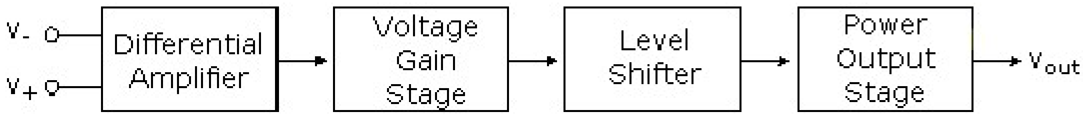
Section G5: The Typical Op-Amp

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.



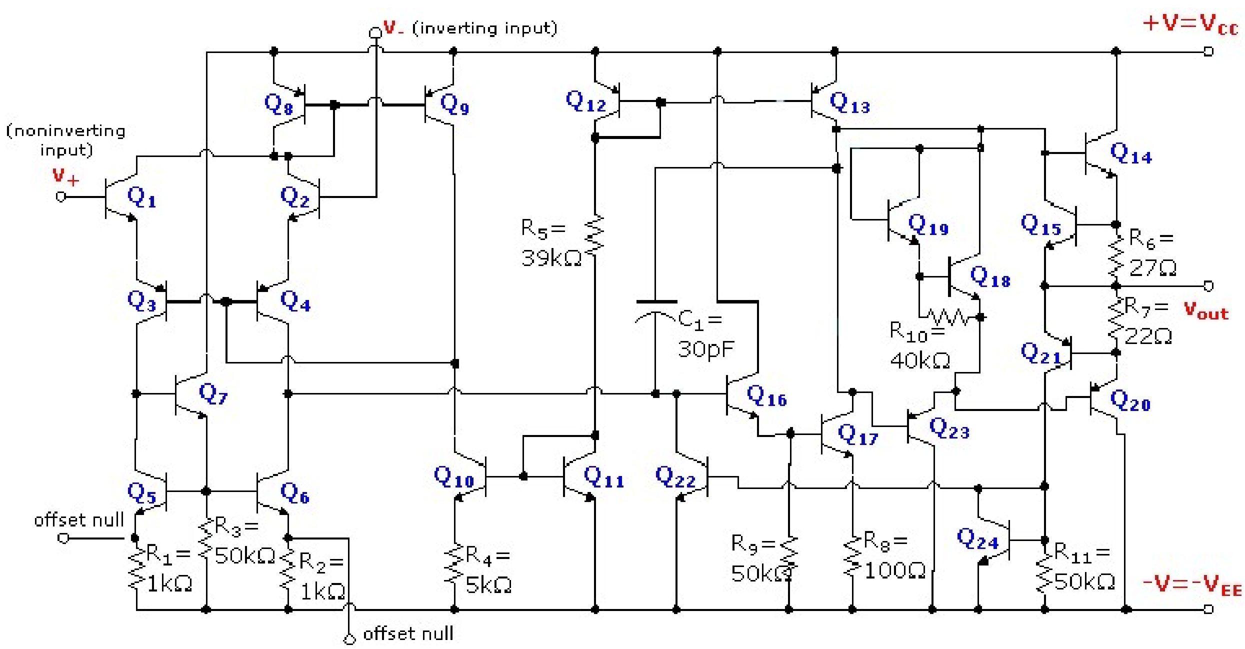
A brief recap of the main function(s) of each stage is as follows:

- 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 Q_{11} and Q_{12} and the resistor R_5. The bias current for the first stage is generated in the collector of Q_{10} from the Widlar current source composed of Q_{10}, Q_{11} and R_4. The current mirror formed by transistors Q_8 and Q_9 provide the bias current (I_{EE}) of the differential amplifier formed by Q_1, Q_2, Q_3 and Q_4.

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 Q_{15}, Q_{21}, Q_{22}, Q_{24}, R_6 and R_7. 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 Q_{15} is is the normally off state. If the current in the emitter leg of Q_{14} becomes too large, the voltage drop across R_6 will become large enough to turn Q_{15} on. Once Q_{15} is turned on, its collector will bleed off some of the current supplied by Q_{13}, thereby reducing the base current to Q_{14} and the emitter current of Q_{14}. This limits the maximum current that the op-amp can source, or supply from the output terminal in the outward direction.
- The current through Q_{20} is limited in a similar fashion, where the relevant components are Q_{21}, Q_{22}, Q_{24}, and R_7. If the current through Q_{20} becomes too large, the voltage drop across R_7 turns Q_{21} on. Once Q_{21} is turned on, its collector will bleed off some of the current supplied by the current mirror formed by Q_{22} and Q_{24}, reducing the base current (and therefore the emitter current) of Q_{20}. 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 Q_1 through Q_7 and resistors R_1 through R_3. Transistors Q_1 and Q_2 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 Q_3 and Q_4. Level shifting is provided in the input stage by the lateral pnp transistors, Q_3 and Q_4. 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 Q_3 and Q_4 is the protection of the input transistors (Q_1 and Q_2) 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 Q_5, Q_6, and Q_7 and resistors R_1, R_2, and R_3 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 Q_6.

Intermediate Stage

The intermediate stage of the 741 is composed of transistors Q_{13}, Q_{16}, Q_{17}, and resistors R_8 and R_9. The single-ended output of the input stage is connected to the base of Q_{16}, 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 Q_{17} is configured as a common-emitter with R_8 in the emitter lead. The load for the CE amplifier is the large output resistance of the pnp current source (Q_{13}), that is used as an active load, in parallel with the input resistance of the output stage (found by looking into the base of Q_{23}).

The output of the intermediate stage is taken from the collector of Q_{17}. The capacitor C_1 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 Q_{14}, Q_{18}, Q_{19}, Q_{20}, and Q_{23}. The input to the final stage is at Q_{23}, 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.