changes in open-loop gain (1000 to 100 in this case) give rise to much smaller corresponding changes in the closed-loop gain.

To illustrate, let us apply negative feedback with $\beta = 0.01$ to the amplifier whose open-loop voltage transfer characteristic is depicted in Fig. 11.6. The resulting transfer characteristic of the closed-loop amplifier, v_O versus v_S, is shown in Fig. 11.6 as curve (b). Here the slope of the steepest segment is given by

$$A_{f1} = \frac{1000}{1 + 1000 \times 0.01} = 90.9$$

and the slope of the next segment is given by

$$A_{f2} = \frac{100}{1 + 100 \times 0.01} = 50$$

Thus the order-of-magnitude change in slope has been considerably reduced. The price paid, of course, is a reduction in voltage gain. Thus if the overall gain has to be restored, a preamplifier should be added. This preamplifier should not present a severe nonlinear-distortion problem, since it will be dealing with smaller signals.

Finally, it should be noted that negative feedback can do nothing at all about amplifier saturation, since in saturation the gain is very small (almost zero) and hence the amount of feedback is almost unity.

11.3 The Feedback Voltage Amplifier

Based on the quantity to be amplified (voltage or current) and on the desired form of output (voltage or current), amplifiers can be classified into four categories. These categories were discussed in Chapter 1. In this section we study the most common amplifier type: the voltage amplifier. We begin by identifying the appropriate configuration for applying negative feedback to a voltage amplifier. Then, we present a simple method for the analysis of the feedback voltage amplifier. The method makes use of the loop gain $A\beta$, whose determination was discussed in Section 11.1.3.

11.3.1 The Series–Shunt Feedback Topology

Voltage amplifiers are intended to amplify an input voltage signal and provide an output voltage signal. The voltage amplifier is essentially a voltage-controlled voltage source. The input resistance is required to be high, and the output resistance is required to be low. Since the signal source is essentially a voltage source, it is appropriately represented in terms of a Thévenin equivalent circuit. As the output quantity of interest is the output voltage, the feedback network should *sample* the output *voltage*, just as a voltmeter measures a voltage. Also, because of the Thévenin representation of the source, the feedback signal x_f should be a *voltage* that can be *mixed* with the source voltage in *series*.

From the discussion above, it follows that the most suitable feedback topology for the voltage amplifier is the **voltage-mixing**, **voltage-sampling** one shown in Fig. 11.7. Because of the series connection at the input and the parallel or shunt connection at the output, this feedback topology is also known as **series–shunt feedback**. As will be shown, this topology not only stabilizes the voltage gain V_o/V_s but also results in a higher input resistance R_{in} (intuitively, a result of the series connection at the input) and a lower output resistance R_{out}

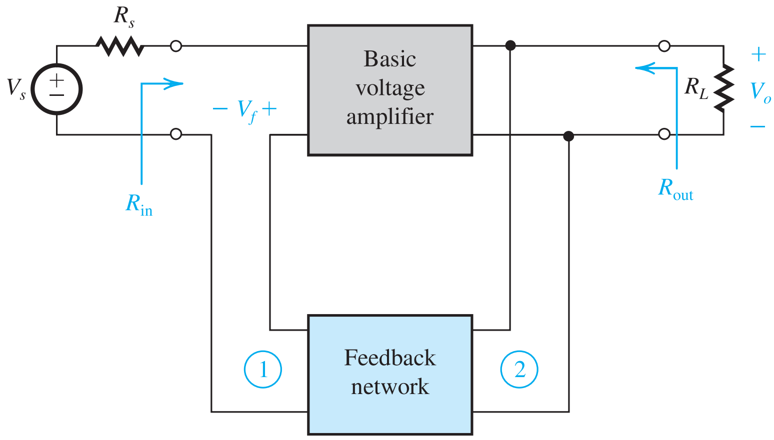

Figure 11.7 Block diagram of a feedback voltage amplifier. Here the appropriate feedback topology is series–shunt.

(intuitively, a result of the parallel connection at the output), which are desirable properties for a voltage amplifier.

The increased input resistance results because V_f subtracts from V_s, resulting in a smaller signal V_i at the input of the basic amplifier. The lower V_i, in turn, causes the input current to be smaller, with the result that the resistance seen by V_s will be larger. We shall derive a formula for the input resistance of the feedback voltage amplifier in the next section.

The decreased output resistance results because the feedback works to keep V_o as constant as possible. Thus if the current drawn from the amplifier output changes by ΔI_o, the change ΔV_o in V_o will be lower than it would have been if feedback were not present. Thus the output resistance $\Delta V_o/\Delta I_o$ will be lower than that of the open-loop amplifier. In the following section we shall derive an expression for the output resistance of the feedback voltage amplifier.

11.3.2 Examples of Series–Shunt Feedback Amplifiers

Three examples of series–shunt feedback amplifiers are shown in Fig. 11.8. The amplifier in Fig. 11.8(a) is the familiar noninverting op-amp configuration. The feedback network, composed of the voltage divider (R_1, R_2), develops a voltage V_f that is applied to the negative input terminal of the op amp. The subtraction of V_f from V_s is achieved by utilizing the differencing action of the op-amp differential input. For the feedback to be negative, V_f must be of the same polarity as V_s, thus resulting in a smaller signal at the input of the basic amplifier. To ascertain that this is the case, we follow the signal around the loop, as follows: As V_s increases, V_o increases and the voltage divider causes V_f to increase. Thus the change in V_f is of the same polarity as the change in V_s, and the feedback is negative.

The second feedback voltage amplifier, shown in Fig. 11.8(b), utilizes two MOSFET amplifier stages in cascade. The output voltage V_o is sampled by the feedback network composed of the voltage divider (R_1, R_2), and the feedback signal V_f is fed to the source terminal of Q_1. The subtraction is implemented by applying V_s to the gate of Q_1 and V_f to its source, with the result that the signal at this amplifier input $V_i = V_{gs} = V_s - V_f$. To ascertain that the feedback is negative, let V_s increase. The drain voltage of Q_1 will decrease, and since this is applied to the gate of Q_2, its drain voltage V_o will increase. The feedback network will

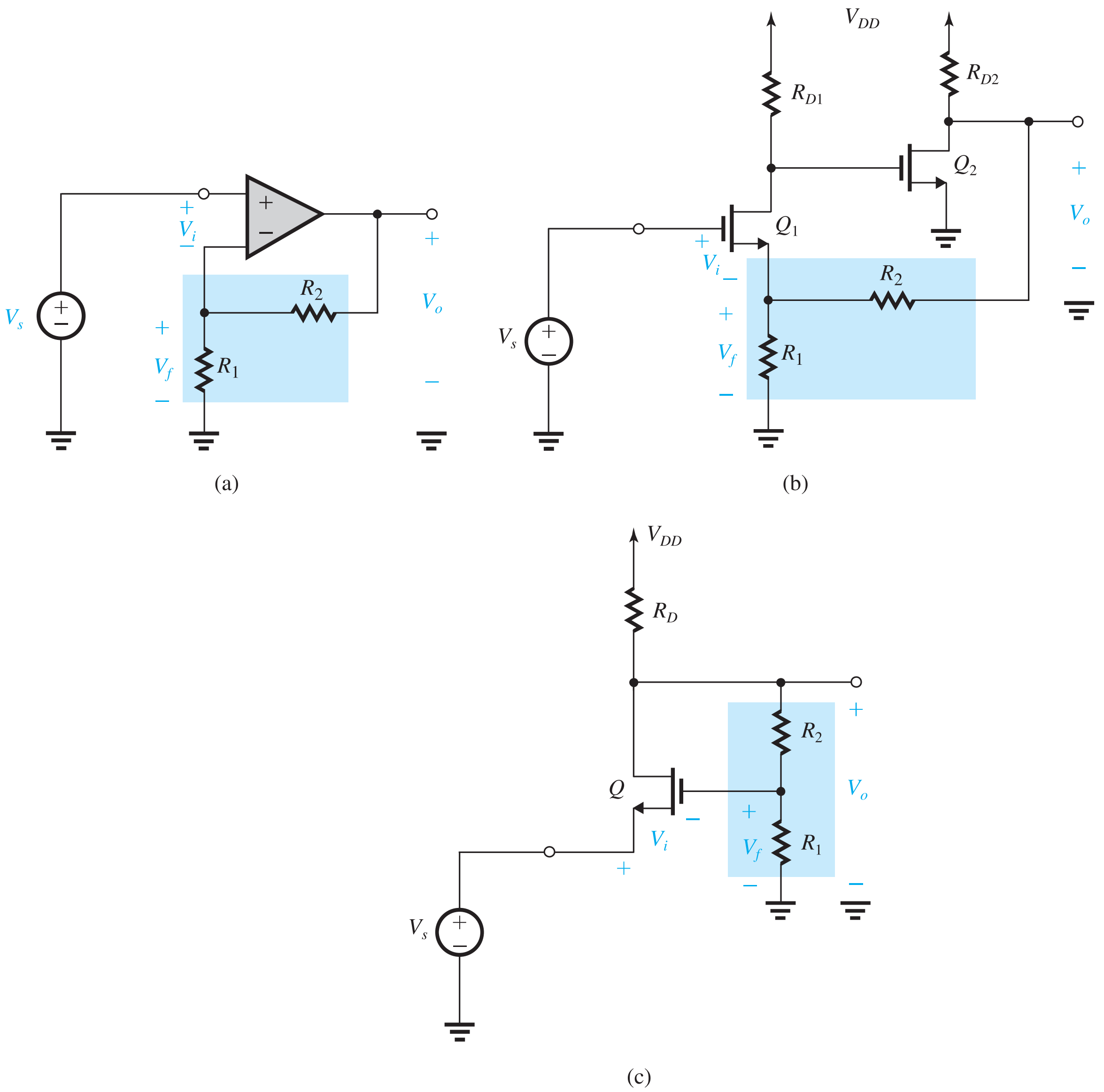

Figure 11.8 Examples of a feedback voltage amplifier. All these circuits employ series–shunt feedback. Note that the dc bias circuits are only partially shown.

then cause V_f to increase, which is the same polarity initially assumed for the change in V_s. Thus the feedback is indeed negative.

The third example of series–shunt feedback, shown in Fig. 11.8(c), utilizes a CG transistor Q with a fraction V_f of the output voltage V_o fed back to the gate through a voltage divider (R_1, R_2). Observe that the subtraction of V_f from V_s is effected by applying V_s to the source, thus the input V_i to the CG amplifier is obtained as $V_s - V_f$. As usual, however, we must check the polarity of the feedback: If V_s increases, V_d (which is V_o) will increase and V_f will correspondingly increase. Thus V_f and V_s change in the same direction, verifying that the feedback is negative.

FEEDBACK—HISTORICAL NOTE:

The idea of feedback as an element of self-regulating behavior dates back to the eighteenth century, but the term itself did not appear in the context of a discussion on economics until the 1860s. Still later, in 1909, Karl Ferdinand Braun, a German physicist working at the University of Strasbourg, referred publicly to feedback as an undesired coupling between components of a vacuum-tube electronic system. The occasion was the lecture Braun delivered as a recipient of the Nobel Prize in Physics, shared with Guglielmo Marconi (often solely credited as the inventor of radio).

In 1927, Harold Black, at Bell Labs, invented the negative-feedback amplifier, which he described in detail in a seminal paper, "Stabilized Feedback Amplifiers," published in 1934. This invention was motivated by the need to provide low-distortion amplifiers that could be concatenated in long-distance transcontinental telephone circuits.

11.3.3 Analysis of the Feedback Voltage Amplifier Utilizing the Loop Gain

The feedback analysis method studied in Section 11.1 *cannot* be directly applied to a practical feedback voltage amplifier such as those in Fig. 11.8. This is because the analysis method of Section 11.1 is predicated on the assumption that the feedback network does not load the basic amplifier. Unfortunately, this assumption does not hold in most practical amplifier circuits. As shown in the circuits of Fig. 11.8, the feedback network is a simple resistive circuit that obviously loads the basic amplifier. As an example, in the circuit of Fig. 11.8(b), the values of the resistances R_2 and R_1, which comprise the feedback network, affect the gain of the common-source stage Q_2, which is part of the basic amplifier. Also, the value of the feedback-network resistance R_1 affects the gain of the Q_1 amplifier stage, which is part of the basic amplifier. It follows that we cannot easily disassemble a practical amplifier circuit to determine A and β and thus be able to use the feedback formulas of Sections 11.1 and 11.2.

While it is not easy to determine A and β, their product, the loop gain $A\beta$, can always be determined using the method presented in Section 11.1.3. Also, we can easily obtain the value of β by identifying and isolating the feedback network (e.g., the resistive divider (R_1, R_2) in each of the circuits in Fig. 11.8). We can then use the values of $A\beta$ and β to determine A and A_f. This loop-gain method is simple, and we shall use it in this section to perform the analysis of the feedback voltage amplifier. The method, however, has limitations that will be mentioned later. A more accurate and systematic approach for the analysis of feedback voltage amplifiers will be presented in the next section.

The loop-gain analysis method comprises four steps:

1. Identify the feedback network and use it to determine the value of β.
2. Determine the ideal value of the closed-loop gain A_f as $1/\beta$. This value of A_f is approached when $A\beta \gg 1$. The ideal or upper-bound value of A_f can be used in the initial design of the feedback amplifier. It also serves as a check on the actual value of A_f calculated below.
3. Use the method described in Section 11.1.3 to determine the loop gain $A\beta$. Recall that in breaking the loop, care should be taken to not change the conditions in the loop. Thus, if we break a feedback loop at XX′, as shown in Fig. 11.9(a), and apply a test voltage V_t to the terminals thus created to the left of XX′, the terminals to the right of XX′ must be connected to an impedance Z_t. The value of Z_t is equal