ELEC 301 - Frequency compensation

L28 - Nov 18

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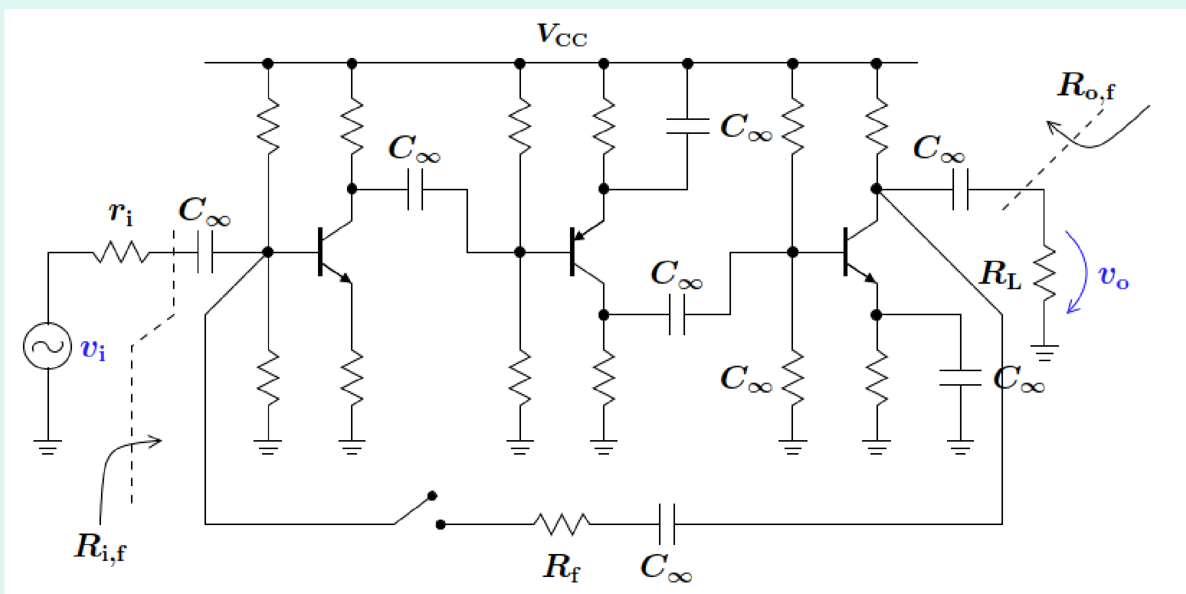


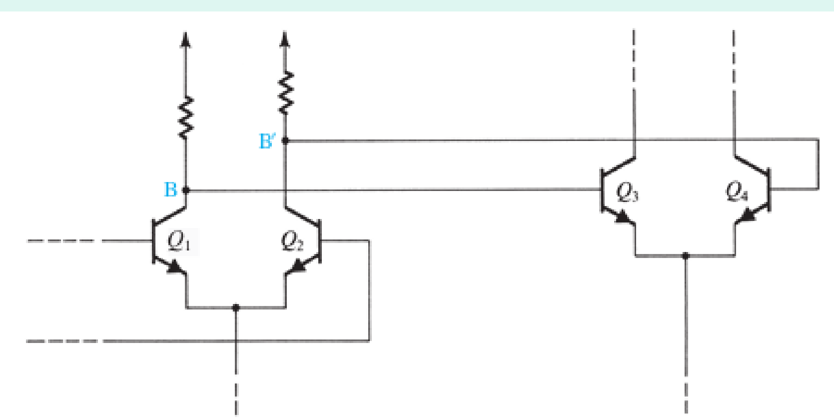
Last time

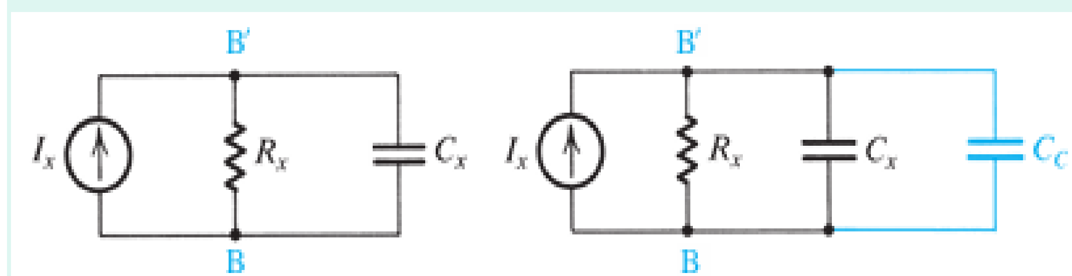
- Frequency compensation on Bode plots - addition of LF pole (**dominant pole compensation**), or shifting a pole
- The "**Closure rule of thumb**" - if at the intersection of $20\log|1/\beta(j\omega)|$ and $20\log|A(j\omega)|$, the difference of slopes (called the **rate of closure**) should not exceed 20db/dec, then the amplifier is stable
- PID (PD, PI) compensators - root locus design aspects

Circuit implementation

- Amplifier formed by cascaded gain blocks
- Assume f_{p1} given by the interface between the two differential stages
- Add compensating capacitor C_c
- Adding C_c might change the position of other poles => iterative approach
- C_c may be large (>100pF) => impractical in IC - Miller compensation as alternative (C_c in the feedback path)

$$\omega_{p1} = \frac{1}{R_x C_x} \xrightarrow{+C_C} \omega_{p1}' = \frac{1}{R_x\left(C_x + C_c\right)}$$





Frequency compensation techniques

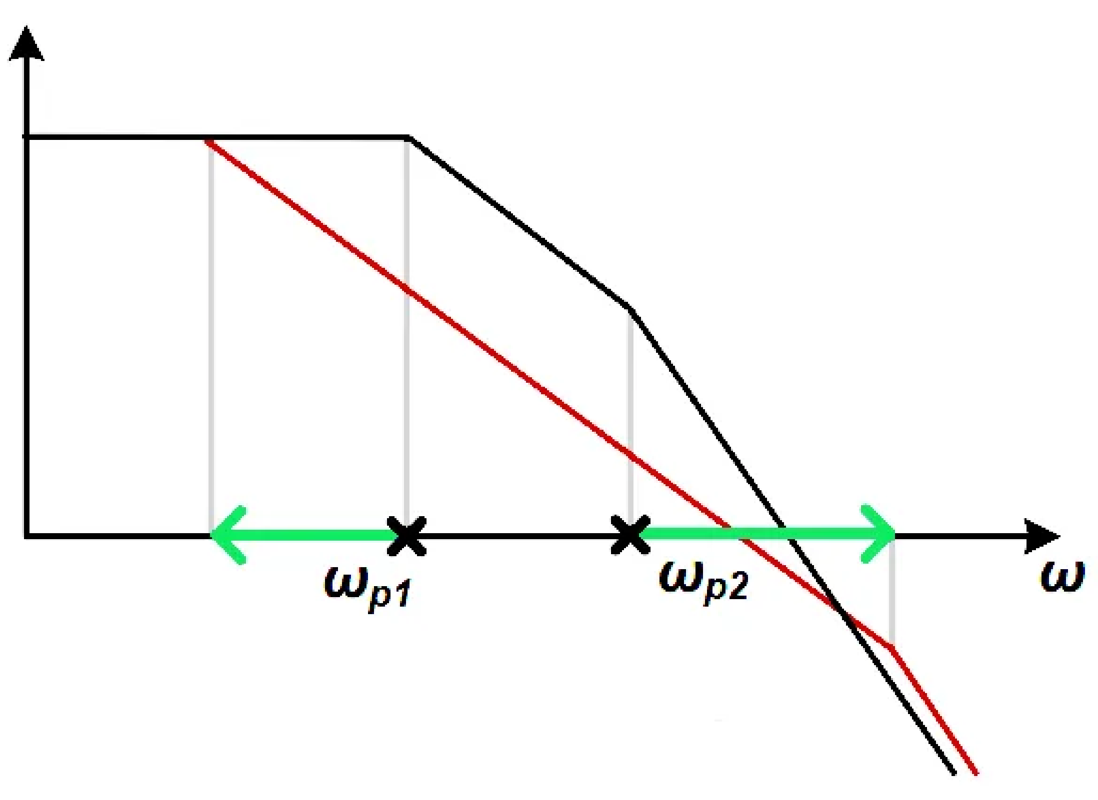
- Some common methods:
  - Phase-lag and phase-lead compensation - introduce additional phase lag or lead at low frequencies to stabilize the circuit
  - **Miller compensation** - add a feedback capacitor to reduce the closed-loop gain
  - Isolation resistor placement - resistors to dampen the output before reaching a capacitive load or set a zero in TF

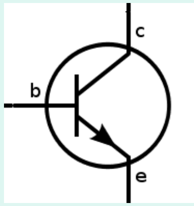
Miller compensation

- Technique: a capacitor introduced between the input and output of an amplifier
- Goal: moving the pole lowest in frequency (usually an input pole) to lower frequency => increased stability
- Use the gain of the amplifier to amplify the effect of the introduced capacitance through negative feedback
- Usually accompanied by **pole splitting** phenomenon - the subdominant pole (usually an output pole) moves to a higher frequency

Pole splitting

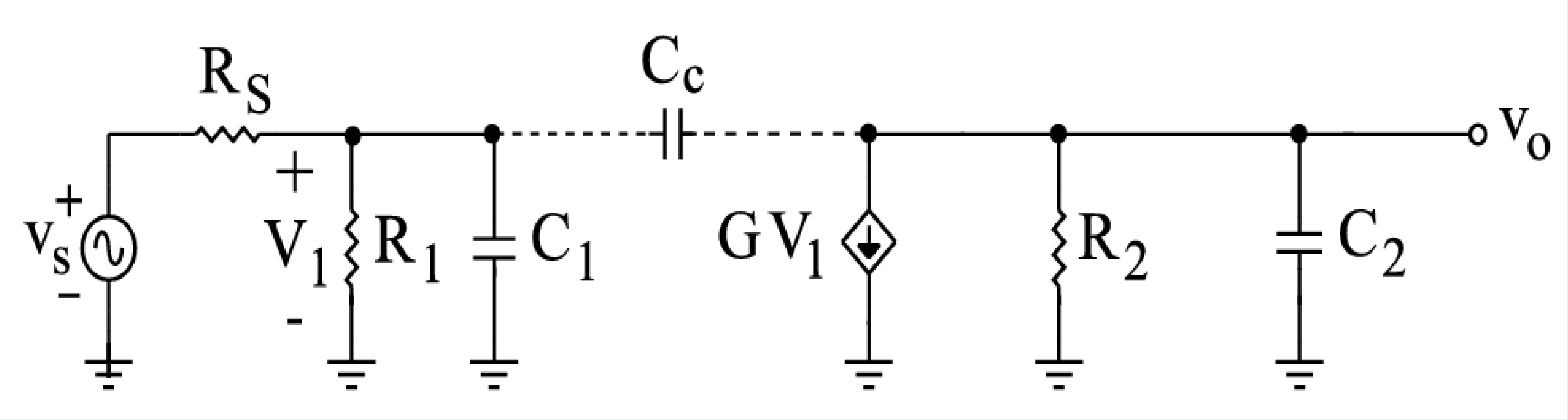
- The dominant pole moves to a lower frequency, while the higher pole is shifted to a higher frequency => improves phase margin, the system behaves as a single-pole circuit





Miller compensation

- The inclusion of a small feedback capacitor (single transistor CE amplifier case) has reduced the frequency of the dominant HF pole by a relatively large amount via the Miller effect
- Small signal model of a **transconductance amplifier**:

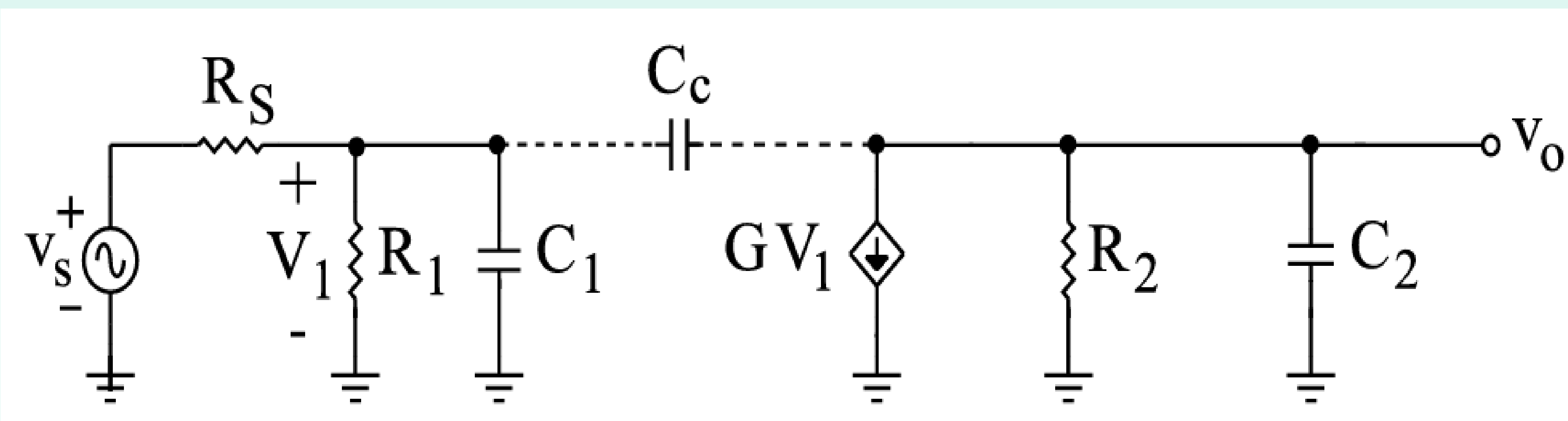


- To further lower the location of the dominant HF pole - introduce a large **compensating capacitor** C_c, that will be magnified by the Miller effect

Miller compensation (2)

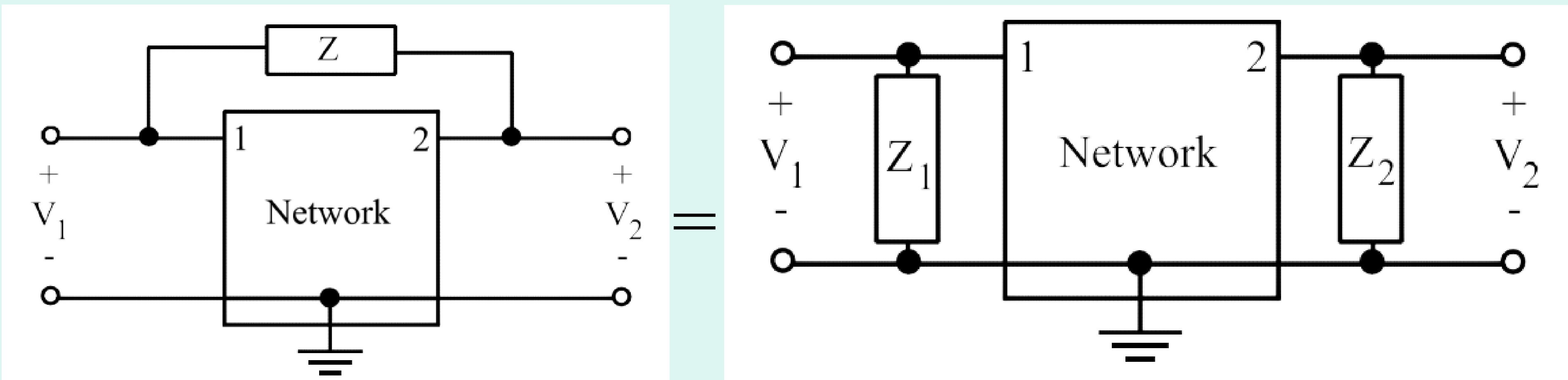
- Assume the dominant pole, prior to the application of the compensating capacitor, is: $$\omega_{p1} = \frac{1}{R_s \parallel R_1 C_1}$$

- The location of the subdominant pole: $$\omega_{p2} = \frac{1}{R_2 C_2}$$



Miller's theorem - decoupling feedback

- Replace the Z feedback with two impedances Z_1 and Z_2



$$V_2 = kV_1$$

$$V_2 = kV_1$$

$$Z_1 = Z\frac{1}{1-k} \qquad Z_2 = Z\frac{k}{k-1}$$

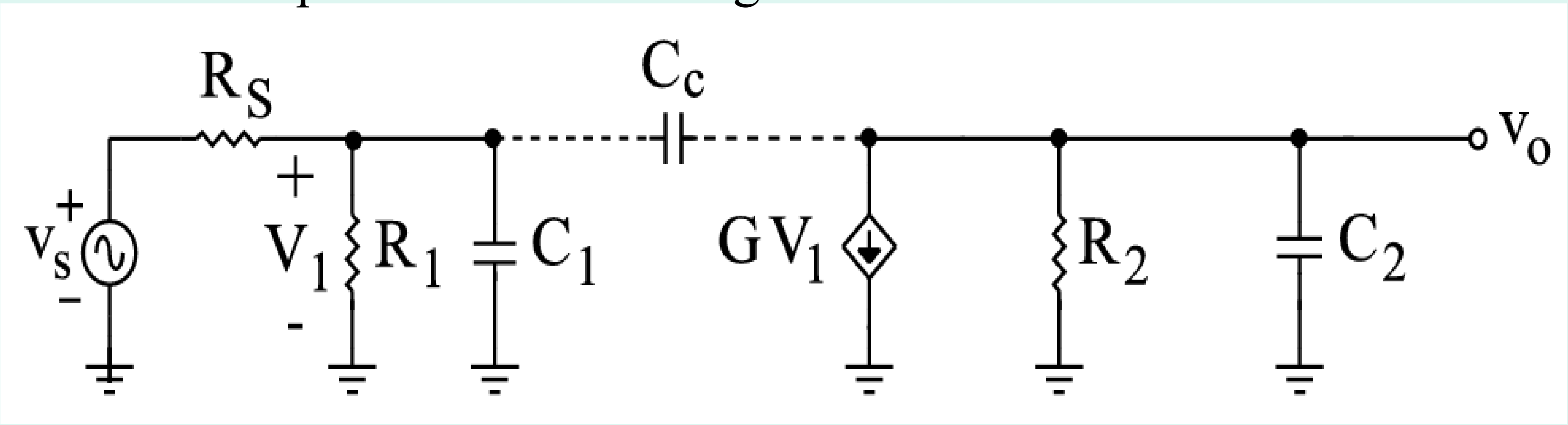
Miller compensation (3)

- When C_c is introduced into the circuits, the poles change
- The dominant HF pole:
- The subdominant HF pole: (Cc as SC far beyond ω_{p1}')

$$\omega_{p1}^{'} \approx \frac{1}{R_s \parallel R_1 \left(C_1 + C_c \left(1 + GR_2 \right) \right)}$$

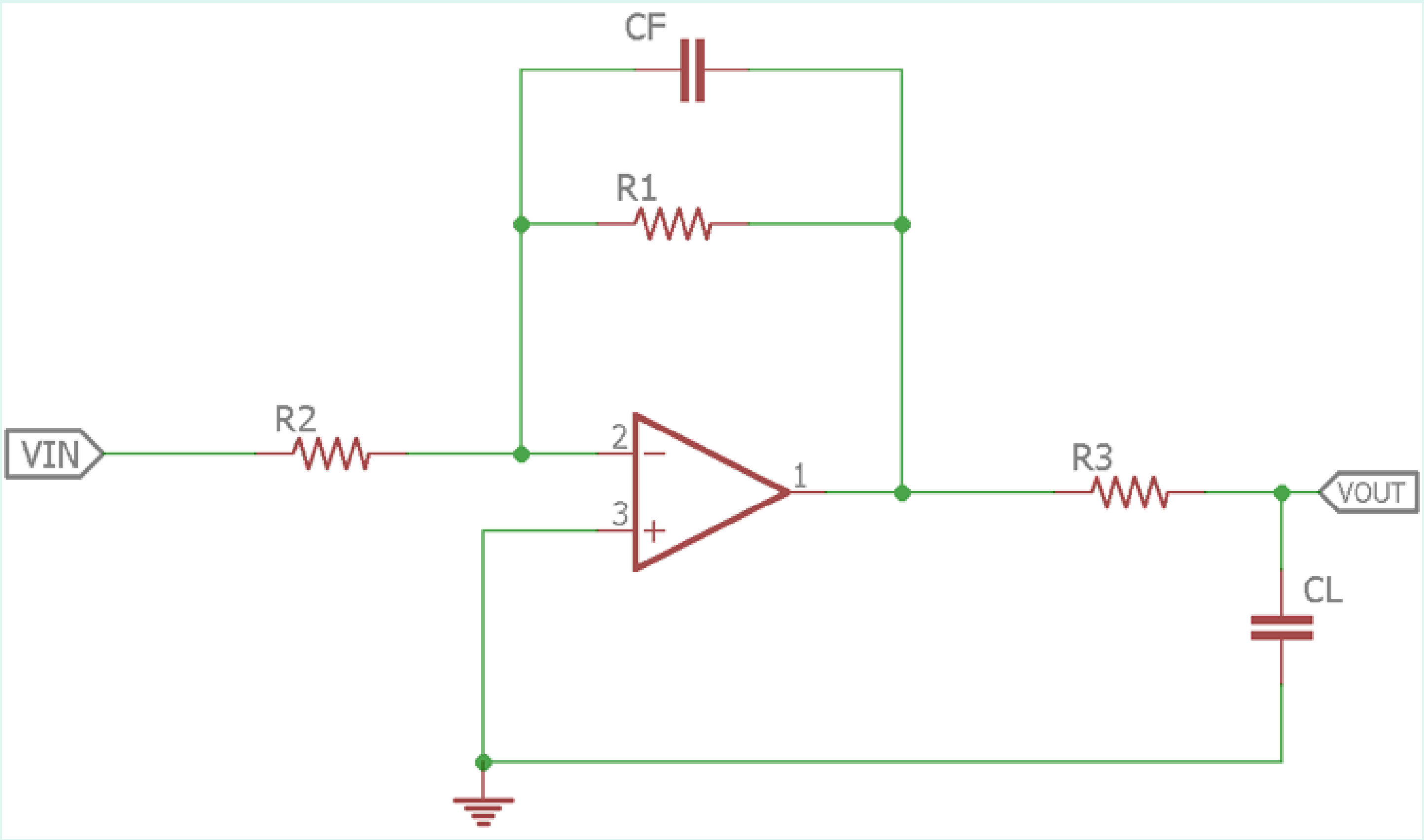
$$\omega_{p2}^{'} \approx \frac{1}{\left(C_1 + C_2 \right) \left(\frac{1}{G} + R_2 \parallel R_s \parallel R_1 \right)} \approx \frac{G}{C_1 + C_2}$$

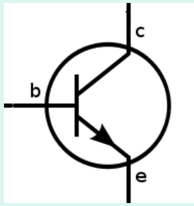
- pole-splitting effect: dominant pole shifted far to the left, subdominant pole shifted to the right



Miller compensation circuit in op-amps

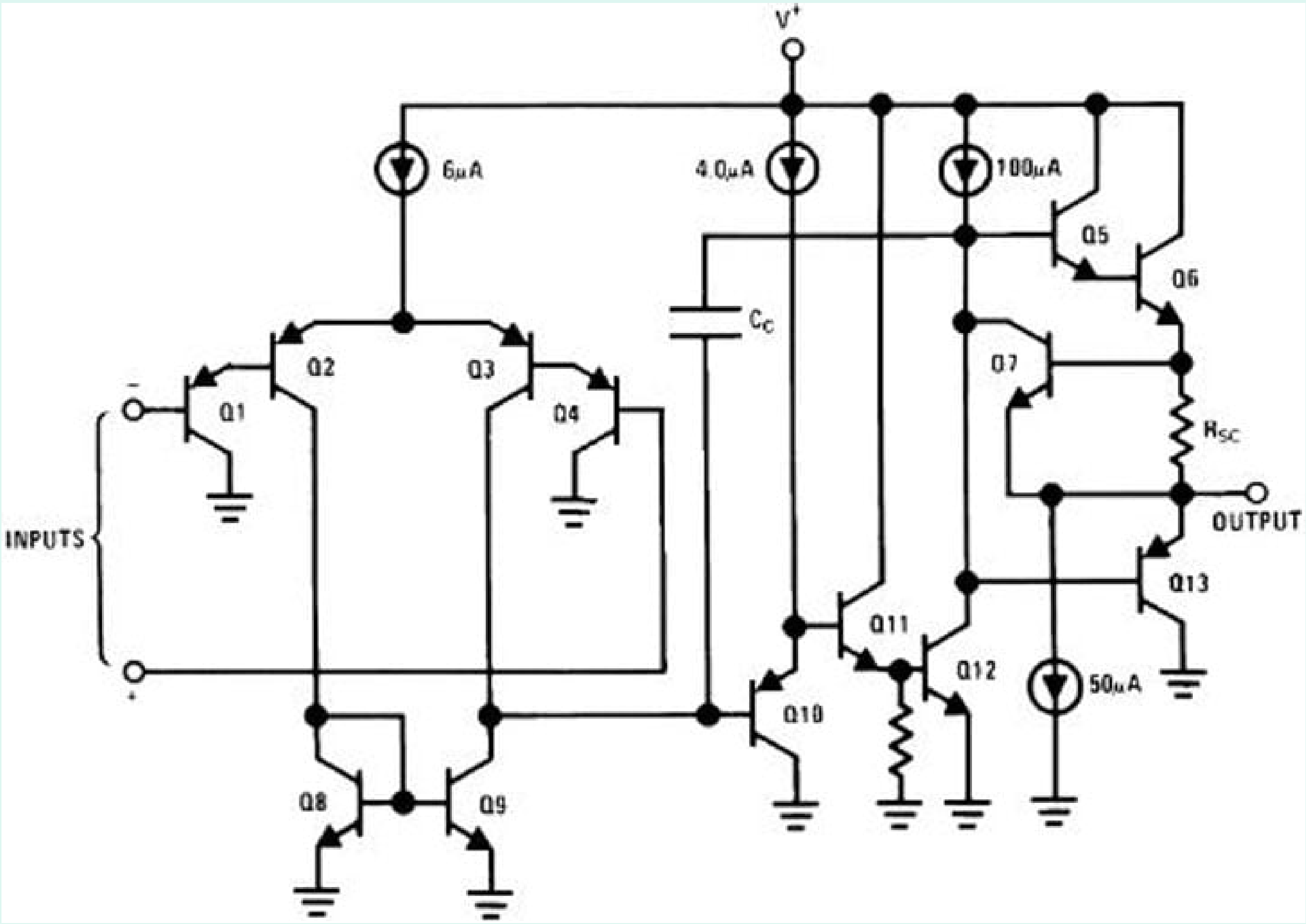
- C_F plays the role of the Miller capacitor

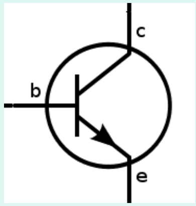




Internal compensation in op-amps

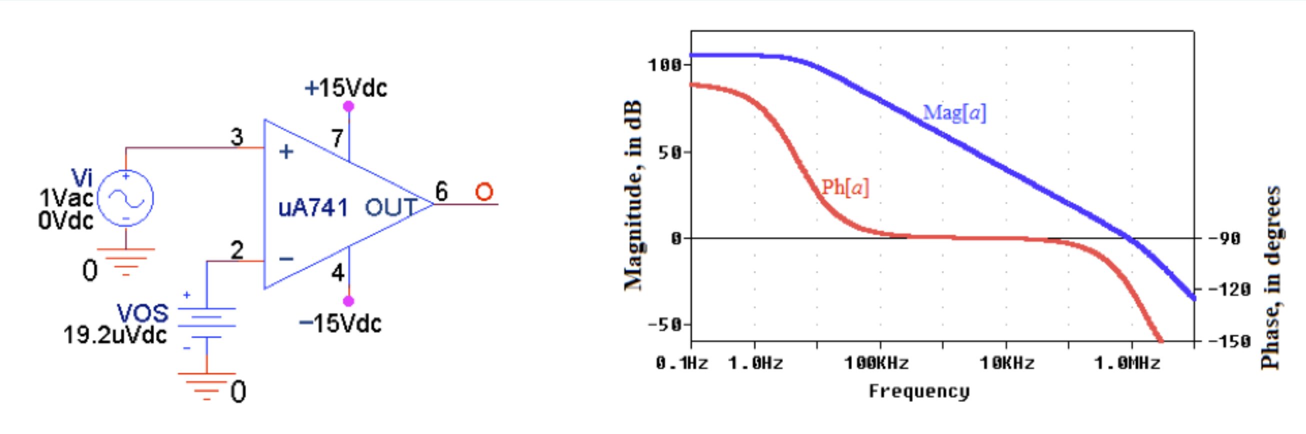
- A small feedback capacitor connected inside the op-amp IC
- Exm: LM358 opamp:





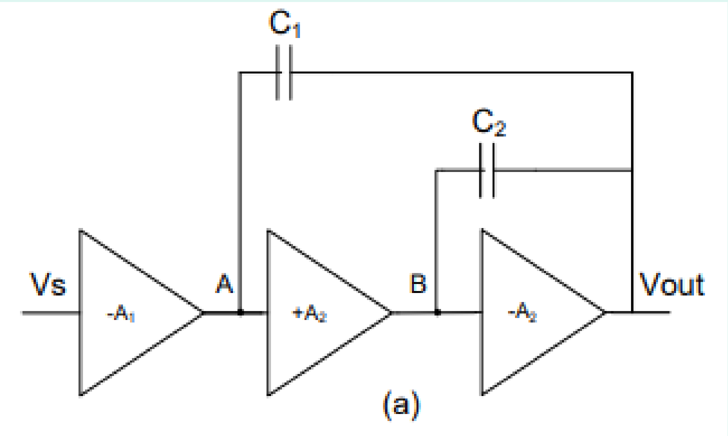
Bits of history

- First IC op-amp that incorporated full compensation: μA741 (Fairchild Semiconductor, 1968) - used a 30pF on-chip capacitor for Miller compensation
- Before μA741, all IC op-amps had to be compensated externally by the user (e.g. LM301, National Semiconductor, offered single-pole compensation, double-pole compensation, and feedforward compensation)

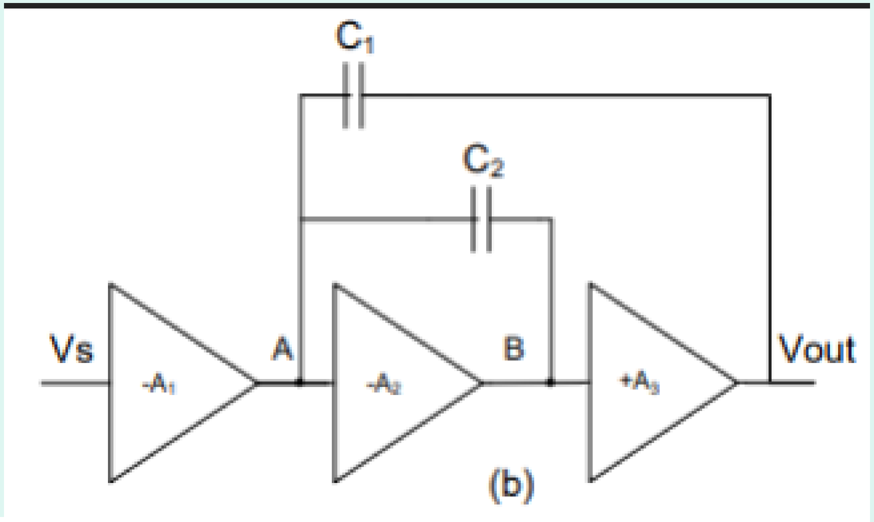


More advanced Miller compensation techniques

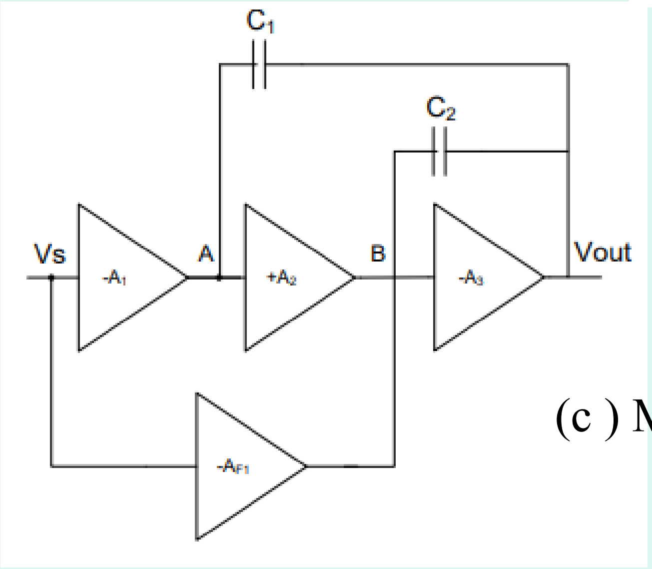
- More involved alternatives:



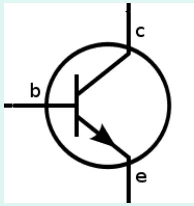
(a) Nested Miller compensation



(b) Reversed nested Miller compensation

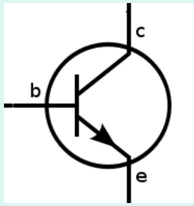


(c) Multipath nested Miller compensation



Passive filters

- **Passive filters** - we analyzed RC filters (LP, HP and BP filters) - how multiple single-pole filters could be combined to form higher order filters
- Most commonly used: low-pass (LP), high-pass (HP), band-pass (BP) filters
- Other types:
  - Notch (band-reject) filters: filter out localized frequency ranges
  - all-pass filters (allow all frequencies to pass but shape the phase)
- Theory of (ideal) LC passive filter synthesis: Cauer, Foster

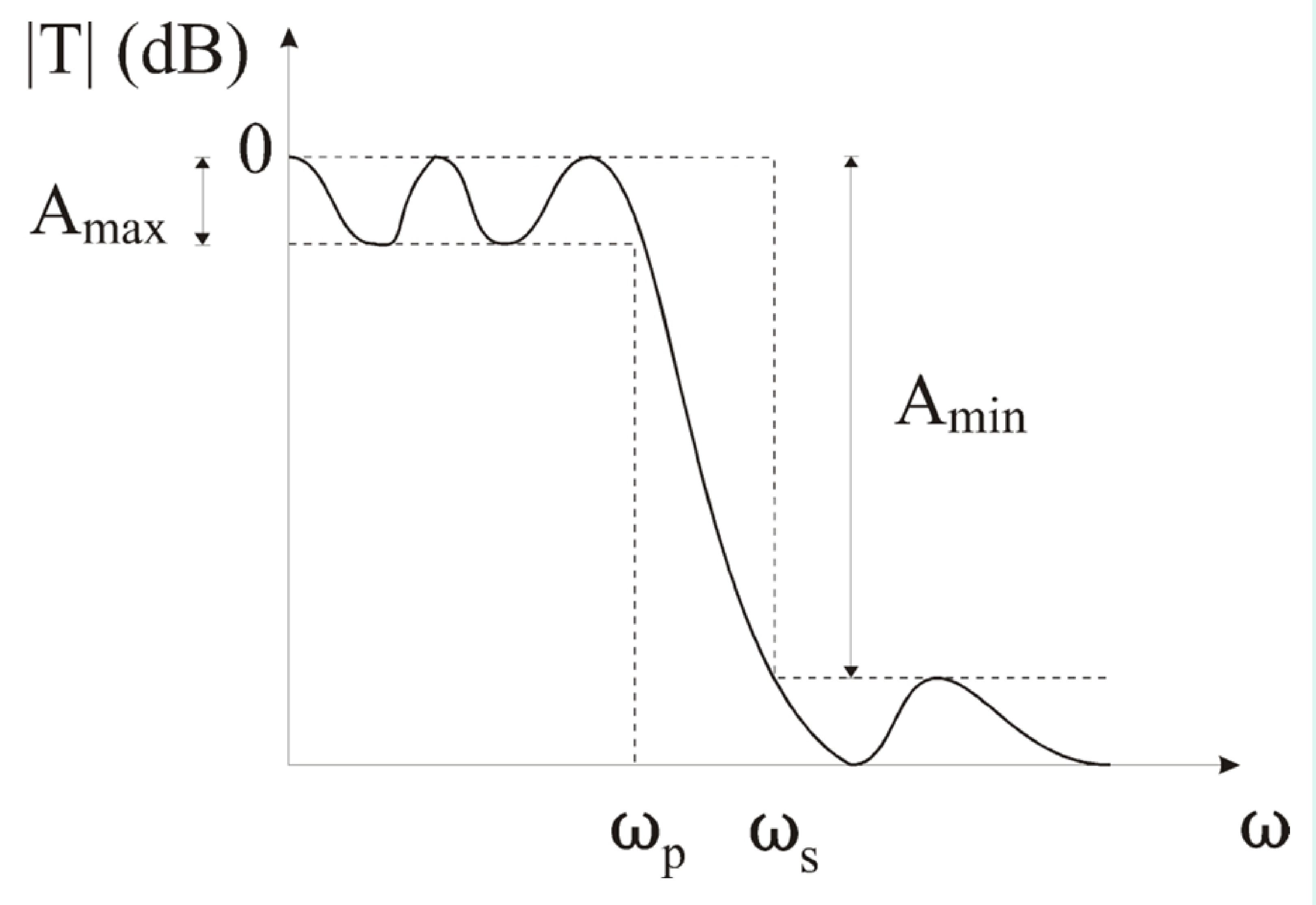


Active vs passive filters

- Passive filters may be impractical:
  - Large/bulky components for LF applications
  - Large inductors cannot be fabricated monolithically
- **Active filters** - we will study Butterworth and Chebyshev filters (no Ls, only op-amps +Rs+Cs)

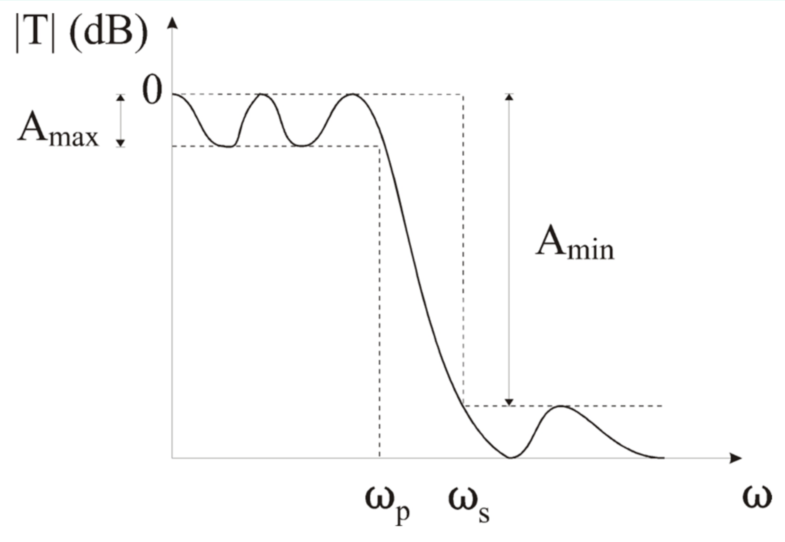
Filters terminology

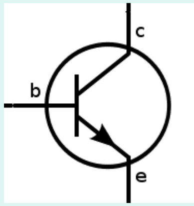
- A generic LP filter



Filter specification and terminology

- Standard properties of a filter - the example of LP filter
- Pass-band = range of frequencies allowed to pass ($<\omega_p$)
- Stop-band = frequency range that is attenuated ($>\omega_s$)
- Transition-band ($\omega_p<\omega<\omega_s$)
- Selectivity factor = ω_p/ω_s
- Maximum ripple level tolerated in the pass-band (A_{max}[dB])
- A_{min}[dB]=min amount of attenuation between the stop-band and the transmission peak in the pass-band

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