Open electronics :

From sensor to readout

Ecole Polytechnique PHY564#2 2017

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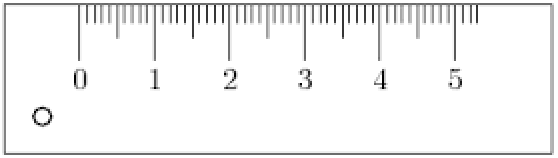
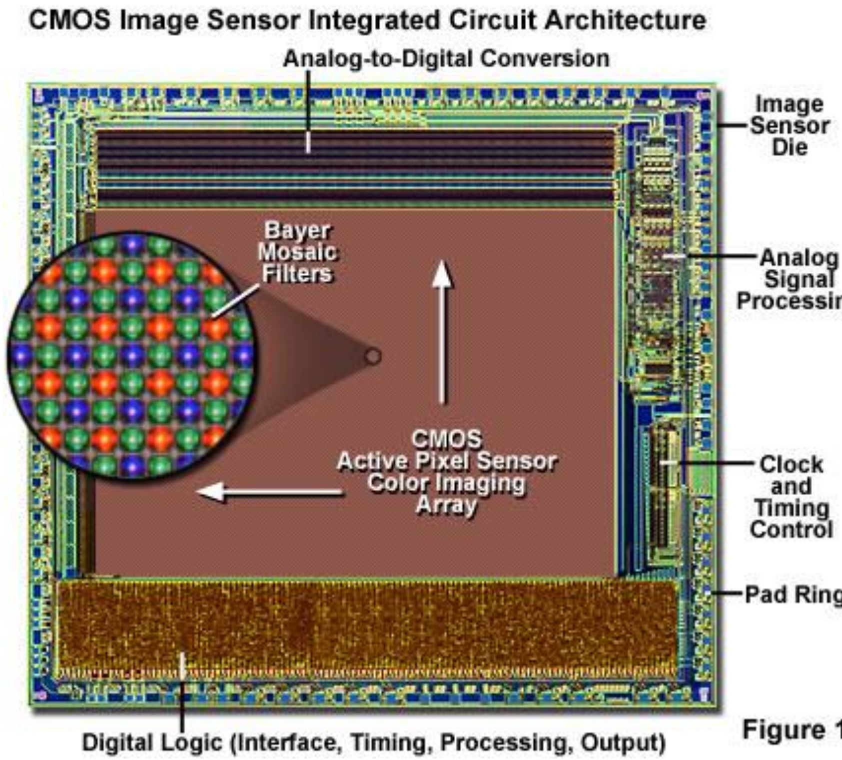
- Each measurement needs a tool…

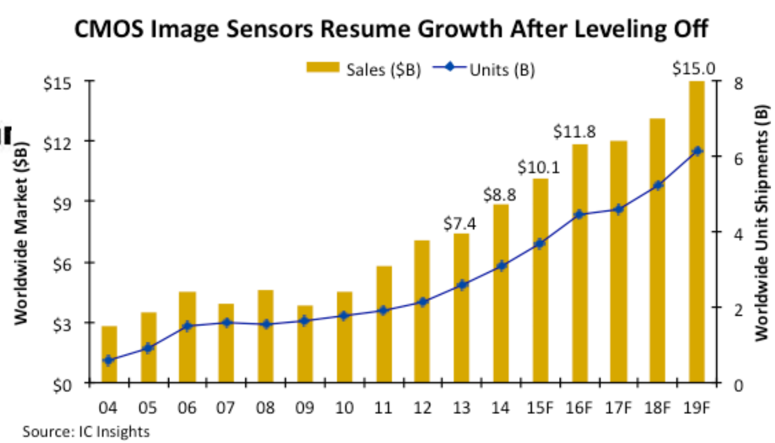


mm : 0.1 €

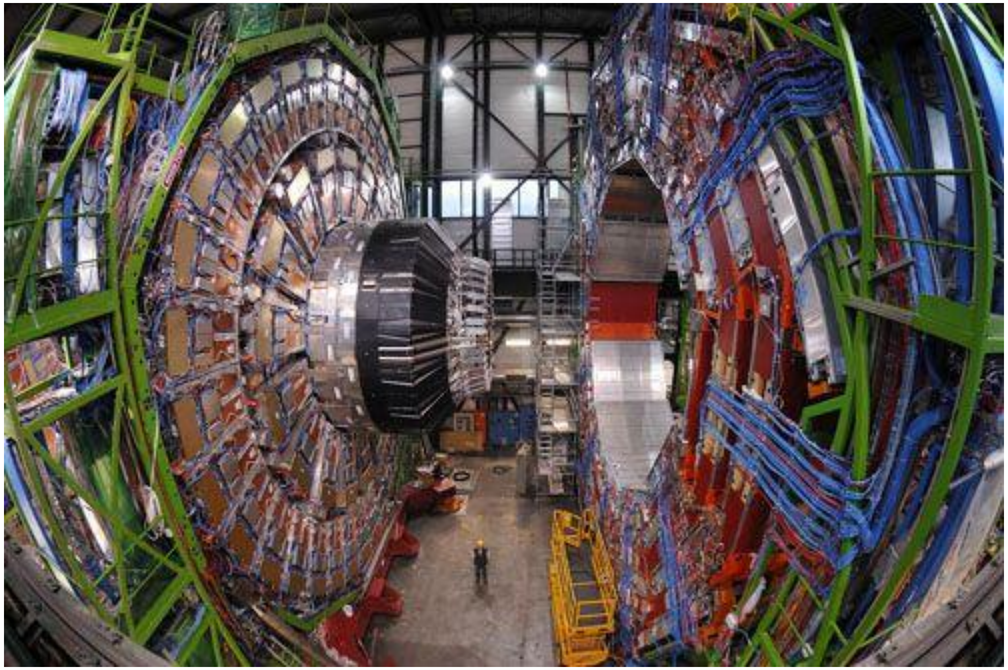
Higgs Boson 1 G€

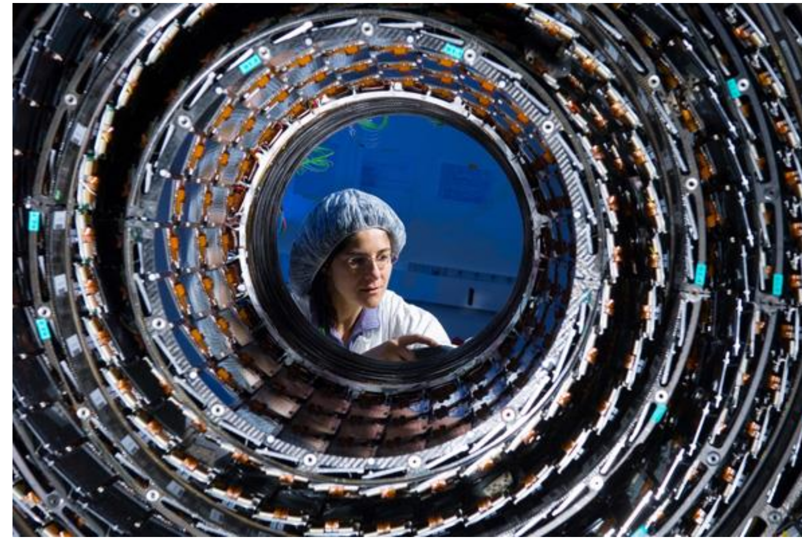
- CMOS technology for cameras

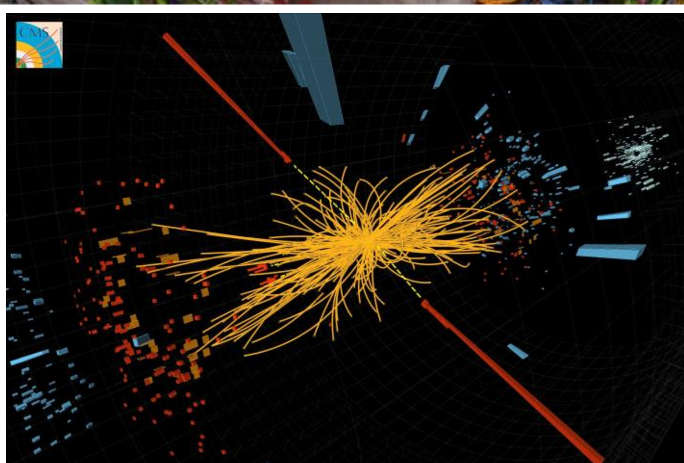


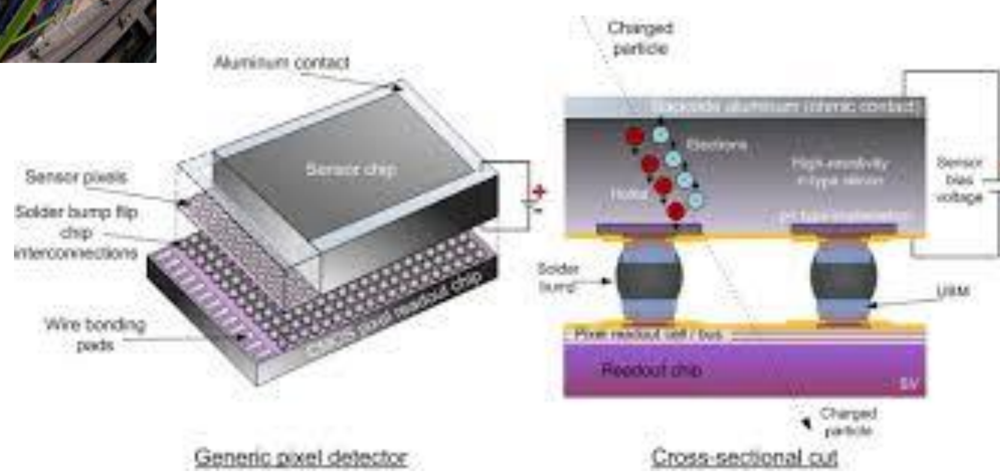


- Measurement of tracks and energy



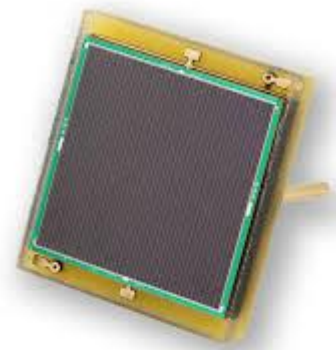


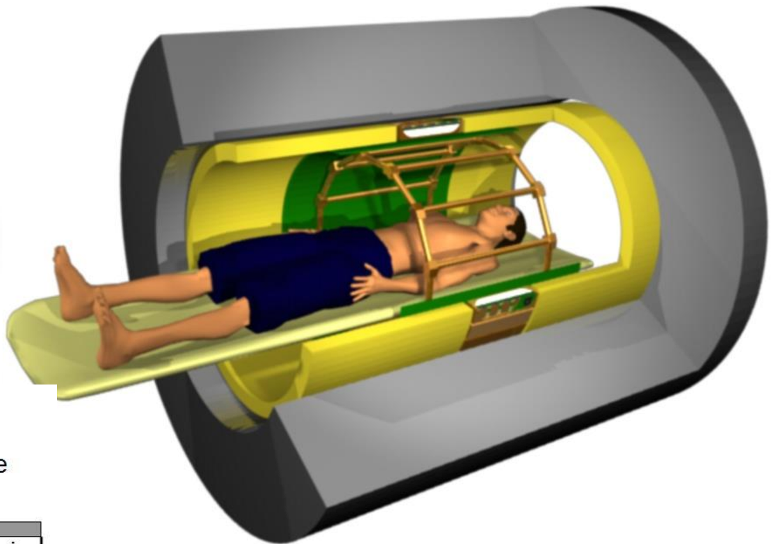


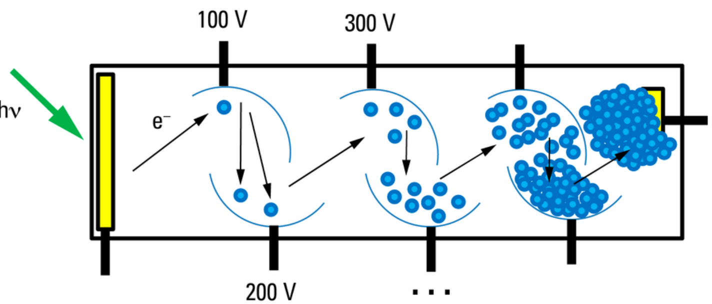


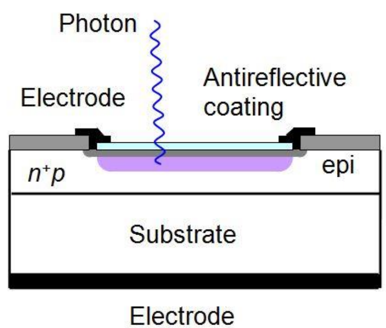
Single photon sensors

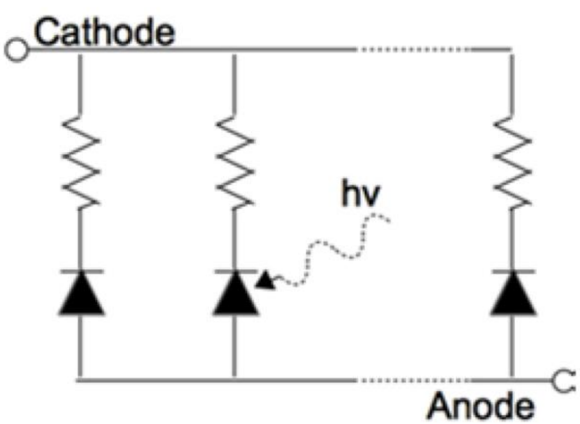
- Photomultipliers, silicon photomultipliers

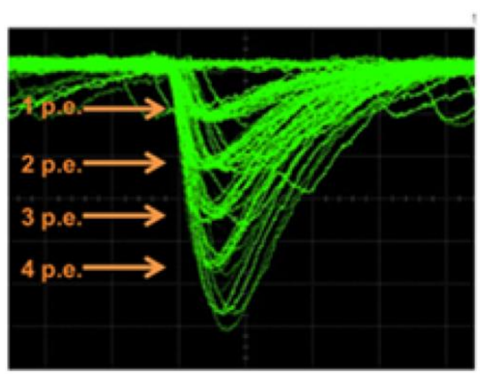


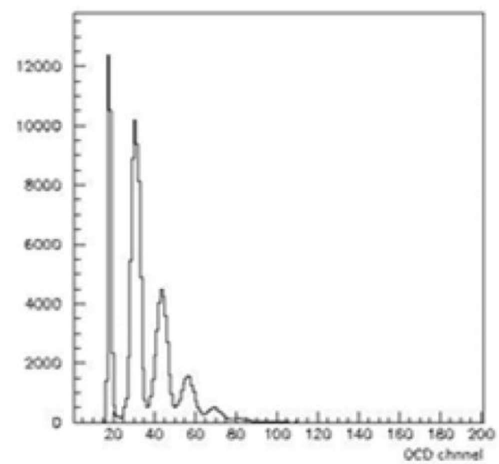




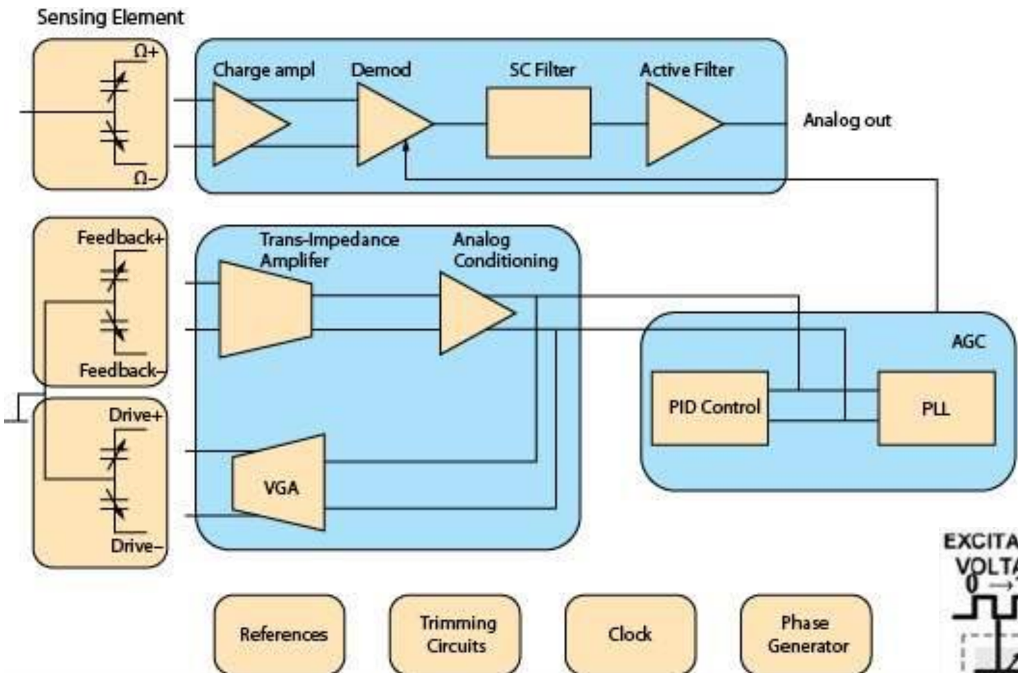


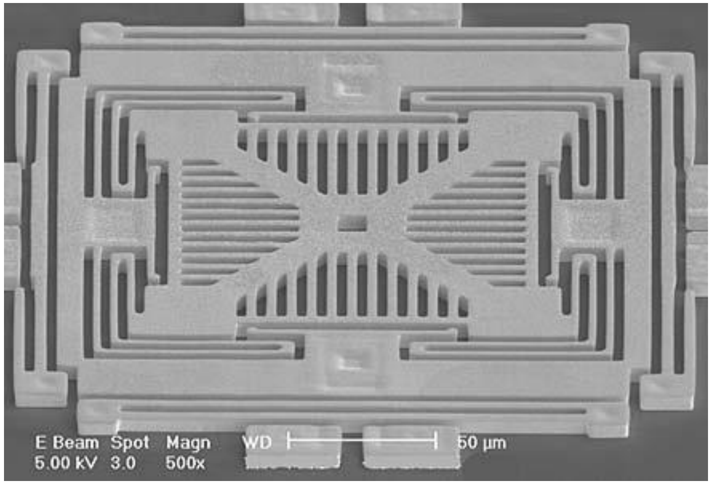


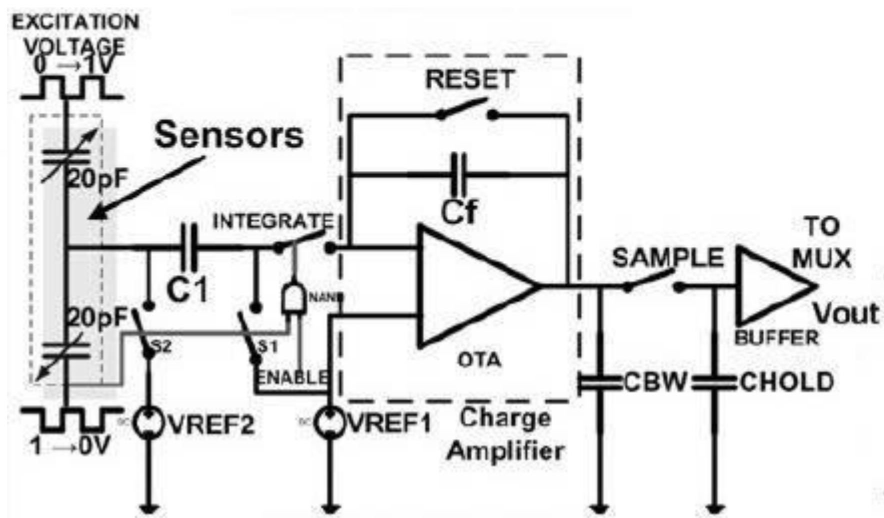




- Accelerometer readout : variation of capacitance

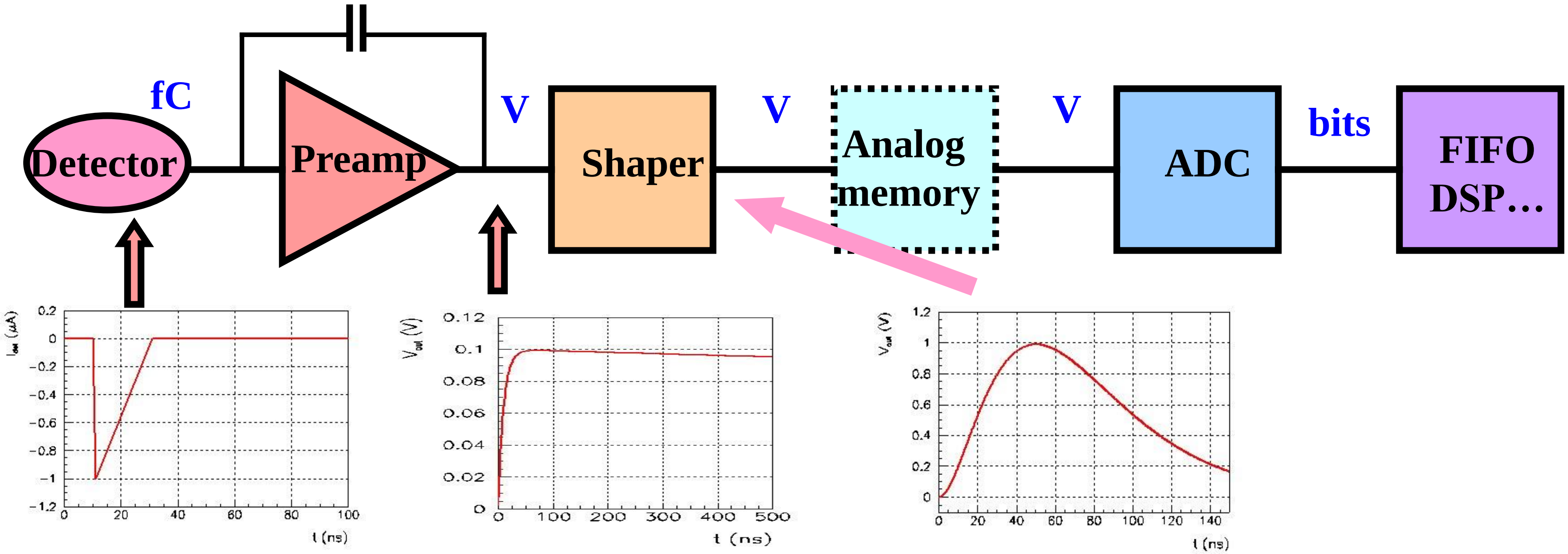






Readout chain

- Most front-ends follow a similar architecture



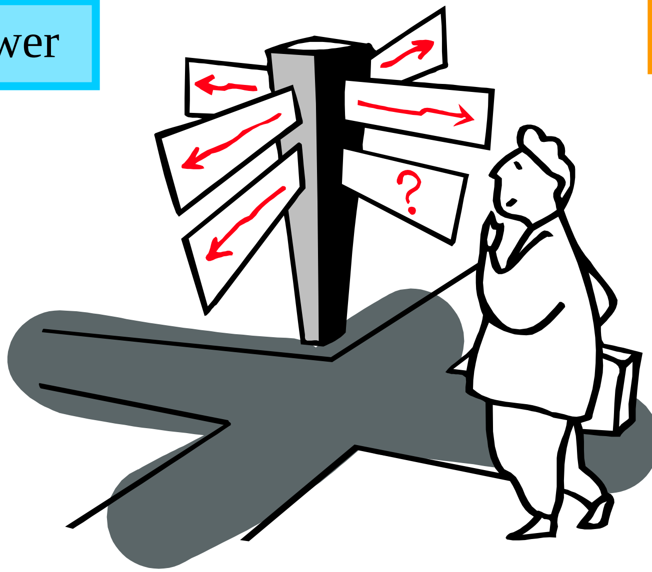
- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels
- Trends : high speed, low power

Readout electronics : requirements

Low noise

Low power

High speed



Large dynamic range

High reliability

Radiation hardness

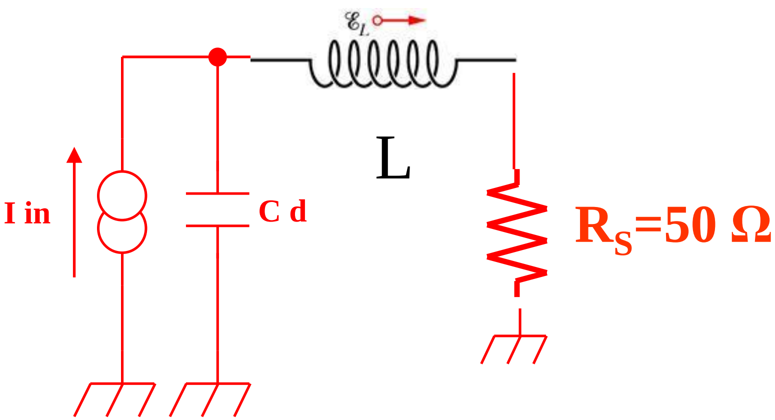
Low material

Low cost !

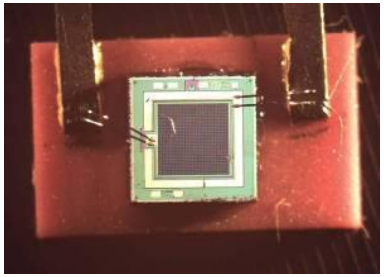
(and even less)

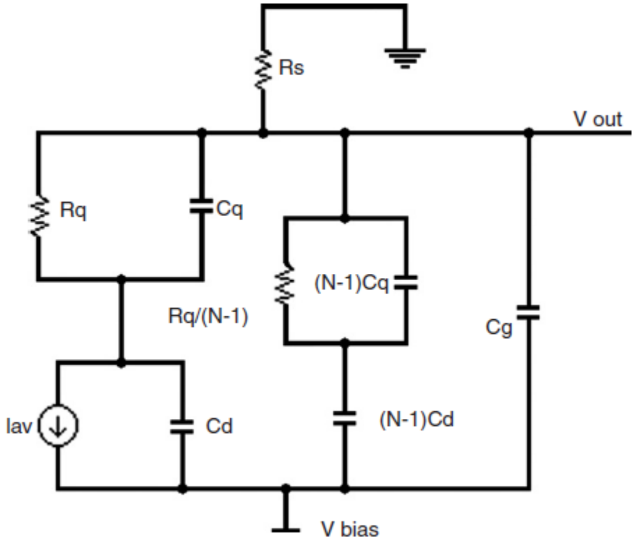
Modelizing the sensor

- Vacuum Photomultipliers
- $G = 10^5 - 10^7$
- $Cd \sim 10$ pF
- $L \sim 10$ nH



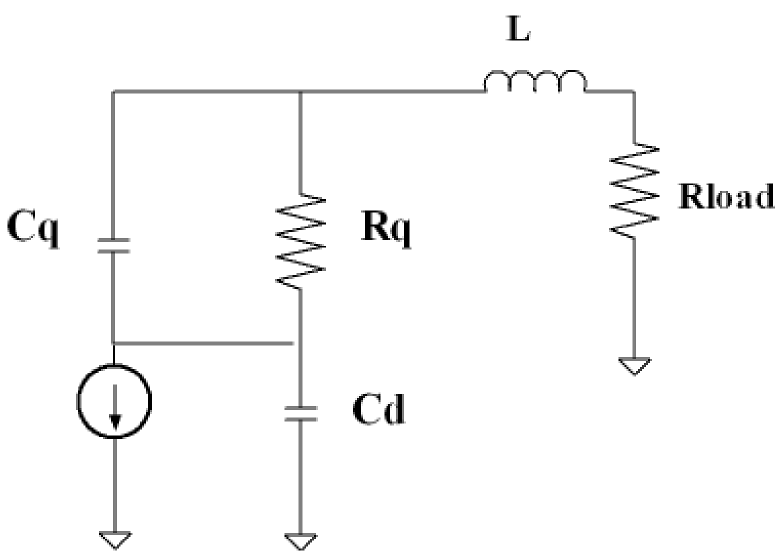
- Silicon Photomultipliers
- $G = 10^5 - 10^7$
- C = 10 - 400 pF
- L = 1 – 10 nH

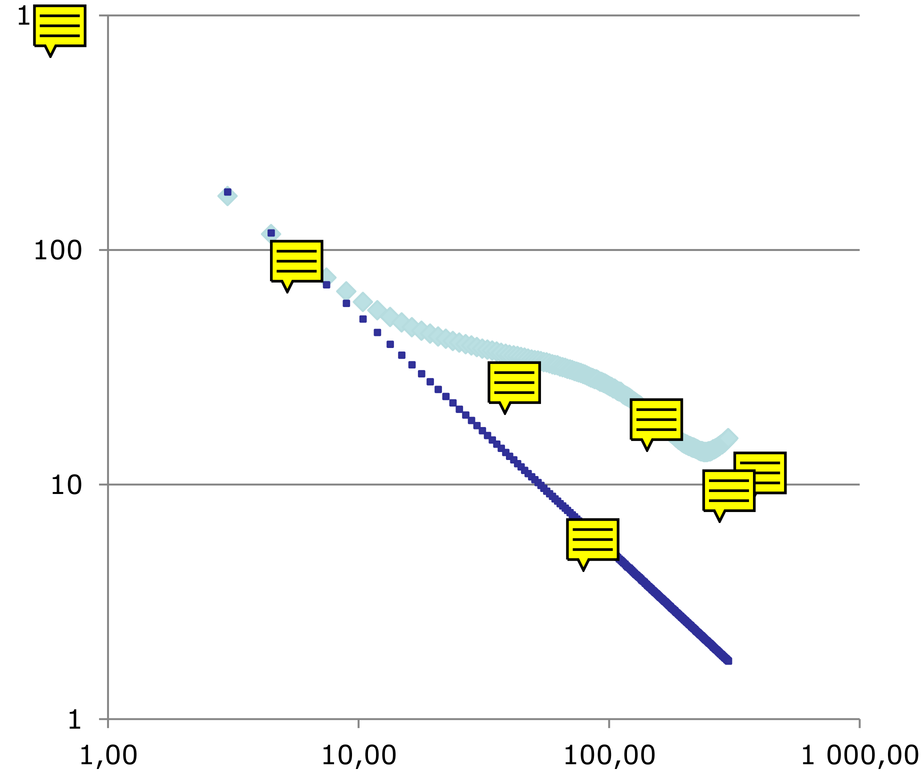




SiPM impedance and model

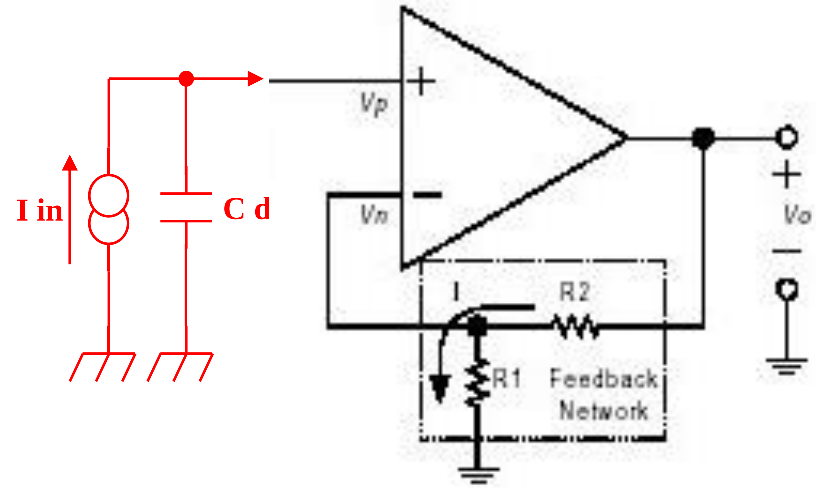
- RLC too simple, inaccurate at high frequency
- $C_dR_qC_qLR$ OK
  - May better explain HF noise behaviour



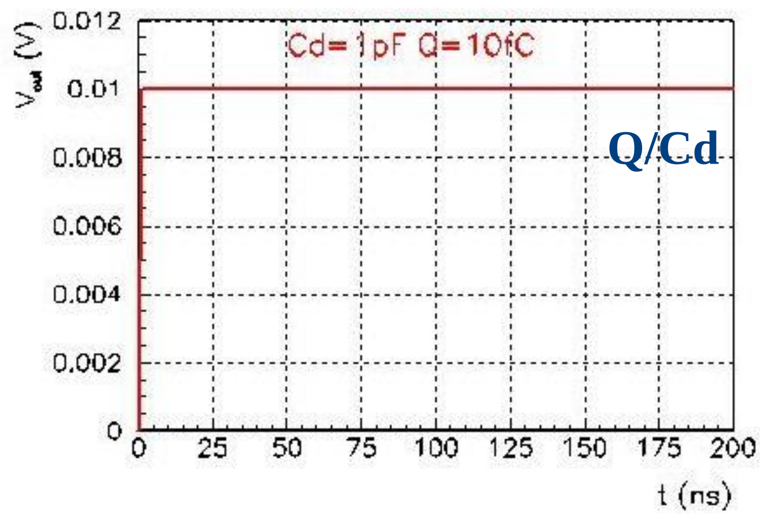


Measured impedance
MPPC HPK 3x3 mm
Line : C = 320 pF

- Signal
  - Signal = current source
  - Detector = capacitance C_d
  - Quantity to measure
    - Charge => integrator needed
    - Time => discriminator + TDC



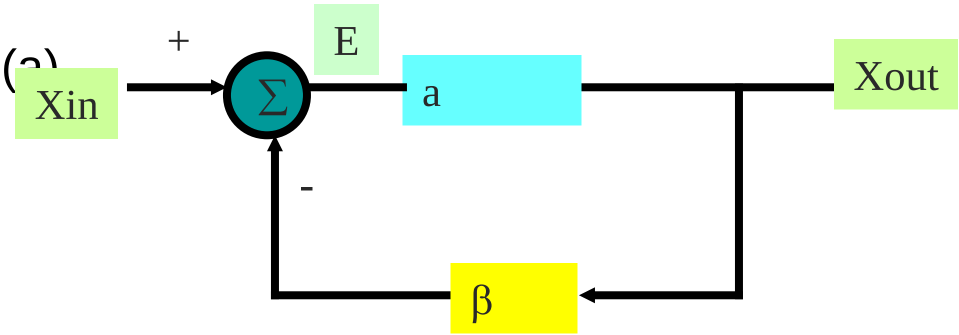
- Integrating on Cd
  - Simple : $V = Q/C_d$
  - « Gain » : $1/C_d$: 1 pF -> 1 mV/fC
  - Need a follower to buffer the voltage… => parasitic capacitance
  - Gain loss, possible non-linearities
  - crosstalk
  - Need to empty Cd…



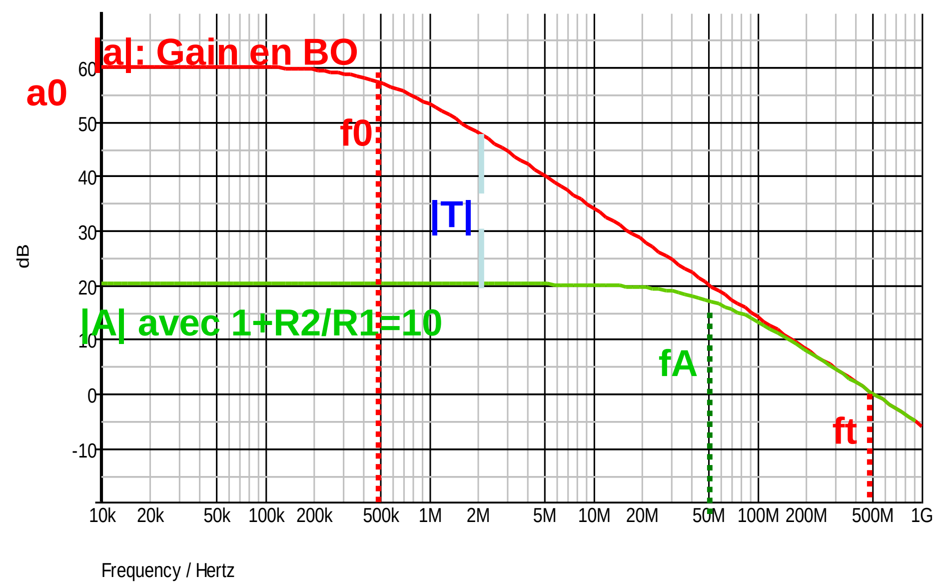
- Exercise : calculate BW with opamp

Feedback : an essential tool

- Improves gain performance
  - Less sensitivity to open loop gain (a)
  - Better linearity
- Essential in low power design
- Potentially unstable
- Feedback constant : β = E/Xout
- Open loop gain : a = Xout/E
- Closed loop gain : Xout/Xin -> 1/β
- Loop gain : T = aβ

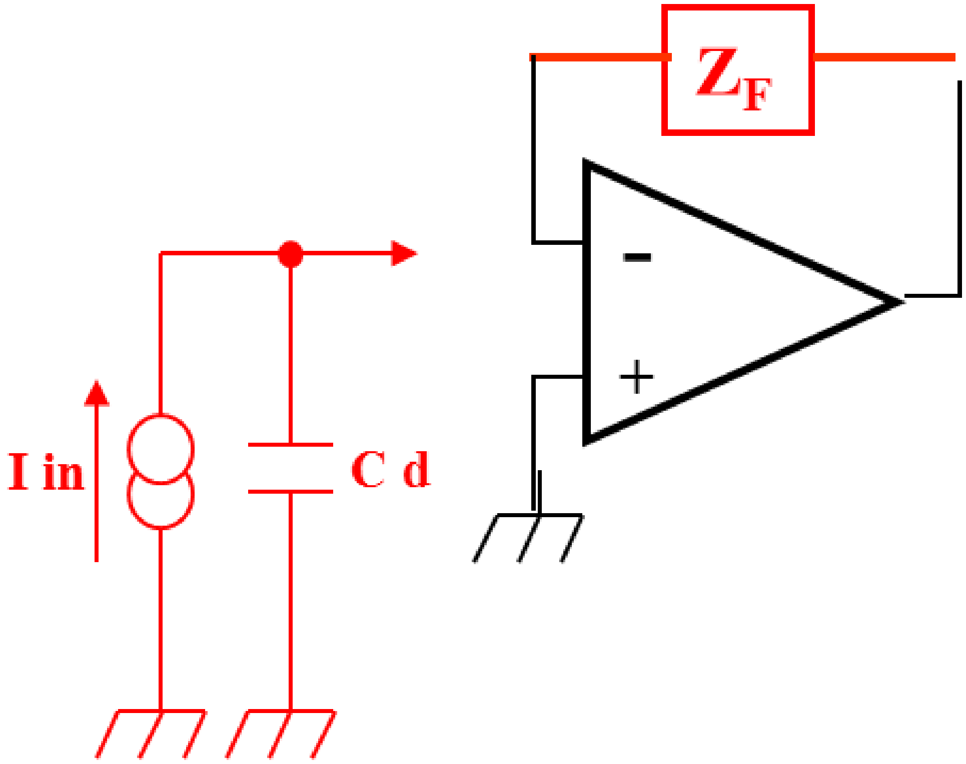


$$\frac{Xout}{Xin} = \frac{a}{1 + a\beta} = \frac{1/\beta}{1 + 1/a\beta}$$



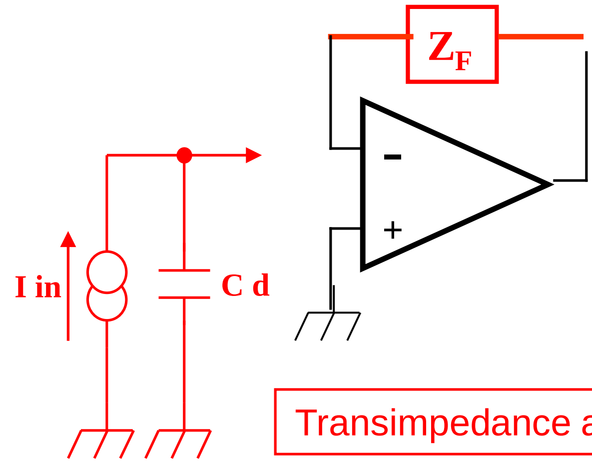
Transimpedance configuration

- Calculate transimpedance
- Calculate β = Vin-/Vout and graphically BW



Transimpedance configuration

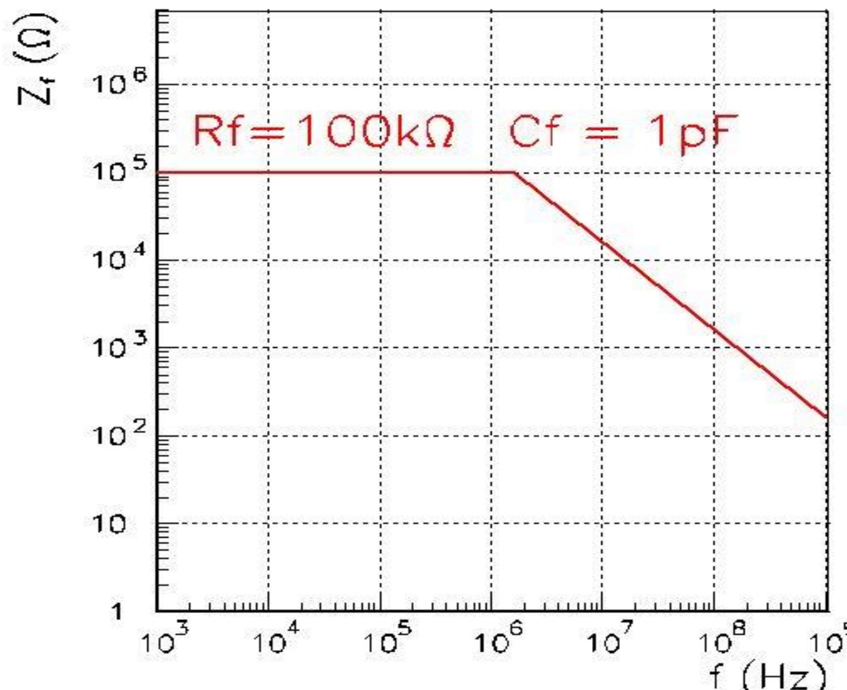
- Transfer function
  - Using a VFOA with gain G
    - $V_{out} - v_{in} = - Z_f \, i_f$
    - $V_{in} = Z_d \, (i_{in} - i_f) = - v_{out}/G$
  - $V_{out}(\omega)/i_{in}(\omega) = - Z_f \, / \, (1 + Z_f \, / G Z_d)$



Transimpedance amplifier

- $Zf = Rf \, / \, (1 + j\omega \, RfCf)$
  - At $f << 1/2\pi RfCf$:
    $V_{out}(\omega)/i_{in}(\omega) = - R_f$
    current preamp
  - At $f << 1/2\pi RfCf$:
    $V_{out}(\omega)/i_{in}(\omega) = - 1/j\omega C_f$
    charge preamp

- Ballistic deficit with charge preamp
  - Effect of finite gain : G_0
  - Output voltage «only» Q C_d/G_0C_f



Transfer function

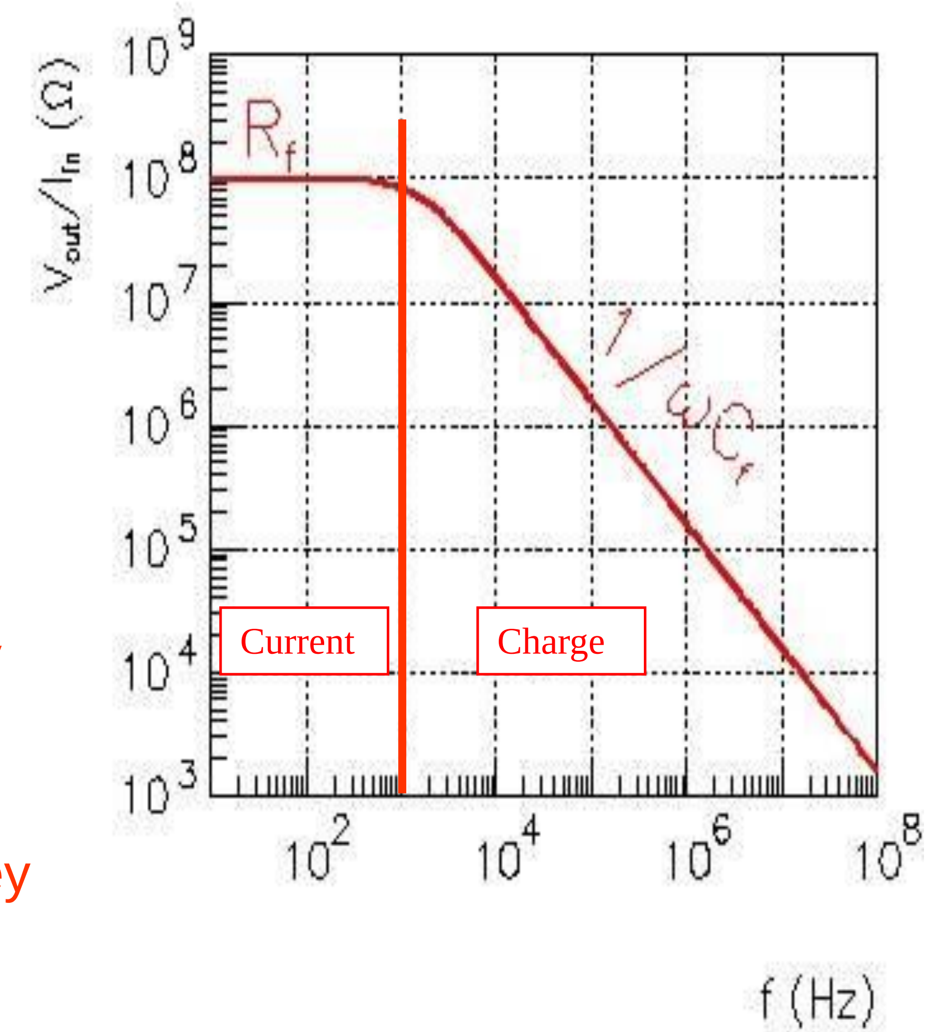
Charge vs Current preamps

- Charge preamps
  - Best noise performance
  - Best with short signals
  - Best with small capacitance

- Current preamps
  - Best for long signals
  - Best for high counting rate
  - Significant parallel noise

- Charge preamps are <u>not slow</u>, they are <u>long</u>

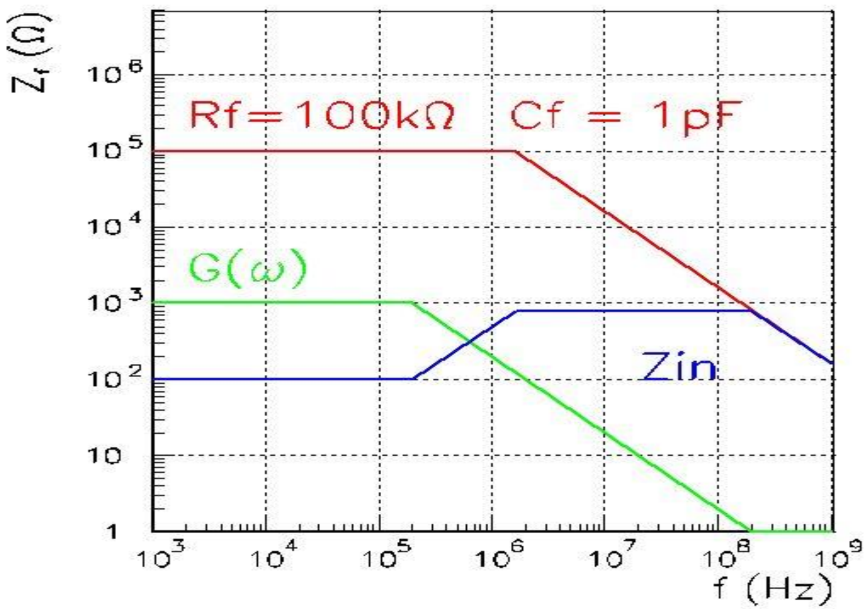
- Current preamps are <u>not faster</u>, they are <u>shorter</u> (but easily unstable)



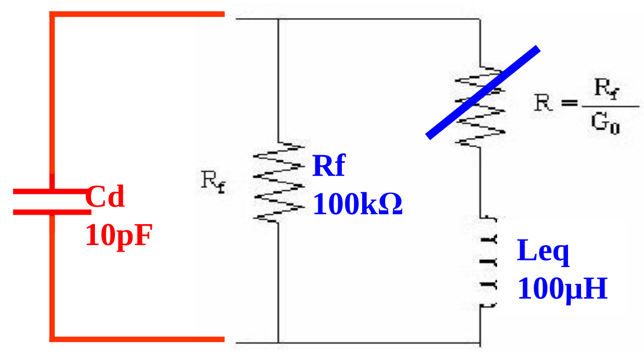
Input impedance

- Input impedance
  - Zin = Zf / G+1
  - Zin->0 virtual ground
  - Minimizes sensitivity to detector impedance
  - Minimizes crosstalk

- Equivalent model
  - $G(\omega) = G_0/(1 + j\ \omega/\omega_0)$
- Terms due to Cf
  - $Zin = 1/j\omega\ G_0C_f + 1/\ G_0\omega_0\ C_f$
  - Virtual resistance : $Req = 1/\ G_0\omega_0\ C_f$
- Terms due to Rf
  - $Zin = R_f/\ G_0 + j\ \omega\ R_f/\ G_0\omega_0$
  - Virtual inductance : $Leq = R_f/\ G_0\omega_0$
- Possible oscillatory behaviour with capacitive source



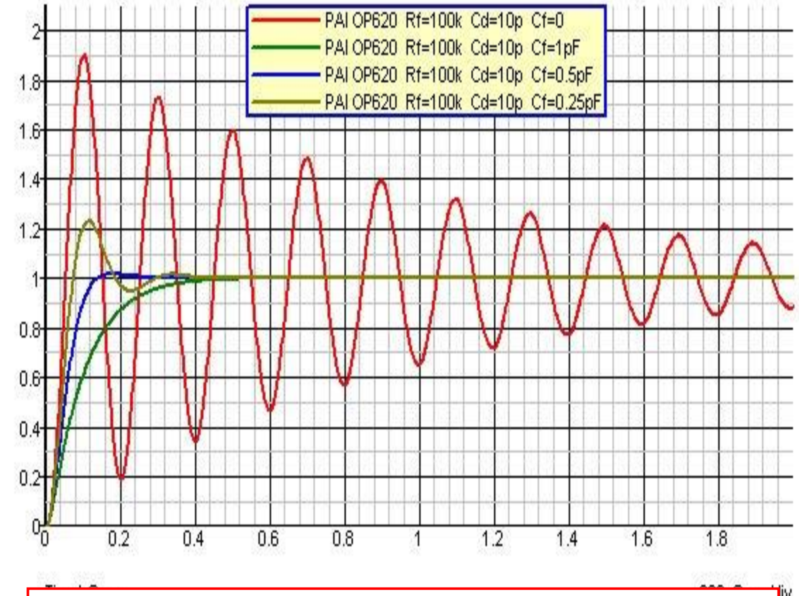
Input impedance or TZA



Equivalent circuit at the input

Current preamplifiers :

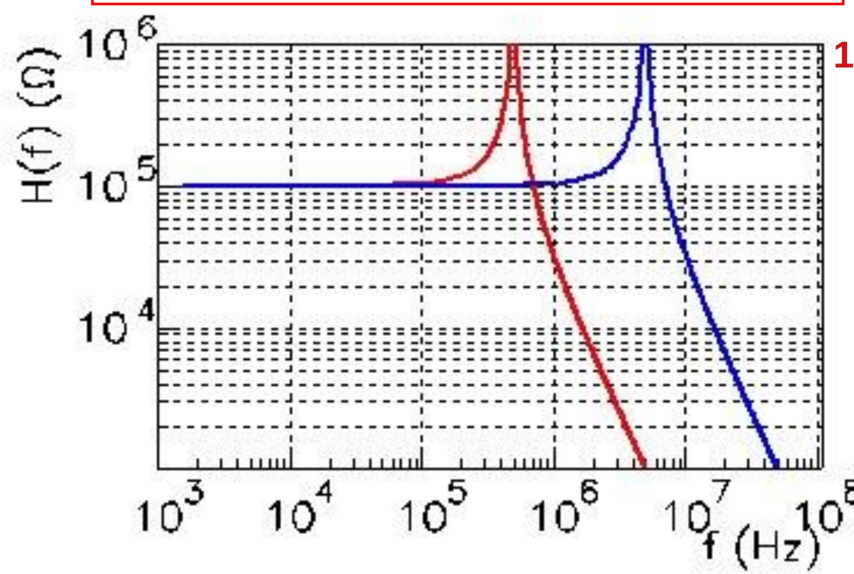
- Easily oscillatory
  - Unstable with capacitive detector
  - Inductive input impedance : L_e
    $= R_f / \omega_C$
  - Resonance at : $f_{res} = 1/2\pi \sqrt{L_{eq}C_d}$
  - Quality factor : $Q = R / \sqrt{L_{eq}/C_d}$
    - $Q > 1/2$ -> ringing
  - Damping with capacitance C_f
    - $C_f = 2 \sqrt{(C_d/R_f G_0\omega_0)}$
    - Easier with fast amplifiers



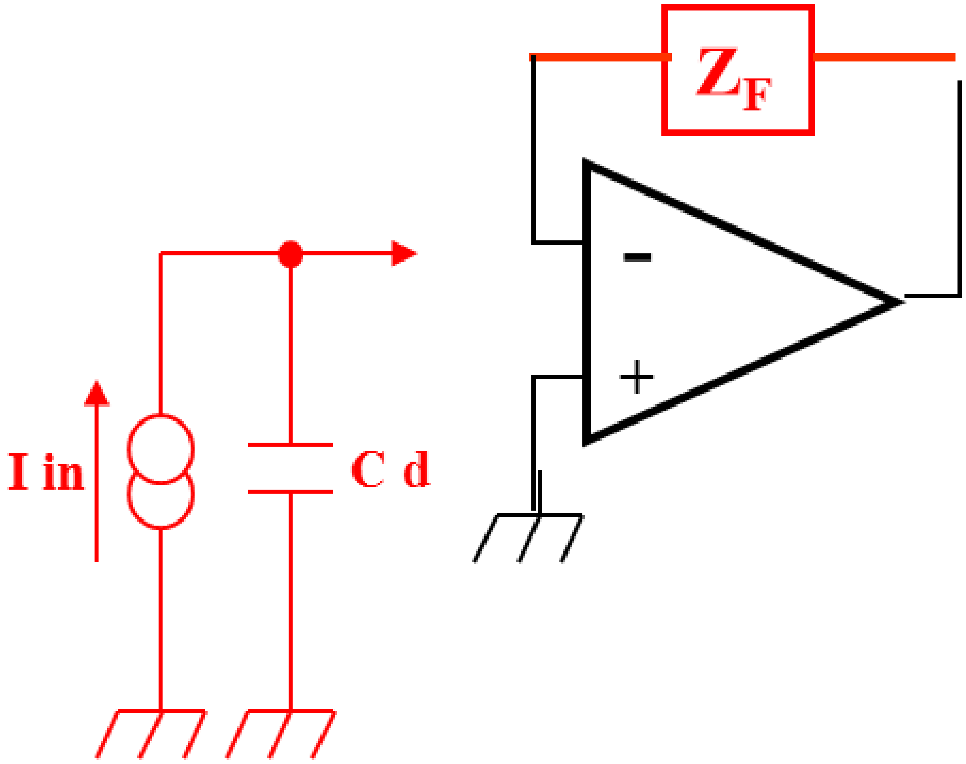
Step response of current sensitive preamp

- In frequency domain
  - $H(j\omega) = -Rf / (1 + j\omega\, RfC_d/G(\omega))$
  - $G(\omega) = G_0 / (1+j\omega/\omega_0)$

  $H = -Rf / (1 + j\omega\, R_fC_d/G_0 - \omega^2 R_fC_d / G_0\omega_0)$

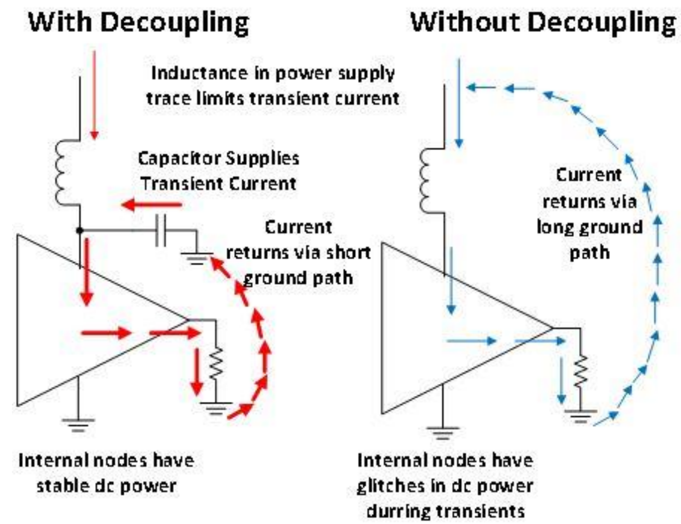


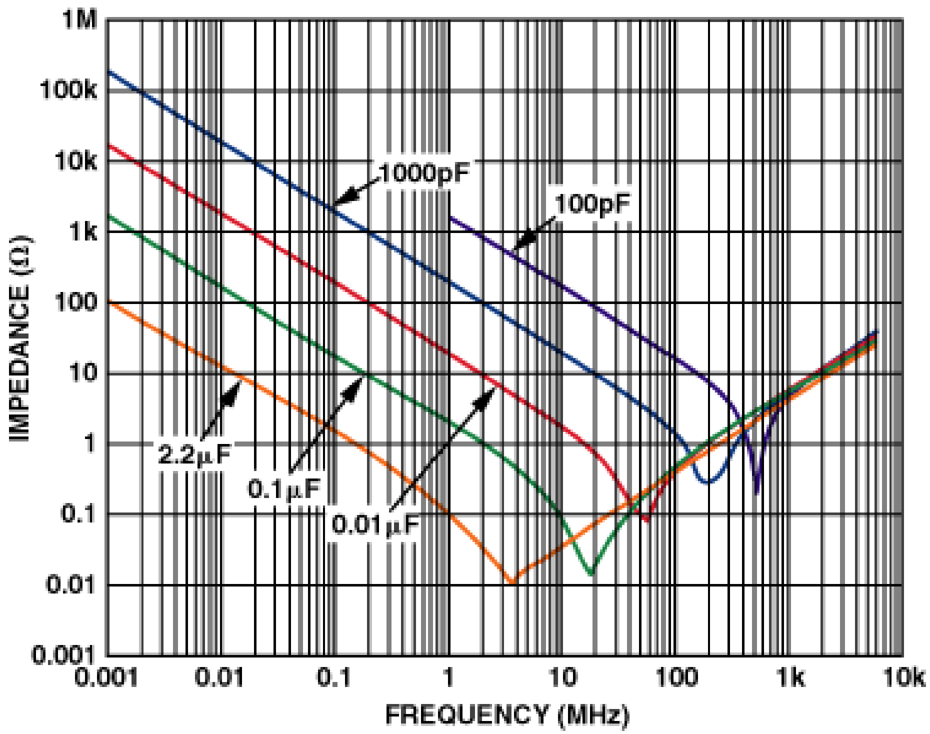
- Determine the current path…
- Effect of inductors in various parts

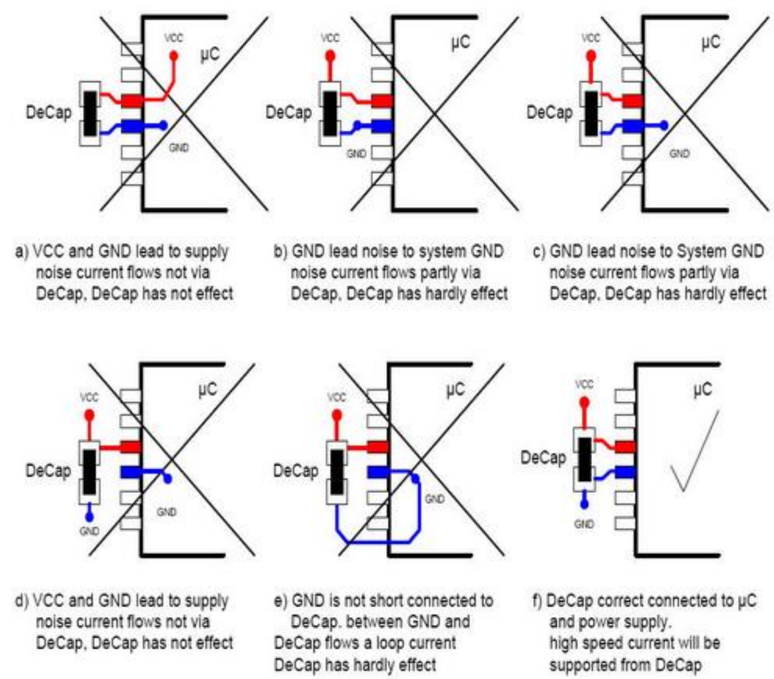


Decoupling capacitors

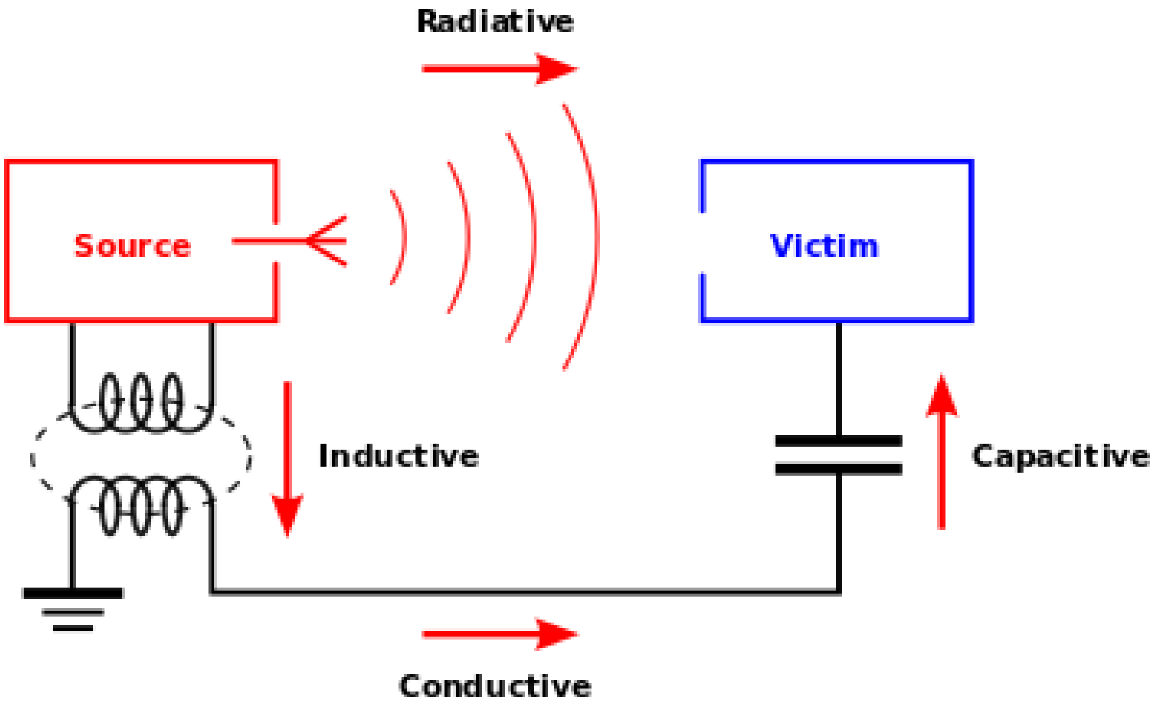
- Exhibit parasitic resistance (ESR) and inductance
- Pay attention to components and PCB layout





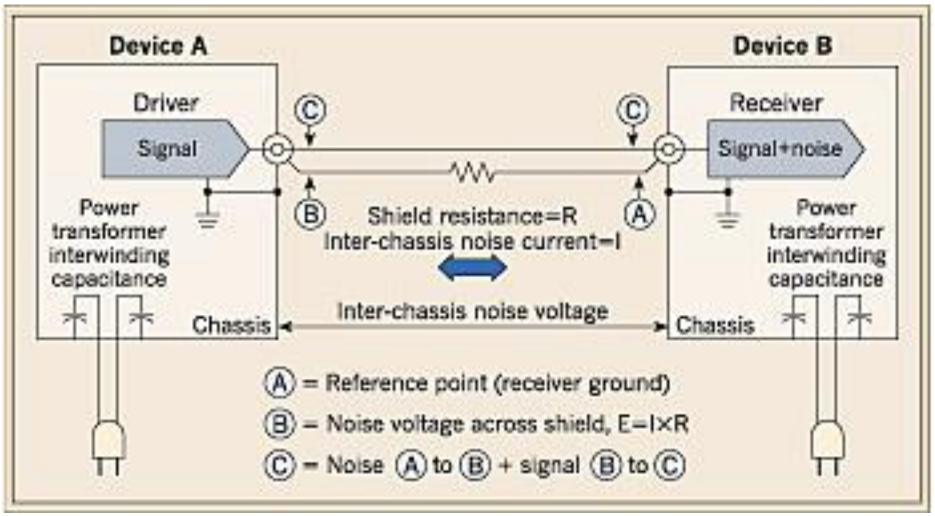


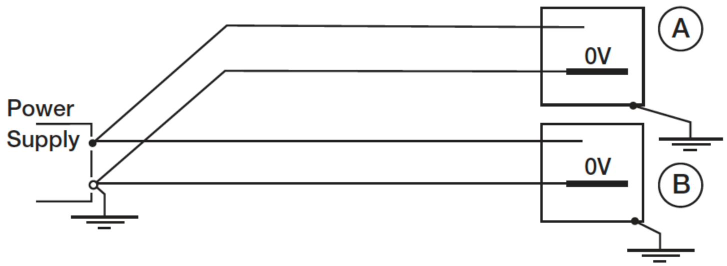
- Radiated and conducted noise

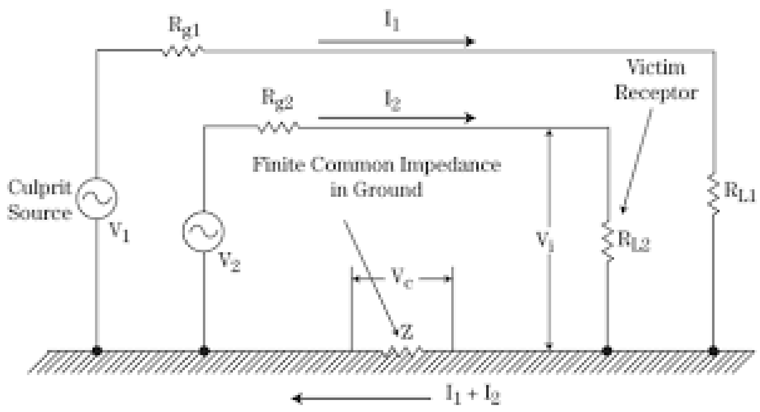


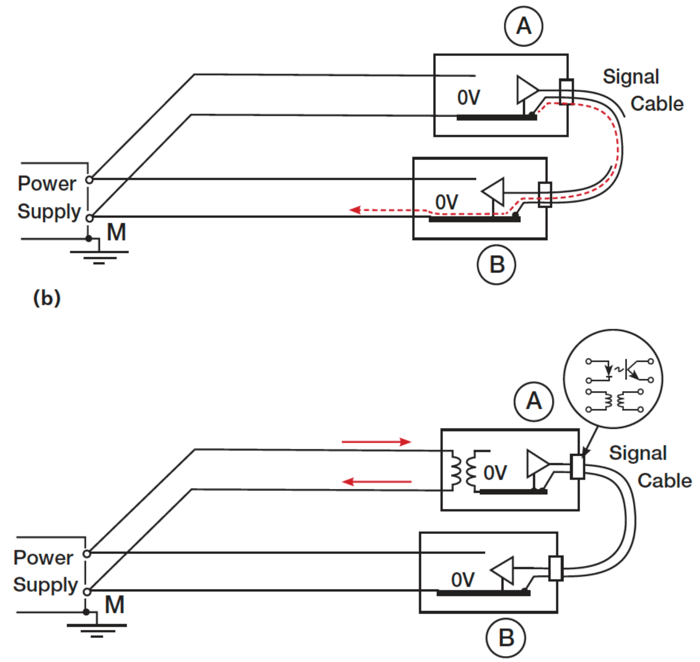
Coupling by common impedance

- Parasitic signals from ground/substrate currents
- Star configuration (Single Ground Point) for DC or low frequency

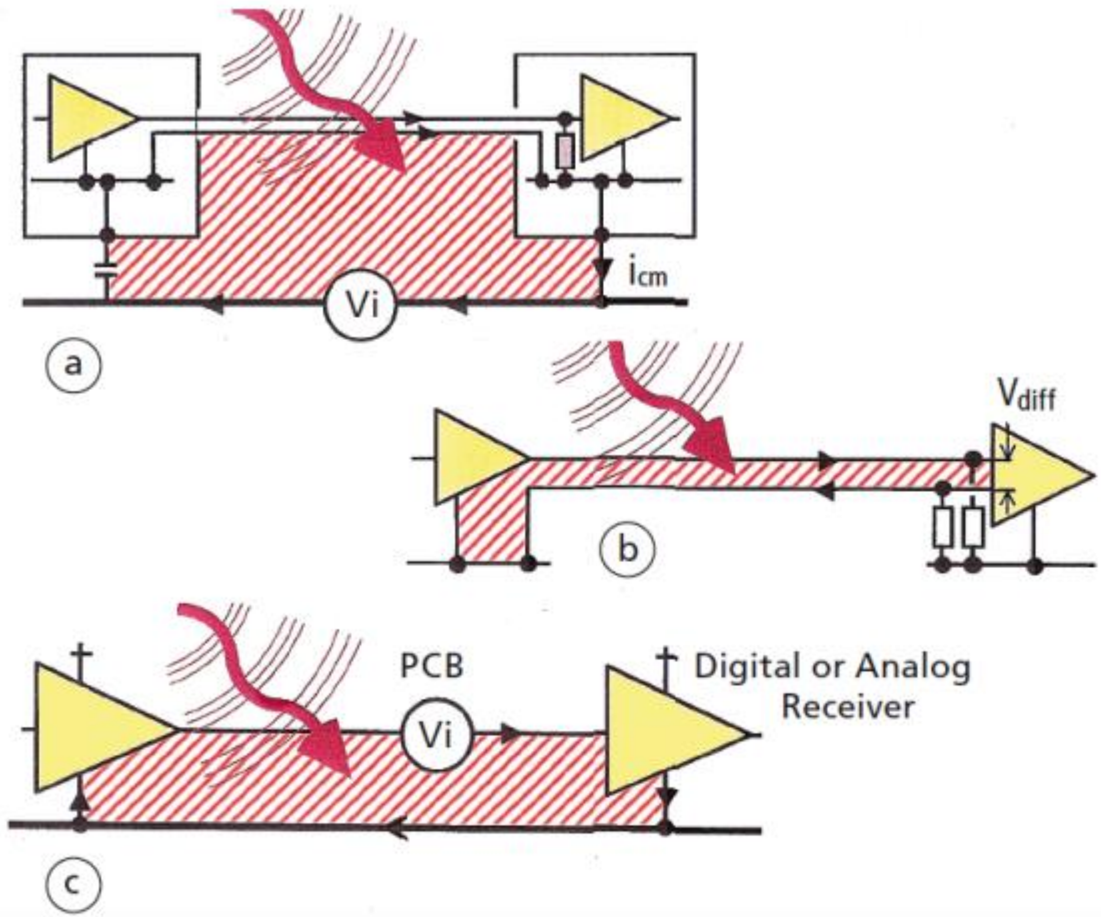






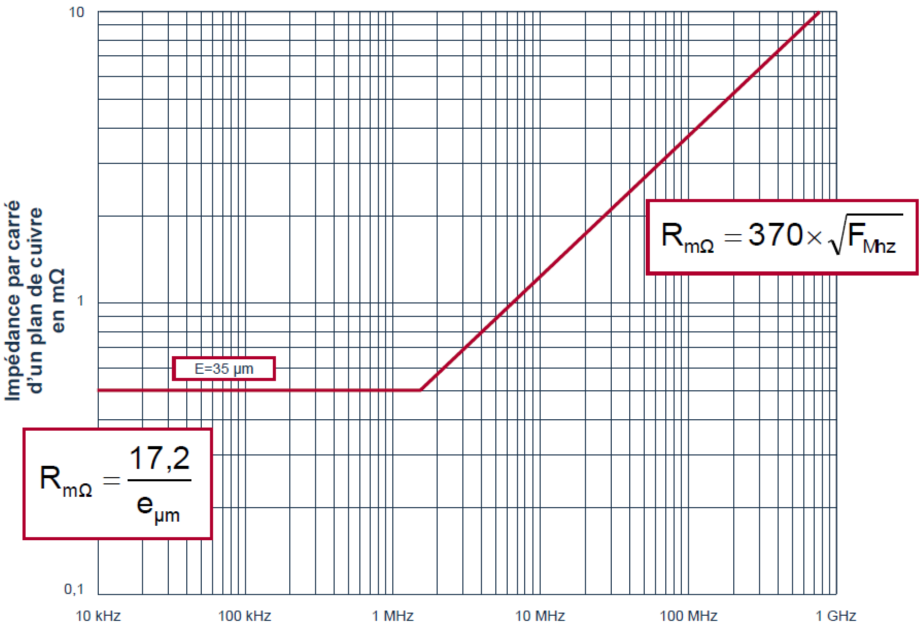


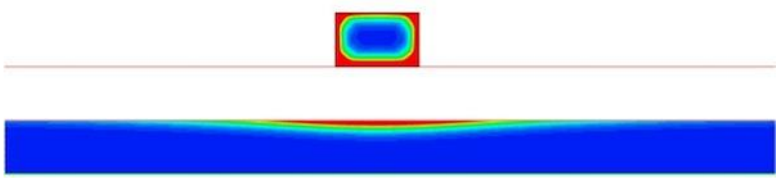
- Noise coupling in loops
  - Reduce loop area, use coax or twisted pairs in long distances
  - Avoid floating the shield « breaking the ground loop » : works only at very low frequency

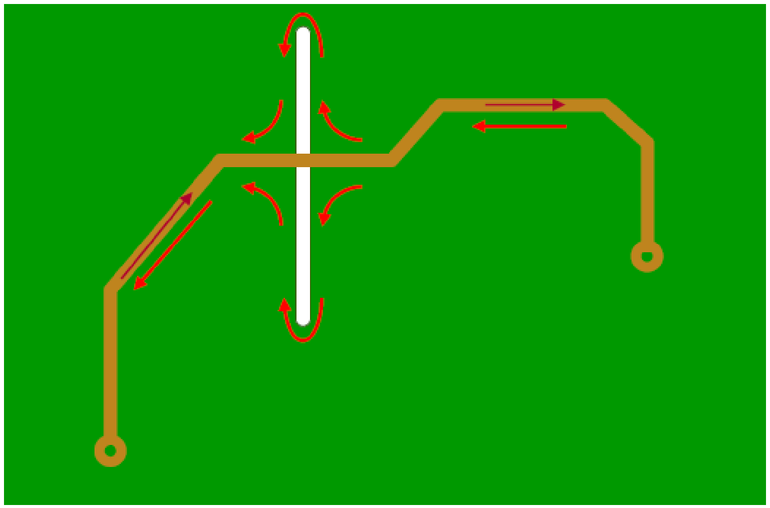


Ground impedance

- Ground plane impedance, current return, ground slit = 1 nH/mm
- Line impedance : R = 0.5 L/W mΩ L = 1 nH/mm
- Skin depth : $\delta \sim 2 / \sqrt{F(GHz)}$ (μm) (1 GHz = 2 μm)



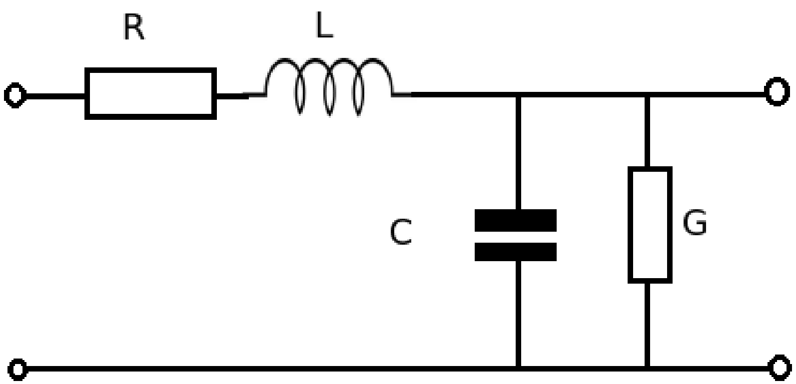




Transmission lines

- Ideal line : R = 0, G = 0
  - Characteristic impecance : Zc = sqrt(L/C)
  - Delay : td = sqrt(LC)
  - Speed depends only on dielectric $v = c/\sqrt{\varepsilon_r}$
  - delay td = L / v, typically 5 ns/m (FR4)

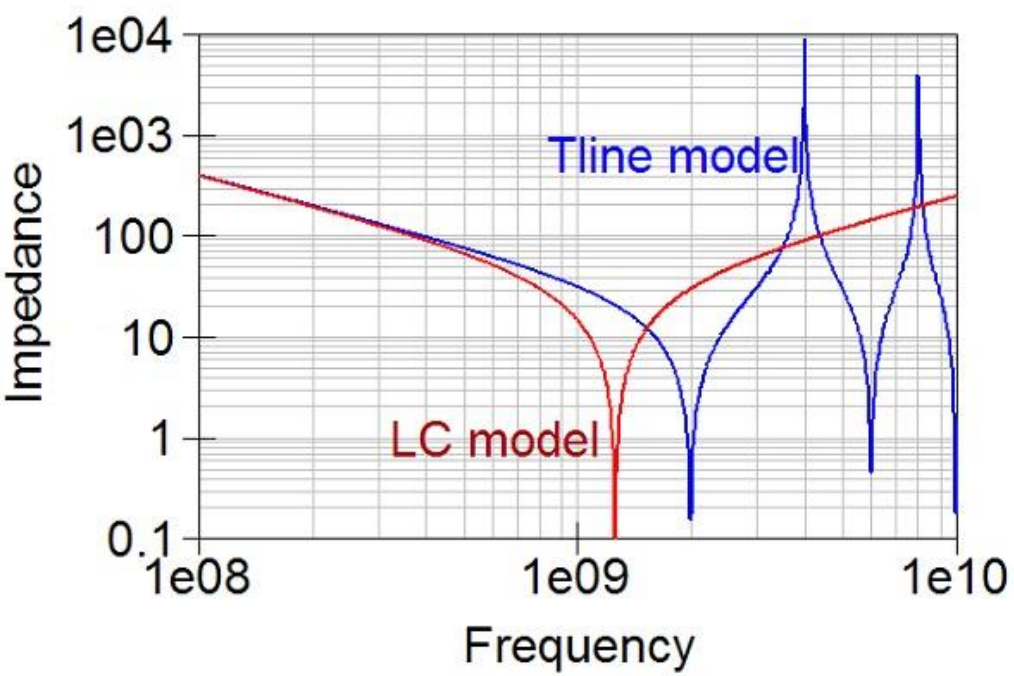
$$Z_o = \sqrt{\frac{R + jwL}{G + jwC}}$$



Equivalent circuit per unit length

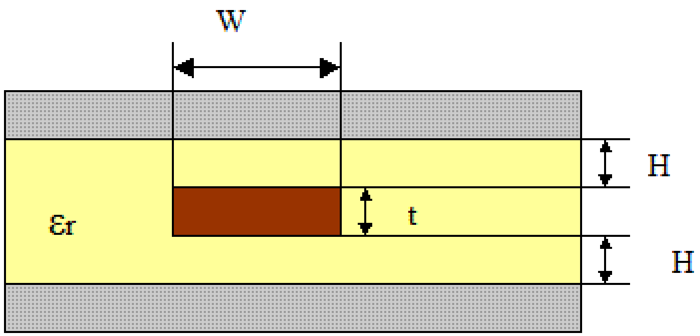
R is resistance of wire/track
L is the inductance
C is the capacitance
G is the conductance of the dielectric

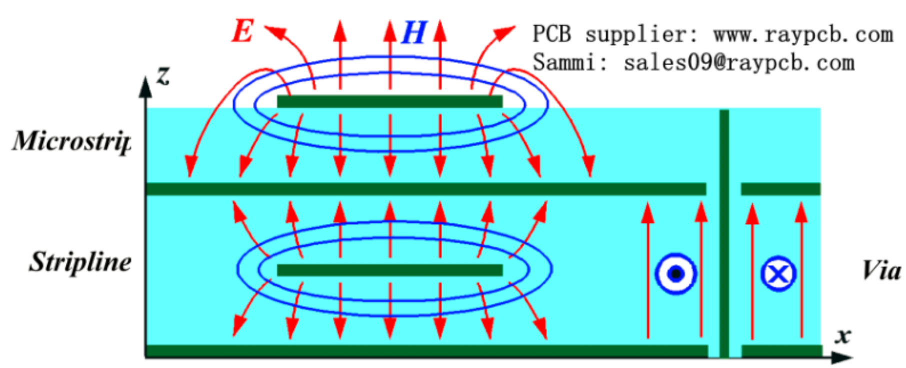
- Real line : R ≠ 0 and R(ω)



Transmission lines

- Strip lines, microstrip

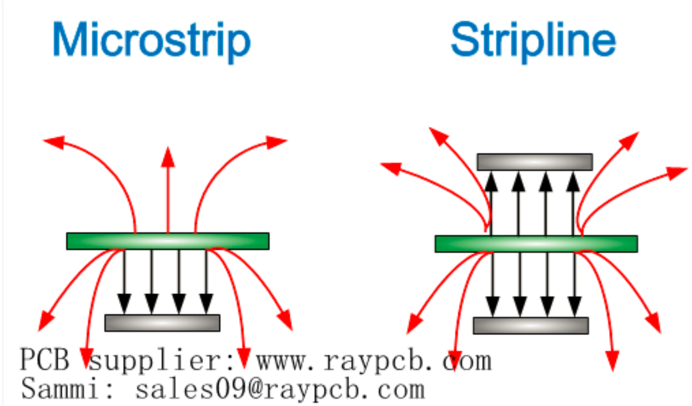


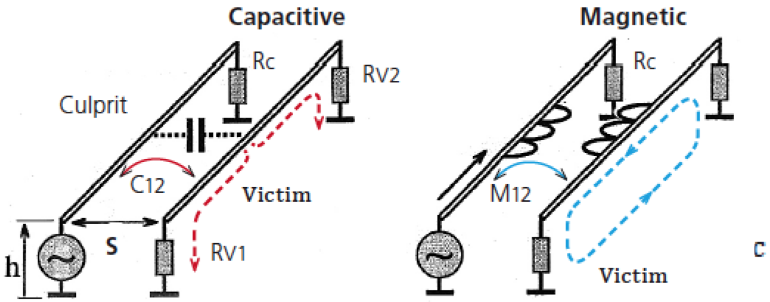


$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} Ln\left(\frac{1.9(2H+T)}{(.8W+T)}\right)$$

$$C_0 = \frac{5.55 \cdot 10^{-11} \varepsilon_r}{Ln[3.81H/(.8W+T)]}$$

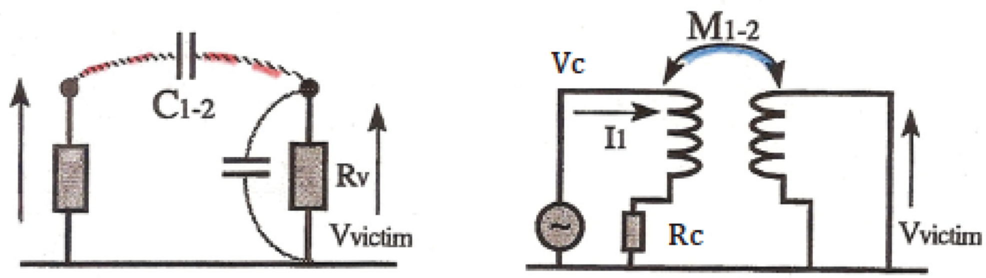
$$t_{pd} = 3.34 \cdot 10^{-9} \sqrt{\varepsilon_r}$$





CAPACITIVE

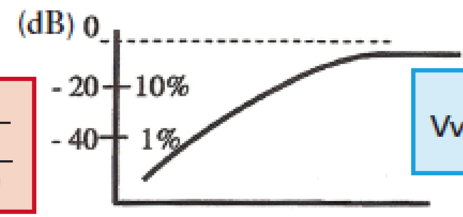
INDUCTIVE



- Capacitive/inductive coupling
  - Capacitive as dV/dt
  - Inductive as dI/dt
- Capacitive coupling easier to shield
- Prefer microstrip lines
- Rule of thumb :
  - Spacing = 5 * distance to ground plane

$$V_{vict} = V_{cx} \frac{R_v}{R_v + \frac{1}{C_{1\text{-}2}\omega}}$$

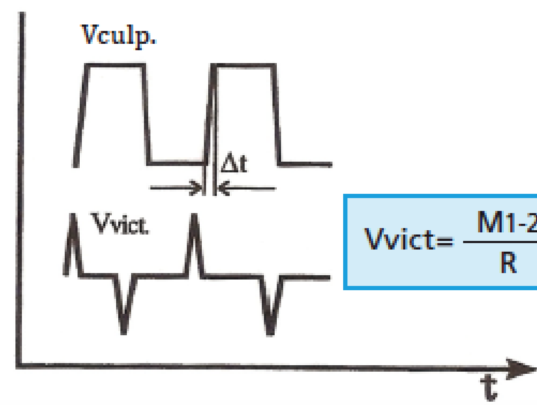
FREQUENCY Domaine



$$V_{vict} = \frac{V_{coup.}}{R_{coup.}} \times M_{1\text{-}2}\,\omega$$

TIME Domaine

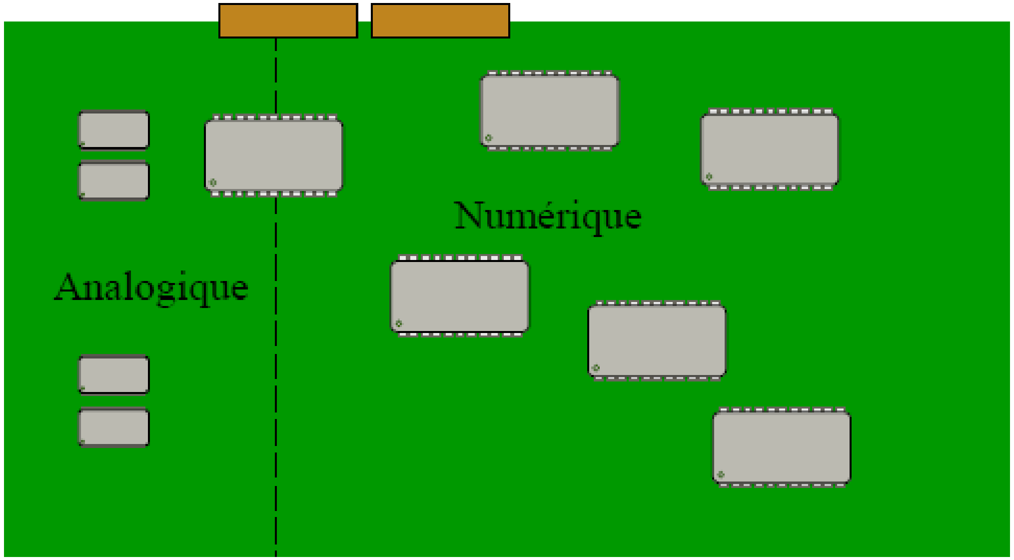
$$V_{vict} = R_v\, C_{1\text{-}2}\, \Delta V/\Delta t$$



$$V_{vict} = \frac{M_{1\text{-}2}}{R} \times \Delta V/\Delta t$$

Mixed signal boards

- Component placement
  - Separate analog and digital parts
  - Place analog on one side
  - Bring power supplies from the digital side
- Ground management
  - Use a common ground plane analog/digital
  - Avoid ground splits

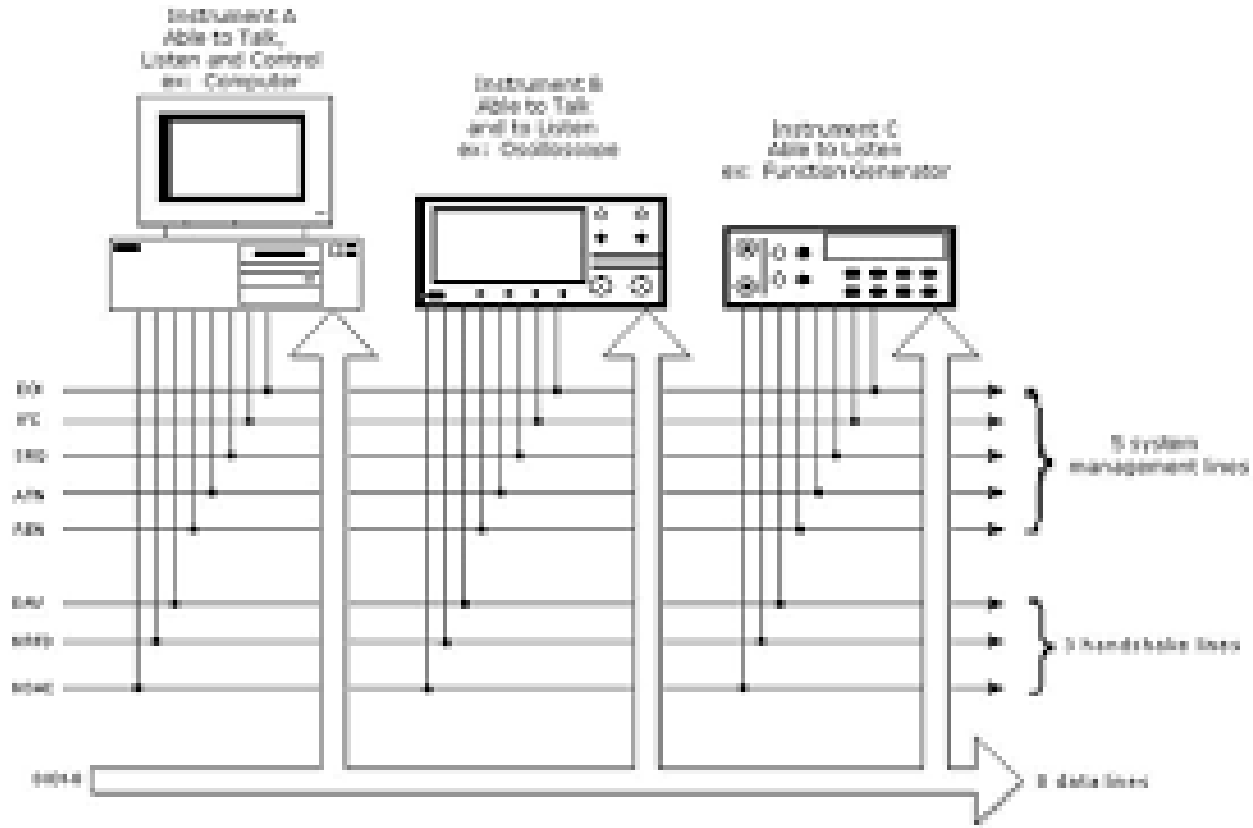


Field bus

- GPIB
- I^2C
- CAN
- JTAG
- USB
- Ethernet

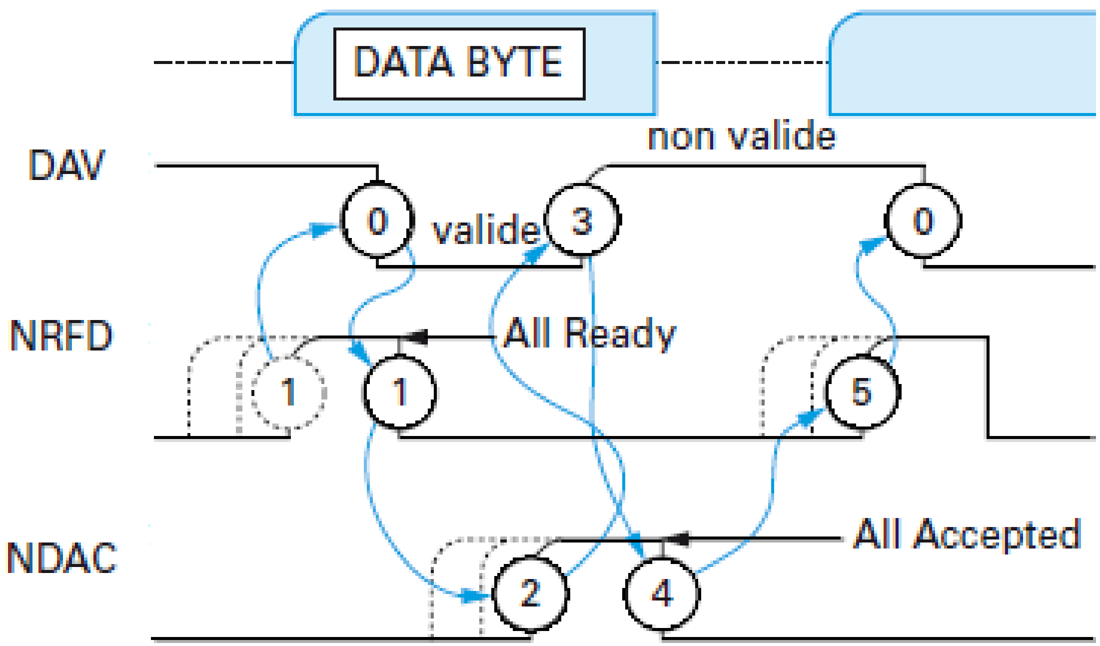
GPIB bus

- General Purpose Interface Bus IEEE488 1975
  - Connection between computer and measurement apparatus
  - Bi-directional, asynchronous, 8bits parallel,
  - 1 Mbyte/s, 24 instruments, 20 m open collector 5 V
  - Instruments (slaves) are controlled by the computer (master)



GPIB bus description

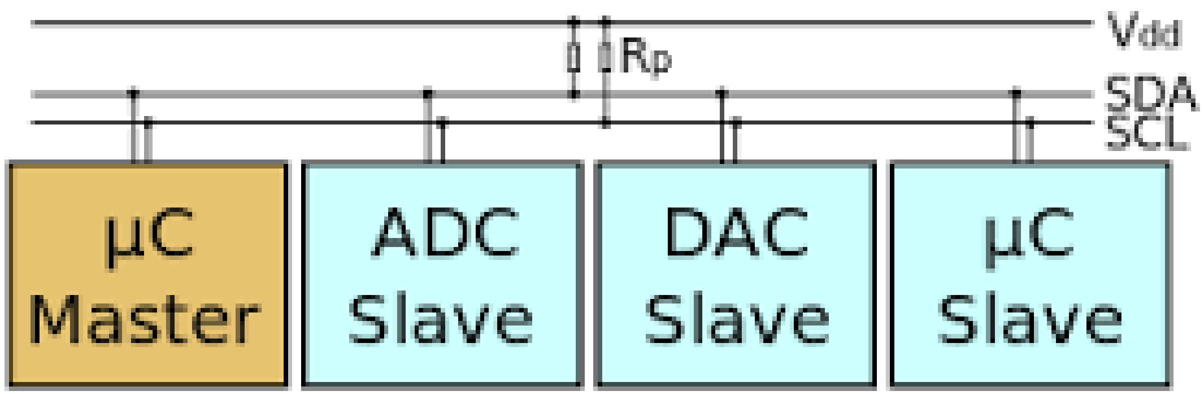
- 8 data lines (OC)
- 3 control lines (OC) : DAV (data valid), NRFD (not ready for data), NDAC (no data accepted)
- 5 management lines : ATN, IFC, REN, SRQ, EOI
- No conflicts possible : instruments talk only when requested to do so



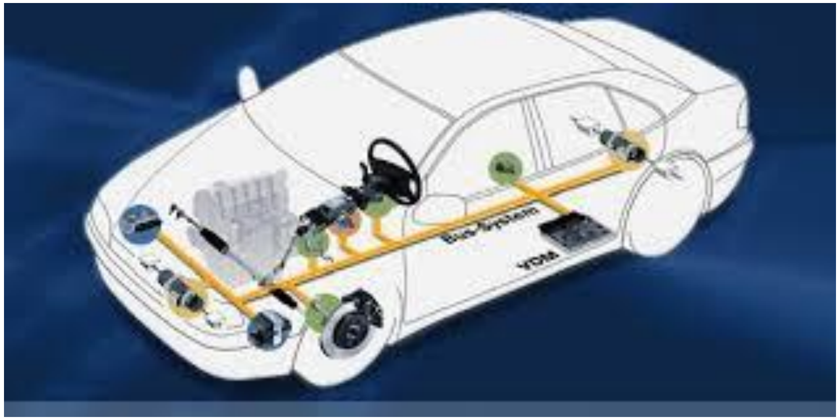
- Inter Integrated Circuits
  - Connection between chips in televisions (Philips 1982)
  - Bidirectionnal, synchronous, 8 bits serial
  - 2 lines : SDA (serial data) and SCL (serial clock)
  - 400 kb/s, 1024 instruments

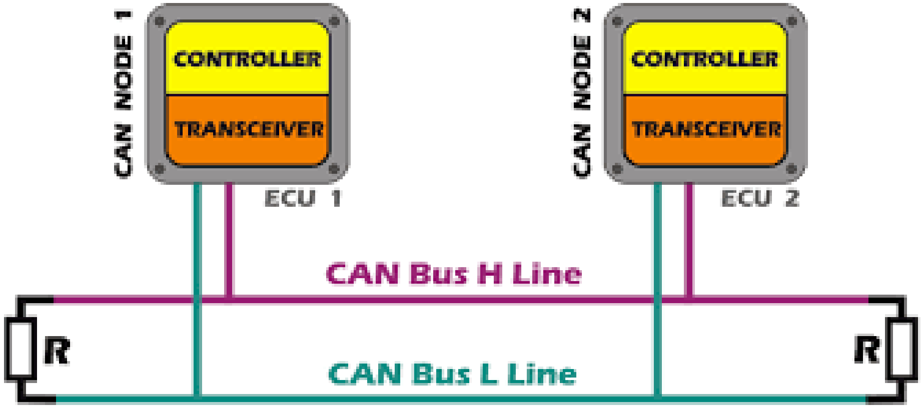
- Conflit management
  - Any circuit can broadcast when the line is free
  - In case of collisions, the most important recipient (lowest address) is prioritary

I²C BUS

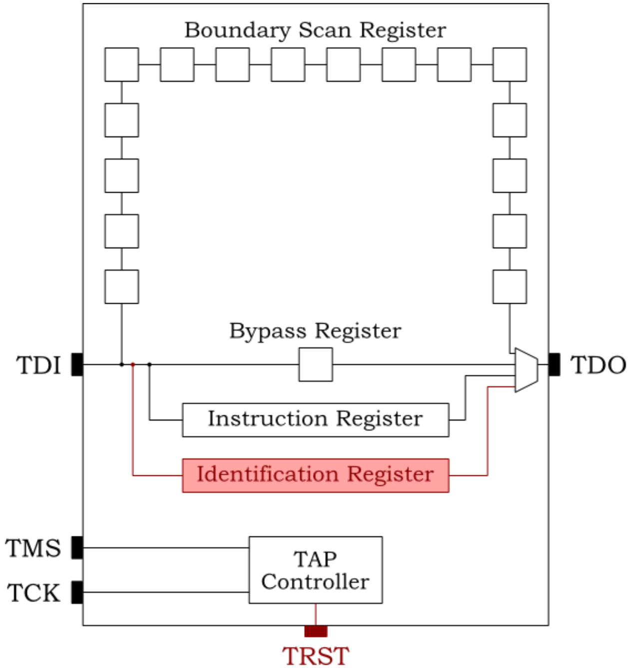


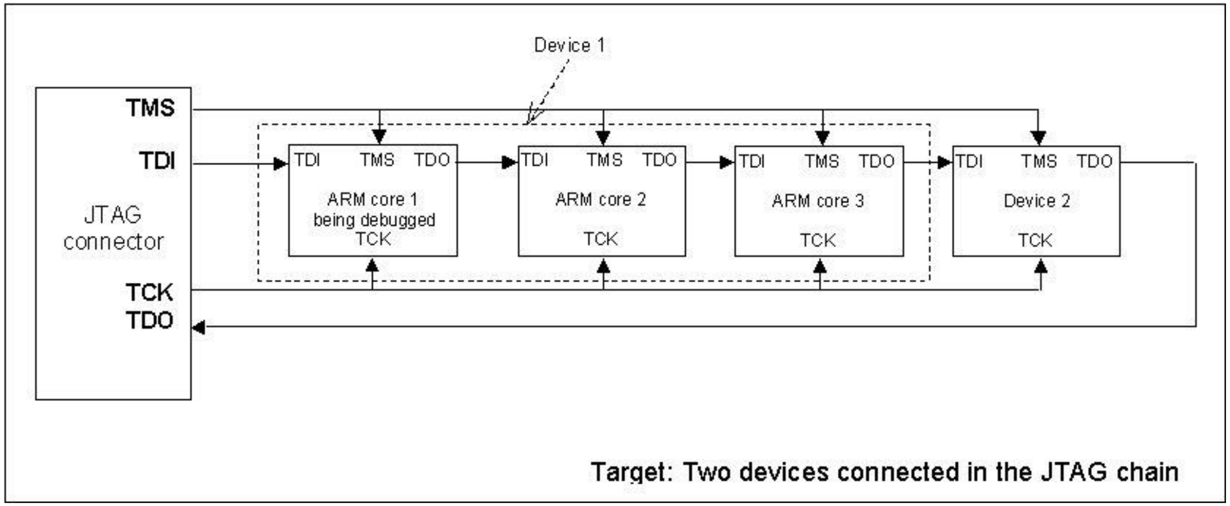
- Controller Area Network (Bosch Gmbh 1983)
  - Serial bus to reduce amount of cables in cars
  - Bi-directionnal, synchronous, serial 100 bits
  - 2 wires 100 Ω line, 1 Mbits/s, 64 circuits, 2048 messages, 1 km
- Conflit management
  - Any circuit can broadcast when the line is free
  - In case of collisions, the most important message is prioritary





- Join Test Action Group (1990) IEEE 1149.1
  - Goal : probeless test of digital Ics on a PCB (boundary scan)
  - Unidirectional, synchronous, serial, 5 lines, 50 Mbit/s
  - 5 lines : TDI (test data in) TDO (test data out) TMS (test mode select) TCK (clock) TRST* (resetb)

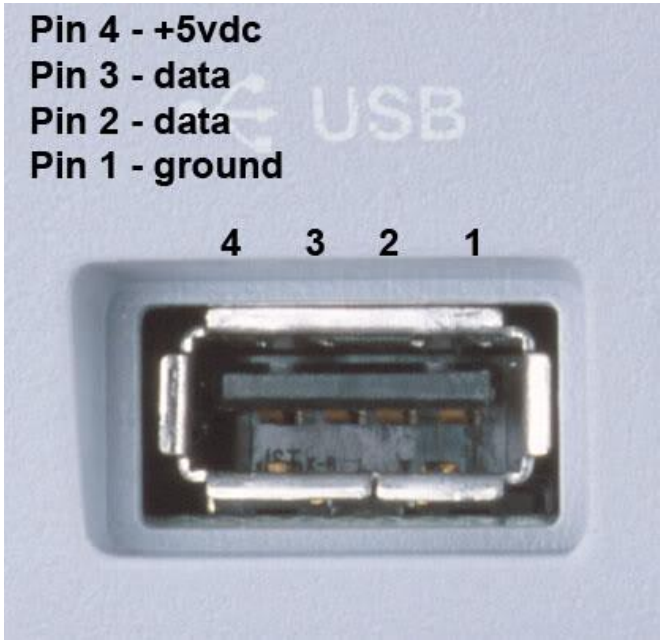




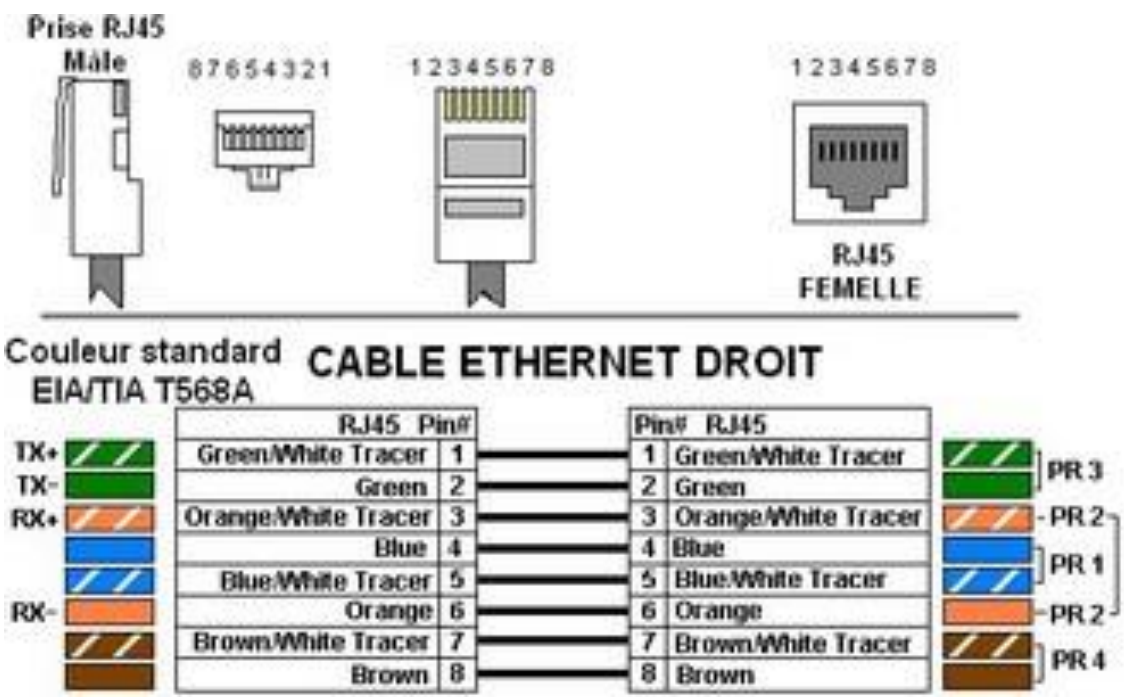
USB

- Universal Serial Bus (1996)
  - goal : replace various incompatible I/O ports on computers
  - USB1 (96) : 12 Mb/s, USB2 (01) : 480 Mb/s, USB3 (08) 4.8 Gb/s
  - Low cost, wide use, power service 5 V 500 mA
  - High rate, autodetection of devices, hot plug&play
  - Up to 127 devices per computer, but limited to 5 m

- Architecture : master/slave
  - tree-based (host), point to point connection
  - 3 transfer types : isochronous, interrupt, bulk



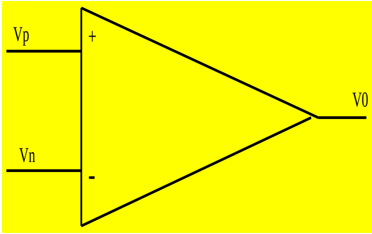
- Network connection for computers (1985) IEEE 802.3
  - Created in 1970, normalized in 1985
  - Unique MAC address, serial transmission (frames)
  - Coaxial cable or twisted pairs, optical fiber or wireless
  - CSMA-CD : Carrier Sense (listen before talking) Multiple Access (anyone can talk) Collision Detection (detect multiple talkers)

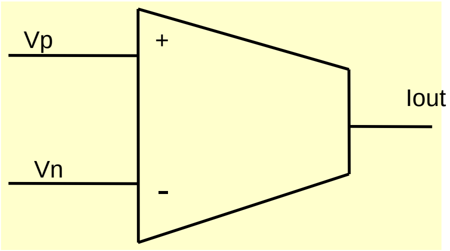


backup

Amplifiers : a large zoo

- Voltage feedback operationnal amplifier (VFOA)
- Voltage amplifiers, RF amplifiers (VA,LNA)
- Current feedback operationnal amplifiers (CFOA)
- Current conveyors (CCI, CCII +/-)
- Current (pre)amplifiers (ISA,PAI)
- Charge (pre)amplifiers (CPA,CSA,PAC)
- Transconductance amplifiers (OTA)
- Transimpedance amplifiers (TZA,TIA, OTZ)

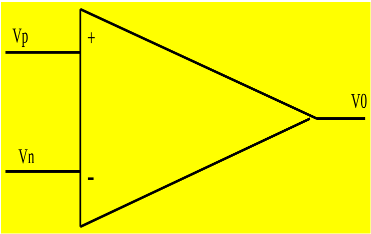




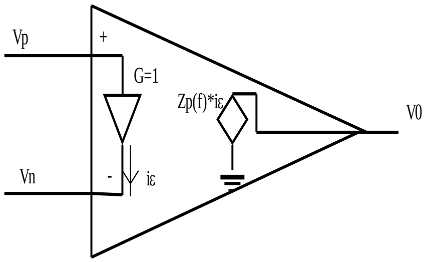
- Mixing up open loop (OL) and closed loop (CL) configurations !

Only 4 open-loop configurations

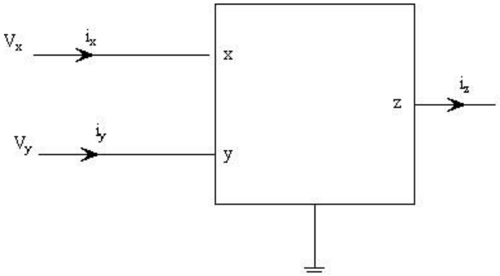
- Voltage operationnal amplifiers (OA, VFOA)
  - Vout = G(ω) Vin diff
  - Zin+ = Zin- = ∞ Zout = 0



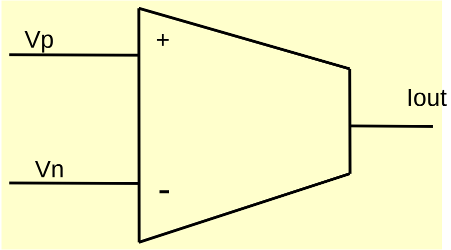
- Transimpedance operationnal amplifier (CFOA !)
  - Vout = Z(ω) iin
  - Zin- = 0 Zout = 0



- Current conveyor (CCI,CCII)
  - Iout = G(ω) Iin
  - Zin = 0 Zout = ∞

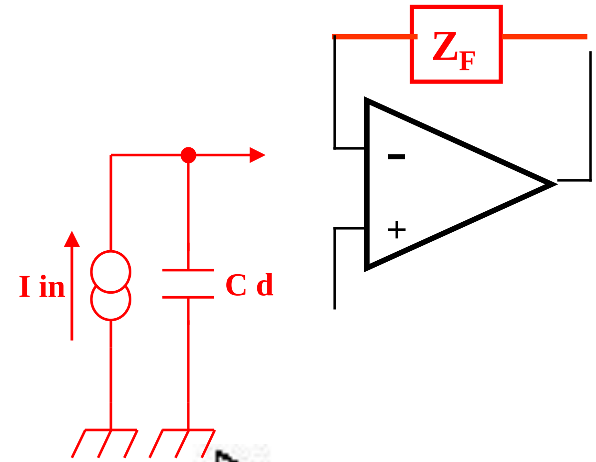


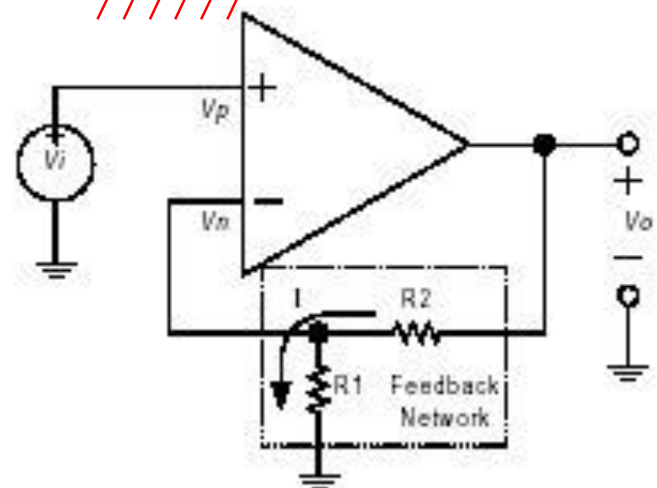
- Transconductance amplifier (OTA)
  - Iout = Gm(ω) Vin diff
  - Zin+ = Zin- = ∞ Zout = ∞



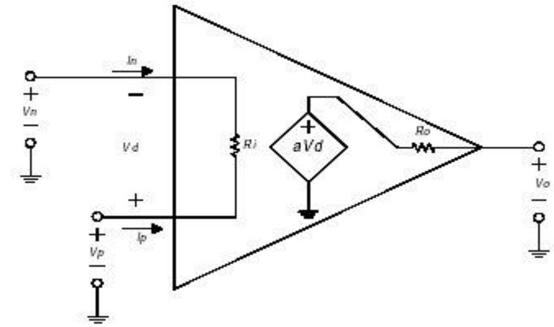
Only 4 feedback configurations

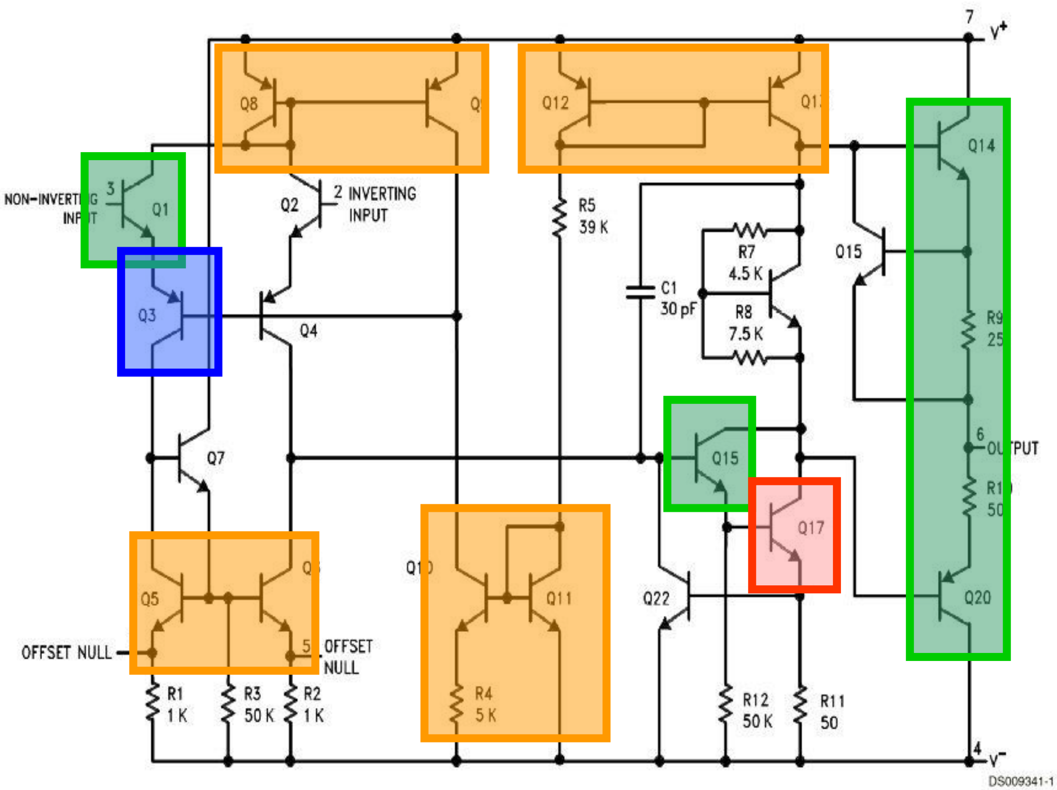
- Shunt-shunt = transimpedance
  - Small Zin (= Zin(OL)/T) -> current input
  - small Zout (= Zout(OL)/T) -> voltage output
  - De-sensitizes transimpedance = 1/β = Zf
- Series-shunt
  - Large Zin (= Zin(OL)*T) -> voltage input
  - Small Zout (= Zout(OL)/T) -> voltage outpu
  - Optimizes voltage gain (= 1/β)
- Shunt series
  - Small Zin (= Zin(OL)/T) -> current input
  - Large Zout (= Zout(OL)*T) -> current outpu
  - Current conveyor
- Series-series
  - Large Zin (= Zin(OL)*T) -> voltage input
  - Large Zout (= Zout(OL)*T) -> current output
  - Transconductance
  - Ex : common emitter with emitter degenration

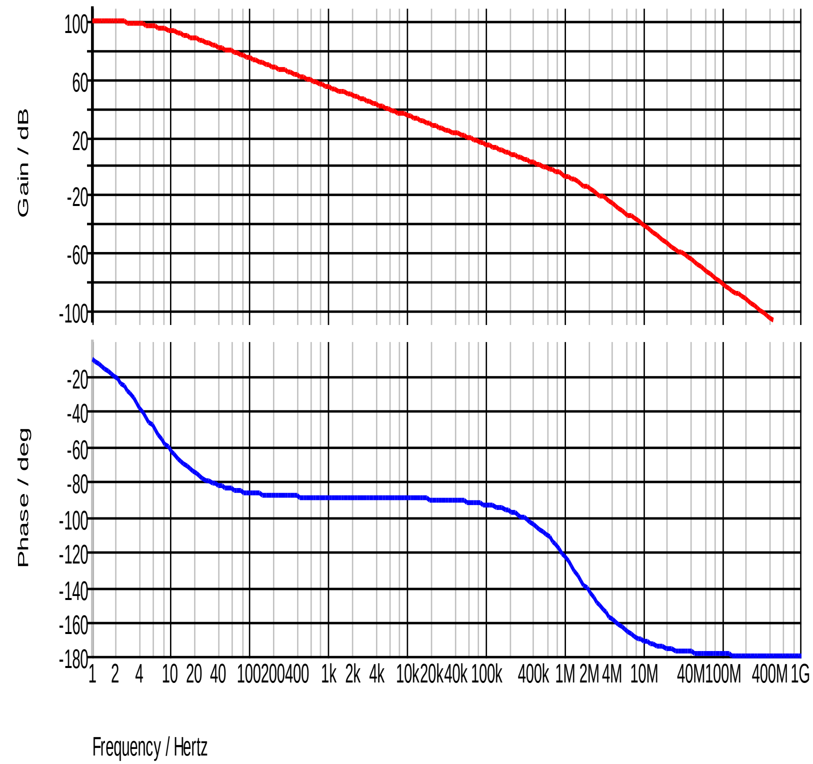




- Back to the 70's : LM741
  - 3 stages : Paraphase=CE, Darlington=CE,
  - G0 = 200 000, f0 = 5Hz, GBW = 1 MHz, Pd



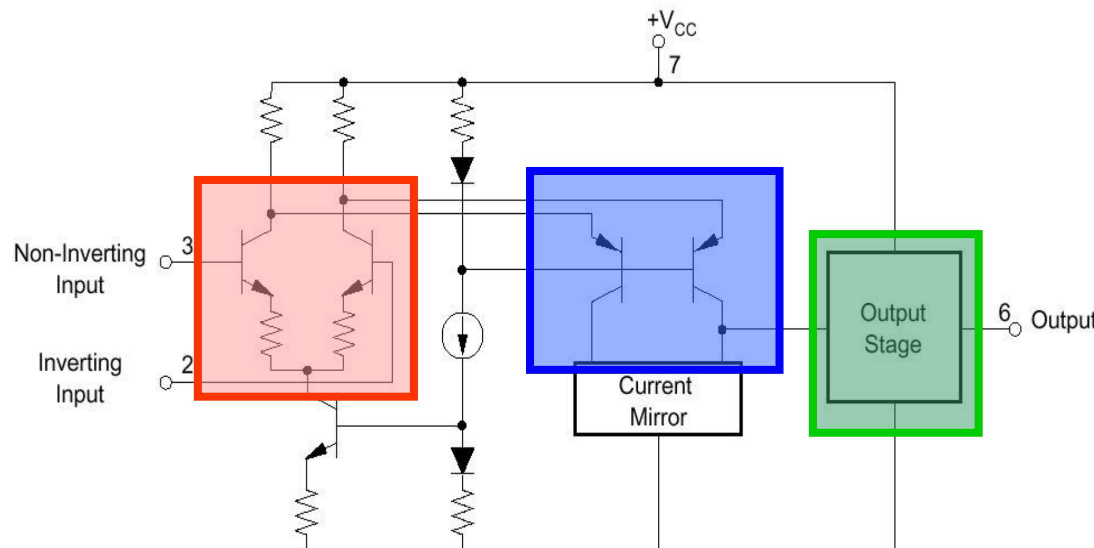


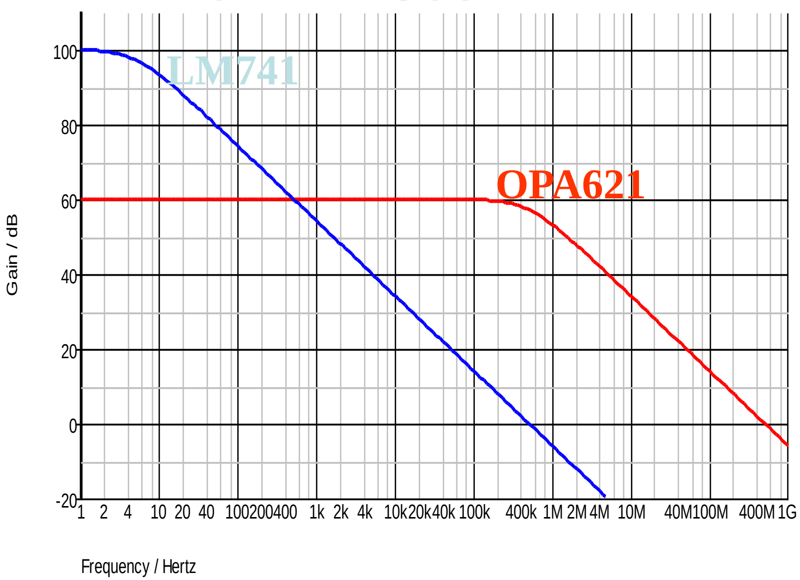


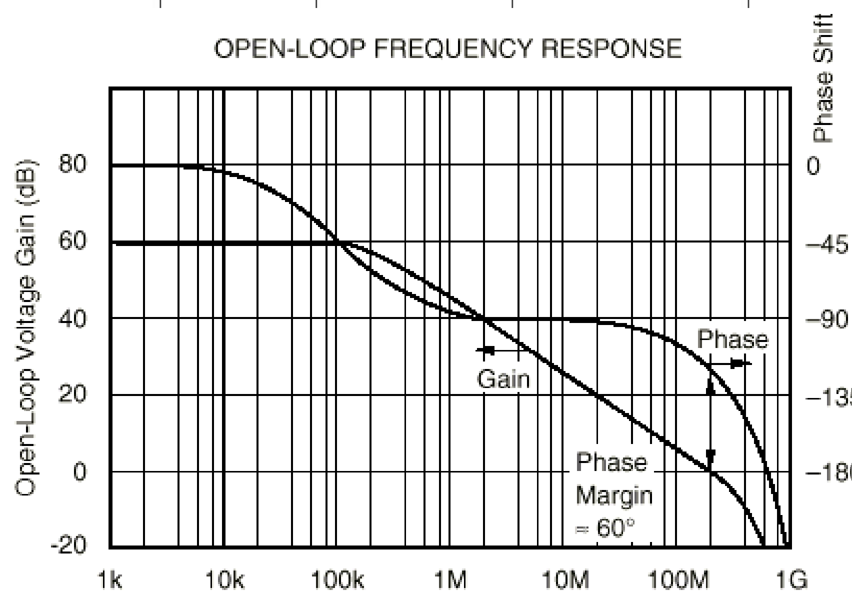
Schematic diagramm of a LM741 (1970) ©National Semiconductors

Voltage Feedback Operationnal Amplifiers (2)

- Breakthrough in the 90's : OP620-621
  - 2 stages : Cascode=CE, Push-pull = CC
  - Pd = 250 mW
  - G0 = 1 000
  - f0 = 500kHz
  - GBW = 500 MHz



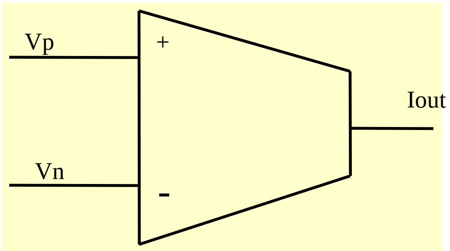




Open loop frequency response of OP620

Transconductance amplifier (OTA)

- Voltage input : large Zin
- Current output : large Zout
- V2I conversion : Iout= Gm(ω) Vin diff



- Differential pair for voltage to current conversion
- Active load for differential to unipolar
- Current mirrors for symmetrical output