EE 3444
Operational Amplifier

An operational amplifier typically consists of 3 stages: differential amplifier, a single ended amplifier, and an output stage. Some have only two stages and others may have 4 or more. Each of the three stages in the typical amplifier are designed to provide very specific functions.

First Stage This stages provides a differential input, a high input impedance, a conversion to a single ended output and some DC level shifting.

Second Stage This stage provides high voltage gain and high input impedance so as not to load down the first stage.

Third Stage This is usually a class B amplifier using complementary transistors connected in the emitter follower configuration. As such the gain is less than 1, but it provides high input impedance so as not to load down the second stage, and low output impedance. The output transistors are often made larger than the others in order to handle relatively high output power.

CA 3096 Operational Amplifier
A diagram for the CA 3096 is shown in various texts. It consists of a differential amplifier (Q1 and Q2), a common emitter PNP transistor (Q4) for gain and level shifting, and the class B output stage (Q3 and Q5).

\[
\begin{align*}
I_{EE} &= \frac{-V_{BE1} - (V_{EE})}{R_3} \\
&= I_{C1} + I_{C2} \\
&= 2I_{C2}
\end{align*}
\]
Since the output is at 0 volts, the collector of the PNP second stage is at zero ($V_C = 0$). Therefore the voltage across $R_5$ is

$$V_{R5} = -I_C R_5 = -V_{EE}$$

Using the Kirchhoff voltage law,

$$I_{C2} R_2 = I_C R_4 + V_{EB4}$$

The voltage at the collectors of Q1 and Q2 is

$$V_C1 = V_C2 = V_CC - I_C R_2$$

**Small Signal Circuit.** The overall gain of the amplifier is

$$A_v = \frac{v_o}{v_{id}} = A_{v1} \cdot A_{v2} \cdot A_{v3}
= \frac{v_{C2}}{v_{id}} \cdot \frac{v_{C4}}{v_{C2}} \cdot \frac{v_o}{v_{C4}}.$$

For $A_{v1}$ use the half circuit for differential gain.

$$A_{v1} = g_{m2}(r_{o2||R_2||R_{id}})/2$$

where $R_{id} \approx r_{\pi4} + (1 + \beta_4)R_4$. For $A_{v3}$ the transistor configuration is a common emitter with emitter degeneracy. The gain for this configuration is

$$A_{v2} = \frac{-g_{m4} R_5}{1 + g_{m4} R_4}$$

For $A_{v3}$, either the NPN or PNP is on while the other is off. Here, assume Q3 is on and Q5 is off. The gain for an emitter follower is approximately 1, so use $A_{v3} = 1$. The total gain is then,

$$A_v = \frac{g_{m2} R_2}{2} \cdot \frac{-g_{m4} R_5}{1 + g_{m4} R_4} \cdot 1$$

The differential input resistance is approximately $2r_{\pi}$. The output resistance at Q3 is

$$R_{o3} = \frac{r_{\pi3} + R_5}{1 + \beta_3}$$

As a numerical example consider that circuit has the following values.

$V_{CC} = V_{EE} = 15$, $R_L = 10$ k$\Omega$, $\beta_1 = \beta_2 = \beta_3 = 390$, and $\beta_4 = 75$. Try to achieve $A_{v1} = 40$ and $A_{v2} = 10$.

$I_{C2} R_2$ determines also $I_C R_4$. For $R_2 = 10$ k$\Omega$,

$$I_{C2} = A_{v1} 2 V_T / R_2 = 208 \mu A$$

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Then $I_{C4}R_4 = 1.48$ V. For large $\beta$,

$$A_{v2} = \frac{-g_{m4}R_5}{1 + g_{m4}R_4} \approx \frac{R_5}{R_4}$$

For $A_{v2} \approx 10$ choose $R_5 = 30 \, \text{k} \Omega$. So $R_4 = \frac{R_5}{A_{v2}} = 3000 \, \Omega$. Therefore

\[
I_{C4} = \frac{1.48}{R_4} = 493.3 \, \mu\text{A}
\]

\[
g_{m4} = 189.7 \, \text{mS}
\]

The actual gain for the second stage is 9.827 and the total system gain is $A_v = 393.1$.

The input resistance to Q4 is

\[
R_{i4} = r_{\pi4} + (1 + \beta_4)R_4
\]

\[
= 231.95 \, \text{k} \Omega
\]

Since this is large, it does not load the first stage appreciably. For the first stage,

\[
R_{id} = 2r_{\pi2}
\]

\[
= 97.5 \, \text{k} \Omega
\]

The output resistance will be based on the average collector current of Q5 which is $I_{C5} = 7.4$ mA since $(V_{CC} - V_{CEsat}) = 14.8$ mA. The output resistance is then

\[
R_o = \frac{r_{\pi3} + R_5}{1 + \beta_3}
\]

\[
= 80.23 \, \Omega
\]

**The μA741 Operational Amplifier**

The μA741 operational amplifiers were first introduced in 1966 and of course since then many improvements have been made in circuit design for special applications. Most of the new designs of the voltage feedback operational amplifier type retain much of the same architecture. The μA741 itself remains as a standard device till this day. Like the CA 3096, the μA741 has basically 3 stages:

1. Differential stage – high gain and high $Z_{in}$
2. Single ended stage – high gain
3. Output stage – low $Z_{out}$, high power
Stage 1, Q1 - Q7

The input to the whole operational amplifier is the differential amplifier, Q1 and Q2. The load for this circuit is in the emitter, i.e. Q3 and Q4. This connection provides a large value for $R_{id}$ It also gives a large voltage to Q3 and Q4 which are in a common base configuration.

Q5 and Q6 are active loads for Q3 and Q4. Their large resistance preserves the large voltage gain. Q7 reduces the error between $I_{C5}$ and $I_{C6}$ by supplying base current to Q5 and Q6 from the power supply rather than robbing it from $I_{C5}$.

Stage 2. Q16, Q17

Q16 is an emitter follower which has low output impedance. Thus Q17 is not loaded by Q16. The resistance, $R_s$, provides voltage level shifting above $V_{EE}$ and its feedback stabilizes the gain of Q17. Transistor Q13B provides the bias current for Q17. The output of Q17 is fed into Q23.

Stage 3. Q23, Q14, Q20 and ancillary transistors

Transistor Q23 is used to isolate or buffer the output of Q17 from Q14, Q20. The signal is applied to the base of Q14 and Q20 which is a class B amplifier. The load on the emitter of Q23A sees Q18, Q19 is series with Q13A. This is all in parallel with Q14 or Q20, whichever is conducting at the moment.

The internal capacitance, C, is used for compensation. This is typically 30 pF.
**DC Analysis**

The DC currents must be determined first before finding the AC equivalent circuit values. The collector of Q12 is \( V_{CC} - V_{EB12} \). The collector of Q11 is \( V_{EE} + V_{BE11} \). Therefore the current flowing through \( R_5 \) is

\[
I_{R5} = \frac{V_{CC} - V_{EB12} - V_{EE} - V_{BE11}}{R_5}
\]

When the typical values of \( V_{CC} = -V_{EE} = 15 \), \( |V_{BE}| = 0.6 \), and \( R_5 = I_{C12} = I_{C11} = 715 \mu A \).

Transistors Q11 and Q10 form a Widlar current mirror, so \( I_{C10} \) is determined to be 18.9 \( \mu A \) which is the same as \( I_{C9} \). This current splits evenly down the first stage.

\[
I_{C1} = I_{C2} = I_{C3} = I_{C4} = I_{C5} = I_{C6} = 9.45 \mu A
\]

Transistors Q12 and Q13 form a current mirror where Q13B takes 3/4 of the current and Q13A takes 1/4 of the current. In the transistor layout this is done by making the A part take 1/4 of the collector area and the B part take 3/4 of the collector area.

For Q16,

\[
I_{C16} = I_{B17} + \frac{V_{R9}}{R_9}
= \frac{I_{C17}}{\beta_{17}} + \frac{V_T \ln(I_{C17}/I_{S17}) + I_{C17} \cdot R_8}{R_9}
\]

But \( I_{C17} \) is the same as \( I_{C13B} \). So a value for \( I_{C16} \) can be found. This is typically \( \approx 17.4 \mu A \). New values for \( I_{C18} \) and \( I_{C19} \) can be found.

\[
I_{C18} = -I_{C13A} - I_{C19}
\]

where

\[
I_{C19} \approx \frac{V_{BE18}}{R_{10}} = 14 \mu A
\]

and therefore

\[
I_{C14} = -I_{C20} = \sqrt{I_{C18}I_{C19}} \sqrt{\frac{I_{S14}I_{S20}}{I_{S18}I_{S19}}} = 144 \mu A
\]

The protection circuit transistors, Q15 and Q21, are normally off. The resistances \( R_6 \) and \( R_7 \) have small values typically around 22 to 27 \( \Omega \). When Q14, for example, draws a large current to the load, then \( V_{R6} > V_{BE15} \) so that Q15 turns on. It shunts the base current, \( I_{B14} \) directly to the load, thus keeping Q14 from burning up.