**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](http://en.wikipedia.org/wiki/Differential_amplifier) — provides low noise amplification, high [input impedance](http://en.wikipedia.org/wiki/Input_impedance), usually a differential output.
2. Voltage amplifier — provides high voltage gain, a single-pole frequency [roll-off](http://en.wikipedia.org/wiki/Roll-off), usually single-ended output.
3. Output amplifier — provides high current driving capability, low [output impedance](http://en.wikipedia.org/wiki/Output_impedance), current limiting and short circuit protection circuitry.

**Input stage**

The input stage is a composed [differential amplifier](http://en.wikipedia.org/wiki/Differential_amplifier) with a complex biasing circuit and a current mirror [active load](http://en.wikipedia.org/wiki/Active_load).

**Differential amplifier**

It is implemented by two cascaded stages satisfying the conflicting requirements. The first stage consists of the NPN-based input [emitter followers](http://en.wikipedia.org/wiki/Emitter_follower) Q1 and Q2 that provide high input impedance. The next is the PNP-based [common base](http://en.wikipedia.org/wiki/Common_base) pair Q3 and Q4 that eliminates the undesired [Miller effect](http://en.wikipedia.org/wiki/Miller_effect), shifts the voltage level downwards and provides a sufficient voltage gain to drive the next class A amplifier. The PNP transistors also help to increase the reverse *V*BE rating (the base-emitter 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).[[10]](http://en.wikipedia.org/wiki/Operational_amplifier#cite_note-14)

**Biasing circuit**

The classical [emitter-coupled differential stage](http://en.wikipedia.org/wiki/Differential_amplifier#Long-tailed_pair) is biased from the side of the emitters by connecting a constant current source to them. The series negative feedback (the emitter degeneration) makes the transistors act as voltage stabilizers; it forces them to adjust their *V*BE voltages so that to pass the current through their collector-emitter junctions. As a result, *the quiescent current is β-independent*.

Here, the Q3/Q4 emitters are already used as inputs. Their collectors are separated and cannot be used as inputs for the quiescent current source since they behave as current sources. So, the quiescent current can be set only from the side of the bases by connecting a constant current source to them. To make it not depend on β as above, a negative but parallel feedback is used. For this purpose, the total quiescent current is mirrored by Q8-Q9 current mirror and the negative feedback is taken from the Q9 collector. Now it makes the transistors Q1-Q4 adjust their *V*BE voltages so that to pass the desired quiescent current. The effect is the same as at the classical emitter-coupled pair — *the quiescent current is β-independent*. It is interesting fact that "to the extent that all PNP βs match, this clever circuit generates just the right β-dependent base current to produce a β-independent collector current".[[9]](http://en.wikipedia.org/wiki/Operational_amplifier#cite_note-Lee-13) The biasing base currents are usually provided only by the negative power supply; they should come from the ground and enter the bases. But to ensure maximum high input impedances, the biasing loops are not internally closed between the base and ground; it is expected they will be closed externally by the input sources. So, the sources have to be galvanic (DC) to ensure paths for the biasing currents and low resistive enough (tens or hundreds kilohms) to not create significant voltage drops across them. Otherwise, additional DC elements should be connected between the bases and the ground (or the positive power supply).

The quiescent current is set by the 39 kΩ resistor that is common for the two current mirrors Q12-Q13 and Q10-Q11. The current determined by this resistor acts also as a reference for the other bias currents used in the chip. The [Widlar current mirror](http://en.wikipedia.org/wiki/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 collector current the same as the Q3 and Q4 collector currents and succeeds with the help of the negative feedback. The Q9 collector voltage changes until the ratio between the Q3/Q4 base and collector currents becomes equal to β. Thus Q3 and Q4's combined base currents (which are of the same order as the overall chip's input currents) are a small fraction of the already small Q10 current.

Thus the quiescent current is set by Q10-Q11 current mirror without using a current-sensing negative feedback. The voltage-sensing negative feedback only helps this process by stabilizing Q9 collector (Q3/Q4 base) voltage.[[nb 5]](http://en.wikipedia.org/wiki/Operational_amplifier#cite_note-15) The feedback loop also isolates the rest of the circuit from [common-mode signals](http://en.wikipedia.org/wiki/Common-mode_signal) by making the base voltage of Q3/Q4 follow tightly 2*V*BE below the higher of the two input voltages.

**Current mirror active load**

The differential amplifier formed by Q1–Q4 drives an [active load](http://en.wikipedia.org/wiki/Active_load) implemented as an improved current mirror (Q5–Q7) whose role is to convert the differential current input signal to a single ended voltage signal without the intrinsic 50% losses and to greatly increase the gain. This is achieved by copying the input signal from the left to the right side where the magnitudes of the two input signals add (Widlar used the same trick in μA702 and μA709). For this purpose, the input of the current mirror (Q5 collector) is connected to the left output (Q3 collector) and the output of the current mirror (Q6 collector) is connected to the right output of the differential amplifier (Q4 collector). 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.

**Operation**

**Differential mode**

The input voltage sources are connected through two "diode" strings, each of them consisting of two connected in series base-emitter junctions (Q1-Q3 and Q2-Q4), to the common point of Q3/Q4 bases. So, if the input voltages change slightly in opposite directions, Q3/Q4 bases stay at relatively constant voltage and the common base current does not change as well; it only vigorously steers between Q3/Q4 bases and makes the common quiescent current distribute between Q3/Q4 collectors in the same proportion.[[nb 6]](http://en.wikipedia.org/wiki/Operational_amplifier#cite_note-16) The current mirror inverts Q3 collector current and tries to pass it through Q4. In the middle point between Q4 and Q6, the signal currents (current changes) of Q3 and Q4 are subtracted. In this case (differential input signal), they are equal and opposite. Thus, the difference is twice the individual signal currents (Δ*I* − (−Δ*I*) = 2Δ*I*) and the differential to single ended conversion is completed without gain losses. The open circuit signal voltage appearing at this point is given by the product of the subtracted signal currents and the total circuit impedance (the paralleled collector resistances of Q4 and Q6). Since the collectors of Q4 and Q6 appear as high differential resistances to the signal current (Q4 and Q6 behave as current sources), the open circuit voltage gain of this stage is very high.[[nb 7]](http://en.wikipedia.org/wiki/Operational_amplifier#cite_note-17)

More intuitively, the transistor Q6 can be considered as a duplicate of Q3 and the combination of Q4 and Q6 can be thought as of a varying voltage divider composed of two voltage-controlled resistors. For differential input signals, they vigorously change their instant resistances in opposite directions but the total resistance stays constant (like a potentiometer with quickly moving slider). As a result, the current stays constant as well but the voltage at the middle point changes vigorously. As the two resistance changes are equal and opposite, the effective voltage change is twice the individual change.

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.

**Common mode**

If the input voltages change in the same direction, the negative feedback makes Q3/Q4 base voltage follow (with 2*V*BE below) the input voltage variations. Now the output part (Q10) of Q10-Q11 current mirror keeps up the common current through Q9/Q8 constant in spite of varying voltage. Q3/Q4 collector currents and accordingly, the output voltage in the middle point between Q4 and Q6, remain unchanged.

**Class A gain stage**

The section outlined in [magenta](http://en.wikipedia.org/wiki/Magenta) is the [class A](http://en.wikipedia.org/wiki/Electronic_amplifier#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 the two NPN transistors Q15/Q19 connected in a [Darlington configuration](http://en.wikipedia.org/wiki/Darlington_transistor) and uses the output side of a current mirror as its collector (dynamic) load to achieve high [gain](http://en.wikipedia.org/wiki/Gain). The transistor Q22 prevents this stage from saturating by diverting the excessive Q15 base current (it acts as a [Baker clamp](http://en.wikipedia.org/wiki/Baker_clamp)).

The 30 pF capacitor provides frequency selective negative feedback around the class A gain stage as a means of [frequency compensation](http://en.wikipedia.org/wiki/Frequency_compensation) to stabilise the amplifier in feedback configurations. This technique is called [Miller compensation](http://en.wikipedia.org/wiki/Miller_effect) and functions in a similar manner to an op-amp [integrator](http://en.wikipedia.org/wiki/Integrator) circuit. It is also known as 'dominant [pole](http://en.wikipedia.org/wiki/Pole_%28complex_analysis%29) compensation' because it introduces a dominant pole (one which masks the effects of other poles) into the [open loop](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/BIBO_stability) of the amplifier in negative feedback configurations where the feedback network is non-reactive and the [closed loop](http://en.wikipedia.org/wiki/Electronic_feedback_loops) gain is [unity](http://en.wikipedia.org/wiki/Unity_%28mathematics%29) 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 such as the 748 may require external compensation or closed-loop gains significantly higher than unity.

**Output bias circuitry**

The circuit presented as a negative feedback amplifier with constant input voltage

The green outlined section (based on Q16) is a voltage level shifter named *rubber diode*, *transistor Zener* or *VBE multiplier*. In the circuit as shown, Q16 provides a constant voltage drop across its collector-emitter junction regardless of the current through it (it acts as a voltage stabilizer). This is achieved by introducing a negative feedback between Q16 collector and its base, i.e. by connecting a voltage divider with ratio β = 7.5 kΩ / (4.5 kΩ + 7.5 kΩ) = 0.625 composed by the two resistors. If the base current to the transistor is assumed to be zero, the negative feedback forces the transistor to increase its collector-emitter voltage up to 1 V until its base-emitter voltage reaches 0.625 V (a typical value for a BJT in the active region). This serves to bias the two output transistors slightly into conduction reducing [crossover distortion](http://en.wikipedia.org/wiki/Crossover_distortion) (in some discrete component amplifiers, this function is usually achieved with a string of two silicon diodes).

The circuit can be presented as a negative feedback voltage amplifier with constant input voltage of 0.625 V and a feedback ratio of β = 0.625 (a gain of 1/β = 1.6). The same circuit but with β = 1 is used in the input current-setting part of the classical [BJT current mirror](http://en.wikipedia.org/wiki/Current_mirror#Basic_bipolar_transistor_mirror).

**Output stage**

The output stage (outlined in [cyan](http://en.wikipedia.org/wiki/Cyan)) is a [Class AB](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Crossover_distortion) and [quiescent current](http://en.wikipedia.org/wiki/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.