Electronics Primer

- ohms law
- Kirchhoff's current node rule

- define resistor
- define capacitor

- high/low pass RC filters
- s = jw notation, w = 2pi f
- filter transfer functions

Amplifiers and Analog Signal Processing

- Most bioelectric signals are small
  - voltages in micro-volts range
  - currents in pA and nA range common

- Small signals require amplification and filtering
  - op-amp, resistors and capacitors
  - integrated circuit and surface-mount technology

- Most modern signal processing tasks (filtering) are performed on a digital signal processor.
  - little change in amplification/filtering requirements over last 40 years
  - but new interest in putting DSP algorithms into analog circuits
    - due to demand for low power portable/implantable instruments

Ideal Op-Amp

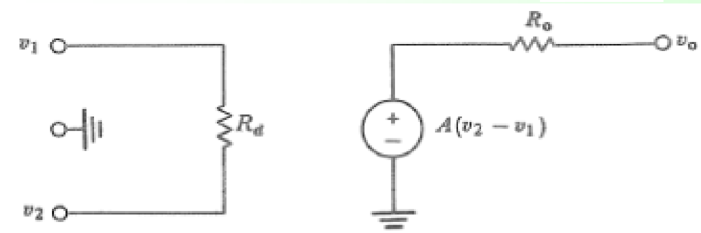
- Operational amplifier (op-amp) is a high-DC-gain differential amplifier

- Design circuits assuming op-amps are ideal
  - then verify/modify using simulations/prototyping

- Ideal op-amp model
  - "open loop" gain: $A = \infty$
  - differential input resistance: $R_d = \infty$
  - output resistance: $R_o = 0$
    - input current = 0
  - output voltage:
    - $v_o = 0$ when $v_1 - v_2 = 0$

ideal op-amp

$$A = \infty$$
$$v_o = 0$$
$$R_d = \infty$$
$$R_o = 0$$



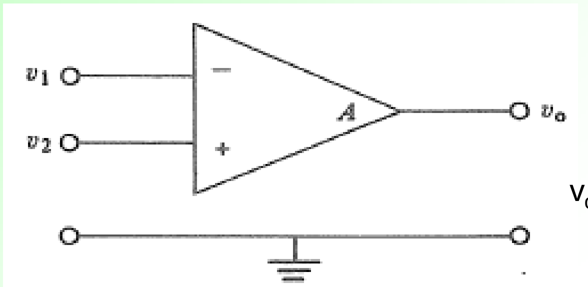
ideal op-amp small signal model

Op-Amp Properties

- Properties
  - open-loop gain: ideally infinite: practical values 20k-200k
    - high open-loop gain → virtual short between + and - inputs
  - input impedance: ideally infinite: CMOS opamps are close to ideal
  - output impedance: ideally zero: practical values 20-100Ω
  - zero output offset: ideally zero: practical value <1mV
  - gain-bandwidth product (GB): practical values ~MHz
    - frequency where open-loop gain drops to 1 V/V

- Commercial opamps provide many different properties
  - low noise
  - low input current
  - low power
  - high bandwidth
  - low/high supply voltage
  - special purpose: comparator, instrumentation amplifier

Basic Op-Amp Principles



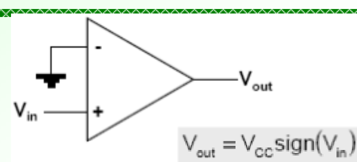
typical op-amp schematic symbol

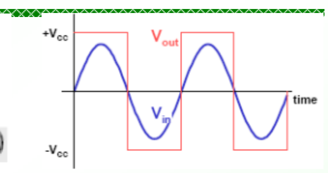
v_o, v_1, v_2 referenced to ground

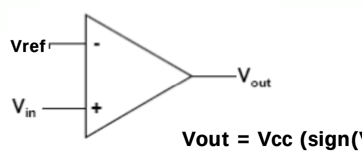
- Open loop gain: $v_o = A\,(v_2 - v_1)$
  - since A is very large, v_1-v_2 must be very small
- When the op-amp output is in its linear range
  - two input terminals are at (essentially) the same voltage
  - i.e., "virtual ground" between op-amp inputs
    - rely on this for DC/bias calculations
- Single vs. Dual Supply Voltage
  - most modern ICs use single supply
    - "ground" in a dual supply becomes VDD/2 in single supply
      - mid way between VDD and Ground

Basic Opamp Configuration

- Voltage Comparator
  - digitize input
  - assumes very high DC gain
  - Vcc = supply voltage

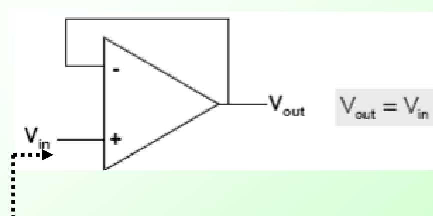






Vout = Vcc (sign(Vin-Vref))

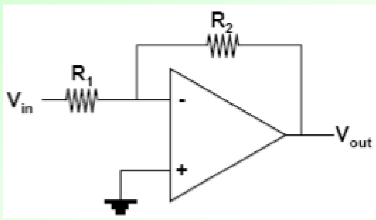
- Negative Feedback
  - output tied back into negative input terminal
  - generally avoid positive feedback
- Voltage Follower
  - buffer
  - prevents input signal from being loaded down by a low-resistance load

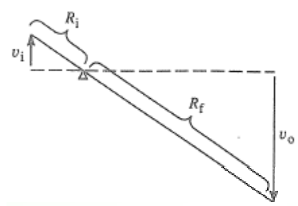


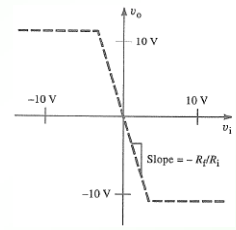
Rin = ∞

Inverting/Non-Inverting Configurations

- Inverting Amplifier (uses negative feedback)



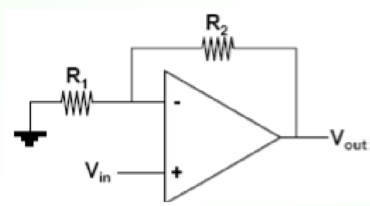


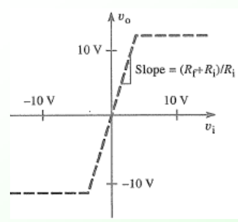


$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

$$A = \frac{v_o}{v_i} = \frac{-R_f}{R_i}$$

- Non-Inverting Amplifier (also uses negative feedback)



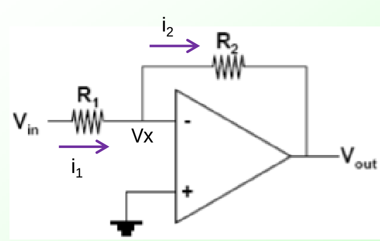


$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

$$A = \frac{v_o}{v_i} = 1 + \frac{R_f}{R_i} = \frac{R_i + R_f}{R_f}$$

Transfer Function Derivation

- Ideal op-amp conditions (simplify derivation)
  - virtual short at inputs (voltage at + same as at -)
  - no current into input terminals
- Inverting amplifier gain transfer function
  - write equations of operation from schematic using Ohms law
    - Vx – Vin = R1 * i1
    - Vout – Vx = R2 * i2
  - apply ideal op-amp conditions
    - virtual short → Vx = 0
    - no input current → i1 = i2 = i
  - thus
    - -Vin = R1 * i → i = -Vin/R1
    - Vout = R2 * i → i = Vout/R2
  - and setting i = i...
    - → -Vin/R1 = Vout/R2 → Vout= -Vin (R2/R1)

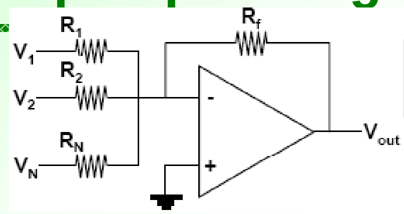


$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

MICHIGAN STATE UNIVERSITY

More Opamp Configurations

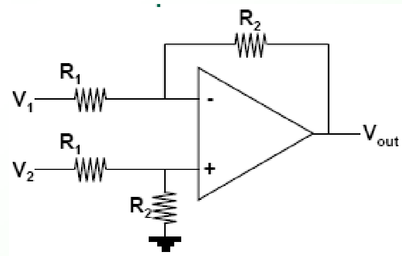
- Summing Amp
  - weighted sum of multiple inputs
  - inverting or non??



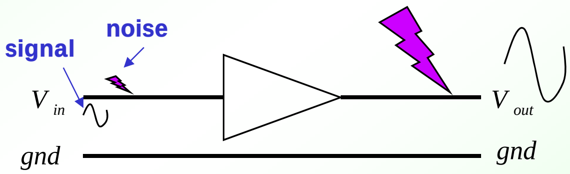
$$V_{out} = -\left(V_1\frac{R_f}{R_1} + V_2\frac{R_f}{R_2} + \cdots + V_N\frac{R_f}{R_N}\right)$$

- Differential Amp
  - match R_1s and R_2s
  - inverting or non??

$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$



Single-Ended Amplifier Representation



$$A_v = \frac{\Delta V_{out}}{\Delta V_{in}}$$

Noise Amplification

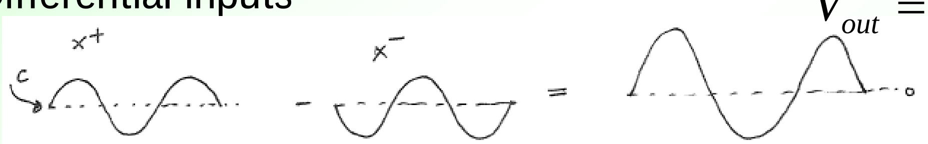
- even small interference at input gets amplified at output

MICHIGAN STATE UNIVERSITY

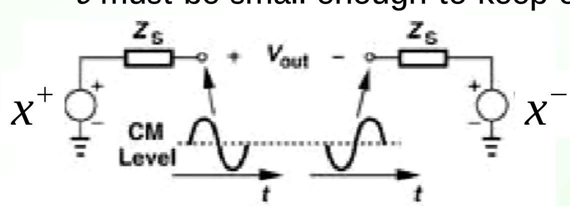
Differential vs. Common Mode Signal

- Define
  - x^+ = input at + terminal
  - x^- = input at – terminal
  - c = common mode signal on both inputs
- Differential inputs

$$V_{out} = x^+ - x^-$$



- Add common mode input
  - *c* rejected by differential amplifier (not amplified)
  - *c* must be small enough to keep op-amp biased in linear operation

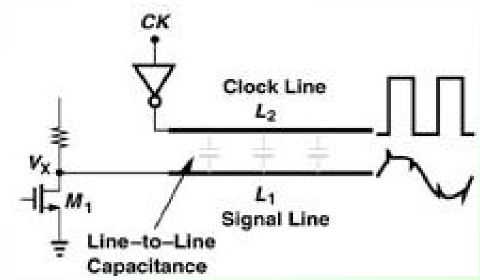


$$V_{out} = (x^+ + c) - (x^- + c)$$

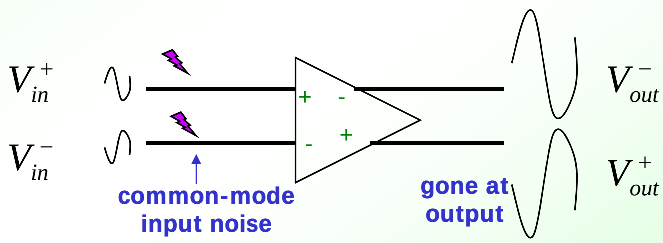
$$c = \frac{x^+ + x^-}{2}$$

Noise in Differential Amplifiers

- Global interference (e.g., supply voltage variations)
  - assumed to be located far away from amp. input terminals
    - same interference on both the terminals
  - appear as <u>common mode</u> disturbance.
  - example: clock noise

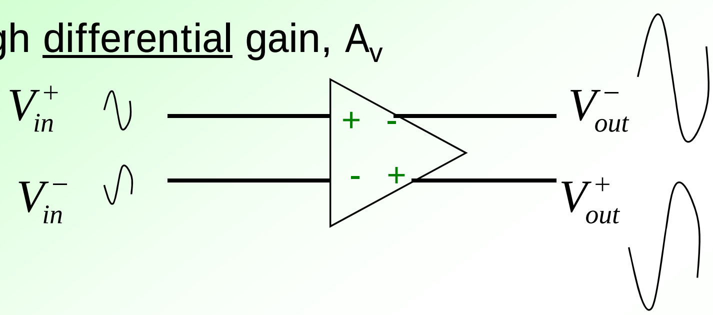


- Differential amplifiers
  - amplify only the difference
  - reject the interference (common-mode)



Desirable Properties of Amplifiers

- High <u>differential</u> gain, A_v

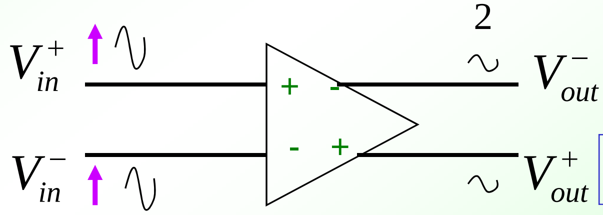


$$A_v = \frac{\Delta V_{out}^{+} - \Delta V_{out}^{-}}{\Delta V_{in}^{+} - \Delta V_{in}^{-}}$$

- Low common mode gain, A_{cm}

 = high "common mode rejection"

Common-mode signal $\frac{\Delta V_{in}^{+} + \Delta V_{in}^{-}}{2}$

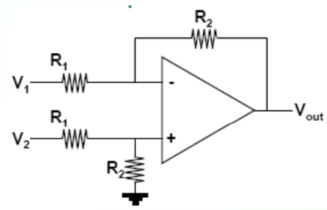


$$A_{CM} = \frac{\Delta V_{out}^{+} - \Delta V_{out}^{-}}{\frac{\Delta V_{in}^{+} + \Delta V_{in}^{-}}{2}}$$

common mode rejection ratio: $\mathrm{CMRR} = \frac{A_v}{A_{cm}}$

3-Op-Amp Instrumentation Amplifier

- Differential amplifiers
  - low common mode gain = Great!
  - lower than ideal input resistance – Bad!

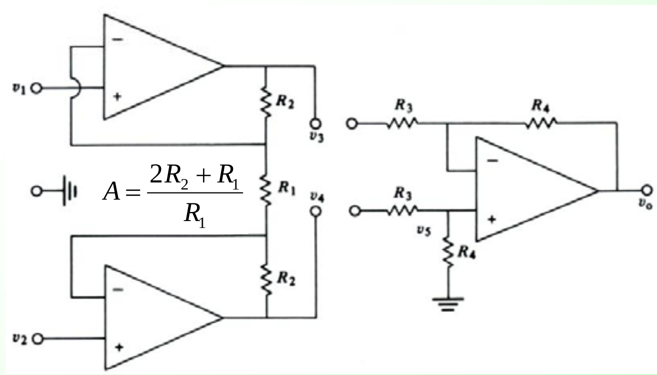


- 3-op-amp structure
  - keeps low common mode gain
  - provides very high input resistance
    - why?
  - call “instrumentation amp”
    - will discuss in detail later

total differential gain

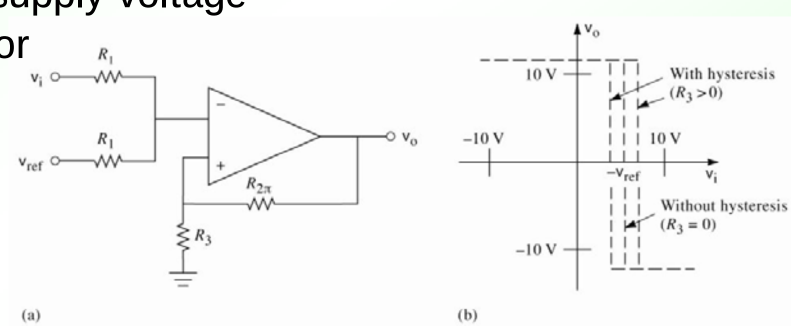
$$G_d = \frac{2R_2 + R_1}{R_1}\left(\frac{R_4}{R_3}\right)$$

$$A_{com} = 1$$



Comparator

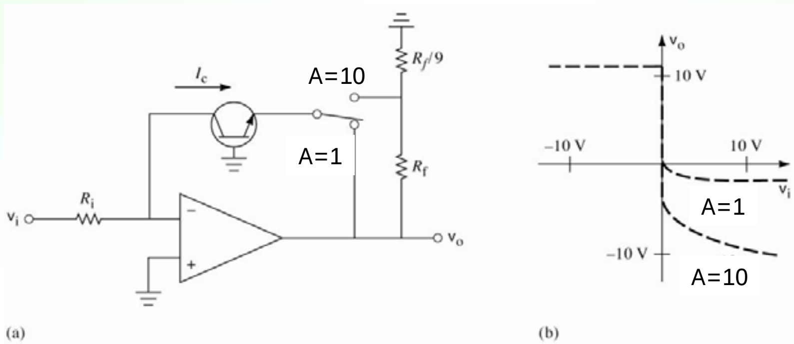
- Compare an input voltage v_i to a reference voltage v_{ref}
- Output digital value (hi/low)
  - low if $v_i > v_{ref}$ why low and not hi?
  - high if $v_i < v_{ref}$
- Output voltage = supply voltage
- Op-amp comparator



- Add hysteresis to improve noise immunity
  - hysteresis = rising transition point different that falling transition point
  - R3 controls hysteresis

Logarithmic Amplifiers

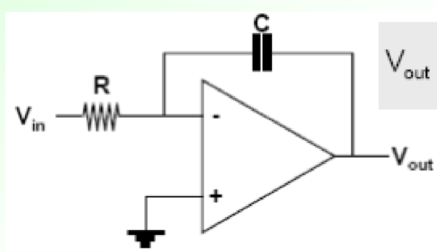
- Uses non-linear current-voltage relationship of BJT in feedback path $V_{BE} = k \log\left(\frac{I_C}{I_S}\right)$
- Useful for computing logarithms and anti-logs
  - for compressing and multiplying/dividing signals



Integrating/Differentiating Configurations

- Integrating Amp

$$v = \frac{1}{C}\int_o^t i\, dt$$

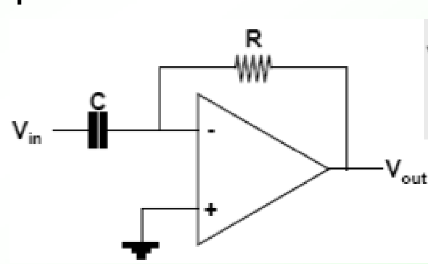


$$V_{out} = -\frac{1}{j\omega CR} V_{in} = -\frac{1}{RC}\int V_{in} dt$$

$$\omega = 2\pi f$$

- Differentiating Amp

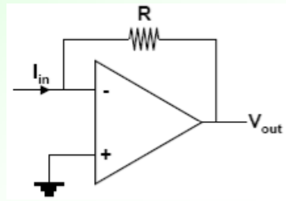
$$i = C\frac{dv}{dt}$$



$$V_{out} = -\frac{R}{\frac{1}{j\omega C}} V_{in} = -RC\frac{dV_{in}}{dt}$$

Converting Configuration

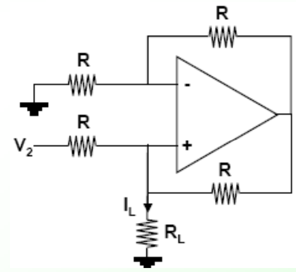
- Current-to-Voltage



$$V_{out} = -I_{in}R$$

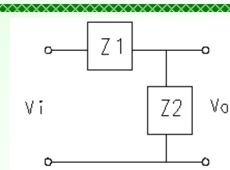
- Voltage-to-Current

$$I_L = \frac{V_{in}}{R}$$



Active Filters

- Passive low pass filter

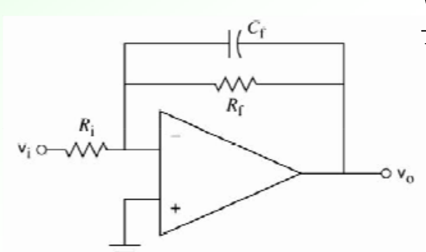


$$\frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2}$$

If Z1 is a resistor (R) and Z2 is a capacitor (1/sC) then

$$\frac{V_o}{V_i} = \frac{\frac{1}{sC}}{\frac{1}{sC} + R} = \frac{1}{1 + sCR}$$

- Active low pass filter



$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{Z_f}{Z_i} = -\frac{\dfrac{(R_f / j\omega C_f)}{[(1/j\omega C_f) + R_f]}}{R_i}$$

$$= -\frac{R_f}{(1 + j\omega R_f C_f)R_i} = -\frac{R_f}{R_i}\frac{1}{1 + s/\omega_0}$$

-3dB frequency

$$\omega_0 = 1/R_f C_f$$

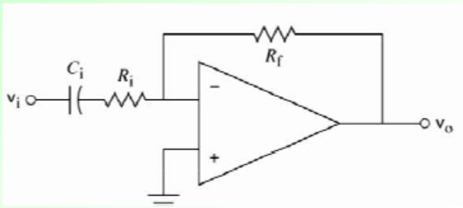
$\omega = 2\pi f$

$$\frac{V_o}{V_i} = \frac{H_o \omega_o}{s + \omega_o}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{R_f}{R_i}\frac{1}{1 + j\omega R_f C_f}$$

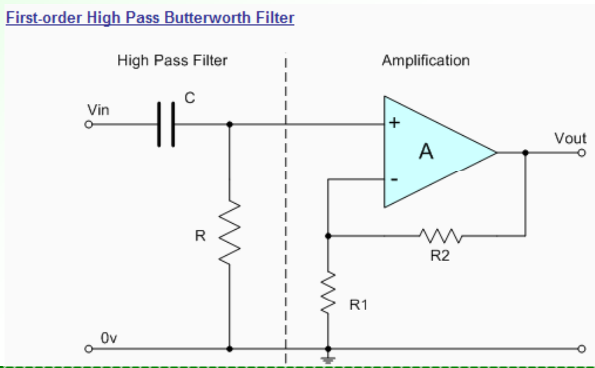
Active Filters

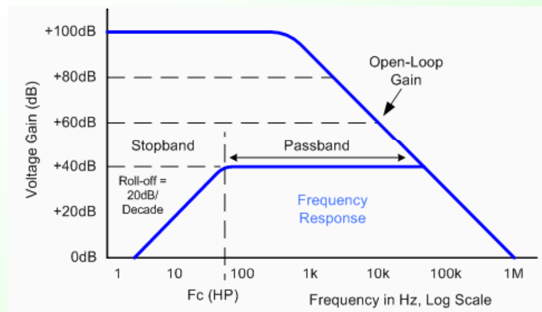
- Active high pass filter



$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{R_f}{R_i}\frac{j\omega R_i C_i}{1 + j\omega R_i C_i}$$

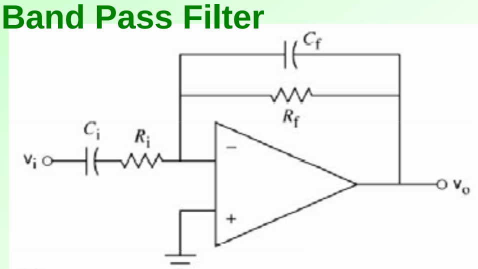
$$\frac{V_o}{V_i} = H_0 \frac{s}{s+\omega_0} \qquad \omega_0 = 1/R_iC_i$$





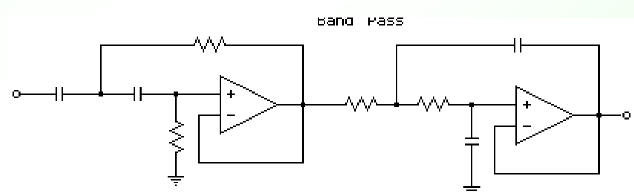
Active Filters

Band Pass Filter

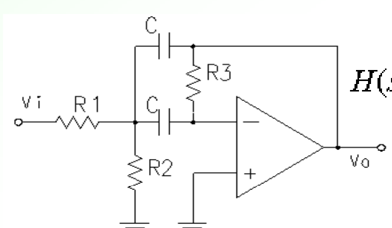


$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{R_f}{R_i}\frac{j\omega R_f C_i}{(1 + j\omega R_f C_f)(1 + j\omega R_i C_i)}$$

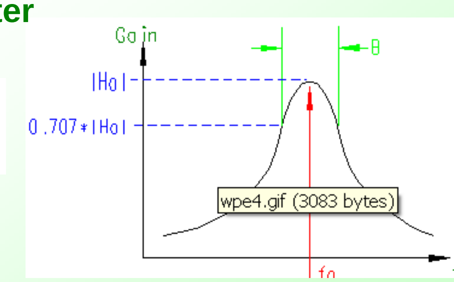
2-stage Band Pass Filter



High Q (narrow frequency) Band Pass Filter



$$H(s) = \frac{V_o}{V_i} = \frac{H_o \beta s}{s^2 + \beta s + \omega_o^2}$$



Non-ideal Characteristics

- Offset voltage
  - output not zero when the inputs to the amplifiers are equal
    - could be in order of millivolts
  - cancel offset voltage by adding an external "nulling" potentiometer
- Temperature Drift
  - offset voltage can drift by 0.1 microvolts over one degree variation
- Finite (lower than infinite) input impedance
  - can cause errors at input
- High output impedance
  - limits load driving capabilities
- Noise
  - Thermal noise or high-frequency noise
  - Flicker noise: low-frequency noise