The current regulator cannot supply a constant 100 mA for all values of V_{OUT}. As the load impedance is increased, there is a corresponding increase in V_{OUT}, which reduces the difference with respect to V_{IN}. This differential eventually forces the transistor into saturation when its collector-base junction becomes forward biased. Using the estimate of $V_{CE(SAT)} = 0.3$ V provides us with a minimum voltage drop across the transistor for the regulator to maintain 100 mA. The voltage drop across R_{SET}, 2.6 V, must also be factored into the V_{IN}/V_{OUT} differential. The maximum V_{OUT} must be evaluated along with minimum V_{IN} to analyze the limiting scenario: $V_{OUT(MAX)} = V_{IN(MIN)} - 2.6\text{ V} - 0.3\text{ V} = 7.1$ V. This circuit can therefore be guaranteed to function properly up to 7.1 V. Of course, if V_{IN} is at the upper end of its range, V_{OUT} can be higher as well. But the worst-case scenario is what should be used when specifying the guaranteed parameters of a circuit.

Analysis of the regulator's dropout voltage shows that the drop across R_{SET} is the dominant term within the regulator circuit. If dropout voltage is a concern, the drop across the resistor should be minimized. This is why a low-voltage Zener has been selected rather than a 5- or 6-V diode. The drop across R_{SET} is the difference between V_{ZENER} and V_{BE}. Minimizing V_{ZENER} minimizes the drop across R_{SET}.

Calculating power dissipation to perform a thermal analysis requires bounding the output voltage at a practical minimum, because the transistor's power dissipation increases with increasing V_{CE} and, hence, decreasing V_{OUT}. R_{SET} has a constant voltage drop at constant current, so it has constant power dissipation of 0.26 W. For the sake of discussion, we can pick $V_{OUT(MIN)} = 0$ V. Along with $V_{IN(MAX)} = 15$ V, the power dissipation of the transistor is $I_{OUT}(V_{IN} - I_{OUT}R_{SET} - V_{OUT}) = 1.24$ W. The TIP32 and TIP 31 have equivalent power and thermal ratings. The transistor is rated at 2 W without a heat sink at an ambient temperature of 25°C, and a conservative design methodology might call for a heat sink on the TO-220 package in this case. A heat sink enables calculation of the package temperature for a given power dissipation and ambient temperature, which in turn enables us to take advantage of the manufacturer's power derating curve expressed in terms of package temperature.

A small TO-220 heat sink can provide a thermal resistance of 30°C/W with natural convection. Much lower values are achievable when a fan is blowing air across the heat sink and with a larger heat sink. A temperature rise of 37°C is attained with $P_D = 1.24$ W. Therefore, a 40°C ambient temperature would result in a transistor case temperature of 77°C. The TIP32's power derating curve shows that the transistor is capable of over 20 W at this case temperature.* The heat sink thereby enables a very conservative design with minimal cost or complexity.

17.5 LINEAR REGULATORS

Most voltage and current regulation requirements, especially in digital systems, can be solved with ease by using integrated off-the-shelf regulators that provide high-quality regulation characteristics. Constructing a regulator from discrete parts can be useful when its requirements are sufficiently outside the mainstream to dictate a custom approach. However, designing a custom regulator brings with it the challenges of meeting the load's regulation requirements over a potentially wide range of operating conditions. Power supplies for digital circuits have the benefit that the voltages are common across the industry. This has enabled semiconductor manufacturers to design broad families of integrated regulators that are preadjusted for common supply voltages: 5, 3.3, 2.5, 1.8, and 1.5 V. Manufacturers also offer adjustable regulators that can be readily customized to a specific output voltage. The result is the ability to treat regulators largely as "black boxes" once their overall charac-

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* TIP32 Series, Fairchild Semiconductor, 2000, p. 2.

teristics have been quantified and accounted for. High-quality off-the-shelf regulators are inexpensive and provide a quality of regulation that is far more difficult to attain with discrete design.

One of the basic types of off-the-shelf regulators is the *linear regulator.* A linear regulator is an analog integrated circuit that essentially implements a more complex version of the transistor-based series regulator already discussed. Instead of one transistor, it includes more than a dozen. All of the functions of voltage reference, error feedback, and voltage control are included. For the sake of comparison, this is akin to buying a 74LS00 IC instead of constructing NAND gates from discrete transistors. Most linear regulators have three terminals: an input, an output, and either a ground or voltage sense input. Fixed regulators have a ground pin, and adjustable regulators use the third pin as a voltage feedback.

Perhaps the most classic and widely used fixed linear regulator family is the LM78xx, with common variants including the 7805 and 7812, which provide fixed outputs of +5 V and +12 V, respectively. These parts are available in a variety of packages with current ratings from 100 mA to 3 A. Small TO-92 packages, commonly used for low-power transistors, and small surface-mount packages house the 100 mA versions, whereas TO-220 packages and the surface mount equivalent DPAK house the higher current variants. The 78xx family provides line and load regulation performance in the range of 100 mV: over the possible range of input voltages and output loads, the output voltage will not change by more than 100 mV. Application of the 78xx family is illustrated in Fig. 17.9 using the example of a 7805. It is recommended that high-frequency bypass capacitors be placed at the input and output nodes to reduce noise and improve the overall circuit's high-frequency response. Although 0.33-μF and 0.1-μF values are the common manufacturer's recommendations, larger high-frequency capacitors can be used. Depending on the specific application, a reverse-bias protection diode is also recommended to prevent device damage when the system is powered off. The regulator is not designed to handle an output voltage that is higher than the input voltage by more than one diode drop. If the load has sufficient capacitance to briefly maintain a nominal voltage after power is turned off, current could flow through the regulator in reverse and damage it. The diode becomes forward biased in this situation, shunting current away from the regulator.

Complementary to the 78xx positive voltage regulator family is the 79xx negative voltage regulator family. These devices are very similar to the 78xx but require larger capacitors on the input and output because of their internal structure. At least 2 μF and 1 μF on the input and output, respectively, are recommended, along with a smaller 0.1-μF high-frequency capacitor on the output.

Aside from power dissipation, which is simply the product of the input/output differential and the load current, a main consideration when designing with linear regulators is their dropout voltage. Standard linear regulators such as the 78xx have dropout voltage specifications in the 2.5-V range. If a 5-V output is desired, at least 7.5 V on the input is required.

As digital supply voltages have steadily decreased, it has become common to find systems with multiple low-voltage supplies. For example, a system may use 3.3- and 2.5-V components. Higher dropout voltages can complicate an otherwise simple power subsystem design in such instances.

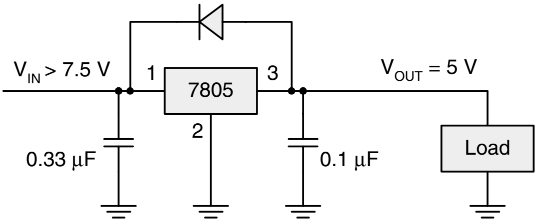

FIGURE 17.9 LM7805 circuit.