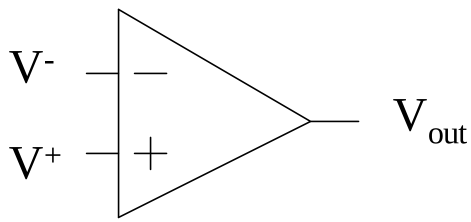
Basics of Transconductance – Capacitance Filters

Dr. Paul Hasler

Operational Amplifiers

<u>OP Amp</u>:

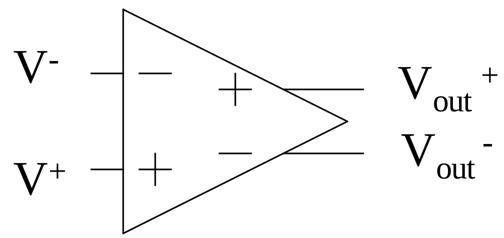
$V_{out} = A_v (V^+ - V^-)$



<u>Balanced Op Amp</u>:

$V_{out}^+ = A_v (V^+ - V^-)$

$V_{out}^- = A_v (V^- - V^+)$

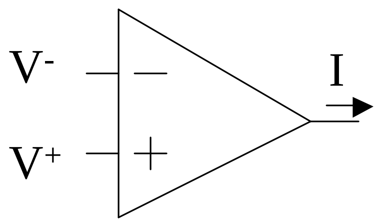


A_v is frequency dependent

Transconductance Amplifiers

OTA:

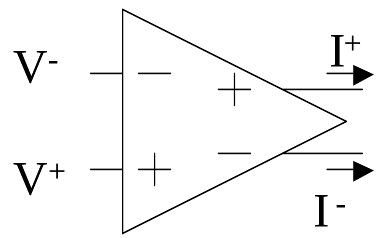
$I = G_m (V^+ - V^-)$



Balanced OTA:

$I^+ = G_m (V^+ - V^-)$

$I^- = G_m (V^- - V^+)$



- Most op-amps can be used as OTAs, most OTAs can be used as op-amps. (depends which application is being optimized)

Major Issues for OTAs

Major Issues for OTAs:

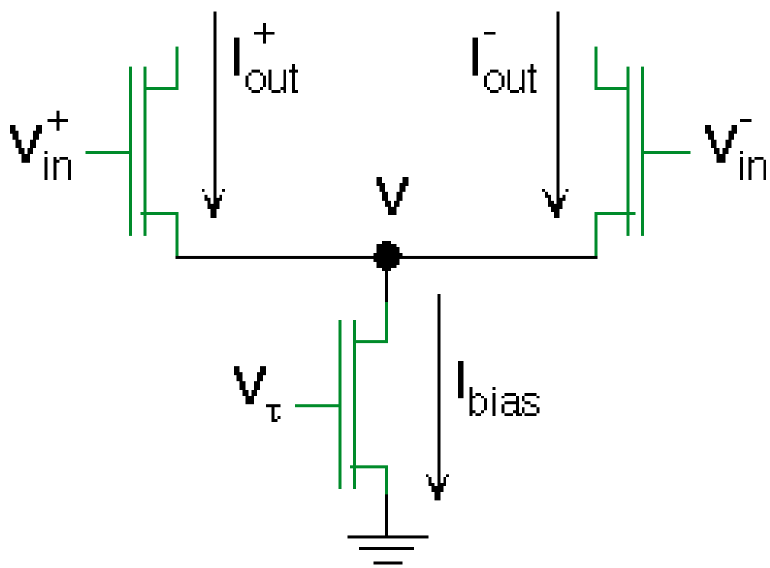
- Linearity
- Offsets
- Output Resistance (depends upon application)

How to Build OTAs

Basic transistor differential amplifer,
Wide-output-range differential amplifier …

Build with cascodes or folded cascode or differential approaches.

Analysis of Diff-Pair



$$I_{out}^{+} = I_o \, e^{\kappa V_{in}^{+} / U_T} \, e^{V / U_T}$$

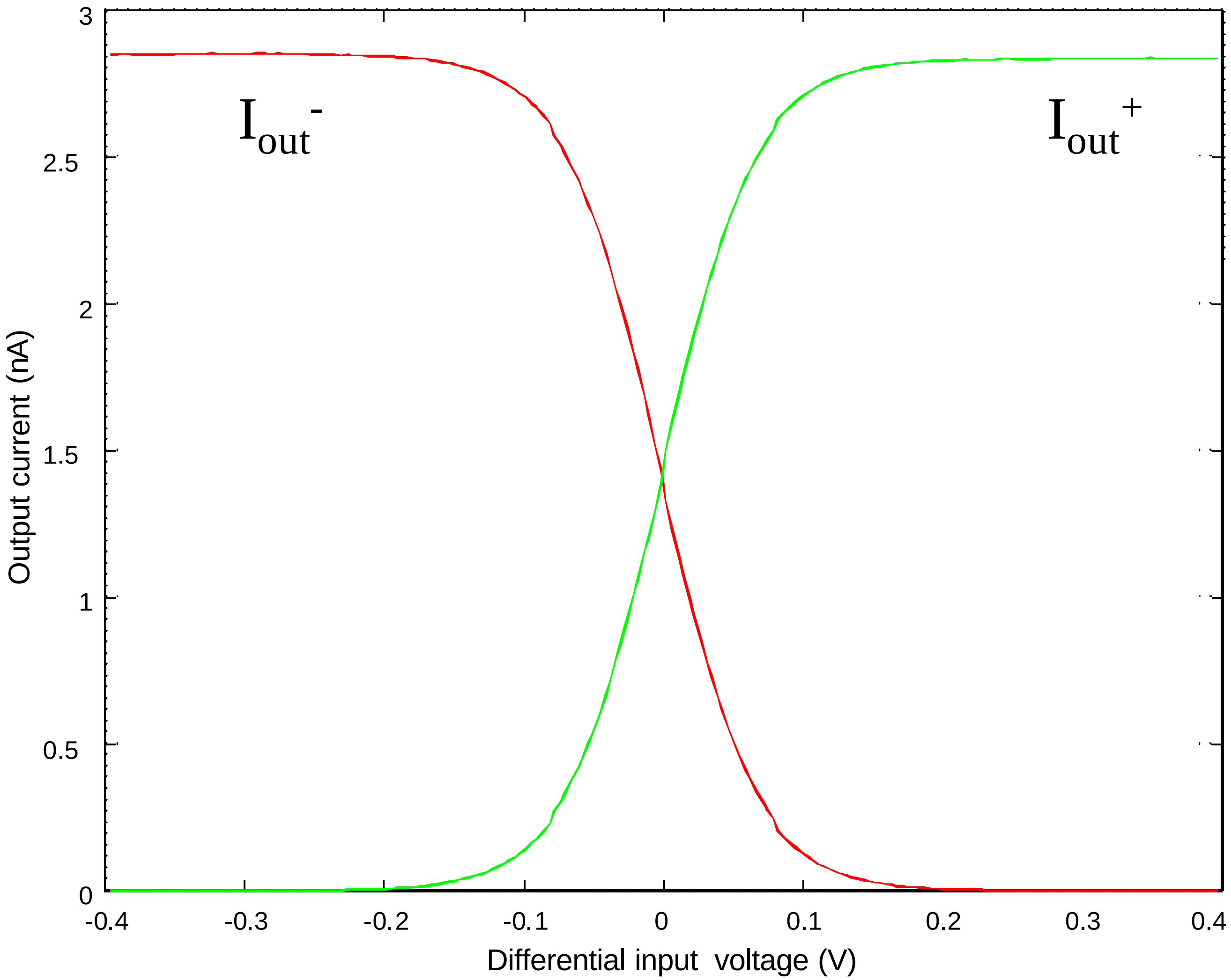
$$I_{out}^{-} = I_o \, e^{\kappa V_{in}^{-} / U_T} \, e^{V / U_T}$$

$$I_{out}^{+} = I_{bias} \frac{e^{\kappa V_{in}^{+} / U_T}}{e^{\kappa V_{in}^{+} / U_T} + e^{\kappa V_{in}^{-} / U_T}}$$

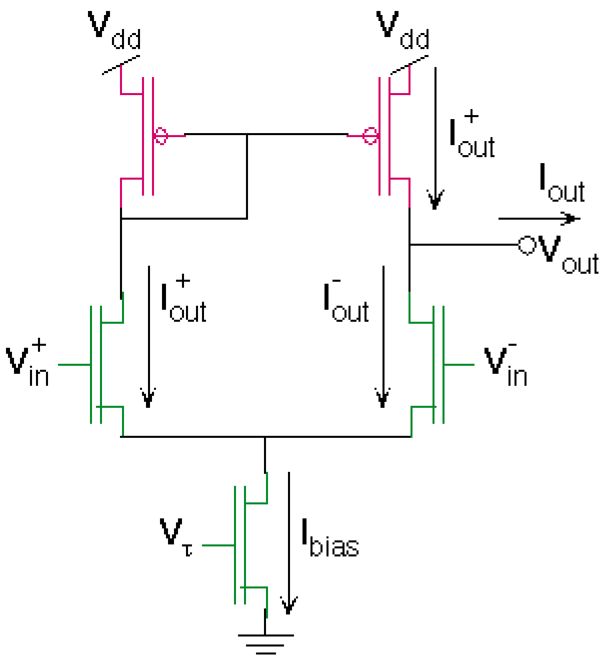
$$= I_{bias} \frac{1}{1 + e^{\kappa (V_{in}^{-} - V_{in}^{+}) / U_T}}$$

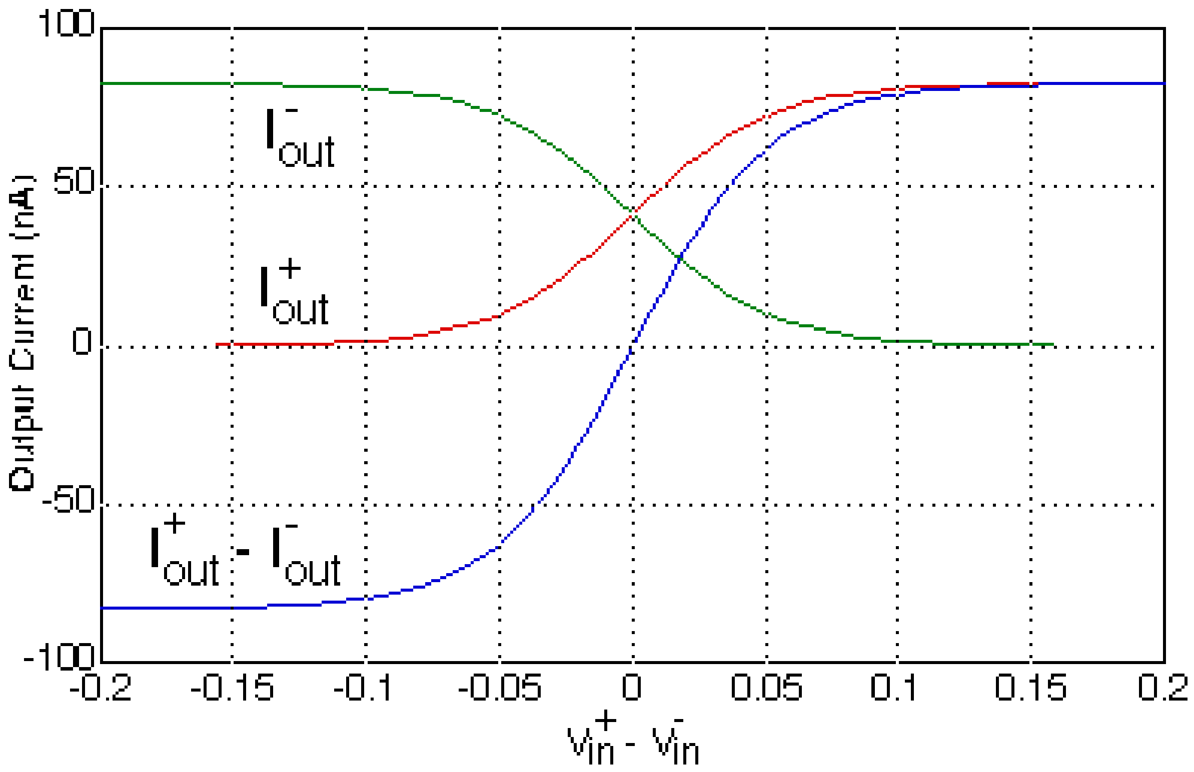
$$I_{out}^{-} = I_{bias} \frac{1}{1 + e^{\kappa (V_{in}^{+} - V_{in}^{-}) / U_T}}$$

Differential Pair Currents

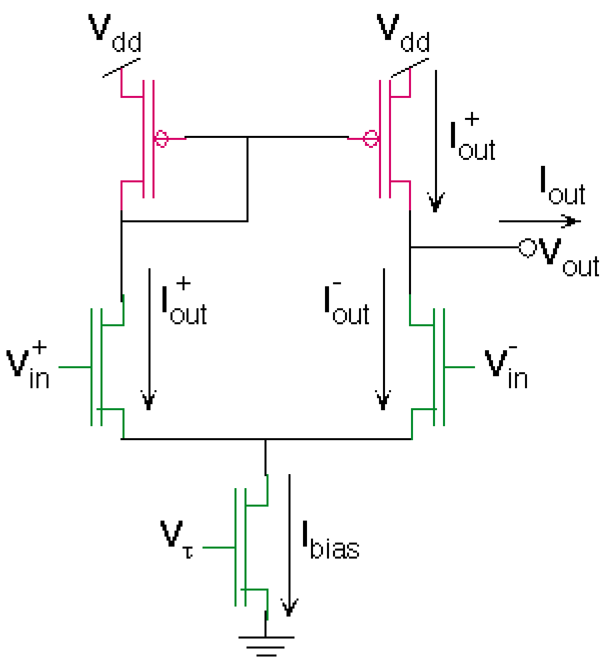


Basic Differential Amplifier

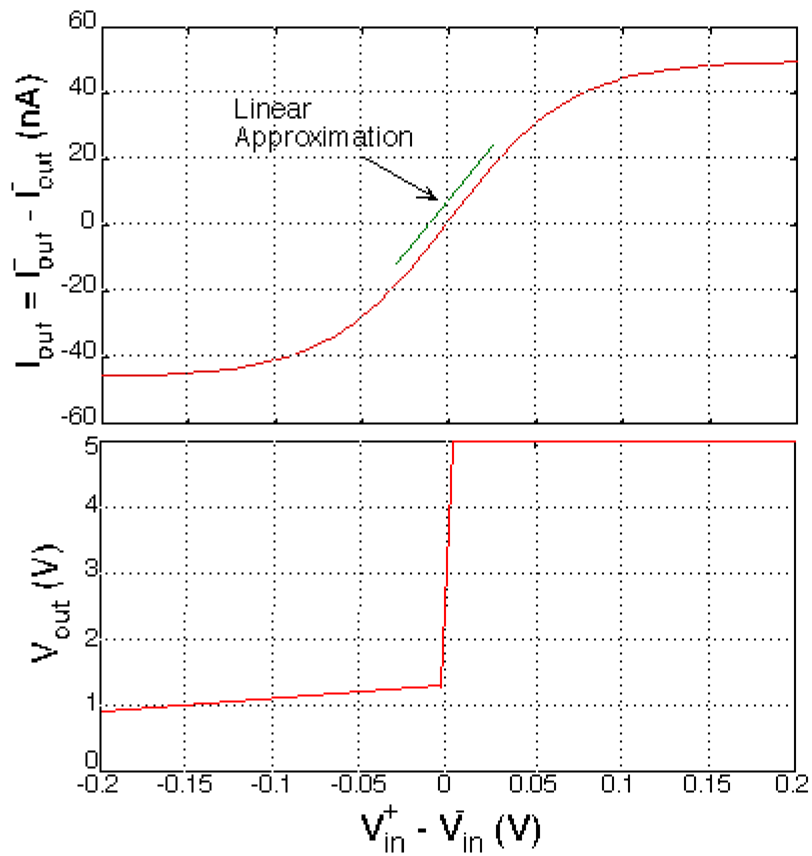




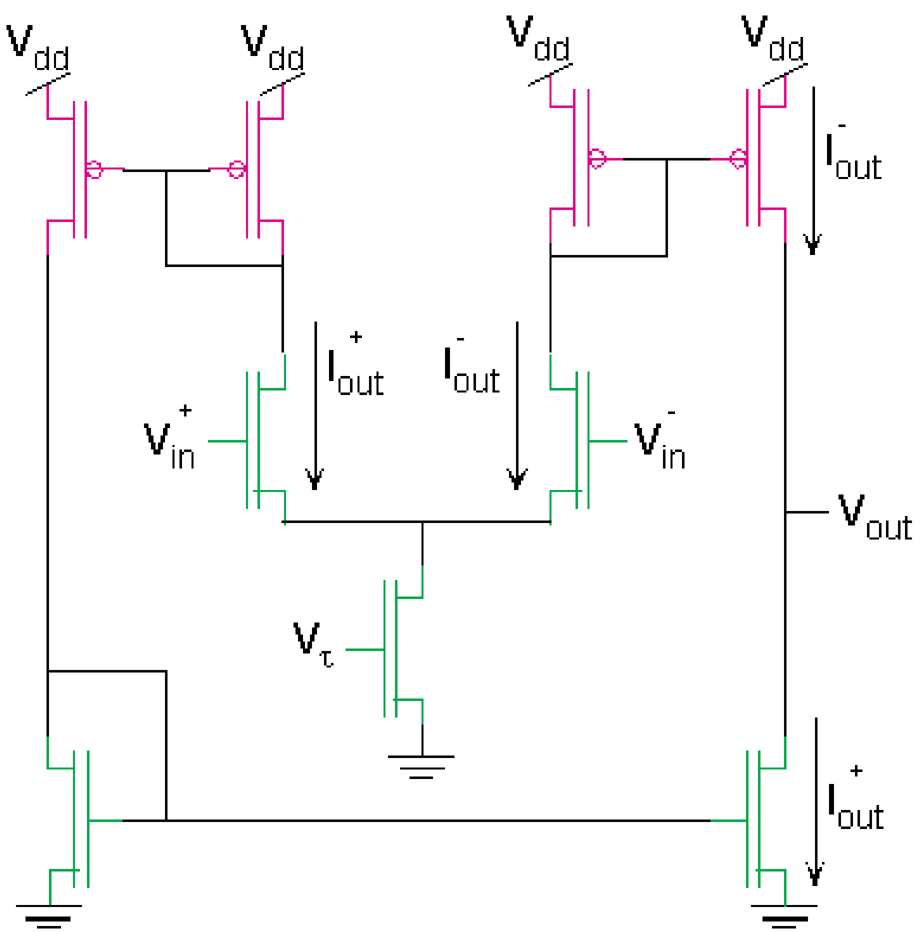
Transfer Functions



$$I_{out} - I_{out} = I_{bias} \tanh\left(\frac{\kappa \, (V_{in}^{+} - V_{in}^{-})}{2\, U_T} \right)$$



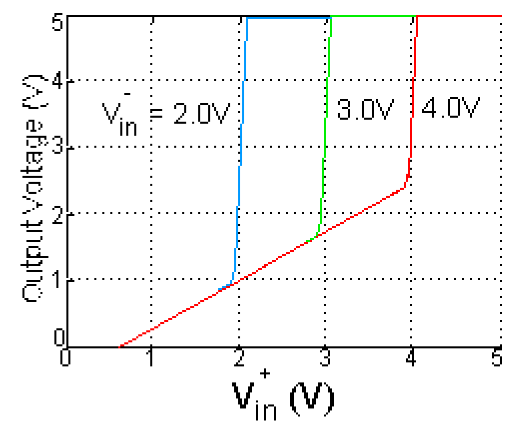
Wide-Output Range Differential Amplifier



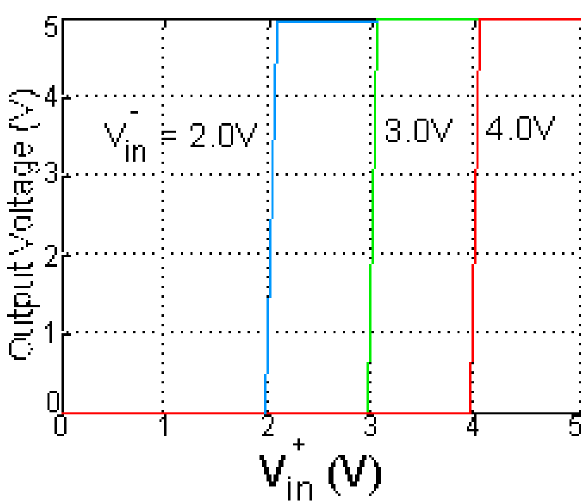
High gain region: $V_{out} = \frac{\kappa V_o}{2 U_T} (V_{in}^{+} - V_{in}^{-})$

Simple differential amplifer

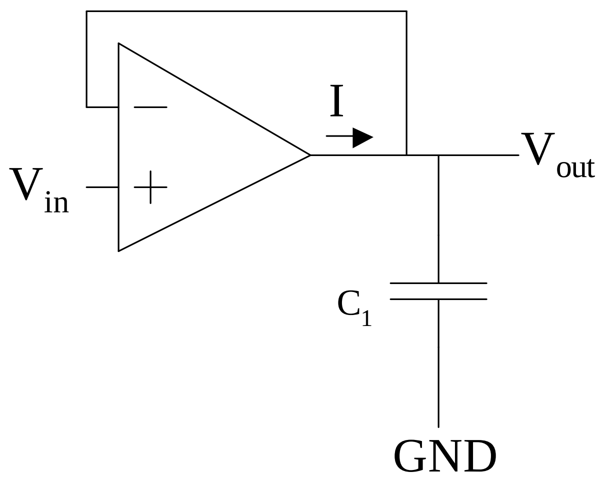
"Vmin" effect



Wide-output range amplifier



Simplest Gm-C Filter



If an ideal op-amp, then $V_{in} = V_{out}$

By KCL: $G_m(V_{in} - V_{out}) = C_1 \frac{dV_{out}(t)}{dt}$

Defining $\tau = C_1 / G_m$

$$V_{in} = V_{out} + \tau \frac{dV_{out}(t)}{dt}$$

We can set Gm and build C sufficiently big enough (slow down the amplifier), or set by C (smallest size to get enough SNR), and change Gm.

Also, should mention the high-pass version as well.

Tuning Frequency using Bias Current

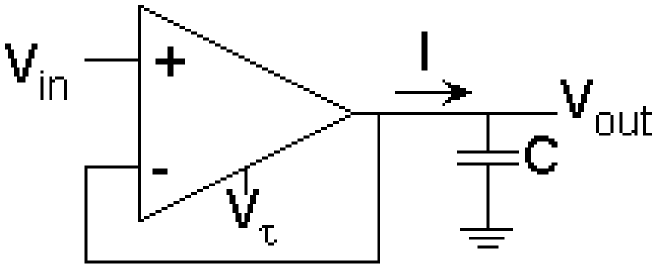
Bias Current	Transconductance	Cutoff Frequency
1mA	1/250Ω	600MHz
1μA	1/25kΩ	6MHz
1nA	1/25MΩ	6kHz
1pA	1/25GΩ	6Hz

C = 1pF, W/L of input transistors = 30, I_{th} ~ 10μA.

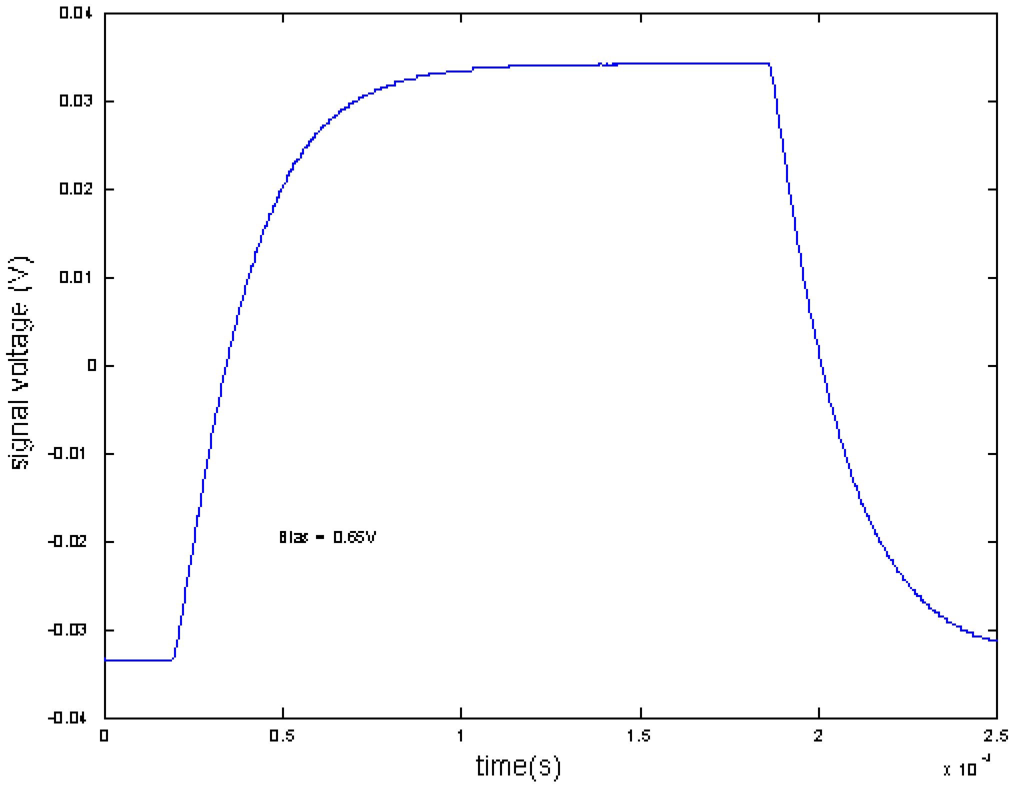
This approach is the most power-efficient approach for any filter.

All electronically tunable: Advantage: we can electronically change the corner
Disadvantage: we need a method to set this frequency (tuning)

A Low-Pass Filter



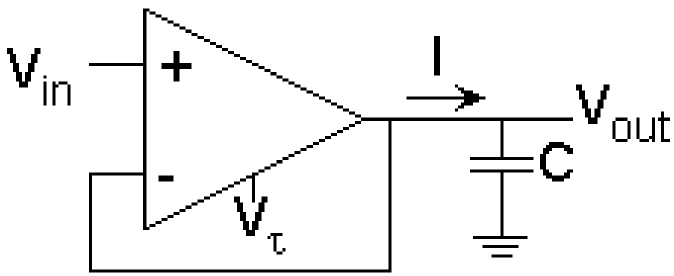
$$C\,(dV_{out}/dt) = I$$
$$= I_{bias}\tanh(\kappa(V_{in} - V_{out})/(2\,U_T))$$
$$= ((\kappa\,I_{bias})/(2\,U_T))\,(V_{in} - V_{out})$$



$$\tau\,(dV_{out}/dt) + V_{out} = V_{in}$$
$$\tau = C\,U_T\ /\ \kappa\,I_{bias}$$

Time-constant changes with bias

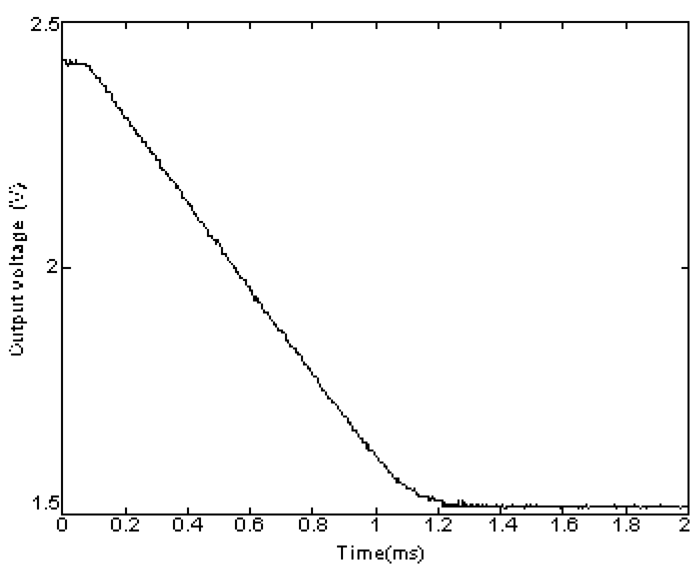
Linear Range

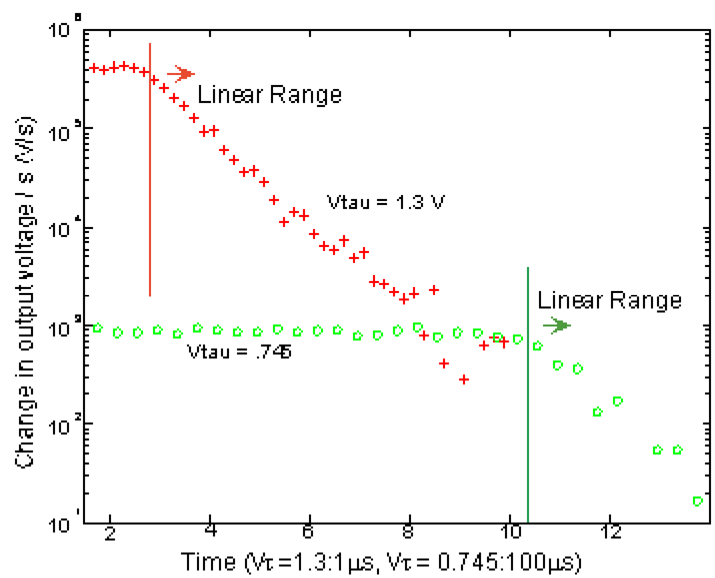


This is not linear….

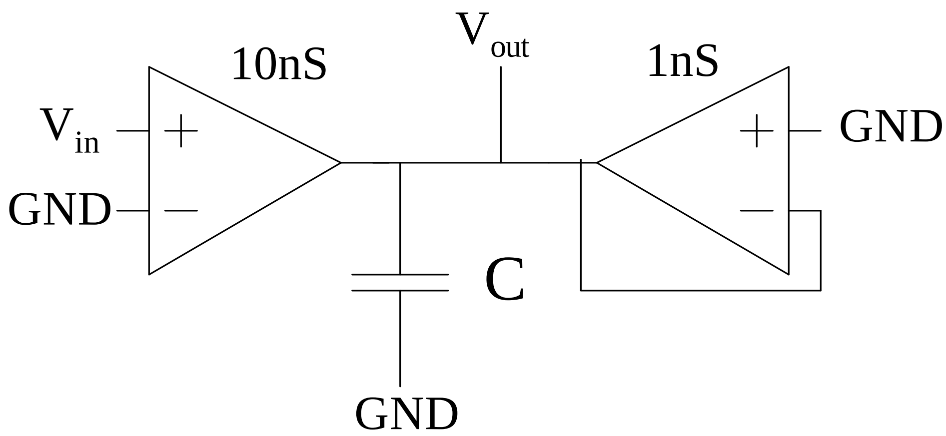
"Small-signal analysis:
How small is "small"?

$$C\,(dV_{out}/dt) = I_{bias}\tanh(\kappa(V_{in} - V_{out})/(2\,U_T))$$





Another First-Order Low-Pass Filter

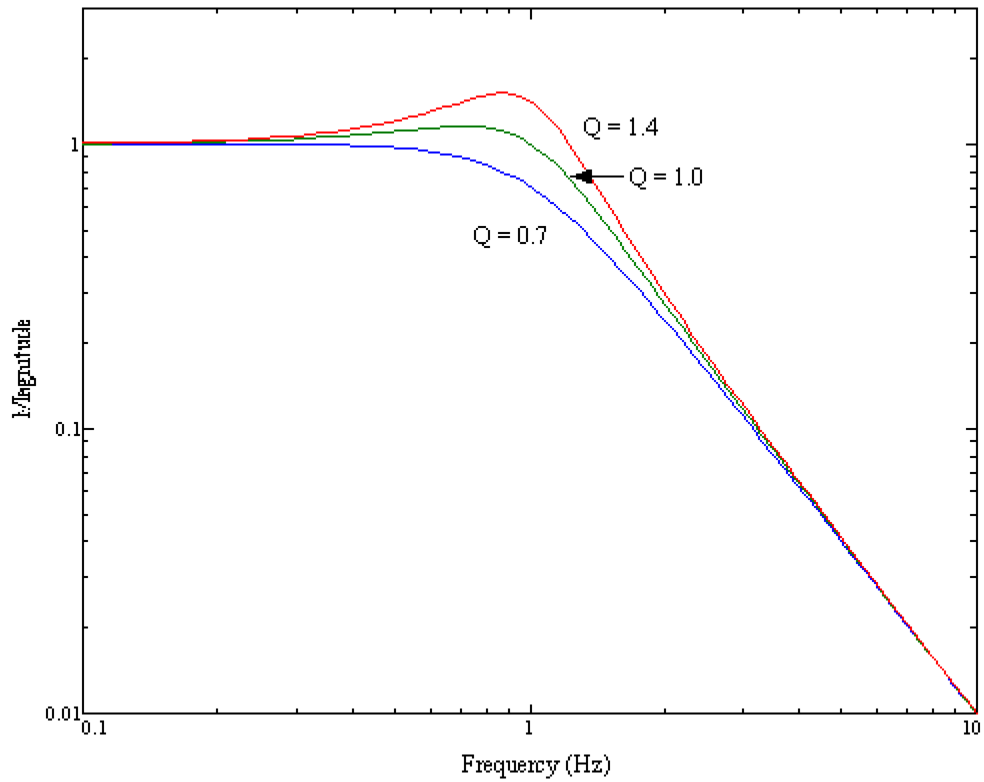


Second-Order Behavior

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 + (\tau/Q)\, s + \tau^2 s^2}$$

Gain = Q

at $\omega = 1/\tau$,



Second-Order Behavior

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 + (\tau/Q)\, s + \tau^2 s^2}$$

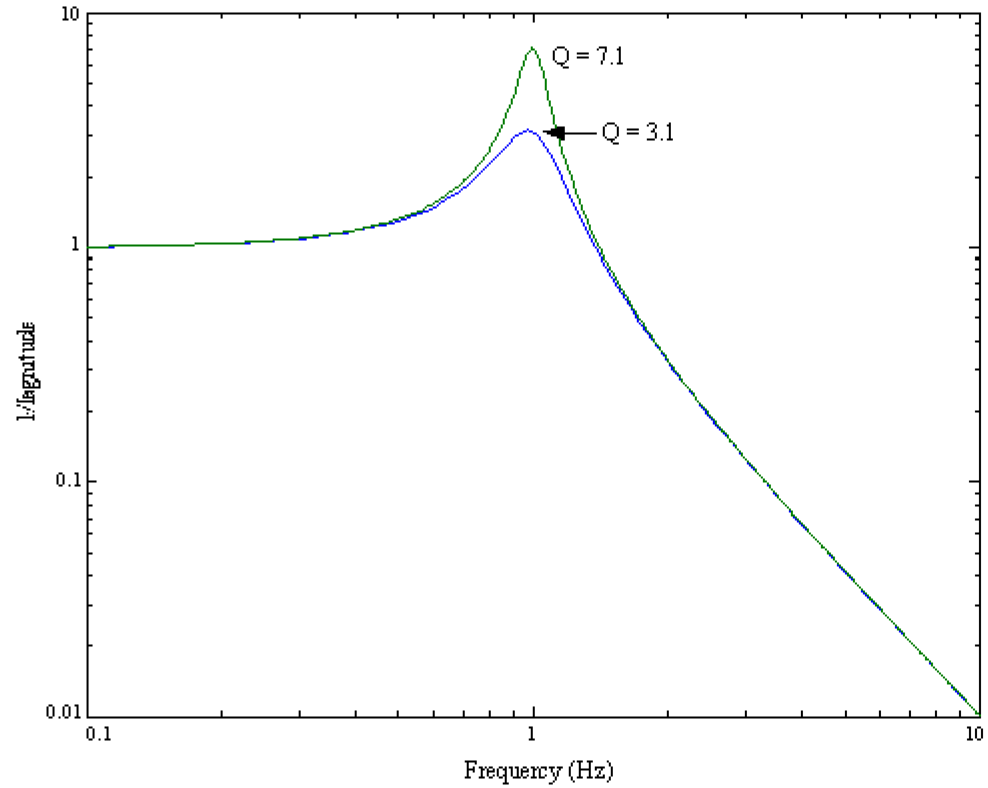
Gain = Q

at $\omega = 1/\tau$,

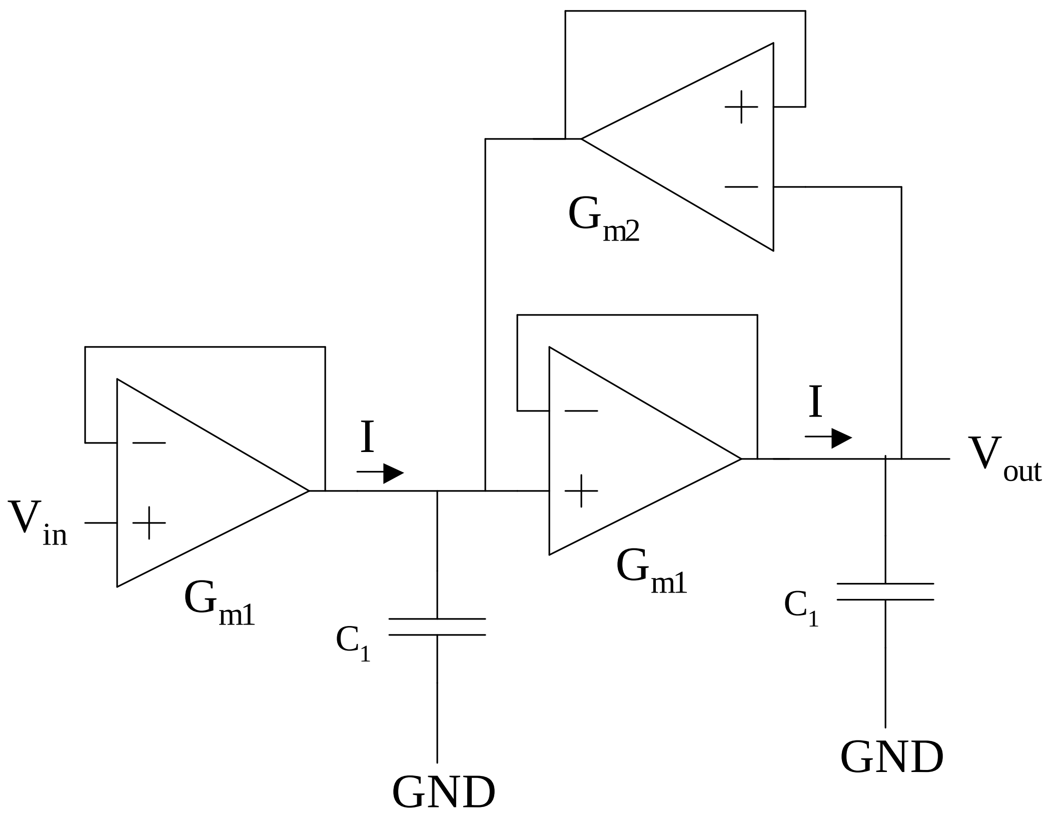
High Q =

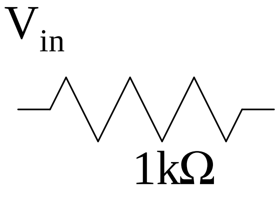
very narrow band

(width $\propto$ 1/Q)

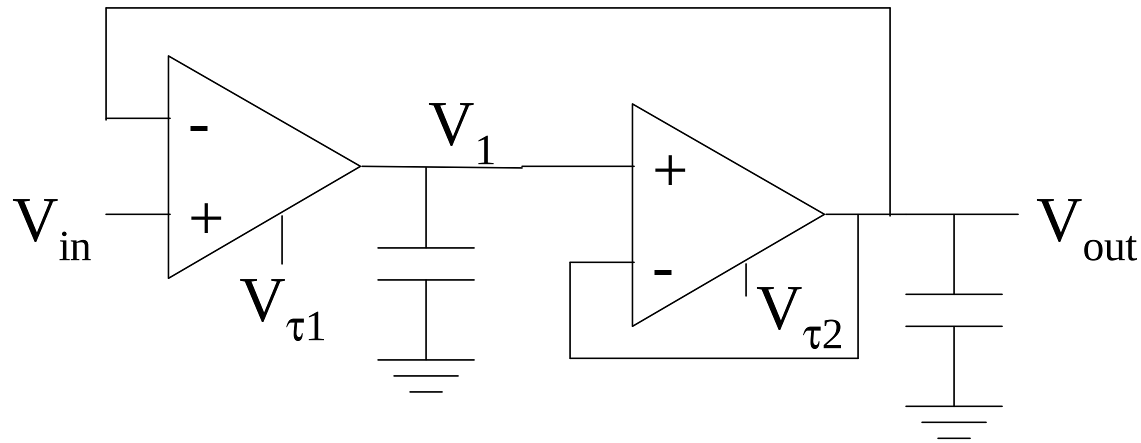


Basic Second-Order Sections





Diff2 Based Second-Order Filter

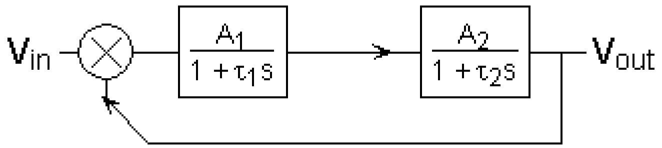


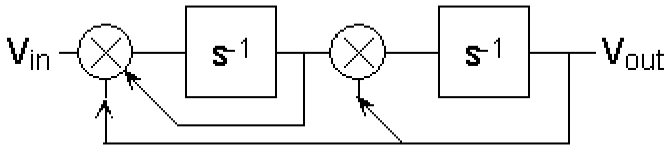
$$\frac{V_{out}}{V_{in}} = \frac{1}{1 + (\tau/Q)\, s + \tau^2 s^2}$$

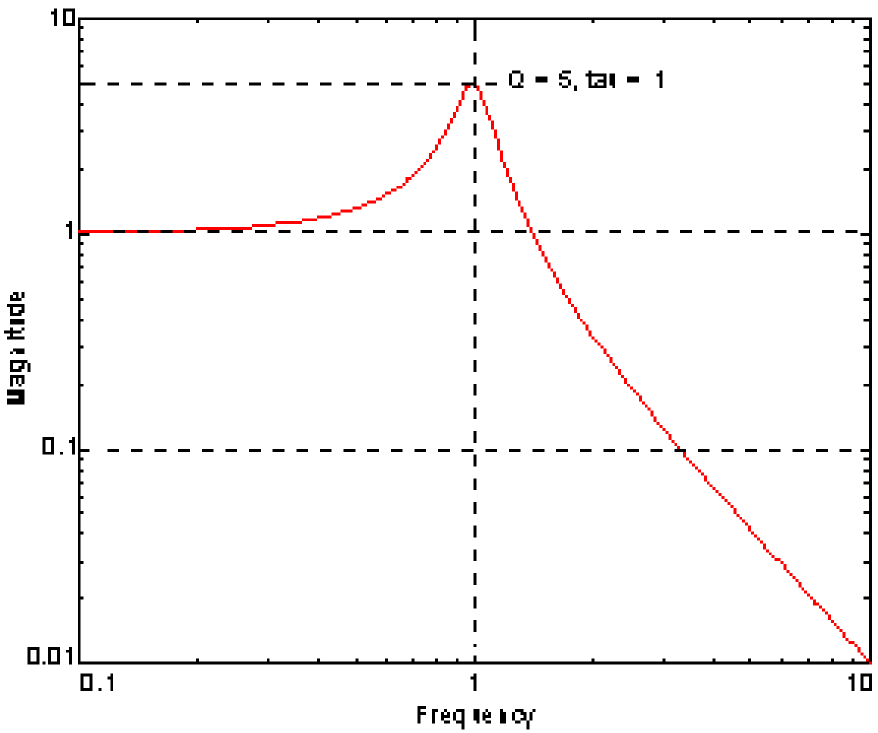
$$\tau = (\tau_1\, \tau_2)^{1/2}$$

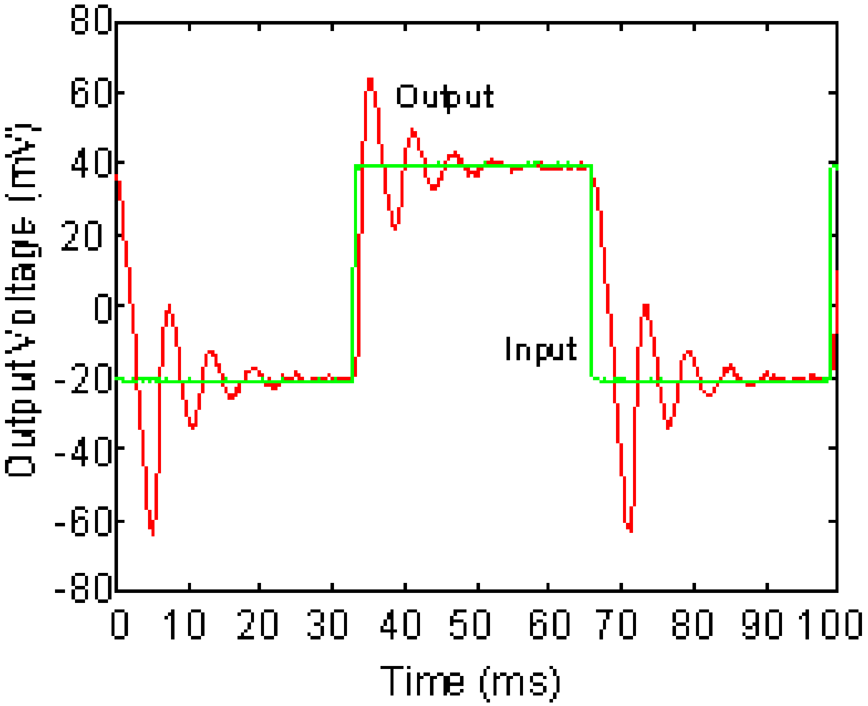
$$Q = (\tau_2/\tau_1)^{1/2}$$

Diff2 Responses

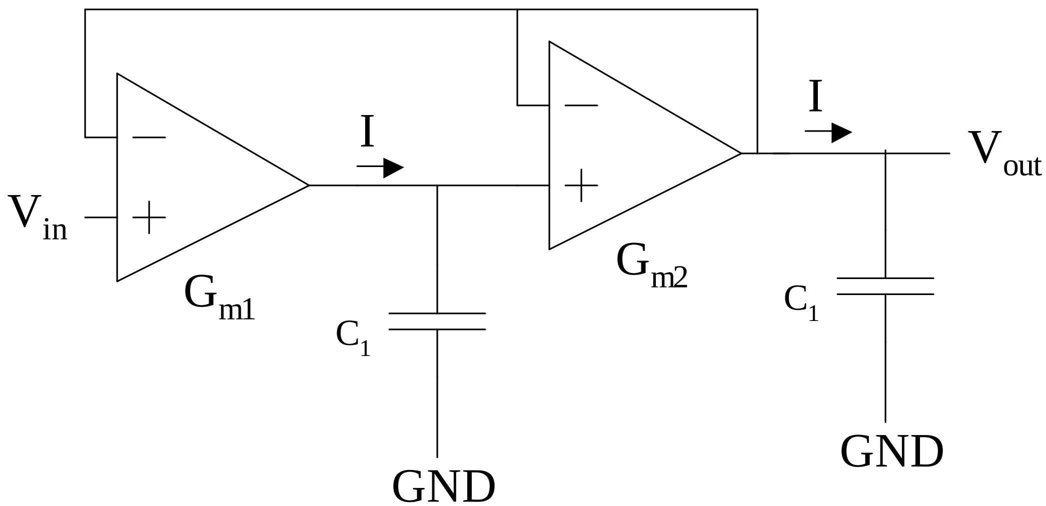








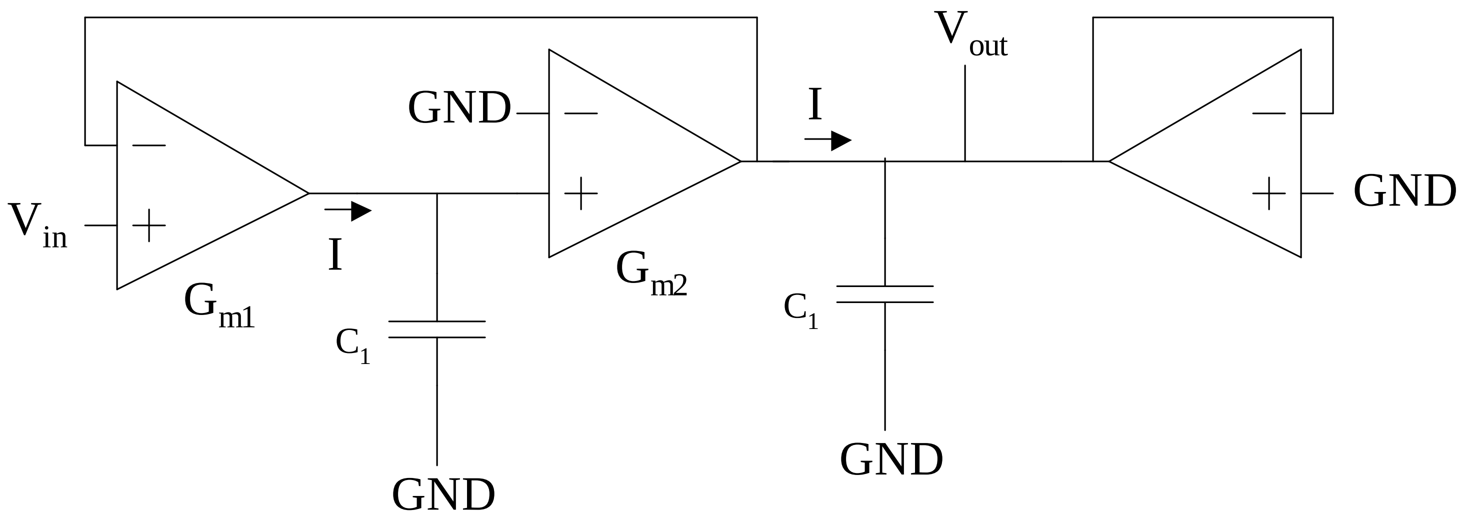
Diff2 Second-Order Section



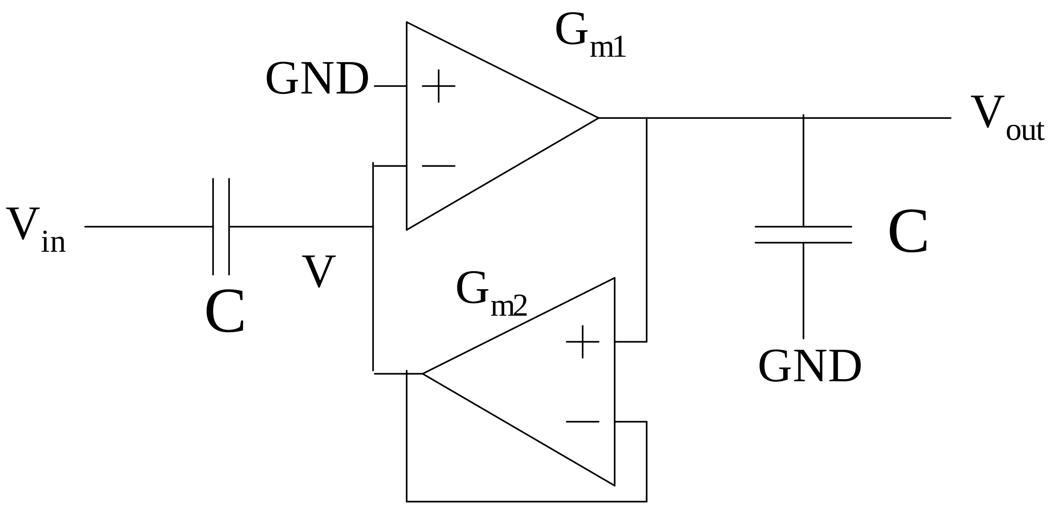
We will see this circuit again :
sample and hold elements

Issue of feedback with an outp
buffer for an op-amp.

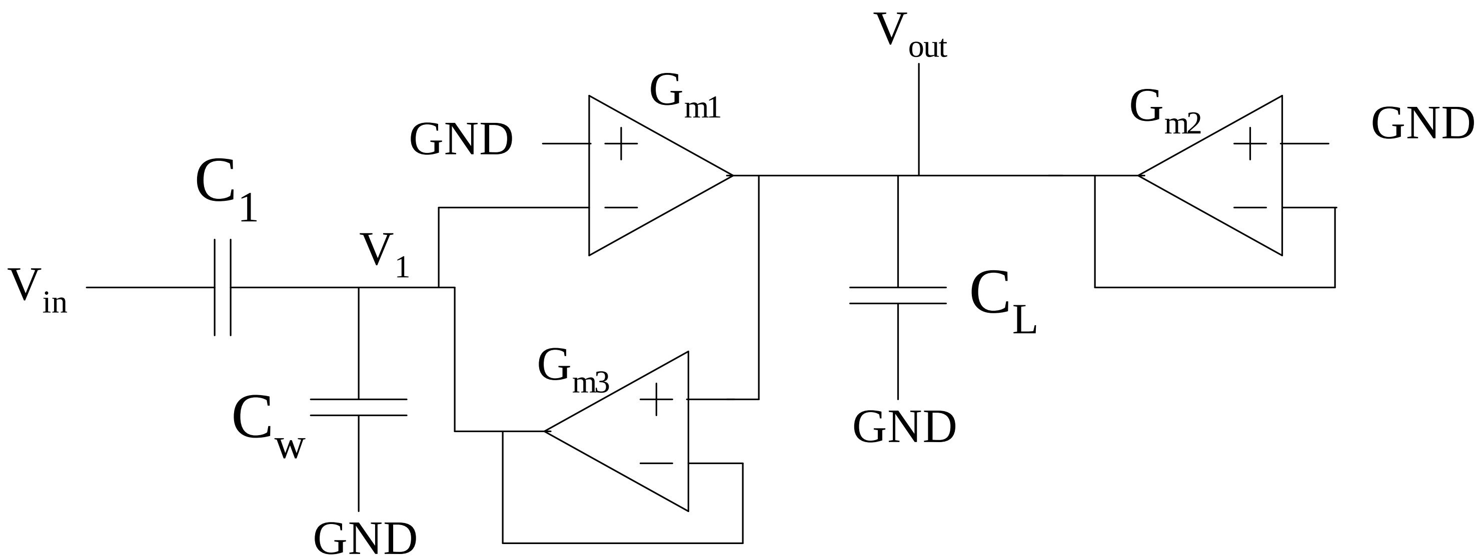
Tow-Thomas
Second-Order Section



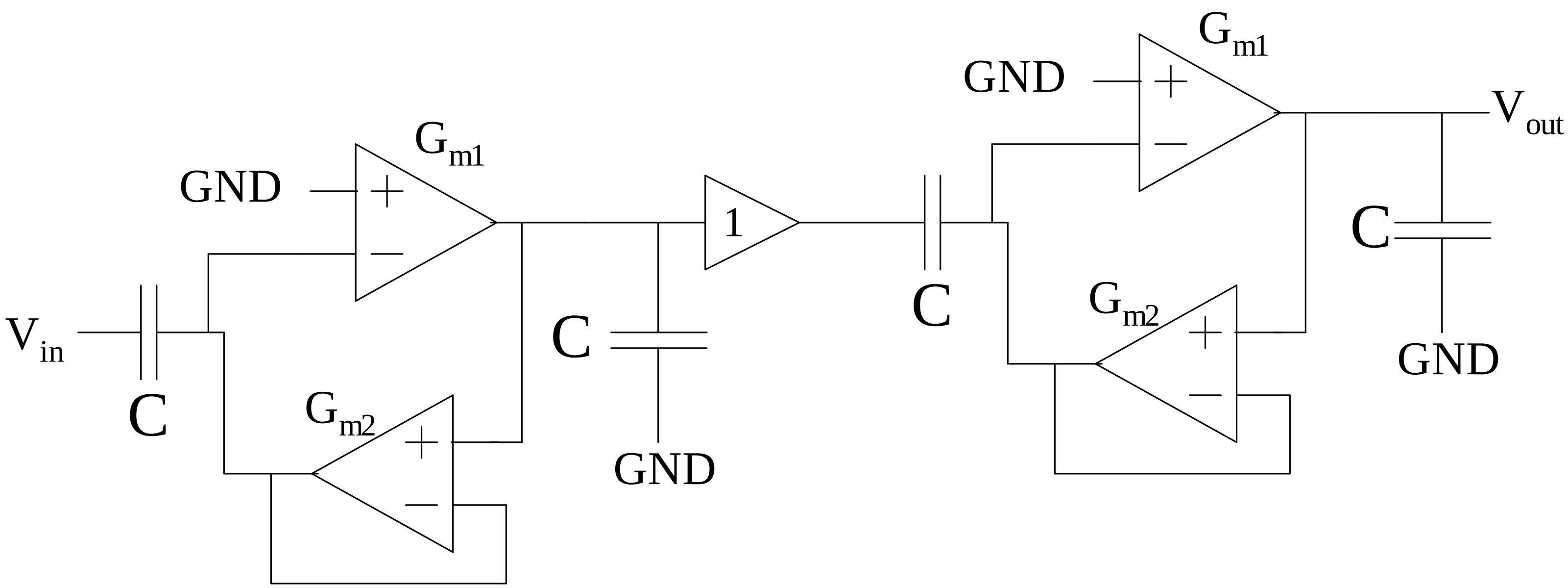
Bandpass Second-Order Section



Another Second-Order Section



Even Bigger Gm-C Filter



Filter Design Problem

Design example(s):

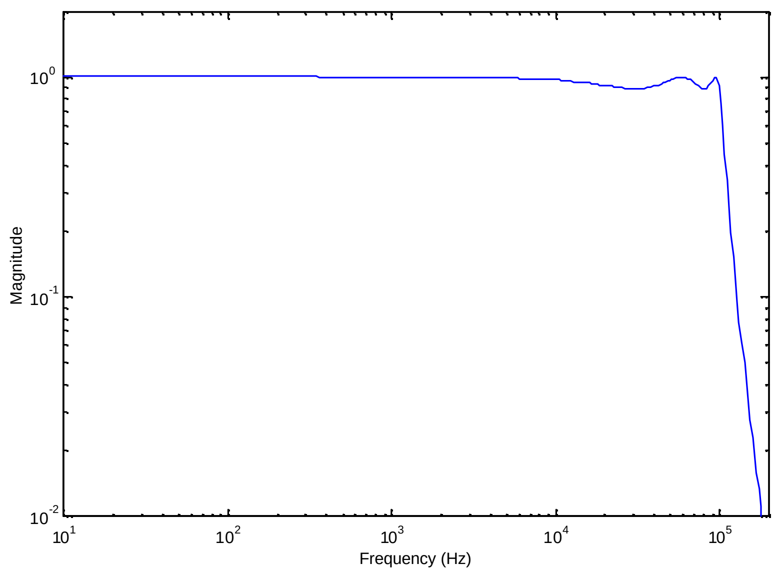
Design a Chebyshev filter with the following specs:

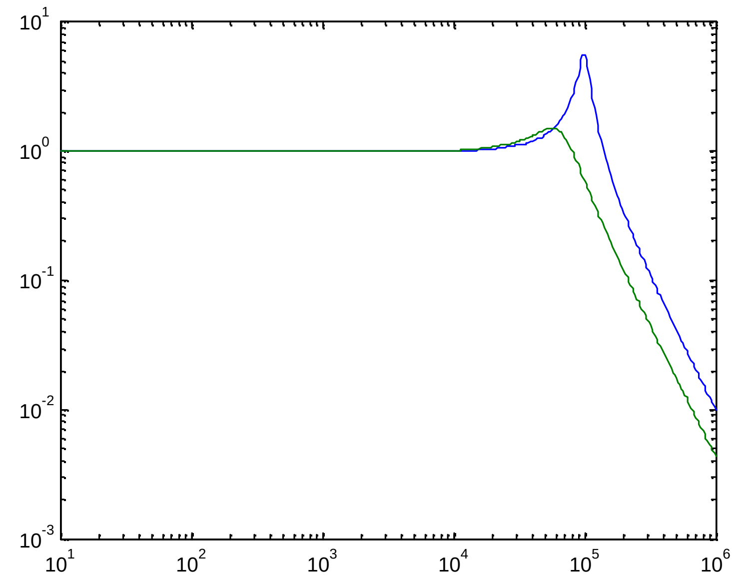
Tpb	-1dB (0.5088)
Tsb	-25dB
fpb	100kHz
fsb	150kHz

From our MATLAB functions, we get the following τ's and Q's:

We get the following filter:

Filter Design Example





From MATLAB code: N = 5

Q = 5.5561e+000, tau = 1.6009e-006
Q = 1.3987e+000, tau = 2.4290e-006

tau = 5.4974e-006