ELECTRONICS Lecture for PSI Course

A. Schöning, August 2013

Overview

- Pulse terminology
- Cables and signal transmissions
- Noise + filters
- Components analog / digital
- Signal Standards

Book: W. R. LEO
Techniques for Nuclear and
Particle Physics Exp.

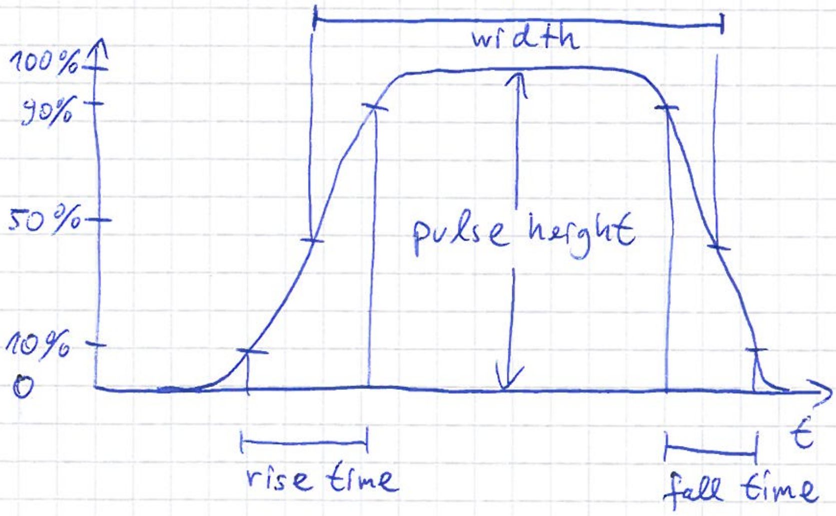
Transmission of Signals

pulse deformation

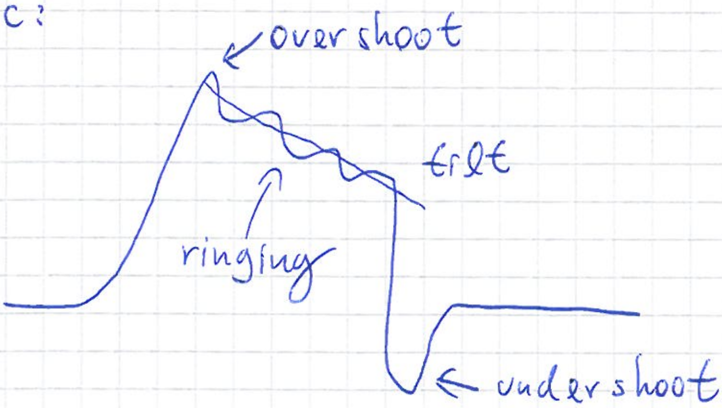
depends on:

- resistance (→ power consumption)
- noise (capacities, induction)
- signal quality (deformation, attenuation)
- signal transmission speed
- digital / analog
- bandwidth (frequency behaviour)

o Pulse Terminology



realistic:



o Cable Types

1 wire/cord (Litze)

2 flat ribbon

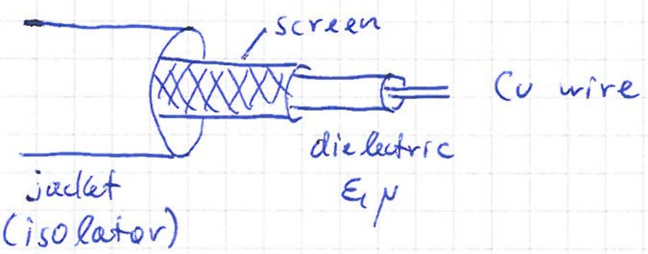
3 twisted pair

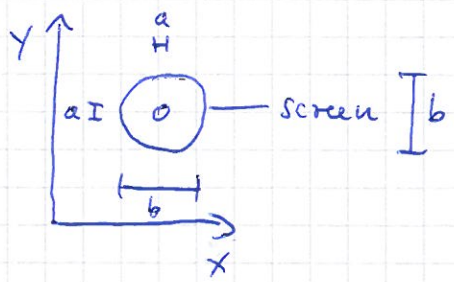
$Q = Q_+ - Q_-$

4 coax

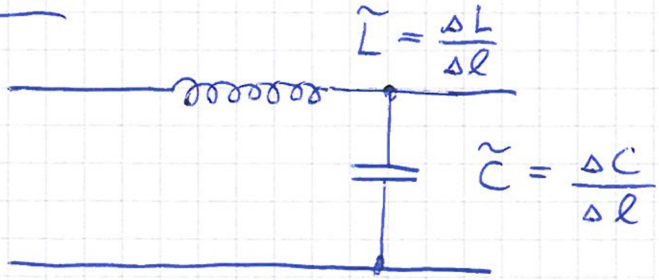
1,2,3 ⇒ large signal deformation
- only short distances
- only low frequencies ($\leq 1 MHz$)

Coax Cable





Circuit:



$\tilde{L}, \tilde{C} > 0$ leads to losses
- dielectric losses
- skin effect

every cable has a capacity and inductance!

$$\tilde{C} = \frac{\Delta C}{\Delta l} = \frac{2\pi \varepsilon}{\ln(b/a)} = \frac{\varepsilon_r \cdot 55.6\,pF/m}{\ln(b/a)}$$

$\varepsilon_r = 2.3$ for PE

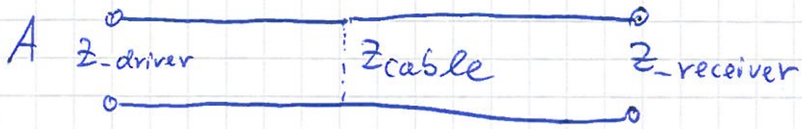
ε = dielectricity
ε_r = dielectric constant
$\varepsilon = \varepsilon_0 \varepsilon_r$

$$\tilde{L} = \frac{\Delta L}{\Delta l} = \frac{\mu}{2\pi} \ln(b/a) = \mu_r \cdot 0.2\,\mu H/m \cdot \ln(b/a)$$

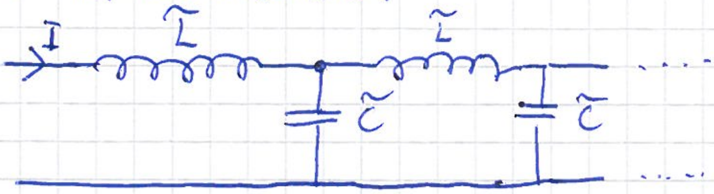
$\mu = \mu_0 \mu_r$ permeability $\quad \mu_r \approx 1$ for PE

Signal transmission in wave guide

transmission from $A \to B$



wire representation:



Induction:

$$\Delta V = -\tilde{L} \cdot \Delta z \cdot \frac{\partial I}{\partial t}(z,t) \qquad \left(U_{ind} = -L \frac{\partial I}{\partial t} \right)$$

Condensator:

$$\Delta I = -\tilde{C} \cdot \Delta z \ \frac{\partial V}{\partial t}(z,t) \qquad \left(Q = C \cdot U \qquad I = \frac{\partial Q}{\partial t} \right)$$

$$\frac{\partial}{\partial z} \Big| \quad \frac{\partial U}{\partial z} = -\tilde{L} \frac{\partial I}{\partial t} \quad \Rightarrow \quad \frac{\partial^2 U}{\partial z^2} = -\tilde{L} \frac{\partial^2 I}{\partial z \partial t}$$

$$\frac{\partial}{\partial t} \Big| \quad \frac{\partial I}{\partial z} = -\tilde{C} \frac{\partial V}{\partial t} \quad \Rightarrow \quad \frac{\partial^2 I}{\partial z \partial t} = \tilde{C} \frac{\partial^2 V}{\partial t^2}$$

$\Rightarrow$ combination:

$$\frac{\partial^2 V}{\partial z^2} = \underbrace{\tilde{L}\tilde{C}}_{1/v^2} \frac{\partial^2 V}{\partial t^2} \qquad \text{(wave equation)}$$

$\Rightarrow$ group velocity $v = \frac{1}{\sqrt{\tilde{L}\tilde{C}}}$

$\Rightarrow$ plugging in numbers: $v = \frac{1}{\sqrt{\frac{2\pi \varepsilon_r \varepsilon_0}{\ln(b/a)} \cdot \frac{\mu_0 \mu_r}{2\pi} \ln b/a}} = \frac{1}{\sqrt{\varepsilon_0 \mu_0 \varepsilon_r \mu_r}}$

speed of light: $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \quad \Rightarrow V = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \approx \frac{c}{\sqrt{2.3}} = 0.66\, c$

$\hat{=}$ 20 cm/ns

Solution of wave equation:

$\Rightarrow$ sine wave (cosine)

$$U = U_0 \, e^{i(kz - wt)} \qquad I = I_0 \, e^{i(kz - wt)}$$

$$\frac{\partial U}{\partial t} = -iw V_0 \, e^{i(kz-wt)} \qquad \frac{\partial I}{\partial t} = i k I_0 \, e^{i(kz-wt)}$$

$$\frac{\partial U}{\partial t} = -iw U_0 \qquad \frac{\partial I}{\partial t} = i k I$$

from previous calculation (capacity)

$$\frac{\partial I}{\partial z} = -\tilde{C} \frac{\partial U}{\partial t}$$

$$ikI = +\tilde{C} \, iwU$$

Definition of impedance

impedance: $Z = \frac{V}{I} = \frac{k}{w \tilde{C}}$

using $v = \frac{w}{k} = \frac{1}{\sqrt{\tilde{L}\tilde{C}}}$

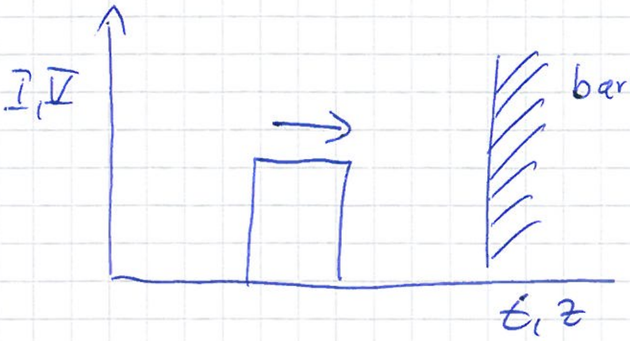
$$\Rightarrow Z = \sqrt{\frac{\tilde{L}}{\tilde{C}}} = \sqrt{\frac{\mu_r \mu_0 \ln(b/a)}{2\pi \, 2\pi \, \varepsilon_0 \varepsilon_r / \ln(b/a)}} = \frac{\ln(b/a)}{2\pi} \sqrt{\frac{\mu_r \mu_0}{\varepsilon_r \varepsilon_0}} = 50 \text{–} 75\,\Omega$$

comment: $1000\,\Omega$ impossible

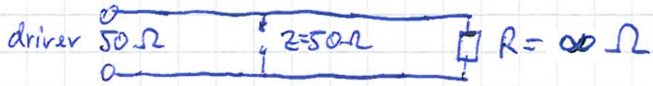
Note: $Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\,\Omega$ (vacuum impedance)

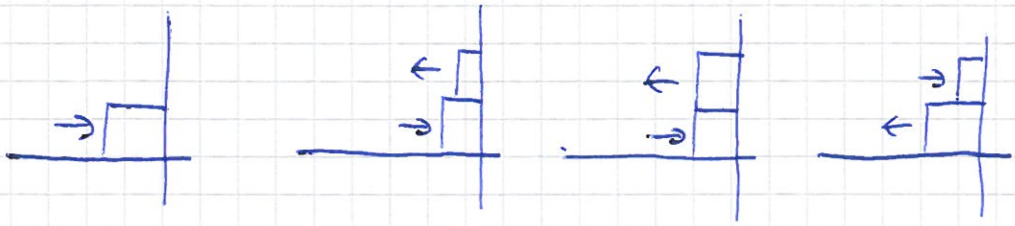
Comment: real losses due to resistance of cables are negligible

Reflection and Termination



Schematics:

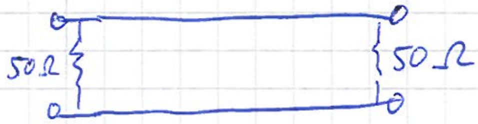




Signal is <u>twice</u> as big

- Solution:

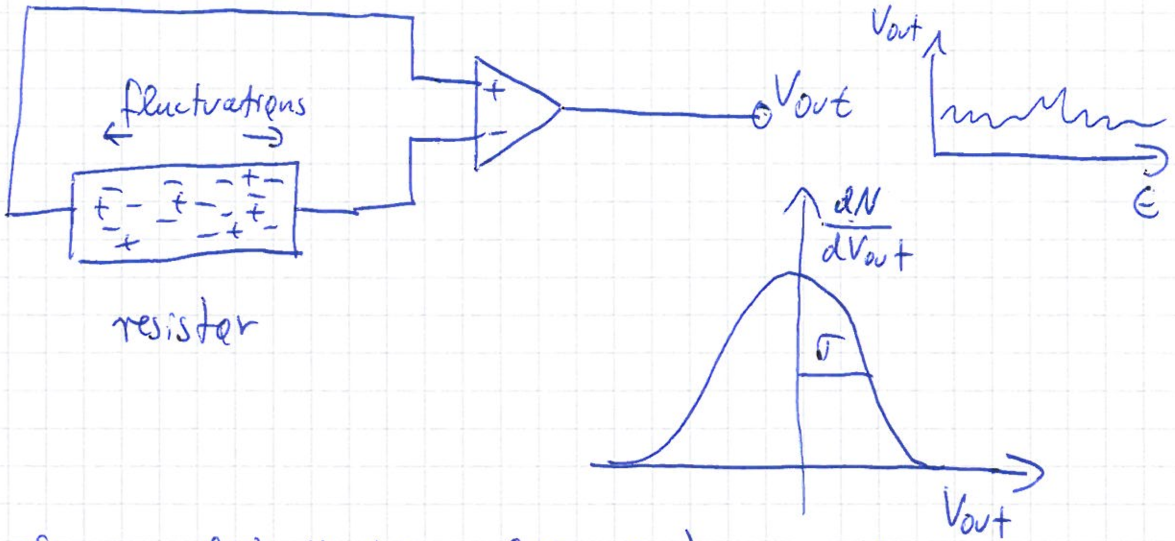
  ⇒ correct termination



- Oscilloscope has two different input settings:
  - 50 Ω
  - 1 MΩ

Noise

- Johnson Noise (Nyquist) $\Rightarrow$ thermal noise



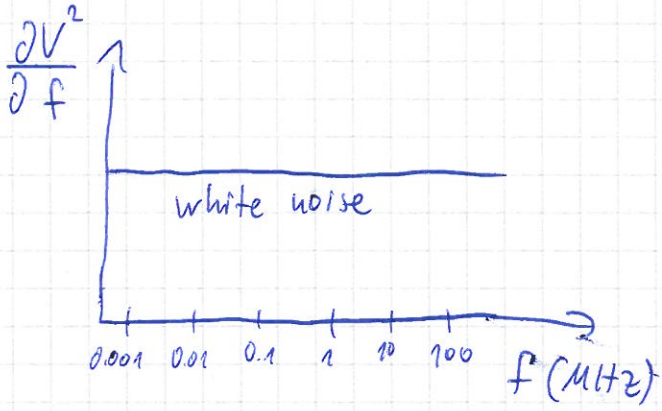
Width of noise distribution (Gaussian) given by:

$$\sigma = V_{RMS} = \sqrt{4 k_B T \cdot R \cdot \Delta f}$$

k_B = Boltzmann constant $= 1.38 \cdot 10^{-23}$ J/K

T = temperature

Δf = bandwidth (frequency cutoff)



Example:

$R = 10\ k\Omega$

$T = 300\ K$

$\Delta f = 100\ MHz$

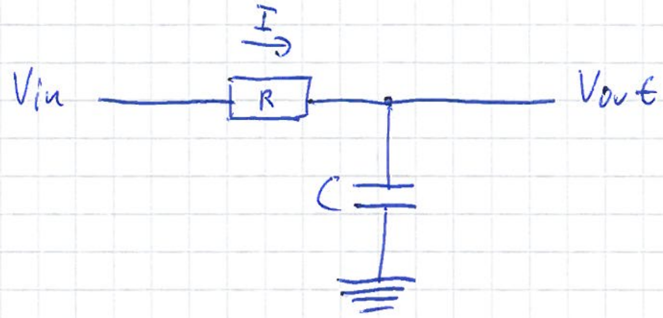
$\Rightarrow V_{RMS}^{noise} = 0.13\ mV$

Noise dependence:

- temperature
- resistance
- bandwidth

Rising Times and Bandwidth

Low Pass Filter



$U_R = R \cdot I$

$V_{in} = V_R + V_{out}$

$$I = \frac{dQ}{dt} = C \frac{dV_{out}}{dt}$$

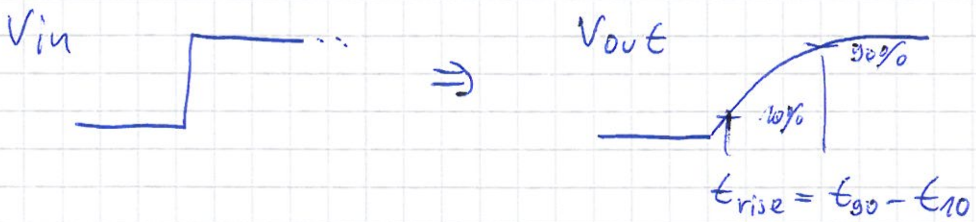
$$\Rightarrow V_{in} = R \cdot C \frac{dV_{out}}{dt} + V_{out}$$

differential equation

solved by separating variables

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

Solution: $V_{out} = V_{in}\left(1 - e^{-t/RC}\right)$



$$t = -\ln\left(1 - \frac{V(t)}{V_{in}}\right) \cdot RC$$

$$t_{90} = -\ln(0.1) \cdot RC$$

$$t_{10} = -\ln(0.9)\ RC$$

$$t_{90} - t_{10} = \ln(9) \cdot RC = 2.2 \cdot RC$$

Rising time given by time constant $\boxed{\tau = RC}$

Low Pass Filter (cont'd)

A low pass filter is an <u>integrator</u> (RC-circuit)

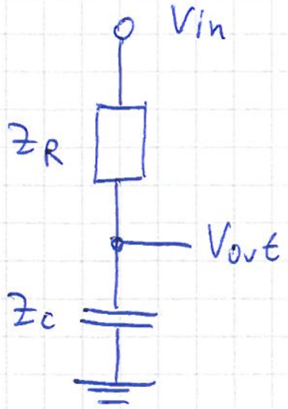
$$V_{in} = RC \frac{dV_{out}}{dt} + V_{out} \qquad \left(\text{using } I = \frac{dQ}{dt} = C \frac{dV_{out}}{dt}\right)$$

for $V_{out} \ll V_{in}$ (short time pulse)

$$\Rightarrow V_{in} = RC \frac{dV_{out}}{dt} \Leftrightarrow \boxed{V_{out} = \int dt \, \frac{V_{in}}{RC}}$$ integration!

Solution for arbitrary frequencies

voltage divider:



$$V_{out} = V_{in} \cdot \frac{Z_C}{Z_R + Z_C}$$

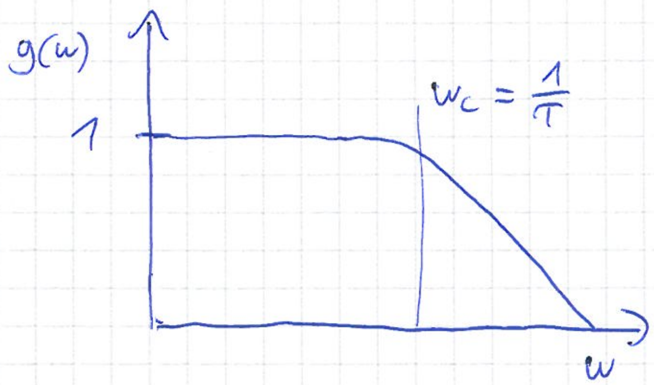
$Z_R = R$

$Z_C = \frac{1}{i\omega C}$

$\tau = RC$

$$\Rightarrow \frac{V_{out}}{V_{in}} = \frac{1}{1 + i\omega RC} = \frac{1}{1 + \omega\tau}$$

ratio $$g(\omega) = \left| \frac{V_{out}}{V_{in}} \right| = \frac{1}{\sqrt{1 + \omega^2 \tau^2}}$$

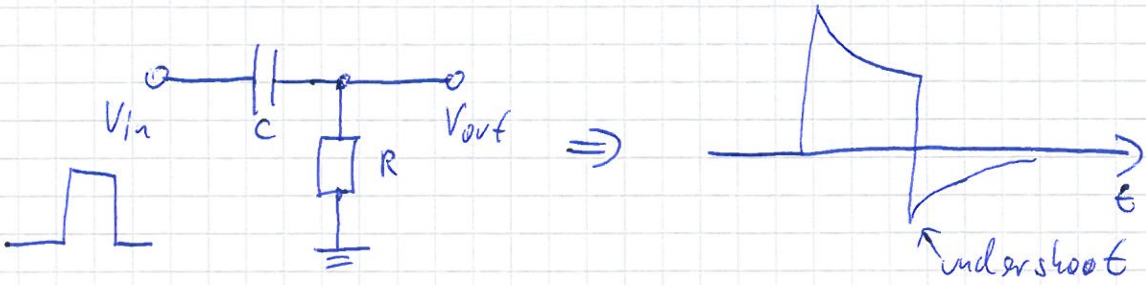


$\omega\tau \ll 1 \Rightarrow g(\omega) = 1$

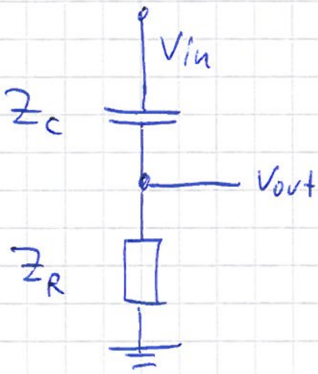
$\omega\tau \gg 1 \Rightarrow g(\omega) = \frac{1}{\omega\tau}$

High Pass Filter (differentiator)

CR circuit:

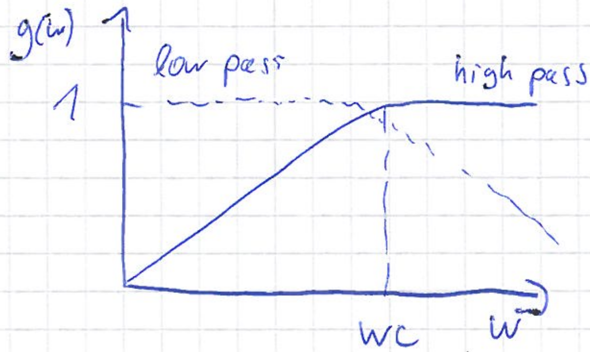


drawn as voltage divider:



$$V_{out} = V_{in} \frac{Z_R}{Z_R + Z_C} = \frac{R}{R + \frac{1}{i\omega C}}$$

$$g(\omega) = \left| \frac{V_{out}}{V_{in}} \right| = \frac{\omega RC}{\sqrt{1+\omega^2 R^2 C^2}} = \frac{\omega \tau}{\sqrt{1+\omega^2 \tau^2}}$$



- By combining <u>low pass</u> and <u>high pass</u> filters only small frequency range is selected $\Rightarrow$ suppresses noise!

- decibel:

$$E \propto g^2(\omega) \qquad L = 10 \log_{10}\left(\frac{g(\omega)^2}{g(0)^2}\right) = 20 \log_{10}\left(\frac{g(\omega)}{g(0)}\right)$$

$$\frac{g(\omega)}{g(0)} = \frac{1}{\sqrt{2}} \Rightarrow L = 20 \cdot \log_{10} \frac{1}{\sqrt{2}} = -3 \text{ dB}$$

Pulse Shaping

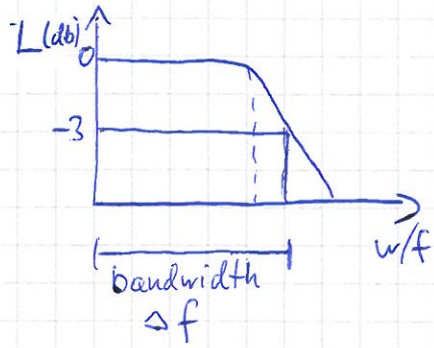
- combination of CR – CR circuits shapes pulses:

- general case → Fourier transformation:

$$f(\omega) = \frac{1}{\pi} \int dt \, f(t) \cos(\omega t)$$

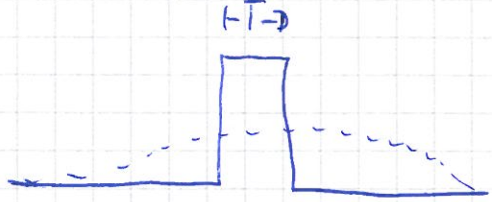
↑ signal

- example: low pass filter:



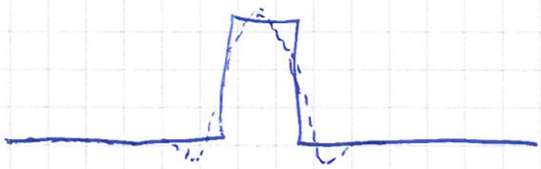
−3db defines bandwidth Δf

A: $\Delta f = \frac{0.1}{T}$

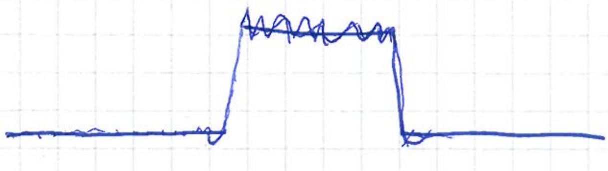


small bandwidth

B: $\Delta f = \frac{1}{T}$



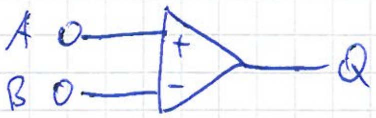
C: $\Delta f = \frac{10}{T}$



high bandwidth

Amplification

- operational amplifyer $\Rightarrow$ ideal amplifyer



$I_Q = +\infty$ if $V_A > V_B$

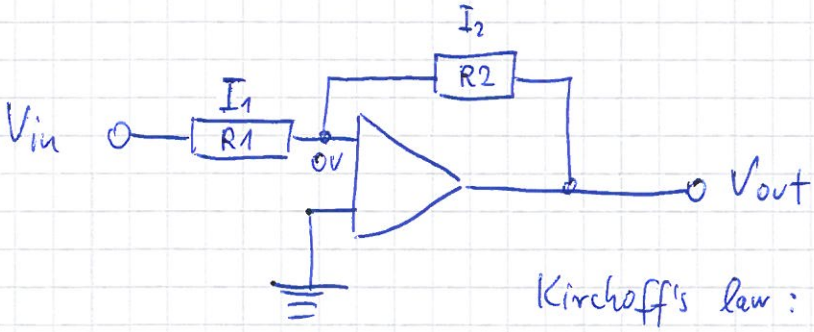
$I_Q = -\infty$ if $V_A < V_B$

$I_Q = 0$ if $V_A = V_B$

low output impedance: $Z_Q = 0$

high input impedance: $Z_A = Z_B = \infty$

Example: voltage amplifyer



Kirchoff's law: $I_1 = I_2$

$$I = \frac{V_{in}}{R_1} = \frac{-V_{out}}{R_2} \Rightarrow V_{out} = -V_{in}\frac{R_2}{R_1}$$

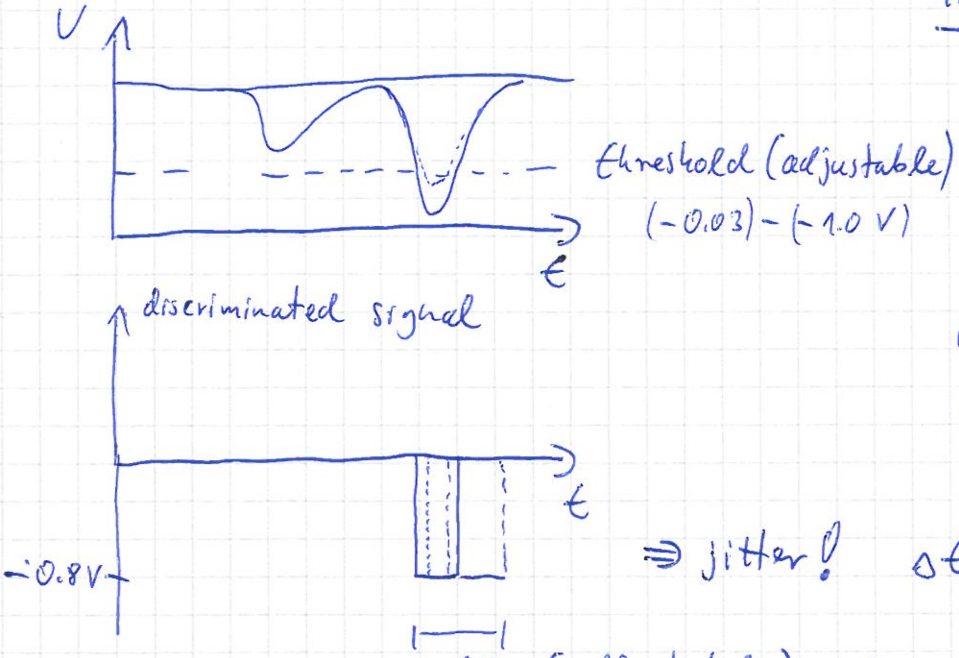
for $\frac{R_2}{R_1} > 1$ amplification

Note: also (thermal) noise is amplified

$\rightarrow$ limitation $\frac{R_2}{R_1} < 1000$

Discriminators

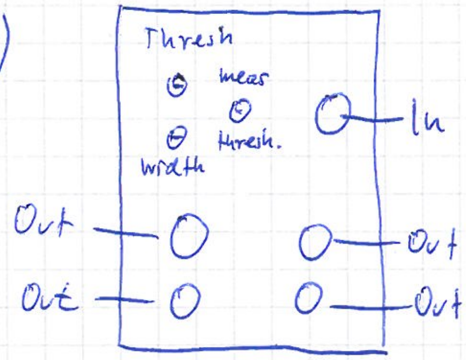
Constant Threshold



width (adjustable) 10us .. 100us

⇒ jitter! $\Delta t \approx 1$ us

Hardware:



different operational modes:

- updating (signal end wrt. to last falling edge)
- non-updating (signal ends wrt rising edge)

Constant Fraction

⇒ for good timing

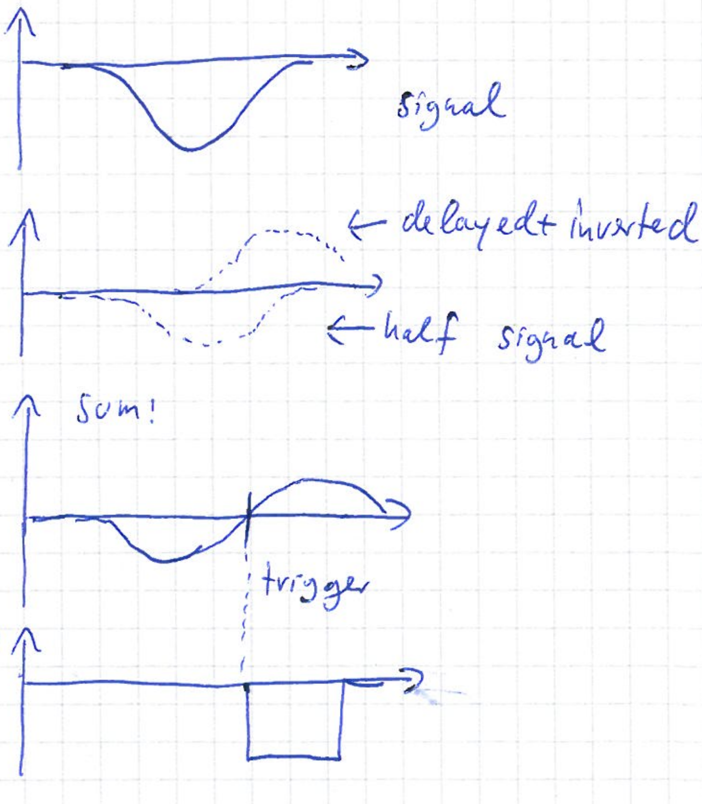
- split signal
- invert and delay
- sum
- zero-crossing defines time!

note: delay should correspond to signal width

→ trigger independent of signal height! $V_{max}/V_{min} \approx 1000$

⇒ reduced jitter $\Delta t \approx 20$ps

Method:



Digital Electronics

- logic states "low" and "high"
  → different signal standards:
  e.g. NIM fast "low" = 0V "high" ≈ −0.8V !

- applications:
  - processors
  - networks
  - memories

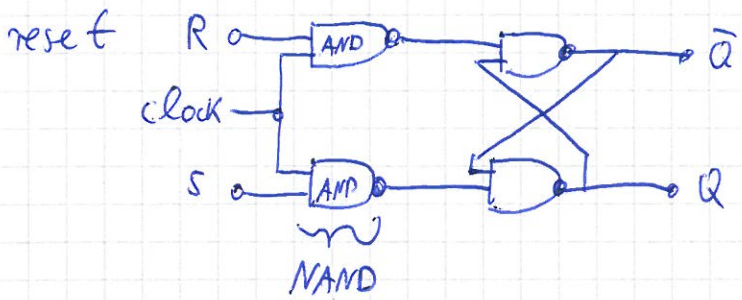
- Signal transmission:
  electronically ≈ 1 Gbit/s per channel

- Components
  - converter ADC (analog to digital)
    DAC (digital to analog)
    e.g. ADC, TDC, TAC, ...
  - Memories (buffer)
  - Logical operations
    - coincidences
    - Scaler (counter)
    - adder

→ FPGAs (field programmable gate arrays)

Buffer (flip flop)

smallest element of any memory



$\Rightarrow$ bistable

Logic table

R	S	Q	$\bar{Q}$
0	0	$\bar{\bar{Q}}$	$\bar{Q}$
1	0	0	1
0	1	1	0
1	1	1	1

$Q = \bar{\bar{Q}}$

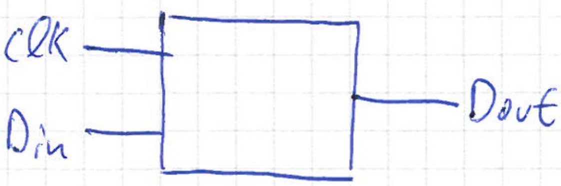
forbidden /undefined)

$\Rightarrow$ RS flip flop

(JK flip flop)
↳ triggers on falling clock edge!

D - flip flop

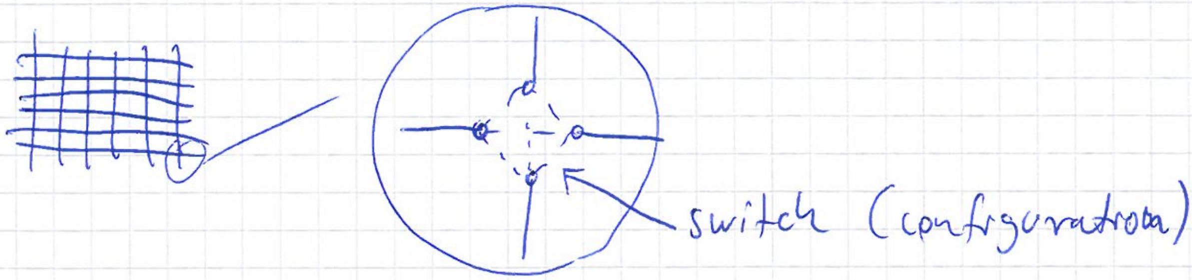
→ used in FPGA



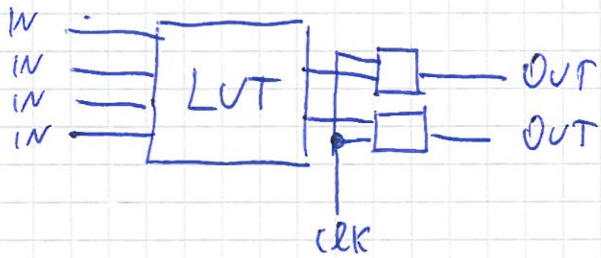
$\Rightarrow$ Dout takes state of Din at rising clock.

FPGA (field programmable gate array)

1. field of wires connection thousends of elements:



2. elements (logical cells)



LUT = lookup table

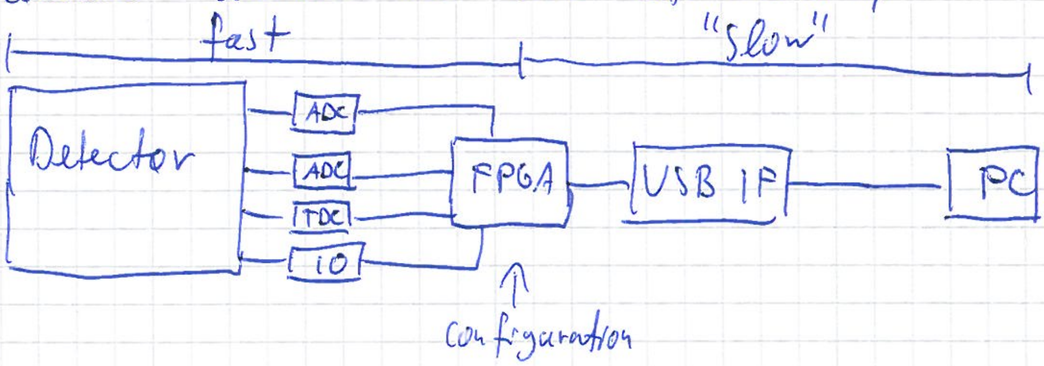
	Adder
0 0 0 0	0 0
0 0 0 1	0 1
0 0 1 0	0 0
0 0 1 1	1 0
0 1 0 0	0 1
0 1 0 1	1 0
0 1 1 0	1 0
0 1 1 1	1 1
⋮	⋮

a lookup table can be configured as:
- adder
- coincidence
- inverter
- etc.

3. <u>Memories</u>

FPGAs contain several KB – MB of memory

4. Usage:



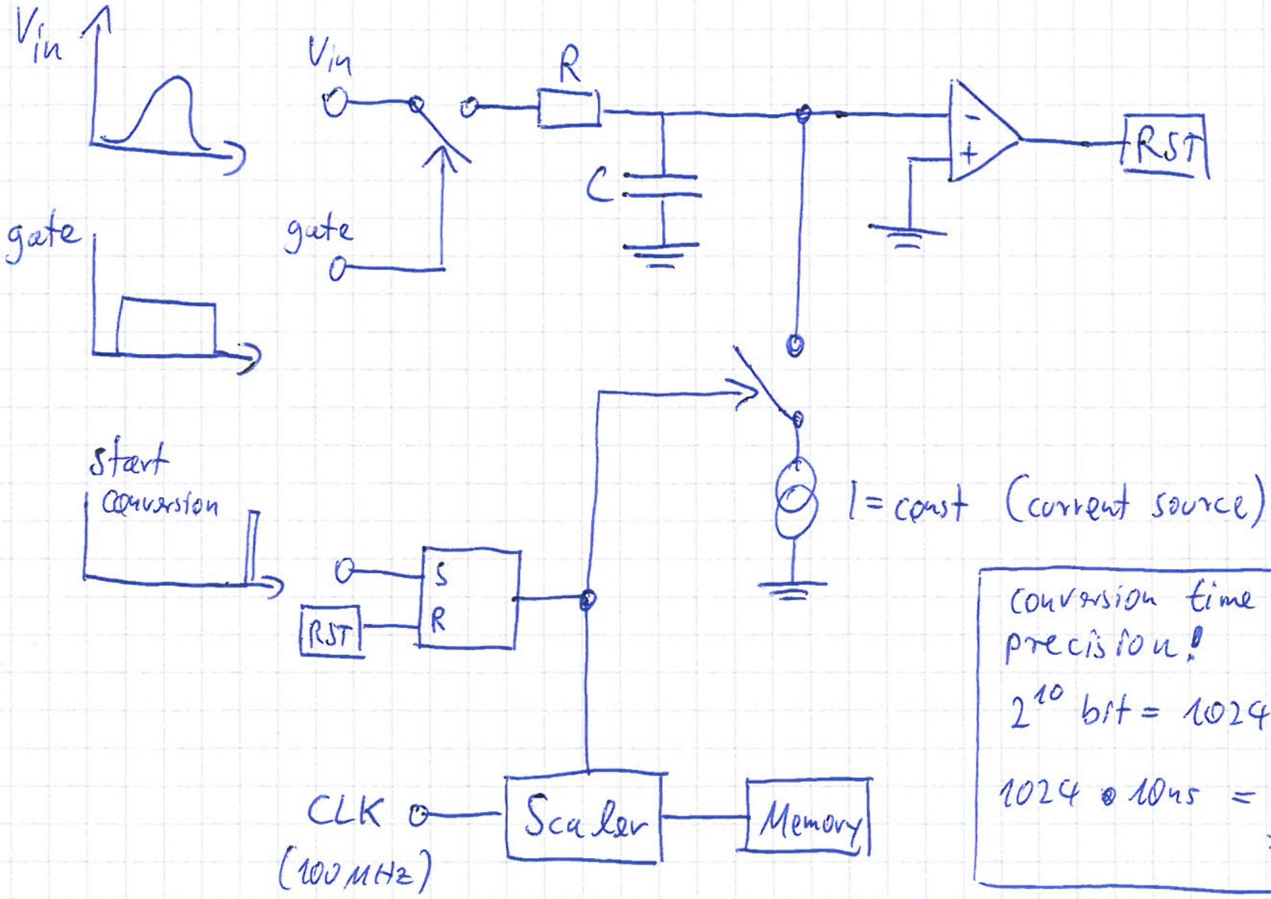
Analog to Digital Converters (ADC)

- Different types:
  - voltage (peak voltage)
  - charge
  - fast ADCs with sampling (e.g. Flash ADC)

- Wilkinson ADC

  method/principal:
  - charge condensator (capacity) when gate open
  - convert charge into a time signal by discharging capacity
  - measure time for discharge with a scaler

    $\Rightarrow$ conversion time



conversion time determines precision!

2^{10} bit = 1024 $\qquad$ 100 MHz $\hat{=}$ 10 ns

1024 $\cdot$ 10 ns = $\underline{\underline{10\,\mu s}}$!

measures time $\quad T \propto Q \propto \int dt\, I(t) \propto \int dt\, \frac{V(t)}{R}$

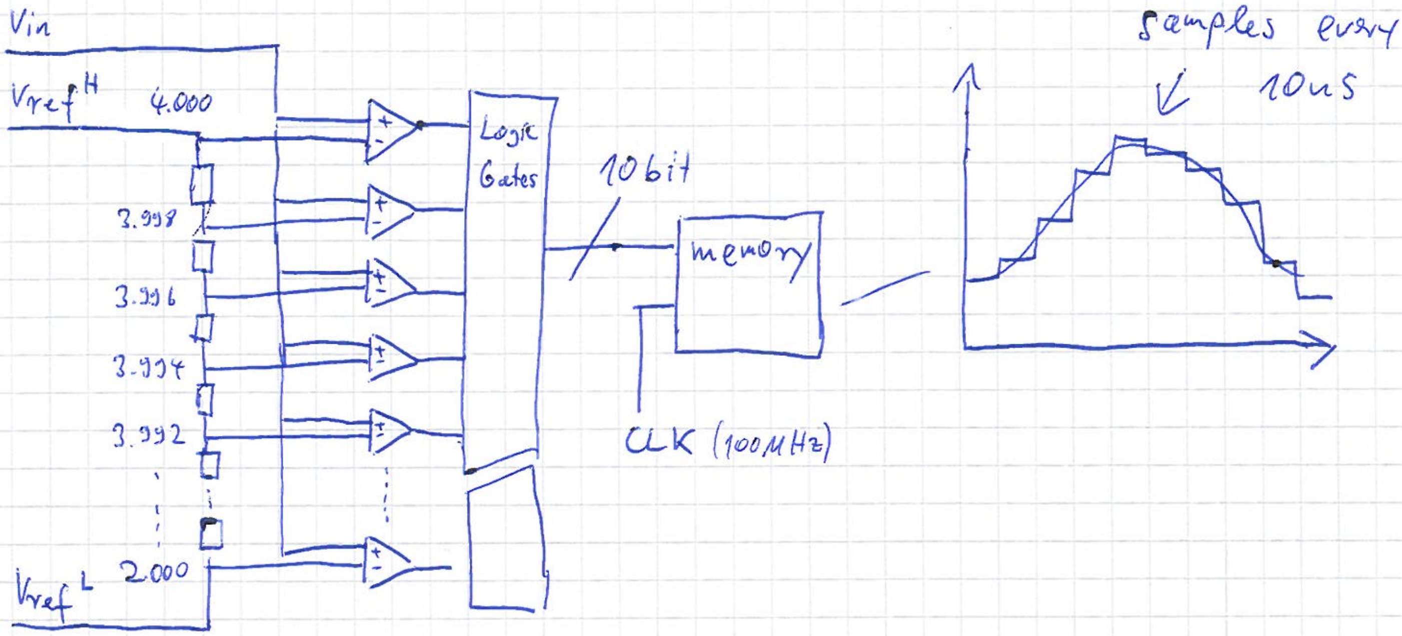
- resistor can be replaced by diode to measure peak of signal!
- "old" TDC has similar design

Fast ADCs

Flash ADC (network / resistor chain)

- 2^n comparators and 2^n precision resistors

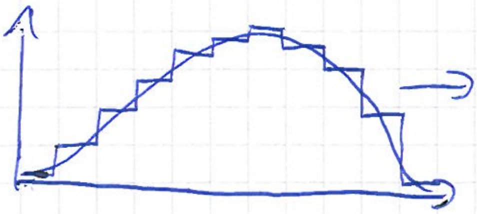
  10 bit ⇒ 1024
  12 bit ⇒ 4096
  16 bit ⇒ 65536



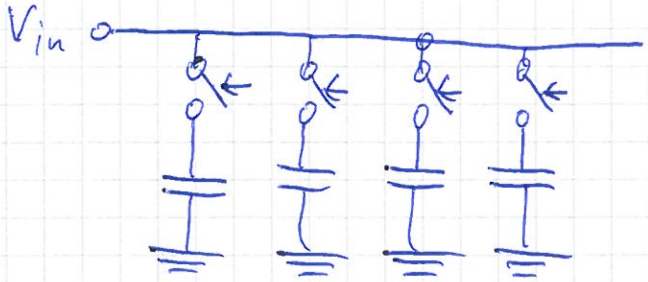
- difficult to build FADC with more than 10-12 bit
- nowadays:

  ⇒ capacity switched ADC

Capacity Switched ADC (fast ADC)



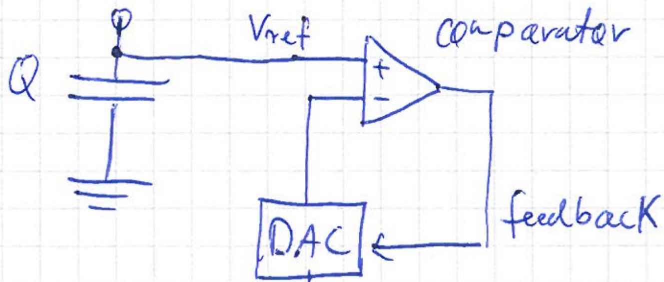
→ store samples in quickly charged capacitors



100 MHz clock (round robin)

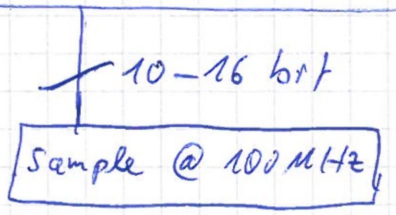
Memory of analog charges

Digitisation



actually several DACs and comparators are used

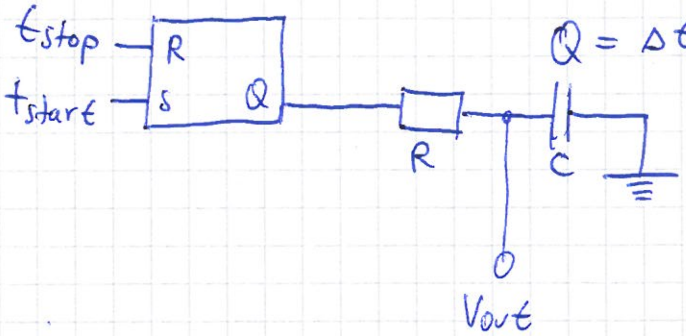
DAC = digital to analog converter



Time to Analog Converter (TAC)

- Method:
  - t_{start} and t_{stop} used to charge capacity:

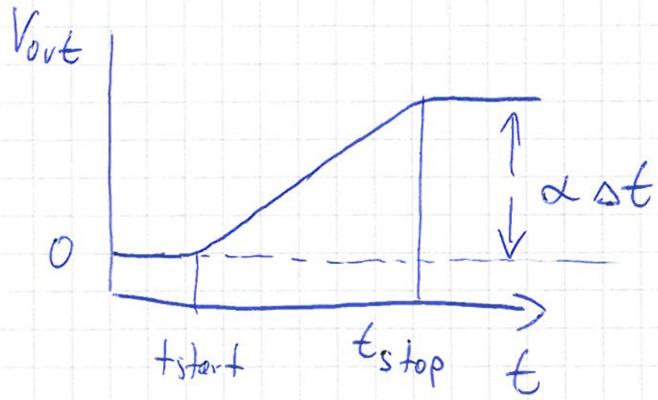
$$Q \propto (t_{start} - t_{stop})$$



$Q = \Delta t \cdot I$ for $\Delta t \ll R \cdot C$ (linearisation)

- Output signal V_{out} is proportional to time difference.

  $\Rightarrow$ input to fast ADC

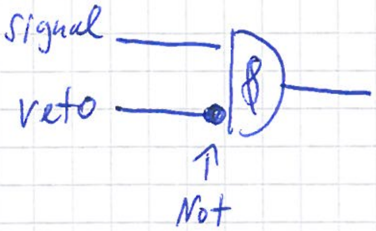


$\Rightarrow$ used to measure very short times. $\approx 20\,ps$

Trigger

○ Different NIM logic components available to implement coincidences, delay, discriminators etc.

— <u>coincidences</u>

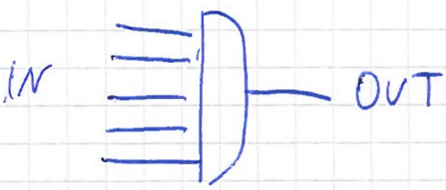


! check timing (synchronisation) of signals !

→ jitter

→ delays

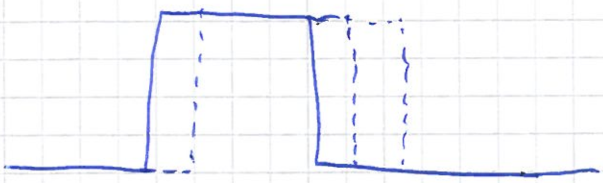
— <u>fan in:</u>



coincidence or analog sum

<u>fan out:</u>

— <u>delay triggers:</u>



→ used to delay signals $\mu s - s$

→ used to generate <u>long</u> signals $\mu s - s$

→ can be configured as buffer (reset)

Signal Standards (in HEP)

Standard	V_{Driver} (V) low (Ø)	V_{Driver} (V) high (1)	I (mA) low	I (mA) high	Z_{in} (Ω)	
NIM fast	[0] -	[-0.7, -0.9]	0	[-14, -18]*	50	fast/negativ
NIM slow	[-2, +1]	[+4, +12]	~0	<[+4, +12]	>1K	slow
ECL	-0.9	-1.75	-18	-36	50 (100)	fast/negativ/high power
TTL 5	[0, 0.8]	5	~1		>1k	industry
TTL 3.3	[0, 0.8]	3.3	~1		>1k	standard