Section G5: The Typical Op-Amp

As was mentioned earlier, practical transistor amplification systems are usually composed of a number of stages connected in series, or cascaded. This strategy allows desired output and/or response characteristics to be achieved without excessive power use and/or signal degradation – remember our watchwords of linearity and efficiency. Specifically with respect to operational amplifiers, a typical configuration is shown in block diagram form in Figure 9.8 of your text, which has been reproduced below.

A brief recap of the main function(s) of each stage is as follows:

- The **input stage**, or **differential amplifier**, provides the common-mode rejection (defined by the CMRR) that is crucial to op-amp operation. It also supplies the large input impedance (recall that an ideal op-amp has infinite input impedance) that allows coupling to a high impedance source without loss of signal level. The differential amplifier may also provide voltage gain if the output of the differential amplifier is connected to an emitter follower with a large emitter resistor. The EF amplifier will provide a high impedance load to the differential amplifier to obtain a high voltage gain.

- The **intermediate stages** are shown as the voltage gain stage and the level shifter in the figure above. The **voltage gain stage** usually consists of one or more CE amplifiers to provide the bulk of the overall voltage gain. Linear operational amplifiers are direct coupled to eliminate the need for coupling capacitors that are too large to be placed on an IC chip (please review D7 for a discussion on direct coupling). The **level shifter stage** may be one or more level shifters that are included to ensure that there is no dc offset in the output signal. In addition, these intermediate stages may be used to convert the signal from differential (double-ended) mode to single-ended mode.

- The **output stage**, or **power output stage**, also serves a dual purpose. It must supply the current required by the load without dissipating too much power in the output transistors. Also, the output stage should provide a low output impedance to allow coupling to a low impedance load without loss of gain (recall that an ideal op-amp has zero output impedance).

Many op-amps require both a positive and negative dc supply as illustrated in Figure 9.12 of your text. The connections for the dc supplies are indicated
on the manufacturer’s spec sheets by +V and -V (compared with \( v_+ \) and \( v_- \) for the non-inverting and inverting inputs). Please refer to section E2 of the WebCT notes and Figures 9.9 through 9.11 of your text for clarification. The dc voltage(s) supplied to the op-amp limits the maximum achievable voltage swing of the output. If the op-amp can be operated from a single dc supply, the manufacturer’s specifications will define the limits of operation.

**The 741 Op-Amp**

The workhorse of the op-amp world is probably the 741. This IC has been around since 1966 and is still produced by almost all analog IC manufacturers. The 741 op-amp circuit is shown below – **note that Figure 9.13 of your text is incorrect**. Please also note that the schematic of the LM741 spec sheet in the back of your text does not include transistors \( Q_{21} \), \( Q_{23} \) and \( Q_{24} \), and that some of the circuitry of the intermediate and output stages may be presented in a slightly different form. This is representative of actual device selection and should not cause too much heartburn – although devices from several manufacturers carry the 741 notation, they may differ slightly in the details of implementation. The circuit presented below and discussed in the remainder of this section is actually slightly more sophisticated than the LM741 schematic of your text.

The 741 is internally compensated by means of an on-chip resistor-capacitor (RC) network. We’re going to talk about frequency response, compensation and stability in future sections, but for now we’re just going to define the internal compensation of the 741 as the means by which the op-amp
maintains stability while still having a high gain and large operational frequency range (i.e., bandwidth).

The 741 consists of three stages: an input differential stage, an intermediate single-ended high gain stage, and an output buffering stage. Other necessary components are a level shifter, bias circuitry, and circuitry that protects the op-amp from short-circuits at the output. Each of these components is studied in the following discussion.

**Bias Circuitry**

The reference bias current for the entire 741 circuit is generated in the branch containing the diode-connected transistors Q₁₁ and Q₁₂ and the resistor R₅. The bias current for the first stage is generated in the collector of Q₁₀ from the Widlar current source composed of Q₁₀, Q₁₁ and R₄. The current mirror formed by transistors Q₈ and Q₉ provide the bias current (Iₑₑ) of the differential amplifier formed by Q₁, Q₂, Q₃ and Q₄.

**Short Circuit Protection Circuitry**

The 741 circuit contains several transistors that are normally off and that turn on (conduct) only when a large current exists at the output. In the circuit above, the short circuit protection is provided by Q₁₅, Q₂₁, Q₂₂, Q₂₄, R₆ and R₇. The function of this network is to limit the current in the output transistors – all to prevent overheating and possible burnout of the IC (i.e., it keeps from letting the smoke out). Refer to the figure above for the following analysis of the short circuit protection circuitry.

- The transistor Q₁₅ is in the normally off state. If the current in the emitter leg of Q₁₄ becomes too large, the voltage drop across R₆ will become large enough to turn Q₁₅ on. Once Q₁₅ is turned on, its collector will bleed off some of the current supplied by Q₁₃, thereby reducing the base current to Q₁₄ and the emitter current of Q₁₄. This limits the maximum current that the op-amp can source, or supply from the output terminal in the outward direction.

- The current through Q₂₀ is limited in a similar fashion, where the relevant components are Q₂₁, Q₂₂, Q₂₄, and R₇. If the current through Q₂₀ becomes too large, the voltage drop across R₇ turns Q₂₁ on. Once Q₂₁ is turned on, its collector will bleed off some of the current supplied by the current mirror formed by Q₂₂ and Q₂₄, reducing the base current (and therefore the emitter current) of Q₂₀. This mechanism limits the maximum current that the op-amp can sink, or draw from the output terminal in the inward direction.
**Input Stage**

The input stage of the 741 involves transistors Q1 through Q7 and resistors R1 through R3. Transistors Q1 and Q2 behave as emitter followers, which yields a large input impedance at the non-inverting and inverting input terminals, and delivers the differential input signal to the common-base amplifier formed by Q3 and Q4. Level shifting is provided in the input stage by the lateral pnp transistors, Q3 and Q4. As we will discuss in later sections, using the common-base configuration (which has a good high frequency response) compensates for the poor high frequency performance of the lateral pnp transistors so that the overall op-amp frequency response is not seriously degraded. An advantage of using the lateral pnp transistors Q3 and Q4 is the protection of the input transistors (Q1 and Q2) against emitter-base junction (EBJ) breakdown. The EBJ breakdown of npn transistors is about 7V, while the EBJ breakdown of a lateral pnp transistor is approximately 50V. Since the pnp transistors are in series with the npn, the breakdown voltage of the entire input circuit is increased.

Transistors Q5, Q6, and Q7 and resistors R1, R2, and R3 form the active load circuit of the input stage. This load circuit provides a high resistance load and converts the signal from differential (double-ended) to single-ended with no loss of gain or common-mode rejection (CMRR). The single-ended output of the input stage is taken from the collector of Q6.

**Intermediate Stage**

The intermediate stage of the 741 is composed of transistors Q13, Q16, Q17, and resistors R8 and R9. The single-ended output of the input stage is connected to the base of Q16, which is in the emitter-follower configuration. The EF configuration is used since it has a high input impedance, which minimizes the loading of the first stage and avoids the loss of gain. Transistor Q17 is configured as a common-emitter with R8 in the emitter lead. The load for the CE amplifier is the large output resistance of the pnp current source (Q13), that is used as an active load, in parallel with the input resistance of the output stage (found by looking into the base of Q23).

The output of the intermediate stage is taken from the collector of Q17. The capacitor C1 is in the feedback path of the intermediate stage to provide frequency compensation – something we’ll get into a little later!

**Output Stage**

The output stage of the 741 consists of transistors Q14, Q18, Q19, Q20, and Q23. The input to the final stage is at Q23, which is configured as an emitter-
follower amplifier to minimize the loading effect of the output stage on the intermediate stage. The EF configuration also provides additional buffering, an advantage that makes the op-amp gain almost independent of the output transistor parameters.

Transistors \( Q_{14} \) and \( Q_{20} \) are a complementary symmetry (push-pull) pair, or Class AB amplifier, a strategy that increases efficiency without sacrificing current gain as discussed in section F4. Your author notes that some op-amps use Darlington pair complementary symmetry to increase the output capability.

The Darlington pair made up of \( Q_{18} \) and \( Q_{19} \) is fed by the current source \( Q_{13} \) and is used to bias the output transistors \( Q_{14} \) and \( Q_{20} \). The Darlington pair replaces the diodes in the diode-compensated complementary symmetry output stage and is preferred over two individual transistors connected as diodes since it can be fabricated in a smaller area.

**Whew!**

The 741 is a pretty well behaved IC that can be treated as a single device. However, since the early days, many advancements have been made in op-amp circuitry – providing specialized devices and those that even more closely approach the ideal. Adding more amplification stages, providing isolating of the input circuits, and decreasing the output impedance by adding more emitter followers in the output stage are just some of the strategies that may further improve the operational characteristics of the op-amp. These, and other, improvements result in an increased common-mode rejection ratio (CMRR), higher input impedance, lower output impedance, larger bandwidth and/or increased power.

Manufacturer’s specifications provide the characteristics and major parameters of the op-amp under various operational conditions. Spec sheets may also provide recommended typical applications and examples of external circuits, as well as IC pinouts and device requirements.