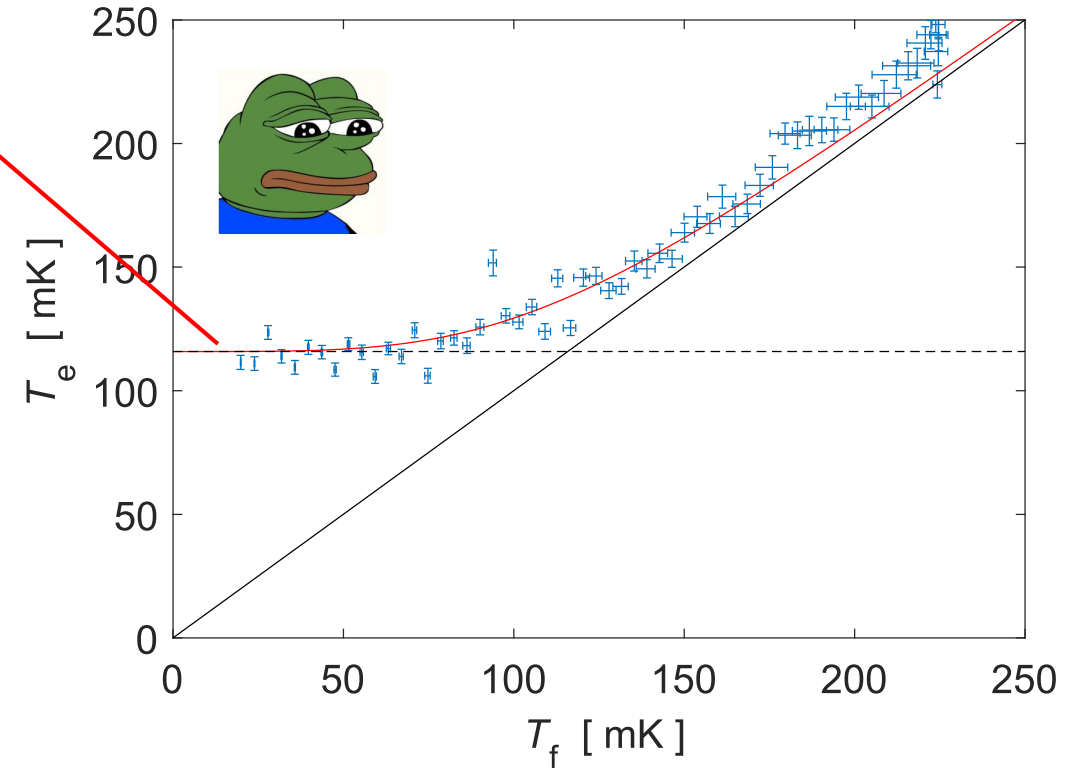
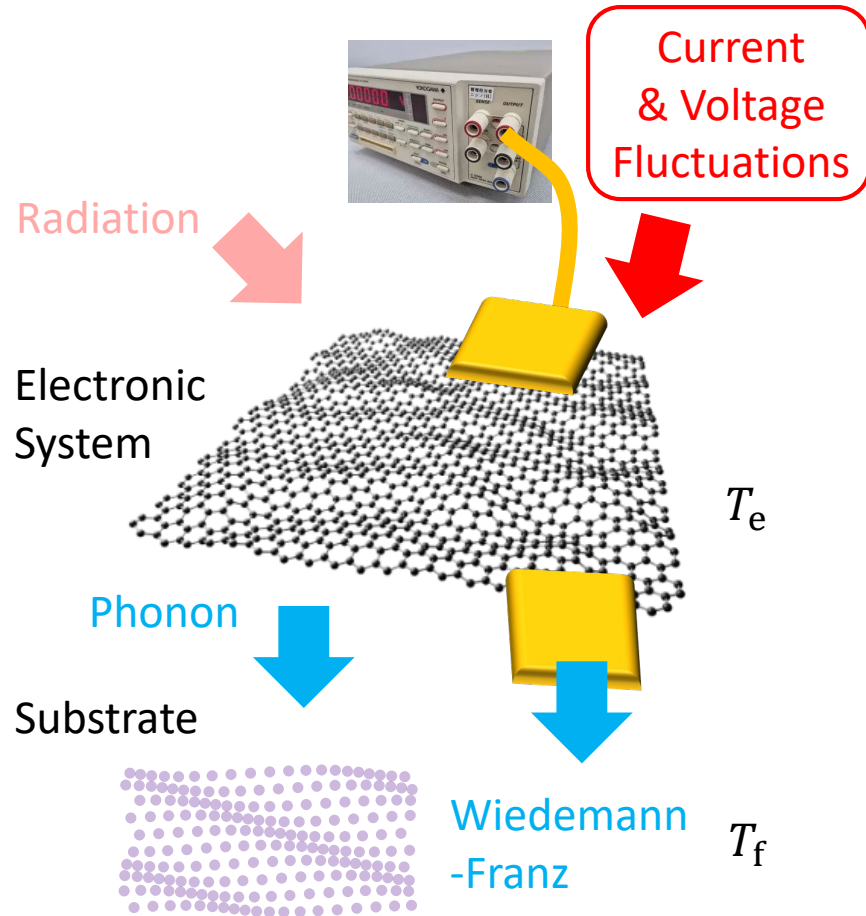


Good Practice for Lowering Electron Temperature and Electronic Noise

The 15th School of Mesoscopic Physics

Dongsung T. Park, POSTECH, Korea

Electron Temperature & Electronic Noise



Heating Power \approx constant
 Cooling Power $\propto (T_e^\delta - T_f^\delta)$
 $T_e > T_f$

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

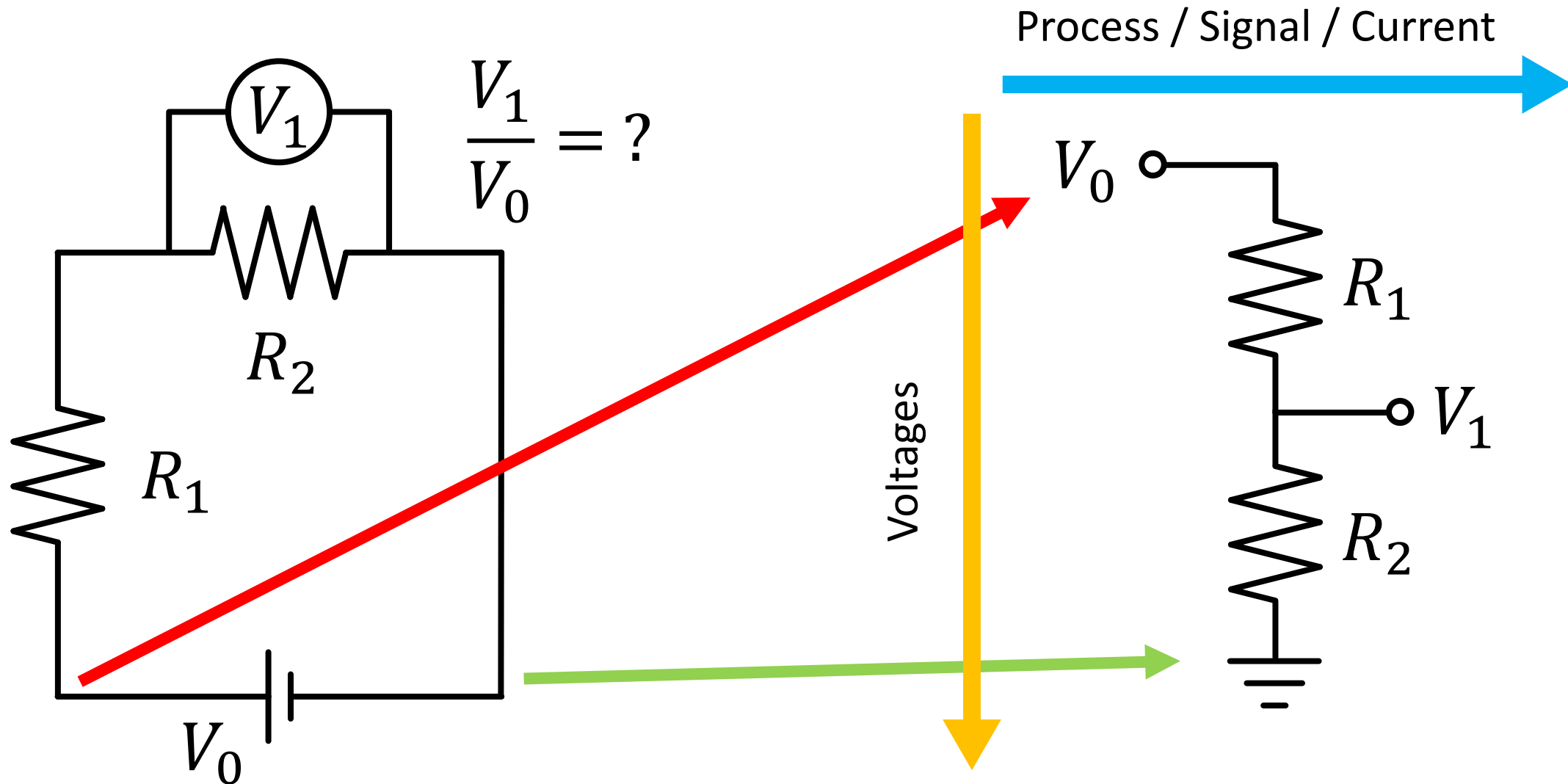
3. Noise & Ground

- Impedance (2), Ground & Common Problems, Earth

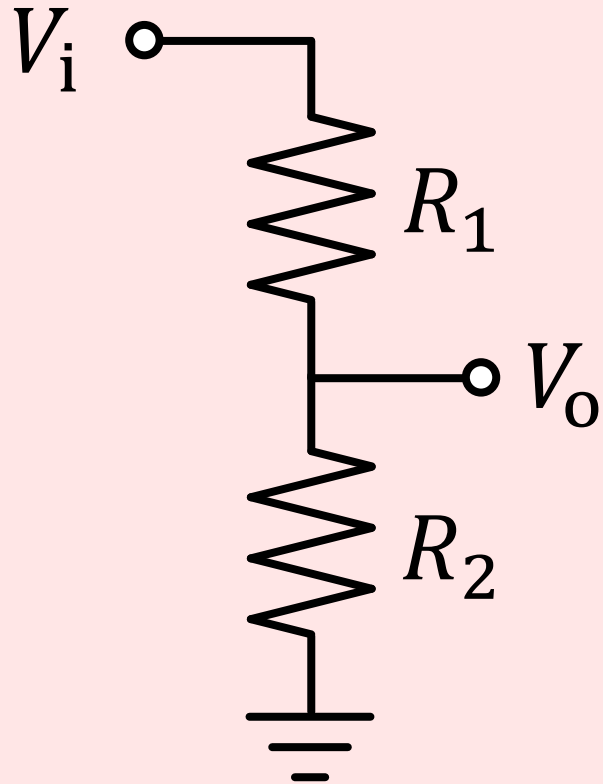
4. Instrumentation

- Voltmeters, Lock-in amplifiers
- Breakout boxes, Signal Lines

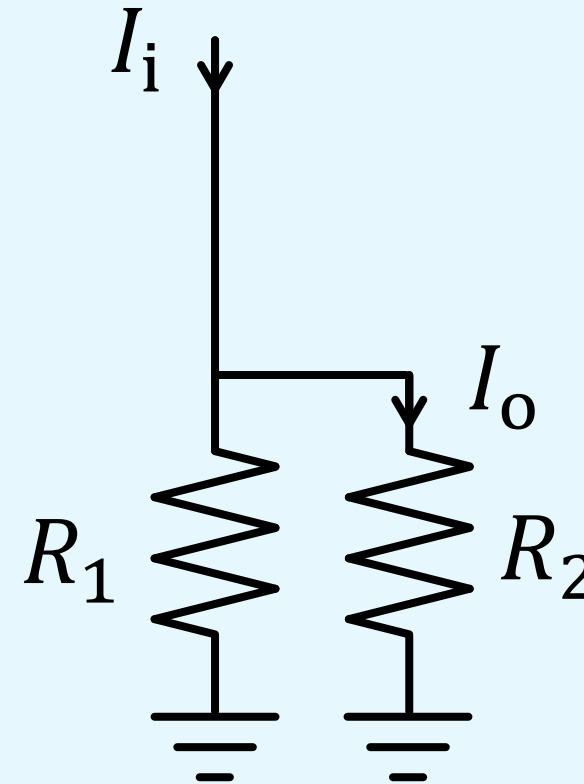
Circuit Schematics



Voltage & Current Divider


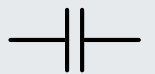



Voltage Divider:
$$\frac{V_o}{V_i} = \frac{R_2}{R_1 + R_2}$$

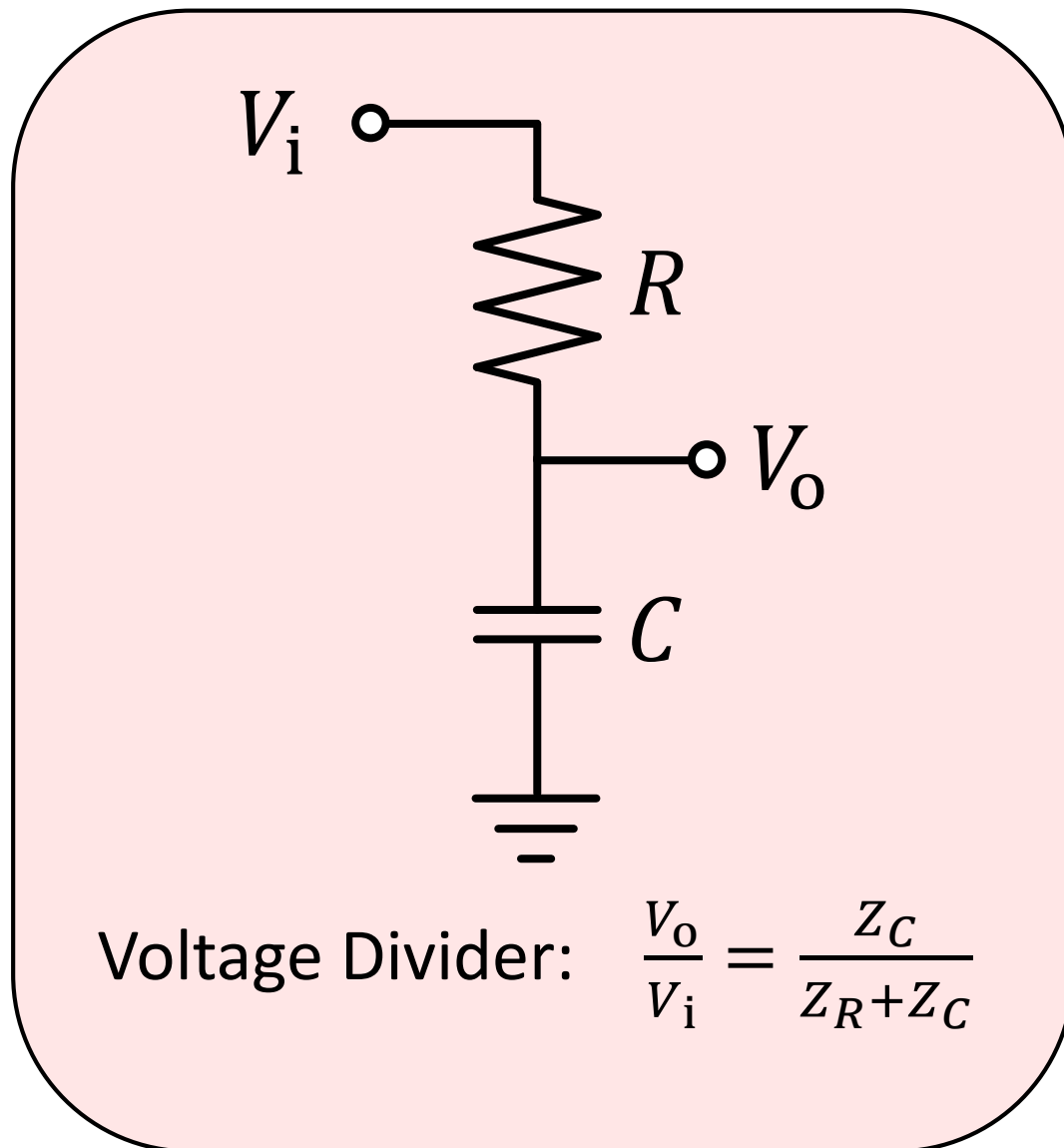


Current Divider:
$$\frac{I_o}{I_i} = \frac{R_2^{-1}}{R_1^{-1} + R_2^{-1}}$$

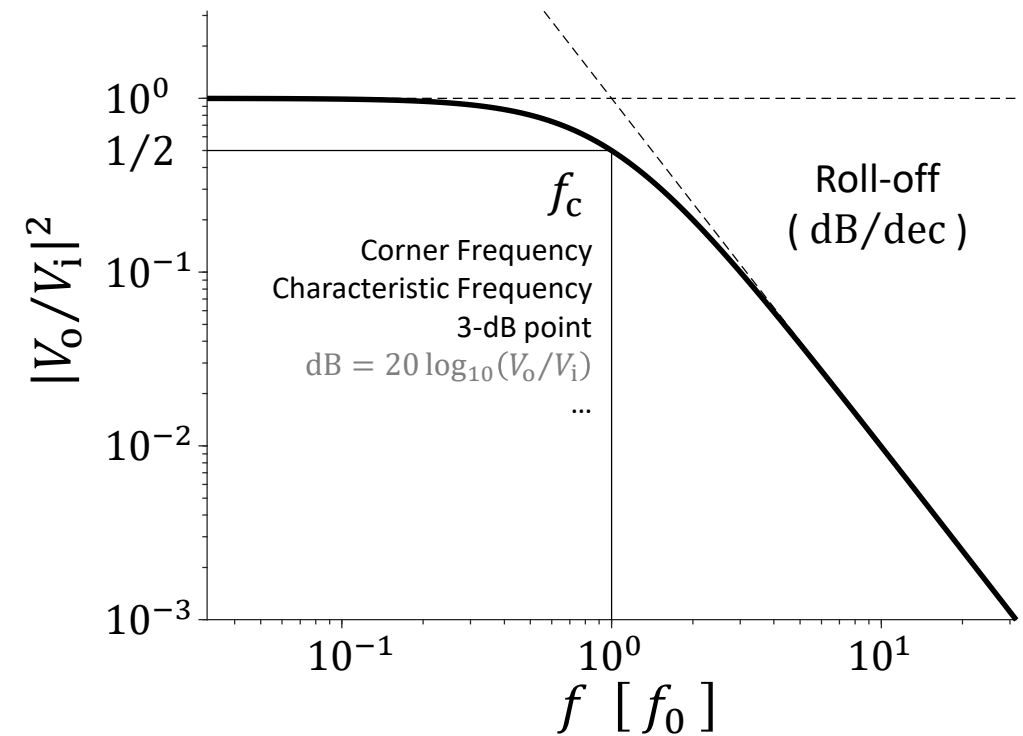
Impedance of Passive Components

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 	$V = L\dot{I}$ ($\varepsilon = \dot{\Phi}$)	$V = V_0 \sin(\omega t)$ $V_0 = I_0 \times (\omega L)$	$V_0 = I_0 \times (i\omega L)$	$Z_L = i\omega L$

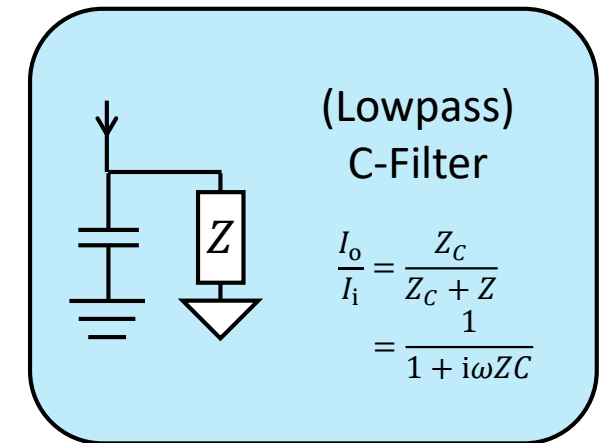
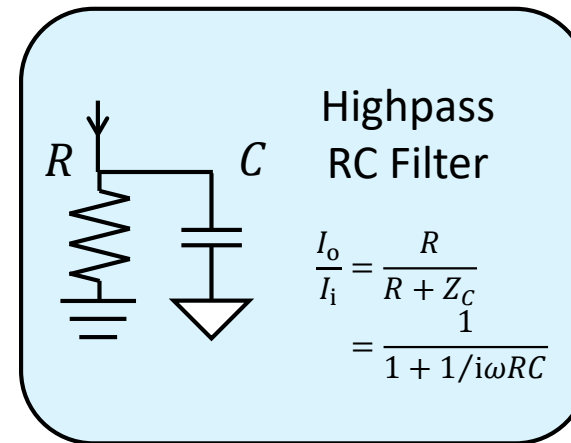
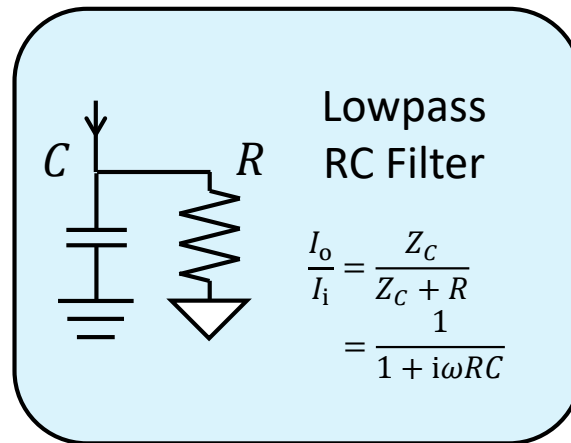
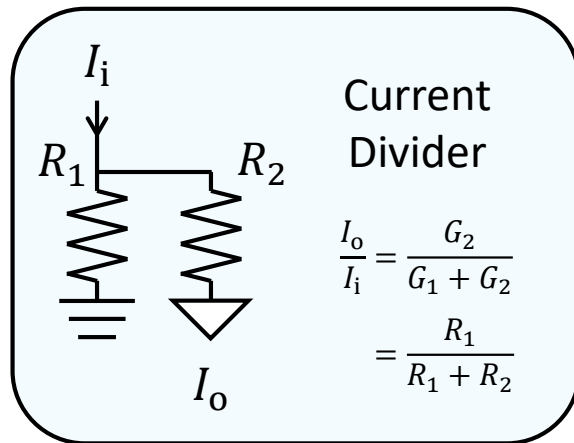
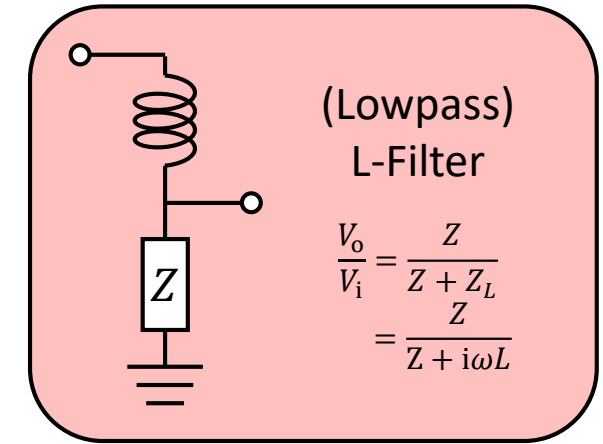
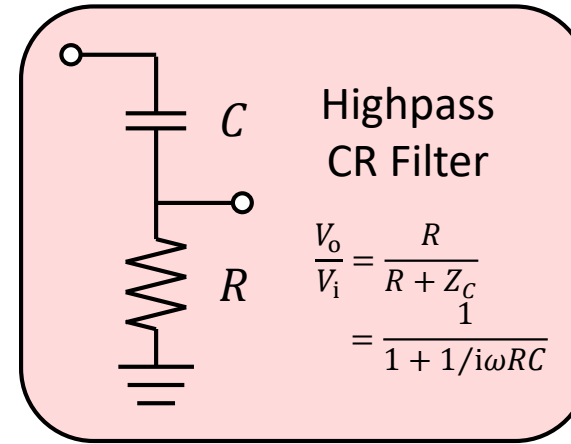
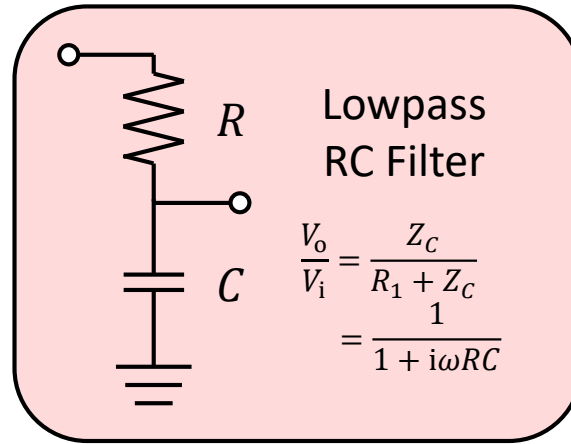
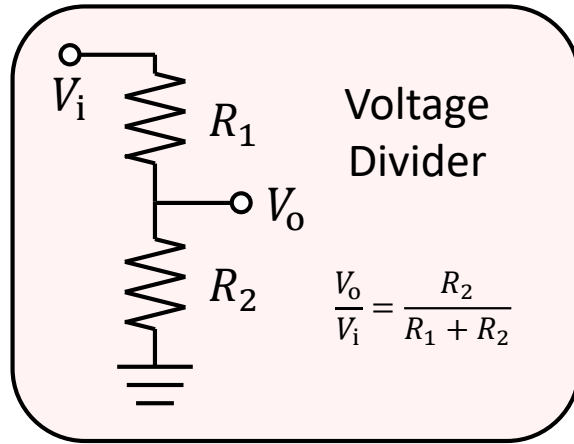
Passive Filters



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

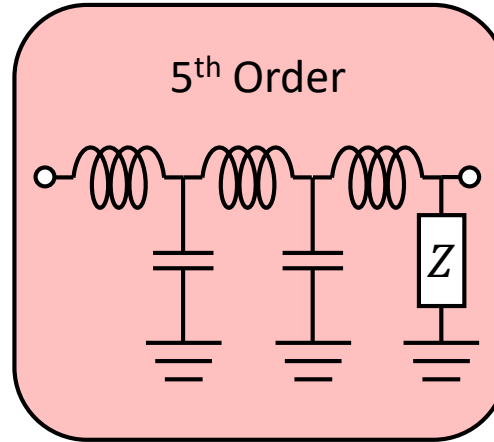
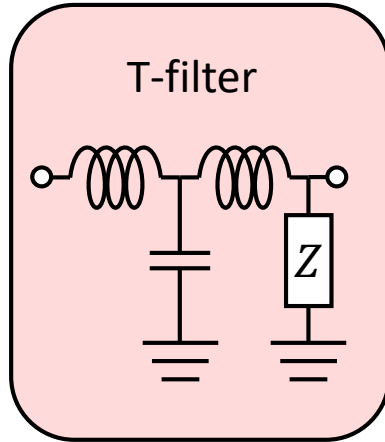
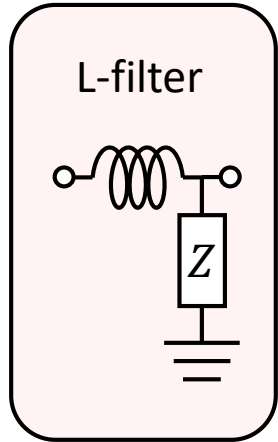


Passive Filters



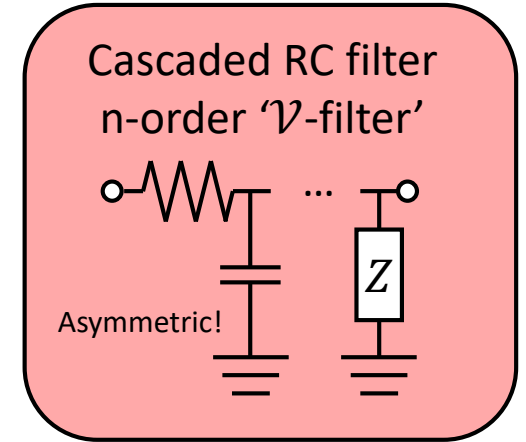
Synthetic Filters

“Voltage Filters” (Lowpass)



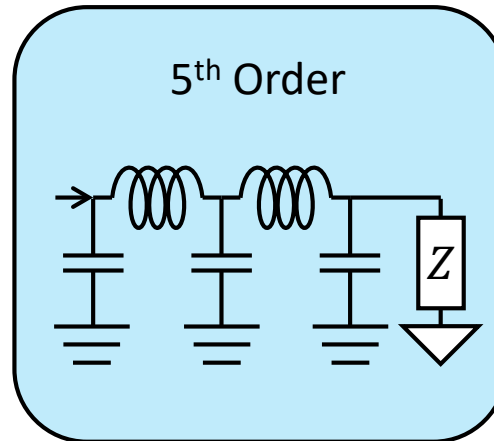
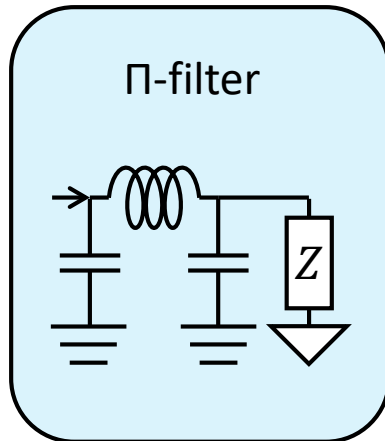
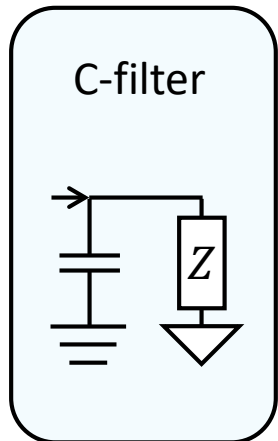
...

Poor man’s R-based Filters

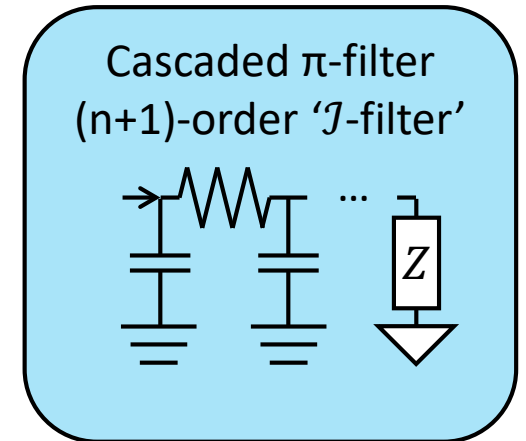


n-order/pole roll-off = $20 \cdot n$ dB/dec

“Current Filters” (Lowpass)

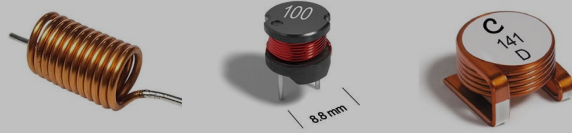


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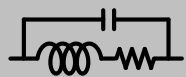


Inductors & Ferrites

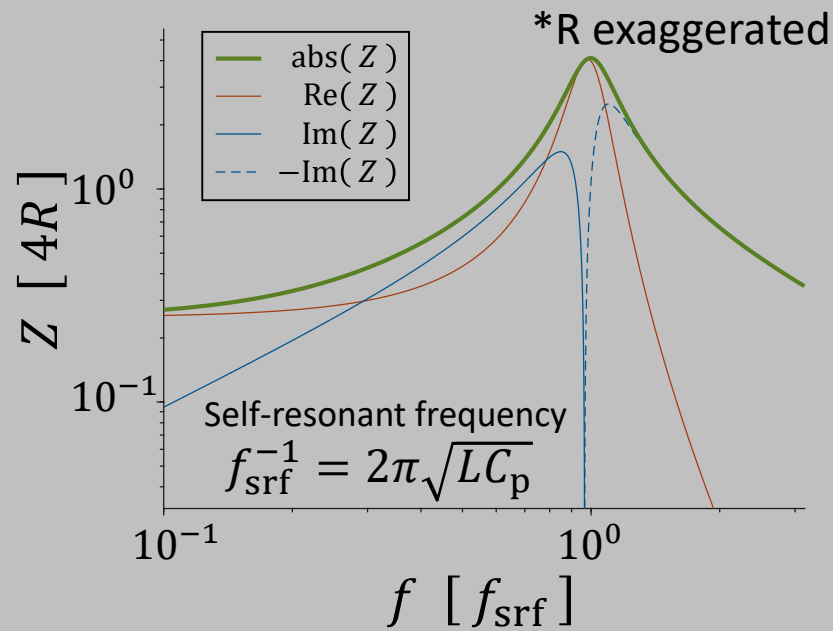
Inductor



Model



Resistance from wire ohmic
Capacitance from parasitics

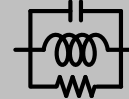


Low loss but small inductance

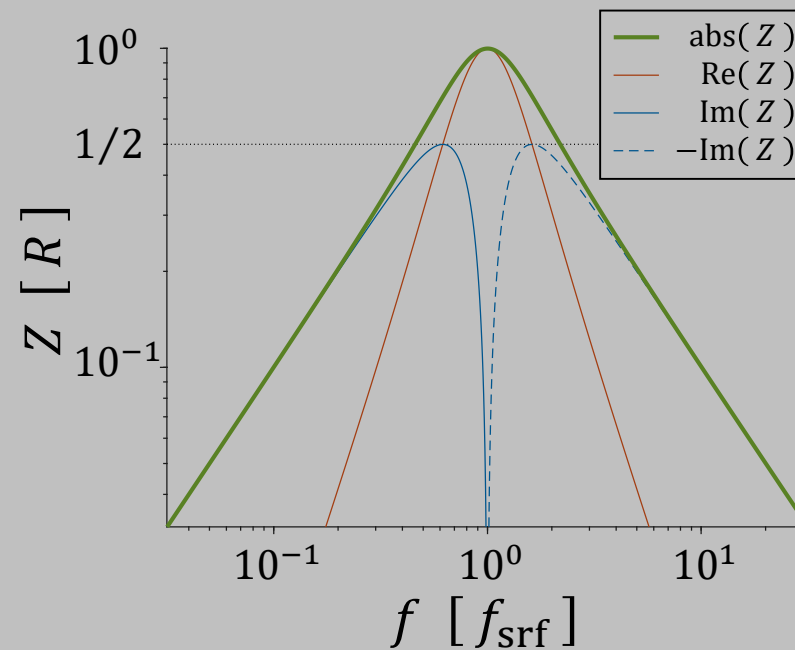
Ferrite



Model



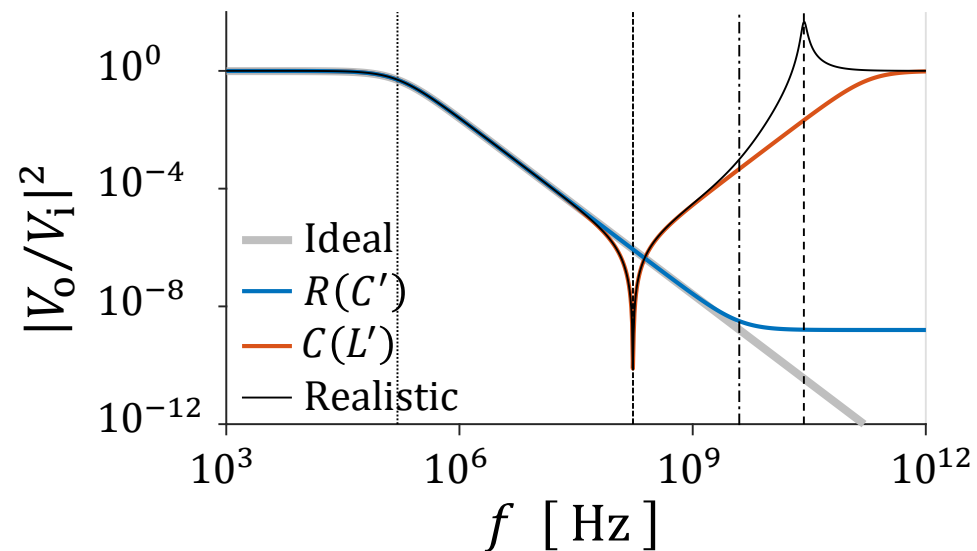
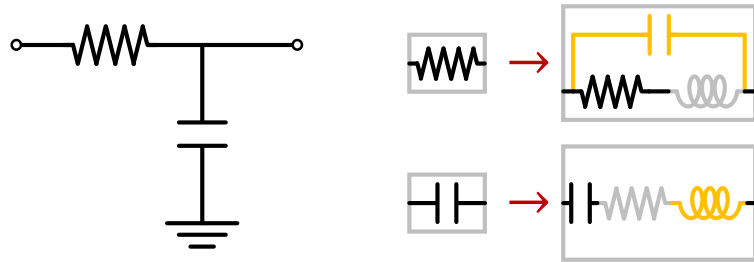
Resistance from ferrite loss
Capacitance from parasitics



Large inductance but low SRF

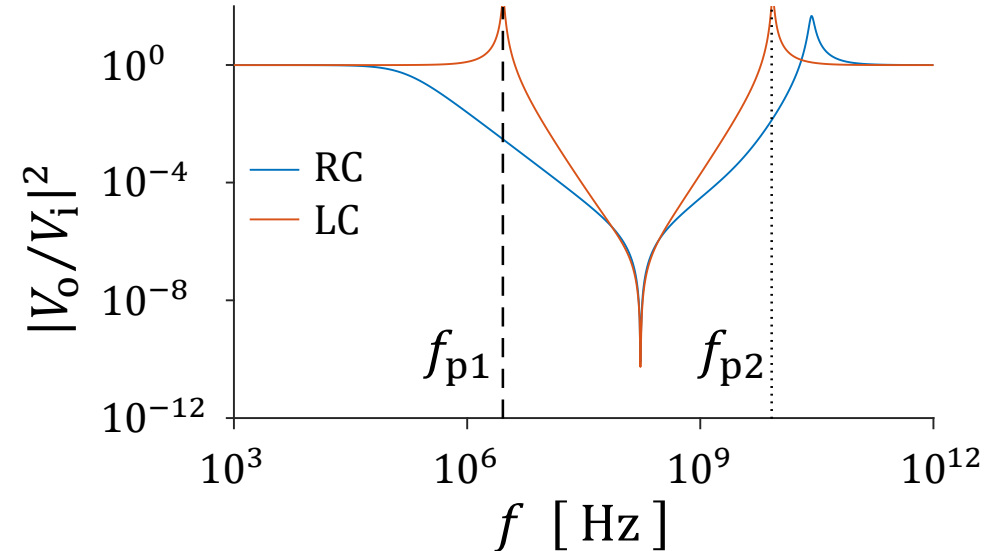
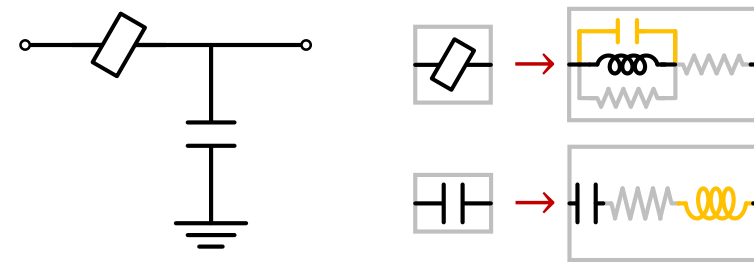
Parasitics

RC Filter

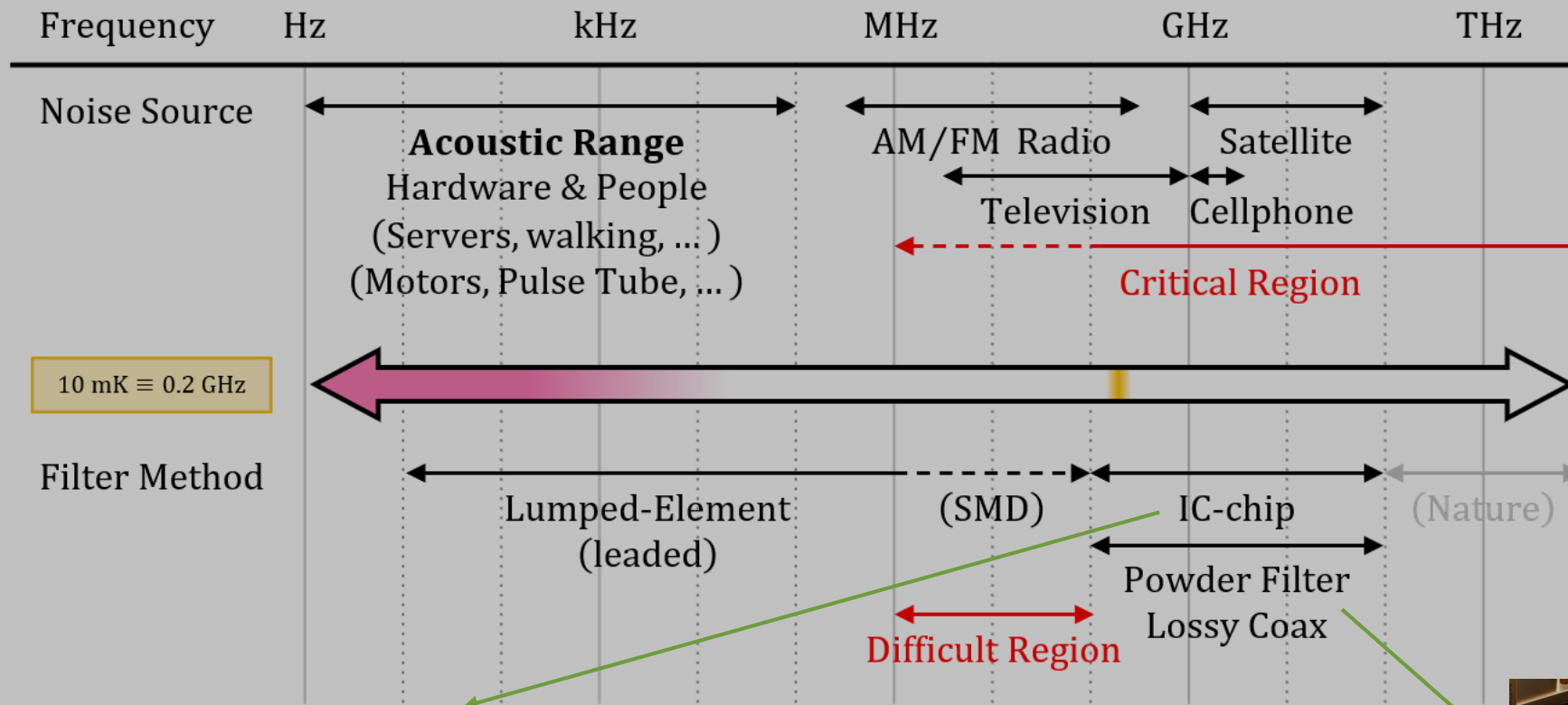


Parasitics must be mediated below 100 MHz
e.g. using smaller SMDs, or duplicate parts

LC Filter



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

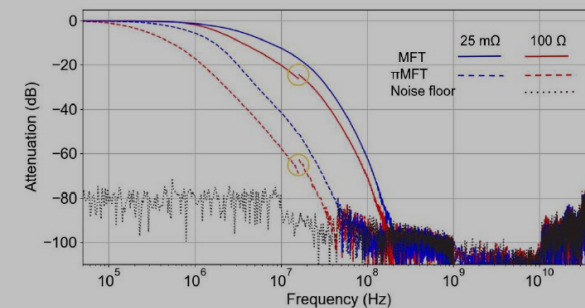


LFCN-80+
TYPICAL FREQUENCY RESPONSE

F4-F5 | 225-1550

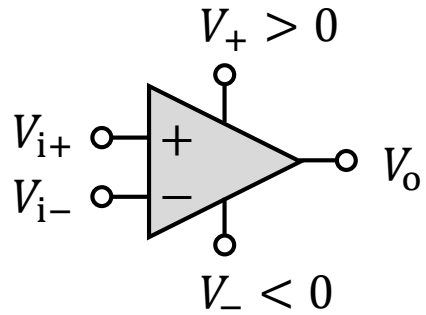
LFCN	F4/MHz	F5/MHz
80	225	1550
:	:	:
630	1020	3500

40dB rejection; often cascaded for wider band rejection

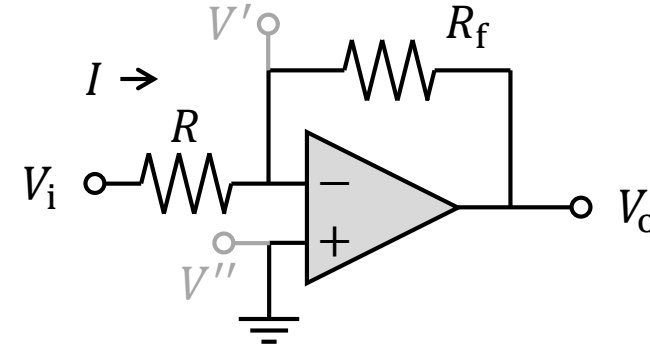


For filters,
Buy Basel

Operational Amplifier (Op-amp)



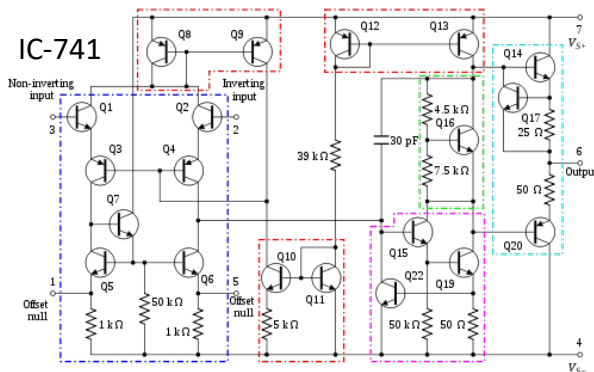
$$V_o = \begin{cases} V_+, & V_{i+} > V_{i-} \\ V_-, & V_{i+} < V_{i-} \end{cases}$$



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

Virtual Ground

$$V' = V'' = 0$$

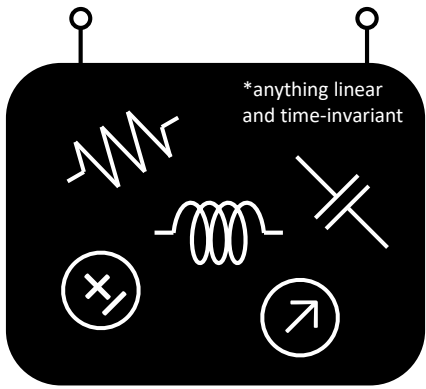


As a Voltage Amplifier: $\frac{V_o}{V_i} = -\frac{R}{R_f} < 0$

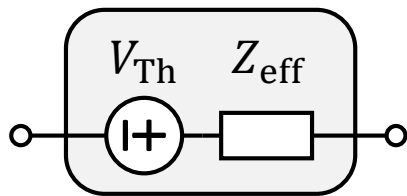
As a Current Amplifier: $V_o = -IR_f$

Generalized Amplifiers

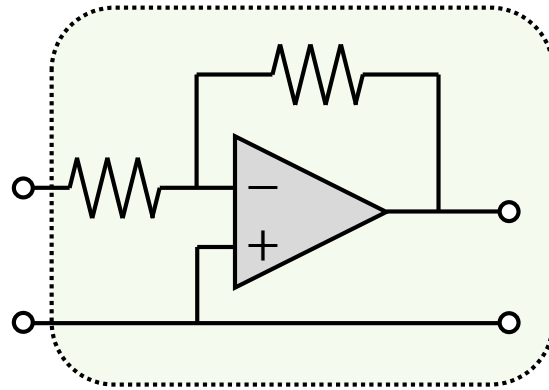
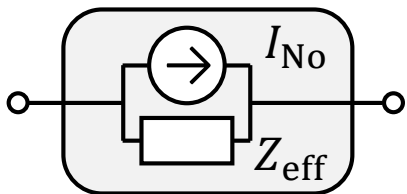
Thevenin-Norton Theorem



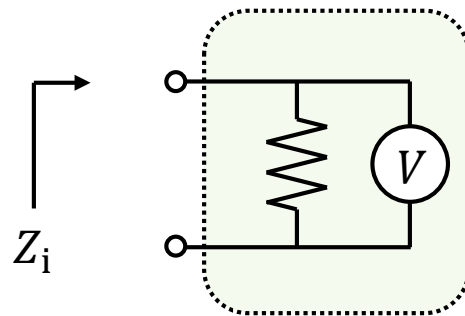
is equivalent to



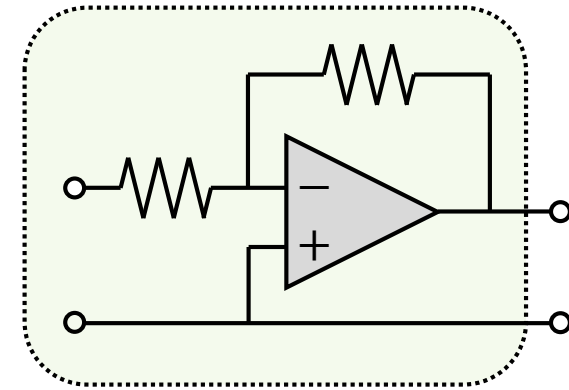
and



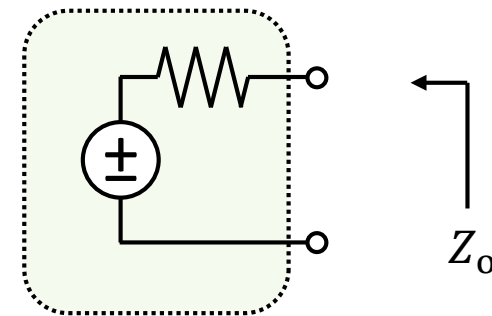
may as well be



Input Impedance



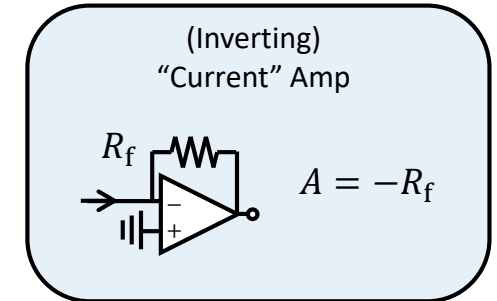
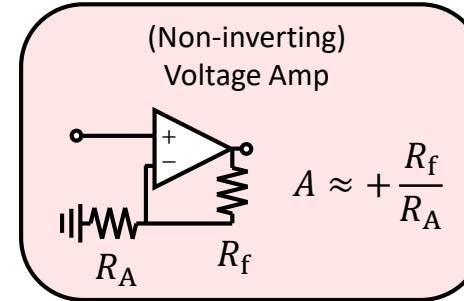
may as well be



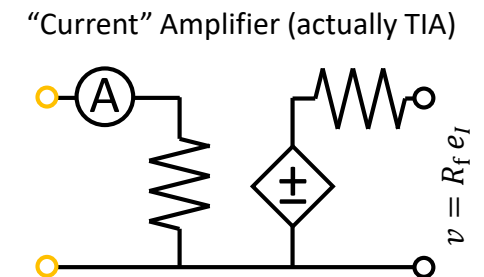
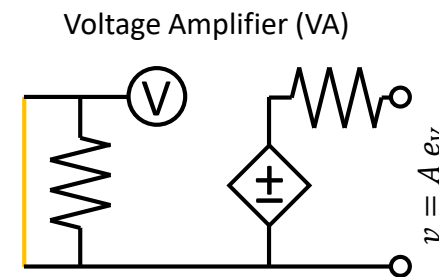
Output Impedance

Generalized Amplifiers

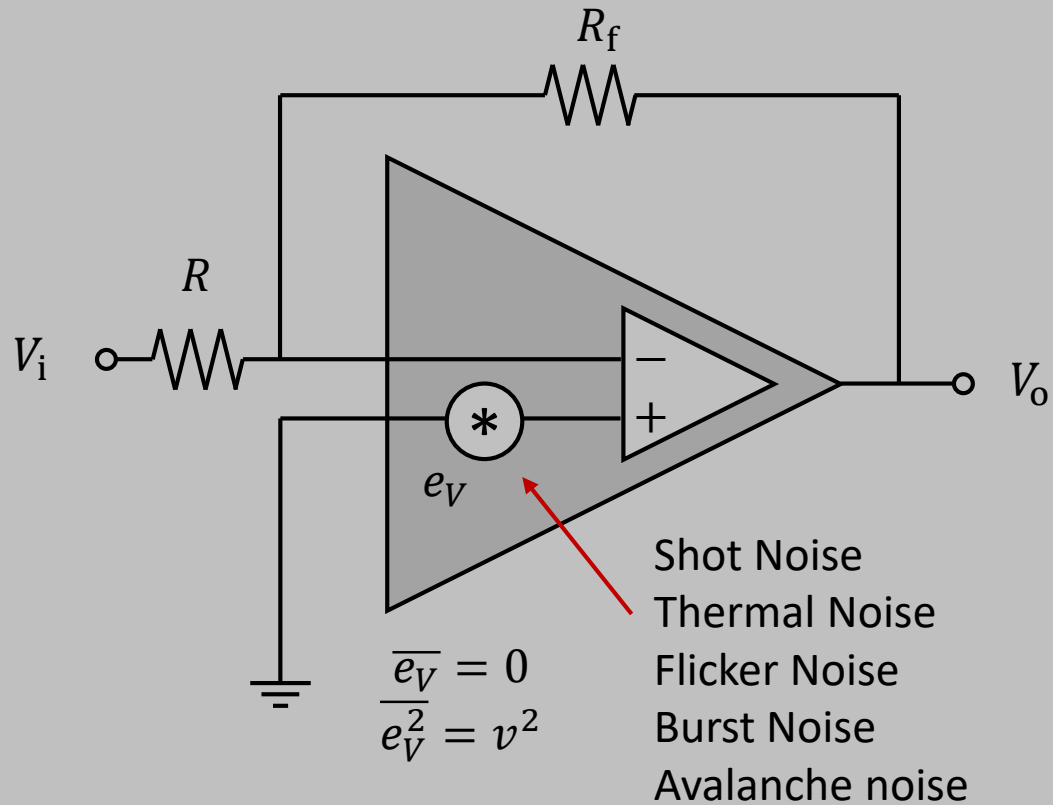
$o \setminus i$	Voltage	Current
Voltage	<p>Voltage Amplifier (VA)</p>	<p>Transimpedance Amplifier (TIA)</p>
Current	<p>Transconductance Amplifier (TCA)</p>	<p>Current Amplifier (CA)</p>



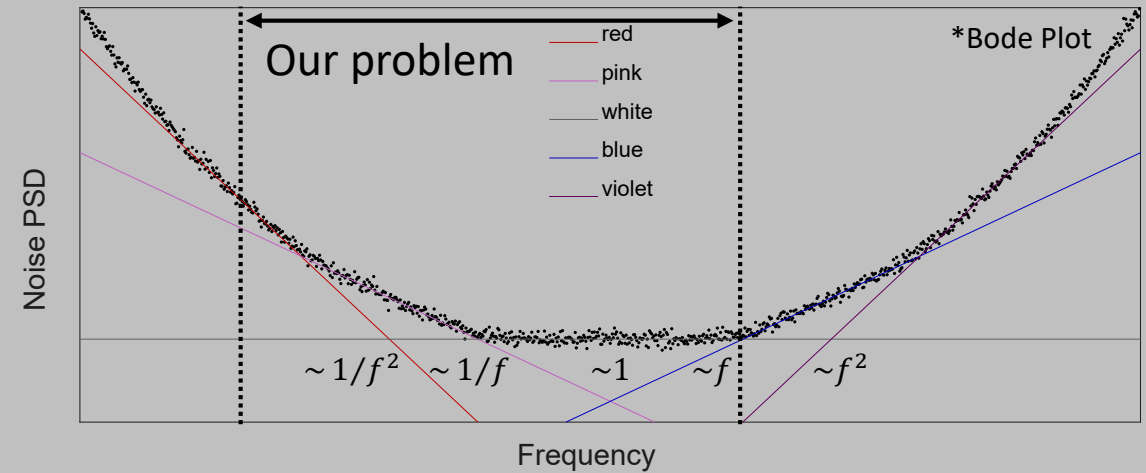
Input Referred Noise



Amplifier Noise Model



$(e_V \rightarrow V_O)$ smaller for larger R



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



Op Amps For Everyone

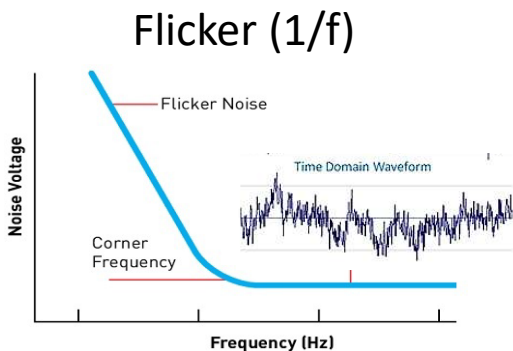
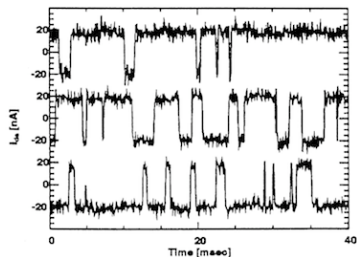
Ron Mancini, Editor in Chief

Noise & Interference

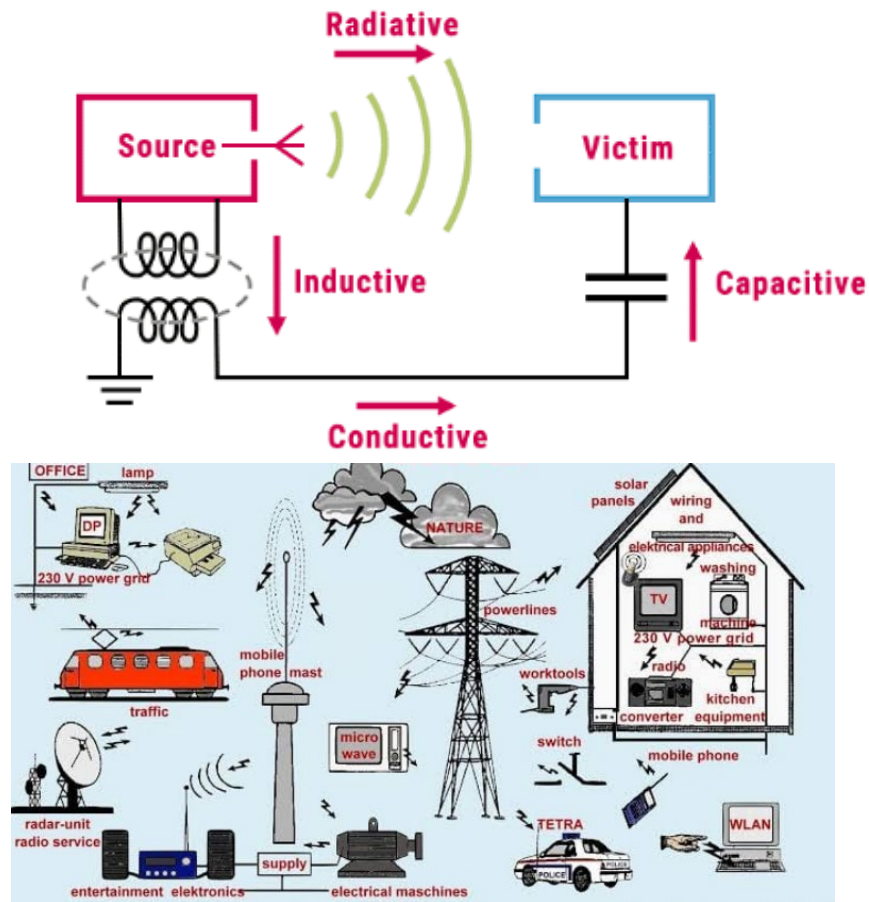
“Intrinsic” Noise



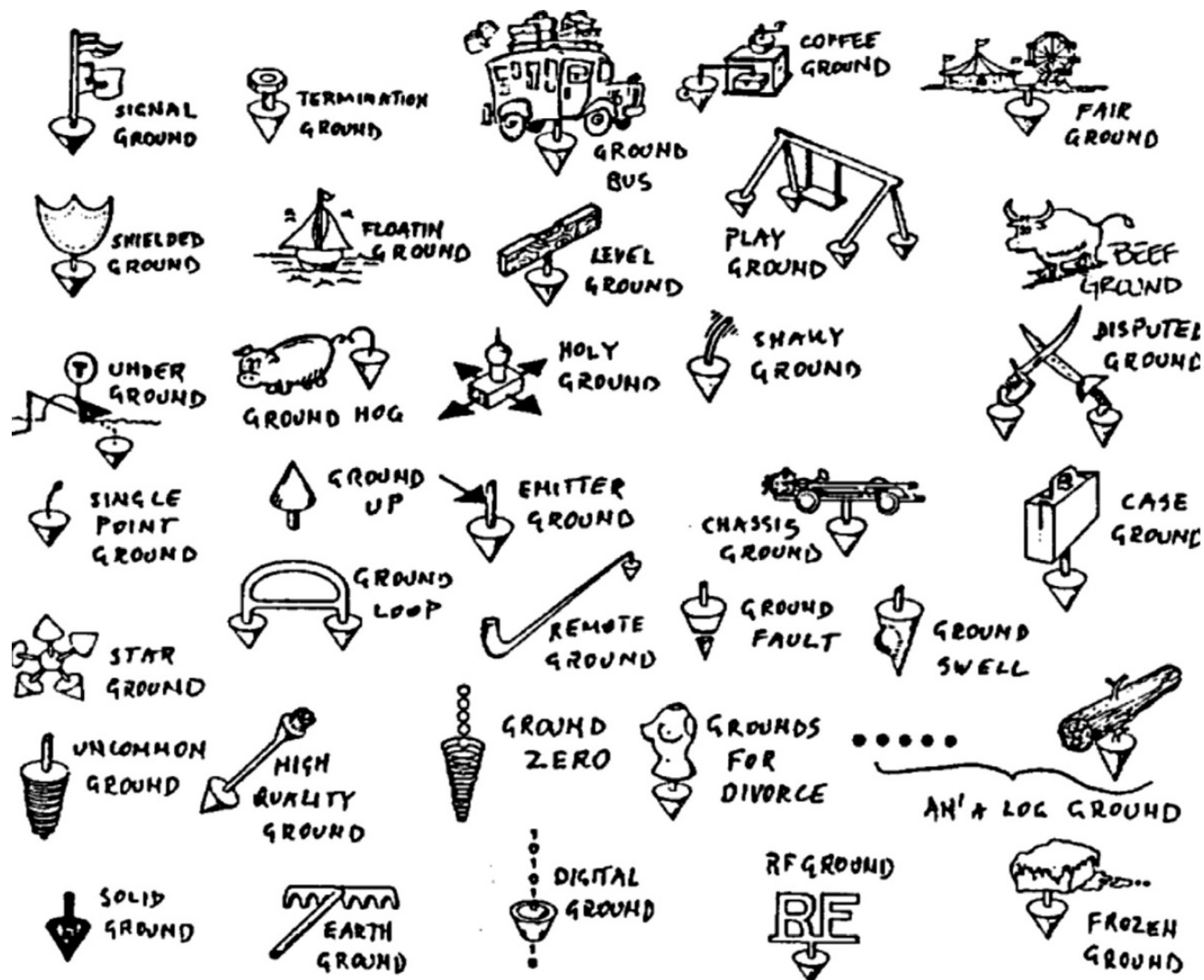
Burst (telegraph, popcorn)

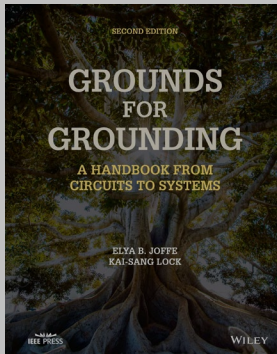


“Extrinsic” Noise i.e. EMI



Ground? Earth?





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- > Chapter 2 Fundamental Concepts
- > Chapter 3 The Grounds for Grounding
- > Chapter 4 Fundamentals of Grounding Design
- > Chapter 5 Bonding Principles
- > Chapter 6 Grounding in Power Transmission and Distribution Networks
- > Chapter 7 Grounding for Generators, UPSs, VSDs, and Instrumentation
- > Chapter 8 Grounding for Lightning Protection Systems
- > Chapter 9 Integrated Facility and Mobile/Transportable Vehicle Grounding Systems
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- 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.

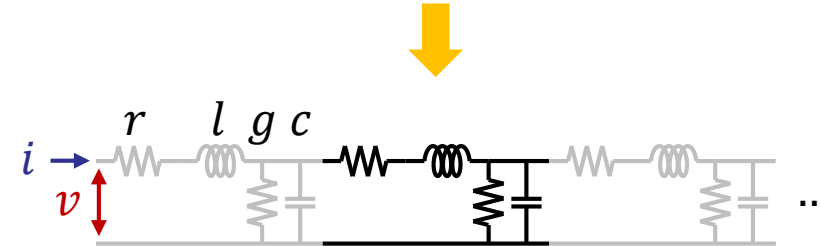
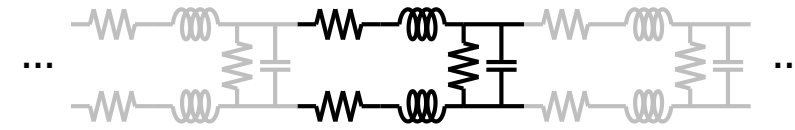
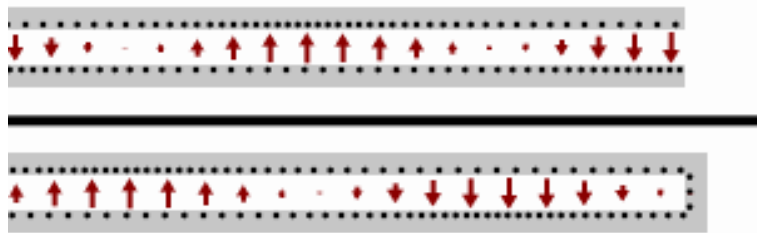
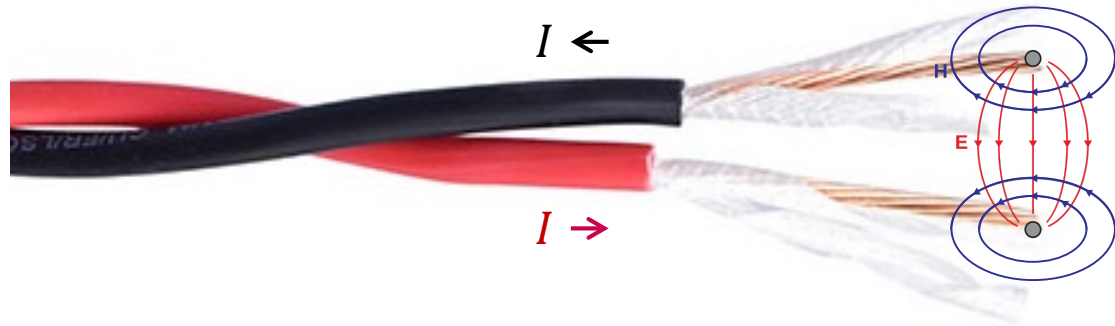
A single point ground that is effective over a large area is not possible. A common mistake by designers and installers is to have the bonding network connected to the facility steel at few (e.g. two or three) points only. The connection should be made to an earth return either at a single point, or 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



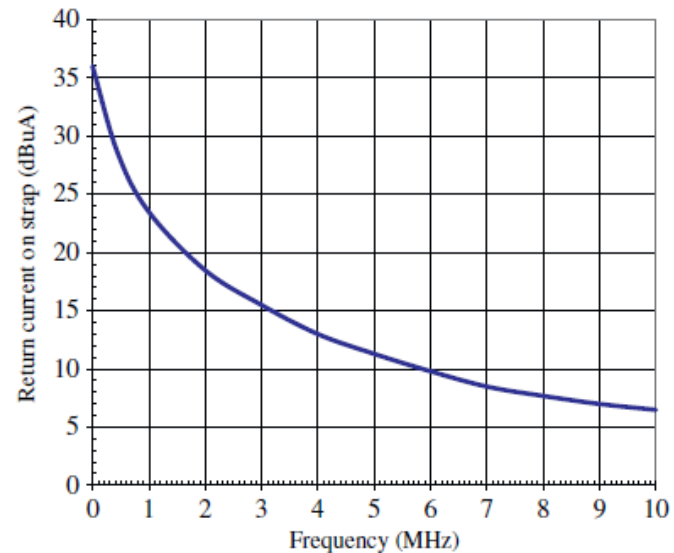
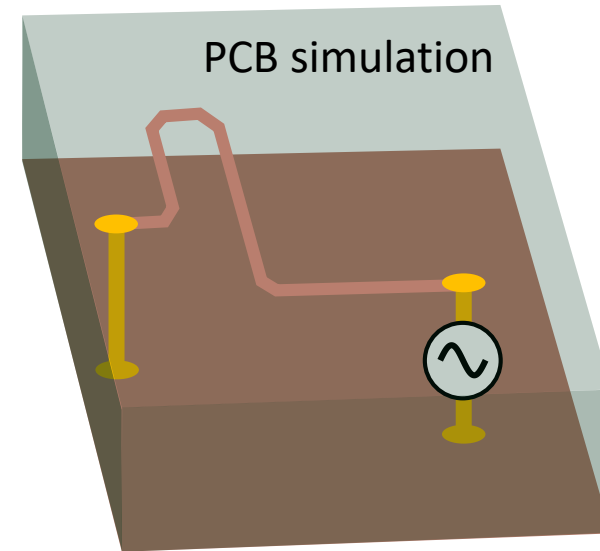
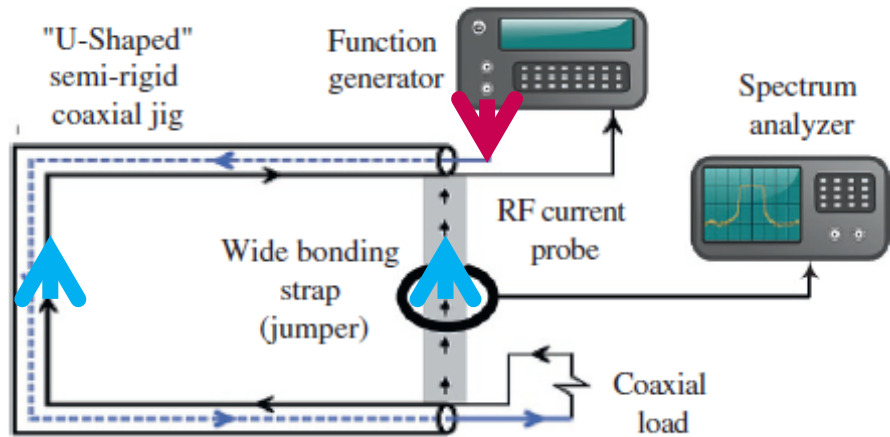
$$[\partial^2 - k^2] \begin{pmatrix} v \\ i \end{pmatrix} = 0$$

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

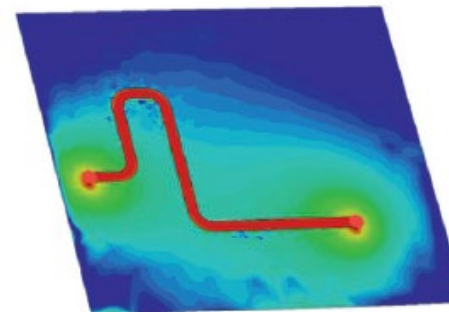
$$I_{\parallel} = \oint d\vec{l} \cdot \vec{H}, \quad V_{\perp} = \int d\vec{l} \cdot \vec{E}, \quad Z_{\text{RF}} = \frac{V_{\perp}}{I_{\parallel}}$$

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

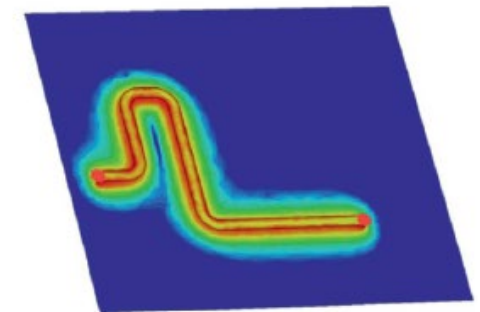
Ground = Current Return Path



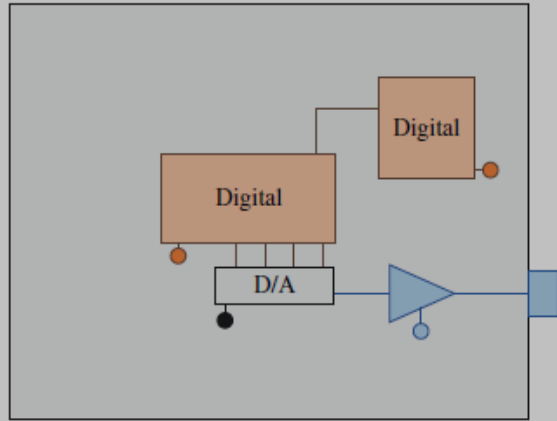
Low- f



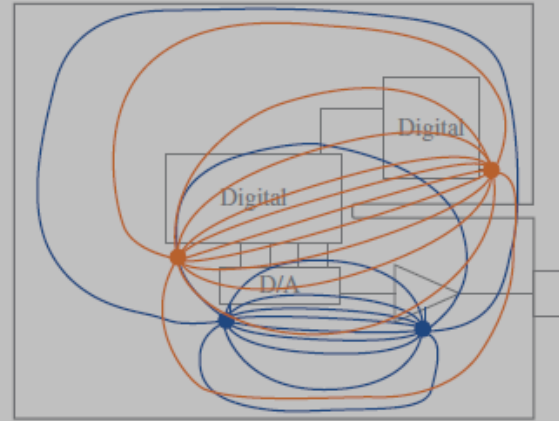
High- f



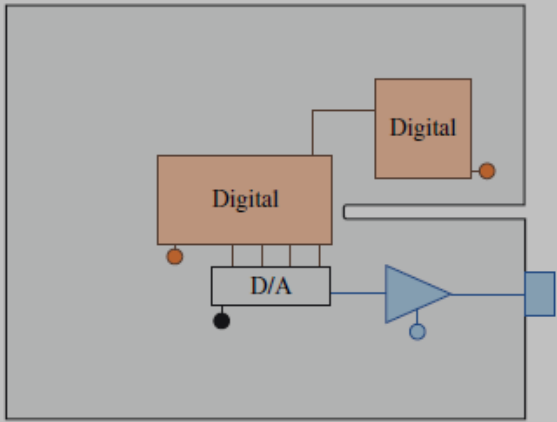
RF-PCB examples



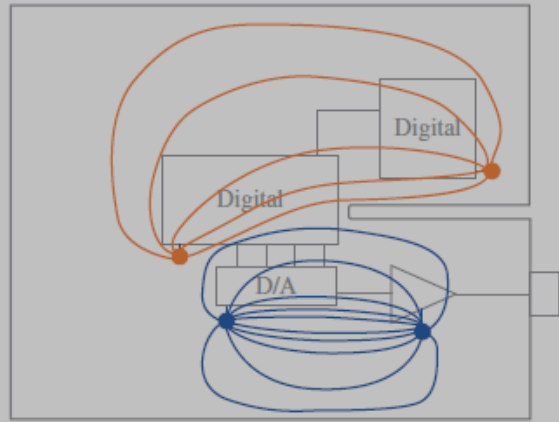
(a)



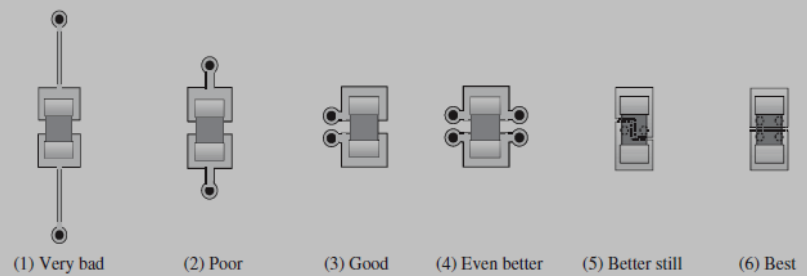
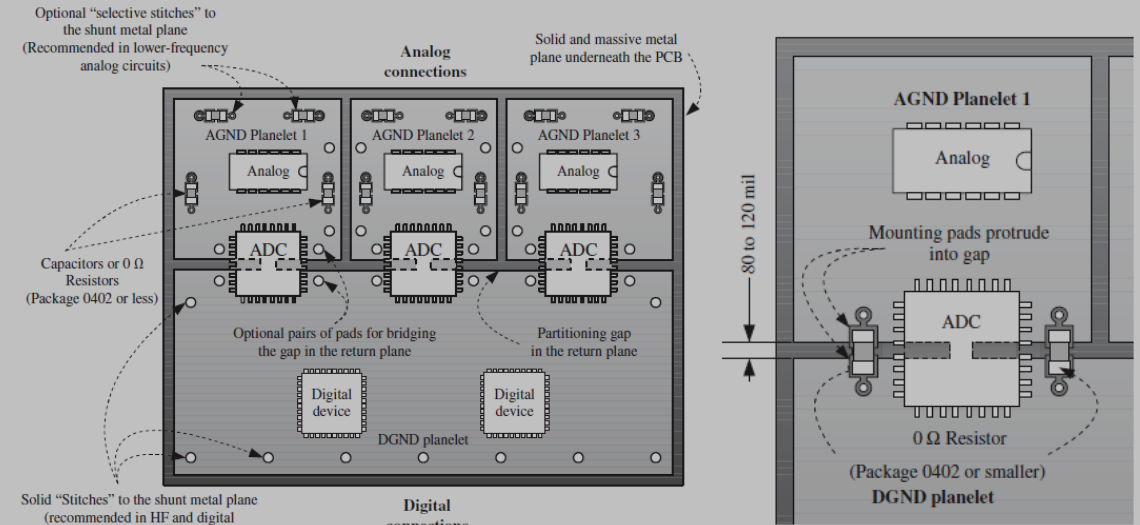
(b)



(a)



(b)

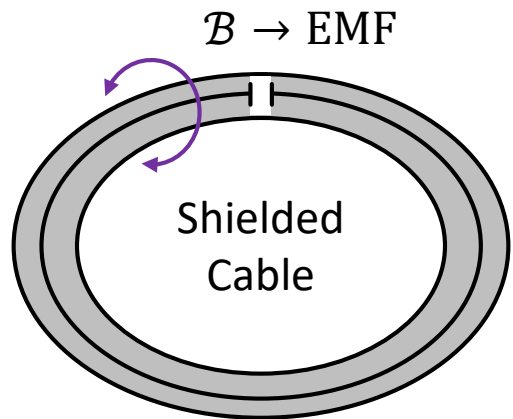
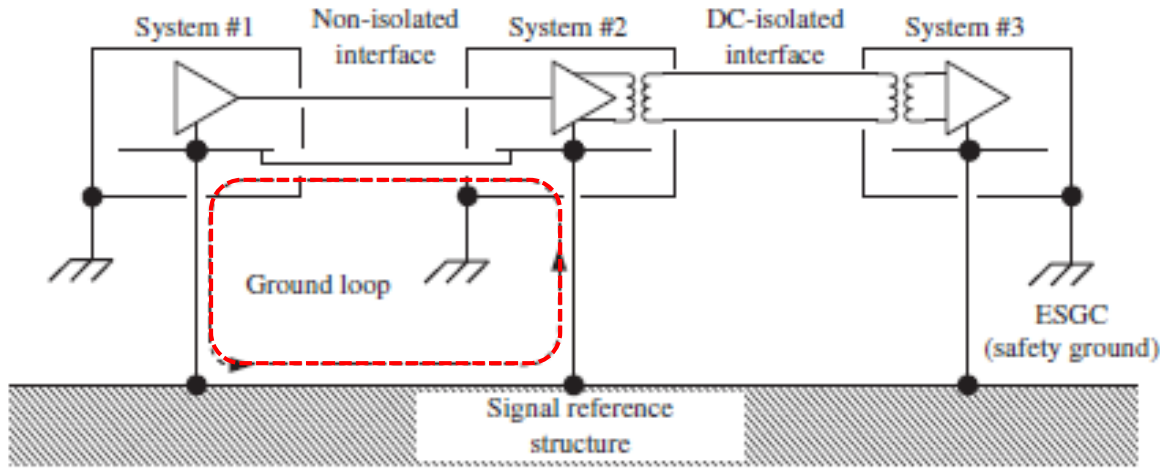


Standard MLCC chip design

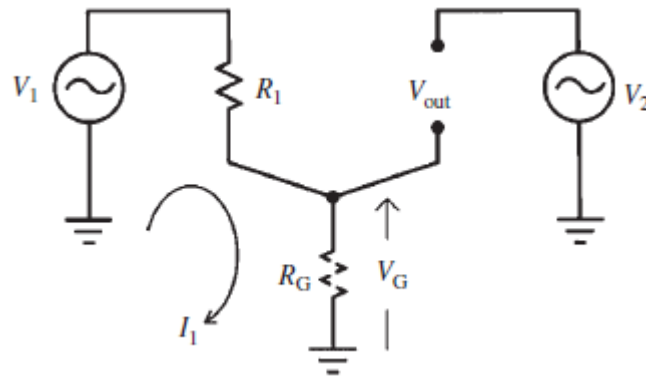


Low-ESL (LICC) ("Reverse Geometry") MLCC Chip Design

Problem 1: Ground Loops

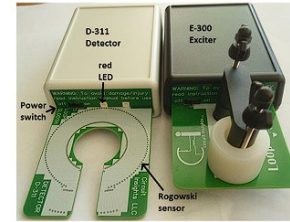


AC loop is still a loop
Also, hot loops too



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

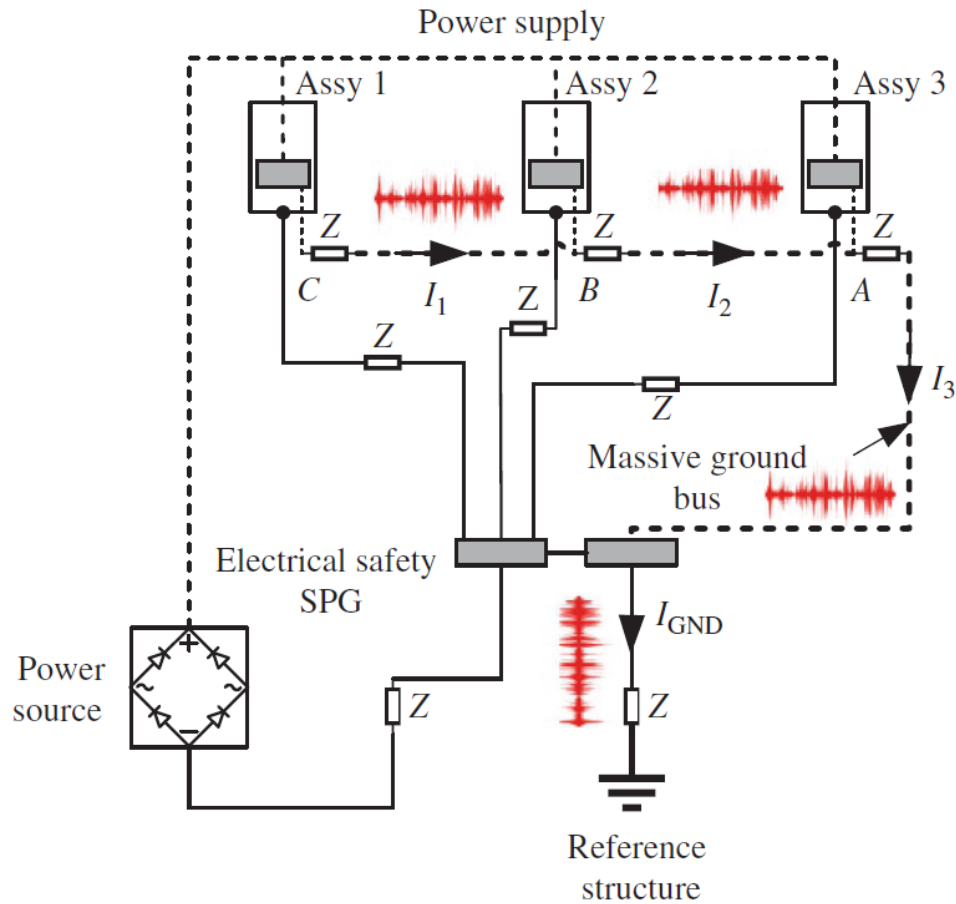
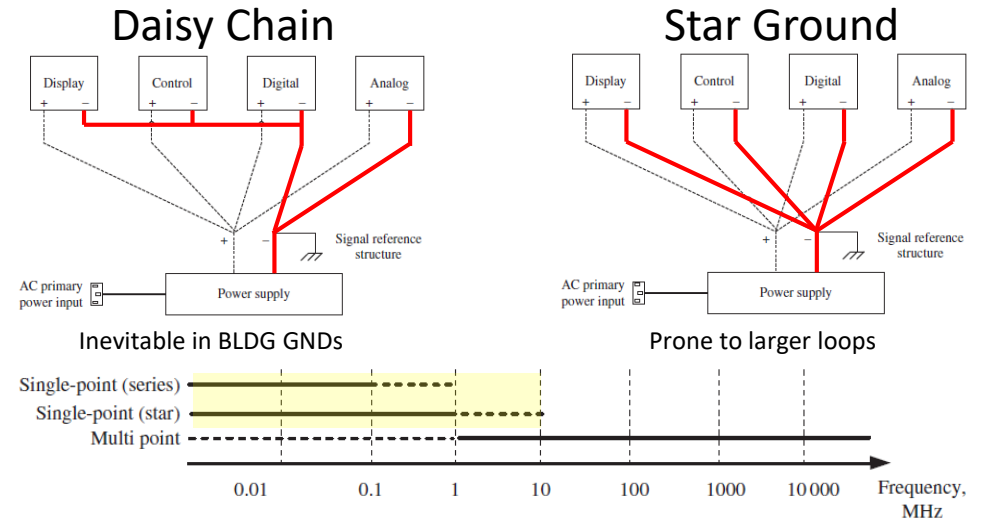
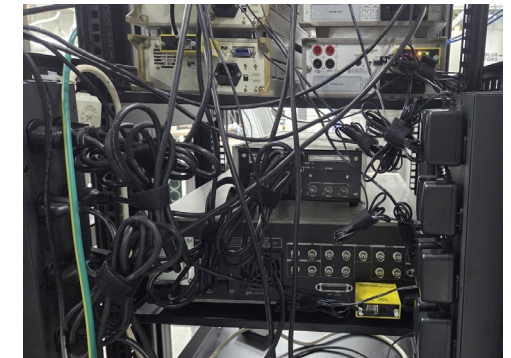


Figure 4.30 Common impedance coupling is not eliminated in the “daisy chain” (series connection) single-point grounding scheme.

- Solution 1: One Star ground for one system



- Solution 2: Just... clean up



Problem 3: Bad Connections

Anodized areas = bad conduction



Alligators and bananas are weak

AI 개요

Ideally, a crocodile (alligator) clip should have a very low electrical resistance of under 0.1Ω . However, typical budget test leads often range from 0.5Ω to 1.5Ω due to thin wires and poor crimping. [EEVblog +1](#)

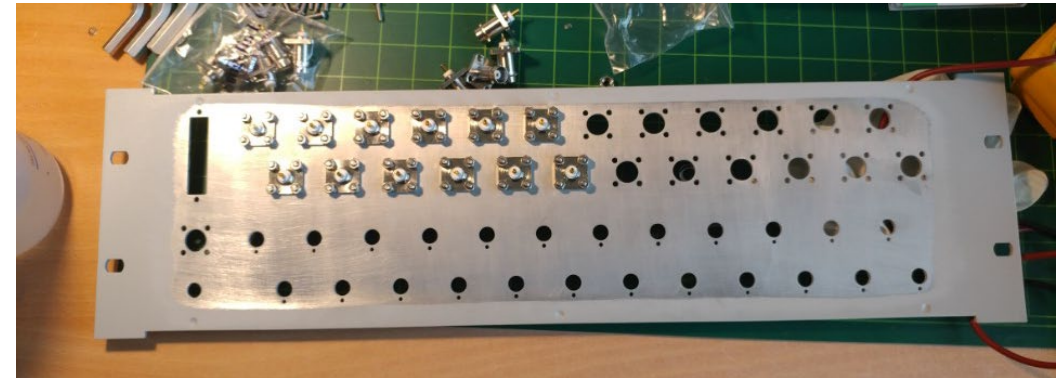


Not enough

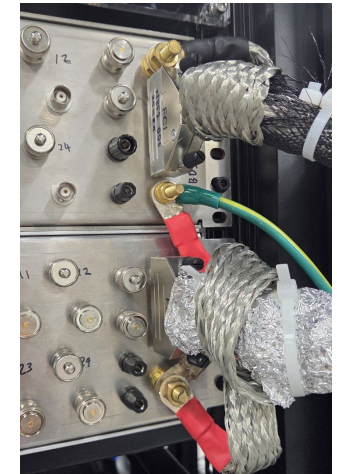
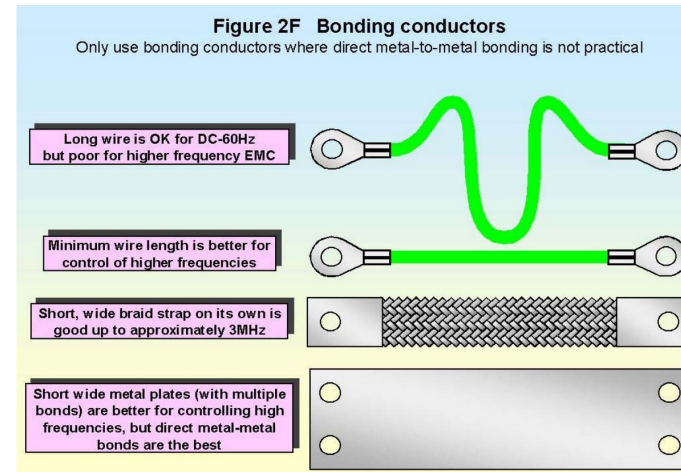


Too thick

- Solution 1: Sand away anodizations

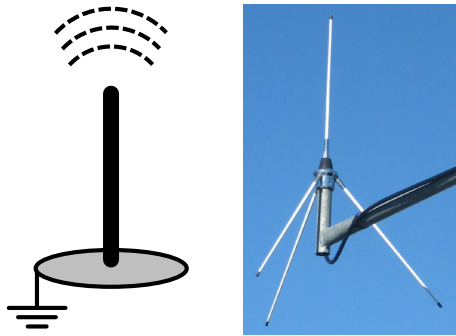


- Solution 2: Use thick braids and strong bolts!



Resistance between grounds are competitions in $m\Omega$ ranges!!!

Problem 4: Antenna



Shortest Antenna
= Quarter-wave
1 GHz = 30 cm
Lumped if < 3 cm

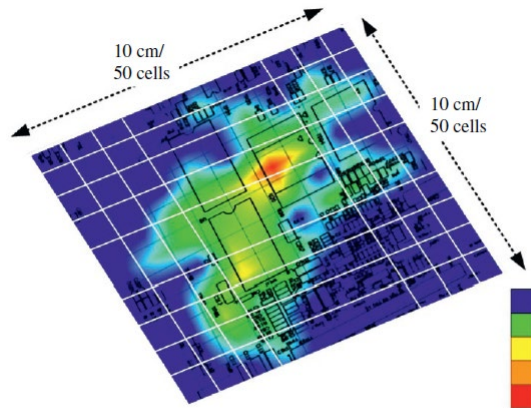
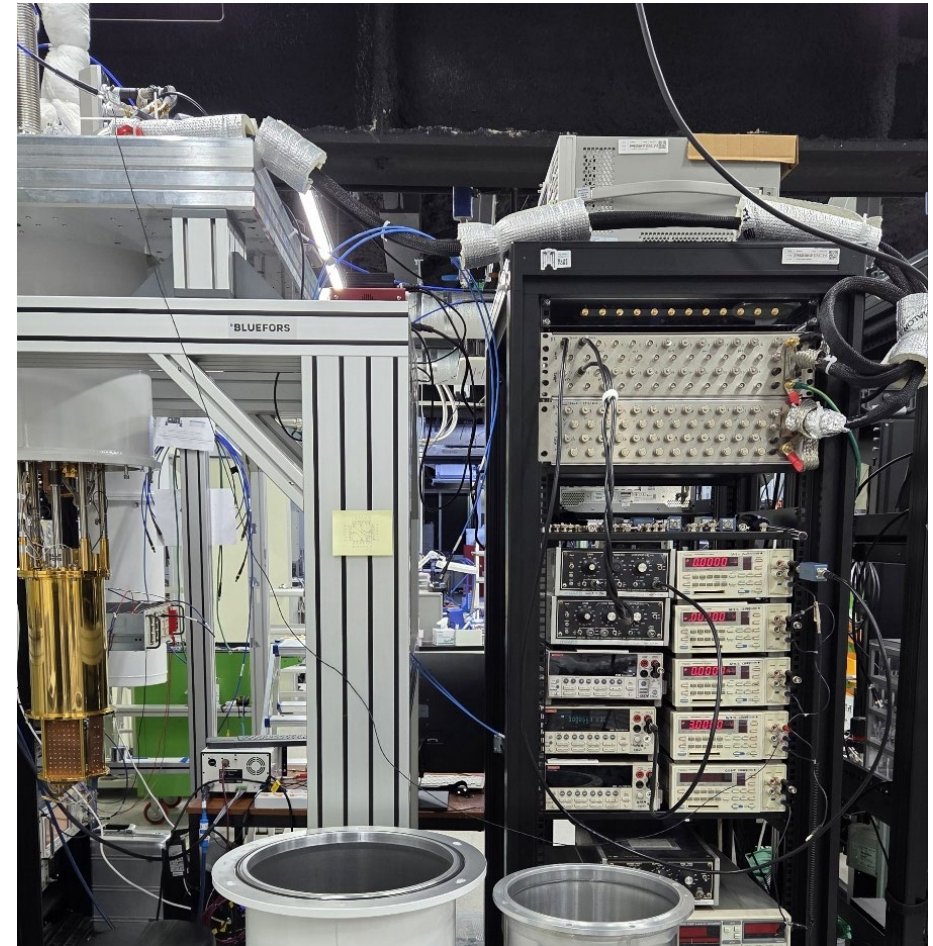


Figure 13.170 Illustration of the manner of peak noise voltage distribution throughout the 2500 meshed circuit nodes across the power and return planes.

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

- Solution: Compactify your setup (short cables)



Problem 5: Bad Neighbors

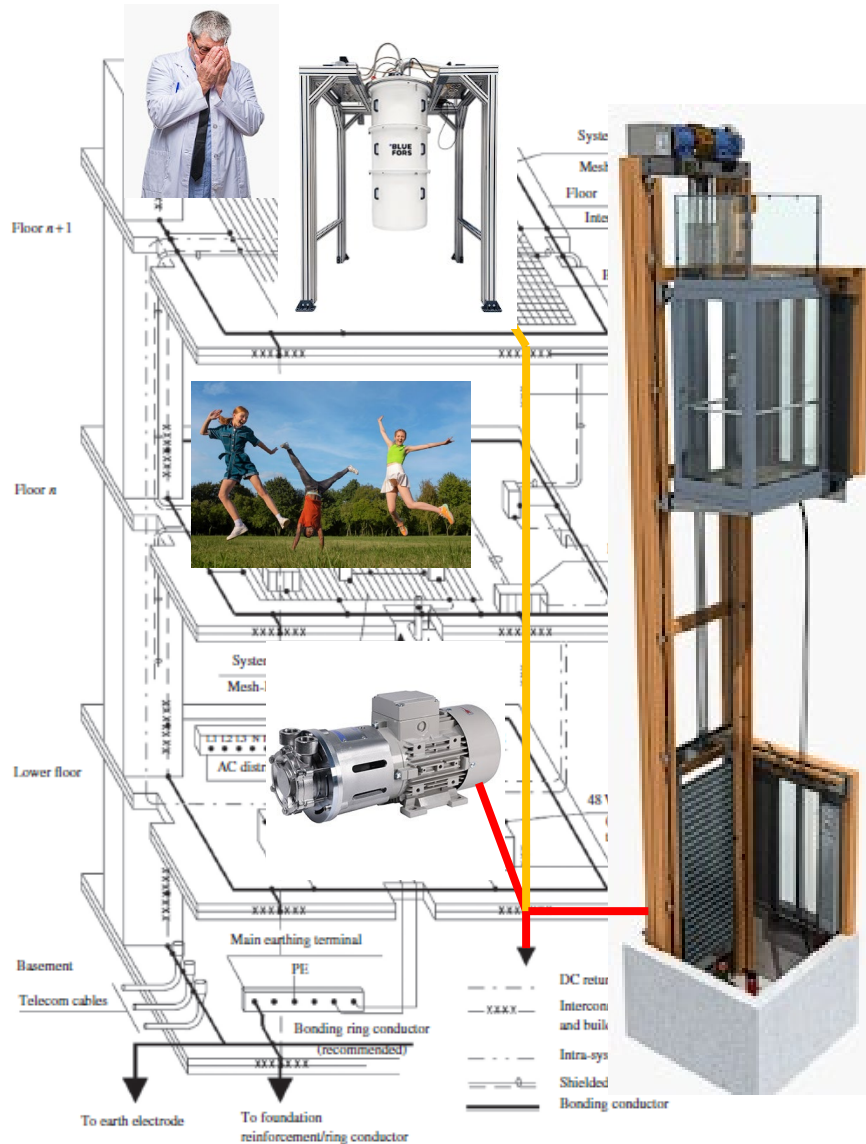


Figure 4.17 Mesh-bonding network installation inside a telecommunication building [3, 4]. Source: ITU-T

- 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

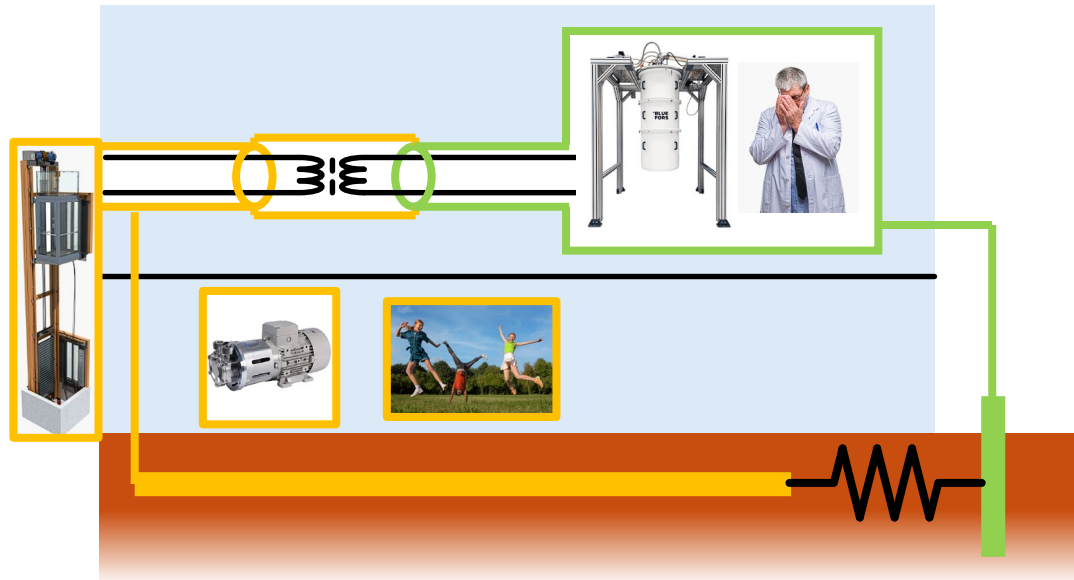


Power Filter:
FN9246-10-06



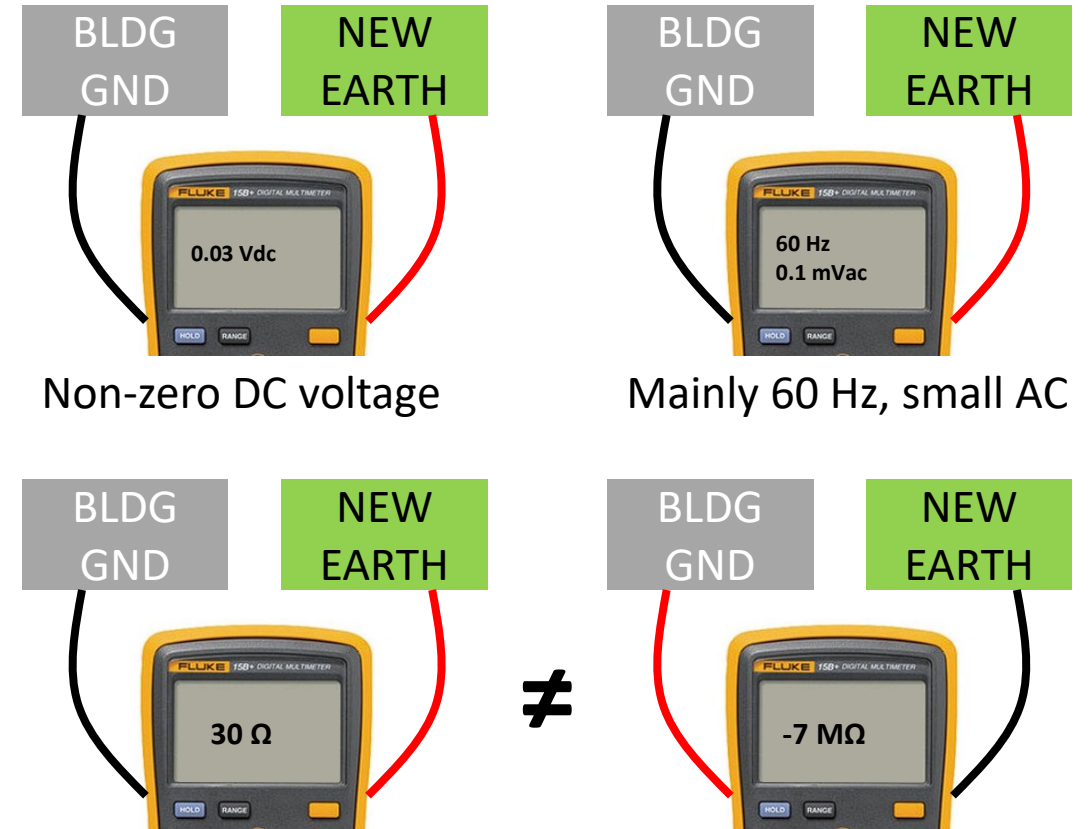
New Earth

Earth "Ground"



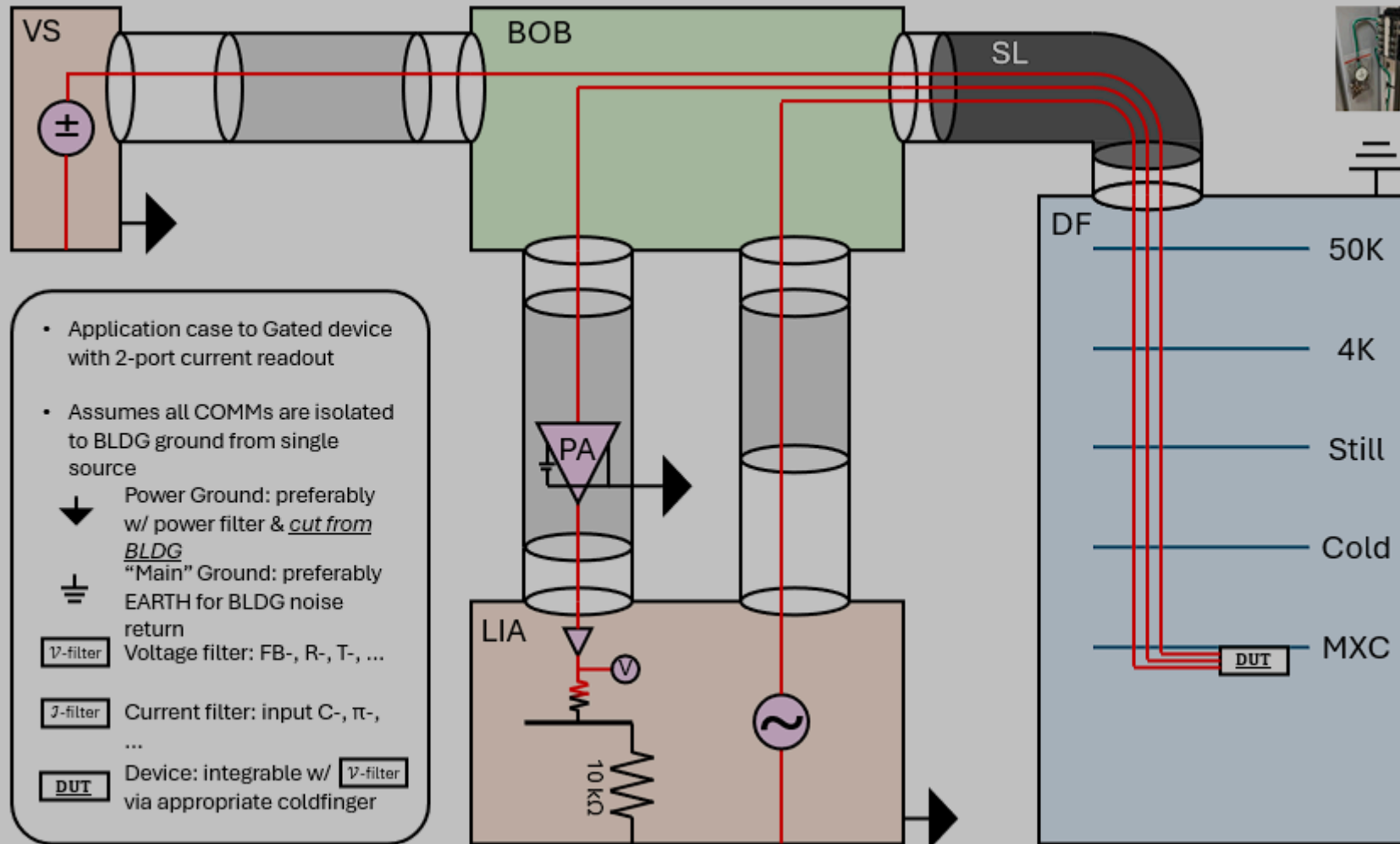
Earth is a **VERY bad** conductor
 Soil : Copper = Glass : Soil

- App note: How to check Earth isolation

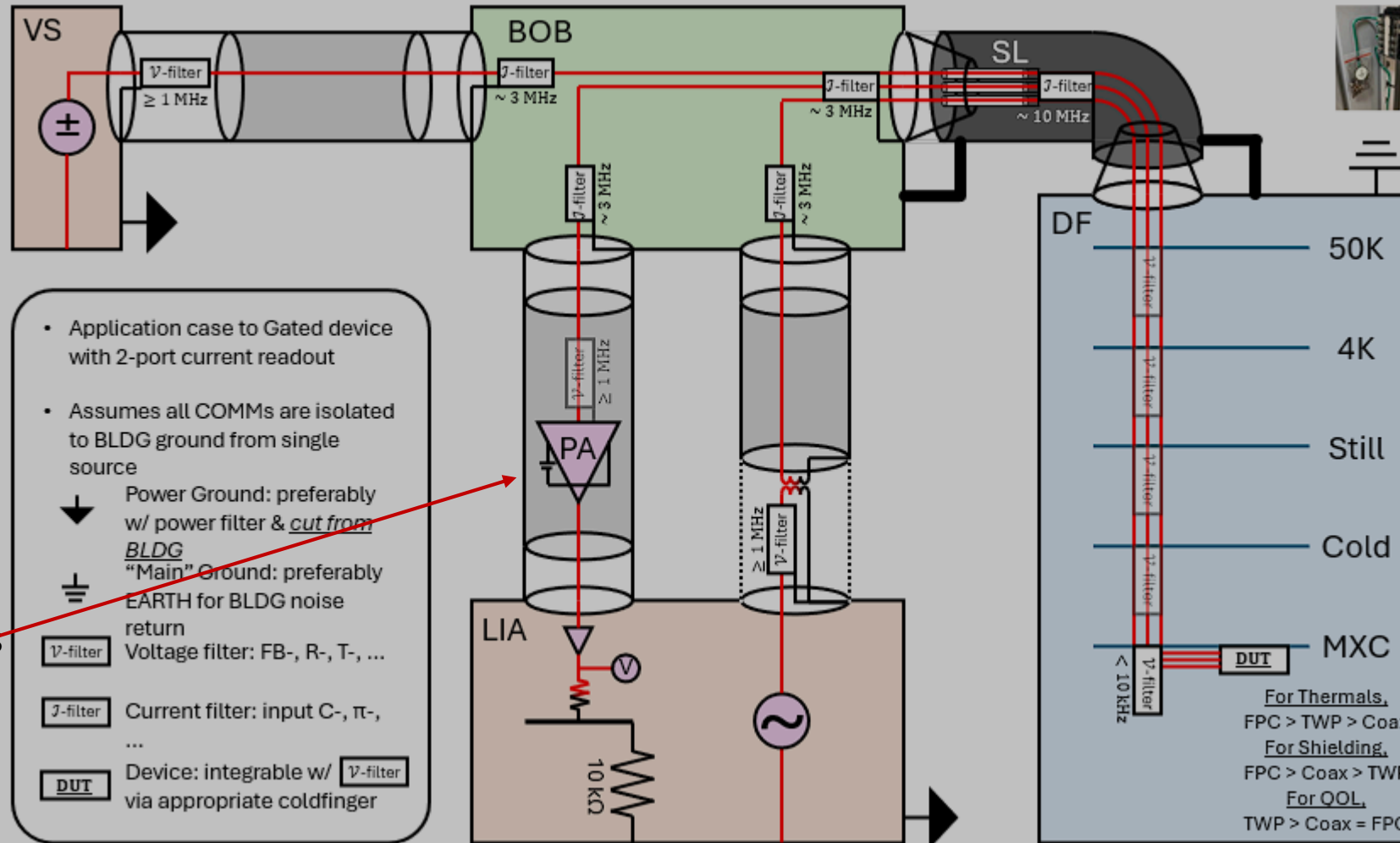


If $V_{dc} \neq 0$, then these two should different
 You can get "negative" resistance readings...

Example: Before & After



Example: Before & After

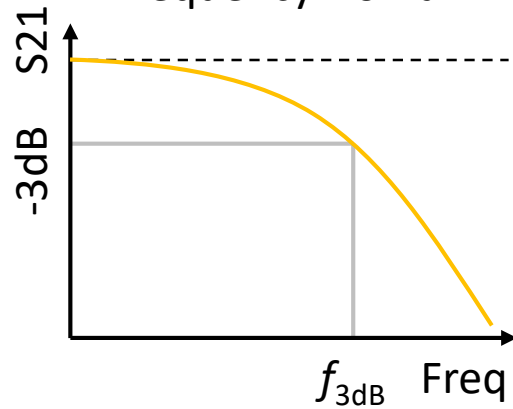


Note: the pre-amp is always most susceptible to noise pick-up!

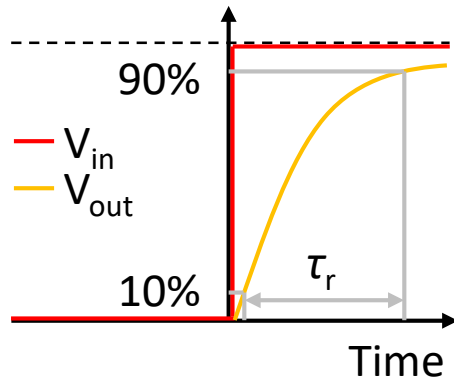
Using Voltmeters

Lowpass-filtering

Frequency Domain



Time Domain

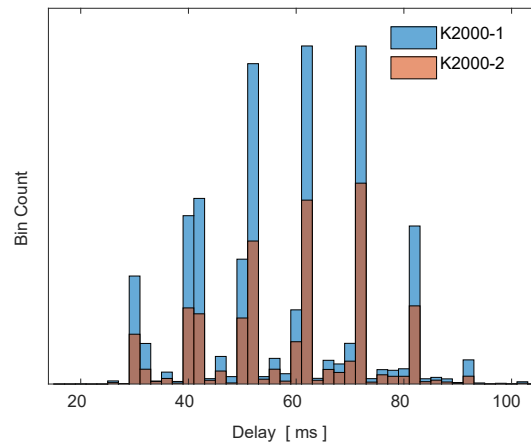


$$\tau_r * f_{3dB} = 0.35$$

Lowpass-filtering



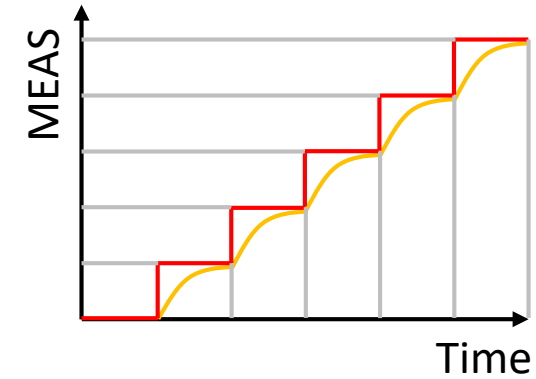
K2000 response delay [2 ms Bin Count of 10001]



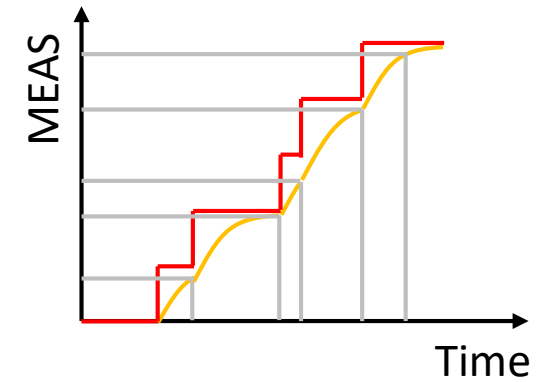
Clock: 1 NPLC = 17 ms

Waitless Measure

Uniform



Jittering

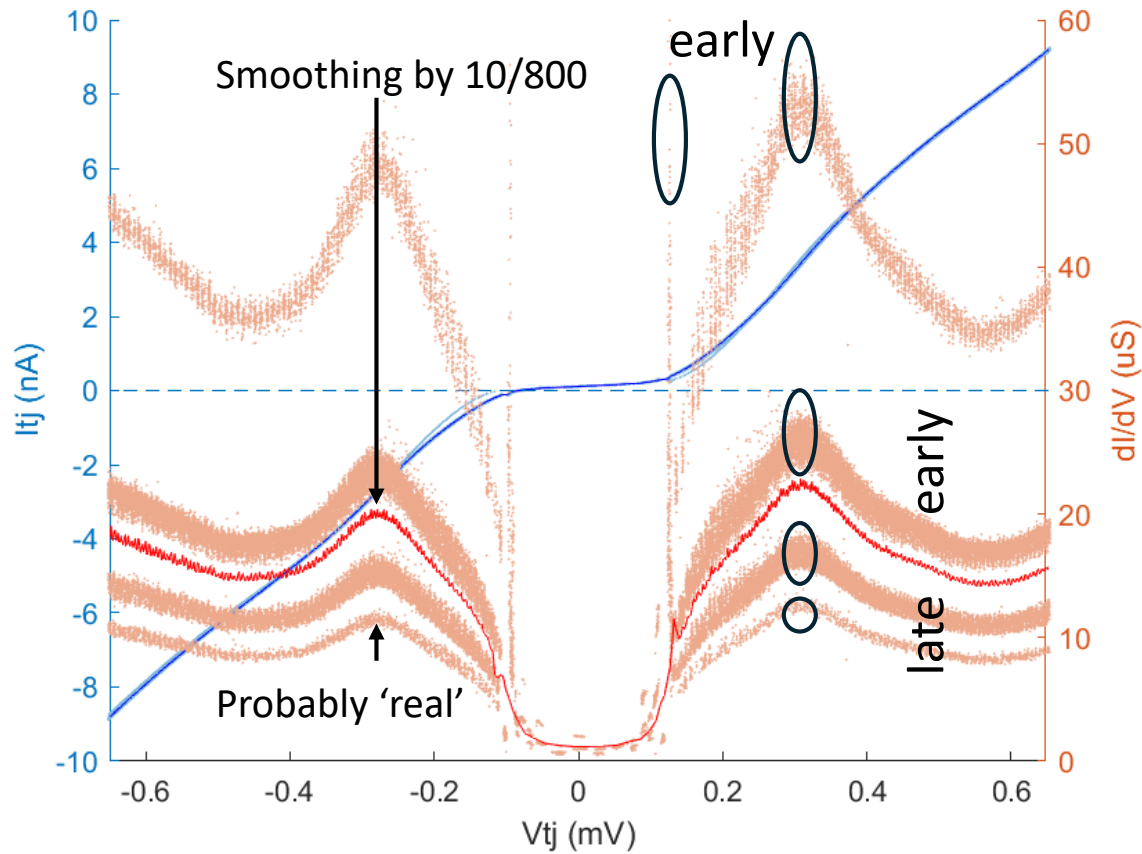


τ is for ENTIRE system

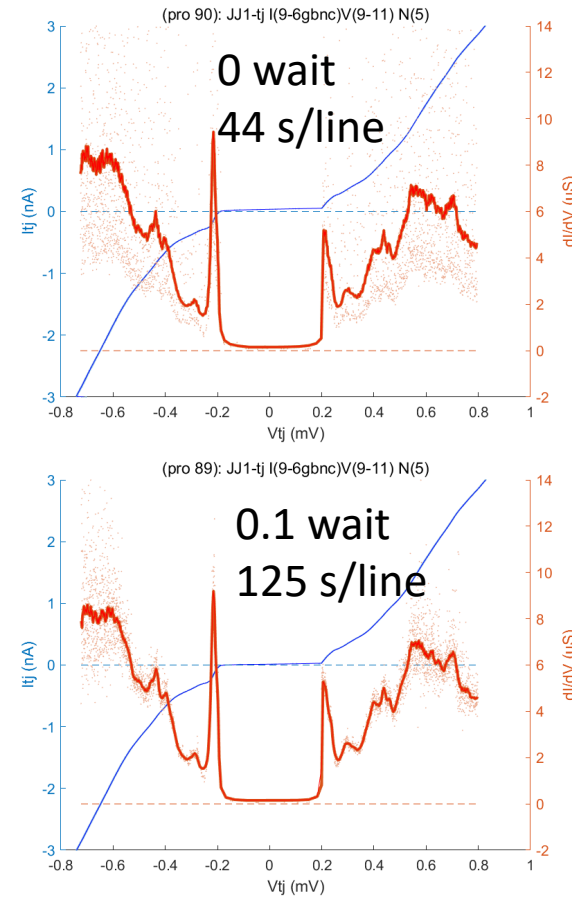
Fridge LPF, DUT, BOB, Ithaco 1201, K2000...

Using Voltmeters

Measuring a Tunnel Junction

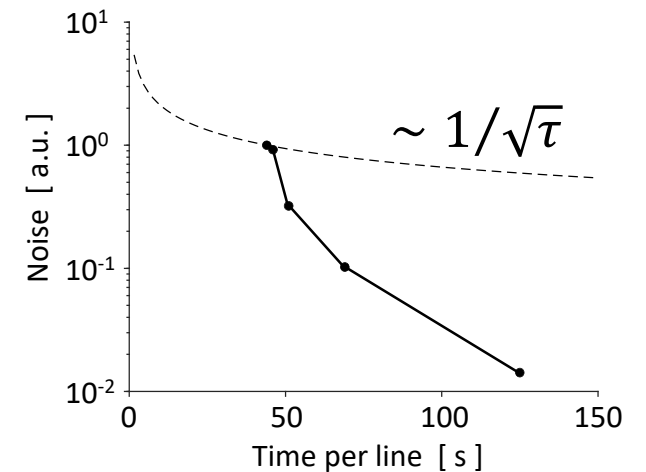


SNR vs. Measurement time



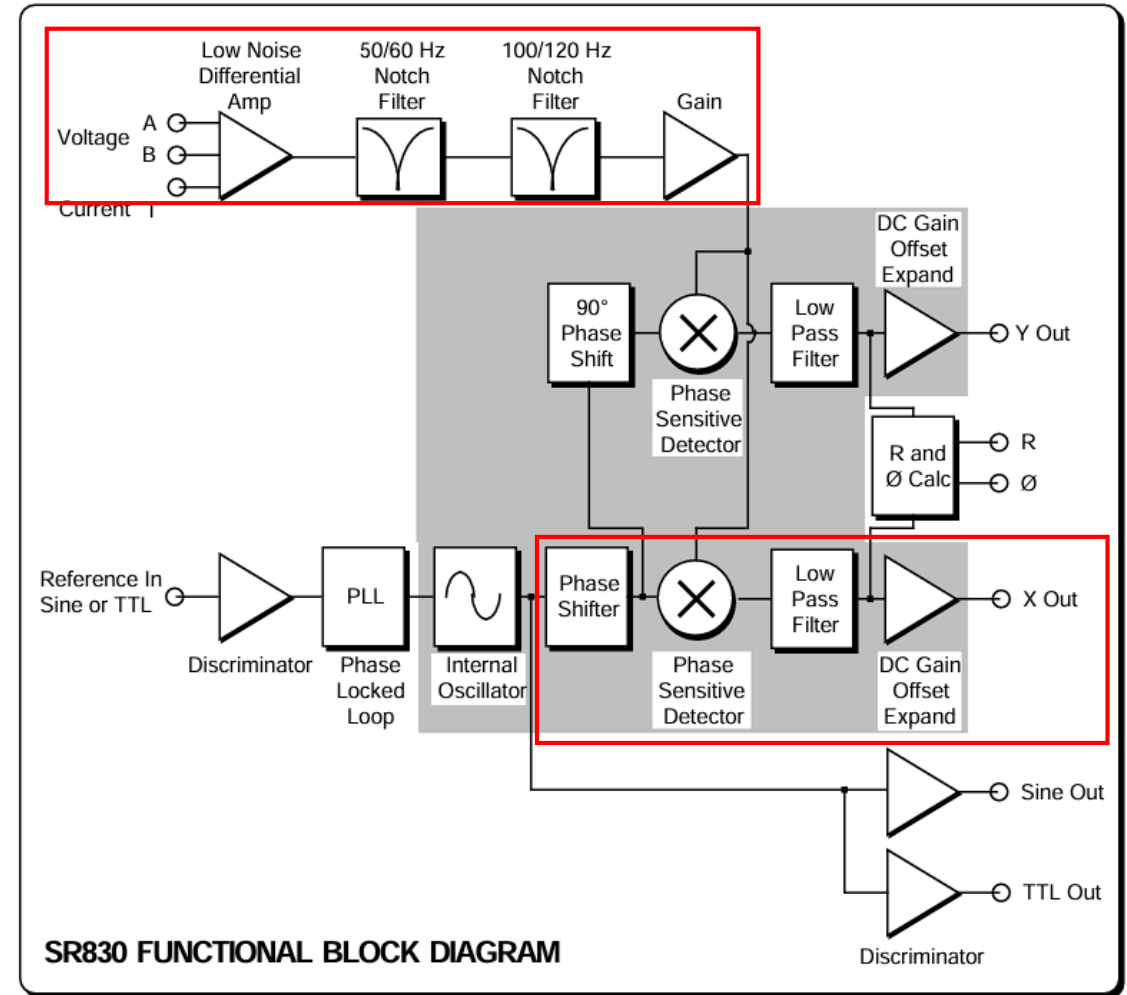
Data $y_i = y_0 + x_i$
 Mean $\bar{y} = N^{-1} \sum y_i$
 'Error' $\epsilon_i = y_i - \bar{y}$
 Noise $\epsilon_{\text{rms}} = \sqrt{N^{-1} \sum \epsilon_i^2}$

By Central Limit Theorem,
 $\epsilon_{\text{rms}}/\bar{y} \approx 1/\sqrt{N} \sim 1/\sqrt{\tau}$



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

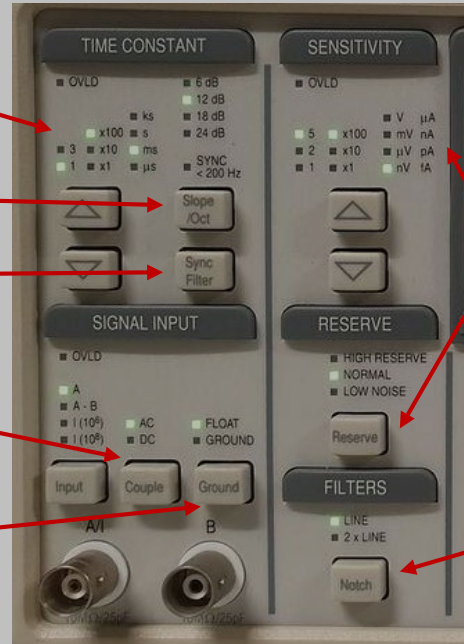
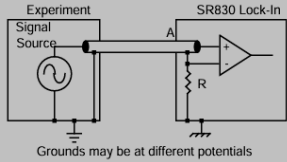
18 dB/oct	DC gain (dB)	min time constant
<62	<62	10 μ s
<92	<92	30 μ s
<122	<122	100 μ s
<152	<152	300 μ s
<182	<182	1 ms

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

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 k Ω and Ground uses 10 Ω . 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



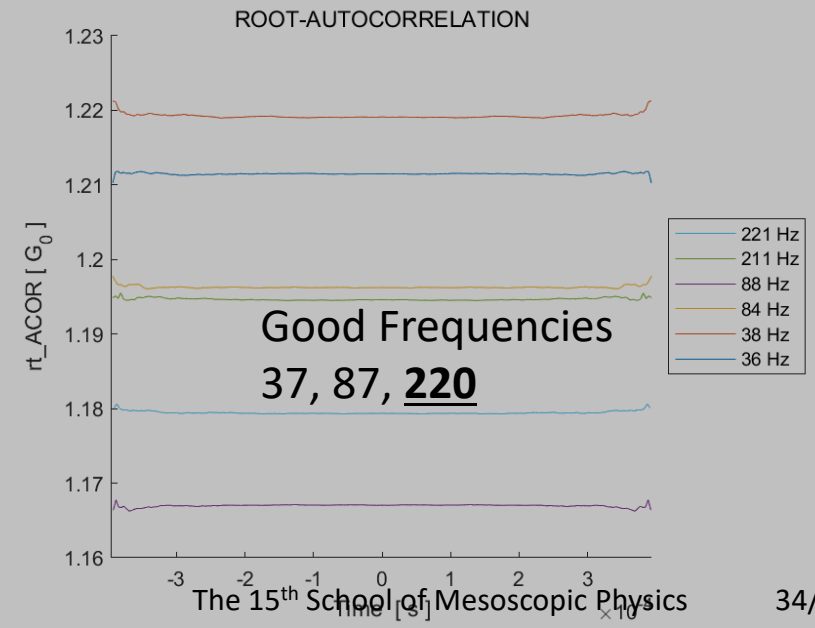
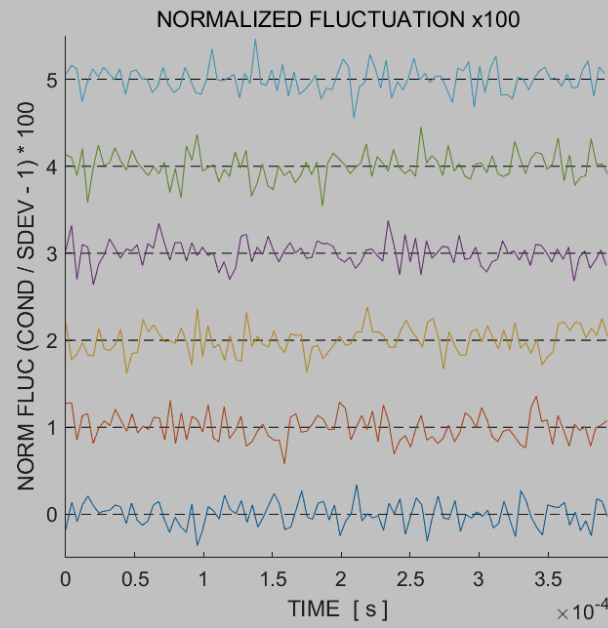
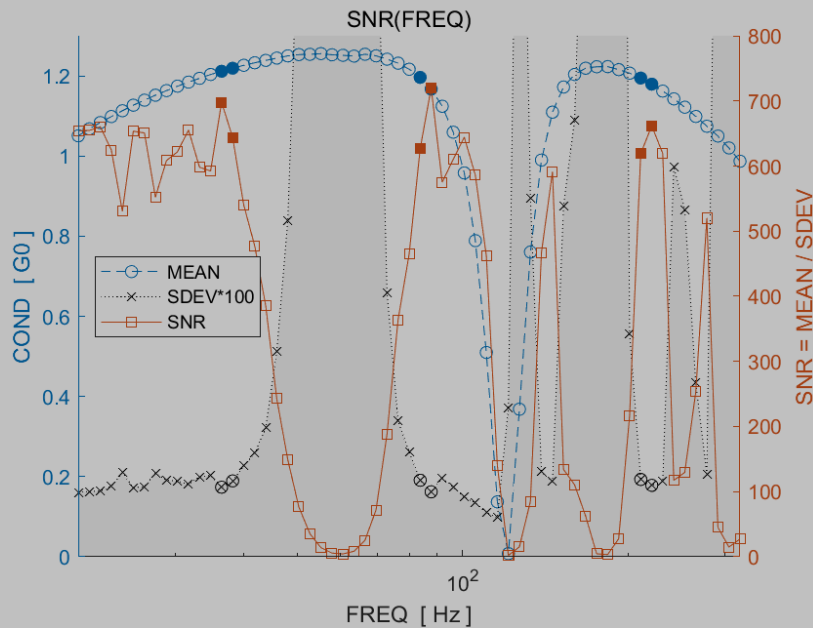
The traditional definition of dynamic reserve is the ratio of the largest tolerable noise signal to the full scale signal, expressed in dB. For example, if full

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 μ V	16	46	66
200 μ V	24	54	74
100 μ V	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

Rule of thumb per frequency $f \ll f_{3dB}$

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	$> 3 * \text{max signal}$
RSRV	as low as possible
FILT	BOTH



Using Lock-in Amplifiers

TIME CONSTANT

- OVL D
- 6 dB
- 12 dB
- 18 dB
- 24 dB
- SYNC < 200 Hz

ks
x100 s
3 x10 ms
1 x1 ms

Slope /Oct
Sync Filter

SENSITIVITY

- OVL D
- 5
- 2
- 1
- x100 mV
- x10 μV
- x1 nV
- V

V
mV
μV
nV

SIGNAL INPUT

- OVL D
- A
- A - B
- 1 (10⁶)
- 1 (10³)
- AC
- DC
- FLOAT
- GROUND

Input Couple Ground

AI 10MW/25pF
B 10MW/25pF

RESERVE

- HIGH RESERVE
- NORMAL
- LOW NOISE

Reserve

FILTERS

- LINE
- 2 x LINE

Notch

Frequency

- $f \ll f_{3dB}$

Time Constant

- Kinda like averaging
- $t_c > \max(3/f, 10 \text{ ms})$

Couple, Ground

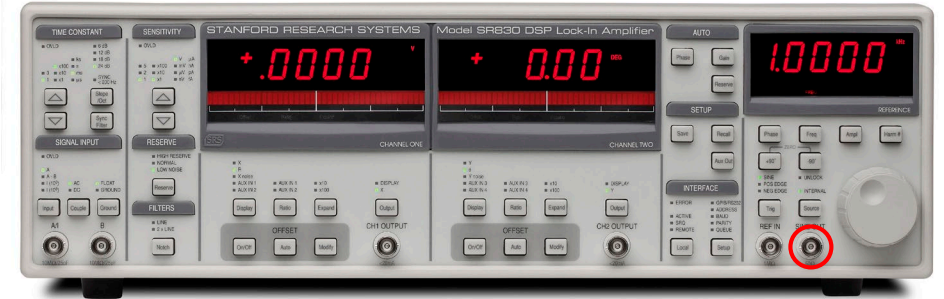
- Try all

Reserve

- As low as possible

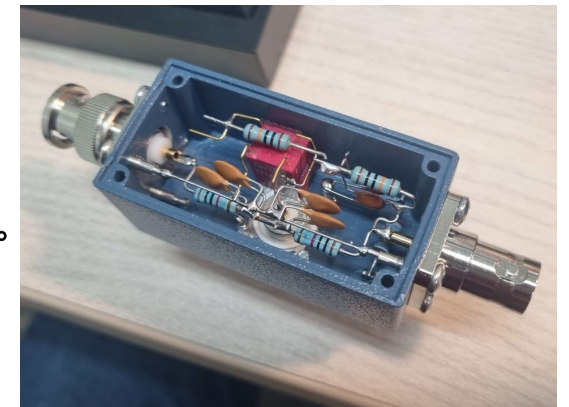
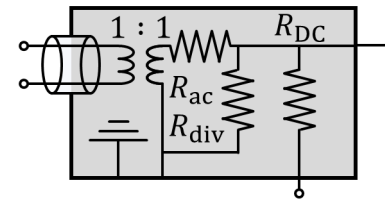
WAIT

- $T > 3 * t_c$

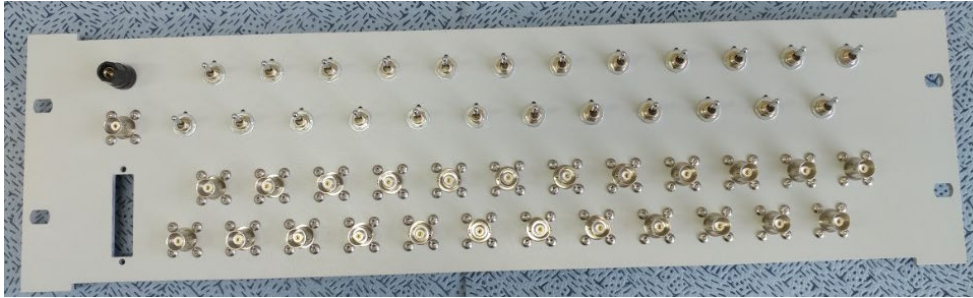


Lock-ins are NOISY machines
Sine-out is connected to power!

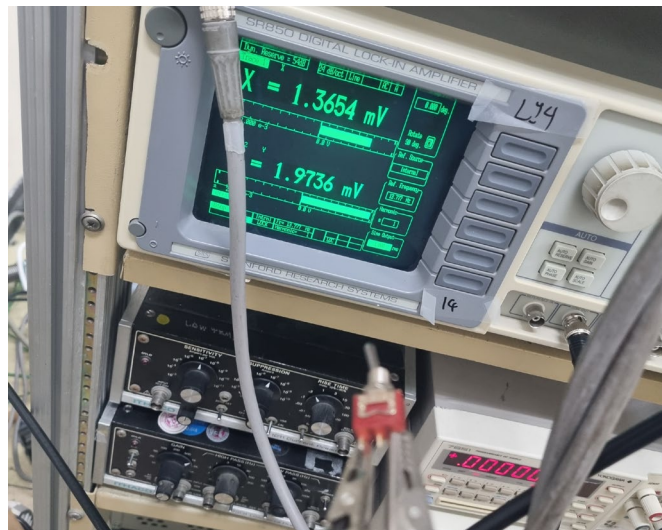
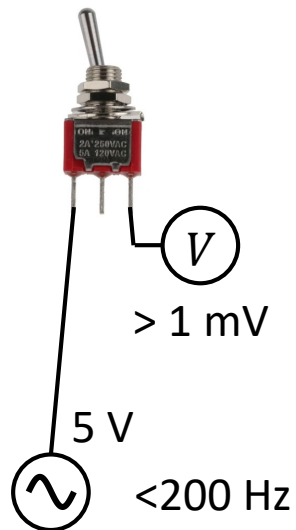
Galvanic Isolation



Breakout Box Switches

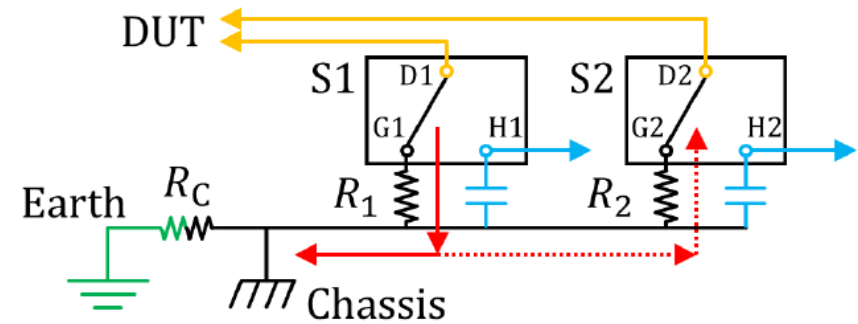


Most BOBs are controlled using switches

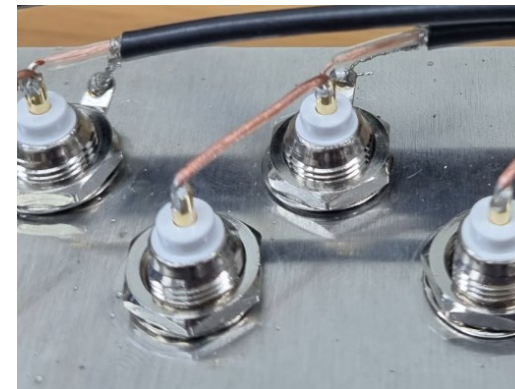


Non-capacitive leaks in most SPDT switches!

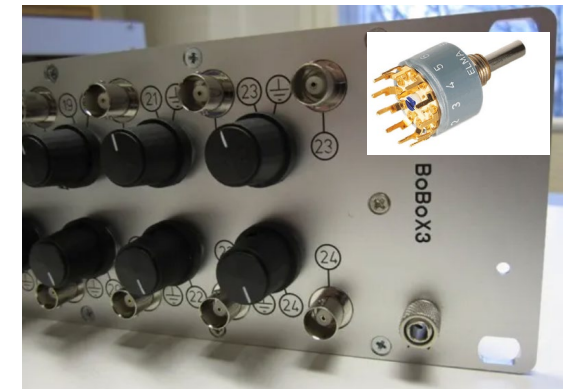
Common-Impedance Coupling



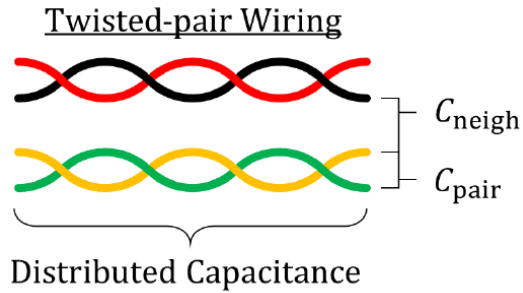
- Solution 1
Switchless BOB



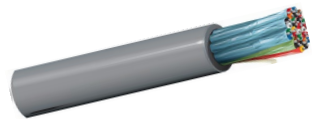
- Solution 2
Good Rotary switches



Signal Line Crosstalk



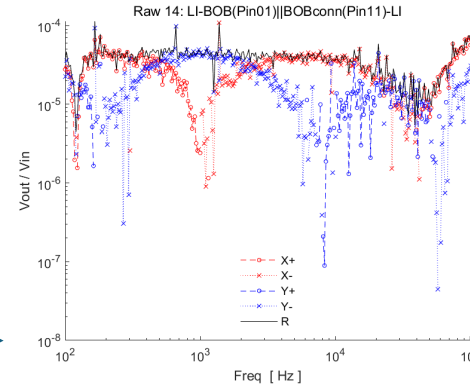
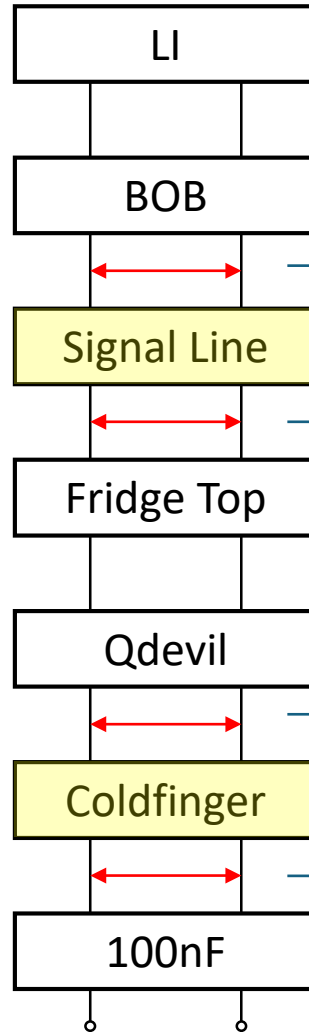
In Bluefors wiring,
 $C_{neigh} \sim 20 \text{ pF}$
 $C_{pair} \sim 220 \text{ pF}$



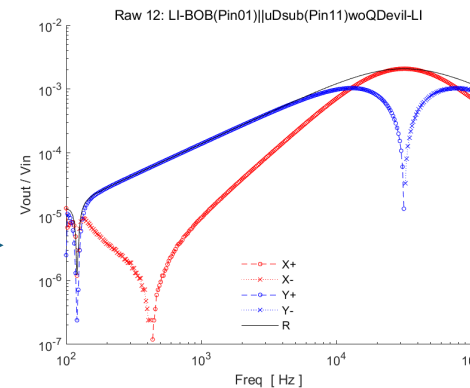
In Belden 9993
 $C_{neigh} \sim 3 \text{ pF/m}$
 $C_{pair} \sim 82 \text{ pF/m}$

All adds up to $\sim \text{nF}$
 Mixed noise path

Crosstalk V2V

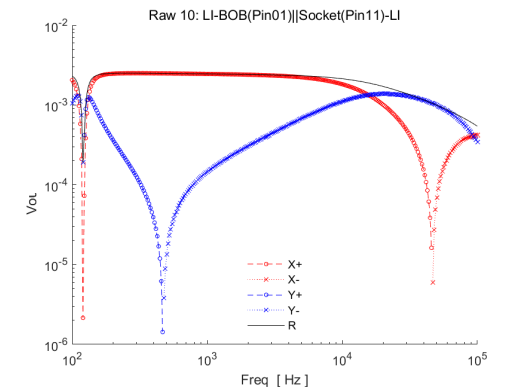
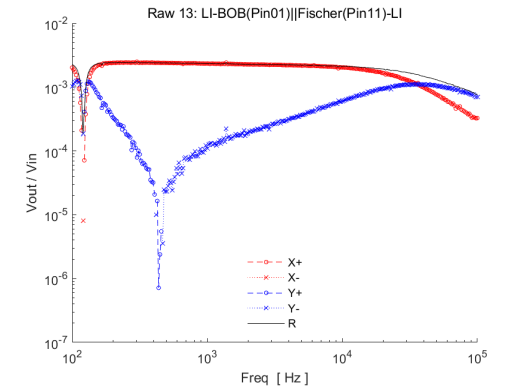


Crosstalk @ SL



Crosstalk returns @ CF

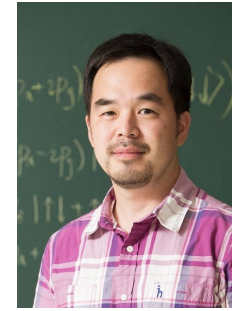
Signal line leakage measured w/ TIA @ 1kHz w/ 1Vrms



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 GNDs, 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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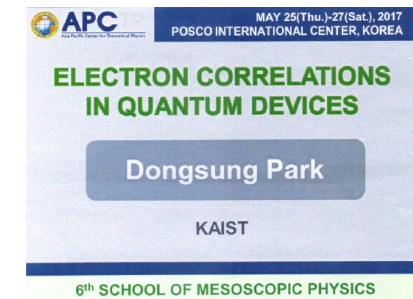
Credits to current Post-doc position



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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"

"Microwave Engineering"
"Microelectronic Circuits"
"Electromagnetic Compatibility Engineering"