  (24-bit ADC common)
- large latency => slower than SAR ADCs
- not very suitable for multiplexed inputs (due to latency and oversampling)



A/D converter architectures

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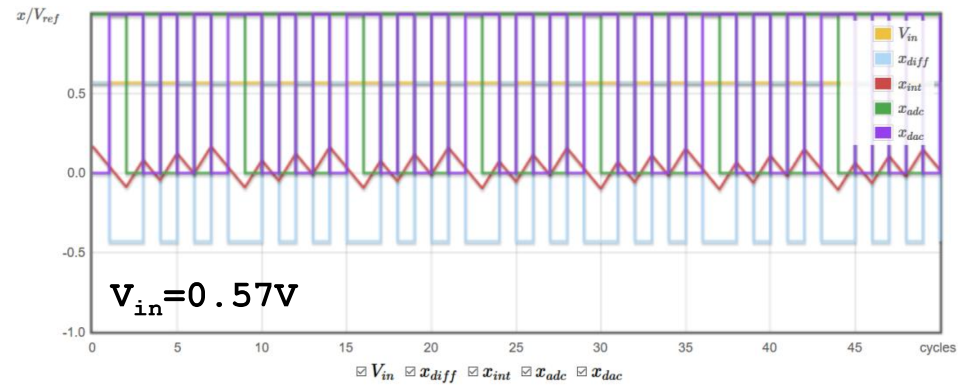

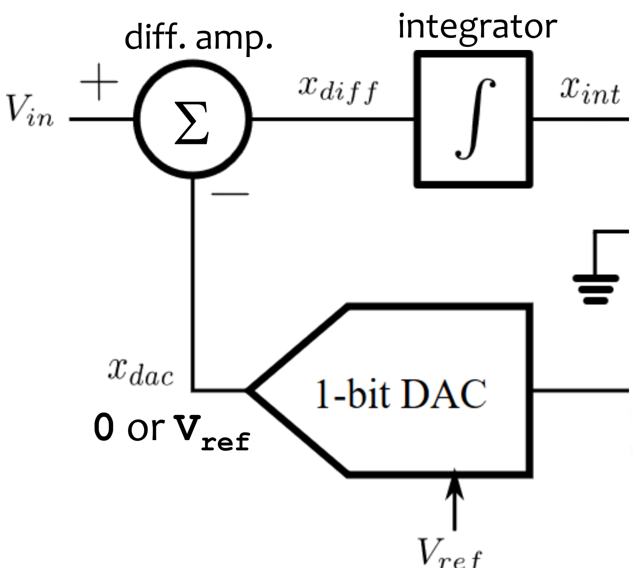

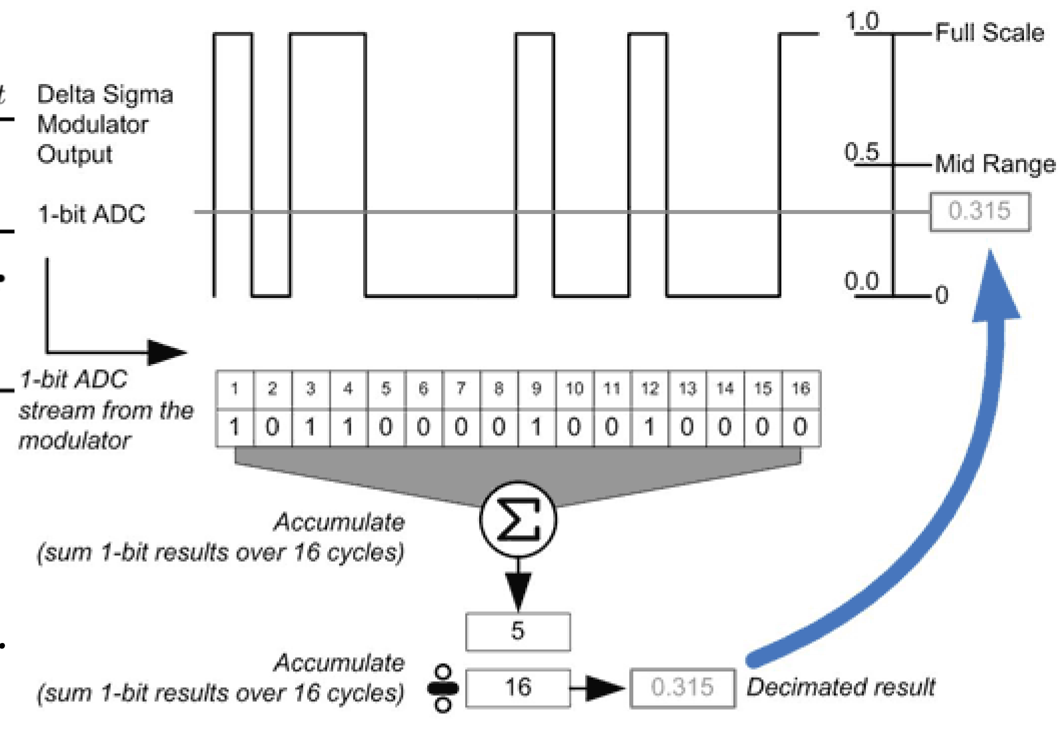

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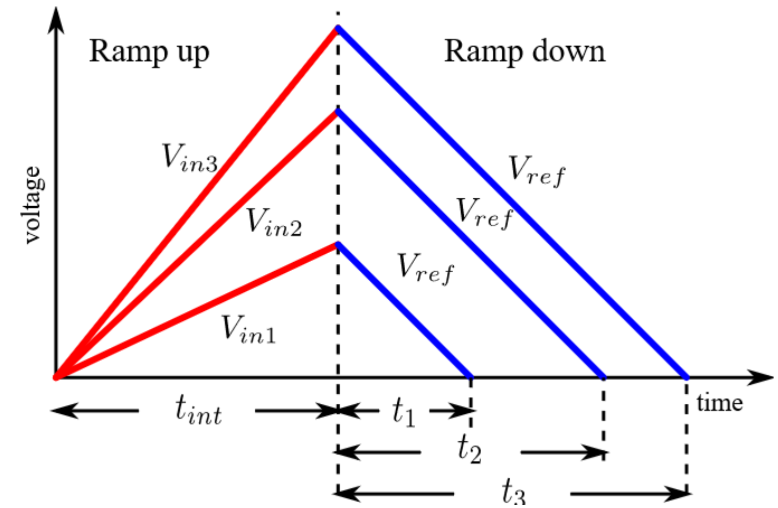
A/D converter architectures

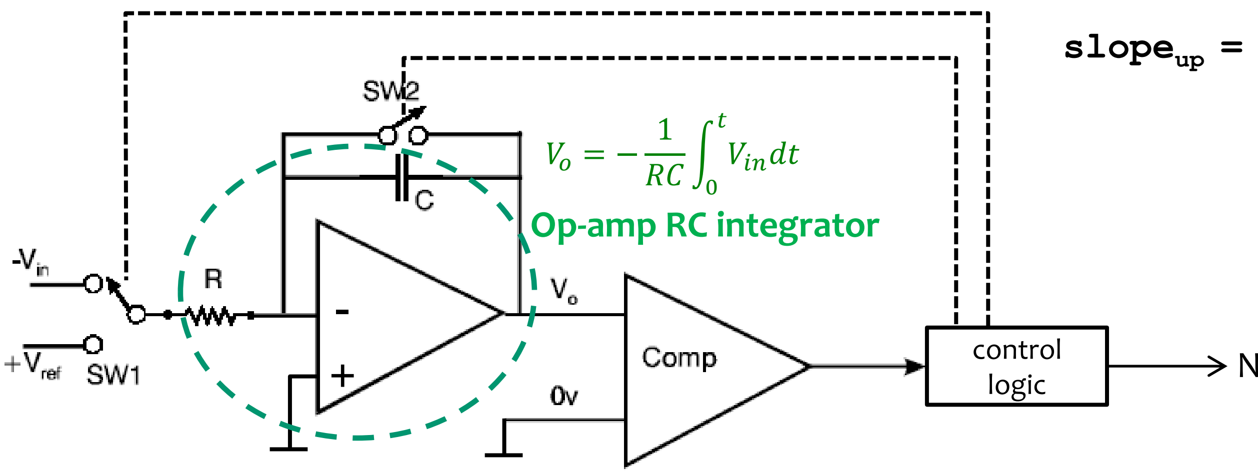
Integrating (Dual-slope) converter ADC s dvojitou integrací

– use counters to generate the output

2 steps:

1. **Ramp up**: voltage ramps up with slope proportional to the input voltage V_{in} for a fixed period of time t_{int}
2. **Ramp down**: output voltage ramps down with slope proportional to a fixed voltage V_{ref}





$\text{slope}_{up} = V_{in}/RC \quad \text{slope}_{down} = -V_{ref}/RC$

$$V_{in} = V_{ref}\ t/t_{int}$$

\+ very precise

(only sources of errors: 1) V_{ref}, 2) comparator; clock and RC int. instabilities compensated)

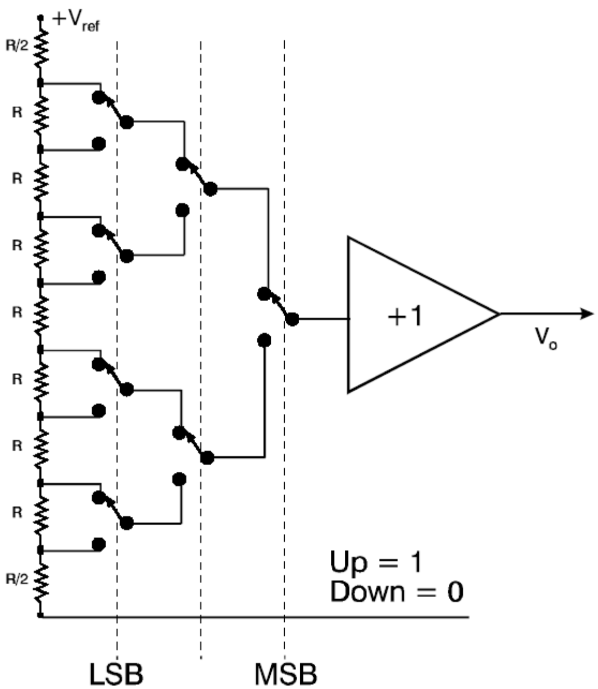
\- slow

(and doubles with each bit added)

D/A converter architectures

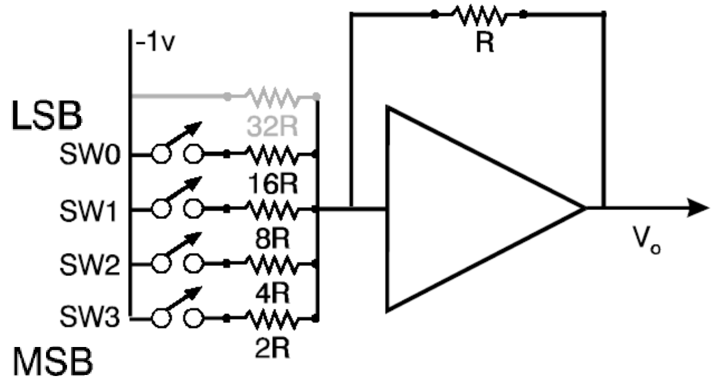
Kelvin divider (Resistor string) DAC

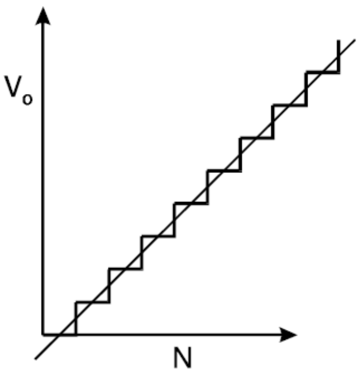
DAC s odporovým řetízkem



Binary weighted network DAC

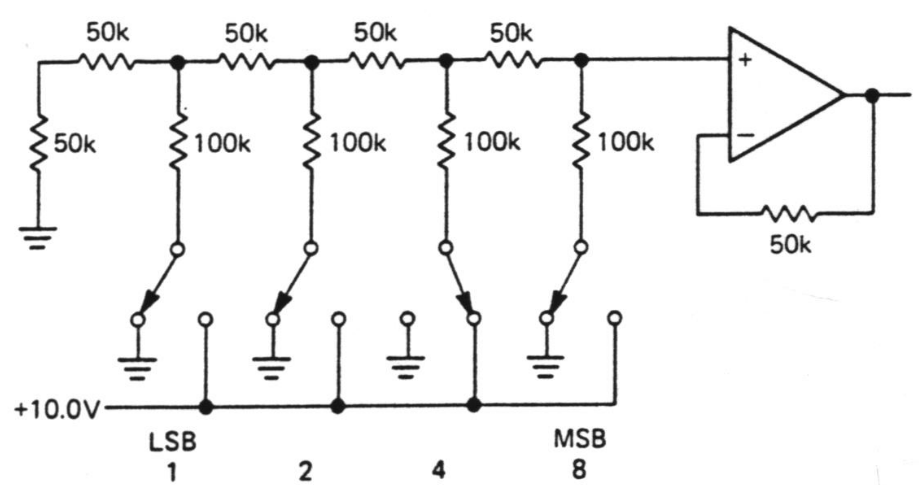
Sumační DAC





R–2R ladder network

DAC s odporovým žebříčkem R–2R



Switches realized by
digital change-over switches
between reference and ground

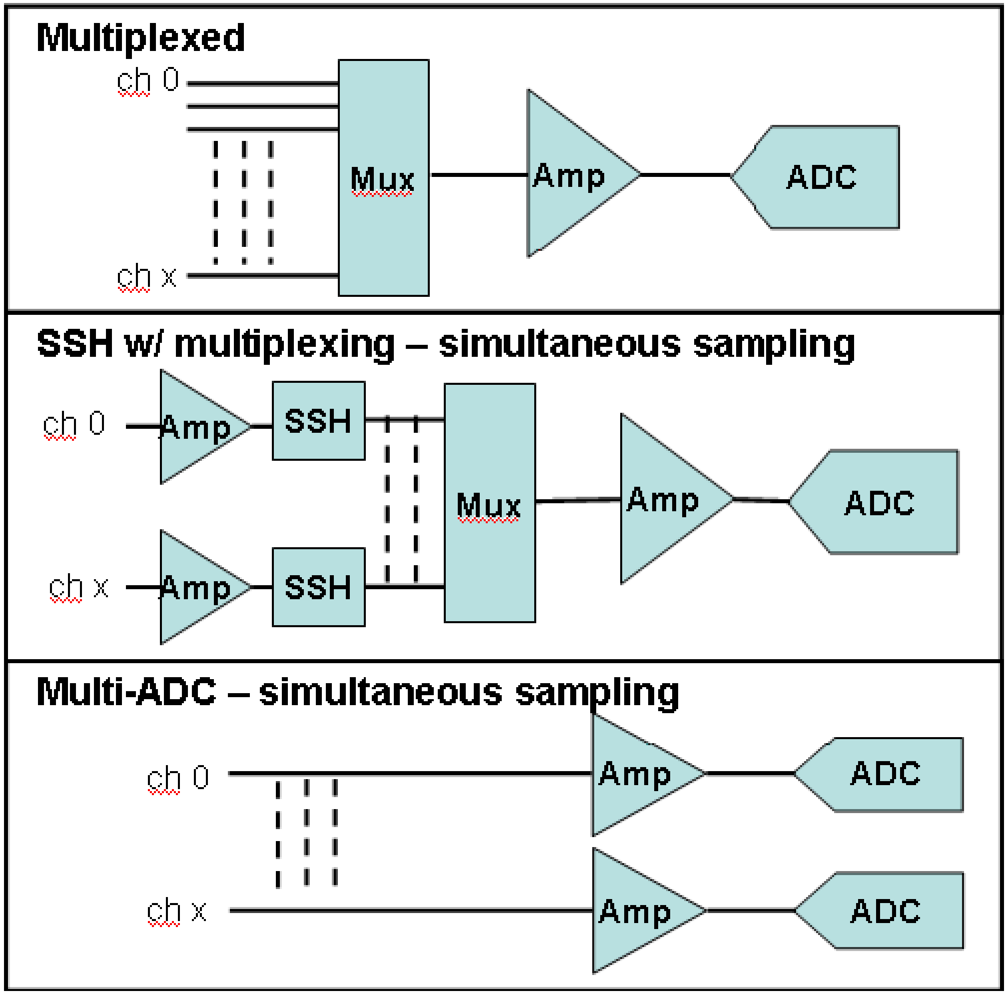
Multichannel sampling

Multiplex sampling
– sampling of more channels at different times
– OK for processes with δt >> *sampling rate*

Simultaneous sampling architectures
– sampling of more channels at the *exactly* same time

Simultaneous Sample and Hold (SSH)
– derivative of multiplexed architecture (most common in mid- to high-channel-count data acquisition devices)
– SSH circuits track incoming signals; at scan beginning they are put in hold and scanned with delays

Multi-analog-to-digital converter (multi-ADC)
– derivative of multiplexed architecture (most common in mid- to high-channel-count data acquisition devices)



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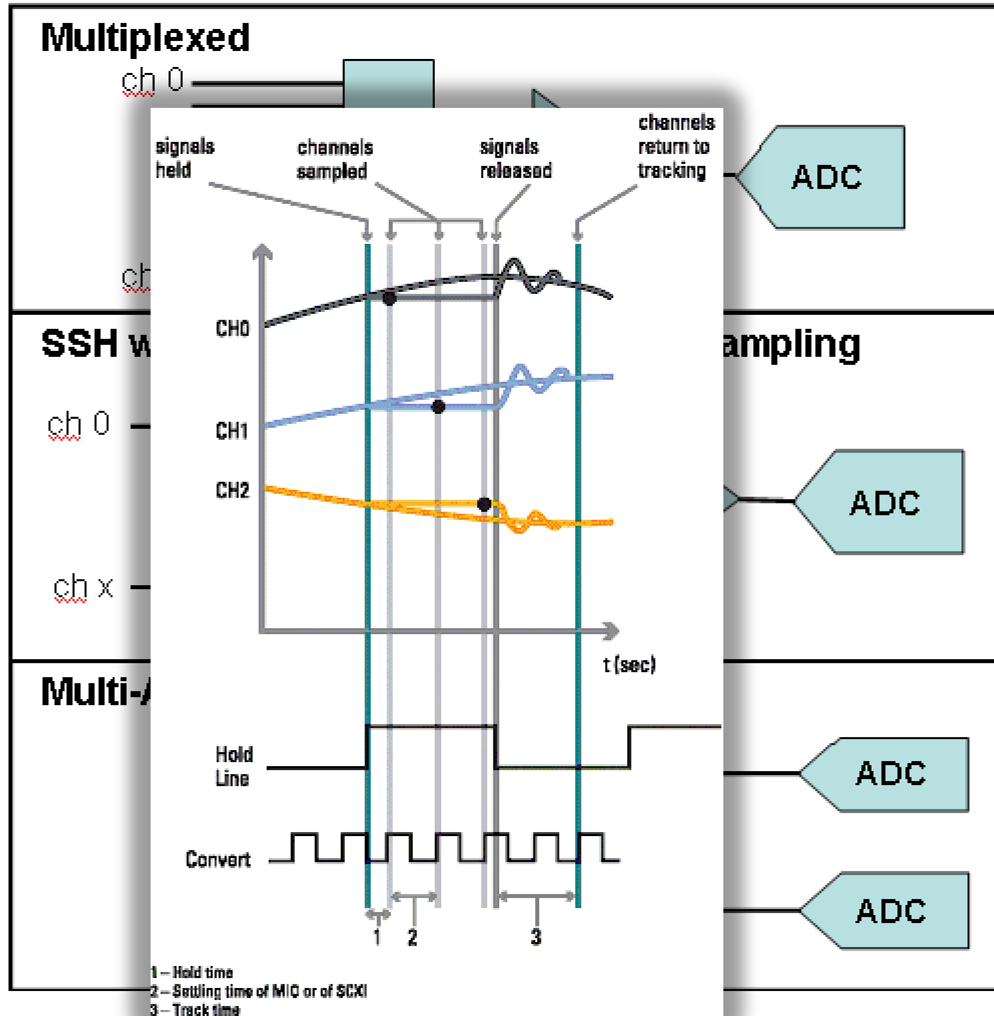


Experimental data acquisition and processing IV

Time series I

* Logic signals
* Timing of logic signals & timing errors
* Time and frequency measurement
  * counters
  * indirect and direct methods

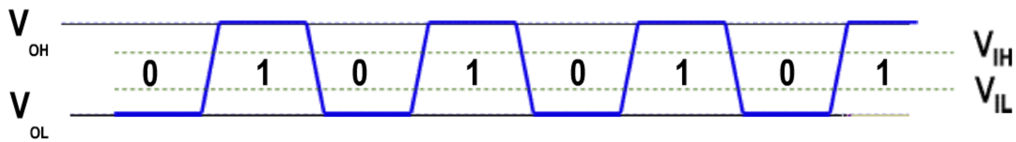
Logic signals – basic definitions

Logic signals

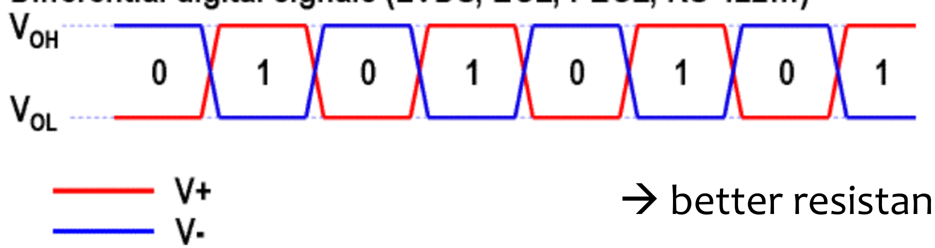
Single-ended digital signals (TTL, CMOS, RS-232…) signal + reference (gnd)

H = logic „1“

L = logic „0“

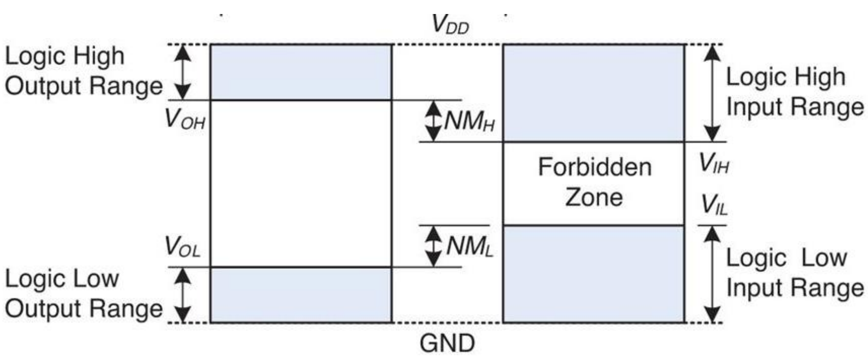


Differential digital signals (LVDS, ECL, PECL, RS-422…) 2 complementary signals



→ better resistance to elmg. noise

Logic levels



Family	Voltage Range	SE	Diff
CMOS	0 to 5V	*	
TTL	0 to 5V	*	
LVTTL	0 to 3.3V	*	
LVCMOS	0 to 3.3V	*	
ECL	-1.6 to -0.8V		*
PECL	3.4 to 4.2V		*
LVDS	1.03 to 1.38V		*
Other…			

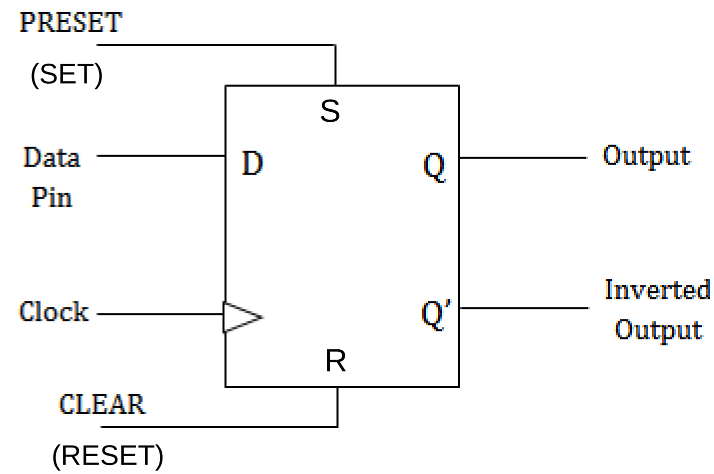
- **Combinational logic** – output depends on present value(s) only
- **Sequential logic** – output depends on present value(s) & input history (=> needs memory)

Logic signals

D Flip-flop

– "Data" or "delay" flip-flop

– memory element: Input (D) captured for a definite portion of the clock cycle and carried to output (Q); at other times Q doesn't change



D Flip Flop Truth Table

CL (Note 1)	D	R	S	Q	$\overline{Q}$
↑	0	0	0	0	1
↑	1	0	0	1	0
↓	x	0	0	Q	$\overline{Q}$
x	x	1	0	0	1
x	x	0	1	1	0
x	x	1	1	1	1

No Change
x = Don't Care Case

Note 1: Level Change

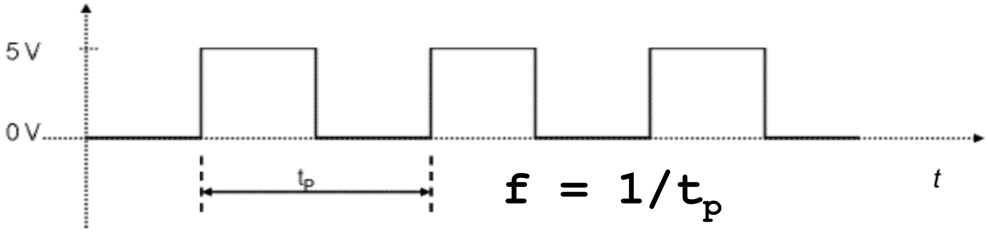
Logic signals timing – basics

Clock signal

– oscillates between L & H

– most commonly square signal with 50% duty cycle

– synchronization at rising edge, falling edge, or both (double data rate) → **active edge**



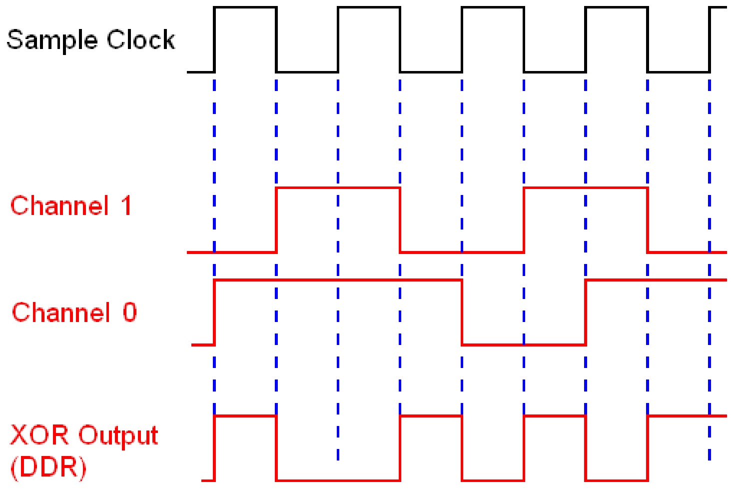
kvalifikátor

Qualifier signal – additional signal, determines when D is considered valid (and hence recorded); used in specific cases

Digital timing diagram

= representation of signal set in time domain

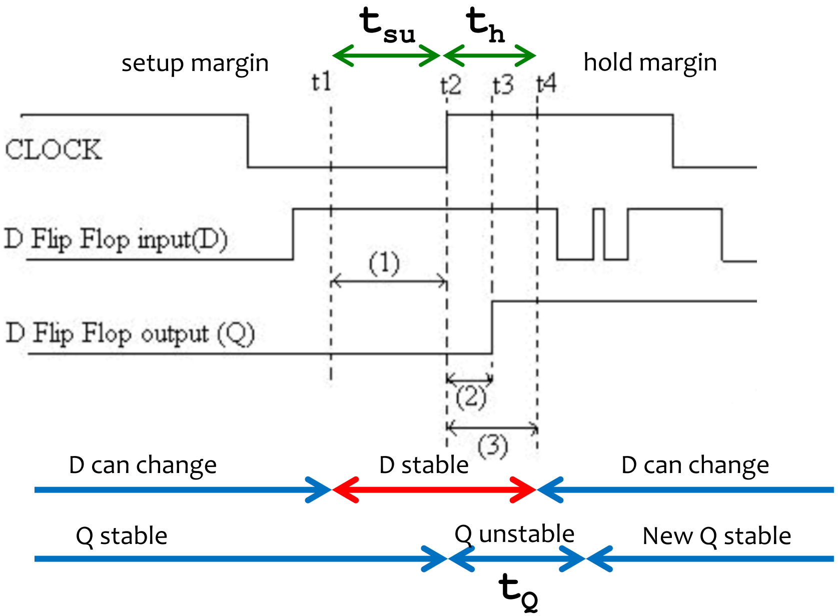
XOR example



Setup and hold diagram

předstih **setup time** = min. time of const. input **before** clk tick

přesah **hold time** = min. time of const. input **after** clock tick

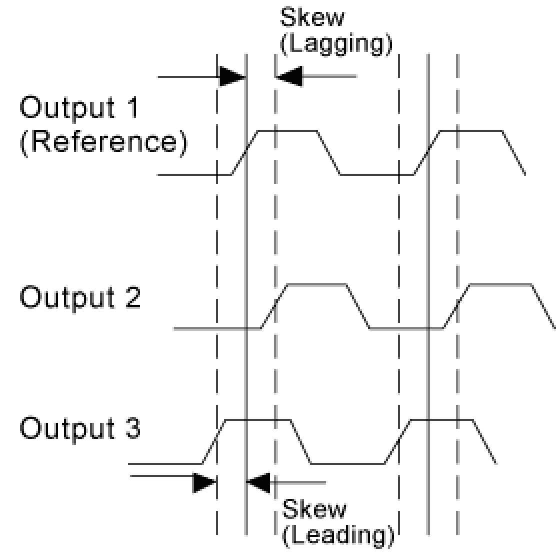


Timing signal accuracy and errors

Skew zpoždění

– caused by static mismatches (positive or negative) → **Slew rate** (strmost)

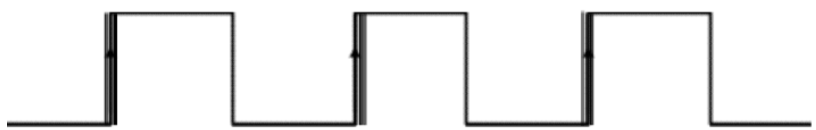
=> constant from cycle to cycle (does not change period)



Jitter fázová nestabilita

– temporal uncertainty of clock edge

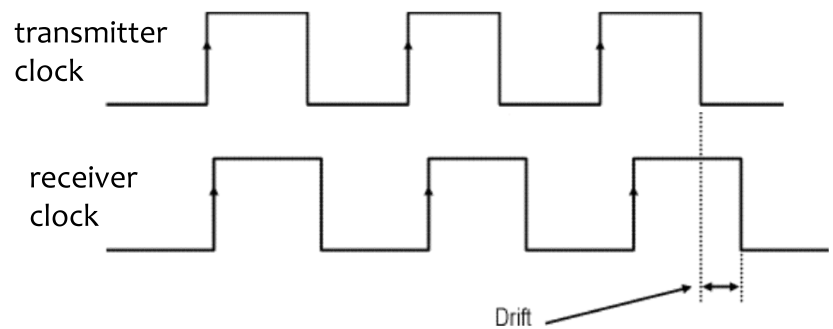
=> changes on a cycle-to-cycle basis (temporal period variations)



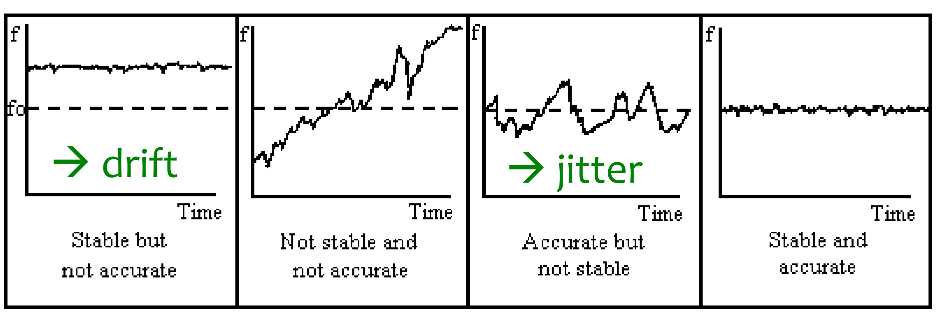
Drift

– progressive clock de-synchronization

=> accumulates over time (systematic period variation)



Components of Clock Error



Synchronization = process of setting clocks to the same **time**

Syntonization = process of setting oscillators to the same **frequency**

Time & frequency measurements

Types of time and frequency information

- **Date and Time-of-Day**
  – records when an event happened
- **Time Interval**
  – duration between two events
- **Frequency**
  – rate of a repetitive event

International standard for the **second**: 9,192,631,770 periods of an electron transition between 2 hyperfine levels of the ground state in ^{133}Cs
Best cesium clock accuracy ~5×10^{-16} (<1 s in 50M years) – most accurate standard

Frequency bands (radio- and micro-wave region)

Band	Description	Frequency	Wavelength
VLF	Very Low	3 – 30 kHz	100 – 10 km
LF	Low	30 – 300 kHz	10 – 1 km
MF	Medium	300 – 3000 kHz	1 km – 100 m
HF	High	3 – 30 MHz	100 – 10 m
VHF	Very High	30 – 300 MHz	10 – 1 m
UHF	Ultra High	300 – 3000 MHz	1 m - 10 cm
SHF	Super High	3 – 30 GHz	10 - 1 cm
EHF	Extremely High	30 – 300 GHz	1 cm – 1 mm

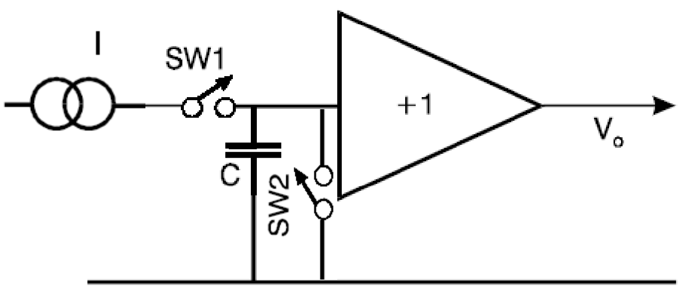
Time & frequency measurements

Indirect measurement

1. Time (period, pulse length) or frequency of input signal converted to analog signal
2. AD conversion → amplitude determination

Duration of very short pulses

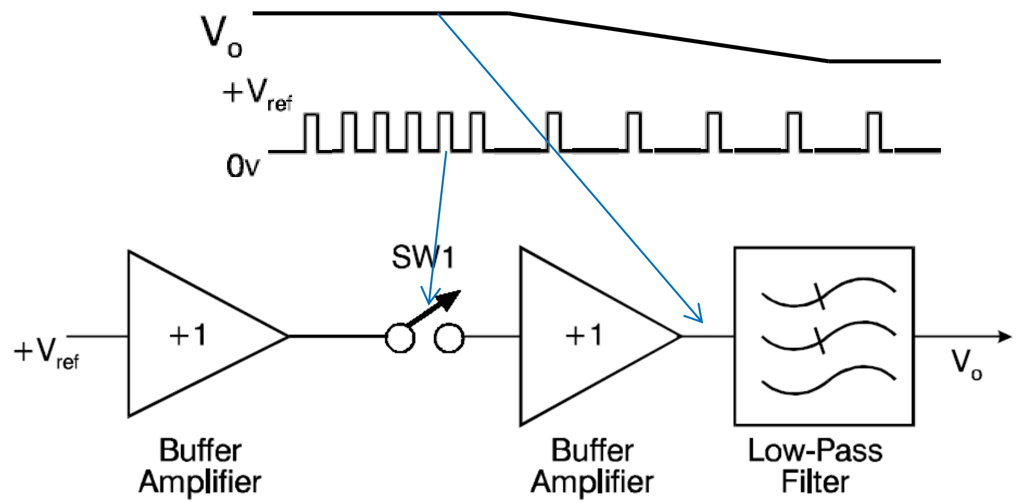
– voltage (charge) on C ~ pulse duration controlling SW1
– for $<10^{-9}$ s



$$V_o = I/C * \Delta t$$

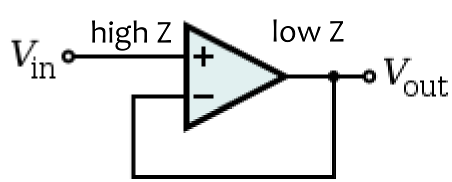
Frequency of constant-length pulses

– voltage V_o ~ pulse duration controlling SW1



$$V_o = \langle f * \tau \rangle * V_{ref}$$

Buffer amplifier
(A=1 → V follower)



Clocks and counters

Clock

1. frequency source (oscillator)
2. counter
3. output device

Counter

= digital sequential logic device that will go through a certain predefined states (e.g. counting up or down) based on input pulses

Up-down (bidirectional) counter – allows counting in both directions

Types of counters

- **Asynchronous** (ripple cnt.) – output of one flip-flop feeds the clock of the following flip-flop
- **Synchronous** – each flip-flop clocked by the same clock => cumulative delay eliminated

Main parameters

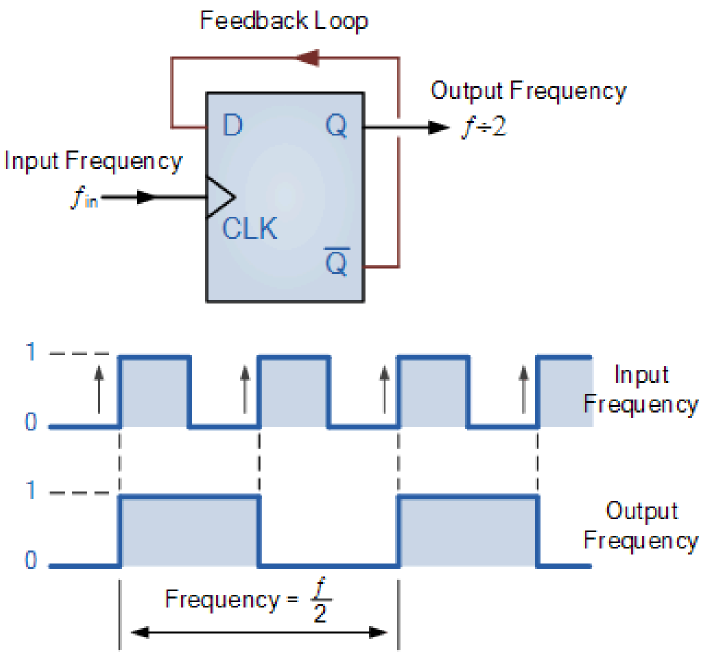
- Max. frequency
- Length (in bits)
- Oscillator stability

Applications

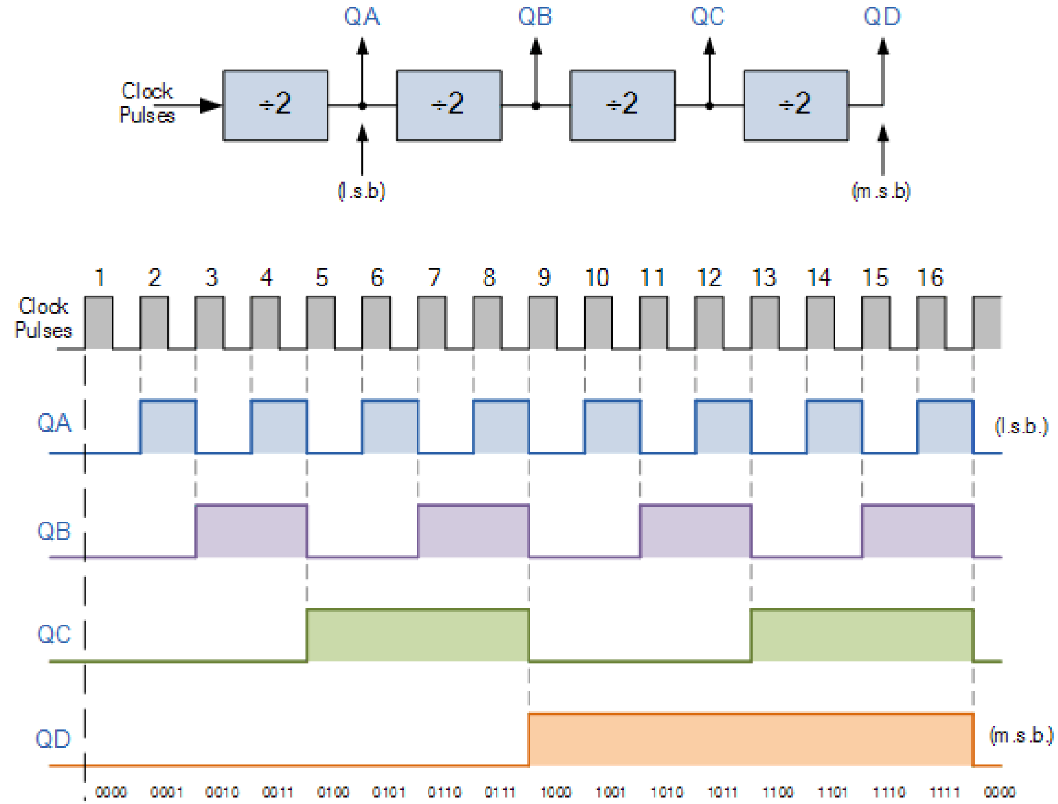
- Frequency counters
- Digital clocks
- Incremental (position) sensor
- Analog-to-digital convertors
- Frequency divider
- TTL signal generator

Counters

Divide-by-2 counter



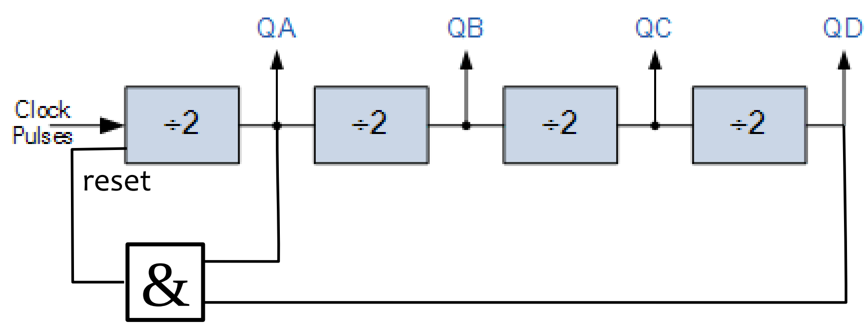
4-bit (modulo-16) counter



BCD (mod-10) counter

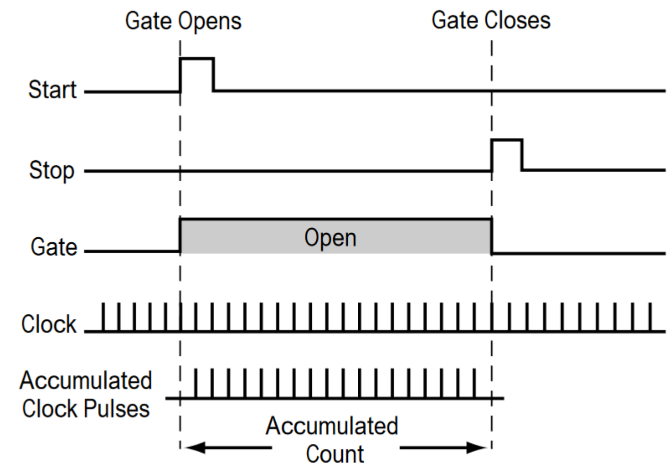
Truth Table

count	Q_D	Q_C	Q_B	Q_A
0 [start]	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
10 [new cycle]	0	0	0	0



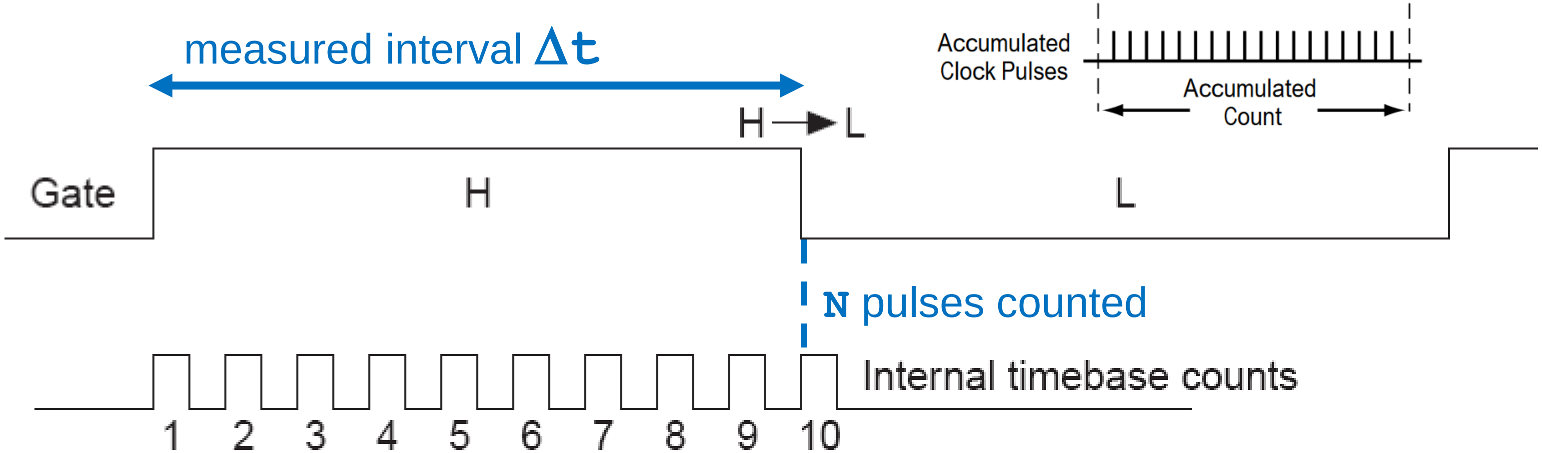
Time & frequency measurements

Direct time measurement (digital gate method)
– using counter and reference frequency source: $F=1/T$



$\Delta t = N/F$

Accuracy: N accuracy ± 1 => $\delta t = 2T$



Timebase = 20 MHz, Period = 1000 ns, Frequency = 1 MHz, with an error of 100 ns

Accuracy refinement:

- **Residual ramp interpolator** – compensation of uncomplete start and stop periods
- **Vernier scale (nonius) method** – 2 similar incommensurate frequencies, 2 counters

  $$T=(N_1-1)/F_1-(N_2-1)/F_2$$

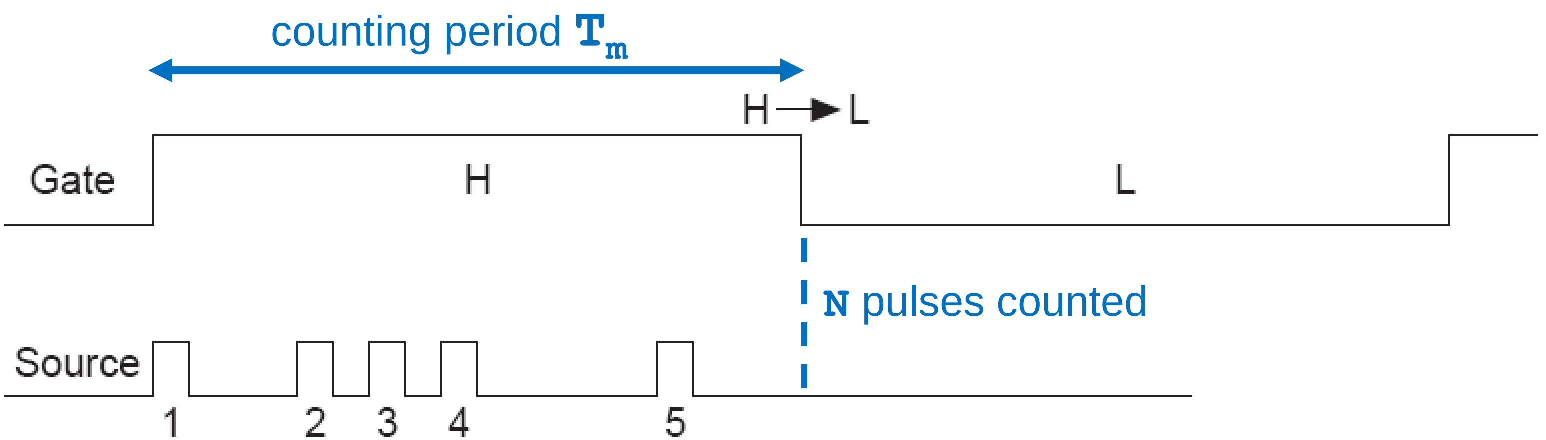
- Repetitive signals – averaging

Time & frequency measurements

Direct frequency measurement (digital gate method)
– using counter and reference frequency source: $F=1/T$

$$T_m = m*T \;\; \Rightarrow \;\; f = N/T_m = N*F/m$$

Accuracy: depends on stability of F and magnitude of N ($<2^n$, n … bit-size of counter)



Gate high period = 1 second, measured Frequency = 5 Hz

Accuracy refinement:

- Larger counting period or counter bit-size
-
- Very low frequencies: better to measure period

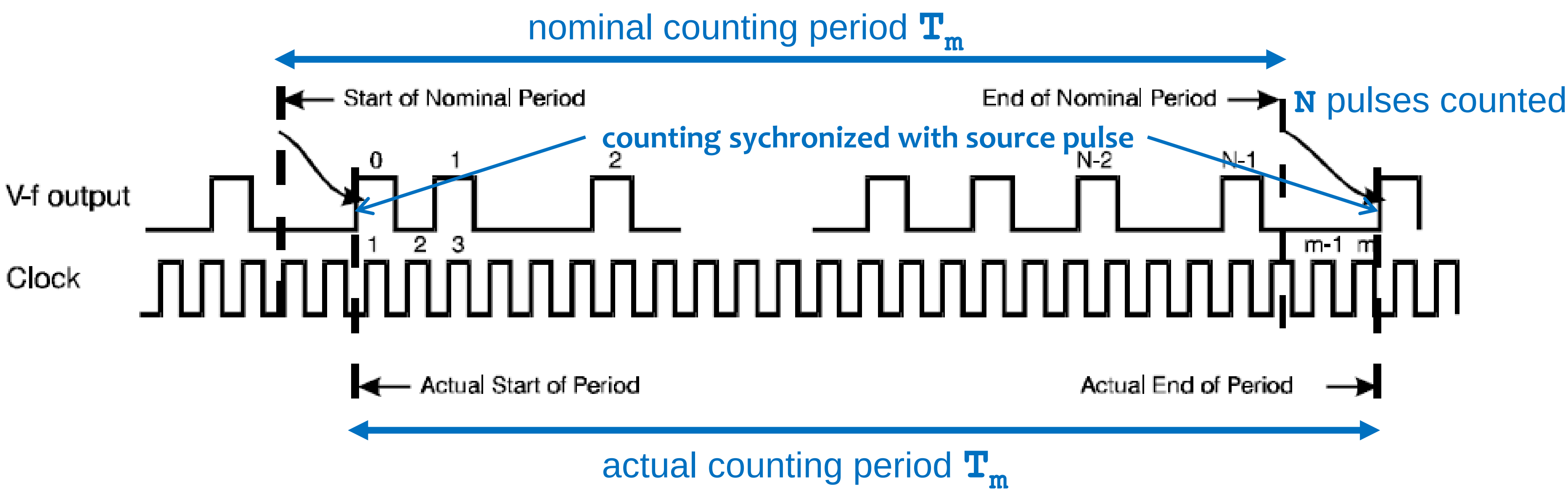
Time & frequency measurements

Direct frequency measurement (digital gate method)
– using counter and reference frequency source: $F=1/T$

$T_m = m*T$ => $f = N/T_m = N*F/m$

Accuracy: depends on stability of F and magnitude of N ($<2^n$, n … bit-size of counter)

$$f = N/T_x = N*F/(m \pm 1)$$



Accuracy refinement:

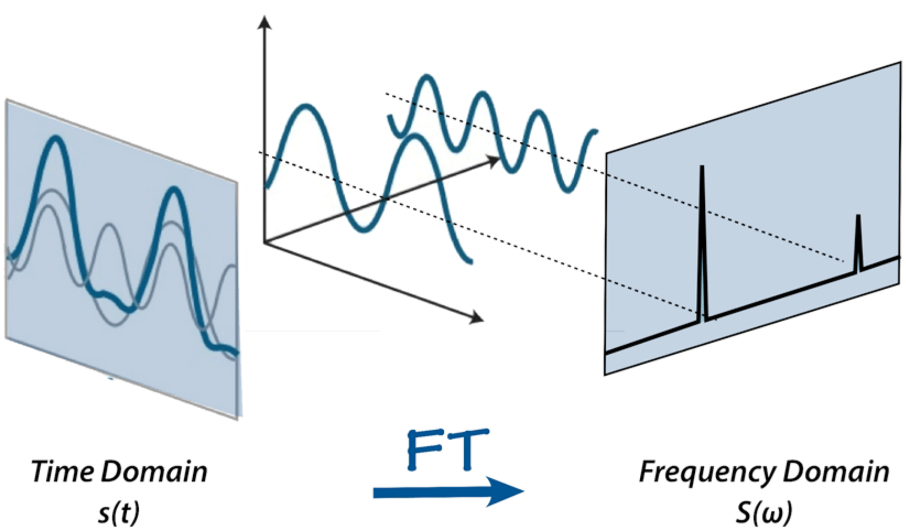
- Larger counting period or counter bit-size
- Source pulse synchrozination
- Very low frequencies: better to measure period

Fourier transform

Any periodic signal $s(t)$ can be written as a sum of sine waves:

$$s(t) = a_0 + a_1 \sin(\omega t + \phi_1) + a_2 \sin(2\omega t + \phi_2) + a_3 \sin(3\omega t + \phi_3) + \cdots$$

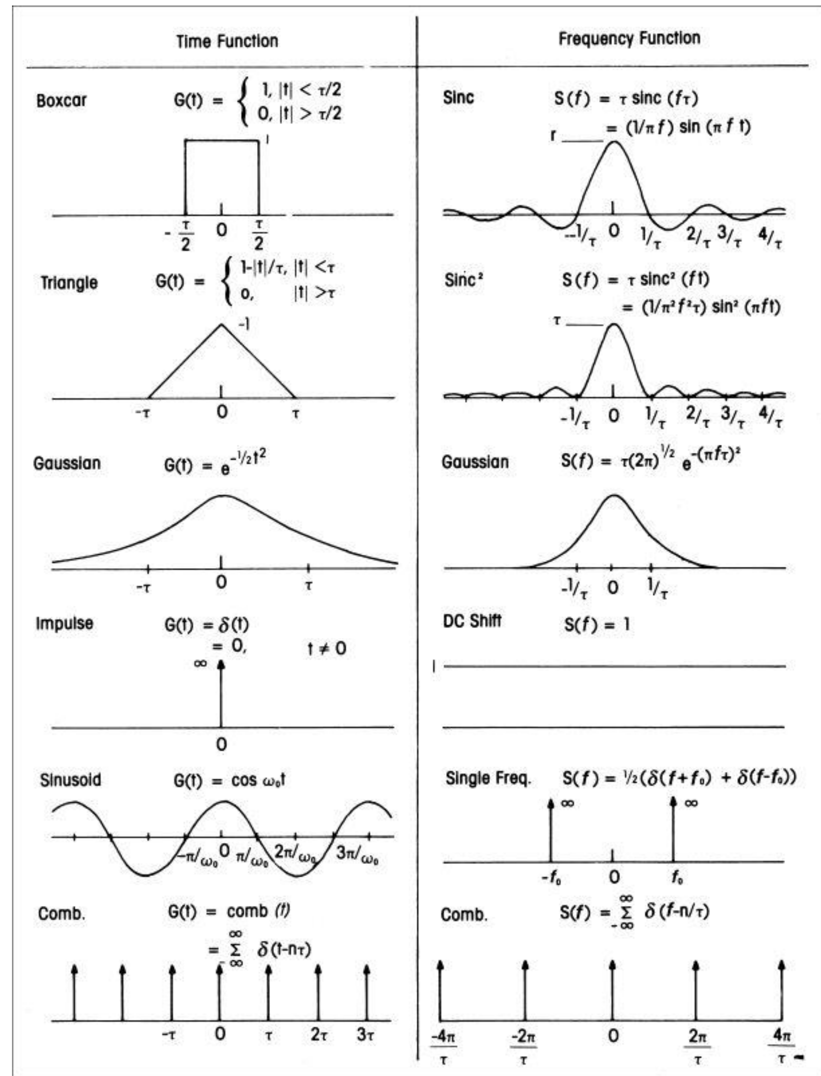
a … amplitudes
ϕ … phase shifts
ω … fundamental frequency
Higher order frequencies (2ω, 3ω, …) = harmonics



$$s(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) e^{i\omega t} \, d\omega$$

$$S(\omega) = \int_{-\infty}^{\infty} s(t) e^{-i\omega t} \, dt$$

Fourier Transform Pairs (only the real part of the transform shown)



Metody zpracování fyzikálních měření

EVF 112

Měření analogových a digitálních signálů v elektronové spektroskopii

Doc. RNDr. Karel Mašek, Dr.
Skupina fyziky povrchů KEVF

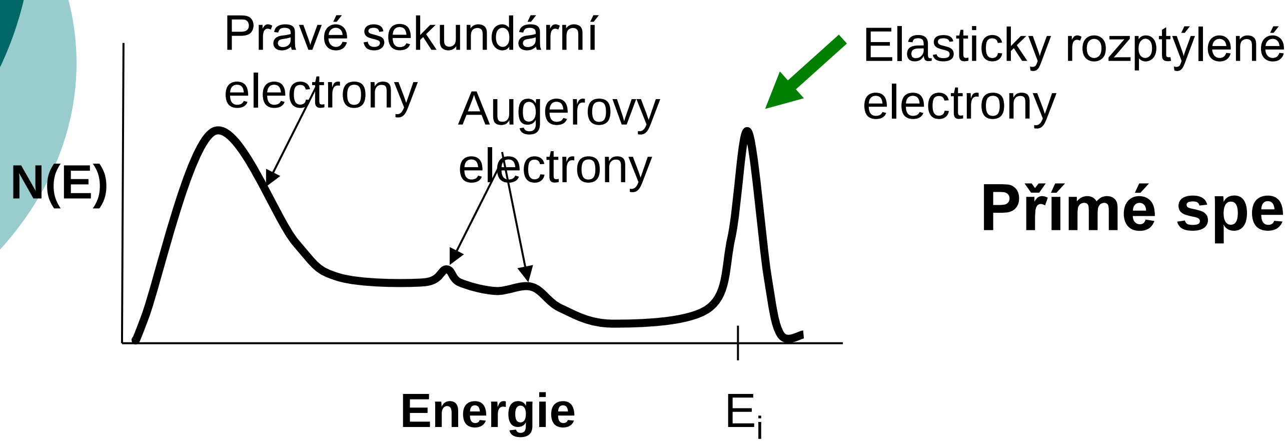
Elektronové spektroskopie na KEVF

- XPS (X-ray photoelectron spectroscopy) fotoelektronová spektroskopie
- AES (Auger electron spectroscopy) Augerova elektronová spektroskopie
- UPS (ultraviolet photoelectron spectroscopy) ultrafialová fotoelektronová spektroskopie
- EELS (electron energy loss spectroscopy) spektroskopie charakteristických ztrát
- APS (appearance potential spectroscopy) spektroskopie prahových potenciálů
- SRPES (synchrotron radiation photoelectron spectroscopy) fotoelektronová spektroskopie buzená synchrotronovým zářením

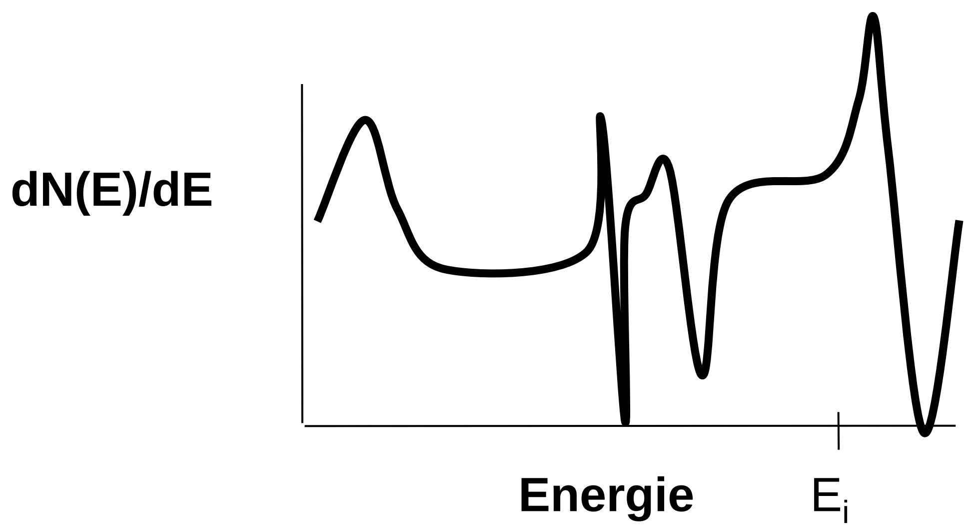
Spektroskopie obecně

- Primární činidlo – rtg záření, elektrony, ultrafialové záření, synchrotronové záření
- Měříme – energetické rozdělení vyletujících (sekundárních) elektronů
- Zjišťované informace – chemické složení, chemický stav, čistota, vazby (hloubka informace)
- SPEKTRUM = závislost intenzity na měřené energii elektronů
- Intenzita – většinou počet pulsů za vteřinu, proud

Spektrum sekundárních elektronů

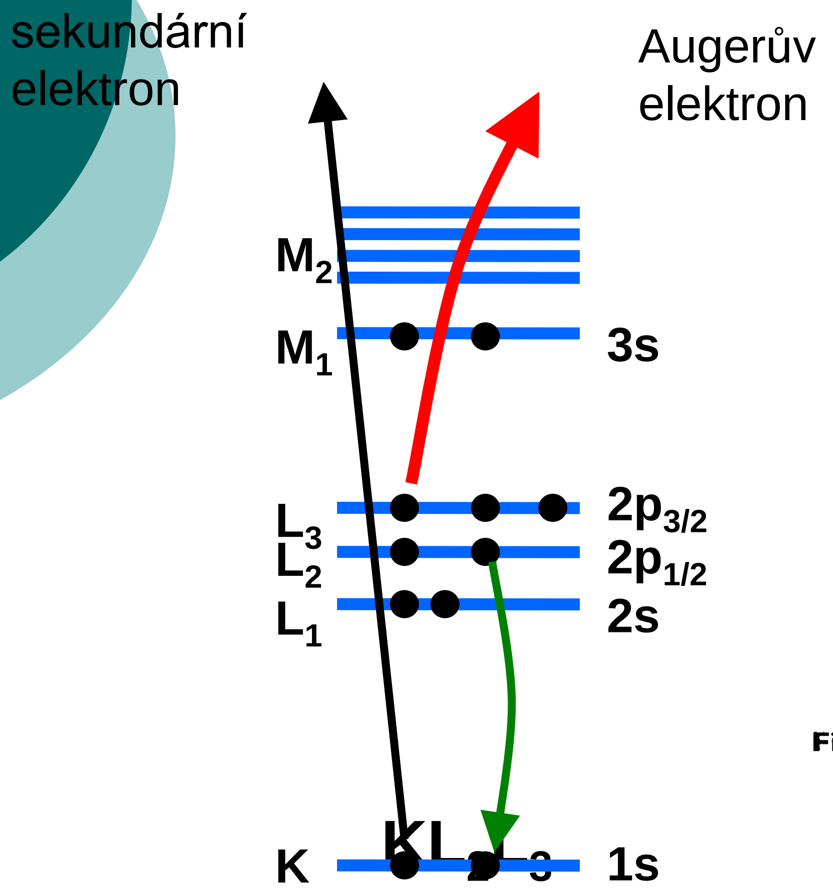


Přímé spektrum



Derivace

Augerův jev



- Excitace elektrony
- Excitace rtg zéřením

Auger

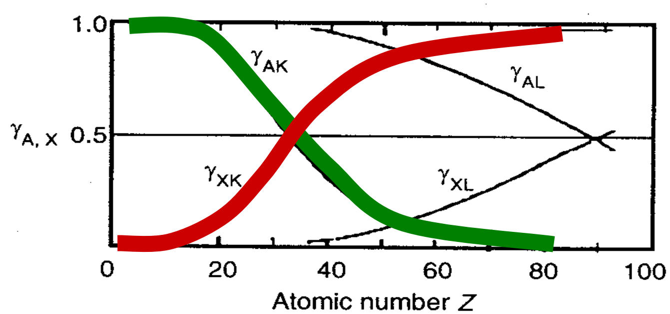
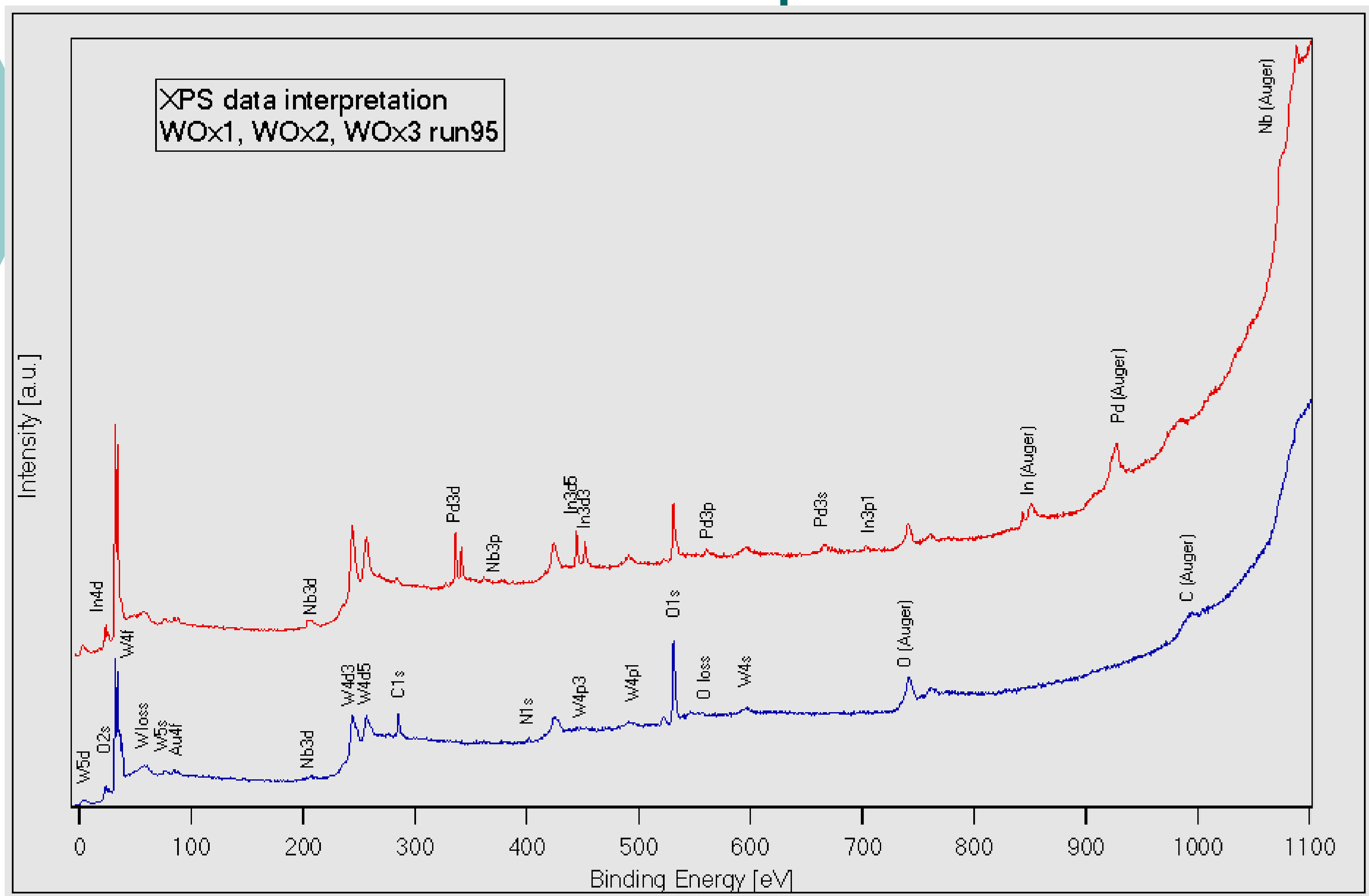


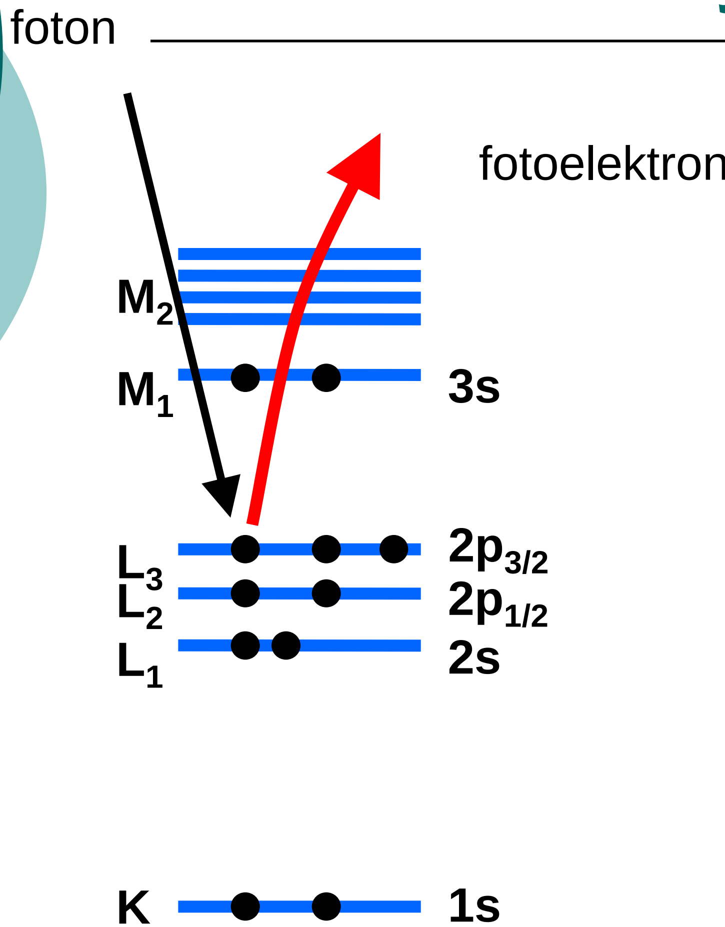
Figure 4.6. Emission probability of an Auger electron (A) or photon (X)

Emise fotonu
(rtg fluorescence)

Fotoelektronové spektrum



Fotoelektrický jev

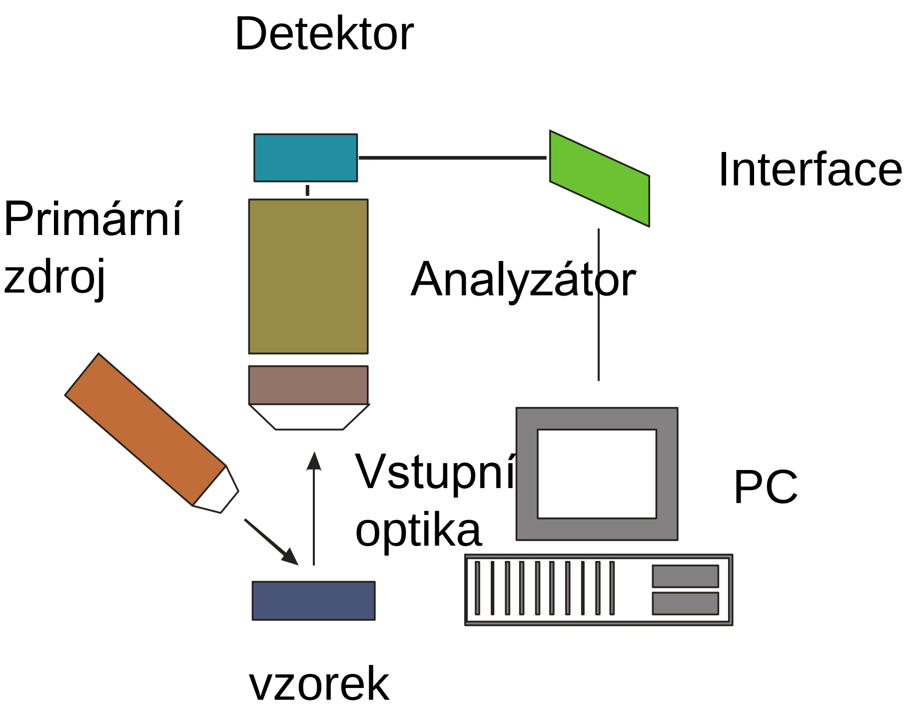


L3

$$BE = h\nu - KE = E_f - E_i$$

BE vazebná energie
hv energie fotonu
KE kinetická energie
E_f energie konečného stavu
E_i energie počátečního stavu

Instrumentální vybavení

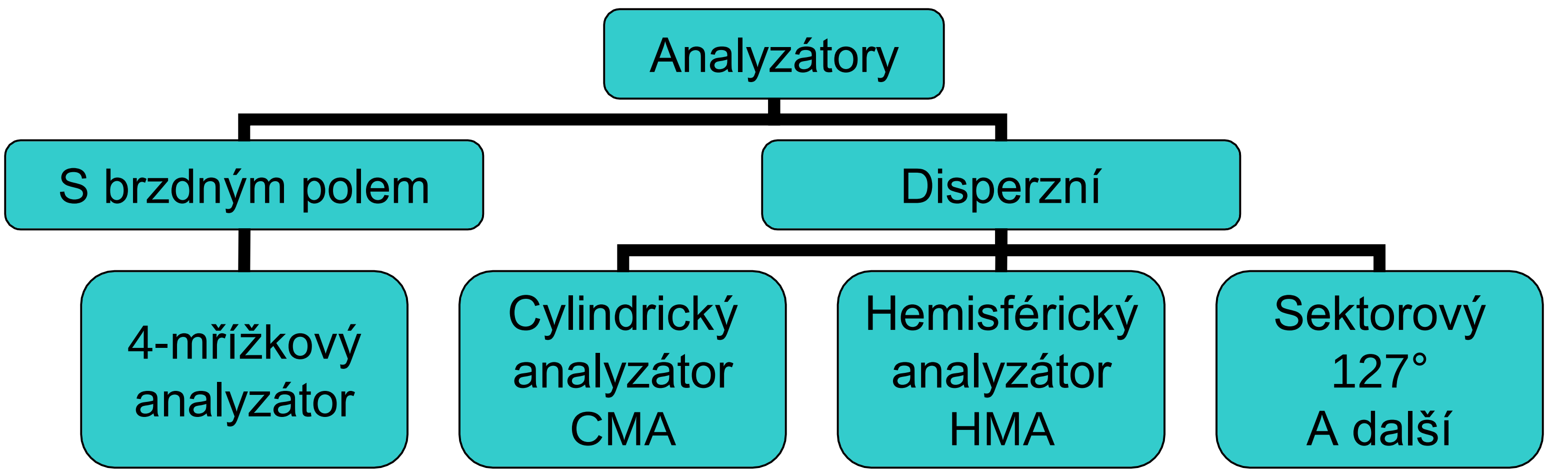


Primární zdroj

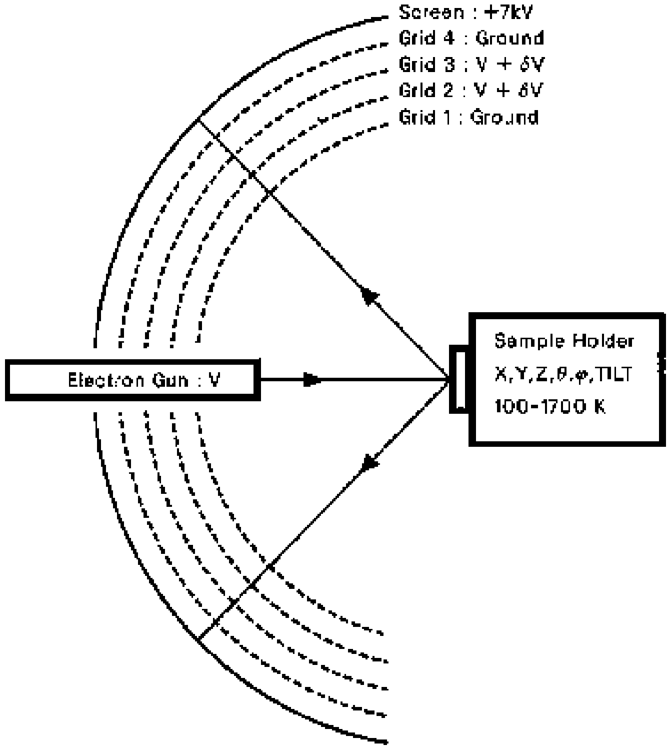
-Rtg záření Al, Mg Kα

- elektrony 50 – 5000 eV
- UV záření He výboj
- synchrotronové záření
  40 – 1000 eV

Analyzátory



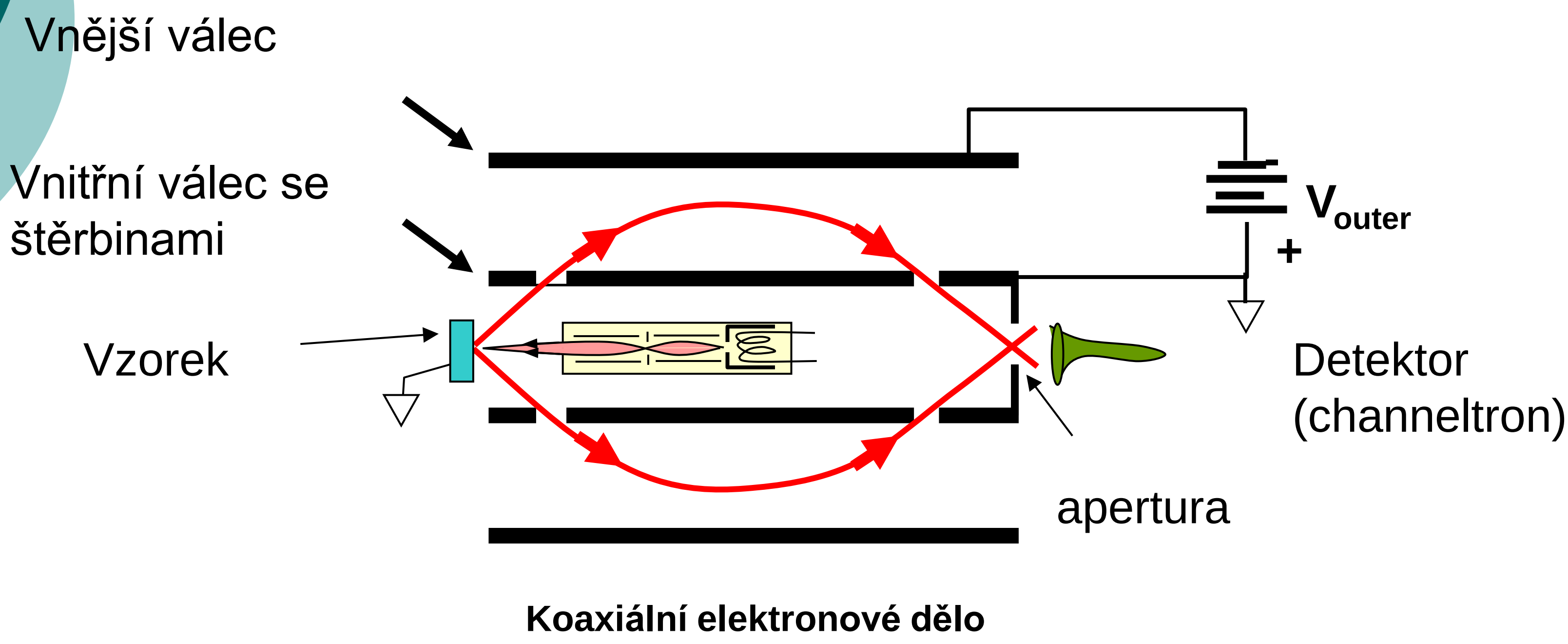
4-mřížkový analyzátor



LEED – difrakce nízkoenergetických elektronů
AES – Augerova spektroskopie

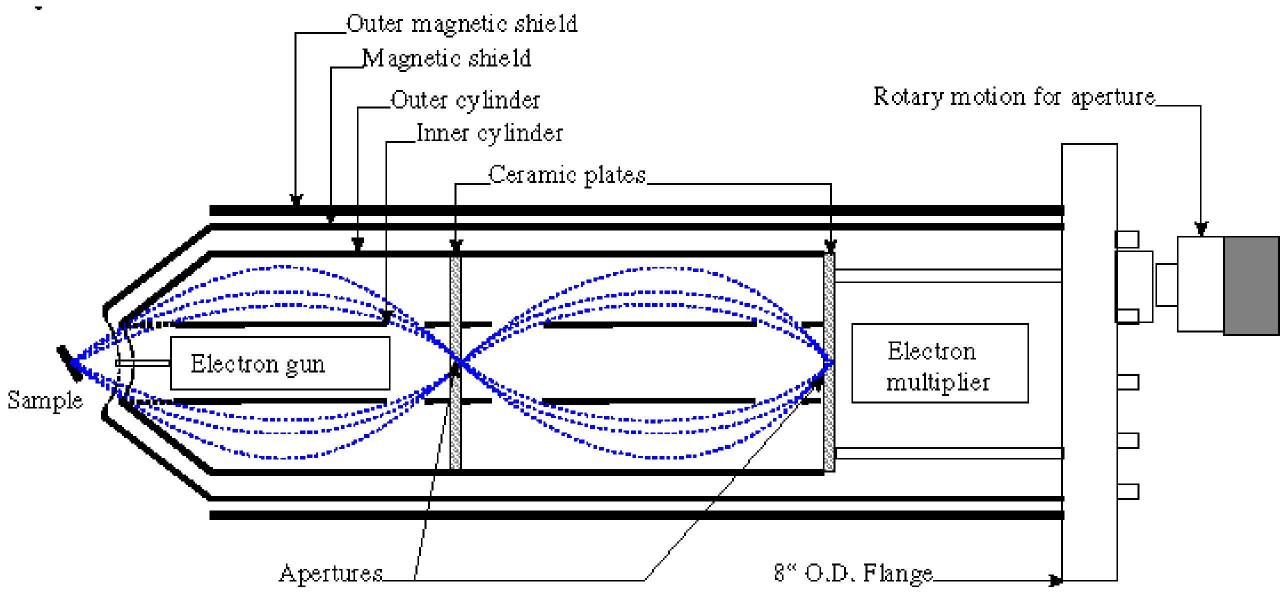
Cylindrický analyzátor (CMA)

Jednoduchý CMA

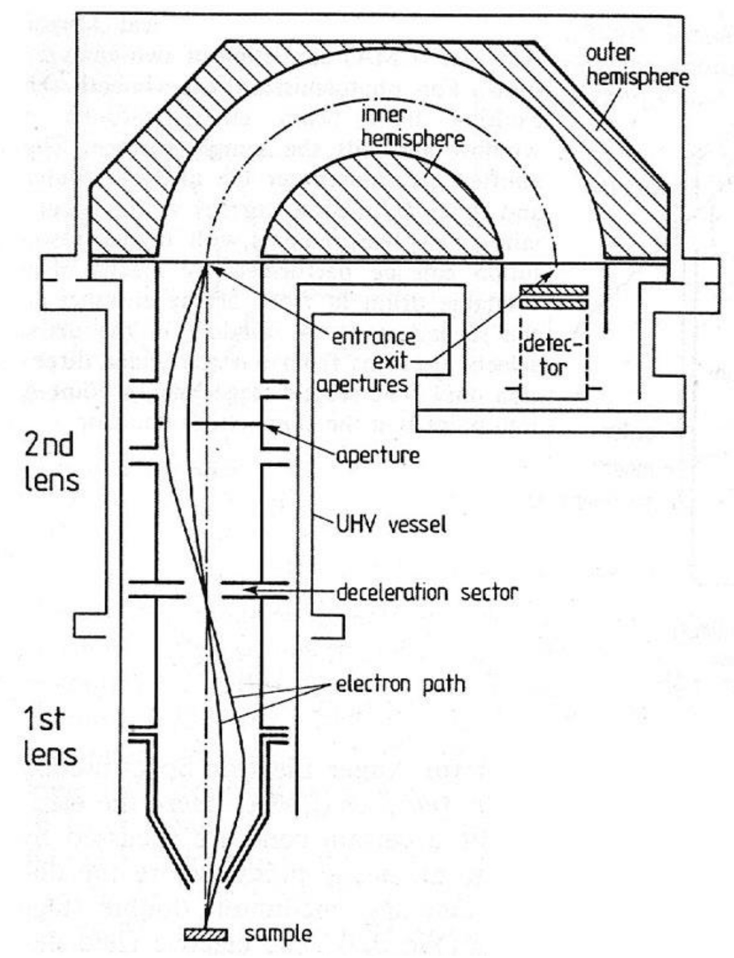


Cylindrický analyzátor (CMA)

Dvojitý CMA (s brzdnýmpolem)



Hemisférický analyzátor HMA

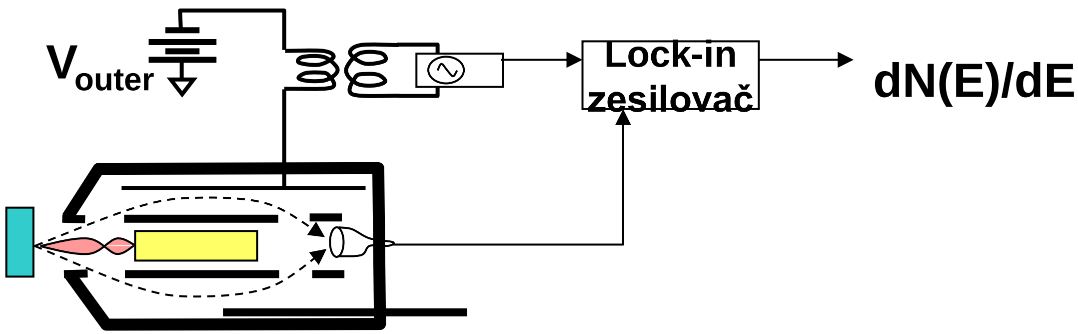


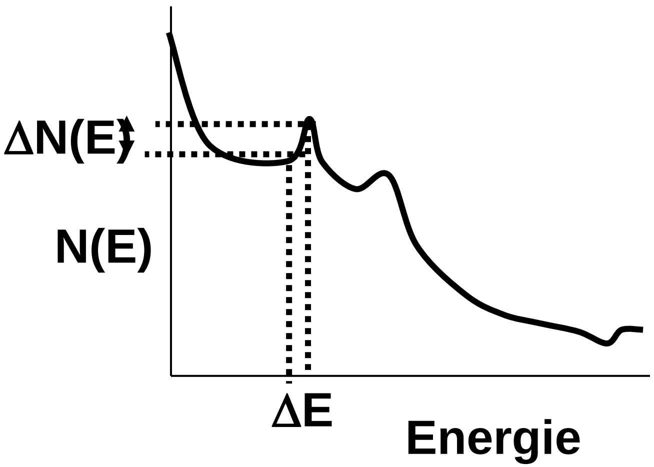
Elektronové spektroskopie – XPS, UPS, AES, EELS, SRPES
Lepší rozlišení
Citlivost závisí na velikosti sfér

Způsob měření

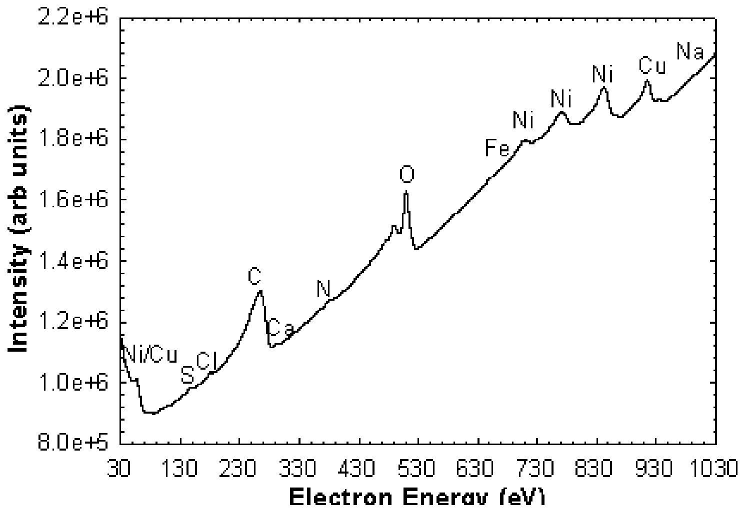
- Přímé spektrum – proud nebo počet pulsů za jednotku času
- Derivované spektrum – první derivace (někdy i druhá derivace) signálu, v případě analyzátoru s brzdným polem získáme přímé spektrum

střídavá modulace
(~1 V, 10 kHz)

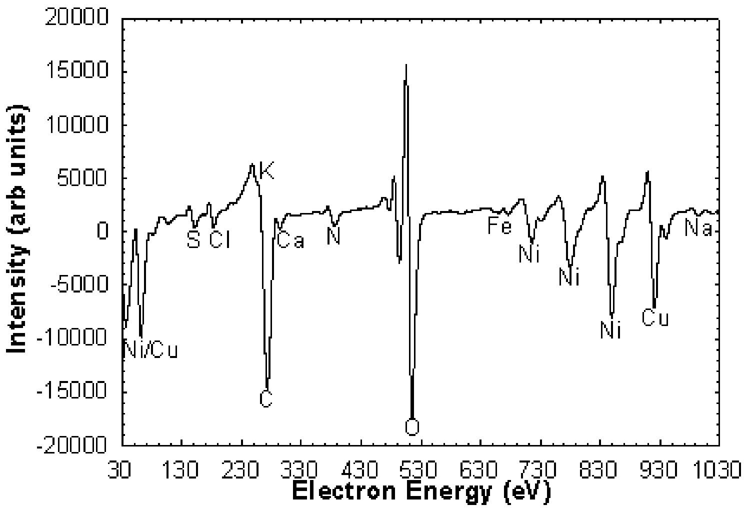




Způsob měření

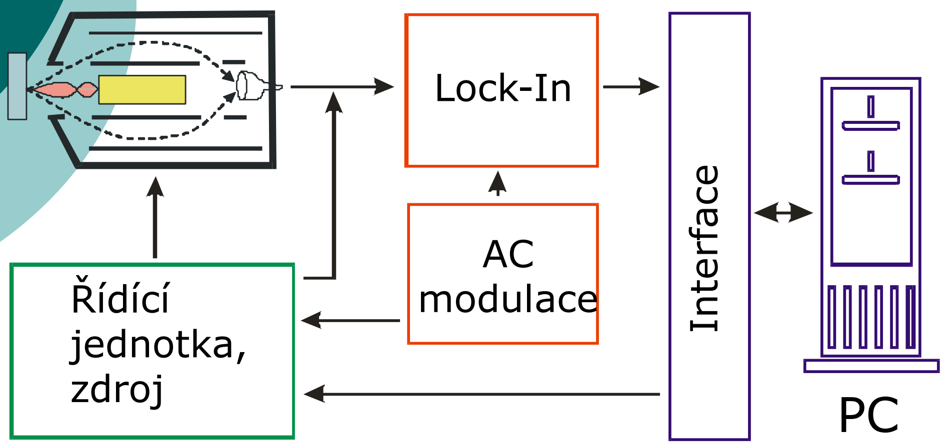


Přímé spektrum



Derivované spektrum

Způsob měření



Detektor

- násobič
- kanálek (channeltron)
- pole kanálků
- kanálková destička (channelplate)

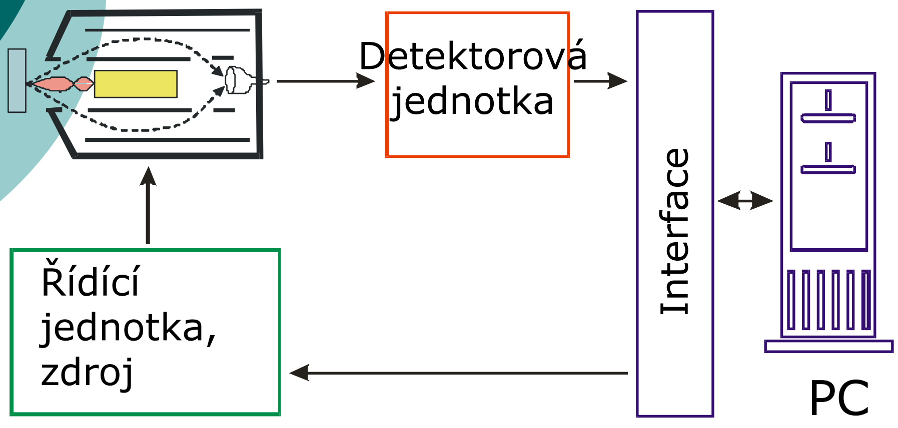
Elektronika analyzátoru

- potřebná řídící a napájecí napětí
- komunikace s počítačem
- Snímání signálu z detektoru

PC a interface(převodníky, čítače, komunikační karty)

- komunikace s řídící jednotkou analyzátoru
- generování řídících příkazů nebo signálů
- akumulace dat, jejich záznam a zobrazení

Způsob měření



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Zpracování spekter

- Jednoúčelové programy pro snímání spekter – SPECTRA, SPECSLAB, EIS

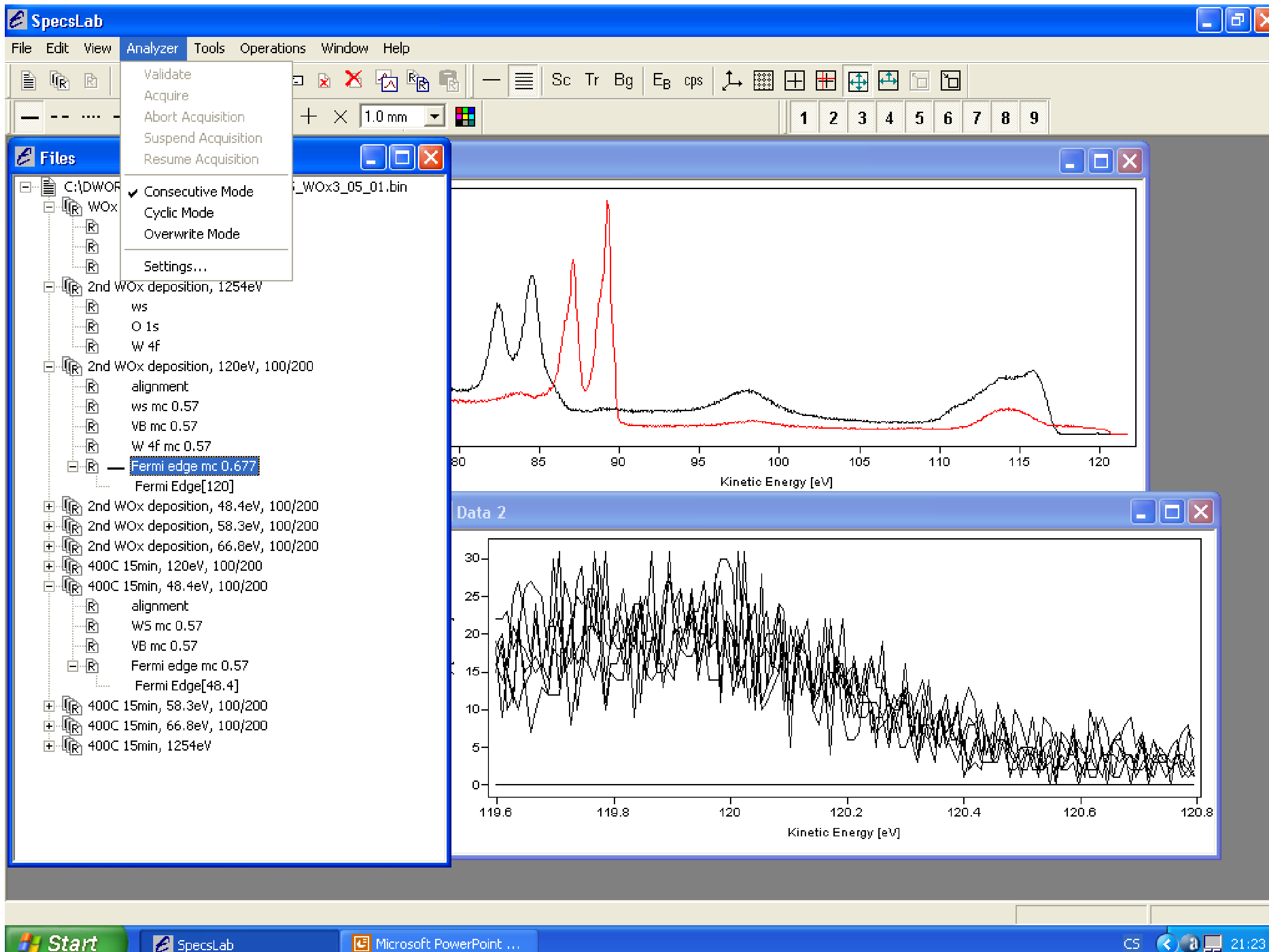
- Jednoúčelové programy pro zpracování spekter – CasaXPS, XPSpeak, FITT

- Víceúčelové programy – tabulkové procesory – Excel, Origin, Igor, MatLab, IDL, Mathematica

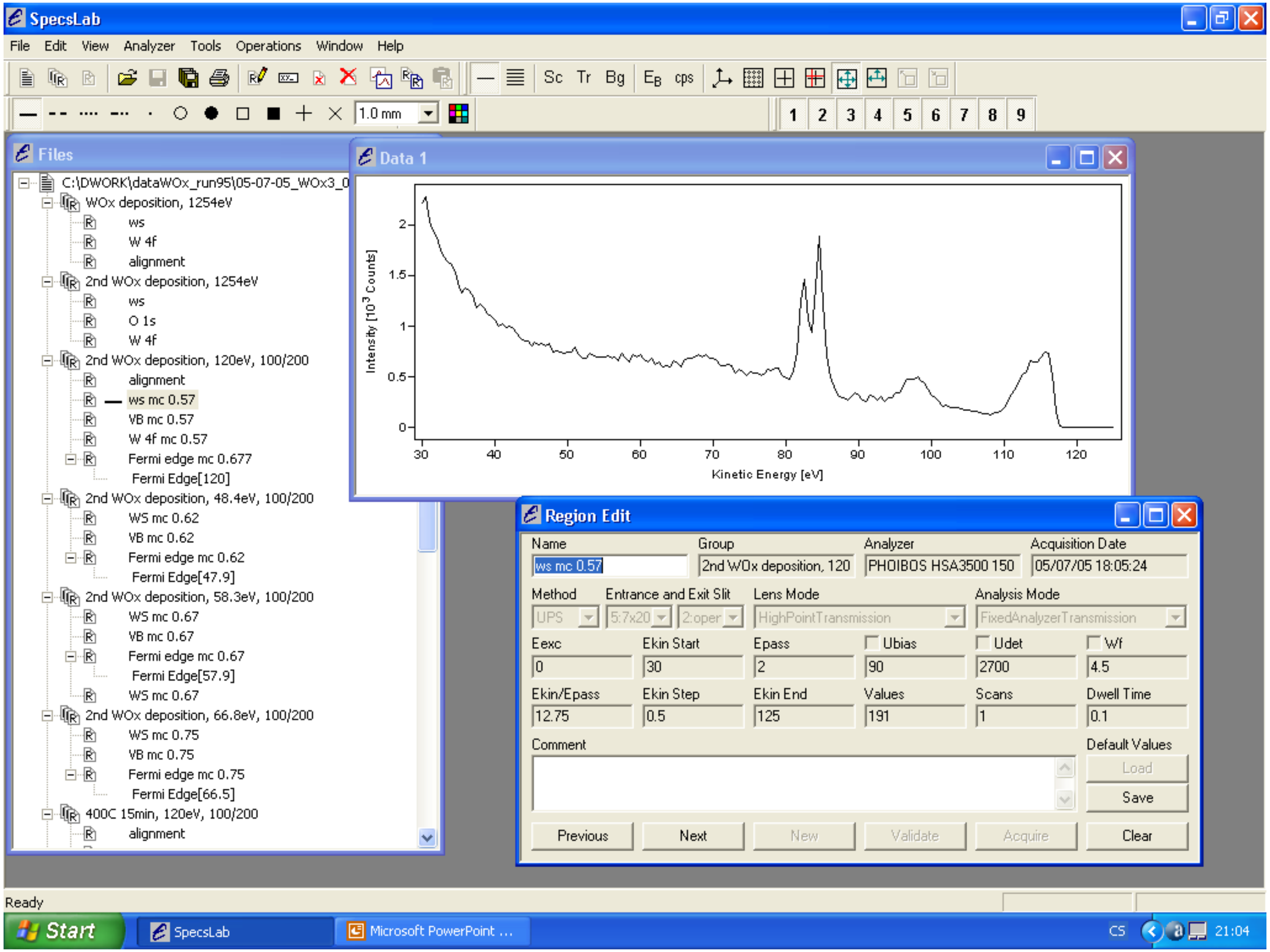
Jednoúčelové programy

- Nastavení měřícího přístroje
- Měření a záznam dat
- Zobrazení měřených dat
- Základní operace s daty
- Export do různých formátů
- Každý program má určité zaměření

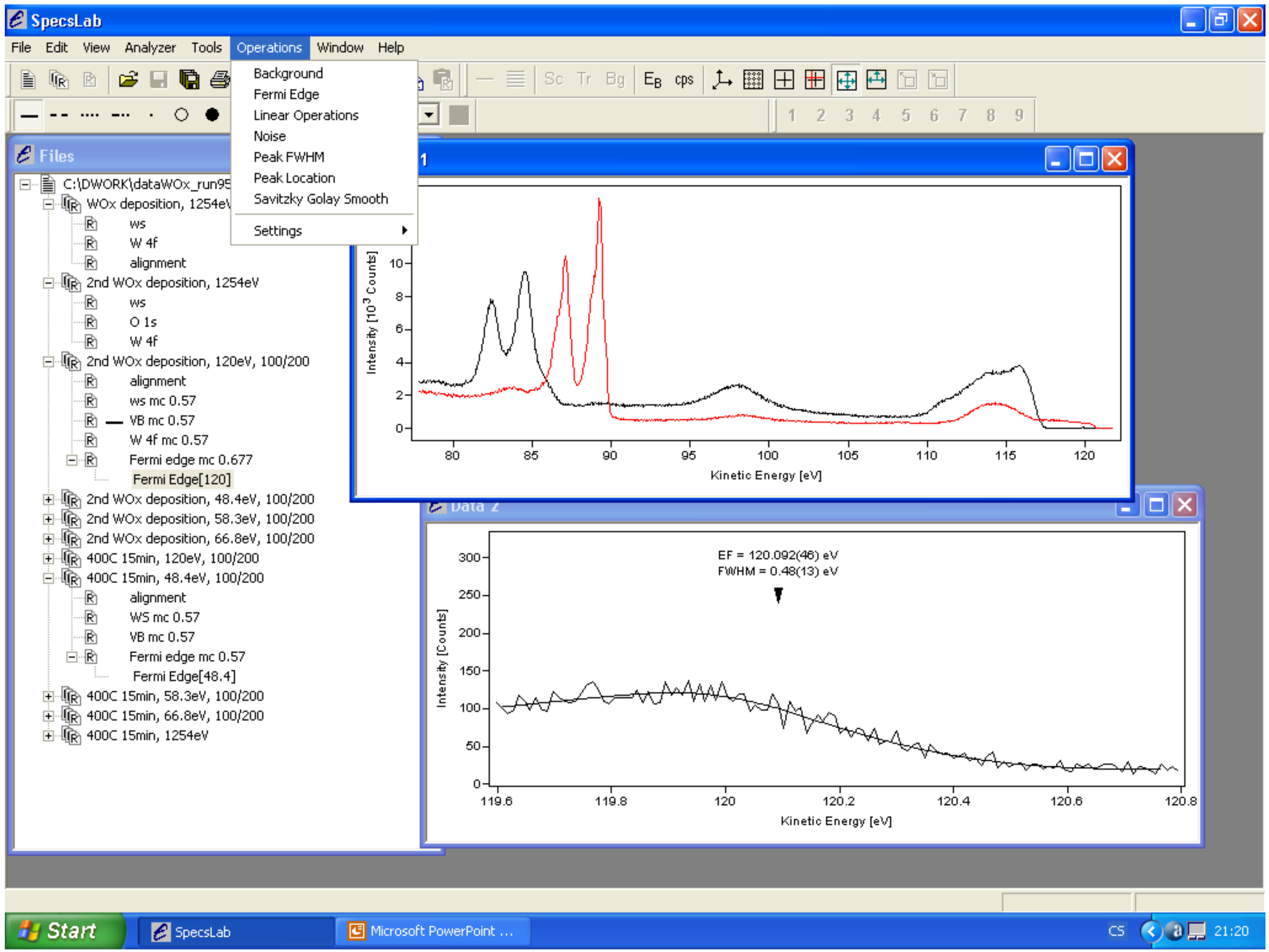
SPECSLAB - měření



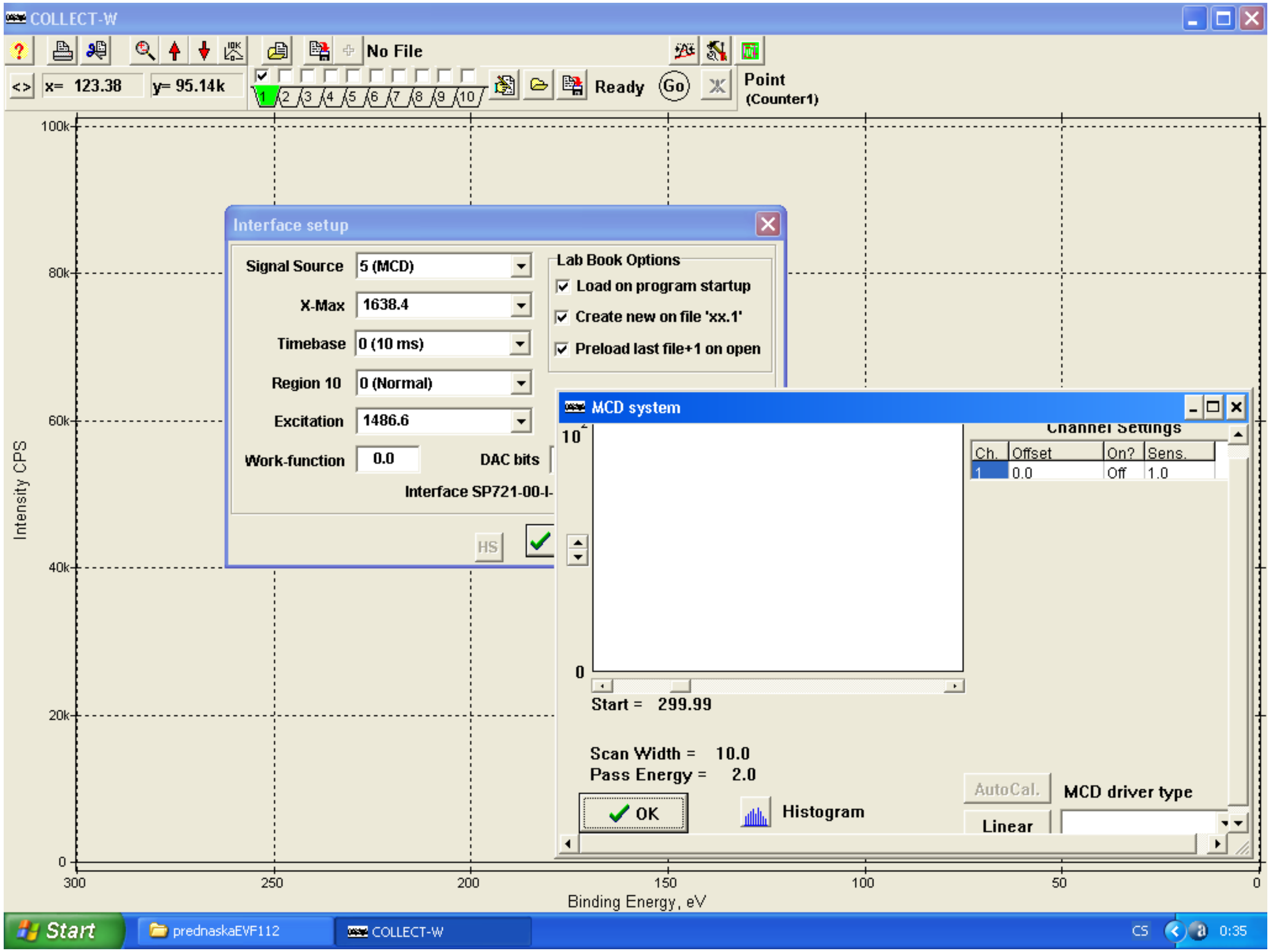
SPECSLAB – měření a zobrazení



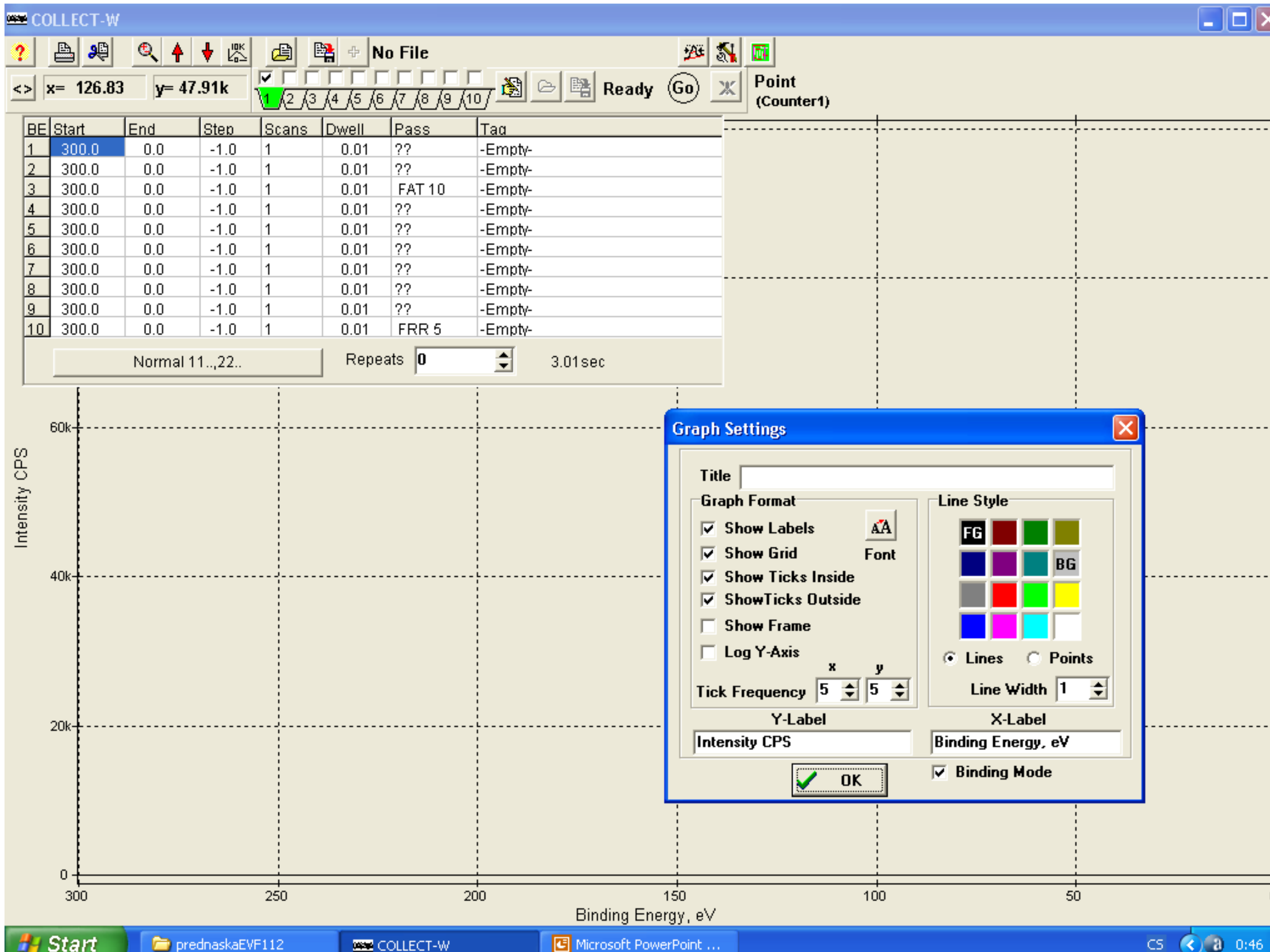
SPECSLAB – jednoduché operace



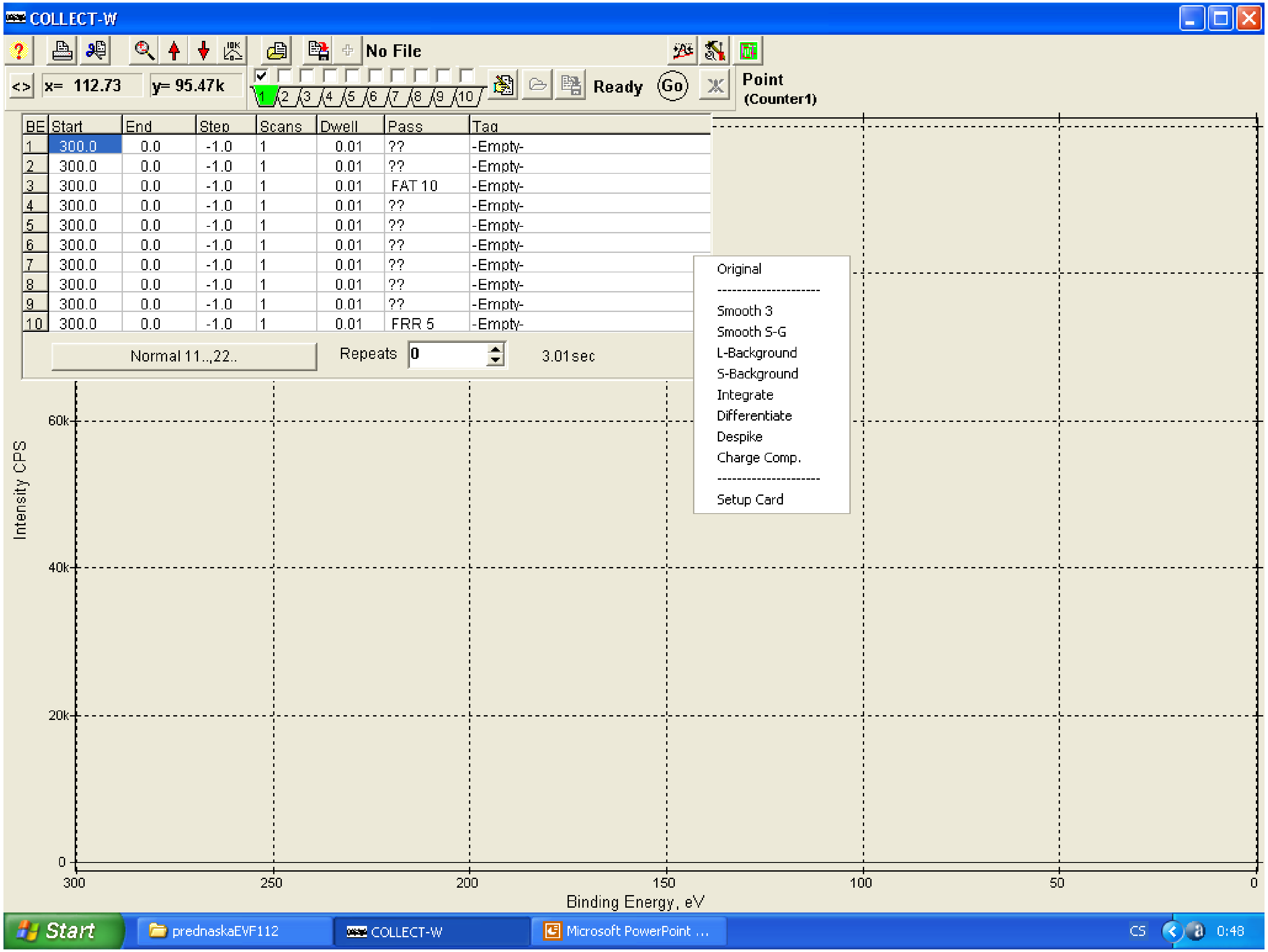
WSPECTRA – MCD systém



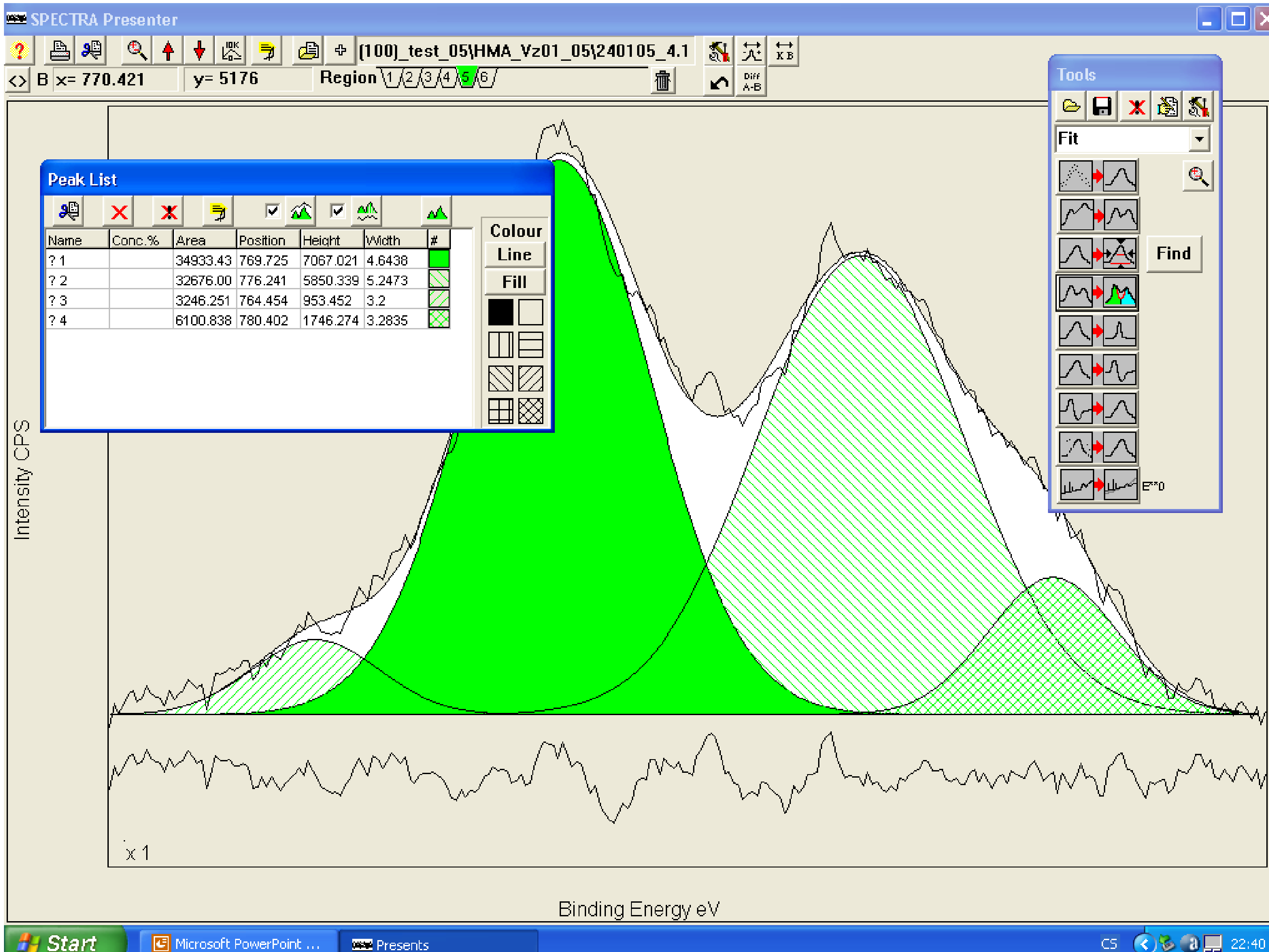
WSPECTRA - nastavení



WSPECTRA - funkce



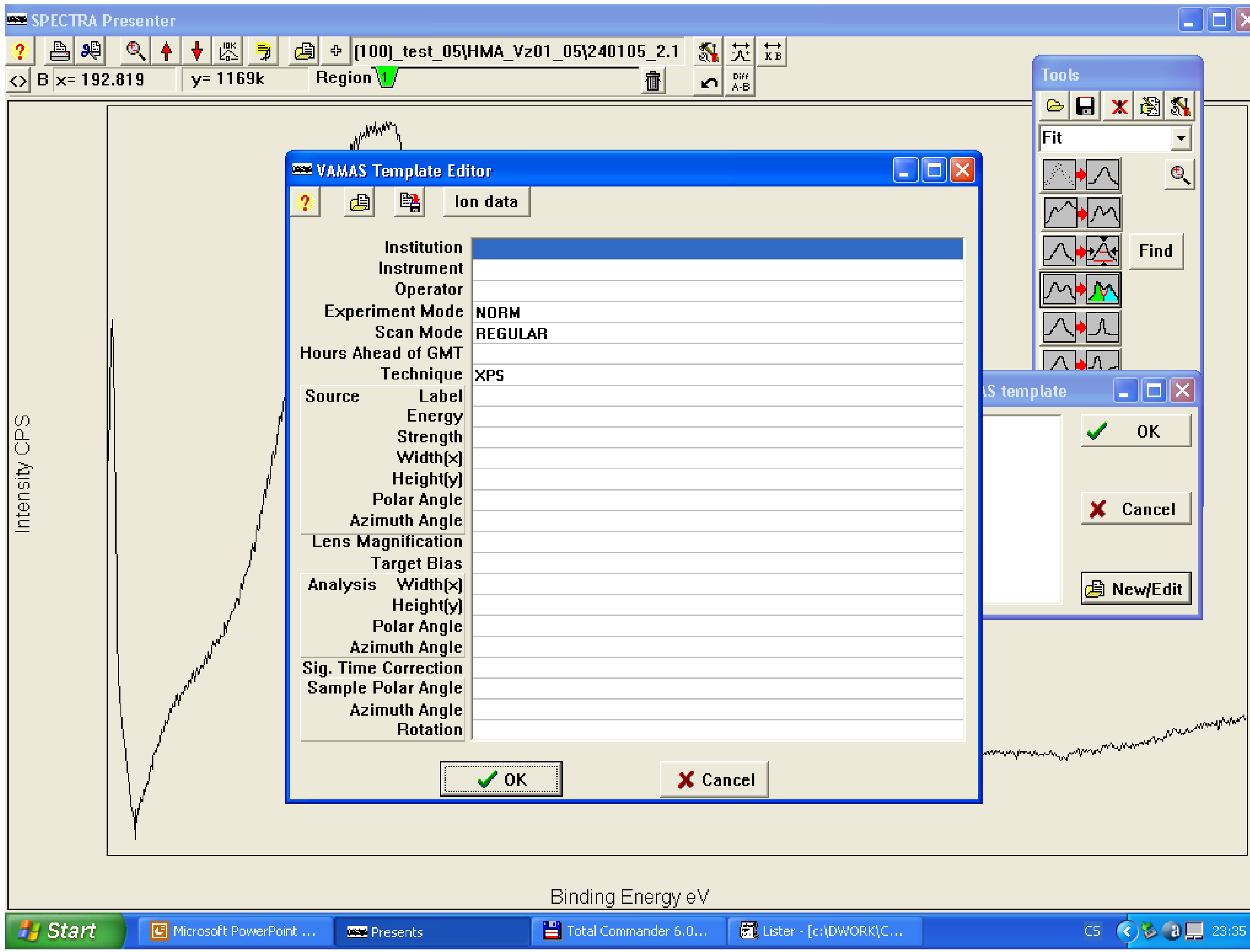
WSPECTRA Presenter



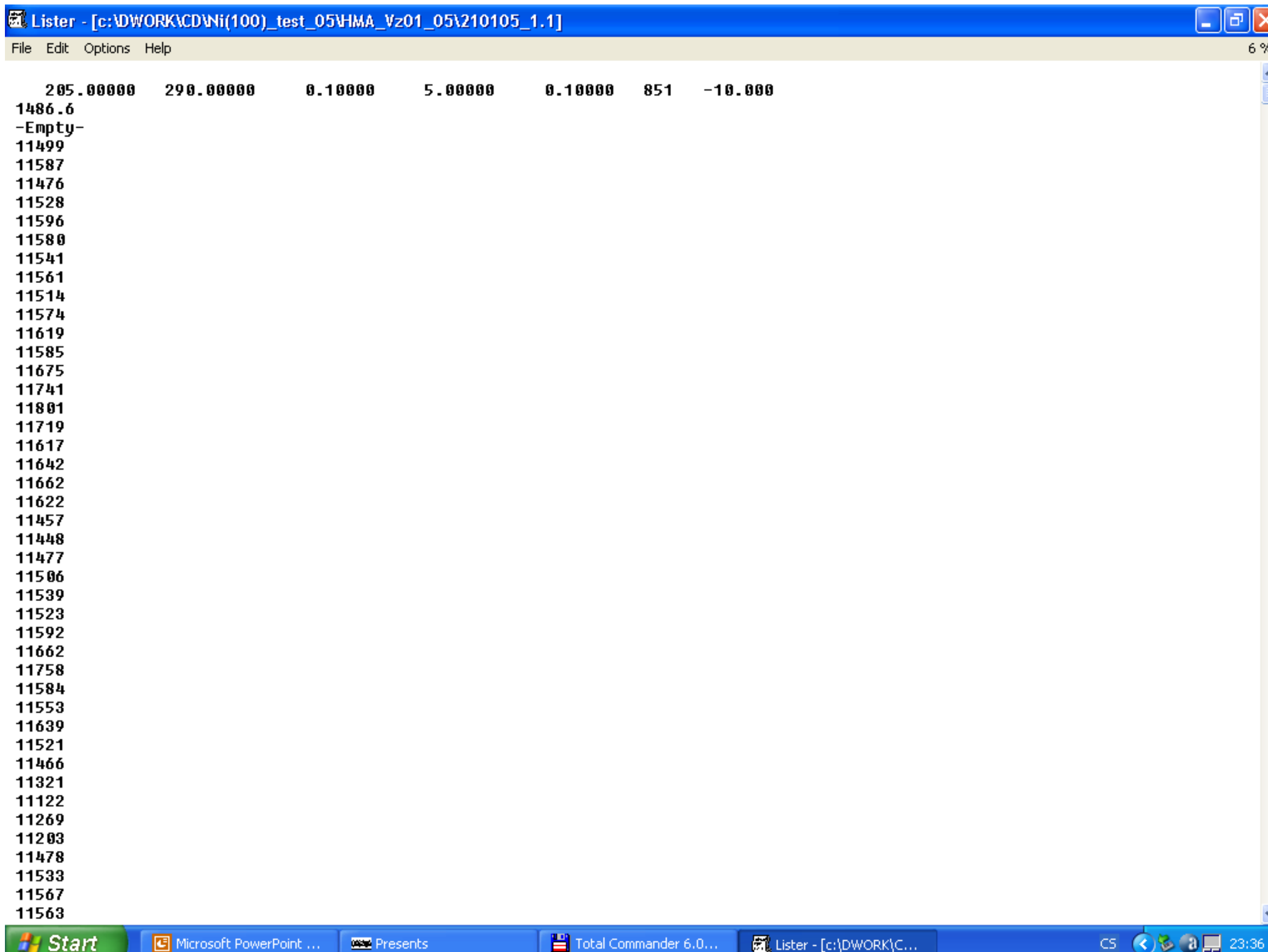
Formáty dat v el. spektroskopii

- Binární
- Speciální, dle výrobce programu
- VAMAS
- Energie – intenzita (x-y)

Formáty - VAMAS

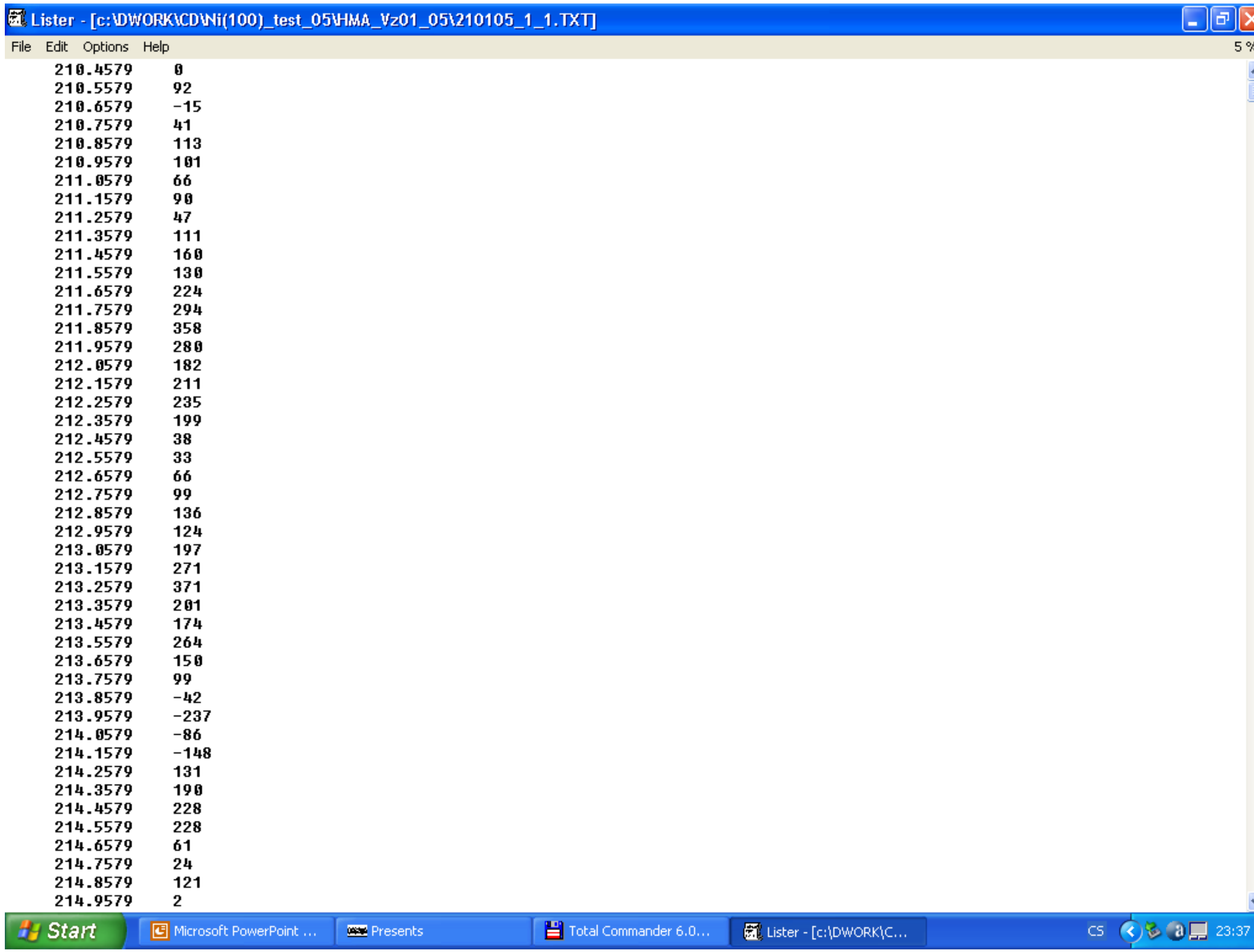


Formáty - Spectra




```
   205.00000  290.00000    0.10000    5.00000    0.10000   851   -10.000
1486.6
-Empty-
11499
11587
11476
11528
11596
11580
11541
11561
11514
11574
11619
11585
11675
11741
11801
11719
11617
11642
11662
11622
11457
11448
11477
11506
11539
11523
11592
11662
11758
11584
11553
11639
11521
11466
11321
11122
11269
11203
11478
11533
11567
11563
```

Formáty – x-y



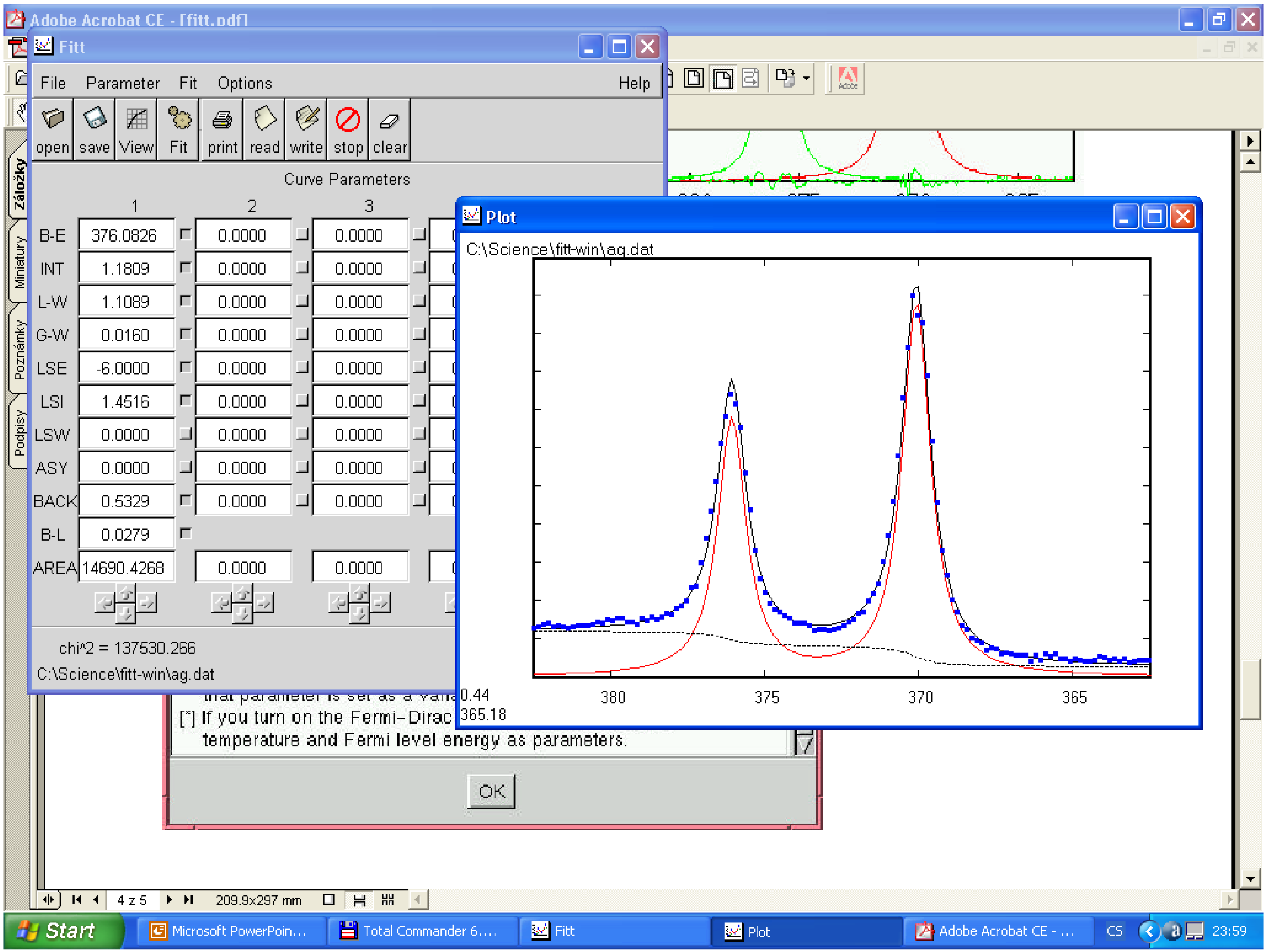
210.4579	0
210.5579	92
210.6579	-15
210.7579	41
210.8579	113
210.9579	101
211.0579	66
211.1579	90
211.2579	47
211.3579	111
211.4579	160
211.5579	130
211.6579	224
211.7579	294
211.8579	358
211.9579	280
212.0579	182
212.1579	211
212.2579	235
212.3579	199
212.4579	38
212.5579	33
212.6579	66
212.7579	99
212.8579	136
212.9579	124
213.0579	197
213.1579	271
213.2579	371
213.3579	201
213.4579	174
213.5579	264
213.6579	150
213.7579	99
213.8579	-42
213.9579	-237
214.0579	-86
214.1579	-148
214.2579	131
214.3579	190
214.4579	228
214.5579	228
214.6579	61
214.7579	24
214.8579	121
214.9579	2

Specializovaný software

- Zpracování a prezentace spekter
- Kvantitativní vyhodnocení spekter
- Fitování spekter

- - např. CasaXPS, FITT, XPSPeak

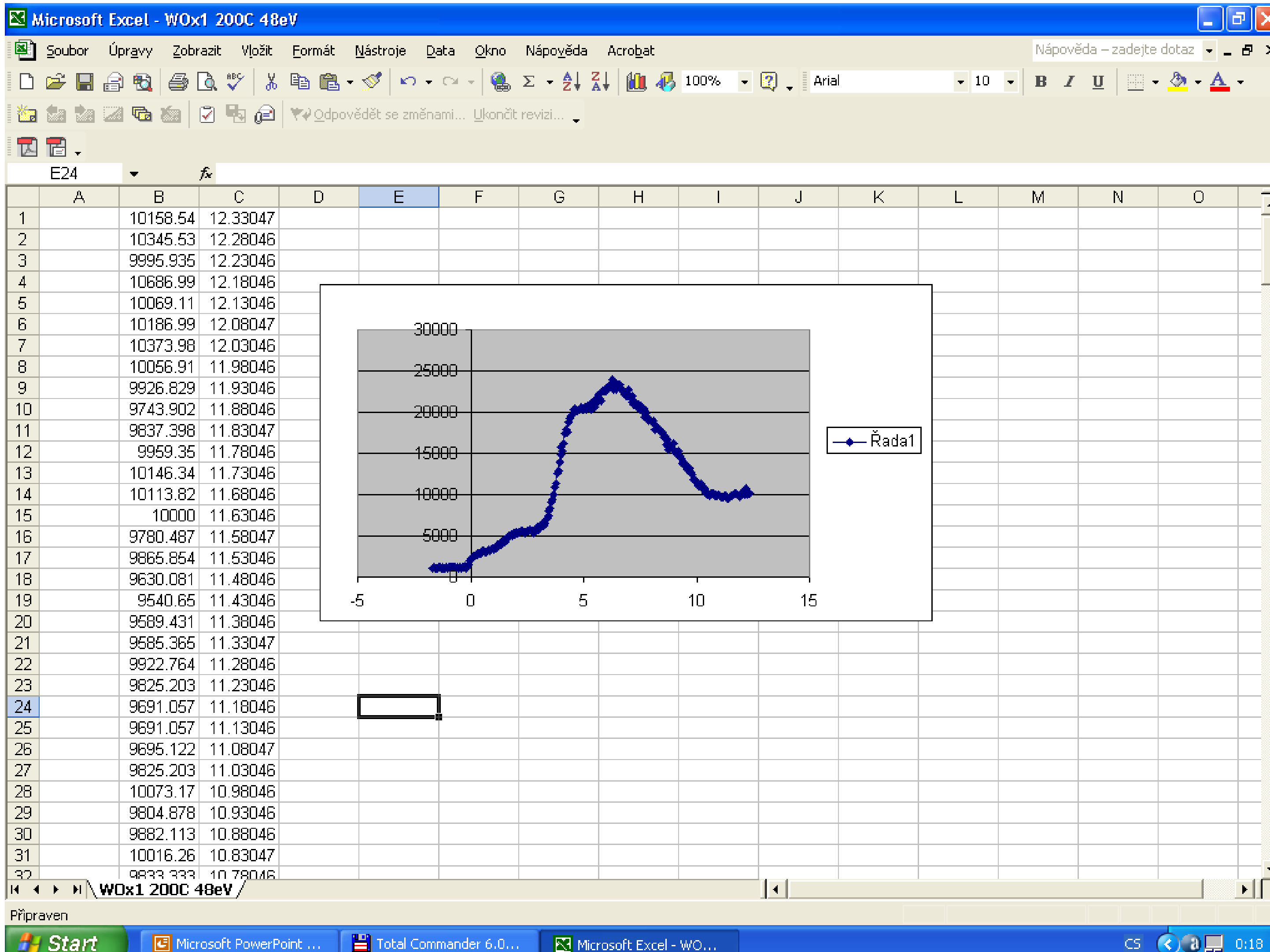
FITT - Ag


Adobe Acrobat CE - [fitt.pdf]
Fitt
File Parameter Fit Options Help
open save View Fit print read write stop clear
Curve Parameters
1 2 3
B-E 376.0826 0.0000 0.0000
INT 1.1809 0.0000 0.0000
L-W 1.1089 0.0000 0.0000
G-W 0.0160 0.0000 0.0000
LSE -6.0000 0.0000 0.0000
LSI 1.4516 0.0000 0.0000
LSW 0.0000 0.0000 0.0000
ASY 0.0000 0.0000 0.0000
BACK 0.5329 0.0000 0.0000
B-L 0.0279
AREA 14690.4268 0.0000 0.0000
chi^2 = 137530.266
C:\Science\fitt-win\ag.dat
Plot
C:\Science\fitt-win\ag.dat
380 375 370 365
0.44
365.18
[*] If you turn on the Fermi-Dirac
temperature and Fermi level energy as parameters.
OK
4 z 5 209.9x297 mm
Start Microsoft PowerPoin... Total Commander 6.... Fitt Plot Adobe Acrobat CE - ... CS 23:59

Zpracování a prezentace spekter

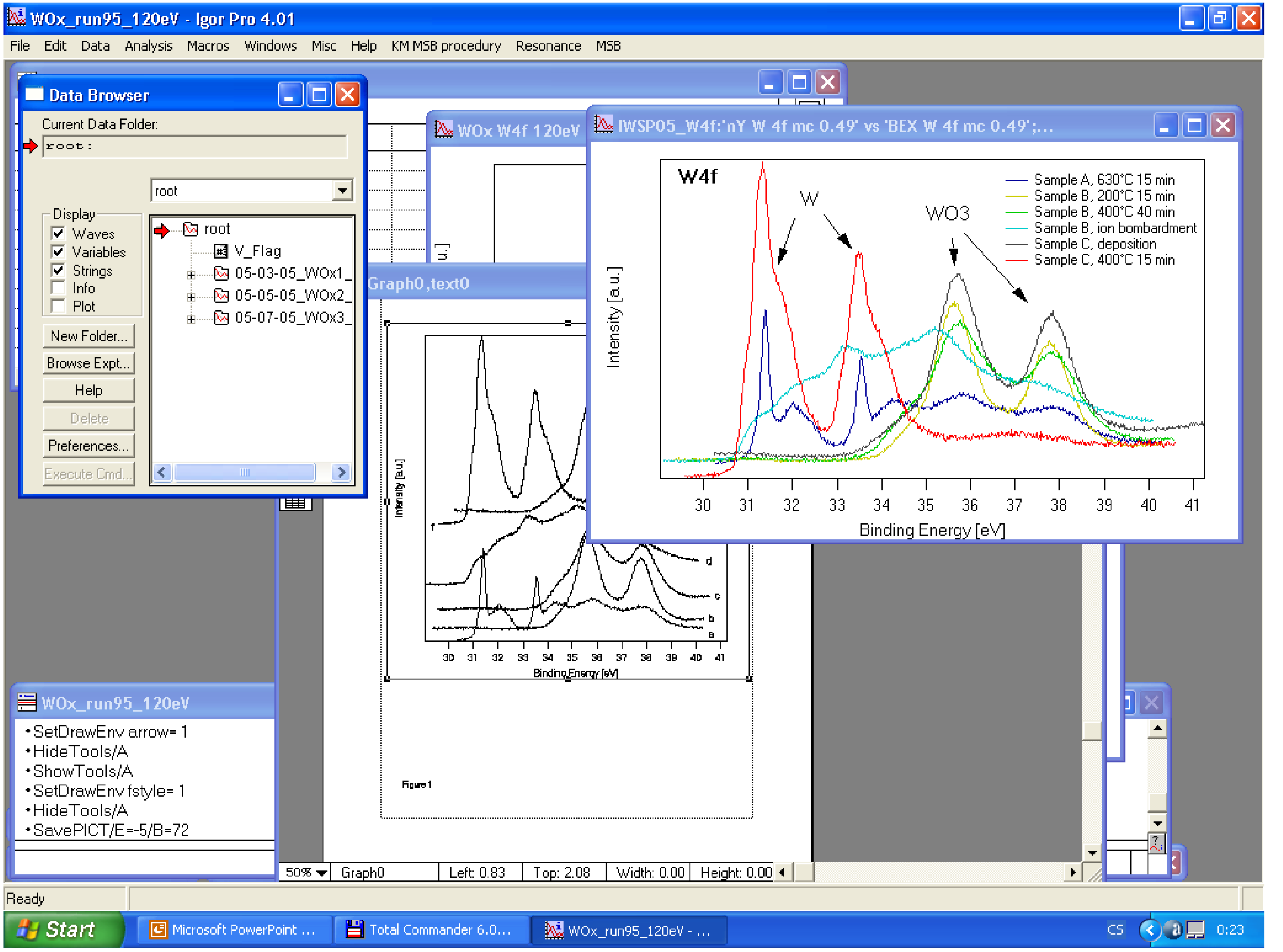
- Víceúčelové programy – tabulkové procesory – Excel, Origin, Igor, MatLab, IDL, Mathematica

Excel – Microsoft Office



	A	B	C
1		10158.54	12.33047
2		10345.53	12.28046
3		9995.935	12.23046
4		10686.99	12.18046
5		10069.11	12.13046
6		10186.99	12.08047
7		10373.98	12.03046
8		10056.91	11.98046
9		9926.829	11.93046
10		9743.902	11.88046
11		9837.398	11.83047
12		9959.35	11.78046
13		10146.34	11.73046
14		10113.82	11.68046
15		10000	11.63046
16		9780.487	11.58047
17		9865.854	11.53046
18		9630.081	11.48046
19		9540.65	11.43046
20		9589.431	11.38046
21		9585.365	11.33047
22		9922.764	11.28046
23		9825.203	11.23046
24		9691.057	11.18046
25		9691.057	11.13046
26		9695.122	11.08047
27		9825.203	11.03046
28		10073.17	10.98046
29		9804.878	10.93046
30		9882.113	10.88046
31		10016.26	10.83047
32		9833.333	10.78046

Igor Pro

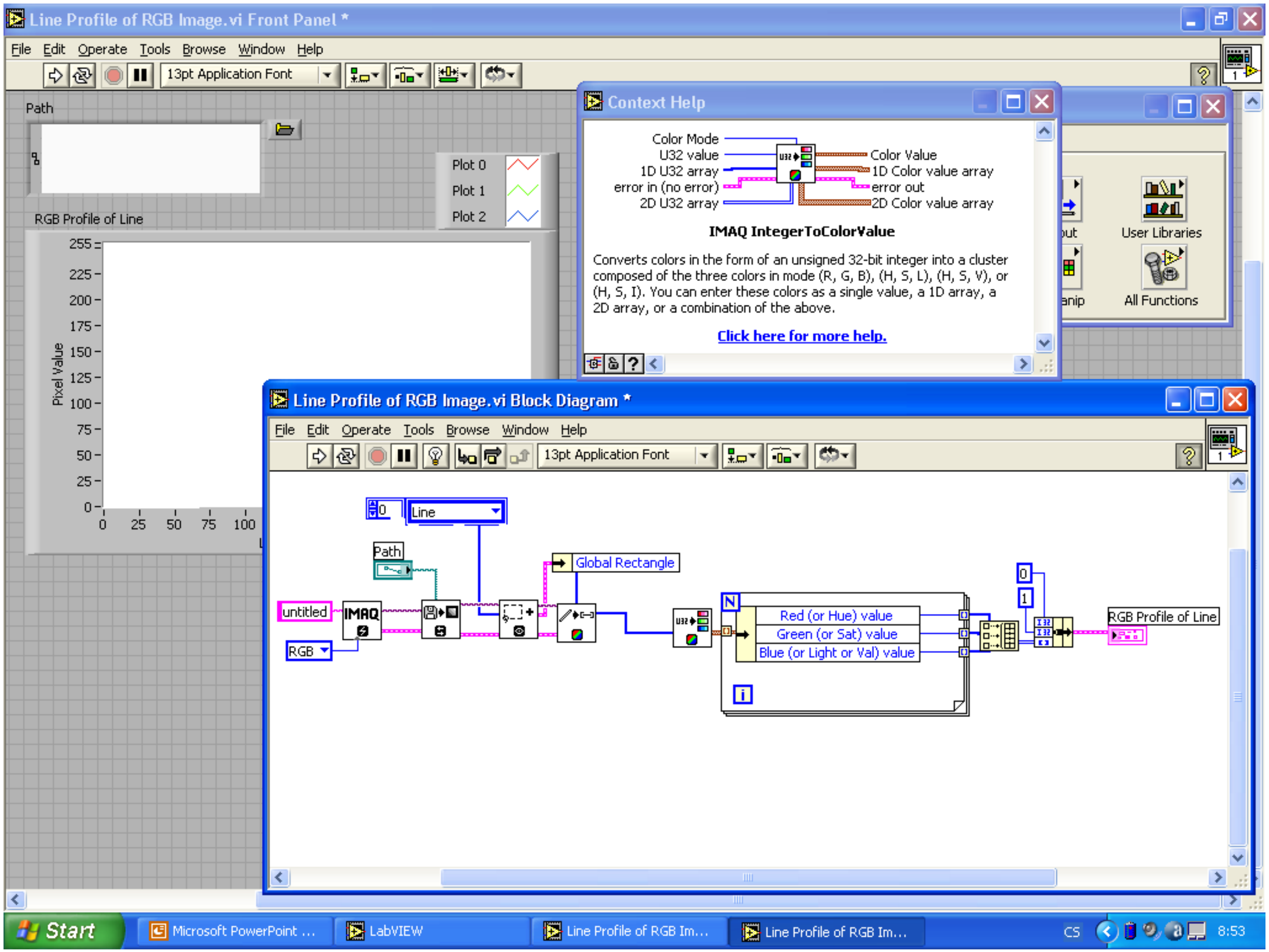


WOx_run95_120eV - Igor Pro 4.01
File Edit Data Analysis Macros Windows Misc Help KM MSB procedury Resonance MSB
Data Browser
Current Data Folder:
root:
root
Display
Waves
Variables
Strings
Info
Plot
New Folder...
Browse Expt...
Help
Delete
Preferences...
Execute Cmd...
root
V_Flag
05-03-05_WOx1_
05-05-05_WOx2_
05-07-05_WOx3_
WOx W4f 120eV
IWSP05_W4f:'nY W 4f mc 0.49' vs 'BEX W 4f mc 0.49';...
W4f
W
WO3
Sample A, 630°C 15 min
Sample B, 200°C 15 min
Sample B, 400°C 40 min
Sample B, ion bombardment
Sample C, deposition
Sample C, 400°C 15 min
Intensity [a.u.]
30 31 32 33 34 35 36 37 38 39 40 41
Binding Energy [eV]
Graph0,text0
WOx_run95_120eV
•SetDrawEnv arrow= 1
•HideTools/A
•ShowTools/A
•SetDrawEnv fstyle= 1
•HideTools/A
•SavePICT/E=-5/B=72
50% Graph0 Left: 0.83 Top: 2.08 Width: 0.00 Height: 0.00
Ready
Start
Microsoft PowerPoint ...
Total Commander 6.0...
WOx_run95_120eV - ...
CS
0:23

Labview

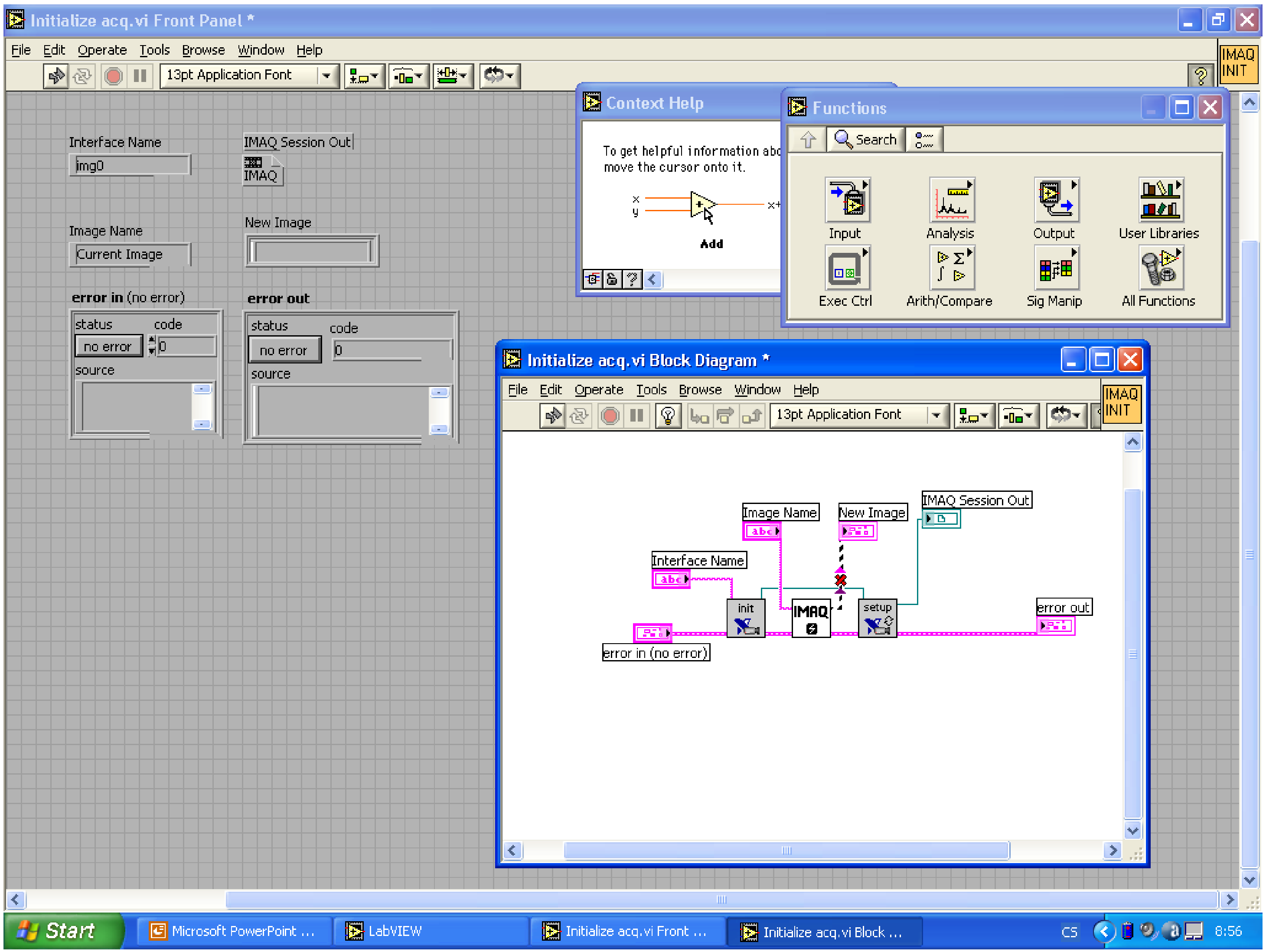
- Grafické programování
- Modulární systém (Labview, Diadem, Simulation, Real-Time, FPGA, PDA, Datalogging, NI Vision, Toolkit, Matrix, Signal Processing, Vision Assistent, Device Drivers)
- Knihovny vzorových programů
- Kód pro jazyk C++

Labview



Line Profile of RGB Image.vi Front Panel *
File Edit Operate Tools Browse Window Help
13pt Application Font
Path
Plot 0
Plot 1
Plot 2
RGB Profile of Line
Pixel Value
Context Help
Color Mode
U32 value
1D U32 array
error in (no error)
2D U32 array
Color Value
1D Color value array
error out
2D Color value array
IMAQ IntegerToColorValue
Converts colors in the form of an unsigned 32-bit integer into a cluster composed of the three colors in mode (R, G, B), (H, S, L), (H, S, V), or (H, S, I). You can enter these colors as a single value, a 1D array, a 2D array, or a combination of the above.
Click here for more help.
User Libraries
All Functions
Line Profile of RGB Image.vi Block Diagram *
Line
Path
Global Rectangle
untitled
IMAQ
RGB
Red (or Hue) value
Green (or Sat) value
Blue (or Light or Val) value
RGB Profile of Line
Start
Microsoft PowerPoint ...
LabVIEW
Line Profile of RGB Im...
8:53

Labview


Initialize acq.vi Front Panel *
File Edit Operate Tools Browse Window Help
13pt Application Font
Interface Name
img0
IMAQ Session Out
IMAQ
Image Name
Current Image
New Image
error in (no error)
status
code
no error
0
source
error out
Context Help
To get helpful information abo
move the cursor onto it.
Add
Functions
Search
Input
Analysis
Output
User Libraries
Exec Ctrl
Arith/Compare
Sig Manip
All Functions
Initialize acq.vi Block Diagram *
IMAQ INIT
init
setup
error out
error in (no error)
Start
Microsoft PowerPoint ...
LabVIEW
Initialize acq.vi Front ...
Initialize acq.vi Block ...
8:56

Metody zpracování fyzikálních měření

EVF 112

Zpracování obrazové informace

Doc. RNDr. Karel Mašek, Dr.
Skupina fyziky povrchů KEVF

Obrazová informace – užití ve fyzice tenkých vrstev, fyzice povrchů …

- Elektronová difrakce LEED (Low Energy Electron Diffraction) a RHEED (Reflection High Energy Electron Diffraction)
- TEM (Transmission Electron Microscopy) a TED (Transmission Electron Diffraction)
- SEM (Scanning Electron Microscopy)
- STM (Scanning Tunneling Microscopy)
- HRTEM (High Resolution TEM)
- A další

Zpracování obrazu - informace

- Úpravy a prezentace obrazu
- Profilová analýza, intenzitní měření
- Vyhledávání a určování polohy a velikosti objektů v obrazu

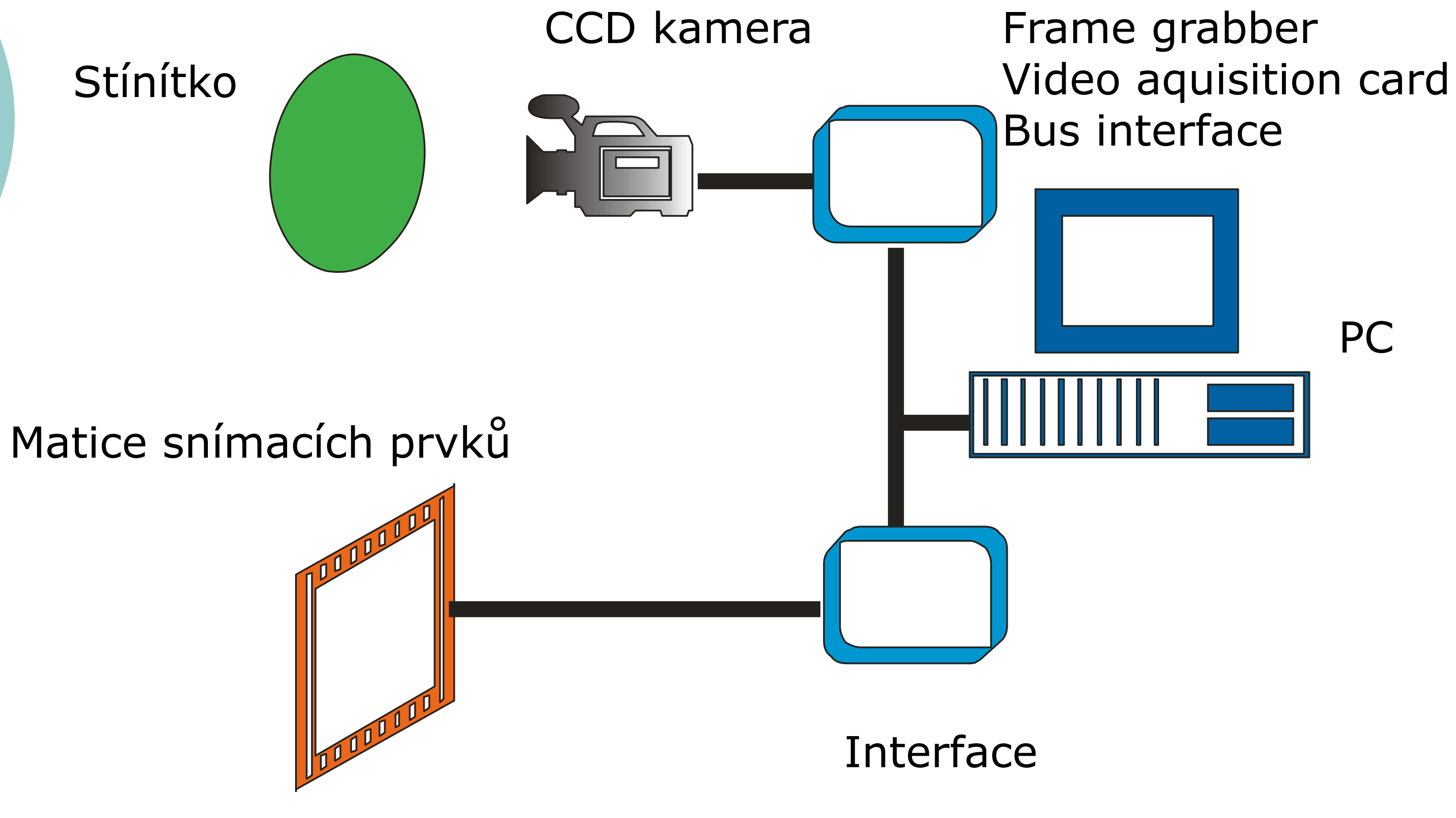
- Korekce vad zobrazovacího systému

Získávání obrazové informace

- Digitální informace
- Fotografie – skenování obrazu
- Stínítko – kamera, přenos v digitální formě, digitalizace videosignálu
- Matice citlivých prvků (CCD)

- Výsledek – obrazový soubor v nějakém formátu

Získávání obrazové informace



Software pro zpracování obrazu

- Speciální software – dodávaný výrobci zařízení (mikroskopů)
- Specializované programovatelné prostředí – např. Labview
- Obecnější programy – ACDSee, MatLab, …..

Digitální obraz

- Obraz = 2D matice intenzity světla v úrovních šedi nebo v barvách
- Konvence – počátek vlevo nahoře, vodorovně osa x a svisle osa y
- Rozlišení m x n – m počet sloupců a n počet řad
- Bitová hloubka = počet bitů použitých k vyjádření hodnoty jednoho pixelu, 8 bitů = 256 úrovní, 16 bitů = od 0 do 65536 nebo od -32767 do 32767
- Počet rovin = počet matic, které vytvářejí obraz, v úrovních šedi a pseudo-barvách – 1 rovina, „true color" – 3 roviny RGB (červená, zelená, modrá), HSL (odstín, saturace, jas)

Typy obrazu

- V úrovních šedi, barevné, komplexní

Image Type	Number of Bytes per Pixel Data
8-bit (Unsigned) Integer Grayscale (1 byte or 8-bit)	 8-bit for the grayscale intensity
16-bit (Signed) Integer Grayscale (2 bytes or 16-bit)	 16-bit for the grayscale intensity

Typy obrazu

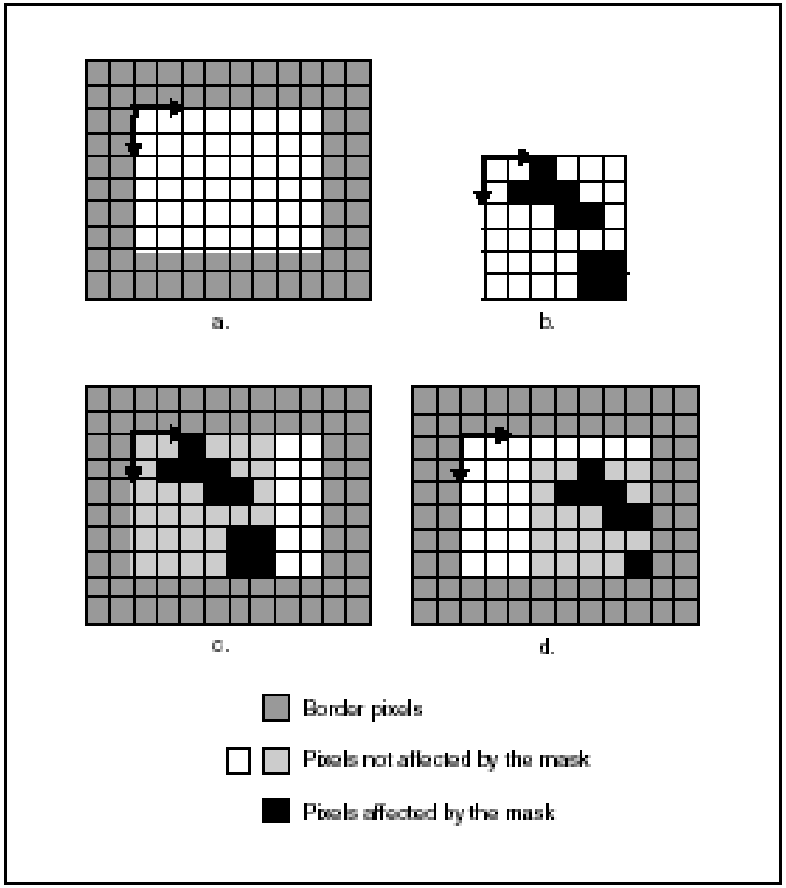
Image Type	Number of Bytes per Pixel Data
32-bit Floating-Point Grayscale (4 bytes or 32-bit)	32-bit for the grayscale intensity
RGB Color (4 bytes or 32-bit)	8-bit for the alpha value (not used); 8-bit for the red intensity; 8-bit for the green intensity; 8-bit for the blue intensity
HSL Color (4 bytes or 32-bit)	8-bit not used; 8-bit for the hue; 8-bit for the saturation; 8-bit for the luminance
Complex (8 bytes or 64-bit)	32-bit floating for the real part 32-bit for the imaginary part

Obrazové soubory

- Bitmap (BMP)
- Tagged image file format (TIFF)
- Portable network graphics (PNG)
- Joint Photographic Experts Group format (JPEG)
- …

Okraje obrazu a maska obrazu

- Okraje obrazu – záleží na počtu sousedů, které využívají funkce obrazového zpracování
- Maska – určuje část obrazu ke zpracování



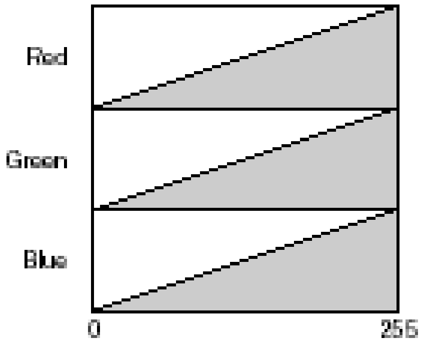
Zobrazení obrazu

- 8-bit zobrazení => 256 barev
- 16-bit zobrazení => 65536 barev
- 24 nebo 32-bit zobrazení => 16.7mil barev, kódováno od RGB
- 16-bit obraz v úrovních šedi
  - ignorují se méně významné bity
  - užití mapovacích metod

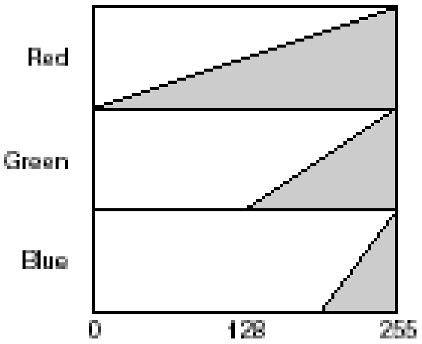
Palety

- Tabulka barev, která přiřazuje každé intenzitě barevnou hodnotu
- Různé vizuální prezentace bez změny hodnot jednotlivých pixelů
- Zdůraznění malých rozdílů, pseudobarvy

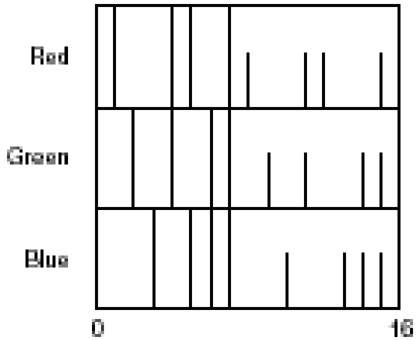
Palety



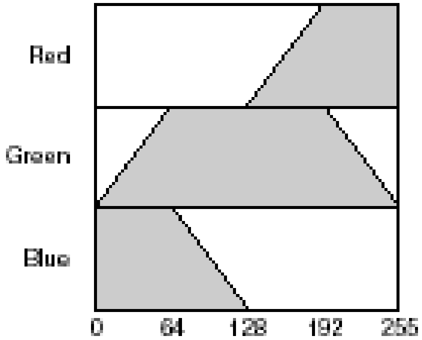
Paleta šedi



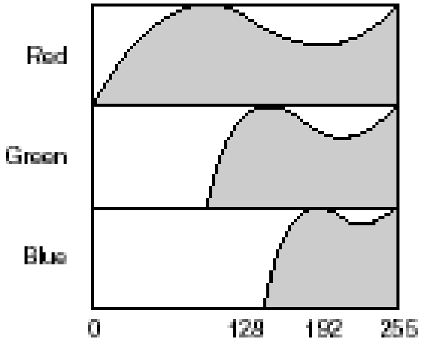
Paleta teplotní



Paleta binární



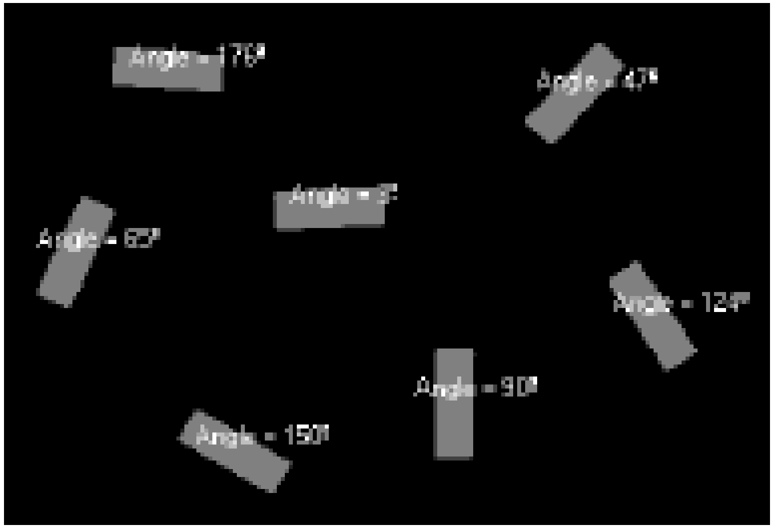
Paleta duhová



Paleta gradientní

Overlay

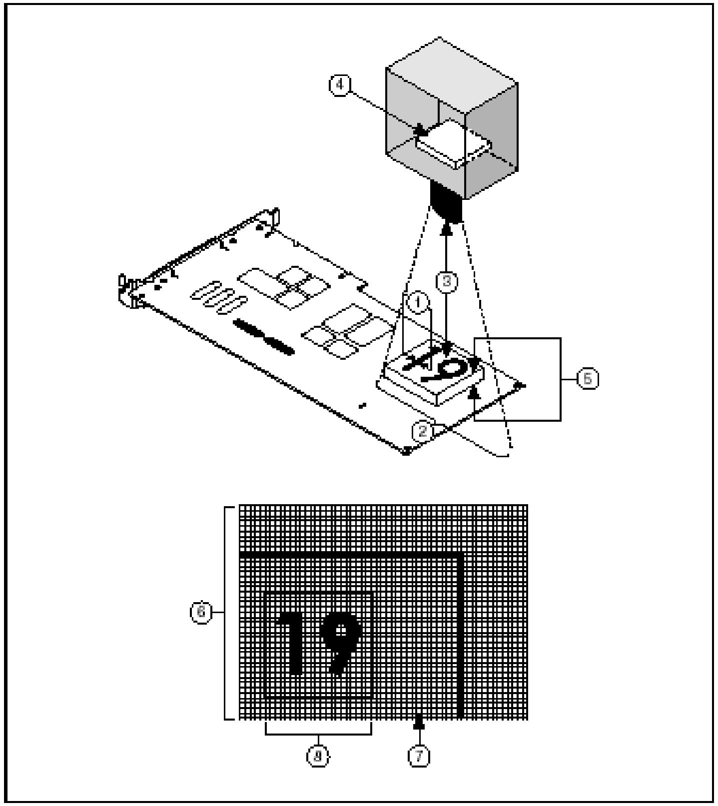
- Popisy obrazu, zvýraznění částí, linie, tvary bez změny původního obrazu
- Ovlivňuje pouze zobrazení



Zobrazovací systém

<u>Vlastnosti:</u>

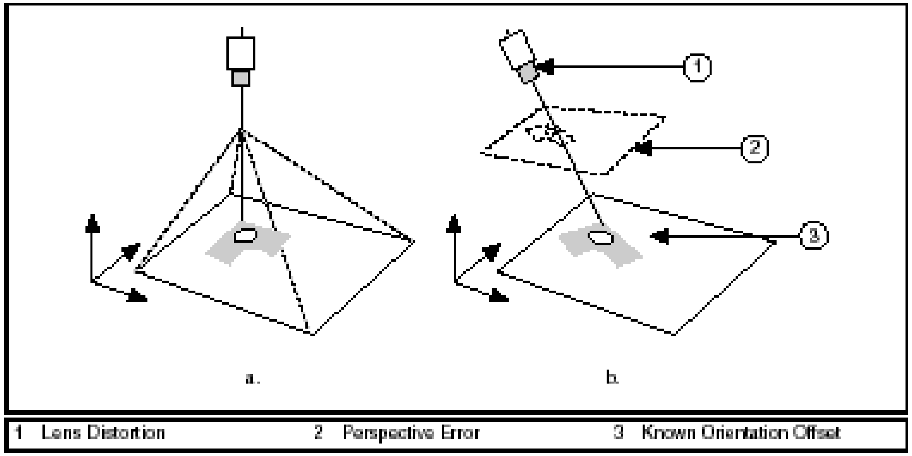
- Rozlišení
- Rozlišení v pixelech
- Zorné pole
- Pracovní vzdálenost (délka zaostření)
- Kontrast
- Velikost senzoru
- Hloubka ostrosti

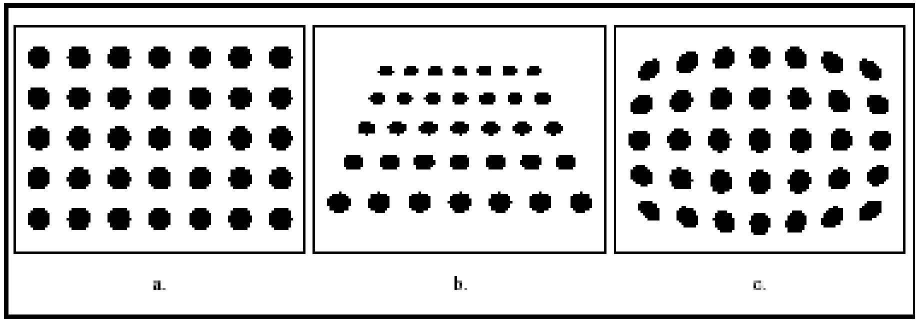


1 Resolution
2 Field of View
3 Working Distance
4 Sensor Size
5 Depth of Field
6 Image
7 Pixel
8 Pixel Resolution

Chyby zobrazovacího systému

- Distorze obrazu, perspektiva, otočení

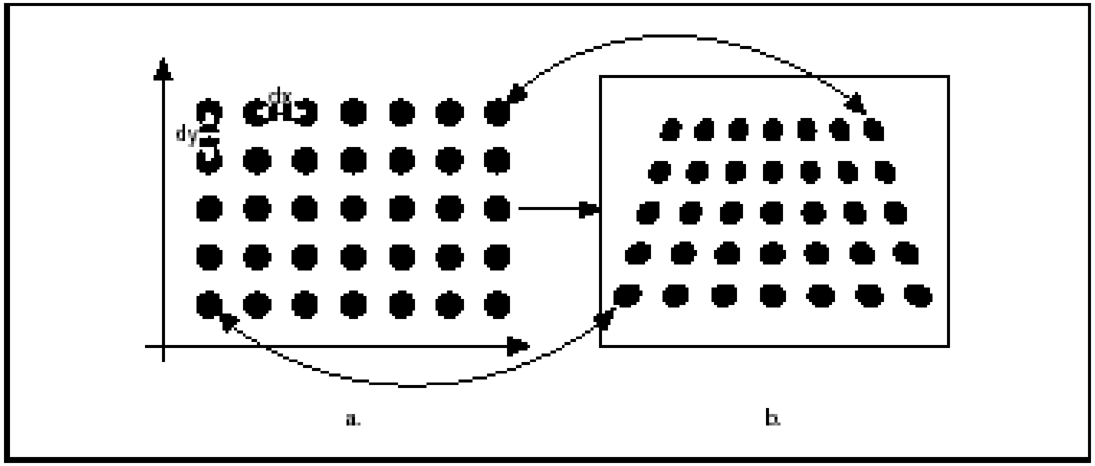




originál perspektiva distorze

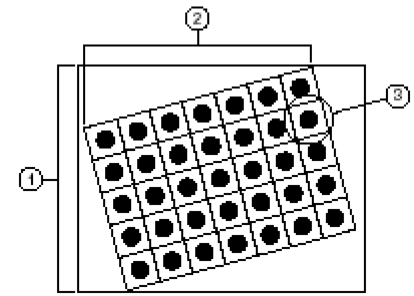
Prostorová kalibrace

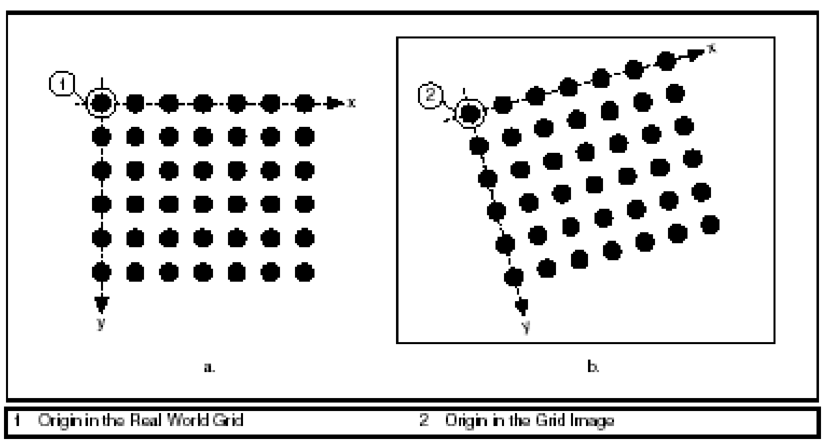
- Umožňuje převod do reálných jednotek a odstranění vad zobrazovacího systému, nastavení koordinačního systému
- Transformace mezi naměřeným a vzorovým obrazem



Prostorová kalibrace

- Koordinační systém
- Kalibrační algoritmy – pro korekci perspektivy, nonlineární algoritmus





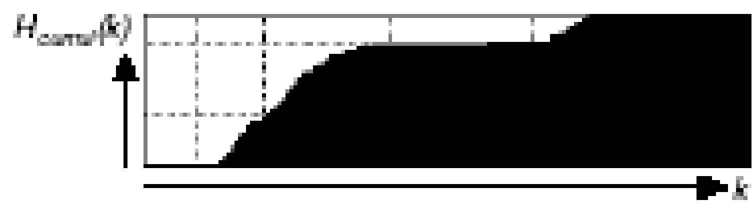
Chybová hodnota

$$e(i,j) = \sqrt{(x - x_{true})^2 + (y - y_{true})^2}$$

Obrazová analýza

- Histogram = počet pixelů určité úrovně šedi, pomáhá při nastavení podmínek snímání obrazu
- Lineární histogram, pravděpodobnost
- Kumulativní histogram, pravděpodobnost

$H_{Linear}(k) = n_k$ $\quad$ $P_{Linear}(k) = n_k/n$

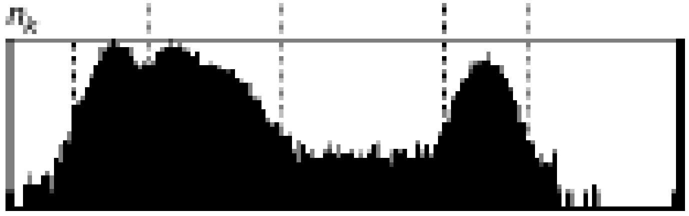


$$H_{Cumul}(k) = \sum_{i=0}^{k} n_i \qquad P_{Cumul}(k) = \sum_{i=0}^{k} \frac{n_i}{n}$$

Obrazová analýza

- Lineární škálování histogramu
- Logaritmické škálování – zvýrazní malé hodnoty v histogramu

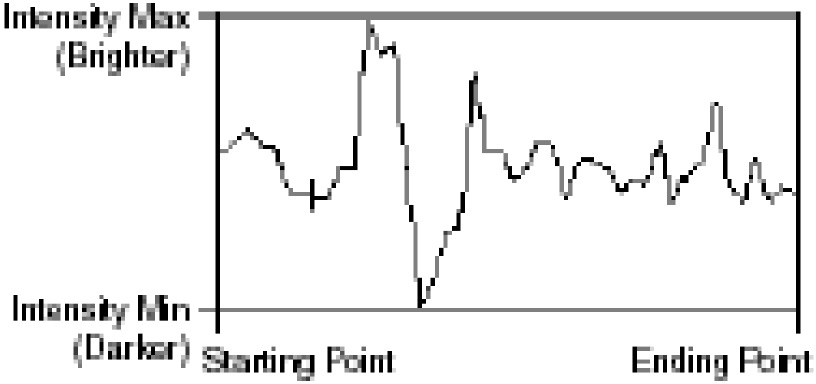
a. Linear Vertical Scale



b. Logarithmic Vertical Scale

Obrazová analýza

- Intenzitní profil – průběh intensity podél linie v obrazu
- Intenzitní měření – minimální a maximální hodnota, střední hodnota, standartní odchylka



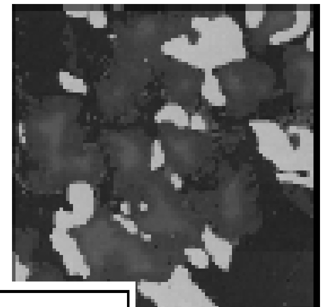
Zpracování obrazu

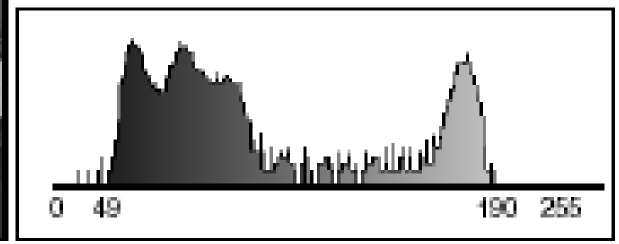
- LUT = Lookup Table
- Základní funkce zpracování obrazu využívající LUT:
- - vyrovnání pomocí histogramu
- - gamma korekce
- - exponenciální korekce
- - logaritmická korekce

- Využití: úprava kontrastu a jasu

Zpracování obrazu

- Příklad

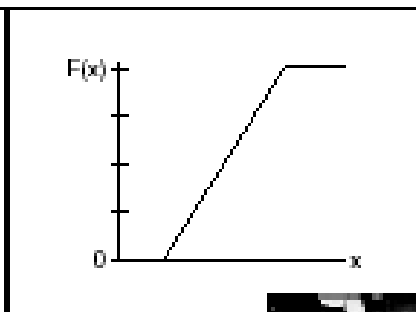


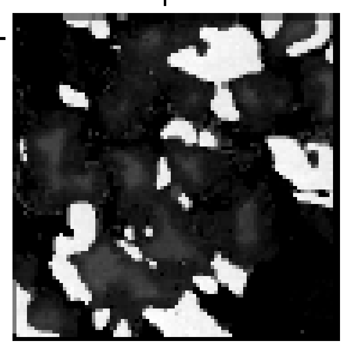


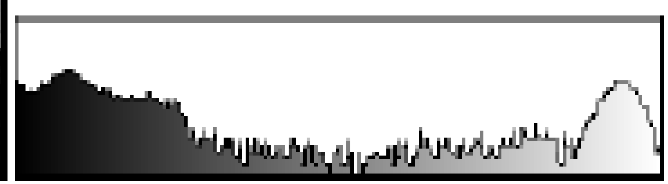
$If\ x \in [0, 49],\ F(x) = 0$

$If\ x \in [191, 254],\ F(x) = 255$

$else\ F(x) = 1.81 \times x - 89.5$

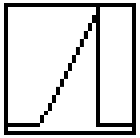
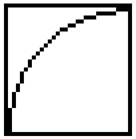
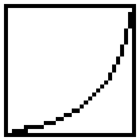






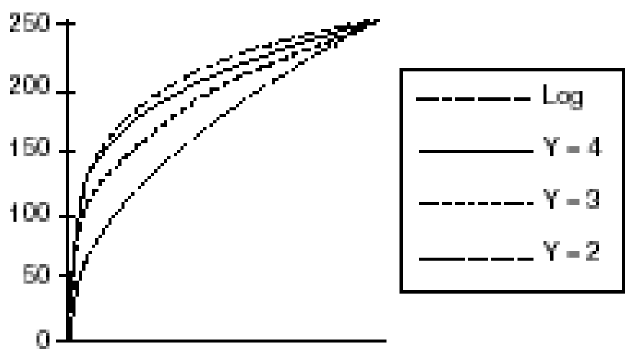
Zpracování obrazu

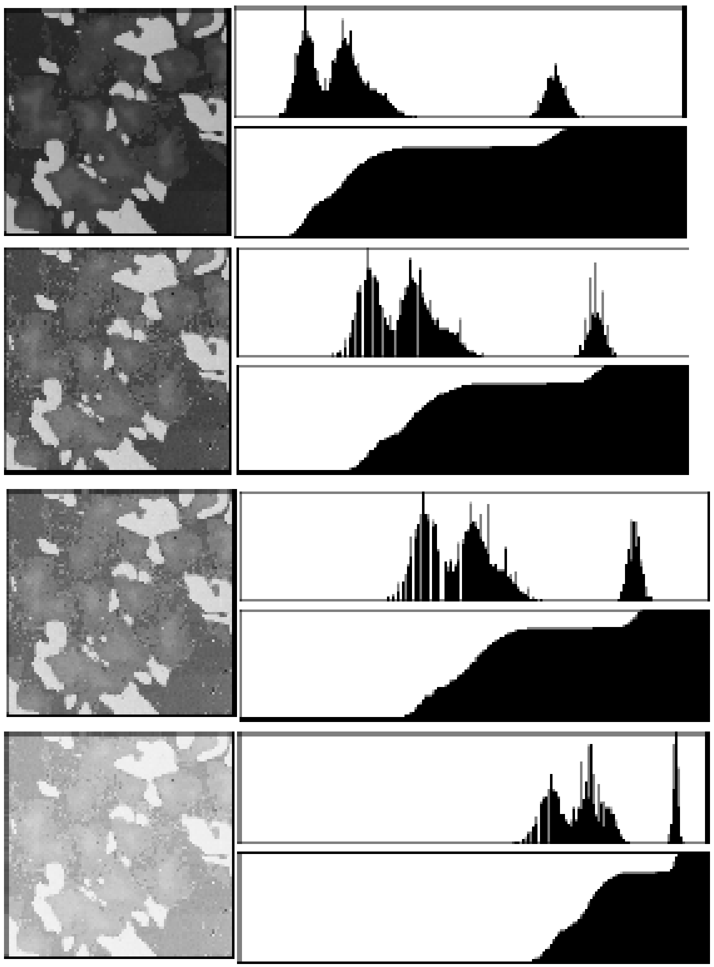
- Příklad obvyklých předdefinovaných LUT

LUT	Transfer Function	Shading Correction
Linear		Increases the intensity dynamic by evenly distributing a given gray-level interval [min, max] over the full gray scale [0, 255]. Min and max default values are 0 and 255 for an 8-bit image.
Logarithmic Power 1/Y Square Root		Increases the brightness and contrast in dark regions. Decreases the contrast in bright regions.
Exponential Power Y Square		Decreases the brightness and contrast in dark regions. Increases the contrast in bright regions.

Zpracování obrazu

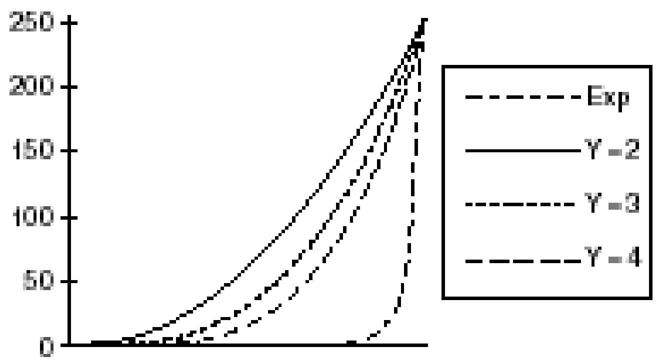
- Logaritmická a inverzní gamma korekce – rozšiřuje intervaly v nízkých úrovních šedi

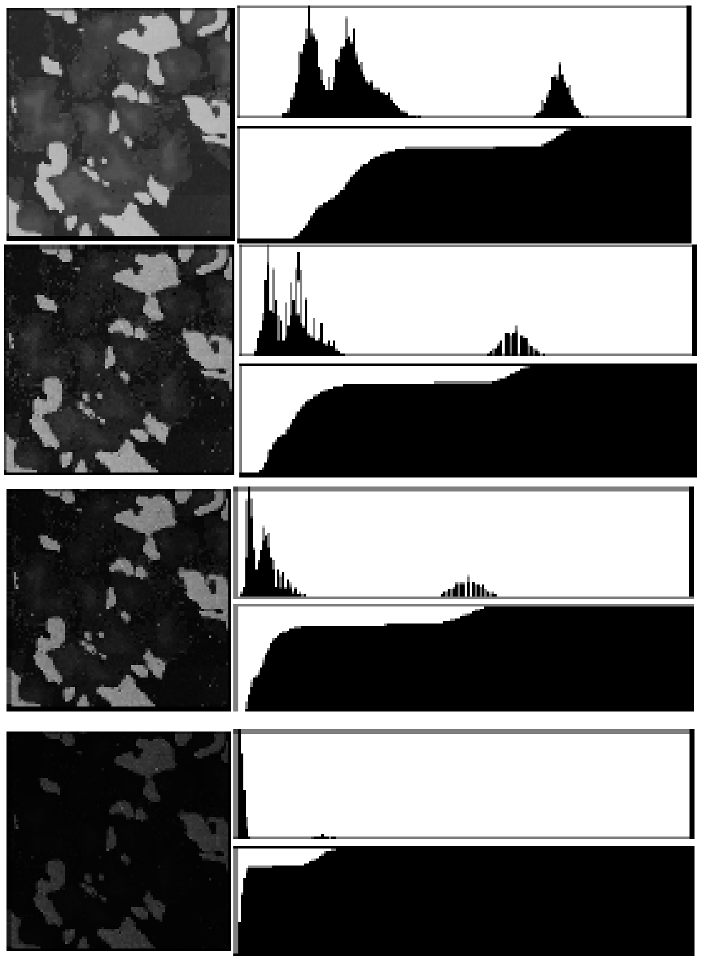




Zpracování obrazu

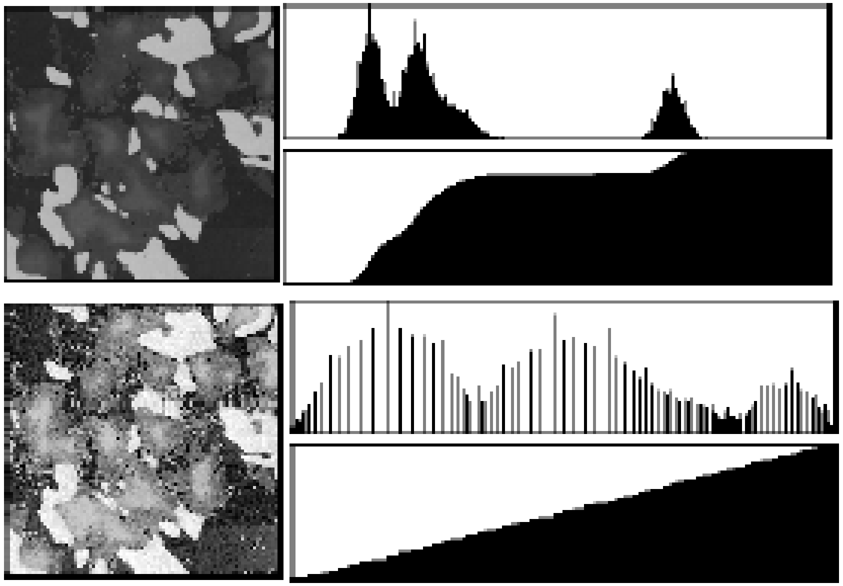
- Exponenciální a gamma korekce – rozšiřuje intervaly ve vysokých úrovních šedi





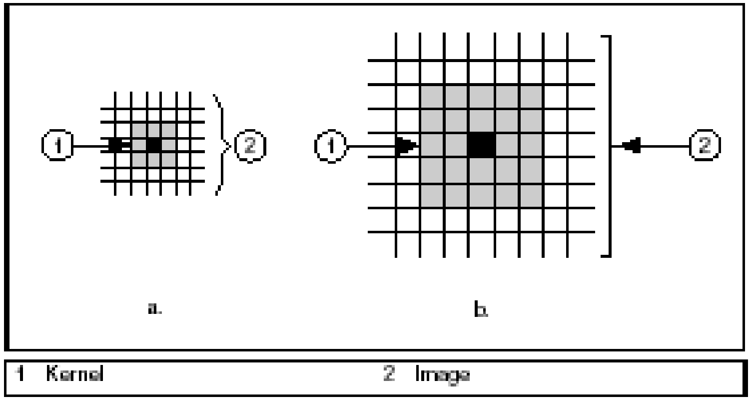
Zpracování obrazu

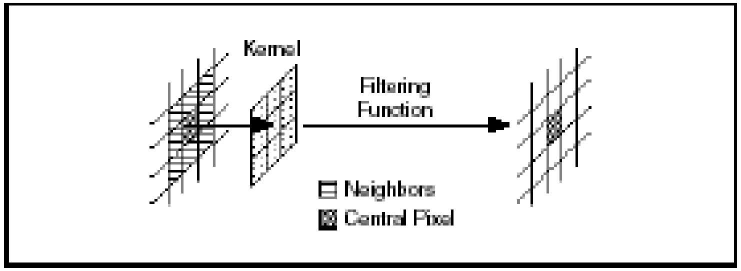
- Vyrovnání – LUT je vypočtena z obsahu obrazu



Zpracování obrazu

- Základní konvoluční operace = 2d filtry které aplikujeme na obraz
- Koeficienty definují jak je hodnota vypočtena na základě hodnot nejbližších sousedů
- Filtry 3x3, 5x5, 7x7





Zpracování obrazu

- Filtry = lineární (konvoluční), nelineární
- Konvoluce = gradientní, Laplaceovské, vyhlazovací, Gaussovské
- Užití filtrů: detekce hran, kontury, odstranění šumu, vyhlazování, ostření, …

Zpracování obrazu

- Typy prostorových filtrů

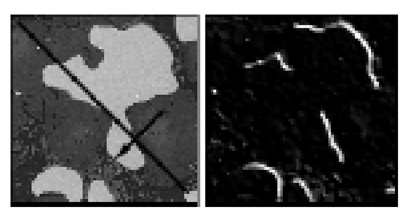
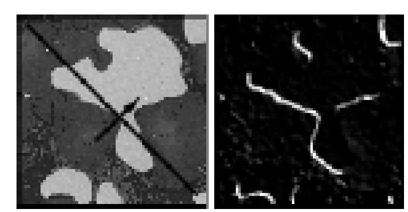
Filter Type	Filters
Linear	
Highpass	Gradient, Laplacian
Lowpass	Smoothing, Gaussian
Nonlinear	
Highpass	Gradient, Roberts, Sobel, Prewitt, Differentiation, Sigma
Lowpass	Median, Nth Order, Lowpass

Zpracování obrazu

- Příklad: gradientní filtr

Zvýraznění hran a textur

$$\begin{matrix} a & -b & c \\ b & x & -d \\ c & d & -a \end{matrix}$$

Prewitt #10	Prewitt #2
$\begin{matrix} 0 & -1 & -1 \\ 1 & 0 & -1 \\ 1 & 1 & 0 \end{matrix}$	$\begin{matrix} 0 & 1 & 1 \\ -1 & 0 & 1 \\ -1 & -1 & 0 \end{matrix}$
Prewitt #10 highlights pixels where the light intensity increases along the direction going from northeast to southwest. It darkens pixels where the light intensity decreases along that same direction. This processing outlines the northeast front edges of bright regions such as the ones in the illustration.	Prewitt #2 highlights pixels where the light intensity increases along the direction going from southwest to northeast. It darkens pixels where the light intensity decreases along that same direction. This processing outlines the southwest front edges of bright regions such as the ones in the illustration.
	

Zpracování obrazu

- Laplaceovský filtr – zvýraznění kontur
- Vyhlazovací filtr – sražení hran, rozmazání obrazu
- Gaussovský filtr – potlačuje detaily, průměruje

….

Zpracování obrazu

- Morfologické funkce – filtrování šumu, úprava pozadí
- Erozní funkce – snižuje jas pixelu obklopeného pixely s nízkou intenzitou
- Dilatační funkce - zvyšuje jas pixelu obklopeného pixely s vysokou intenzitou
- Funkce otevření – eroze následovaná dilatací, odstraňuje světlé stopy v tmavé oblasti, vyhlazení hranic
- Funkce uzavření – dilatace následovaná erozí, odstraňuje tmavé stopy ve světlé oblasti, vyhlazení hranic

Operátory

- Aritmetické a logické operace s obrazy

$$p_n = (p_a)(Op)(p_b)$$

- Aritmetické operátory

Operator	Equation
Multiply	$p_n = \min(p_a \times p_b, 255)$
Divide	$p_n = \max(p_a / p_b, 0)$
Add	$p_n = \min(p_a + p_b, 255)$
Subtract	$p_n = \max(p_a - p_b, 0)$
Modulo	$p_n = p_a \bmod p_b$
Absolute Difference	$p_n = \lvert p_a - p_b \rvert$

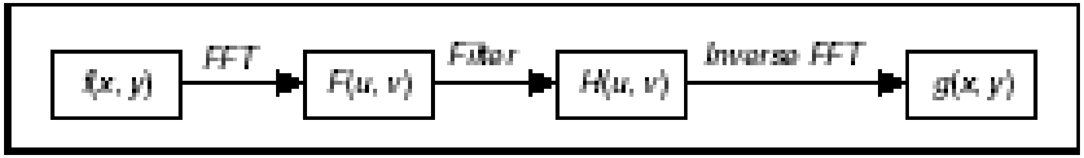
Operátory

- logické operátory

Operator	Equation
Logical Operators	
AND	$p_u = p_a$ AND p_b
NAND	$p_u = p_a$ NAND p_b
OR	$p_u = p_a$ OR p_b
NOR	$p_u = p_a$ NOR p_b
XOR	$p_u = p_a$ XOR p_b
Logic Difference	$p_u = p_a$ AND (NOT p_b)
Comparison Operators	
Mask	*if* $p_b = 0$, *then* $p_u = 0$, *else* $p_u = p_a$
Mean	$p_u = \text{mean}[p_a, p_b]$
Max	$p_u = \max[p_a, p_b]$
Min	$p_u = \min[p_a, p_b]$

Frekvenční analýza

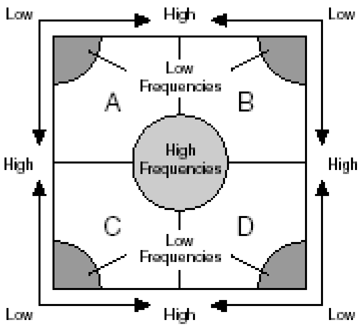
- FFT (Fast Fourier Transform)



- Nízkopásmový filtr – vyhlazený obraz, snížení šumu, potlačené detaily a kontury
- Vysokopásmový filtr – zaostřený, zvýrazněné detaily

Frekvenční analýza

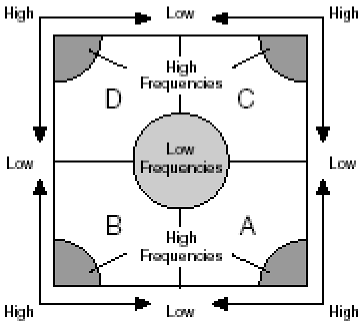
- Standartní FFT reprezentace, komplexní



a. Original Image

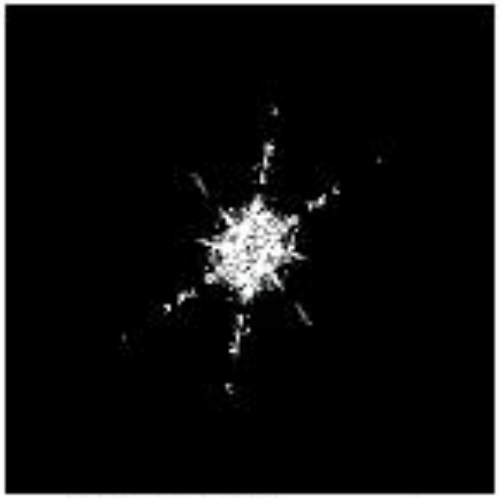
b. FFT in Standard Representation

Frekvenční analýza



- Optická FFT reprezentace, komplexní

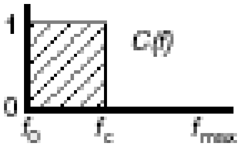
a. Original Image

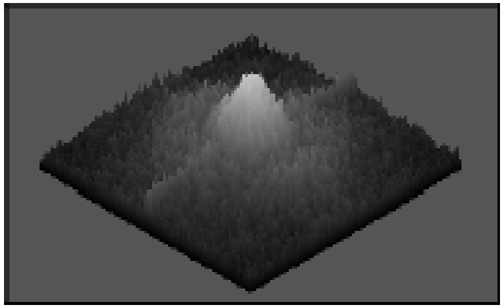


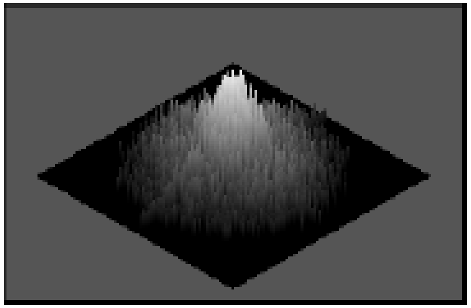
b. FFT in Optical Representation

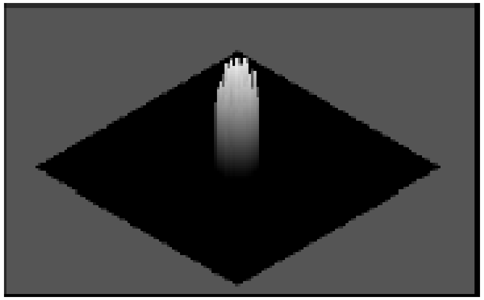
Nízkopásmové filtry

- Nízkopásmový útlum
- Nízkopásmové odříznutí



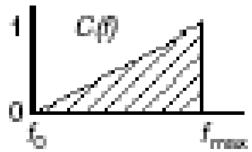


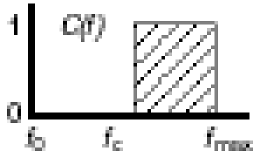


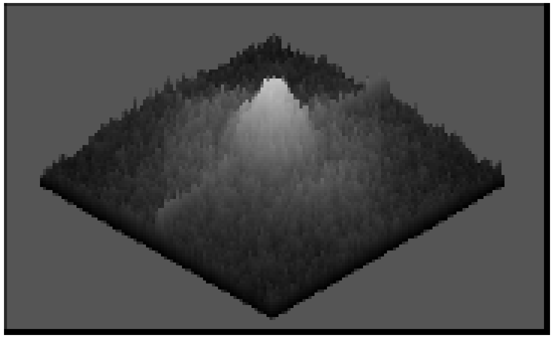


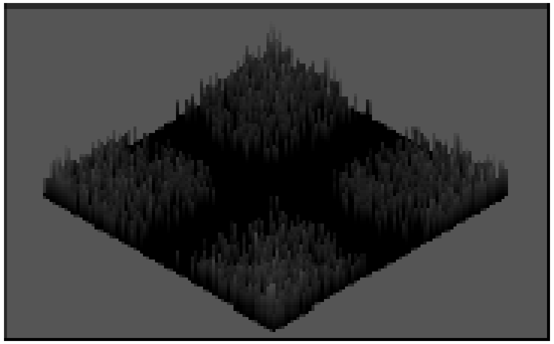
Vysokopásmové filtry

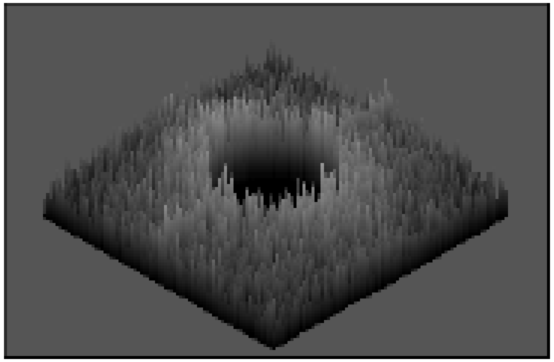
- Vysokopásmový útlum
- Vysokopásmové odříznutí







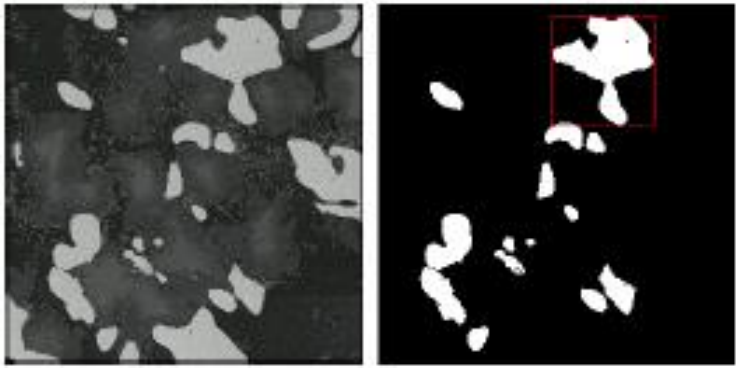




Analýza částic

- Prahování
- Binární morfologické funkce
- Měření částic

Analýza částic



Particle Measurement	Values
Area	2456
Number of Holes	1
Bounding Rect	
Left	127
Top	8
Right	200
Bottom	86
Center of Mass	
X	167.51
Y	37.61
Orientation	82.36°
Dimensions	
Width	73
Height	78

Prahování

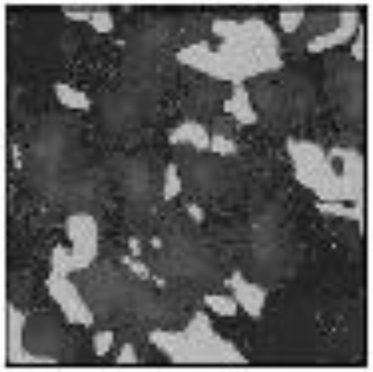
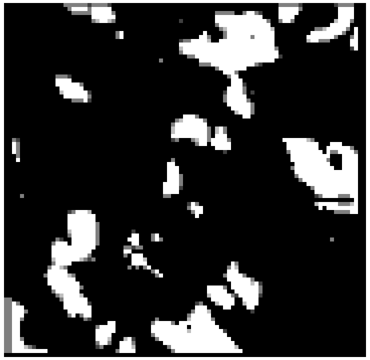
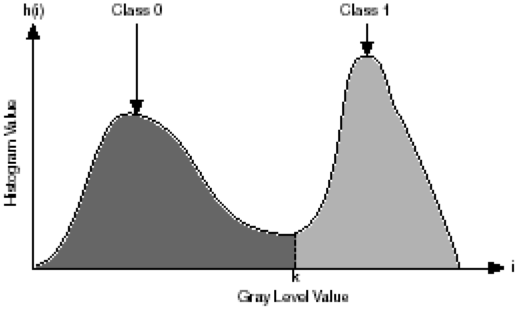



Image Histogram
Threshold
Interval
0
166
255




h(i)
Class 0
Class 1
Histogram Value
k
i
Gray Level Value

Binární morfologické funkce

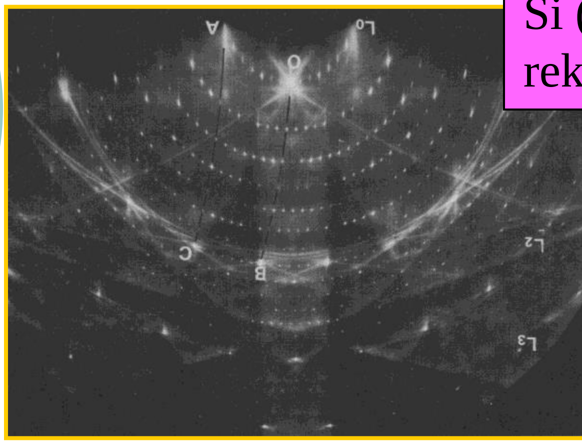
Úprava binárních obrazů

- -eroze
- -dilatace
- -otevření
- -uzavření
- -ztenčení
- -ztluštění
- -gradient
- -automedian

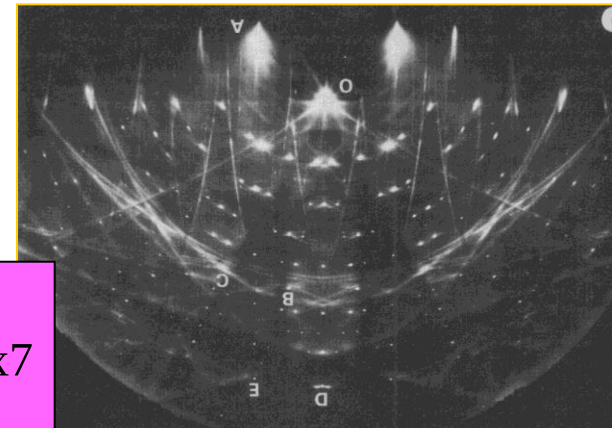
Měření částic

- Hraniční obdélník
- Průměr
- Plocha
- Ekvivalentní čtverec
- Ekvivaletní elipsa
- Segmentová délka
- Moment těžiště

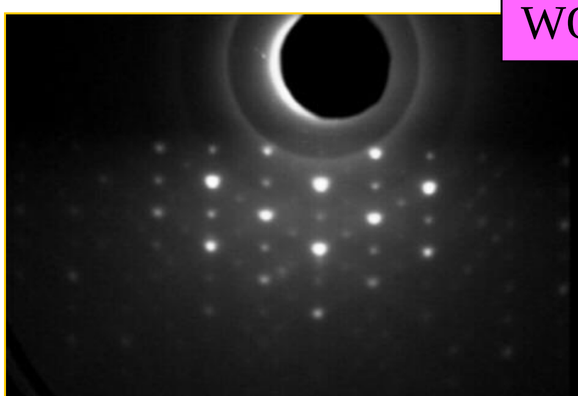
RHEED, LEED



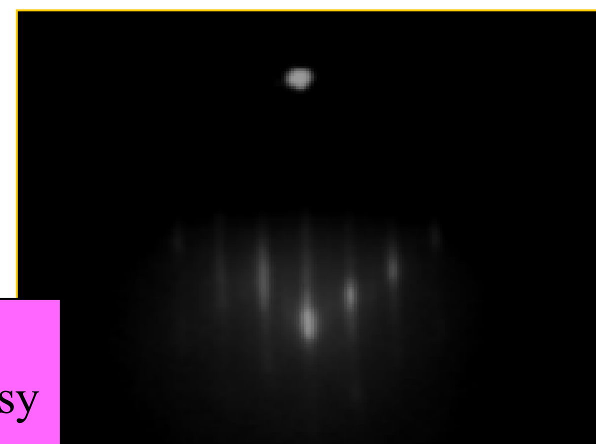
Si (111)
rekonstrukce 7x7



Si (111)
rekonstrukce 7x7
po depozici Au

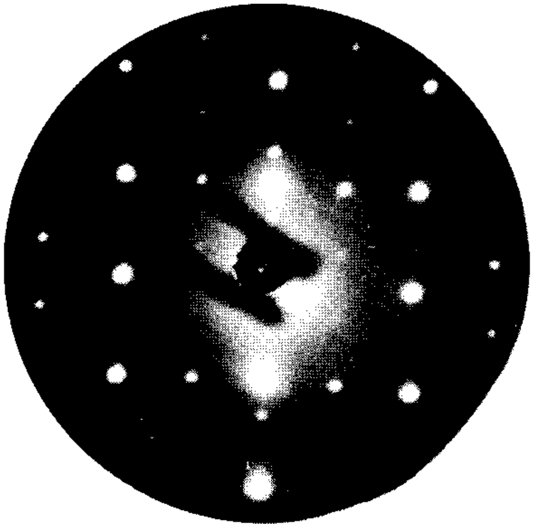


WO_2 / Al_2O_3 (0001)

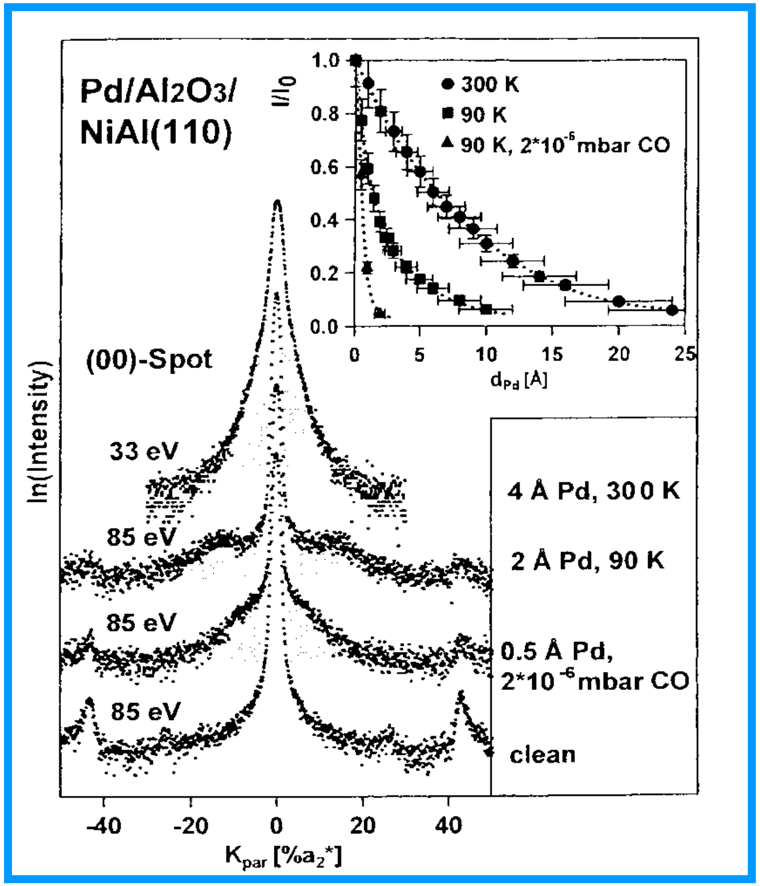


Al_2O_3 (0001)
otáčení okolo osy
kolmé k povrchu

RHEED, LEED

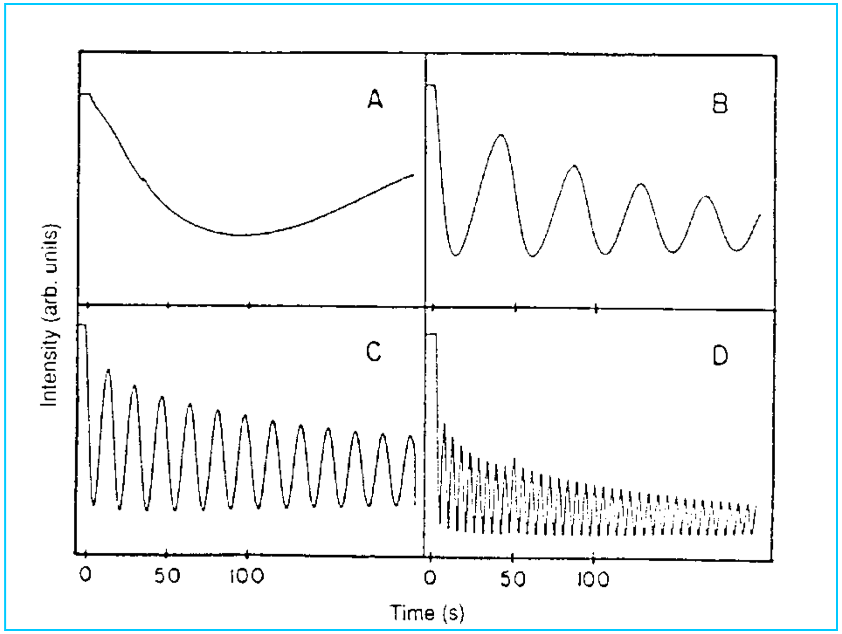


Intenzitní profil



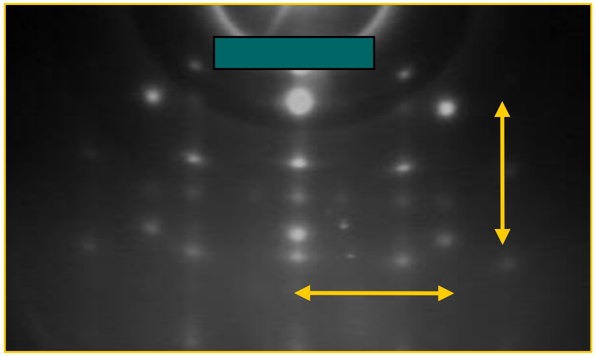
RHEED, LEED

Časový vývoj intenzity

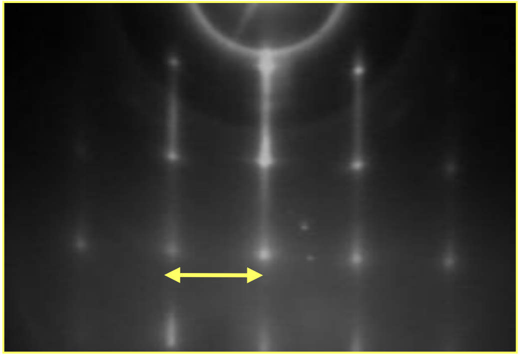


RHEED, LEED

vzorek



Růst Al na NaCl (001)



R||

R⊥

R, d_{hkl}

$$d_{hkl} = \frac{L\lambda}{R}$$

Pro kubickou mříž

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

a ||

a⊥

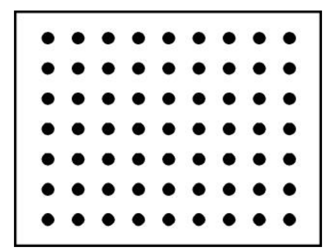
Určení vzdálenosti stop

Určení vzdáleností stop

Určení polohy stop:

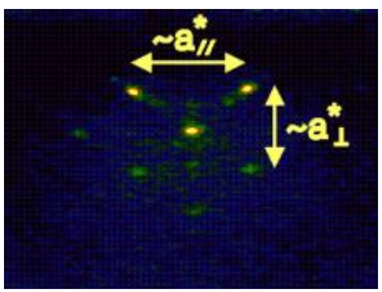
- prosté měření
- měřením z intenzitních profilů
- fitování modelových funkcí

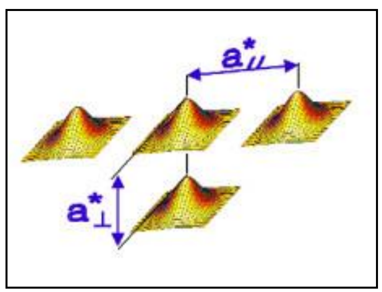
Virtuální kamera



odstranění zobrazovacích vad detekčního systému

Subpixelová detekce

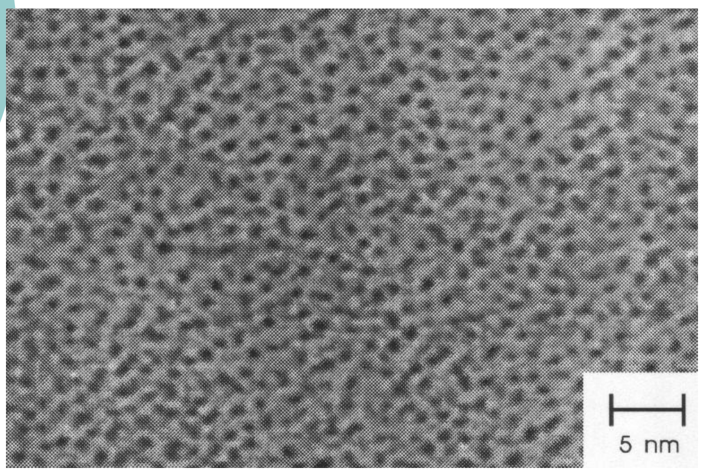


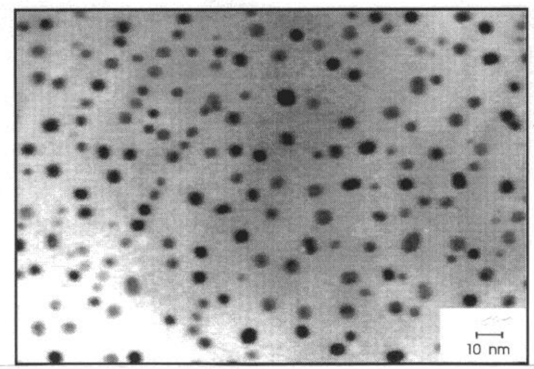


funkce:
Gauss, Lorentz, Voigt (pseudo-Voigt)

přesnost vyšší než rozměr pixelu

TEM





TEM photography of Au particles deposited on KCl. The magnify is 750 000.

Rh / NaCl - replika

Au / KCl - replika

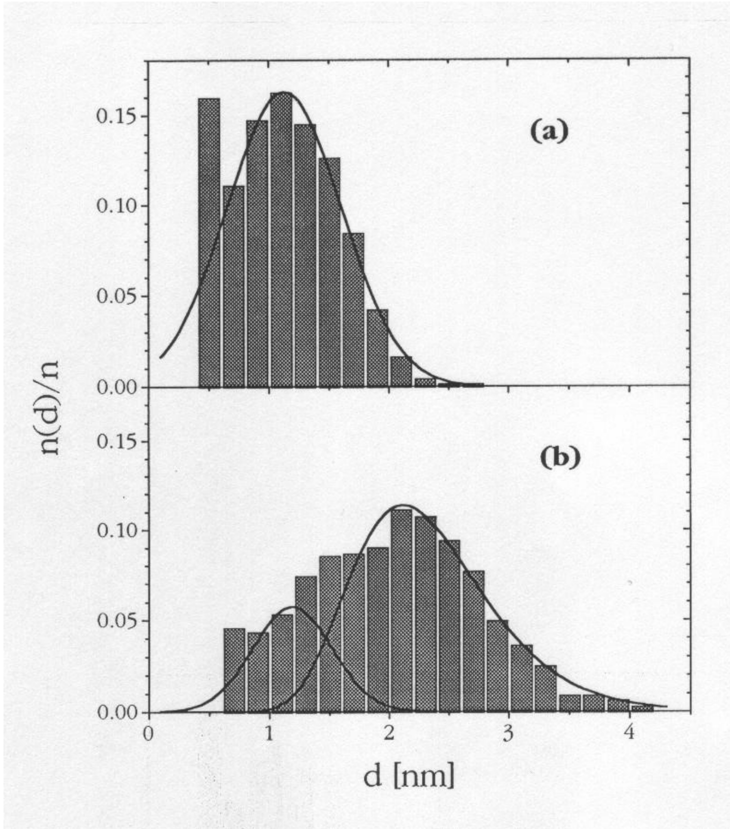
Morfologické metody popisu ostrůvkových struktur

- **hustota částic = počet / plocha, cm^{-2}, řádu 10^{12}**
- **pokrytí povrchu – bezrozměrné číslo**
- **střední velikost částic**
- **rozdělení velikostí**
- **radiální rozdělovací funkce – radial distribution function**
- **rozdělení N nejbližších sousedů – distribution of Nth nearest neighbours (center to center, random point to center)**
- **kvadratické metody (variance)**
- **covariance**
- **chord-length distribution**

Morfologické metody popisu ostrůvkových struktur

ROZDĚLENÍ VELIKOSTÍ

➢**gaussovo rozdělení – růst připojováním atomů**
➢**koalescence - odvozeno teoreticky (C.G. Granqvist and R.A. Buhrman, Statistical model for coalescence of islands indiscontinuous films, Applied Physics Letters 27 (12) (1975) 693)**
➢**koalescence - log-normální rozdělení – σ =1.28±0.06 – (platí např. pro Ag/am C, Pt/NaCl, Au/am C, Au/NaCl, Au/SiO, Pd/NaCl, Rh/NaCl …)**
➢**Ostwaldův ripening**



$$f(x) = \frac{1}{(2\pi)^{1/2} \ln\sigma} \cdot \exp\left\{ -\frac{1}{2} \left[\frac{\ln\left(\frac{x}{x}\right)^2}{\ln\sigma} \right] \right\}$$