0.0.1 Types of Feedback: Positive and Negative Feedback

Feedback is one of the most fundamental and powerful concepts in the field of electronics and control systems engineering. In the context of electronic amplifiers, feedback is defined as the process of extracting a fraction of the amplifier's output signal (either voltage or current) and routing it back to the input, where it is combined with the original external source signal. This seemingly simple mechanism profoundly alters the operational characteristics of the system, transforming a basic, potentially unpredictable amplifier into a highly precise and robust functional block.

Before diving into the specific types of feedback, it is essential to understand the general architecture of a feedback amplifier. A generalized feedback system consists of four primary components. First, there is the **source signal**, which provides the external input to the system. Second, the **mixing network** (or comparator) is responsible for algebraically adding or subtracting the feedback signal with the source signal. Third, the **basic amplifier** (also known as the open-loop amplifier) processes the combined signal to generate the output. Finally, the **feedback network**, typically composed of passive linear components such as resistors and capacitors, samples the output signal and determines the exact fraction (denoted by the feedback factor, β) that must be returned to the input.

Based on the phase relationship between the external source signal and the signal returned by the feedback network, feedback is broadly classified into two distinct categories: Positive Feedback and Negative Feedback.

title=Positive Feedback (Regenerative Feedback)

Positive feedback occurs when the feedback signal returned to the input is exactly *in phase* with the original external input signal. As a result, the feedback signal algebraically adds to the input source signal, causing the total input to the basic amplifier to increase.

In a positive feedback system, the mixing network sums the source signal (V_s) and the feedback signal (V_f). Therefore, the effective input signal acting on the amplifier (V_i) is given by the equation $V_i = V_s + V_f$. Since the basic amplifier has a gain of A, the output voltage is $V_o = A \cdot V_i$. The feedback network samples this output and returns a fraction of it, meaning $V_f = \beta \cdot V_o$. If we substitute these relationships, we can derive the overall closed-loop gain (A_f) of the system:

$$A_f = \frac{V_o}{V_s} = \frac{A}{1 - A\beta}$$

The block diagram for a positive feedback amplifier is illustrated below. Notice the '+' sign at the feedback input of the mixing network, indicating that the signals are additive.

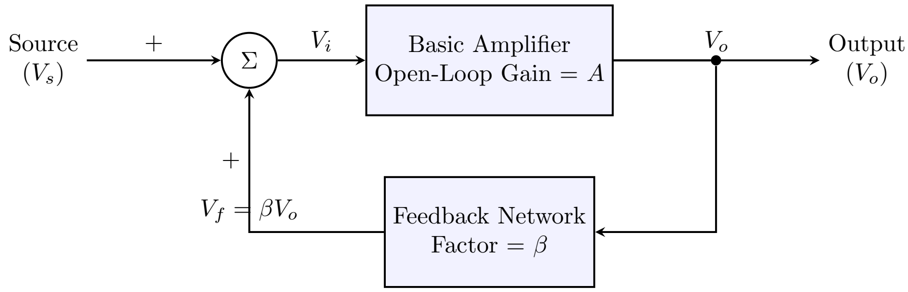

Figure 1: Block Diagram of a Positive Feedback System

The primary consequence of the denominator $(1 - A\beta)$ in the gain equation is that the overall closed-loop gain A_f is strictly greater than the open-loop gain A. While increasing the gain might initially seem advantageous, positive feedback inherently leads to instability in linear amplifiers. If the product $A\beta$ approaches unity (i.e., $A\beta = 1$), the denominator becomes zero, and the theoretical gain approaches infinity. In physical terms, this means the system can produce a substantial output signal even when the external input signal (V_s) is completely removed. The feedback signal continuously reinforces itself, driving the amplifier to its saturation limits. This self-sustaining action is the fundamental principle behind **electronic oscillators**, such as the RC Phase Shift oscillator, Hartley oscillator, and Colpitts oscillator, which rely exclusively on positive feedback to generate continuous sinusoidal or square waveforms.

title=Negative Feedback (Degenerative Feedback)

Negative feedback occurs when the feedback signal returned to the input is exactly 180° *out of phase* with the original external input signal. As a result, the feedback signal opposes or subtracts from the input source signal, causing the total effective input to the basic amplifier to decrease.

In a negative feedback system, the mixer acts as a subtractor. The effective input voltage acting upon the basic amplifier terminals is reduced: $V_i = V_s - V_f$. Following the same algebraic substitution as before, the closed-loop gain equation for a negative feedback system is:

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

The term $(1 + A\beta)$ is critically important and is widely known as the **desensitivity factor** or the amount of feedback. Because both A and β are typically positive values in this context, the denominator is greater than 1, meaning that the overall closed-loop gain A_f is strictly less than the open-loop gain A.

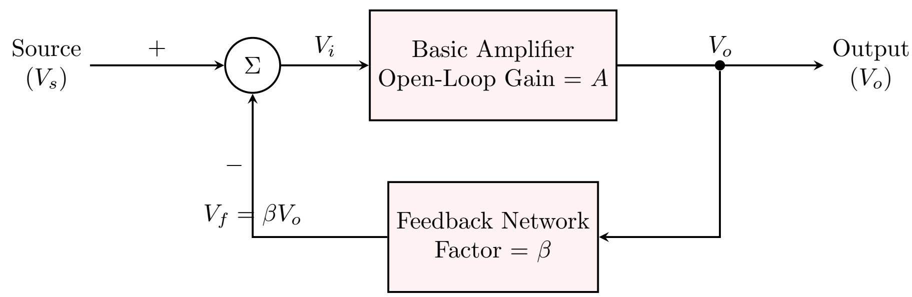

Figure 2: Block Diagram of a Negative Feedback System

Notice the '−' sign at the mixing network in Figure 2, which visually distinguishes it from the positive feedback topology. A novice engineer might wonder: *Why would we intentionally design a circuit that drastically reduces the gain of an amplifier?* The answer lies in the engineering trade-offs. While negative feedback sacrifices a portion of the amplifier's gain, it spectacularly improves almost every other performance parameter of the circuit. It stabilizes the gain against temperature fluctuations, reduces non-linear distortion, expands the operational bandwidth, and allows precise control over input and output impedances. Consequently, negative feedback is universally employed in the design of linear amplifiers, operational amplifiers, and high-fidelity audio equipment.

Negative feedback trades raw voltage or current gain for highly enhanced stability, linearity, and bandwidth. It is the cornerstone of modern linear electronic design.

While the general block diagram shows a generic voltage subtraction, negative feedback amplifiers are practically classified into four distinct topologies based on how the signal is sampled at the output and how it is mixed at the input:

- **Voltage-Series Feedback:** Samples output voltage, mixes in series with the input.
- **Voltage-Shunt Feedback:** Samples output voltage, mixes in parallel (shunt) with the input.
- **Current-Series Feedback:** Samples output current, mixes in series with the input.
- **Current-Shunt Feedback:** Samples output current, mixes in parallel (shunt) with the input.

The next section provides a detailed analysis of the most common configuration: Voltage Series Negative Feedback.

0.0.2 Voltage Series Negative Feedback

Voltage Series Negative Feedback is arguably the most widely utilized feedback topology, particularly because it represents the fundamental architecture of an ideal voltage amplifier. To understand its operation, we must dissect the name into its two defining characteristics: **Voltage Sampling** at the output, and **Series Mixing** at the input.

In terms of two-port network theory, this topology is frequently referred to as a **Series-Shunt** configuration. The word "Series" refers to the input connection, and the word "Shunt" refers to the parallel connection at the output.

Voltage Sampling (Shunt Connection at the Output)

At the output side of the amplifier, the feedback network is connected in parallel (shunt) across the output terminals. Because parallel components share the exact same voltage, the feedback network inherently samples the output voltage (V_o). The objective of a voltage sampling network is to sense any fluctuations in the output voltage caused by changes in the load resistance or internal device parameters, and relay this information back to the input to counteract the change.

Because the feedback mechanism constantly strives to maintain the desired output voltage regardless of the current drawn by the load, it effectively makes the amplifier behave like an ideal voltage source. As a direct mathematical consequence, voltage sampling drastically **decreases the output impedance** (Z_o) of the amplifier, allowing it to drive low-impedance loads without a significant drop in output voltage.

Series Mixing (Series Connection at the Input)

At the input side, the feedback network introduces a feedback voltage (V_f) that is connected in series with the external signal source (V_s). According to Kirchhoff's Voltage Law (KVL) applied around the input loop, the voltages add algebraically. Because this is a negative feedback system, the feedback voltage is configured to have a polarity that directly opposes the source voltage.

The actual voltage that is applied across the input terminals of the basic amplifier is the difference between the source and the feedback: $V_i = V_s - V_f$. Because the effective voltage driving the internal amplifier is reduced, the current drawn from the external source is proportionally reduced. A decrease in drawn current for a given applied source voltage means that the apparent resistance looking into the amplifier terminals has increased. Thus, series mixing drastically **increases the input impedance** (Z_i) of the amplifier.

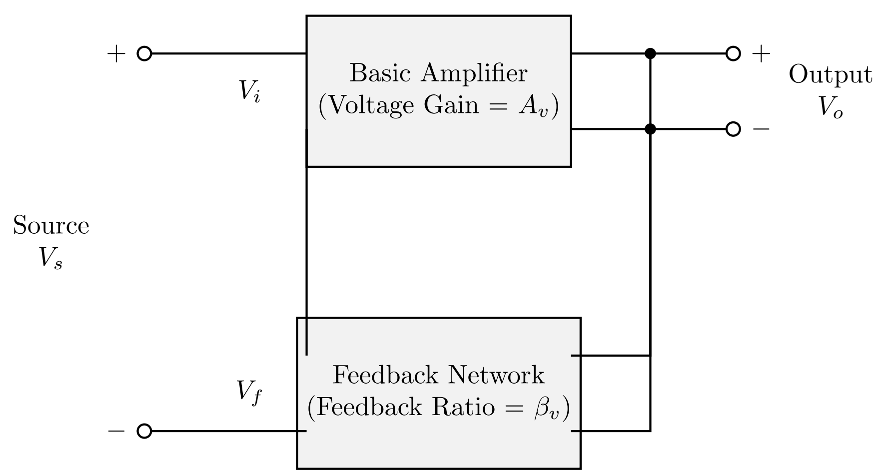

Figure 3: Detailed Two-Port Block Diagram of Voltage-Series Negative Feedback

The block diagram in Figure 3 clearly illustrates the physical wiring required for this topology. On the right side, the sampling wires tap directly across the two output lines, observing the exact load voltage V_o. On the left side, the input forms a single contiguous loop comprising the source V_s, the amplifier input V_i, and the feedback output V_f.

If we trace the signal mathematically, the amplifier produces an output $V_o = A_v \cdot V_i$. The feedback network scales this voltage down, yielding $V_f = \beta_v \cdot V_o$. Substituting the KVL equation $V_i = V_s - V_f$, we can derive the overall closed-loop voltage gain:

$$A_{vf} = \frac{V_o}{V_s} = \frac{A_v}{1 + A_v \beta_v}$$

Because Voltage-Series feedback simultaneously increases input impedance and decreases output impedance, it perfectly aligns with the required characteristics of an ideal voltage amplifier (which should ideally possess infinite input impedance and zero output impedance). This makes it highly desirable for interfacing stages in multi-stage amplification systems, as it prevents loading effects from previous and subsequent circuits.

title=Practical Example: Non-Inverting Operational Amplifier

The classic non-inverting operational amplifier circuit is the quintessential real-world example of voltage-series negative feedback. In this circuit, the input signal (V_s) is applied directly to the non-inverting terminal (+). The output voltage (V_o) is tapped by a resistive voltage divider network (comprising resistors R_1 and R_2 connected to ground), which acts as the parallel voltage sampling network. The node between R_1 and R_2 feeds a fraction of the output voltage back to the inverting terminal ($-$) of the op-amp.
Because the op-amp fundamentally amplifies the differential voltage between its terminals ($V^+ - V^-$), applying the feedback to the inverting terminal while the source is at the non-inverting terminal achieves the series subtraction required: $V_i = V_s - V_f$. The resulting circuit boasts an extraordinarily high input impedance (often in the giga-ohms range) and a fractional output impedance, making it a perfect voltage buffer.

0.0.3 Advantages and Disadvantages of Negative Feedback

The application of negative feedback represents one of the most critical paradigm shifts in amplifier design. An amplifier built strictly with active devices (like BJTs or MOSFETs) operating in an open-loop configuration is inherently flawed. Active devices are non-linear, generate internal noise, and their parameters (such as the current gain β_{dc} or transconductance g_m) vary wildly with temperature changes, aging, and manufacturing tolerances. Attempting to build a precision instrument out of such unreliable components is practically impossible without feedback.

Negative feedback resolves these issues by essentially overpowering the erratic behavior of the active components with the highly stable, predictable behavior of passive components (like precision metal-film resistors) used in the feedback network. While this process sacrifices a substantial amount of the raw voltage or current gain, the resulting improvements in other parameters are immense. Below is a comprehensive analysis of the advantages and disadvantages introduced by negative feedback.

Advantages of Negative Feedback

1. **Stabilization of Voltage Gain (Desensitivity):** The most profound advantage of negative feedback is the stabilization of the amplifier's gain against variations in the active devices. In a non-feedback amplifier, if the transistor's inherent gain (A) changes by 20% due to a rise in ambient temperature, the overall output will identically surge by 20%. However, in a closed-loop system, the gain equation is $A_f = A/(1 + A\beta)$. If the open-loop gain is deliberately designed to be extremely large (such that $A\beta \gg 1$), the equation simplifies dramatically:

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

   This is a remarkable result. The closed-loop gain A_f becomes almost entirely independent of the amplifier's internal gain A, and relies solely on the feedback factor β. Because β is determined by highly stable passive resistors, the amplifier's gain becomes incredibly stable and immune to temperature shifts, transistor aging, or even replacing a burned-out transistor with a slightly different one. The mathematical reduction in gain variation is given by $\frac{dA_f}{A_f} = \frac{1}{1+A\beta}\frac{dA}{A}$.

2. **Reduction in Non-Linear Distortion:** Transistors do not amplify signals perfectly; their transfer characteristics exhibit curvature. When a large sinusoidal signal is applied, the positive and negative half-cycles are amplified slightly differently, resulting in harmonic distortion at the output. Negative feedback acts as an automatic correction mechanism. If a distortion spike occurs at the output, the feedback network samples this distortion and feeds it back to the input inverted (180° out of phase). The amplifier then amplifies this inverted distortion, which effectively cancels out the original distortion generated in the output stage. The non-linear distortion D is reduced by the same desensitivity factor: $D_f = \frac{D}{1+A\beta}$. *Note: Negative feedback can only reduce distortion generated within the amplifier loop itself; it cannot "clean up" a distorted input signal.*

3. **Reduction in Internal Noise:** Similar to distortion, active components generate random electrical noise (such as thermal noise and shot noise). If this noise originates in the later stages of the amplifier (where signal levels are higher), negative feedback will sample this noise and feed it back out of phase, suppressing it significantly. The internal noise N is reduced to $N_f = \frac{N}{1+A\beta}$. It is important to note that noise introduced directly at the input terminals alongside the source signal will not be reduced relative to the signal, as the feedback treats it as part of the valid input.

4. **Modification of Input and Output Impedances:** As explored in the Voltage Series topology, negative feedback provides designers with precise control over the input and output impedances of the amplifier. Depending on the chosen configuration, impedance can be increased or decreased by the factor $(1 + A\beta)$.

   - **Series Mixing:** Increases Input Impedance ($Z_{if} = Z_i(1 + A\beta)$).
   - **Shunt Mixing:** Decreases Input Impedance ($Z_{if} = Z_i/(1 + A\beta)$).
   - **Voltage Sampling:** Decreases Output Impedance ($Z_{of} = Z_o/(1 + A\beta)$).
   - **Current Sampling:** Increases Output Impedance ($Z_{of} = Z_o(1 + A\beta)$).

This flexibility allows engineers to design ideal voltage amplifiers, current amplifiers, transconductance amplifiers, or transresistance amplifiers simply by changing the feedback topology.

5. **Extension of Bandwidth (Frequency Response):** Every amplifier has a finite bandwidth, limited by a lower cutoff frequency (f_L) and an upper cutoff frequency (f_H). In linear amplifiers, the product of the gain and the bandwidth is a constant mathematical property (the Gain-Bandwidth Product). When negative feedback reduces the mid-band gain by a factor of $(1+A\beta)$, the bandwidth expands by that exact same factor to maintain the constant product. The new extended cutoff frequencies become:

$$f_{Hf} = f_H(1 + A\beta) \quad \text{and} \quad f_{Lf} = \frac{f_L}{1 + A\beta}$$

This results in a much wider, flatter frequency response, enabling the amplifier to handle high-frequency signals with much greater fidelity.

Disadvantages of Negative Feedback

Despite its overwhelming benefits, negative feedback is not without its costs and design challenges.

1. **Reduction in Overall Gain:** The most obvious penalty is the severe reduction in voltage or current gain. To achieve a specific desired final gain, the designer must cascade multiple stages of amplification to create an enormous open-loop gain A, simply so they can afford to throw away a large portion of it through feedback. This requirement increases the component count, complexity, power consumption, and physical size of the circuit.

2. **Potential for High-Frequency Instability (Oscillation):** This is the most dangerous disadvantage and the primary challenge in feedback amplifier design. Negative feedback relies on the feedback signal being precisely 180° out of phase with the input. However, all physical amplifiers contain internal parasitic capacitances (such as base-collector capacitance in BJTs). At high frequencies, these reactive components naturally introduce additional phase shifts into the signal as it propagates through the amplifier.

   If the frequency is high enough, the amplifier's internal phase shift might add another 180° to the signal. Combined with the 180° subtraction at the mixing network, the total loop phase shift becomes 360° (which is mathematically identical to 0°). At this specific frequency, the negative feedback has accidentally transformed into **positive feedback**. If the loop gain $|A\beta|$ is greater than or equal to 1 at this frequency, the amplifier will violently break into sustained oscillations, rendering it completely useless as an amplifier.

title=Stability and Compensation

To prevent accidental oscillations at high frequencies, engineers must employ **frequency compensation techniques**. This usually involves intentionally adding small capacitors to the circuit (like the internal compensation capacitor found in a 741 operational amplifier) to artificially roll off the gain at high frequencies before the phase shift can reach the critical 180° point. This ensures absolute stability, but limits the maximum achievable high-frequency performance.

Summary Comparison

The following table summarizes the profound impact of negative feedback on the key performance parameters of an amplifier:

Amplifier Parameter	**Basic Amplifier (Without Feedback)**	**Amplifier With Negative Feedback**
Overall Gain	High (A)	Significantly reduced ($A_f = \frac{A}{1+A\beta}$)
Gain Stability	Poor (Highly sensitive to temperature and device parameters)	Excellent (Depends primarily on stable passive feedback components)
Non-Linear Distortion	High	Substantially reduced
Internal Noise	High	Substantially reduced
Bandwidth	Narrow	Significantly widened
Input Impedance	Fixed by internal device design	Can be precisely increased (Series) or decreased (Shunt)
Output Impedance	Fixed by internal device design	Can be precisely decreased (Voltage) or increased (Current)
Risk of Oscillation	None (if inherently stable)	High at high frequencies (requires careful phase compensation)

Table 1: Comparison of Amplifier Parameters With and Without Negative Feedback