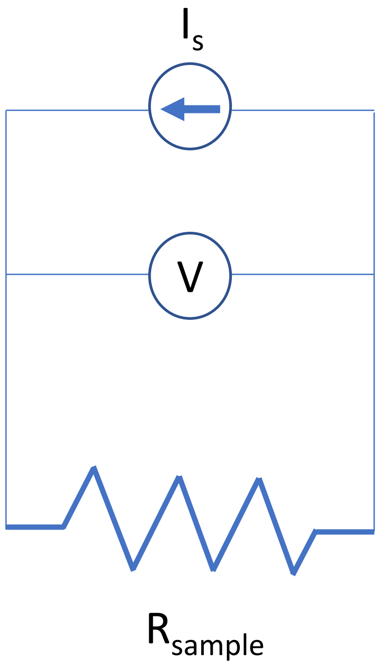
Sample Preparation and Electrical Transport

Yun Suk Eo (yeo@ttu.edu)

Acknowledgement: Dr. Ian Hayes, Dr. Rahul Sharma

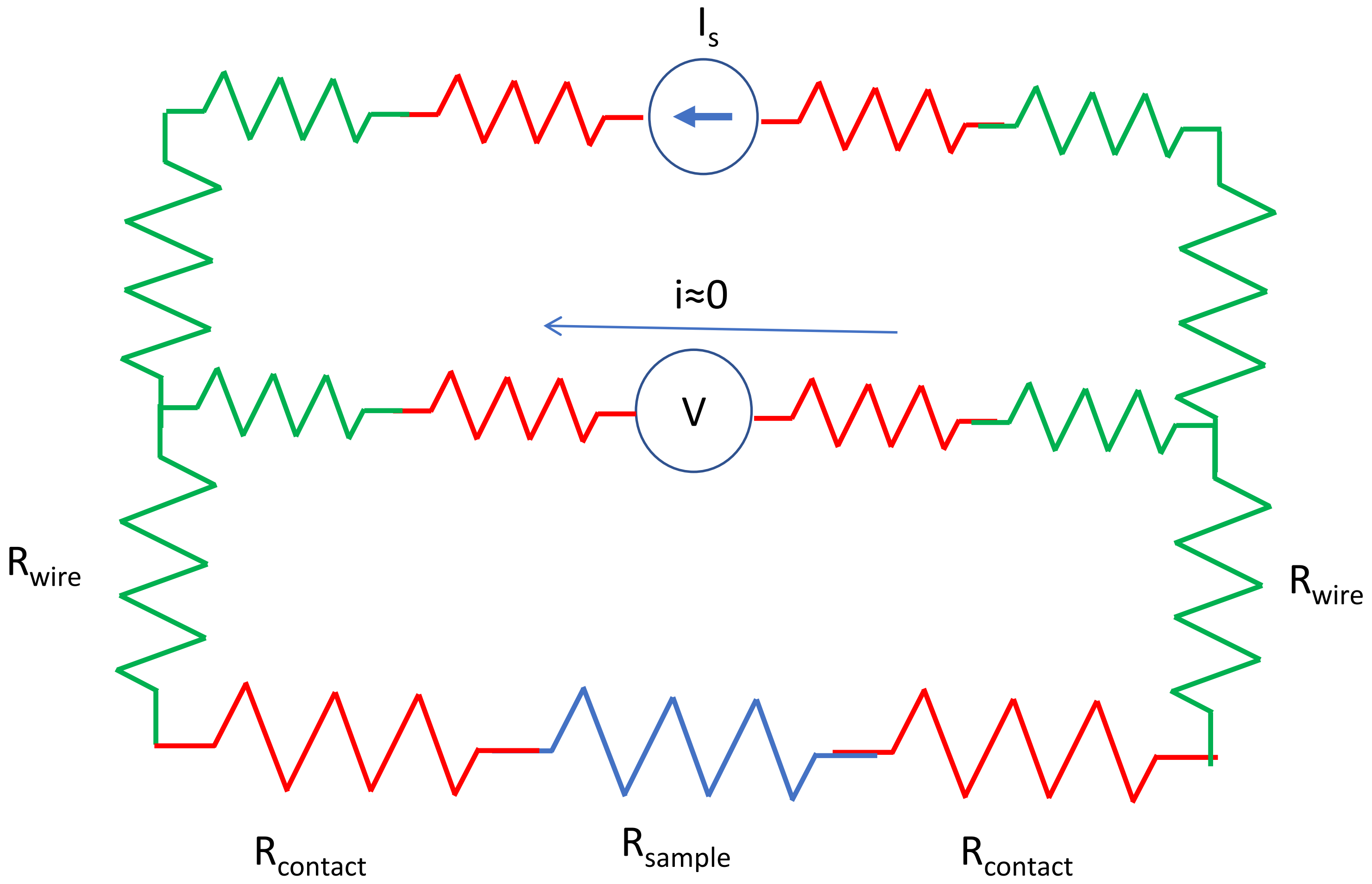
Two Terminal vs. Four Terminal Measurements

Two Terminal Measurement

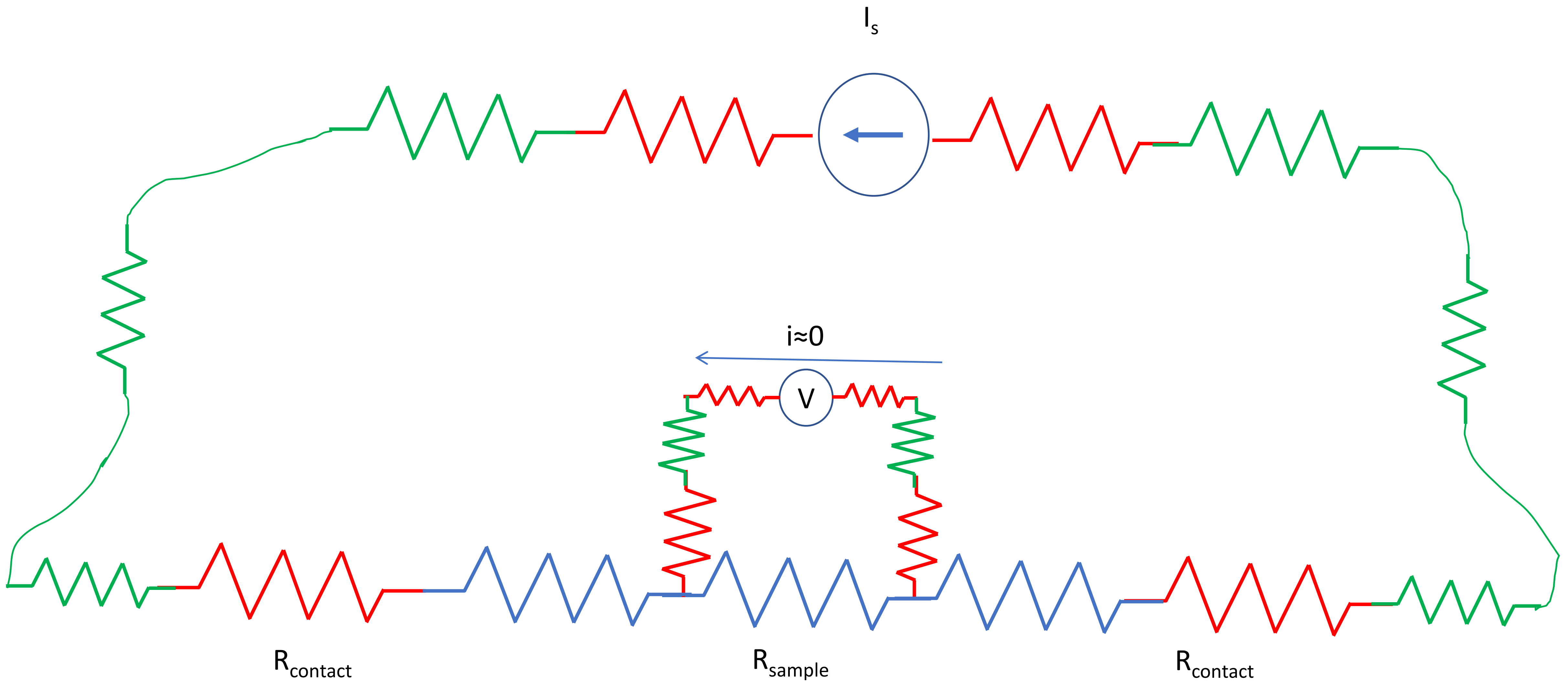


Problem


FLUKE 115 TRUE RMS MULTIMETER
0L
HOLD
MIN MAX
RANGE
OFF
COM
Sample


I_s
i≈0
V
R_{wire}
R_{wire}
$R_{contact}$
R_{sample}
$R_{contact}$

4-terminal measurement



Now you can measure the sample-only resistance

How do I connect this information to a property of a crystal?

Measure

$$\boxed{R} = \frac{V}{I}$$

Integrate

$j = \sigma E$

$$R = \boxed{\rho}\boxed{\frac{L}{Wt}}$$

How reliable is this formula? What are the assumptions?

Intrinsic property

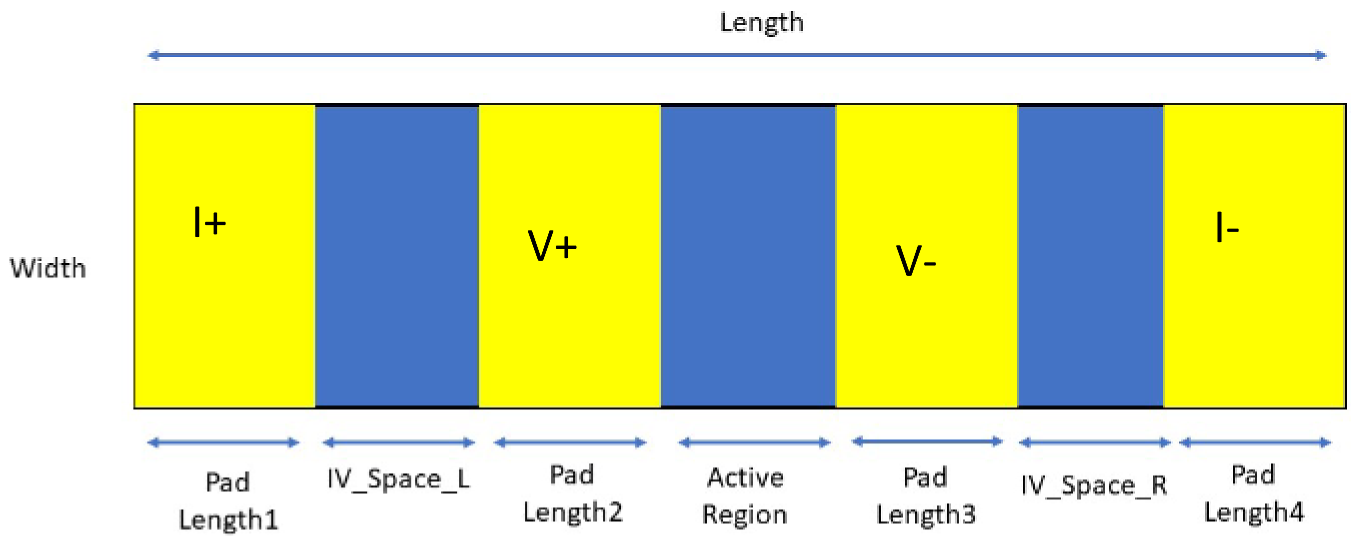
$$\frac{1}{\rho} = \sigma = ne\mu$$

Try to Answer the Following Questions

- 1) What happens if the sample is too thick?

- 2) When do you want to make your contacts as small as possible?

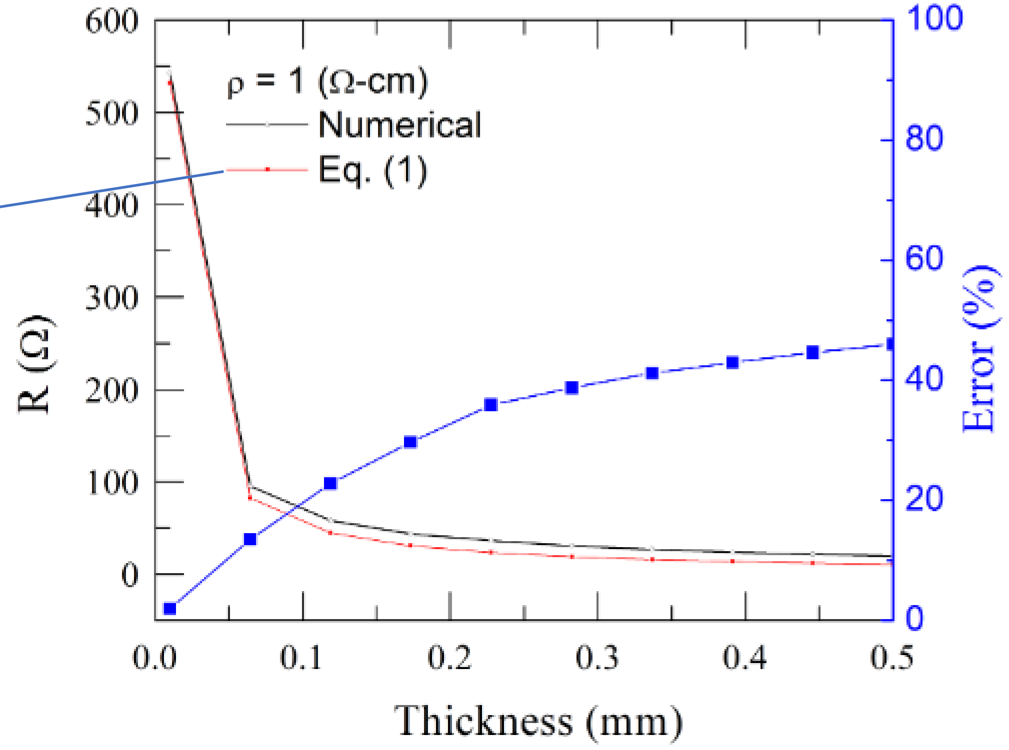
(Try to solve the questions in your worksheet)



260 micron

- Length = 2 mm
- Width = 0.5 mm
- Thickness = 0.2 mm
- Pad Lengths are all 0.3 mm
- IV Space = IV Space = 0.266 mm
- Active Region = 0.266 mm

$$R = \rho \frac{L}{Wt}$$



What if you turn on the magnetic field?

$$0 = e(\vec{\mathcal{E}} + \vec{v} \times \vec{B}) - \frac{m^* \vec{v}}{\tau}$$

$$(ne\mu)\mathcal{E}_x = \mu B J_y + J_x,$$

$$(ne\mu)\mathcal{E}_y = -\mu B J_x + J_y,$$

Conductivity tensor

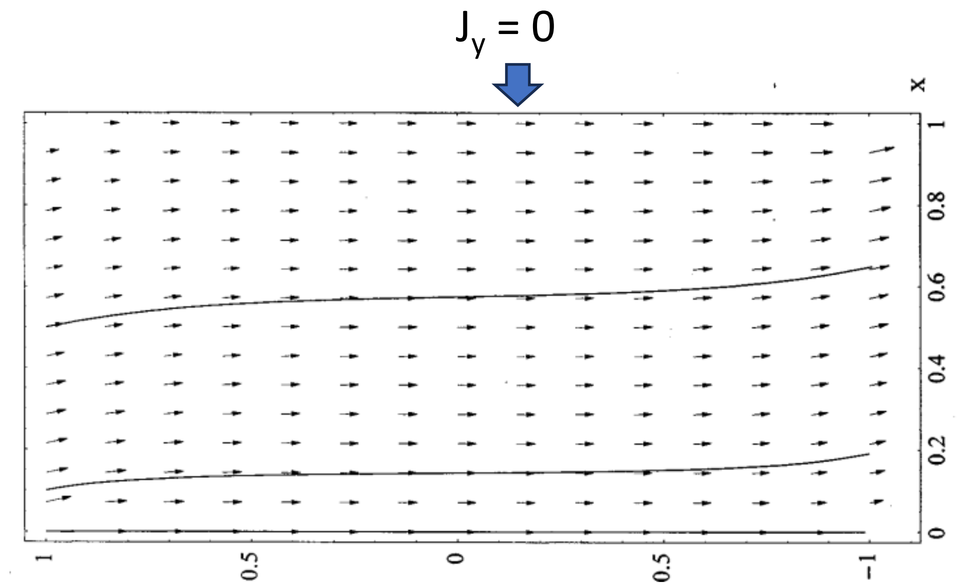
$$\vec{J} = \frac{ne\mu}{1 + (\mu B)^2} \begin{pmatrix} 1 & \mu B \\ -\mu B & 1 \end{pmatrix} \vec{\mathcal{E}}$$

Resistivity tensor

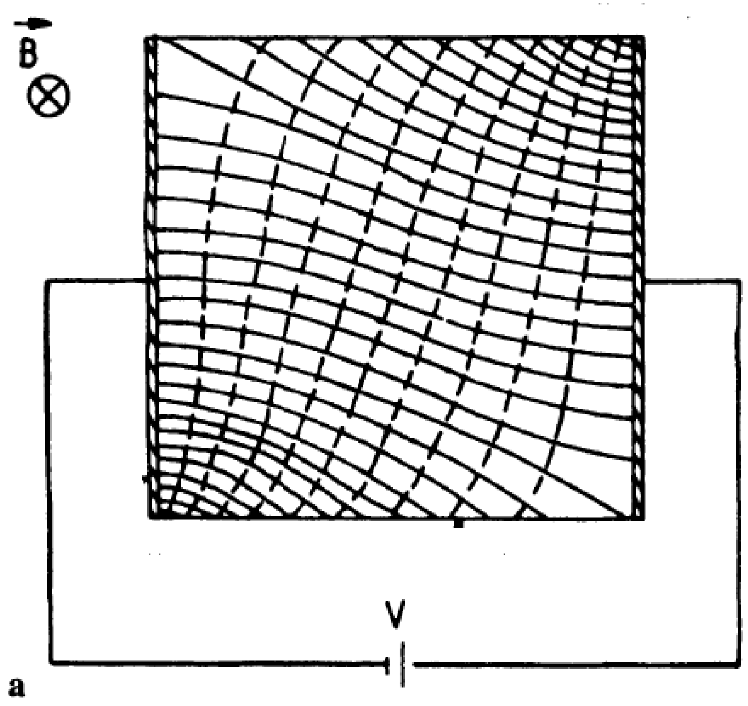
$$\begin{pmatrix} \frac{1}{ne\mu} & -\frac{B}{ne} \\ \frac{B}{ne} & \frac{1}{ne\mu} \end{pmatrix} \vec{J} = \vec{\mathcal{E}}$$

If $j_y = 0$, $\quad R_{\mathrm{Hall}} = \frac{V_y}{I_x} = \frac{\mathcal{E}_y W}{J_x W} = -\frac{B}{ne}.$

Magnetotransport

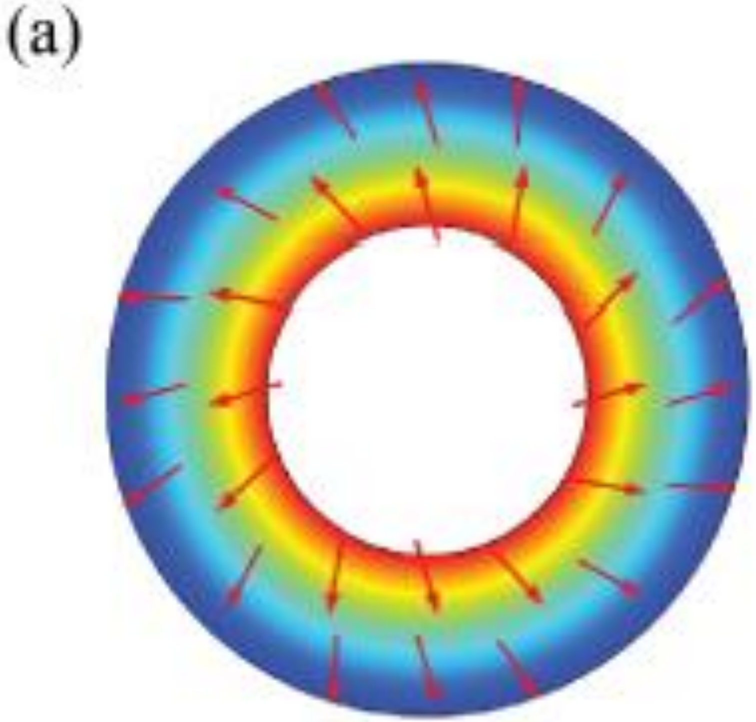


Matthew J. Moelter et al. Am. J. Phys. 66 (8) (1998)



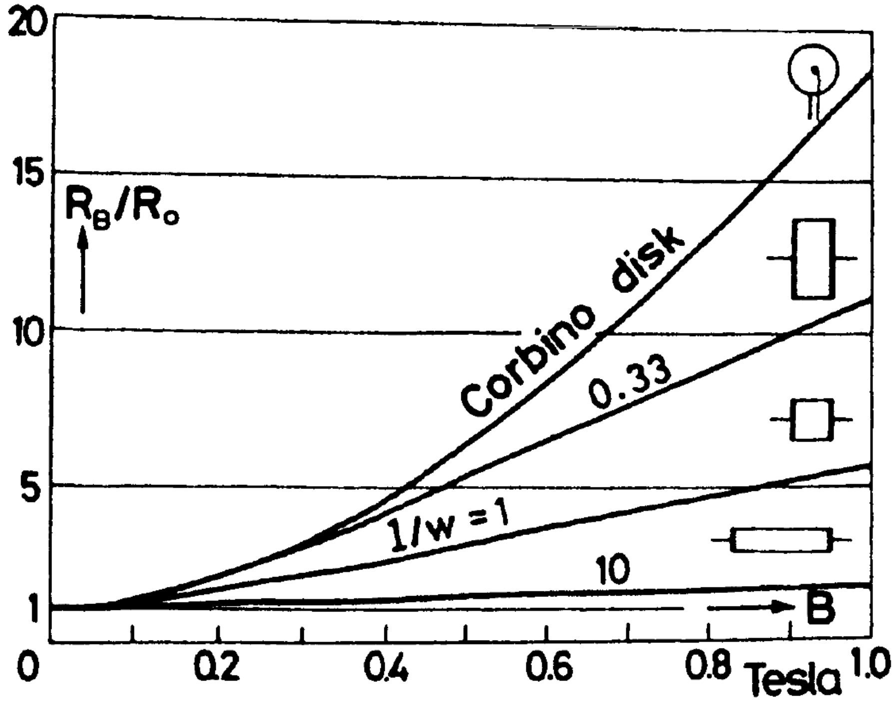
Seeger, Semiconductor Physics (2004)

Corbino disk



$$\vec{J} = \frac{ne\mu}{1+(\mu B)^2} \begin{pmatrix} 1 & \mu B \\ -\mu B & 1 \end{pmatrix} \begin{pmatrix} \cos\phi \ \hat{x} \\ \sin\phi \ \hat{y} \end{pmatrix} \mathcal{E}_r.$$

$$I = \oint \vec{J} \cdot d\vec{l} = \frac{ne\mu}{1+(\mu B)^2} (2\pi r \mathcal{E}_r)$$



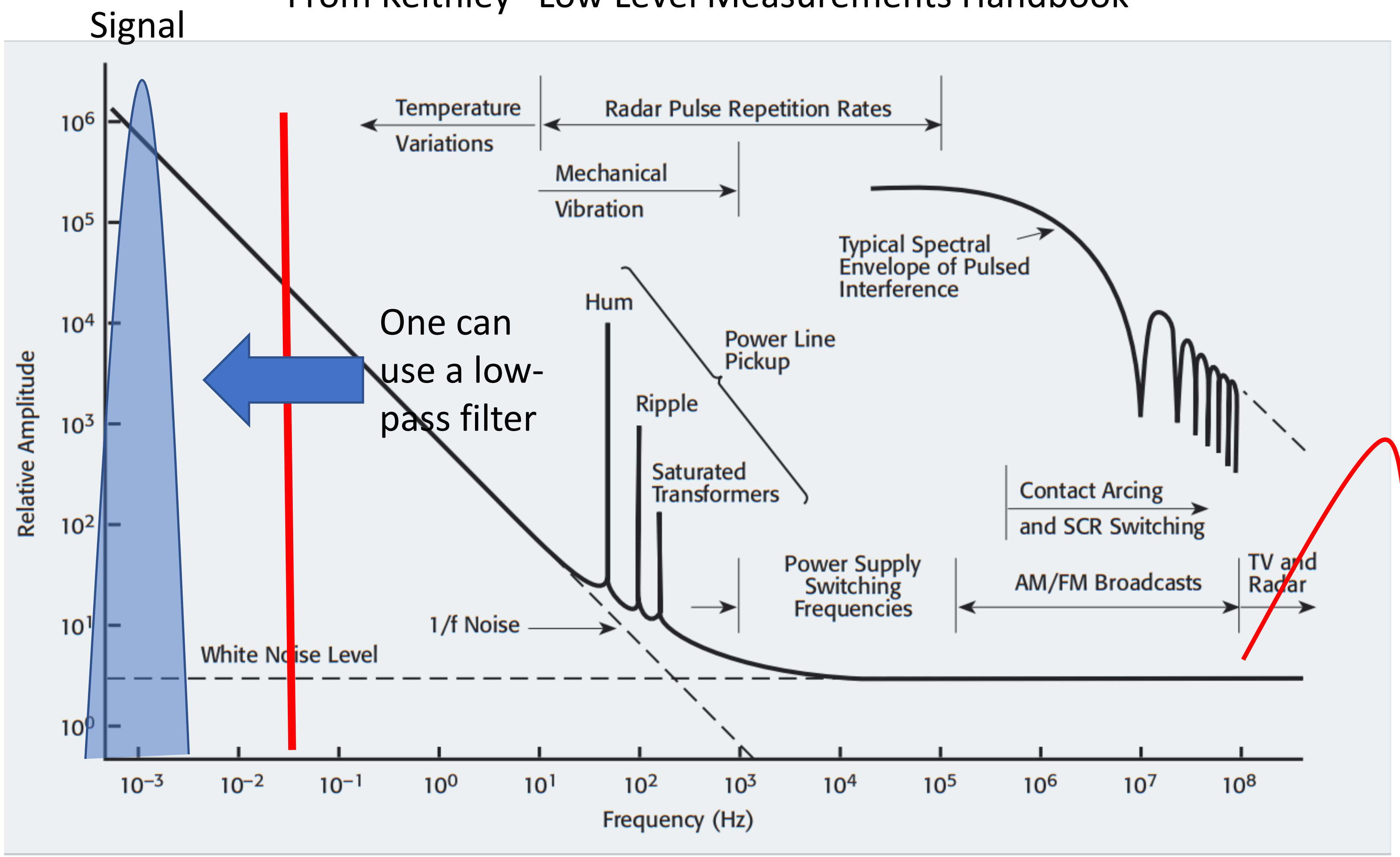
Seeger, Semiconductor Physics (2004)

How can you measure small signals in the presence of a noisy environment?

Limitations of DC Measurements? Noisy

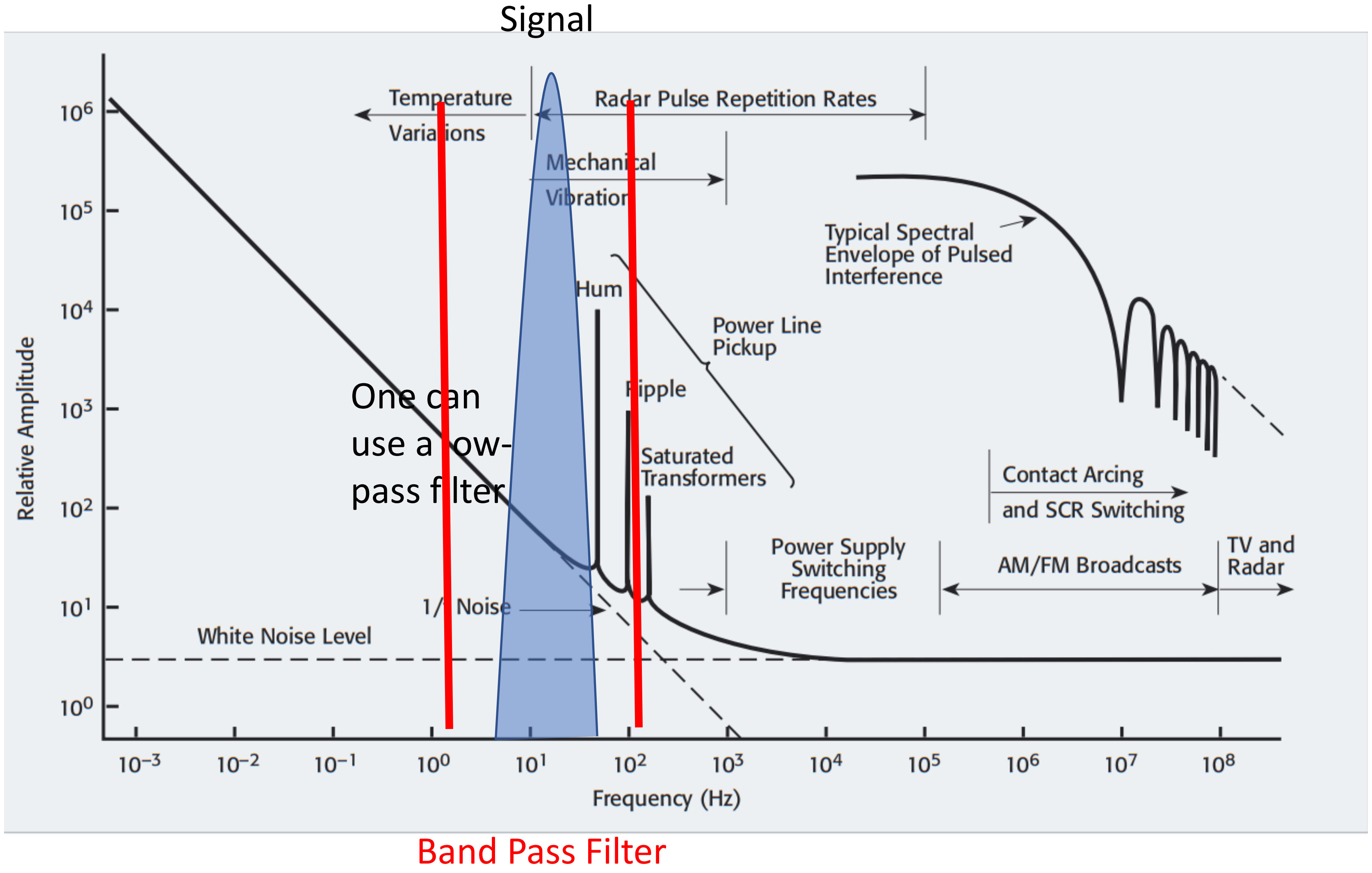
Y-axis often expressed in Power Spectral Density (PSD) $V/\sqrt{Hz}$ or dB

From Keithley "Low Level Measurements Handbook"



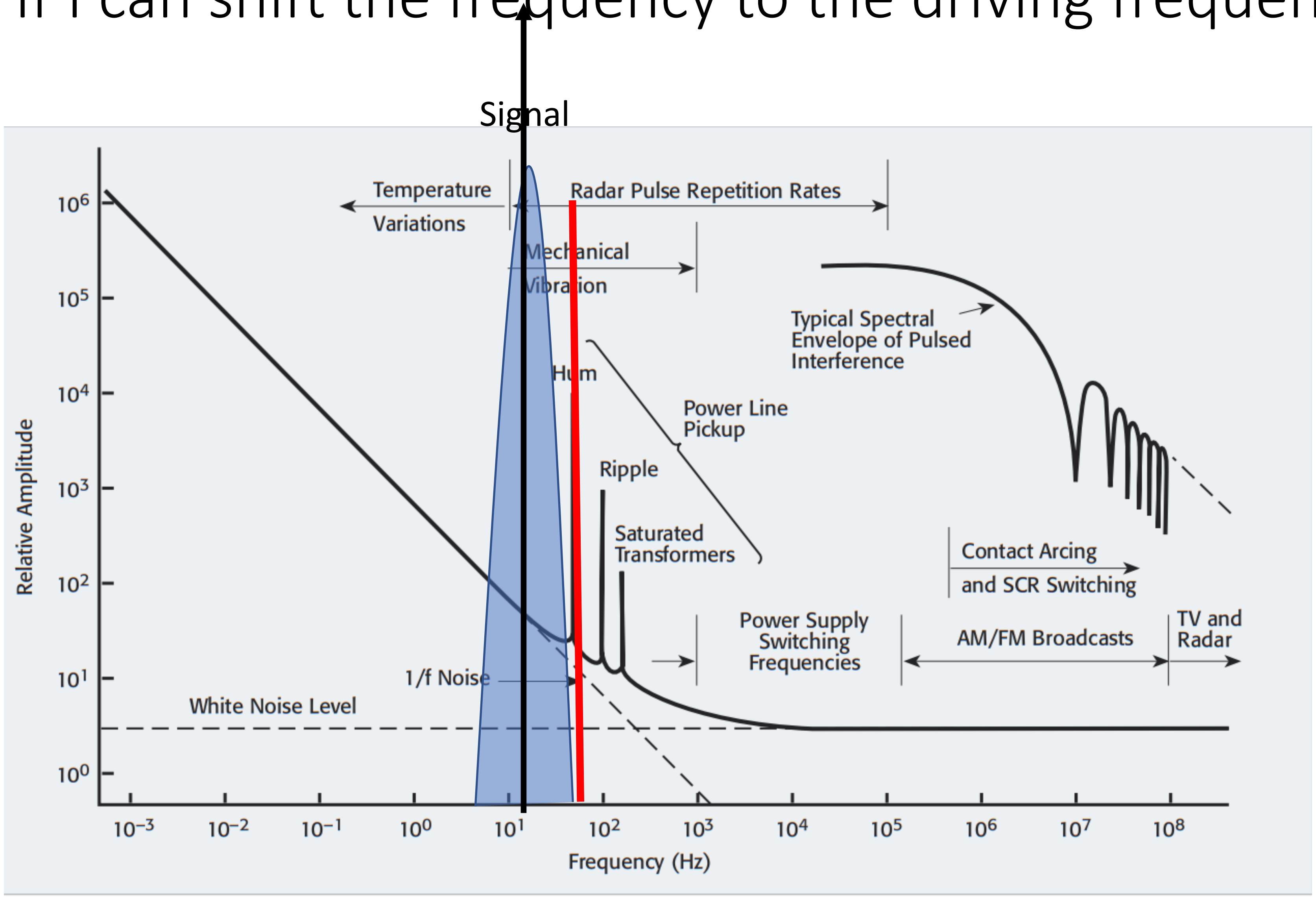
The smallest possible noise you can achieve is this flat line called "Johnson-Nyquist noise" $4k_BTR$

AC measurement: Is it ideal?



From Keithley "Low Level Measurements Handbook"

Can I use a low-pass filter?
If I can shift the frequency to the driving frequency.



From Keithley "Low Level Measurements Handbook"

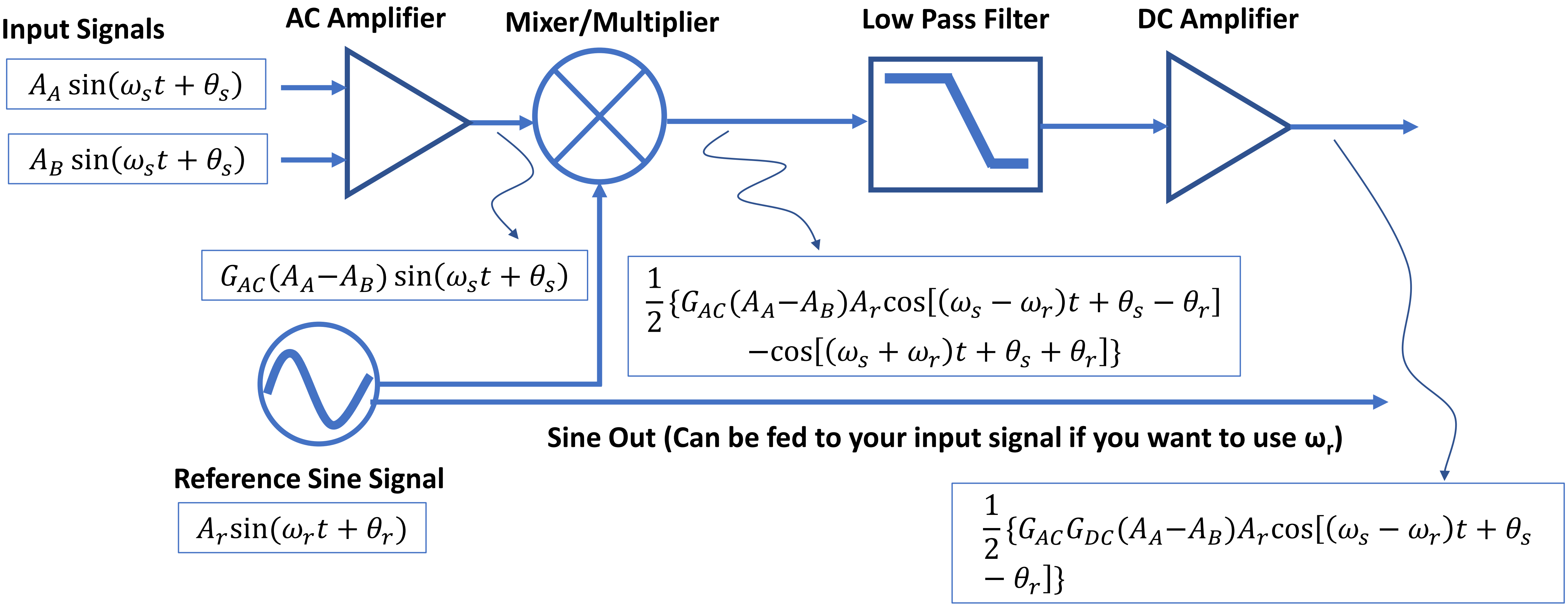
Basic Trigonometry Review

$$\sin A \sin B = \frac{1}{2}\left[\cos(A - B) - \cos(A + B)\right]$$

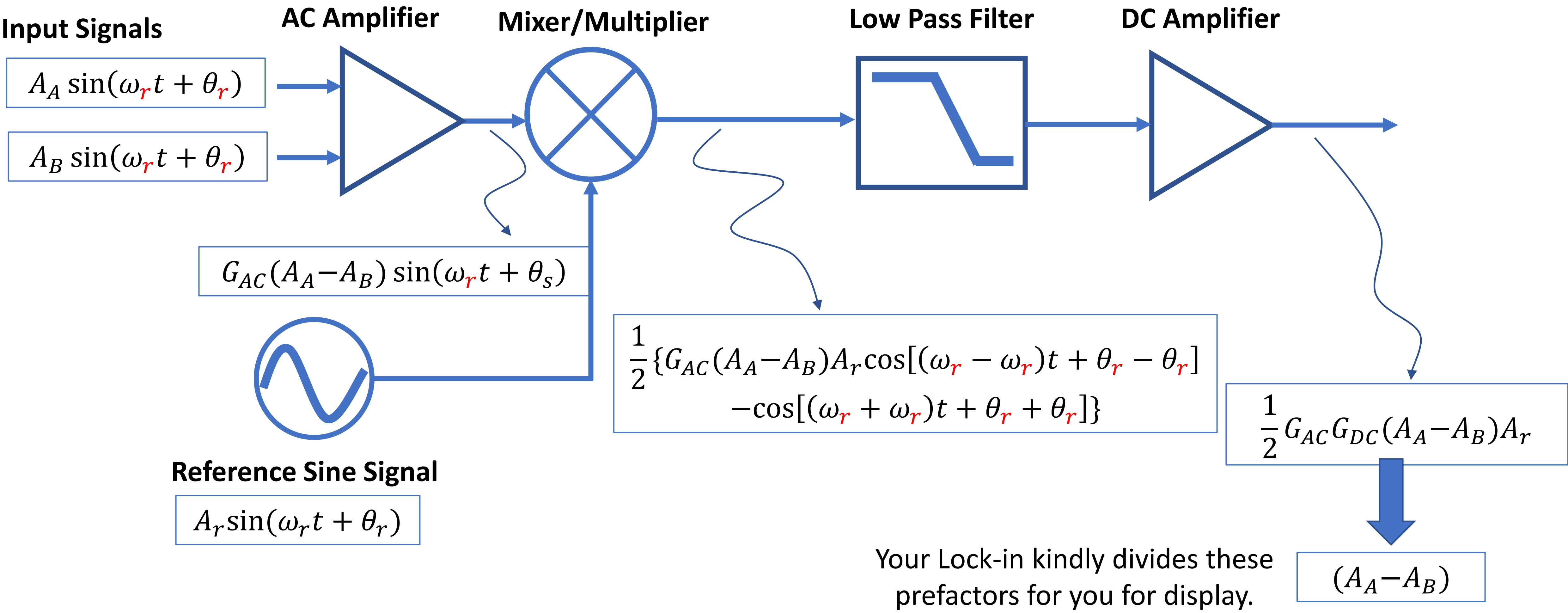
If A and B's are frequencies, you can reduce the frequency to zero if A=B

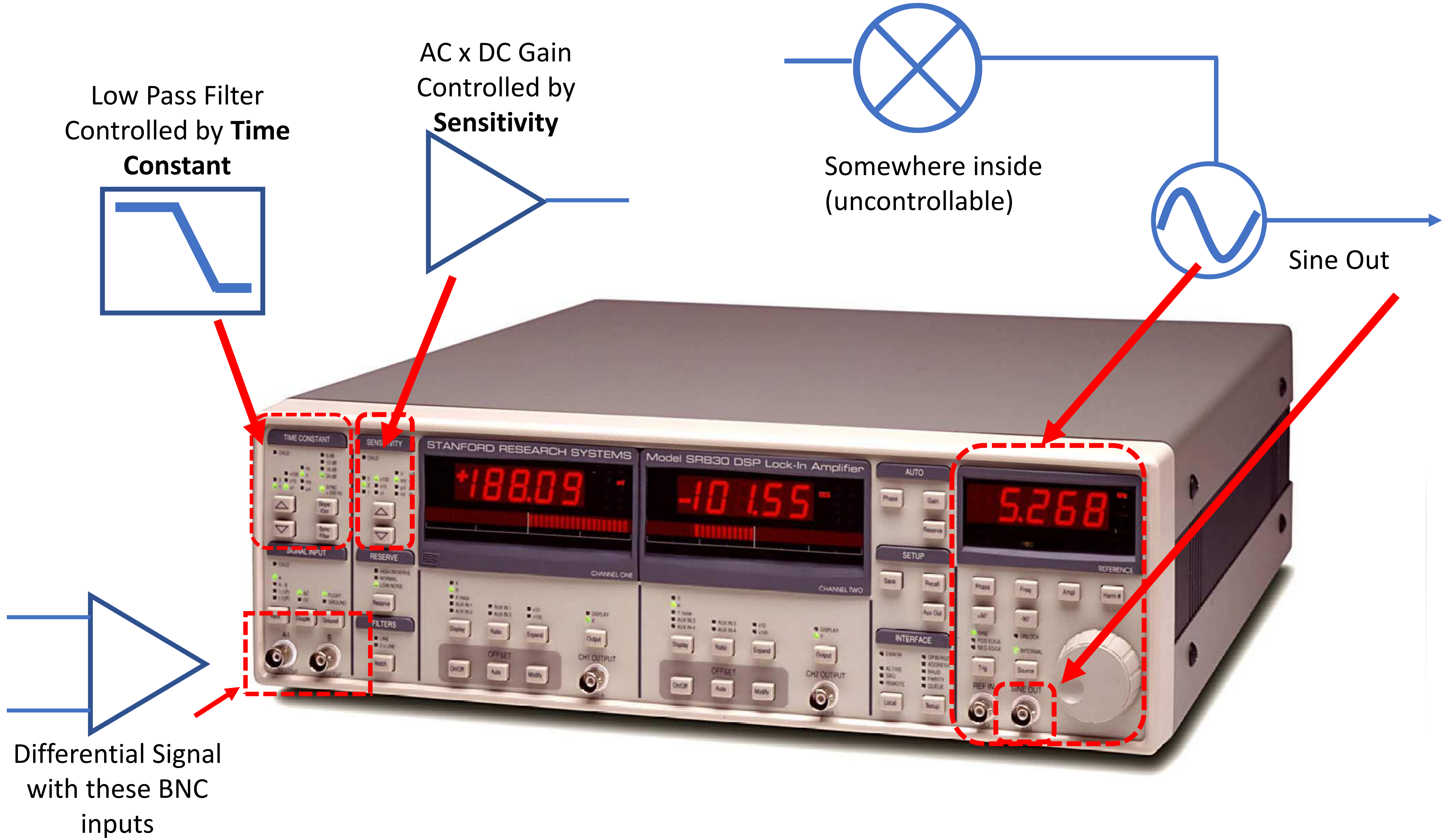
This becomes a higher frequency, so you want to get rid of it.

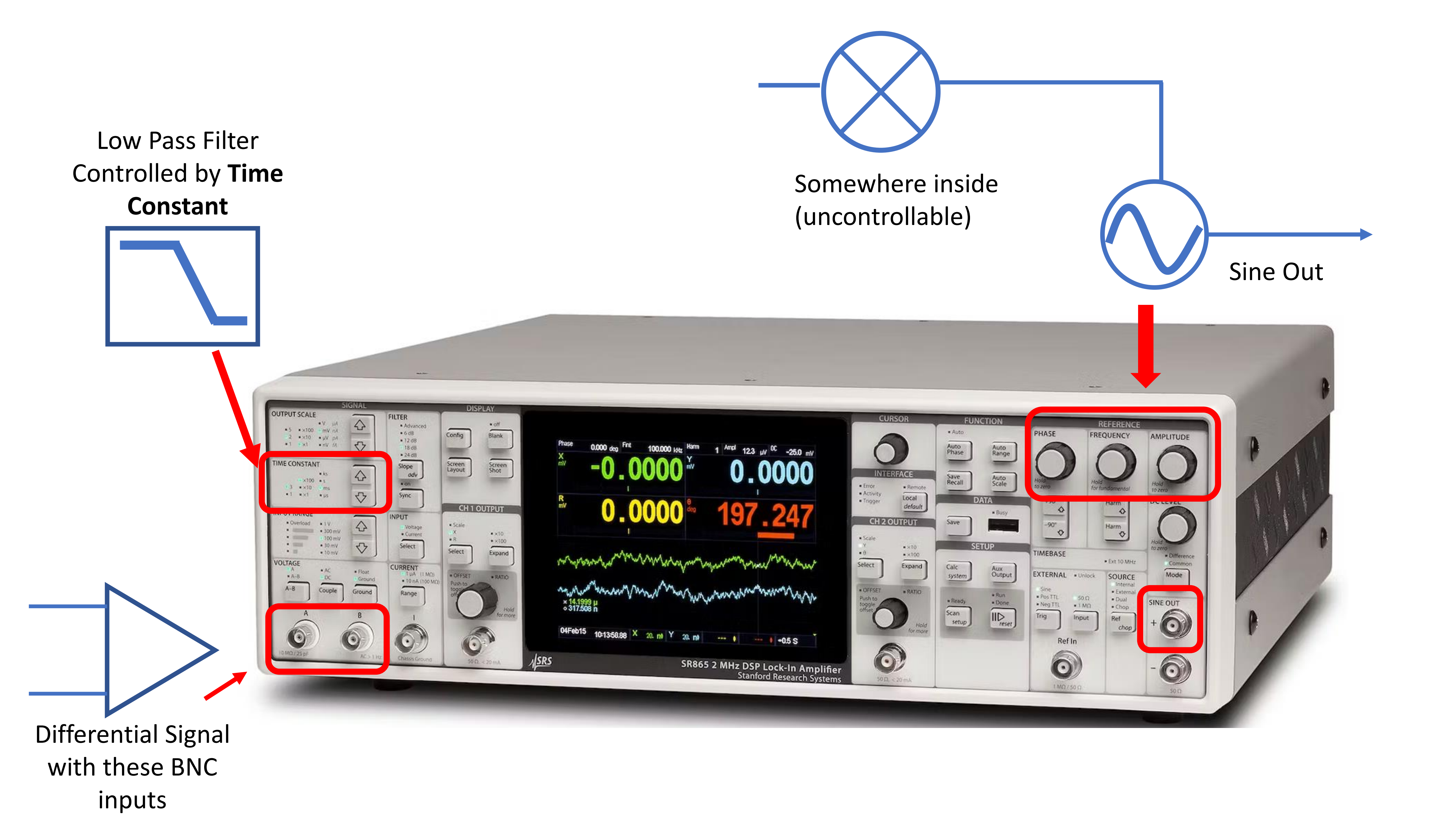
Simple Schematic of a Lock-in Amplifier



If you use ω_r as ω_s, and phase is locked ($\theta_r = \theta_s$)




Low Pass Filter
Controlled by **Time Constant**
AC x DC Gain
Controlled by
Sensitivity
Somewhere inside
(uncontrollable)
Sine Out
Differential Signal
with these BNC
inputs
TIME CONSTANT
SENSITIVITY
SIGNAL INPUT
RESERVE
FILTERS
STANFORD RESEARCH SYSTEMS
Model SR830 DSP Lock-In Amplifier
+188.09
-101.55
CHANNEL ONE
CHANNEL TWO
OFFSET
CH1 OUTPUT
CH2 OUTPUT
AUTO
SETUP
INTERFACE
5.268
REFERENCE
REF IN
SINE OUT

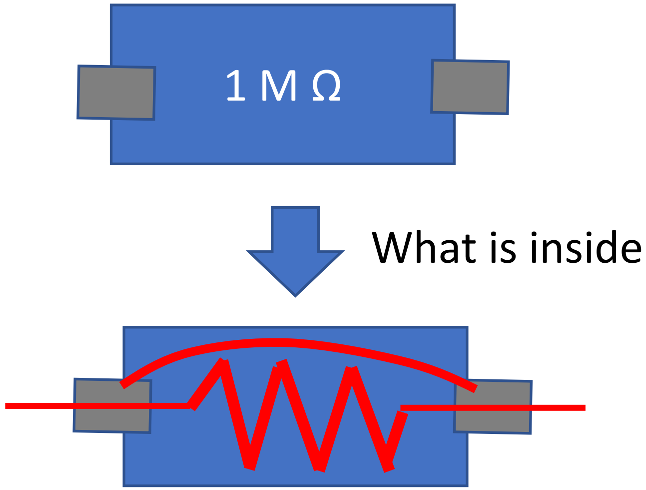

Low Pass Filter
Controlled by **Time Constant**
Somewhere inside
(uncontrollable)
Sine Out
Differential Signal
with these BNC
inputs
TIME CONSTANT
REFERENCE
PHASE
FREQUENCY
AMPLITUDE
SINE OUT
SR865 2 MHz DSP Lock-In Amplifier
Stanford Research Systems

Building Intuition on BNCs

Consider core as "source"

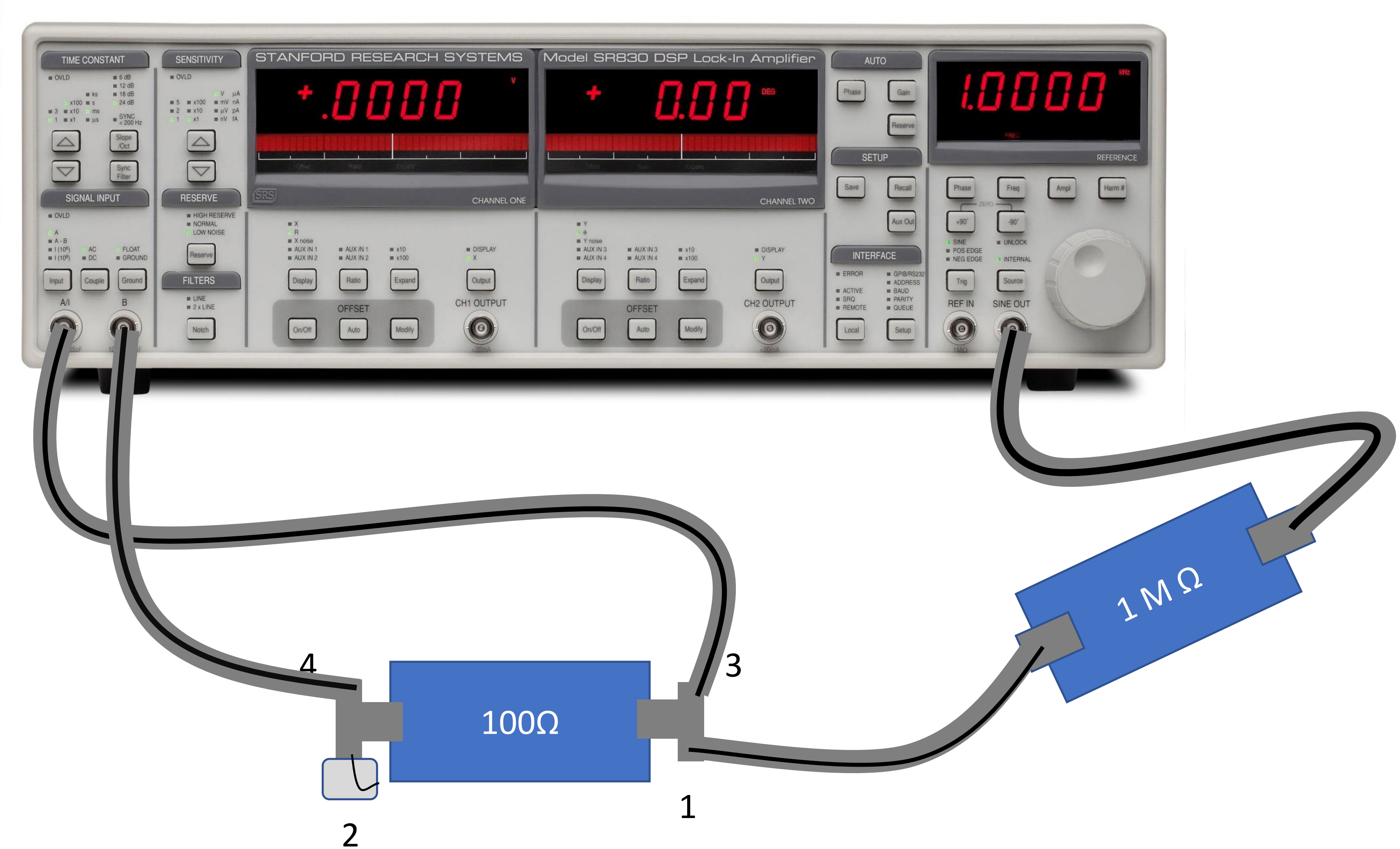
Consider shell as "Ground"

Using a "BNC short" shorts the core and shell. This can be thought as establishing a ground path of your circuit.



The core of the bncs are connected to a resistor and the outershell are shorted together.

Exercise 1: Try to measure a 100 Ohm resistor



Measure the voltage difference between 3 and 4.

Current is flowing from the core of BNCs including terminal 1 to 2 and then returning back to the shell. Conveniently, one can think as if 2 is ground and current is flowing from sine out-> 1 ->2.

Exercise 2: Two terminal resistance measurement

1) Setup a Two-terminal resistance measurement configuration.

2) Create a table and check two terminal resistance.
   - Check linearity and frequency dependence.

Exercise 2: Try to measure the sample (Four-terminal resistance)

1) Setup a four-terminal resistance measurement configuration.

2) What is $R_{3,4;5,6} = V_{5,6}/I_{3,4}$

   - Check linearity and frequency dependence.

3) Change the sensitivity, time constant, etc. settings to good values.

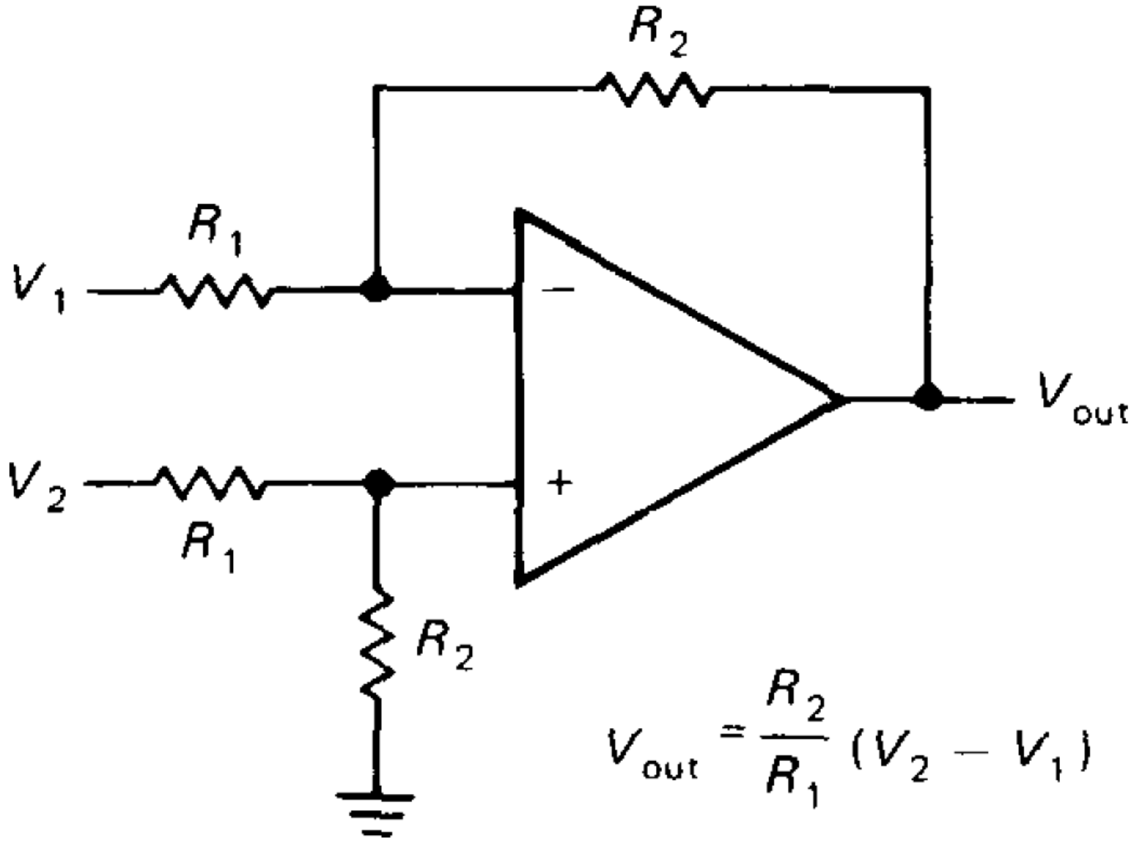
4) If you choose a time constant that is too short, what happens? Is it noise?

Common Mode Rejection Ratio (If Time left):Important if measuring very small resistance

$$V_{\mathrm{o}} = A_{\mathrm{d}}(V_{+} - V_{-}) + \frac{1}{2}A_{\mathrm{cm}}(V_{+} + V_{-})$$

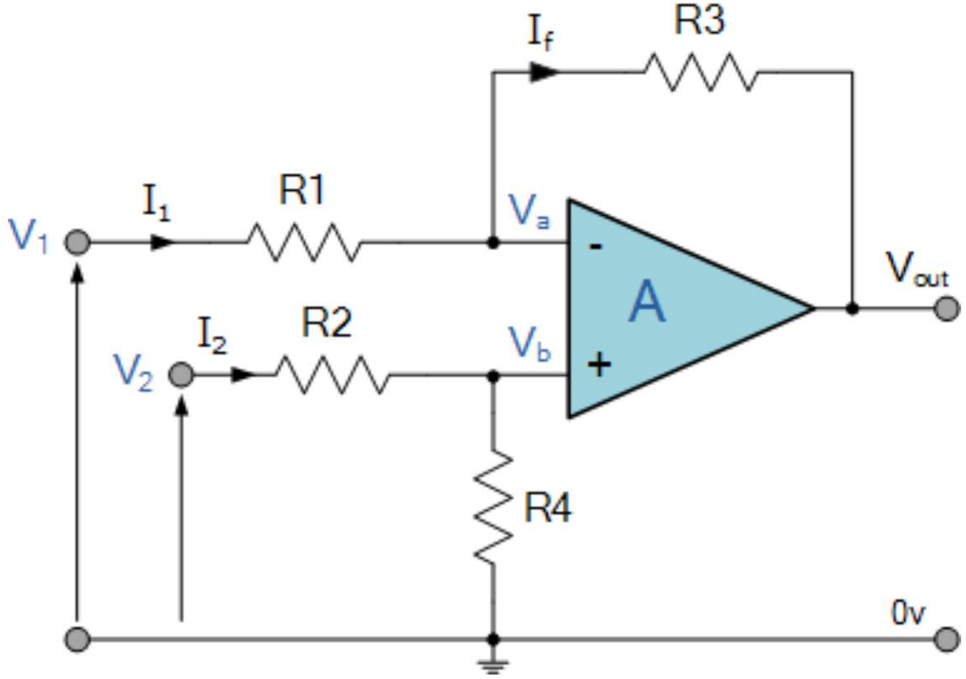
$$\mathrm{CMRR} = \left(\frac{A_{\mathrm{d}}}{|A_{\mathrm{cm}}|}\right) = 10\log_{10}\left(\frac{A_{\mathrm{d}}}{A_{\mathrm{cm}}}\right)^2 \mathrm{dB} = 20\log_{10}\left(\frac{A_{\mathrm{d}}}{|A_{\mathrm{cm}}|}\right)\mathrm{dB}$$

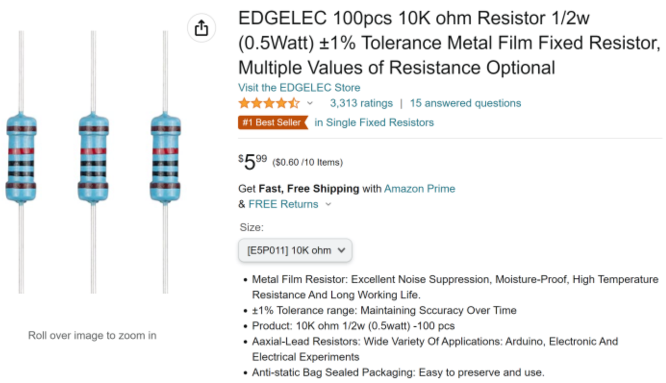
Classic Differential Amplifier



Non-ideal case

https://www.electronics-tutorials.ws/opamp/opamp_5.html





$$V_{out} = -V_1\left(\frac{R_3}{R_1}\right) + V_2\left(\frac{R_4}{R_2+R_4}\right)\left(\frac{R_1+R_3}{R_1}\right)$$

Common mode

$$V_{out} = \left(\frac{\frac{R_3}{R_1} + \frac{R_4}{R_2+R_4}\frac{R_1+R_3}{R_1}}{2}\right)(V_2 - V_1) + \left(\frac{\frac{R_3}{R_1} - \frac{R_4}{R_2+R_4}\frac{R_1+R_3}{R_1}}{2}\right)(V_2 + V_1)$$

Discussion Questions

- In the current 4-terminal measurement configuration, what is the smallest voltage (or resistance) value you can measure?
- Is there a quick way to check if Common mode is significant?
- How can I improve CMRR?