MECH 420
Sensors and Actuators

Presentation Part 4

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Part 4: Signal Conditioning

- Signal Conditioning (subset of Signal Modification)
- Amplifiers
- Filters
- Bridge Circuits

Plan

- **Signal Conditioning**
- **Operational Amplifier**
- **Amplifier Performance Ratings**
- **Voltage, Current, and Power Amplifiers**
- **Instrumentation Amplifier**
- **Noise and Ground Loop Elimination**
- **Analog Filters: Low-pass filter; High-pass filter; Band-pass filter; Band-reject (or notch) filter**
- **Wheatstone Bridge**

Rationale of the Study

- **For application requirements, signal type and characteristics may have to be modified. E.g.,**

Amplification (conditioning)

Analog-digital conversion (conversion)

Modulation (modification)

Difference between: Conditioning, conversion, and modification?

- **In view of noise and other errors, and system requirements, the signals have to be conditioned (e.g., filtering, amplification, offset removal, linearization/calibration)**

Signal Modification Activities/Devices

Signal Conditioning (e.g., amplification, analog and digital filtering)

Signal Conversion (e.g., analog-to-digital conversion, digital-to-analog conversion, voltage-to-frequency conversion, frequency-to-voltage conversion)

Modulation (e.g., amplitude, frequency, phase, pulse-width, pulse-frequency, pulse-code)

Demodulation (reverse process of modulation)

Will study only key ones. Please review others.

Other Useful Signal Modification Operations:

Sample and hold circuits (in digital data acquisition systems)

Analog and digital multiplexing (pick signals sequentially from channels)

Comparators (signal subtraction; signal comparison)

Curve shaping (may be considered as "conditioning")

Offsetting (e.g., dc removal or zero mean; may be considered as "conditioning")

Linearization (may be considered as "conditioning")

Operational Amplifier
(Op-amp)

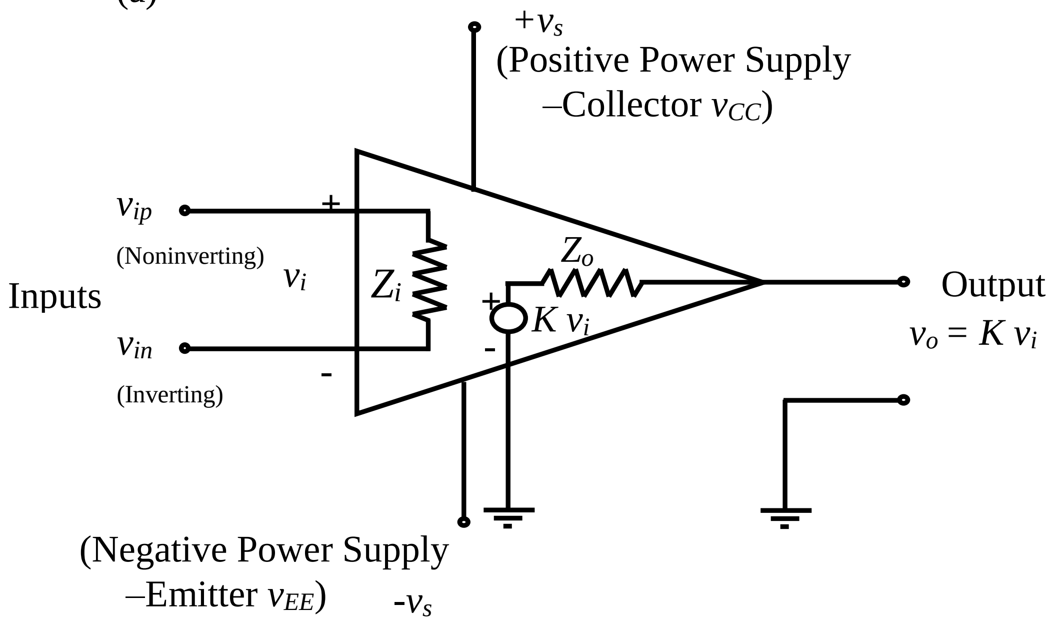
Operational Amplifier

- Operational amplifier (op-amp) is the basic building block of many electronic devices (amplifiers, active filters, etc.)
- Signal amplification: Adjustment of the signal level (power, voltage, current)
- Amplifier is an *active* device (needs external power)
- Op-amps are available as monolithic IC packages
- Use only with feedback

Texas Instruments
TLC1078 Operational Amplifier

Operational Amplifier

(a)



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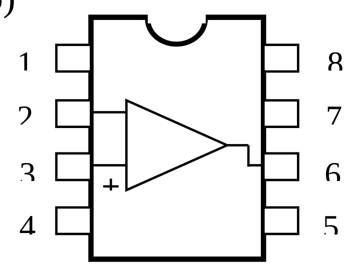
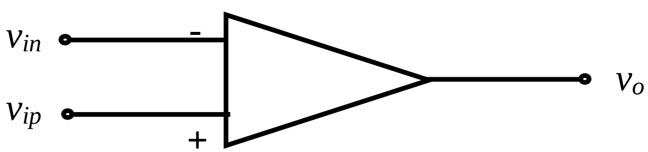


Pin Designations:

1 Offset Null
2 Inverting Input
3 Noninverting Input
4 Negative Power Supply v_{EE}
5 Offset Null
6 Output
7 Positive Power Supply v_{CC}
8 NC (Not Connected)

(c)



Operational Amplifier

$v_o = Kv_i$ **with** $v_i = v_{ip} - v_{in}$

Very high open loop voltage gain K (10^5 to 10^9)

Very high input impedance Z_i (2 MΩ to 10 MΩ)

Low output impedance is low (10 Ω to 75 Ω)

Supply voltage to op amp: V+ = 5V to 18V and V- = -5V to -18

Typical output v_o is 1 to 15 V => $v_i \cong 0$ **=>** $v_{ip} \cong v_{in}$

***Note*: If we apply a large voltage differential v_i (say, 10 V) =>**

op amp saturates => output voltage ~ 15 V

Properties of Op-amp:

1. **Voltages of the two input leads are (almost) equal**

   (due to high open-loop gain)

2. **Currents through each input lead is (almost) zero**

   (due to high input impedance)

Example

Op-amp: Open-loop gain = 1 × 10^5; Saturation output = 15 V

Determine the differential input output voltages.

v_{ip} = voltage at the positive lead

v_{in} = voltage at the negative lead

v_i = differential input

***Note*: 0V means, terminal is grounded**

Complete the Last Two Columns of This Table:

v_{ip}	v_{in}	v_i	v_o
5 μV	2 μV		
−5 μV	2 μV		
5 μV	−2 μV		
−5 μV	−2 μV		
1 V	0		
0	1 V		

Sources of Error in Op-amp

- **Large and unsteady gain**
- **Offset current at input leads due to bias currents needed to operate solid-state circuitry**
- **Offset voltage at output even when input leads are open or equal voltage**
- **Unequal gains corresponding to the two input leads (i.e., the inverting gain not equal to the non-inverting gain)**
- **Noise and environmental effects (thermal drift, etc.)**

Amplifier Performance Ratings

1. Stability
2. Speed of response (bandwidth, slew rate)
3. Input impedance and output impedance

Unmodeled Signals (a major source of amplifier error):

1. Bias currents
2. Offset signals
3. Common mode output voltage
4. Internal noise.

Some Performance Terminology

$$v_o = K_d(v_{ip} - v_{in}) + K_{cm} \times \frac{1}{2}(v_{ip} + v_{in})$$

Here, What is the inverting gain?
What is the non-inverting gain?

K_d = differential gain; K_{cm} = common-mode gain

Input Offset Voltage: Voltage difference at input terminals (imperfect op-amps) to make output = 0

Common-mode Voltage: Average voltage at input leads $\frac{1}{2}(v_{ip} + v_{in})$

Should be rejected at output ➔ must have $K_{cm} << K_d$

Common-mode Rejection Ratio (CMRR): K_d/K_{cm}), expressed in decibels (dB). Should be high to reject common-mode voltage (e.g., 113 dB)

Gain-Bandwidth Product (GBWP or GBP): Typically, for high gain, the bandwidth should decrease (for a given power level)

Slew Rate: Max rate of change of output voltage, without significantly distorting it. Expressed in V/μs (E.g., 160 V/μs). A high slew rate is desirable; measures speed of response.

What does BW measure? What does slew rate measure?

Operational Amplifier Performance

Definitions

- Open-loop (differential) gain = $\left|\dfrac{\text{Output voltage}}{\text{Voltage difference at input leads}}\right|$ with no feedback.
- Input impedance = $\dfrac{\text{Voltage between an input lead and ground}}{\text{Current through that lead}}$

  (with other input lead grounded and the output in open circuit)
- Output impedance = $\dfrac{\text{Voltage between output lead and ground in open circuit}}{\text{Short-circuit current through that lead}}$ (with normal input conditions)
- Bandwidth = frequency range in which the frequency response is flat (gain is constant).
- Gain bandwidth product (GBP) = Open-loop gain x Bandwidth at that gain

Justify that GBP is approx. constant

- Input bias current = average (DC) current through one input lead
- Input offset current = difference in the two input bias currents
- Differential input voltage = voltage at one input lead with the other grounded when the output voltage is zero.
- Common-mode gain (K_{cm})= $\dfrac{\text{Output voltage when input leads are at the same voltage}}{\text{Common input voltage}}$
- Common-mode rejection ratio (CMRR) = $\dfrac{\text{Open loop differential gain }(K_d)}{\text{Common-mode gain }(K_{cm})}$ (expressed in dB)
- Slew rate = rate of change of output of a unity-gain op-amp, for a step change in input (measure of speed)

Use of Feedback in Op-amps

Op-amp cannot be used as a practical amplifier without modification because gain K is very large and not stable (non-flat high-gain frequency response, drift). Op-amp will saturate

- **Use feedback**
- **Use the properties: High Z_i, low Z_o, and high K**

➔ Output signals will depend on the connected high-precision external elements including feedback elements (R and C)

Amplifier Implementations Using Op-amp

Key Properties of Op-amp

In analysis and practical implementations we use two key properties of an op-amp:

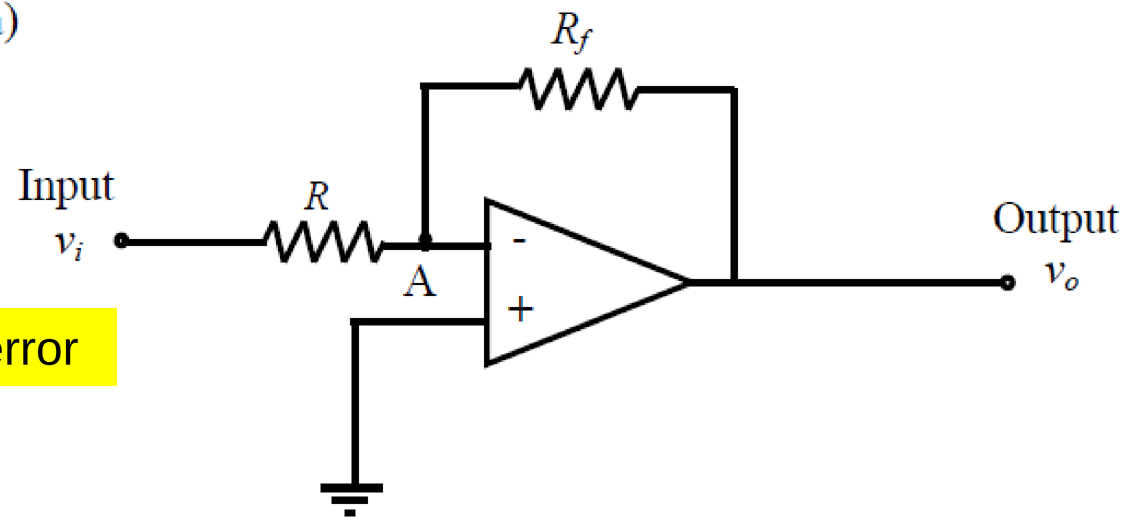
1. **Voltages at the two input leads (inverting and non-inverting) are equal (due to high differential gain)**

2. **Currents at each input lead is zero (due to high input impedance)**

Remember these two. Very important.

Voltage and Current Amplifiers

(a)



$v_o = K_v v_i$

K_v = voltage gain

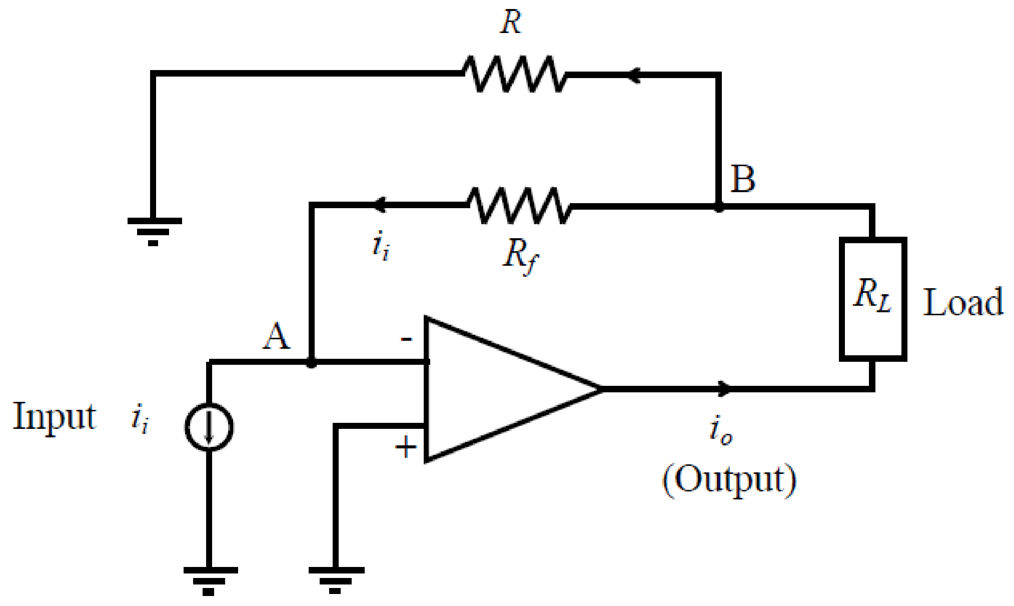
$K_v = -\frac{R_f}{R}$

Note the textbook error

(Disregard –ve sign, because it

can be easily fixed. See my example)

(b)



$i_o = K_i i_i$

K_i = current gain

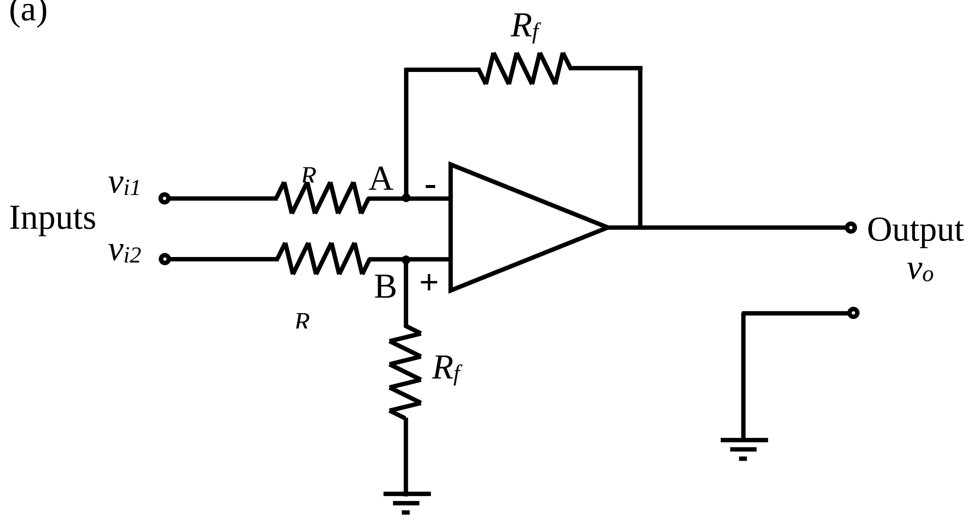
$K_i = 1 + \frac{R_f}{R}$

Note: Feedback

Instrumentation Amplifier (InAmp)

Differential Amp

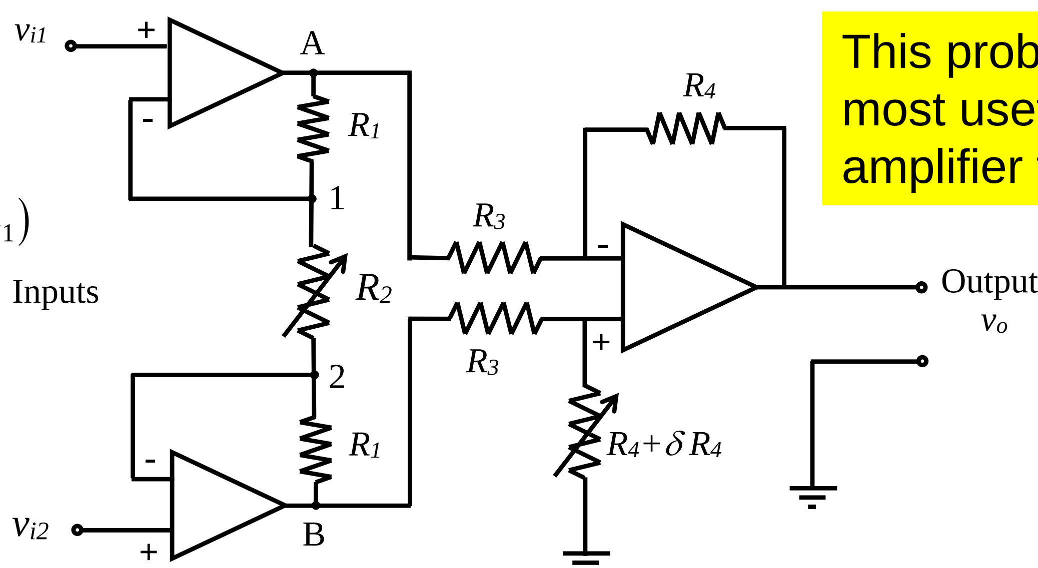
(a)



$$v_o = \frac{R_f}{R}(v_{i2} - v_{i1})$$

Instrumentation Amp

(b)



This probably the most useful amplifier for us

Verify the following:

$$v_B - v_A = \left(1 + \frac{2R_1}{R_2}\right)(v_{i2} - v_{i1})$$

$$v_o = \frac{R_4}{R_3}(v_B - v_A)$$

Instrumentation Amplifier Example

INA827 Instrumentation Amplifier (Texas Instruments)

Applications

•Sensing and Data Acquisition

•Industrial process control

•Power automation

•Medical instrumentation

Features:

- Has input buffer amplifiers (eliminate the need for input impedance matching)
- Very low: DC offset, low drift, low noise
- Very high: open-loop gain, common-mode rejection ratio, input impedance

Signal Conditioning for a Wheatstone Bridge

(Will discuss Wheatstone bridge later. Very important)

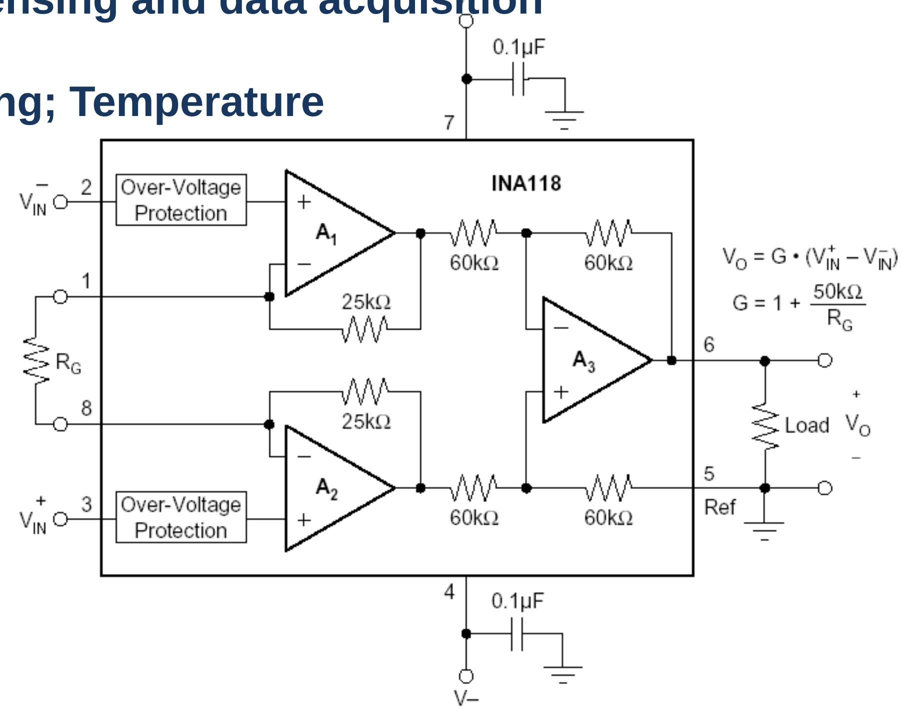
Amp Objectives: 1. Get signal difference (noise cancels); 2. Reduce loading effects

Solution: Use an instrumentation amplifier to pick up the bridge output voltage

Example: INA 118 (Burr-Brown / Texas Instruments)

Instrumentation Amplifier Applications:

- **General engineering instrumentation/sensing and data acquisition (e.g., biomedical)**
- **Wheatstone bridge: Strain-gauge sensing; Temperature sensing (thermocouple, RTD)**

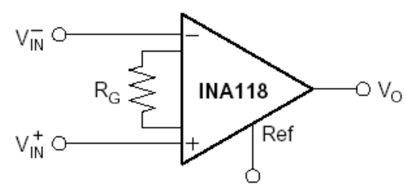


DESIRED GAIN	R_G (Ω)	NEAREST 1% R_G (Ω)
1	NC	NC
2	50.00k	49.9k
5	12.50k	12.4k
10	5.556k	5.62k
20	2.632k	2.61k
50	1.02k	1.02k
100	505.1	511
200	251.3	249
500	100.2	100
1000	50.05	49.9
2000	25.01	24.9
5000	10.00	10
10000	5.001	4.99

NC: No Connection.

$R_{in} = 10^{10}\ \Omega$

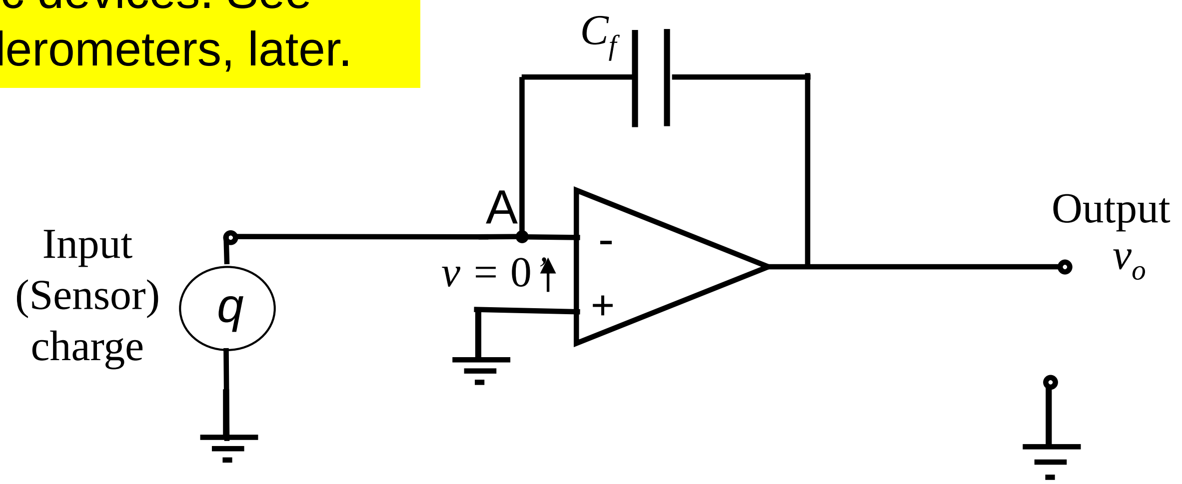
Also drawn in simplified form:



Note: R_G is chosen to get the desired gain

Charge Amplifier

Particularly needed with piezoelectric devices. See under accelerometers, later.



***Note*: Capacitive feedback**

Charge balance at A:

$$q + C_f v_o = 0$$

$$v_o = -\frac{q}{C_f}$$

What happens if a feedback resistor R_f is added in parallel with the capacitor?

What happens in dc?

Commonly used with piezoelectric and other high-impedance sensors

Noise and Ground Loops

Purpose of Grounding

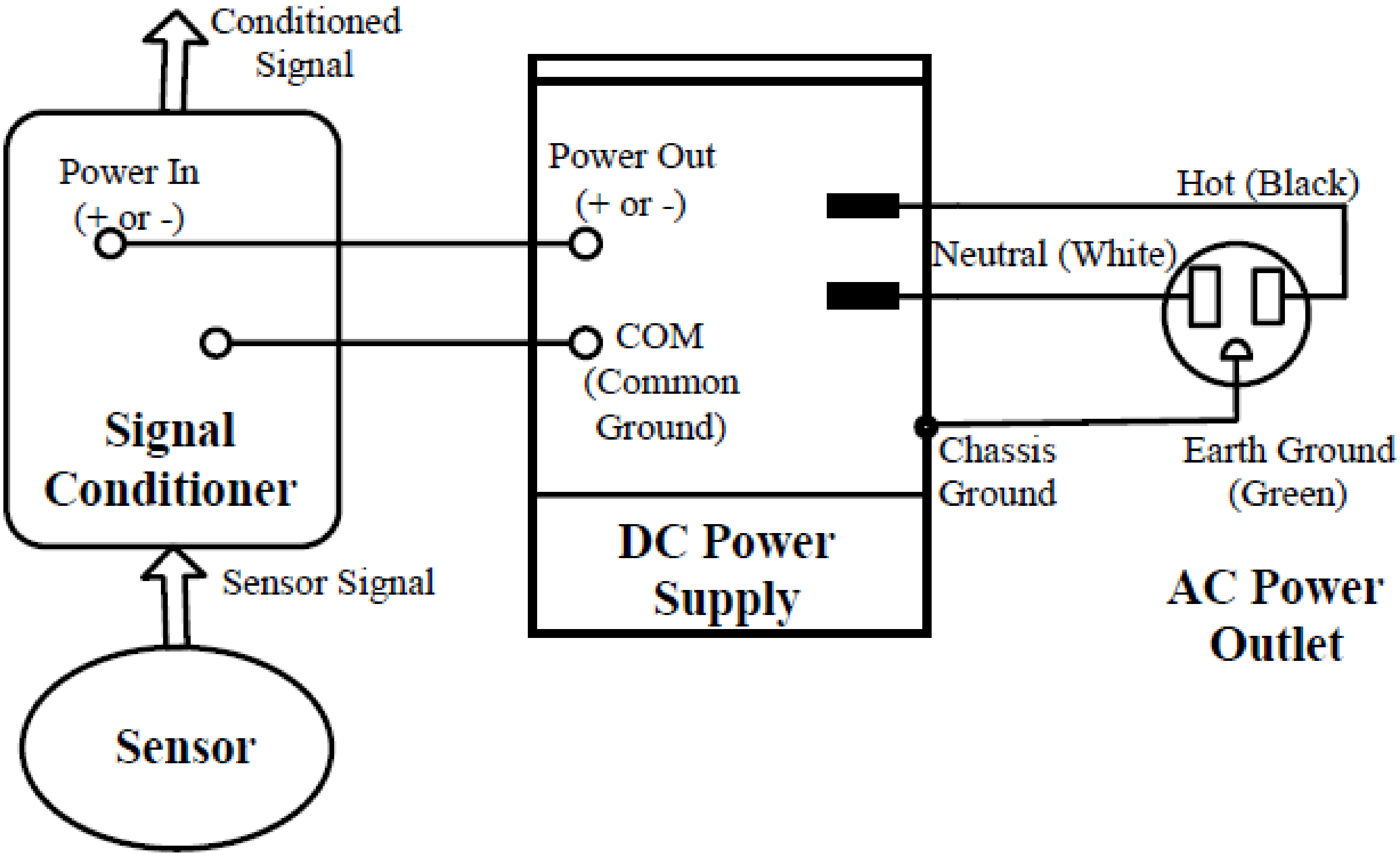
In analysis and practical implementations, we use two key requirements of grounding:

1. **Remove noise (e.g., ground loops) that can corrupt signals (in sensing, PLC, and other instrumentation)—Clean grounds**

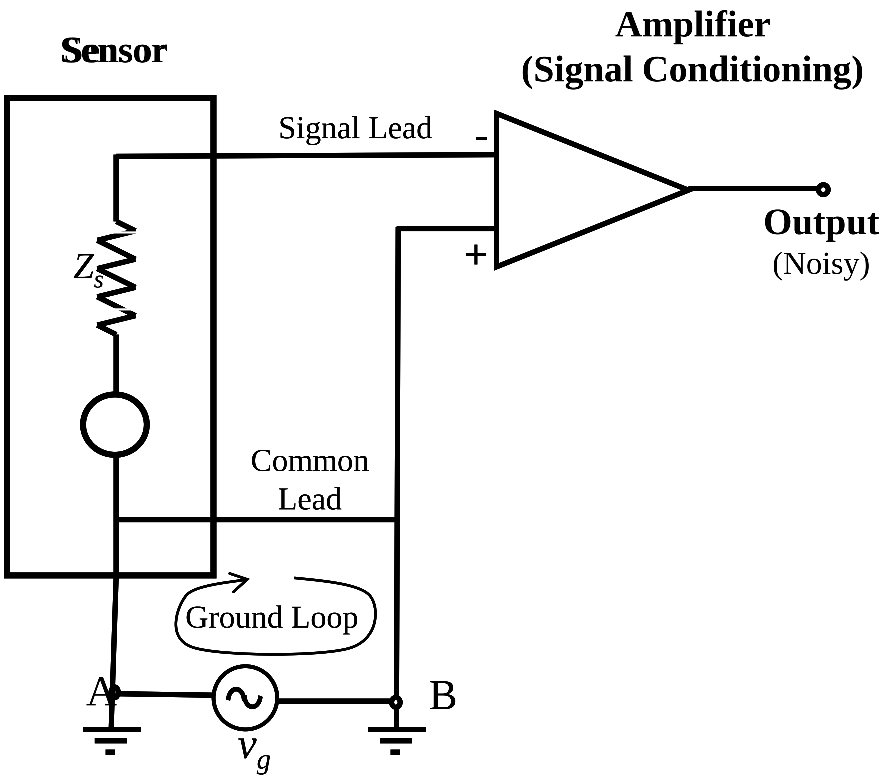
2. **For safety—Power/dirty grounds (typically, high-voltage AC; e.g., AC motors, lighting, switching, power distribution) *Note*: Use heavy-gauge copper wire, going to earth at building base (0 V)**

Compare these two categories of grounding.

An Example of Device (Clean) Grounding

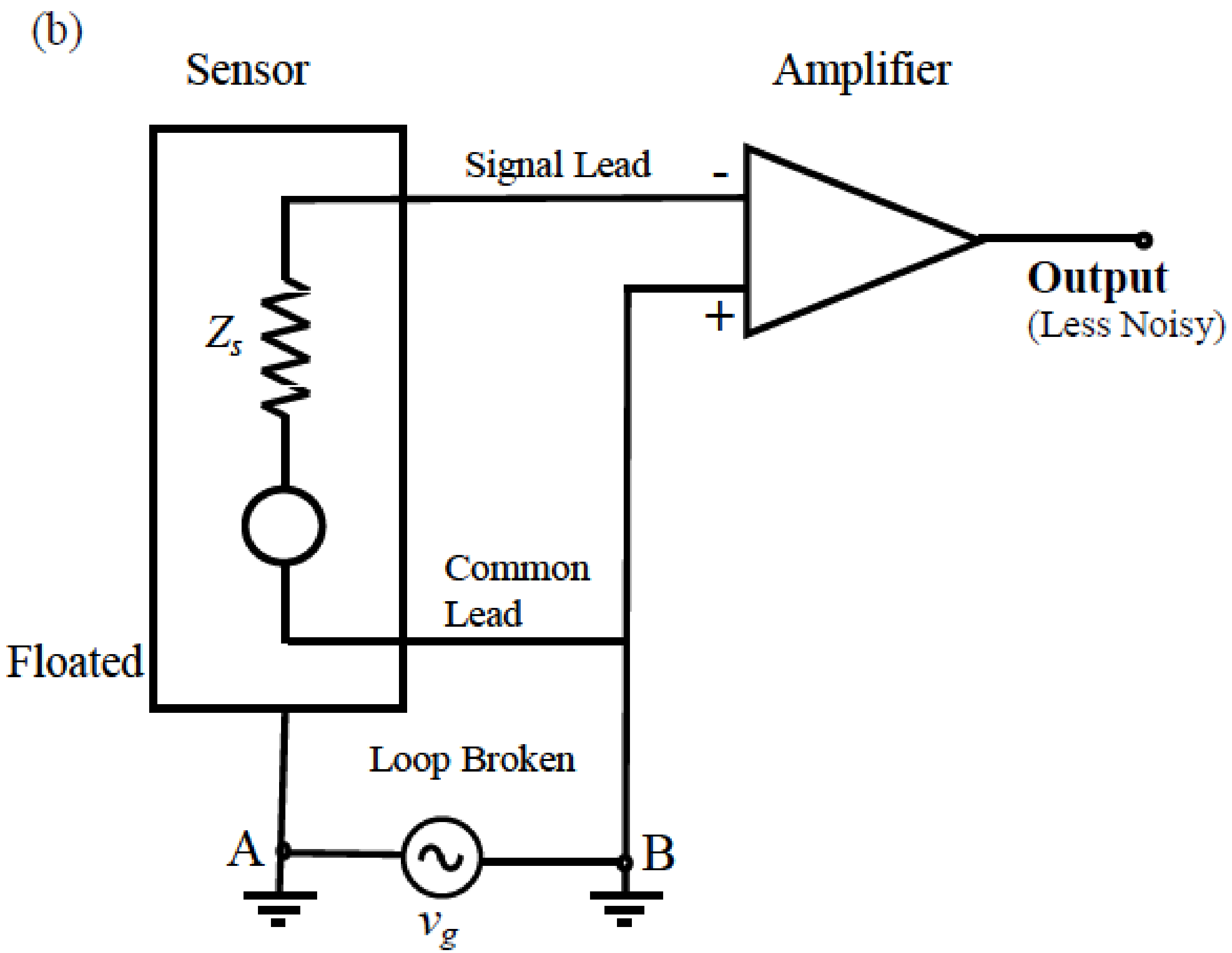


Ground Loop Noise



***Note*: Earth (ground) voltage is not uniformly 0V**

Breaking Ground Loop



Analog Filters

- Low-pass filters
- High-pass filters
- Band-pass filters
- Band-reject (or notch) filters

Filter

Signals have to be filtered (conditioned) to remove noise and other unwanted signals

Analog Filter: **Uses analog circuit. Circuit dynamics determine which signals are allowed through and which signals are rejected**

Active Filter: **Analog filter that uses active components (op-amps), which need external power**

Passive Filter: **Analog filter that uses passive components only (resistors, capacitors), which do not use external power**

Digital Filter: **Inputs are digital, outputs are digital, processing is digital. Digital logic determines filter characteristics (can be software or hardware digital processor)**

Comparison of Active and Passive Filters

Advantages of active filters:

- **Loading effects and dynamic interaction with other components are negligible (have very high input impedance and very low output impedance)**
- **Can be used with low signal levels (because amplification and filtering can be provided by same active circuit)**
- **Widely available in a low-cost IC form**
- **Can be easily integrated with digital devices.**
- **Less susceptible to noise from EMI** Check why.

Disadvantages:

- **Need an external power supply**
- **Susceptible to saturation nonlinearity at high signal levels**
- **Has internal noise and unmodeled signal errors (offset, bias signals, etc.)**

Filter Types

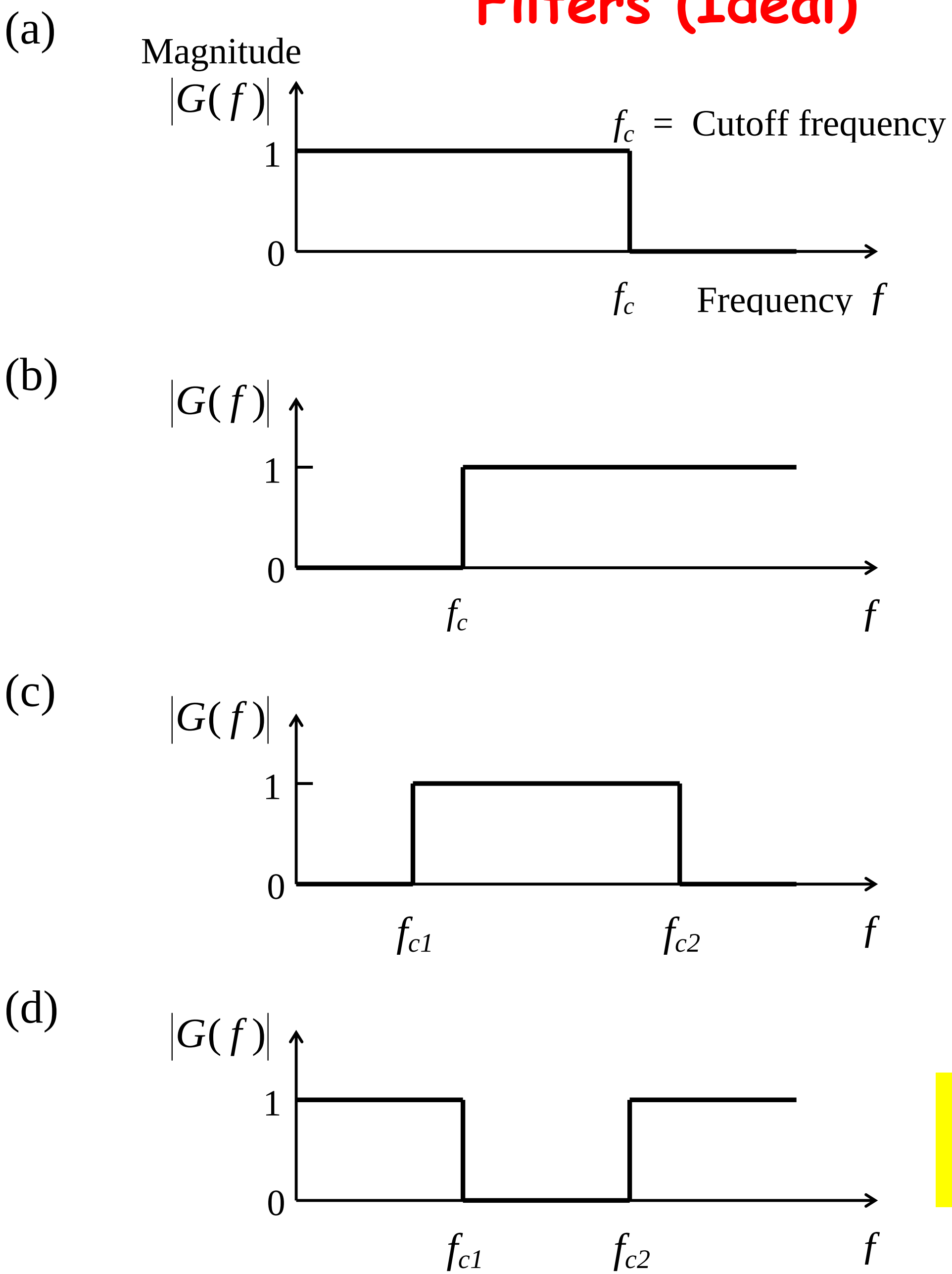
A filter allows through the desirable part of a signal, rejecting the unwanted part, in a specific frequency range

Filters are classified according to the frequency band it allows/rejects

Four Key Types of Filters:

1. **Low-pass filters**
2. **High-pass filters**
3. **Band-pass filters (including tracking filter ← has a variable narrow frequency band)**
4. **Band-reject (or notch) filters**

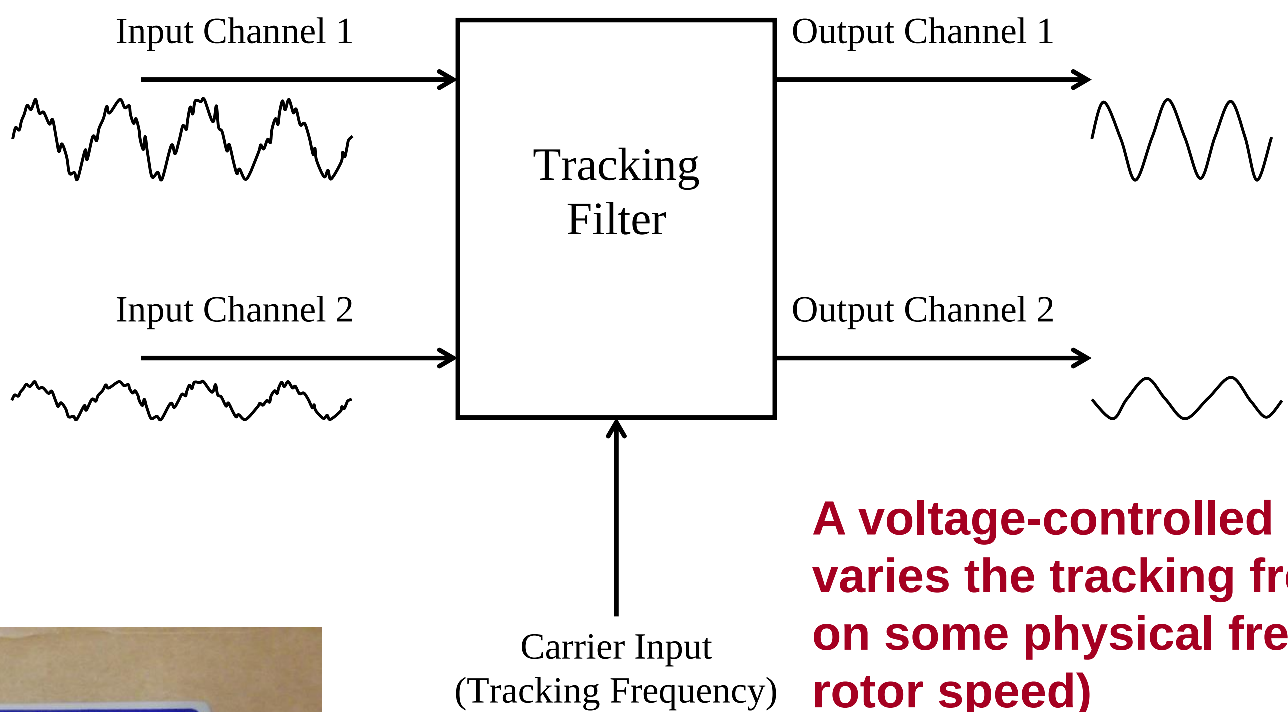
Filters (Ideal)



Give one use of a notch filter.

(a) Low-pass; (b) High-pass; (c) Band-pass; (d) Band-reject (Notch)

Tracking Filter



A voltage-controlled oscillator (VCO) varies the tracking frequency, based on some physical frequency (e.g., a rotor speed)

Give one use of a tracking filter.

Filter Summary

<u>Active Filters (Need External Power)</u>

<u>Advantages</u>:

- Smaller loading errors and dynamic interaction (have high input impedance and low output impedance ➔ don't affect the input circuit conditions, output signals and other components)
- Lower cost and component size
- Better accuracy

<u>Passive Filters (No External Power, Use Passive Elements)</u>

<u>Advantages</u>:

- Useable at very high frequencies (e.g., radio frequency)
- No need of a power supply

Filter Types

- Low Pass: Allows frequency components up to cutoff and rejects the higher frequency components
- High Pass: Rejects frequency components up to cutoff and allows the higher frequency components
- Band Pass: Allows frequency components within an interval and rejects the rest
- Notch (or, Band Reject): Rejects frequency components within an interval (usually, a narrow band) and allows the rest

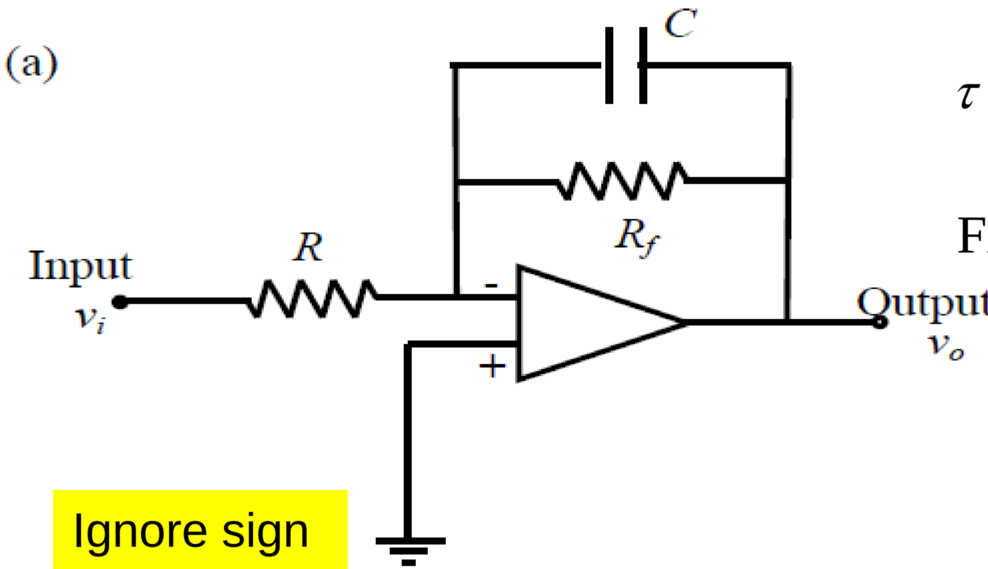
Definitions

- Filter Order: Number of poles in the filter circuit or transfer function
- Anti-aliasing Filter: Low-pass filter with cutoff at less than half the sampling rate (i.e., at less than Nyquist frequency), for digital processing
- Butterworth Filter: A high-order low-pass filter with a quite flat pass band
- Chebyshev Filter: An optimal low-pass filter with uniform ripples in the pass band
- Sallen-Key Fitler: An active filter whose output is in phase with input

A filter may introduce a "phase change" as well to the signal. Why?

Is this a serious problem? Give examples.

Low-pass Filter



$$\frac{v_i}{R}+\frac{v_o}{R_f}+C_f\frac{dv_o}{dt}=0$$

$$\tau\frac{dv_o}{dt}+v_o=-kv_i$$

Filter transfer function: $\frac{v_o}{v_i}=-\frac{k}{\tau s+1}$

Filter time constant: $\tau = R_f C_f$

Filter gain: $k = R_f / R$

Ignore sign and gain

(b)

Normalized TF: $\frac{1}{\tau s+1}$

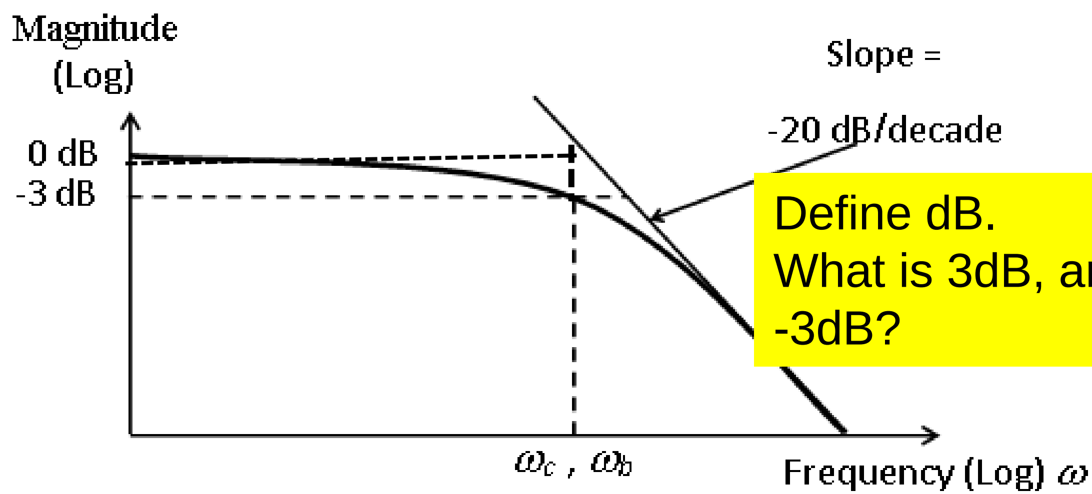
Cut-off = half-power point BW

(-3 dB) = Corner frequency

(where asymptotes meet):

$$\omega_c=\omega_b=\frac{1}{\tau}$$

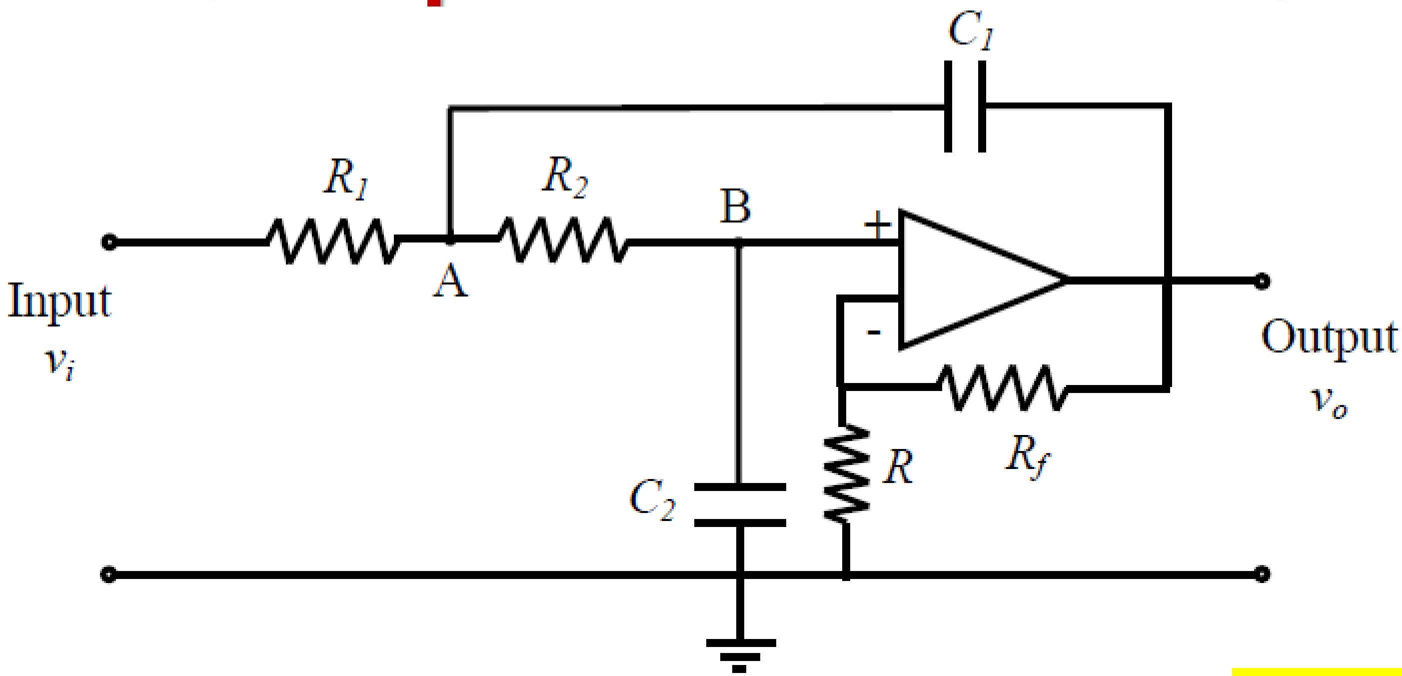
How?



Define dB.
What is 3dB, and -3dB?

(a) A single-pole active low-pass filter; (b) Frequency response characteristic.

Low-pass Butterworth Filter



Note: Correction of *k*

A two-pole low-pass Butterworth filter: Feedback path $\dfrac{v_B}{v_o} = \dfrac{R}{R+R_f} = k \text{ (say)}$

Current Balance at Nodes A and B: $\dfrac{v_i - v_A}{R_1} + C_1 \dfrac{d}{dt}(v_o - v_A) = \dfrac{v_A - v_B}{R_2} = C_2 \dfrac{dv_B}{dt}$

➔ Filter transfer Function (two poles):

$$\frac{v_o}{v_i} = \frac{1}{k\left[\tau_1\tau_2 s^2 + ((1-1/k)\tau_1 + \tau_2 + \tau_3)s + 1\right]} = \frac{\omega_n^2}{k\left[s^2 + 2\zeta\omega_n s + \omega_n^2\right]}$$

$$\tau_1 = R_1C_1, \quad \tau_2 = R_2C_2, \quad \tau_3 = R_1C_2$$

Give detailed derivation

MATLAB Result

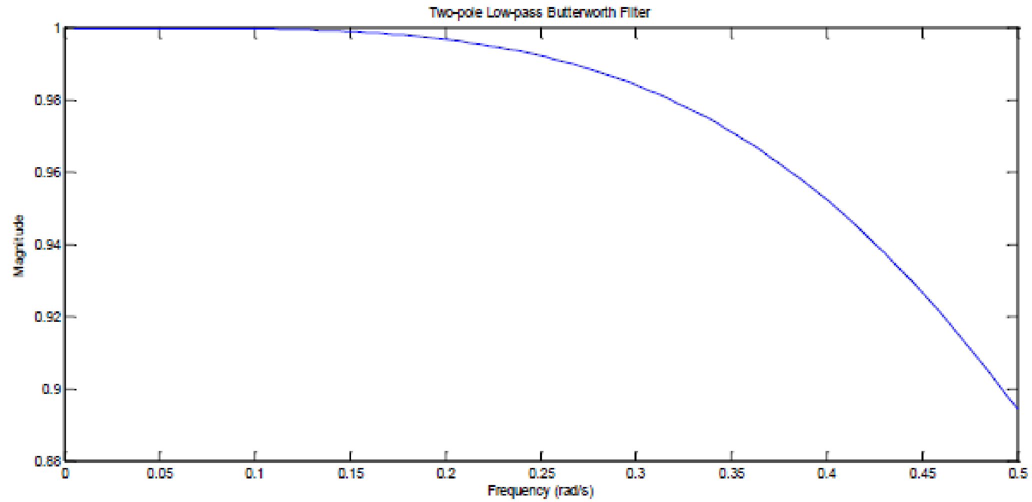
>> [b,a] = butter(n,Wn,'s')

n = filter order; Wn = normalized cutoff frequency (0>, <1); b = numerator coefficient vector of TF; a = denominator coefficient vector of transfer function.

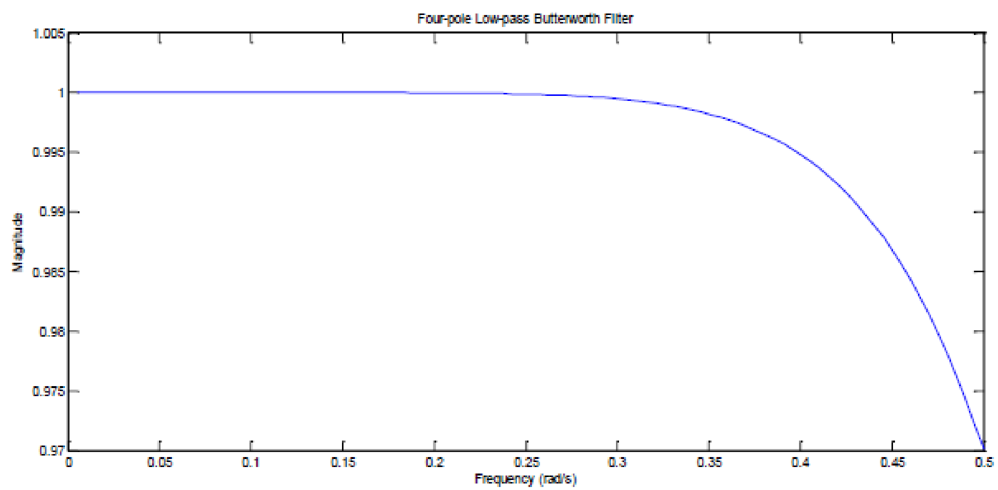
Example

$$\frac{v_o}{v_i} = \frac{0.5}{\left[s^2 + s + 0.5\right]}$$

```
>> [b,a]=butter(2,1/sqrt(2),'s')
b =
       0         0    0.5000
a =
    1.0000    1.0000    0.5000
>> w=linspace(0.005,0.5,101);
>> h = freqs(b,a,w);
>> plot(w,abs(h),'-')
```



Compare with 4-pole filter

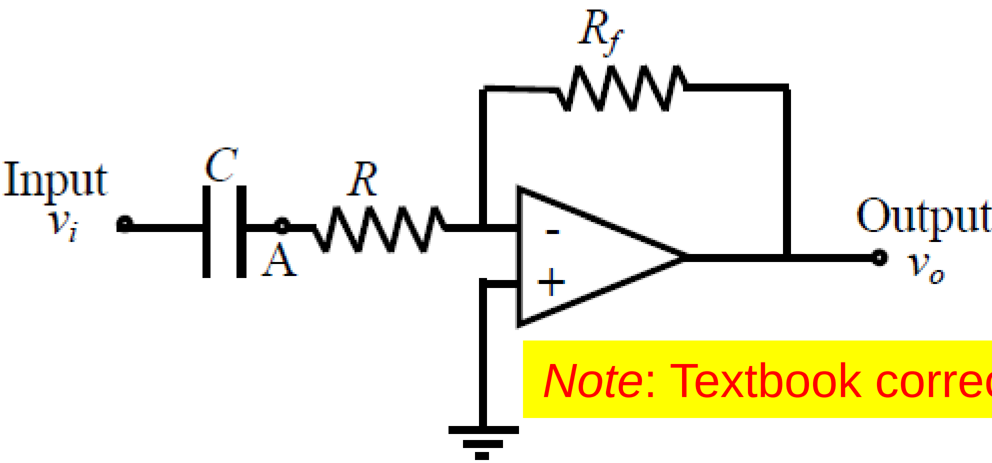


Commercial Low-pass Filters

- Filter modules with different corner frequencies are available
- Software programmable (via USB port) cut-off frequency and gain is available
- May come as a combined uint of instrumentation amplifier and low-pass filter

High-pass Filter (Single-pole)

(a)



Note: Textbook correction.

$$C\frac{d}{dt}(v_i - v_A) = \frac{v_A}{R} = -\frac{v_o}{R_f}$$

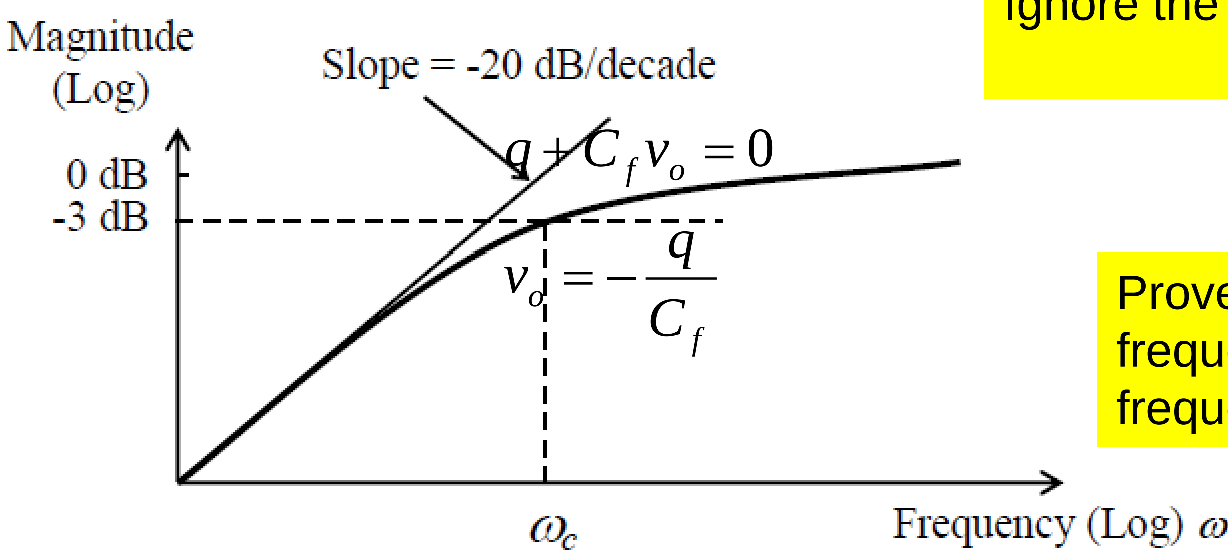
$$\rightarrow \quad k\tau\frac{dv_i}{dt} = -(\tau\frac{dv_o}{dt} + v_o)$$

$$\tau = RC; \qquad k = \frac{R_f}{R}$$

$$\rightarrow \frac{v_o}{v_i} = G(s) = -k\frac{\tau s}{(\tau s + 1)}$$

$$\rightarrow \frac{v_o}{v_i} = G(s) = \frac{\tau s}{(\tau s + 1)}$$

(b)

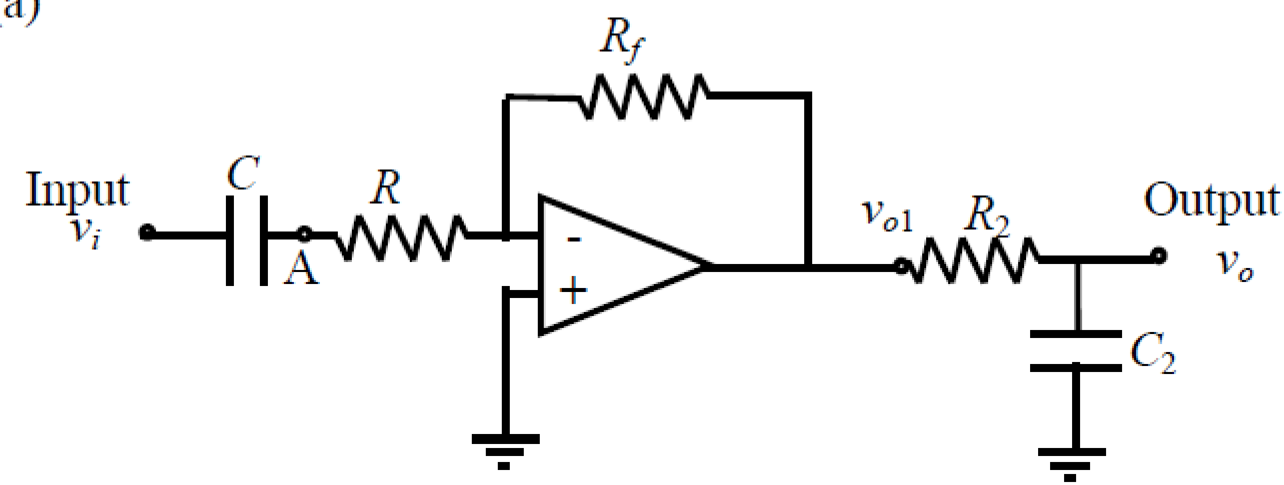


Ignore the sign and the gain

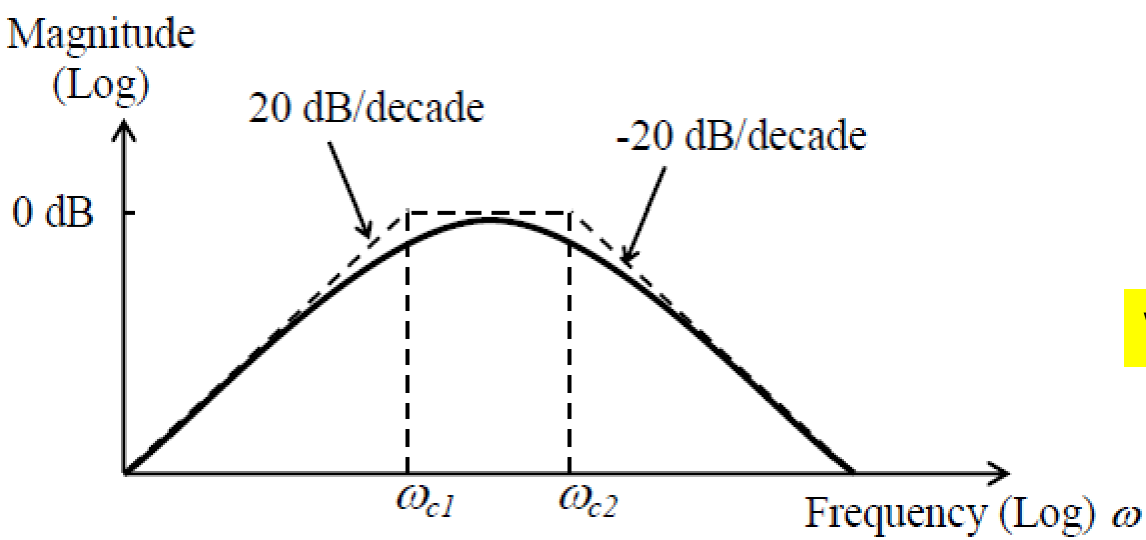
Prove that: 1. Corner frequency, 2. Half-power frequency are both at $1/\tau$

Band-pass Filter

(a)



(b)



Previously-obtained result for high-pass filter (1st stage): $R = R_f$

$$\frac{v_{o1}}{v_i} = \frac{\tau s}{(\tau s + 1)}$$

Any problem here?

2nd Passive stage:

$$\frac{v_{o1} - v_o}{R_2} = C_2 \frac{dv_o}{dt}$$

→

$$\frac{v_o}{v_{o1}} = \frac{1}{(\tau_2 s + 1)}$$

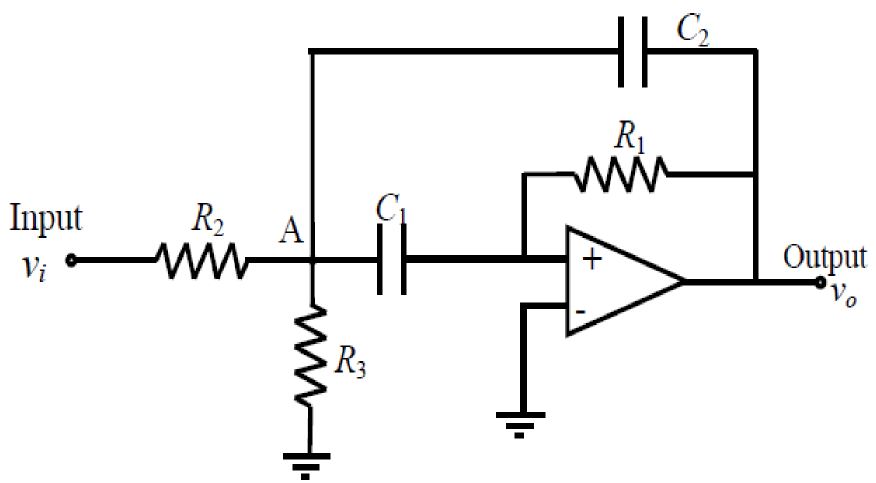
→

$$\frac{v_o}{v_i} = \frac{\tau s}{(\tau s + 1)(\tau_2 s + 1)}$$

What are τ and τ_2 ?

Narrow-band-pass Filter (Resonance Type)

(a)



$$\frac{v_o}{R_1} + C_1 \frac{dv_A}{dt} = 0$$

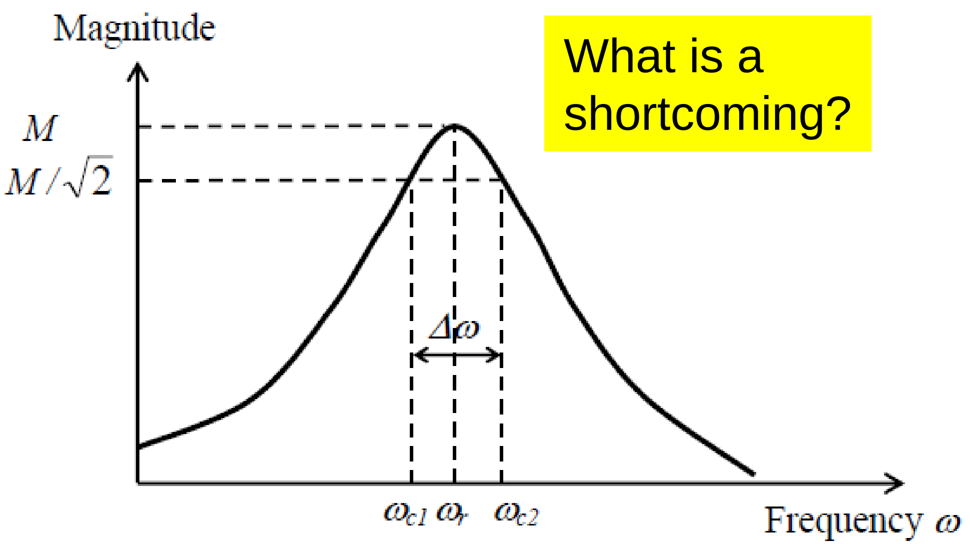
$$\frac{v_i - v_A}{R_2} + C_2 \frac{d}{dt}(v_o - v_A) = \frac{v_A}{R_3} - \frac{v_o}{R_1}$$

$$\frac{v_o}{v_i} = G(s) = -\frac{\tau_1 s}{\left[\tau_1\tau_2 s^2 + (k_1\tau_1 + \tau_2)s + 1 + k_2\right]}$$

$$\tau_1 = R_1 C_1 \quad \tau_2 = R_2 C_2 \quad k_1 = R_2 / R_1 \quad k_2 = R_2 / R_3$$

What is another name/use of this circuit?

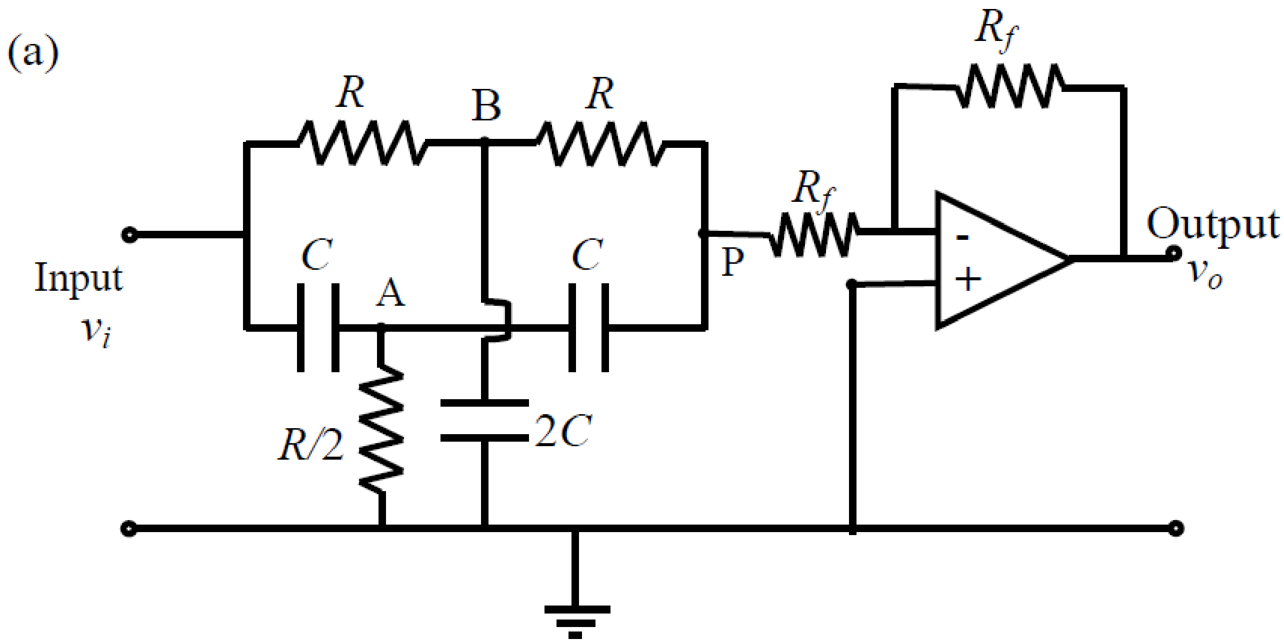
(b)

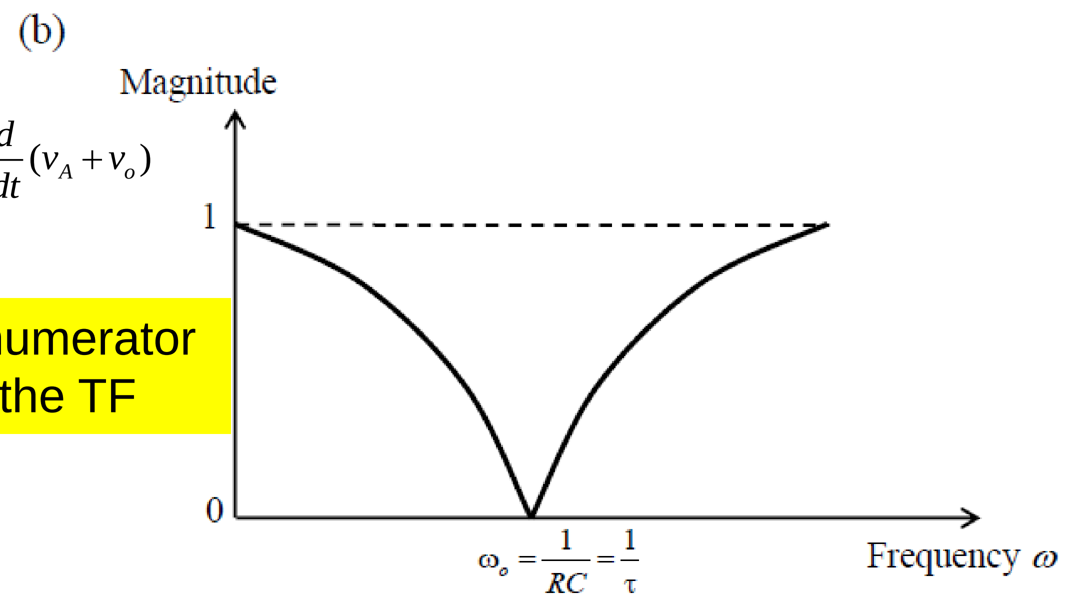


What is a shortcoming?

How do you express the band frequency limits in terms of circuit parameters?
(assume low damping)
Do Example 2.10

Band-reject Filter





$$\frac{v_i - v_B}{R} = 2C\frac{dv_B}{dt} + \frac{v_B + v_o}{R} \quad ; \quad C\frac{d}{dt}(v_i - v_A) = \frac{v_A}{R/2} + C\frac{d}{dt}(v_A + v_o)$$

$$\frac{v_B + v_o}{R} + C\frac{d}{dt}(v_A + v_o) = \frac{-v_o}{R_f}$$

$$\frac{v_o}{v_i} = G(s) = -\frac{(\tau^2 s^2 + 1)}{[\tau^2 s^2 + (4+k)\tau s + 1 + 2k]}$$

$\tau = RC$ $\qquad k = R / R_f$

Note the numerator (zeros) of the TF

Bridge Circuits

Bridge Circuits (Homework)

1. Read Section 2.8 (Bridge circuits. Straightforward but very important)

2. Do Example 2.11. The correct answer: $\dfrac{\delta v_o}{v_{ref}} = \dfrac{\delta R}{2R}$

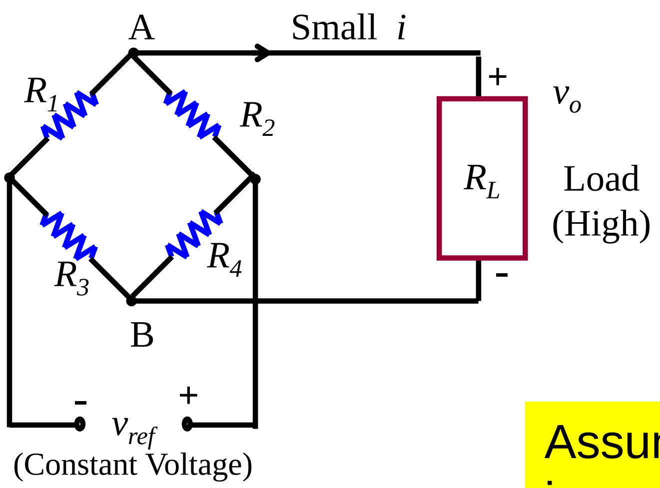
3. Read Chapter 2

Bridge Circuits

1. **Typically used to sense a change in electrical resistance (generally, electrical impedance)**
2. **Full bridge: Has 4 arms of impedance**
3. **Half bridge: Has two arms of impedance**
4. **DC bridge: Excited by dc**
5. **AC bridge: Excited by ac**
6. **Voltage bridge: Excited by a voltage**
7. **Current bridge: Excited by a current**
8. **Balanced bridge: The impedances in the arm are such that the bridge output = 0**

Wheatstone Bridge Circuit

What category of bridge does this belong to?



Assume: Open-circuit or impedance circuit (like instrumentation amp) at output

$$v_o = v_A - v_B = \frac{R_1 v_{ref}}{(R_1 + R_2)} - \frac{R_3 v_{ref}}{(R_3 + R_4)} = \frac{(R_1 R_4 - R_2 R_3)}{(R_1 + R_2)(R_3 + R_4)} v_{ref}$$

When the bridge is balanced: $v_o = 0 \quad \rightarrow$

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

True for any R_L

Bridge Measurement

Always start in the "balanced" condition of the bridge

(a) Null Balance Method:

1. When stain gage (active element) in the bridge deforms, the balance is upset.

2. Balance is restored by changing a variable resistor

➔ Amount of change → change in stain

***Note*: Note real time; Time consuming – servo balancing can be used**

(b) Direct Measurement of Output Voltage:

1. Measure the output voltage resulting from the imbalance

2. Use calibration constant (Bridge sensitivity) to determine the strain

$$\frac{\delta v_o}{v_{\text{ref}}} = \frac{\left(R_2 \delta R_1 - R_1 \delta R_2\right)}{\left(R_1 + R_2\right)^2} - \frac{\left(R_4 \delta R_3 - R_3 \delta R_4\right)}{\left(R_3 + R_4\right)^2}$$

Derive this. When is this relation valid?

Automatically compensate for temperature changes

Why?

***Note*: To compensate for temperature changes, temperature coefficients of adjacent pairs should be the same**

Bridge Constant

Bridge Output: $$\frac{\delta v_o}{v_{ref}} = k\frac{\delta R}{4R}$$

For all four arms having equal resistances *R*

Bridge Constant: $$k = \frac{\text{bridge output in the general case}}{\text{bridge output if only one strain gage is active}}$$

- **More than one resistor in the bridge can be active**
- **If all four resistors are active ➔ best sensitivity**
- **If *R*1 and *R*4 increase and *R*2 and *R*3 decrease ➔ largest bridge constant**

Why?

Signal Conditioning for a Wheatstone Bridge

Objective: Reduce loading effects

Solution: use an instrumentation amplifier to pick up the bridge output voltage

Example: INA 118 (Burr-Brown / Texas Instruments)

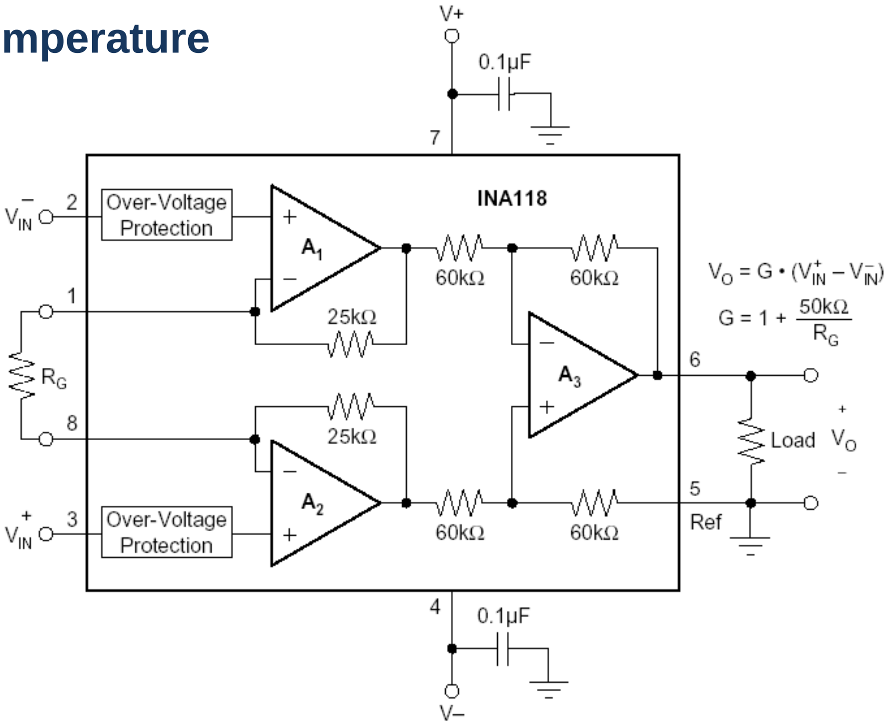
Instrumentation Amplifier Applications:

- **General engineering instrumentation/sensing and data acquisition (e.g., biomedical)**
- **Wheatstone bridge: Strain-gauge sensing; Temperature sensing (thermocouple, RTD)**

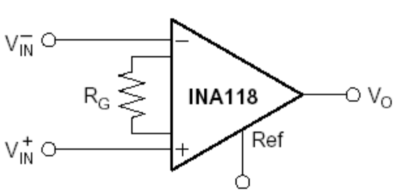
$R_{in} = 10^{10}\ \Omega$

DESIRED GAIN	R_G (Ω)	NEAREST 1% R_G (Ω)
1	NC	NC
2	50.00k	49.9k
5	12.50k	12.4k
10	5.556k	5.62k
20	2.632k	2.61k
50	1.02k	1.02k
100	505.1	511
200	251.3	249
500	100.2	100
1000	50.05	49.9
2000	25.01	24.9
5000	10.00	10
10000	5.001	4.99

NC: No Connection.

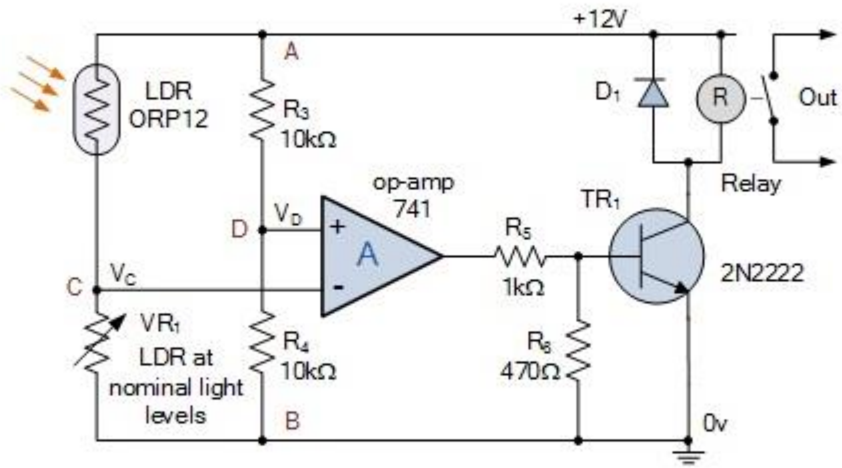


Also drawn in simplified form:



Note: Gain is changed by changing R_G
Check the numbers in this table from the formula we derived for instrumentation amplifier.

Light Sensor with Wheatstone Bridge



Light Sensor:

- **Photo-resistor is one arm of Wheatstone bridge**
- **Potentiometer (variable resistor) is the 2nd arm of bridge**
- **The other two arms are fixed resistors (10 kΩ each)**
- **The light intensity may be measured by: 1. balancing the bridge using the pot, or 2. through the bridge output under imbalanced condition**

Applications of Bridge Circuits

•Sensing light, strain, pressure, temperature (resistance bridge)

•Measuring capacitance, inductance, impedance, frequency, etc. (impedance bridge)