F11 – Feedback and Stability

Outline

- General feedback structure and systematic analysis
- Feedback topologies
  - Feedback voltage amplifier (series-shunt)
  - Feedback transconductance amplifier (series-series)
  - Feedback transresistance amplifier (shunt-shunt)
  - Feedback current amplifier (shunt-series)
- Stability considerations and Nyquist plot
- Effects of feedback on pole location
- Stability analysis using Bode plots, gain and phase margin
- Frequency compensation (pole splitting)

Reading Guide *Sedra/Smith 7ed int*

- Chapter 10.1-4, 10.6 (voltage feedback)
- (Chapter 10.5 (other feedback))
- Chapter 10.7-9 (amplifier stability)
- (Chapter 10.10 (freq. compensation))

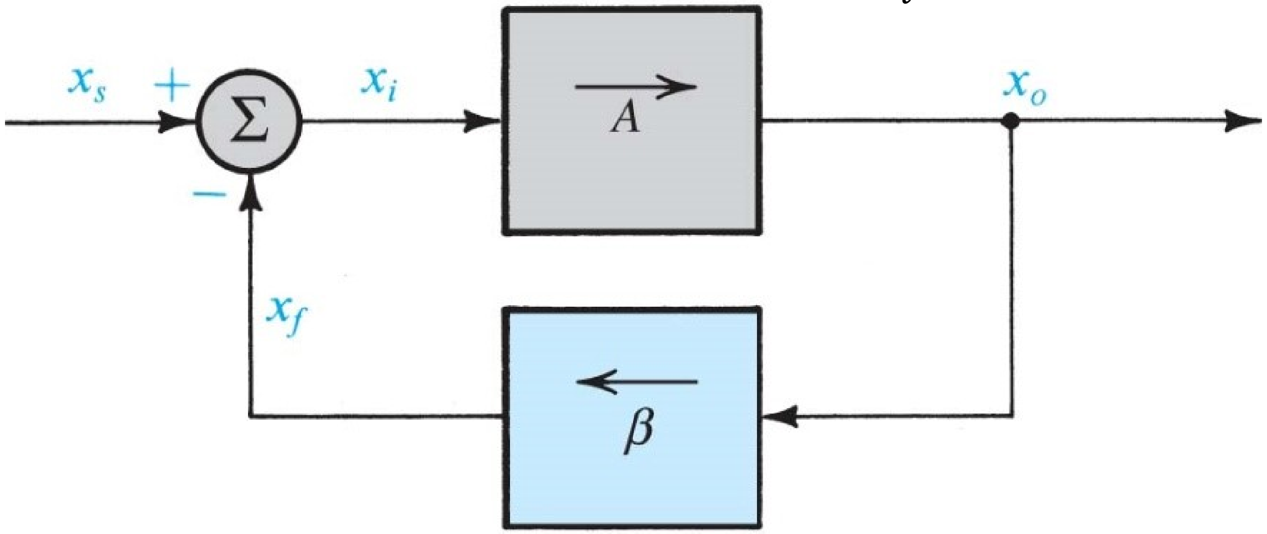
Problems *Sedra/Smith 7ed int*

- P10.7, 10.8, 10.17, 10.28, 10.30

General Negative Feedback Structure

- Open loop gain, A
- Feedback factor
  (feedback transfer function), β
- Loop gain
  (loop transfer function), $A\beta$
  - Signal gain from x_i to x_f
  - Always dimensionless
- Amount of feedback, $1 + A\beta$
- Gain with feedback
  (closed loop transfer function), $A_f = \frac{x_o}{x_s} = \frac{A}{1+A\beta}$

$$x_o = Ax_i$$
$$x_f = \beta x_o$$
$$x_i = x_s - x_f$$
$$\frac{x_f}{x_i} = A\beta$$



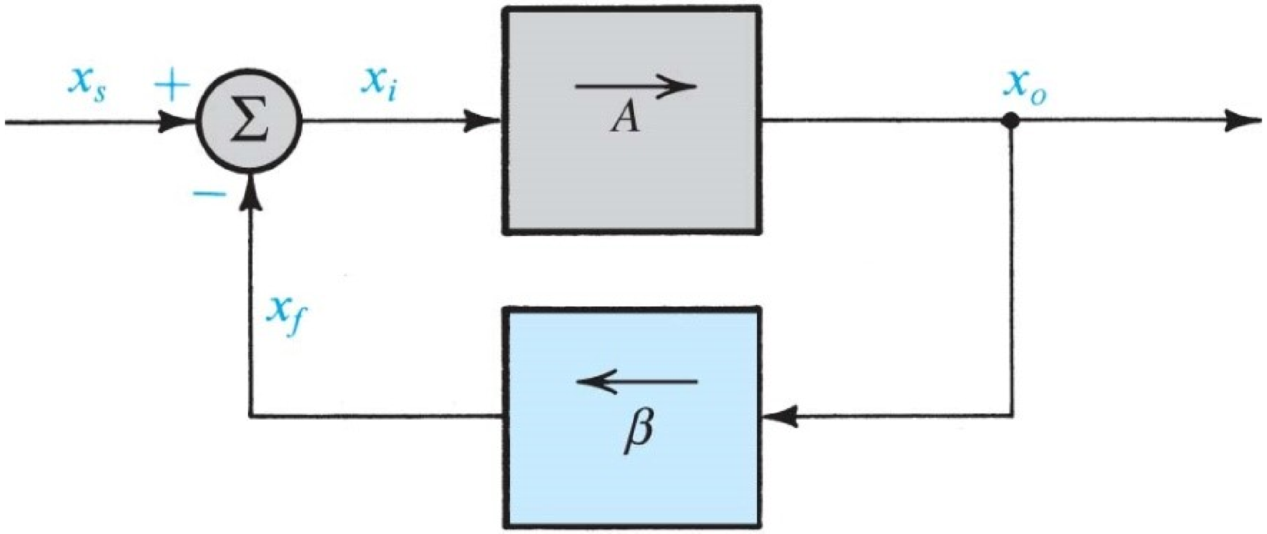
Transfer function is a more general term, non-scalar, for signal gain or factor.

Benefits of Feedback

- Gain with feedback is reduced by the amount of feedback, $1 + A\beta$

$$A_f = \frac{A}{1 + A\beta}$$

- The amount of feedback also quantifies…
  - Gain desensitivity
  - Bandwidth extension
  - Reduction of nonlinear distortion
  - Input resistance idealisation (increase/ decrease)
  - Output resistance idealisation (increase/ decrease)
  - Interference reduction



Feedback improvements come at the cost of gain, and at the risk of instability.

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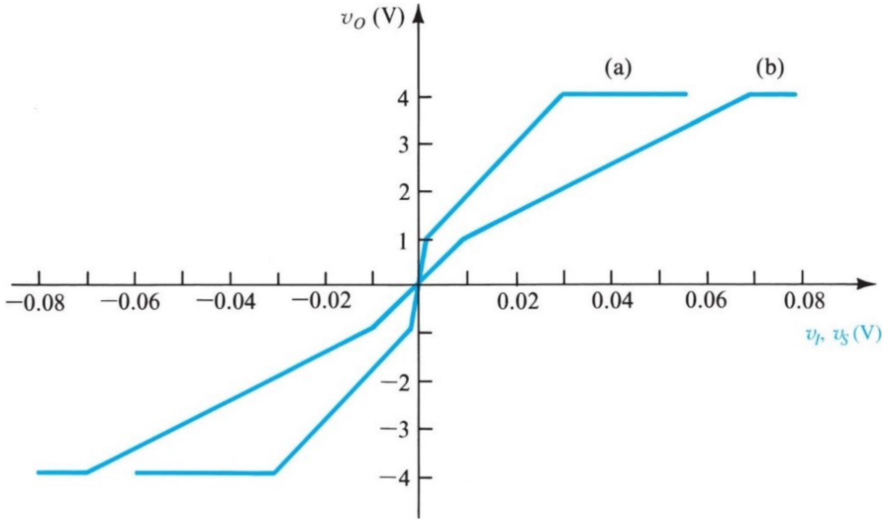
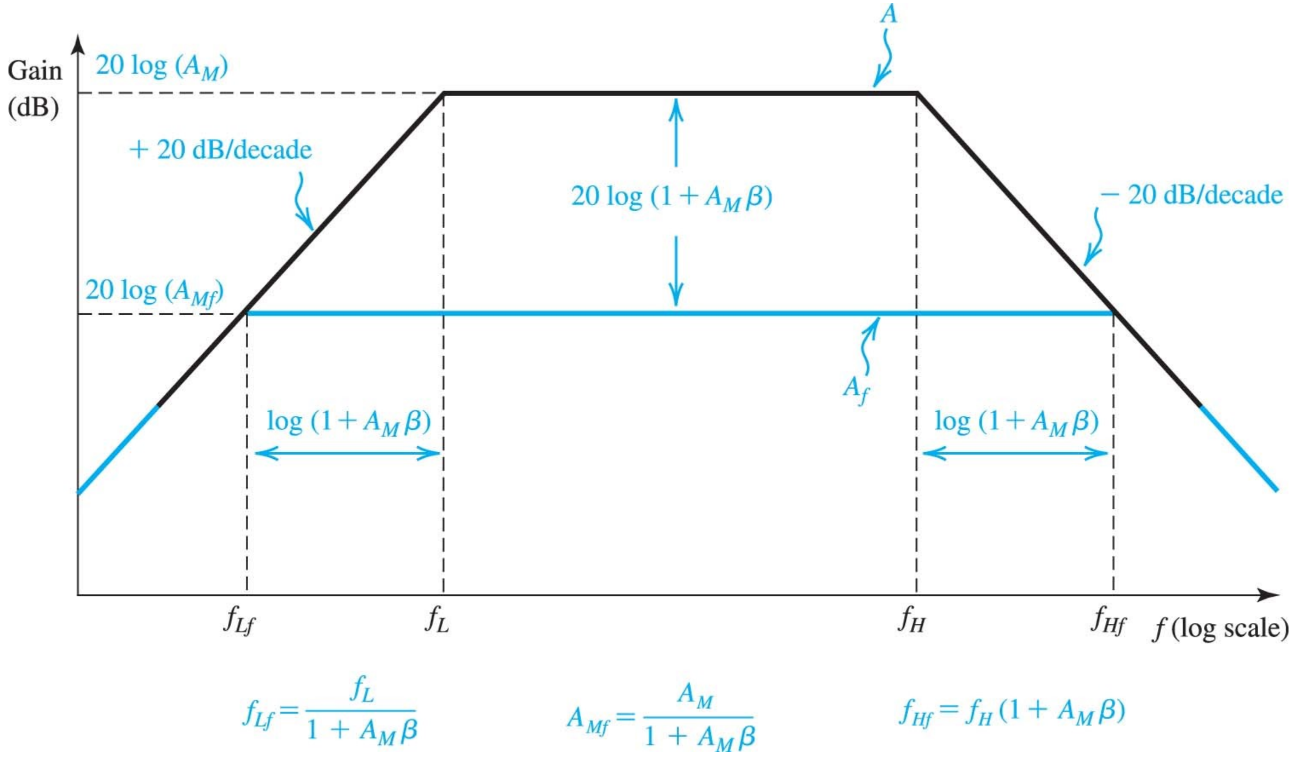




$$A_f = \frac{A}{1 + A\beta}$$

Feedback improvements come at the cost of gain, and at the risk of instability.

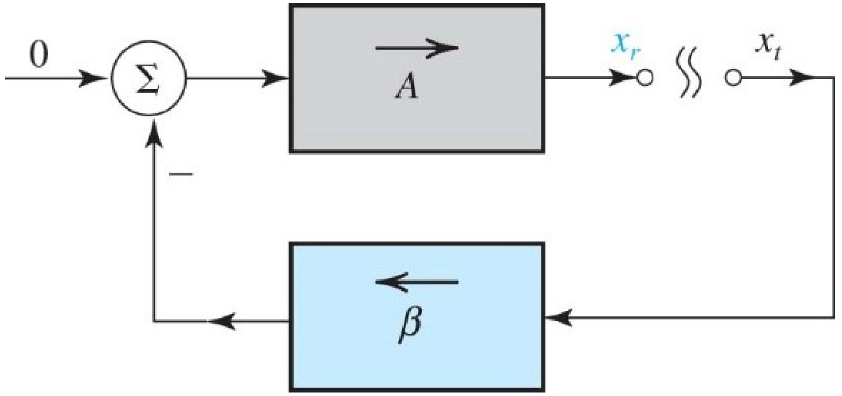
Ideal Feedback Analysis

- Quantification method
  - Cancel source, break loop, inject test signal, and measure return
- Sign of the loop gain
  - Negative feedback: $A\beta > 0$
  - Positive feedback: $A\beta < 0$ (reduced stability)
- Magnitude of the loop gain, $|A\beta|$
  - Determines amount of feedback, $(1 + A\beta)$, and ideality of closed loop gain

$$A_f = \frac{A}{1 + A\beta}, \qquad A_f\Big|_{A\beta \gg 1} \approx \frac{1}{\beta}$$

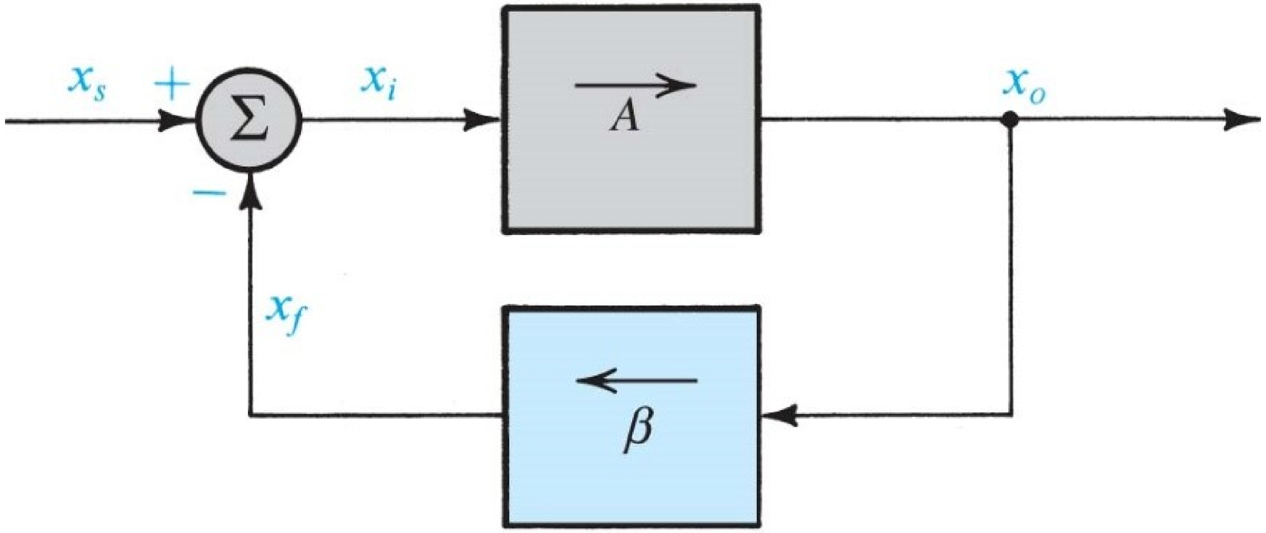
- Amount of feedback quantifies the benefits of feedback

$$x_s = 0$$
$$x_r = -A\beta x_t$$
$$A\beta = \frac{-x_r}{x_t}$$



Feedback loop does not load amplifier, no internal feedback, and unilateral blocks.

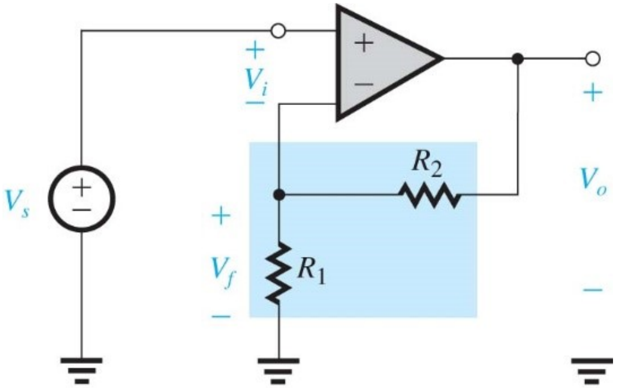
Where did we already encounter feedback?

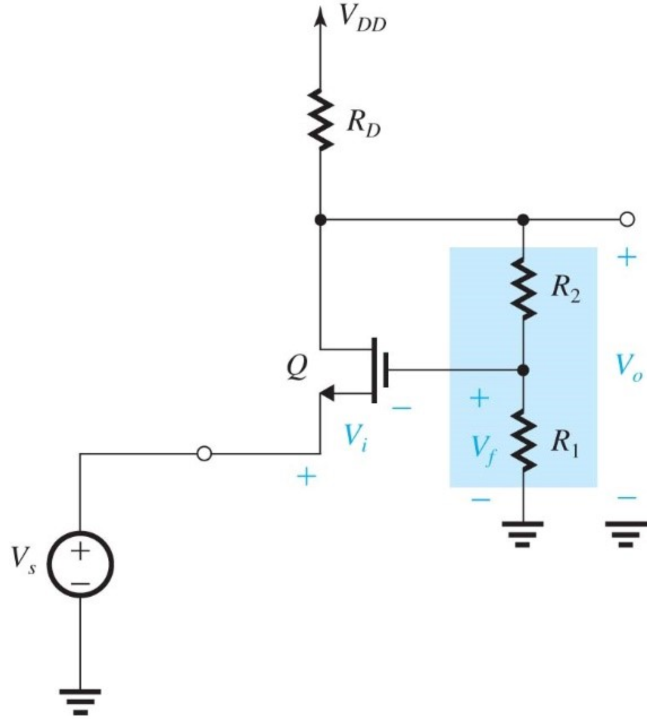


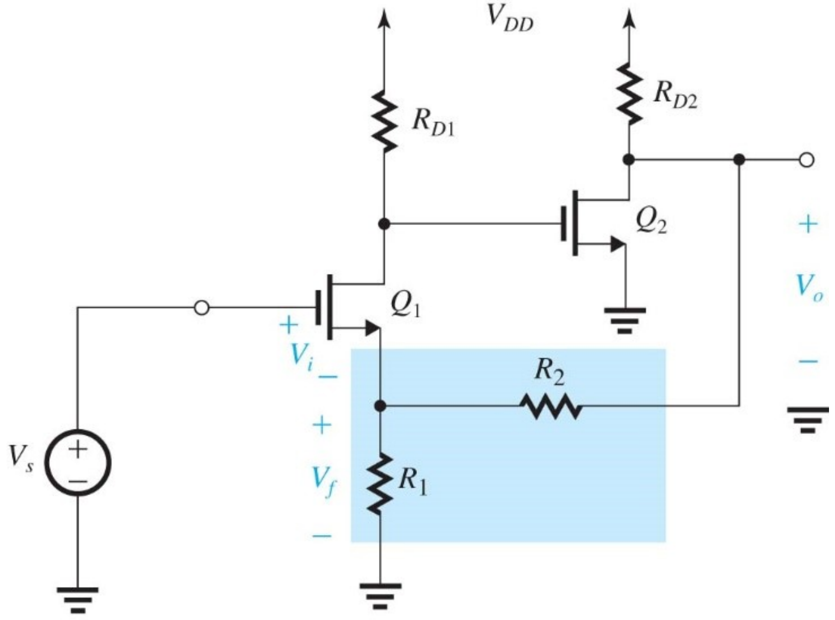
Examples of Series-Shunt (Voltage) Feedback Amplifiers

- Amplifier circuit
  - Some kind of circuit with gain, preferably voltage amplifier

- Voltage feedback network
  - Series voltage mixing on input
  - Shunt voltage sampling over output





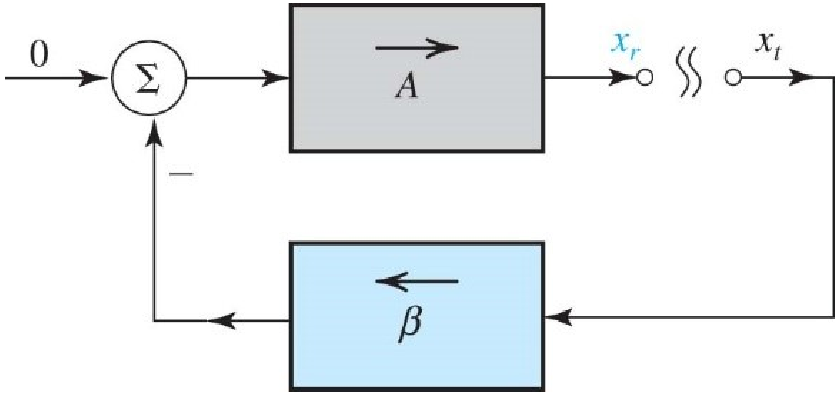


The feedback network is treated as an add-on to the amplifier.

Loop (Voltage) Gain Analysis

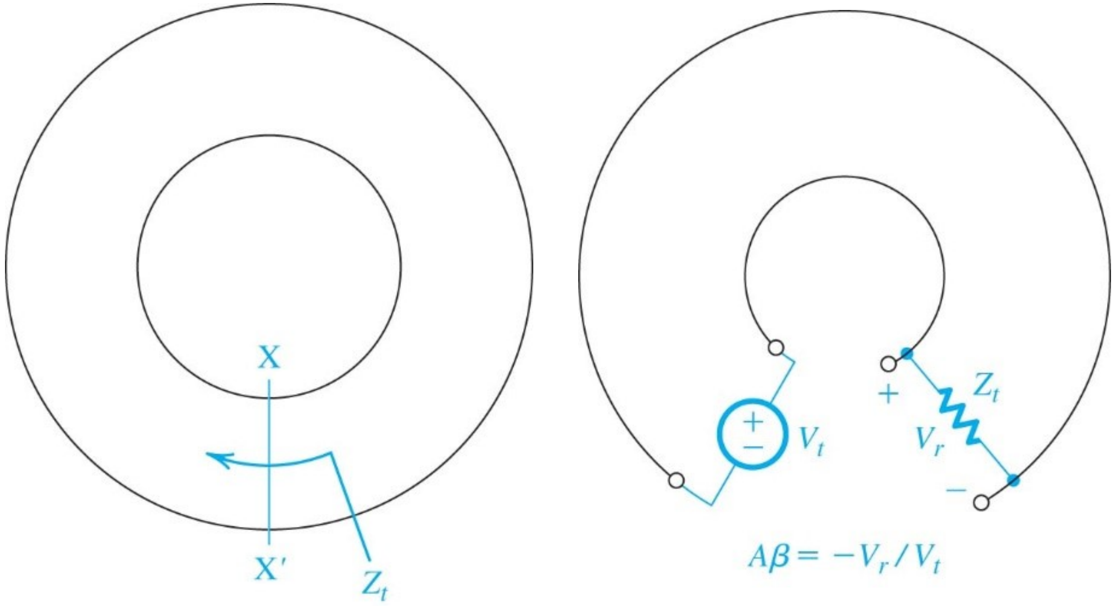
- Identify feedback network
  - Determine feedback factor, β
  - Determine ideal gain with feedback (closed loop gain)

$$A_f = \frac{A}{1 + A\beta} \approx \frac{1}{\beta}$$



- Determine loop gain $\quad A\beta = -\frac{V_r}{V_t}$
  - Cancel source signal
  - Break loop (ideally at infinite impedance)
  - Terminate return path (as required)
  - Apply a test voltage to the feedback loop
  - Measure the returned termination voltage

- Determine the open loop gain from feedback factor and loop gain $\quad A = \frac{A\beta}{\beta}$



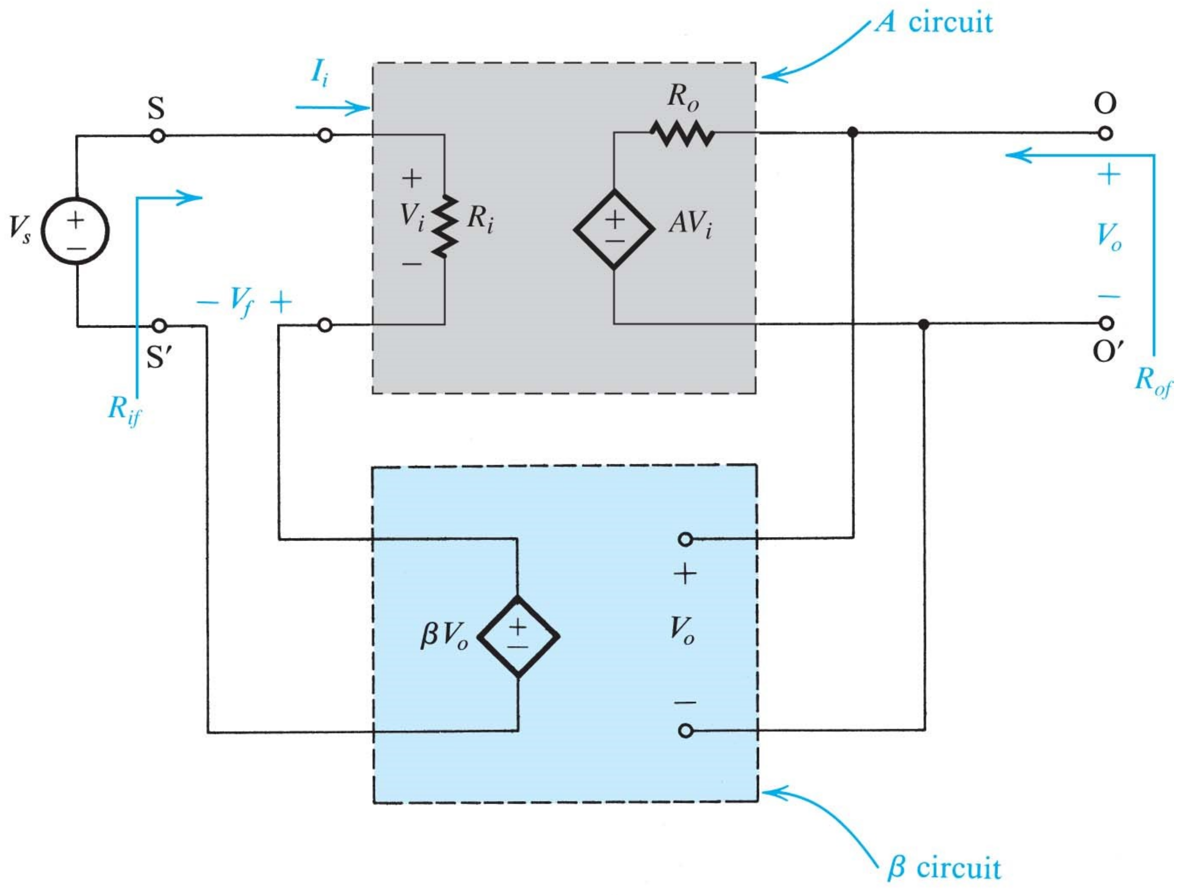
Sensing, Mixing, and Feedback Topology

- Mixing on the input
  - Voltage (series) or current (shunt)

- Sensing on the output
  - Voltage (shunt) or current (series)

- Feedback topologies
  - Series-shunt (voltage)
  - Series-series (transconductance)
  - Shunt-shunt (transresistance)
  - Shunt-shunt (current)

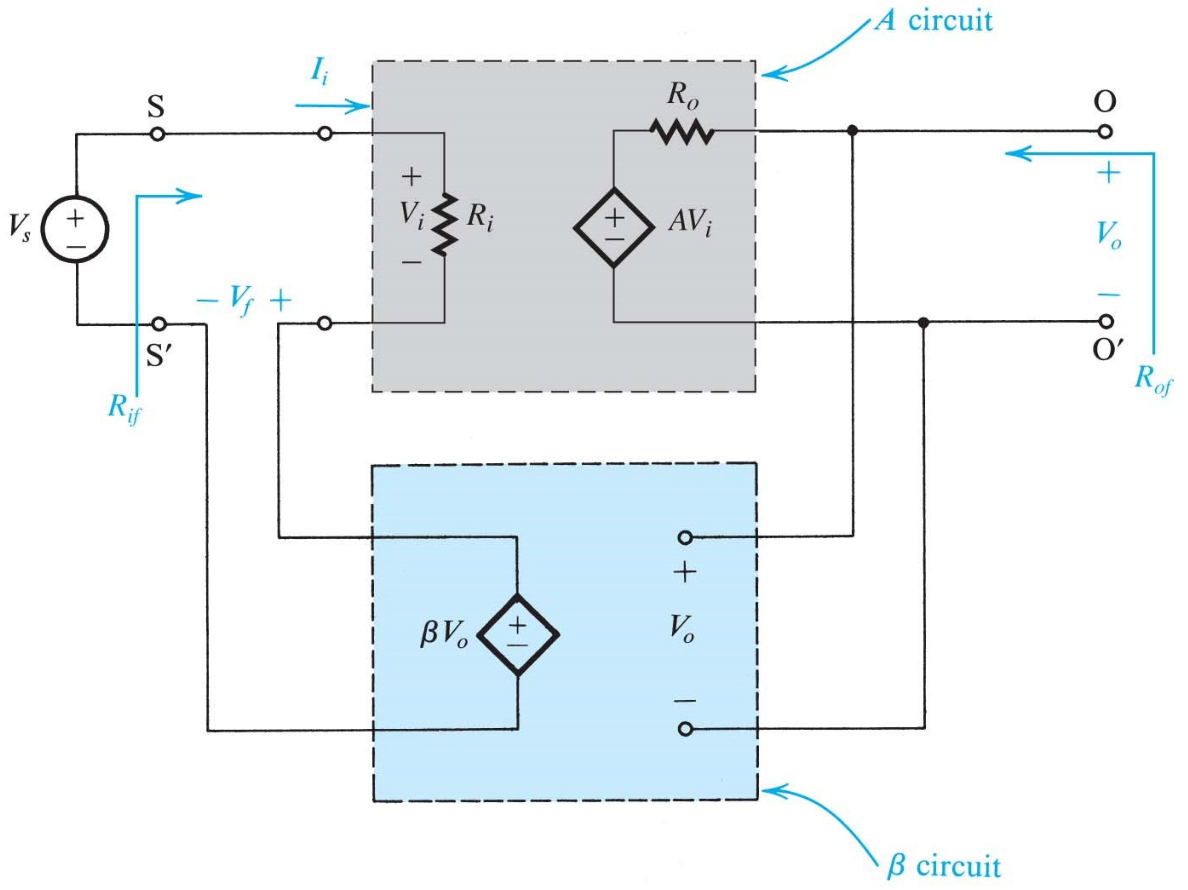
- Feedback network typically loads circuit (not ideal probe and source)

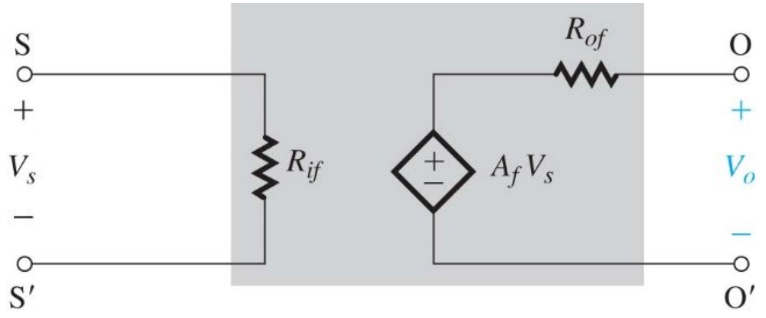


The appropriate feedback topology depends on amplifier type.

Series-Shunt Feedback Voltage Amplifier

- Series-shunt feedback
  - Input
    - Voltage mixing
    - Increased input resistance
  - Output
    - Voltage sampling
    - Reduced output resistance





BREAK

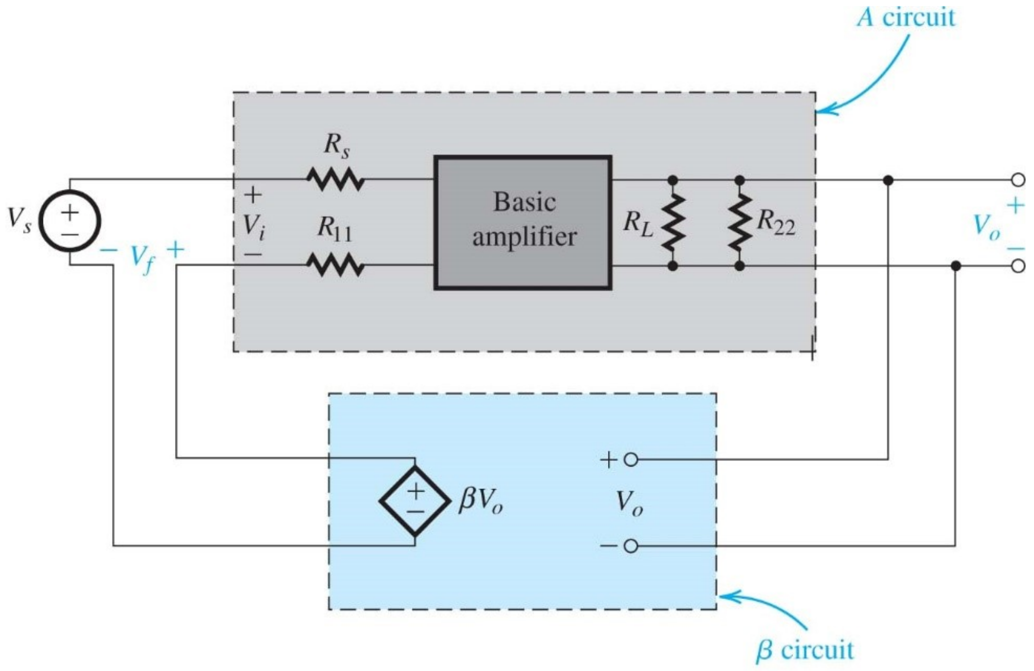
Series-Shunt Feedback Voltage Amplifier Analysis

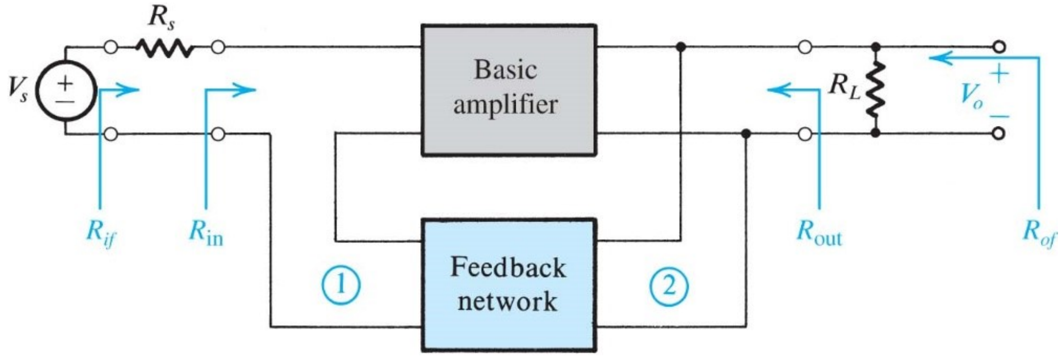
- Include source, load and feedback loading

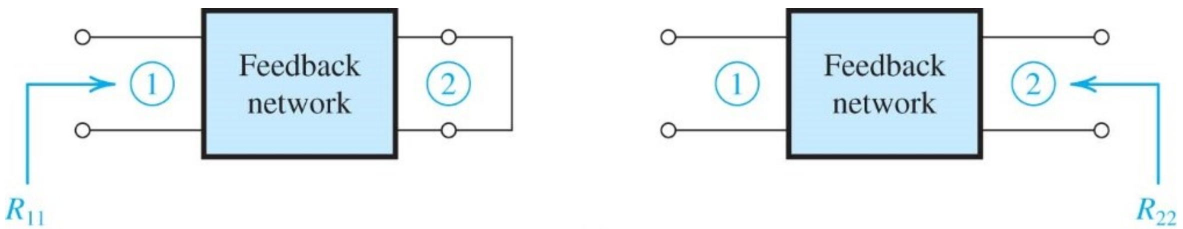
$$R_{if} = R_{s1}(1 + A\beta), \qquad R_{of} = R_{L2}/(1 + A\beta)$$

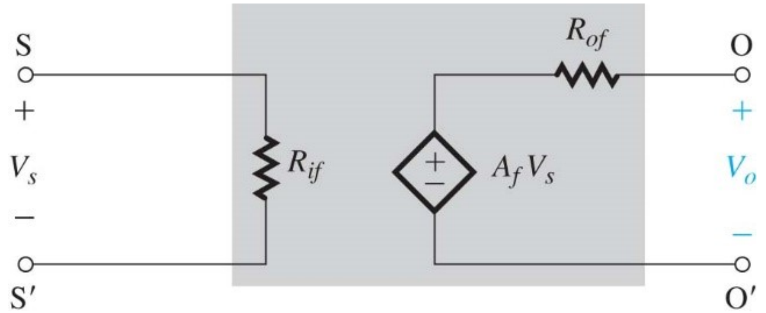
$$R_i = R_{if} - R_s, \qquad R_o = 1\Big/\left(\frac{1}{R_{of}} - \frac{1}{R_L}\right)$$

- Determine β, R_{11}, R_{22}, A_f, R_i, and R_o





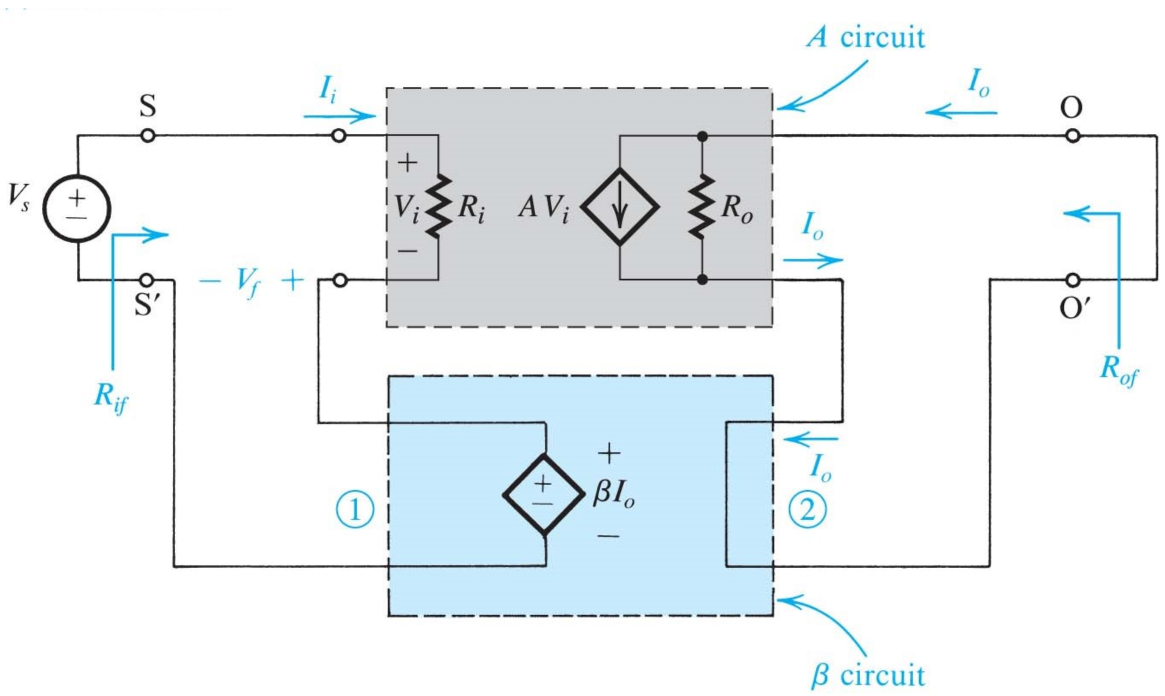


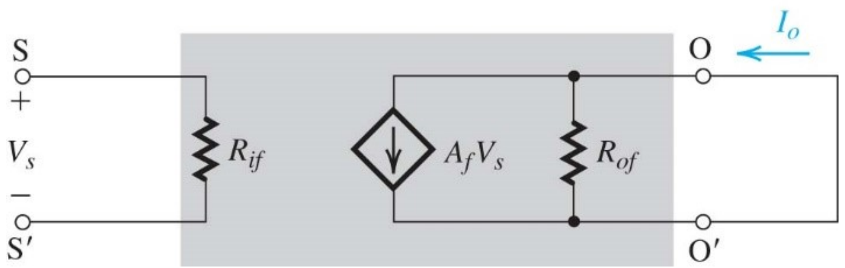


Shunt short; series sever.

(Series-Series Feedback Transconductance Amplifier)

- Series-series feedback
  - Input
    - Voltage mixing
    - Increased input resistance
  - Output
    - Current sampling
    - Increased output resistance

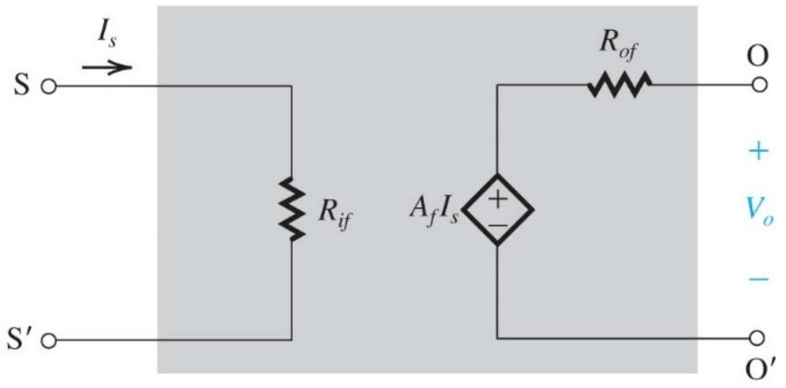


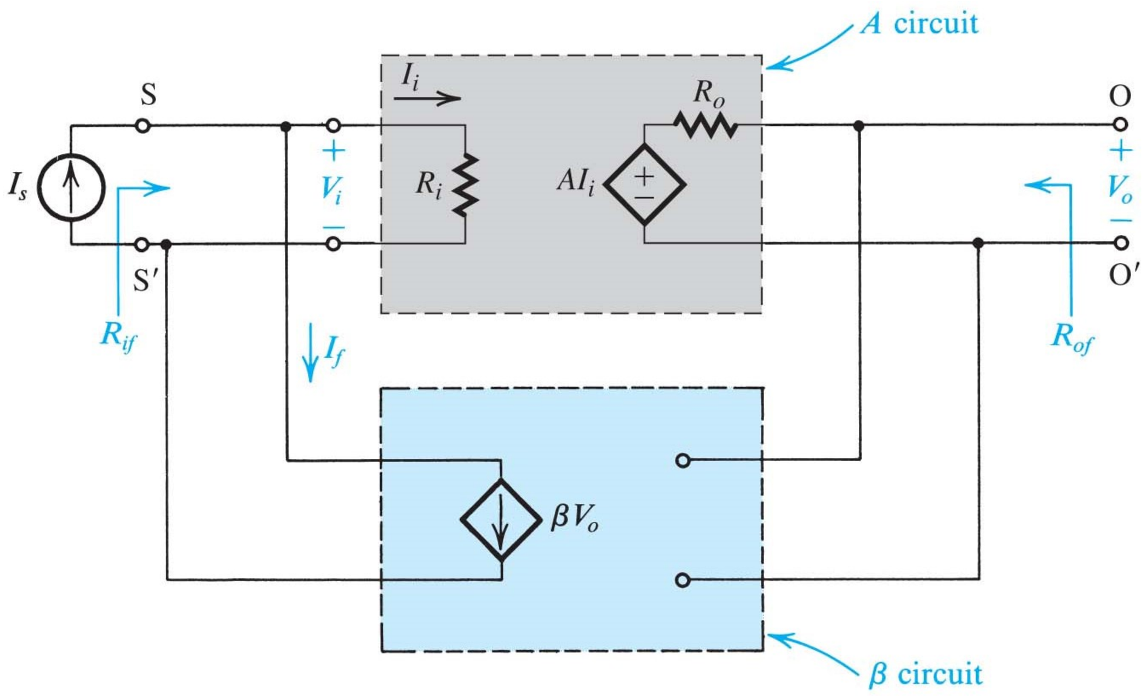


Shunt short; series sever.

(Shunt-Shunt Feedback Transresistance Amplifier)

- Shunt-shunt feedback
  - Input
    - Current mixing
    - Reduced input resistance
  - Output
    - Voltage sampling
    - Reduced output resistance

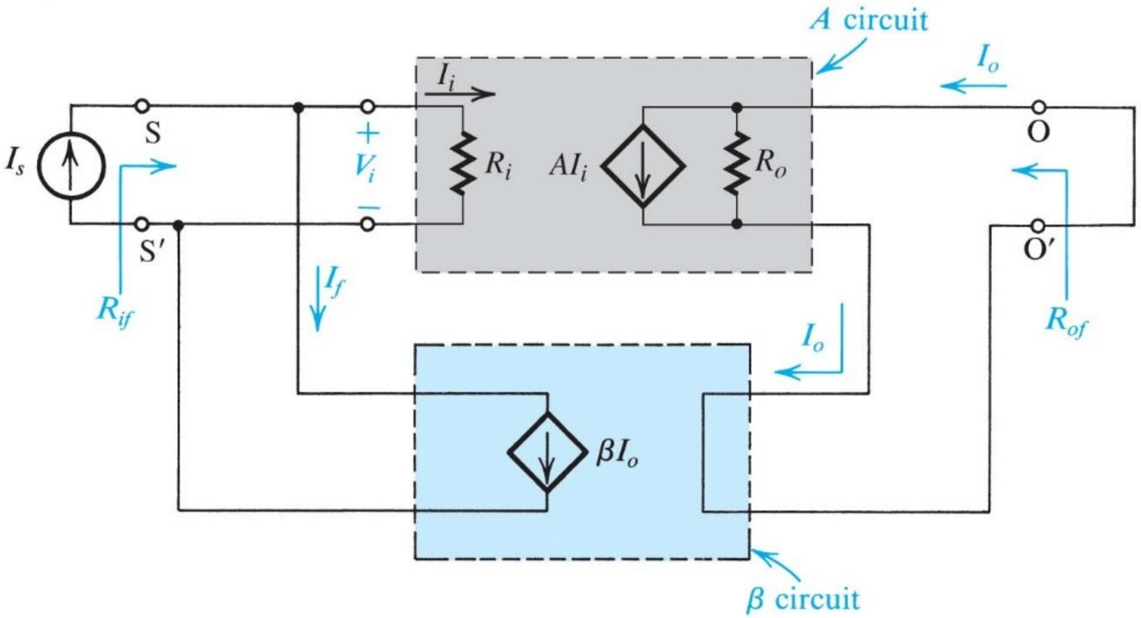


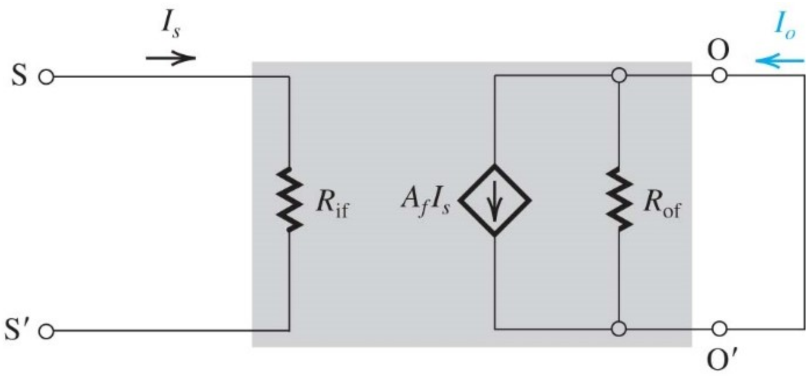


Shunt short; series sever.

(Shunt-Series Feedback Current Amplifier)

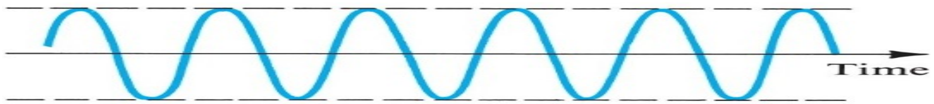
- Shunt-series feedback
  - Input
    - Current mixing
    - Reduced input resistance
  - Output
    - Current sampling
    - Increased output resistance

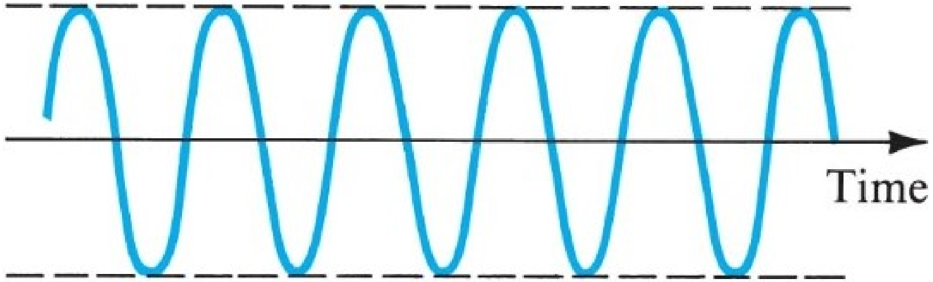


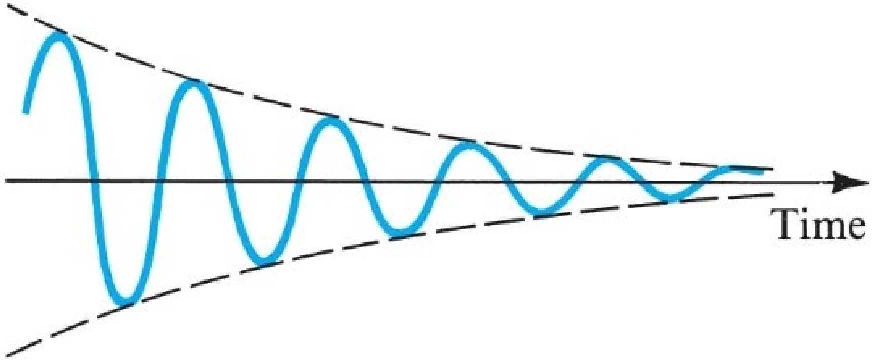


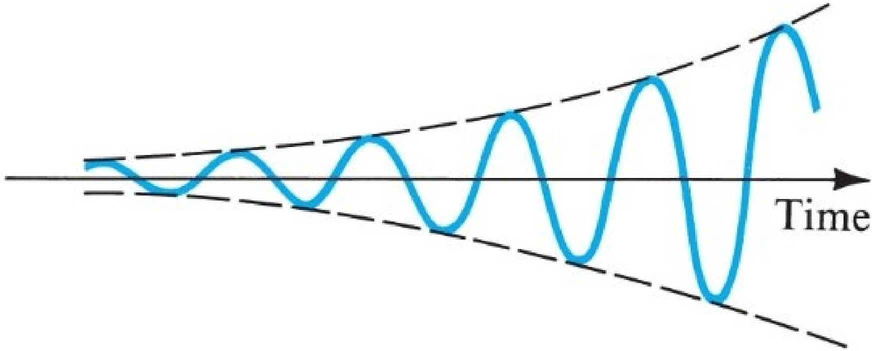
Shunt short; series sever.

An amplifier must be stable; why?









Stability

- Negative feedback stabilises the amplifier
  - Input signal is reduced ($x_i = x_s - x_f$)

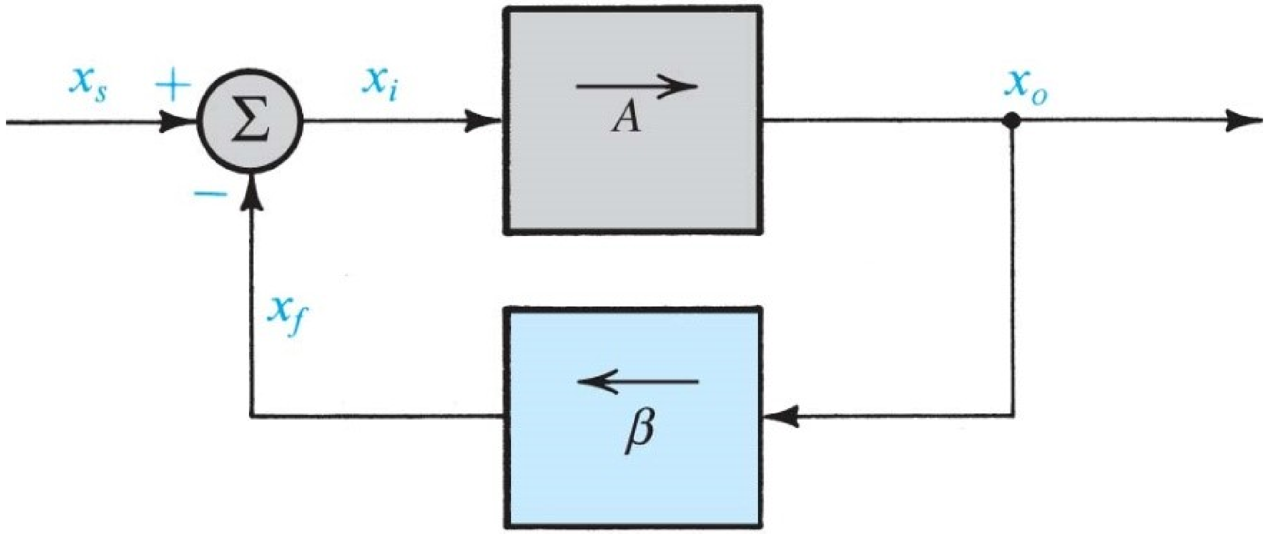
- Positive feedback risks instability
  - Input signal is boosted ($x_i = x_s + x_f$)
  - Stable oscillations if A\beta=-1
  - Regenerative oscillations if A\beta<-1

- Loop gain is frequency dependent

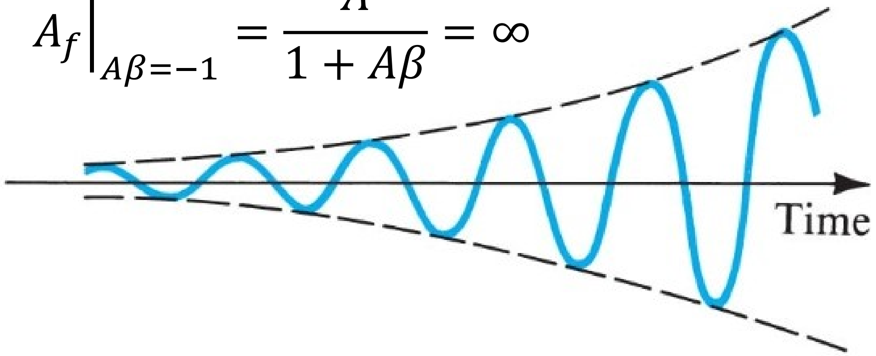
$$A_f(j\omega) = \frac{A(j\omega)}{1 + A(j\omega)\beta(j\omega)} = \frac{A(j\omega)}{D(j\omega)}$$

- Characteristic equation of feedback poles

$$D(j\omega) = 1 + A(j\omega)\beta(j\omega) = 0$$



$$A_f\Big|_{A\beta=-1} = \frac{A}{1 + A\beta} = \infty$$



Nyquist Plot

- Loop gain, $A(j\omega)\beta(j\omega)$, plotted in complex plane
  - Complex function (polar format)

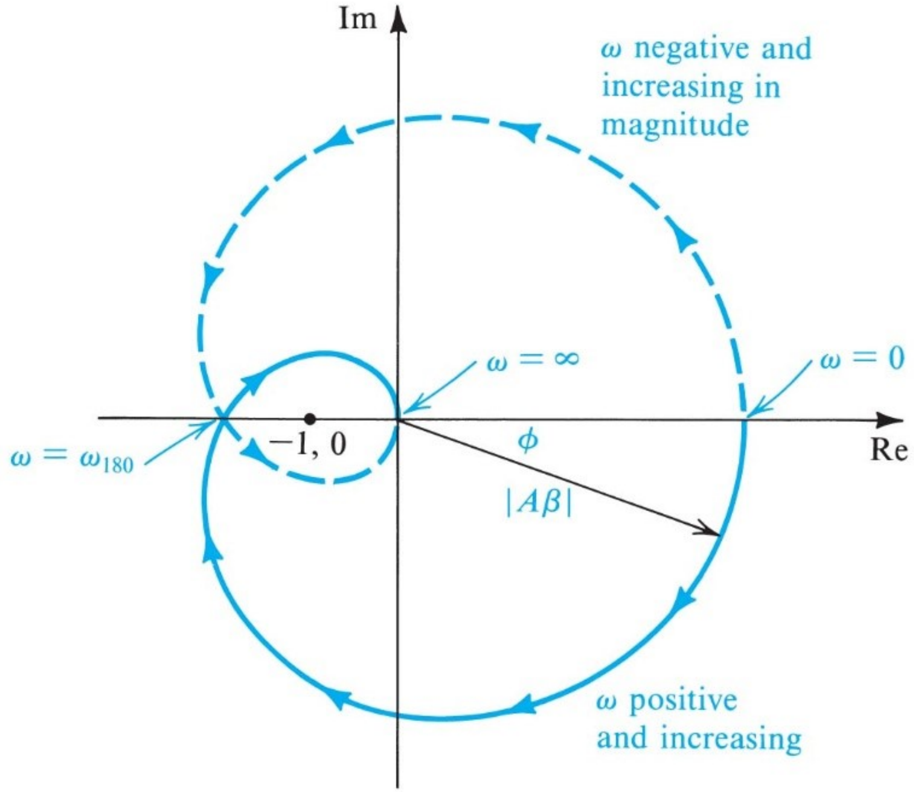
    $$A(j\omega)\beta(j\omega) = |A(j\omega)\beta(j\omega)| \exp[j\Phi(j\omega)]$$

  - Phase inversion frequency, ω_{180}

    $$\Phi(j\omega_{180}) = 180°$$

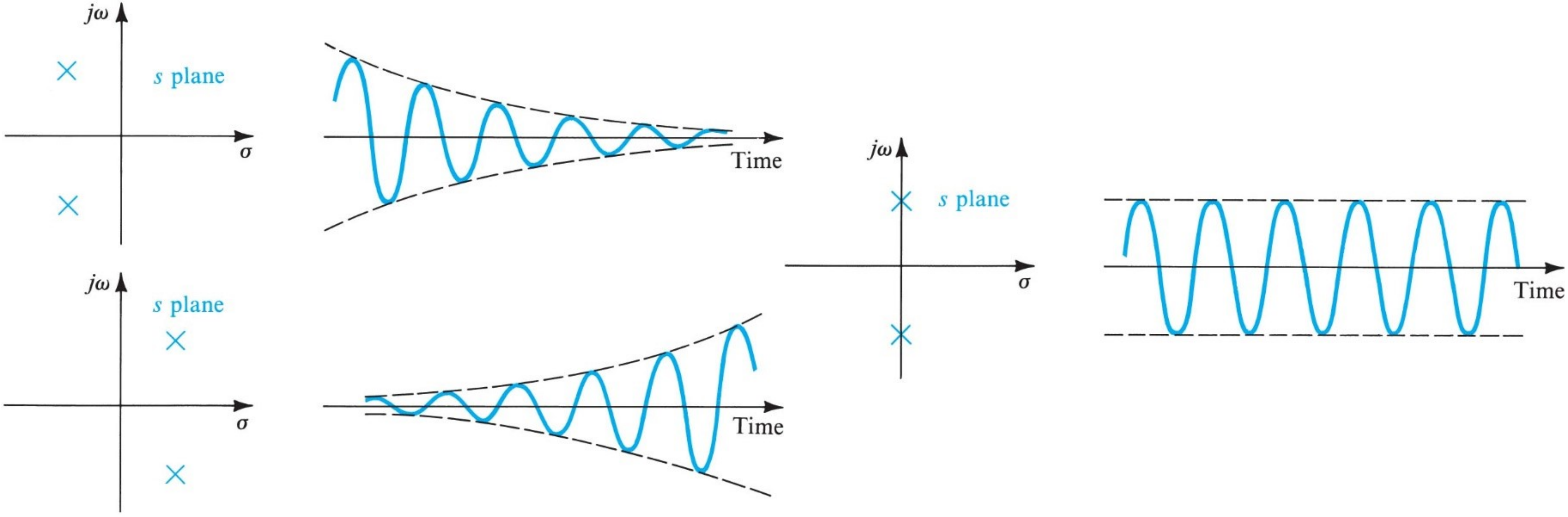
  - Feedback amplifier must be stable
    if NOT encircling point (-1,0)

    $$|A(j\omega)\beta(j\omega)|_{\omega=\omega_{180}} < 1$$



$$A_f(j\omega) = \frac{A(j\omega)}{1 + A(j\omega)\beta(j\omega)} = \frac{A(j\omega)}{D(j\omega)}$$

Stability and Pole Location



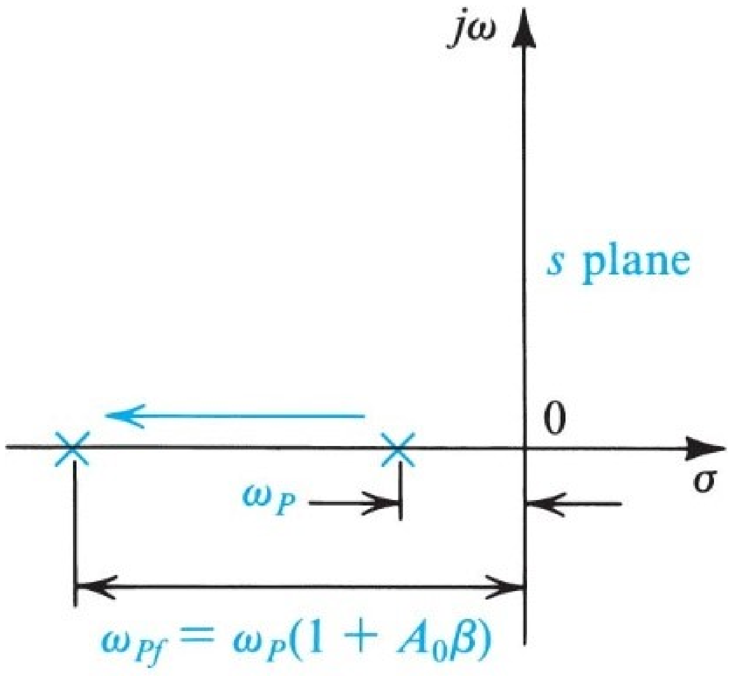
Poles must be kept in negative (left) half-plane.

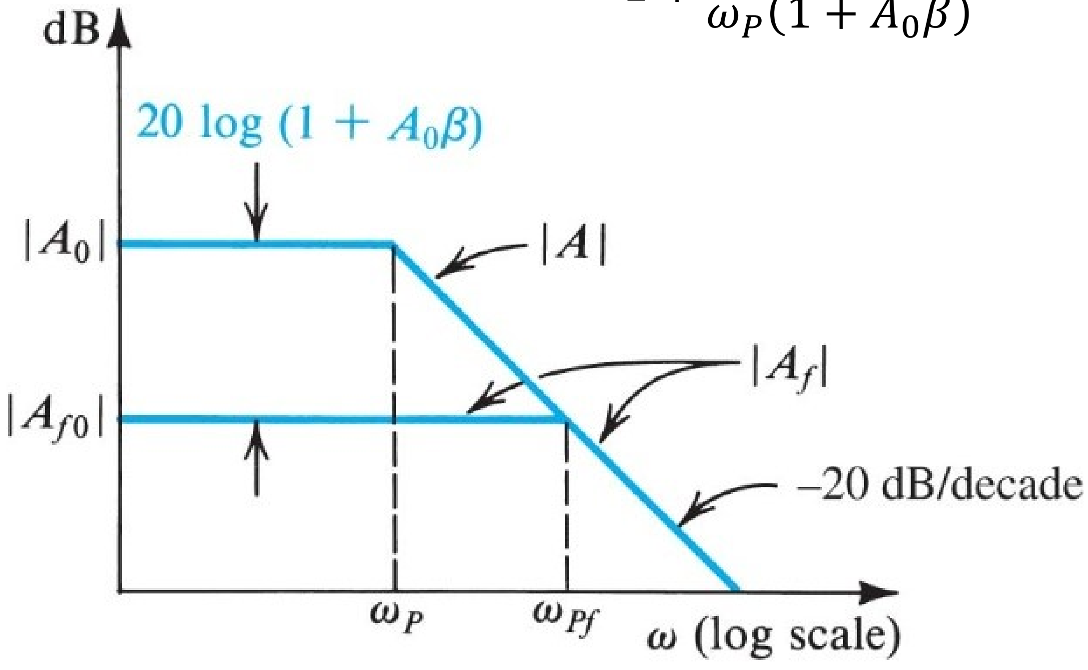
Single Pole Feedback Amplifier

- Feedback moves pole
- Root locus diagram visualises effects on poles
  - Feedback moves pole to higher frequency

$$A(j\omega) = A_0 \frac{1}{1 + \frac{j\omega}{\omega_P}}$$

$$A_f(j\omega) = \frac{A_0/(1 + A_0\beta)}{1 + \frac{j\omega}{\omega_P(1 + A_0\beta)}}$$

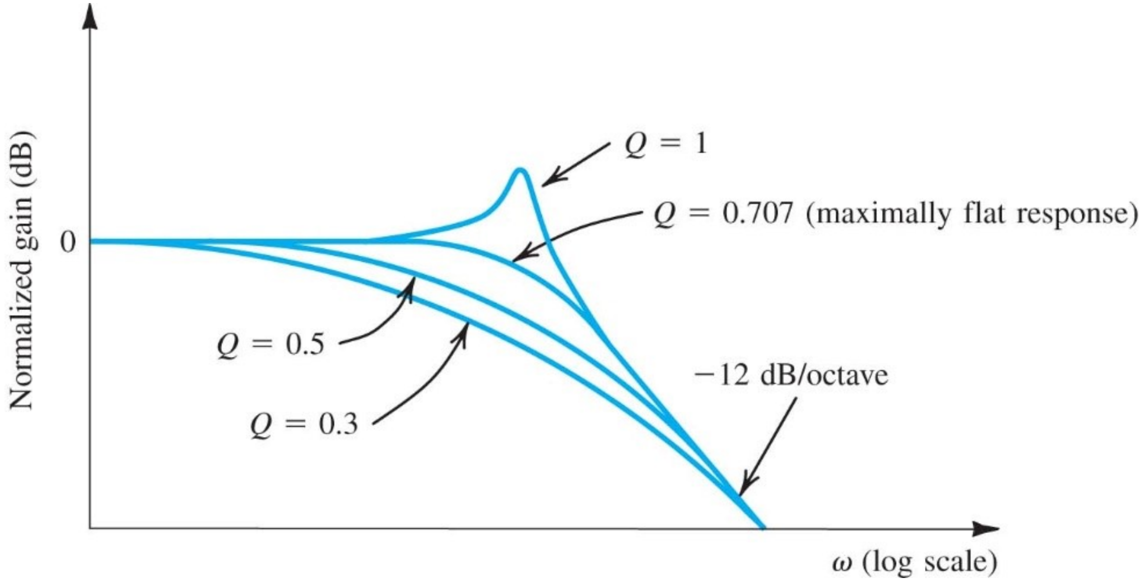


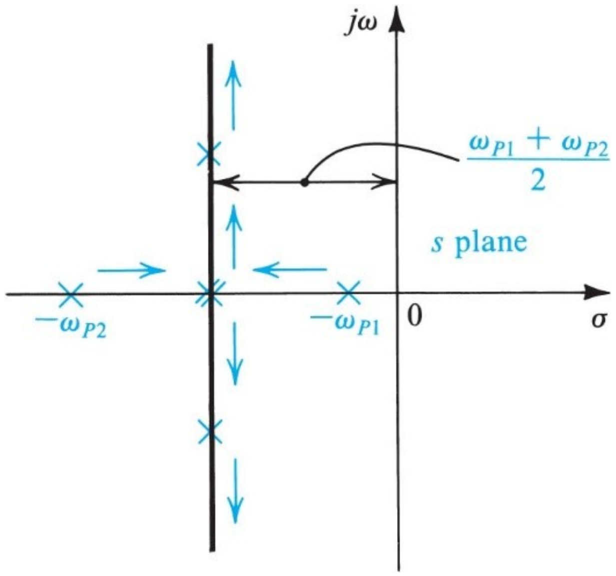


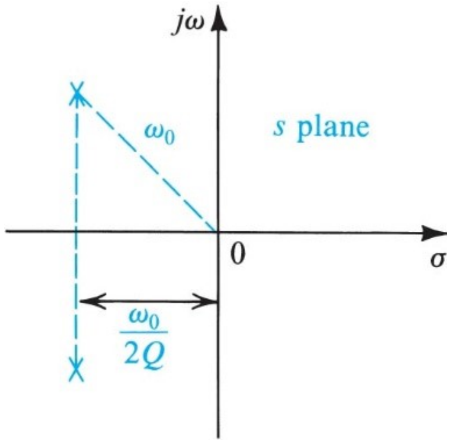
Bandwidth extension from another perspective.

Two Pole Feedback Amplifier

- Feedback merges poles into a resonance
- Root locus diagram visualises effects on (two) poles
  - Feedback first brings poles together, then poles split into conjugate pair

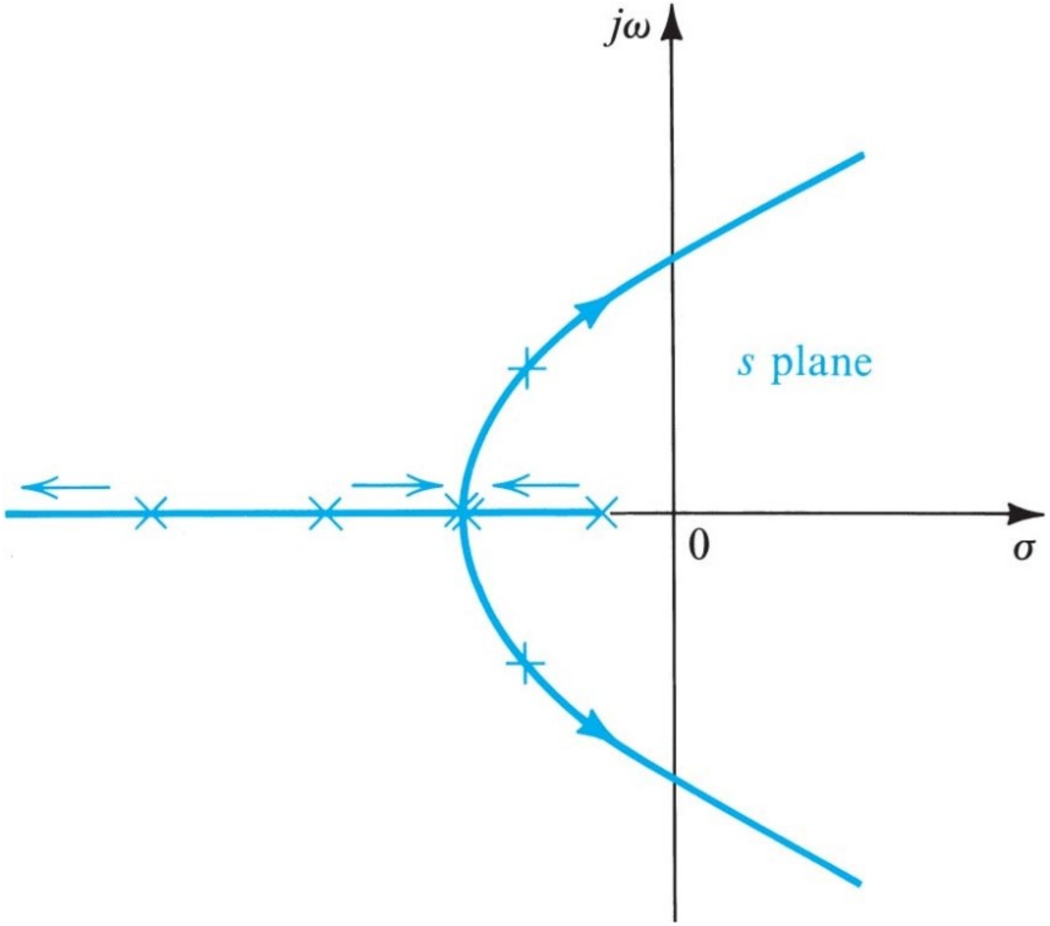






Three (or More) Pole Feedback Amplifier

- Feedback potentially creates instability
- Root locus diagram visualises effects on (three) poles
  - One pole moved to high frequency
  - Feedback brings low poles together, then poles split into conjugate pair
  - Conjugate pair approaches positive half-plane

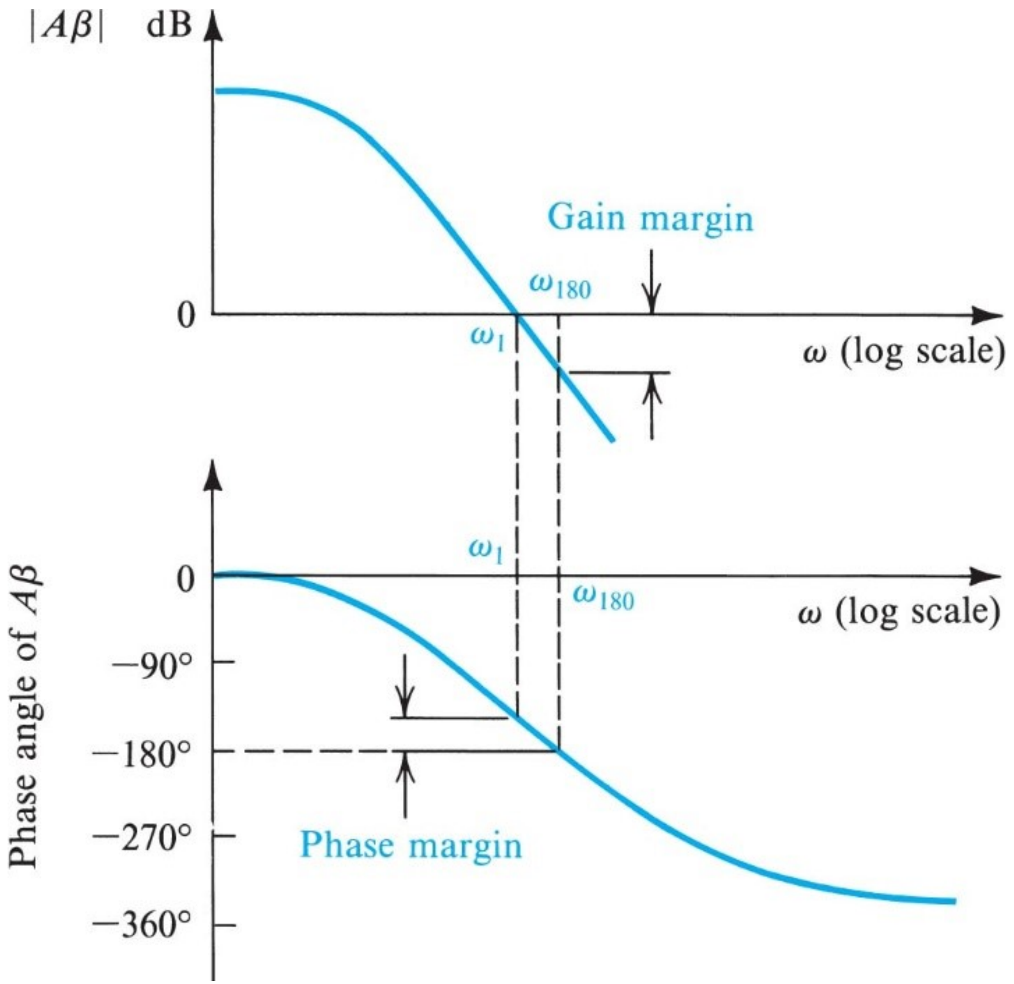


Gain and Phase Margin

- "Destructive" positive feedback
  - Loop gain with phase inversion
  - Risk of oscillation (not an amplifier)

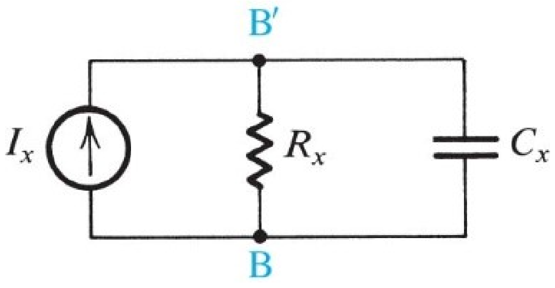
- Gain margin
  - Evaluated at phase inversion

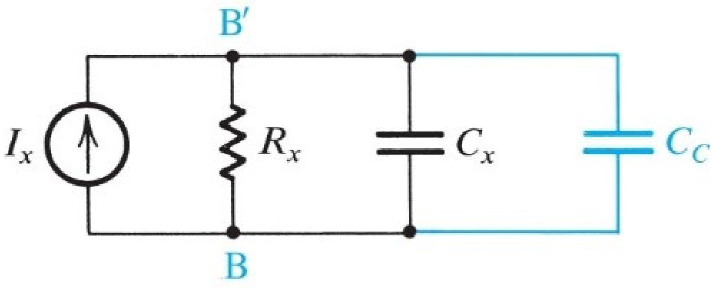
- Phase margin
  - Evaluated at unity gain

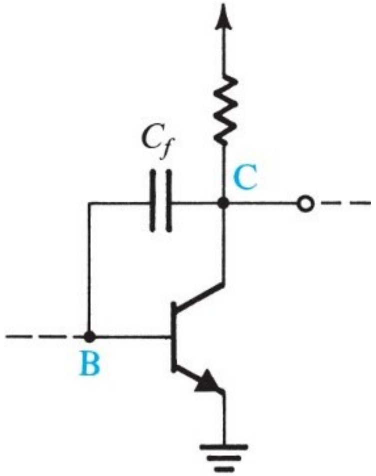


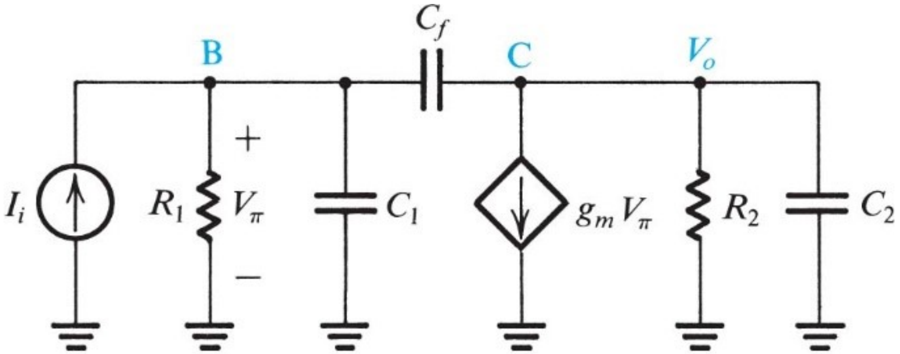
Frequency Compensation and Pole Splitting

- Compensate feedback pole movement
  - Poles split by added capacitance
  - Increased stability
- Frequency compensation
  - Compensate at in-/ output
- Miller compensation
  - Use the Miller effect to magnify effect of capacitor in feedback configuration









Force gain cutoff before phase inversion.