Ch. 4 Voltage Regulators

Two basic categories of voltage regulation are:

- ❑ line regulation

- ❑ load regulation

The purpose of **line regulation** is to maintain a nearly constant output voltage when the **input voltage** varies.

The purpose of **load regulation** is to maintain a nearly constant output voltage when the **load** varies

Line regulation: A change in input (line) voltage does not significantly affect the output voltage of a regulator (within certain limits)

➢Line regulation can be defined as the percentage change in the output voltage for a given change in the input voltage.

$$Line\ regulation = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}} \right) \times 100\%$$

Δ means "a change in"

➢Line regulation can be calculated using the following formula:

$$Line\ regulation = \frac{(\Delta V_{OUT} / V_{OUT}) \times 100\%}{\Delta V_{IN}}$$

Example 4.1: When the ac input voltage of a certain power supply changes, the input to the voltage regulator decreases by 5 V as a result, and the output of the regulator decreases by 0.25 V. The nominal output is 15 V. Determine the line regulation in %/V.

Solution: The line regulation as a percentage change per volt is

Line regulation=(0.25 V/15 V) * 100%/5 V=0.333 %/V

H.W: The input of a certain regulator increases by 3.5 V. As a result, the output voltage increases by 0.42 V. The nominal output is 20 V. Determine the regulation in %/V.

Load regulation: A change in load current (due to a varying R_L) has practically no effect on the output voltage of a regulator (within certain limits)

➢Load regulation can be defined as the percentage change in the output voltage from no-load (NL) to full-load (FL).

$$Load \ regulation = \left(\frac{V_{NL} - V_{FL}}{V_{FL}} \right) \times 100\%$$

where:

V_{NL} = the no-load output voltage

V_{FL} = the full-load output voltage

Example 4.2: A certain voltage regulator has a 12 V output when there is no load. When there is a full-load current of 10 mA, the output voltage is 11.9 V. Express the voltage regulation as a percentage change from no-load to full-load and also as a percentage change for each mA change in load current.

Solution: The load regulation as a percentage change from no-load to full-load is
Load regulation= [(12 V- 11.9 V)/11.9 V]*100%=0.840%

The load regulation can also be expressed as a percentage change per milliamp as
Load regulation=0.840%/10 mA=0.084%/mA

where the change in load current from no-load to full-load is 10 mA.

H.W: A regulator has a no-load output voltage of 18 V and a full-load output of 17.8 V at a load current of 50 mA. Determine the voltage regulation as a percentage change from no-load to full-load and also as a percentage change for each mA change in load current.

➢Sometimes power supply manufacturers specify the equivalent output resistance (R_{out}) instead of its load regulation.

-Thevenin equivalent circuit for a power supply with a load resistor:

$$R_{TH} = R_{OUT}$$

$$V_{OUT} = V_{NL}\left(\frac{R_L}{R_{OUT} + R_L}\right)$$

$$V_{TH} = V_{NL}$$

R_L
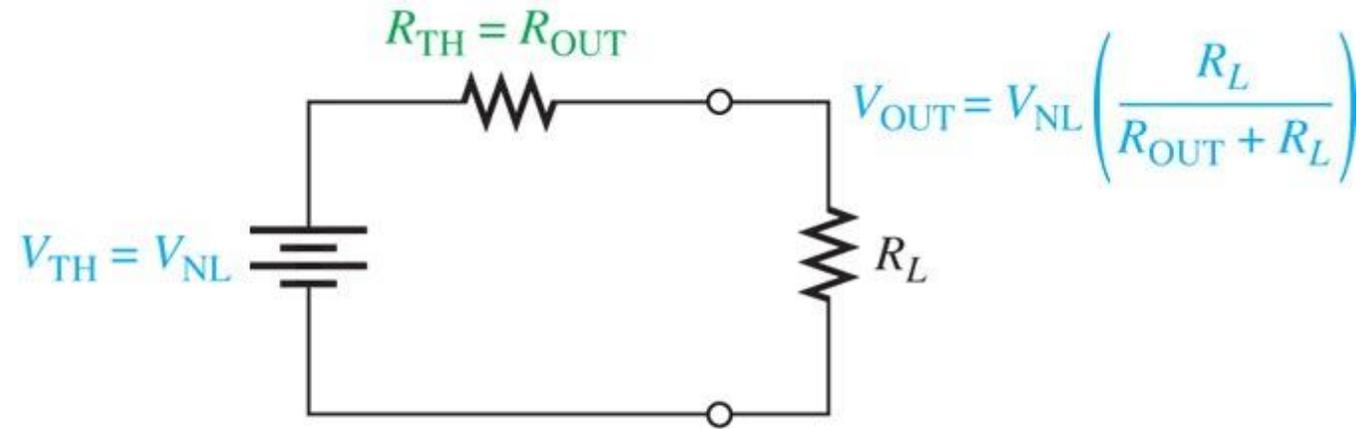
➢R_{FL} equal the smallest-rated load resistance, then V_{FL}:

$$V_{FL} = V_{NL}\left(\frac{R_{FL}}{R_{OUT} + R_{FL}}\right)$$

➤Rearrange the equation:

$$V_{NL} = V_{FL}\left(\frac{R_{OUT} + R_{FL}}{R_{FL}}\right)$$

$$Load\ regulation = \frac{V_{FL}\left(\frac{R_{OUT} + R_{FL}}{R_{FL}}\right) - V_{FL}}{V_{FL}} \times 100\%$$

$$Load\ regulation = \left(\frac{R_{OUT} + R_{FL}}{R_{FL}} - 1\right) \times 100\%$$

$$Load\ regulation = \left(\frac{R_{OUT}}{R_{FL}}\right) \times 100\%$$

H.Ws:

1. The input of a certain regulator increases by 3.5 V. As a result, the output voltage increases by 0.042 V. The nominal output is 20 V. Determine the line regulation in both % and in %/V.   (Solution: 1.2% ; 0.06%/V)

2. If a 5 V power supply has an output resistance of 80 mΩ and a specific maximum output current of 1 A. Calculate the load regulation in % and %/mA. (Solution:1.6%; 0.0016%/mA)

Types of Regulator:

➢ A voltage regulator provides a constant dc output voltage that is essentially independent of the input voltage, output load current, and temperature.
➢ Most voltage regulators fall into two broad categories:
➢ **linear regulators** and **switching regulators**. In the linear regulator category, two general types are the **series regulator** and the **shunt regulator**.

➢ The series regulator is connected in **series** with the load and the shunt regulator is connected in **parallel** with the load.


(a)

(b)
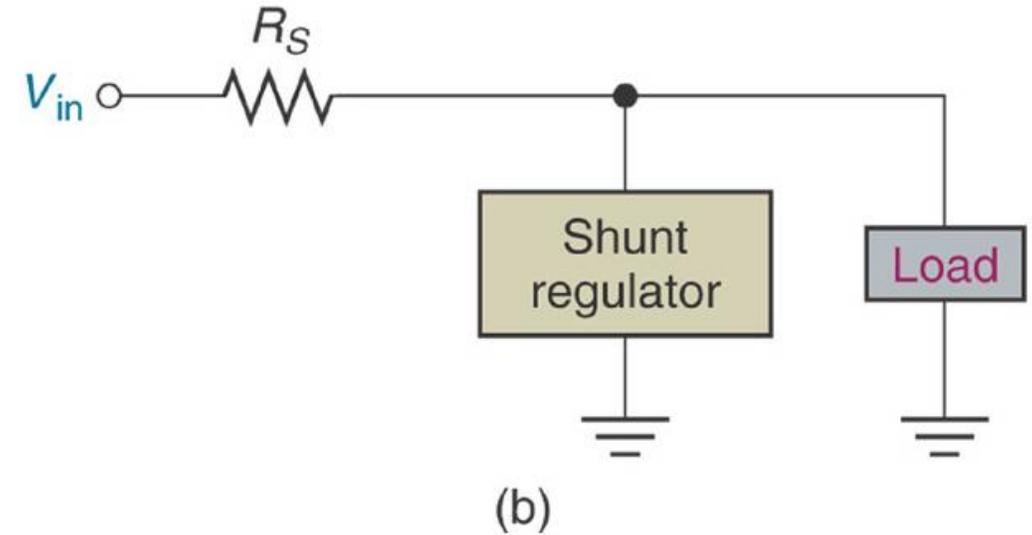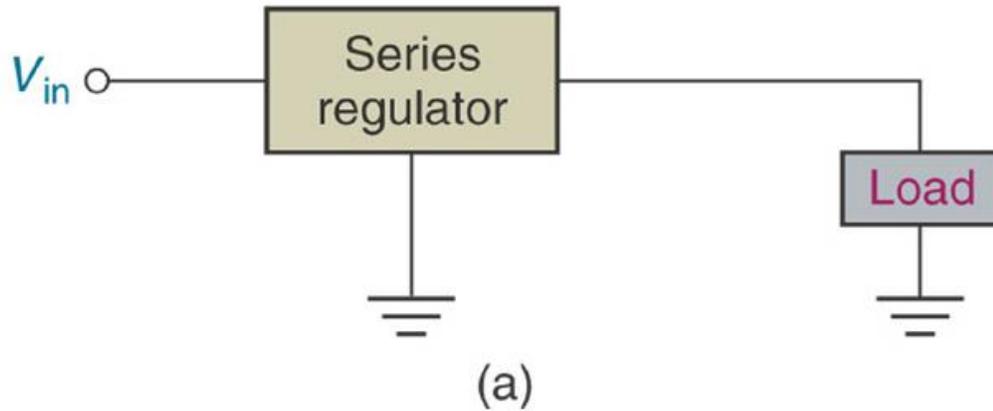
➢ These are normally available for either positive or negative output voltages.

➢ A dual regulator provides both positive and negative outputs.

➢ In the **switching regulator category**, three general configurations are **stepdown, step-up, and inverting**.

Series Regulator Circuit

A basic components of a series type of **linear regulator** is shown in the block diagram in Figure below, It consists from:

- **Control element** in series with load between input and output.

- Output **sample circuit** senses a change in output voltage.

- **Error detector** compares sample voltage with reference voltage → causes control element to compensate in order to maintain a constant output voltage.
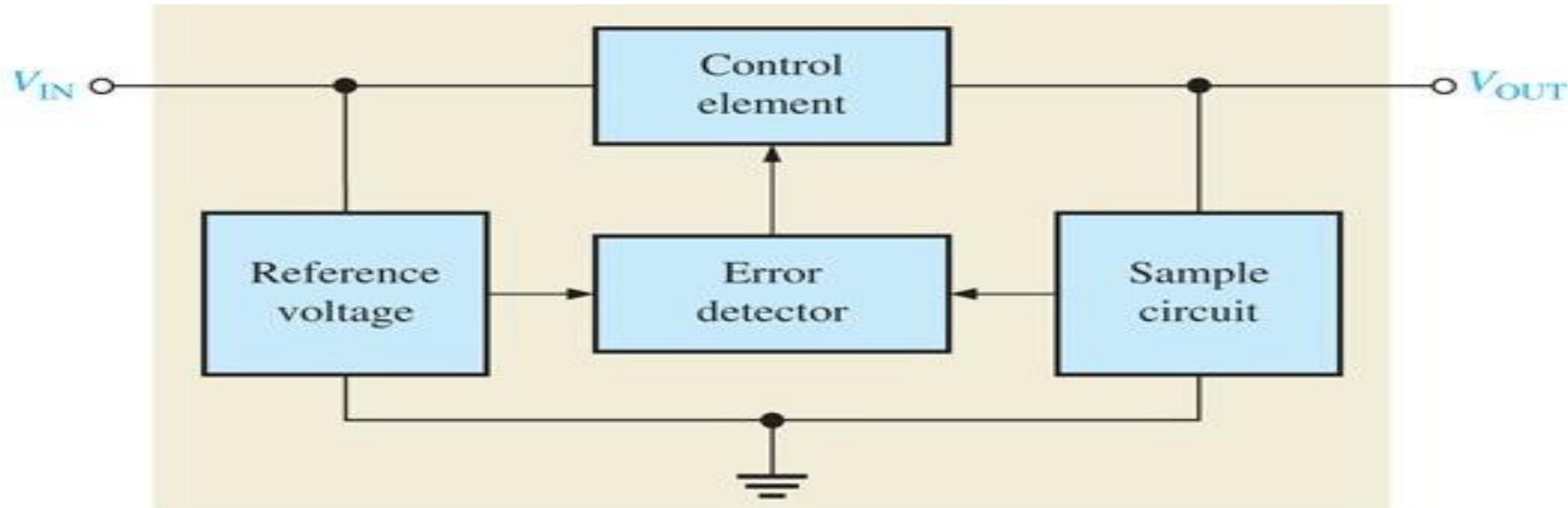
➢ A basic op-amp series regulator is shown in Figure below:
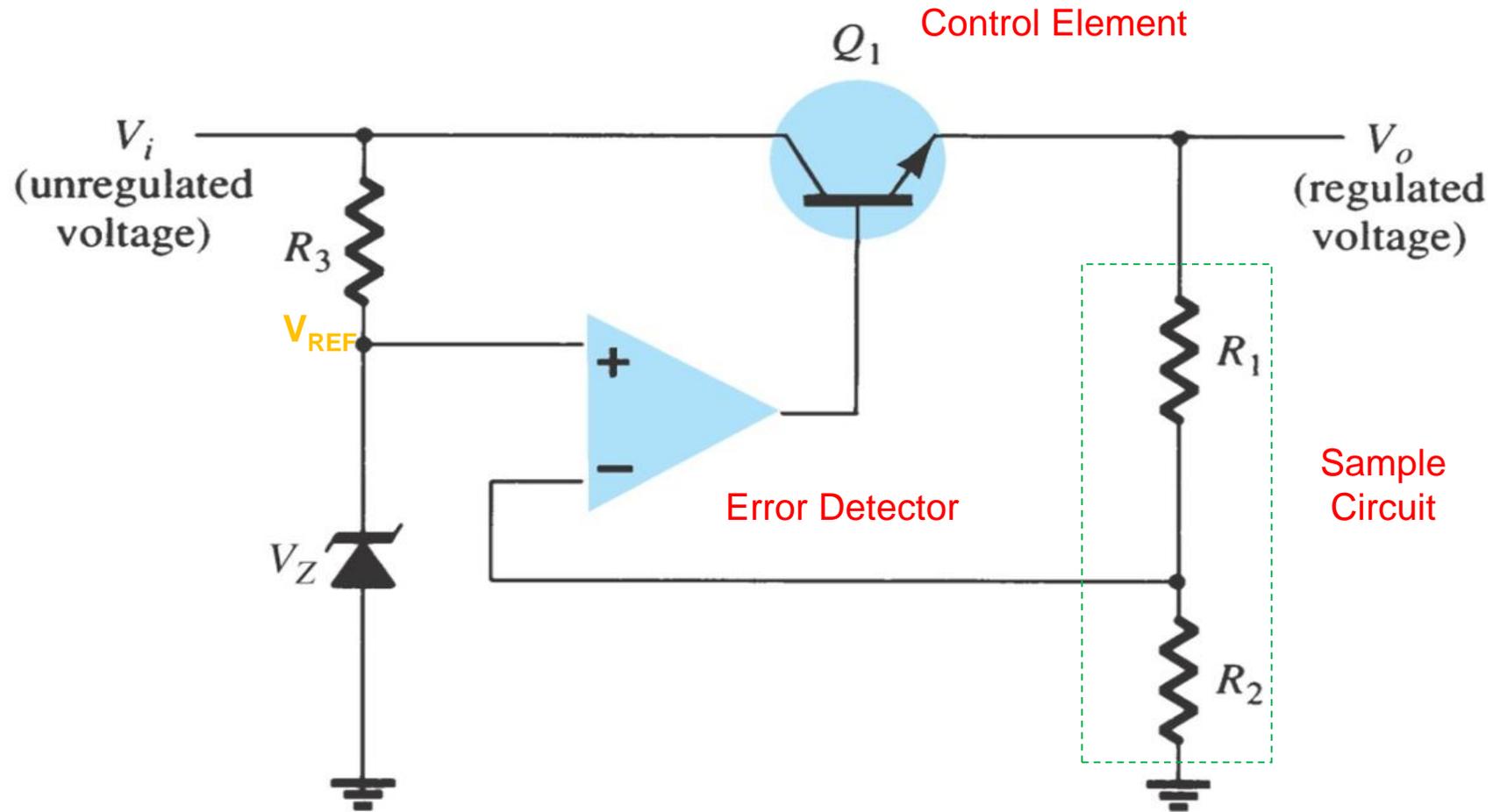
➢The resistor R_1 and R_2 sense a change in the output voltage and provide a feedback voltage.
➢The error detector compares the feedback voltage with a Zener diode reference voltage.
➢The resulting difference voltage causes the transistor Q_1 controls the conduction to compensate the variation of the output voltage.
➢The output voltage will be maintained at a constant value of:

$$V_o = \left(1 + \frac{R_1}{R_2}\right)V_Z$$

➢ The power transistor Q1, is usually used with a heat sink because it must handle all of the load current.

Illustration of series regulator action that keeps V_{OUT} constant when V_{IN} or R_L changes.
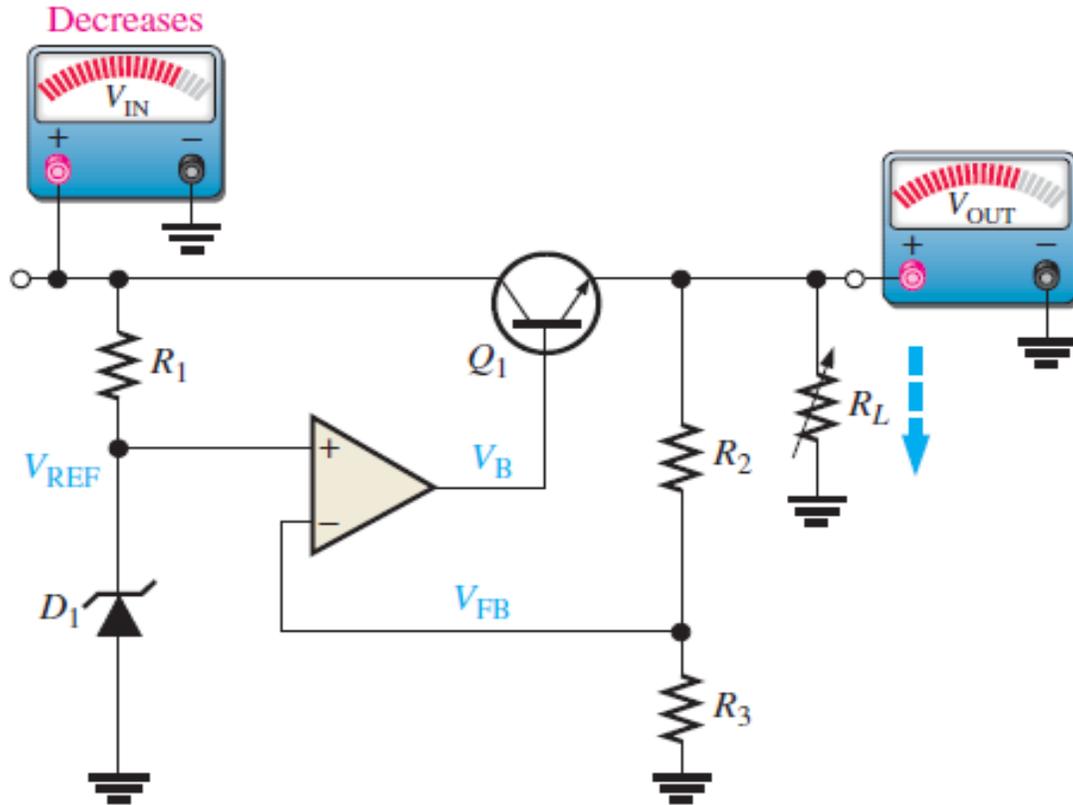
(a) When V_{IN} or R_L decreases, V_{OUT} attempts to decrease. The feedback voltage, V_{FB}, also attempts to decrease, and as a result, the op-amp's output voltage V_B attempts to increase, thus compensating for the attempted decrease in V_{OUT} by increasing the Q_1 emitter voltage. Changes in V_{OUT} are exaggerated for illustration.

When V_{IN} (or R_L) stabilizes at its new lower value, the voltages return to their original values, thus keeping V_{OUT} constant as a result of the negative feedback.
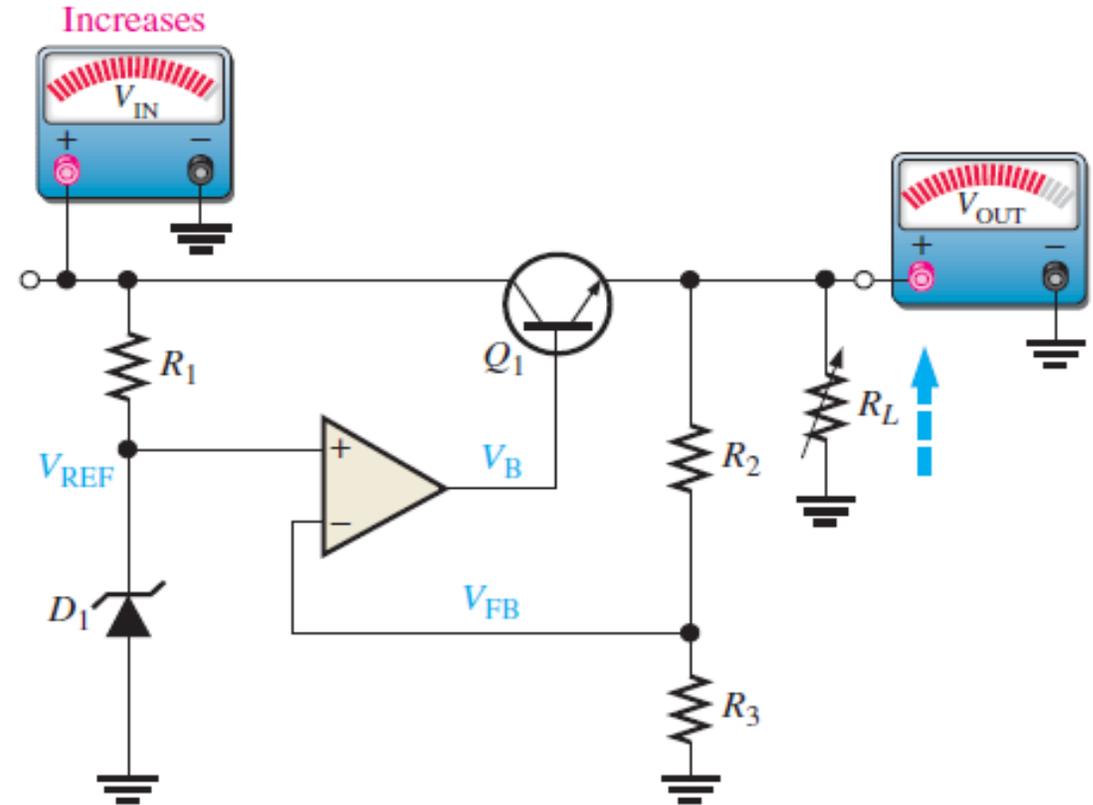
(b) When V_{IN} or R_L increases, V_{OUT} attempts to increase. The feedback voltage, V_{FB}, also attempts to increase, and as a result, V_B, applied to the base of the control transistor, attempts to decrease, thus compensating for the attempted increase in V_{OUT} by decreasing the Q_1 emitter voltage.

When V_{IN} (or R_L) stabilizes at its new higher value, the voltages return to their original values, thus keeping V_{OUT} constant as a result of the negative feedback.

Example 4.3: Determine the output voltage for the regulator shown in Figure below:
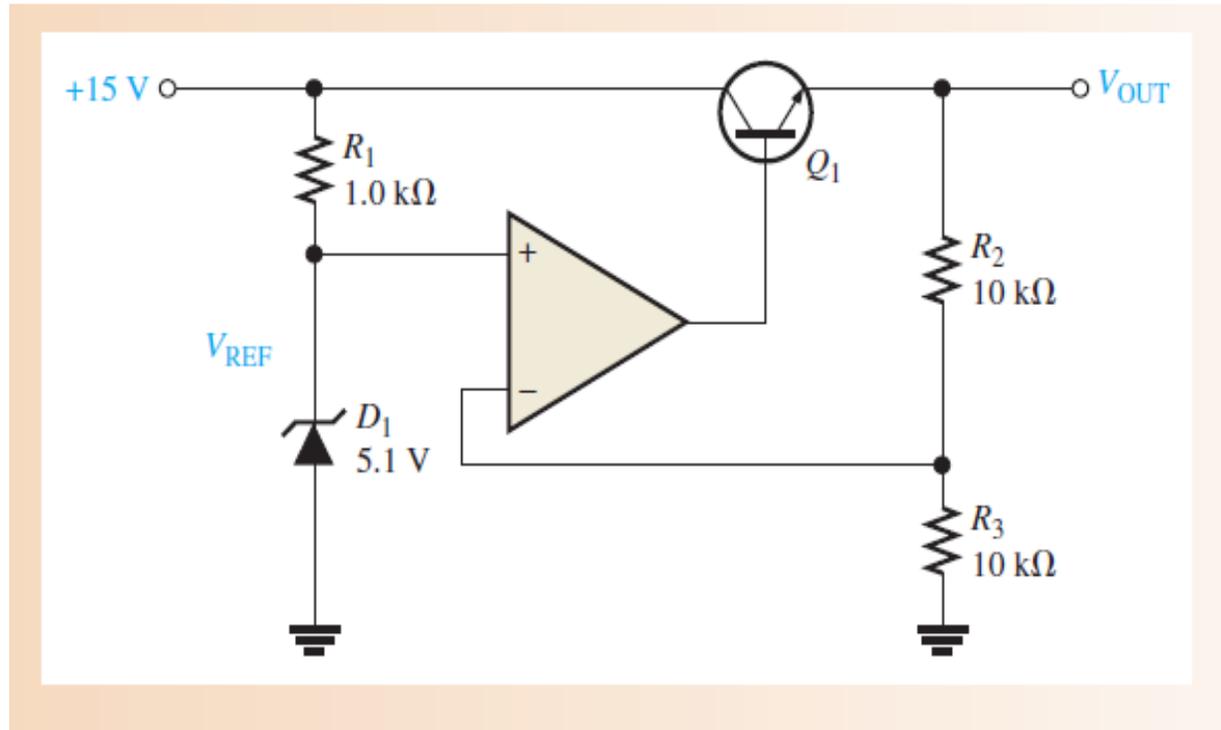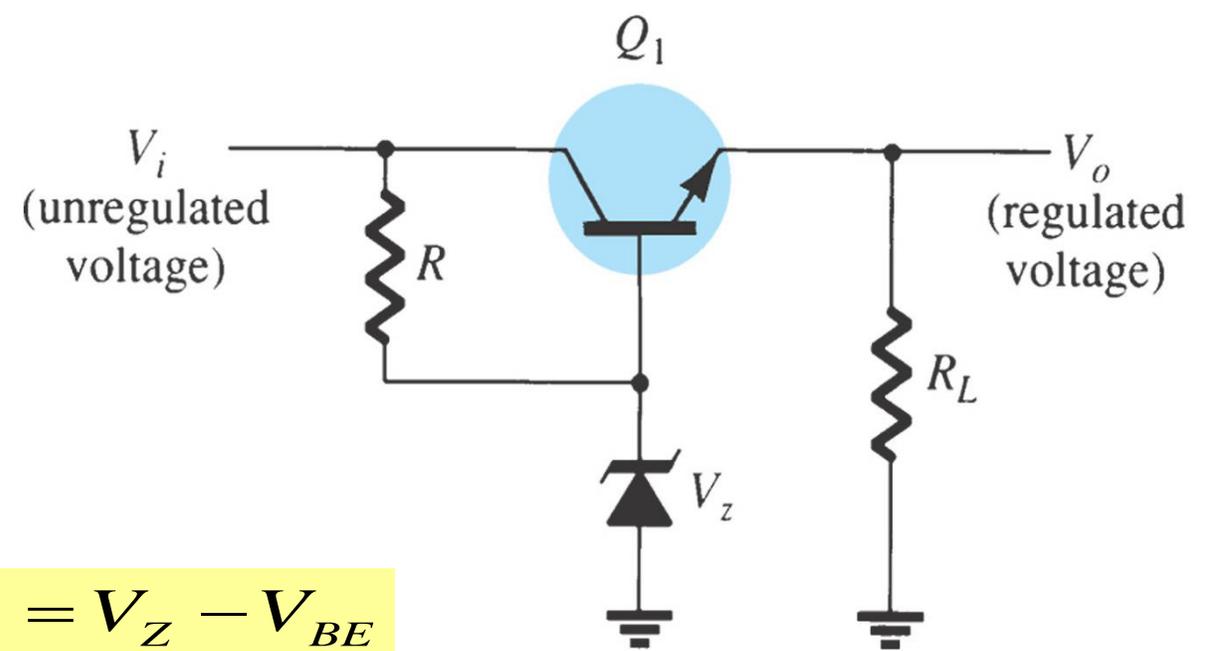

$V_{REF} = 5.1$ V, the zener voltage. The regulated output voltage is therefore

$$V_{OUT} = \left(1 + \frac{R_2}{R_3}\right)V_{REF} = \left(1 + \frac{10\,k\Omega}{10\,k\Omega}\right)5.1\,V = (2)5.1\,V = 10.2\,V$$

Transistor Series Regulator

➢The transistor Q_1 is the series control element.

➢Zener diode provides the reference voltage.

➢Since Q_1 is an npn transistor, V_o is found as:

$$V_o = V_Z - V_{BE}$$

➢The response of the pass-transistor to a change in load resistance as follows:

✓If load resistance increases, load voltage also increases.

✓Since the Zener voltage is constant, the increase in V_o causes V_{BE} to decrease.

✓The decrease in V_{BE} reduces conduction through the pass- transistor, so load current decreases.

✓This offsets the increase in load resistance, and a relatively constant load voltage is maintained

Example 4.4: Calculate the output voltage and Zener current for $R_L = 1k\Omega$.
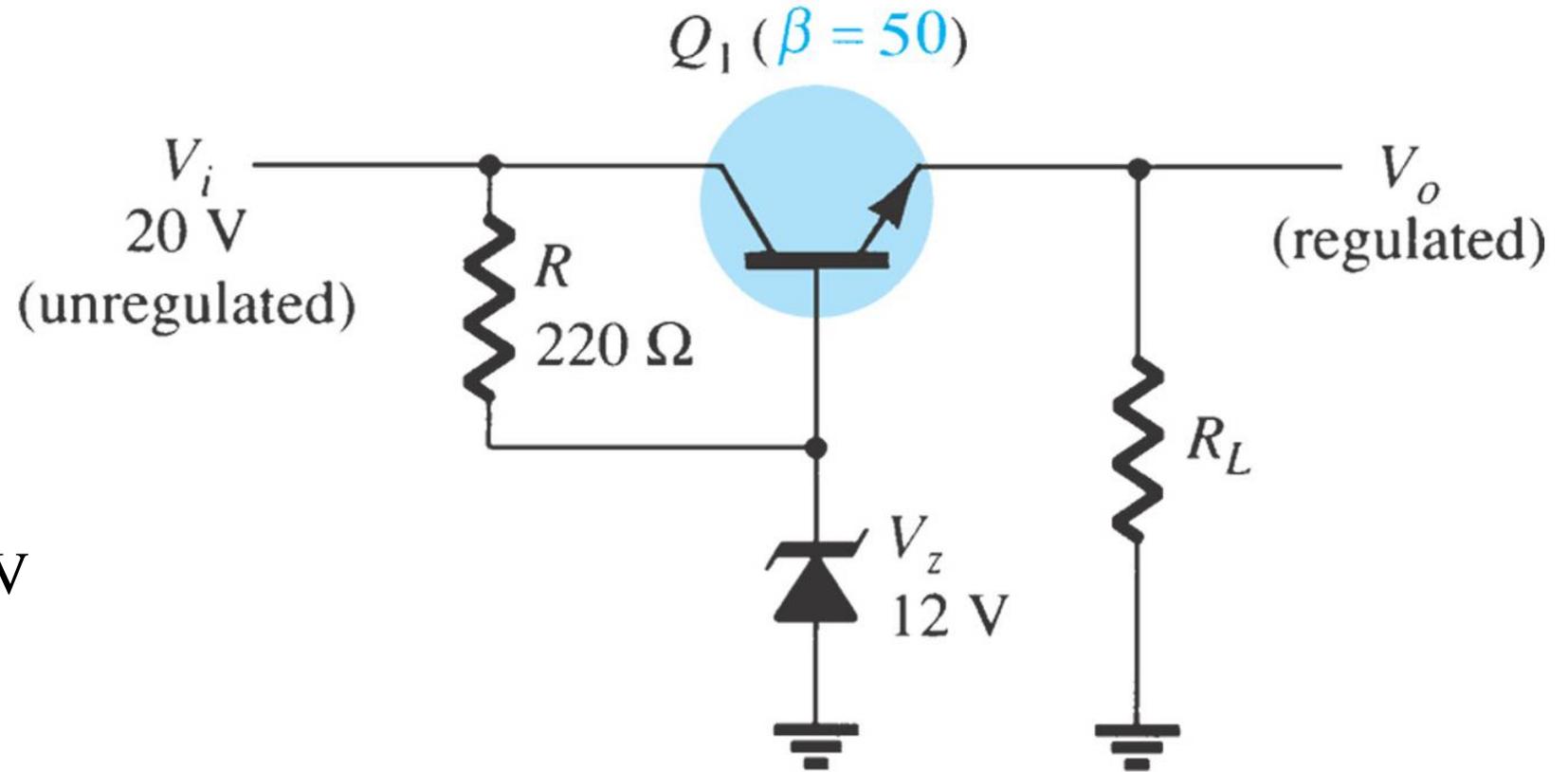
$$V_O = V_Z - V_{BE} = 12 - 0.7 = 11.3 \text{ V}$$
$$V_{CE} = V_i - V_O = 20 \text{ V} - 11.3 \text{ V} = 8.7 \text{ V}$$
$$I_R = 20 \text{ V} - 12 \text{ V}/220 = 36.36 \text{ mA}$$

For $R_L = 1K$,
$$I_L = V_O/R_L = 11.3 \text{ V}/1K = 11.3 \text{ mA}$$
$$I_B = I_C/B = 11.3 \text{ mA}/50 = 226 \text{ uA}$$
$$I_Z = I_R - I_B = 36.36 \text{ mA} - 226 \text{ uA} = 36.134 \text{ mA}$$

Short-Circuit or Overload Protection

➤ If an excessive amount of load current is drawn, the series-pass transistor can be quickly damaged or destroyed.

➤ Most regulators use some type of excess current protection in the form of a current-limiting mechanism.

➤ The Figure below shows one method of current limiting to prevent overloads called *constant-current limiting*. The current-limiting circuit consists of transistor $Q2$ and resistor $R4$ (Rsc).
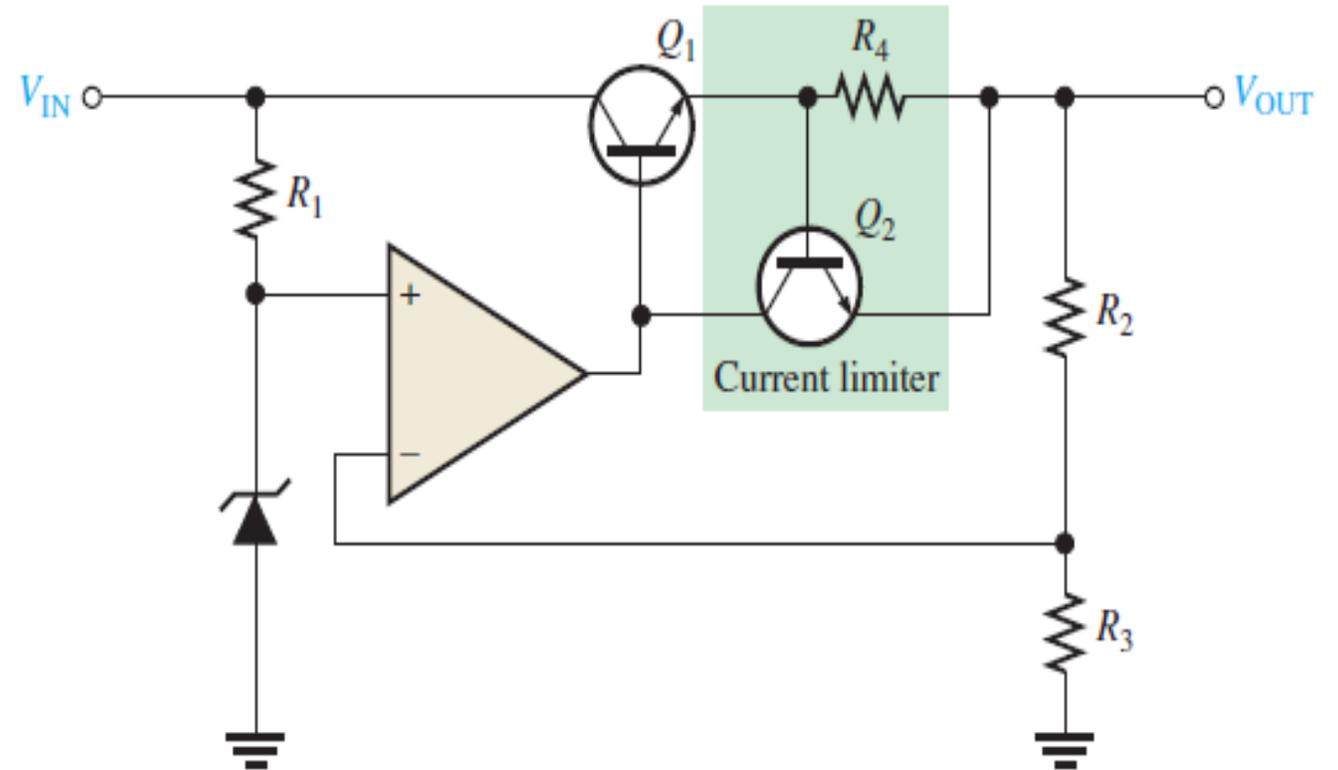
$$I_{L(max)} = \frac{0.7 \text{ V}}{R_4}$$

Example 4.5: Determine the maximum current that the regulator in figure below can provide to a load.

$$I_{L(max)} = \frac{0.7\ V}{R_4} = \frac{0.7\ V}{1.0\ \Omega} = 0.7\ A$$
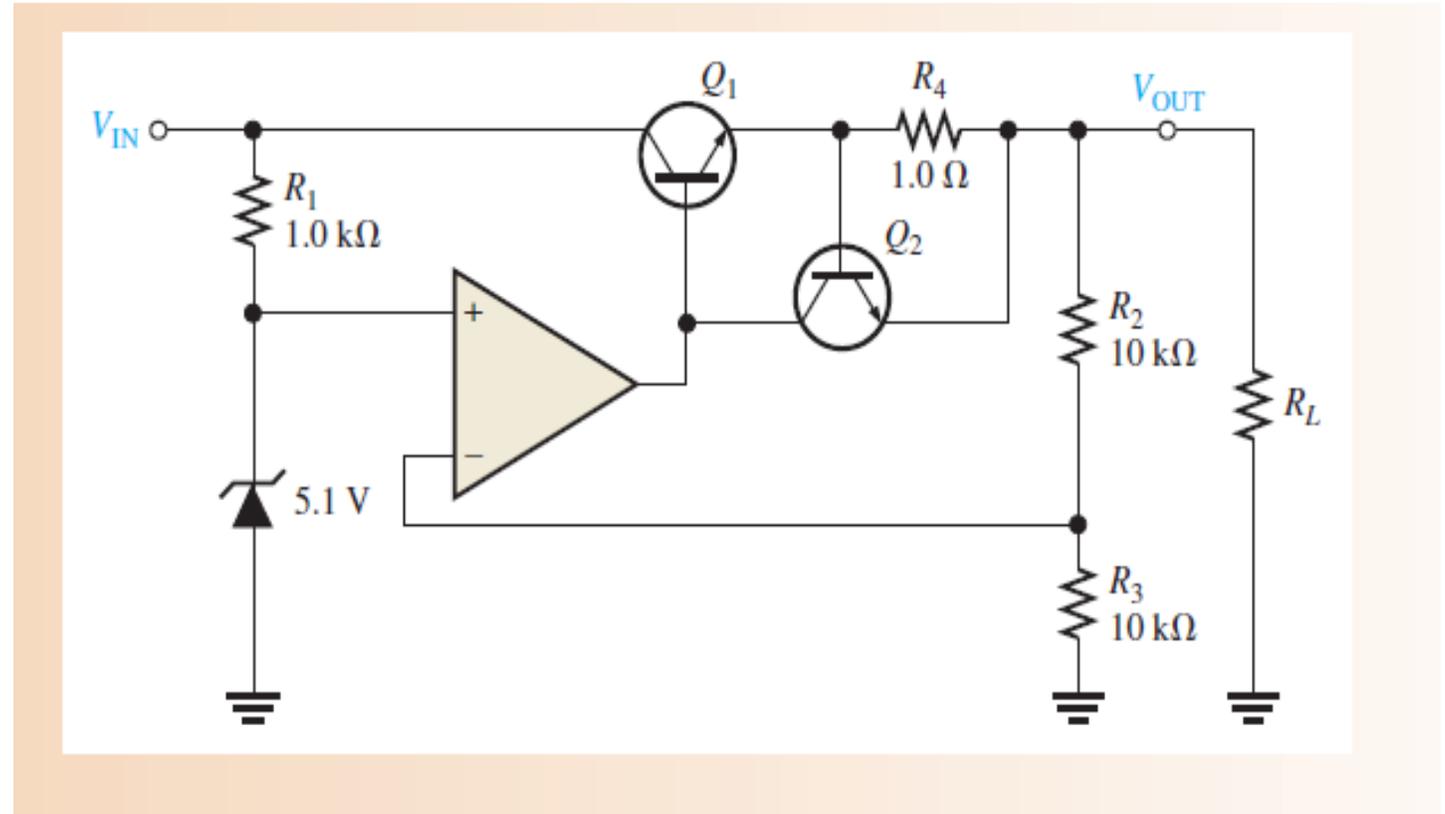
Note that if the output of the regulator in figure above is shorted, what is the current?

Regulator with Fold-Back Current Limiting

➢ In the previous current-limiting technique, the current is restricted to a maximum constant value.

➢ **Fold-back current limiting** is a method used particularly in high-current regulators whereby the output current under overload conditions drops to a value well below the peak load current capability to prevent excessive power dissipation.

➢ The circuit in the green-shaded area is similar to the constant current-limiting arrangement in the previous Figure, with the exception of resistors R5 and R6. The voltage drop developed across R4 by the load current must not only overcome the base-emitter voltage required to turn on Q2, but it must also overcome the voltage across R5. That is, the voltage across R4 must be

$$V_{R4} = V_{R5} + V_{BE}$$
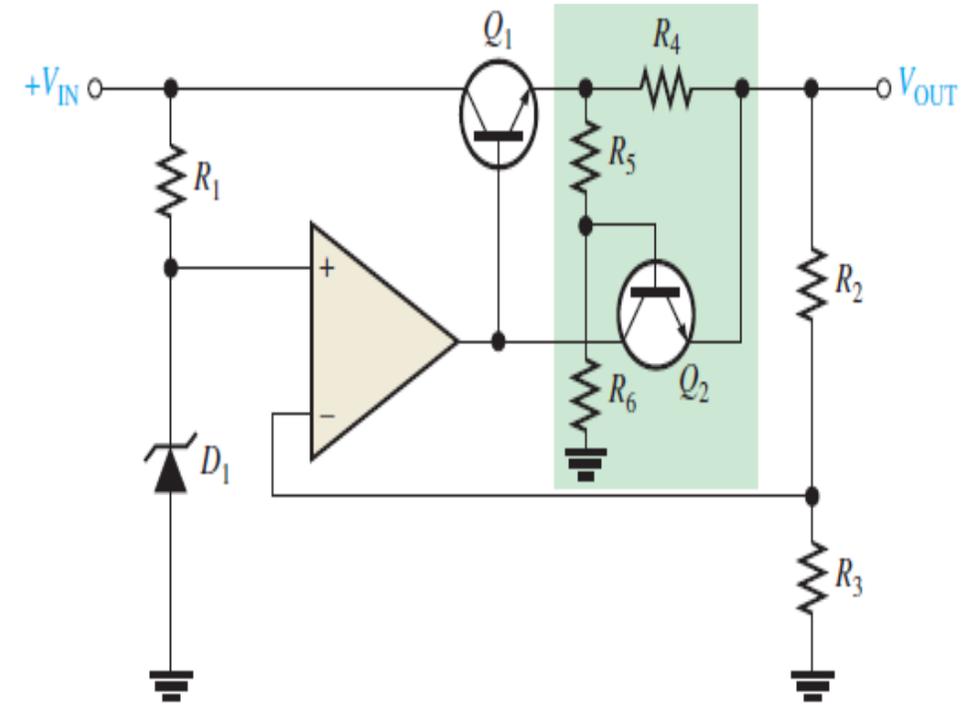
➢ In an overload or short-circuit condition, the load current increases to a value, $I_{L(max)}$ that is sufficient to cause Q2 to conduct. At this point the current can increase no further.

➢ The decrease in output voltage results in a proportional decrease in the voltage across R5. thus, less current through R4 is required to maintain the forward-biased condition of Q1.

➢ So, as V_{OUT} decreases, I_L decreases, as shown in the graph of Figure below:

Note that the advantage of this technique is that the regulator is allowed to operate with peak load current up to $I_{L(max)}$ but when the output becomes shorted, the current drops to a lower value to prevent overheating of the device.
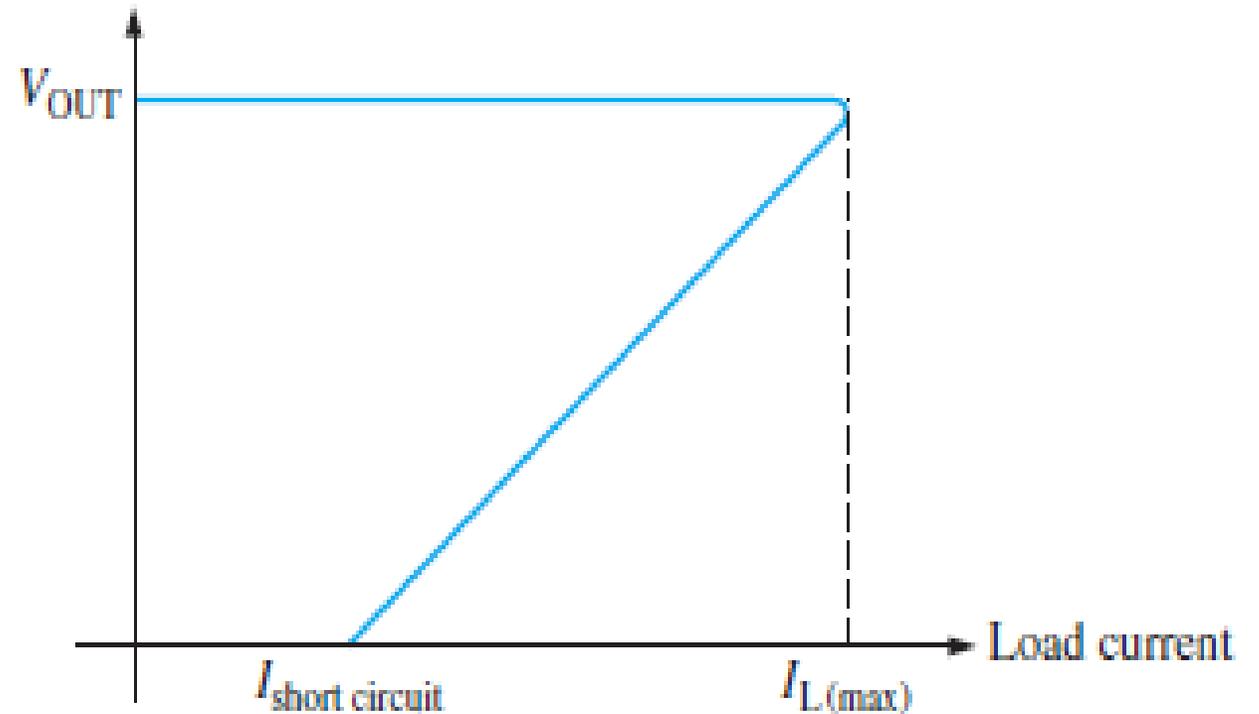
Shunt Regulator Circuit

➢The unregulated input voltage provides current to the load.

➢Some of the current is pulled away by the **control element**.

➢If the load voltage tries to change due to a change in the load resistance, the **sampling circuit** provides a feedback signal to a **comparator**.

➢The resulting difference voltage then provides a control signal to vary the amount of the current shunted away from the load to maintain the regulated output voltage across the load.
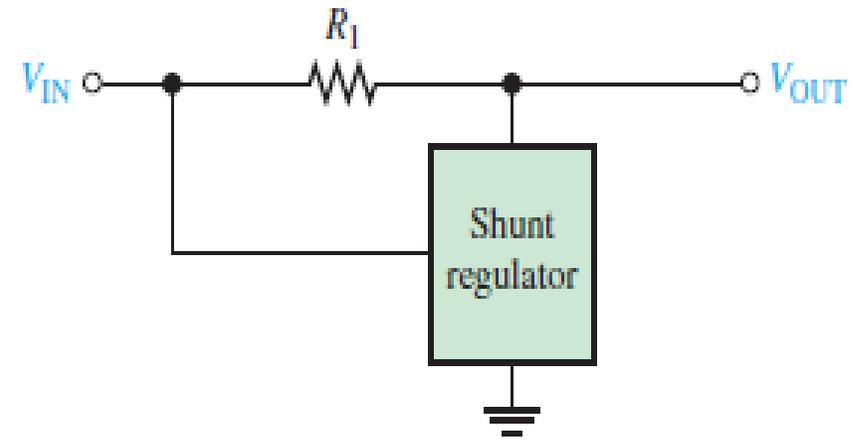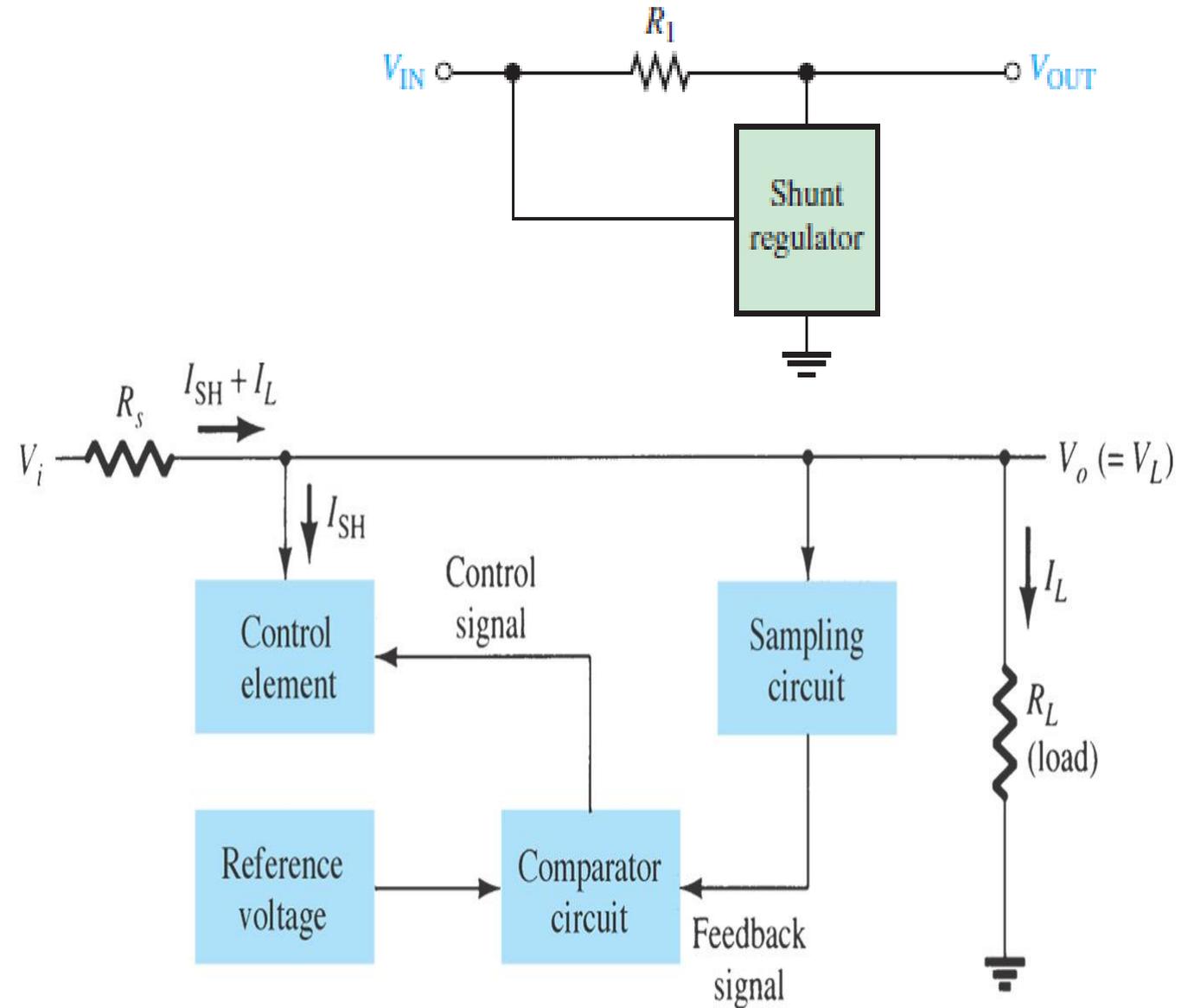
Op-Amp Shunt Regulator

➤When the output voltage tries to decrease due to a change in input voltage or load current caused by a change in load resistance, the decrease is sensed by R_3 and R_4.

➤A feedback voltage obtained from voltage divider R_3 and R_4 is applied to the op-amp's non-inverting input and compared to the Zener voltage to control the drive current to the transistor.

➤The current through resistor R_1 is thus controlled to drop a voltage across R_1 so that the output voltage is maintained.
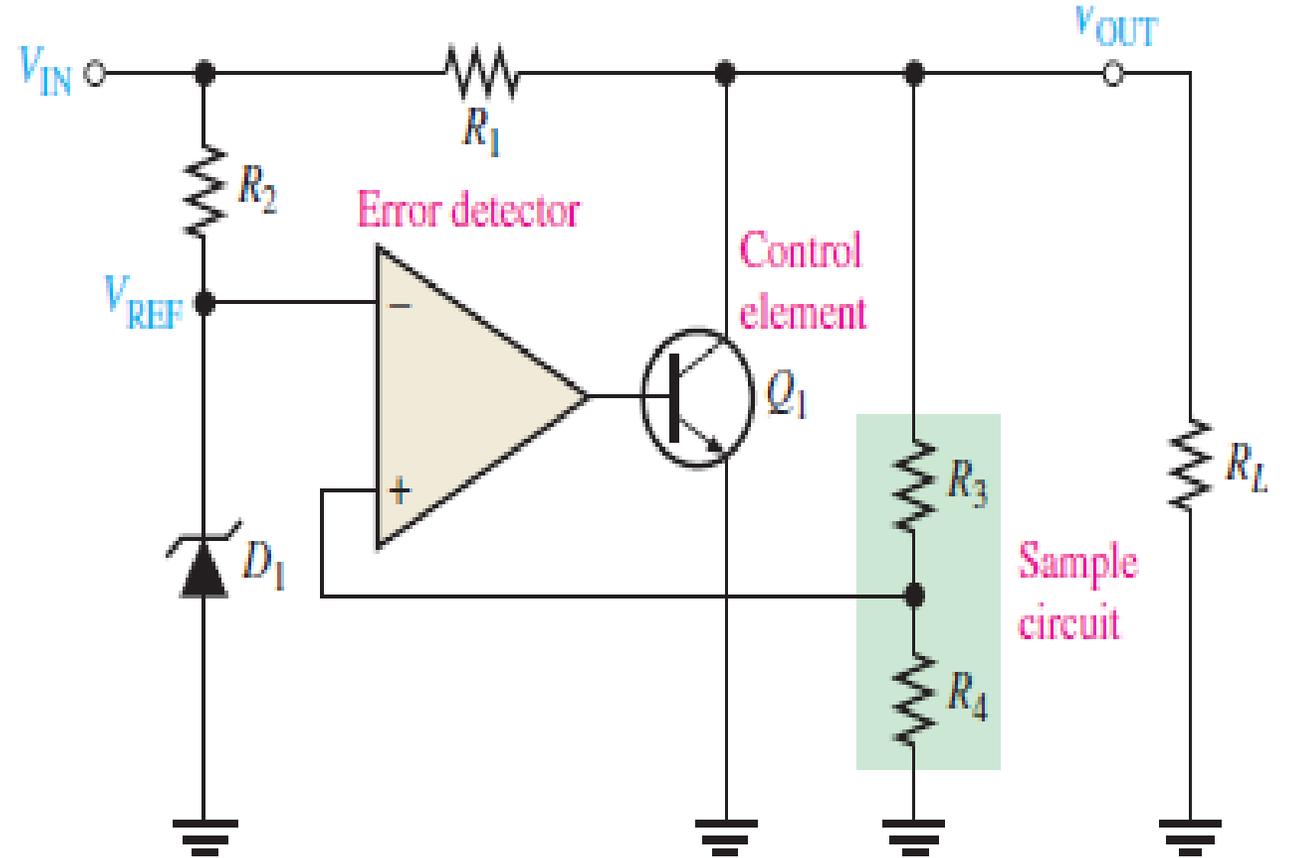
Sequence of responses when V_{OUT} tries to decrease as a result of a decrease in R_L or V_{IN} (opposite responses for an attempted increase).
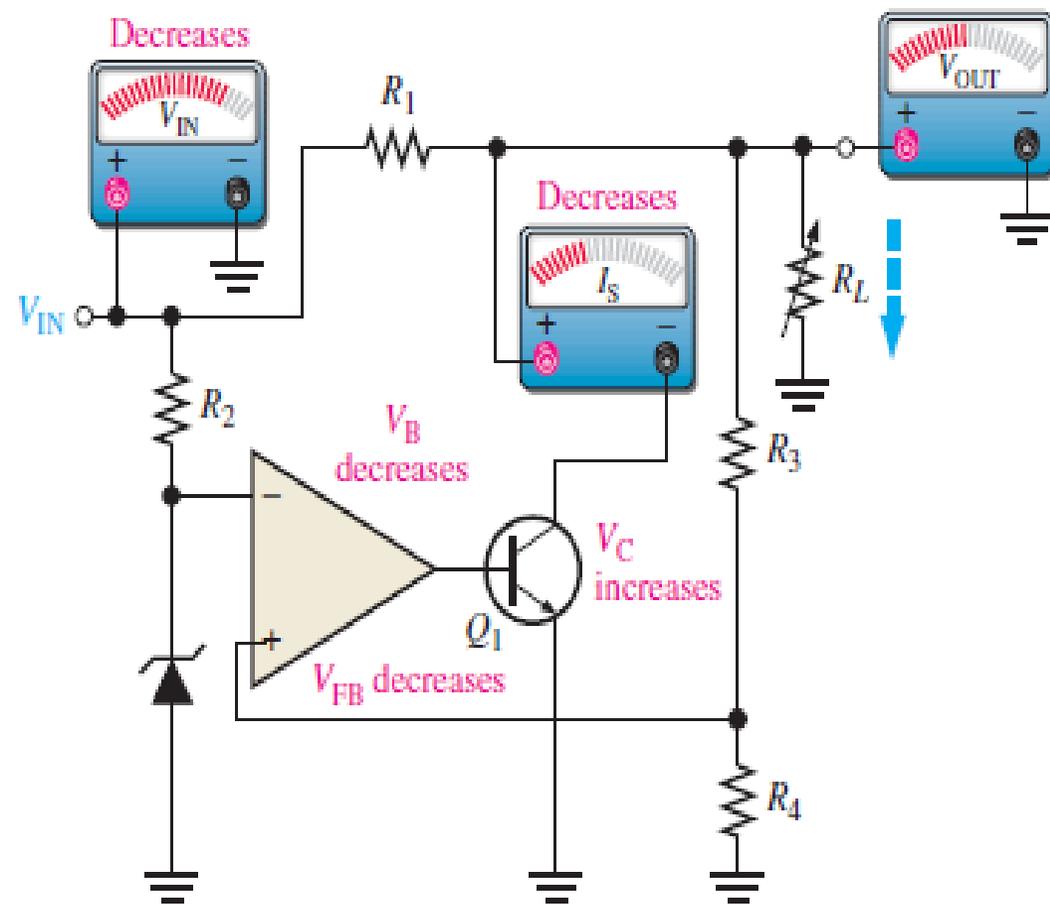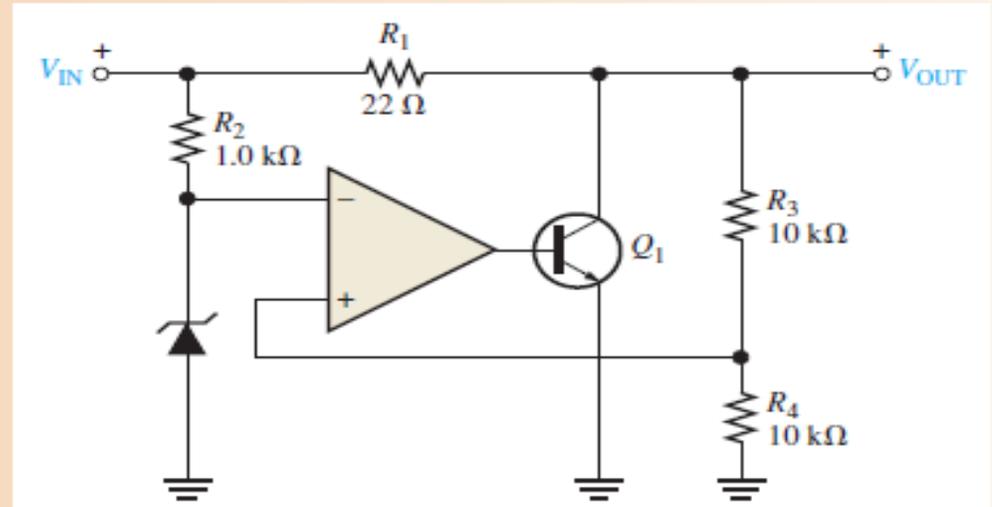

(a) Response to a decrease in V_{IN} or R_L
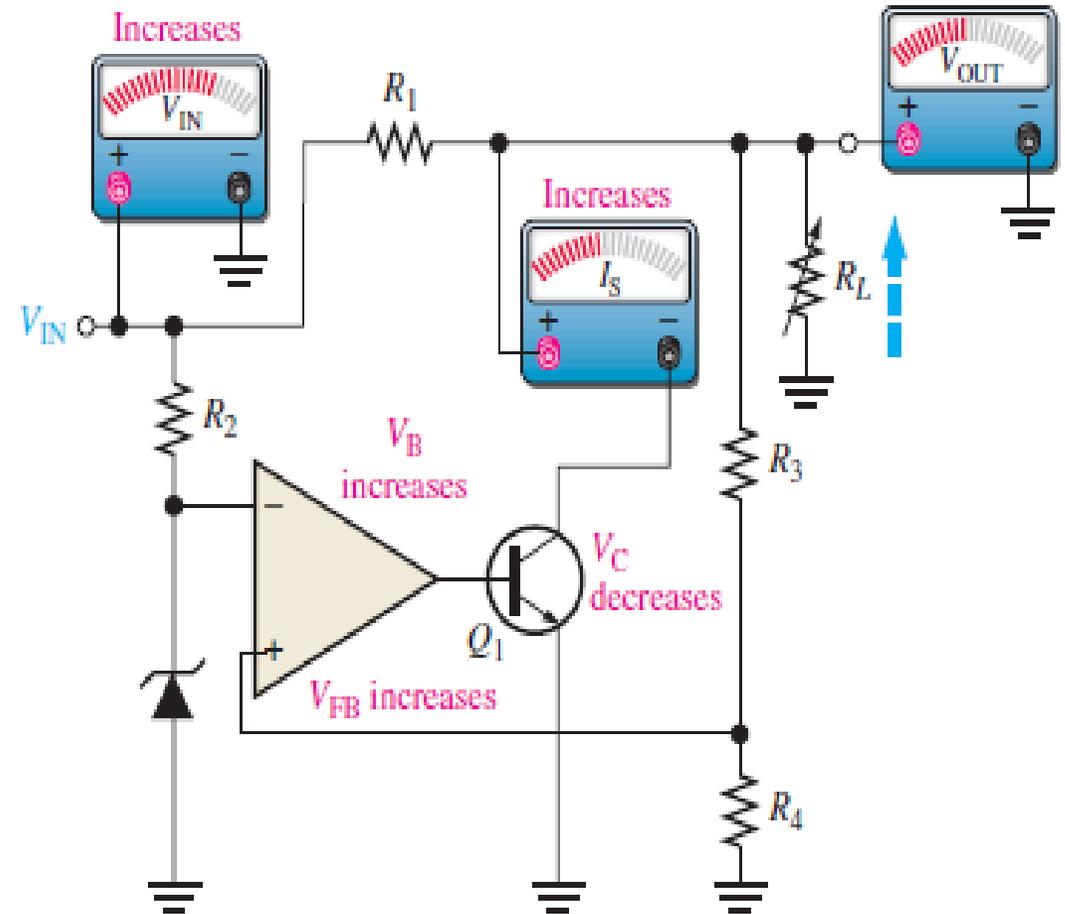
(b) Response to an increase in V_{IN} or R_L

Example 4.6: In figure below, what power rating must R_1 have if the maximum input voltage is 12.5 V?

The worst-case power dissipation in R_1 occurs when the output is short-circuited and $V_{OUT} = 0$. When $V_{IN} = 12.5$ V, the voltage dropped across R_1 is

$$V_{R1} = V_{IN} - V_{OUT} = 12.5 \text{ V}$$

The power dissipation in R_1 is

$$P_{R1} = \frac{V_{R1}^2}{R_1} = \frac{(12.5 \text{ V})^2}{22 \text{ } \Omega} = 7.10 \text{ W}$$

Therefore, a resistor with a rating of at least 10 W should be used. This illustrates that a major disadvantage of this type of regulator is the power wasted in R_1, which makes the regulator inefficient.

Transistor Shunt Regulator

➢The control element is a transistor, in parallel with the load. While, the resistor, R_S, is in series with the load.

➢The operation of the transistor shunt regulator is **similar** to that of the transistor series regulator, except that regulation is achieved by **controlling the current through the parallel transistor**

Shunt regulator
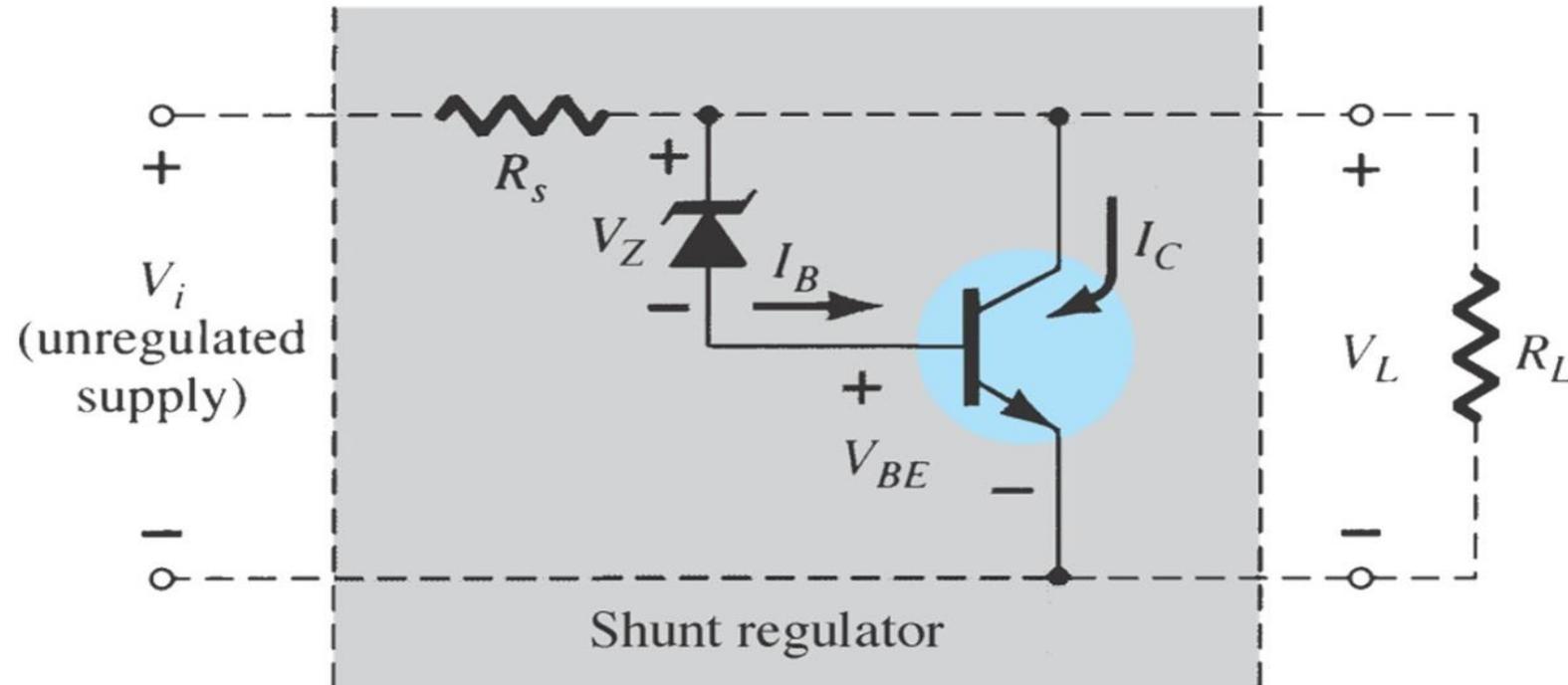
➢Resistor R_S drops the unregulated voltage depends on current supplied to load R_L.

➢Voltage across the load is set by Zener diode and transistor base-emitter voltage.

➢If R_L decrease, a reduced drive current to base of Q1 → shunting less collector current.

➢Load current, I_L is larger, maintaining the regulated voltage across load.

➢The output voltage to the load is: $$V_o = V_L = V_Z + V_{BE}$$

➢voltage across the load is set by the Zener diode voltage and the transistor base-emitter voltage.

➢If the load resistance decreases, the load current will be larger at a value of: $$I_L = \frac{V_L}{R_L}$$

➢The increase in load current causes the collector current shunted by the transistor is to be less: $$I_C = I_S - I_L$$

➢The current through R_S: $$I_S = \frac{V_i - V_L}{R_S}$$

Example: Determine the regulated voltage, V_L and circuit currents.
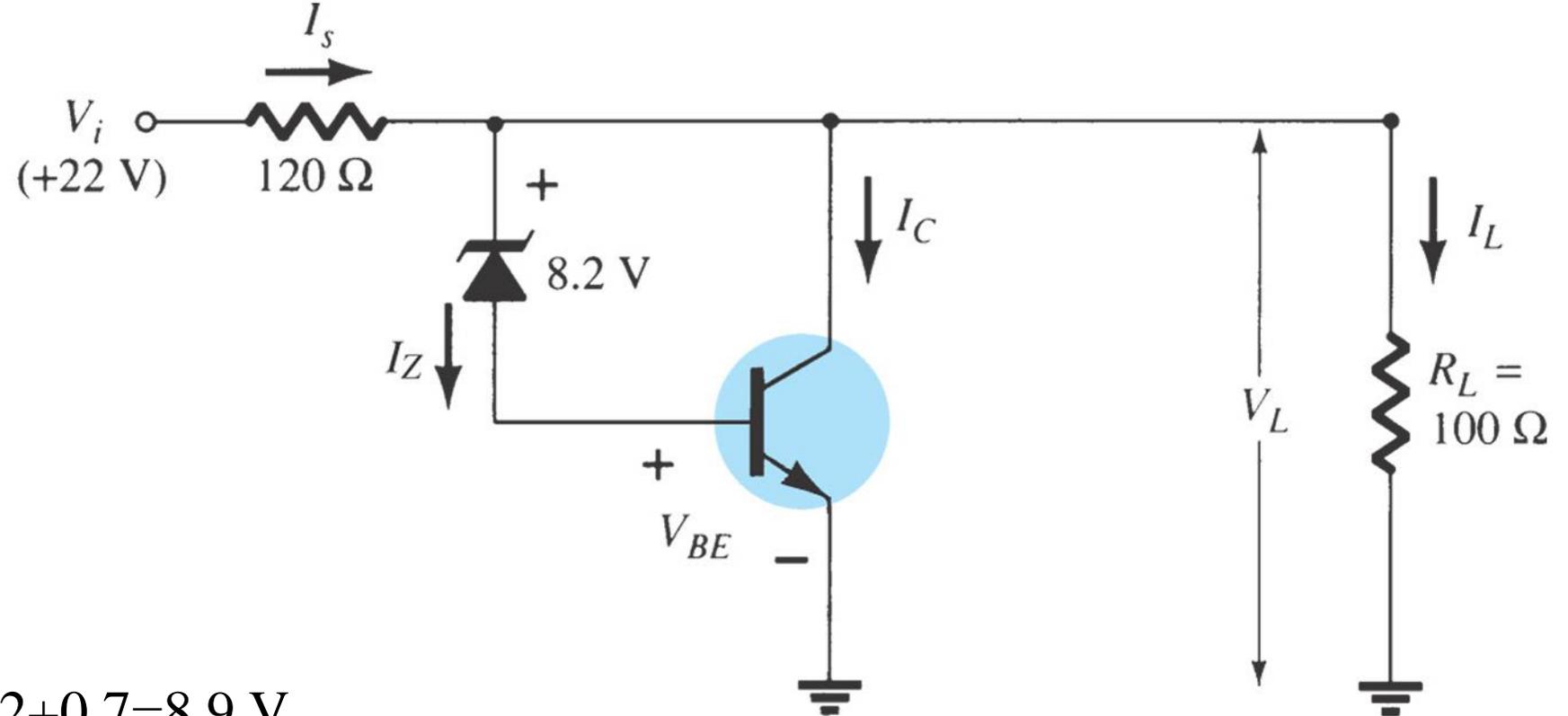

The load voltage is $V_L=8.2+0.7=8.9$ V

$\qquad I_L=V_L/R_L=8.9$ V$/100=89$ mA

$I_S=V_i-V_L/R_S=22-8.9/120=109$ mA

$I_C=I_S-I_L=109-89=20$mA

Switching Regulator

➤The switching regulator is a type of regulator circuit which its efficient transfer of power to the load is greater than series and shunt regulators because the transistor is not always conducting.

➤The switching regulator passes voltage to the load in pulses, which then filtered to provide a smooth dc voltage.

➤The switching regulator is **more efficient** than the linear series or shunt type.

➤This type regulator is ideal for high current applications since less power is dissipated.

➤Voltage regulation in a switching regulator is achieved by the on and off action limiting the amount of current flow based on the varying line and load conditions.

➤With switching regulators 90% efficiencies can be achieved.
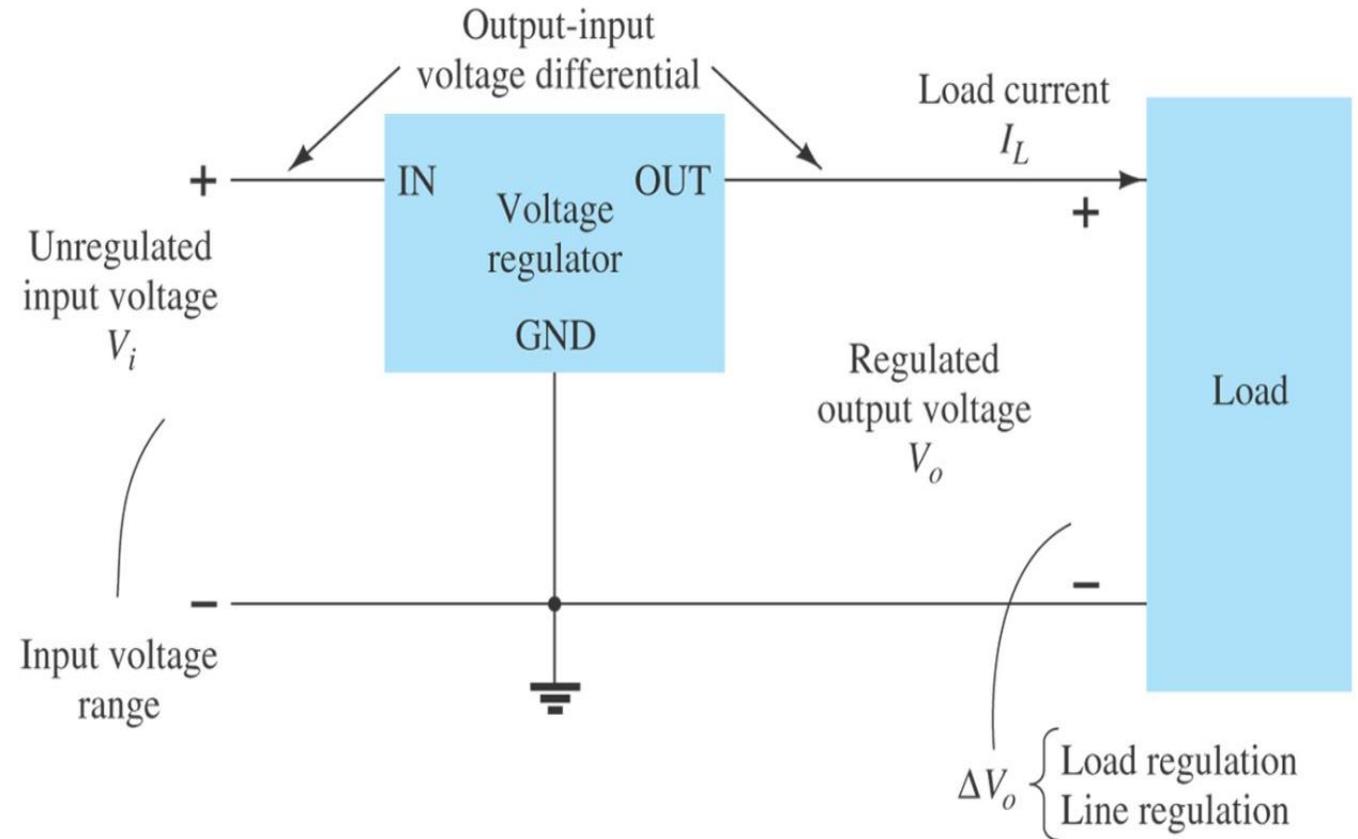
Step-Down Configuration

➢With the step-down (output is less than the input) configuration the control element Q_1 is pulsed on and off at variable rate based on the load current. Also called **buck converter.**

➢The pulsations are filtered out by the LC filter.

Simplified step-down regulator.
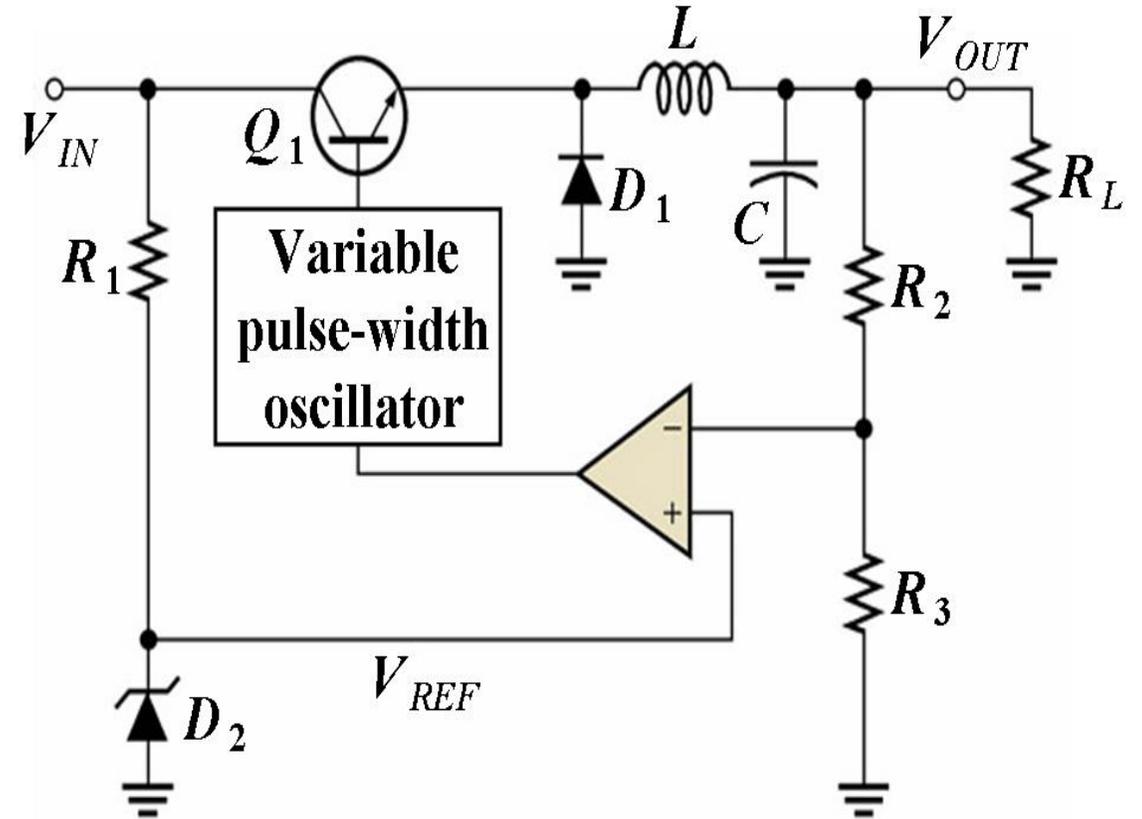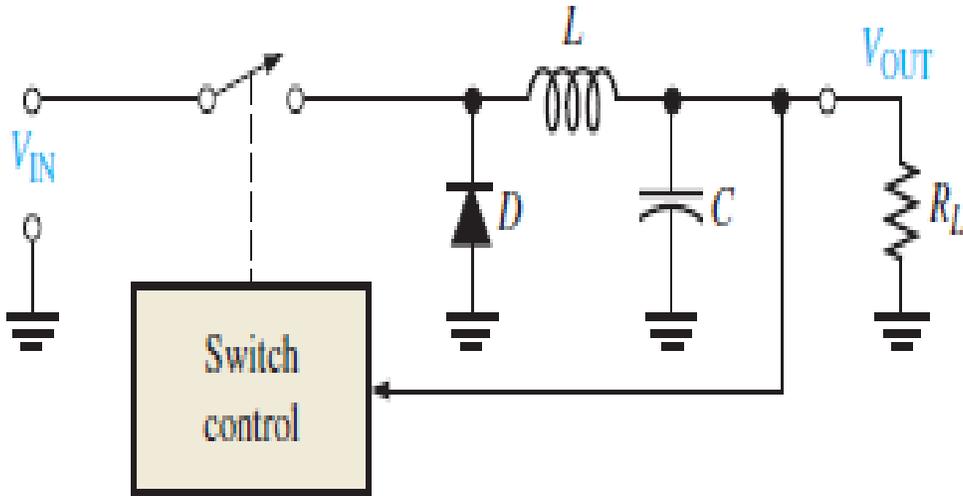
Step-up configuration

➢ Also called a **boost converter**

➢The difference is in the placement of the inductor and the fact that Q_1 is shunt configured.

➢During the time when Q_1 is off the V_L adds to V_C stepping the voltage up by some amount.
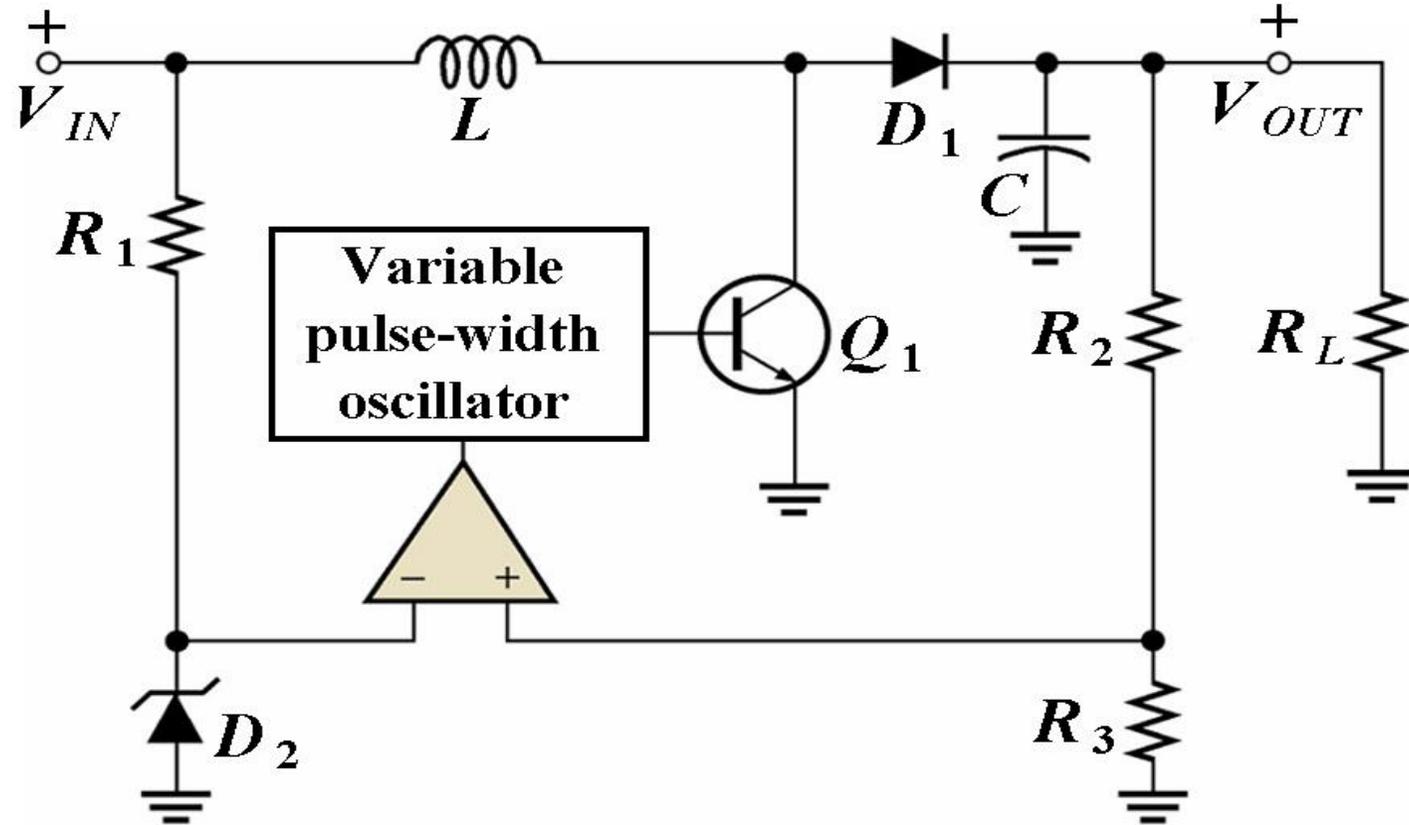
Voltage-inverter configuration

➢output voltage is of opposite polarity of the input. This sometimes called a **buck-boost converter.**

➢This is achieved by V_L forward-biasing reverse-biased diode during the Off times producing current and charging the capacitor for voltage production during the off times.

➢With switching regulators 90% efficiencies can be achieved.
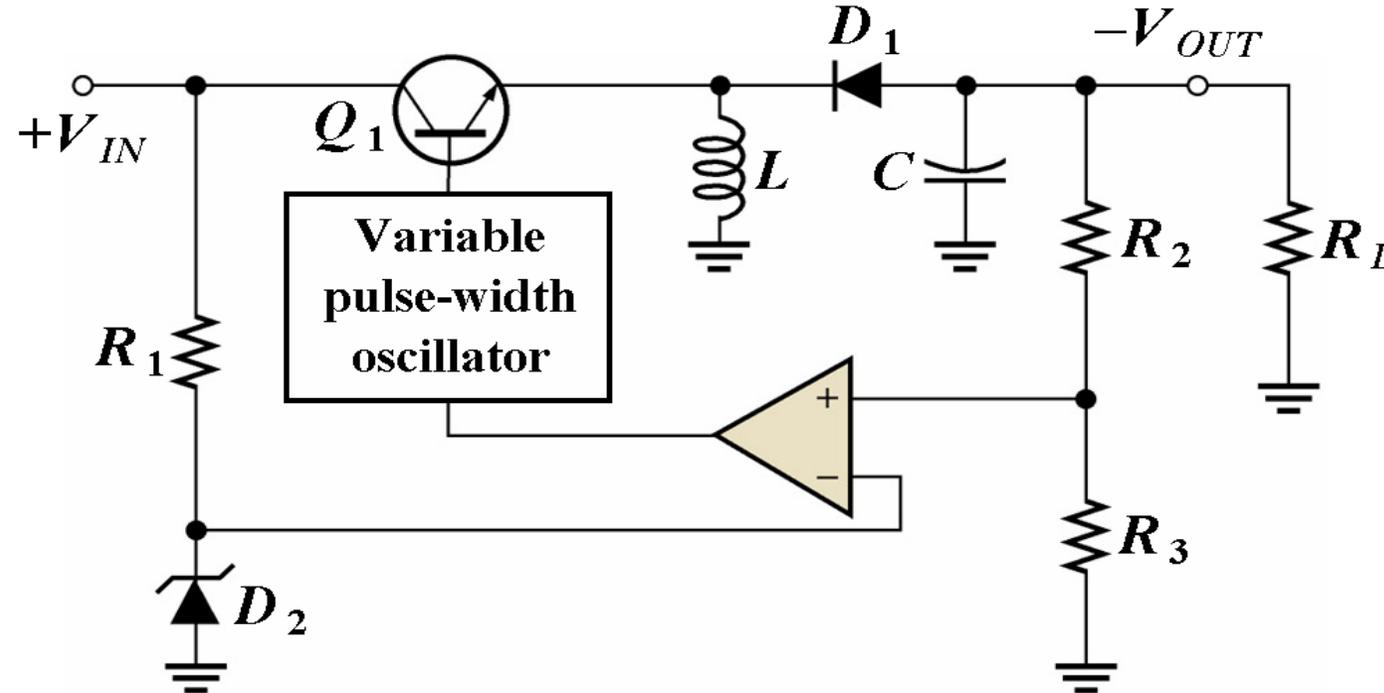
IC Voltage Regulators

➢Regulation circuits in integrated circuit form are widely used.

➢Their operation is no different but they are treated as a single device with associated components.

➢These are generally three terminal devices that provide a positive or negative output.

➢Some types have variable voltage outputs.

➢A typical 7800 series voltage regulator is used for positive voltages.

➢The 7900 series are negative voltage regulators.

➢These voltage regulators when used with heatsinks can safely produce current values of 1A and greater.

➢The capacitors act as line filtration.

➢Several types of both linear (series and shunt) and switching regulators are available in integrated circuit (IC) form.

➢Generally, the linear regulators are three-terminal devices that provides either positive or negative output voltages that can be either fixed or adjustable.
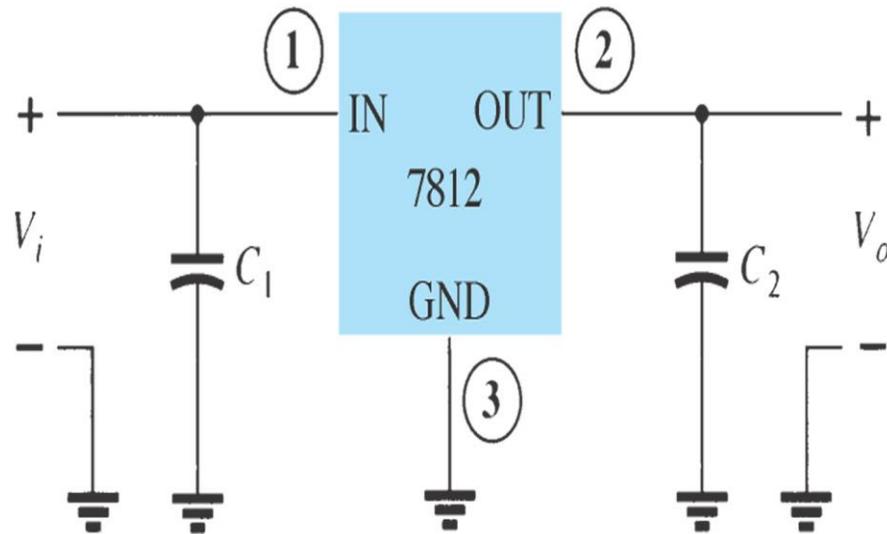
Fixed Voltage Regulator

➢ The fixed voltage regulator has an unregulated dc input voltage V_i applied to one input terminal, a regulated output dc voltage V_o from a second terminal, and the third terminal connected to ground.

Fixed-Positive Voltage Regulator

➢ The series 78XX regulators are the three-terminal devices that provide a fixed positive output voltage.

Pin 1. Input
2. Ground
3. Output
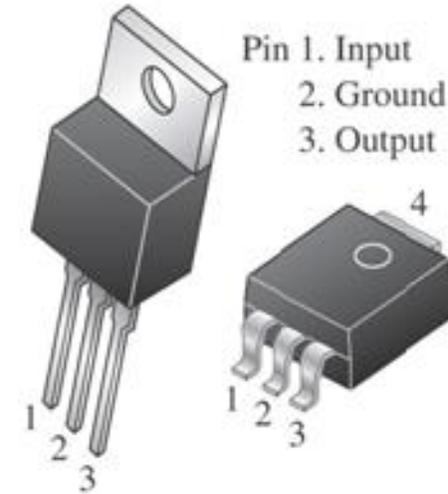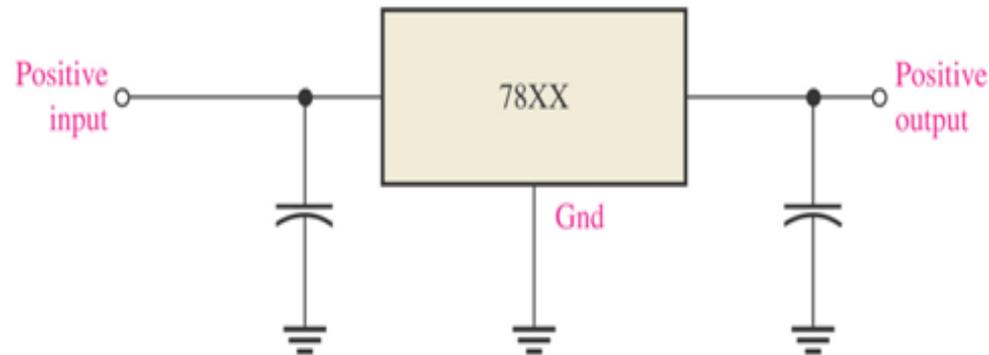
- An unregulated input voltage V_i is filtered by a capacitor C_1 and connected to the IC's IN terminal.
- The IC's OUT terminal provides a regulated +12 V, which is filtered by capacitor C_2.
- The third IC terminal is connected to ground (GND)

Positive-Voltage Regulators in the 78XX Series

IC Part	Output Voltage (V)	Minimum V_i (V)
7805	+5	+7.3
7806	+6	+8.3
7808	+8	+10.5
7810	+10	+12.5
7812	+12	+14.5
7815	+15	+17.7
7818	+18	+21.0
7824	+24	+27.1

Fixed-Negative Voltage Regulator

➢The series 79XX regulators are the three-terminal IC regulators that provide a fixed negative output voltage.

➢This series has the same features and characteristics as the series 78XX regulators except the pin numbers are different.
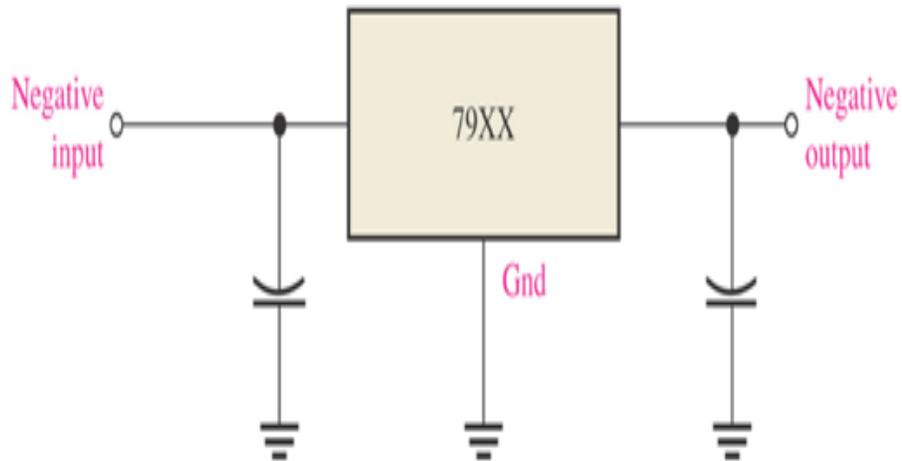

Negative-Voltage Regulators in the 79XX Series

| IC Part	Output Voltage (V)	Minimum V_i (V)
7905	-5	-7.3
7906	-6	-8.4
7908	-8	-10.5
7909	-9	-11.5
7912	-12	-14.6
7915	-15	-17.7
7918	-18	-20.8
7924	-24	-27.1

Adjustable-Voltage Regulator

➢Voltage regulators are also available in circuit configurations that allow to set the output voltage to a desired regulated value.

➢The LM317 is an example of an adjustable-voltage regulator, can be operated over the range of voltage from 1.2 to 37 V.
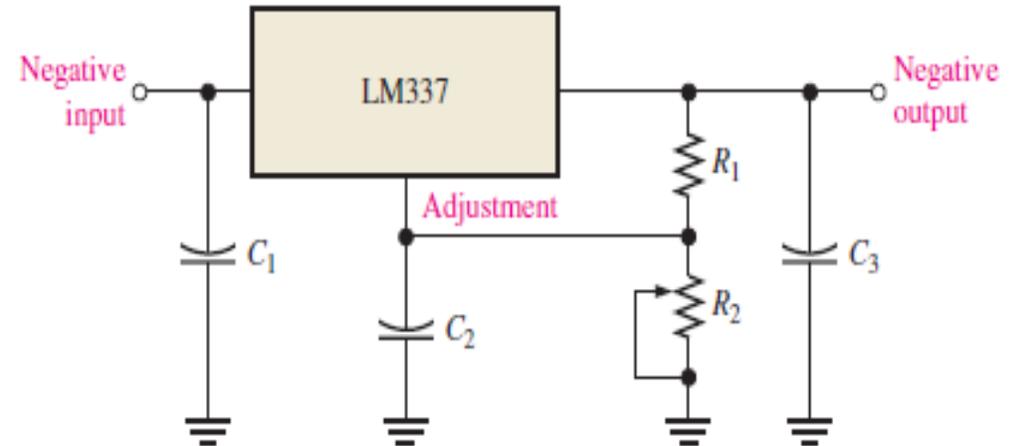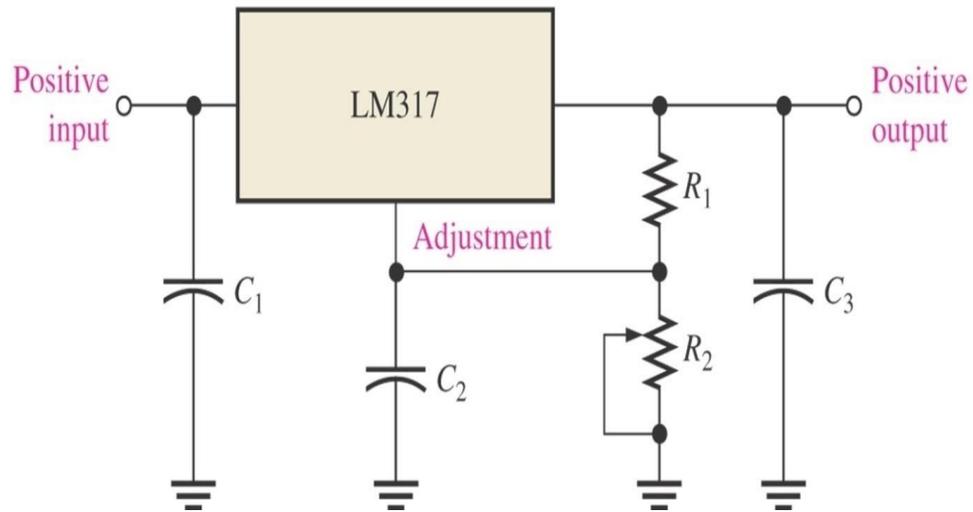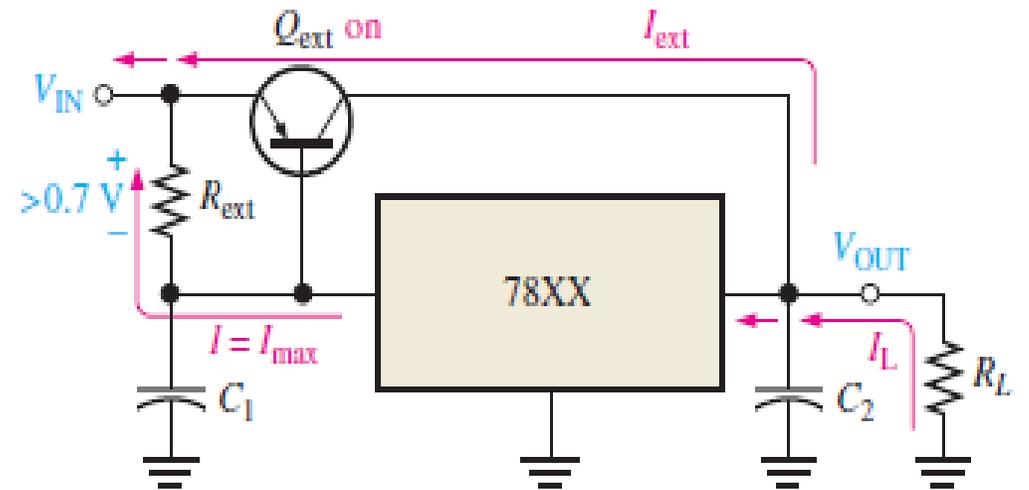
The External Pass Transistor

As you know, an IC voltage regulator is capable of delivering only a certain amount of output current to a load. For example, the 78XX series regulators can handle a peak output current of 1.3 A (more under certain conditions). If the load current exceeds the maximum allowable value, there will be thermal overload and the regulator will shut down. A thermal overload condition means that there is excessive power dissipation inside the device.
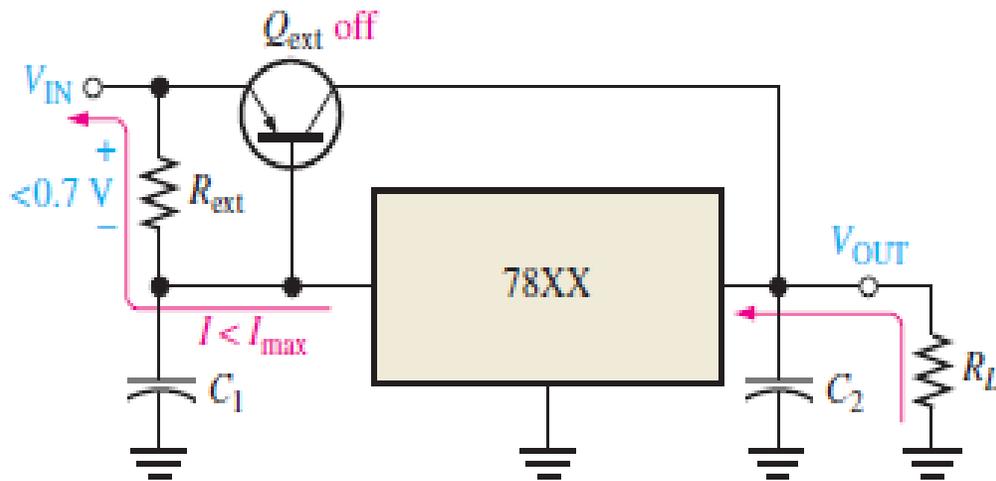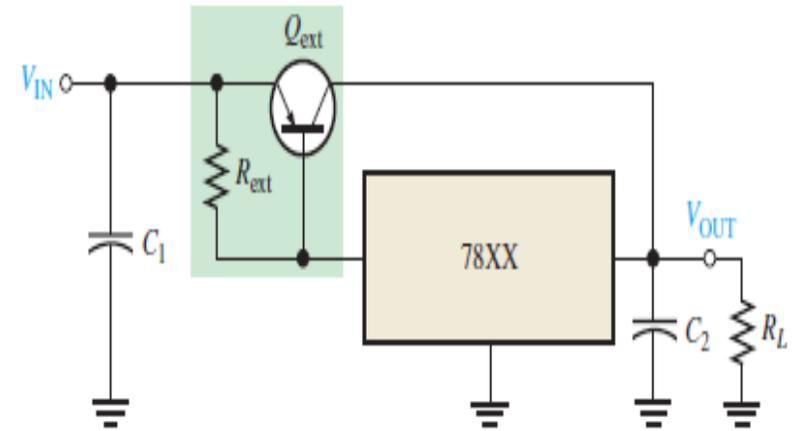

(a) When the regulator current is less than I_{max}, the external pass transistor is off and the regulator is handling all of the current.

(b) When the load current exceeds I_{max}, the drop across R_{ext} turns Q_{ext} on and it conducts the excess current.

Current Limiting

➢ A drawback of the circuit in the previous Figure is that the external transistor is not protected from excessive current, such as would result from a shorted output.

➢ An additional current limiting circuit (Q_{lim} and R_{lim}) can be added as shown in Figure below to protect Q_{ext} from excessive current and possible burn out.
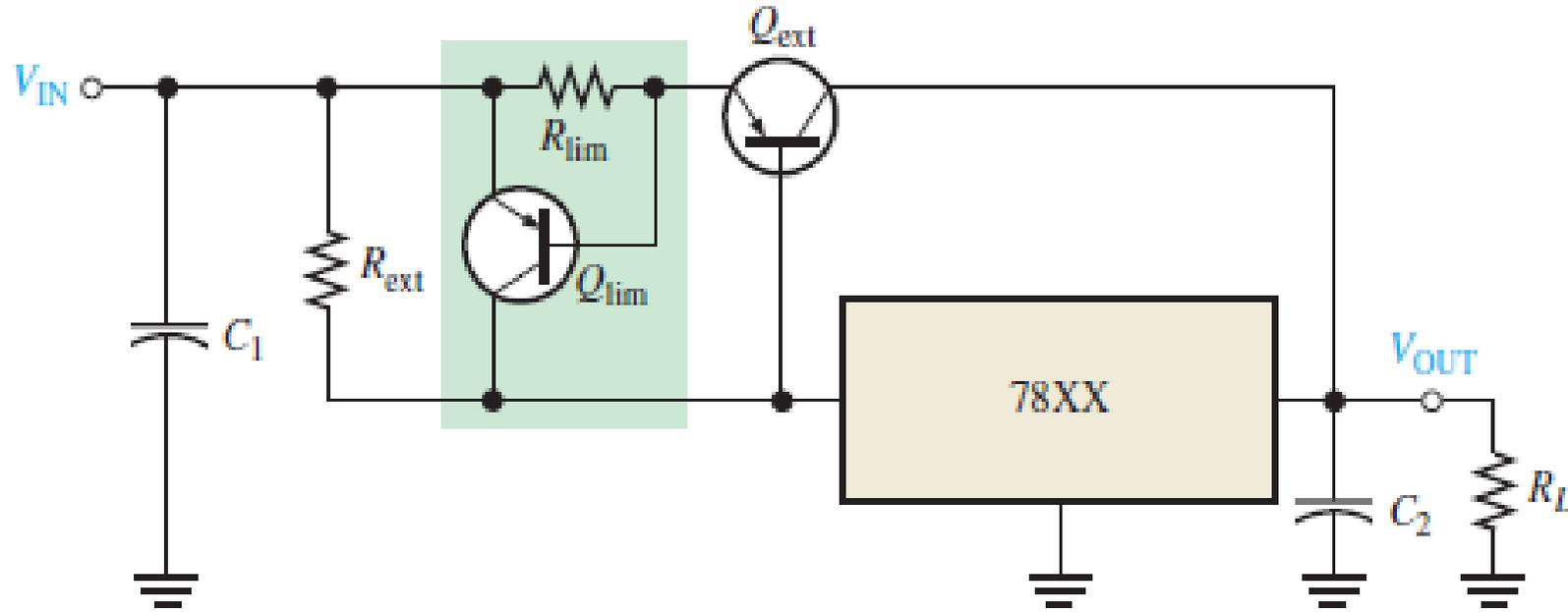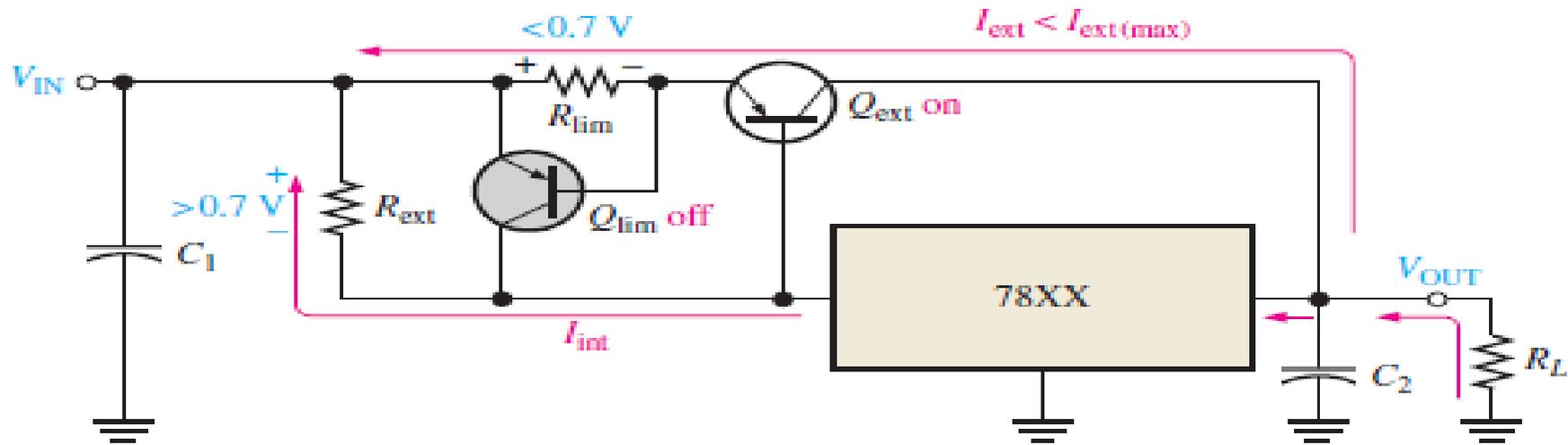
(a) During normal operation, when the load current is not excessive, Q_{lim} is off.
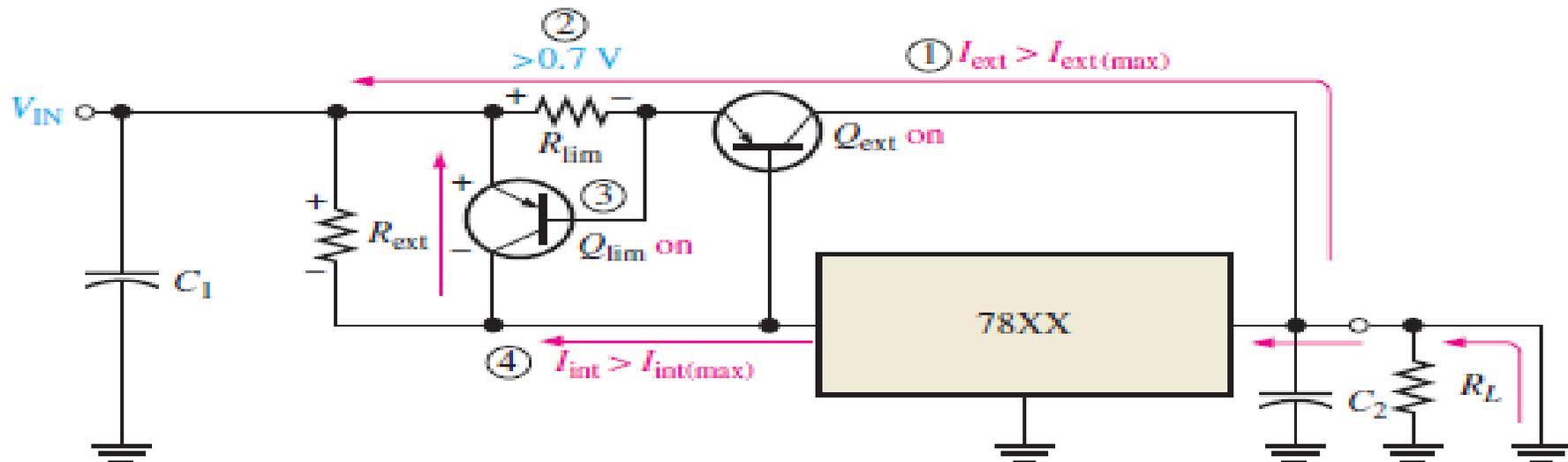
(b) When short occurs ①, the external current becomes excessive and the voltage across R_{lim} increases ② and turns on Q_{lim} ③, which then routes current through the regulator and conducts it away from Q_{ext}, causing the internal regulator current to become excessive ④ which forces the regulator into thermal shut down.

A Current Regulator

➢ The three-terminal regulator can be used as a current source when an application requires that a constant current be supplied to a variable load.

➢ The basic circuit is shown in Figure where is the current-setting resistor.

➢ The regulator provides a fixed constant voltage, between the ground terminal (not connected to ground in this case) and the output terminal. This determines the constant current supplied to the load.
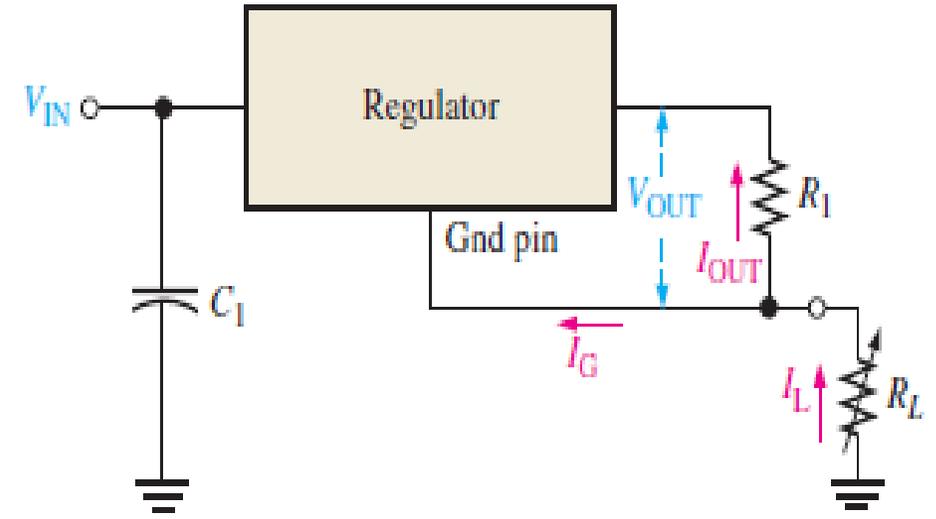
$$I_L = \frac{V_{OUT}}{R_1} + I_G$$

➢ The current I_G, from the ground pin is very small compared to the output current and can often be neglected.

SUMMARY

➤ Voltage regulators keep a constant dc output voltage when the input or load varies within limits.

➤ Line regulation is the percentage change in the output voltage for a given change in the input voltage of a regulator.

➤ Load regulation is the percentage change in output voltage for a given change in load current.

➤ A basic voltage regulator consists of a reference voltage source, an error detector, a sampling element, and a control device. Protection circuitry is also found in most regulators.

➤ Two basic categories of voltage regulators are linear and switching.

➤ Two basic types of linear regulators are series and shunt.

➤ In a linear series regulator, the control element is a transistor in series with the load.

➤ In a linear shunt regulator, the control element is a transistor in parallel with the load.

➤ Three configurations for switching regulators are step-down, step-up, and inverting.

➤ Switching regulators are more efficient than linear regulators and are particularly useful in low-voltage, high-current applications.

➤ Three-terminal linear IC regulators are available for either fixed output or variable output voltages of positive or negative polarities.

➤ The 78XX series are three-terminal IC regulators with fixed positive output voltage.

➤ The 79XX series are three-terminal IC regulators with fixed negative output voltage.

➤ The LM317 is a three-terminal IC regulator with a positive variable output voltage.

➤ The LM337 is a three-terminal IC regulator with a negative variable output voltage.

➤ An external pass transistor increases the current capability of a regulator.