Clearly, a regulator with a 2.5-V dropout voltage is not capable of producing 2.5 V from 3.3 V. Furthermore, when the dropout voltage is on par with the output voltage, the regulator dissipates as much power as the load consumes! The semiconductor industry saw these problems emerging and developed families of *low dropout* (LDO) regulators with dropout voltages well under 0.5 V. There are a wide variety of LDOs on the market today, but they are no longer members of standard families such as the 78xx. Each manufacturer has its own product line. LDOs are advantageous not only because of more flexible input/output voltage relationships, but also because they enable lower power dissipation for a given load current. With a voltage differential of just 0.2 to 0.3 V, a 5-A regulator dissipates an order of magnitude less power than an older 2-V dropout device. These regulators are manufactured by companies including Fairchild Semiconductor, Linear Technology, Maxim, National Semiconductor, and Texas Instruments.

When an output voltage is desired that is not supported by a fixed regulator, adjustable linear regulators such as the ubiquitous LM317 and LM337 can be used for positive and negative voltages, respectively. These devices have an adjustment pin, instead of a ground pin, that is used to vary the output voltage. A basic LM317 circuit is shown in Fig. 17.10. Note the use of a reverse-bias protection diode as employed previously for the fixed regulator. Additionally, a larger capacitor is recommended at the output to improve stability caused by internal differences with the 78xx fixed regulator.

The real difference is in the LM317's voltage adjustment mechanism. An internal circuit maintains a fixed 1.25 V between the output and adjustment pins, resulting in a current through R1 determined by its resistance. This current is also referred to as the *programming current*. Assuming that negligible current flows into the adjustment pin, an accurate approximation is that the current through R1 passes through R2 as well, creating a voltage drop across R2. The drop across R2 plus the 1.25 V across R1 yields the regulated output voltage,

$$V_{OUT} = 1.25\left(1 + \frac{R2}{R1}\right)$$

Typical resistance values for R1 are relatively small, ranging between 120 and 330 Ω. Values for R2 are larger so that higher voltages can be developed as necessary. It is advantageous to select smaller values for R1 and R2 so that the assumption of zero current through the adjustment pin is more accurate. The actual adjustment pin current, I_{ADJ}, is a maximum of 100 μA.* In our example,

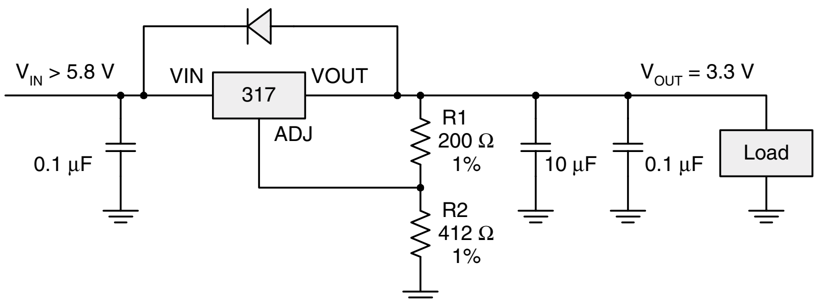

FIGURE 17.10 LM317 circuit.

* LM317, National Semiconductor, 2001, p. 2.

the current through R1 is more than 6 mA—more than two orders of magnitude larger than I_{ADJ}. The actual error imparted by I_{ADJ} = 100 μA is $I_{ADJ}R2$ = 41.2 mV, or roughly 1 percent of the 3.3-V output. This error can be reduced by increasing the programming current, which causes a corresponding decrease in R2.

The LM317 has two key requirements to maintain a regulated output. First, a minimum load current of 10 mA is necessary. This is partially addressed via the programming current—6 mA in our example. If the load cannot be guaranteed to sink the remaining 4 mA, a 120-Ω resistor can be substituted for R1 with an accompanying adjustment to R2. Second, the input must exceed the output by the LM317's dropout voltage, which is as high as 2.5 V, depending on load current and temperature. Dropout voltage decreases with decreasing load current and varies nonmonotonically with temperature.

A further improvement to the basic LM317 circuit is to add a 10 μF bypass capacitor between the adjustment pin and ground to filter ripple noise being fed back through R1. This improves the regulator's ripple rejection. When this capacitor is added, the same issue of safe power-off comes up, because the capacitor will hold charge and discharge through the adjustment pin. As before, the solution is a diode with its anode connected to the adjustment pin and its cathode connected to the output pin. This provides a low-impedance path from the bypass capacitor through two diodes to the input node.

Common three-terminal linear regulators can also be applied as current regulators. While both fixed and adjustable regulators are applicable, the adjustable regulators are more flexible in this role because of the low voltage differential maintained between the output and adjustment pins. In the case of the LM317, this 1.25-V difference allows a constant current to be established by a series output resistor as shown in Fig. 17.11. Note that the maximum output voltage for this circuit to maintain regulation is bounded by an overall dropout voltage that is the sum of the LM317's dropout voltage plus the 1.25-V drop across R_{SET}.

Because it is a series element, a linear regulator dissipates power equal to the product of the load current and the input/output voltage differential. At high currents and voltage differentials, the necessary cooling to prevent a regulator from overheating can be substantial. There is no way to reduce the overall power wasted by a linear regulator. More efficient switching regulators are often used in high-power applications. Yet there are times when the complexity of a switching regulator is undesirable, and absolute power regulation efficiency is not a prime concern. Under these situations, a small trick can be employed to reduce the power dissipated by the regulator by shifting a portion of that heat to a less thermally sensitive power resistor, thereby easing the regulator's cooling requirements.

Consider the example in Fig. 17.12, wherein a large voltage differential exists. The input is a 24-V supply with a 10 percent range. The output is a standard 5-V level for a small digital circuit drawing up to 500 mA. When the input voltage is at its maximum, a worst-case voltage differential of 21.4 V exists, which means nearly 11 W of power to safely dissipate. A large heat sink and/or moving air are normally required to maintain a safe junction temperature at this power level. Instead, a

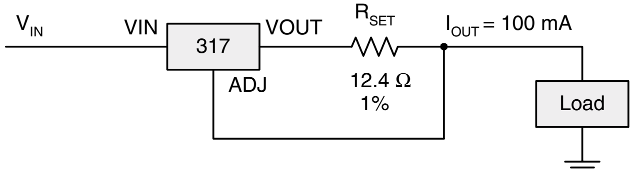

FIGURE 17.11 LM317 current regulator.