# EE 435
# Lecture 13

Cascaded Amplifiers

-- Two-Stage Op Amp Design

**Review from Last Time**

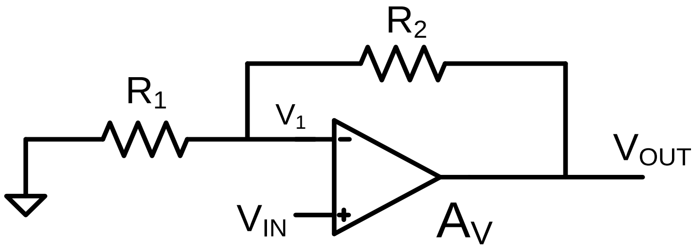
# Routh-Hurwitz Stability Criteria:

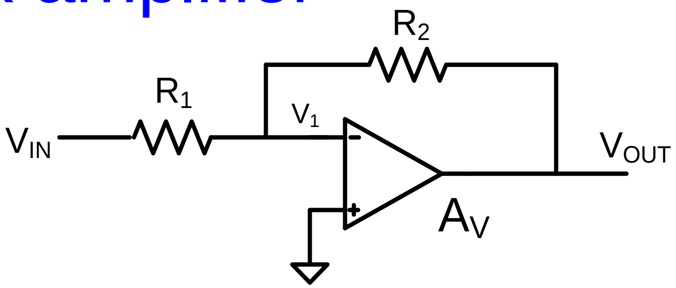
A third-order polynomial $s^3+a_2s^2+a_1s+a_0$ has all poles in the LHP iff all coefficients are positive and $a_1a_2>a_0$

- Very useful in amplifier and filter design
- Can easily determine if poles in LHP without finding poles
- But tells little about how far in LHP poles may be
- RH exists for higher-order polynomials as well

**Review from Last Time**

# Similar implications on amplifier even if not a basic voltage feedback amplifier





$$A_{VF}=\frac{V_{OUT}}{V_{IN}}=\frac{1+\frac{R_2}{R_1}}{1+\frac{1}{A_V}\left(1+\frac{R_2}{R_1}\right)}$$

$$A_{VF}=\frac{V_{OUT}}{V_{IN}}=\frac{A_V}{1+A_V\left(\frac{R_1}{R_2+R_1}\right)}$$

$$A_{VF}=\frac{V_{OUT}}{V_{IN}}=\frac{-\frac{R_2}{R_1}}{1+\frac{1}{A_V}\left(1+\frac{R_2}{R_1}\right)}$$

$$A_{VF}=\frac{V_{OUT}}{V_{IN}}=\frac{A_V\left(\frac{-R_2}{R_1}\right)}{1+A_V\left(\frac{R_1}{R_2+R_1}\right)}$$

## These circuits have

- same β
- same dead network
- same characteristic polynomial
- same poles
- different zeros

$$\beta=\frac{R_1}{R_2+R_1}$$

$D(s)=1+A\beta$ (expressed as polynomial)

Review from Last Time

# Cascaded Amplifier Issues

- Single-stage amplifiers

  -- widely used in industry, little or no concern about compensation

- Two amplifier cascades $4\beta A_{0TOT} > k > 2\beta A_{0TOT}$

  -- widely used in industry but compensation is essential !

- Three amplifier cascades - for ideally identical stages $8 > \beta A_0^3$

  -- seldom used in industry !

- Four or more amplifier cascades - problems even larger than for three stages

  -- seldom used in industry !

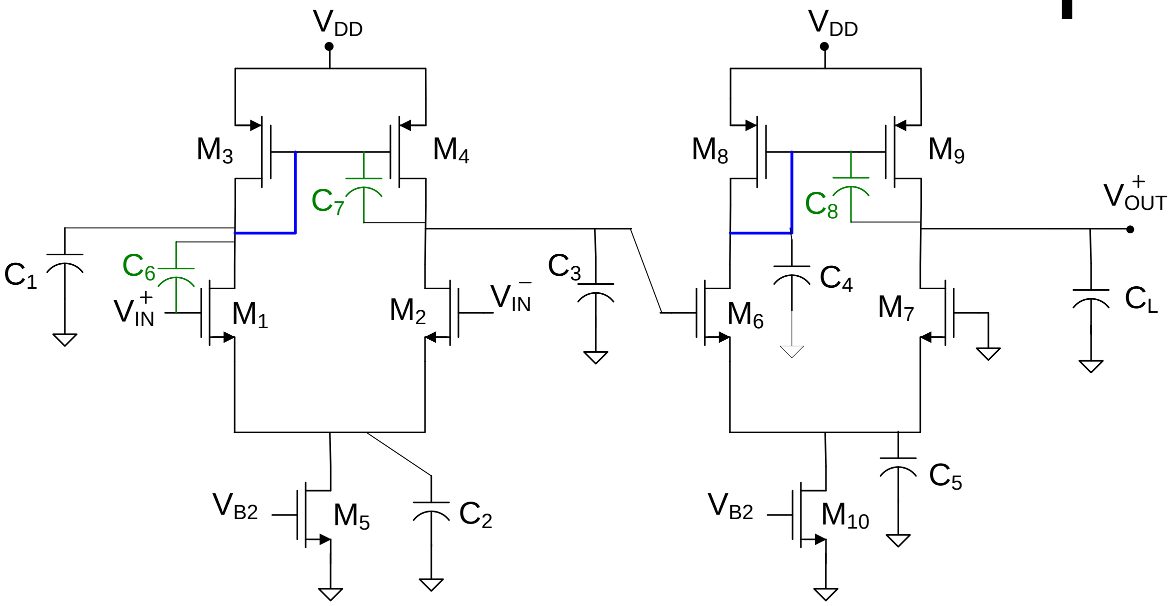
Note: Some amplifiers that are termed single-stage amplifiers in many books and papers are actually two-stage amplifiers and some require modest compensation. Some that are termed two-stage amplifiers are actually three-stage amplifiers. These invariable have a very small gain on the first stage and a very large bandwidth. The nomenclature on this summary refers to the number of stages that have reasonably large gain.

- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op  Amps
- ➡ Two-Stage Op Amp
  - Compensation
  - Breaking the Loop
- Other Basic Gain Enhancement Approaches
- Other Issues in Amplifier Design
- Summary Remarks

# Two-stage op amp design

It is essential to know the poles of the op amp since there are some rather strict requirements about the relative location of the poles

# Poles and Zeros of Amplifiers



Cascaded Amplifier showing <u>some</u> of the capacitors

- There are a large number of parasitic capacitors in an amplifier (appprox 5 for each transistor)
- Many will appear in parallel but the number of equivalent capacitors can still be large
- Order of transfer function is equal to the number of non-degenerate energy storage elements
- Obtaining the transfer function of a high-order network is a lot of work !
- Essentially every node in an amplifier has a capacitor to ground and these often dominate the frequency response of the amplifier (but not always)

# Pole approximation methods

1. Consider all shunt capacitors

2. Decompose these into two sets, those that create low frequency poles and those that create high frequency poles (large capacitors create low frequency poles and small capacitors create high frequency poles)
   $\{C_{L1}, \ldots C_{Lk}\}$ and $\{C_{H1}, \ldots C_{Hm}\}$

3. To find the k low frequency poles, replace all independent voltage sources with ss shorts and all independent current sources with ss opens, all high-frequency capacitors with ss open circuits and, one at a time, select $C_{Lh}$ and determine the impedance facing it, say $R_{Lh}$ if all other low-frequency capacitors are replaced with ss open circuits. Then an approximation for the pole corresponding to $C_{Lh}$ is

$$p_{Lh}=-1/(R_{Lh}C_{Lh})$$

4. To find the m high-frequency poles, replace all independent voltage sources with ss shorts and all independent current sources with ss opens, replace all low-frequency capacitors with ss short circuits and, one at a time, select $C_{Hh}$ and determine the impedance facing it, say $R_{Hh}$ if all other high-frequency capacitors are replaced with ss open circuits. Then the approximation for the pole corresponding to $C_{Hh}$ is

$$p_{Hh}=-1/(R_{Hh}C_{Hh})$$

# Pole approximation methods

These are just pole approximations but are often quite good

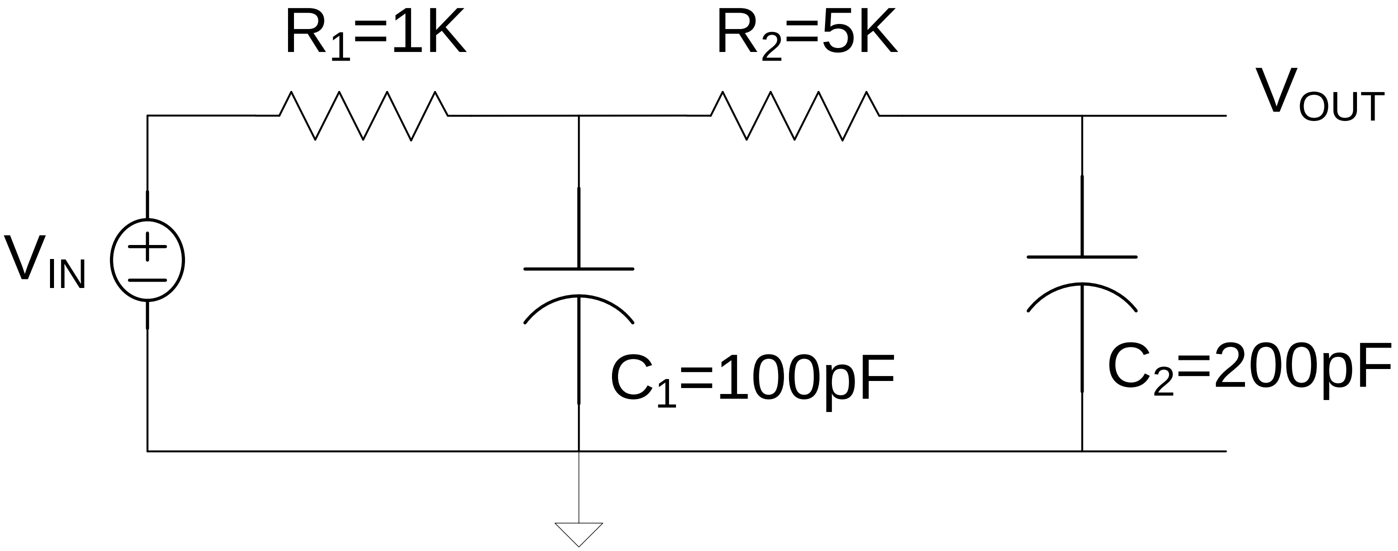
Provides closed-form analytical expressions for poles in terms of components of the network that can be managed during design

Provides considerable insight into what is affecting the frequency response of the amplifier

Pole approximation methods give no information about zero locations

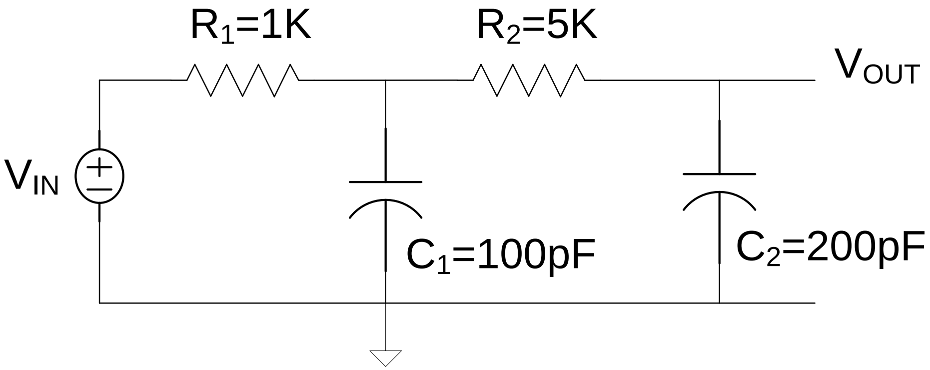
Many authors refer to the “pole on a node” and this notation comes from the pole approximation method discussed on previous slide

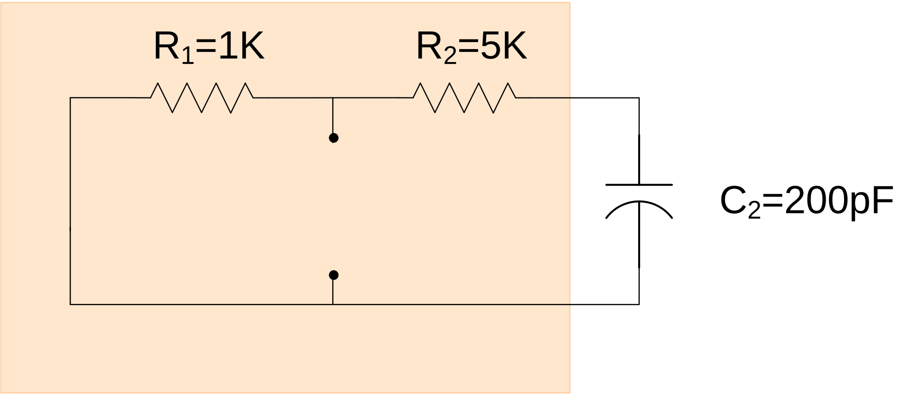
# Example: Obtain the approximations to the poles of the following circuit



Since $C_1$ and $C_2$ and small, have two high-frequency poles

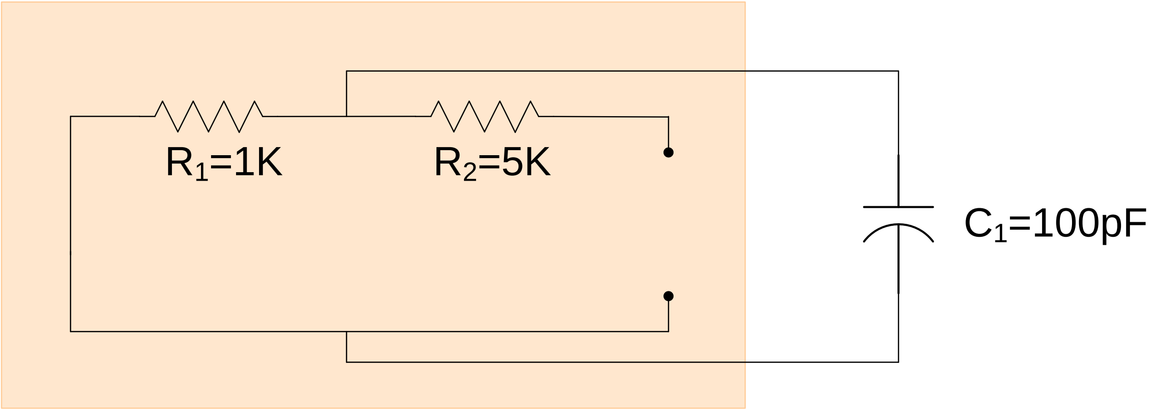
$\{C_1, C_2\}$





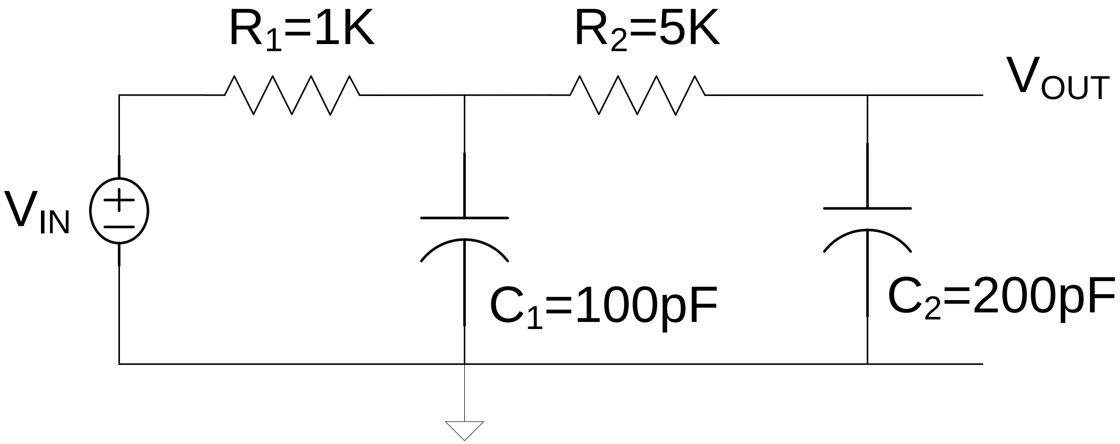
$$p_{H2} = -\frac{1}{C_2\left(R_1+R_2\right)}$$

$$p_{H2} = -833\text{Krad/sec}$$



$$p_{H1} = -\frac{1}{C_1\ R_1}$$

$$p_{H1} = -10\text{M rad/sec}$$



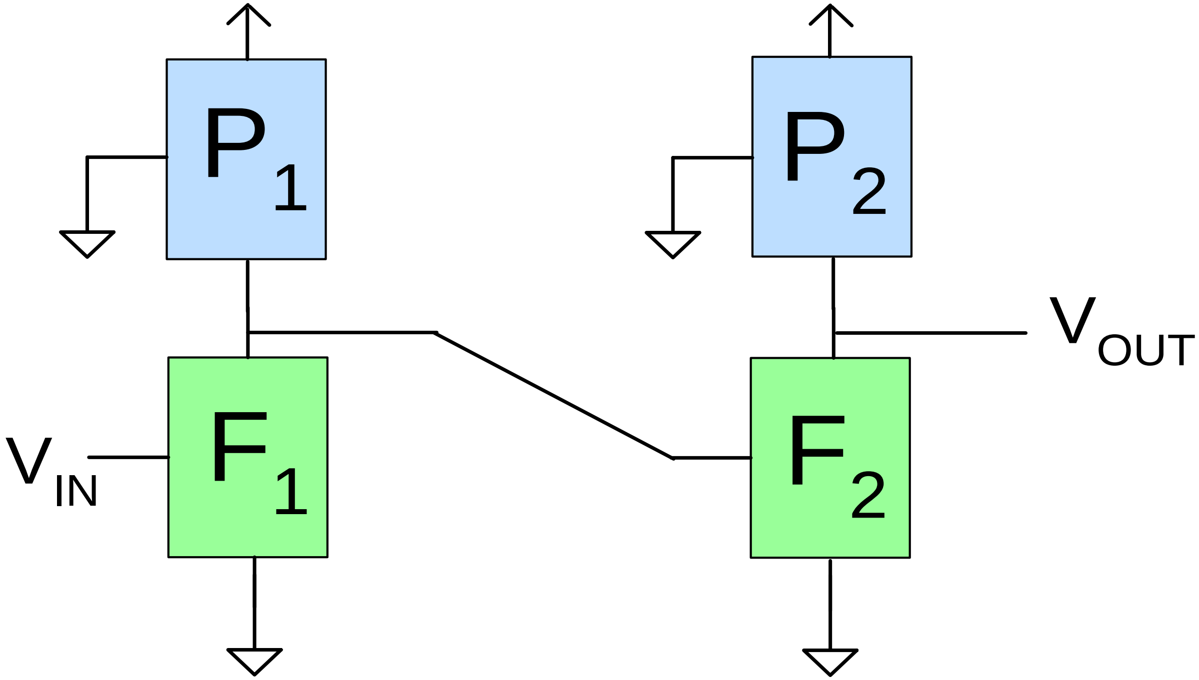
In this case, an exact solution is possible

$$T(s)=\frac{\frac{1}{R_1R_2C_1C_2}}{s^2+\left[\frac{1}{R_1C_1}+\frac{1}{R_2C_2}+\frac{1}{R_2C_1}\right]s+\frac{1}{R_1R_2C_1C_2}}$$

$p_{H1}$ = -12.2M rad/sec (18% error)

$p_{H2}$ = - 821Krad/sec (1.4% error)

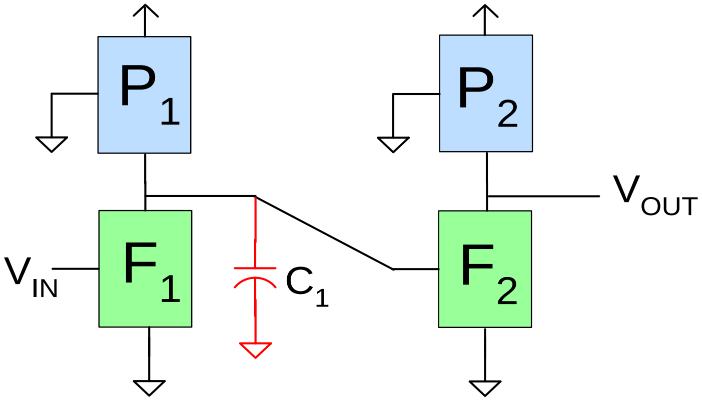
# Basic Two-Stage Cascade



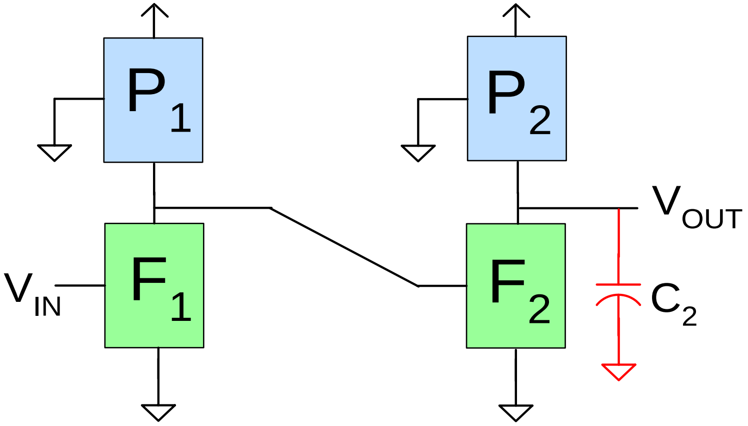
Can be extended to fully differential on first or second stage

- Simple Concept
- Must decide what to use for the two quarter circuits

# Compensation of Basic Two-Stage Cascade



Internally Compensated



Output Compensated

- Modest variants of the compensation principle are often used
- Internally compensated creates the dominant pole on the internal node
- Output compensated created the dominant pole on the external node

Everything else is just details !!

# Two-stage Architectural Choices

Common Source

Cascode

Regulated Cascode

Folded Cascode

**Folded Regulated Cascode**

Current Mirror

**Differential Input**

**Single Ended Input**

Tail Voltage

Tail Current

Stage 1

Common Source

Cascode

Regulated Cascode

Folded Cascode

**Folded Regulated Cascode**

Current Mirror

**Differential Input**

**Single Ended Input**

Tail Voltage

Tail Current

Stage 2

Output Compensated

Internally Compensated

# Two-stage Architectural Choices

Common Source | Cascode | Regulated Cascode | Folded Cascode | **Folded Regulated Cascode** | Current Mirror — 6

**Differential Input** | **Single Ended Input** — 2

Tail Voltage | Tail Current — 2

Stage 1

Common Source | Cascode | Regulated Cascode | Folded Cascode | **Folded Regulated Cascode** | Current Mirror — 6

**Differential Input** | **Single Ended Input** — 2

Tail Voltage | Tail Current — 2

Stage 2

Output Compensated | Internally Compensated — 2

Plus n-channel or p-channel on each stage — 4

2304 Choices !!!

# Two-stage Architectural Choices

Common Source

Cascode

Regulated Cascode

Folded Cascode

**Folded Regulated Cascode**

Current Mirror

**Differential Input**

**Single Ended Input**

Tail Voltage

Tail Current

Stage 1

Common Source

Cascode

Regulated Cascode

Folded Cascode

**Folded Regulated Cascode**

Current Mirror

**Differential Input**

**Single Ended Input**

Tail Voltage

Tail Current

Stage 2

Output Compensated

Internally Compensated

Plus n-channel or p-channel on each stage

Which of these 2304 choices can be used to build a good op amp?

All of them !!

# Two-stage Architectural Choices

There are actually a few additional variants so the number of choices is larger

Basic analysis of all is about the same and can be obtained from the quarter circuit of each stage

A very small number of these are actually used

Some rules can be established that provide guidance as to which structure may be most useful in a given application

# Two-stage Architectural Choices

## Guidelines for Architectural Choices

Tail current source usually used in first stage, tail voltage source in second stage

Large gain usually used in first stage, smaller gain in second stage

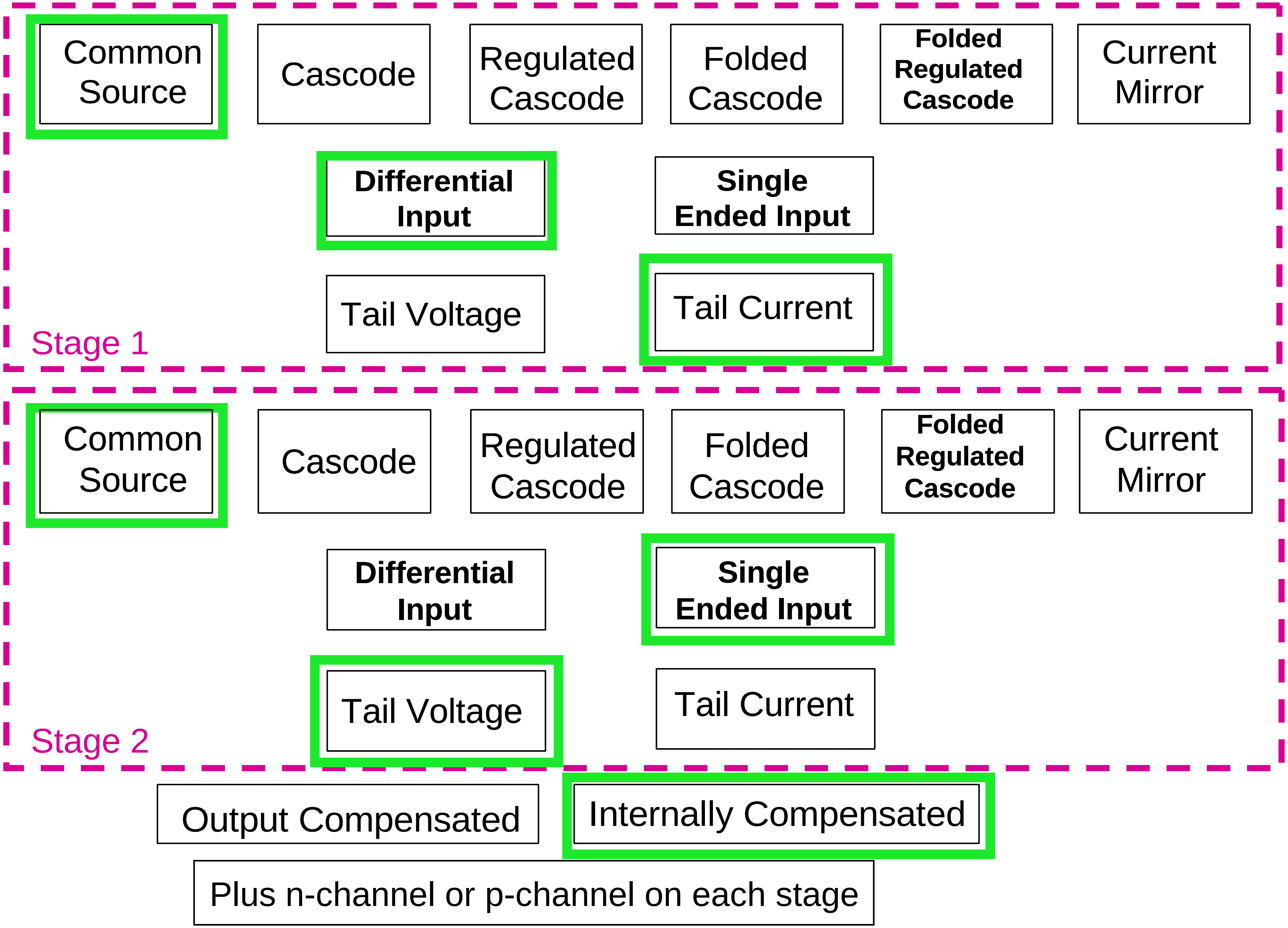
First and second stage usually use quarter circuits of opposite types (n-p or p-n)

Input common mode input range of concern on first stage but output swing of first stage of reduced concern. Output range on second stage of concern.

CMRR of first stage of concern but not of second stage

Noise on first stage of concern but not of much concern on second stage

# Two-stage Architectural Choices



Common Source

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**Folded Regulated Cascode**

Current Mirror

**Differential Input**

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Tail Voltage

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Stage 1

Common Source

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Current Mirror

**Differential Input**

**Single Ended Input**

Tail Voltage

Tail Current

Stage 2

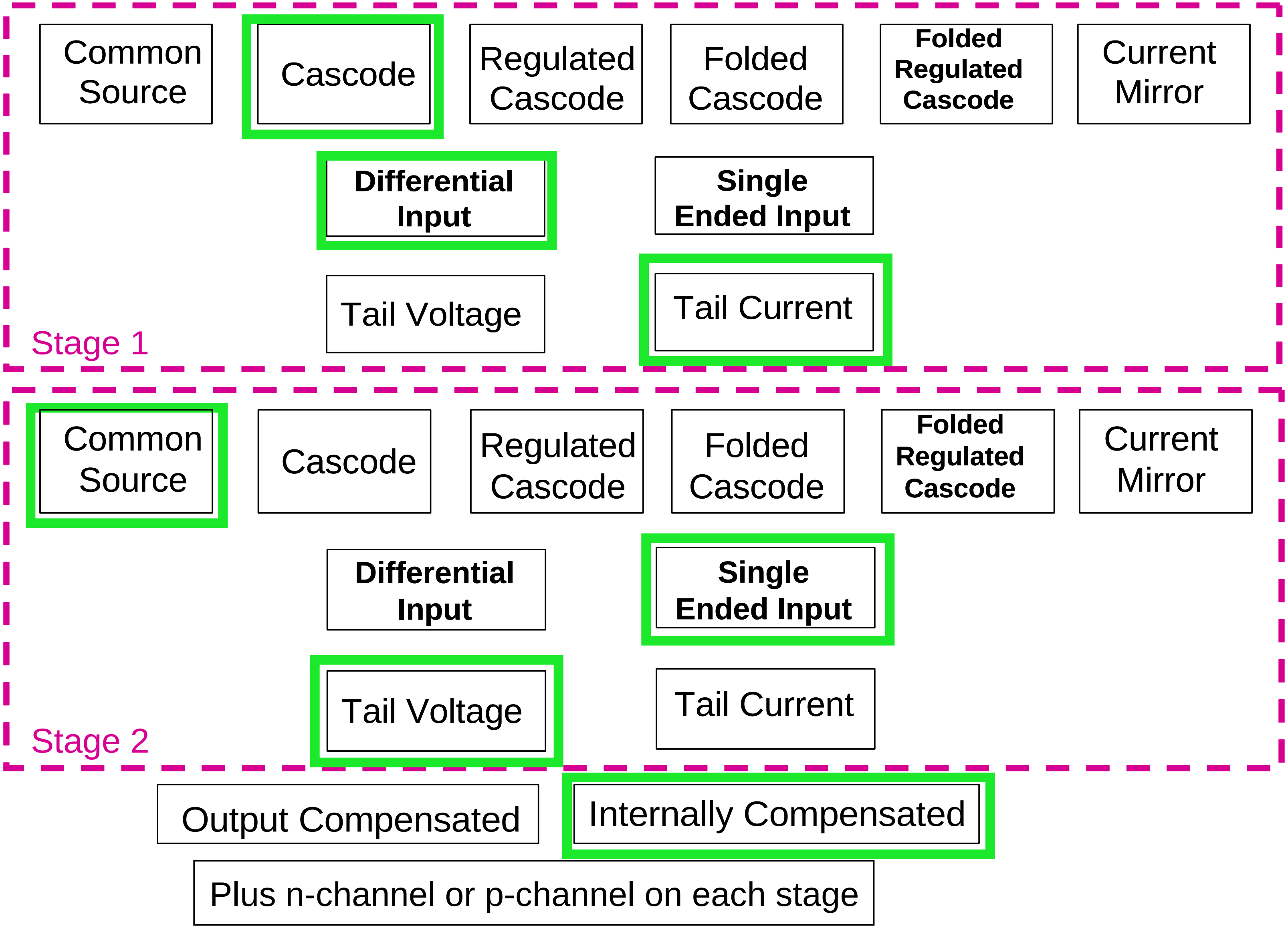
Output Compensated

Internally Compensated

Plus n-channel or p-channel on each stage

**Basic Two-Stage Op Amp**

# Two-stage Architectural Choices



Common Source
[✓ Cascode]
Regulated Cascode
Folded Cascode
**Folded Regulated Cascode**
Current Mirror

[✓ **Differential Input**]
**Single Ended Input**

Tail Voltage
[✓ Tail Current]

Stage 1

[✓ Common Source]
Cascode
Regulated Cascode
Folded Cascode
**Folded Regulated Cascode**
Current Mirror

**Differential Input**
[✓ **Single Ended Input**]

[✓ Tail Voltage]
Tail Current

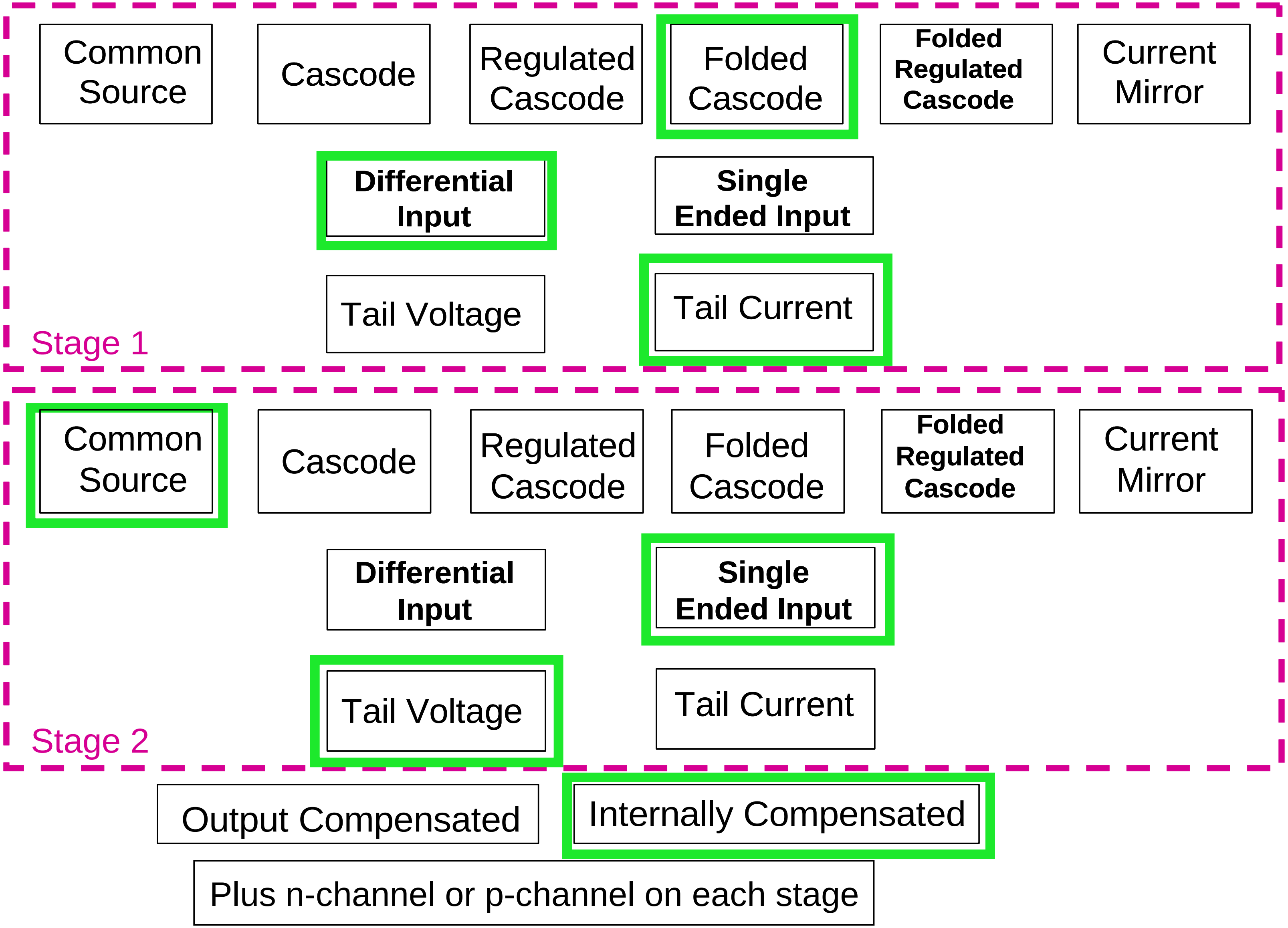
Stage 2

Output Compensated
[✓ Internally Compensated]

Plus n-channel or p-channel on each stage

**Cascode-Cascade Two-Stage Op Amp**

# Two-stage Architectural Choices



Common Source

Cascode

Regulated Cascode

Folded Cascode

**Folded Regulated Cascode**

Current Mirror

**Differential Input**

**Single Ended Input**

Tail Voltage

Tail Current

Stage 1

Common Source

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Regulated Cascode

Folded Cascode

**Folded Regulated Cascode**

Current Mirror

**Differential Input**

**Single Ended Input**

Tail Voltage

Tail Current

Stage 2

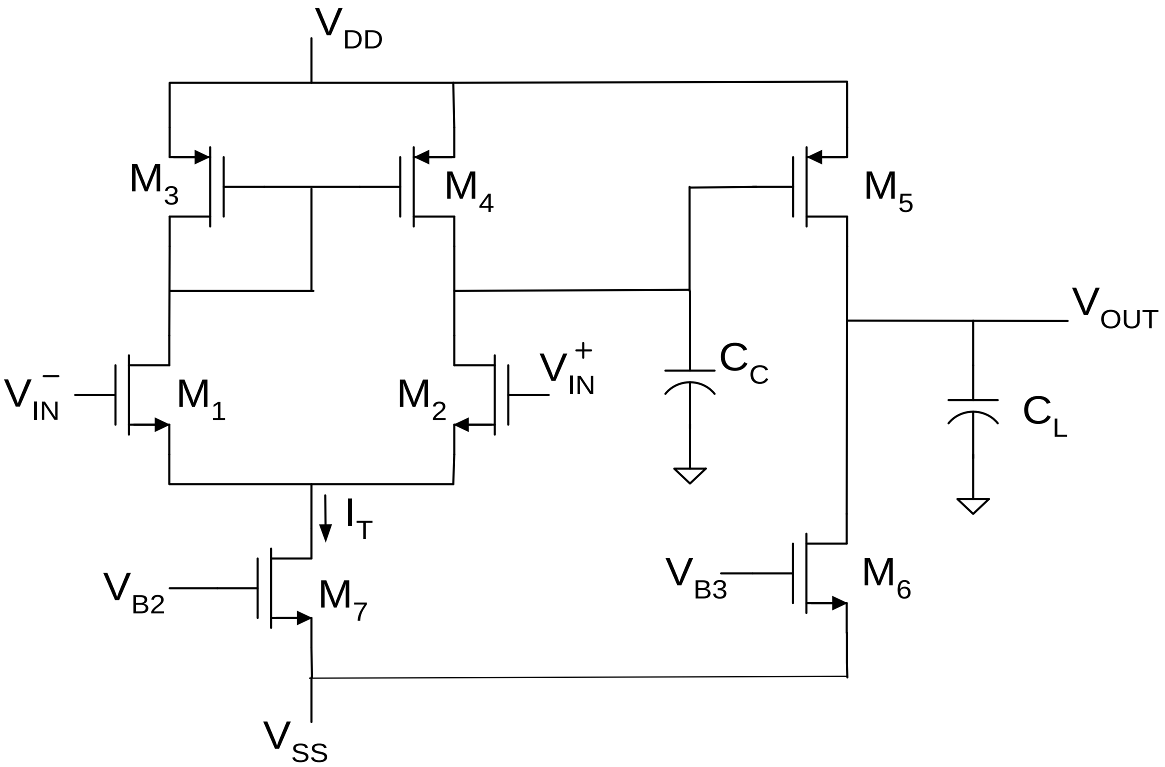
Output Compensated

Internally Compensated

Plus n-channel or p-channel on each stage

## Folded Cascode-Cascade Two-Stage Op Amp

# Basic Two-Stage Op Amp



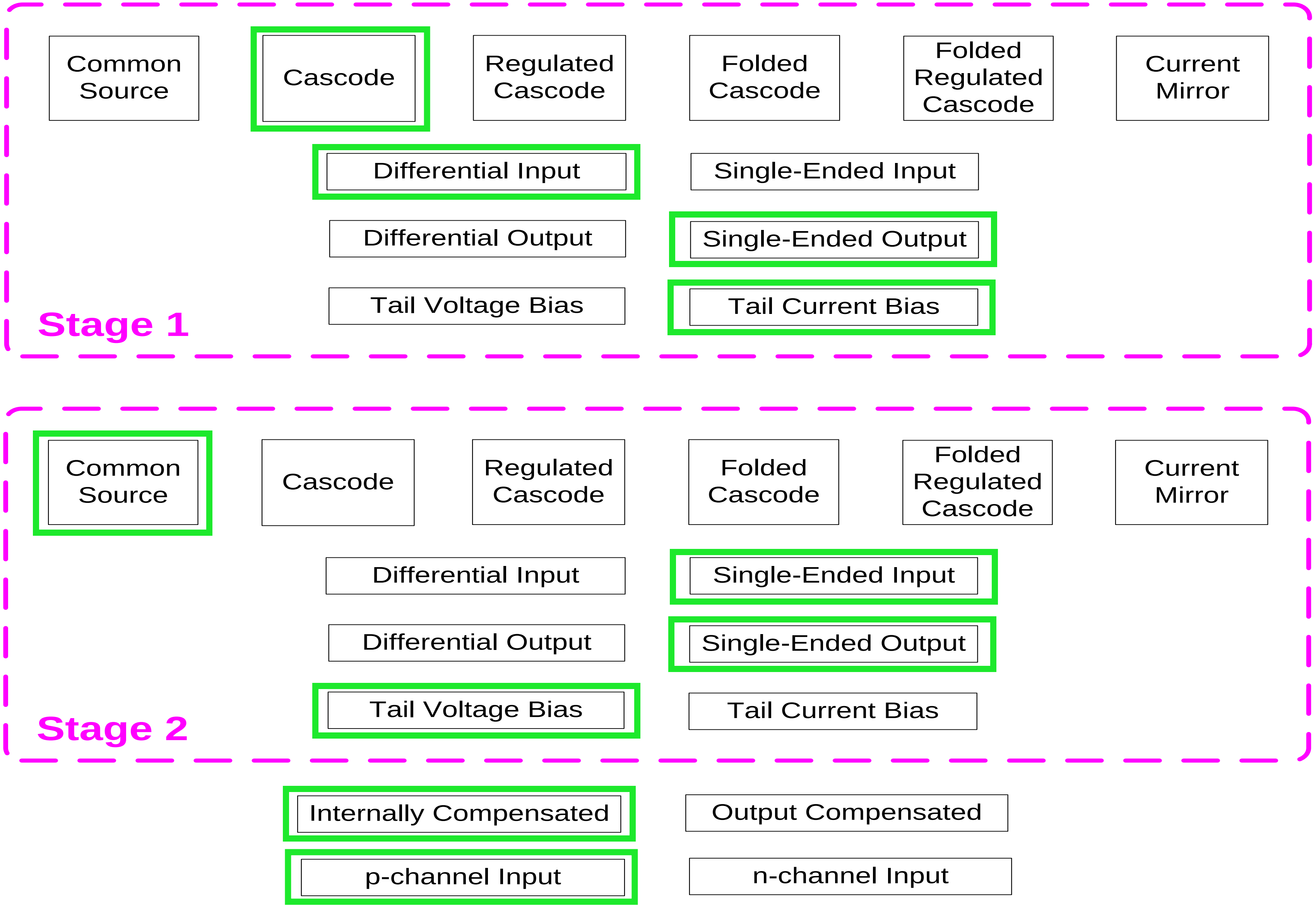
- One of the most widely used op amp architectures
- Essentially just a cascade of two common-source stages
- Compensation Capacitor $C_C$ used to get wide pole separation
- Two poles in amplifier
- No universally accepted strategy for designing this seemingly simple amplifier

Pole spread $\propto \boldsymbol{\beta A_{01} A_{02}}$ makes $C_C$ unacceptably large

# Example:

Sketch the circuit of a two-stage internally compensated op amp with a telescopic cascode first stage, single-ended output, tail current bias first stage, tail voltage bias second stage, p-channel inputs and n-channel inputs on the second stage.

# Two-stage Architectural Choices



Common Source

Cascode

Regulated Cascode

Folded Cascode

Folded Regulated Cascode

Current Mirror

Differential Input

Single-Ended Input

Differential Output

Single-Ended Output

Tail Voltage Bias

Tail Current Bias

**Stage 1**

Common Source

Cascode

Regulated Cascode

Folded Cascode

Folded Regulated Cascode

Current Mirror

Differential Input

Single-Ended Input

Differential Output

Single-Ended Output

Tail Voltage Bias

Tail Current Bias

**Stage 2**

Internally Compensated

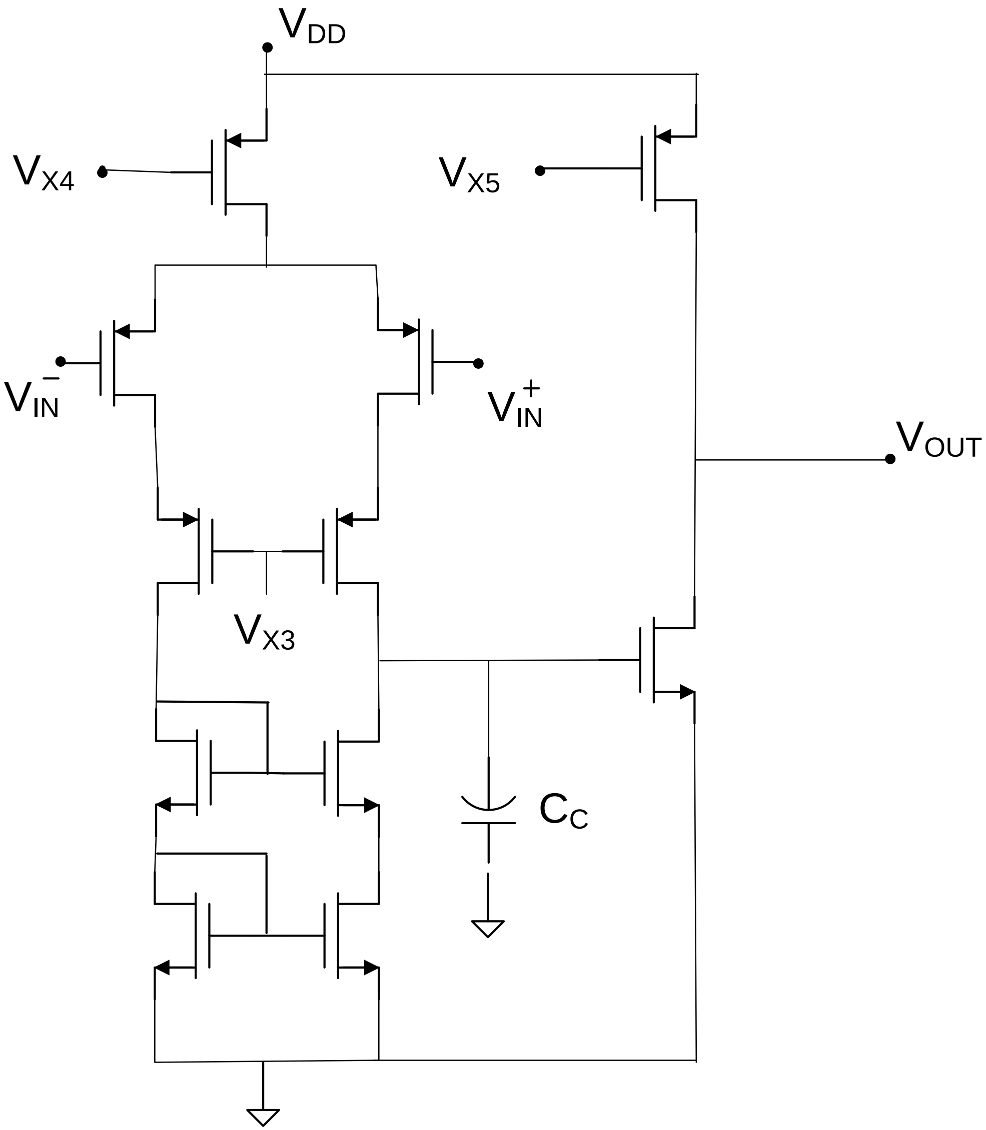
Output Compensated

p-channel Input

n-channel Input

**Cascode-Cascade Two-Stage Op Amp**

# Example Solution



End of Lecture 13