Spring 2002

EEE598D: Analog Filters & Signal Processing Circuits

Instructor:

Dr. Hongjiang Song

Department of Electrical Engineering

Arizona State University

Tuesday March 5, 2002

Today: Active RC and MOS-C Filter Design

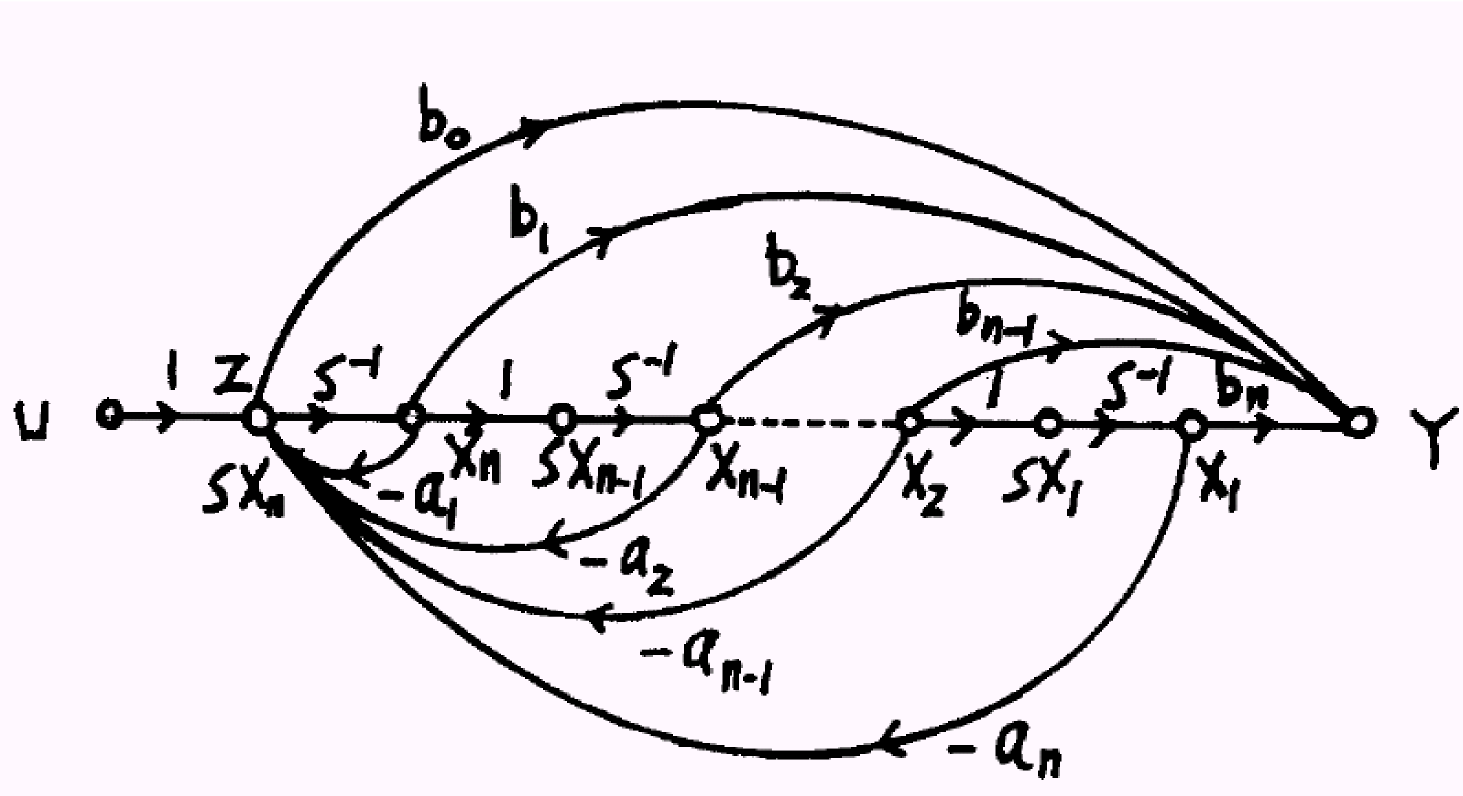
- Basic Filter Structures
- First-Order Filters
- Second-Order Filters
- Cascaded Design of High-Order Filters

Dr. Hongjiang Song, Arizona State University

Basic Circuit Elements

- Opamps
  - Isolation/Decoupling between stages
  - Gain
  - Inversion
- Capacitor
  - Integration
- Resistor/MOS-VCR
  - Linear conversion
  - Tuning

General CT Filter Structure

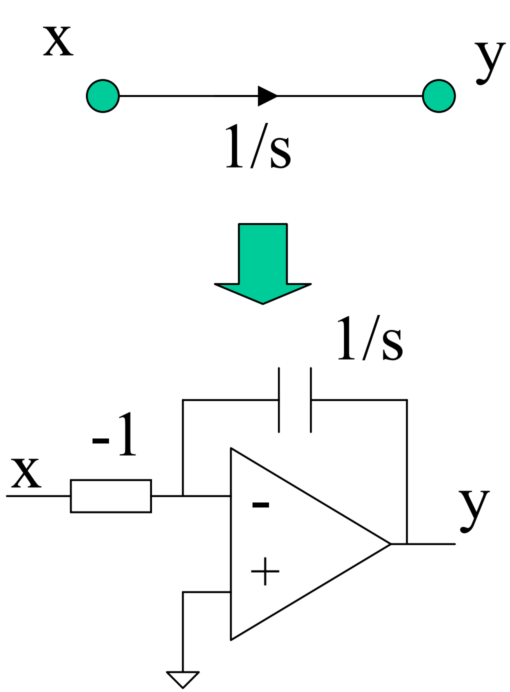


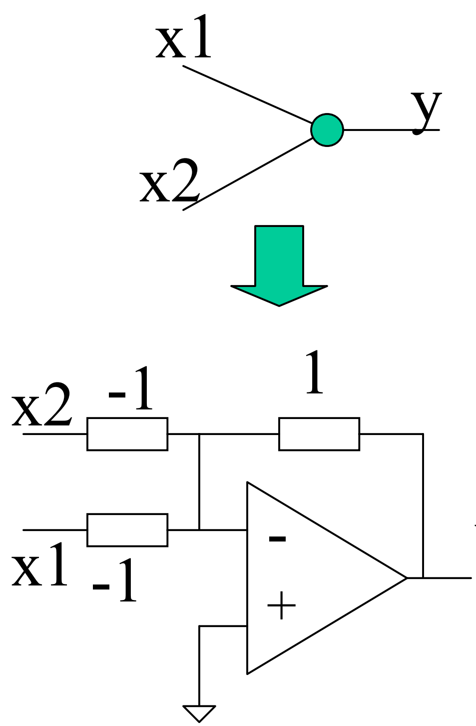
$$H(S) = \frac{Y(s)}{U(s)} = \frac{b_0 S^n + b_1 S^{n-1} + \cdots\cdots + b_n}{S^n + a_1 S^{n-1} + \cdots\cdots a_n}$$

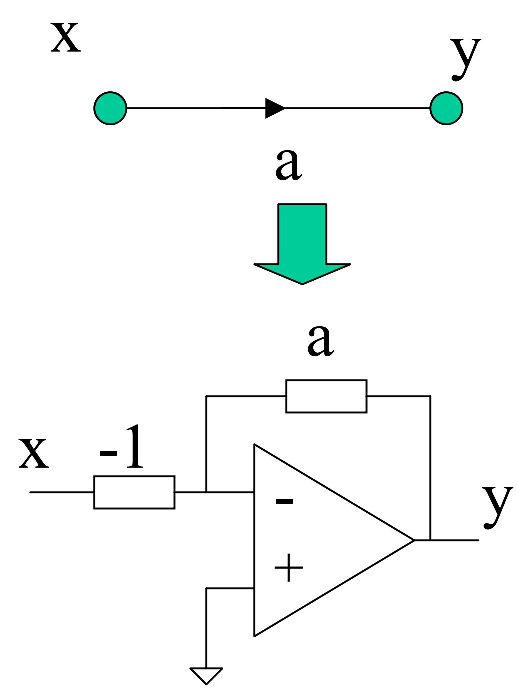
Dr. Hongjiang Song, Arizona State University

Basic Filter Elements

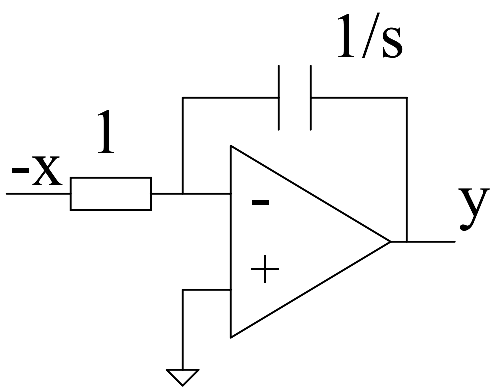
- Integrator
- Adder
- Scaler



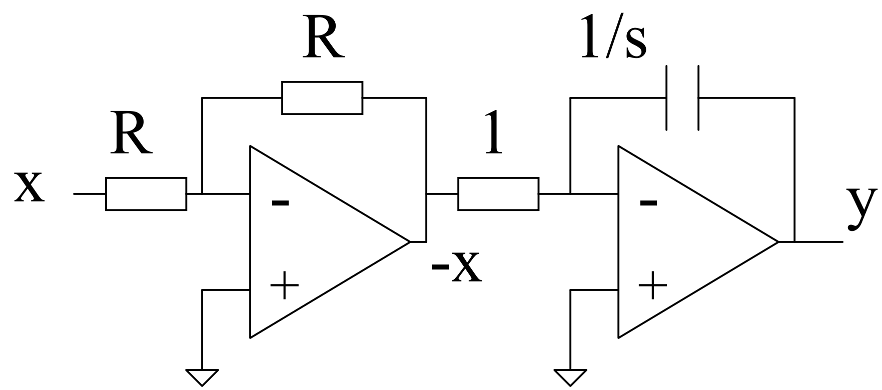




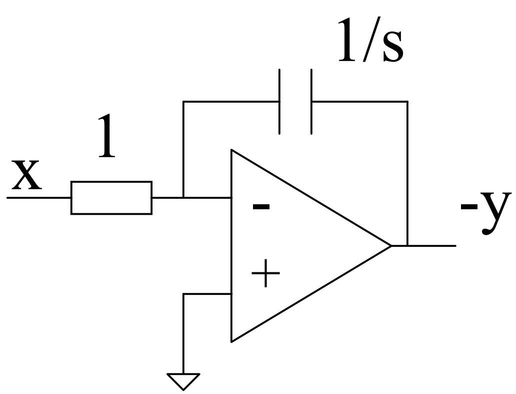
Active RC Integrator Structures



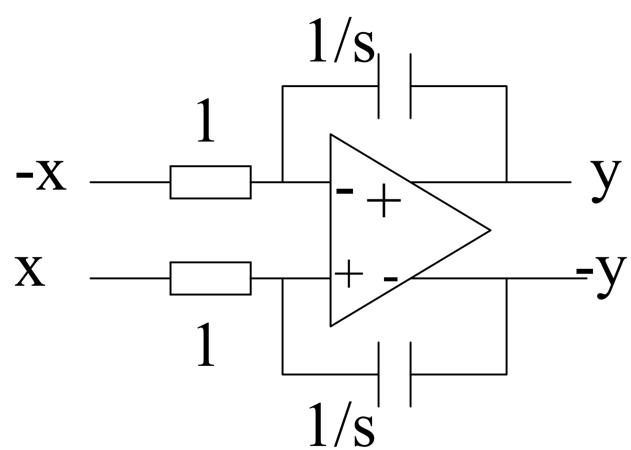
A) Inverted input



C) Internal inversion

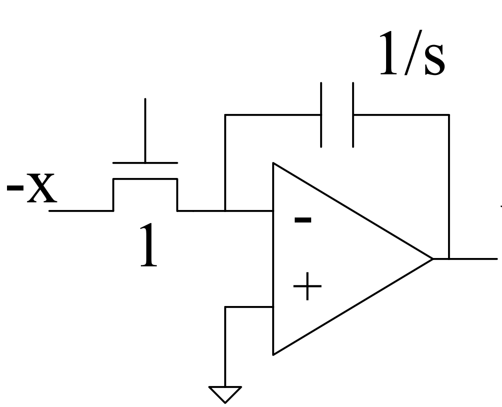


B) Inverted output

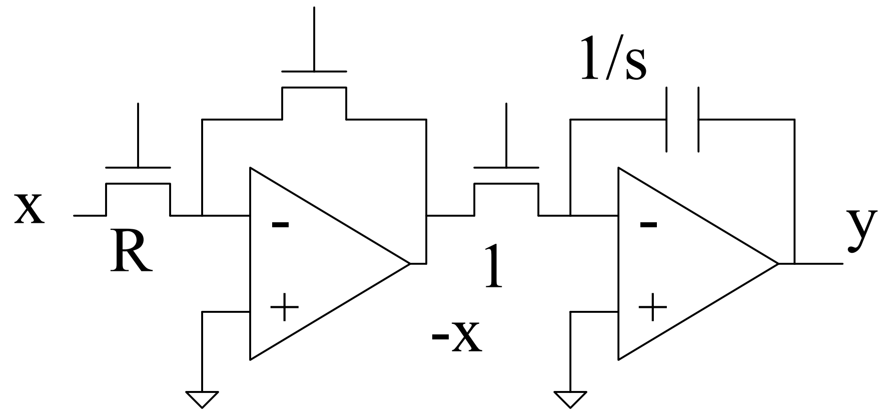


D) Fully differential

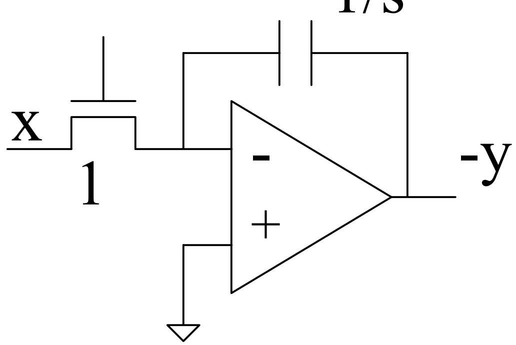
MOS-C Integrator Structures (I)



A) Inverted input



C) Internal inversion



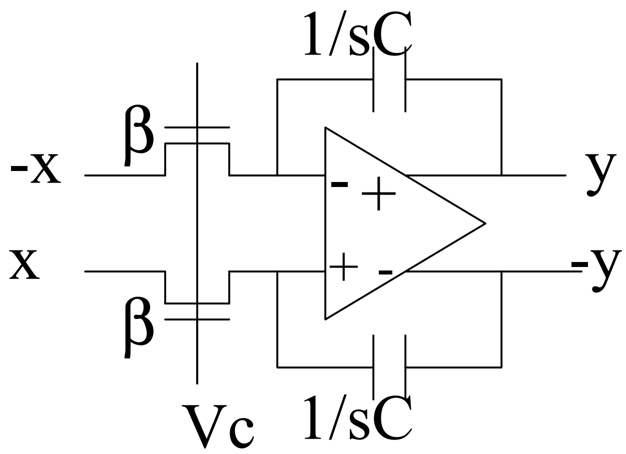
B) Inverted output

Single-end & Single Transistor

- Simple
- Small
- Tunable
- Poor Linearity
- Poor PSRR

MOS-C Integrator Structures (II)

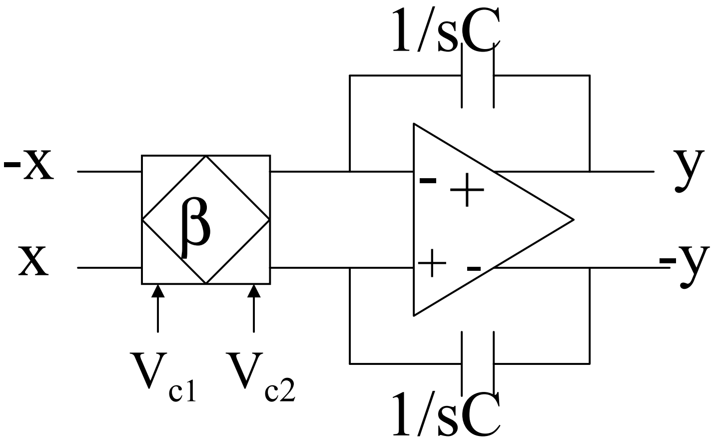
- Fully Differential 2-Transistor
  - Improved Linearity
  - Improved PSRR
  - Tunable



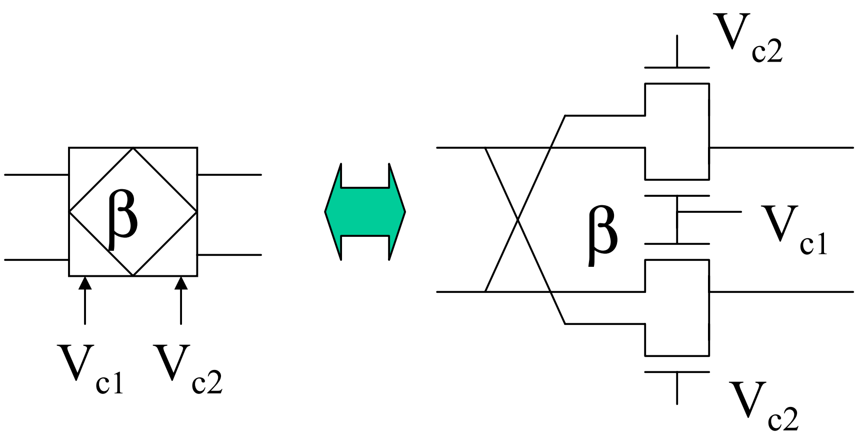
$$H(s) = \frac{1}{s\,\dfrac{C}{\beta(V_C - V_T)}}$$

MOS-C Integrator Structures (III)

- Fully Differential 4-Transistor
  - Better Linearity
  - Better PSRR
  - Tunable
  - Large Area

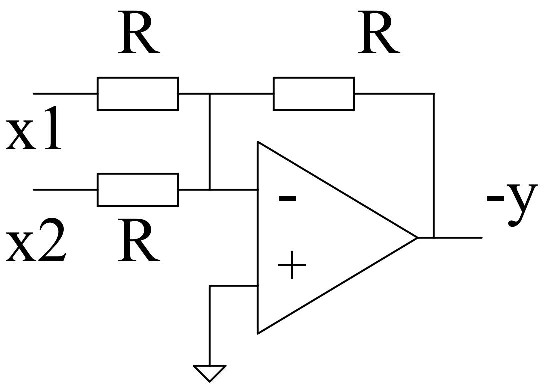


$$H(s)=\frac{1}{s\dfrac{C}{\beta(V_{C1}-V_{C2})}}$$

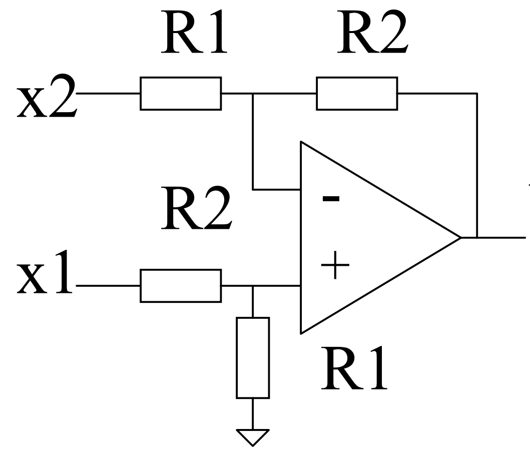


Dr. Hongjiang Song, Arizona State University

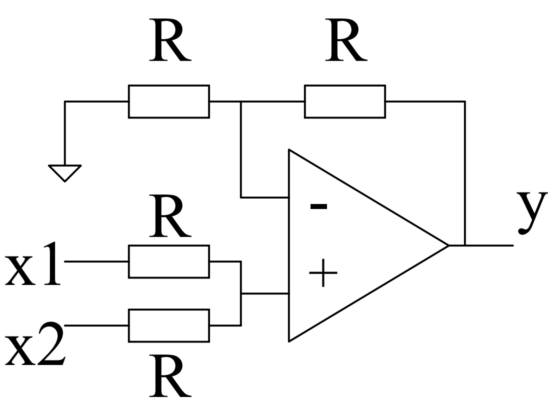
Active RC Adder/Subtractor Structures



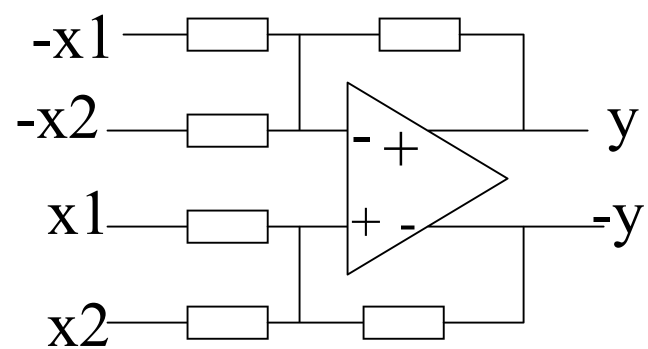
A) Inverted Addition



C) Subtraction



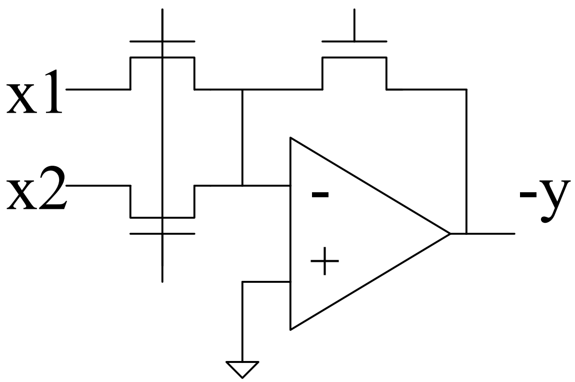
B) Addition



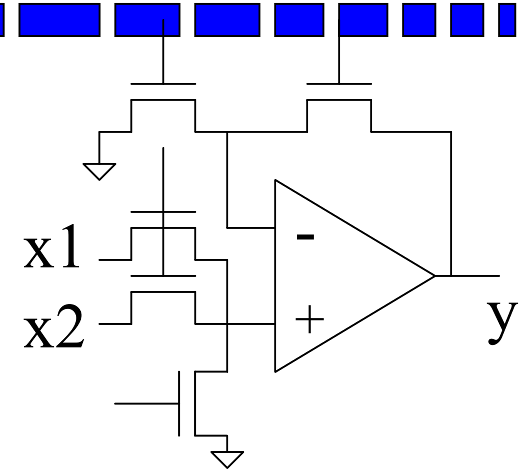
D) Differential addition/subtraction

Dr. Hongjiang Song, Arizona State University

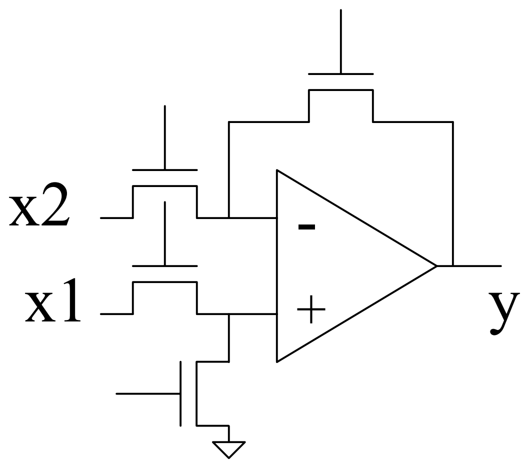
MOS-C Adder/Subtractor Structures (I)



A) Inverted addition



C) Non-inverted addition



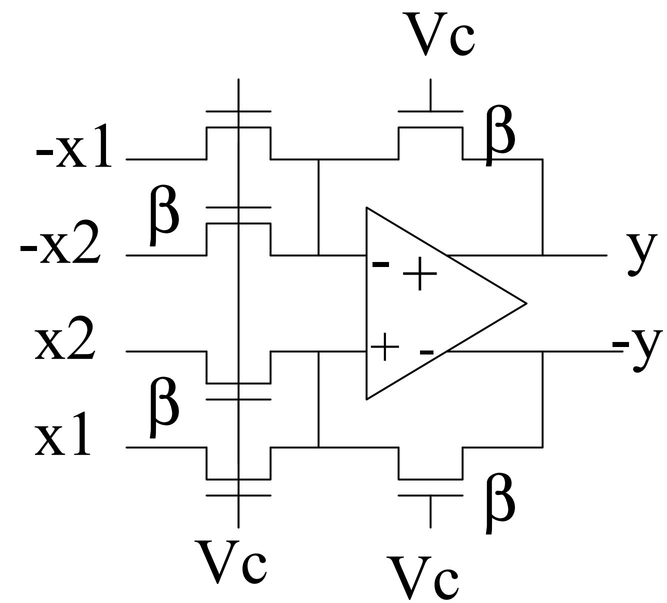
B) Subtraction

Single-end & Single Transistor

- Simple
- Small
- Tunable
- Poor Accuracy
- Poor PSRR

MOS-C Adder/Subtractor Structures (II)

- Fully Differential 2-Transistor
  - Improved Linearity
  - Improved PSRR
  - Tunable

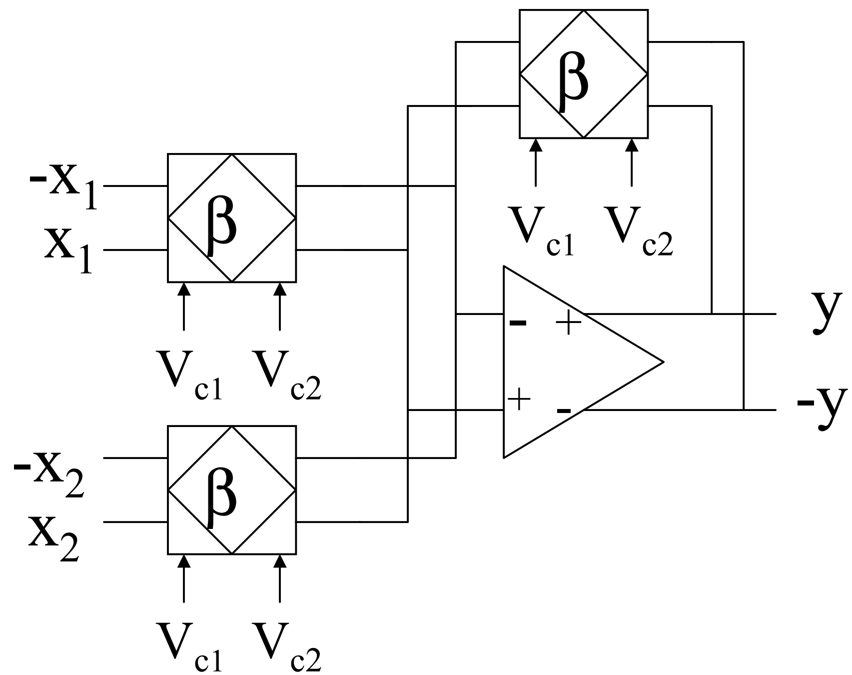


$$y = x_1 + x_2$$

Dr. Hongjiang Song, Arizona State University

MOS-C Adder/Subtractor Structures (III)

- Fully Differential 4-Transistor
  - Better Linearity
  - Better PSRR
  - Tunable
  - Large Area



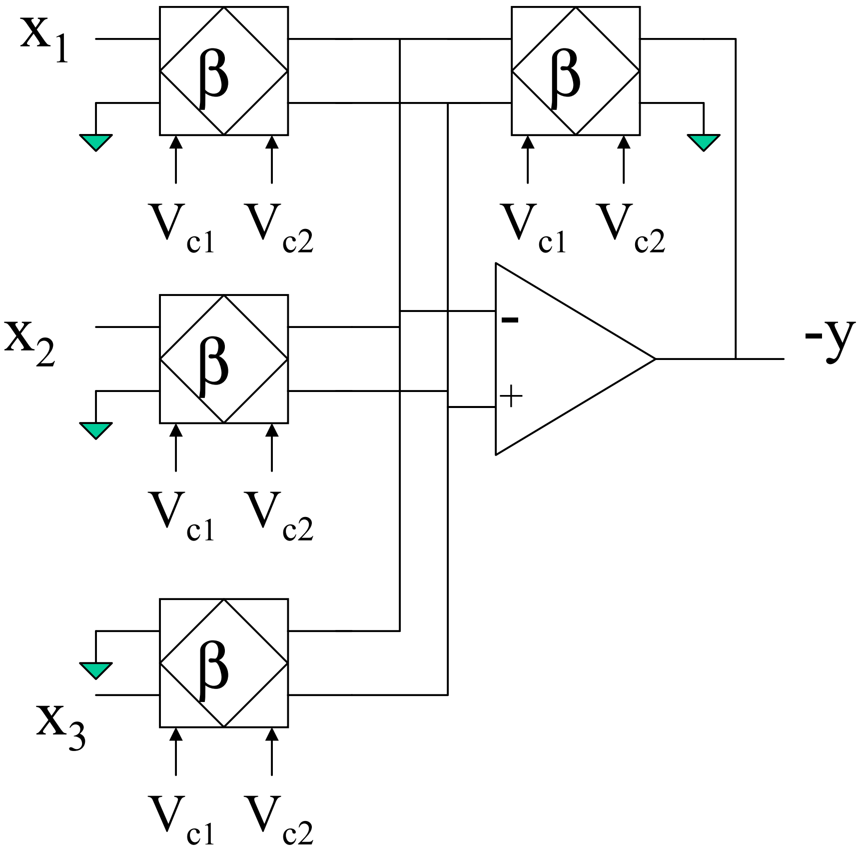
$$y = x_1 + x_2$$

Dr. Hongjiang Song, Arizona State University

MOS-C Adder/Subtractor Structures (IV)

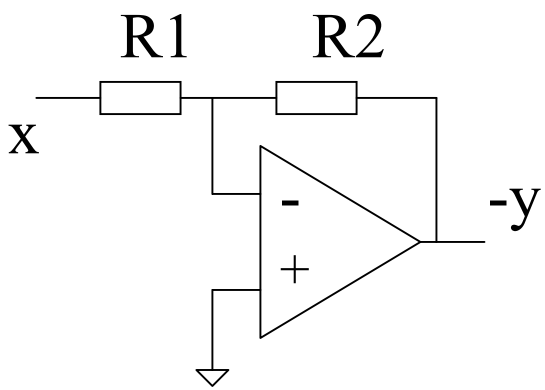
- Single-ended 4-Transistor
  - Good Linearity
  - Tunable
  - Smaller area

$$y = x_1 + x_2 - x_3$$

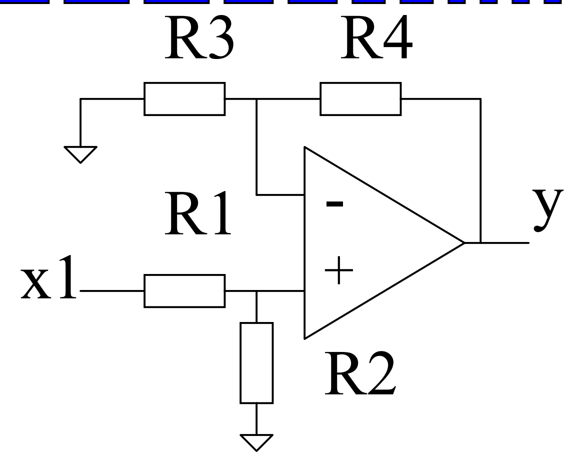


Dr. Hongjiang Song, Arizona State University

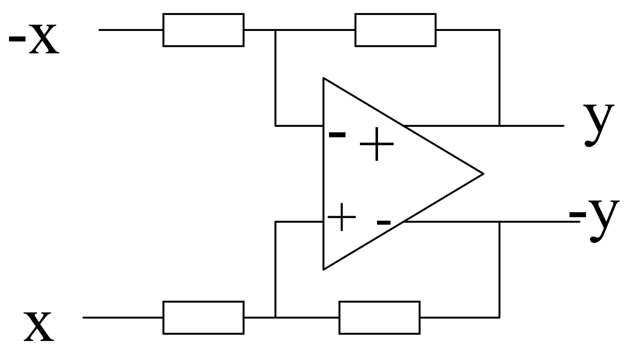
Active RC Scaler Structures



A) Inverted



B) non-inverted



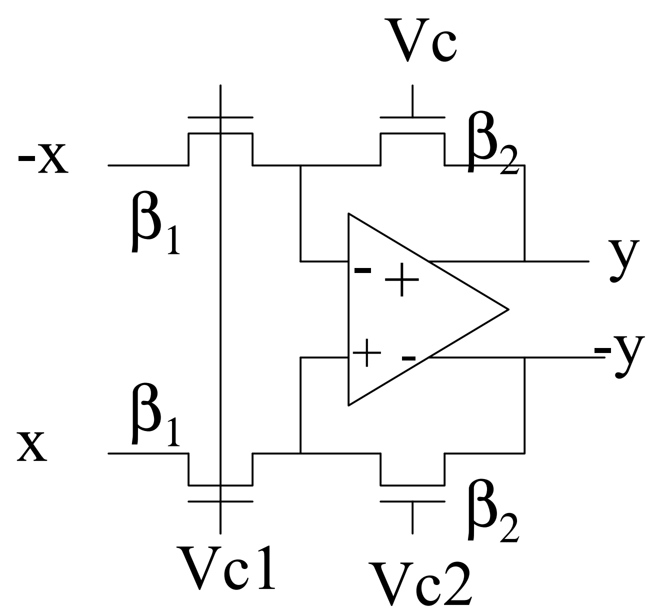
C) Fully Differential

Dr. Hongjiang Song, Arizona State University

MOS-C Scaler Structures (I)

- Fully Differential 2-Transistor

$$\frac{y}{X} = \frac{\beta_1 (V_{c1} - V_T)}{\beta_2 (V_{c2} - V_T)}$$

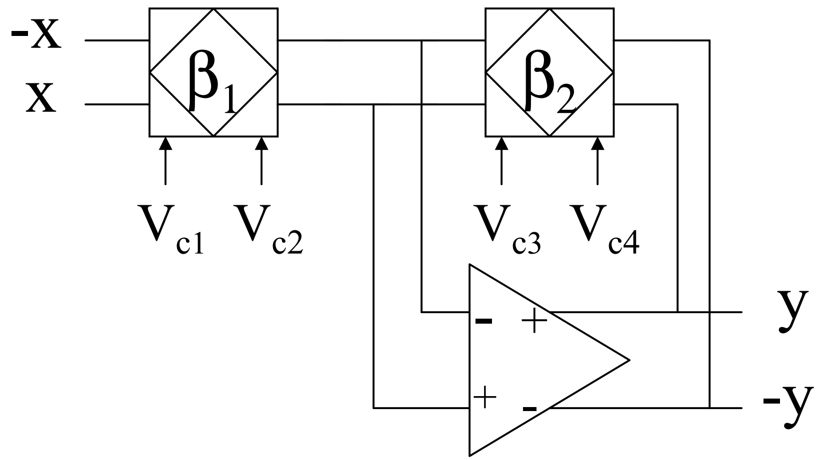


Dr. Hongjiang Song, Arizona State University

MOS-C Scaler Structures (II)

- Fully Differential 4-Transistor VCR

$$\frac{y}{X}=\frac{\beta_1(V_{c1}-V_{c2})}{\beta_2(V_{c3}-V_{c4})}$$

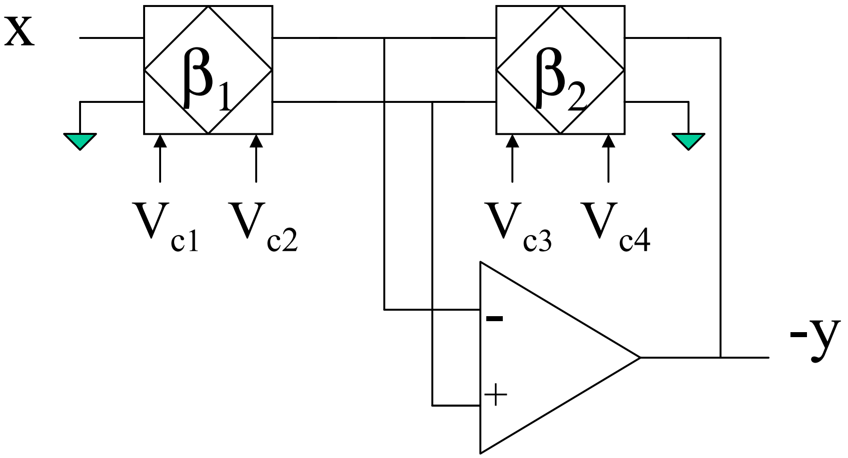


Dr. Hongjiang Song, Arizona State University

MOS-C Scaler Structures (III)

- Single-ended 4-Transistor VCR

$$\frac{y}{X} = \frac{\beta_1(V_{c1} - V_{c2})}{\beta_2(V_{c3} - V_{c4})}$$



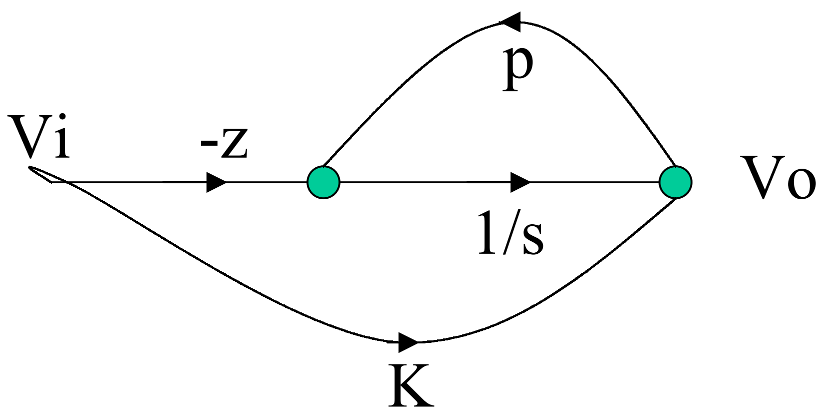
Dr. Hongjiang Song, Arizona State University

First-Order Filters

- TF and SFG

$$H(s) = K\frac{s-z}{s-p}$$

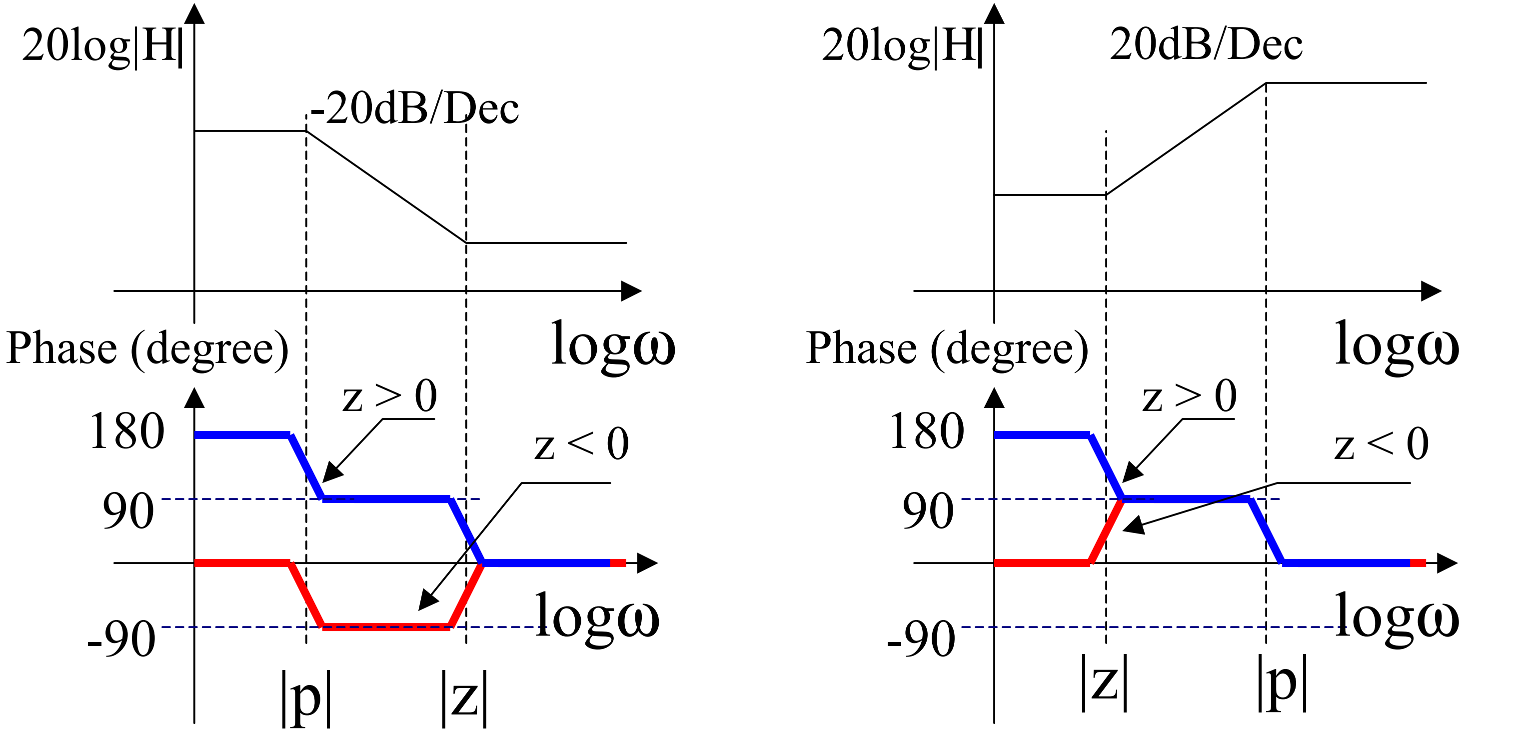
pole :s = p < 0
zero: s = z



Dr. Hongjiang Song, Arizona State University

First-Order Filters

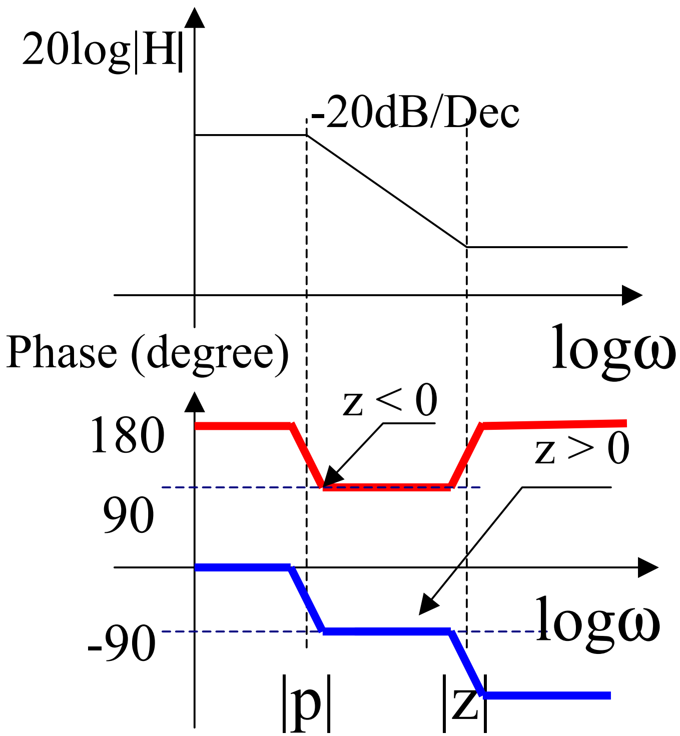
- Bode Plots



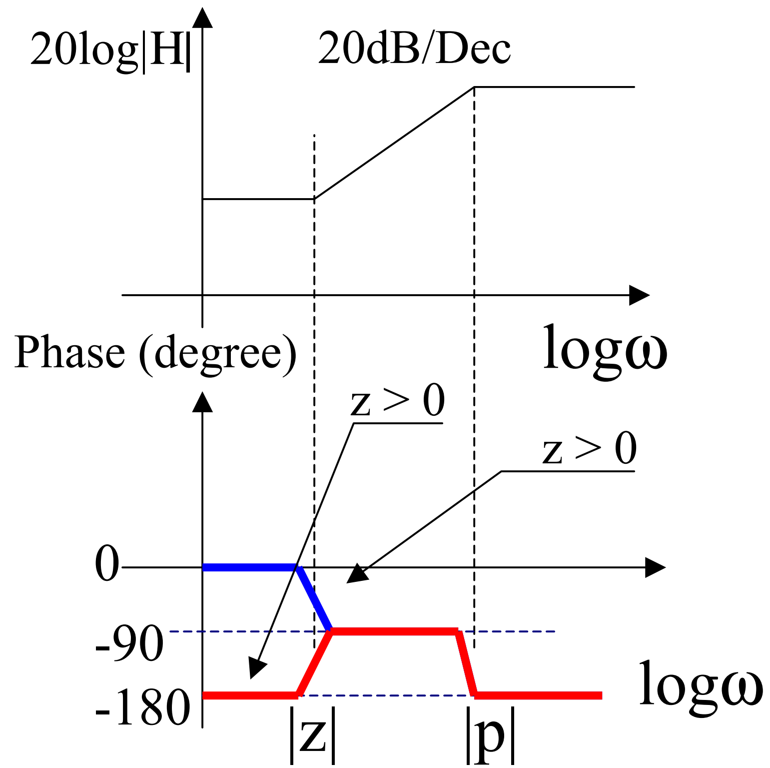
A) |p| < |z|, K > 0 B) |p| > |z|, K > 0

First-Order Filters

- Bode Plots



A) |p| < |z|, K < 0



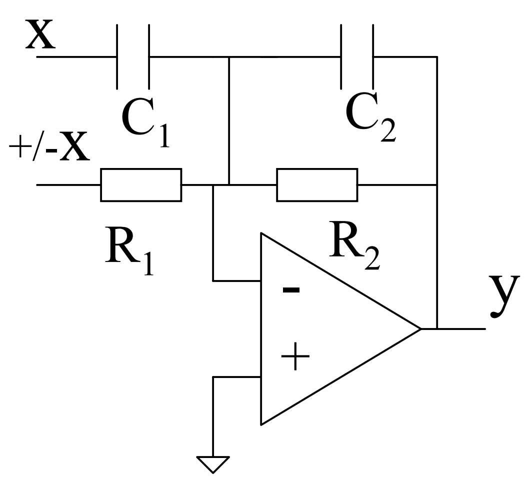
B) |p| > |z|, K < 0

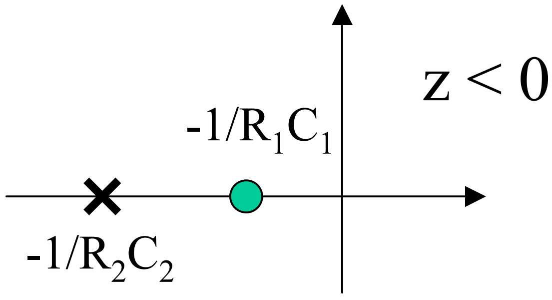
Dr. Hongjiang Song, Arizona State University

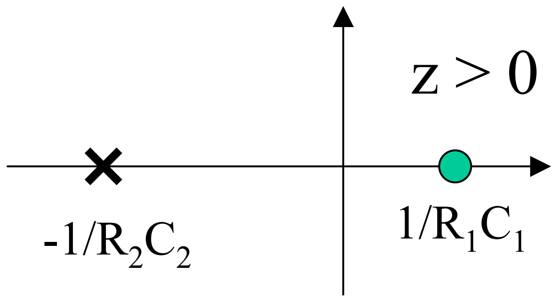
First-Order Active RC Filters

- Single-ended

$$H(s) = -\frac{C_1}{C_2}\frac{s \pm \frac{1}{R_1 C_1}}{s + \frac{1}{R_2 C_2}}$$





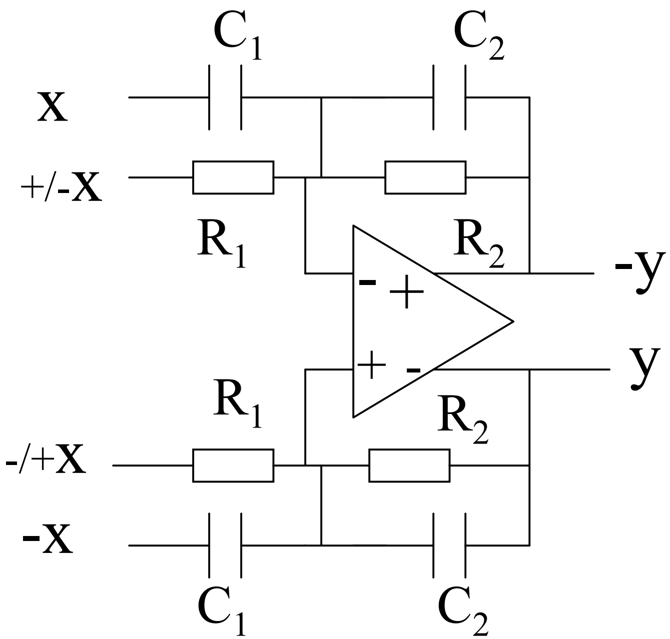


Dr. Hongjiang Song, Arizona State University

First-Order Active RC Filters

- Fully differential

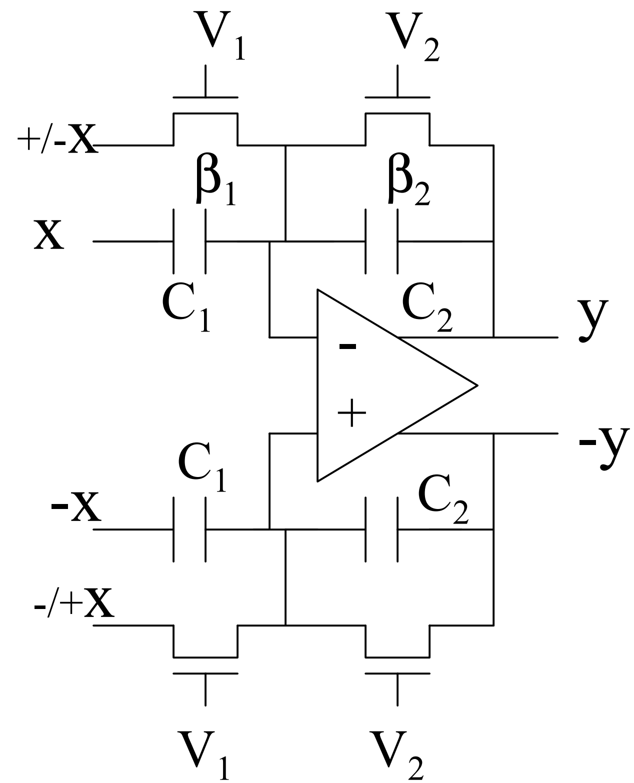
$$H(s) = \frac{C_1}{C_2} \frac{s \pm \frac{1}{R_1 C_1}}{s + \frac{1}{R_2 C_2}}$$



First-Order MOS-C Filters

- Fully differential 2-transistor VCR

$$H(s) = \frac{C_1}{C_2} \frac{s \pm \dfrac{\beta_1 (V_1 - V_T)}{C_1}}{s + \dfrac{\beta_2 (V_2 - V_T)}{C_2}}$$

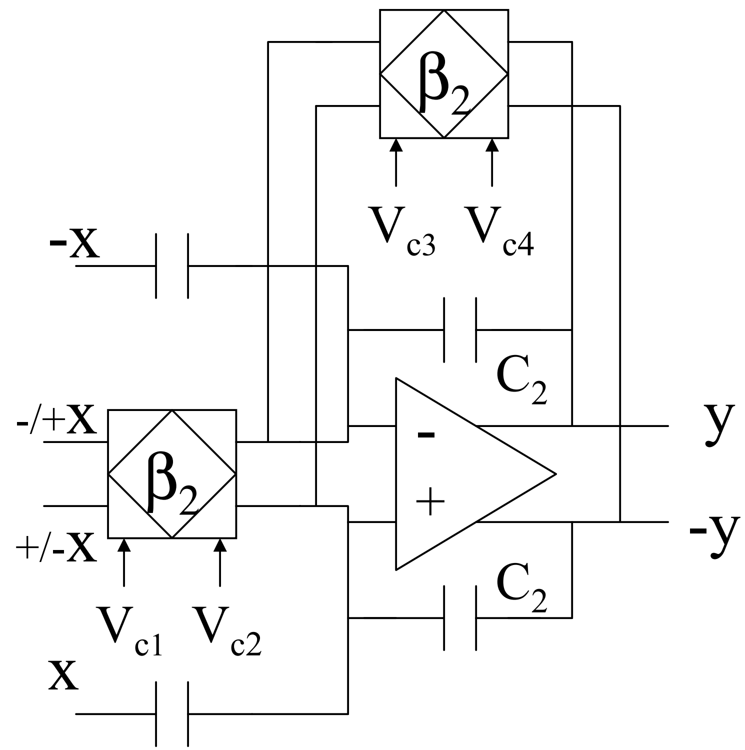


Dr. Hongjiang Song, Arizona State University

First-Order MOS-C Filters

- Fully differential 4-transistor VCR

$$H(s)=\frac{C_1}{C_2}\frac{s\pm\frac{\beta_1(V_{c1}-V_{c2})}{C_1}}{s+\frac{\beta_2(V_{c3}-V_{c4})}{C_2}}$$



Dr. Hongjiang Song, Arizona State University

Second-Order Filters

- LP prototype

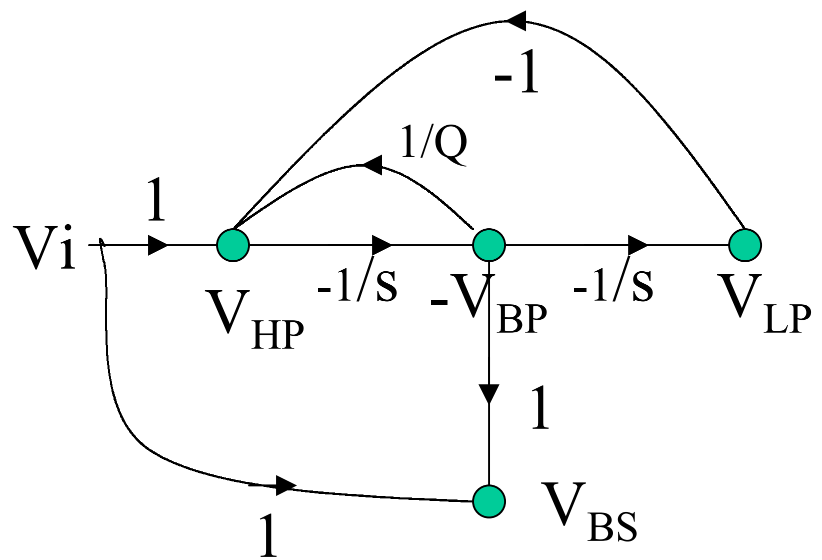
$$H_{LP}(s) = \frac{1}{s^2 + \frac{1}{Q}s + 1}$$

- HP

$$H_{HP}(s) = \frac{s^2}{s^2 + \frac{1}{Q}s + 1}$$

- BP

$$H_{BP}(s) = \frac{s}{s^2 + \frac{1}{Q}s + 1}$$



Dr. Hongjiang Song, Arizona State University

Second-Order Filters

- BS

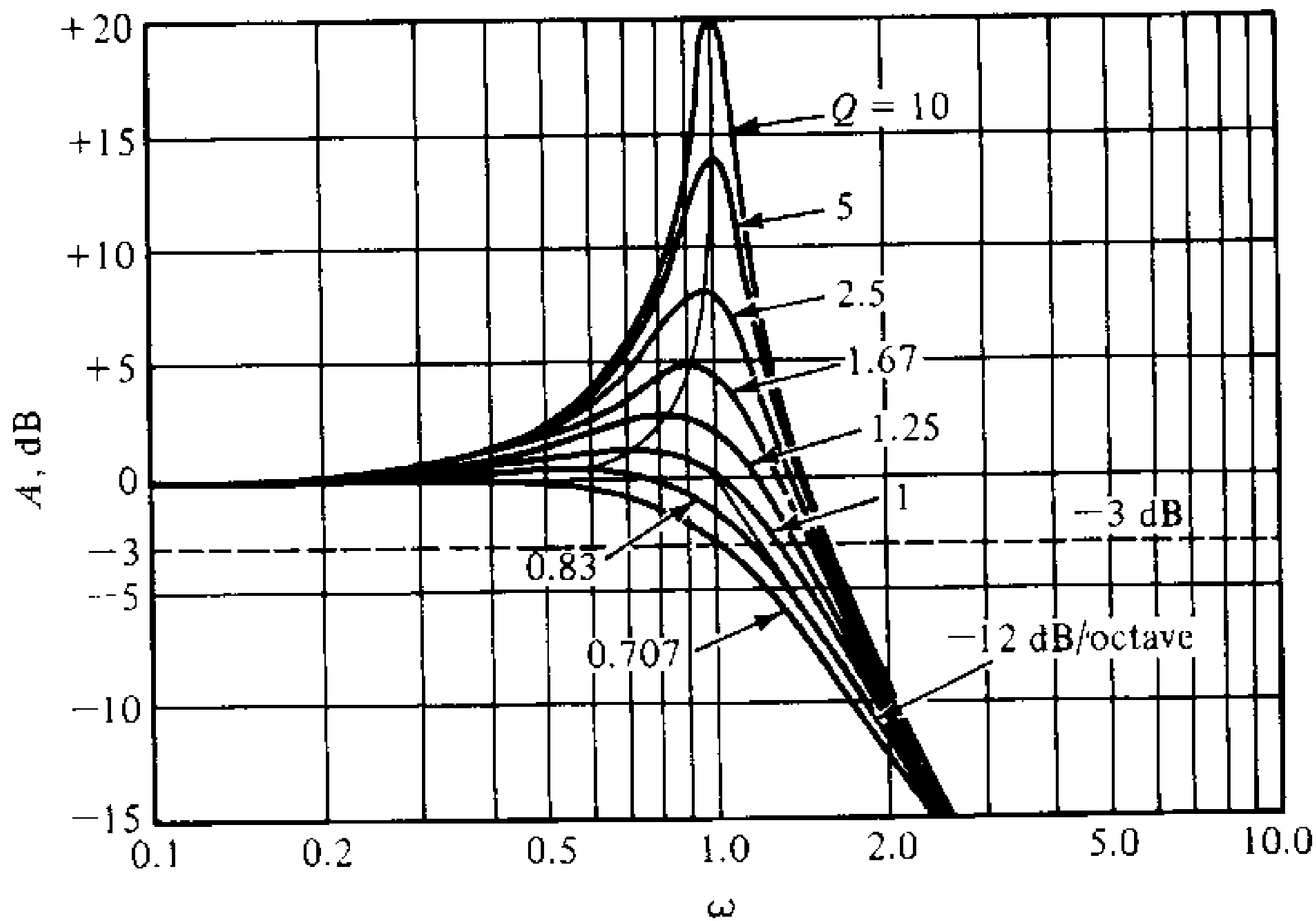
$$H_{BS}(s) = \frac{s^2 + 1}{s^2 + \frac{1}{Q}s + 1}$$

- AP

$$H_{HP}(s) = \frac{s^2 - \frac{1}{Q}s + 1}{s^2 + \frac{1}{Q}s + 1}$$

Second-Order Filters

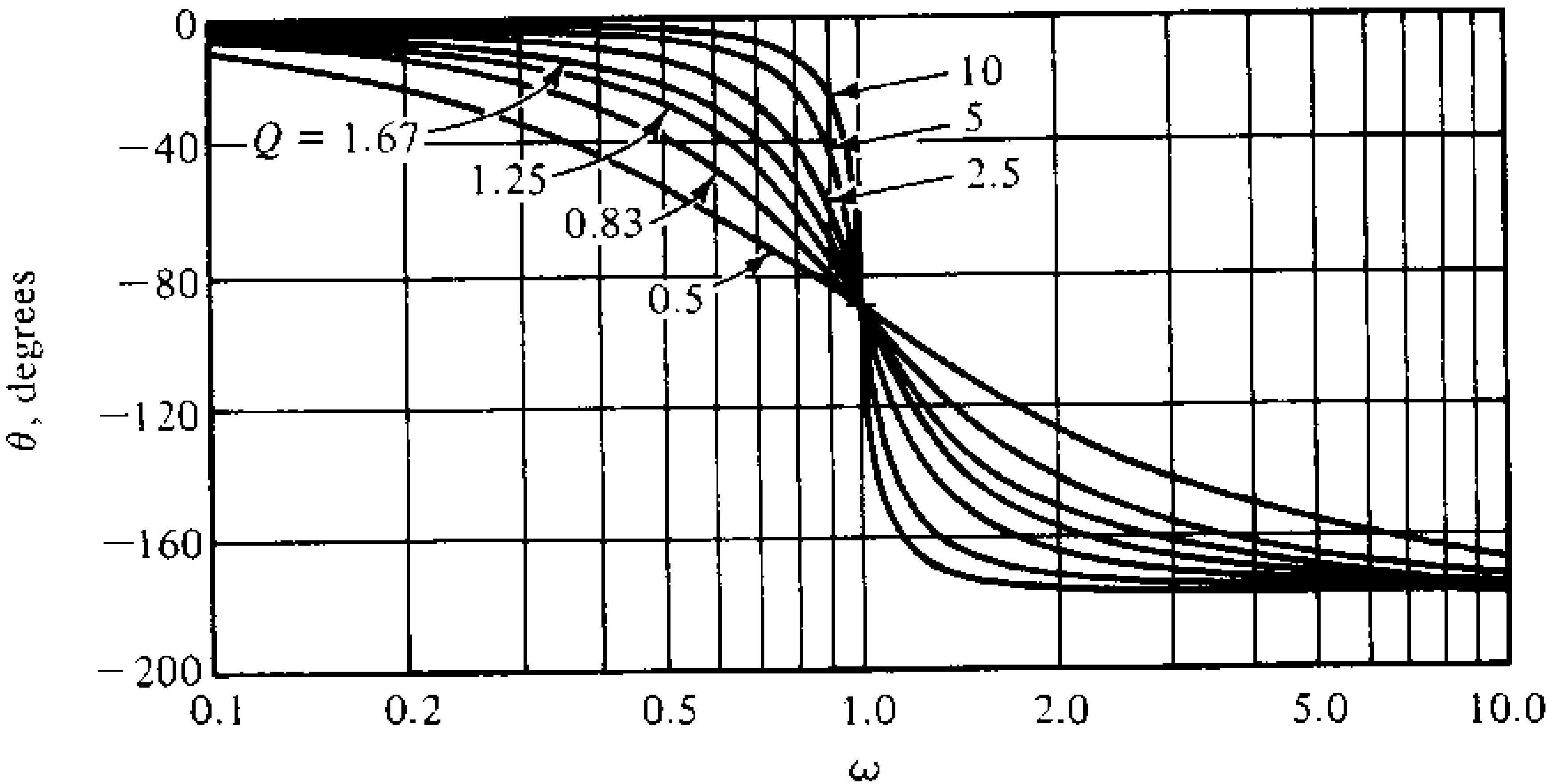
- Bode Plots (LP)



Dr. Hongjiang Song, Arizona State University

Second-Order Filters

- Bode Plots (LP)

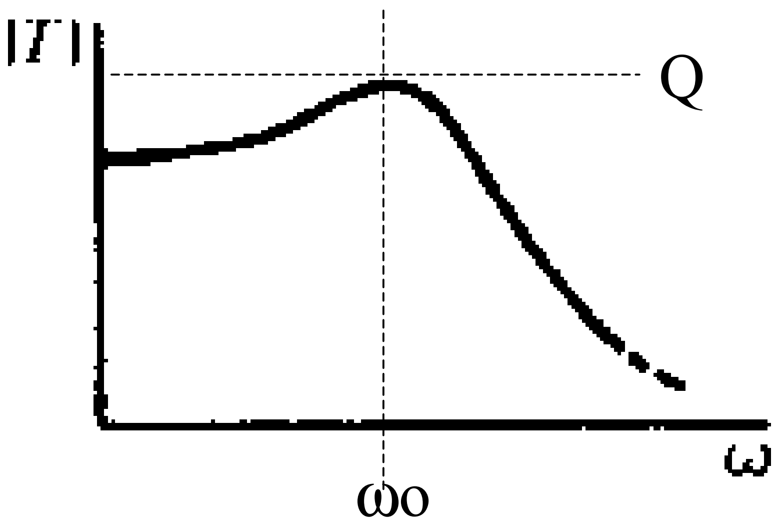


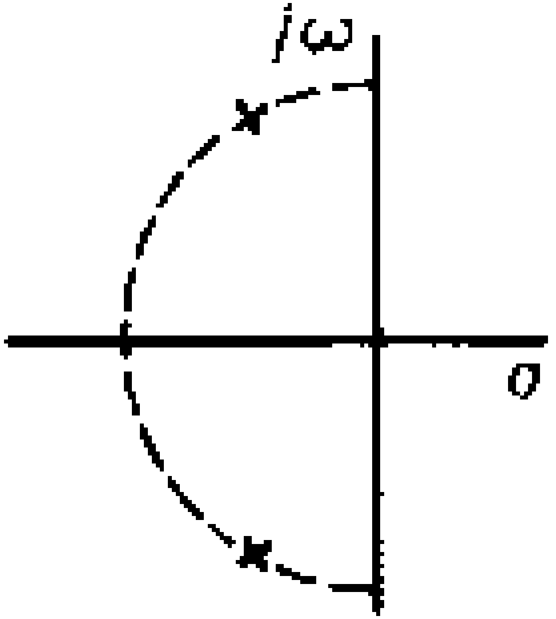
Dr. Hongjiang Song, Arizona State University

Second-Order Filters

- Bode Plots (LP)

$$T_{LP} = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$



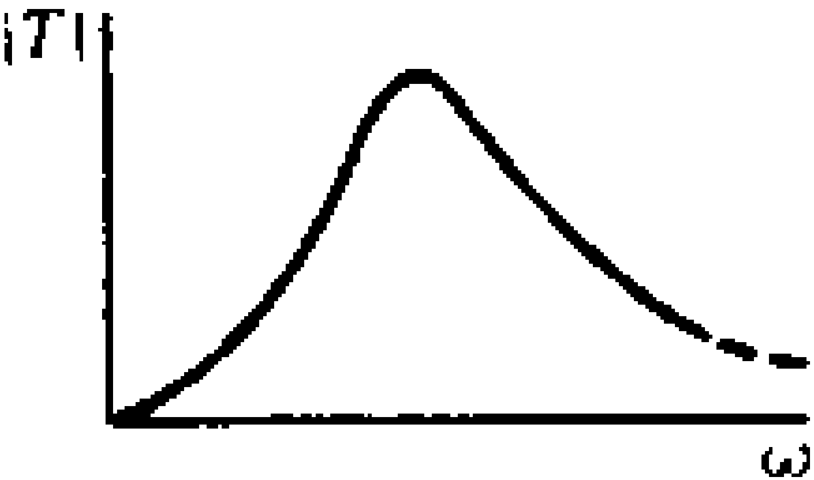


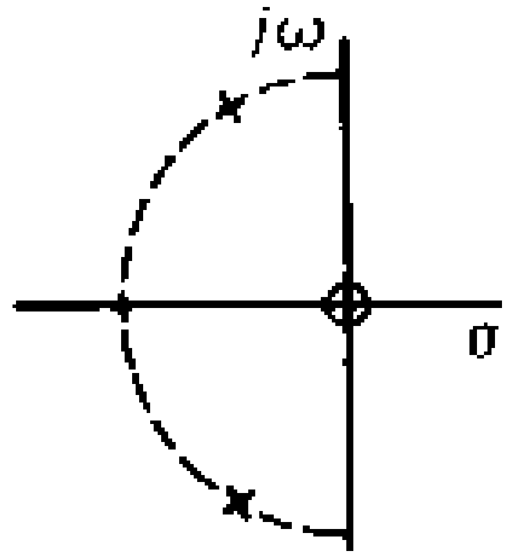
Dr. Hongjiang Song, Arizona State University

Second-Order Filters

- Bode Plots (BP)

$$T_{BP} = \frac{\frac{\omega_0}{Q} s}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$

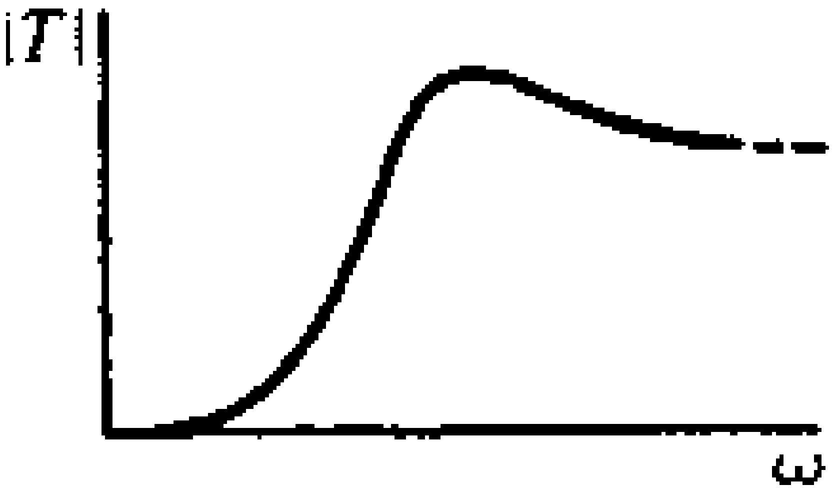


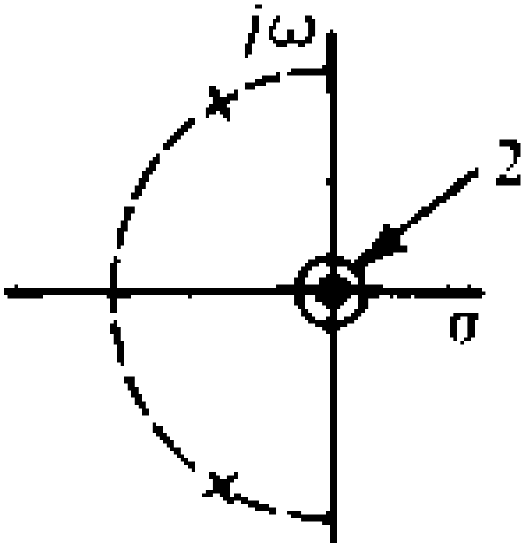


Dr. Hongjiang Song, Arizona State University

- Bode Plots (HP)

$$T_{HP} = \frac{s^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$



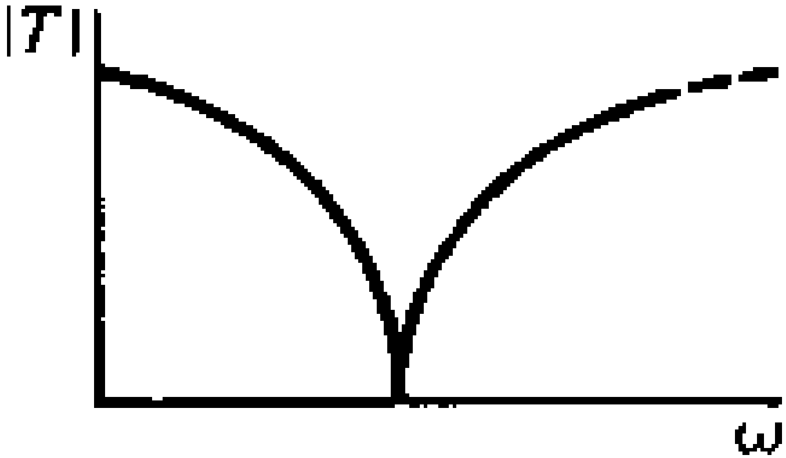


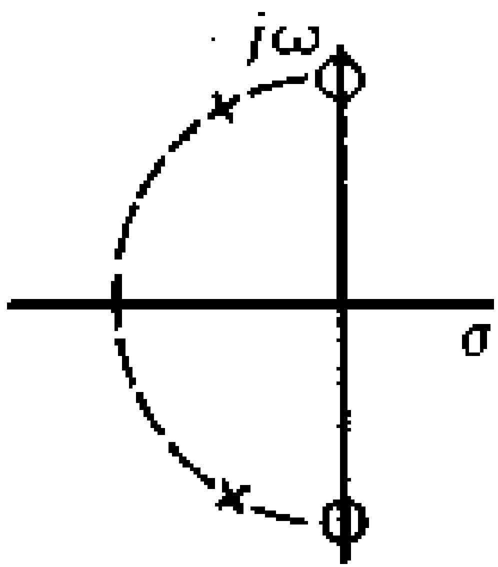
Dr. Hongjiang Song, Arizona State University

Second-Order Filters

- Bode Plots (BS)

$$T_{BE} = \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$



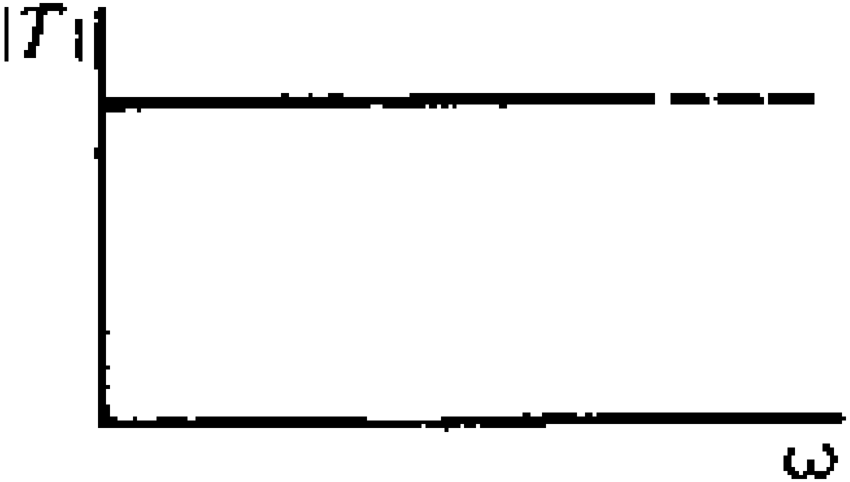


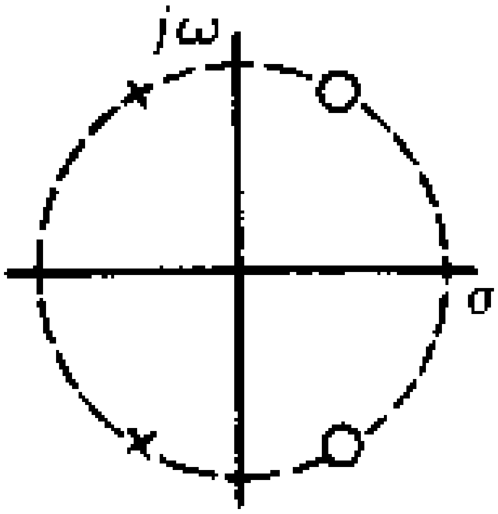
Dr. Hongjiang Song, Arizona State University

Second-Order Filters

- Bode Plots (AP)

$$T_{AP} = \frac{s^2 - \frac{\omega_0}{Q}s + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

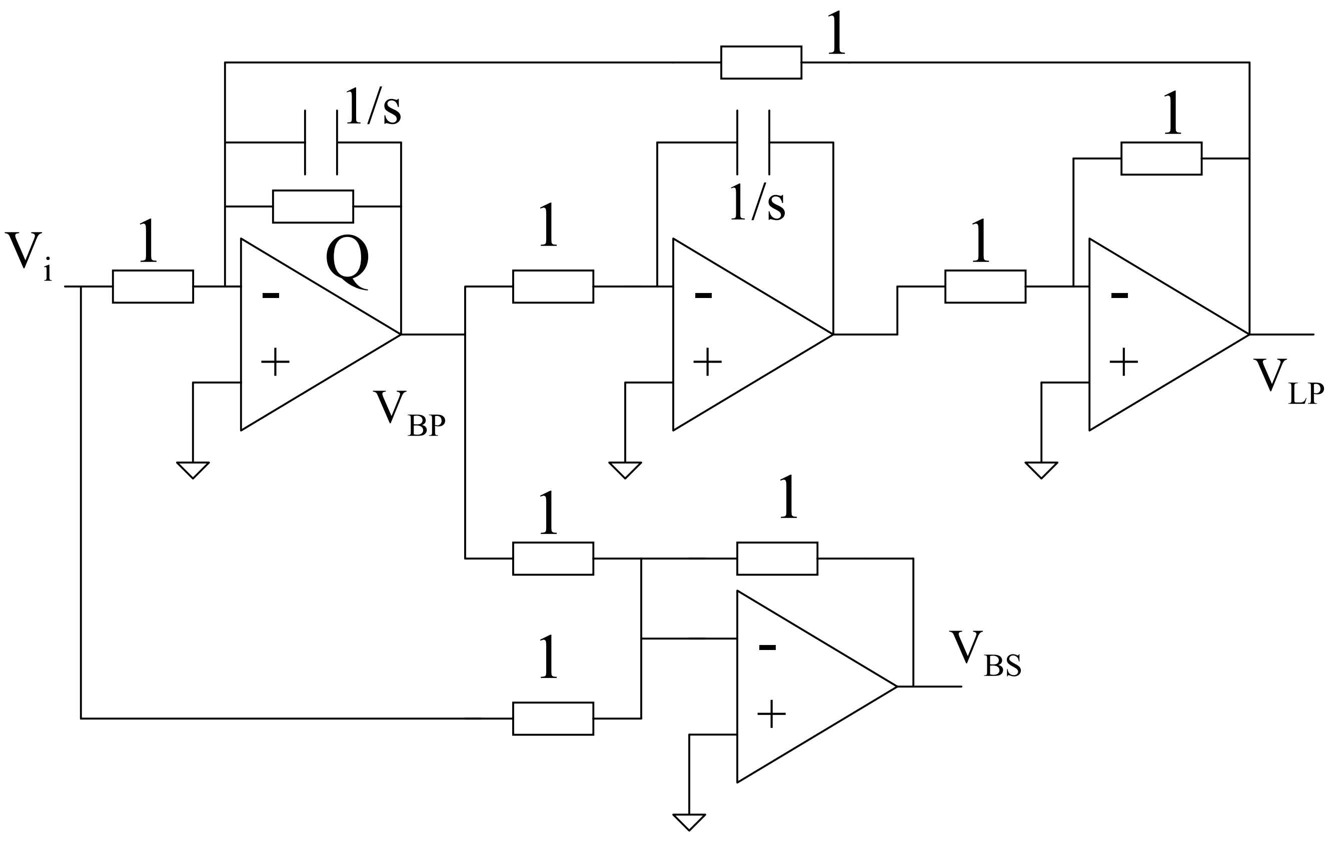




Dr. Hongjiang Song, Arizona State University

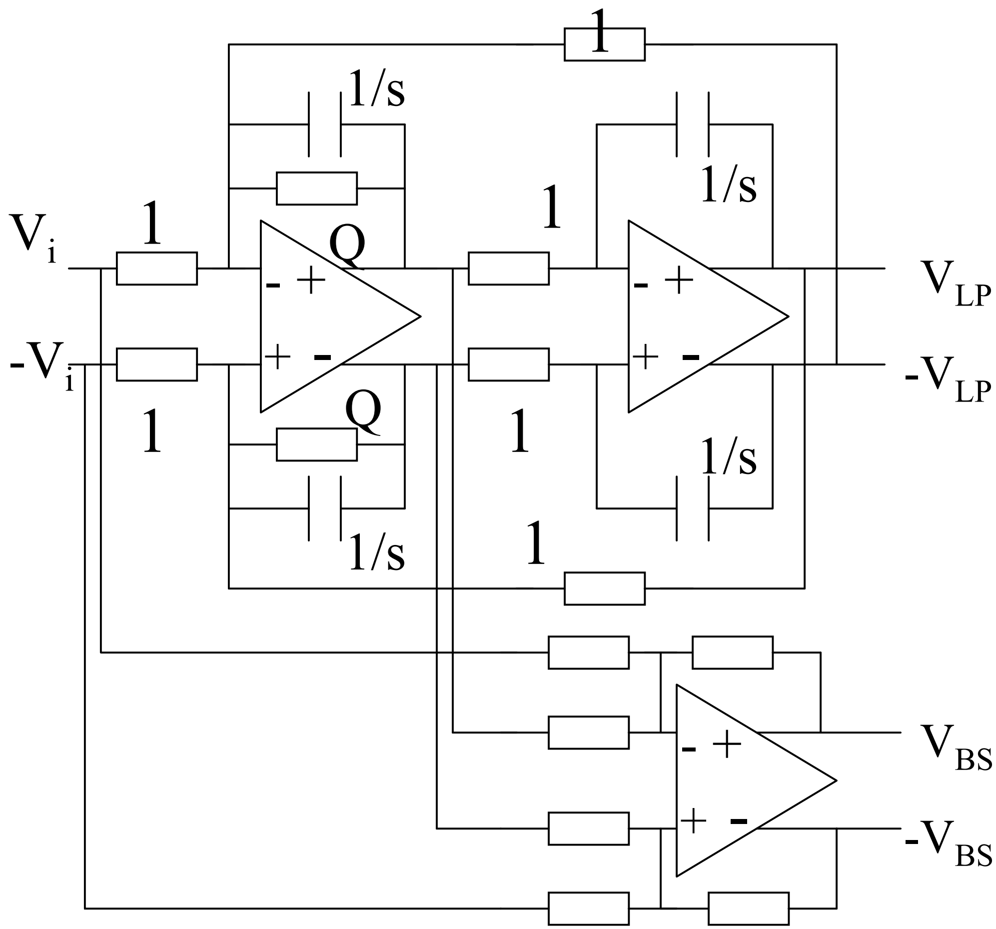
Second-Order Active RC Filters

- Single-ended



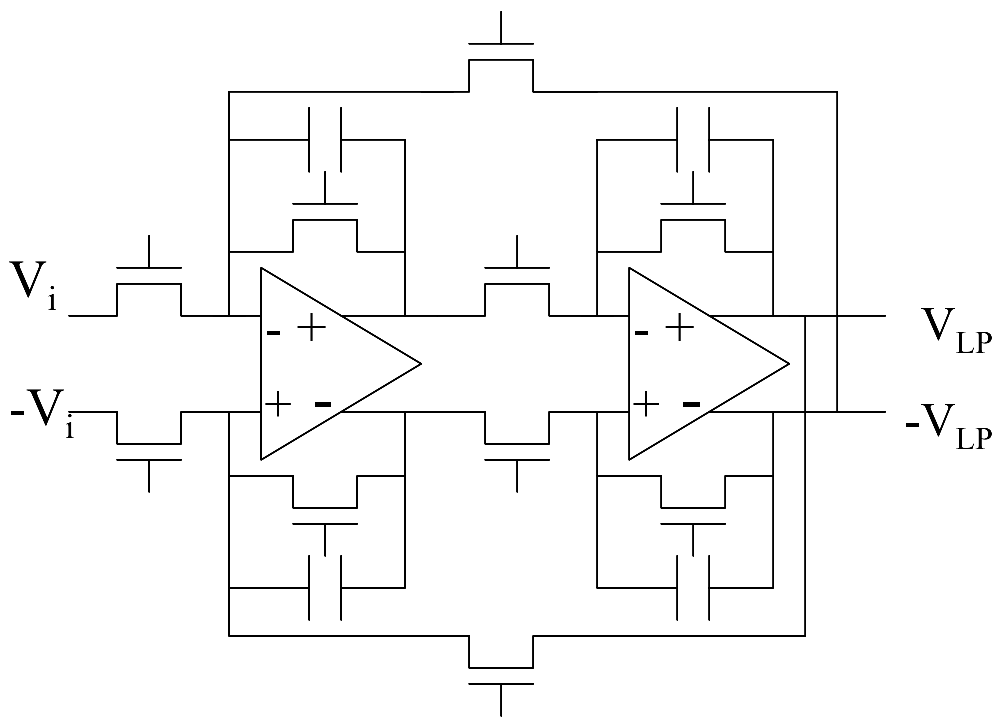
Second-Order Active RC Filters

- Fully differential



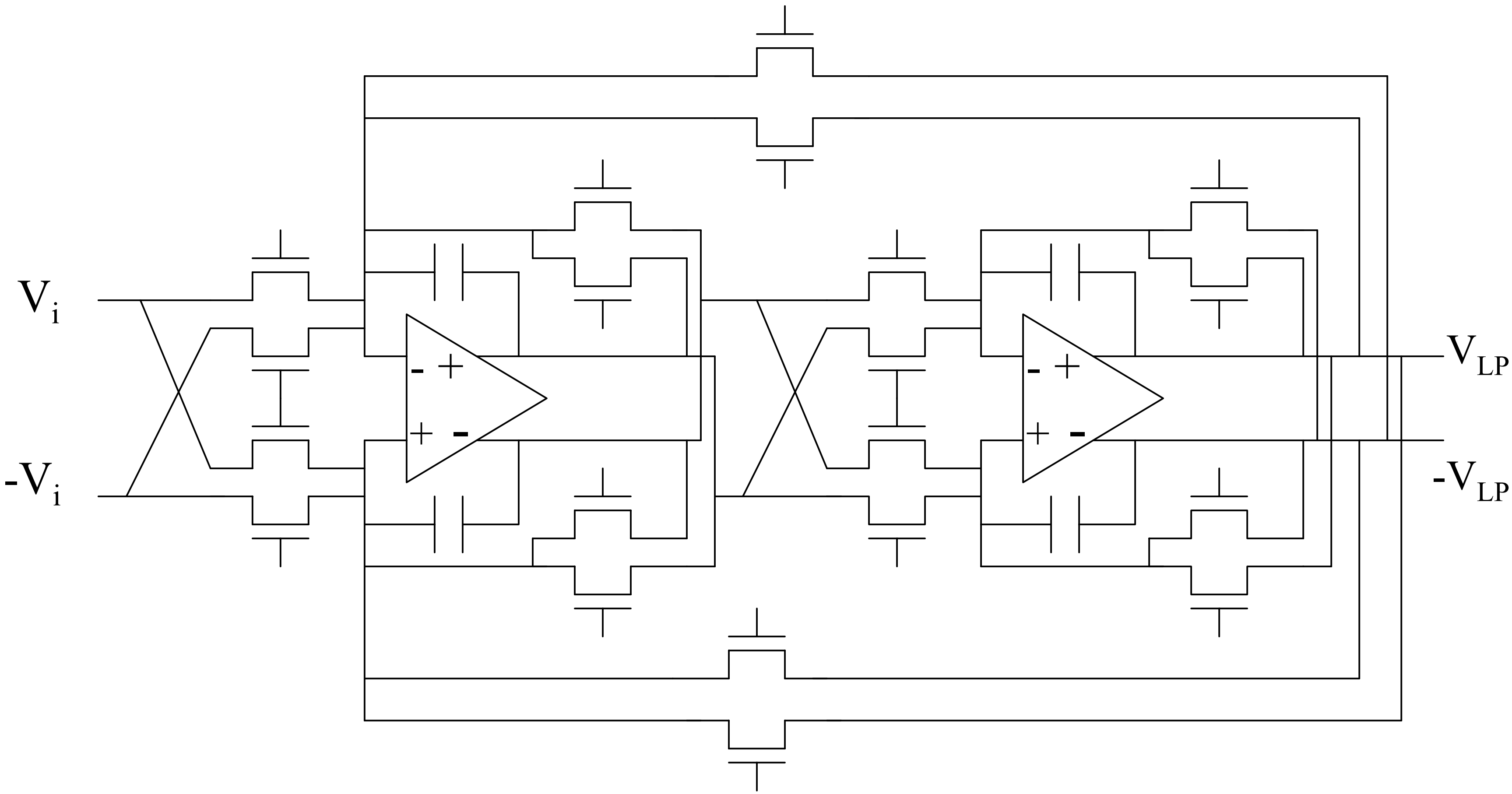
Second-Order MOS-C Filters

- Fully differential 2-transistor



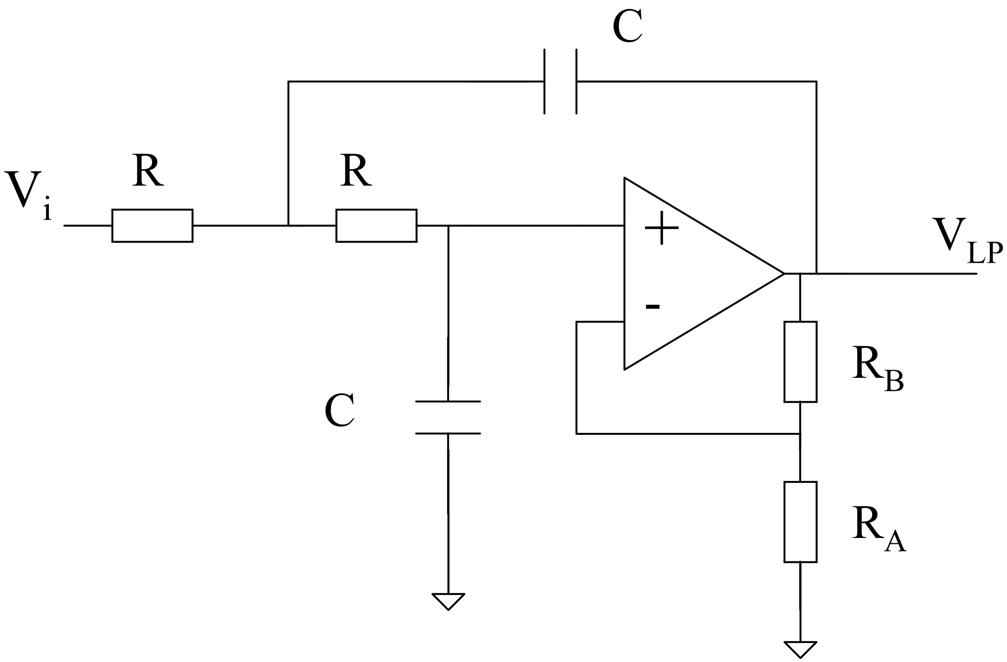
Second-Order MOS-C Filters

- Fully differential 4-transistor



Second-Order Active RC Filters

- Sallen-Key Circuits(I)



$$H_{LP}(s) = \frac{K}{(\frac{s}{\omega_o})^2 + \frac{1}{Q}(\frac{s}{\omega_o}) + 1}$$

$$\omega_o = 1/RC$$
$$K = 1 + R_B / R_A$$
$$Q = 1/(3-K)$$

Dr. Hongjiang Song, Arizona State University

Second-Order Active RC Filters

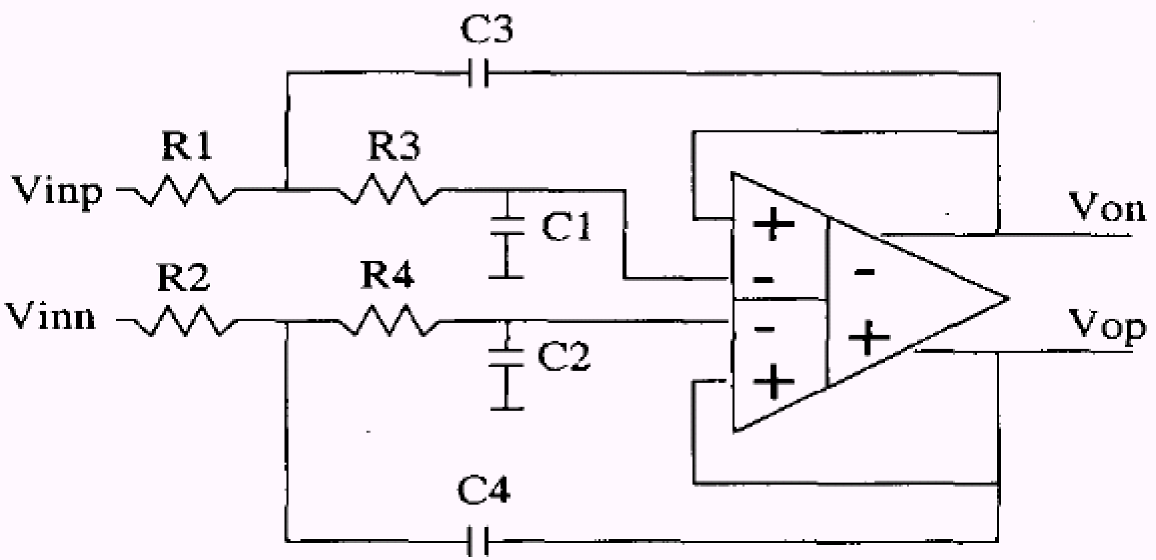
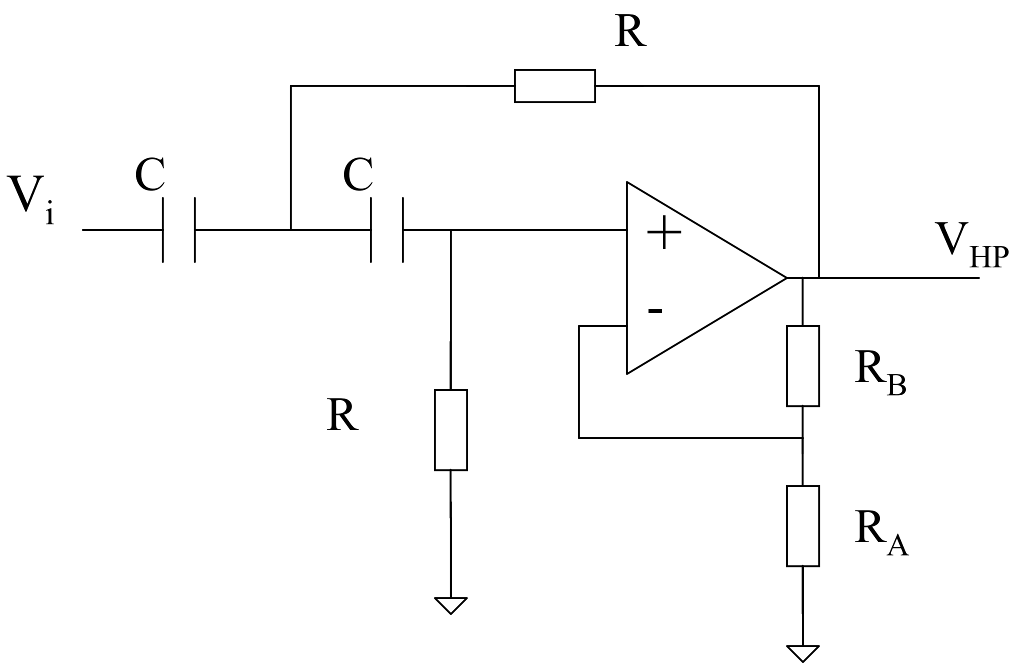


Figure 3: DDA Based Fully-Differential Sallen-Key Filter

Second-Order Active RC Filters

- Sallen-Key Circuits(II)



$$H_{HP}(s) = \frac{K\left(\frac{s}{\omega_o}\right)^2}{\left(\frac{s}{\omega_o}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_o}\right) + 1}$$

$$\omega_o = 1/RC$$

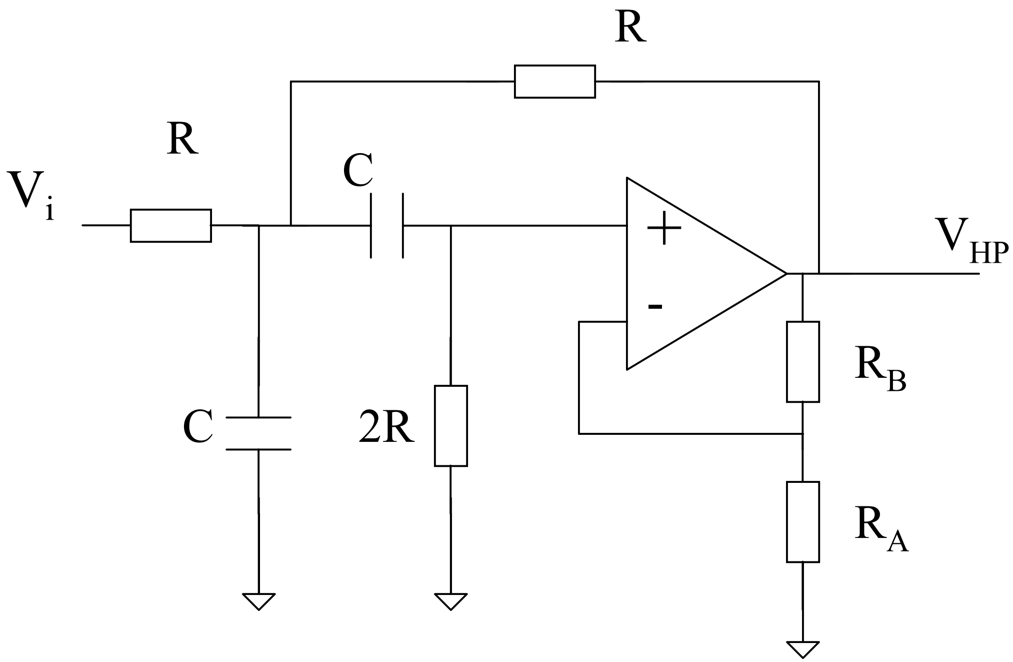
$$K = 1 + R_B / R_A$$

$$Q = 1/(3-K)$$

Dr. Hongjiang Song, Arizona State University

Second-Order Active RC Filters

- Sallen-Key Circuits(III)



$$H_{HP}(s) = \frac{K(\frac{s}{\omega_o})}{(\frac{s}{\omega_o})^2 + \frac{1}{Q}(\frac{s}{\omega_o}) + 1}$$

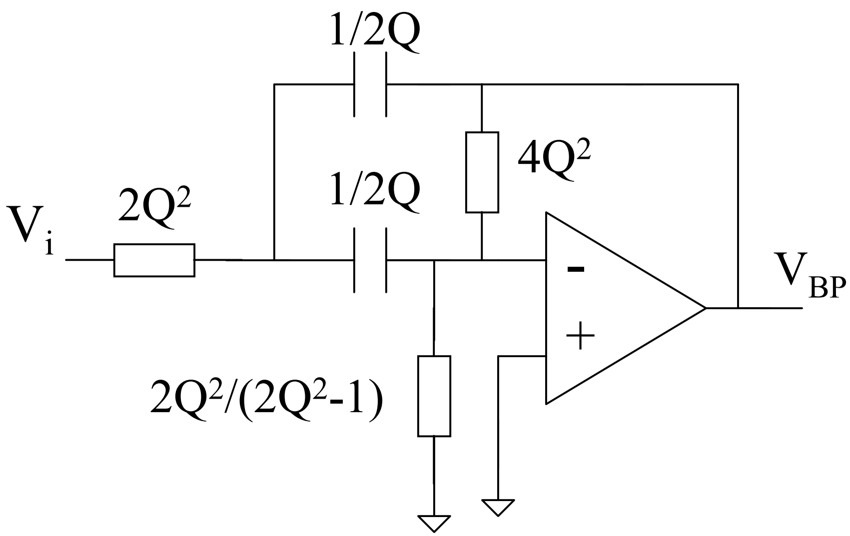
$$\omega_o = 1/RC$$

$$K = 1 + R_B / R_A$$

$$Q = 1/(3 - K)$$

Second-Order Active RC Filters

- Delyiannis-Friend Circuits



$$H_{BP}(s) = \frac{s}{s^2 + \frac{1}{Q}s + 1}$$

Dr. Hongjiang Song, Arizona State University

Cascade Design of High Order Filters

- In general, a high order filter can be implemented by cascading of the first- and second-order filters:

$$H(s) = \frac{\sum_{i=0}^{m} b_i s^i}{\sum_{i=0}^{n} b_i s^i} = \left(\prod_{i=1}^{l} \frac{\alpha_{2i} s^2 + \alpha_{1i} s + \alpha_{0i}}{s^2 + s\frac{\omega_{oi}}{Q_i} + \omega_{oi}^2}\right)\left(\frac{as+b}{s-p}\right)$$

$$= \prod_{i=1}^{l+1} H_i(s)$$

Dr. Hongjiang Song, Arizona State University