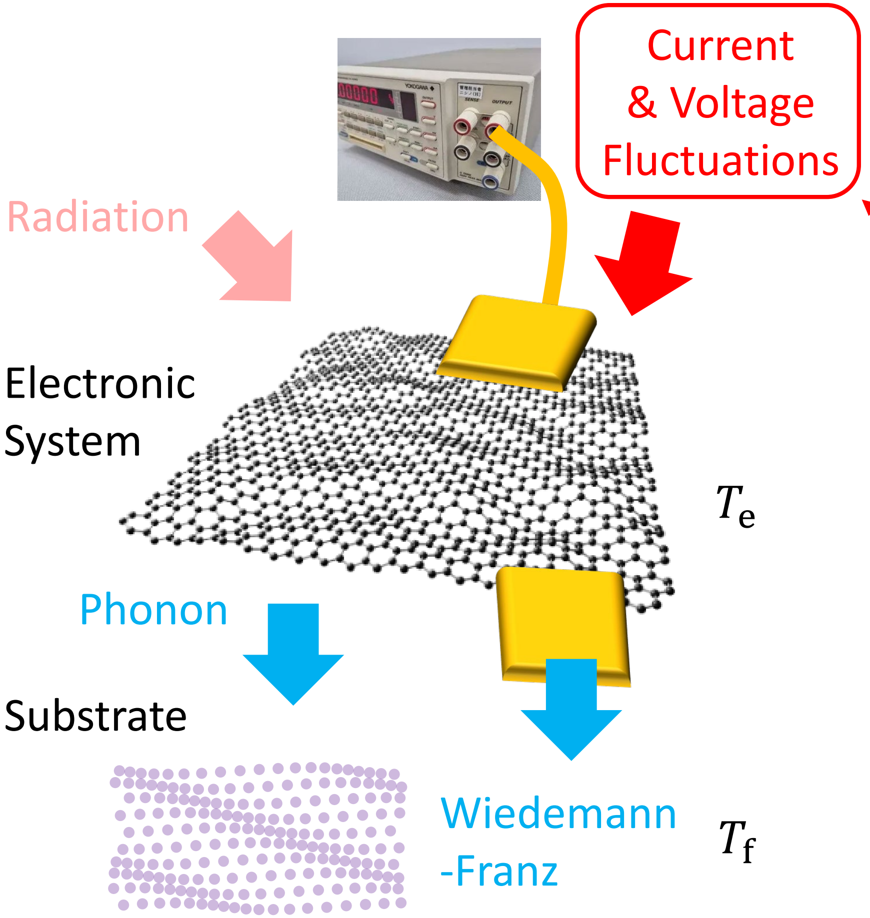
Good Practice for Lowering Electron Temperature and Electronic Noise

The 15th School of Mesoscopic Physics

Dongsung T. Park, POSTECH, Korea

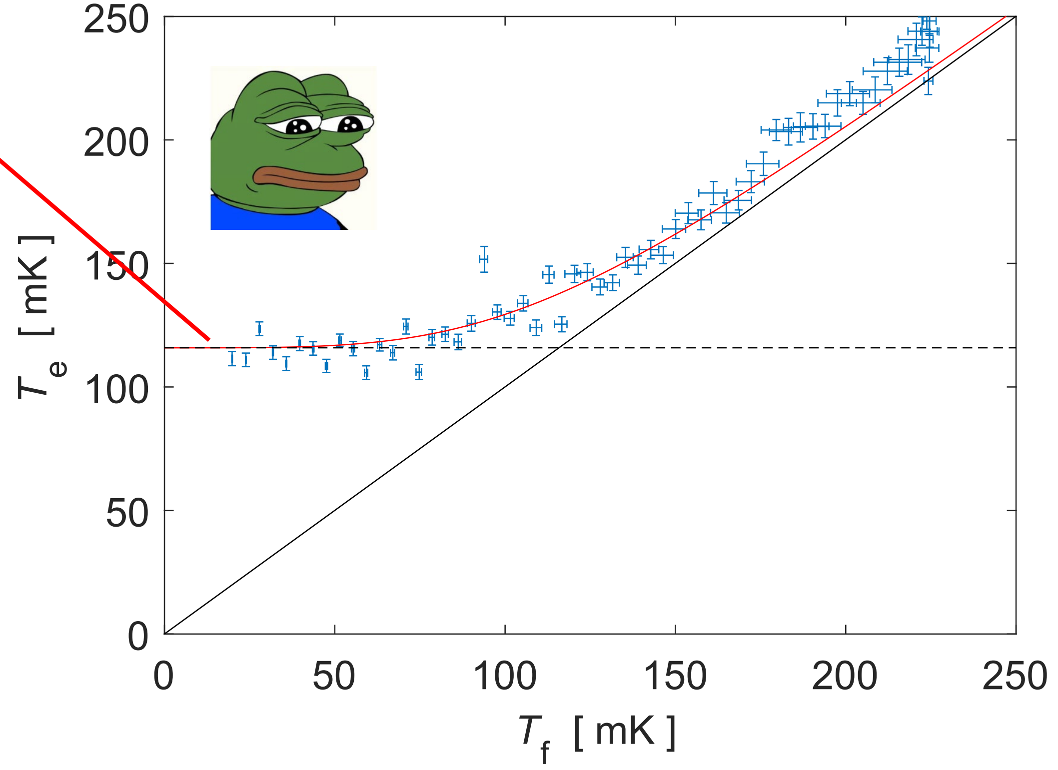
Electron Temperature & Electronic Noise



Heating Power ≈ constant

Cooling Power $\propto \left(T_e^\delta - T_f^\delta\right)$

$T_e > T_f$



Everything under kT_e… gone…

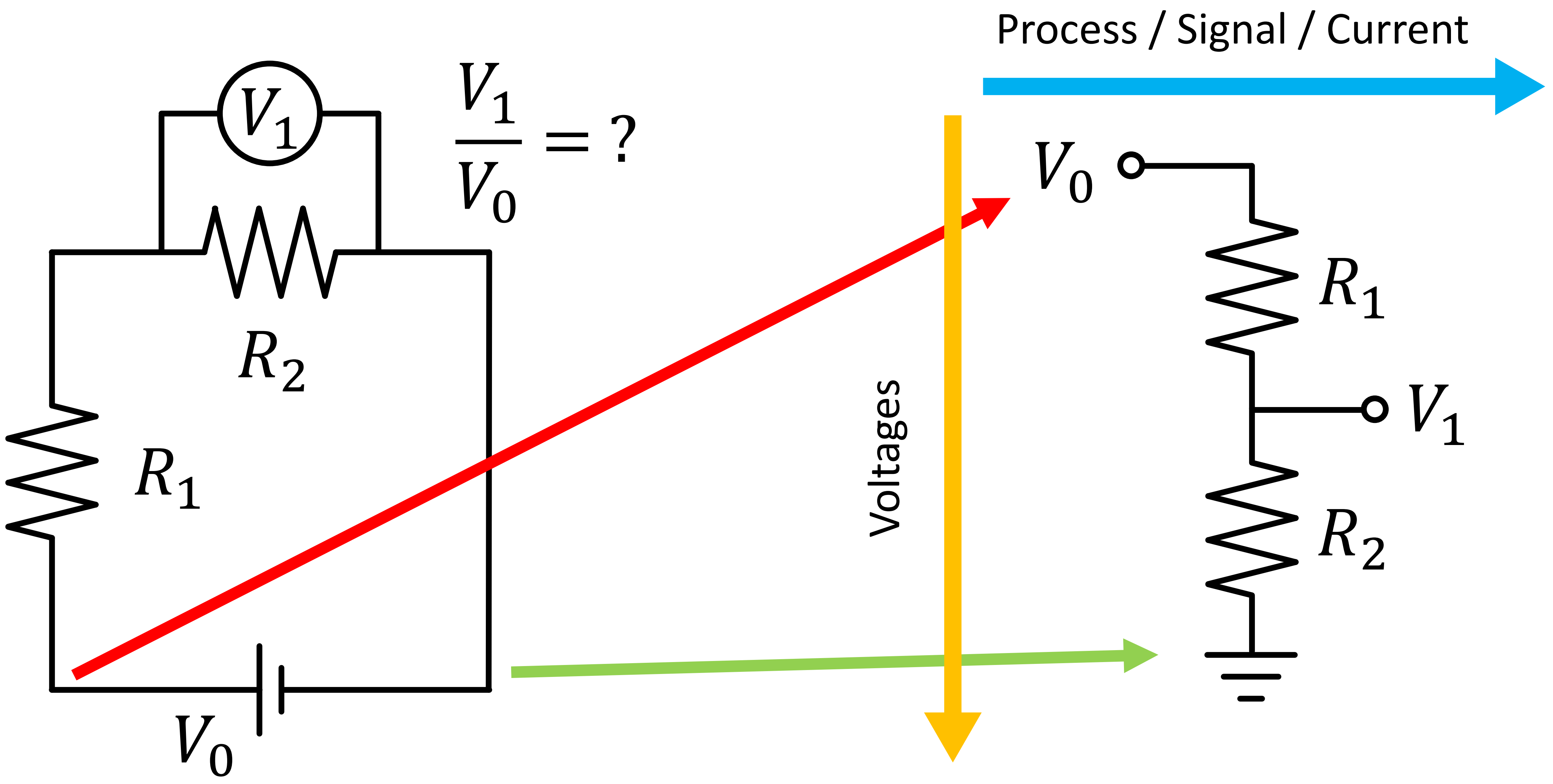
Everything under kT_e… gone…

Everything under kT_e… gone…

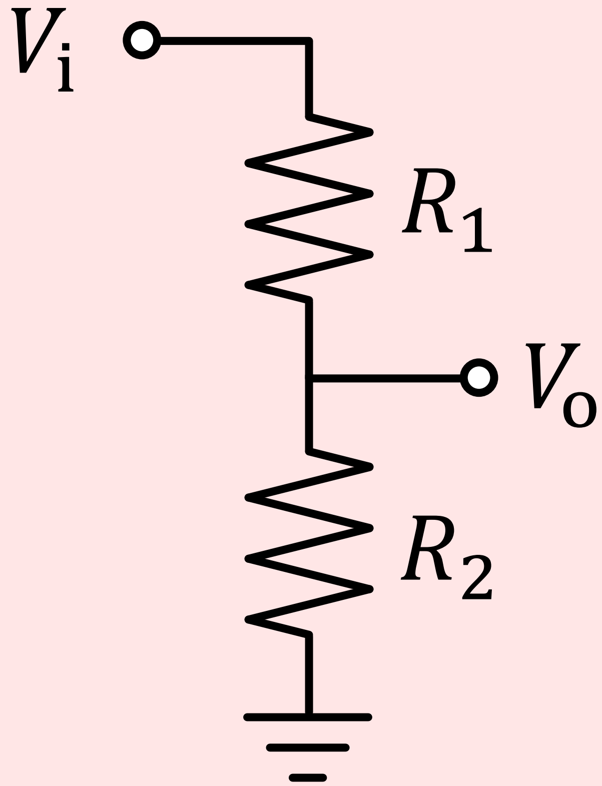
Topics of the day

1. Passive Filters
   - Circuit Schematics, Voltage & Current Divider, Impedance (1)
   - Passive Filters, Synthetic Filters, Parasitics
2. DC Amplifiers
   - Operational Amplifier, Generalized Amplifiers
3. Noise & Ground
   - Impedance (2), Ground & Common Problems, Earth
4. Instrumentation
   - Voltmeters, Lock-in amplifiers
   - Breakout boxes, Signal Lines

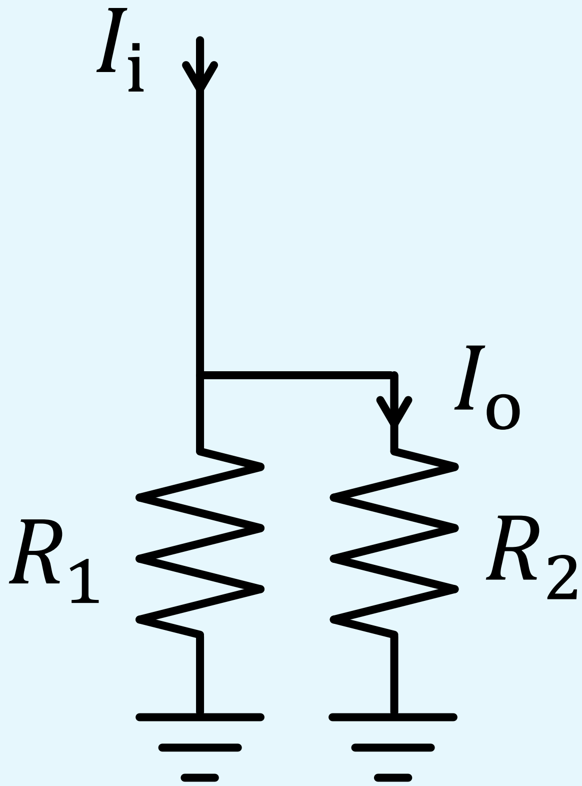
Circuit Schematics



Voltage & Current Divider

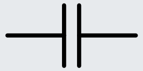
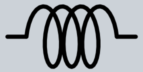


Voltage Divider: $\frac{V_o}{V_i} = \frac{R_2}{R_1 + R_2}$

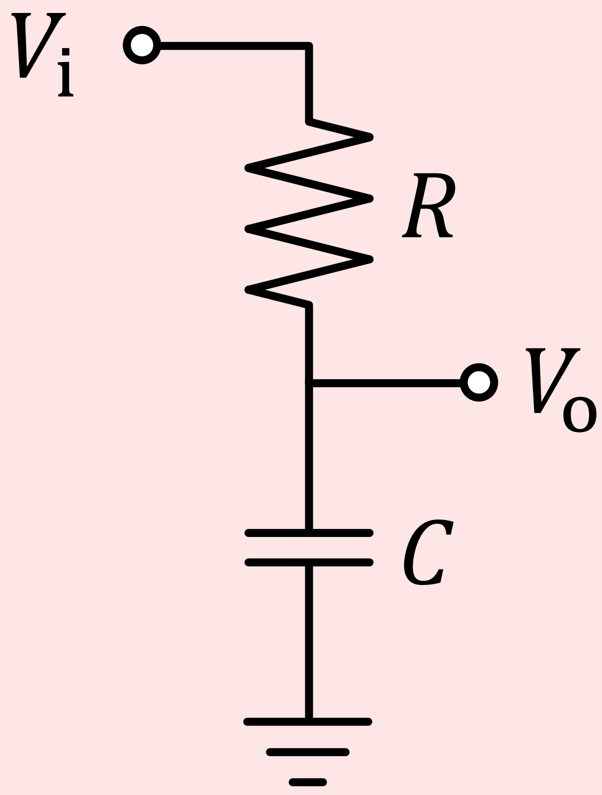


Current Divider: $\frac{I_o}{I_i} = \frac{R_2^{-1}}{R_1^{-1} + R_2^{-1}}$

Impedance of Passive Components

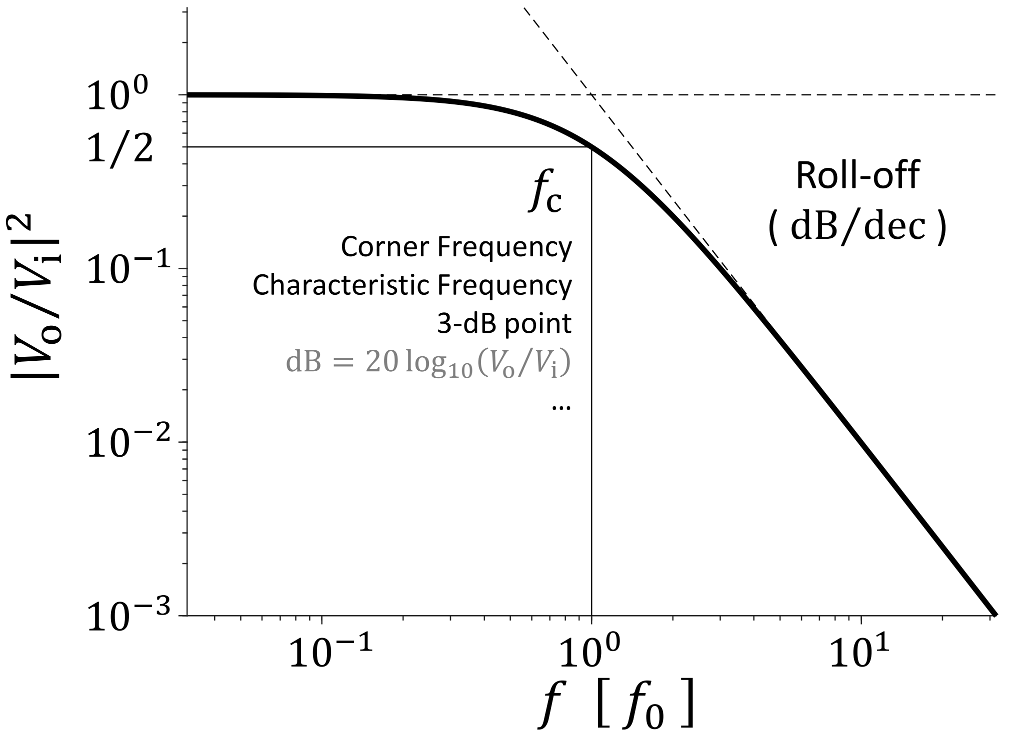
Component	Definition	$I(t) = I_0 \cos(\omega t)$	$V(t) = V_0 \exp(i\omega t)$ $I(t) = I_0 \exp(i\omega t)$	$V_0 = I_0 Z$
Resistor 	$V = IR$	$V = V_0 \cos(\omega t)$ $V_0 = I_0 R$	$V_0 = I_0 R$	$Z_R = R$
Capacitor 	$I = C\dot{V}$ $(Q = CV)$	$V = V_0 \sin(\omega t)$ $V_0 = I_0 \div (-\omega C)$	$V_0 = I_0 \div (i\omega C)$	$Z_C^{-1} = i\omega C$
Inductor 	$V = L\dot{I}$ $(\varepsilon = \dot{\Phi})$	$V = V_0 \sin(\omega t)$ $V_0 = I_0 \times (\omega L)$	$V_0 = I_0 \times (i\omega L)$	$Z_L = i\omega L$

Passive Filters

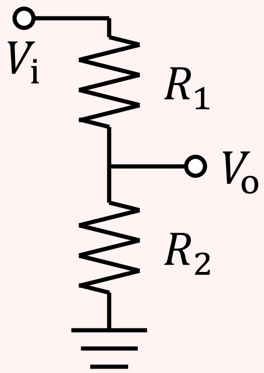


Voltage Divider: $\frac{V_\mathrm{o}}{V_\mathrm{i}} = \frac{Z_C}{Z_R + Z_C}$

$$\left|\frac{V_1}{V_0}\right|^2 = \left|\frac{Z_C}{Z_R + Z_C}\right|^2 = \left|\frac{1}{1 + \mathrm{i}\omega RC}\right|^2 = \frac{1}{1 + (f/f_0)^2}$$

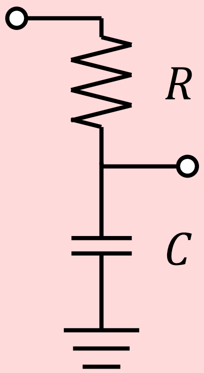


Passive Filters



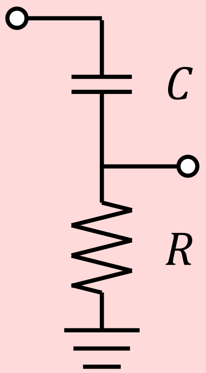
Voltage Divider

$$\frac{V_\mathrm{o}}{V_\mathrm{i}} = \frac{R_2}{R_1 + R_2}$$



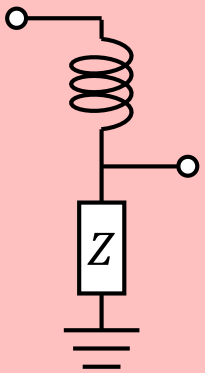
Lowpass RC Filter

$$\frac{V_\mathrm{o}}{V_\mathrm{i}} = \frac{Z_C}{R_1 + Z_C} = \frac{1}{1 + \mathrm{i}\omega RC}$$



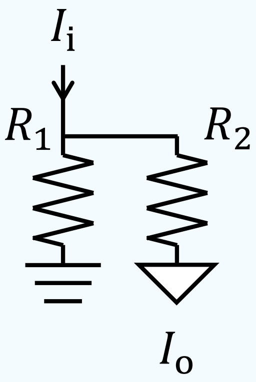
Highpass CR Filter

$$\frac{V_\mathrm{o}}{V_\mathrm{i}} = \frac{R}{R + Z_C} = \frac{1}{1 + 1/\mathrm{i}\omega RC}$$



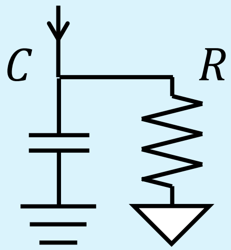
(Lowpass) L-Filter

$$\frac{V_\mathrm{o}}{V_\mathrm{i}} = \frac{Z}{Z + Z_L} = \frac{Z}{Z + \mathrm{i}\omega L}$$



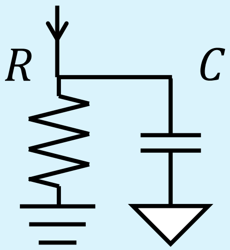
Current Divider

$$\frac{I_\mathrm{o}}{I_\mathrm{i}} = \frac{G_2}{G_1 + G_2} = \frac{R_1}{R_1 + R_2}$$



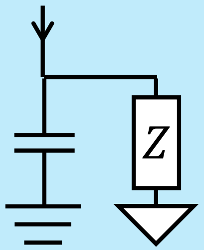
Lowpass RC Filter

$$\frac{I_\mathrm{o}}{I_\mathrm{i}} = \frac{Z_C}{Z_C + R} = \frac{1}{1 + \mathrm{i}\omega RC}$$



Highpass RC Filter

$$\frac{I_\mathrm{o}}{I_\mathrm{i}} = \frac{R}{R + Z_C} = \frac{1}{1 + 1/\mathrm{i}\omega RC}$$



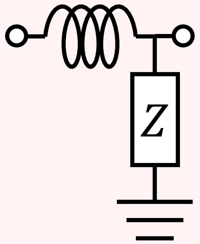
(Lowpass) C-Filter

$$\frac{I_\mathrm{o}}{I_\mathrm{i}} = \frac{Z_C}{Z_C + Z} = \frac{1}{1 + \mathrm{i}\omega ZC}$$

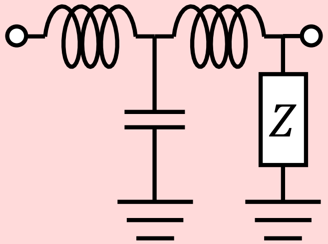
Synthetic Filters

"Voltage Filters" (Lowpass)

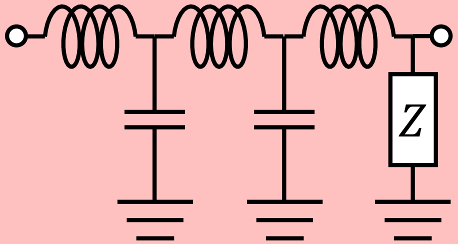
L-filter



T-filter



5th Order



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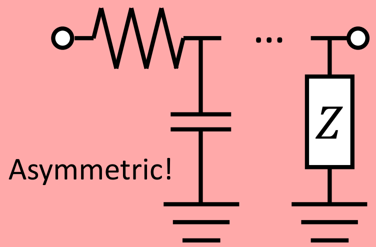
Poor man's R-based Filters

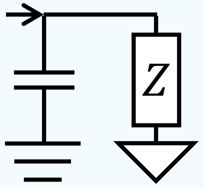
Cascaded RC filter
n-order '$\mathcal{V}$-filter'



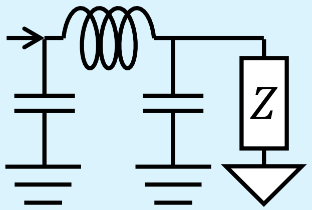
n-order/pole roll-off = 20*n dB/dec

"Current Filters" (Lowpass)

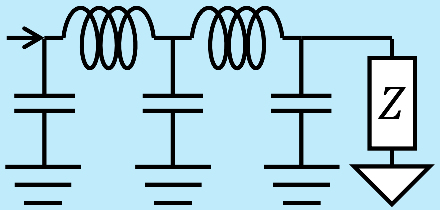
C-filter



Π-filter



5th Order



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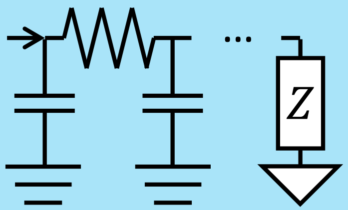
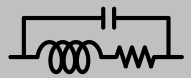
Cascaded π-filter
(n+1)-order '$\mathcal{I}$-filter'



Inductors & Ferrites

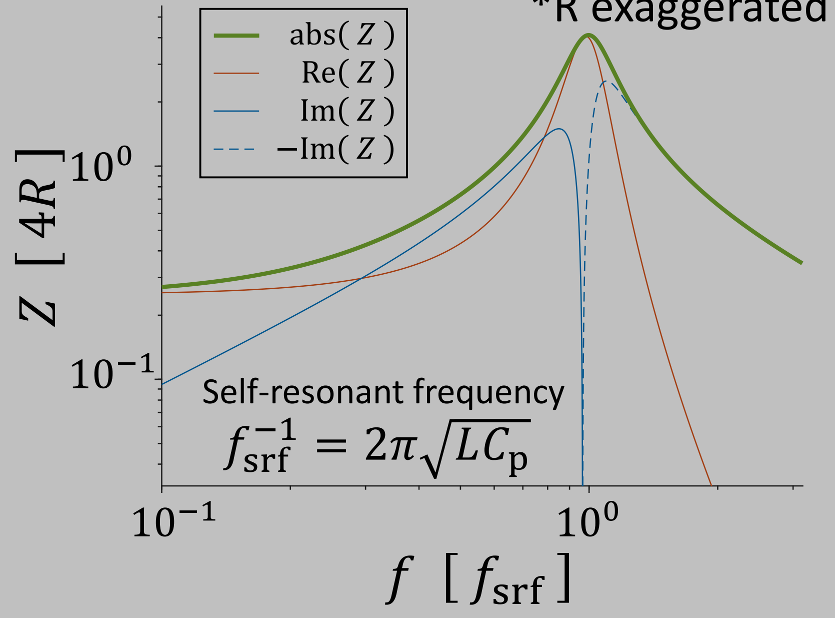
Inductor

Model



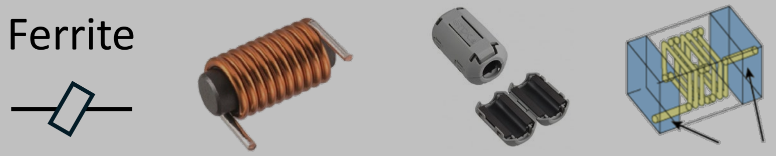
Resistance from wire ohmic
Capacitance from parasitics

*R exaggerated

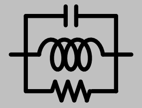


Low loss but small inductance

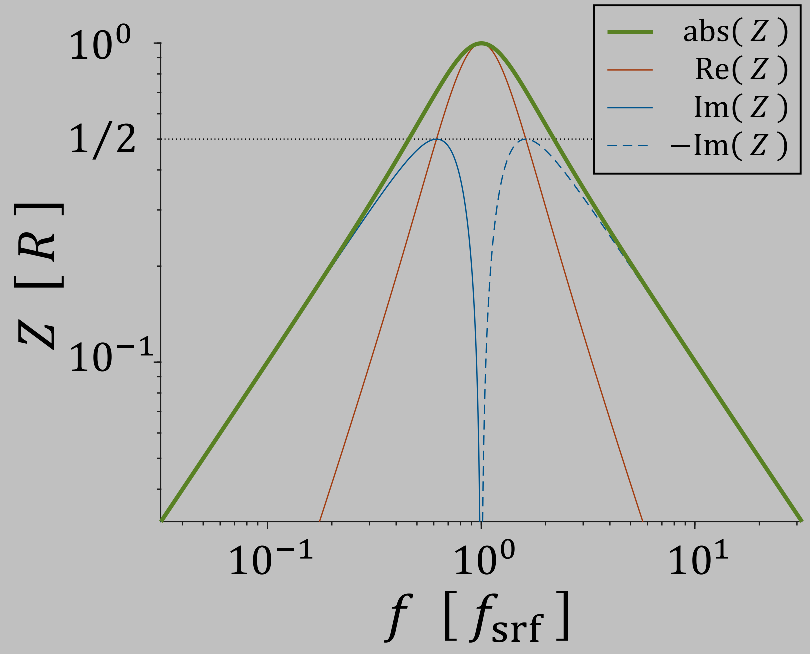
Ferrite



Model



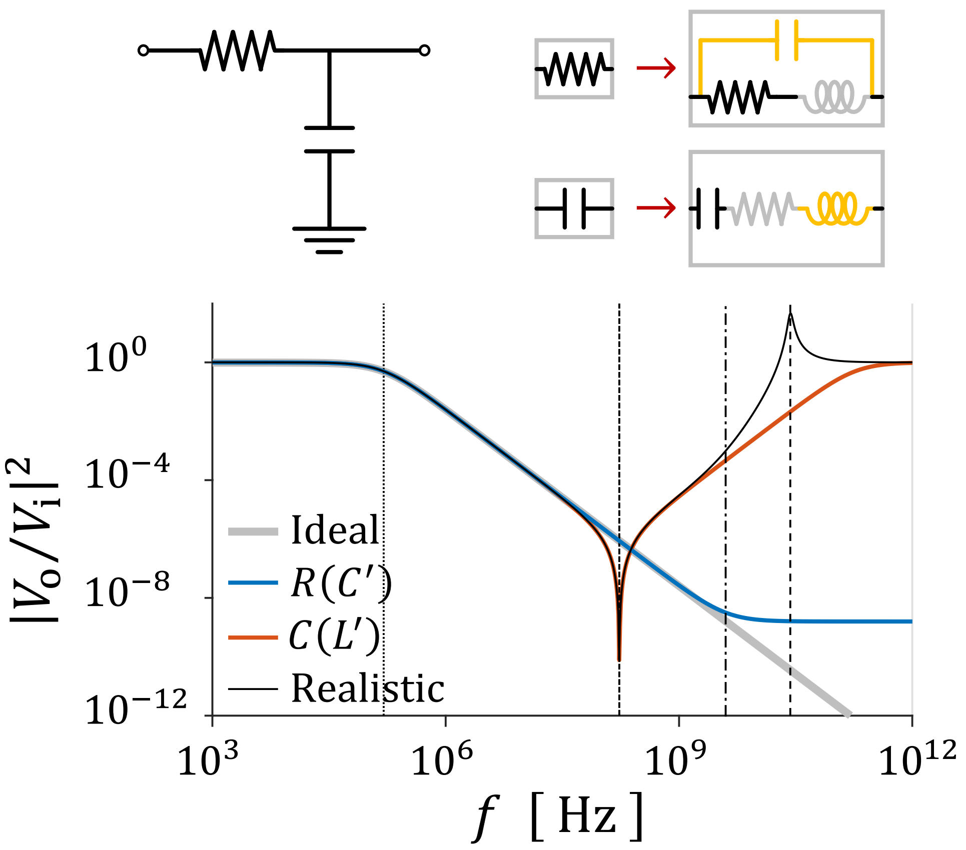
Resistance from ferrite loss
Capacitance from parasitics



Large inductance but low SRF

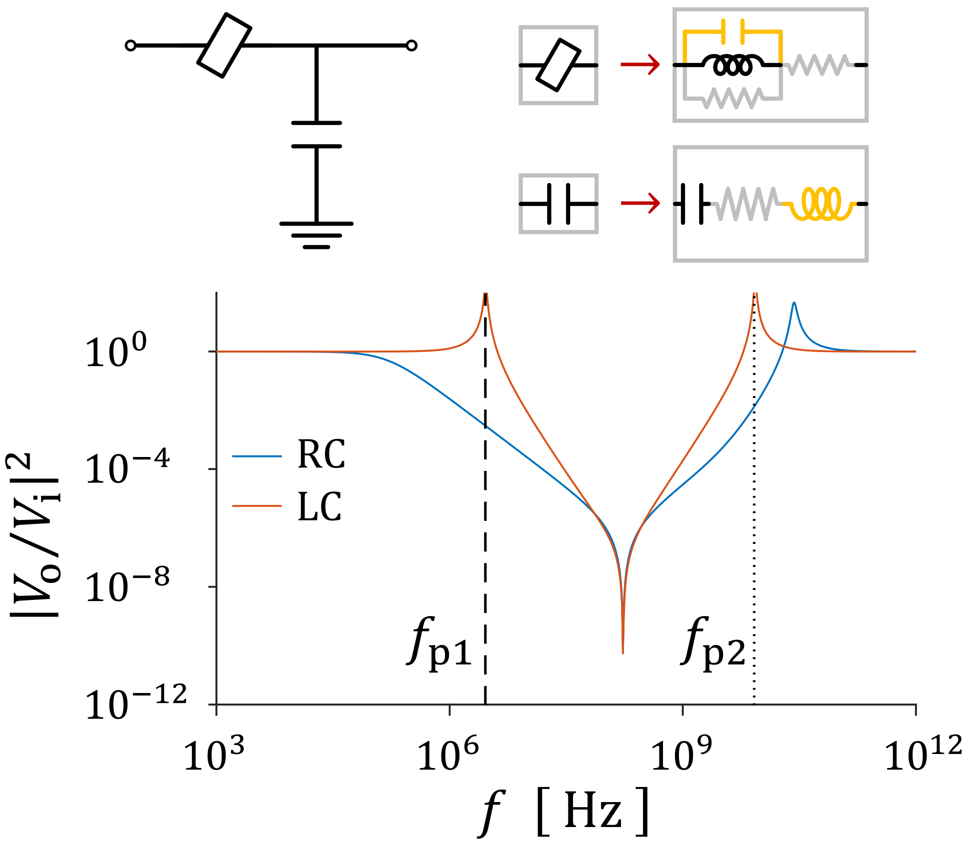
Parasitics

RC Filter

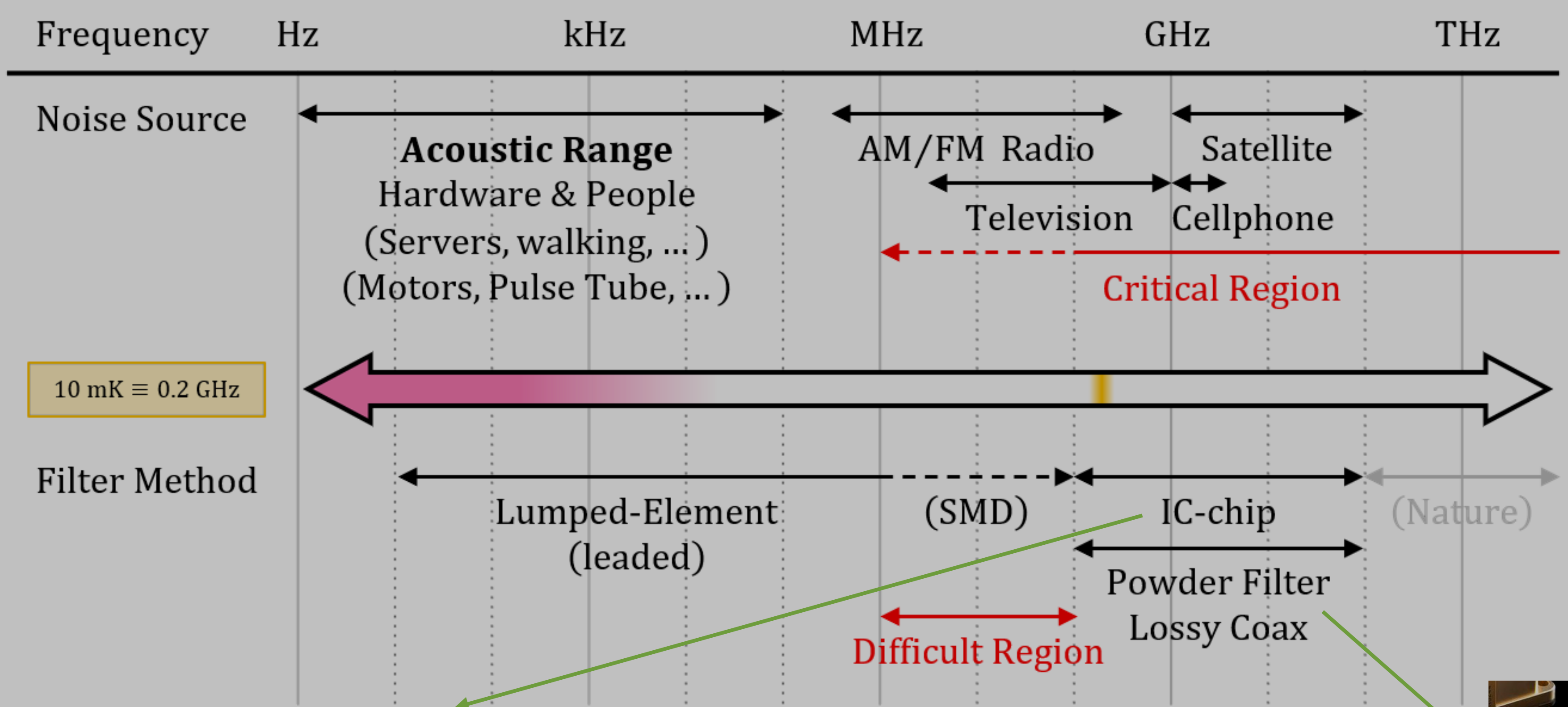


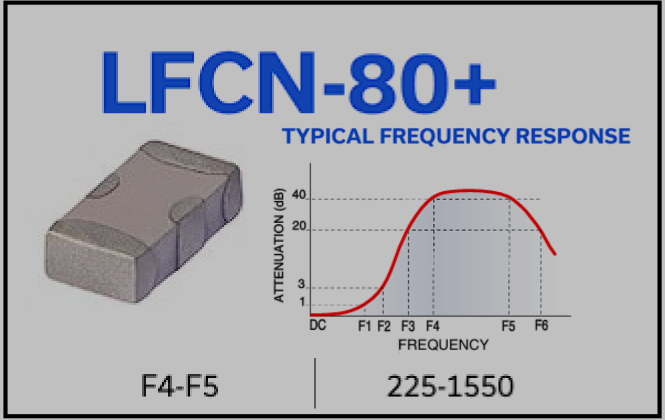
Parasitics must be mediated below 100 MHz
e.g. using smaller SMDs, or duplicate parts

LC Filter



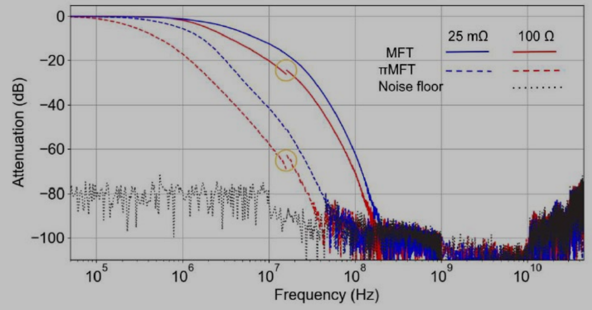
Peaking behavior must be mediated
e.g. damping resistance in serial

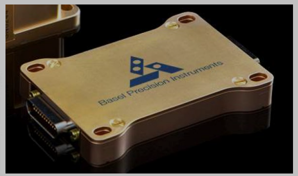




LFCN	F4/MHz	F5/MHz
80	225	1550
:	:	:
630	1020	3500

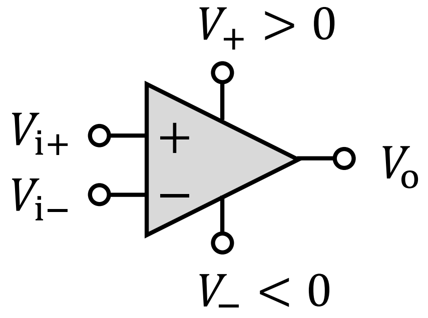
40dB rejection; often cascaded
for wider band rejection



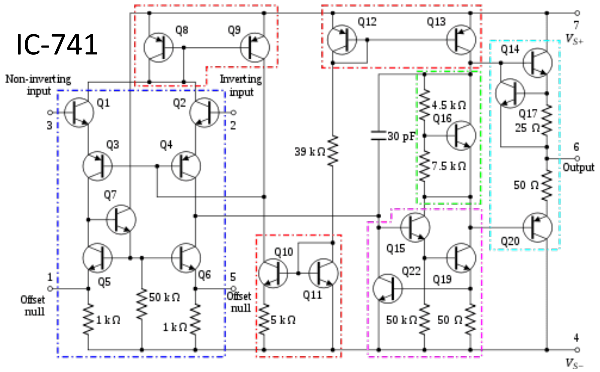


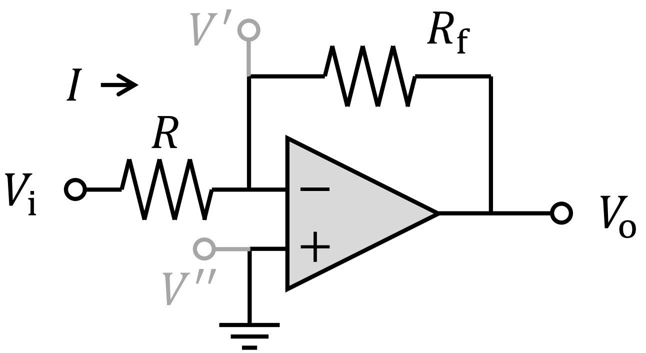
For filters,
Buy Basel

Operational Amplifier (Op-amp)



$$V_o = \begin{cases} V_+ , & V_{i+} > V_{i-} \\ V_- , & V_{i+} < V_{i-} \end{cases}$$





$$\begin{cases} V_i - V' = IR \\ V' - V_o = IR_f \end{cases}$$

Virtual Ground

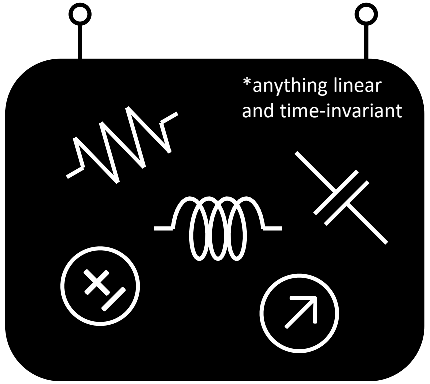
$V' = V'' = 0$

As a Voltage Amplifier: $\frac{V_i}{V_o} = -\frac{R}{R_f} < 0$

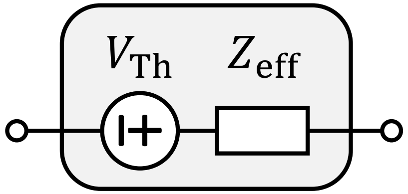
As a Current Amplifier: $V_o = -IR_f$

Generalized Amplifiers

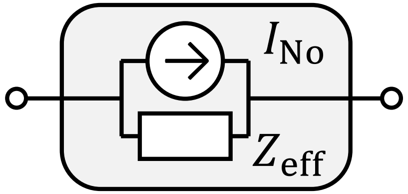
Thevenin-Norton Theorem

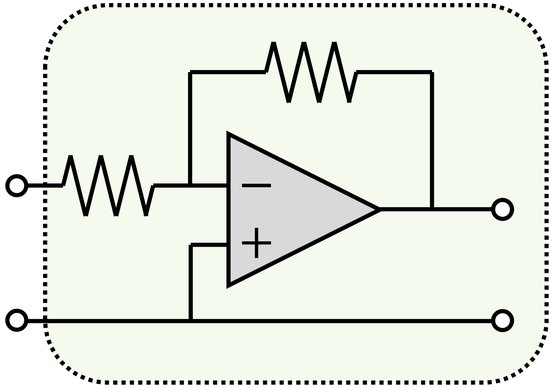


is equivalent to

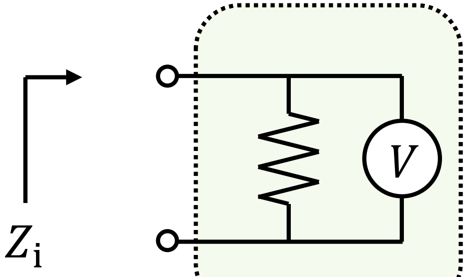


and

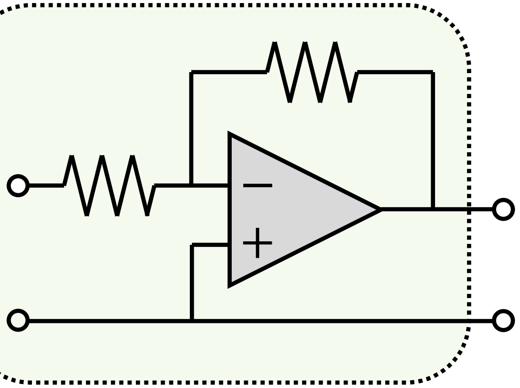




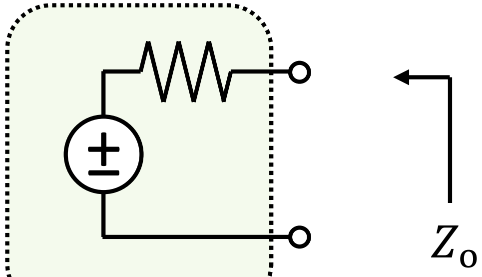
may as well be



Input Impedance

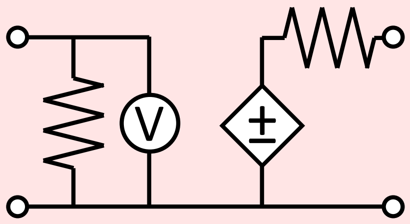
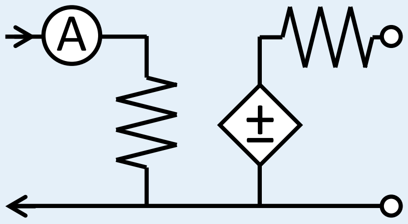
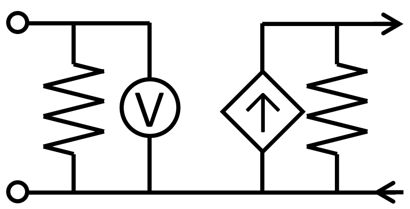
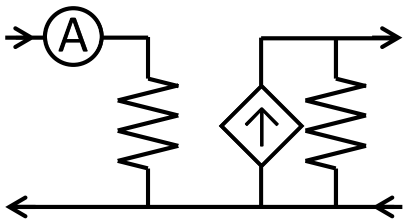


may as well be

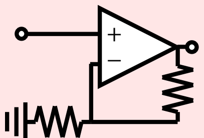


Output Impedance

Generalized Amplifiers

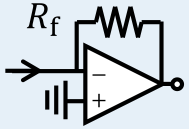
o\i	Voltage	Current
Voltage	Voltage Amplifier (VA) 	Transimpedance Amplifier (TIA) 
Current	Transconductance Amplifier (TCA) 	Current Amplifier (CA) 

(Non-inverting)
Voltage Amp



$$A \approx +\frac{R_\mathrm{f}}{R_\mathrm{A}}$$

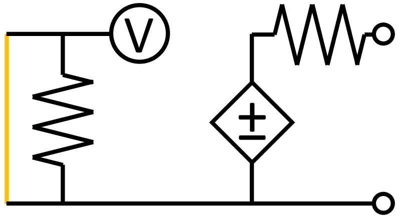
(Inverting)
"Current" Amp



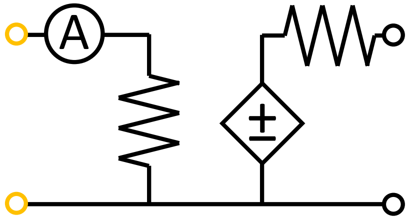
$$A = -R_\mathrm{f}$$

Input Referred Noise

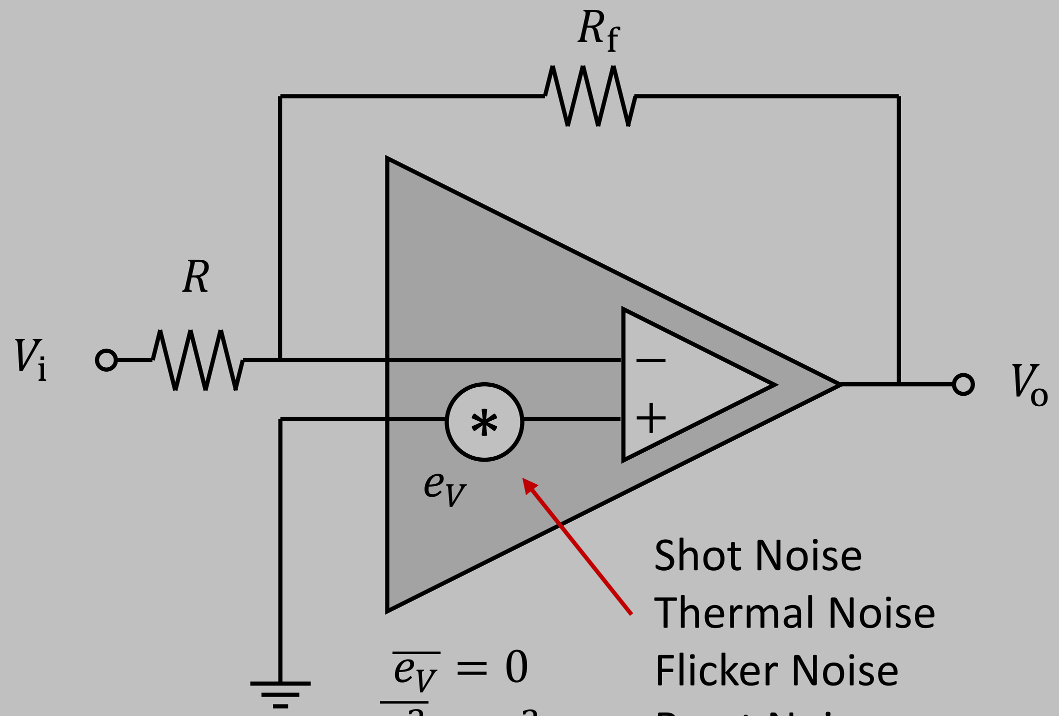
Voltage Amplifier (VA)



"Current" Amplifier (actually TIA)



Amplifier Noise Model

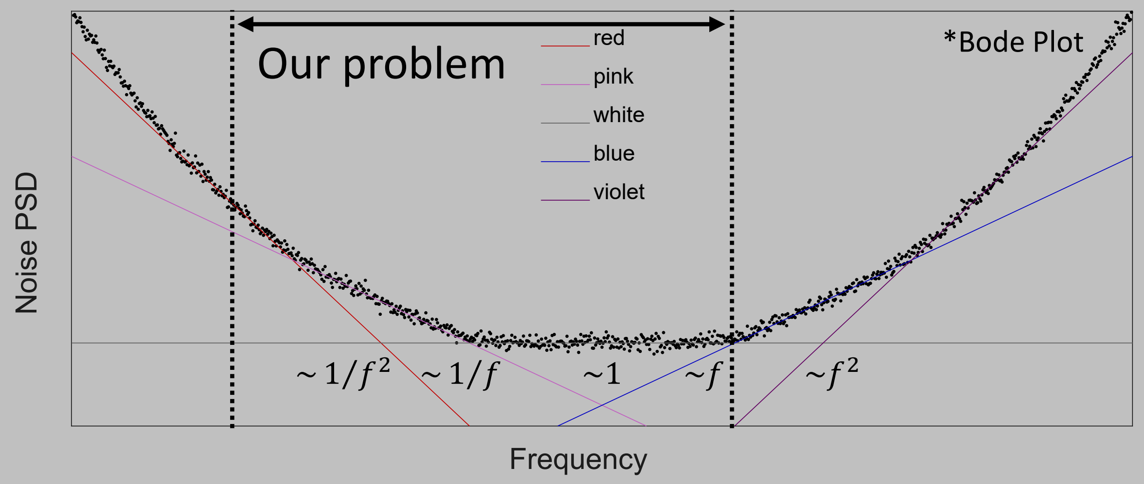


Shot Noise
Thermal Noise
Flicker Noise
Burst Noise
Avalanche noise

$\overline{e_V} = 0$

$\overline{e_V^2} = v^2$

$(e_V \to V_o)$ smaller for larger R



White:	Thermal, Shot
Pink:	Flicker
Red:	Brownian, ~Avalanche, ~Popcorn

Texas Instruments

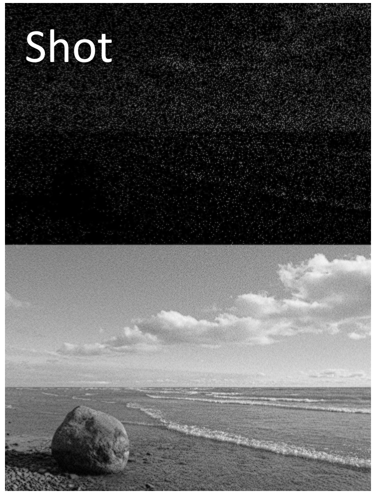
Op Amps For Everyone

Ron Mancini, Editor in Chief

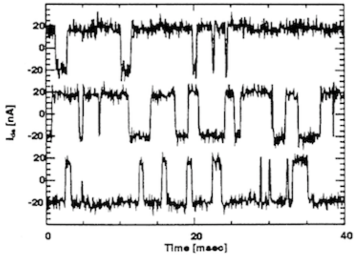
Noise & Interference

"Intrinsic" Noise

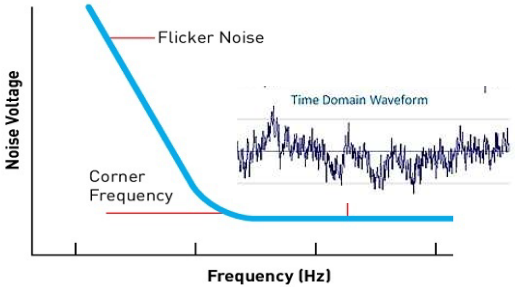
Thermal (Nyquist -Johnson)



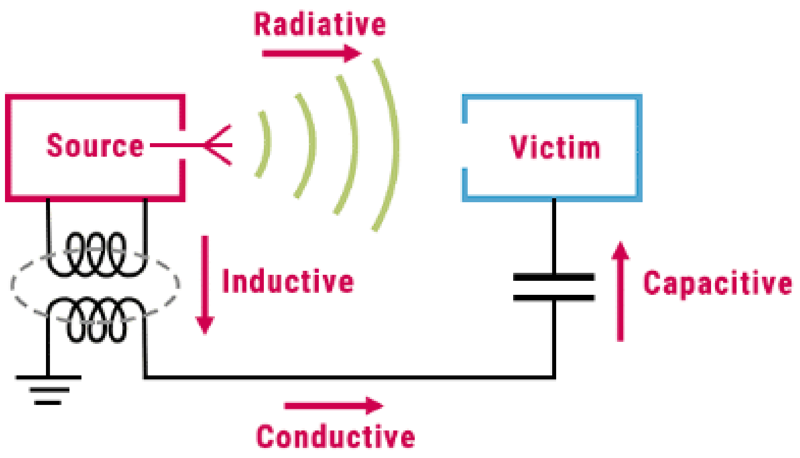
Burst (telegraph, popcorn)

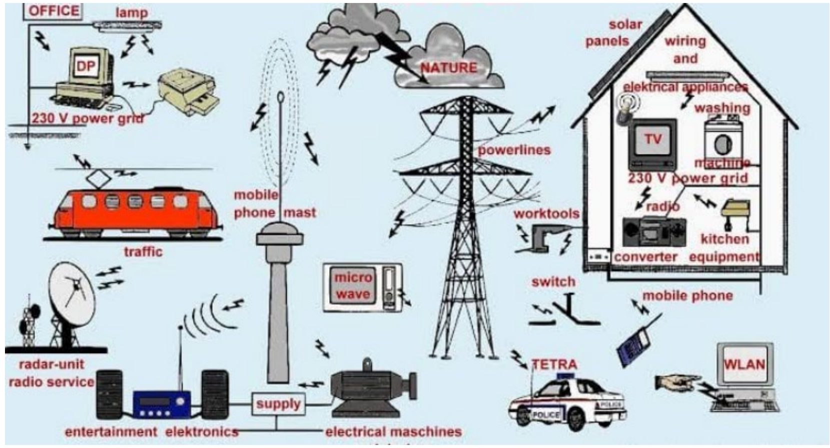


Flicker (1/f)

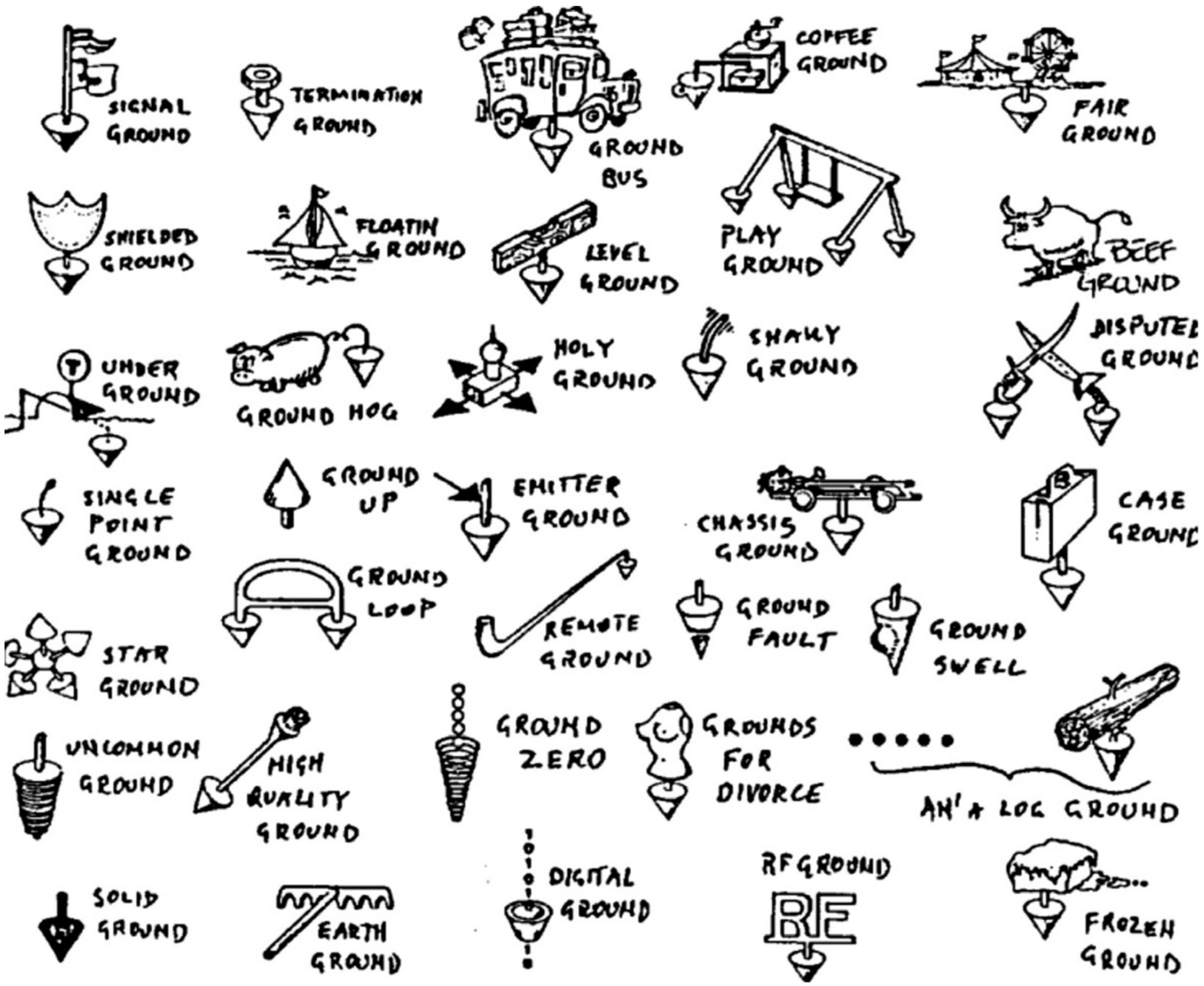


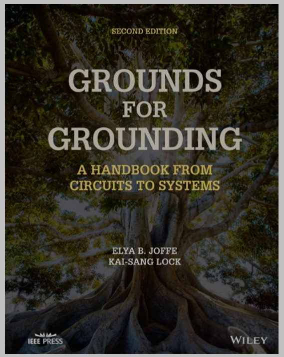
"Extrinsic" Noise
i.e. EMI





Ground? Earth?





> 150 p

3.1.4.1 Myth – Current Goes to Ground *147*
3.1.4.2 Myth – Grounding Brings Everything to Zero Potential, Reducing Touch and Step Voltage to a Safe Value *148*
3.1.4.3 Myth – To Be Safe, Add More Earth Electrodes *148*
3.1.4.4 Myth – Earth Electrodes Keep Us from Getting Shocked *149*
3.1.4.5 Myth – Transient Current in the Grounding Conductors May Introduce Errors in Data Transmission Between Interconnected Equipment *149*
3.1.4.6 Myth – Different Currents Should Flow Through Separate Paths *150*
3.1.4.7 Myth – Electricity (Only) Takes the Path of Least Resistance *151*
3.1.4.8 Myth – Common, Ground, and Neutral Are Equivalent *151*
3.1.4.9 Myth – It Is Advisable to Tie Neutral and Ground Together in Multiple Places *151*
3.1.4.10 Myth – Single Point Ground Is Necessary *151*
3.1.4.11 Myth – for the Sake of Best Equipment Performance, Safety Regulations May Be Compromised *151*

- Ground: A generic term to be avoided, unless used in conjunction with another term, such as "safety ground."
- Reference: A system of conductive paths among interconnected equipment that reduces noise-induced voltages to levels that minimize improper operation [1].
- Signal Return: A current-carrying path between a load and the signal source. It is the low side of the closed-loop energy-transfer circuit between a source–load pair [2].
- Earth: The conductive mass of earth, whose electric potential at any point is conventionally taken as equal to zero [3].

fog and to demystify its concepts. Experience plays a prime role in the final choice of the system's grounding topology. This experience is typically system-specific and is thus not generally transferable to the grounding methodology of another system, even if they employ similar electronic technologies and applications.

increased, leading to one of the greatest myths associated with grounding, namely the belief that a "good ground" was synonymous with good EMI control measures. It was assumed that a good earth connection is mandatory for achieving reliable

exists and a sufficient path exists, current will ultimately flow. Furthermore, ground connections are bidirectional and as current flows into it, it is expected to emerge from it elsewhere; similarly, noise generated somewhere else in the system could emerge from this ground connection. AC currents of course flow back and forth in their path; Ampere's law implies that in a

Obviously, what the system designer had in mind was that the equipment installed in the rack would benefit from isolation of a grounded bus bar from the "noisy" rack, believing that in this manner a "quiet," interference-free grounding system would be maintained. This designer's conviction could not be further from the truth.

A single point ground that is effective over a large area is not possible.

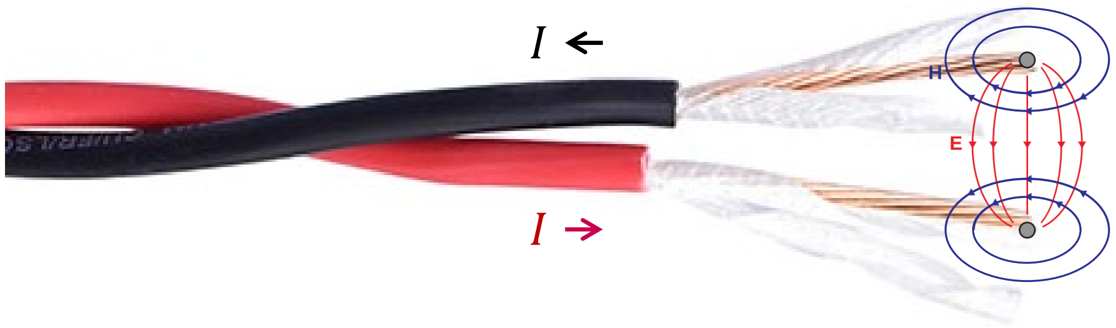
A common mistake by designers and installers is to have the bonding network connected to the facility steel at few (e.g. two or three) points only. The connection should be made to an earth return either at a single point, or at as many points as possible.

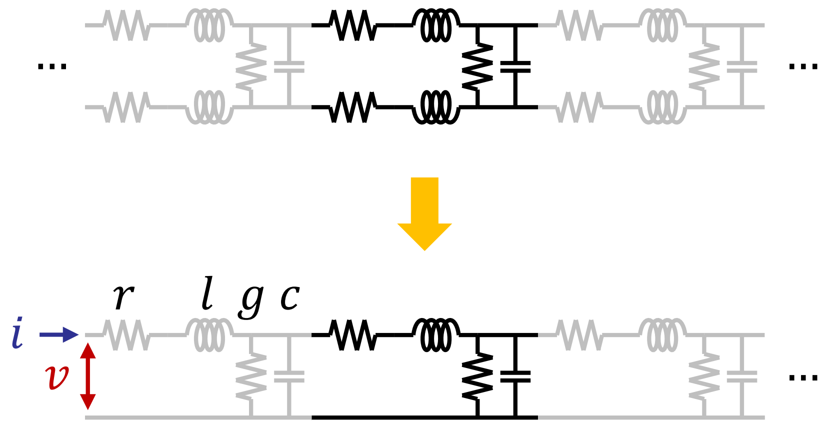
ing system design could, therefore, be stated as follows: "Design the system such that *in spite of the need for grounding*, system performance will not be degraded due to ground-coupled interference."

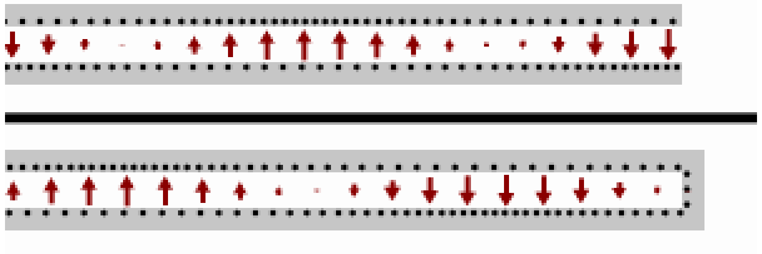
cessing, and high-speed digital circuits, single-point in assemblies processing audio signals). Interconnections between different assemblies should be accomplished by use of appropriate electrical conductors (e.g. coaxial cables for RF and IF signals, and

The earth can be an exceptionally poor conductor. The purpose of earth electrodes is to divert large current transients and surges propagating down the electrical power distribution network away from the building. With the nonzero impedance (ran-

Impedance in Distributed Circuits







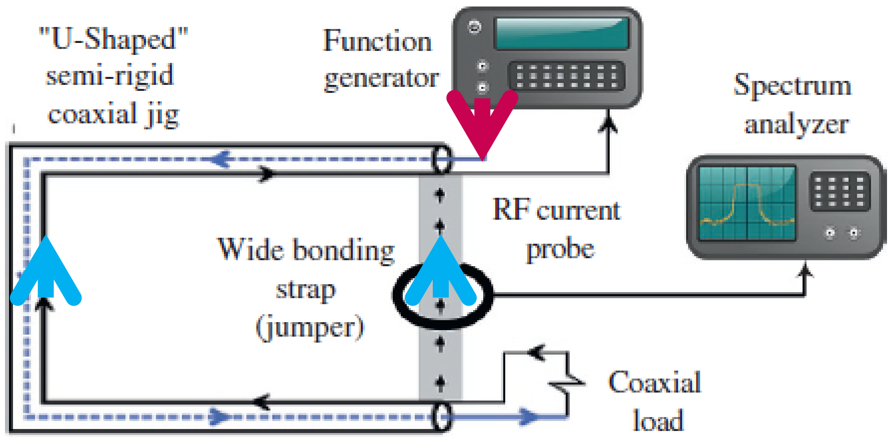
$$[\partial^2 - k^2]\begin{pmatrix} v \\ i \end{pmatrix} = 0$$

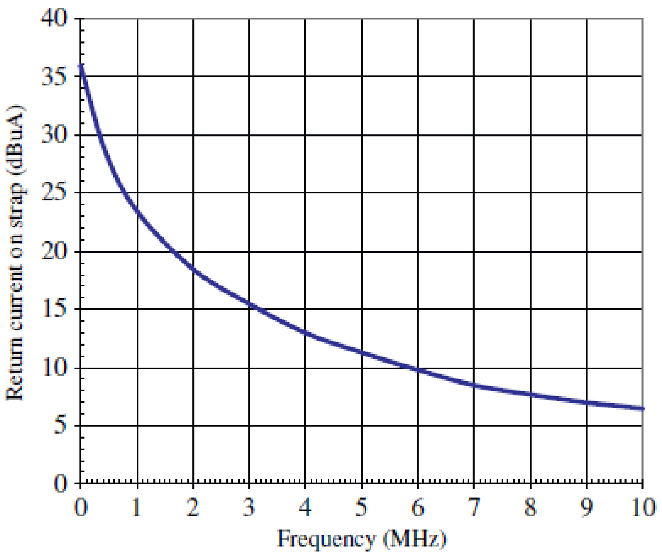
$$\begin{cases} k = \sqrt{(r + i\omega l)\ (g + i\omega c)} \\ Z = \sqrt{(r + i\omega l)/(g + i\omega c)} \end{cases}$$

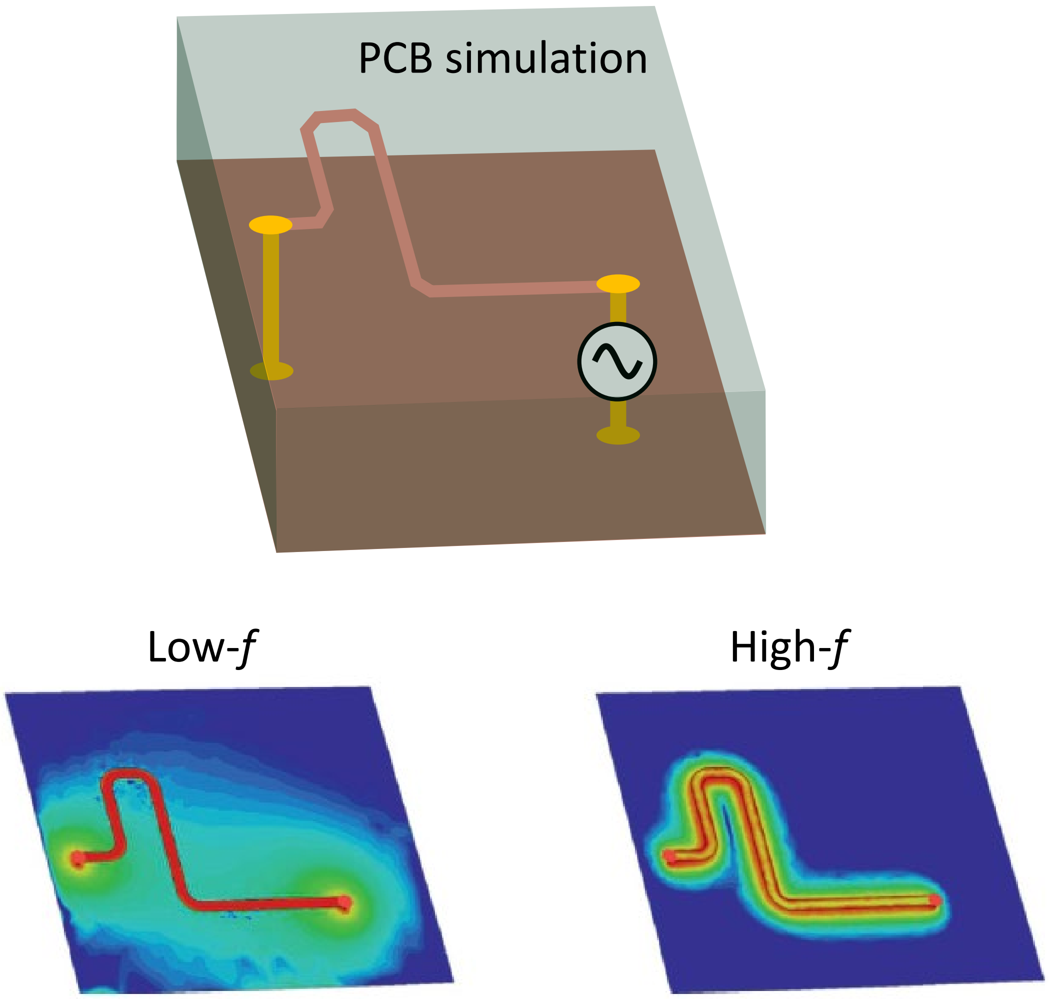
$$I_\parallel = \oint d\vec{l} \cdot \vec{H}, \qquad V_\perp = \int d\vec{l} \cdot \vec{E}, \qquad Z_{\mathrm{RF}} = \frac{V_\perp}{I_\parallel}$$

- Return current minimizes (RF)-impedance
- $V_\parallel = \int d\vec{l} \cdot (\rho\vec{J})$ is NOT zero

Ground = Current Return Path



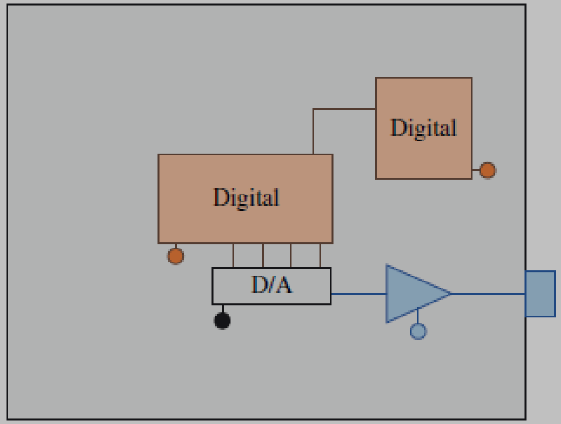




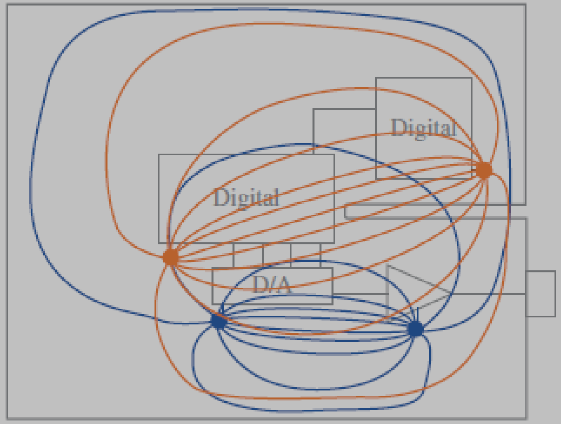
(a)

(b)

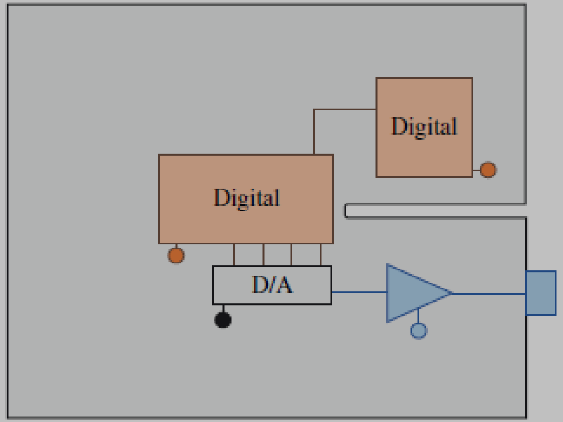
RF-PCB examples



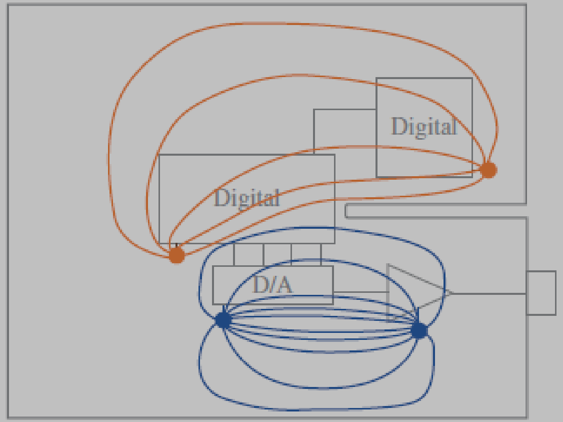
(a)



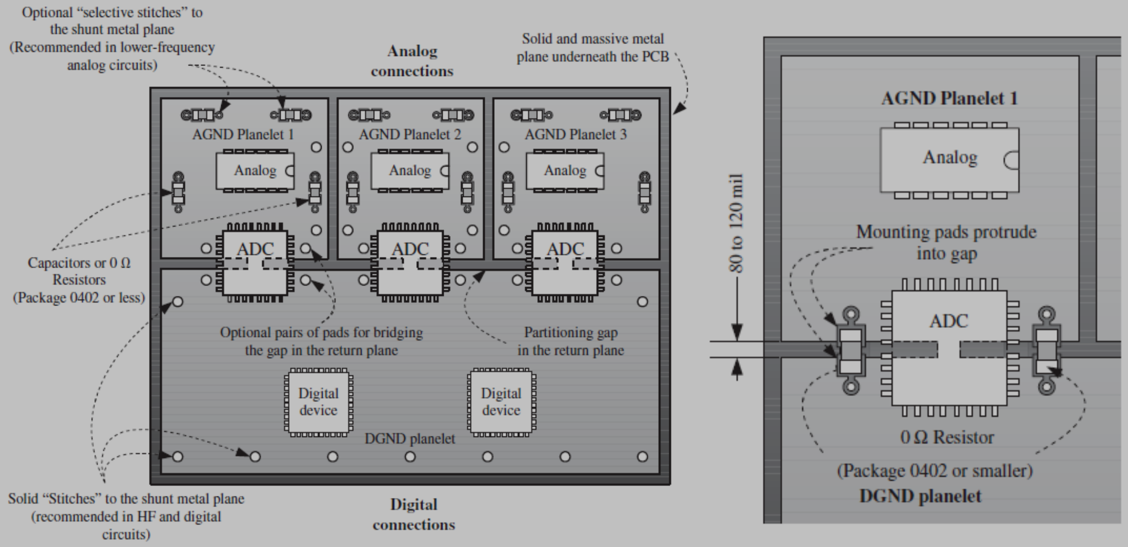
(b)

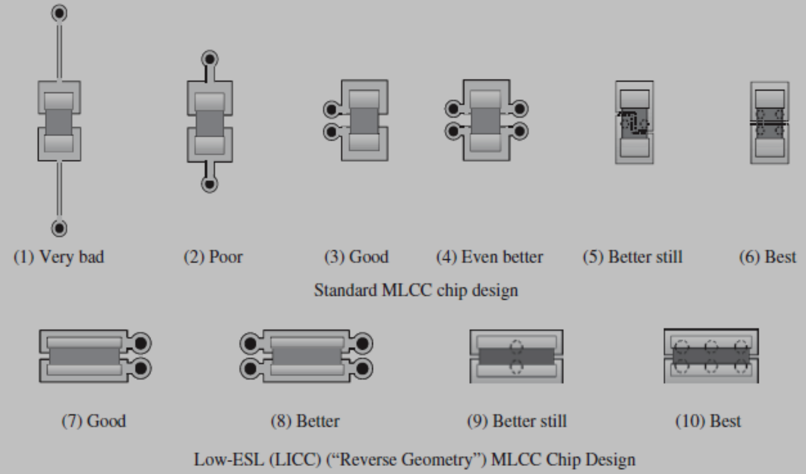


(a)

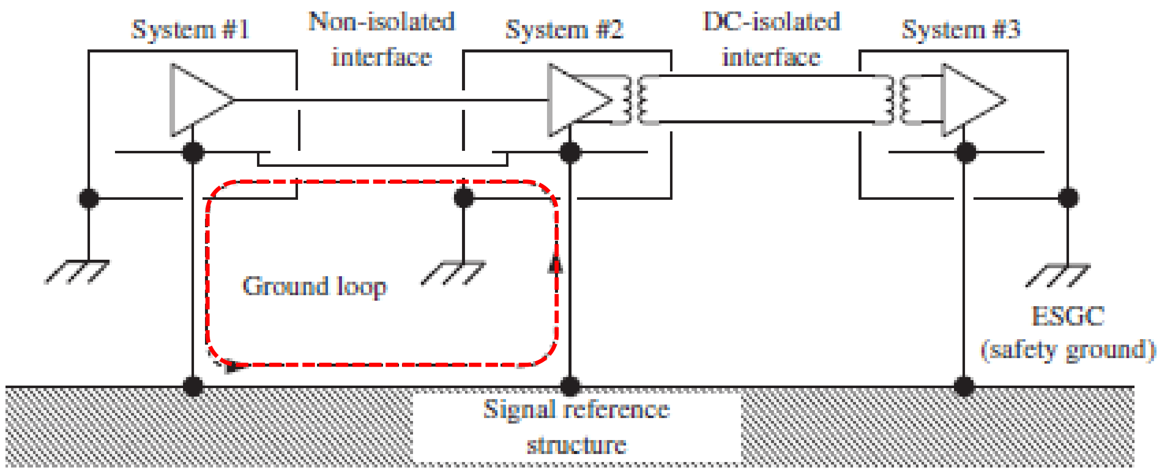


(b)

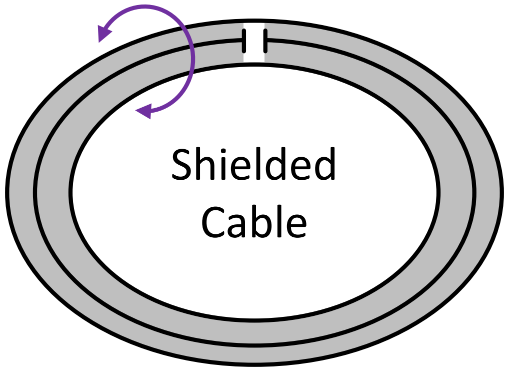




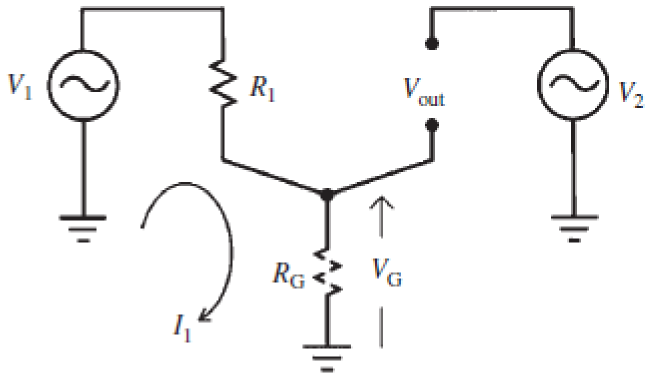
Problem 1: Ground Loops



$\mathcal{B} \rightarrow$ EMF



AC loop is still a loop
Also, hot loops too



EMF has to drop *somewhere*

- Solution 1: find the loops

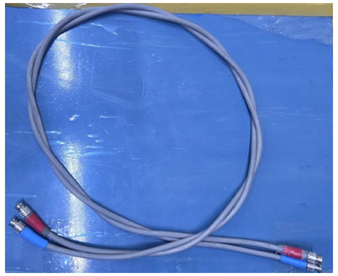
- Solution 2: use isolators for comms

USB Isolator: LTP2884

Ethernet Isolator: EverStar MI-300

GPIB Isolator: GPIB 120-A

- Solution 3: make loops small



Problem 2: Bad Cabling

Common impedance coupling

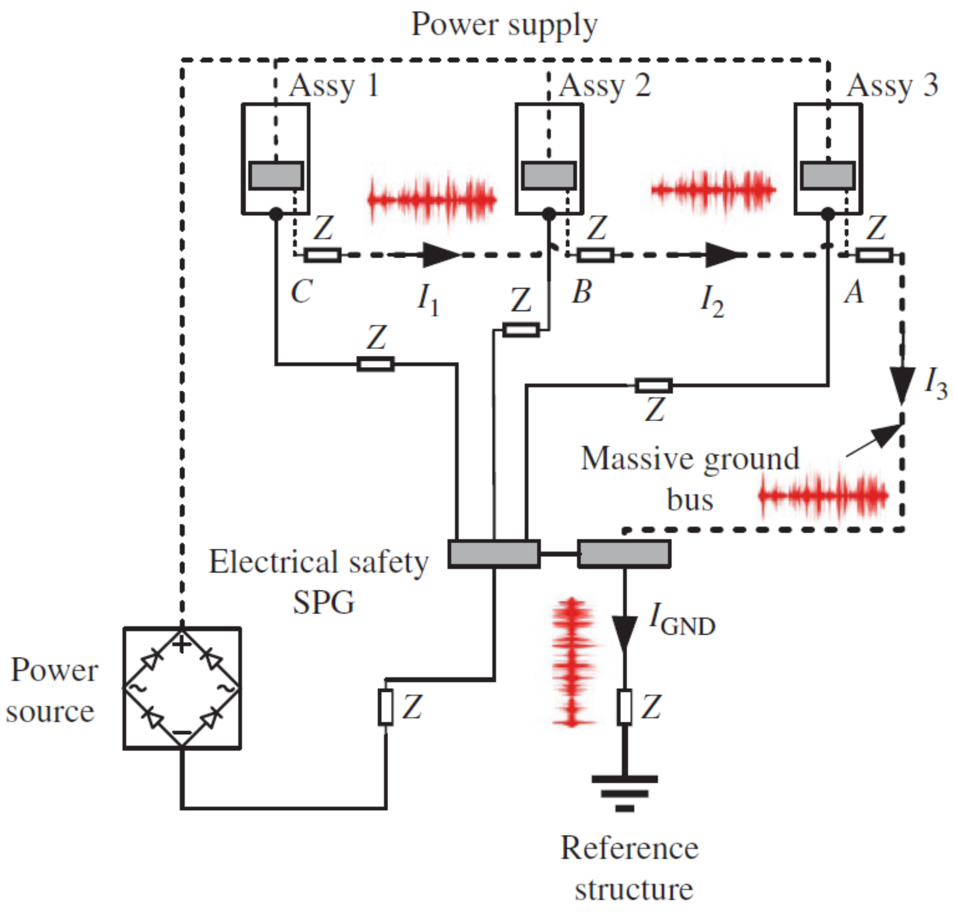
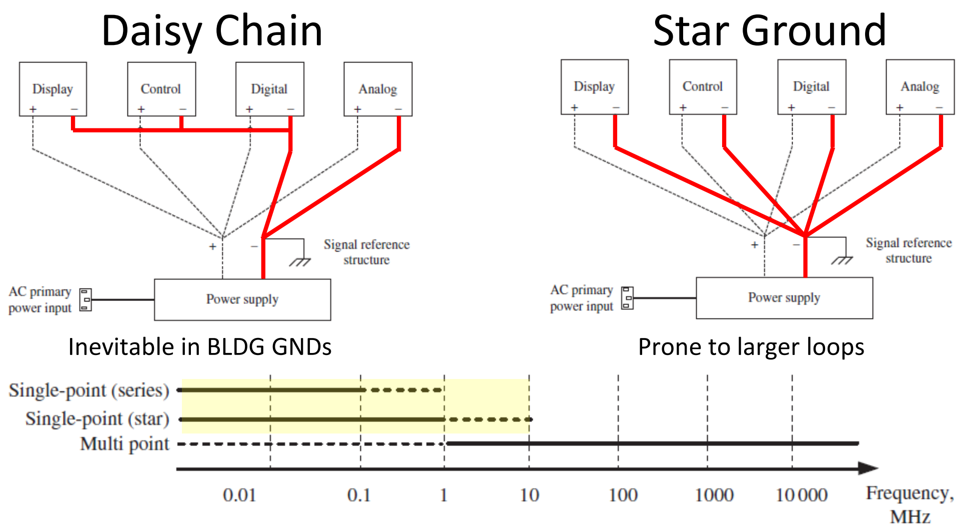
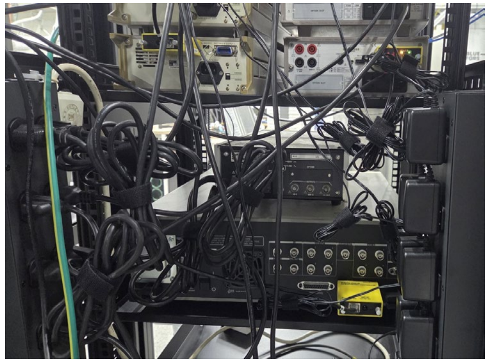


Figure 4.30 Common impedance coupling is not eliminated in the "daisy chain" (series connection) single-point grounding scheme.

- Solution 1: One Star ground for one system



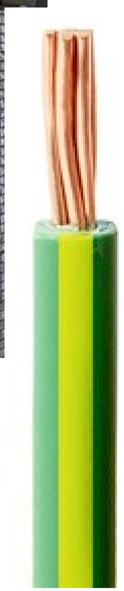
- Solution 2: Just… clean up



Problem 3: Bad Connections

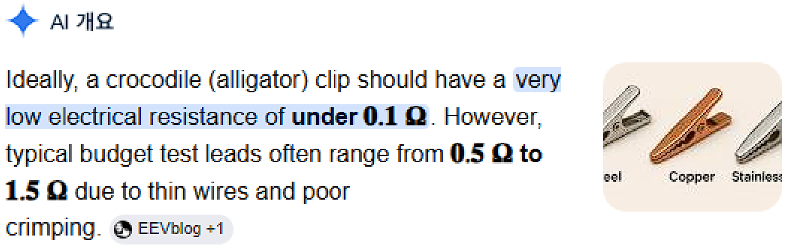
Anodized areas = bad conduction

Not enough



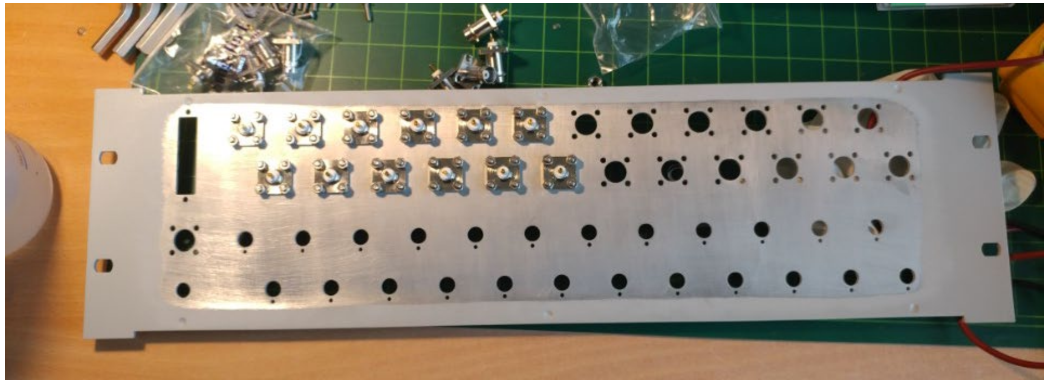
Too thick

Alligators and bananas are weak

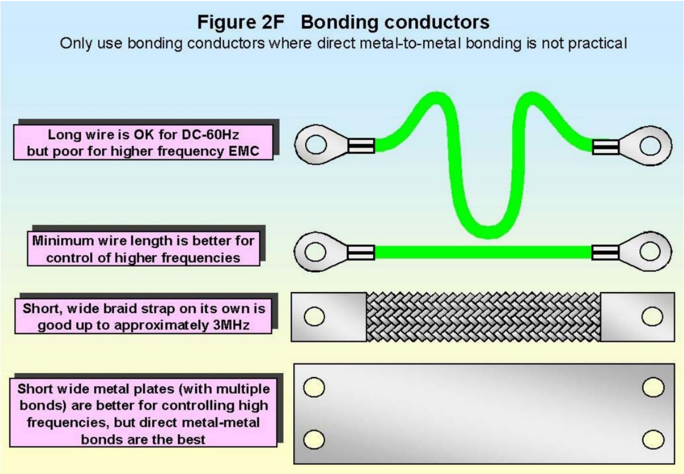


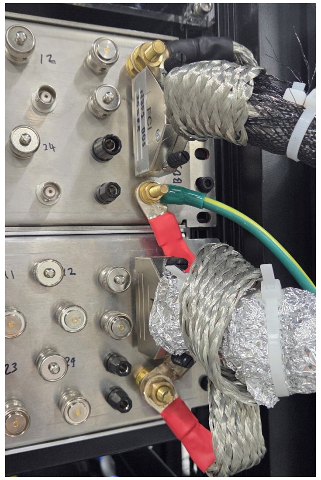
Resistance between grounds are competitions in **mΩ** ranges!!!

- Solution 1: Sand away anodizations

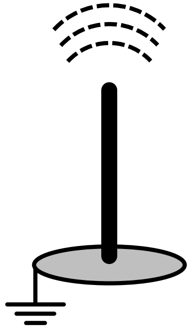


- Solution 2: Use thick braids and strong bolts!





Problem 4: Antenna



Shortest Antenna
= Quarter-wave

1 GHz = 30 cm
Lumped if < 3 cm

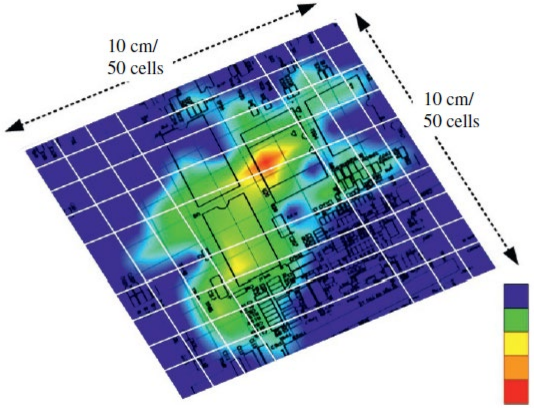
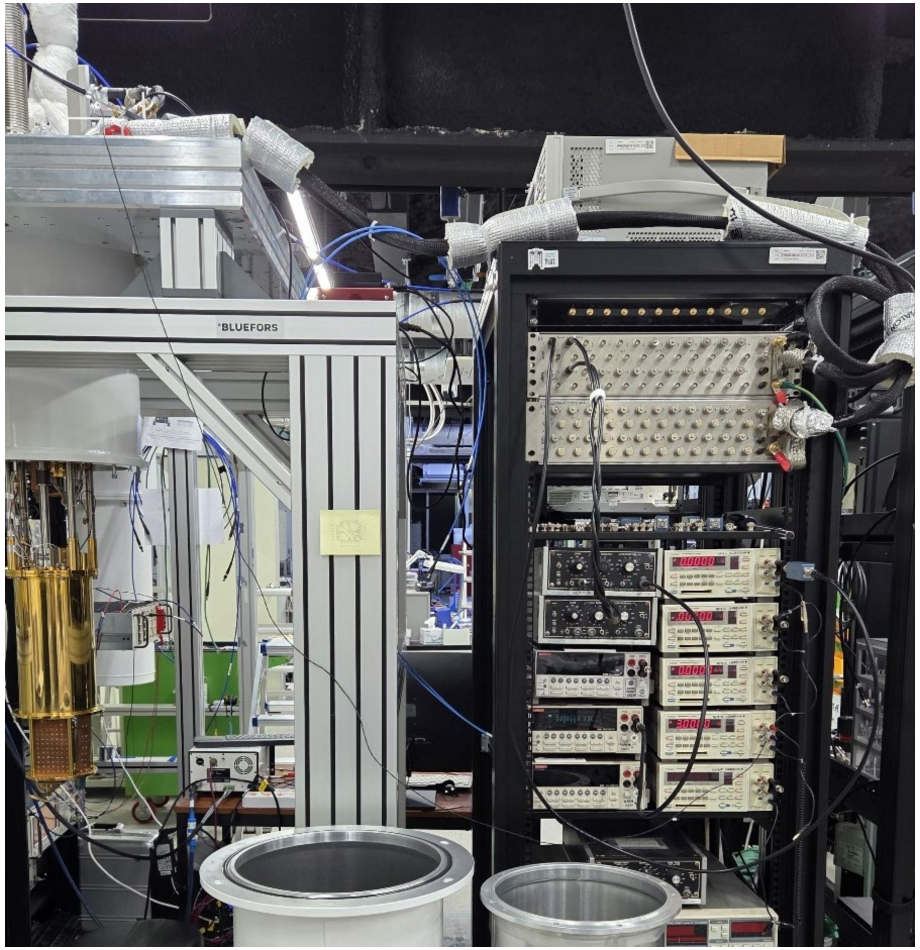


Figure 13.170 Illustration of the manner of peak noise voltage distribution throughout the 2500 meshed circuit nodes across the power and return planes.

Equipotentials in 'Perfect' Grounds extend $< \lambda/10$

- Solution: Compactify your setup (short cables)



Problem 5: Bad Neighbors

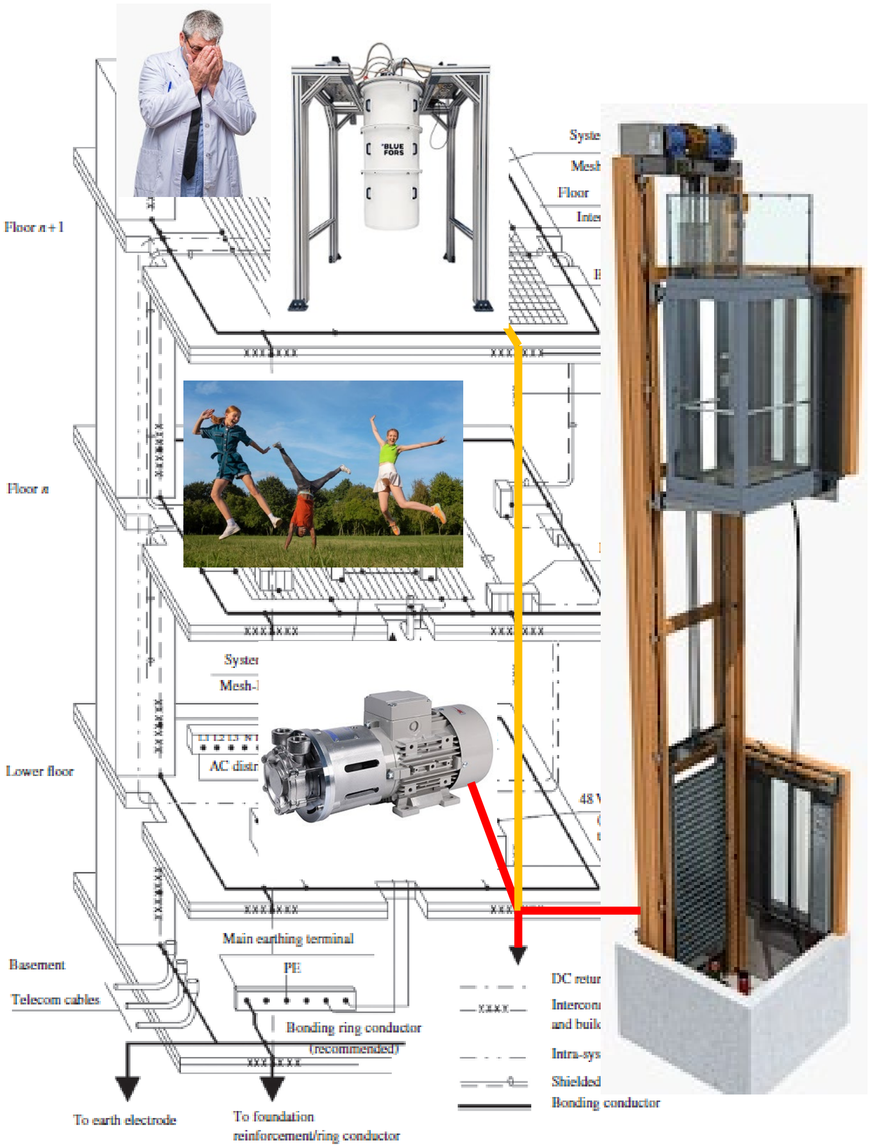
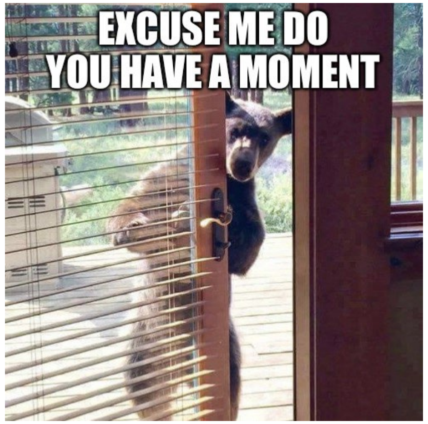


Figure 4.17 Mesh-bonding network installation inside a telecommunication building [3, 4]. *Source:* ITU-T

- Solution 1: Find the perpetrator



Do you have any of the following?

Pumps with faulty insulation; computers connected to the clean ground; fans that are not grounded; incredibly huge ground loops by freshman who is powering their system using outlets across the room; sentient outlets that spark when no one's looking; personal elevators; personal satellite dishes and satellite systems; anything that gives off a lot of EM waves; an idiot who mixed neutral and ground; ninjas touching my experimental setup; Zeus shooting thunder…

Not being crazy, just wondering...

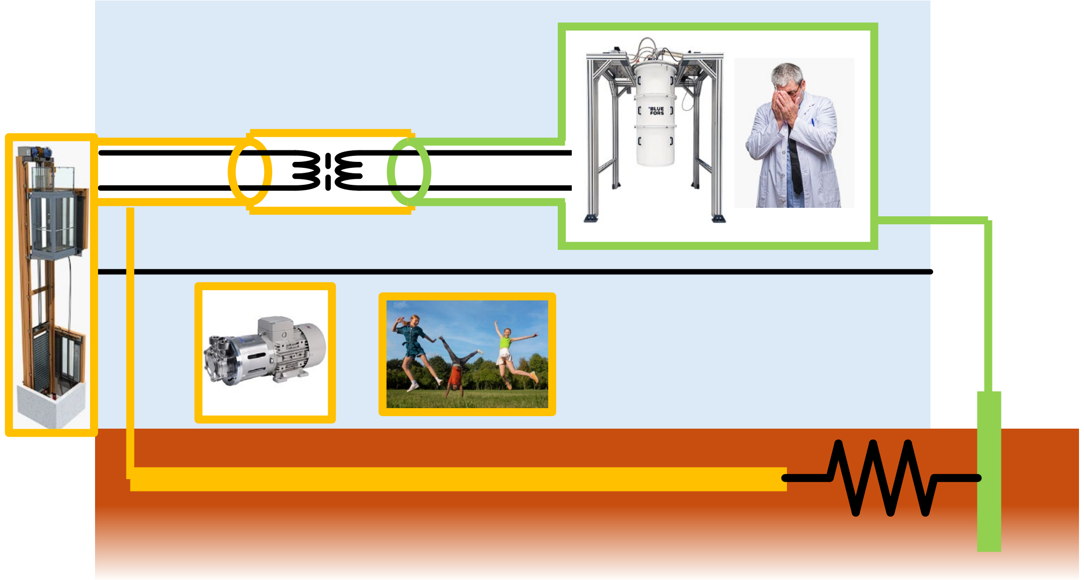
- Solution 2: Isolate & Filter power & use Earth

Isolator AVR : Powertek IT-3000

Power Filter: FN9246-10-06

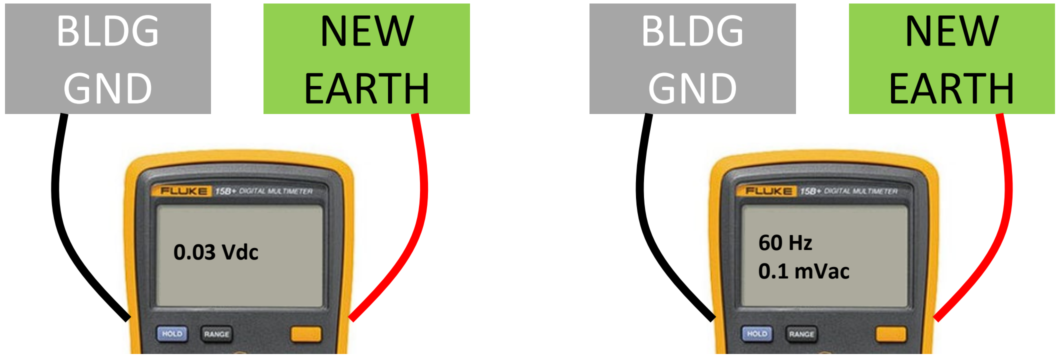
New Earth

Earth “Ground”



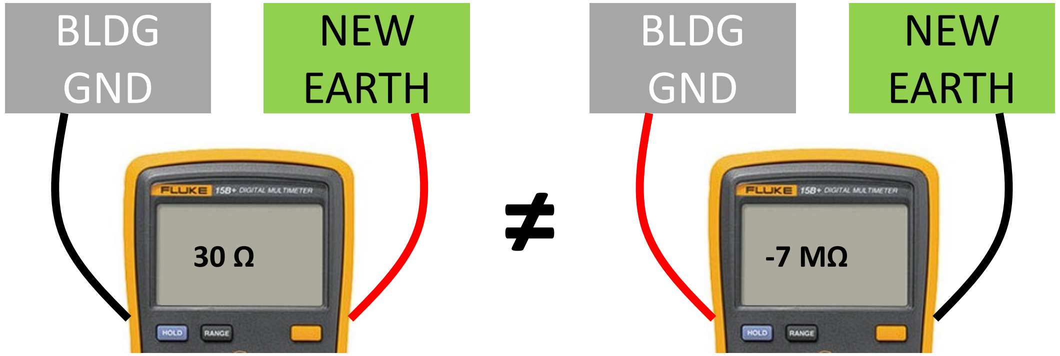
Earth is a **VERY bad** conductor
Soil : Copper = Glass : Soil

- App note: How to check Earth isolation



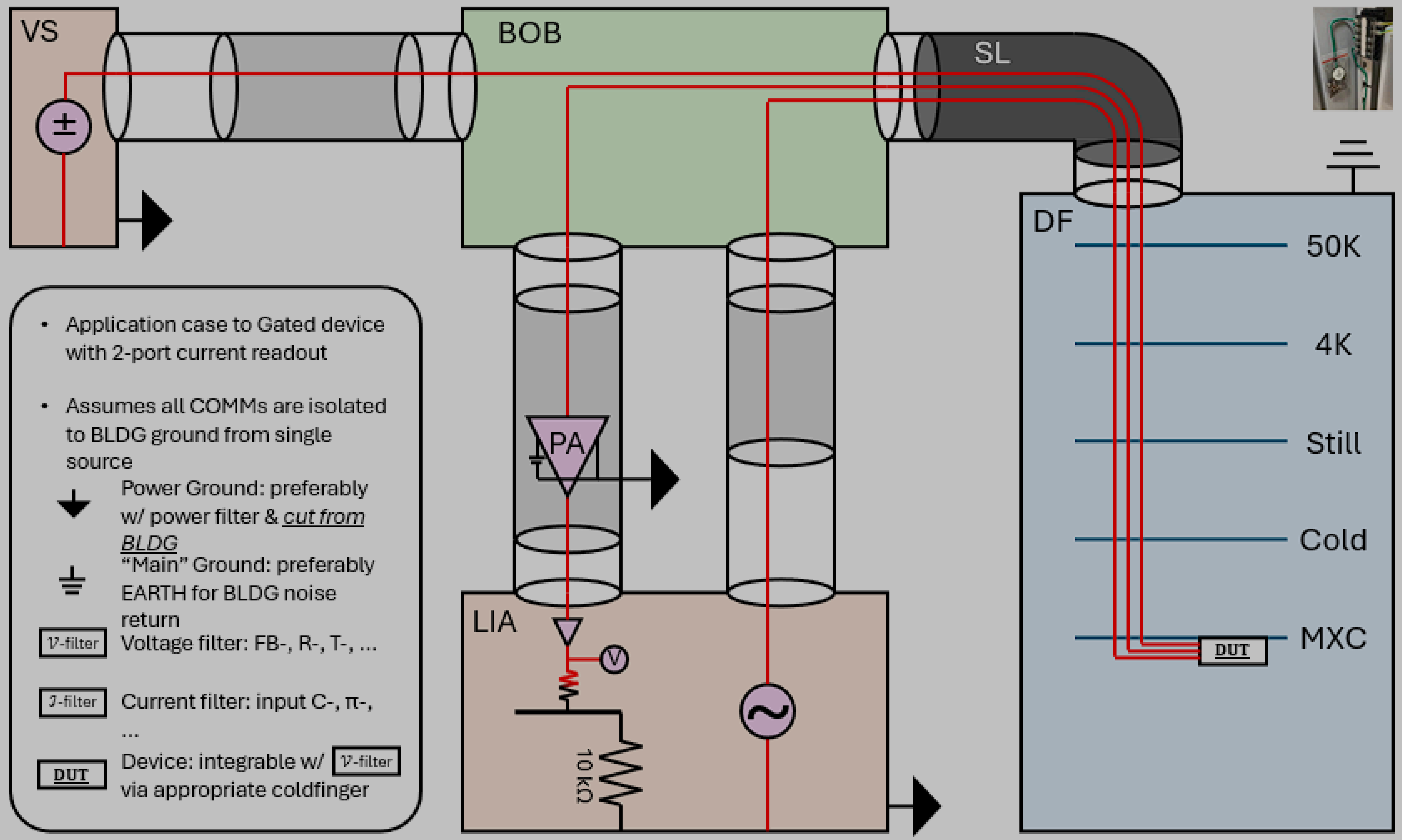
Non-zero DC voltage

Mainly 60 Hz, small AC

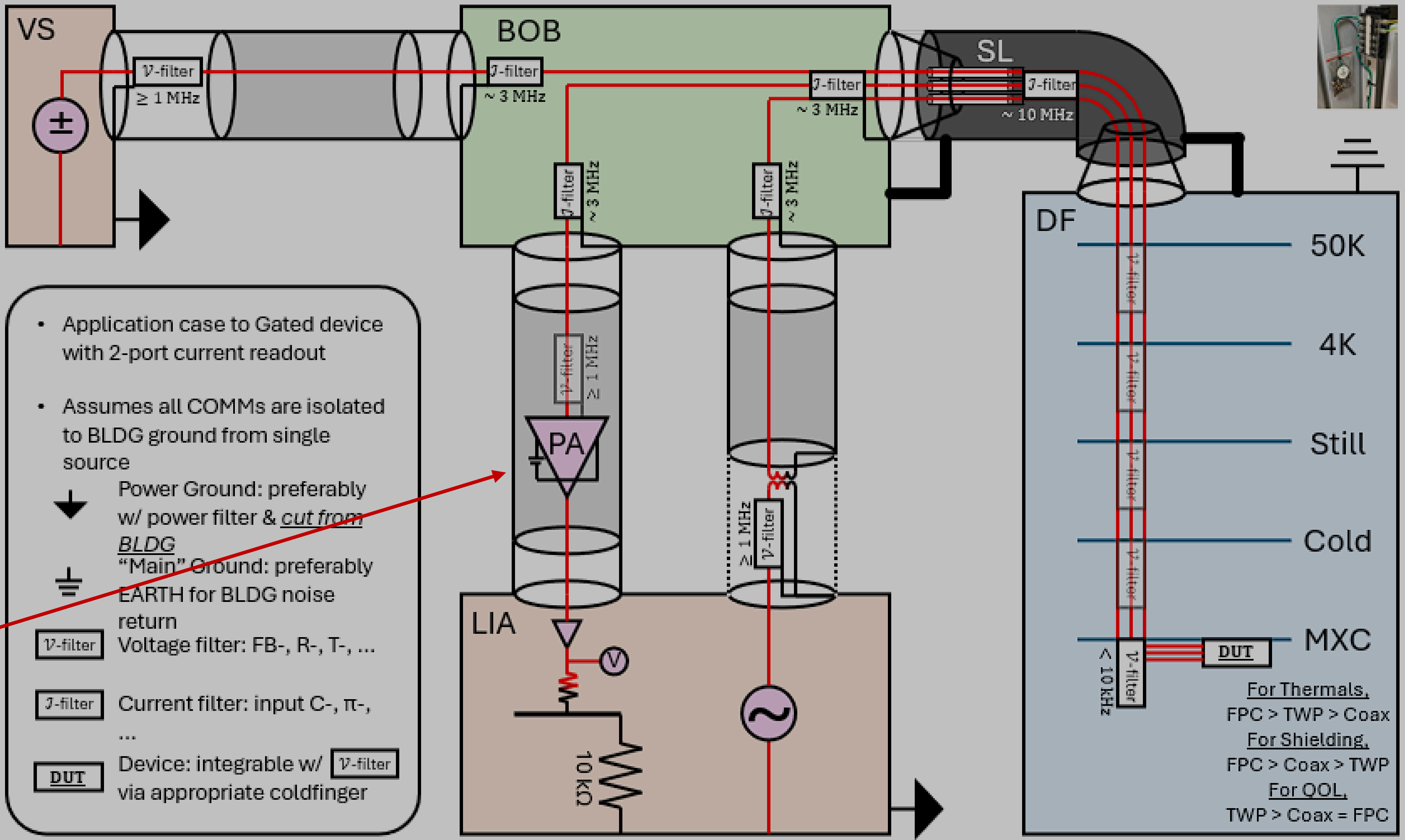


If Vdc ≠0, then these two should different
You can get “negative” resistance readings…

Example: Before & After



Example: Before & After

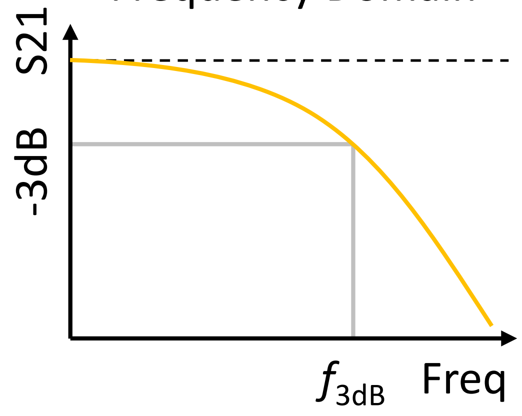


Note: the pre-amp is always most susceptible to noise pick-up!

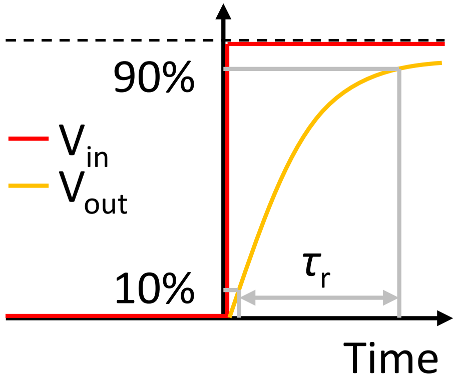
Using Voltmeters

Lowpass-filtering

Frequency Domain

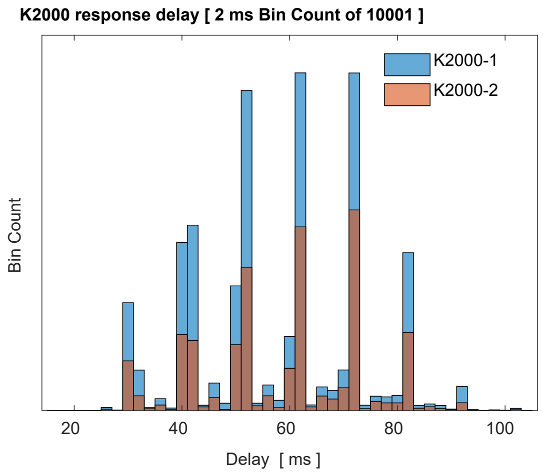


Time Domain



$\tau_r * f_{3dB} = 0.35$

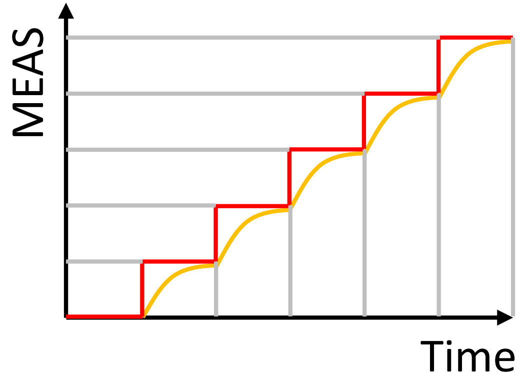
Lowpass-filtering



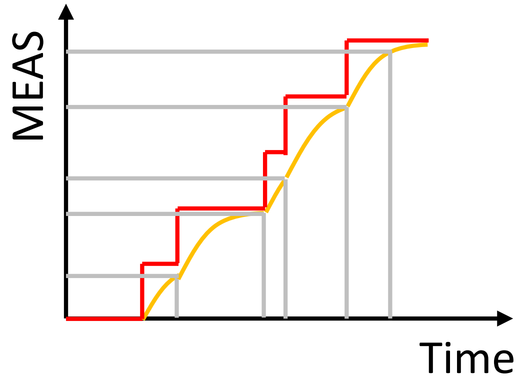
Clock: 1 NPLC = 17 ms

Waitless Measure

Uniform



Jittering

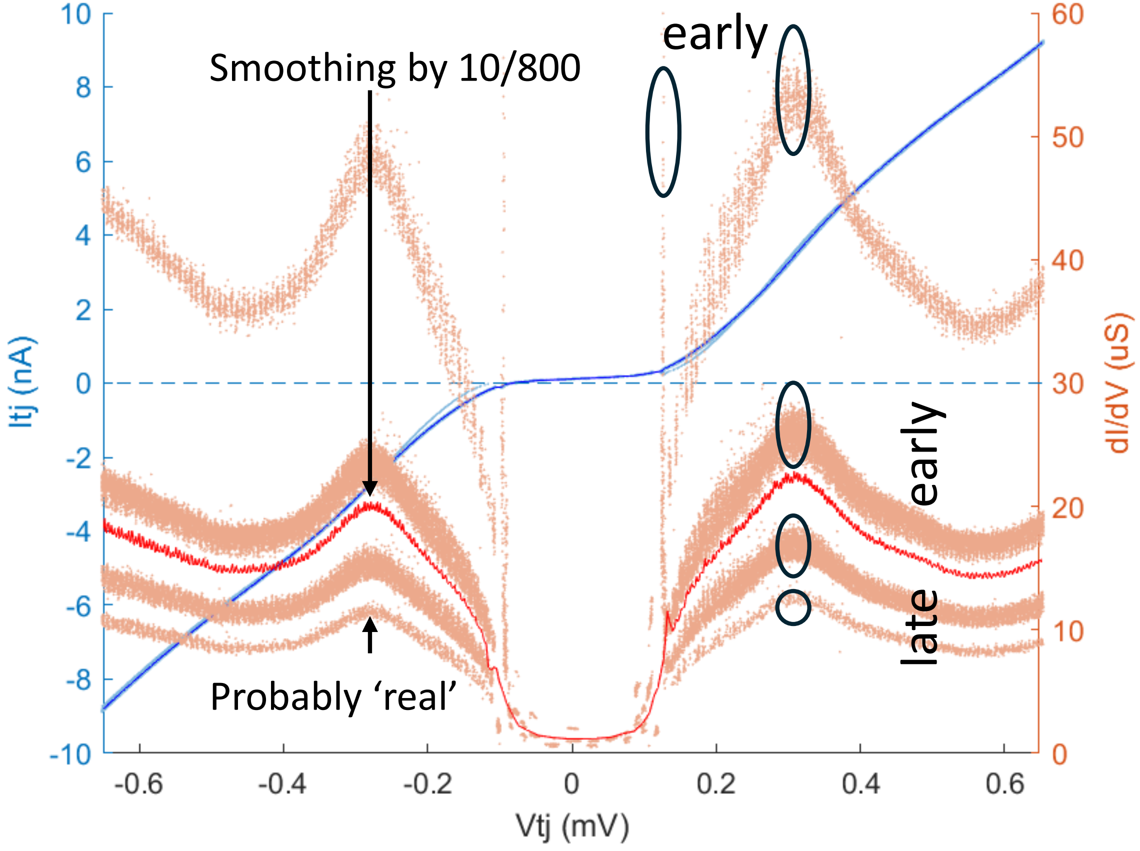


τ is for ENTIRE system

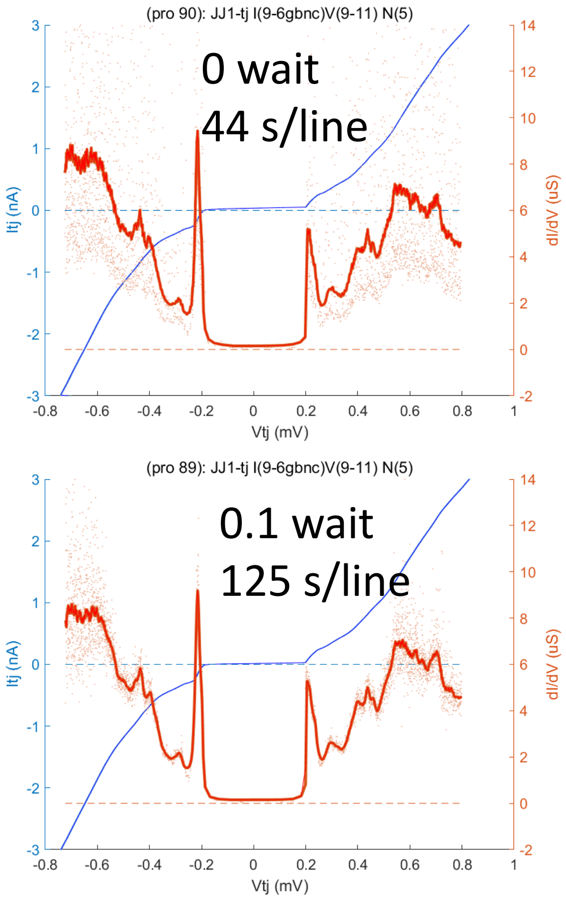
Fridge LPF, DUT, BOB, Ithaco 1201, K2000…

Using Voltmeters

Measuring a Tunnel Junction



SNR vs. Measurement time



Data $y_i = y_0 + x_i$

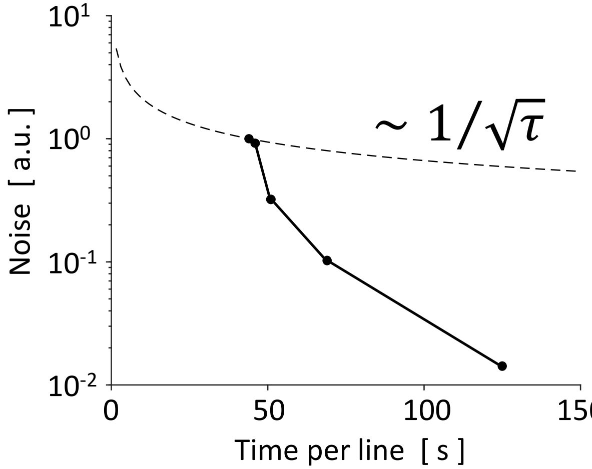
Mean $\bar{y} = N^{-1} \sum y_i$

'Error' $\epsilon_i = y_i - \bar{y}$

Noise $\epsilon_{\mathrm{rms}} = \sqrt{N^{-1} \sum \epsilon_i^2}$

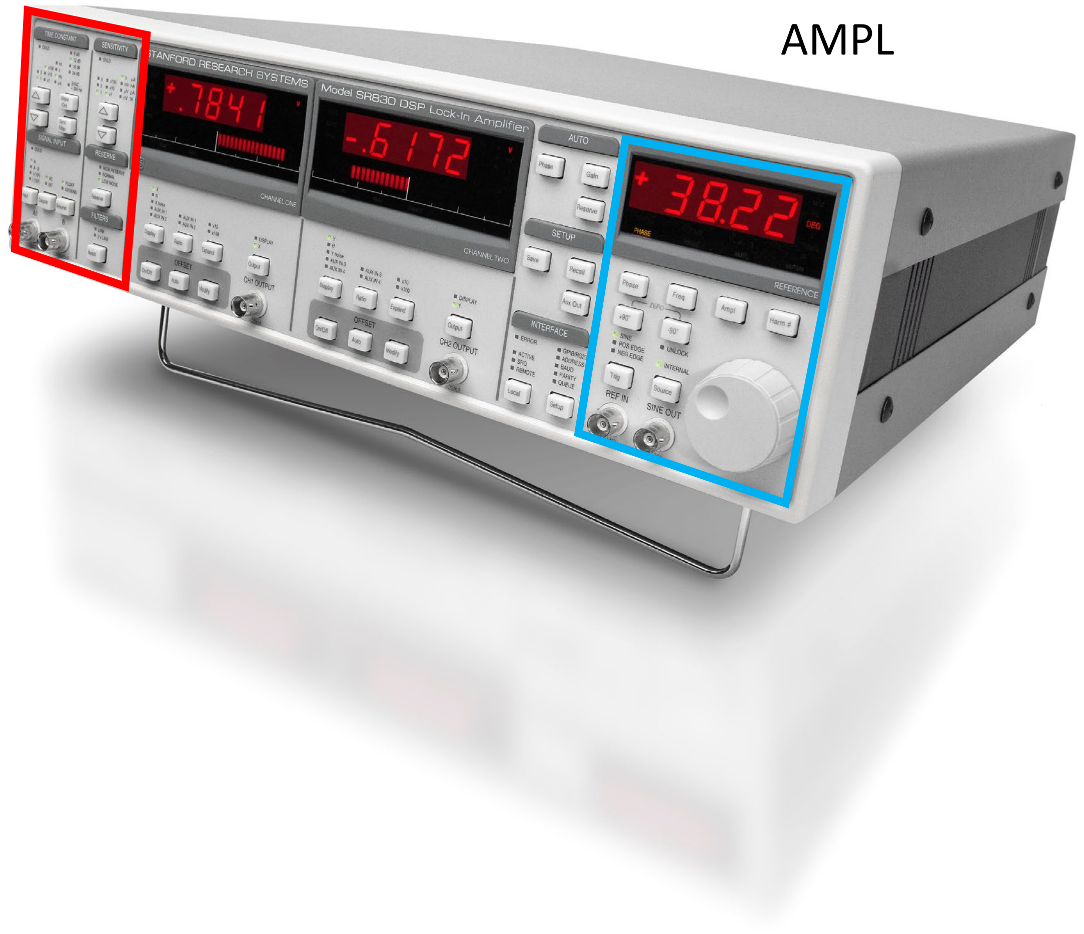
By Central Limit Theorem,

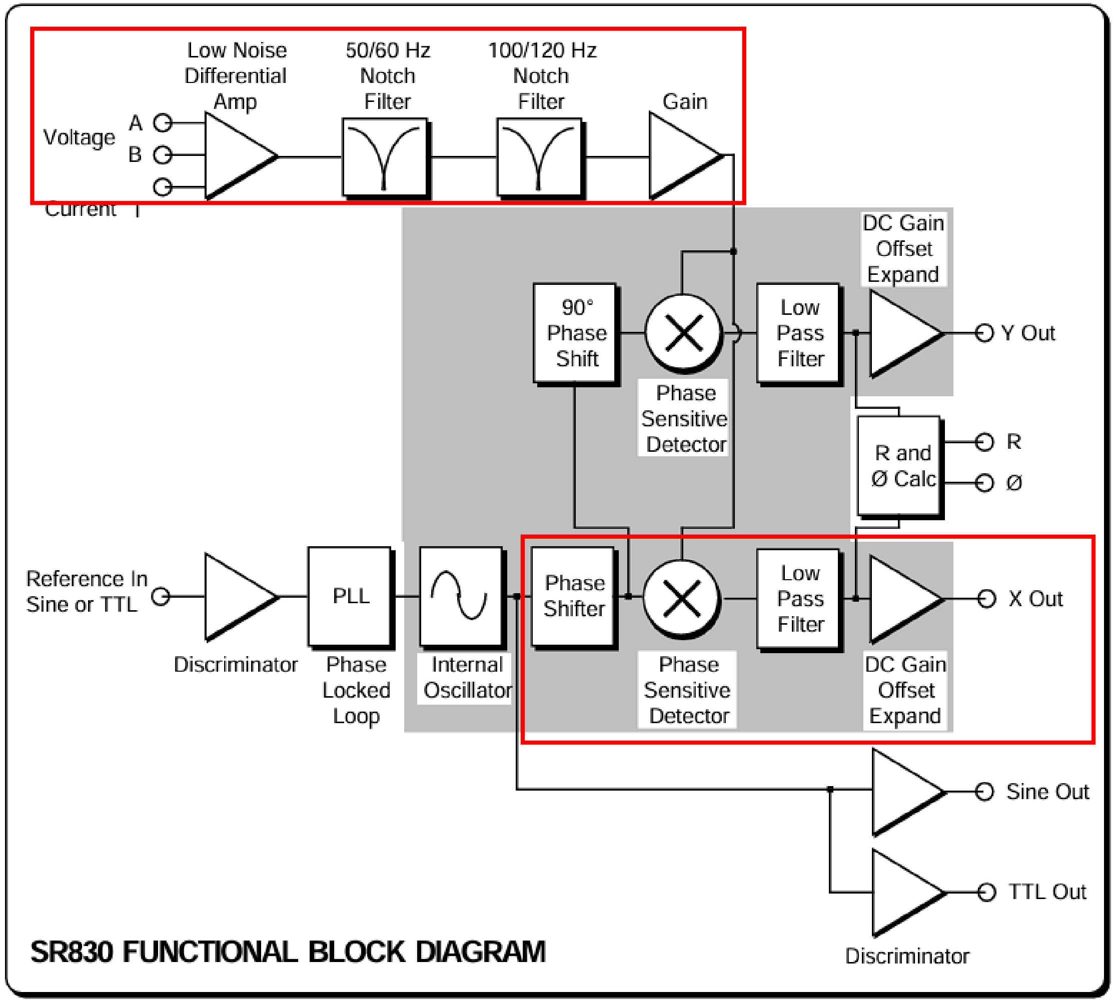
$$\epsilon_{\mathrm{rms}}/\bar{y} \approx 1/\sqrt{N} \sim 1/\sqrt{\tau}$$



Using Lock-in Amplifiers

FREQ
PHAS
AMPL





Slope	ENBW	Wait Time
6 dB/oct	1/(4T)	5T
12 dB/oct	1/(8T)	7T
18 dB/oct	3/(32T)	9T
24 dB/oct	5/(64T)	10T

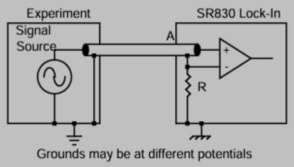
18 dB/oct	DC gain (dB)	min time constant
	<62	10 μs
	<92	30 μs
	<122	100 μs
	<152	300 μs
	<182	1 ms

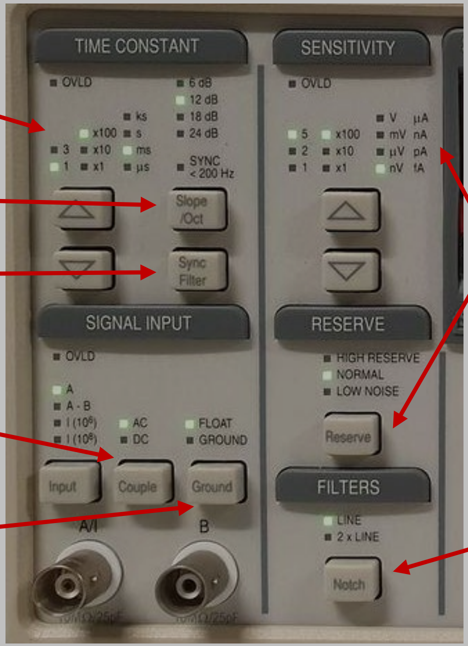
24 dB/oct	DC gain (dB)	min time constant
	<72	10 μs
	<112	30 μs
	<152	100 μs
	<182	300 μs

Synchronous filtering effectively removes output components at multiples of the detection frequency. At low frequencies, this filter is a very effective way to remove 2f without using extremely long time constants.

AC coupling removes the DC component of the signal without any sacrifice in signal as long as the frequency is above 160 mHz.

the user. Float uses 10 kΩ and Ground uses 10Ω. This avoids ground loop problems between the experiment and the lock-in due to differing ground potentials. The lock-in lets the shield 'quasi-float' in order to sense the experiment ground. However, noise pickup on the shield will appear as noise to the lock-in. This is bad since the lock-in cannot





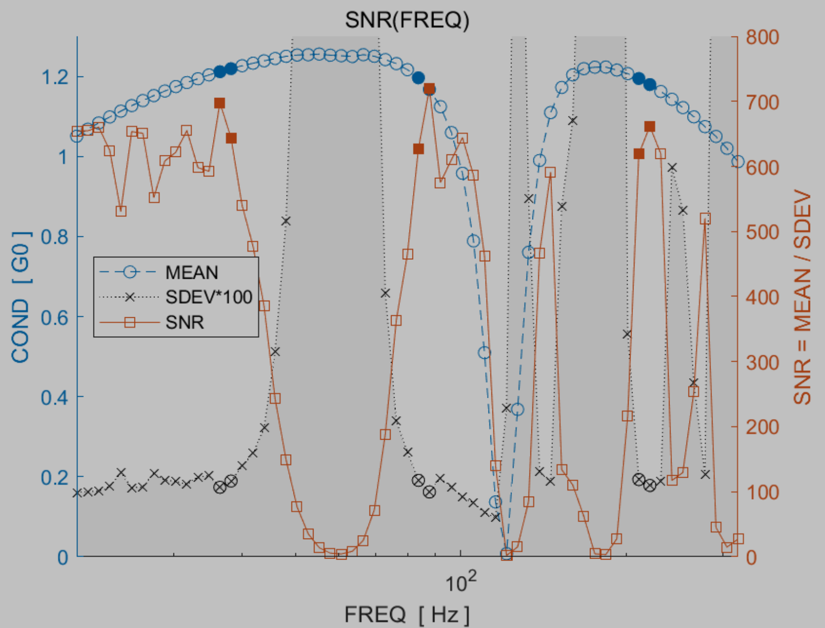
The traditional definition of dynamic reserve is the ratio of the largest tolerable noise signal to the full scale signal, expressed in dB. For example, if full

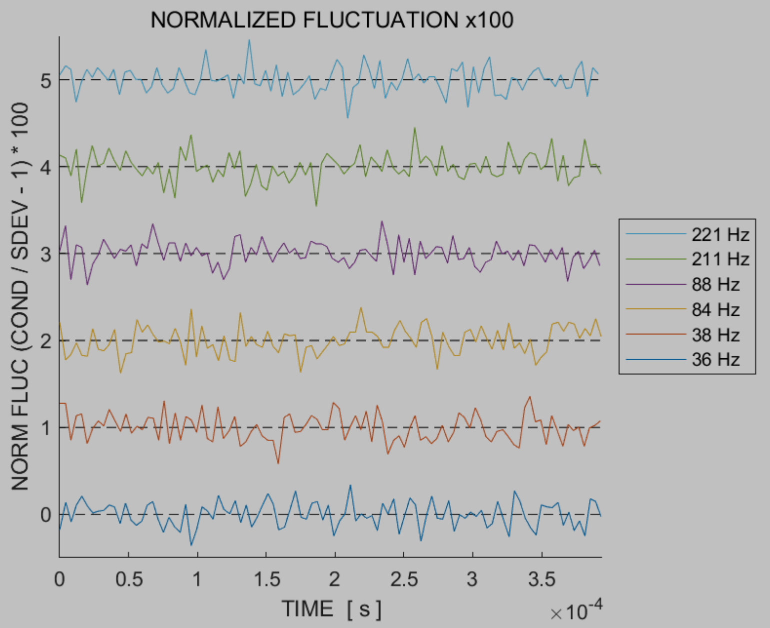
Sensitivity	Low Noise	Normal	High Reserve
50 mV	6	16	26
20 mV	4	24	34
10 mV	0	20	40
5 mV	6	26	46
2 mV	4	34	54
1 mV	10	40	60
500 μV	16	46	66
200 μV	24	54	74
100 μV	30	60	80

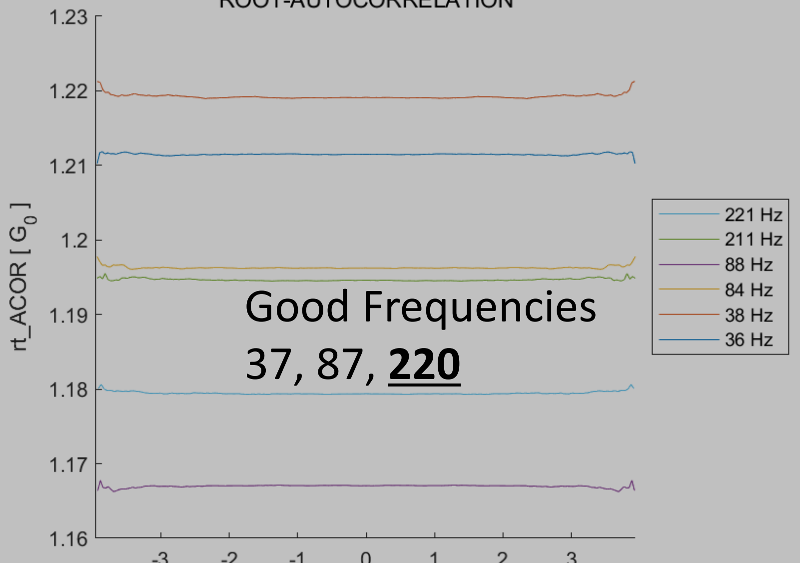
The notch filters are simple single stage, inverting band pass filters summing with their inputs to remove 60 Hz or 120 Hz. Each filter has a depth

<u>Rule of thumb per frequency $f << f_{3dB}$</u>

TCON	$t > \max(3 / f, 10\text{ ms})$
SLOP	24 dB
SYNC	w.r.t. 200 Hz
*WAIT	$T > 3 * t$
COUP	AC
GRND	test
SENS	> 3* max signal
RSRV	as low as possible
FILT	BOTH

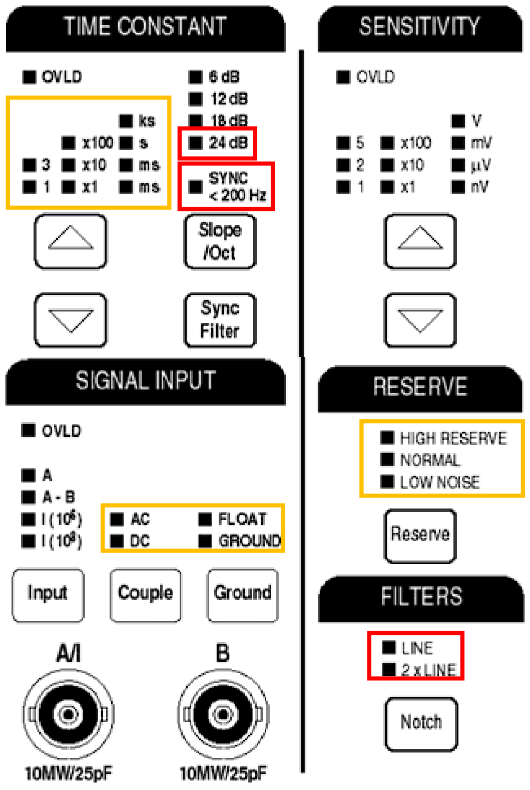






Good Frequencies
37, 87, **<u>220</u>**

Using Lock-in Amplifiers



Frequency

- $f \ll f_{3\mathrm{dB}}$

Time Constant

- Kinda like averaging
- $t_\mathrm{c} > \max(3/f\,, 10\ \mathrm{ms})$

Couple, Ground

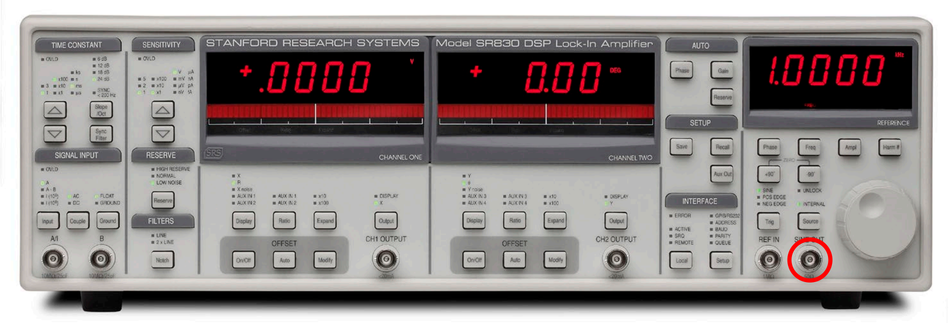
- Try all

Reserve

- As low as possible

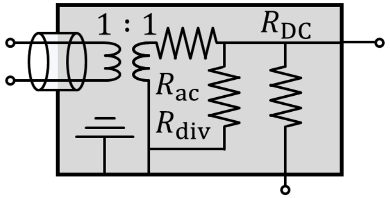
WAIT

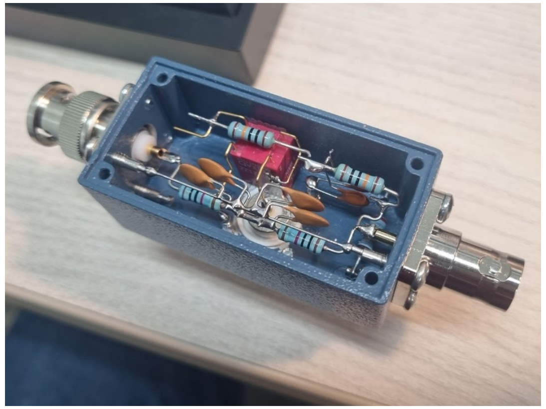
- $T > 3 * t_\mathrm{c}$



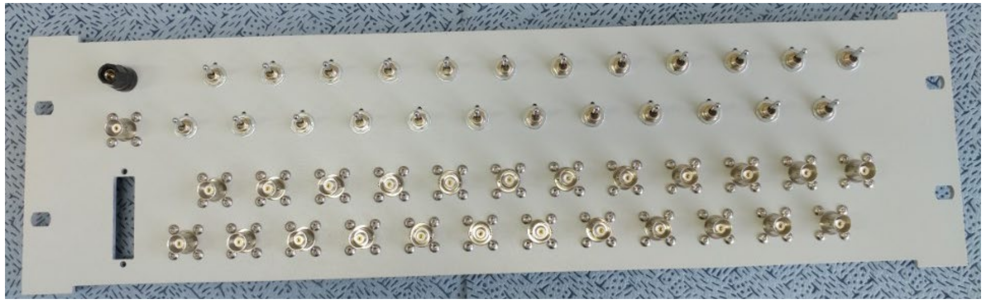
Lock-ins are NOISY machines
Sine-out is connected to power!

Galvanic Isolation

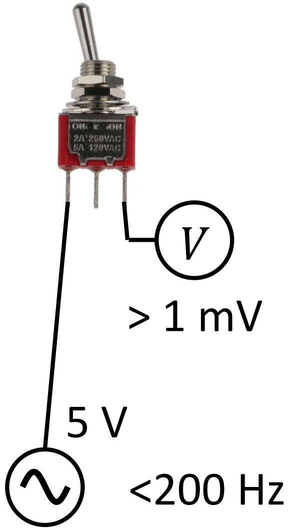


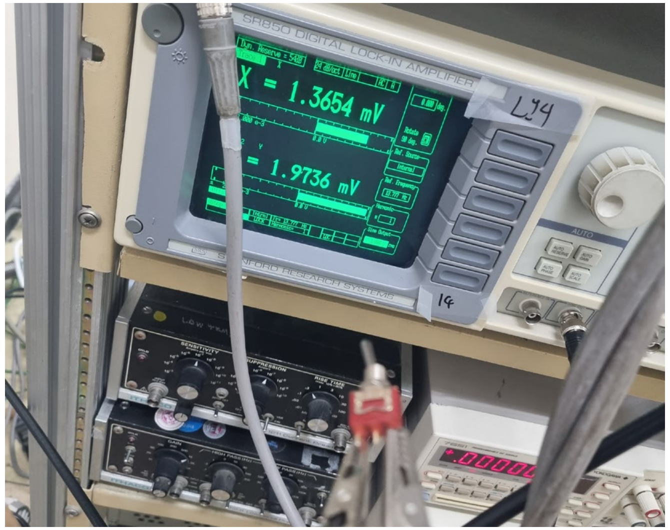


Breakout Box Switches



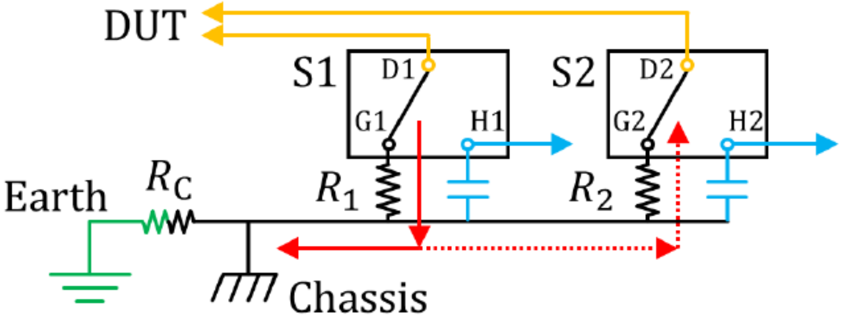
Most BOBs are controlled using switches



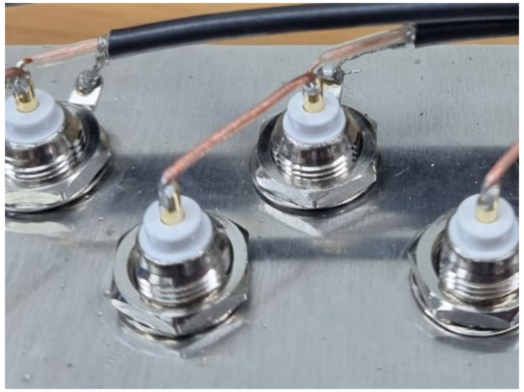


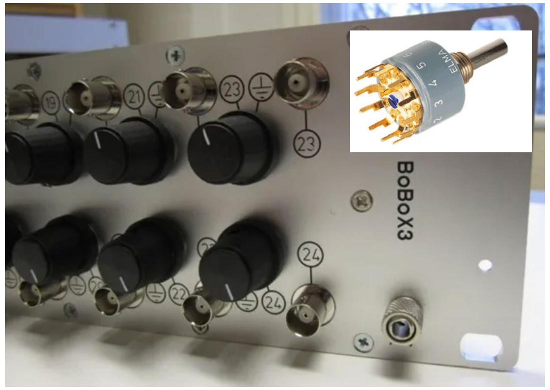
Non-capacitive leaks in most SPDT switches!

<u>Common-Impedance Coupling</u>

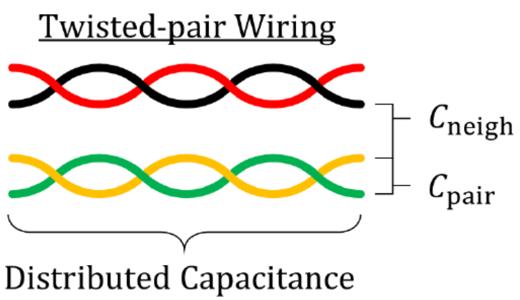


- Solution 1
  Switchless BOB
- Solution 2
  Good Rotary switches

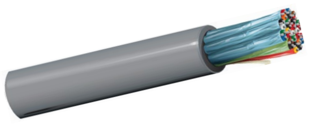




Signal Line Crosstalk



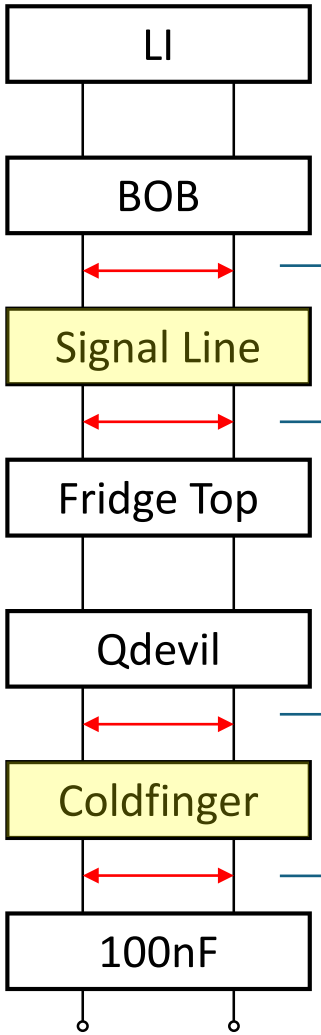
In Bluefors wiring,
$C_{neigh} \sim 20$ pF
$C_{pair} \sim 220$ pF

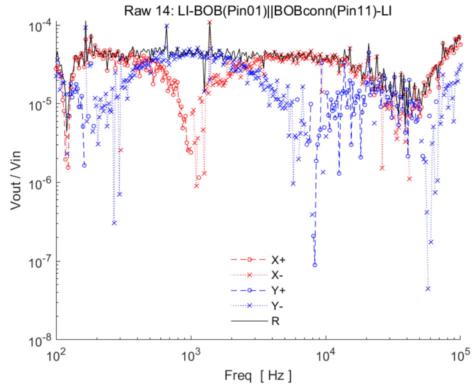


In Belden 9993
$C_{neigh} \sim 3$ pF/m
$C_{pair} \sim 82$ pF/m

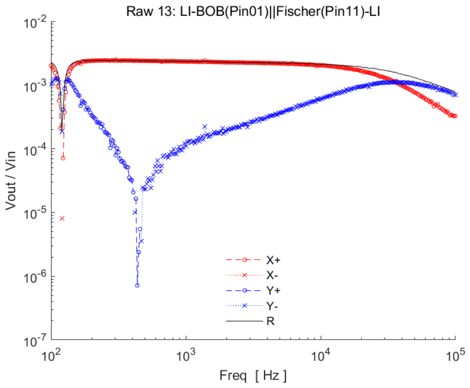
All adds up to ~ nF
Mixed noise path

Crosstalk V2V

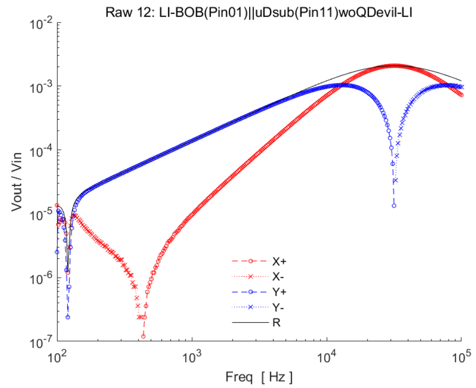


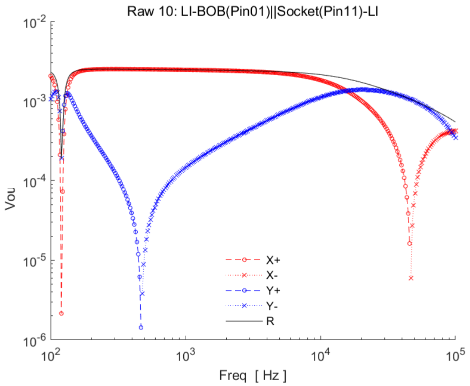


Signal line leakage measured w/ TIA @ 1kHz w/ 1Vrms



Crosstalk @ SL



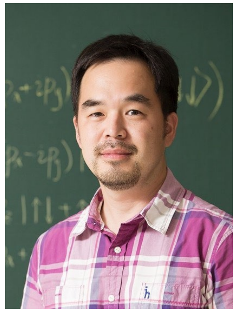


Crosstalk returns @ CF

Take home messages for 'fastest' route

1. Start by planning out local grounding/filtering scheme
2. Make ***good*** BOB, SL, CF, & cryo-cabling
   :: strong GND connection with low res. & imp. paths
   :: good HOT-GND isolation (10 GΩ) & low crosstalk
   :: small SMDs (R, C, π) and thick & tight shields
   > Extra avoidance of low-frequency noise pick-up by
   :: strong GND for electrics (low cap., GND res. & imp.)
   :: mu-metal for magnetics (low mutual ind., add cond.)
   > Extra avoidance of high-frequency noise pick-up by
   :: good shielding with quick GND returns
   > Keep things perfectly fixed from vibration (tribo. & pick-up)
   > Keep things perfectly thermalized for more than 10 cm
3. Strong wideband filters, appropriate cascading & positions
4. Optimize GND network
   > Short noise return path (low res. & imp.)
   > Try **ALL COMBINATIONS** of GND**s**, EARTH, & FLT
   :: Local GNDing should start with the Star scheme
5. Optimize measurement protocol for reliable testing
6. Most corrections seem to be done in reverse order

Credits to my PhD days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S. Lee


U. Kim


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Me!

[Sherz & Monk] "Practical Electronics for Engineers"
[Horowitz & Hill] "The Art of Electronics"
[Joffe & Lock] "Grounds for Grounding"
[Williams & Armstrong] "EMC for Systems and Installations"
[Park] "Coherent transport of 2D electron waves: …", Ch. 3
[Pozar] "Microwave Engineering"
[Sedra & Smith] "Microelectronic Circuits"
[Ott] "Electromagnetic Compatibility Engineering"