Operational amplifier

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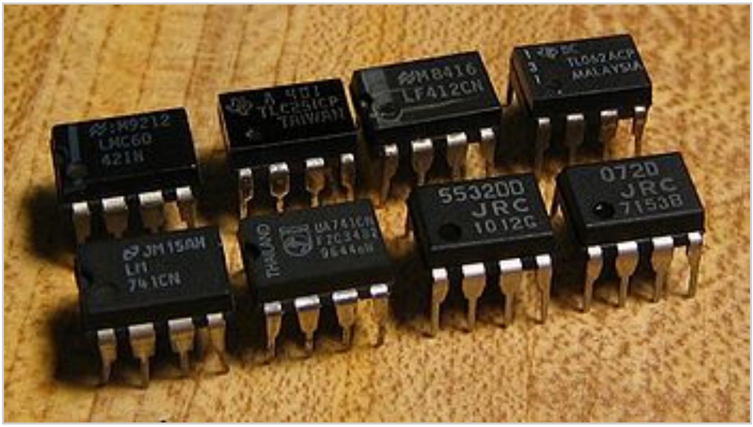

Various op-amp ICs in eight-pin dual in-line packages ("DIPs")

An **operational amplifier**, which is often called an **op-amp**, is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output.[1] An op-amp produces an output voltage that is typically millions of times larger than the voltage *difference* between its input terminals.

Typically the op-amp's very large gain is controlled by negative feedback, which largely determines the magnitude of its output ("closed-loop") voltage gain in amplifier applications, or the transfer function required (in analog computers). Without negative feedback, and perhaps with positive feedback for regeneration, an op-amp essentially acts as a comparator. High input impedance at the input terminals (ideally infinite) and low output impedance at the output terminal(s) (ideally zero) are important typical characteristics.

Op-amps are among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific devices. Many standard IC op-amps cost only a few cents in moderate production volume; however some integrated or hybrid operational amplifiers with special performance specifications may cost over $100 US in small quantities. Op-amps sometimes come in the form of macroscopic components, (see photo) or as integrated circuit cells; patterns that can be reprinted several times on one chip as part of a more complex device.

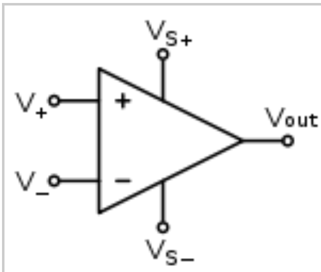
The op-amp is one type of differential amplifier. Other types of differential amplifier include the fully differential amplifier (similar to the op-amp, but with two outputs), the instrumentation amplifier (usually built from three op-amps), the isolation amplifier (similar to the instrumentation amplifier, but with tolerance to common-mode voltages that would destroy an ordinary op-amp), and negative feedback amplifier (usually built from one or more op-amps and a resistive feedback network).

Contents

Circuit notation

The circuit symbol for an op-amp is shown to the right, where:

- V_+: non-inverting input
- V_-: inverting input
- V_{out}: output
- $V_{\mathrm{S+}}$: positive power supply
- $V_{\mathrm{S-}}$: negative power supply



Circuit diagram symbol for an op-amp

The power supply pins ($V_{\mathrm{S+}}$ and $V_{\mathrm{S-}}$) can be labeled in different ways (*See IC power supply pins*). Despite different labeling, the function remains the same — to provide additional power for amplification of the signal. Often these pins are left out of the diagram for clarity, and the power configuration is described or assumed from the circuit.

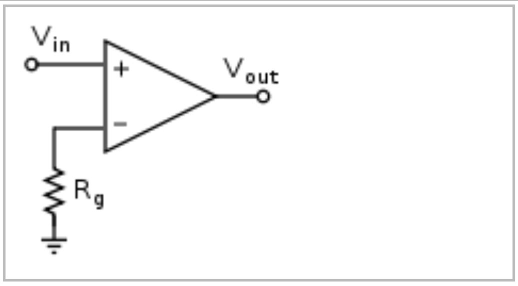
Operation

The amplifier's differential inputs consist of a V_+ input and a V_- input, and ideally the op-amp amplifies only the difference in voltage between the two, which is called the *differential input voltage*. The output voltage of the op-amp is given by the equation,

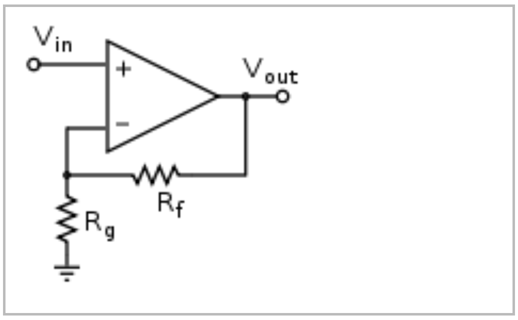
$$V_{\mathrm{out}} = (V_+ - V_-)\, A_{OL}$$

where V_+ is the voltage at the non-inverting terminal, V_- is the voltage at the inverting terminal and A_{OL} is the open-loop gain of the amplifier. (The term "open-loop" refers to the absence of a feedback loop from the output to the input.)

The magnitude of A_{OL} is typically very large—seldom less than a million—and therefore even a quite small difference between V_+ and V_- (a few microvolts or less) will result in amplifier saturation, where the output voltage goes to either the extreme maximum or minimum end of its range, which is set approximately by the power supply voltages. Additionally, the precise magnitude of A_{OL} is not well controlled by the manufacturing process, and so it is impractical to use an operational amplifier as a stand-alone differential amplifier. If linear operation is desired, negative feedback must be used, usually achieved by applying a portion of the output voltage to the inverting input. The feedback enables the output of the amplifier to keep the inputs at or near the same voltage so that saturation does not occur. Another benefit is that if much negative feedback is used, the circuit's overall gain and other parameters become determined more by the feedback network than by the op-amp itself. If the feedback network is made of components with relatively constant, predictable, values such as resistors, capacitors and inductors, the unpredictability and inconstancy of the op-amp's parameters (typical of semiconductor devices) do not seriously affect the circuit's performance.



With no negative feedback, the op-amp acts as a comparator. The inverting input is held at ground (0 V) by the resistor, so if the V_{in} applied to the non-inverting input is positive, the output will be maximum positive, and if V_{in} is negative, the output will be maximum negative. Since there is no feedback from the output to either input, this is an *open loop* circuit. The circuit's gain is just the G_{OL} of the op-amp.



Adding negative feedback via the voltage divider R_f,R_g reduces the gain. Equilibrium will be established when V_{out} is just sufficient to reach around and "pull" the inverting input to the same voltage as V_{in}. As a simple example, if V_{in} = 1 V and $R_f = R_g$, V_{out} will be 2 V, the amount required to

If no negative feedback is used, the op-amp functions as a switch or comparator.

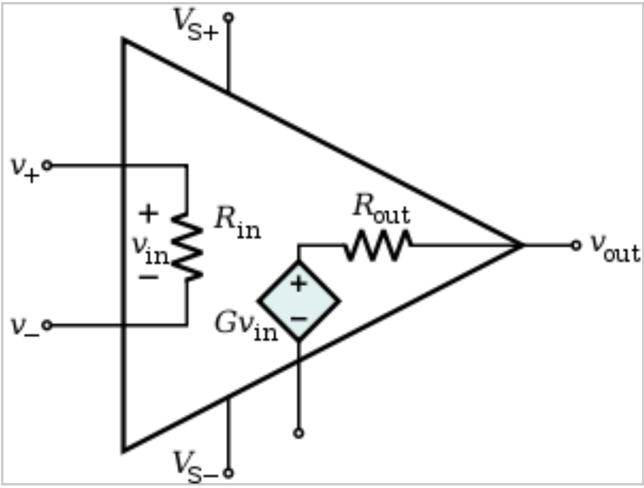
Positive feedback may be used to introduce hysteresis or oscillation.

Ideal and real op-amps

An ideal op-amp is usually considered to have the following properties, and they are considered to hold for all input voltages:

- Infinite open-loop gain (when doing theoretical analysis, a limit may be taken as open loop gain A_{OL} goes to infinity)
- Infinite voltage range available at the output (v_{out}) (in practice the voltages available from the output are limited by the supply voltages $V_{\text{S+}}$ and $V_{\text{S−}}$)
- Infinite bandwidth (i.e., the frequency magnitude response is considered to be flat everywhere with zero phase shift).
- Infinite input impedance (so, in the diagram, $R_{\text{in}} = \infty$, and zero current flows from v_+ to v_-)
- Zero input current (i.e., there is assumed to be no leakage or bias current into the device)
- Zero input offset voltage (i.e., when the input terminals are shorted so that $v_+ = v_-$, the output is a virtual ground or $v_{\text{out}} = 0$).
- Infinite slew rate (i.e., the rate of change of the output voltage is unbounded) and power bandwidth (full output voltage and current available at all frequencies).
- Zero output impedance (i.e., $R_{\text{out}} = 0$, so that output voltage does not vary with output current)
- Zero noise
- Infinite Common-mode rejection ratio (CMRR)
- Infinite Power supply rejection ratio for both power supply rails.

V_{out} will be 2 V, the amount required to keep V_- at 1 V. Because of the feedback provided by R_f,R_g this is a *closed loop* circuit. Its over-all gain V_{out} / V_{in} is called the *closed-loop gain* A_{CL}. Because the feedback is negative, in this case A_{CL} is less than the A_{OL} of the op-amp.



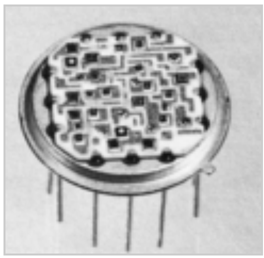
An equivalent circuit of an operational amplifier that models some resistive non-ideal parameters.

In practice, none of these ideals can be realized, and various shortcomings and compromises have to be accepted. Depending on the parameters of interest, a real op-amp may be modeled to take account of some of the non-infinite or non-zero parameters using equivalent resistors and capacitors in the op-amp model. The designer can then include the effects of these undesirable, but real, effects into the overall performance of the final circuit. Some parameters may turn out to have negligible effect on the final design while others represent actual limitations of the final performance, that must be evaluated.

History

1941: First (vacuum tube) op-amp

An op-amp, defined as a general-purpose, DC-coupled, high gain, inverting feedback amplifier, is first found in US Patent 2,401,779 "Summing Amplifier" filed by Karl D. Swartzel Jr. of Bell labs in 1941. This design used three vacuum tubes to achieve a gain of 90dB and operated on voltage rails of ±350V. It had a single inverting input rather than differential inverting and non-inverting inputs, as are common in today's op-amps. Throughout World War II, Swartzel's design proved its value by being liberally used in the M9 artillery director designed at Bell Labs. This artillery director worked with the SCR584 radar system to achieve


ADI's HOS-050: a high speed hybrid IC op-amp (1979).

GAP/R's K2-W: a vacuum-tube op-amp (1953).

extraordinary hit rates (near 90%) that would not have been possible otherwise.[2]

An op-amp in a modern DIP.

1947: First op-amp with an explicit non-inverting input

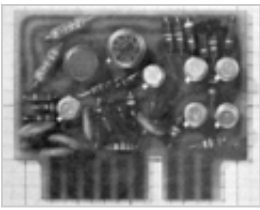
In 1947, the operational amplifier was first formally defined and named in a paper by Professor John R. Ragazzini of Columbia University. In this same paper a footnote mentioned an op-amp design by a student that would turn out to be quite significant. This op-amp, designed by Loebe Julie, was superior in a variety of ways. It had two major innovations. Its input stage used a long-tailed triode pair with loads matched to reduce drift in the output and, far more importantly, it was the first op-amp design to have two inputs (one inverting, the other non-inverting). The differential input made a whole range of new functionality possible, but it would not be used for a long time due to the rise of the chopper-stabilized amplifier.[3]

1949: First chopper-stabilized op-amp

In 1949, Edwin A. Goldberg designed a chopper-stabilized op-amp.[4] This set-up uses a normal op-amp with an additional AC amplifier that goes alongside the op-amp. The chopper gets an AC signal from DC by switching between the DC voltage and ground at a fast rate (60 Hz or 400 Hz). This signal is then amplified, rectified, filtered and fed into the op-amp's non-inverting input. This vastly improved the gain of the op-amp while significantly reducing the output drift and DC offset. Unfortunately, any design that used a chopper couldn't use their non-inverting input for any other purpose. Nevertheless, the much improved characteristics of the chopper-stabilized op-amp made it the dominant way to use op-amps. Techniques that used the non-inverting input regularly would not be very popular until the 1960s when op-amp ICs started to show up in the field.

In 1953, vacuum tube op-amps became commercially available with the release of the model K2-W from George A. Philbrick Researches, Incorporated. The designation on the devices shown, GAP/R, is a contraction for the complete company name. Two nine-pin 12AX7 vacuum tubes were mounted in an octal package and had a model K2-P chopper add-on available that would effectively "use up" the non-inverting input. This op-amp was based on a descendant of Loebe Julie's 1947 design and, along with its successors, would start the widespread use of op-amps in industry.

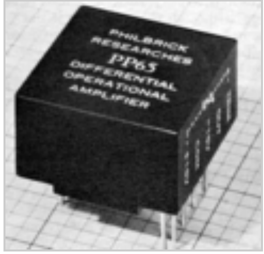
1961: First discrete IC op-amps



GAP/R's model P45: a solid-state, discrete op-amp (1961).

With the birth of the transistor in 1947, and the silicon transistor in 1954, the concept of ICs became a reality. The introduction of the planar process in 1959 made transistors and ICs stable enough to be commercially useful. By 1961, solid-state, discrete op-amps were being produced. These op-amps were effectively small circuit boards with packages such as edge-connectors. They usually had hand-selected resistors in order to improve things such as voltage offset and drift. The P45 (1961) had a gain of 94 dB and ran on ±15 V rails. It was intended to deal with signals in the range of ±10 V.

1962: First op-amps in potted modules



GAP/R's model PP65: a solid-state op-amp in a potted module (1962).

By 1962, several companies were producing modular potted packages that could be plugged into printed circuit boards.[*citation needed*] These packages were crucially important as they made the operational amplifier into a single black box which could be easily treated as a component in a larger circuit.

1963: First monolithic IC op-amp

In 1963, the first monolithic IC op-amp, the μA702 designed by Bob Widlar at Fairchild Semiconductor, was released. Monolithic ICs consist of a single chip as opposed to a chip and discrete parts (a discrete IC) or multiple chips bonded and connected on a circuit board (a hybrid IC). Almost all modern op-amps are monolithic ICs; however, this first IC did not meet with much success. Issues such as an uneven supply voltage, low gain and a small dynamic range held off the dominance of monolithic op-amps until 1965 when the μA709[5] (also designed by Bob Widlar) was released.

1966: First varactor bridge op-amps

Since the 741, there have been many different directions taken in op-amp design. Varactor bridge op-amps started to be produced in the late 1960s; they were designed to have extremely small input current and are still amongst the best op-amps available in terms of common-mode rejection with the ability to correctly deal with hundreds of volts at their inputs.

1968: Release of the μA741

The popularity of monolithic op-amps was further improved upon the release of the LM101 in 1967, which solved a variety of issues, and the subsequent release of the μA741 in 1968. The μA741 was extremely similar to the LM101 except that Fairchild's facilities allowed them to include a 30 pF compensation capacitor inside the chip instead of requiring external compensation. This simple difference has made the 741 *the* canonical op-amp and many modern amps base their pinout on the 741s.The μA741 is still in production, and has become ubiquitous in electronics—many manufacturers produce a version of this classic chip, recognizable by part numbers containing *741*.

1970: First high-speed, low-input current FET design

In the 1970s high speed, low-input current designs started to be made by using FETs. These would be largely replaced by op-amps made with MOSFETs in the 1980s. During the 1970s single sided supply op-amps also became available.

1972: Single sided supply op-amps being produced

A single sided supply op-amp is one where the input and output voltages can be as low as the negative power supply voltage instead of needing to be at least two volts above it. The result is that it can operate in many applications with the negative supply pin on the op-amp being connected to the signal ground, thus eliminating the need for a separate negative power supply.

The LM324 (released in 1972) was one such op-amp that came in a quad package (four separate op-amps in one package) and became an industry standard. In addition to packaging multiple op-amps in a single package, the 1970s also saw the birth of op-amps in hybrid packages. These op-amps were generally improved versions of existing monolithic op-amps. As the properties of monolithic op-amps improved, the more complex hybrid ICs were quickly relegated to systems that are required to have extremely long service lives or other specialty systems.

Recent trends

Recently supply voltages in analog circuits have decreased (as they have in digital logic) and low-voltage opamps have been introduced reflecting this. Supplies of ±5V and increasingly 5V are common. To maximize the signal range modern op-amps commonly have rail-to-rail inputs (the input signals can range from the lowest supply voltage to the highest) and sometimes rail-to-rail outputs.

Classification

Op-amps may be classified by their construction:

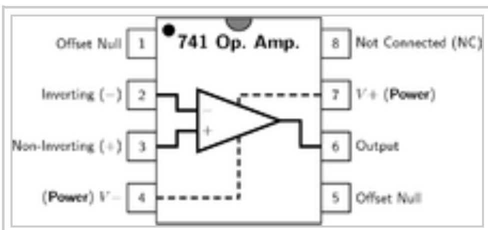
- discrete (built from individual transistors or tubes/valves)
- IC (fabricated in an Integrated circuit) - most common
- hybrid

IC op-amps may be classified in many ways, including:

- Military, Industrial, or Commercial grade (for example: the LM301 is the commercial grade version of the LM101, the LM201 is the industrial version). This may define operating temperature ranges and other environmental or quality factors.
- Classification by package type may also affect environmental hardiness, as well as manufacturing options; DIP, and other through-hole packages are tending to be replaced by Surface-mount devices.
- Classification by internal compensation: op-amps may suffer from high frequency instability in some negative feedback circuits unless a small compensation capacitor modifies the phase- and frequency-responses; op-amps with capacitor built in are termed "*compensated*", or perhaps compensated for closed-loop gains down to (say) 5, others: uncompensated.
- Single, dual and quad versions of many commercial op-amp IC are available, meaning 1, 2 or 4 operational amplifiers are included in the same package.
- Rail-to-rail input (and/or output) op-amps can work with input (and/or output) signals very close to the power supply rails.
- CMOS op-amps (such as the CA3140E) provide extremely high input resistances, higher than JFET-input op-amps, which are normally higher than bipolar-input op-amps.
- other varieties of op-amp include programmable op-amps (simply meaning the quiescent current, gain, bandwidth and so on can be adjusted slightly by an external resistor).
- manufacturers often tabulate their op-amps according to purpose, such as low-noise pre-amplifiers, wide bandwidth amplifiers, and so on.

Applications

Main article: Operational amplifier applications



Use in electronics system design

The use of op-amps as circuit blocks is much easier and clearer than specifying all their individual circuit elements (transistors, resistors, etc.), whether the amplifiers used are integrated or discrete. In the first approximation op-amps can be used as if they were ideal differential gain blocks; at a later stage limits can be placed on the acceptable range of parameters for each op-amp.

DIP pinout for 741-type operational amplifier

Circuit design follows the same lines for all electronic circuits. A specification is drawn up governing what the circuit is required to do, with allowable limits. For example, the gain may be required to be 100 times, with a tolerance of 5% but drift of less than 1% in a specified temperature range; the input impedance not less than one megohm; etc.

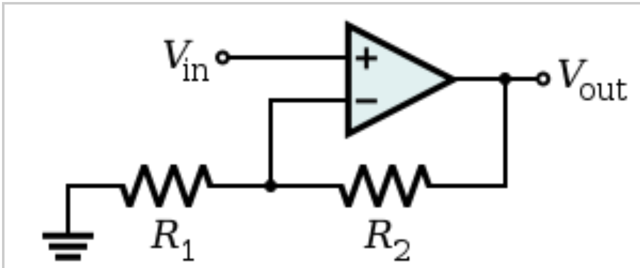
A basic circuit is designed, often with the help of circuit modeling (on a computer). Specific commercially available op-amps and other components are then chosen that meet the design criteria within the specified tolerances at acceptable cost. If not all criteria can be met, the specification may need to be modified.

A prototype is then built and tested; changes to meet or improve the specification, alter functionality, or reduce the cost, may be made.

Basic single stage amplifiers

Non-inverting amplifier

In a non-inverting amplifier, the output voltage changes in the same direction as the input voltage.



An op-amp connected in the non-inverting amplifier configuration

The gain equation for the op-amp is:

$$V_{\rm out} = (V_+ - V_-)\, A_{OL}$$

However, in this circuit V_- is a function of $V_{\rm out}$ because of the negative feedback through the $R_1 R_2$ network. R_1 and R_2 form a voltage divider, and as V_- is a high-impedance input, it does not load it appreciably. Consequently:

$$V_- \ = \beta \cdot V_{\rm out}$$

where

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

Substituting this into the gain equation, we obtain:

$$V_{\rm out} = (V_{\rm in} - \beta \cdot V_{\rm out}) \cdot A_{OL}$$

Solving for $V_{\rm out}$:

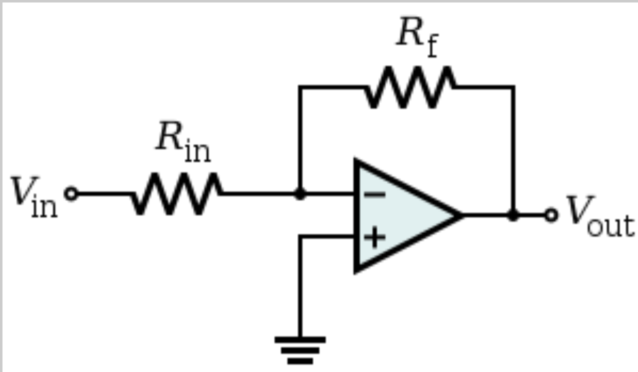
$$V_{\text{out}} = V_{\text{in}} \cdot \left(\frac{1}{\beta + 1/A_{OL}}\right)$$

If A_{OL} is very large, this simplifies to

$$V_{\text{out}} \approx \frac{V_{\text{in}}}{\beta} = \frac{V_{\text{in}}}{\frac{R_1}{R_1+R_2}} = V_{\text{in}}\left(1 + \frac{R_2}{R_1}\right).$$

Inverting amplifier

In an inverting amplifier, the output voltage changes in an opposite direction to the input voltage.



An op-amp connected in the inverting amplifier configuration

As for the non-inverting amplifier, we start with the gain equation of the op-amp:

$$V_{\text{out}} = (V_+ - V_-)\, A_{OL}$$

This time, V_- is a function of both V_{out} and V_{in} due to the voltage divider formed by R_{f} and R_{in}. Again, the op-amp input does not apply an appreciable load, so:

$$V_- = \frac{1}{R_{\text{f}} + R_{\text{in}}}\left(R_{\text{f}} V_{\text{in}} + R_{\text{in}} V_{\text{out}}\right)$$

Substituting this into the gain equation and solving for V_{out}:

$$V_{\text{out}} = -V_{\text{in}} \cdot \frac{A_{OL} R_{\text{f}}}{R_{\text{f}} + R_{\text{in}} + A_{OL} R_{\text{in}}}$$

If A_{OL} is very large, this simplifies to

$$V_{\text{out}} \approx -V_{\text{in}} \frac{R_{\text{f}}}{R_{\text{in}}}.$$

A resistor is often inserted between the non-inverting input and ground (so both inputs "see" similar resistances), reducing the input offset voltage due to different voltage drops due to bias current, and may reduce distortion in some op-amps.

A DC-blocking capacitor may be inserted in series with the input resistor when a frequency response down to DC is not needed and any DC voltage on the input is unwanted. That is, the capacitive component of the input impedance inserts a DC zero and a low-frequency pole that gives the circuit a bandpass or high-pass characteristic.

Positive feedback configurations

Another typical configuration of op-amps is the positive feedback, which takes a fraction of the output signal back to the non-inverting input. An important application of it is the comparator with hysteresis (i.e., the Schmitt trigger).

Other applications

- audio- and video-frequency pre-amplifiers and buffers
- voltage comparators
- differential amplifiers
- differentiators and integrators
- filters
- precision rectifiers
- precision peak detectors
- voltage and current regulators
- analog calculators
- analog-to-digital converters
- digital-to-analog converter
- voltage clamps
- oscillators and waveform generators

Most single, dual and quad op-amps available have a standardized pin-out which permits one type to be substituted for another without wiring changes. A specific op-amp may be chosen for its open loop gain, bandwidth, noise performance, input impedance, power consumption, or a compromise between any of these factors.

Limitations of real op-amps

Real op-amps differ from the ideal model in various respects.

IC op-amps as implemented in practice are moderately complex integrated circuits; see the internal circuitry for the relatively simple 741 op-amp below, for example.

DC imperfections

Real operational amplifiers suffer from several non-ideal effects:

Finite gain
: Open-loop gain is infinite in the ideal operational amplifier but finite in real operational amplifiers. Typical devices exhibit open-loop DC gain ranging from 100,000 to over 1 million. So long as the loop gain (i.e., the product of open-loop and feedback gains) is very large, the circuit gain will be determined entirely by the amount of negative feedback (i.e., it will be independent of open-loop gain). In cases where closed-loop gain must be very high, the feedback gain will be very low, and the low feedback gain causes low loop gain; in these cases, the operational amplifier will cease to behave ideally.

Finite input impedances
: The *differential input impedance* of the operational amplifier is defined as the impedance *between* its

two inputs; the *common-mode input impedance* is the impedance from each input to ground. MOSFET-input operational amplifiers often have protection circuits that effectively short circuit any input differences greater than a small threshold, so the input impedance can appear to be very low in some tests. However, as long as these operational amplifiers are used in a typical high-gain negative feedback application, these protection circuits will be inactive. The input bias and leakage currents described below are a more important design parameter for typical operational amplifier applications.

Non-zero output impedance

Low output impedance is important for low-impedance loads; for these loads, the voltage drop across the output impedance of the amplifier will be significant. Hence, the output impedance of the amplifier limits the maximum power that can be provided. In a negative-feedback configuration, the output impedance of the amplifier is effectively lowered; thus, in linear applications, op-amps usually exhibit a very low output impedance indeed. Negative feedback can not, however, reduce the limitations that R_{load} in conjunction with R_{out} place on the maximum and minimum possible output voltages; it can only reduce output errors *within* that range.

Low-impedance outputs typically require high quiescent (i.e., idle) current in the output stage and will dissipate more power, so low-power designs may purposely sacrifice low output impedance.

Input current

Due to biasing requirements or leakage, a small amount of current (typically ~10 nanoamperes for bipolar op-amps, tens of picoamperes for JFET input stages, and only a few pA for MOSFET input stages) flows into the inputs. When large resistors or sources with high output impedances are used in the circuit, these small currents can produce large unmodeled voltage drops. If the input currents are matched, *and* the impedance looking *out* of *both* inputs are matched, then the voltages produced at each input will be equal. Because the operational amplifier operates on the *difference* between its inputs, these matched voltages will have no effect (unless the operational amplifier has poor CMRR, which is described below). It is more common for the input currents (or the impedances looking out of each input) to be slightly mismatched, and so a small *offset voltage* can be produced. This offset voltage can create offsets or drifting in the operational amplifier. It can often be nulled externally; however, many operational amplifiers include *offset null* or *balance* pins and some procedure for using them to remove this offset. Some operational amplifiers attempt to nullify this offset automatically.

Input offset voltage

This voltage, which is what is required across the op-amp's input terminals to drive the output voltage to zero,[6][nb 1] is related to the mismatches in input bias current. In the perfect amplifier, there would be no input offset voltage. However, it exists in actual op-amps because of imperfections in the differential amplifier that constitutes the input stage of the vast majority of these devices. Input offset voltage creates two problems: First, due to the amplifier's high voltage gain, it virtually assures that the amplifier output will go into saturation if it is operated without negative feedback, even when the input terminals are wired together. Second, in a closed loop, negative feedback configuration, the input offset voltage is amplified along with the signal and this may pose a problem if high precision DC amplification is required or if the input signal is very small.[nb 2]

Common mode gain

A perfect operational amplifier amplifies only the voltage difference between its two inputs, completely rejecting all voltages that are common to both. However, the differential input stage of an operational amplifier is never perfect, leading to the amplification of these identical voltages to some degree. The standard measure of this defect is called the common-mode rejection ratio (denoted CMRR). Minimization of common mode gain is usually important in non-inverting amplifiers (described below) that operate at high amplification.

Temperature effects
: All parameters change with temperature. Temperature drift of the input offset voltage is especially important.

Power-supply rejection
: The output of a perfect operational amplifier will be completely independent from ripples that arrive on its power supply inputs. Every real operational amplifier has a specified power supply rejection ratio (PSRR) that reflects how well the op-amp can reject changes in its supply voltage. Copious use of bypass capacitors can improve the PSRR of many devices, including the operational amplifier.

Drift
: Real op-amp parameters are subject to slow change over time and with changes in temperature, input conditions, etc.

AC imperfections

The op-amp gain calculated at DC does not apply at higher frequencies. To a first approximation, the gain of a typical op-amp is inversely proportional to frequency. This means that an op-amp is characterized by its gain-bandwidth product. For example, an op-amp with a gain bandwidth product of 1 MHz would have a gain of 5 at 200 kHz, and a gain of 1 at 1 MHz. This low-pass characteristic is introduced deliberately, because it tends to stabilize the circuit by introducing a dominant pole. This is known as frequency compensation.

Typical low cost, general purpose op-amps exhibit a gain bandwidth product of a few megahertz. Specialty and high speed op-amps can achieve gain bandwidth products of hundreds of megahertz. For very high-frequency circuits, a completely different form of op-amp called the current-feedback operational amplifier is often used.

Other imperfections include:

Finite bandwidth
: All amplifiers have a finite bandwidth. This creates several problems for op amps. First, associated with the bandwidth limitation is a phase difference between the input signal and the amplifier output that can lead to oscillation in some feedback circuits. The internal frequency compensation used in some op amps to increase the gain or phase margin intentionally reduces the bandwidth even further to maintain output stability when using a wide variety of feedback networks. Second, reduced bandwidth results in lower amounts of feedback at higher frequencies, producing higher distortion, noise, and output impedance and also reduced output phase linearity as the frequency increases.

Input capacitance
: most important for high frequency operation because it further reduces the open loop bandwidth of the amplifier.

Common mode gain
: See DC imperfections, above.

Non-linear imperfections

Saturation
: output voltage is limited to a minimum and maximum value close to the power supply voltages.[nb 3]

Saturation occurs when the output of the amplifier reaches this value and is usually due to:

- In the case of an op-amp using a bipolar power supply, a voltage gain that produces an output that is more positive or more negative than that maximum or minimum; or
- In the case of an op-amp using a single supply voltage, either a voltage gain that produces an output that is more positive than that maximum, or a signal so close to ground that the amplifier's gain is not sufficient to raise it above the lower threshold.[nb 4]

Slewing
: the amplifier's output voltage reaches its maximum rate of change. Measured as the slew rate, it is usually specified in volts per microsecond. When slewing occurs, further increases in the input signal have no effect on the rate of change of the output. Slewing is usually caused by internal capacitances in the amplifier, especially those used to implement its frequency compensation.

Non-linear input-output relationship
: The output voltage may not be accurately proportional to the difference between the input voltages. It is commonly called distortion when the input signal is a waveform. This effect will be very small in a practical circuit if substantial negative feedback is used.

Power considerations

Limited output current
: the output current must be finite. In practice, most op-amps are designed to limit the output current so as not to exceed a specified level — around 25 mA for a type 741 IC op-amp — thus protecting the op-amp and associated circuitry from damage. Modern designs are electronically more rugged than earlier implementations and some can sustain direct short circuits on their outputs without damage.

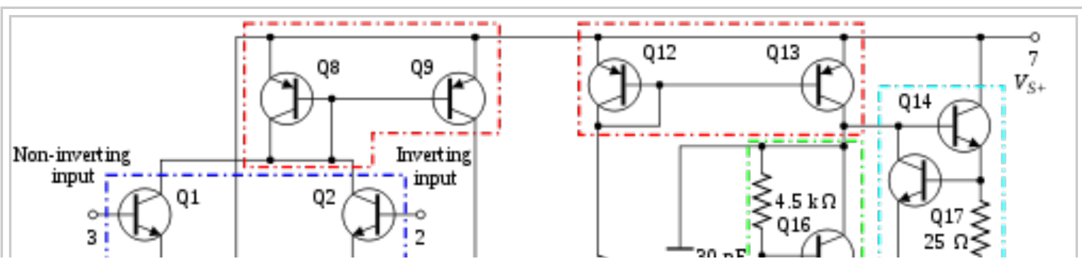
Limited dissipated power
: The output current flows through the op-amp's internal output impedance, dissipating heat. If the op-amp dissipates too much power, then its temperature will increase above some safe limit. The op-amp may enter thermal shutdown, or it may be destroyed.

Modern integrated FET or MOSFET op-amps approximate more closely the ideal op-amp than bipolar ICs when it comes to input impedance and input bias and offset currents. Bipolars are generally better when it comes to input *voltage* offset, and often have lower noise. Generally, at room temperature, with a fairly large signal, and limited bandwidth, FET and MOSFET op-amps now offer better performance.

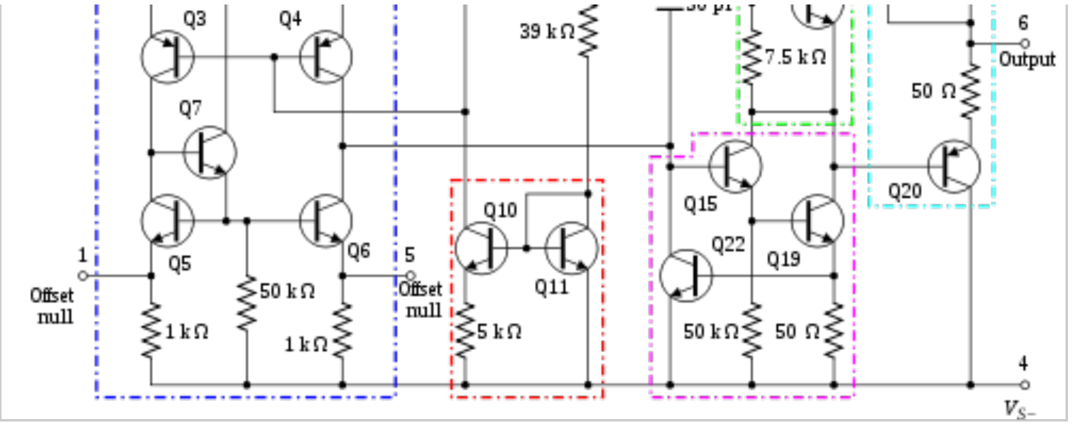
Internal circuitry of 741 type op-amp

Though designs vary between products and manufacturers, all op-amps have basically the same internal structure, which consists of three stages:

1. Differential amplifier – provides low noise amplification, high input impedance, usually a differential output.



2. Voltage amplifier – provides high voltage gain, a single-pole frequency roll-off, usually single-ended output.
3. Output amplifier – provides high current driving capability, low output impedance, current limiting and short circuit protection circuitry.



A component level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

Input stage

Constant-current stabilization system

The input stage DC conditions are stabilized by a high-gain negative feedback system whose main parts are the two current mirrors on the left of the figure, outlined in red. The main purpose of this negative feedback system—to supply the differential input stage with a stable constant current—is realized as follows.

The current through the 39 kΩ resistor acts as a current reference for the other bias currents used in the chip. The voltage across the resistor is equal to the voltage across the supply rails ($V_{S+} - V_{S-}$) minus two transistor diode drops (i.e., from Q11 and Q12), and so the current has value $I_{\text{ref}} = (V_{S+} - V_{S-} - 2V_{be})/(39\ \text{k}\Omega)$. The Widlar current mirror built by Q10, Q11, and the 5 kΩ resistor produces a very small fraction of I_{ref} at the Q10 collector. This small constant current through Q10's collector supplies the base currents for Q3 and Q4 as well as the Q9 collector current. The Q8/Q9 current mirror tries to make Q9's collector current the same as the Q3 and Q4 *collector* currents. Thus Q3 and Q4's combined base currents (which are of the same order as the overall chip's input currents) will be a small fraction of the already small Q10 current.

So, if the input stage current increases for any reason, the Q8/Q9 current mirror will draw current away from the bases of Q3 and Q4, which reduces the input stage current, and vice versa. The feedback loop also isolates the rest of the circuit from common-mode signals by making the base voltage of Q3/Q4 follow tightly $2V_{be}$ below the higher of the two input voltages.

Differential amplifier

The blue outlined section is a differential amplifier. Q1 and Q2 are input emitter followers and together with the common base pair Q3 and Q4 form the differential input stage. In addition, Q3 and Q4 also act as level shifters and provide voltage gain to drive the class A amplifier. They also help to increase the reverse V_{be} rating on the input transistors (the emitter-base junctions of the NPN transistors Q1 and Q2 break down at around 7 V but the PNP transistors Q3 and Q4 have breakdown voltages around 50 V)[7].

The differential amplifier formed by Q1–Q4 drives a current mirror active load formed by transistors Q5–Q7 (actually, Q6 is the very active load). Q7 increases the accuracy of the current mirror by decreasing the amount of signal current required from Q3 to drive the bases of Q5 and Q6. This configuration provides differential to single ended conversion as follows:

The signal current of Q3 is the input to the current mirror while the output of the mirror (the collector of Q6) is connected to the collector of Q4. Here, the signal currents of Q3 and Q4 are summed. For differential input signals, the signal currents of Q3 and Q4 are equal and opposite. Thus, the sum is twice the individual signal currents. This completes the differential to single ended conversion.

The open circuit signal voltage appearing at this point is given by the product of the summed signal currents and the paralleled collector resistances of Q4 and Q6. Since the collectors of Q4 and Q6 appear as high resistances to the signal current, the open circuit voltage gain of this stage is very high.

It should be noted that the base current at the inputs is not zero and the effective (differential) input impedance of a 741 is about 2 MΩ. The "offset null" pins may be used to place external resistors in parallel with the two 1 kΩ resistors (typically in the form of the two ends of a potentiometer) to adjust the balancing of the Q5/Q6 current mirror and thus indirectly control the output of the op-amp when zero signal is applied between the inputs.

Class A gain stage

The section outlined in magenta is the class A gain stage. The top-right current mirror Q12/Q13 supplies this stage by a constant current load, via the collector of Q13, that is largely independent of the output voltage. The stage consists of two NPN transistors in a Darlington configuration and uses the output side of a current mirror as its collector load to achieve high gain. The 30 pF capacitor provides frequency selective negative feedback around the class A gain stage as a means of frequency compensation to stabilise the amplifier in feedback configurations. This technique is called Miller compensation and functions in a similar manner to an op-amp integrator circuit. It is also known as 'dominant pole compensation' because it introduces a dominant pole (one which masks the effects of other poles) into the open loop frequency response. This pole can be as low as 10 Hz in a 741 amplifier and it introduces a −3 dB loss into the open loop response at this frequency. This internal compensation is provided to achieve unconditional stability of the amplifier in negative feedback configurations where the feedback network is non-reactive and the closed loop gain is unity or higher. Hence, the use of the operational amplifier is simplified because no external compensation is required for unity gain stability; amplifiers without this internal compensation may require external compensation or closed loop gains significantly higher than unity.

Output bias circuitry

The green outlined section (based on Q16) is a voltage level shifter or rubber diode (i.e., a V_{BE} multiplier); a type of voltage source. In the circuit as shown, Q16 provides a constant voltage drop between its collector and emitter regardless of the current through the circuit. If the base current to the transistor is assumed to be zero, and the voltage between base and emitter (and across the 7.5 kΩ resistor) is 0.625 V (a typical value for a BJT in the active region), then the current through the 4.5 kΩ resistor will be the same as that through the 7.5 kΩ, and will produce a voltage of 0.375 V across it. This keeps the voltage across the transistor, and the two resistors at 0.625 + 0.375 = 1 V. This serves to bias the two output transistors slightly into conduction reducing crossover distortion. In some discrete component amplifiers this function is achieved with (usually two) silicon diodes.

Output stage

The output stage (outlined in cyan) is a Class AB push-pull emitter follower (Q14, Q20) amplifier with the bias set by the V_{be} multiplier voltage source Q16 and its base resistors. This stage is effectively driven by the collectors of Q13 and Q19. Variations in the bias with temperature, or between parts with the same type number, are common so crossover distortion and quiescent current may be subject to significant variation. The output range of the amplifier is about one volt less than the supply voltage, owing in part to V_{be} of the output transistors Q14 and Q20.

The 25 Ω resistor in the output stage acts as a current sense to provide the output current-limiting function which limits the current in the emitter follower Q14 to about 25 mA for the 741. Current limiting for the negative output is done by sensing the voltage across Q19's emitter resistor and using this to reduce the drive into Q15's base. Later versions of this amplifier schematic may show a slightly different method of output current limiting. The output resistance is not zero, as it would be in an ideal op-amp, but with negative feedback it approaches zero at low frequencies.

Note: while the 741 was historically used in audio and other sensitive equipment, such use is now rare because of the improved noise performance of more modern op-amps. Apart from generating noticeable hiss, 741s and other older op-amps may have poor common-mode rejection ratios and so will often introduce cable-borne mains hum and other common-mode interference, such as switch 'clicks', into sensitive equipment.

The "741" has come to often mean a generic op-amp IC (such as uA741, LM301, 558, LM324, TBA221 - or a more modern replacement such as the TL071). The description of the 741 output stage is qualitatively similar for many other designs (that may have quite different input stages), except:

- Some devices (uA748, LM301, LM308) are not internally compensated (require an external capacitor from output to some point within the operational amplifier, if used in low closed-loop gain applications).
- Some modern devices have rail-to-rail output capability (output can be taken to positive or negative power supply rail within a few millivolts).

See also

- Operational amplifier applications
- Differential amplifier
- Instrumentation amplifier
- Active filter
- Current-feedback operational amplifier
- Operational transconductance amplifier
- George A. Philbrick
- Analog computer
- Negative feedback amplifier

Notes

1. ^ This definition hews to the convention of measuring op-amp parameters with respect to the zero voltage point in the circuit, which is usually half the total voltage between the amplifier's positive and negative power rails.
2. ^ Many older designs of operational amplifiers have offset null inputs to allow the offset to be manually adjusted away. Modern precision op-amps can have internal circuits that automatically cancel this offset using choppers or other circuits that measure the offset voltage periodically and subtract it from the input voltage.
3. ^ That the output cannot reach the power supply voltages is usually the result of limitations of the amplifier's output stage transistors. See "Output stage," below.
4. ^ The output of older op-amps can reach to within one or two volts of the supply rails. The output of newer so-called "rail to rail" op-amps can reach to within millivolts of the supply rails when providing low output currents.

References

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6. ^ D.F. Stout *Handbook of Operational Amplifier Circuit Design* (McGraw-Hill, 1976, ISBN 007061797X) pp. 1–11.
7. ^ The uA741 Operational Amplifier (http://ecow.engr.wisc.edu/cgi-bin/get/ece/342/schowalter/notes/chapter10/theua741operationalamplifier.ppt)

External links

- Introduction to op-amp circuit stages, second order filters, single op-amp bandpass filters, and a simple intercom (http://www.bowdenshobbycircuits.info/opamp.htm)
- Hyperphysics – descriptions of common applications (http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/opampvar.html)
- Single supply op-amp circuit collection (http://instruct1.cit.cornell.edu/courses/bionb440/datasheets/SingleSupply.pdf)
- Op-amp circuit collection (http://www.national.com/an/AN/AN-31.pdf)
- Another introduction (http://web.telia.com/~u85920178/begin/opamp00.htm)
- Op-Amp Handbook (http://www.engineering.uiowa.edu/~bme080/supplementary_info/BBTI_AppCkts.pdf)
- Opamps for everyone (http://focus.ti.com/lit/an/slod006b/slod006b.pdf) Downloadable book.
- *MOS op amp design: A tutorial overview* (http://www.ee.unb.ca/Courses/EE3122/DFL/AdditionalMaterial/OpAmps/MOS_OpAmpTutorial.pdf)
- *High Speed OpAmp Techniques* (http://cds.linear.com/docs/Application%20Note/an47fa.pdf) very practical and readable - with photos and real waveforms
- Op Amp Applications (http://www.analog.com/library/analogDialogue/archives/39-05/op_amp_applications_handbook.html) Downloadable book. Can also be bought
- Operational Amplifier Noise Prediction (All Op Amps) (http://www.intersil.com/data/an/an519.pdf) using spot noise
- Operational Amplifier Basics (http://www.williamson-labs.com/480_opam.htm)
- History of the Op-amp (http://www.analog.com/library/analogDialogue/archives/39-

05/Web_ChH_final.pdf) from vacuum tubes to about 2002. Lots of detail, with schematics. IC part is somewhat ADI-centric.
- IC Op-Amps Through the Ages (http://www.calvin.edu/~pribeiro/courses/engr332/Handouts/ho18opamp.pdf)
- ECE 209: Operational amplifier basics (http://www.tedpavlic.com/teaching/osu/ece209/support/opamp_basics.pdf) – Brief document explaining zero error by naive high-gain negative feedback. Gives single OpAmp example that generalizes typical configurations.