Semiconductor Technology from A to Z

Analog & Mixed-Signal Design

Operational Amplifiers

Fundamentals & the Ideal Op-Amp

The operational amplifier (op-amp) is the central building block of analog circuit design. It amplifies the voltage difference between its two inputs – the inverting (–) and the non-inverting (+) input – by a very large factor, the open-loop gain A_0.

The ideal op-amp has four properties that serve as a simplification for hand analysis of circuits:

- infinite open-loop gain ($A_0 \to \infty$)
- infinite input resistance (no input current)
- zero output resistance (ideal voltage source at the output)
- infinite bandwidth

In a negative-feedback circuit (e.g. an amplifier with a resistor network), the high open-loop gain gives rise to the virtual ground: feedback drives the voltage difference between the two inputs to nearly zero, even though there is no direct conductive path between them. This principle underlies the analysis of nearly all basic op-amp circuits (inverting amplifier, non-inverting amplifier, integrator, difference amplifier).

Real op-amps deviate from this ideal: finite gain, finite bandwidth, input currents (bias currents drawn by the transistor input stage), and a non-zero output resistance. These non-ideal effects are quantified in the following sections.

Differential Pair & Current Mirror as Input Stage

The input stage of an op-amp is almost always a differential pair: two transistors whose sources (MOS) or emitters (bipolar) connect to a shared current source. The difference between the two input voltages steers how the shared bias current splits between the two branches.

In modern CMOS designs, the active load is typically a current mirror: a reference transistor sets a current that is mirrored to one or more further branches through the ratio of transistor widths (W/L). In the op-amp input stage, the current mirror converts the differential current signal into a single-ended voltage signal – this step largely sets the gain of the first stage.

Key parameters of this stage are the transconductance g_m of the input transistors (determining gain and noise performance) and the common-mode input range – the range within which both input voltages may lie without pushing a tail-current or differential-pair transistor out of saturation.

Topologies: Miller OTA, Telescopic Cascode, Folded Cascode

For integrated op-amps (usually implemented as an OTA, Operational Transconductance Amplifier, without a low-impedance output buffer), several standard topologies have become established, each offering a different trade-off between gain, bandwidth, output swing, and area.

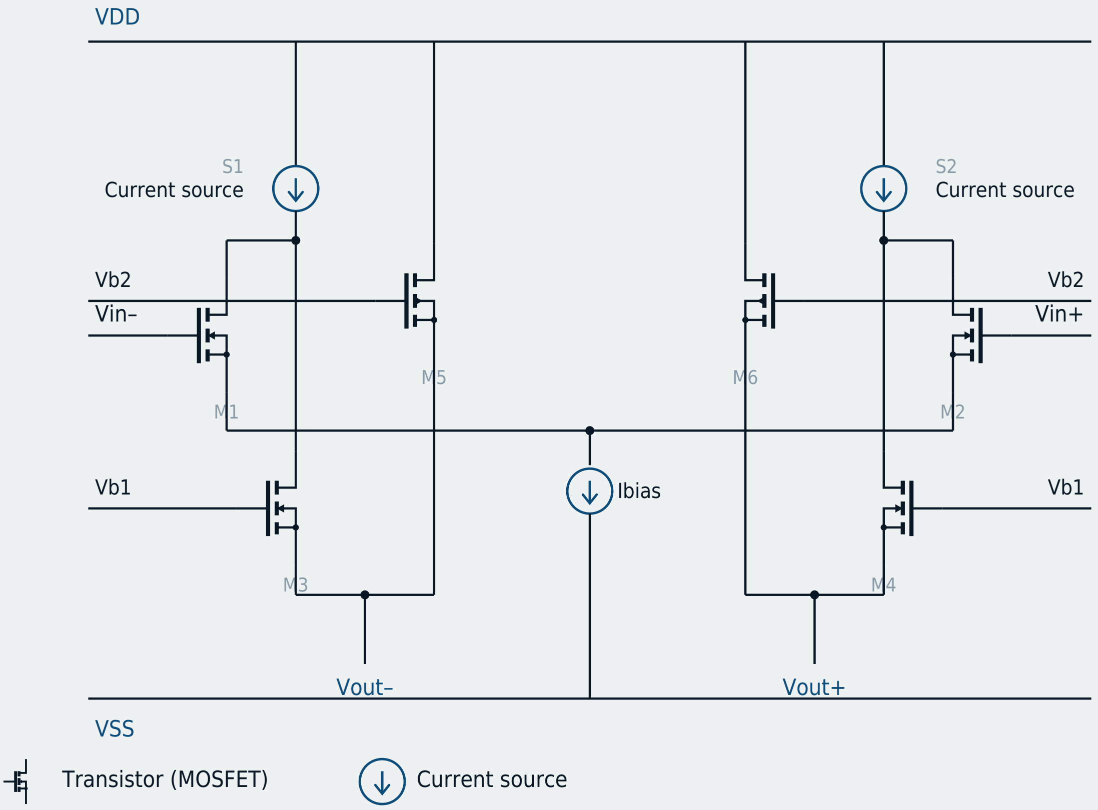
Two-stage Miller OTA: a differential input stage (high gain) followed by a second gain stage (large output swing), connected through a Miller compensation capacitor. This topology achieves very high gain and a large output voltage swing, but is harder to compensate because of the second stage.

Telescopic cascode: cascoding both the differential-pair transistors and the current-mirror load within a single stage substantially raises the output resistance and therefore the gain (typically 60–80 dB) without requiring a second stage. Drawback: the stacked transistors severely limit the usable output swing – unsuitable for low-supply-voltage designs.

Folded cascode: resolves the swing limitation of the telescopic cascode by "folding" the signal path after the input stage onto a complementary cascode branch. This allows a larger output swing at only a modest increase in current consumption, and is the single-stage topology most commonly used in practice.

Folded-Cascode Operational Amplifier

Simplified schematic (single-stage OTA)



The input pair M1/M2 is folded through current sources S1/S2 into cascode branches (M3–M6) toward the output nodes Vout–/Vout+.

Key Parameters: Gain, GBW, Slew Rate, PSRR/CMRR, Offset

Real op-amps are characterized by several parameters found in datasheets and used throughout circuit design:

- Open-loop gain (A_0): gain without feedback, typically 60–120 dB. Determines the accuracy of the closed-loop circuit (residual error ≈ $1/A_0$).
- Gain-bandwidth product (GBW): product of gain and bandwidth at a given operating point; approximately constant across frequency for single-pole behavior. Sets the maximum usable signal bandwidth for a given closed-loop gain.
- Slew rate (SR): maximum rate of change of the output voltage (V/µs), limited by the maximum available charge/discharge current into the compensation capacitor. For large signal steps, slew rate – not bandwidth – limits the actual rise time.
- PSRR (Power Supply Rejection Ratio) and CMRR (Common Mode Rejection Ratio): a measure of how well supply-voltage disturbances and common-mode input signals are rejected.

- Offset voltage: a systematic input voltage difference caused by device mismatch (threshold voltage, W/L ratios) that produces an output error even under ideal feedback.

Frequency Compensation

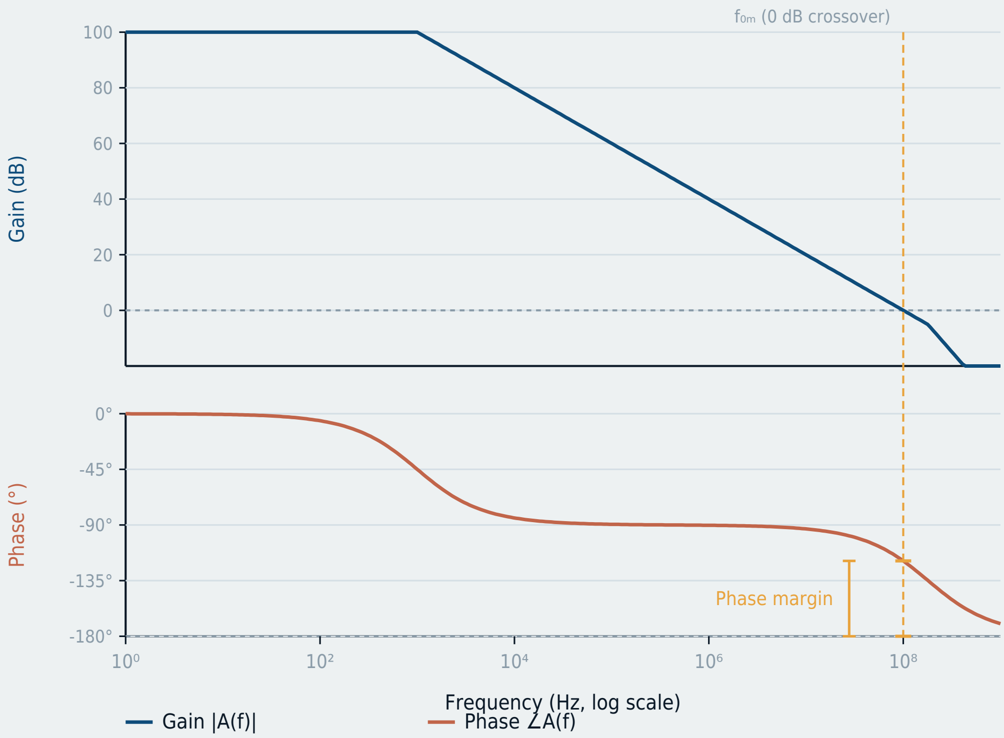
Multi-stage op-amps exhibit several poles in their frequency response. Left uncompensated, this leads to instability (oscillation) under feedback, since the phase shift can reach or exceed 180° at the frequency where the loop gain drops to 0 dB.

The phase margin – the difference between the phase and –180° at the 0 dB crossover frequency – is the central stability criterion. A phase margin of at least 45–60° is generally considered adequate for good settling behavior without excessive overshoot.

The most common technique is Miller compensation: a capacitor between the output and the intermediate node of the second stage exploits the Miller effect to push the dominant pole to a lower frequency (pole splitting), keeping the remaining poles outside the relevant bandwidth. A nulling resistor placed in series with the compensation capacitor cancels the right-half-plane zero it introduces, which would otherwise degrade the phase margin.

Bode Plot with Phase Margin

Gain and phase of a compensated two-stage op-amp



Phase margin = distance of the phase curve to –180° at the 0 dB crossover frequency.

Practice: Common Basic Circuits

Op-amps form the basis of numerous basic analog circuits found in nearly every mixed-signal system:

- Voltage follower (buffer): unity gain, extremely high input and low output resistance – used for impedance transformation between circuit stages.
- Integrator: resistor at the input, capacitor in the feedback path – produces an output voltage that is the time integral of the input; a core building block of filters, sigma-delta modulators, and PLL loop filters.
- Instrumentation amplifier: a combination of several op-amps for precise, low-noise amplification of small differential signals with high common-mode rejection – typically used in sensor signal conditioning.

These basic circuits connect the Operational Amplifiers chapter to the upcoming ADC/DAC architecture and PLL chapters, where OTAs are reused as integrators, gain stages, and charge pumps.