

ELT 061 – Dispositivos e Circuitos Eletrônicos Básicos

Transistor Bipolar



DEPARTAMENTO DE ENGENHARIA ELETRÔNICA
UNIVERSIDADE FEDERAL DE MINAS GERAIS

Transistor Bipolar


Bipolar



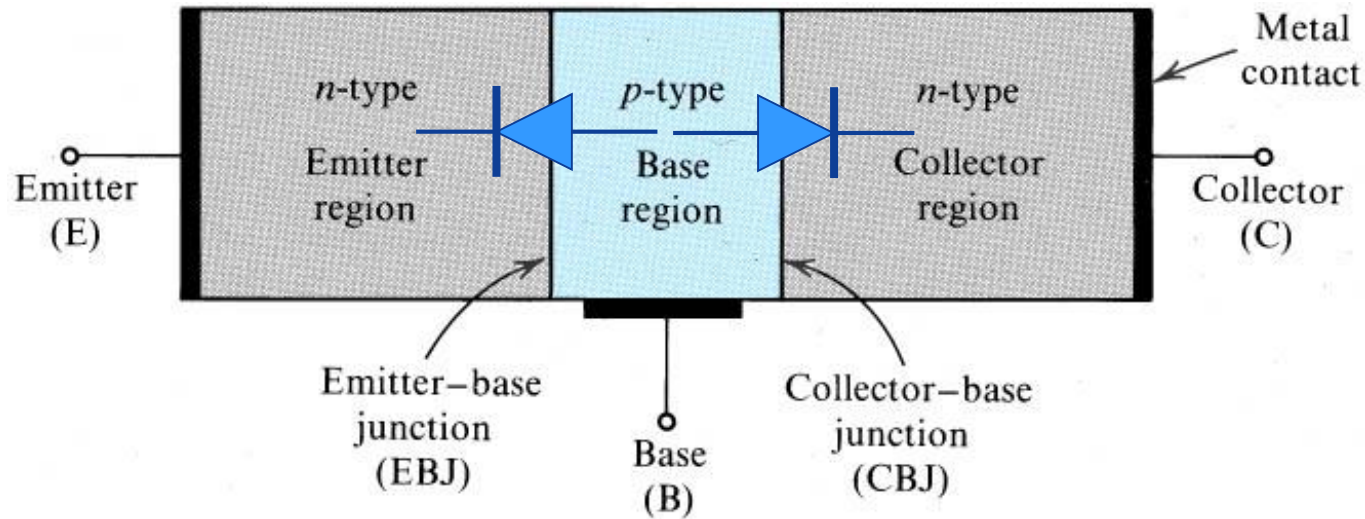
Elétrons e buracos participam do processo de condução de corrente

Foi inventado em 1948 nos Laboratórios Bell

Aplicações:

1. Amplificadores de Rádio Frequência
2. Circuitos lógicos de alta velocidade – ECL
3. MOSFET + BIPOLAR  BiCMOS

Transistor NPN



MODO	J EB	J CB
Corte	Reversa	Reversa
Ativa	Direta	Reversa
Ativa reversa	Reversa	Direta
Saturação	Direta	Direta

Figure 5.1 A simplified structure of the *npn* transistor.

Transistor PNP

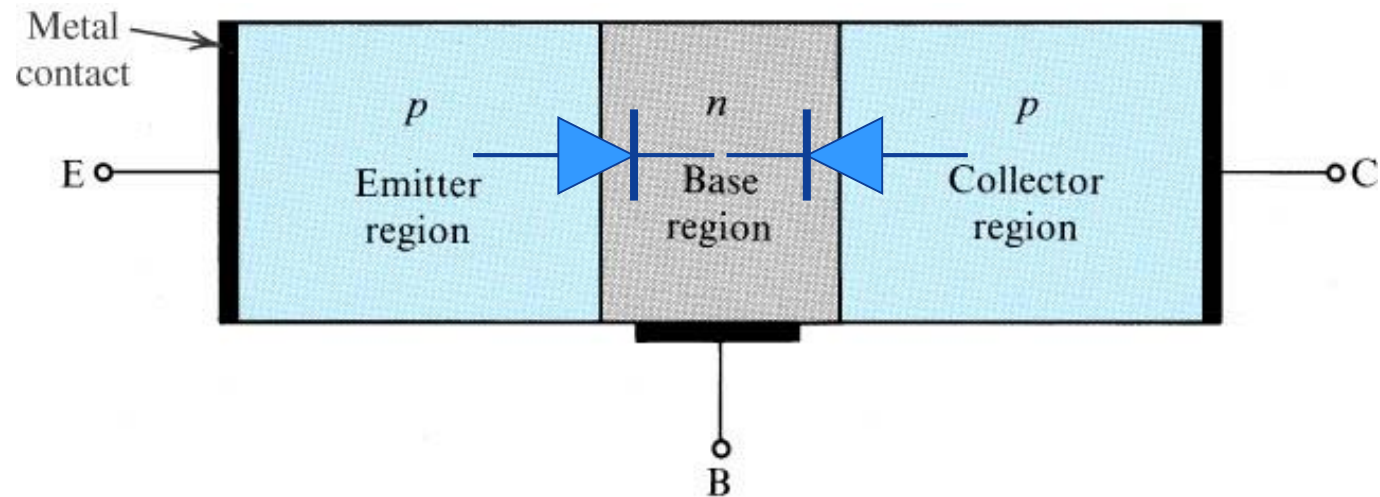


Figure 5.2 A simplified structure of the *pnp* transistor.

Símbolos dos Transistores

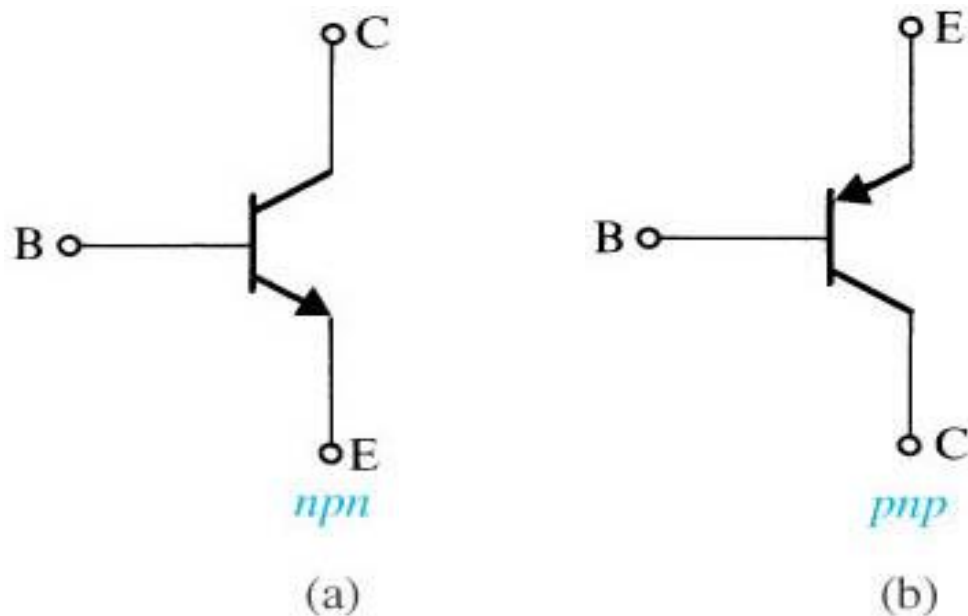


Figure 5.13 Circuit symbols for BJTs.

Conveções de sinais

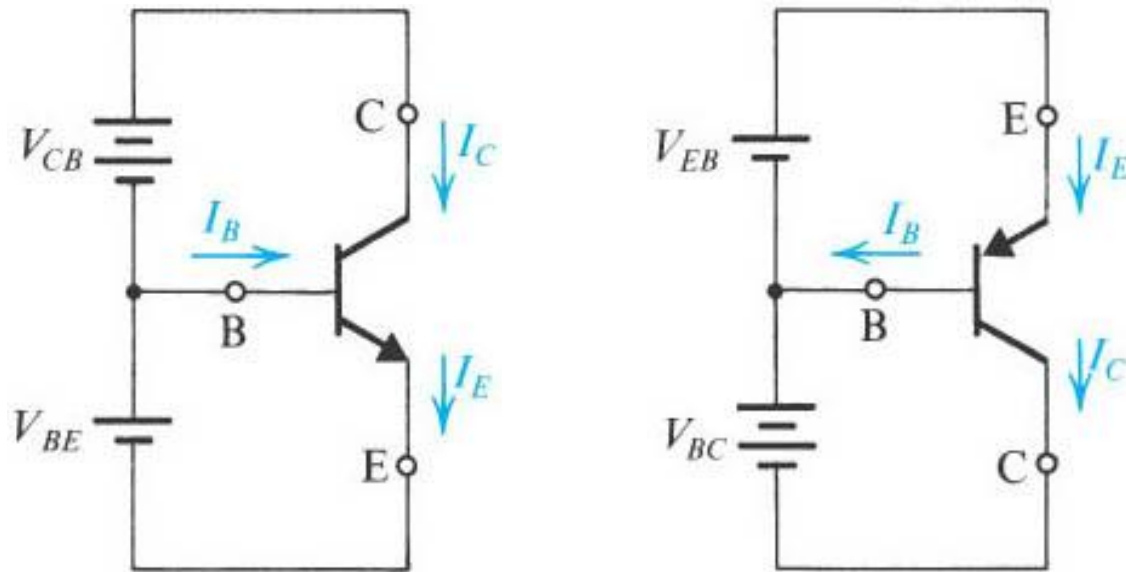
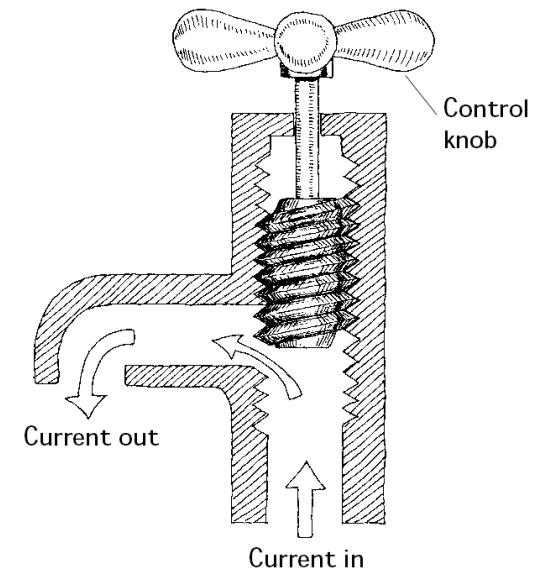
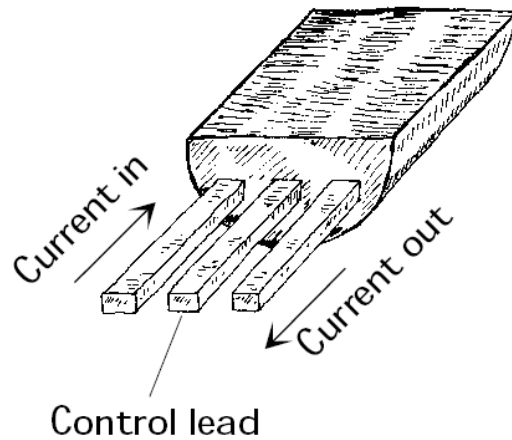
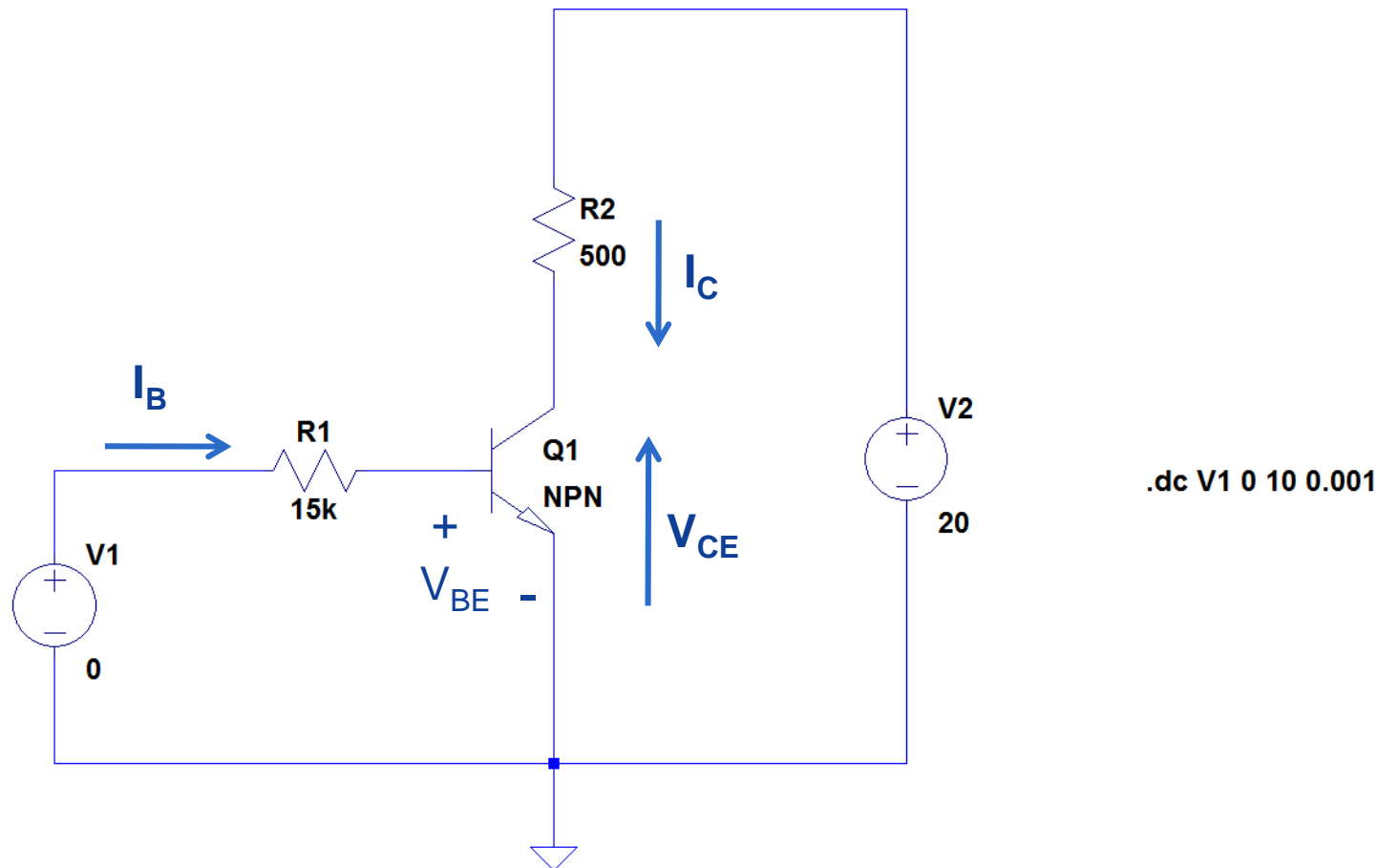


Figure 5.14 Voltage polarities and current flow in transistors biased in the active mode.

Transistor - analogia com uma torneira



Circuito básico em emissor comum



Princípio de operação do transistor NPN

Transistor normalmente não condutor (região de corte).

A corrente convencional circula de coletor para emissor. Opera portanto com $V_C > V_E$.

Condição para condução: fazer circular pelo terminal de controle (Base) uma corrente positiva. A corrente começa a circular quando $V_1 \geq 0,7V$. Quando isto acontece a tensão base emissor (V_{BE}) permanece praticamente constante e próxima a $0,7V$. A partir daí, a corrente de coletor será proporcional à corrente de base (região ativa).

$$I_C = \beta I_B$$

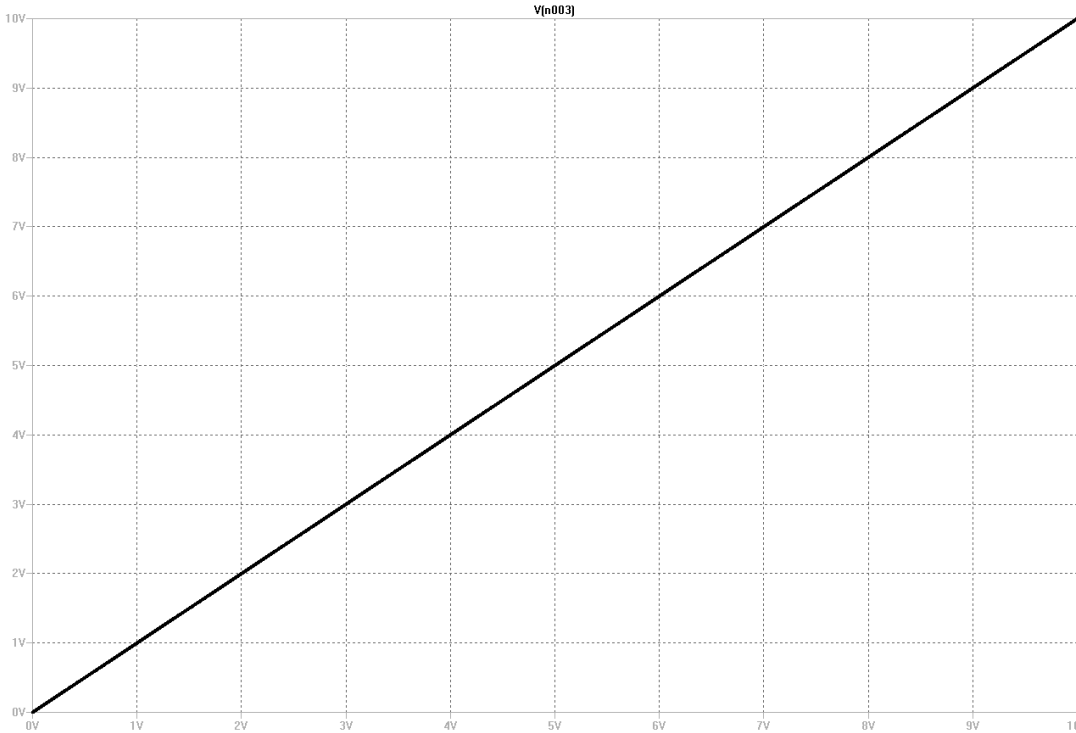
O valor mínimo para a tensão entre emissor e coletor é $V_{CE} = 0,2V$. A partir daí a corrente de base pode aumentar que a corrente de coletor permanece constante. O transistor comporta-se como uma chave fechada (região de saturação).

Tensão V1

10V

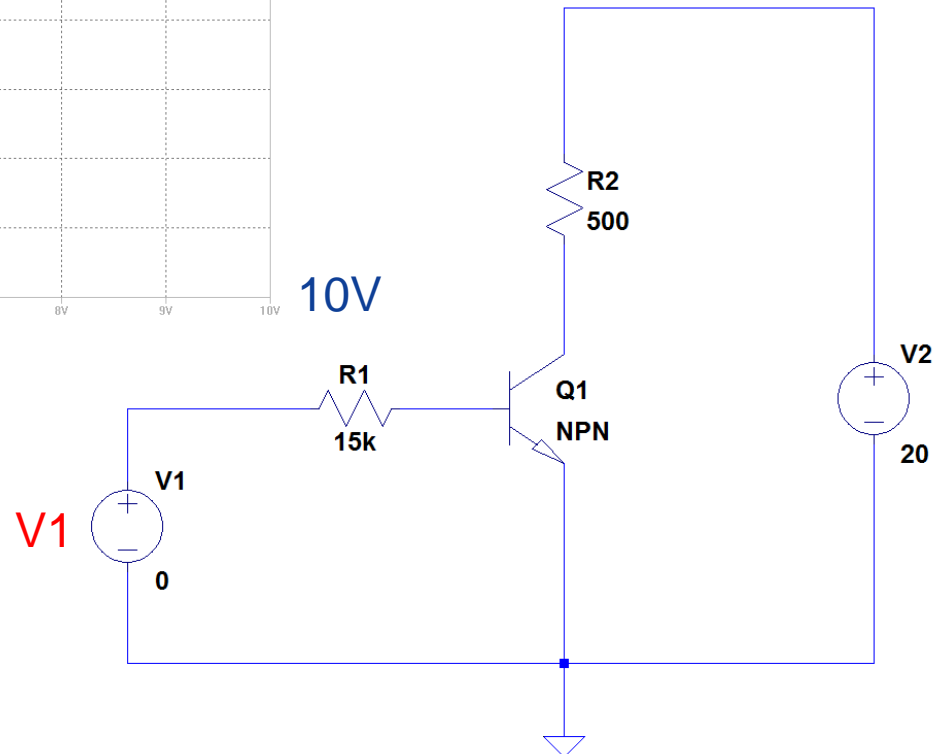
V1

0

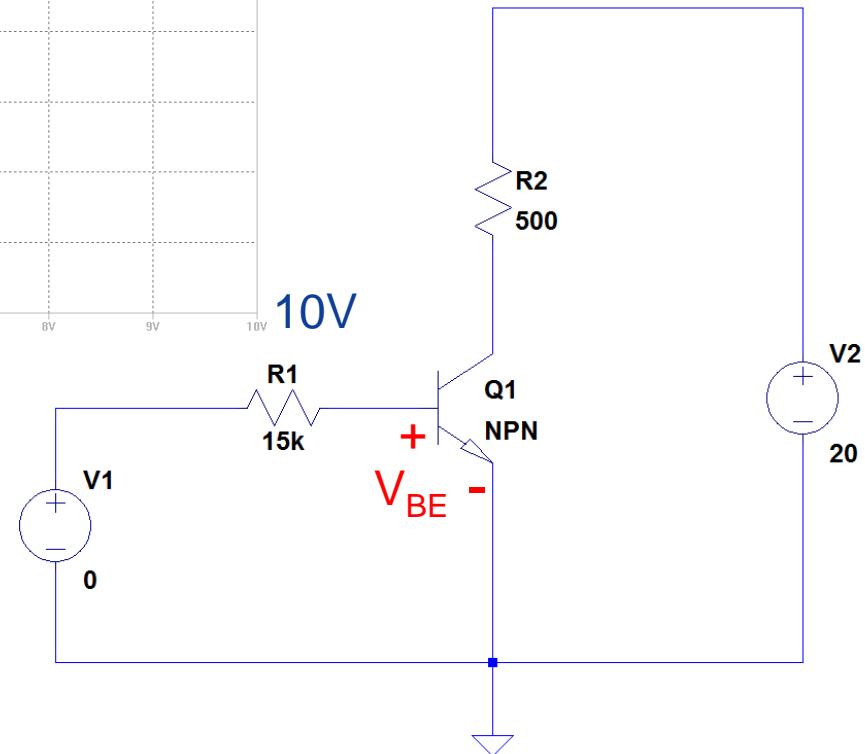
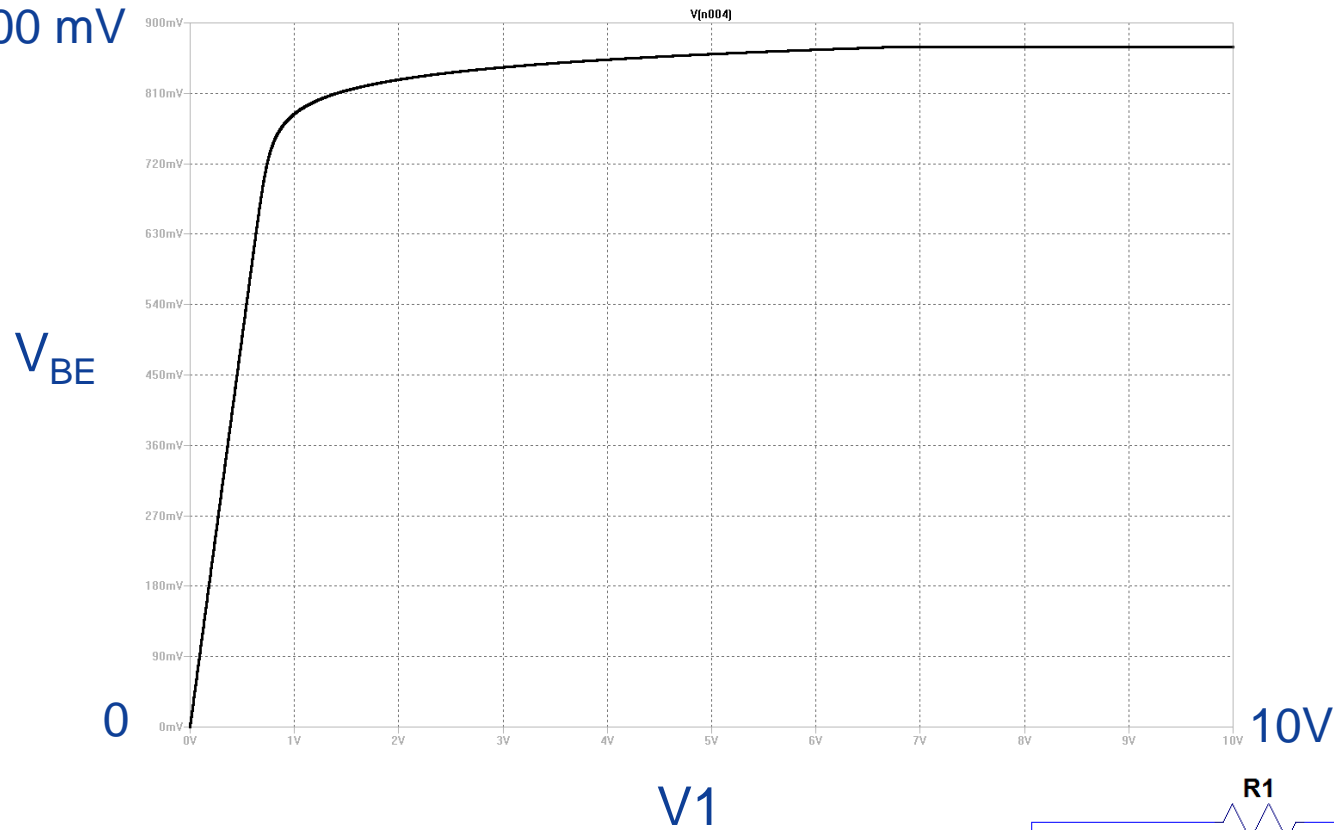


V1

10V



Tensão V_{BE}



Corrente I_B

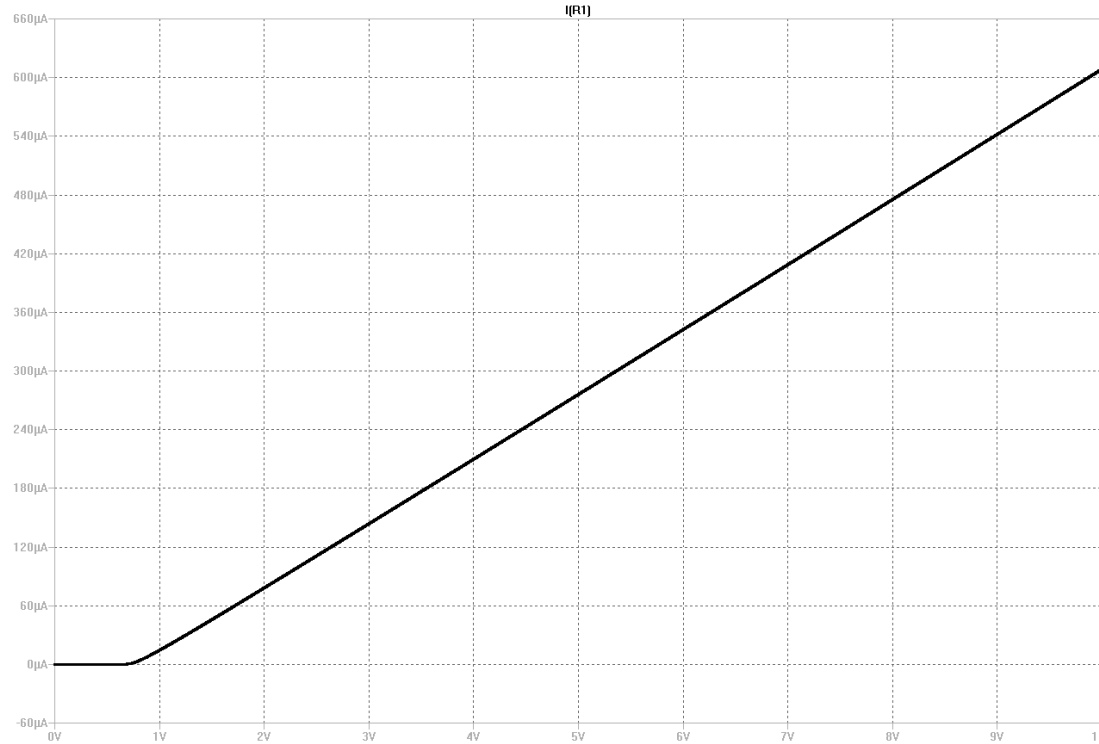
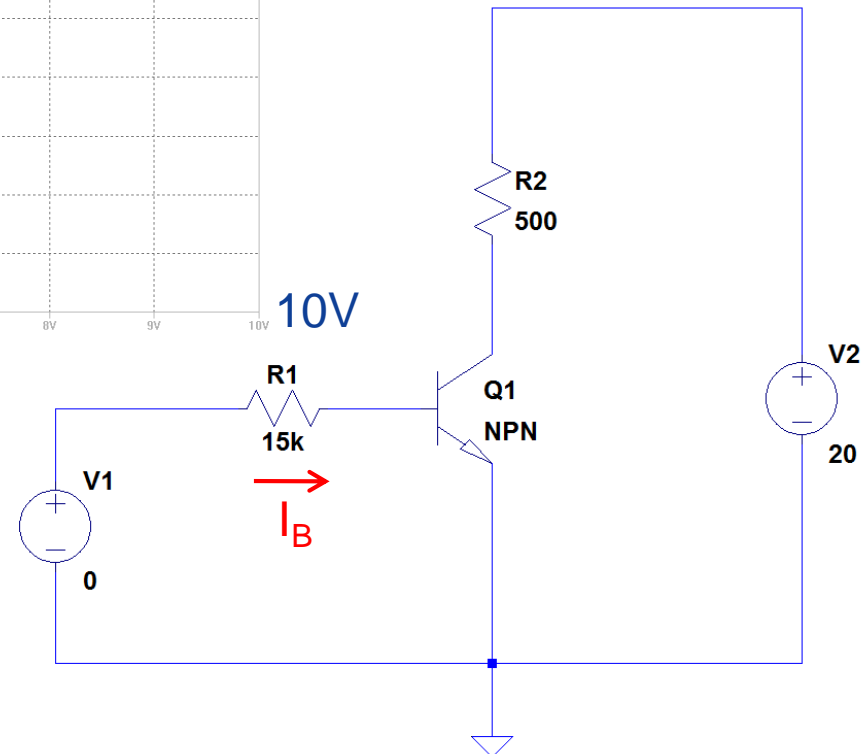
600 μA

I_B

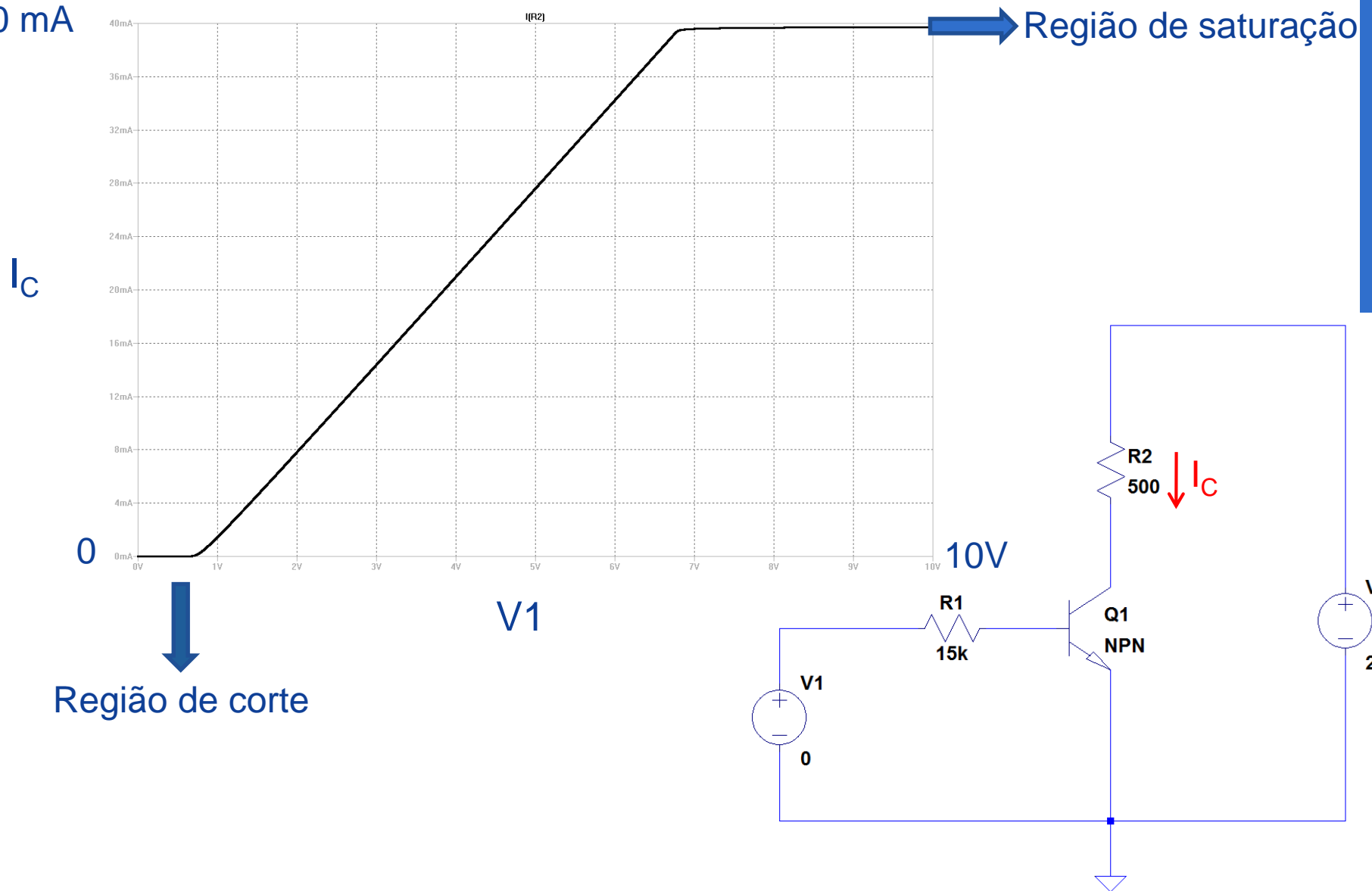
0

V1

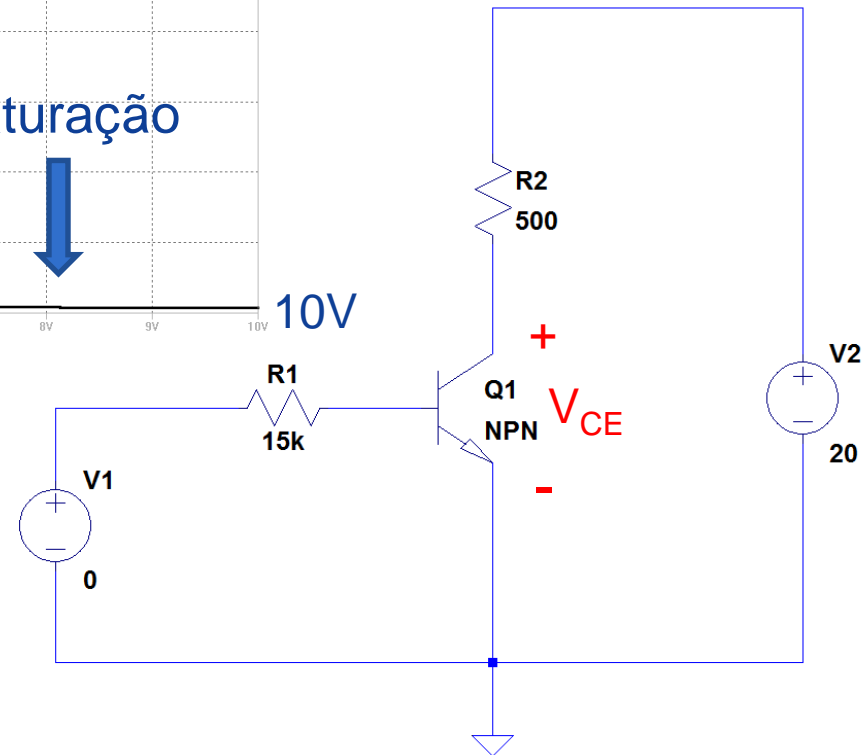
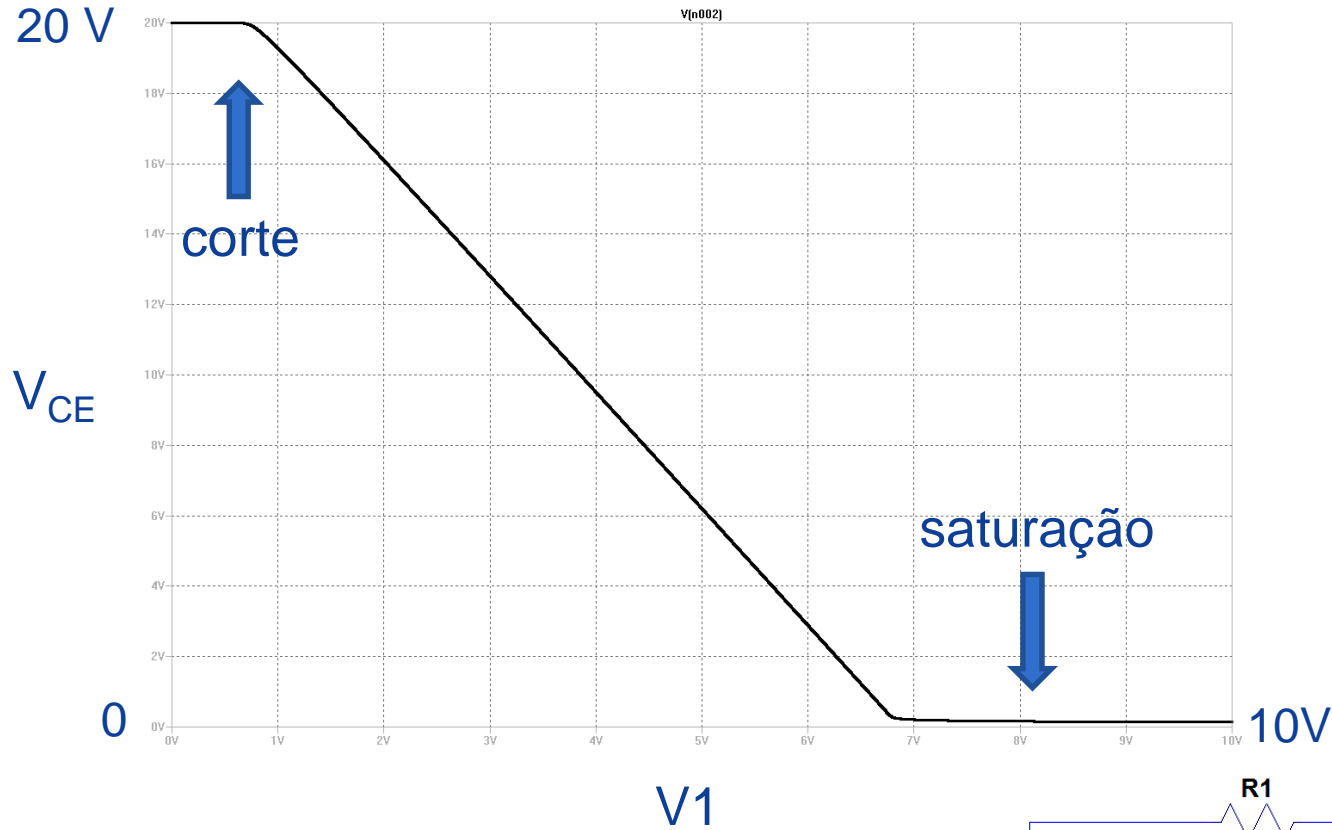
10V



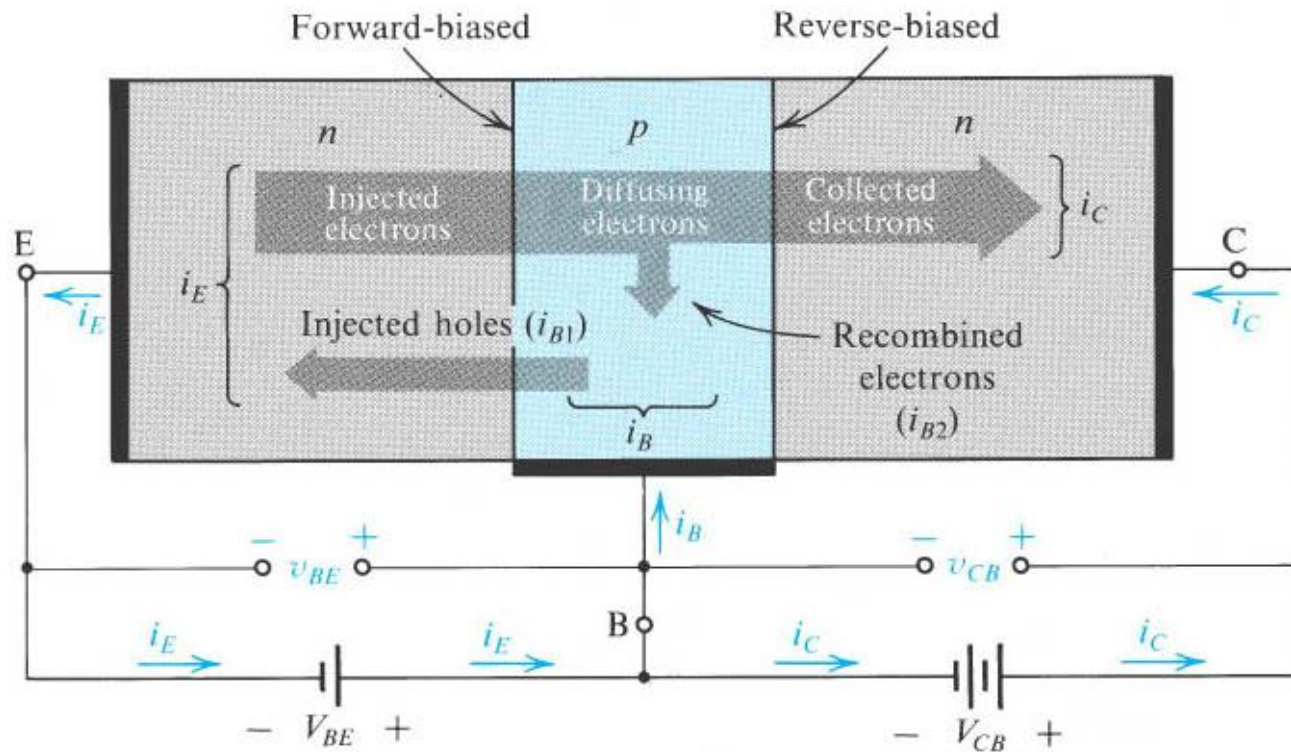
Corrente de Coletor I_C



Tensão V_{CE}



Operação na região ativa



Região de base pouco dopada
Região de emissor muito dopada

Equação do Transistor na região ativa

$$i_C = I_S e^{\frac{v_{BE}}{v_T}}$$

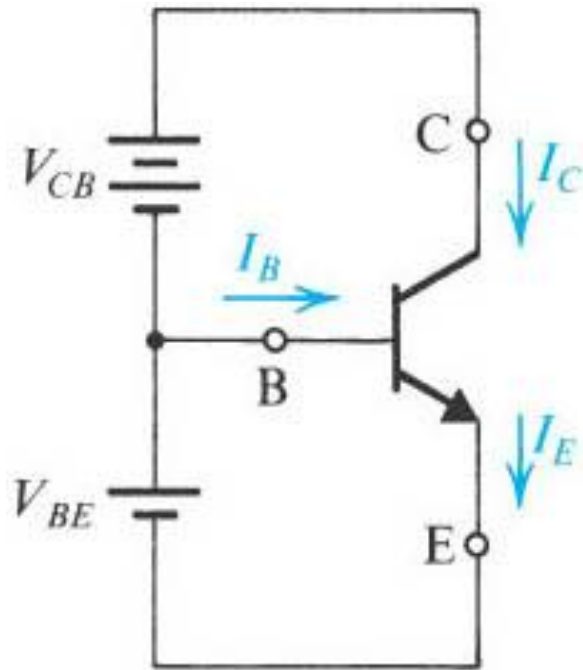
$$I_S \propto A_E$$

$$i_C = \beta i_B$$

I_S – corrente de saturação ou corrente de escala

1. Tipicamente varia entre 10^{-12} A a 10^{-18} A.
2. É inversamente proporcional à largura da base.
3. É proporcional à área da seção da junção base emissor.
4. É muito dependente da temperatura (n_i).
5. Dobra de valor para cada 5 °C de aumento da temperatura.

Relações entre as correntes



$$i_C = \beta i_B$$

$$i_E = i_C + i_B = i_C + \frac{i_C}{\beta} = \frac{\beta + 1}{\beta} i_C$$

$$\alpha = \frac{\beta}{\beta + 1} \quad i_C = \alpha i_E$$

α - Ganho de corrente em base comum ($\sim 0,99$)

β - Ganho de corrente em emissor comum (50 a 200)

Exercício 5.10

$$V_E = -0,7V$$

$$\beta = 50$$

Determine:

$$I_E, I_B, I_C \text{ e } V_C$$

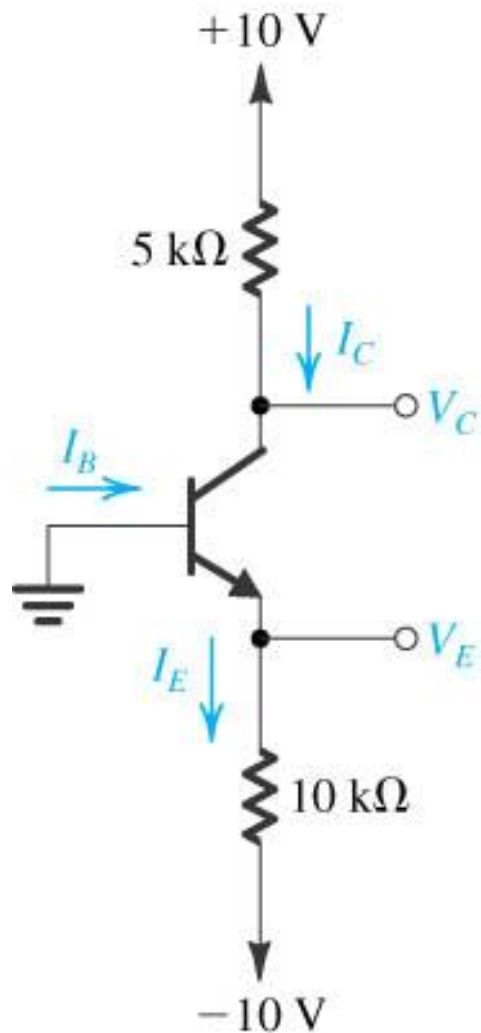


Figure E5.10

Exercício 5.11

$$V_B = 1 \text{ V}$$

$$V_E = 1,7 \text{ V}$$

Determine:

α , β e V_C .

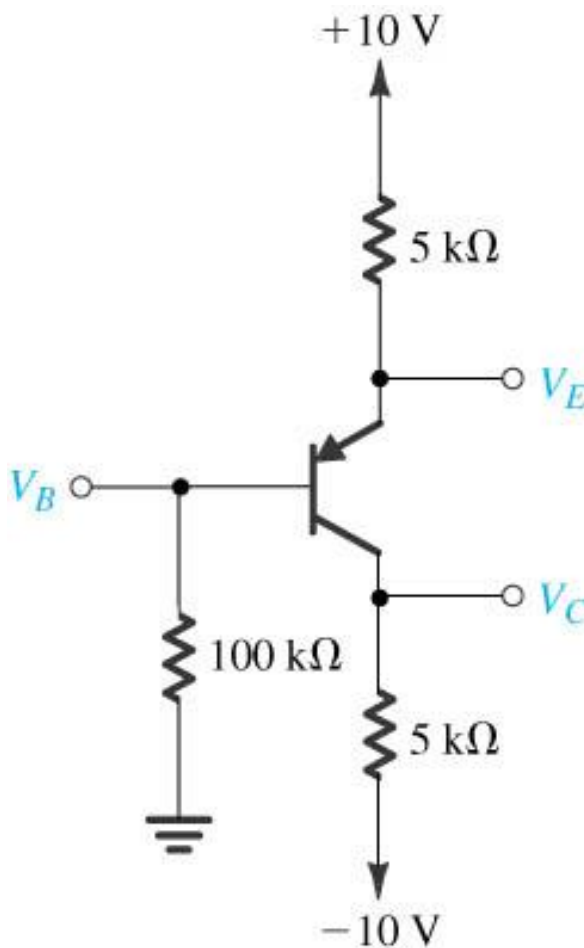


Figure E5.11

Exemplo 5.10

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

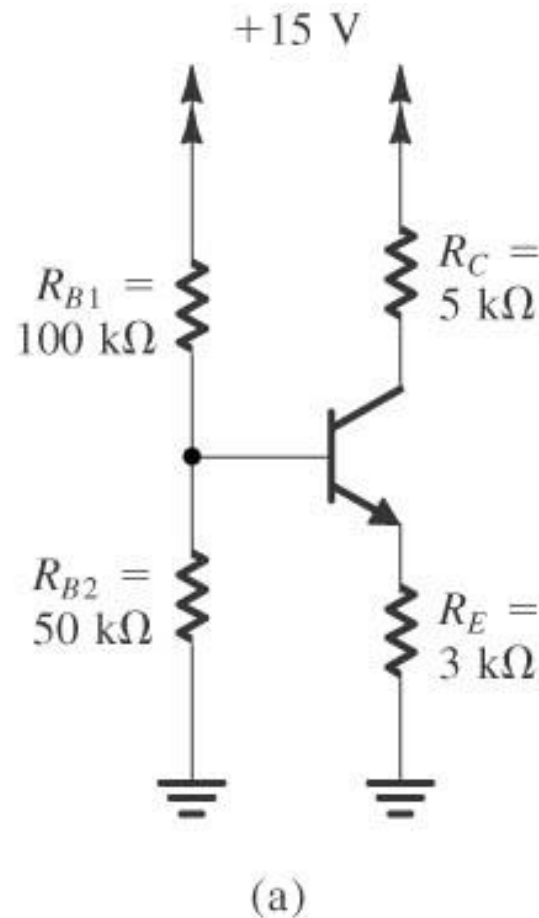


Figure 5.40 Circuits for Example 5.10.

Exemplo 5.10

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

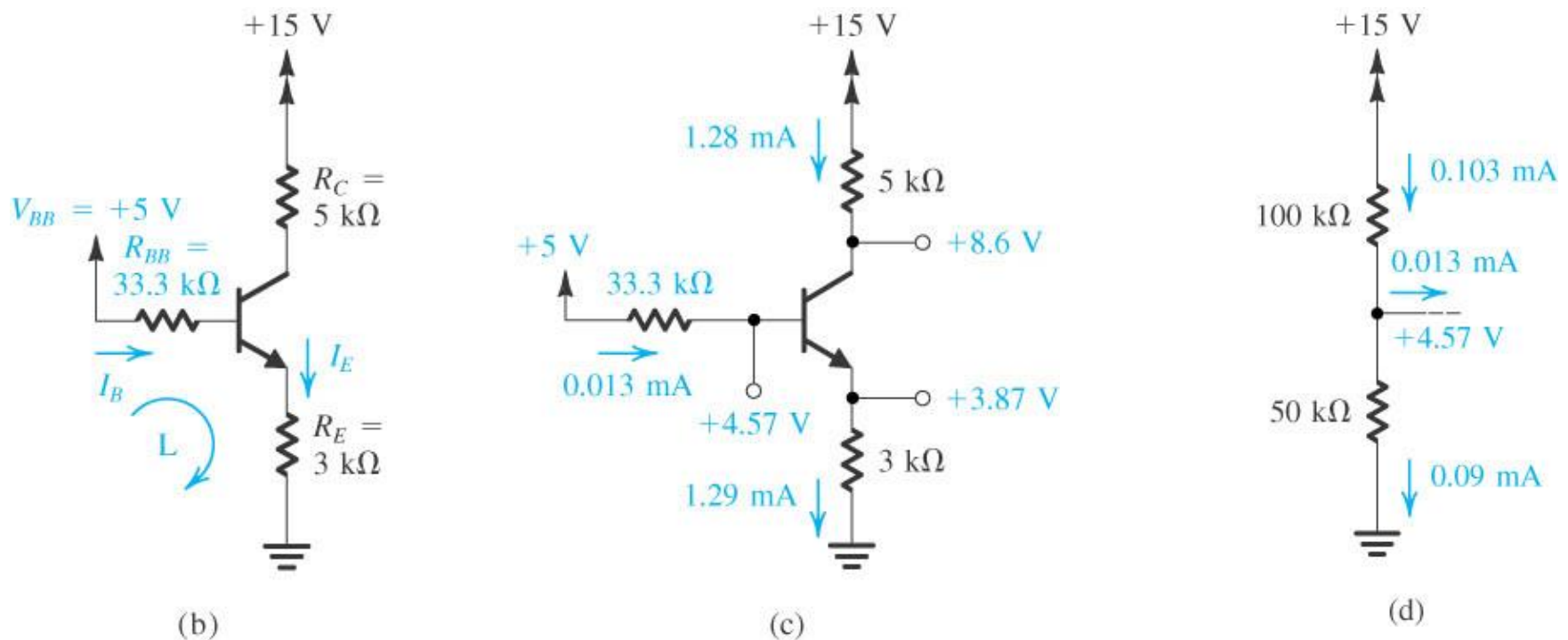


Figure 5.40 Circuits for Example 5.10.

Característica $i_C \times v_{BE}$

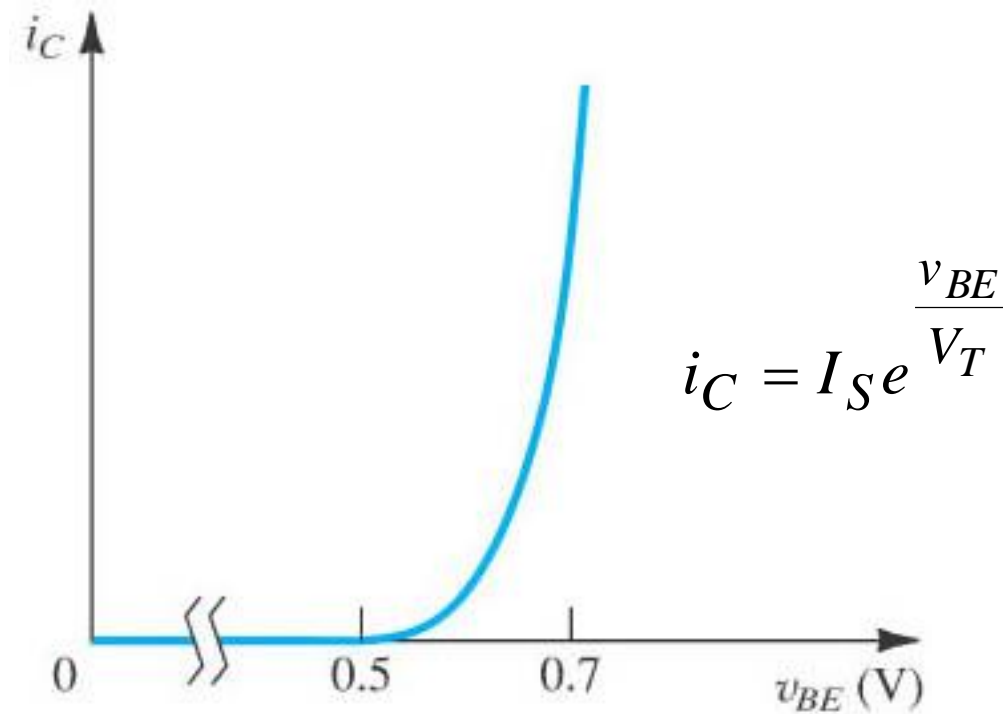


Figure 5.16 The i_C – v_{BE} characteristic for an *npn* transistor.

Efeito da temperatura

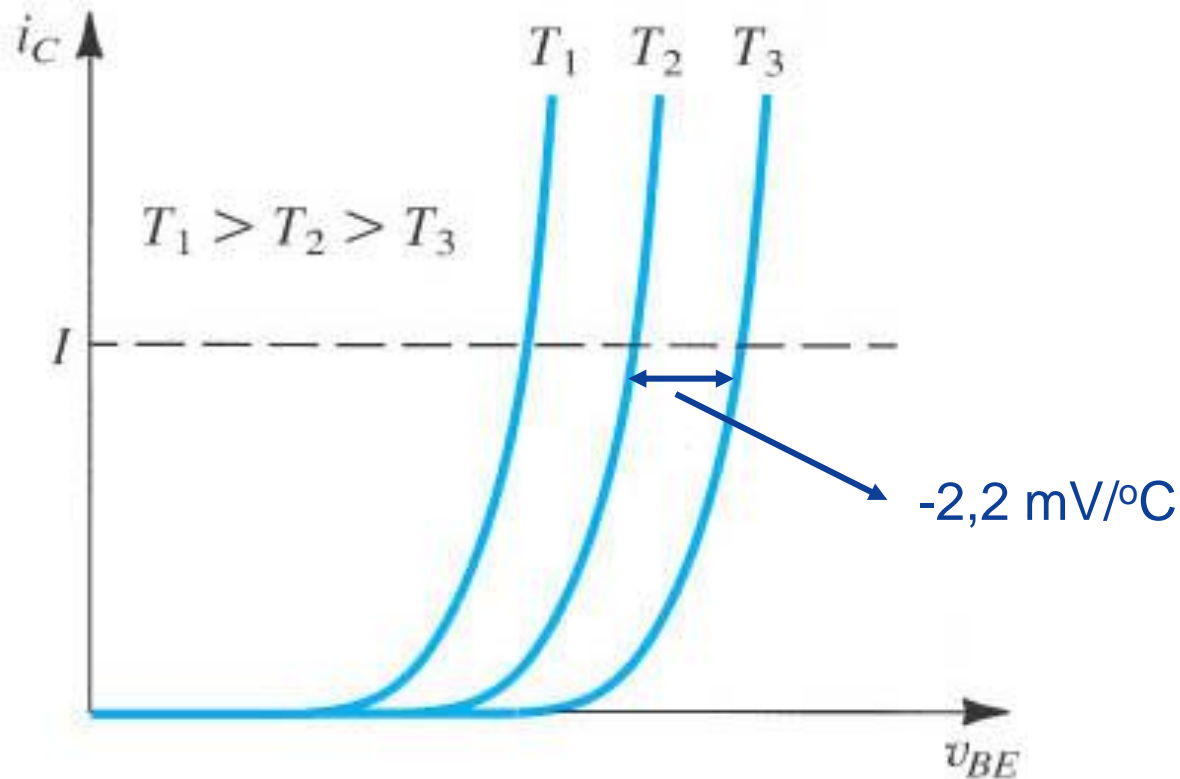


Figure 5.17 Effect of temperature on the i_C - v_{BE} characteristic. At a constant emitter current (broken line), v_{BE} changes by $-2 \text{ mV}/^\circ\text{C}$.

Operação do transistor como chave

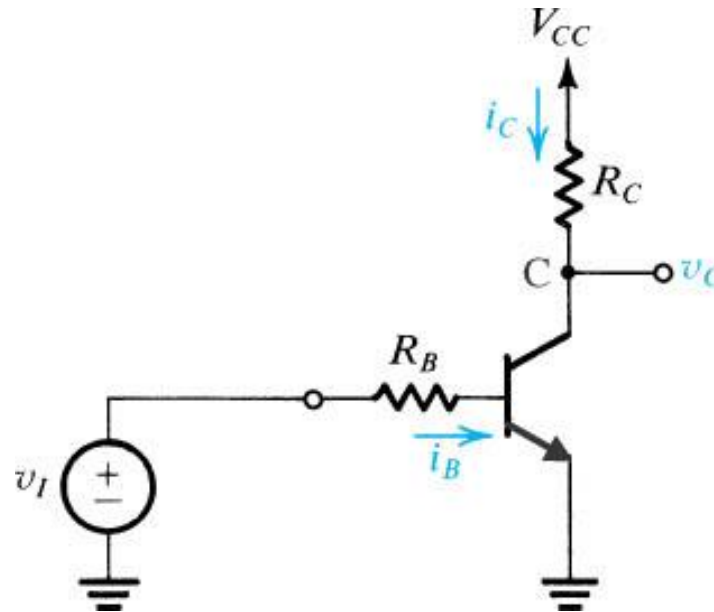


Figure 5.32 A simple circuit used to illustrate the different modes of operation of the BJT.

Exemplo 5.3

O transistor da figura tem β entre 50 e 150. Determine o valor de R_B que resulta na saturação forçada do transistor por um fator de 10 vezes.

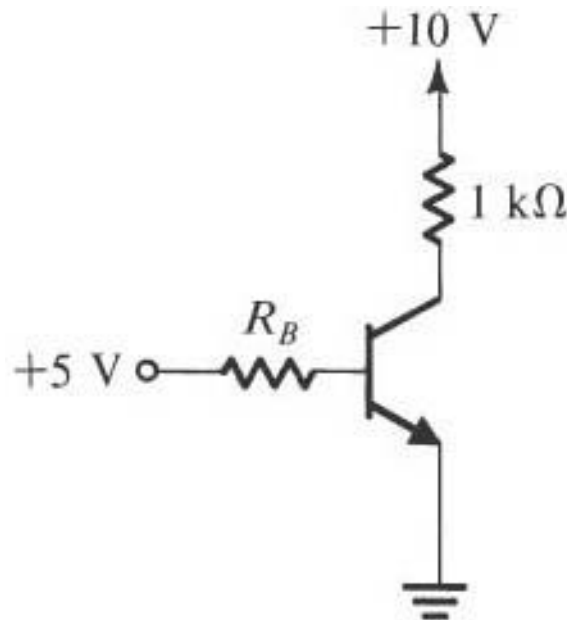
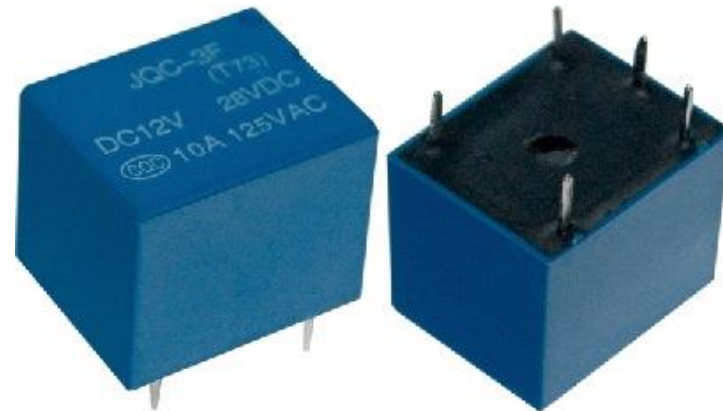
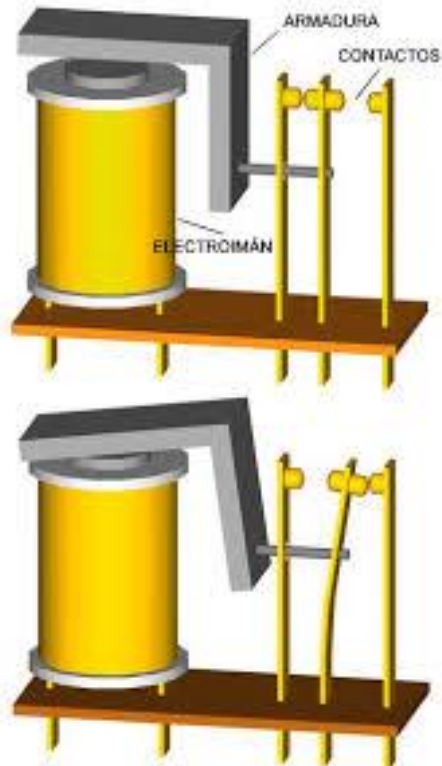


Figure 5.33 Circuit for Example 5.3.

Operação do transistor como chave – Carga indutiva

Rele



Operação do transistor como chave

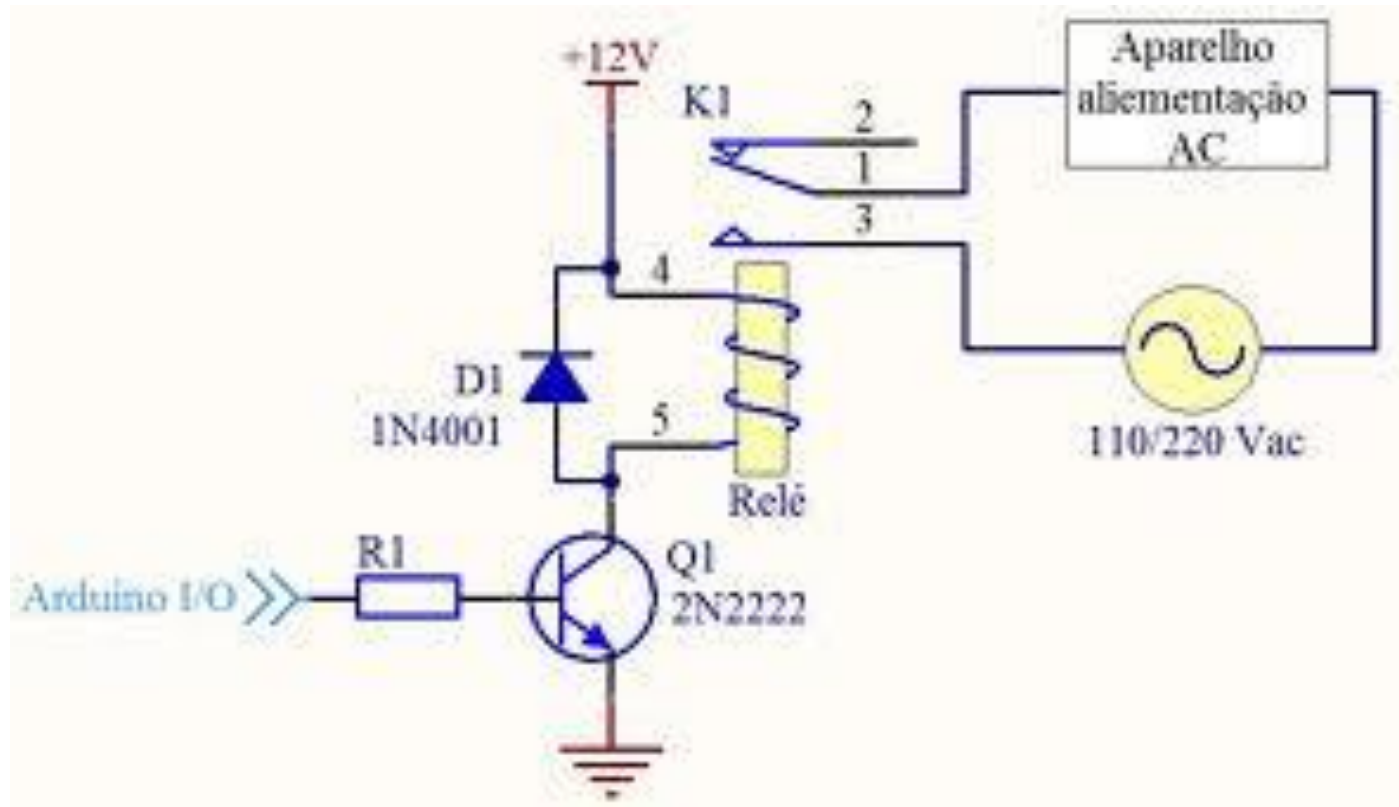
– Carga indutiva

Características da bobina

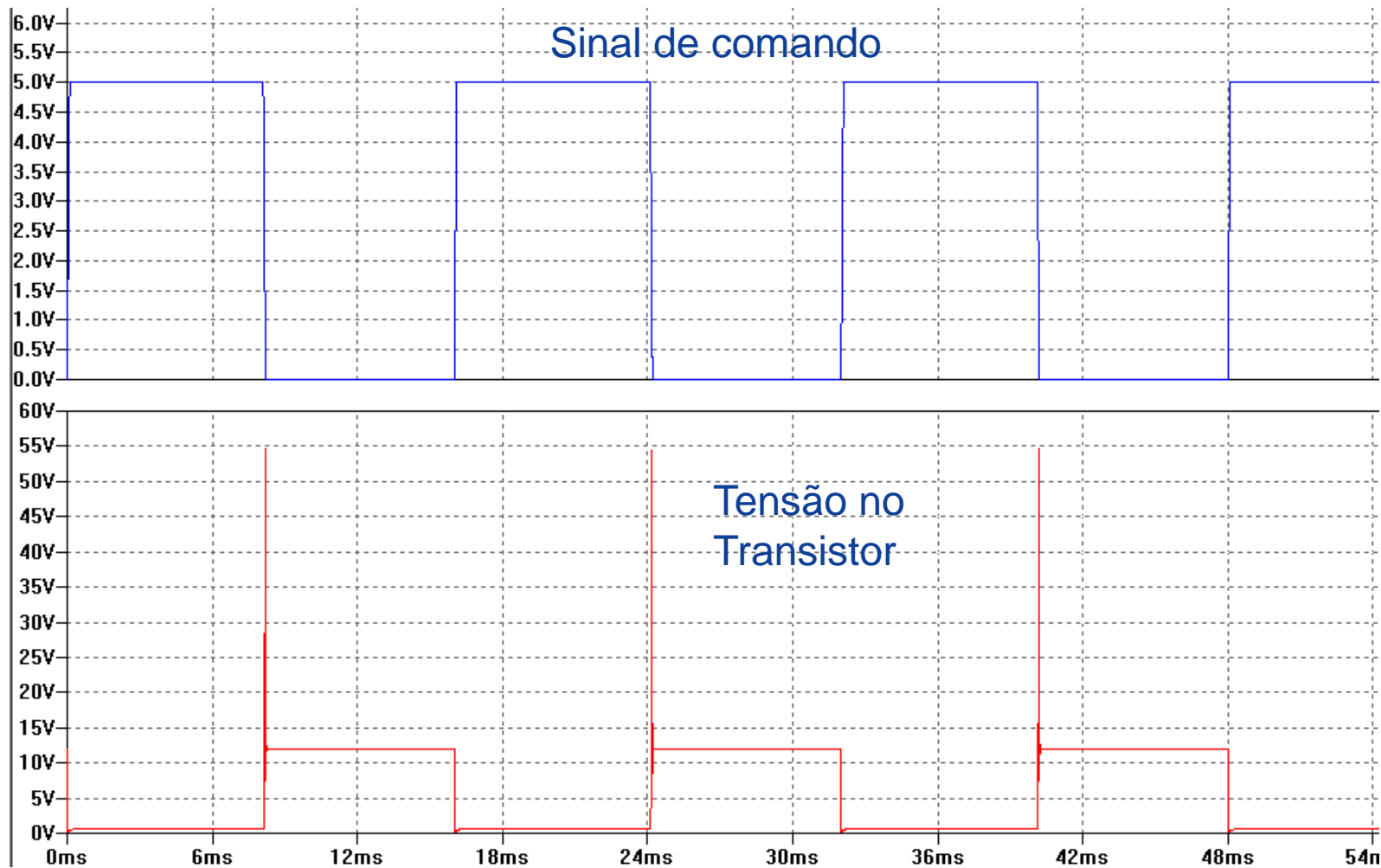
Dados da versão DC

Tensão nominal U_N	Código bobina	Campo de funcionamento		Resistência	Corrente nominal $I_a U_N$
V		U_{min}	U_{max}	R	$I_a U_N$
Ω		V	V	Ω	mA
5	7.005	3.5	7.5	130	38.4
12	7.012	8.4	18	840	14.2
24	7.024	16.8	36	3350	7.1
48	7.048	33.6	72	12300	3.9
60	7.060	42	90	19700	3

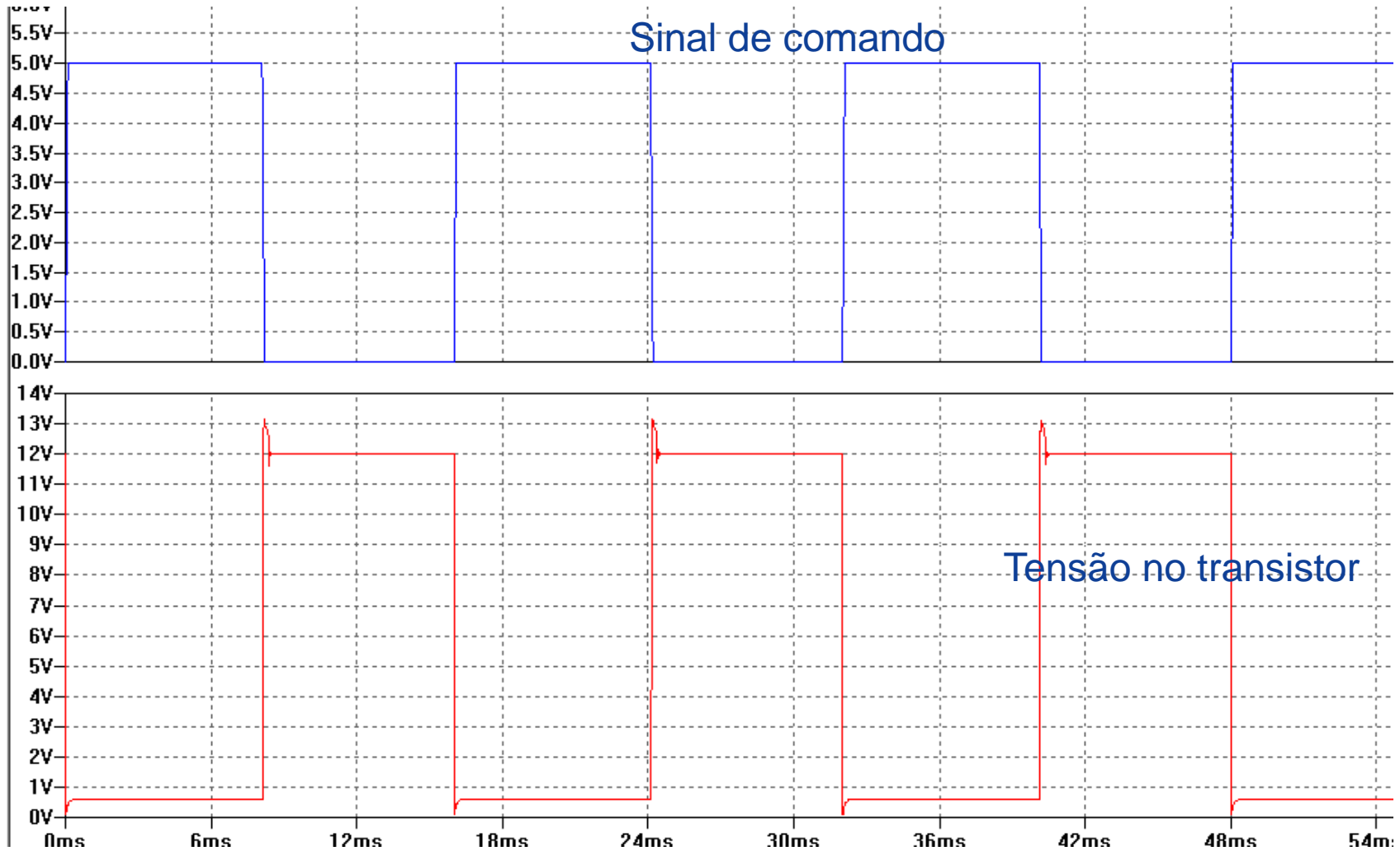
Operação do transistor como chave – Carga indutiva



Comando do rele sem o diodo de roda-livre



Comando do rele com o diodo de roda-livre



Análise gráfica de um amplificador

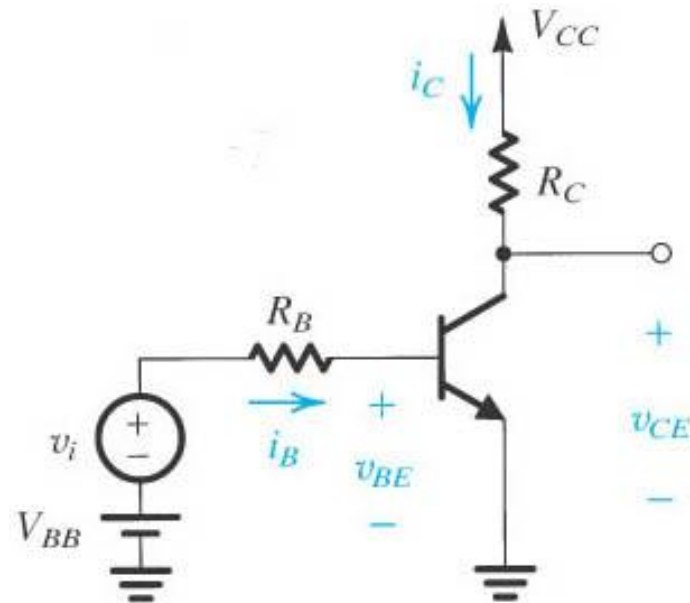


Figure 5.27 Circuit whose operation is to be analyzed graphically.

Determinação da corrente de base

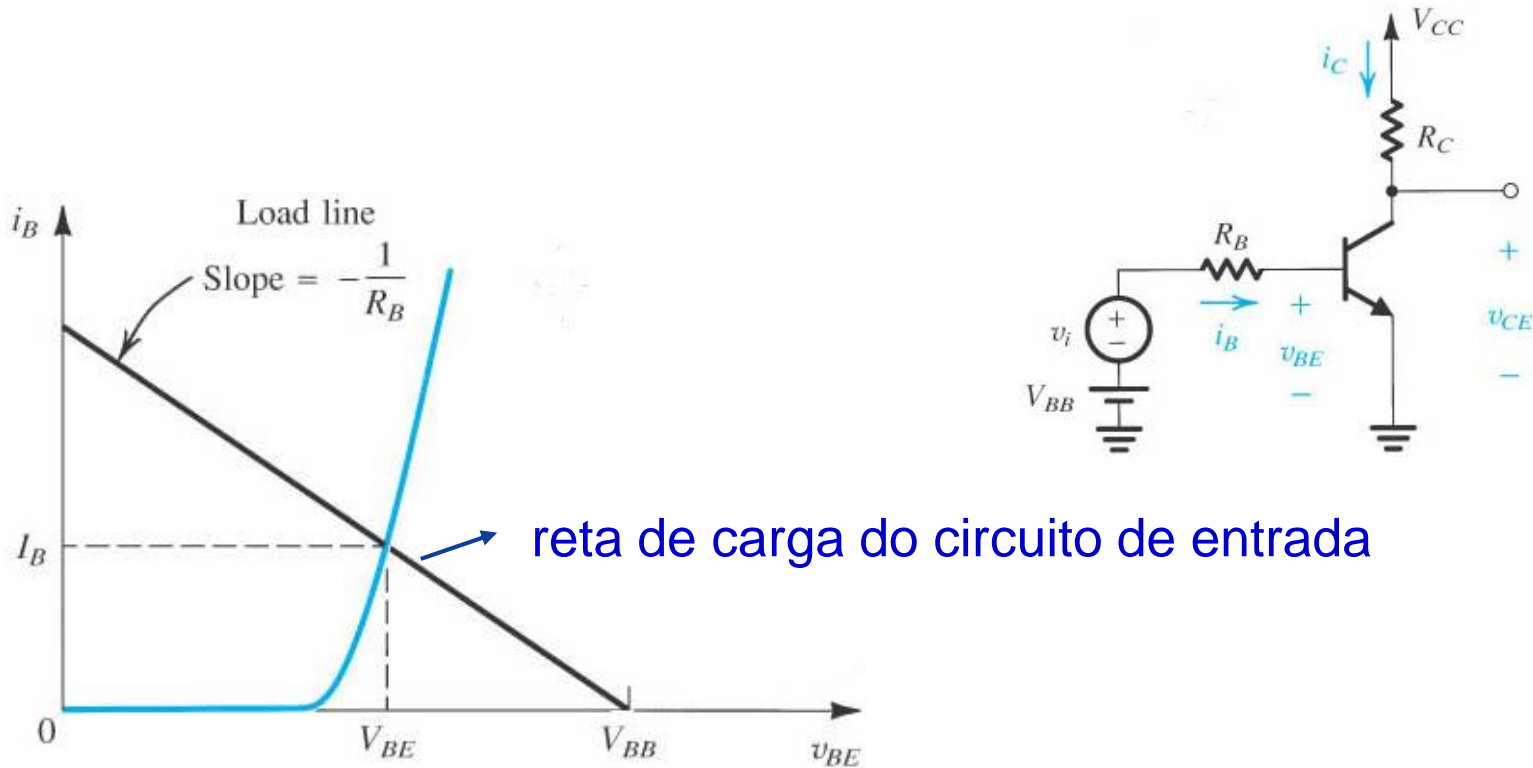


Figure 5.28 Graphical construction for the determination of the dc base current in the circuit of Fig. 5.27.

Determinação da corrente de coletor

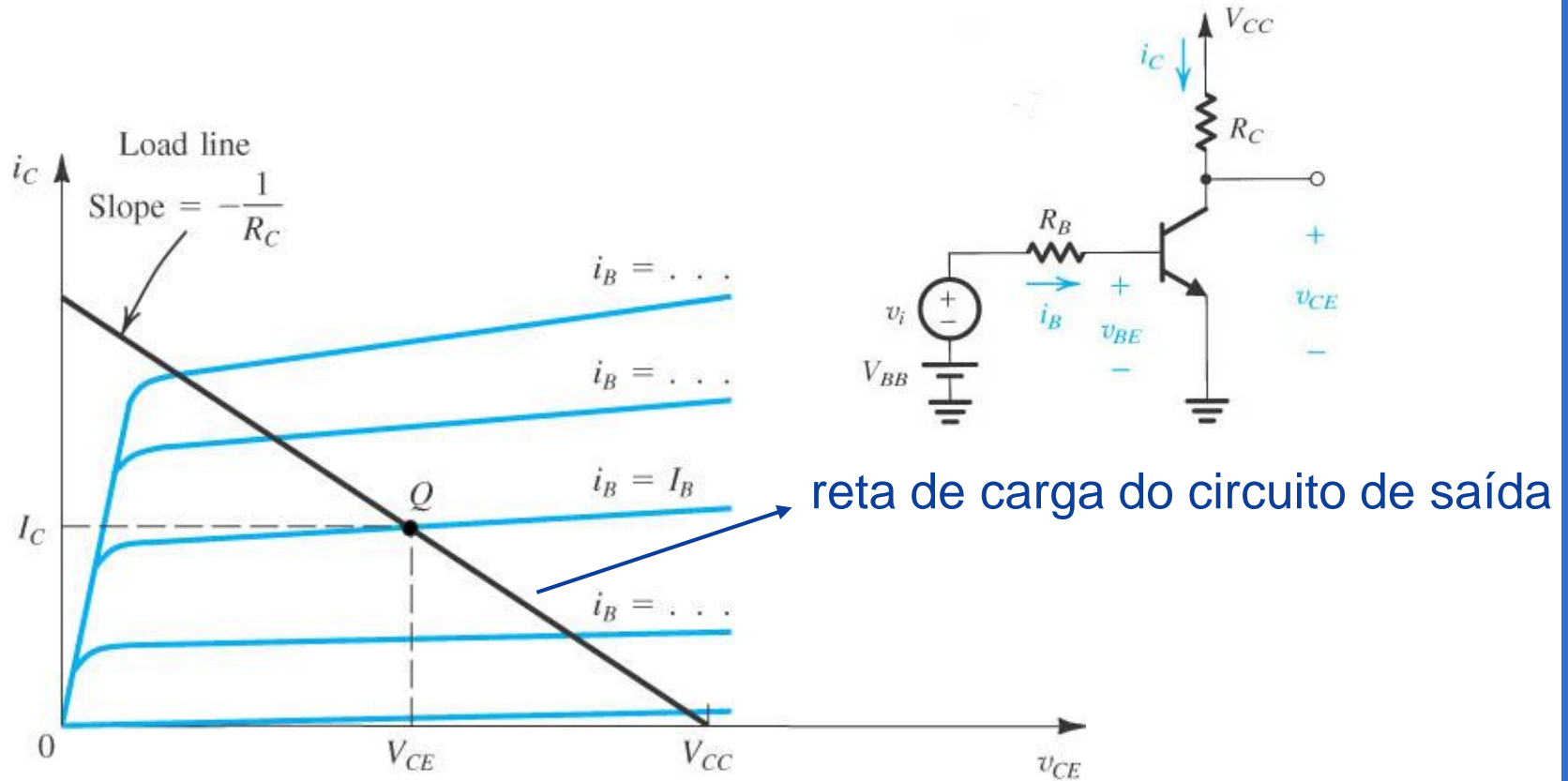


Figure 5.29 Graphical construction for determining the dc collector current I_C and the collector-to-emitter voltage V_{CE} in the circuit of Fig. 5.27.

Análise em C.A

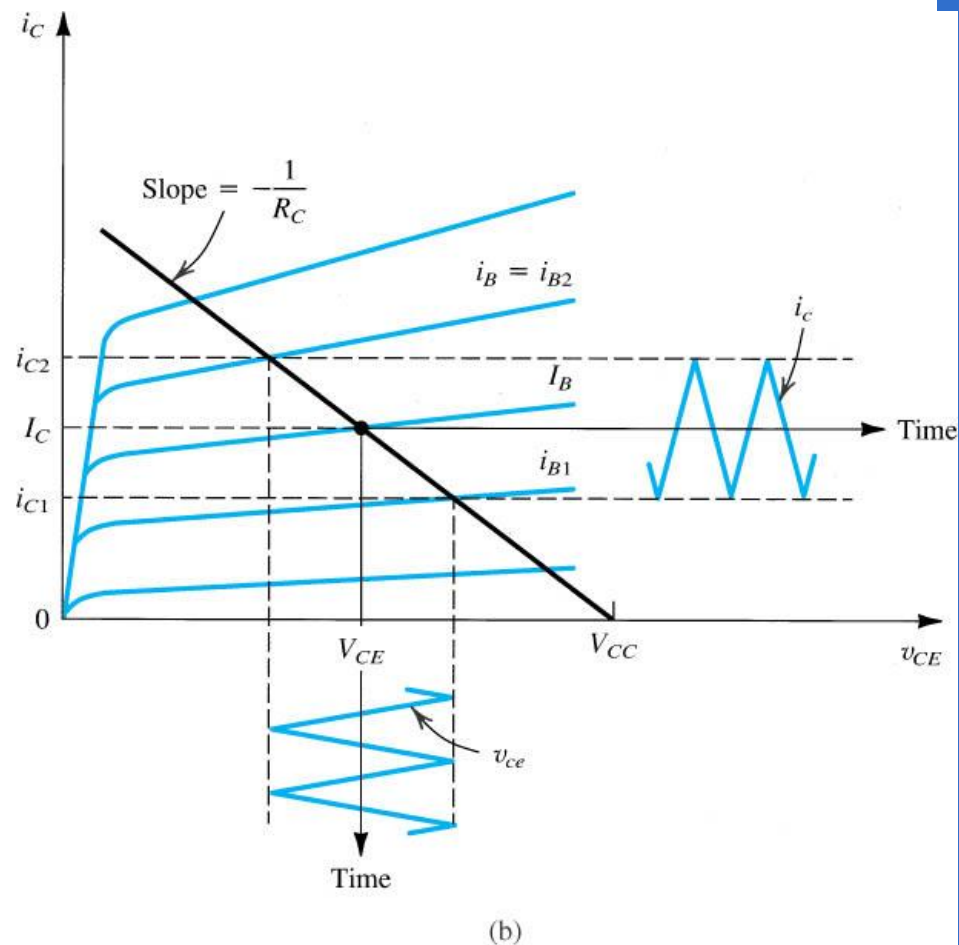
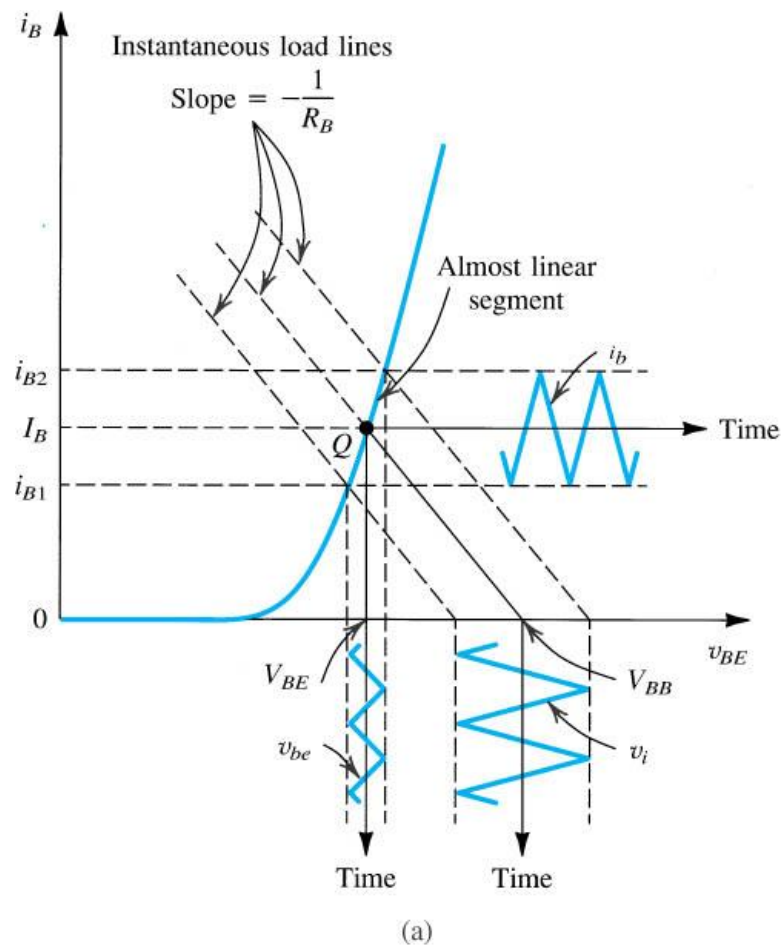
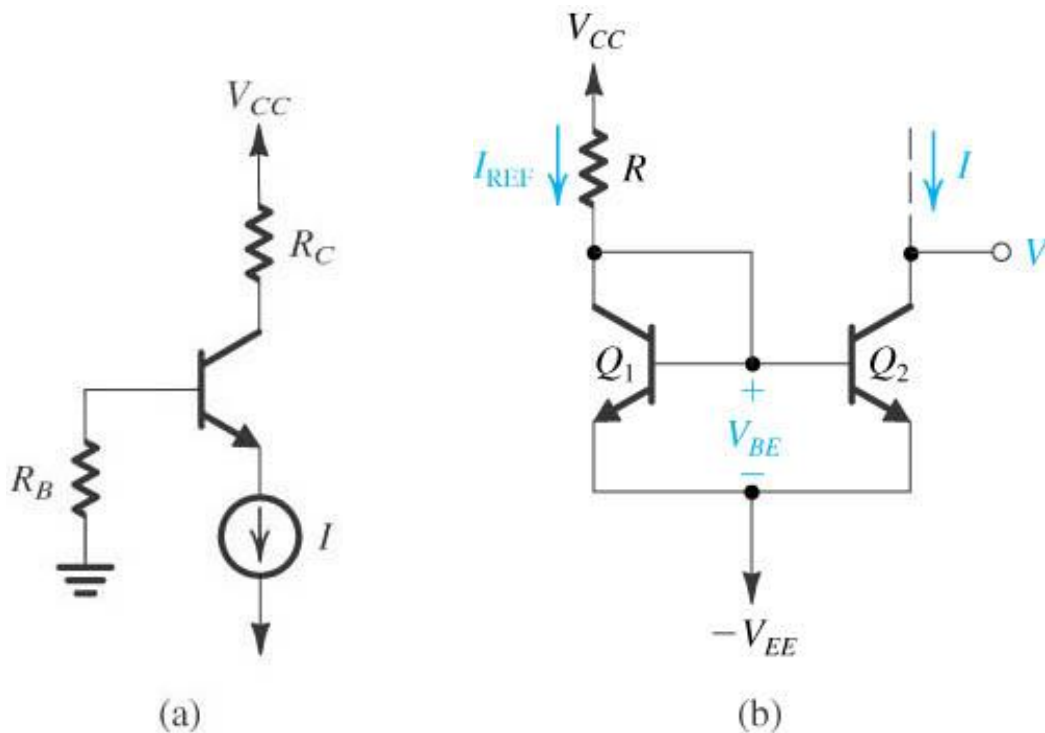


Figure 5.30 Graphical determination of the signal components v_{be} , i_b , i_c , and v_{ce} when a signal component v_i is superimposed on the dc voltage V_{BB} (see Fig. 5.27).

Polarização com fonte de corrente constante



$$I_{REF} = \frac{V_{CC} + V_{EE} - V_{BE}}{R}$$

Figure 5.47 (a) A BJT biased using a constant-current source I . (b) Circuit for implementing the current source I .

Exemplo 5.4

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

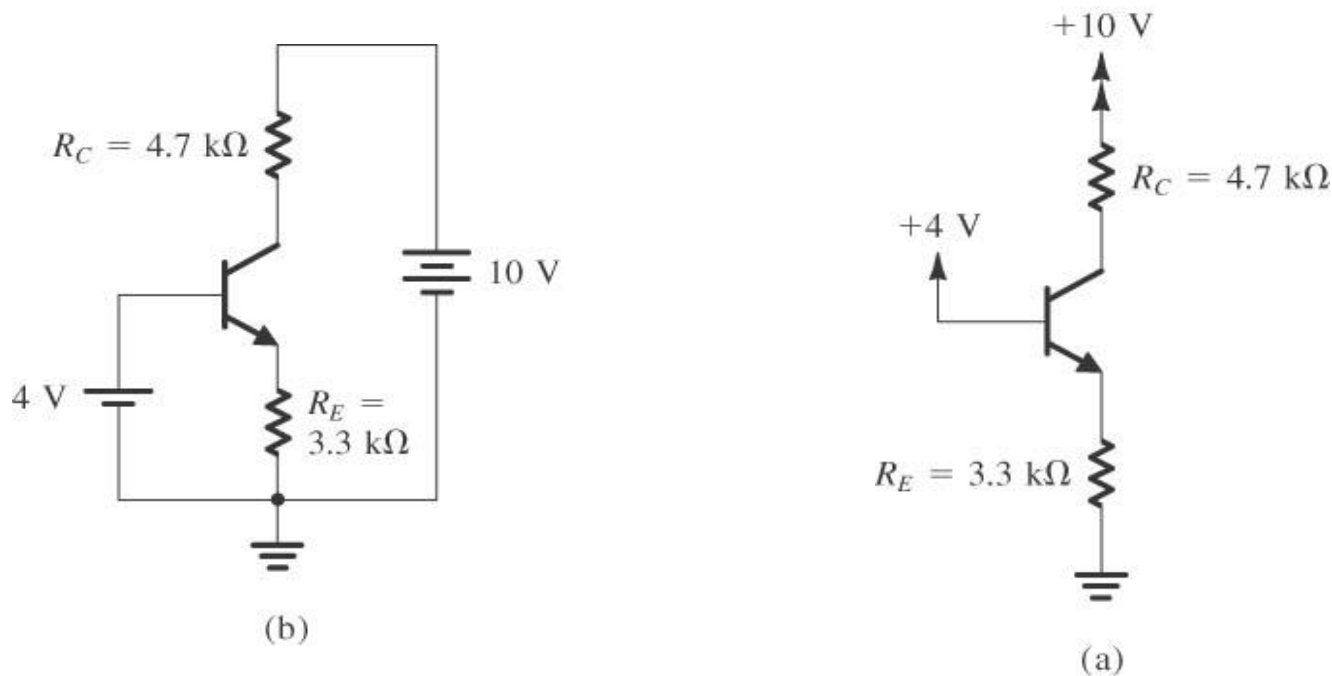


Figure 5.34 Analysis of the circuit for Example 5.4: **(a)** circuit; **(b)** circuit redrawn to remind the reader of the convention used in this book to show connections to the power supply; **(c)** analysis with the steps numbered.

Exemplo 5.4 - solução

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

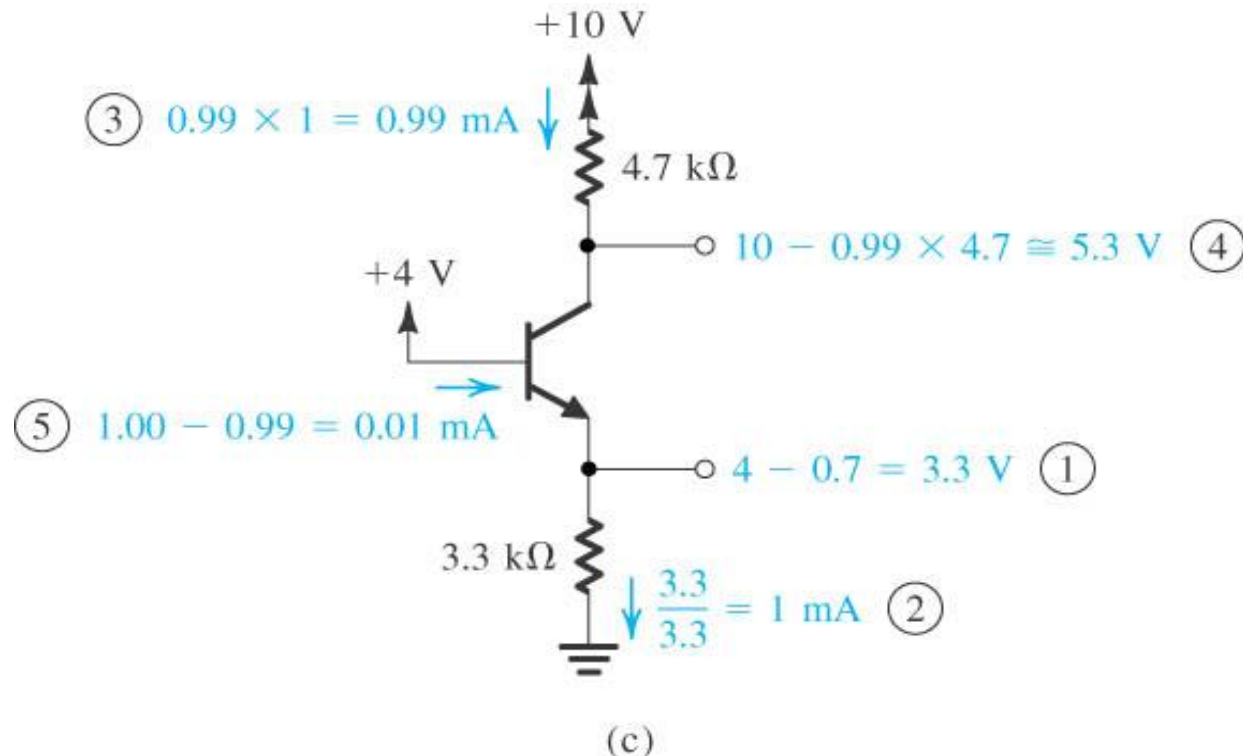


Figure 5.34 Analysis of the circuit for Example 5.4: (a) circuit; (b) circuit redrawn to remind the reader of the convention used in this book to show connections to the power supply; (c) analysis with the steps numbered.

Exemplo 5.5

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta \geq 50$.

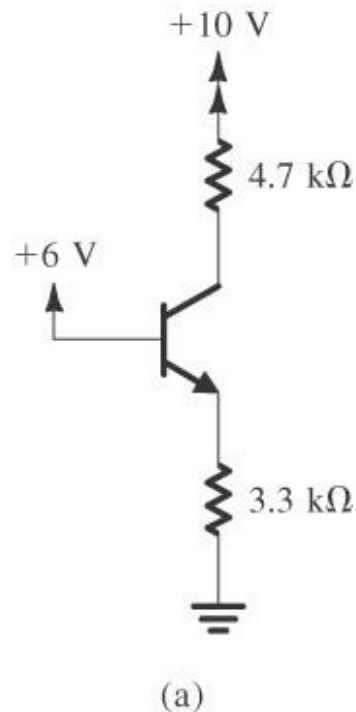
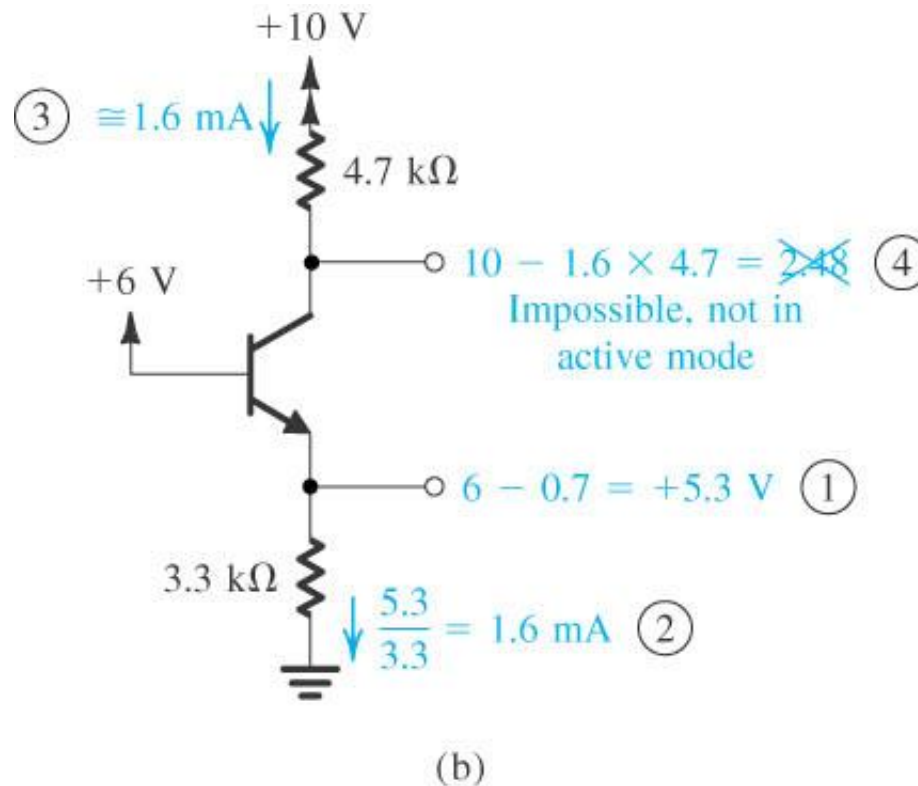


Figure 5.35 Analysis of the circuit for Example 5.5. Note that the circled numbers indicate the order of the analysis steps.

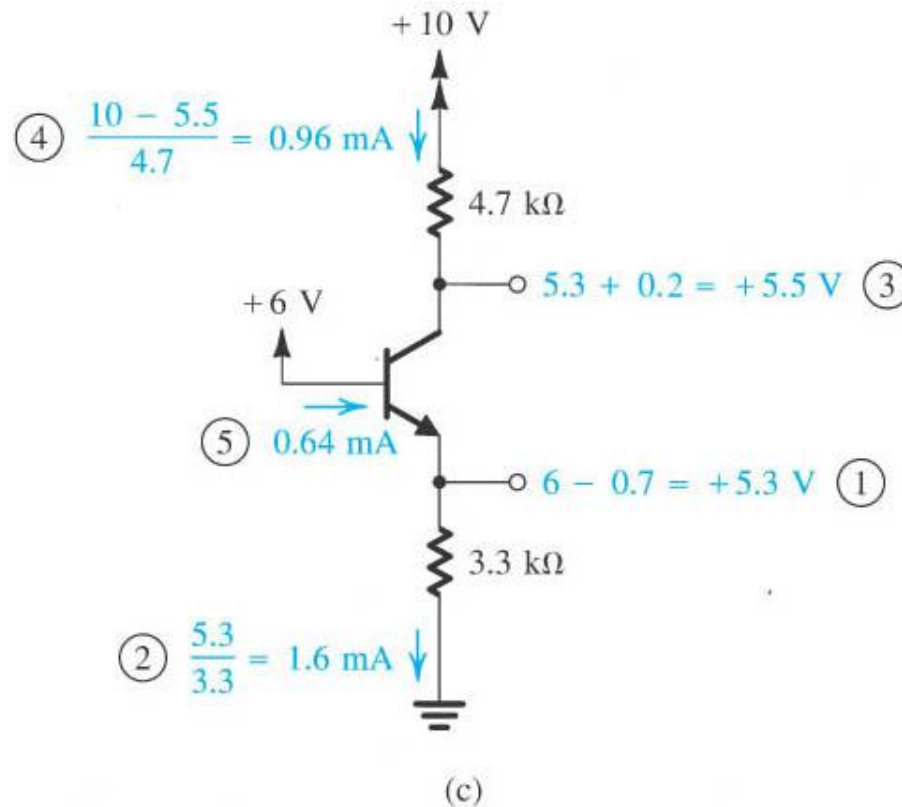
Exemplo 5.5 - solução

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta \geq 50$.



Exemplo 5.5 - solução

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta \geq 50$.



Exemplo 5.6

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

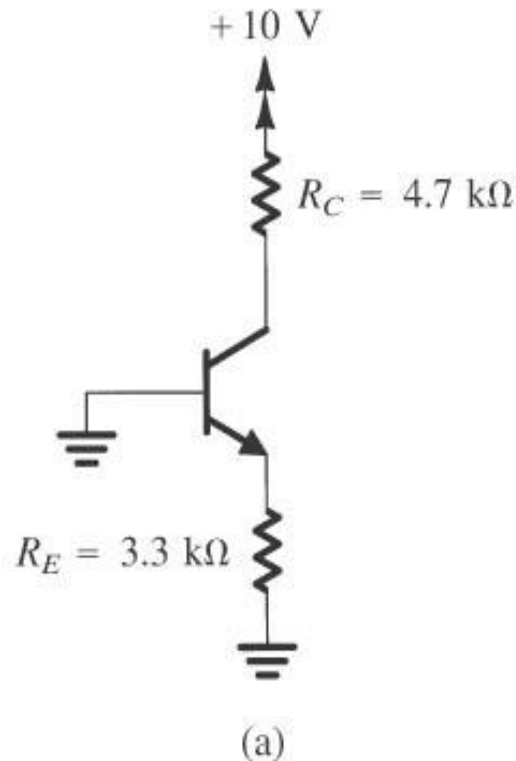


Figure 5.36 Example 5.6: **(a)** circuit; **(b)** analysis with the order of the analysis steps indicated by circled numbers.

Exemplo 5.6 - solução

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

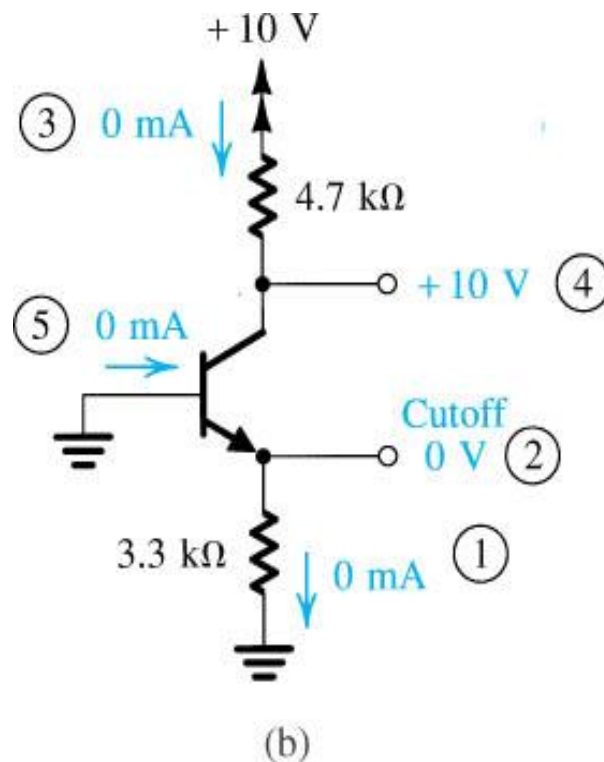


Figure 5.36 Example 5.6: (a) circuit; (b) analysis with the order of the analysis steps indicated by circled numbers.

Exemplo 5.7

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

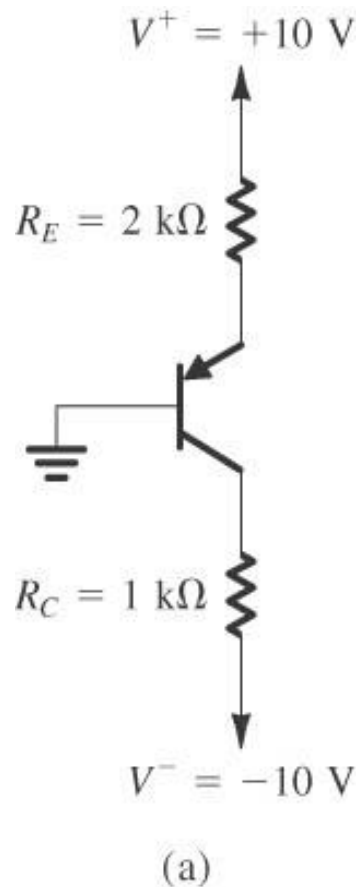


Figure 5.37 Example 5.7: **(a)** circuit; **(b)** analysis with the steps indicated by circled numbers.

Exemplo 5.7 - solução

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

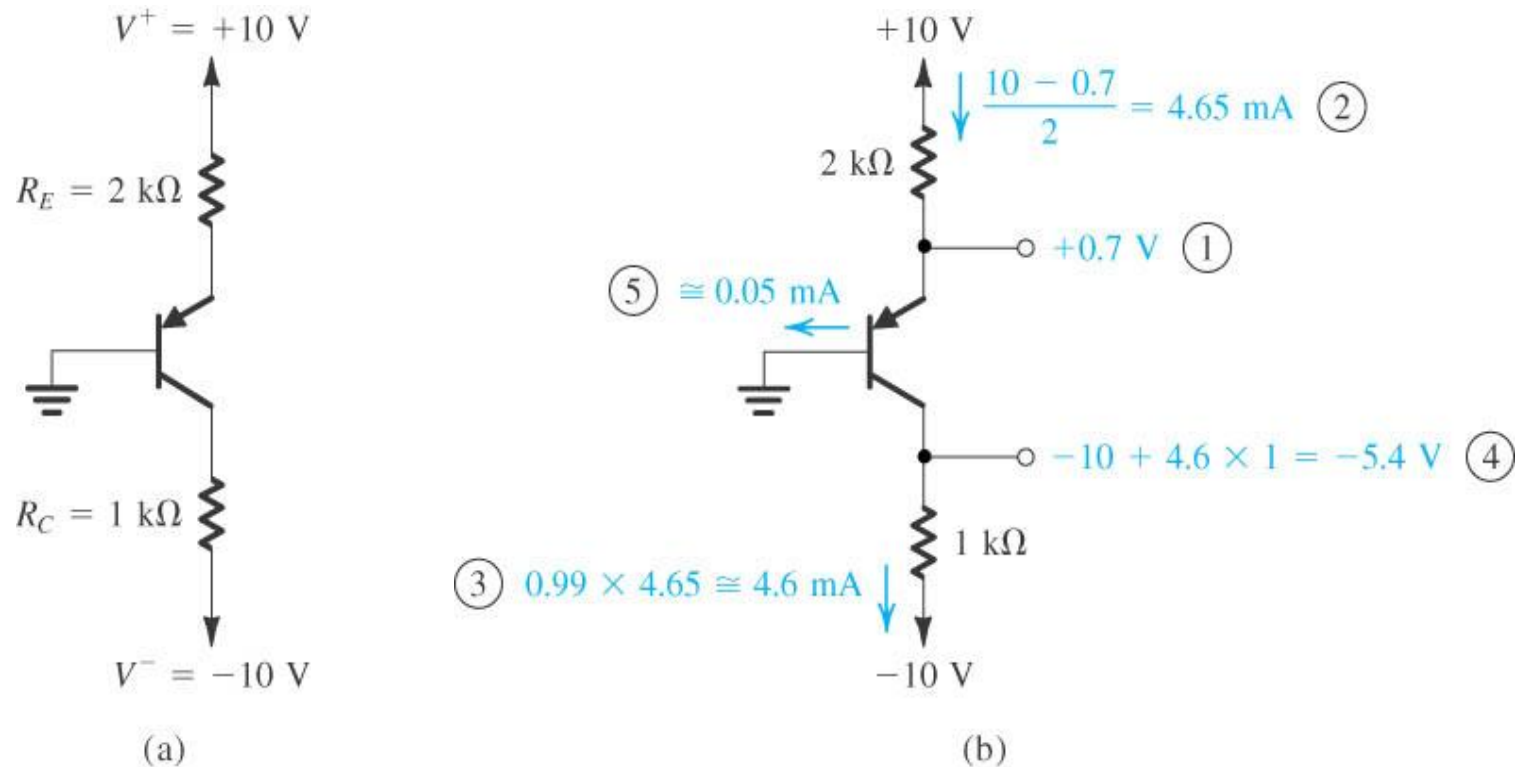


Figure 5.37 Example 5.7: (a) circuit; (b) analysis with the steps indicated by circled numbers.

Exemplo 5.8

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

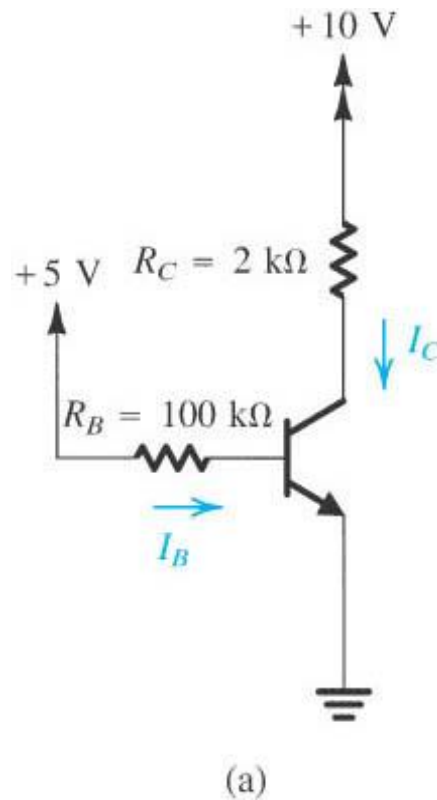


Figure 5.38 Example 5.8: **(a)** circuit; **(b)** analysis with the steps indicated by the circled numbers.

Exemplo 5.8 - solução

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

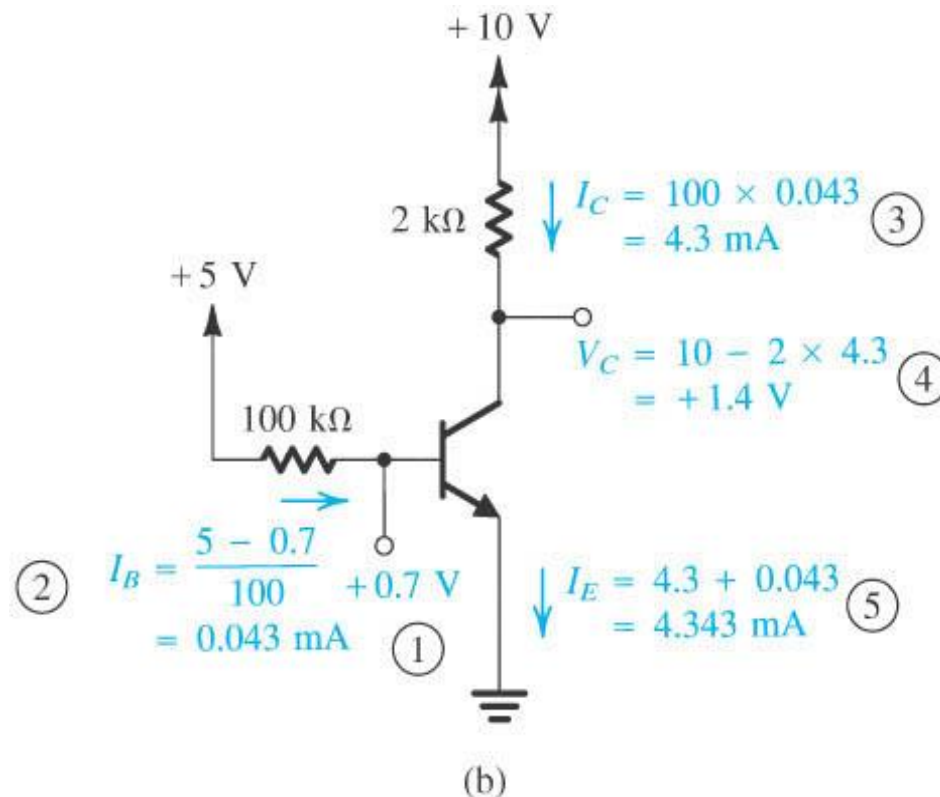


Figure 5.38 Example 5.8: (a) circuit; (b) analysis with the steps indicated by the circled numbers.

Exemplo 5.9

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta \geq 30$.

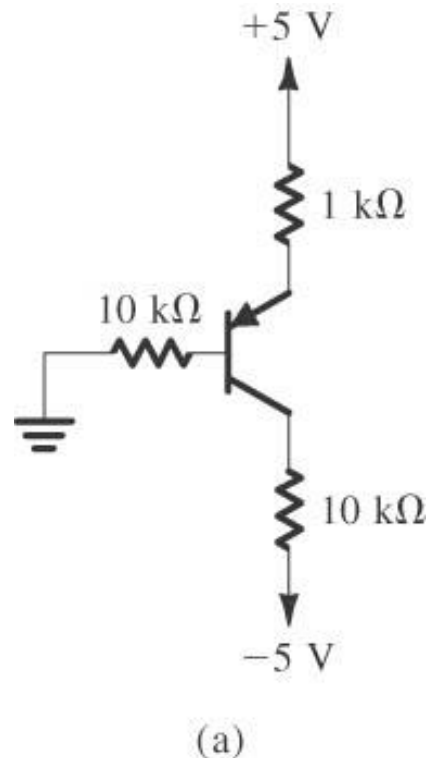


Figure 5.39 Example 5.9: **(a)** circuit; **(b)** analysis with steps numbered.

Exemplo 5.9 - solução

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta \geq 30$.

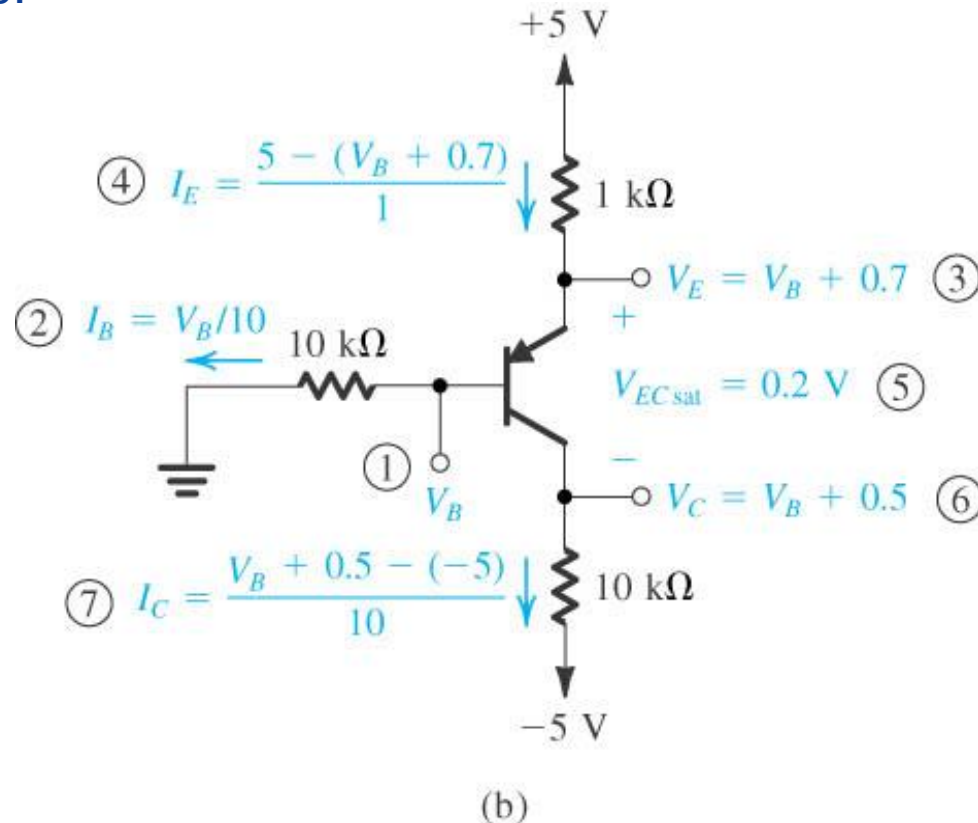


Figure 5.39 Example 5.9: (a) circuit; (b) analysis with steps numbered.

Exemplo 5.10

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

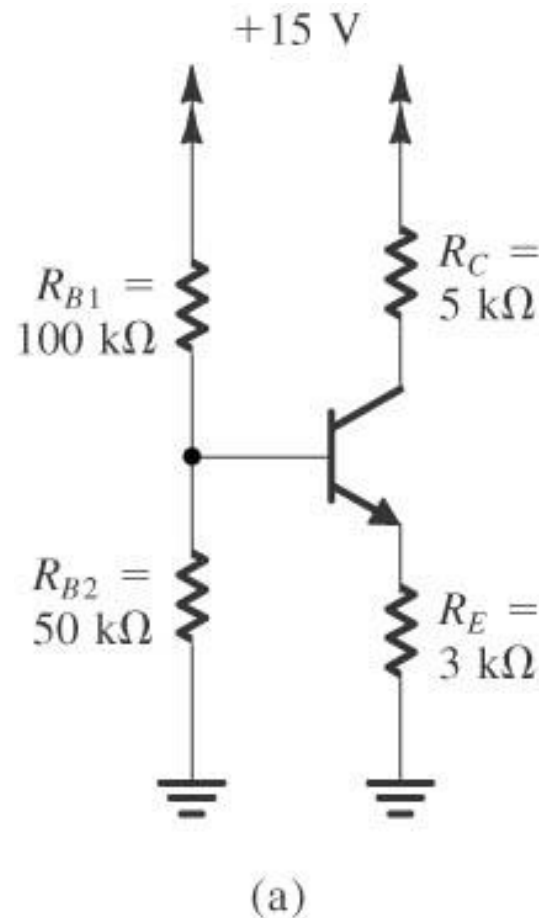


Figure 5.40 Circuits for Example 5.10.

Exemplo 5.10

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

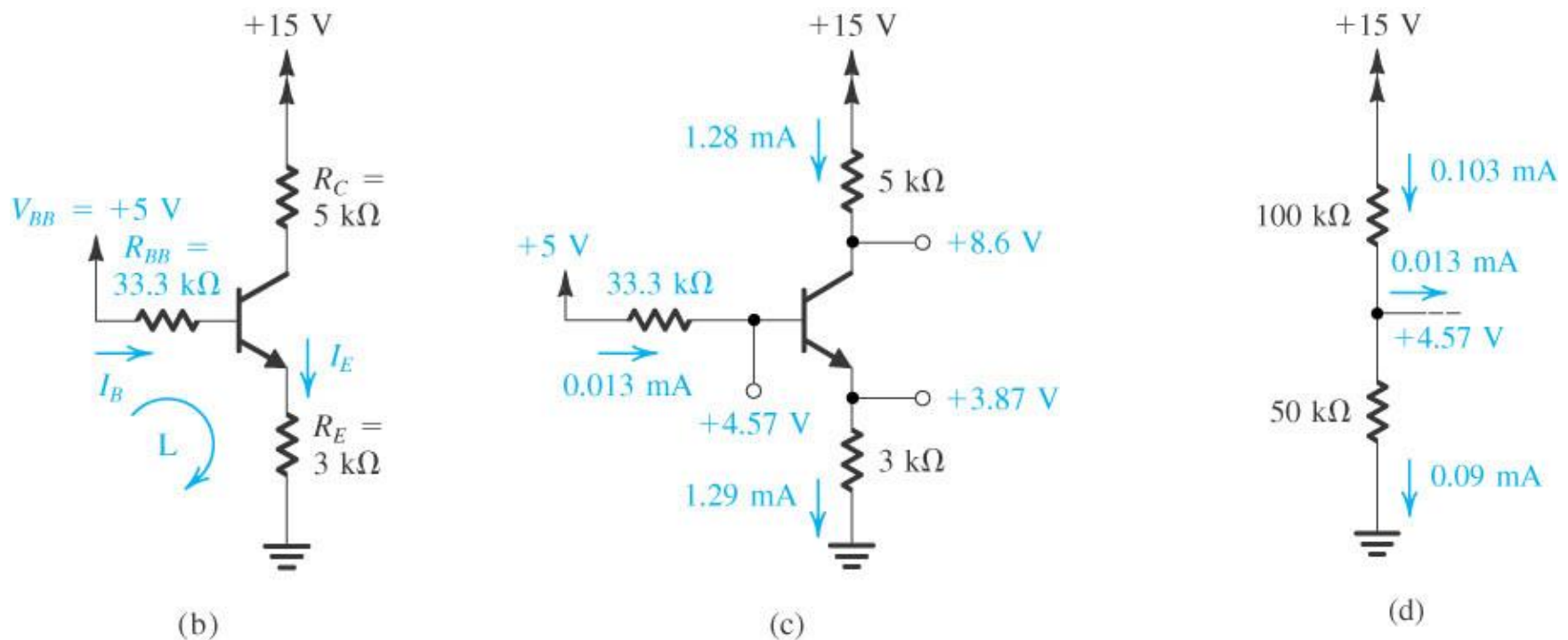


Figure 5.40 Circuits for Example 5.10.

Exemplo 5.11

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

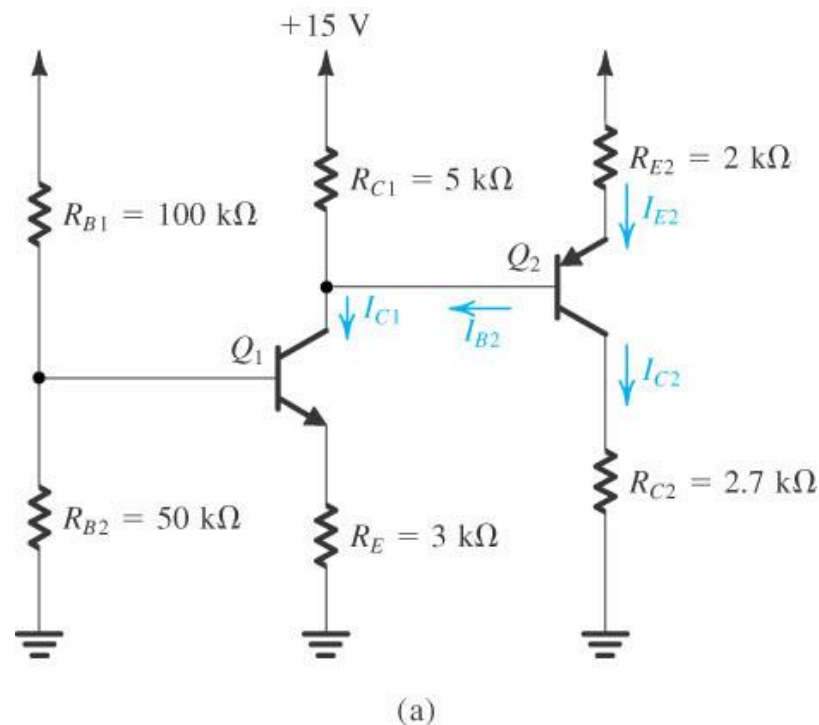


Figure 5.41 Circuits for Example 5.11.

Exemplo 5.11 - solução

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

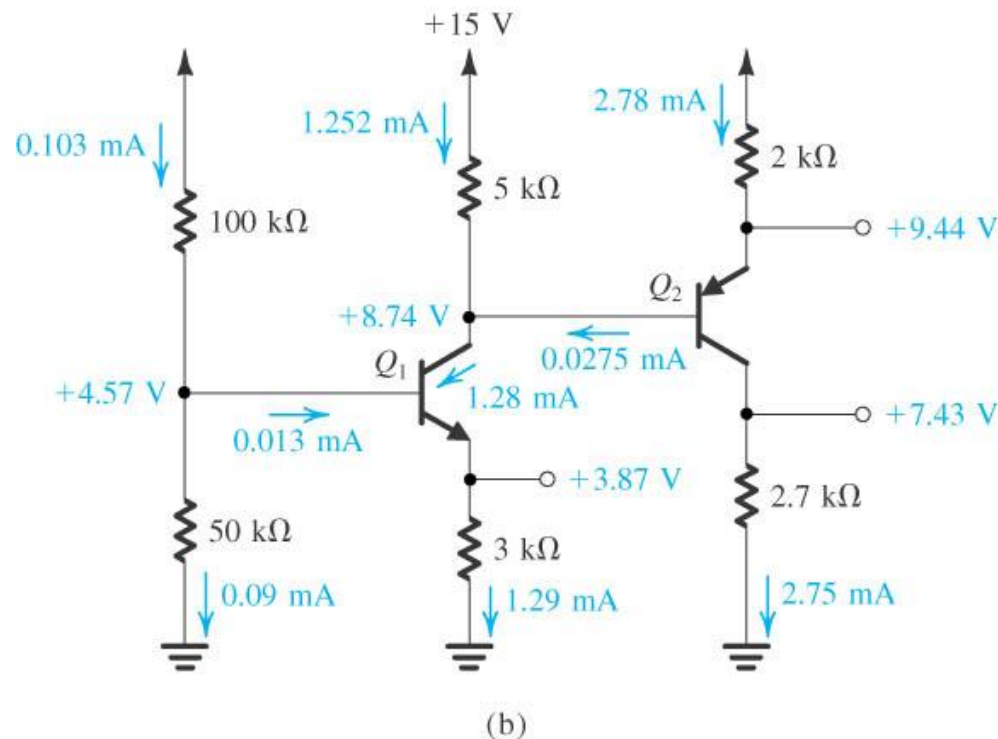
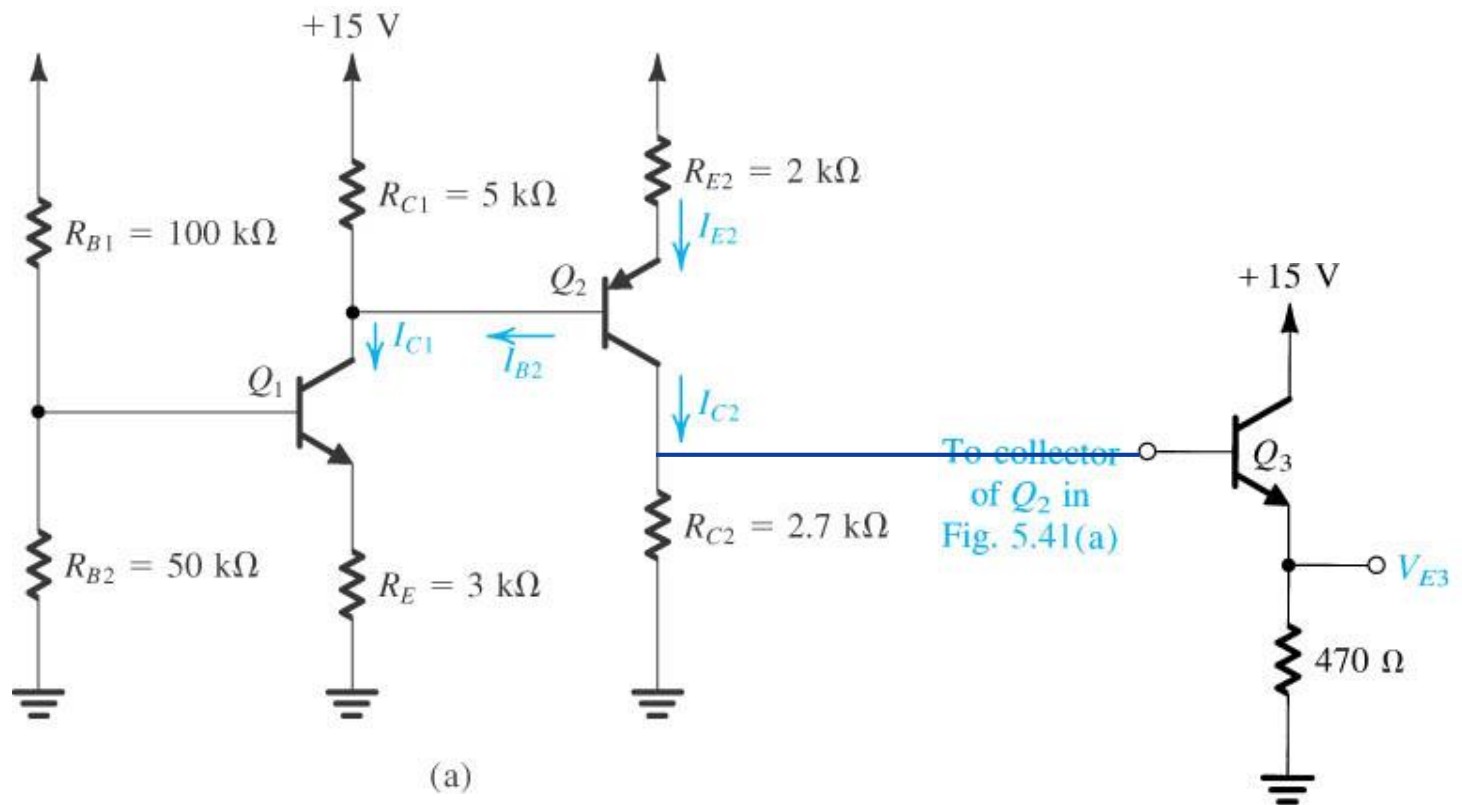


Figure 5.41 Circuits for Example 5.11.

Exercício 5.30

O circuito abaixo deve ser conectado na figura 5.41a como indicado. Se Q_3 tem $\beta = 100$. Determine o novo valor de V_{C2} e os valores de V_{E3} e I_{C3} .



(a)

Figure E5.30

Exemplo 5.12

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

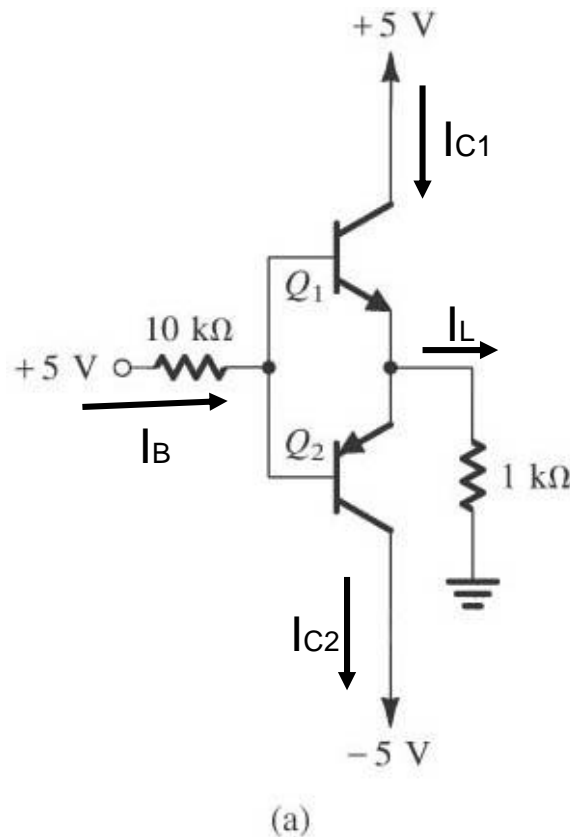


Figure 5.42 Example 5.12: **(a)** circuit; **(b)** analysis with the steps numbered.

Exemplo 5.12

Analise o circuito para determinar todas as tensões de nós e correntes. Assuma $\beta = 100$.

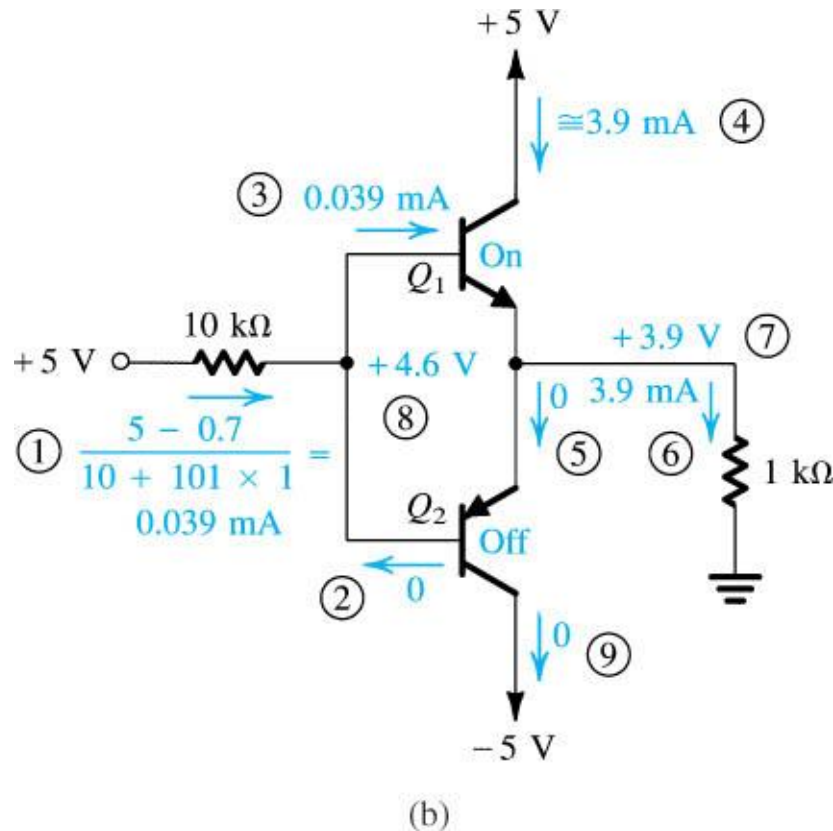


Figure 5.42 Example 5.12: (a) circuit; (b) analysis with the steps numbered.

Circuito de polarização – V_{BE} constante

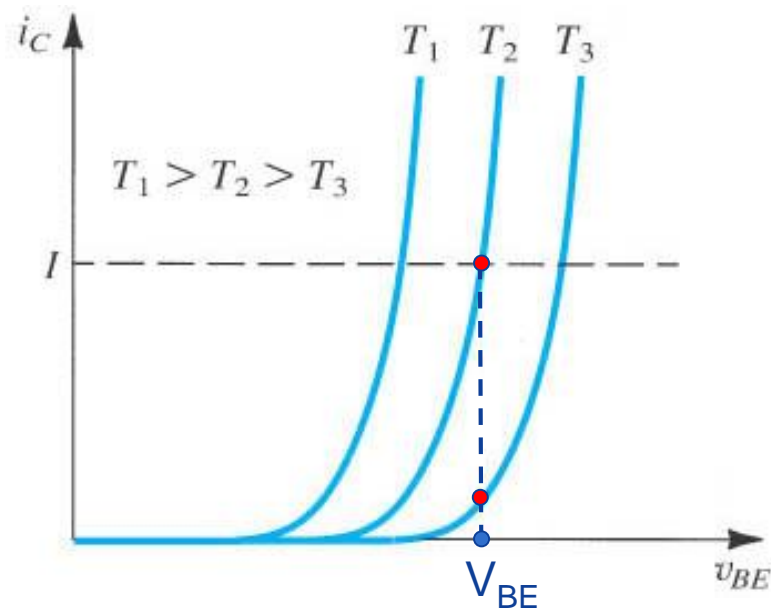
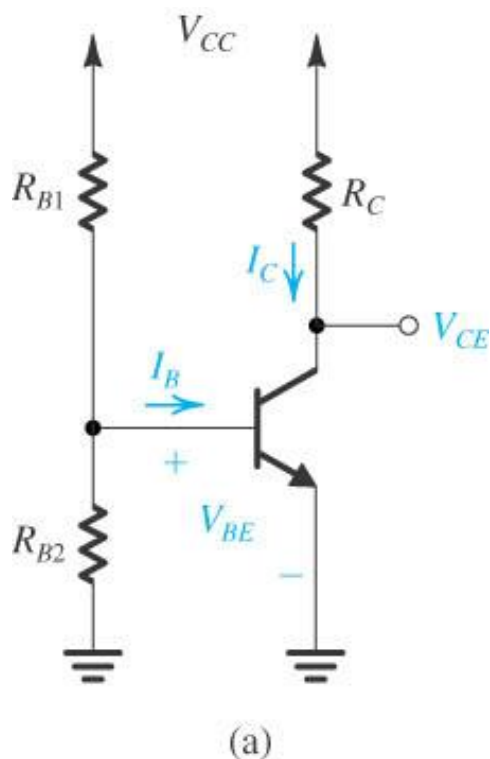


Figure 5.43 Two obvious schemes for biasing the BJT: **(a)** by fixing V_{BE} ; **(b)** by fixing I_B . Both result in wide variations in I_C and hence in V_{CE} and therefore are considered to be “bad.” Neither scheme is recommended.

Circuito de polarização – I_B constante

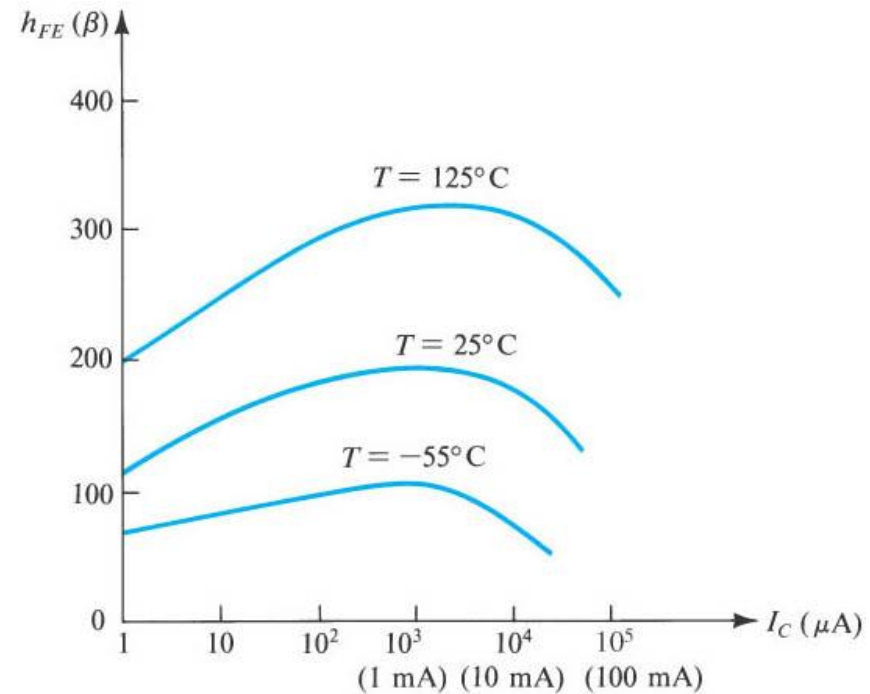
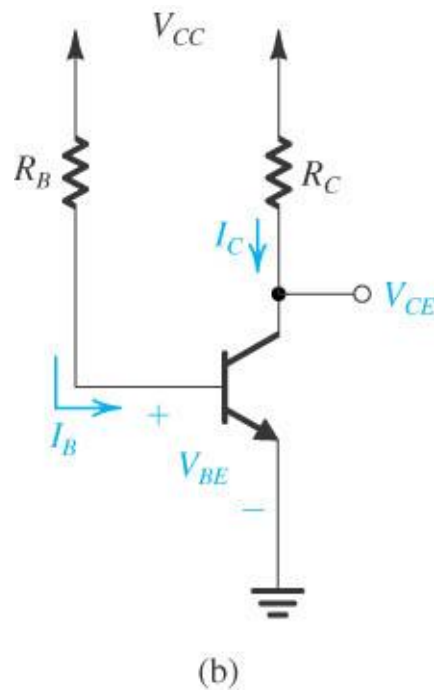
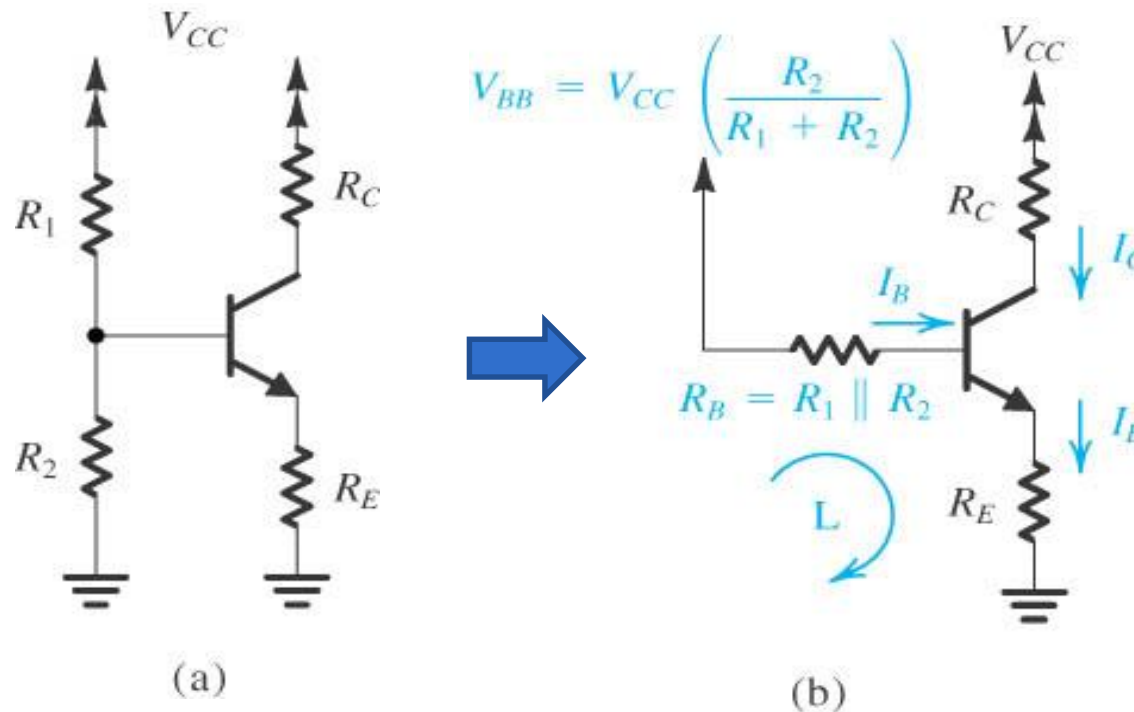


Figure 5.43 Two obvious schemes for biasing the BJT: **(a)** by fixing V_{BE} ; **(b)** by fixing I_B . Both result in wide variations in I_C and hence in V_{CE} and therefore are considered to be “bad.” Neither scheme is recommended.

Circuito de polarização com fonte única



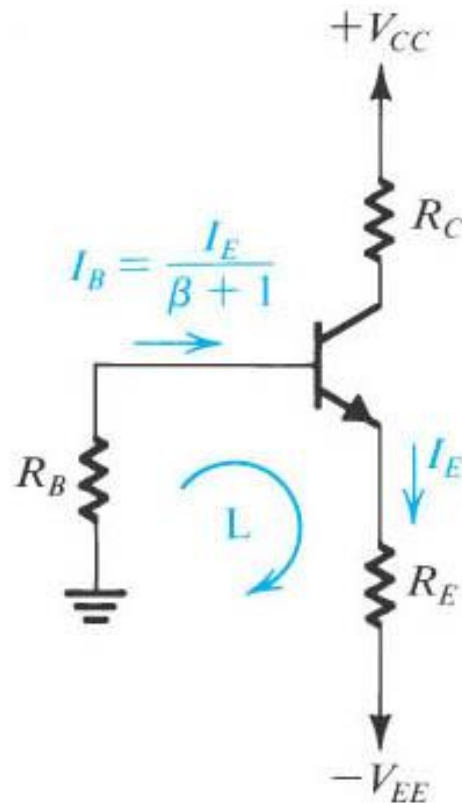
$$I_E = \frac{V_{BB} - V_{BE}}{R_E + R_B / (\beta + 1)}$$

$$V_{BB} \gg V_{BE}$$

$$R_E \gg \frac{R_B}{\beta + 1}$$

Figure 5.44 Classical biasing for BJTs using a single power supply: **(a)** circuit; **(b)** circuit with the voltage divider supplying the base replaced with its Thévenin equivalent.

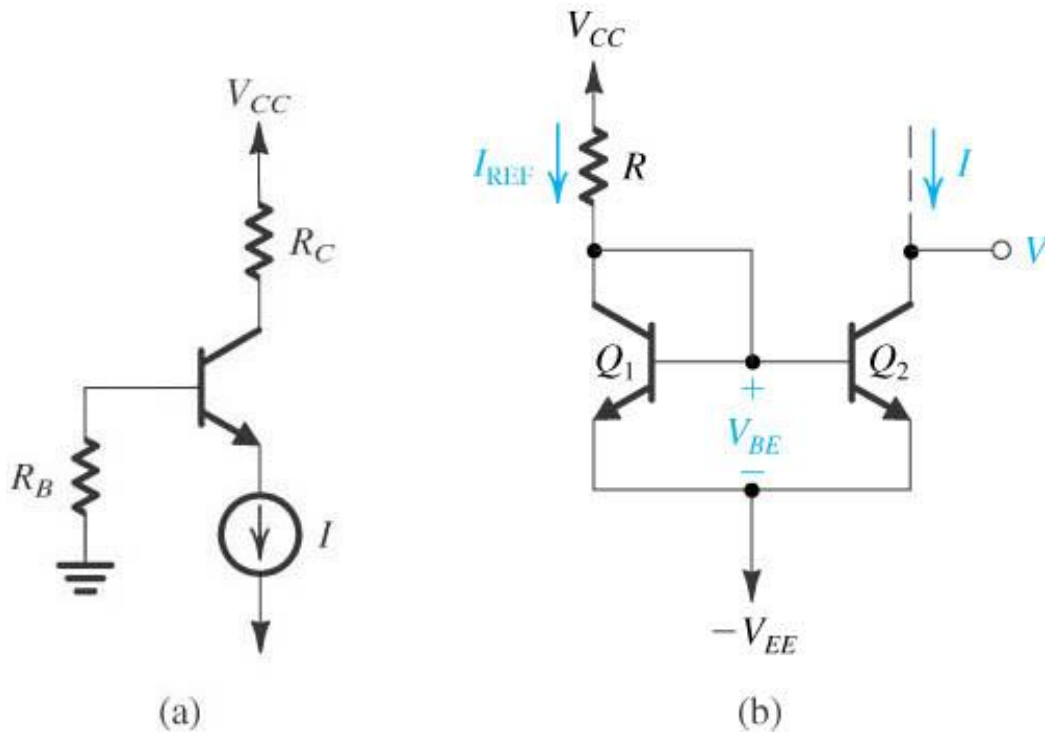
Polarização com fontes simétricas



$$I_E = \frac{V_{EE} - V_{BE}}{R_E + \frac{R_B}{\beta + 1}}$$

Figure 5.45 Biasing the BJT using two power supplies. Resistor R_B is needed only if the signal is to be capacitively coupled to the base. Otherwise, the base can be connected directly to ground, or to a grounded signal source, resulting in almost total β -independence of the bias current.

Polarização com fonte de corrente constante

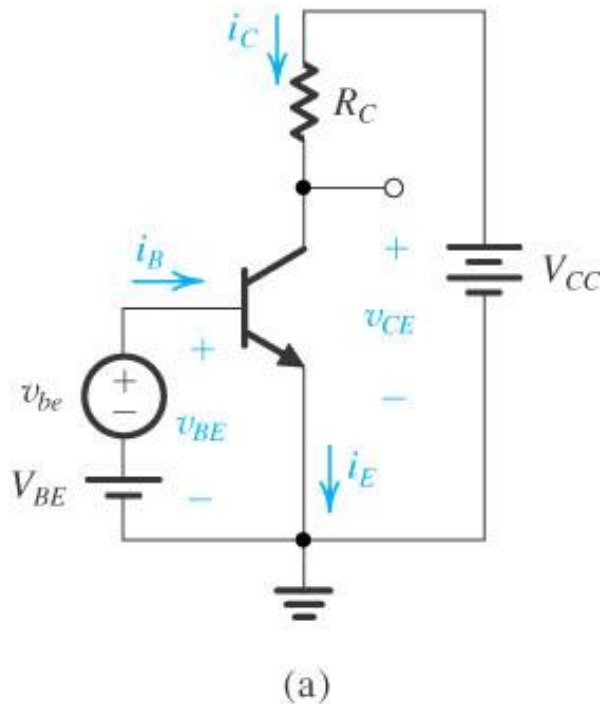


$$I_{REF} = \frac{V_{CC} + V_{EE} - V_{BE}}{R}$$

Figure 5.47 (a) A BJT biased using a constant-current source I . (b) Circuit for implementing the current source I .

Amplificadores com pequenos sinais

Amplificador



Polarização

$$I_C = I_S e^{\frac{V_{BE}}{V_T}}$$

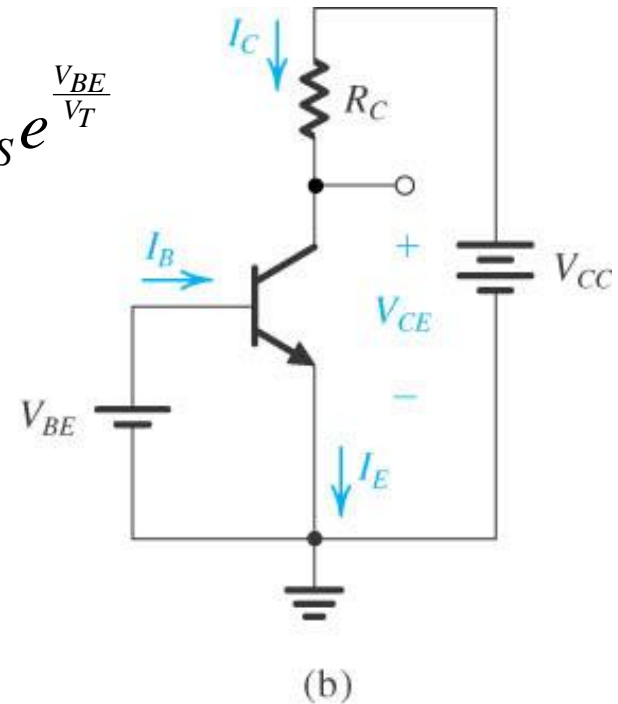
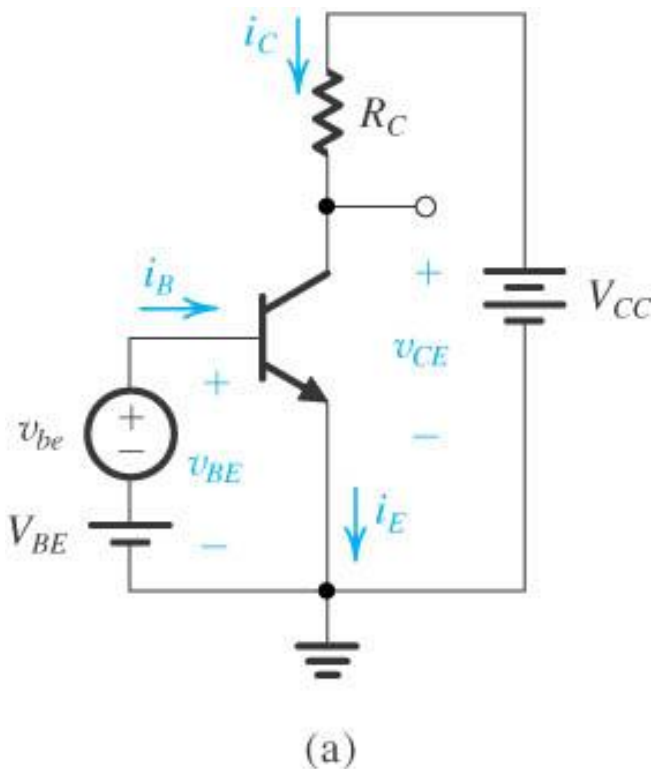


Figure 5.48 (a) Conceptual circuit to illustrate the operation of the transistor as an amplifier. (b) The circuit of (a) with the signal source v_{be} eliminated for dc (bias) analysis.

Amplificadores com pequenos sinais

$$v_{BE} = V_{BE} + v_{be} \quad i_C = I_S e^{\frac{v_{BE}}{V_T}} = I_S e^{\frac{(V_{BE} + v_{be})}{V_T}} = I_S e^{\frac{V_{BE}}{V_T}} e^{\frac{v_{be}}{V_T}} = I_C e^{\frac{v_{be}}{V_T}}$$

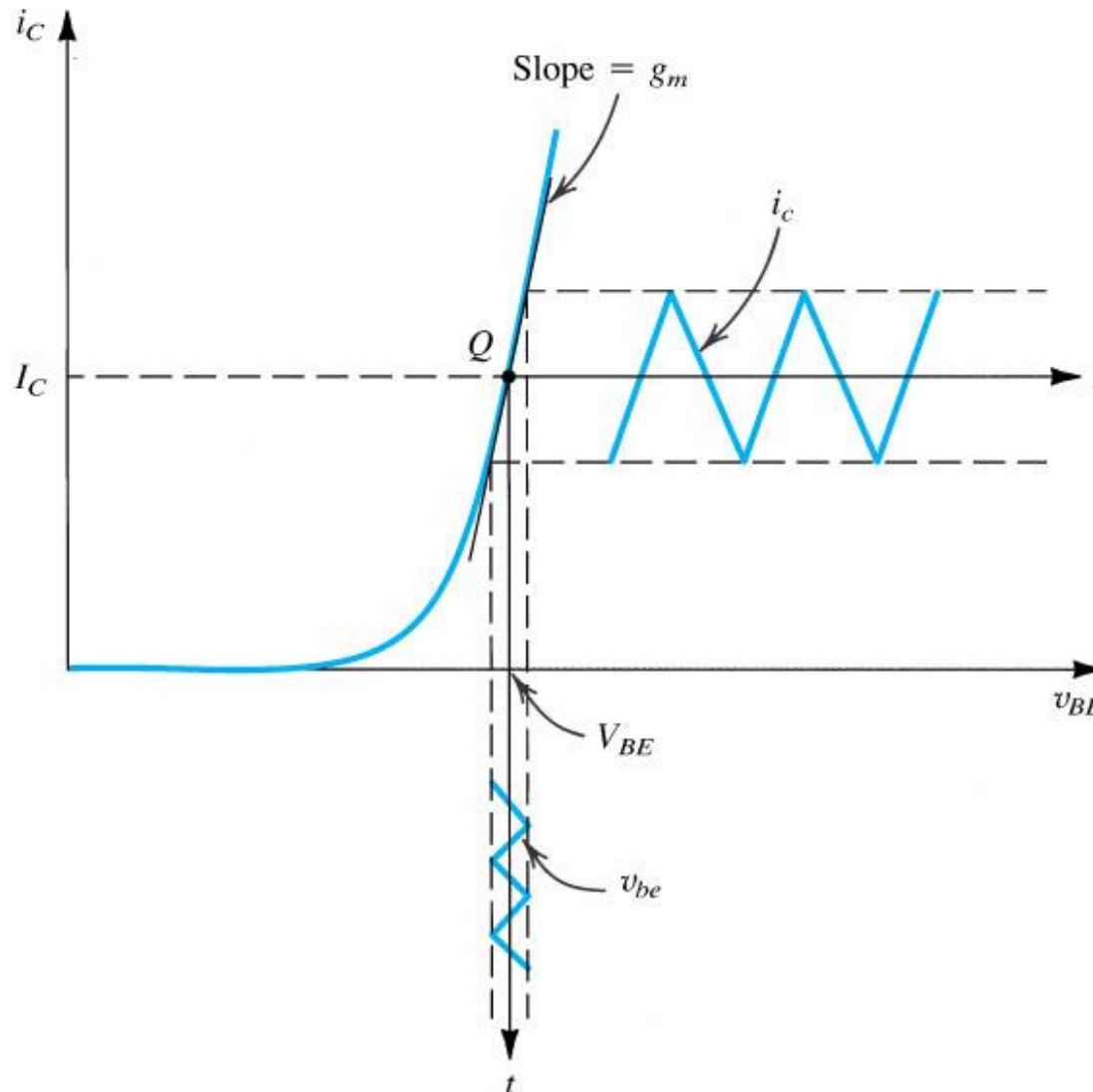


$$i_C \approx I_C + \frac{I_C}{V_T} v_{be}$$

$$i_c = g_m v_{be}$$

$$g_m = \frac{I_C}{V_T}$$

Interpretação gráfica de g_m



$$g_m = \frac{I_C}{V_T}$$

Amplificadores com pequenos sinais

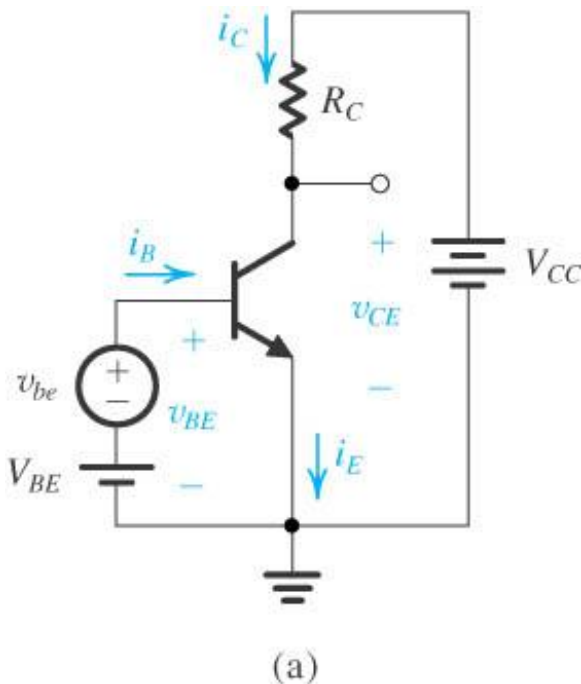
$$i_C \approx I_C + \frac{I_C}{V_T} v_{be}$$

$$i_B = \frac{i_C}{\beta} = \frac{I_C}{\beta} + \frac{1}{\beta} \frac{I_C}{V_T} v_{be}$$

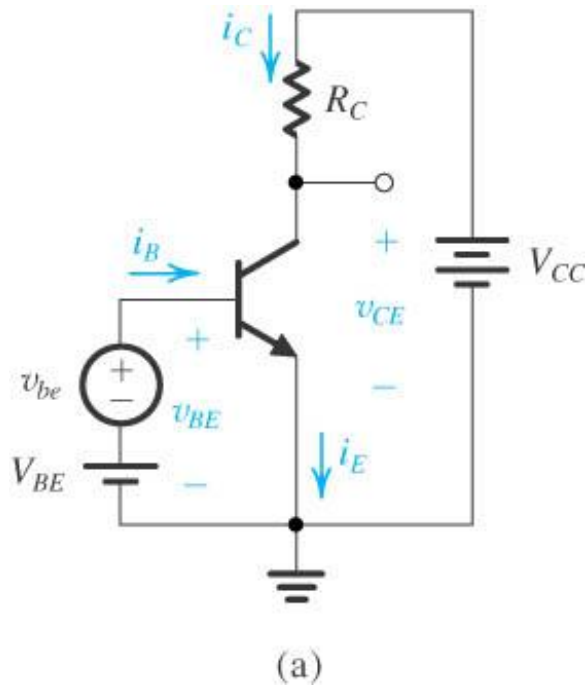
$$i_B = I_B + i_b$$

$$i_b = \frac{1}{\beta} \frac{I_C}{V_T} v_{be} = \frac{g_m}{\beta} v_{be}$$

$$r_\pi = \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = \frac{V_T}{I_B}$$



Amplificadores com pequenos sinais



$$i_C \approx I_C + \frac{I_C}{V_T} v_{be}$$

$$i_E = \frac{i_C}{\alpha} = \frac{I_C}{\alpha} + \frac{I_C}{\alpha V_T} v_{be}$$

$$i_E = I_E + i_e$$

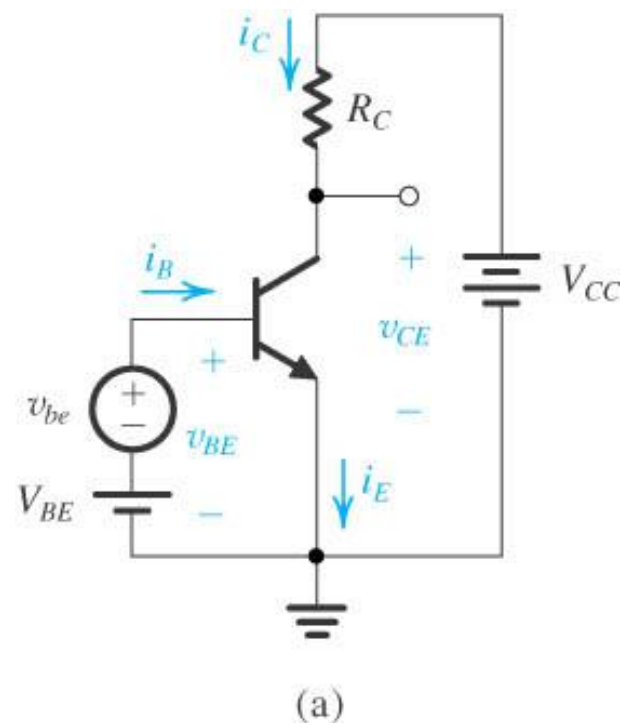
$$i_e = \frac{1}{\alpha} \frac{I_C}{V_T} v_{be} = \frac{g_m}{\alpha} v_{be}$$

$$r_e = \frac{v_{be}}{i_e} = \frac{\alpha}{g_m} = \frac{V_T}{I_e}$$

Amplificadores com pequenos sinais

$$v_{BE} = V_{BE} + v_{be}$$

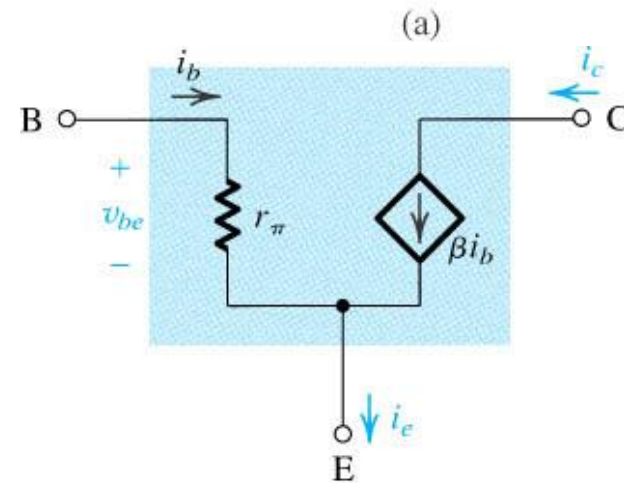
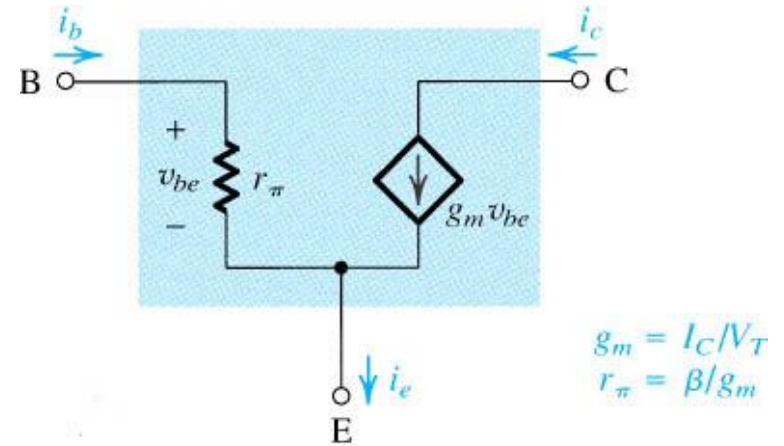
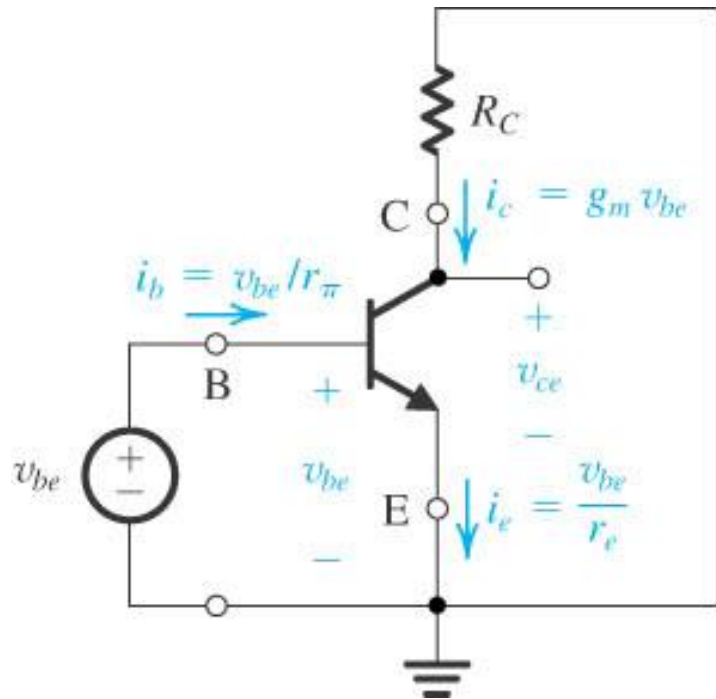
$$v_C = V_{CC} - R_C i_C = V_{CC} - R_C (I_C + i_c) = V_{CC} - R_C I_C - R_C i_c = V_C + v_c$$



$$v_c = -i_c R_C = -g_m R_C v_{be}$$

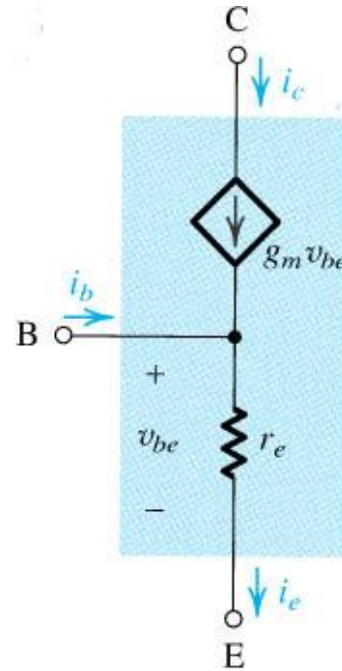
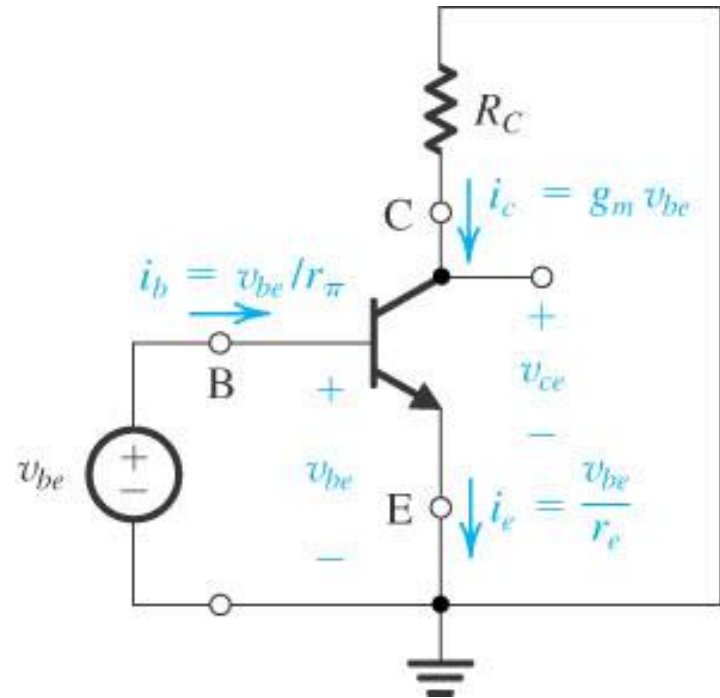
$$A_v = \frac{v_c}{v_{be}} = -g_m R_C = -\frac{I_C R_C}{V_T}$$

Modelo híbrido Pi



(b)

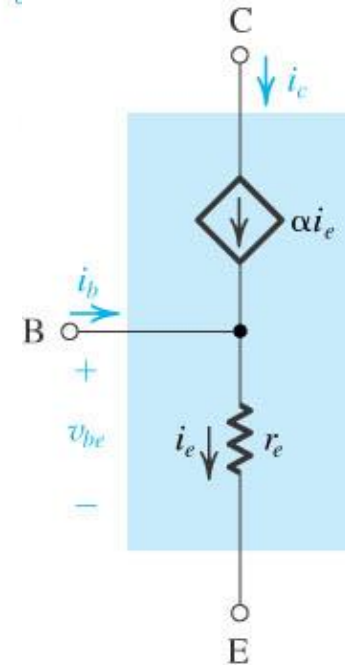
Modelo híbrido T



(a)

$$g_m = I_C / V_T$$

$$r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m}$$



(b)

Exemplo 5.14

Determine o ganho de tensão do amplificador. O ganho $\beta = 100$.

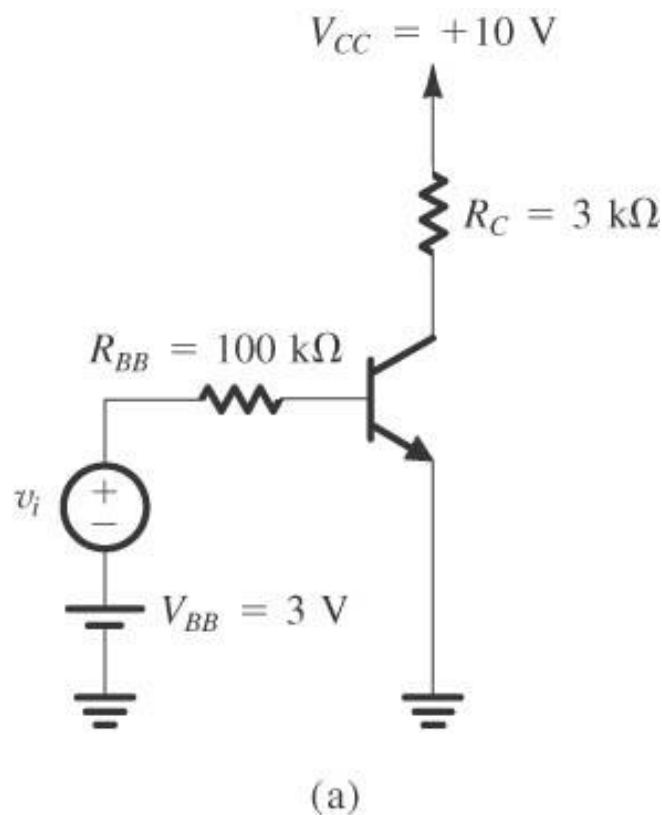
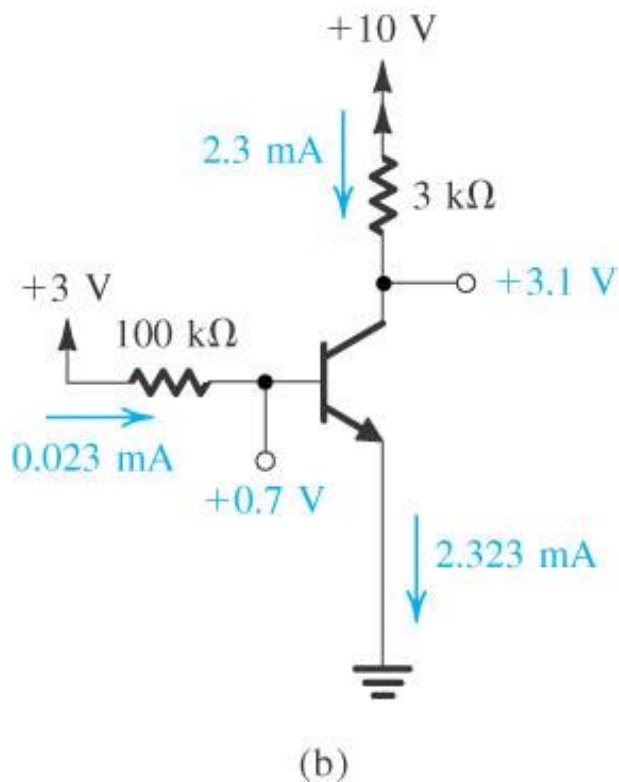


Figure 5.53 Example 5.14: **(a)** circuit; **(b)** dc analysis; **(c)** small-signal model.

Exemplo 5.14 - solução

Análise C.C.



Análise C.A.

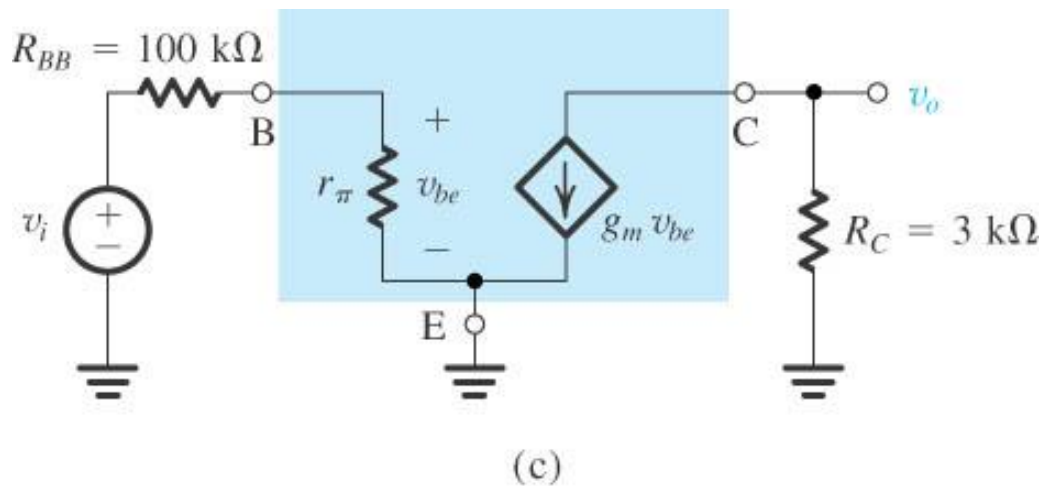
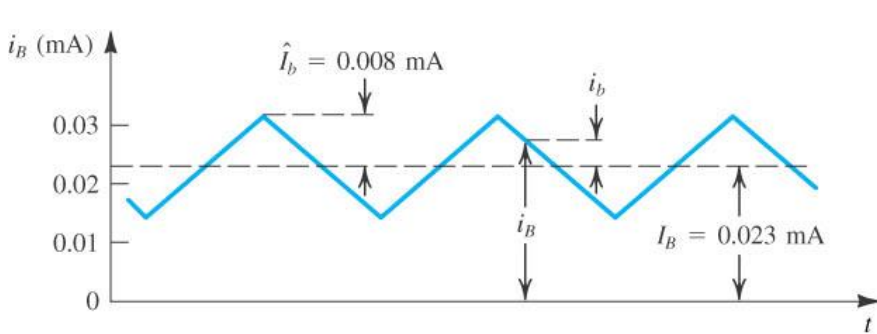
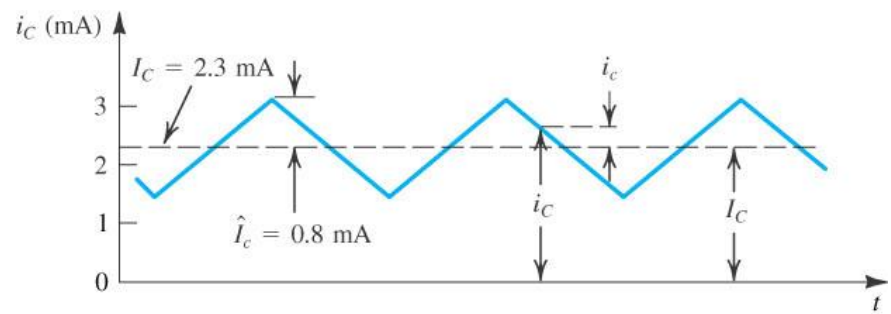


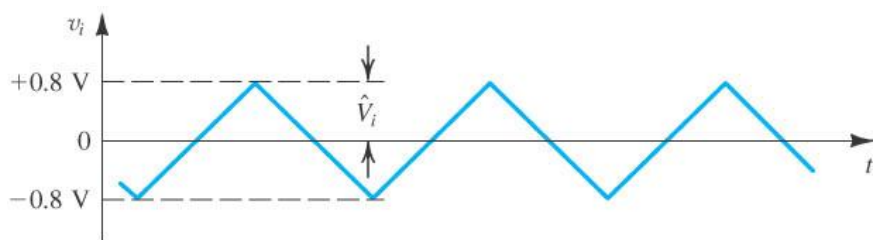
Figure 5.53 Example 5.14: (a) circuit; (b) dc analysis; (c) small-signal model.



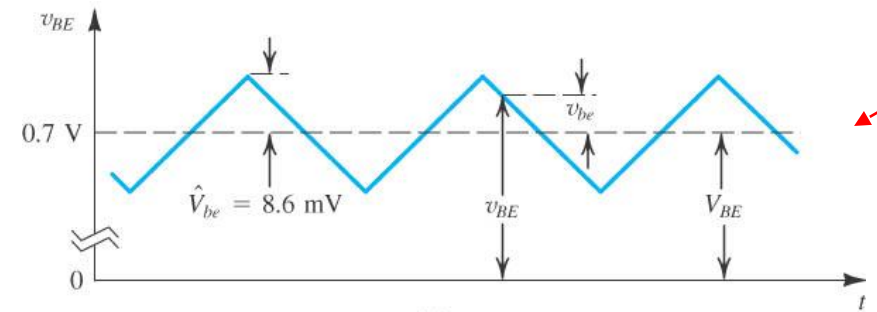
(b)



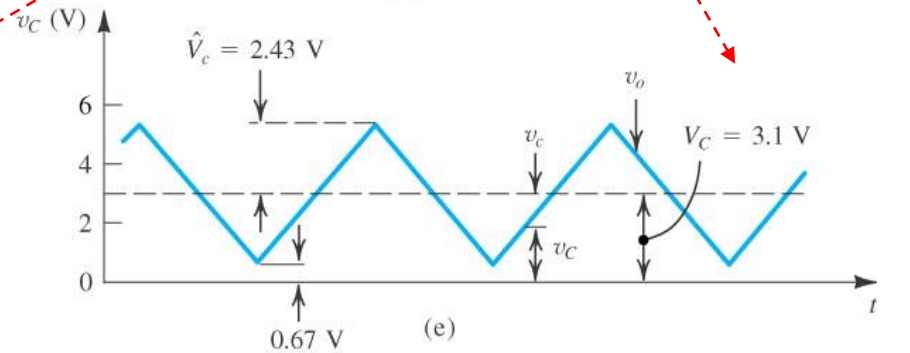
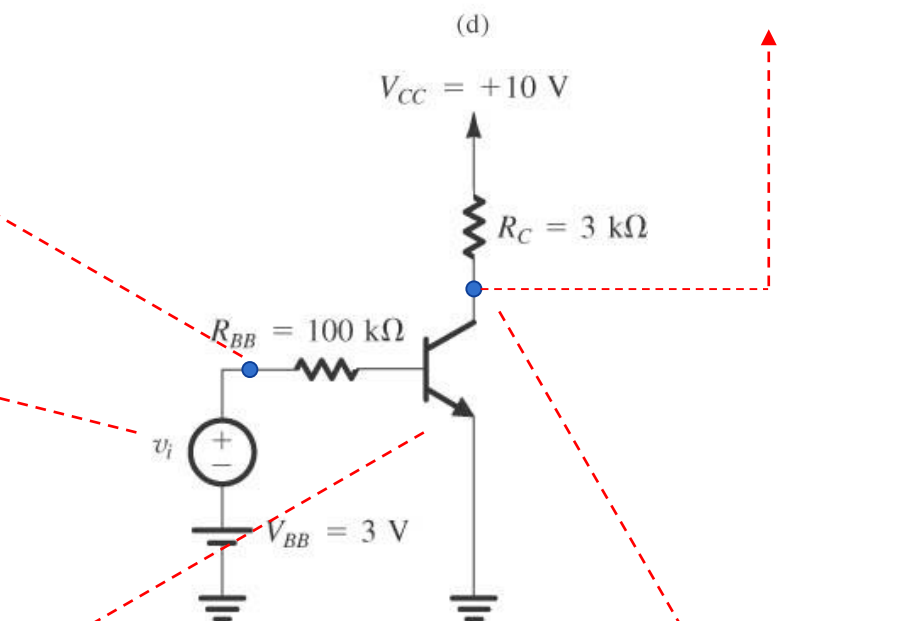
(d)



(a)



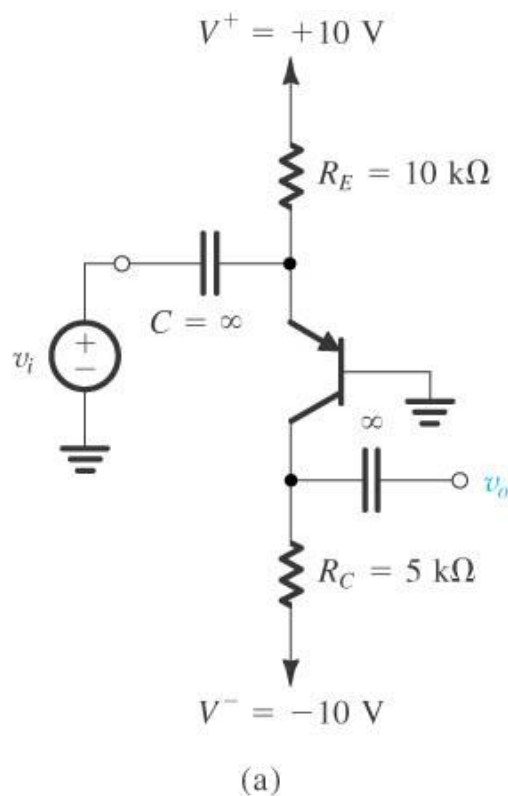
(c)



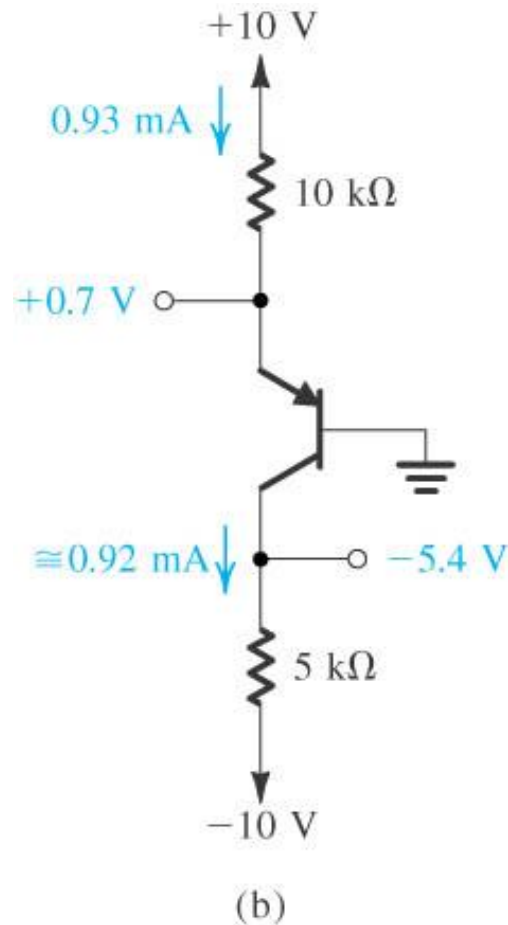
(e)

Exemplo 5.16

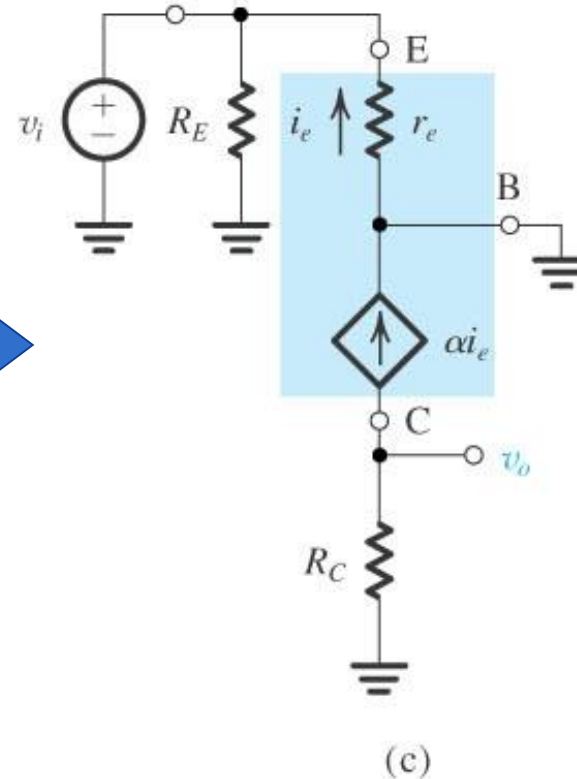
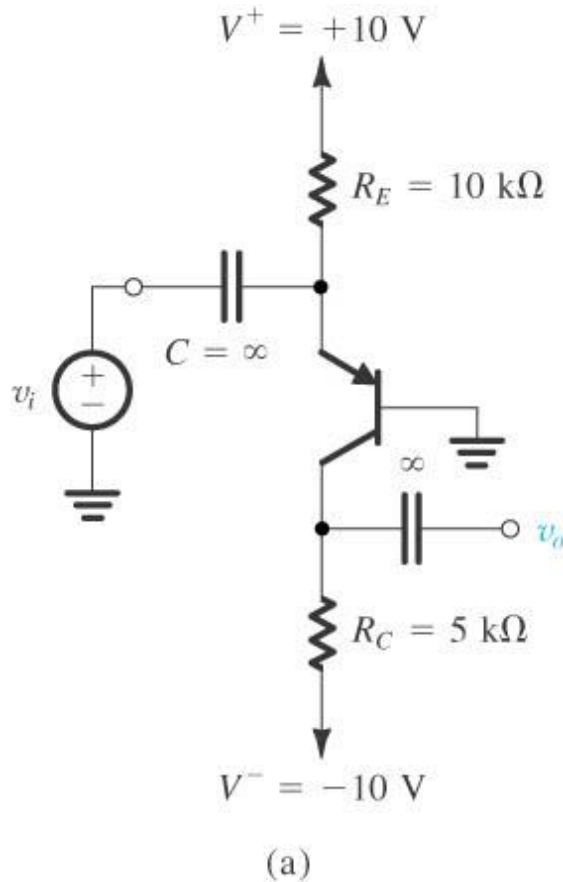
Determine o ganho do amplificador. $\beta = 100$



Exemplo 5.16 – Análise c.c.

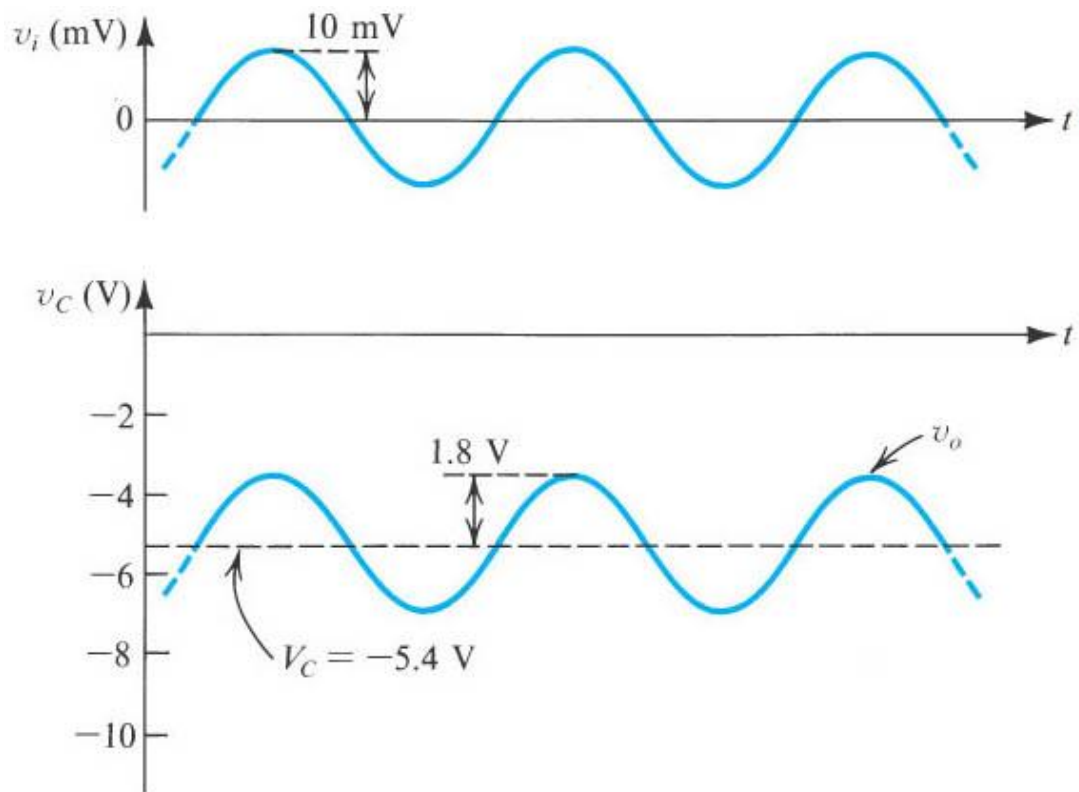
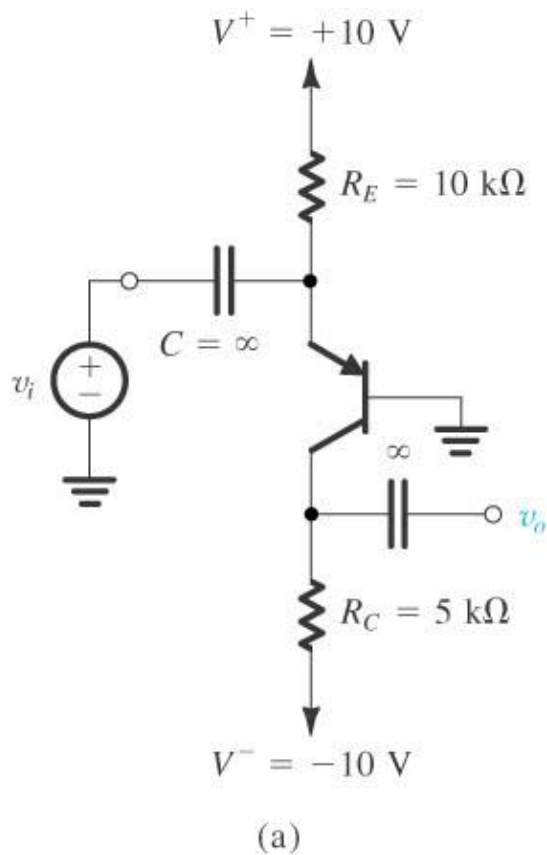


Exemplo 5.16 – Análise c.a.

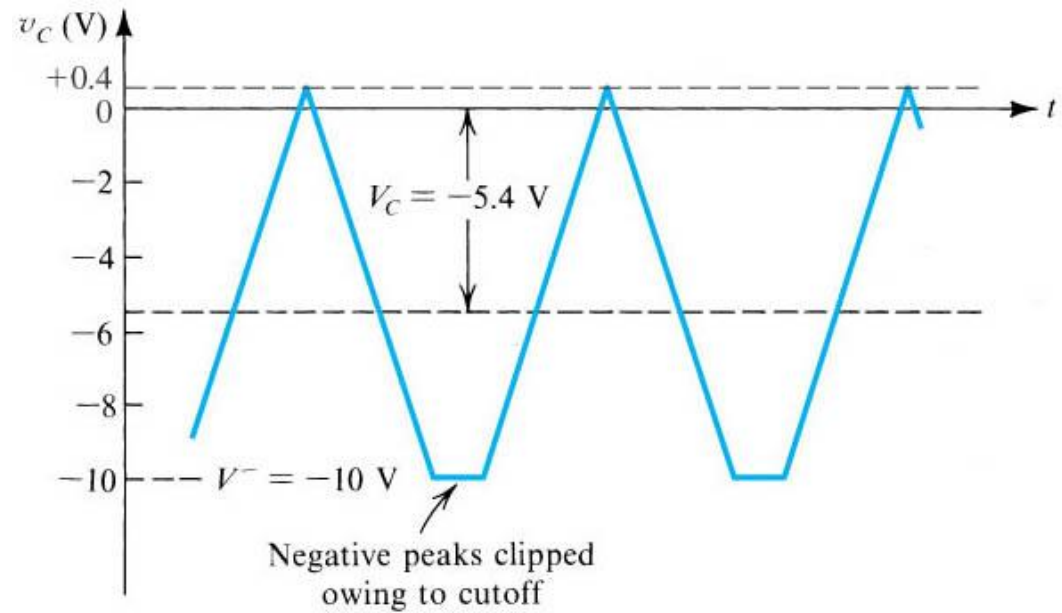
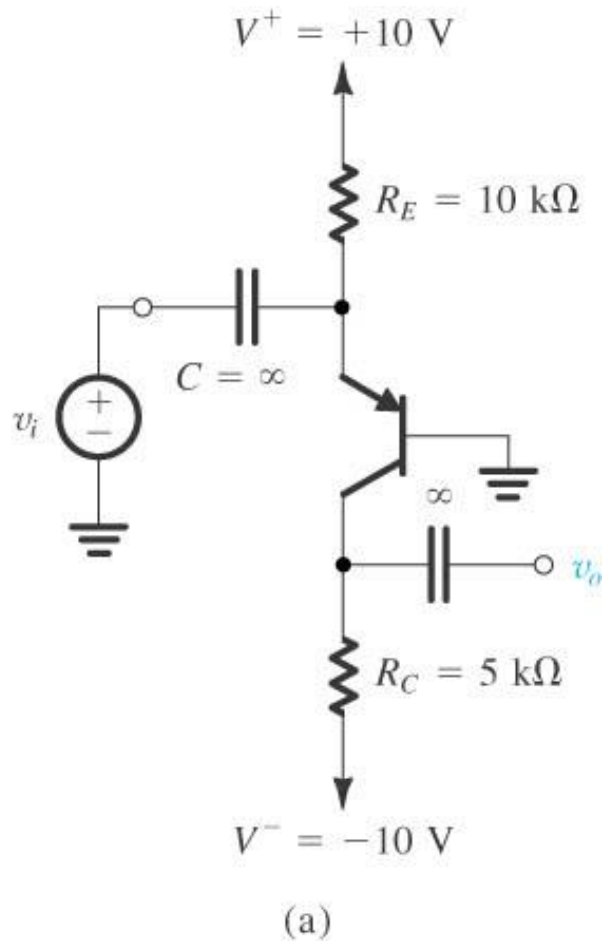


$$\begin{aligned}
 i_e &= -\frac{v_i}{r_e} \\
 v_o &= -\alpha i_e R_C \\
 &= \frac{\alpha R_C}{r_e} v_i
 \end{aligned}$$

Exemplo 5.16



Exemplo 5.16



Modelo pi completo

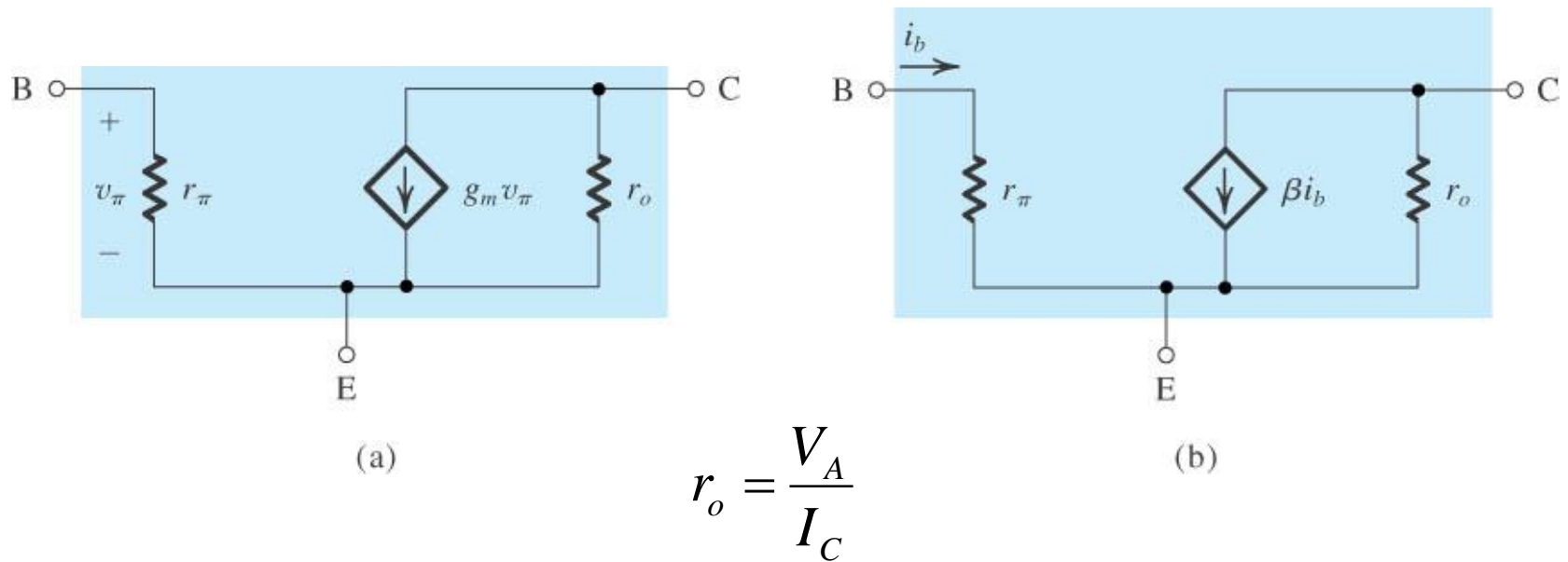


Figure 5.58 The hybrid- p small-signal model, in its two versions, with the resistance r_o included.

Exercício 5.40

$\beta = 100$ e $V_A = 100V$.

1. Determine as tensões C.C. na base, emissor e coletor.
2. Determine g_m , r_π e r_o .
3. Com Z aterrado, uma fonte de sinal conectada em X com resistência $R_{sig} = 2\text{ K}\Omega$ e uma carga $R_L = 8\text{ K}\Omega$ em Y. Determine o ganho V_Y/V_{sig} .

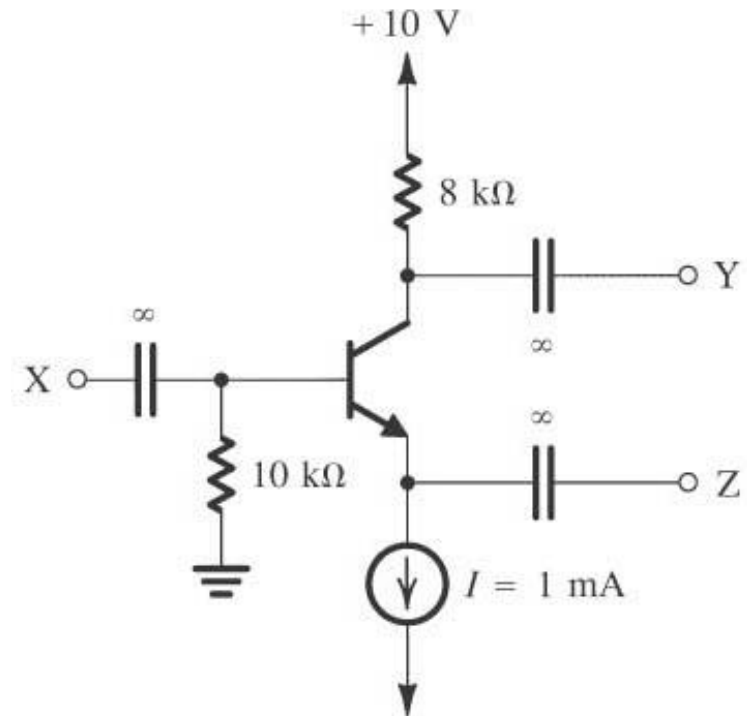


Figure E5.40

Circuito básico de polarização

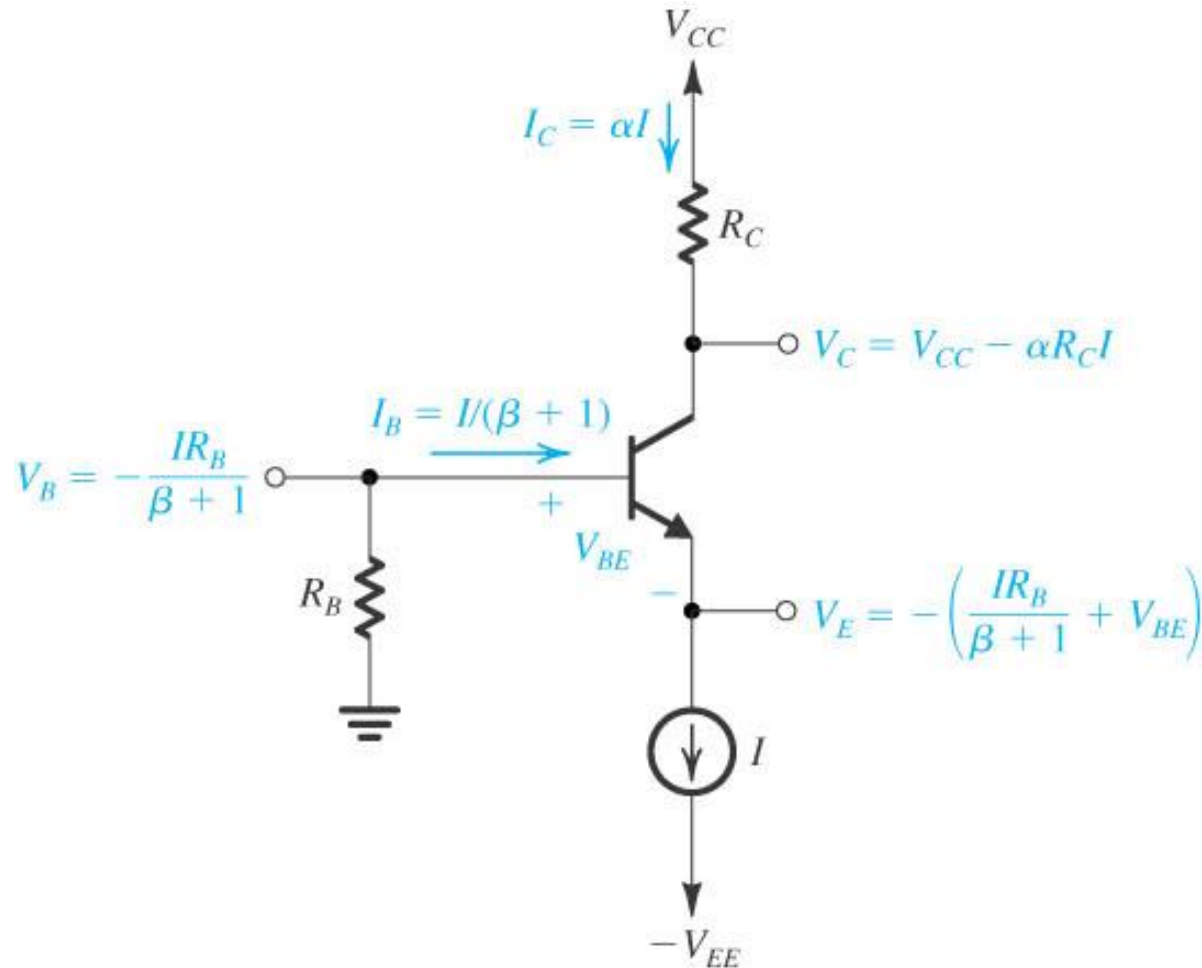


Figure 5.59 Basic structure of the circuit used to realize single-stage, discrete-circuit BJT amplifier configurations.

Exercício 5.41

Se $\beta = 100$, determine as correntes e tensões C.C. no circuito.
 O que acontece se $\beta = 50$.
 Determine os parâmetros dos modelos T e pi.

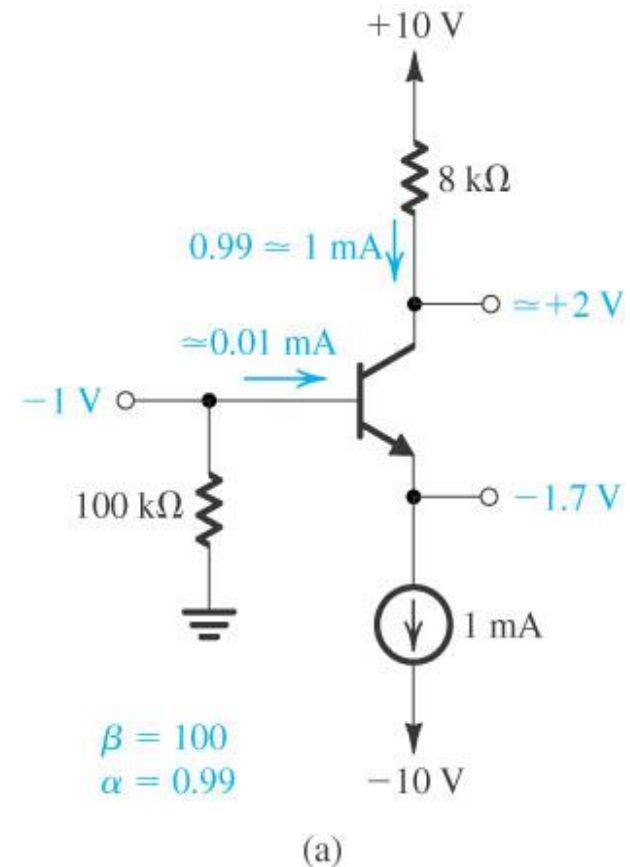
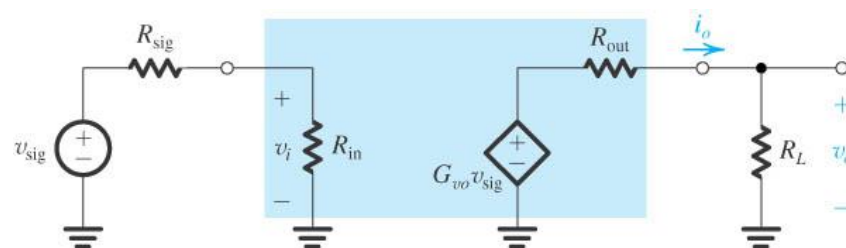
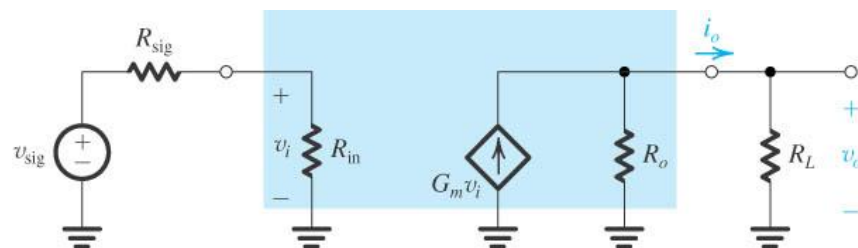
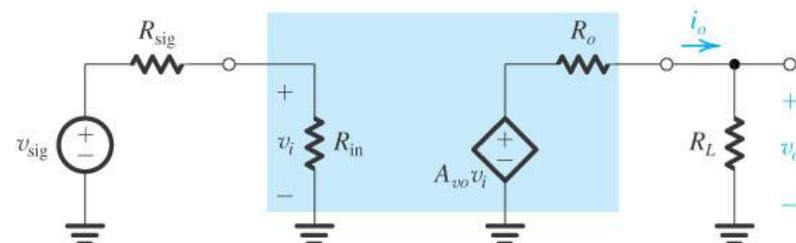
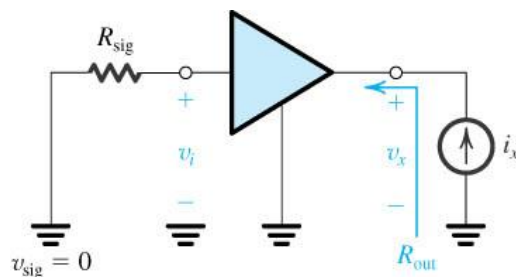
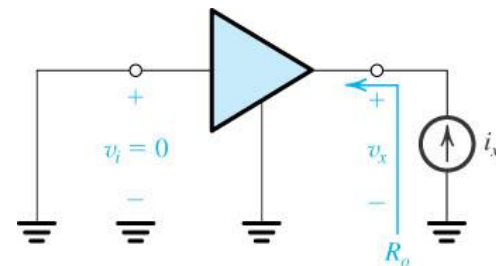
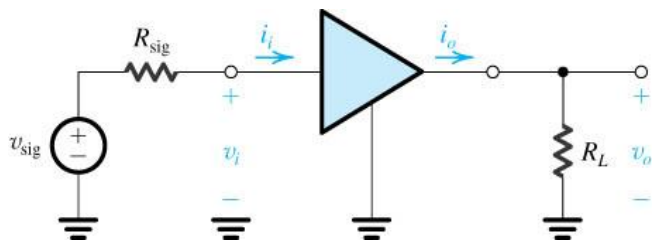


Figure E5.41

Tabela 5.5.



Amplificador emissor comum

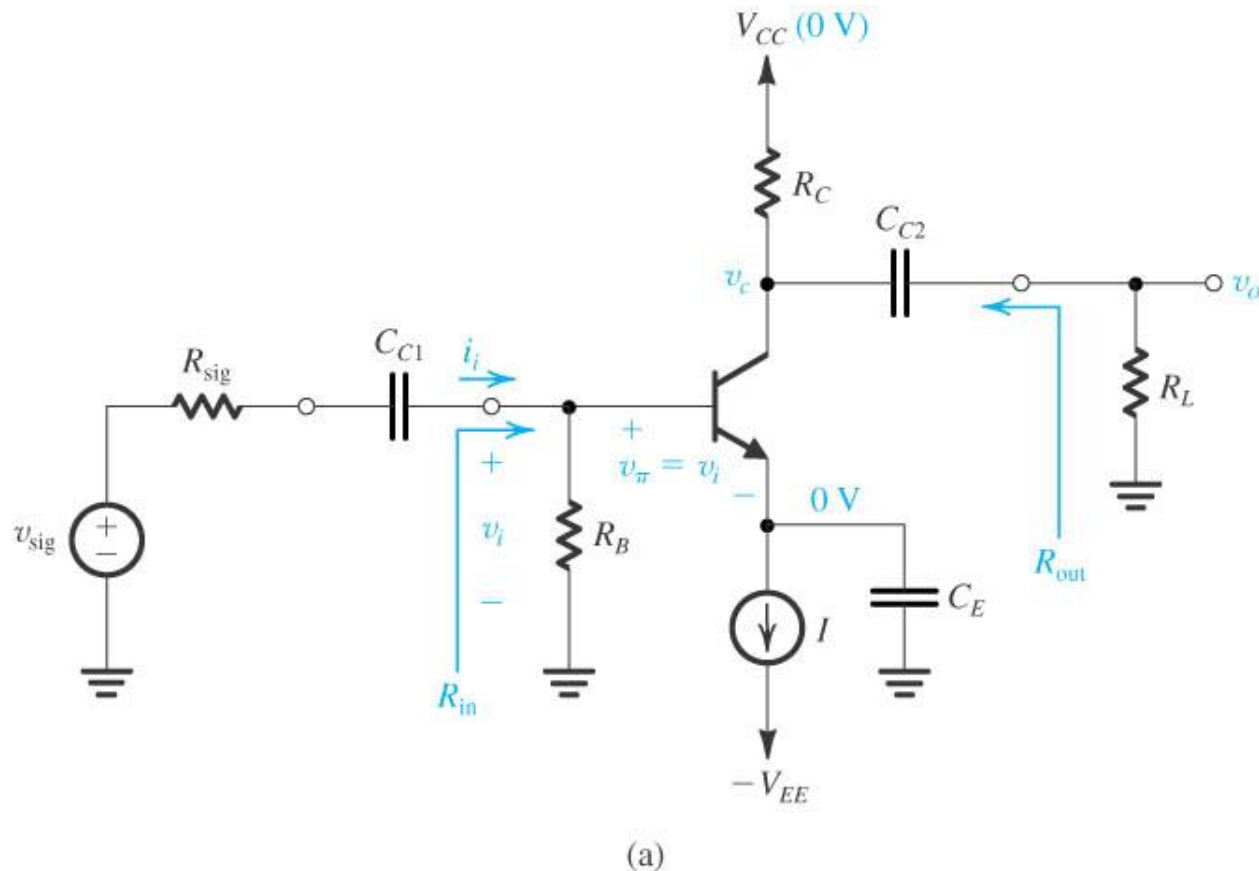
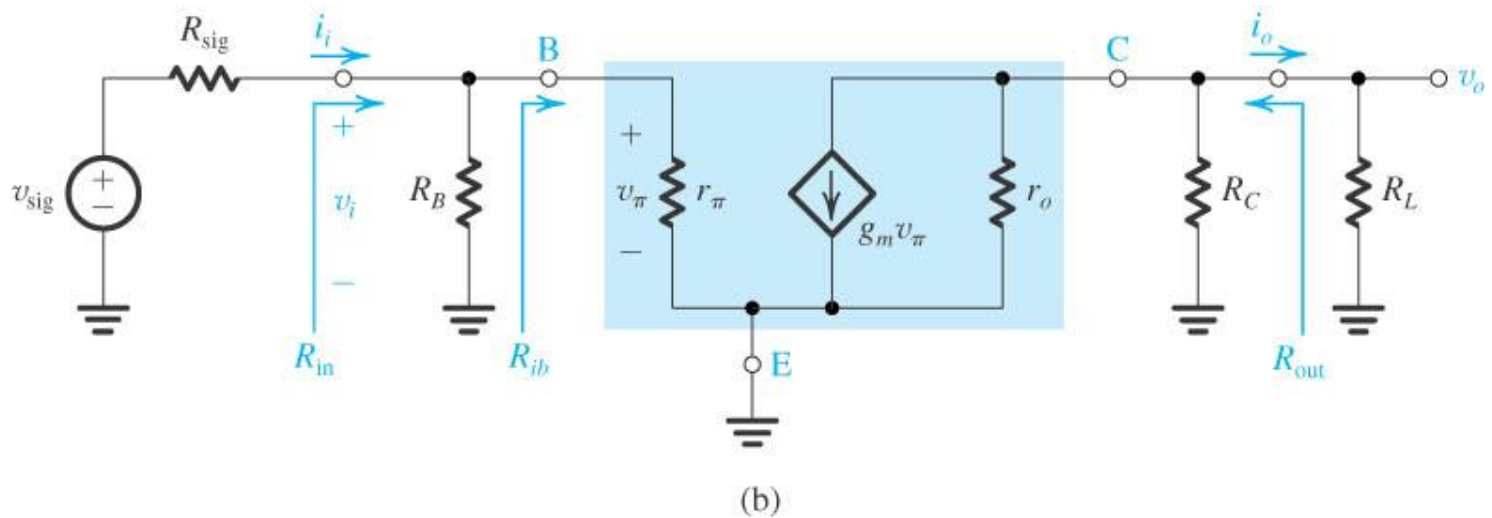
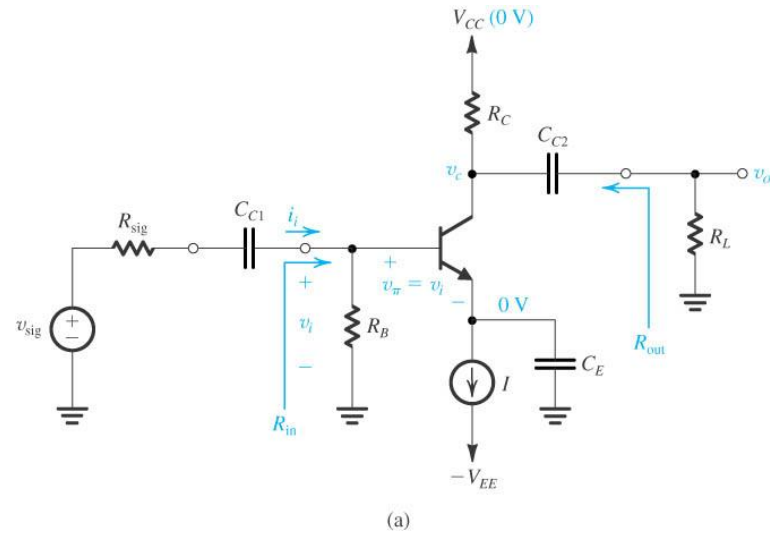
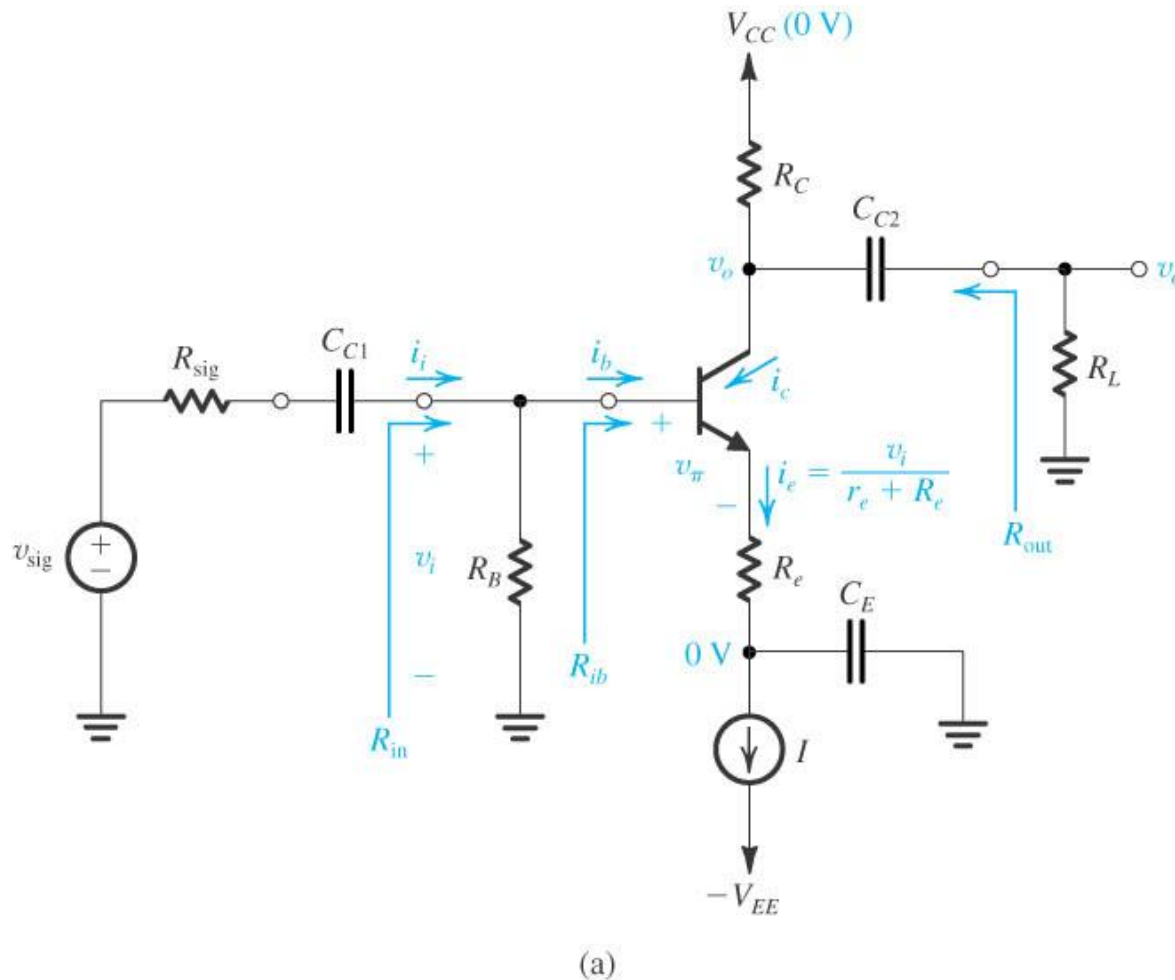


Figure 5.60 (a) A common-emitter amplifier using the structure of Fig. 5.59. **(b)** Equivalent circuit obtained by replacing the transistor with its hybrid- π model.

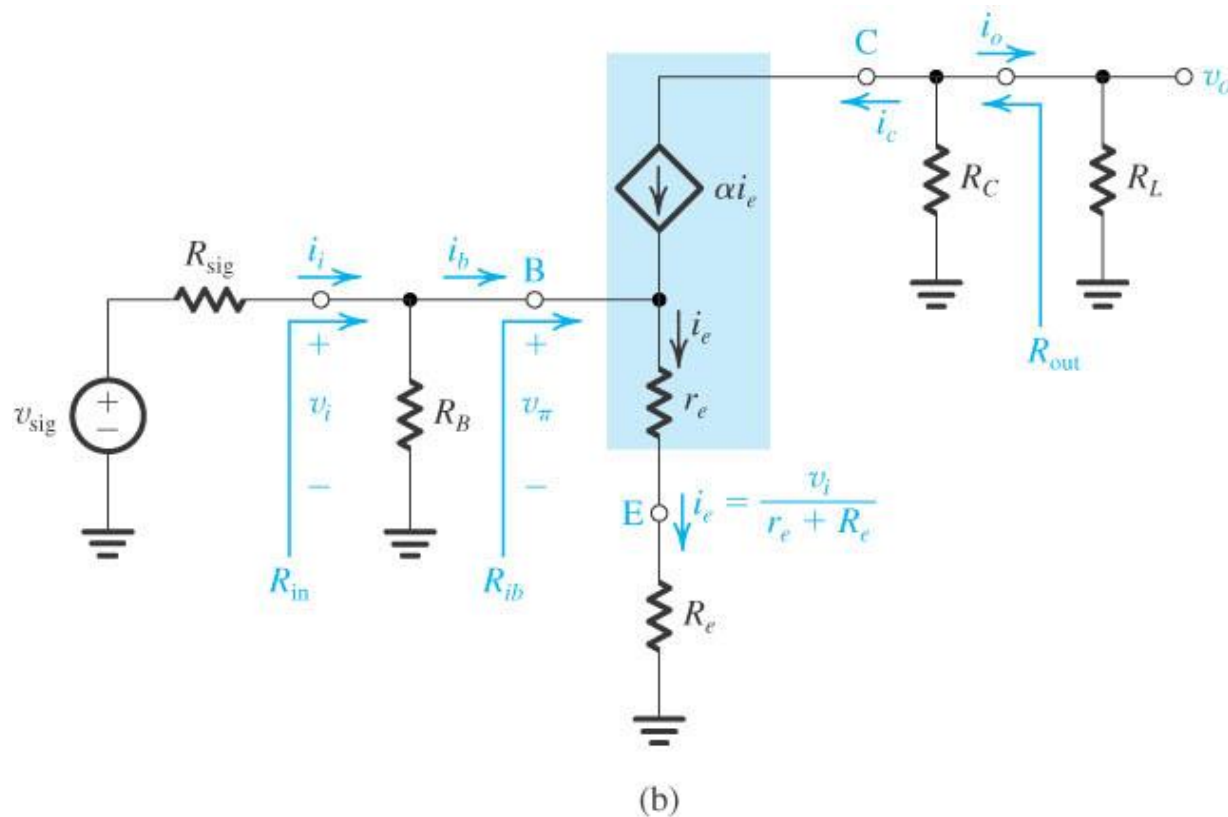
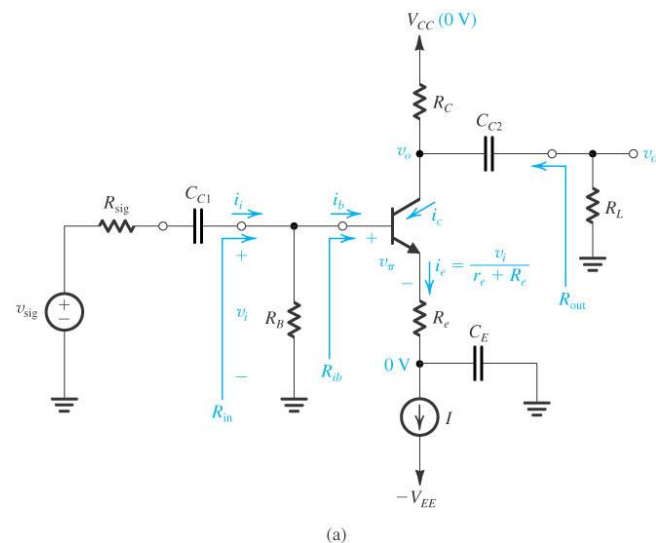
Amplificador emissor comum



Emissor comum com resistor de emissor



Emissor comum com resistor de emissor



Amplificador Base Comum

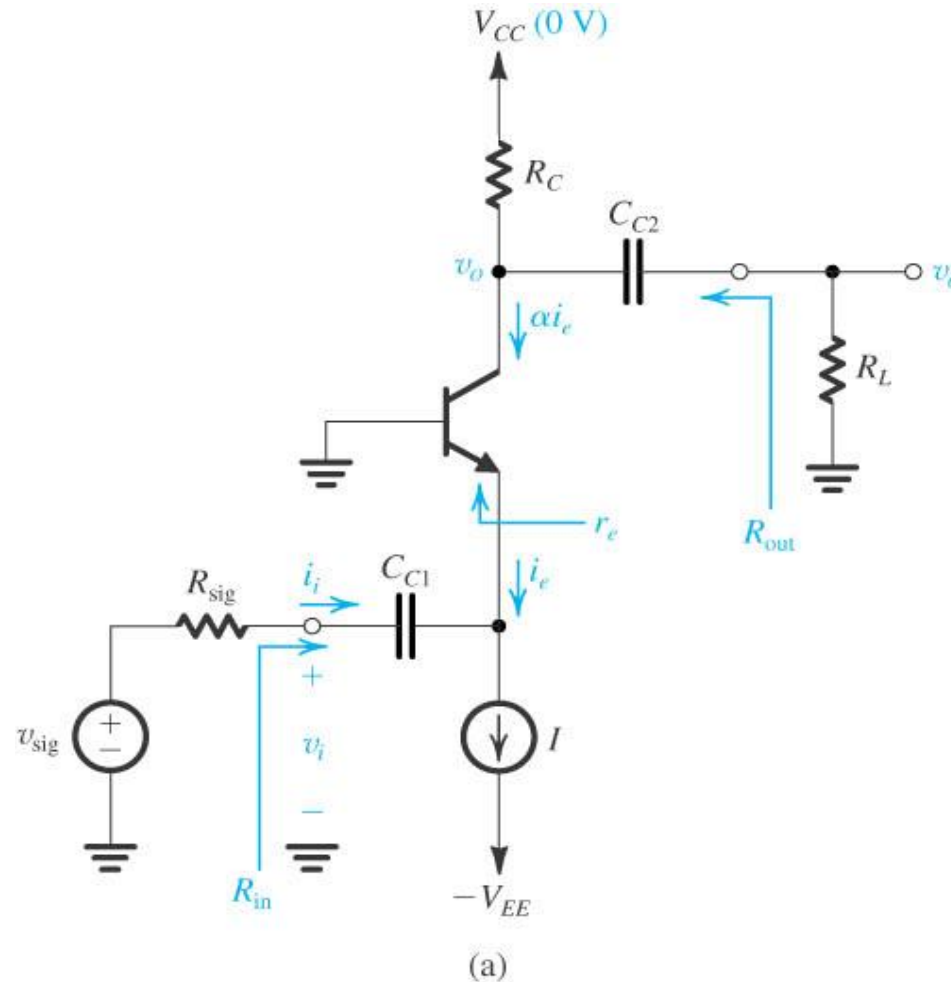


Figure 5.62 (a) A common-base amplifier using the structure of Fig. 5.59. **(b)** Equivalent circuit obtained by replacing the transistor with its T model.

Amplificador Base Comum

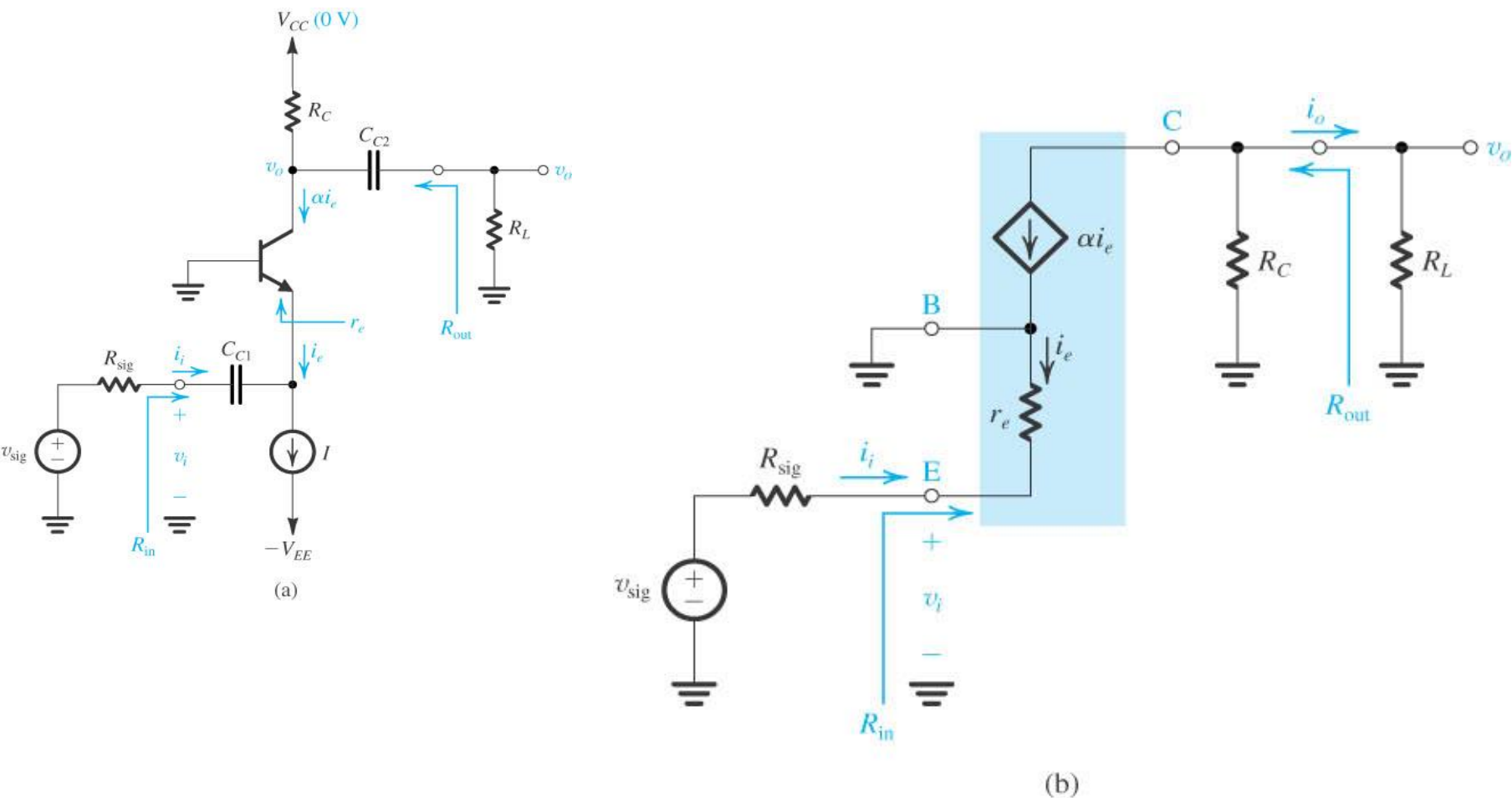


Figure 5.62 (a) A common-base amplifier using the structure of Fig. 5.59. (b) Equivalent circuit obtained by replacing the transistor with its T model.

Amplificador Coletor Comum

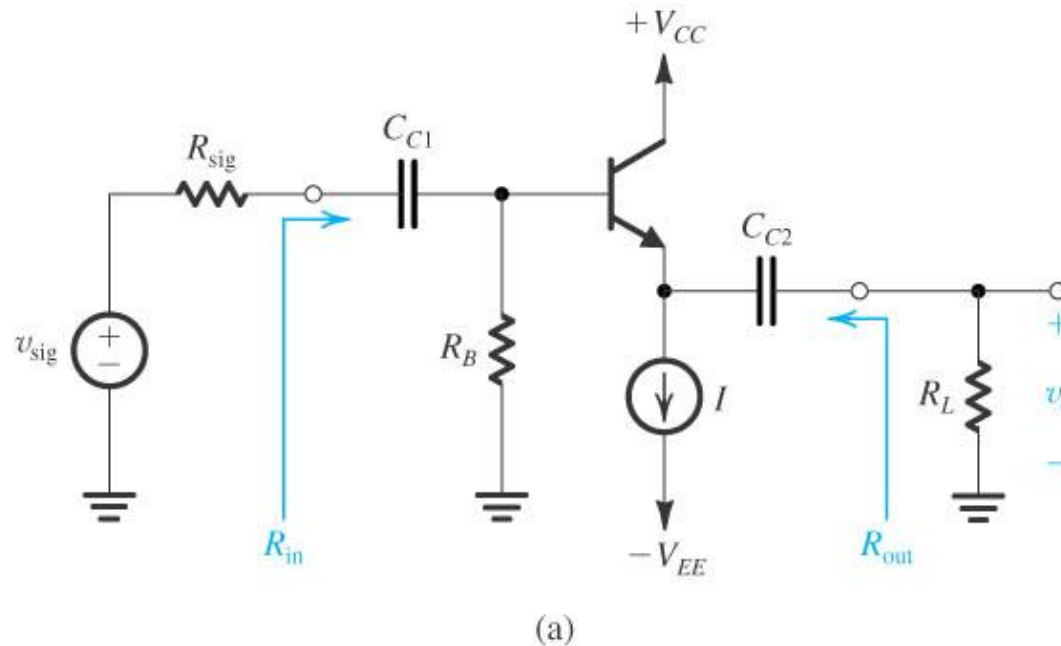
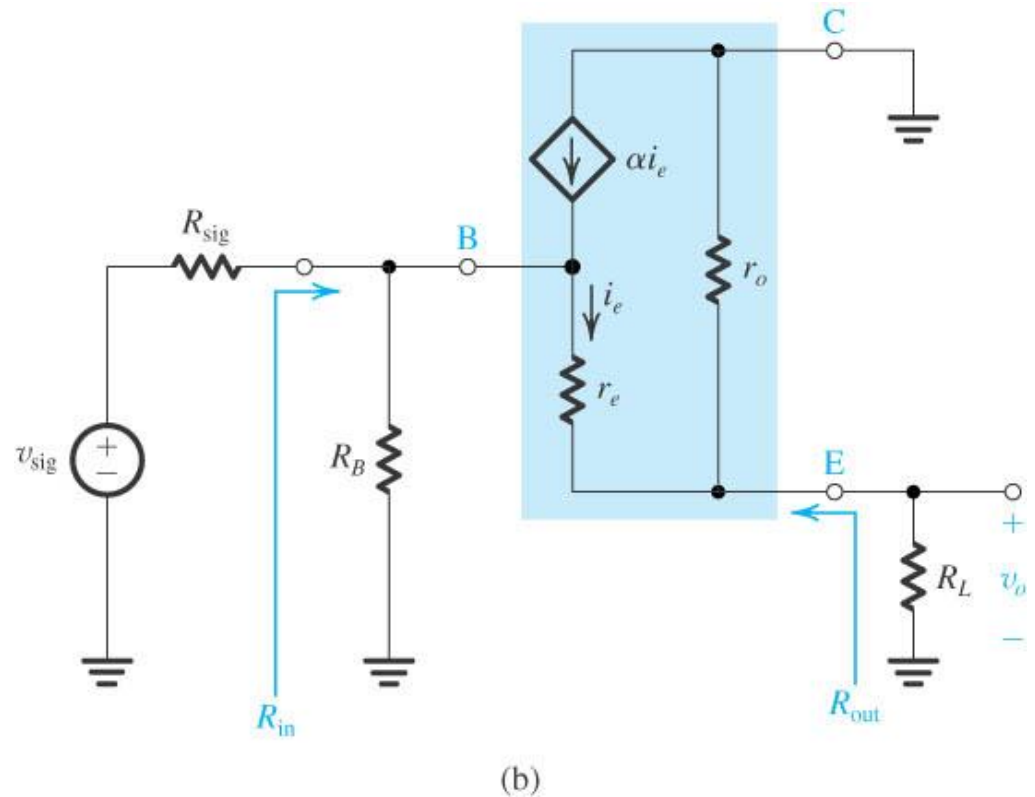
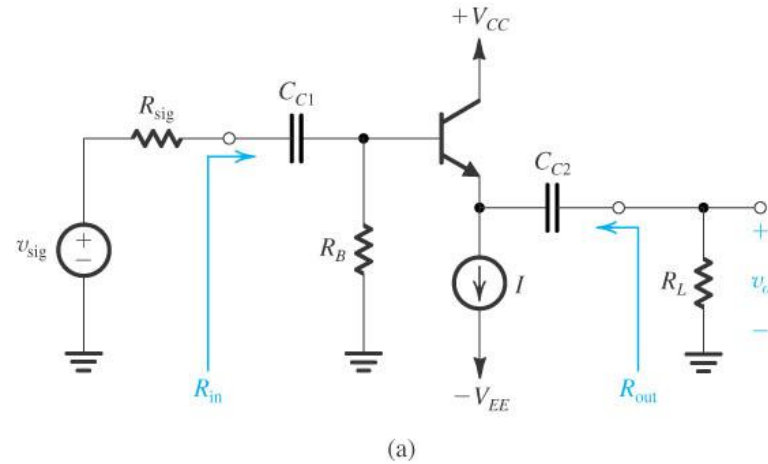
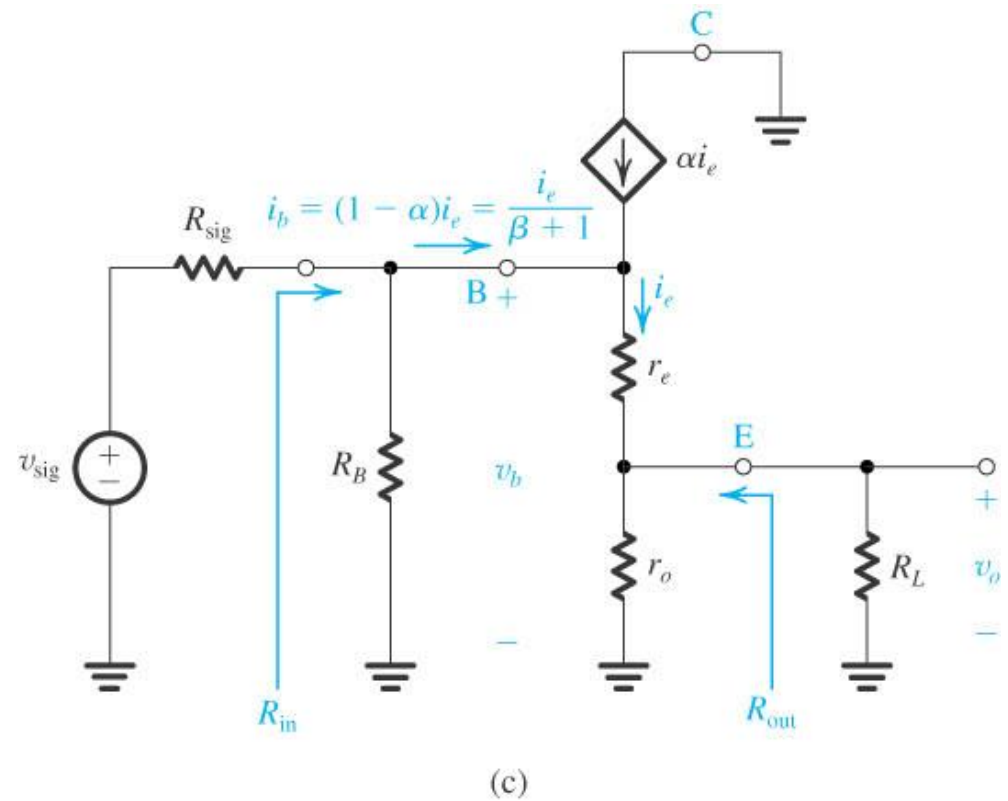
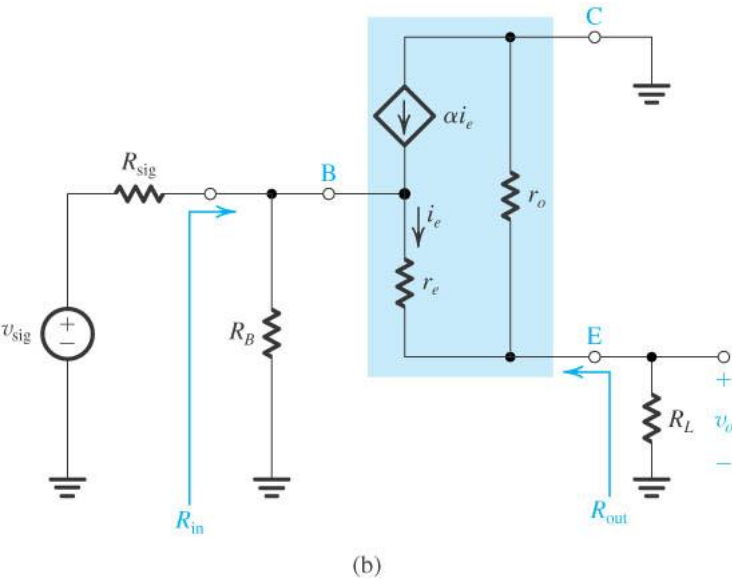


Figure 5.63 (a) An emitter-follower circuit based on the structure of Fig. 5.59. (b) Small-signal equivalent circuit of the emitter follower with the transistor replaced by its T model augmented with r_o . (c) The circuit in (b) redrawn to emphasize that r_o is in parallel with R_L . This simplifies the analysis considerably.

Amplificador Coletor Comum



Amplificador Coletor Comum



Modelo de Altas frequências

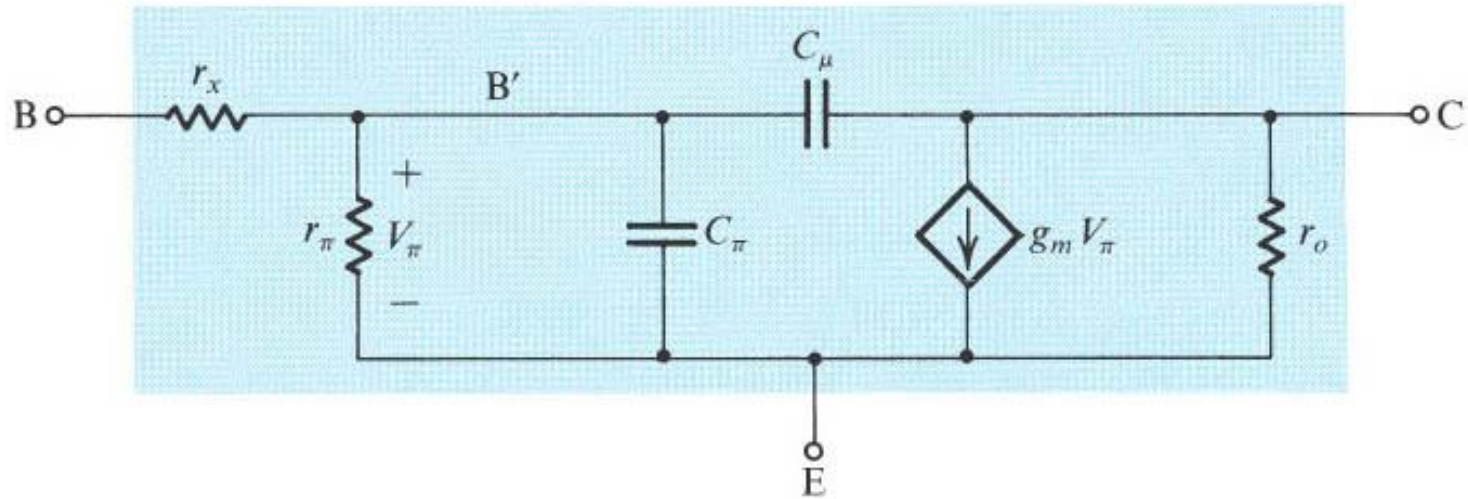


Figure 5.67 The high-frequency hybrid-p model.

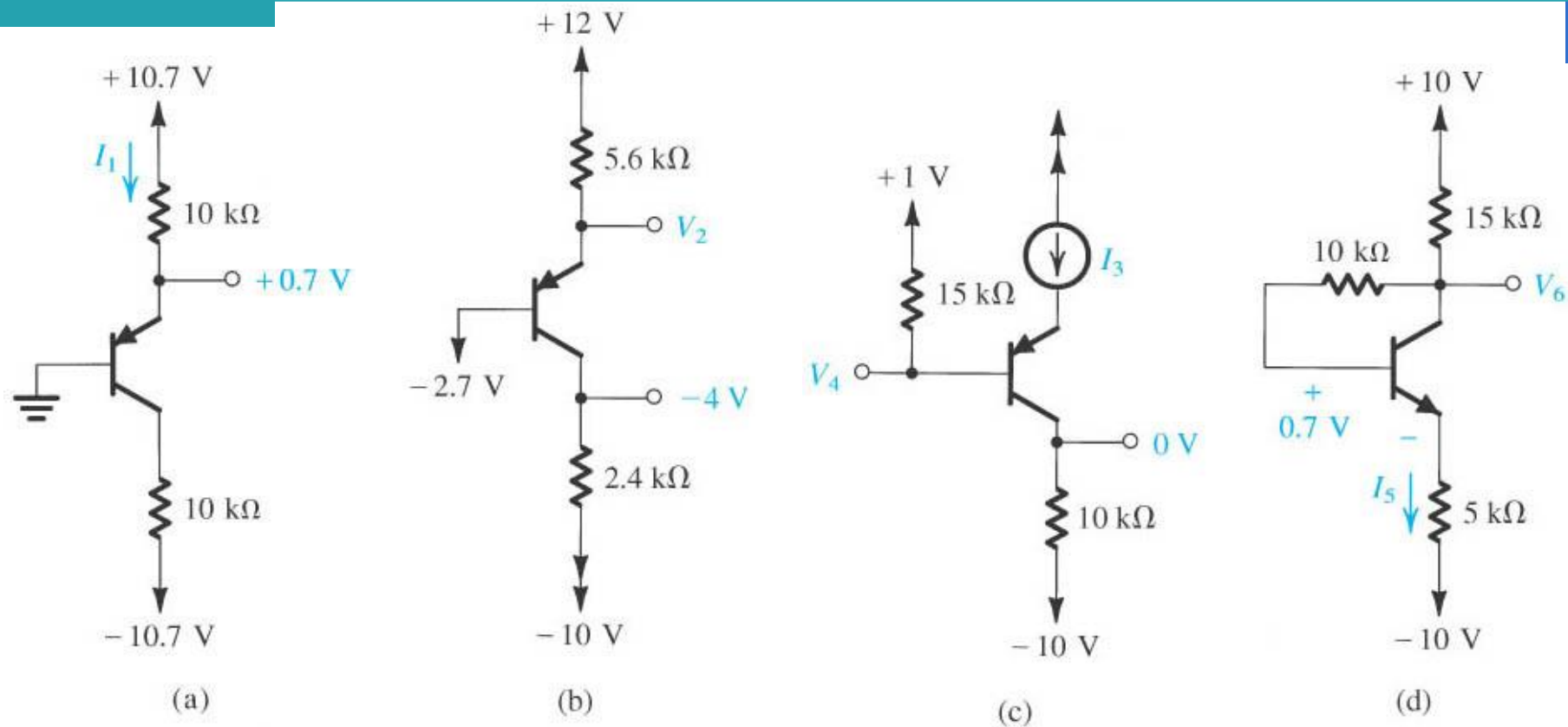


Figure P5.20

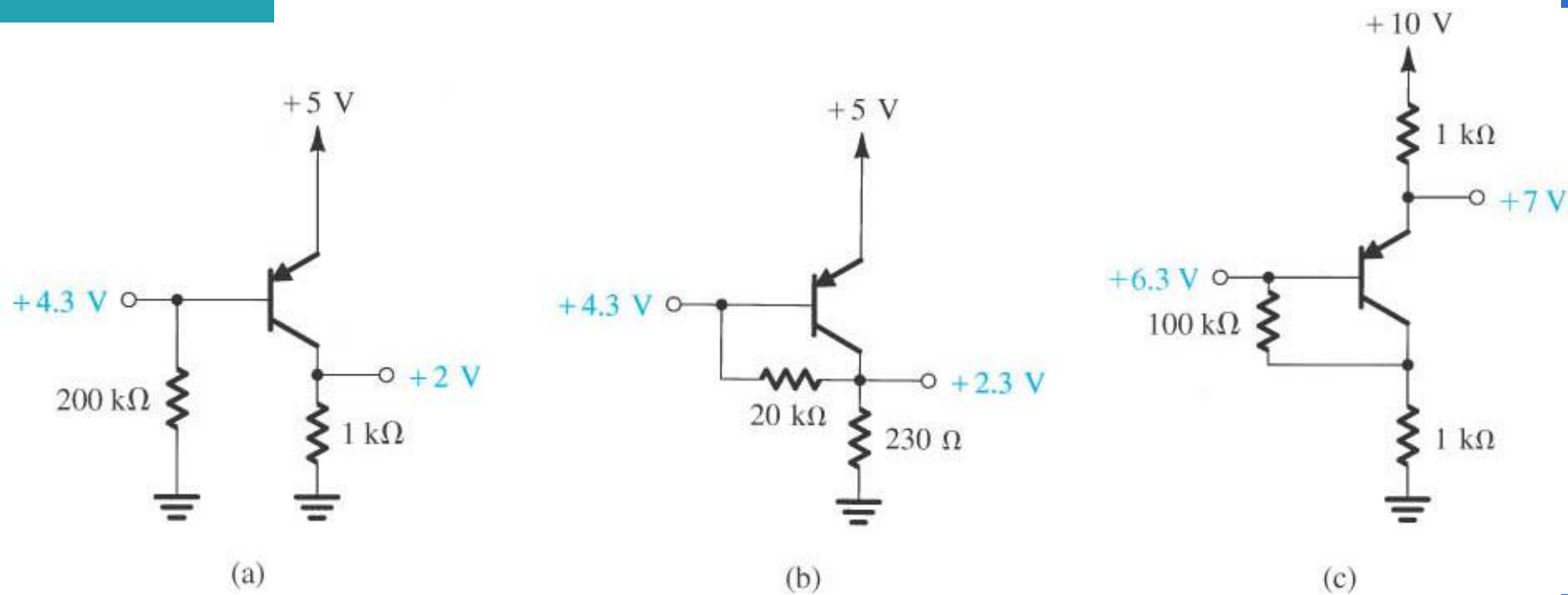


Figure P5.21

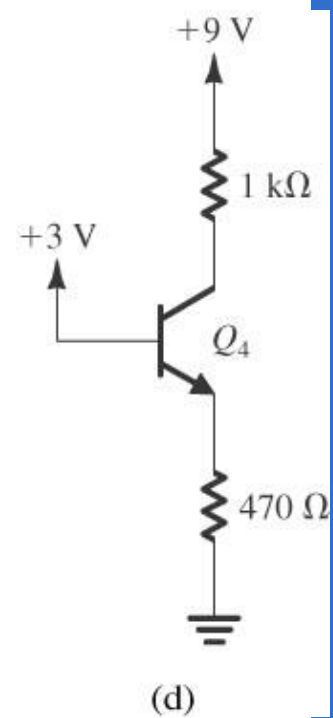
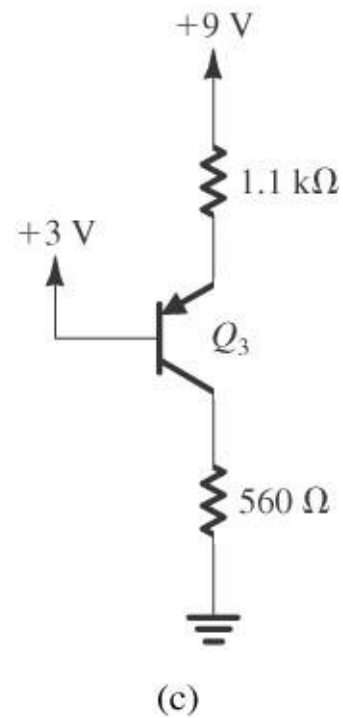
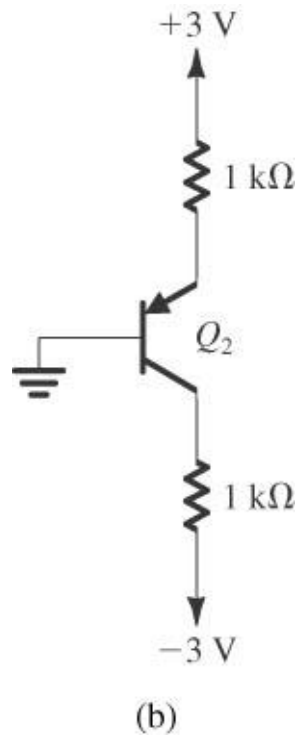
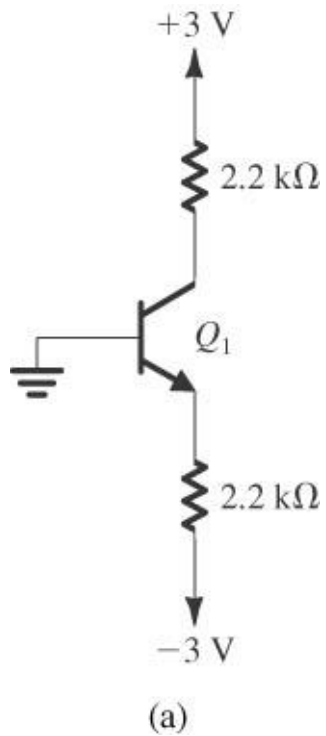


Figure P5.24

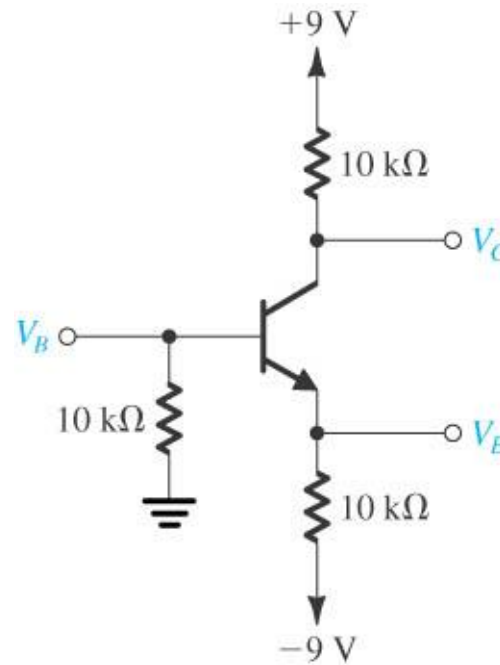


Figure P5.26

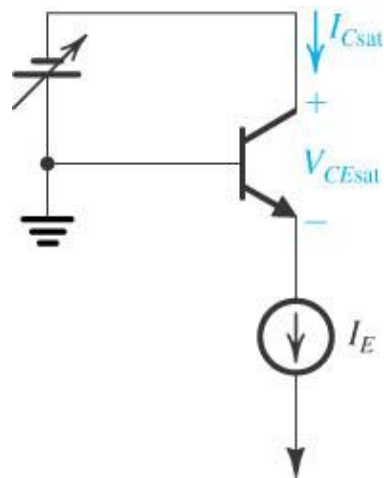


Figure P5.36

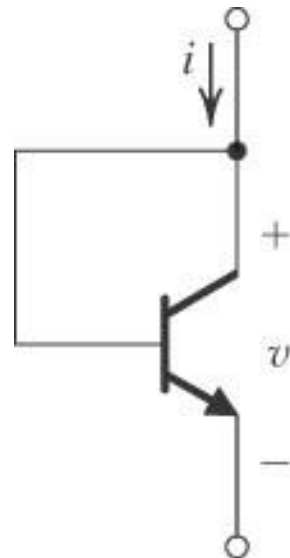


Figure P5.44

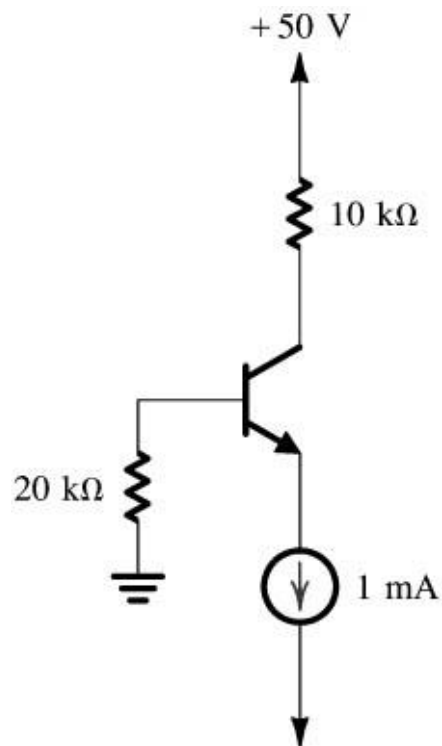


Figure P5.53

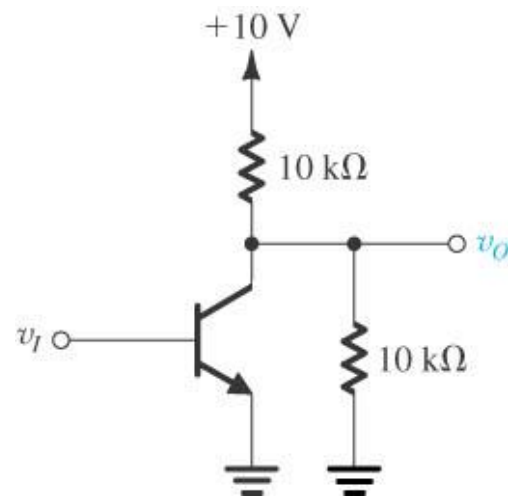


Figure P5.57

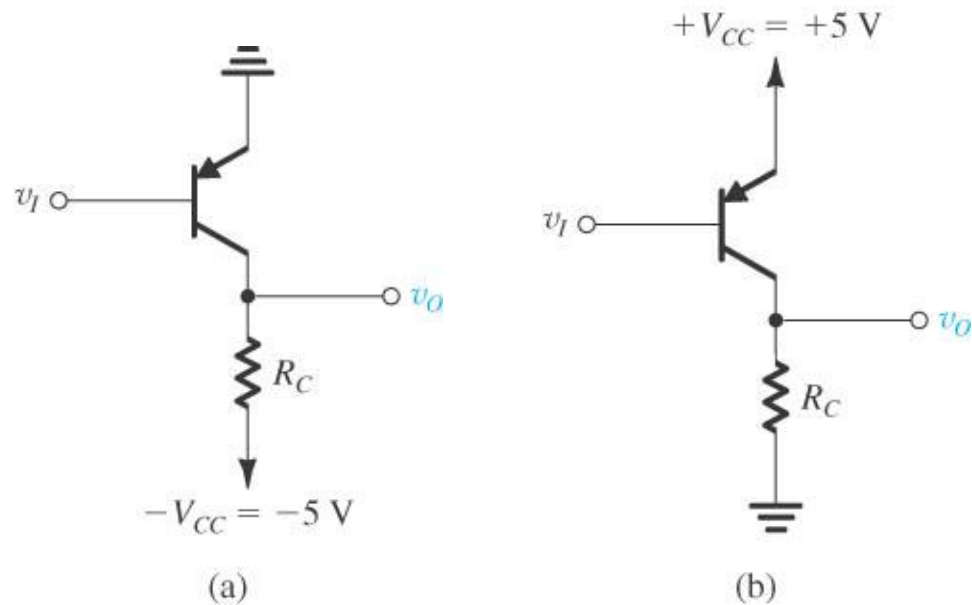


Figure P5.58

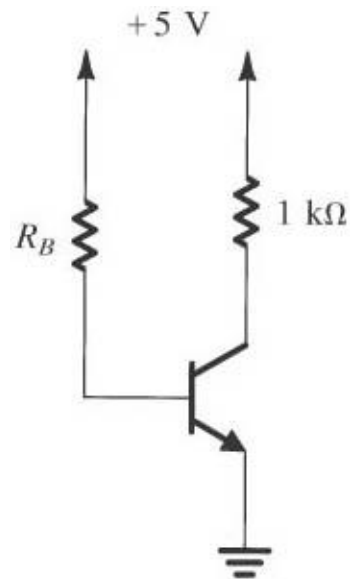


Figure P5.65

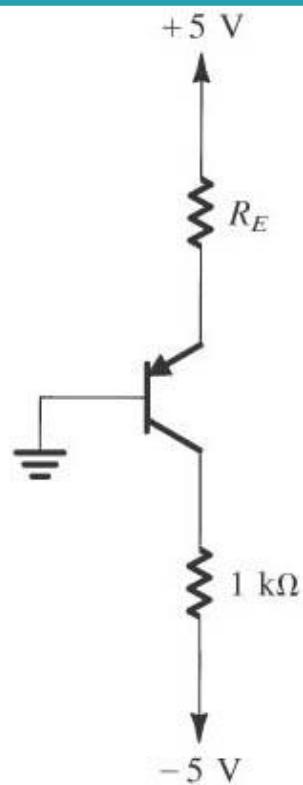


Figure P5.66

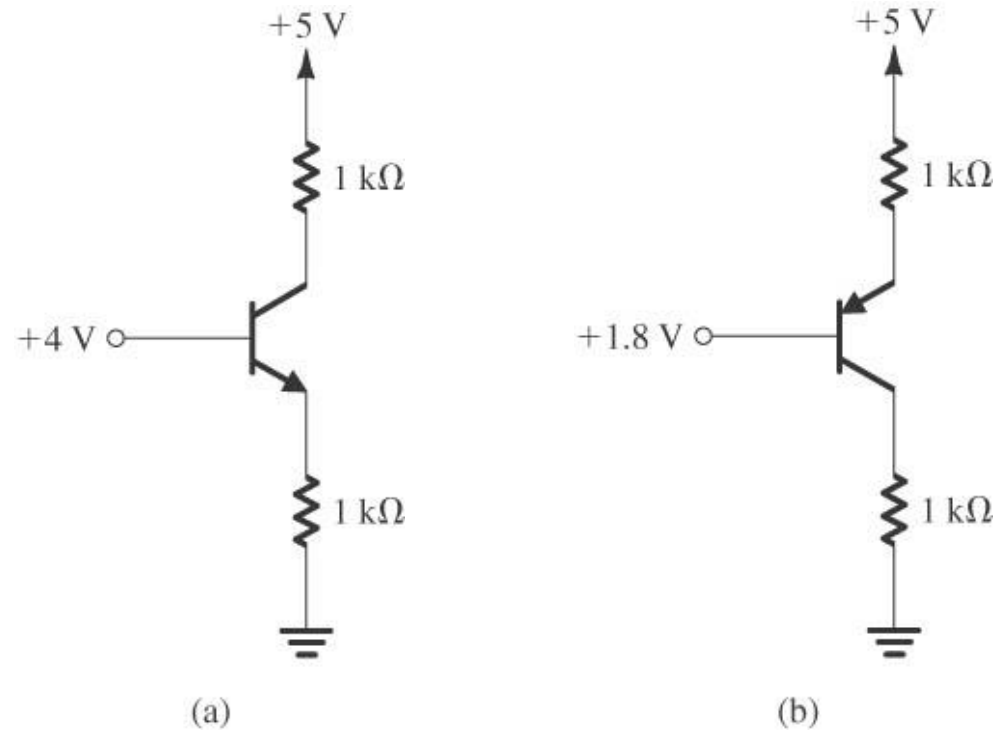


Figure P5.67

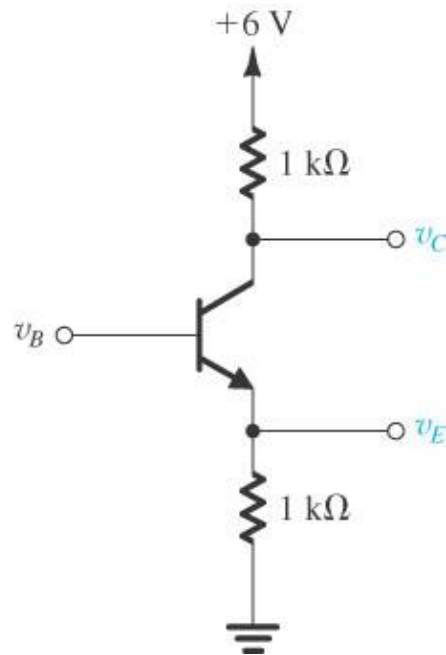


Figure P5.68

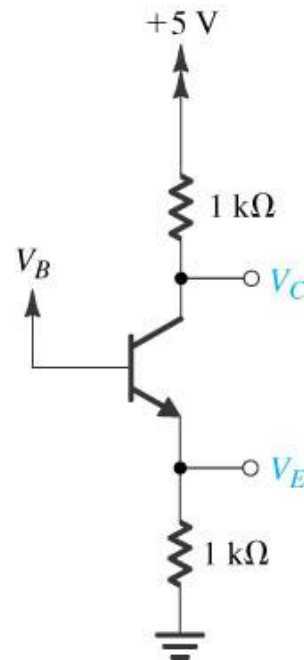


Figure P5.69

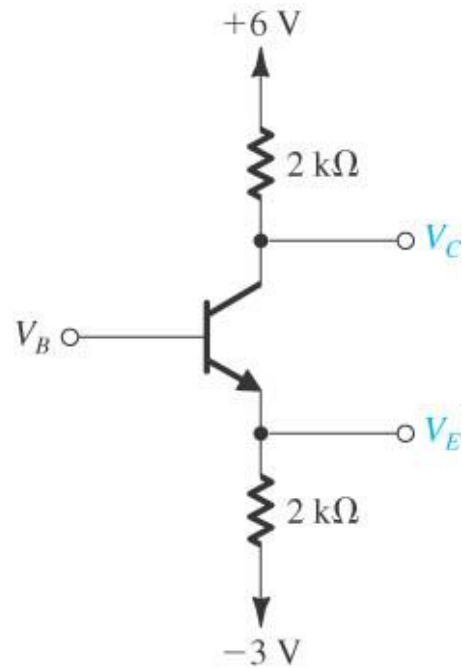


Figure P5.71

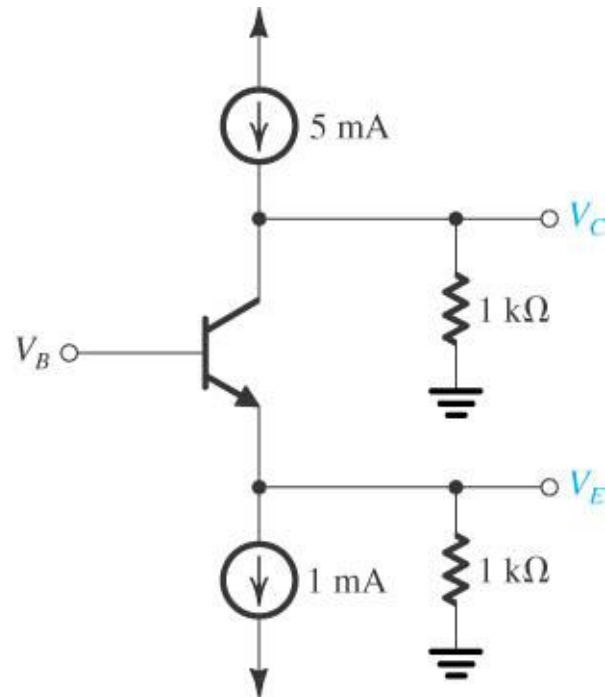


Figure P5.72

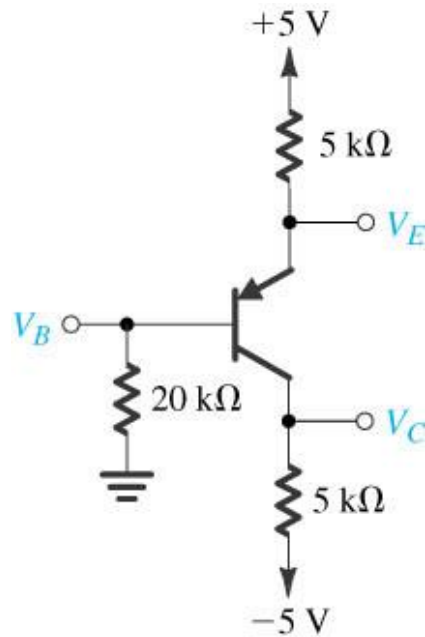


Figure P5.74

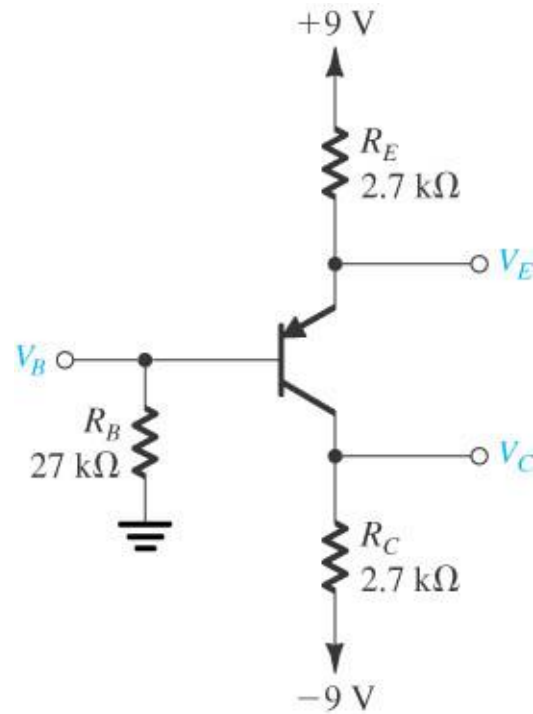


Figure P5.76

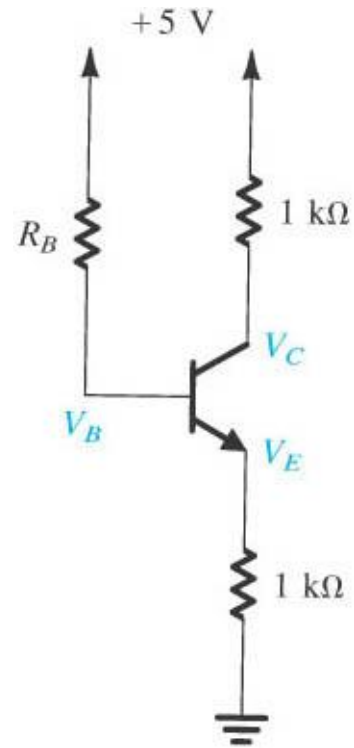


Figure P5.78

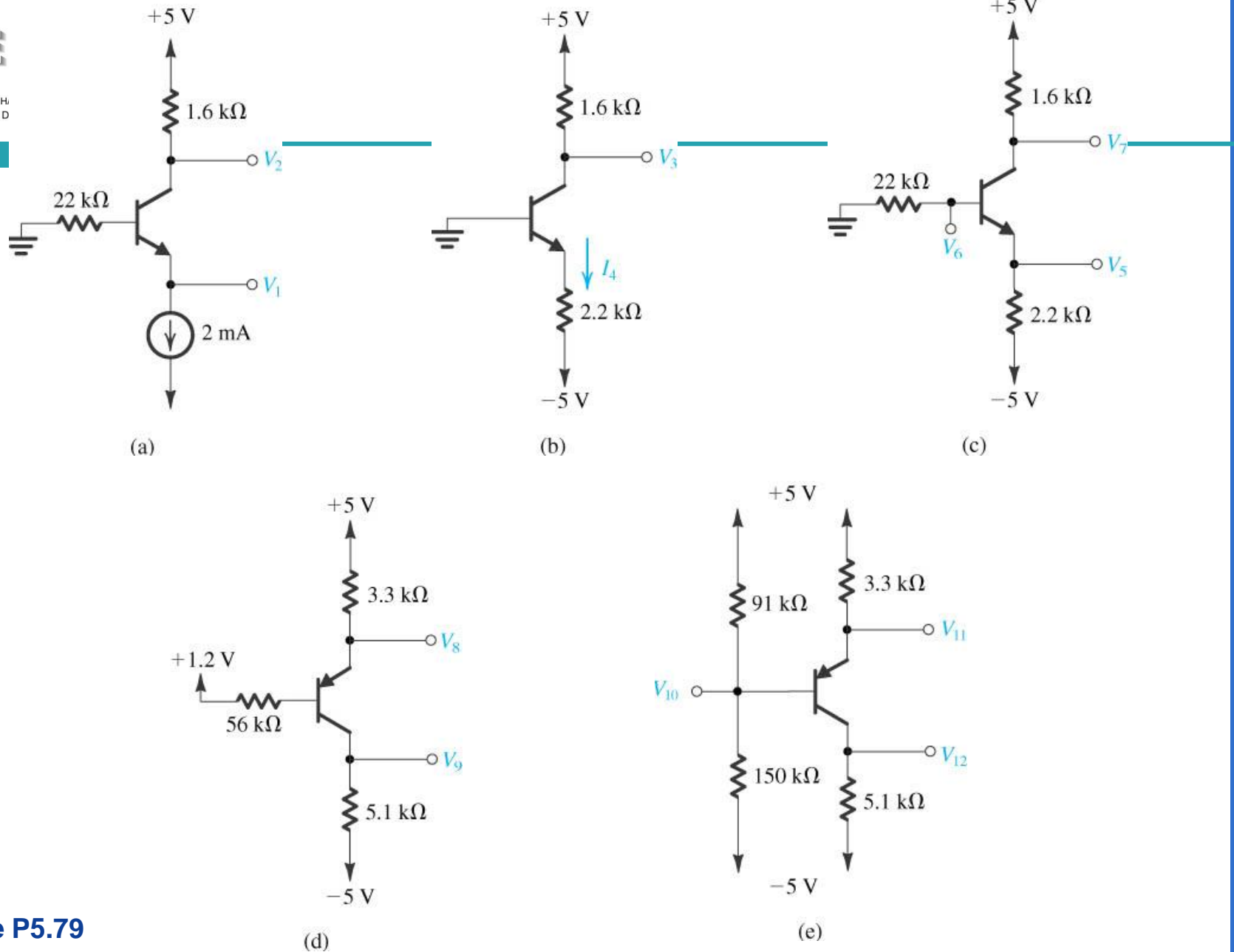


Figure P5.79

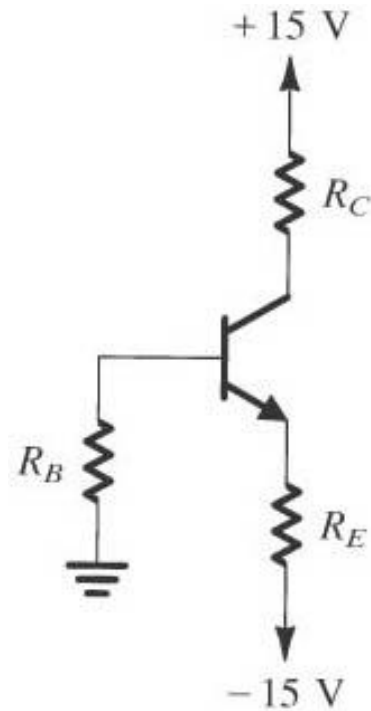


Figure P5.81

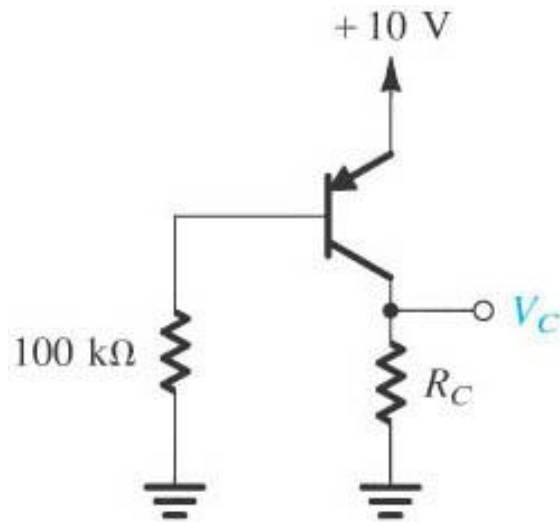


Figure P5.82

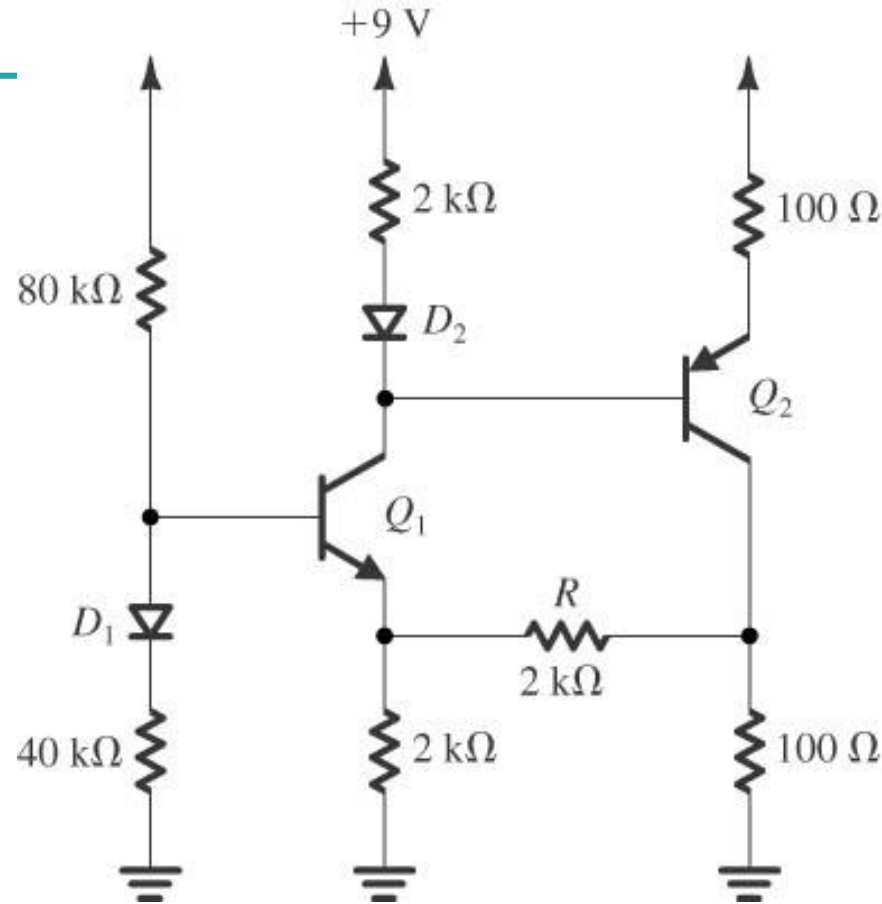


Figure P5.83

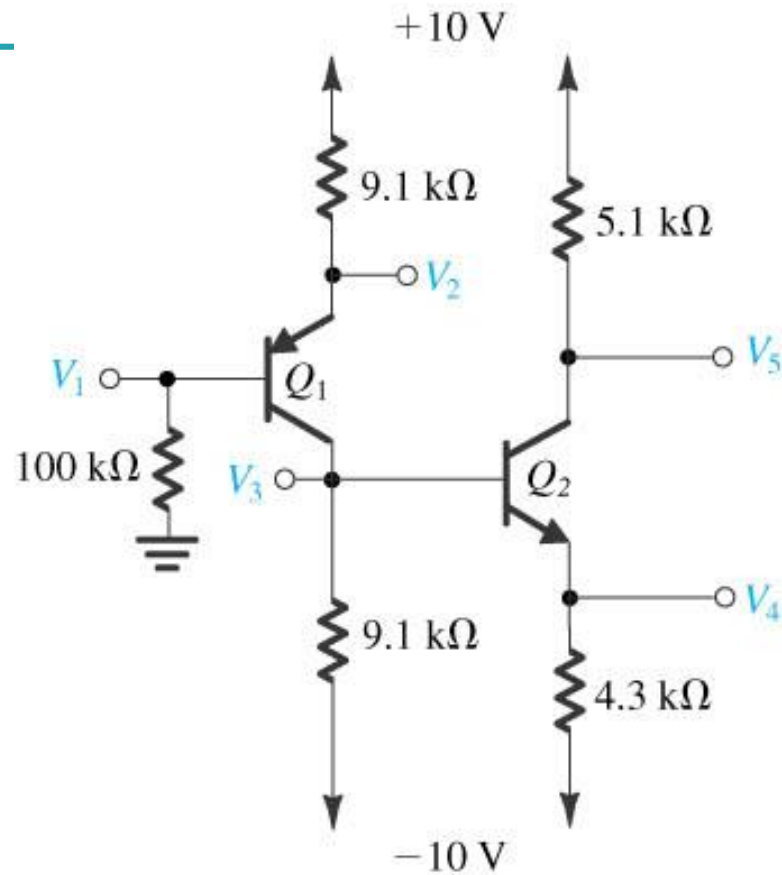


Figure P5.84

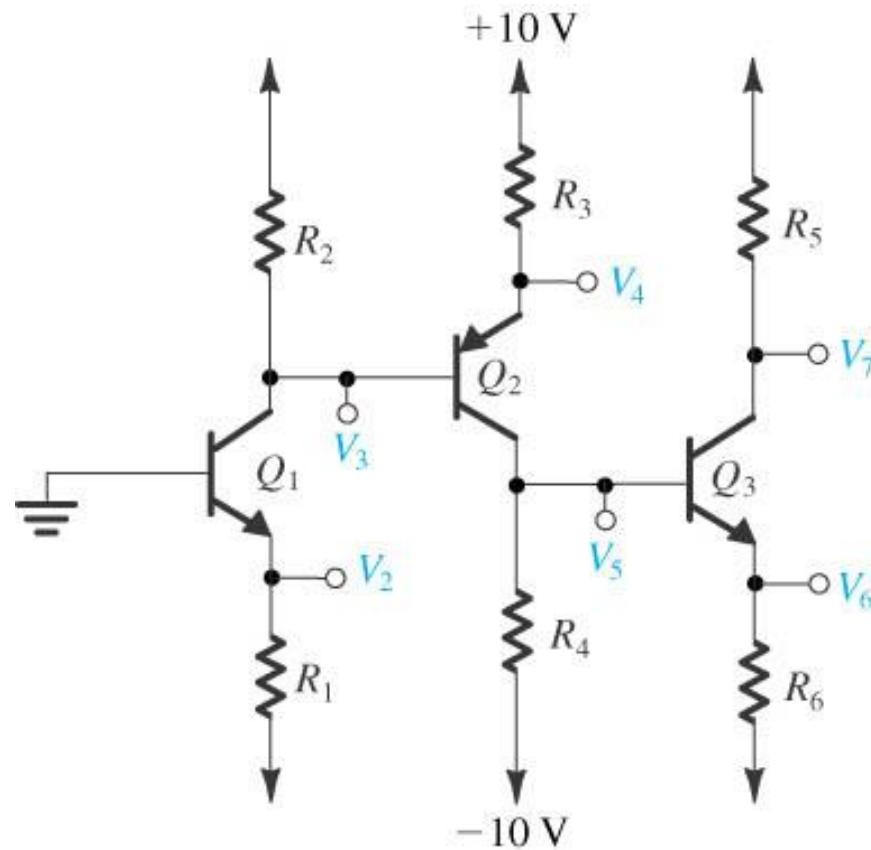


Figure P5.85

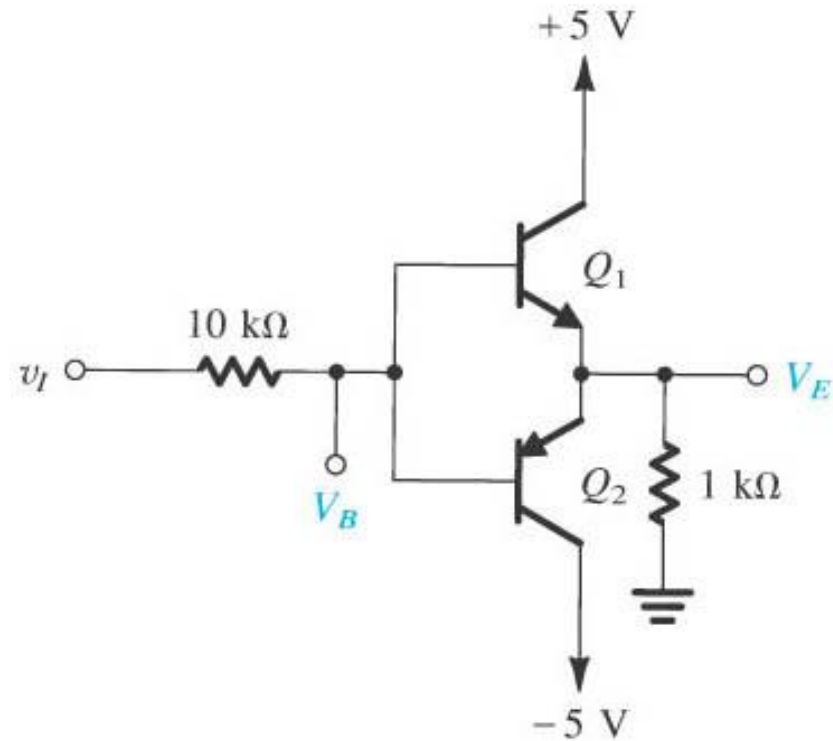


Figure P5.86

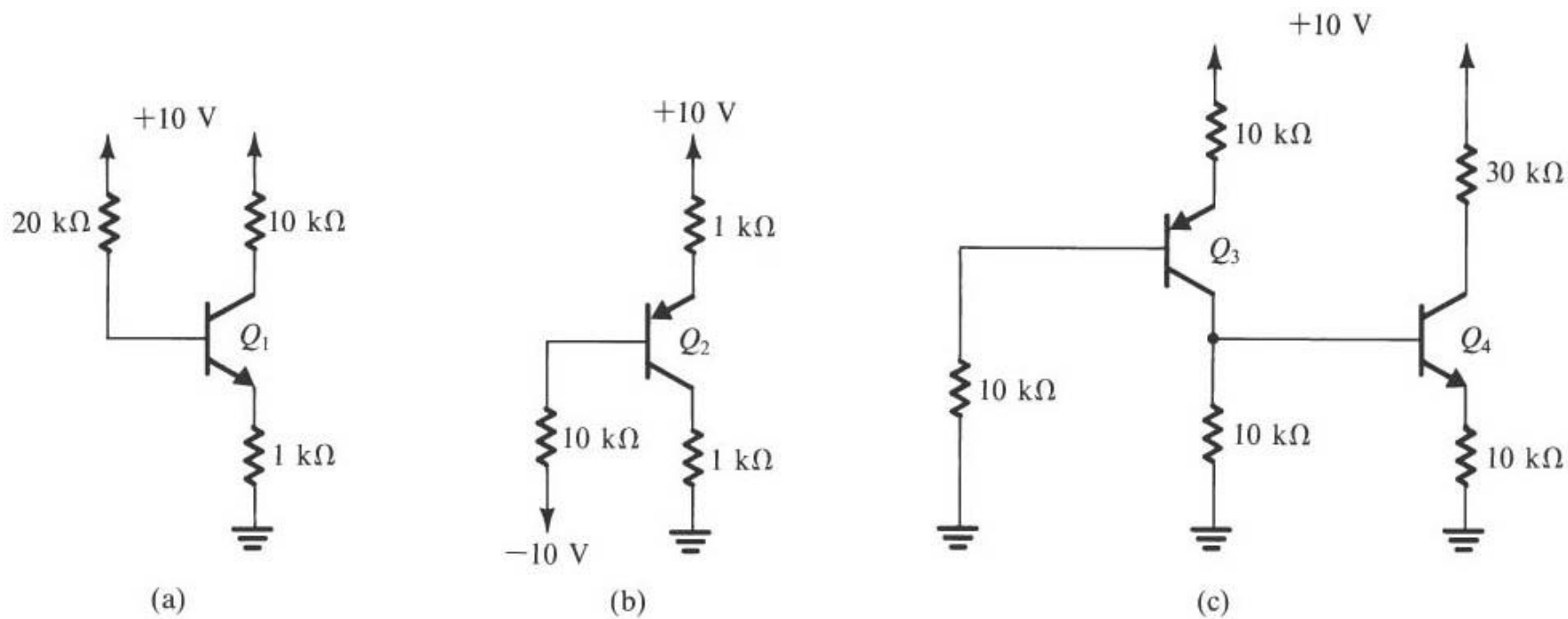


Figure P5.87

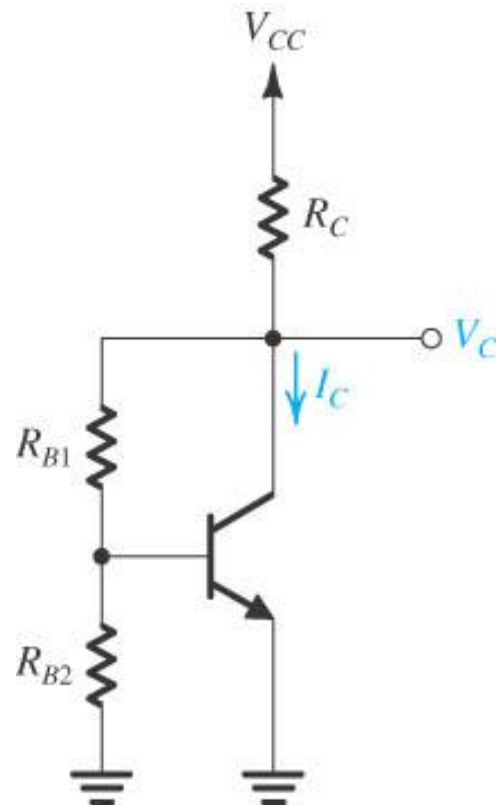


Figure P5.96

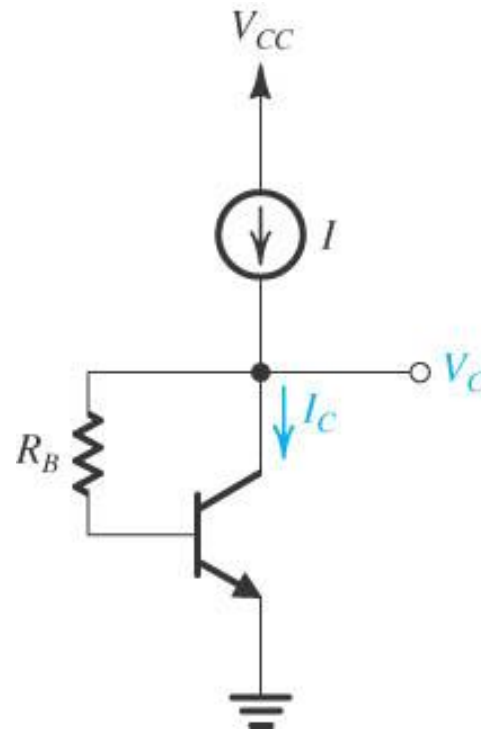


Figure P5.97

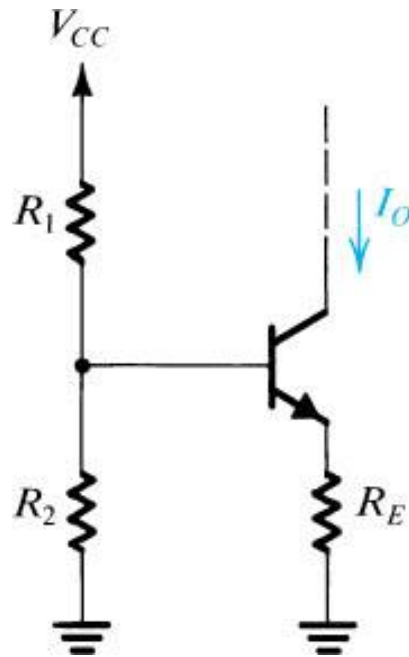


Figure P5.98

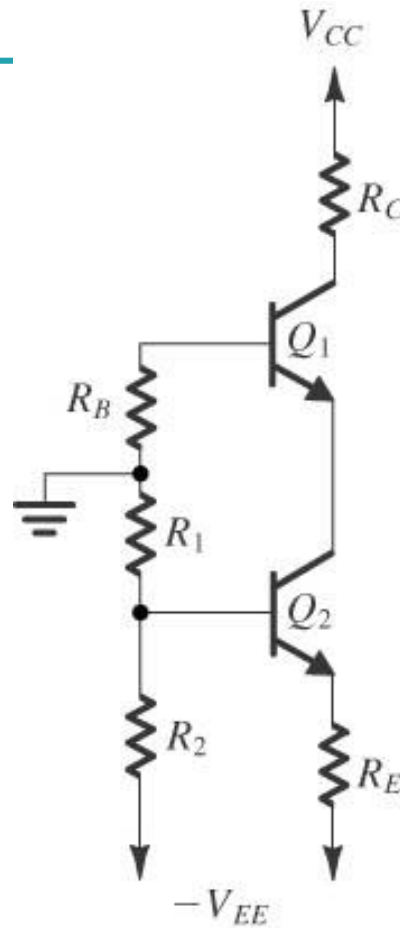


Figure P5.99

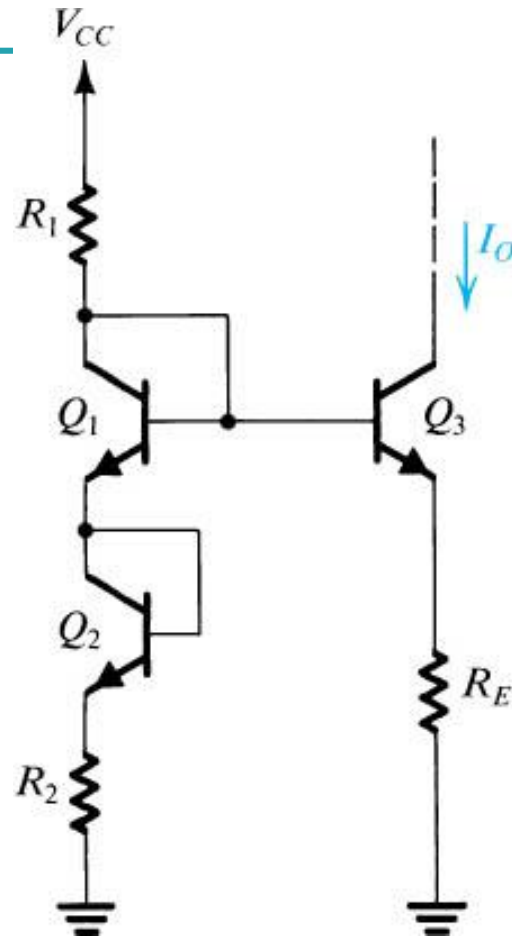


Figure P5.100

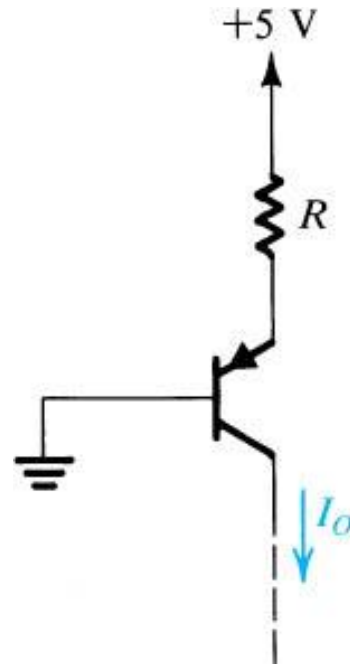


Figure P5.101

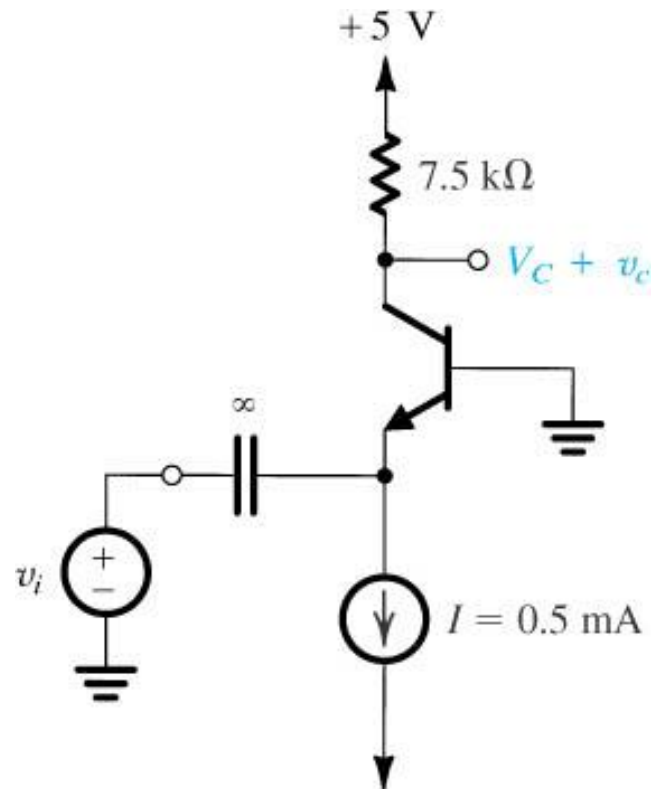


Figure P5.112

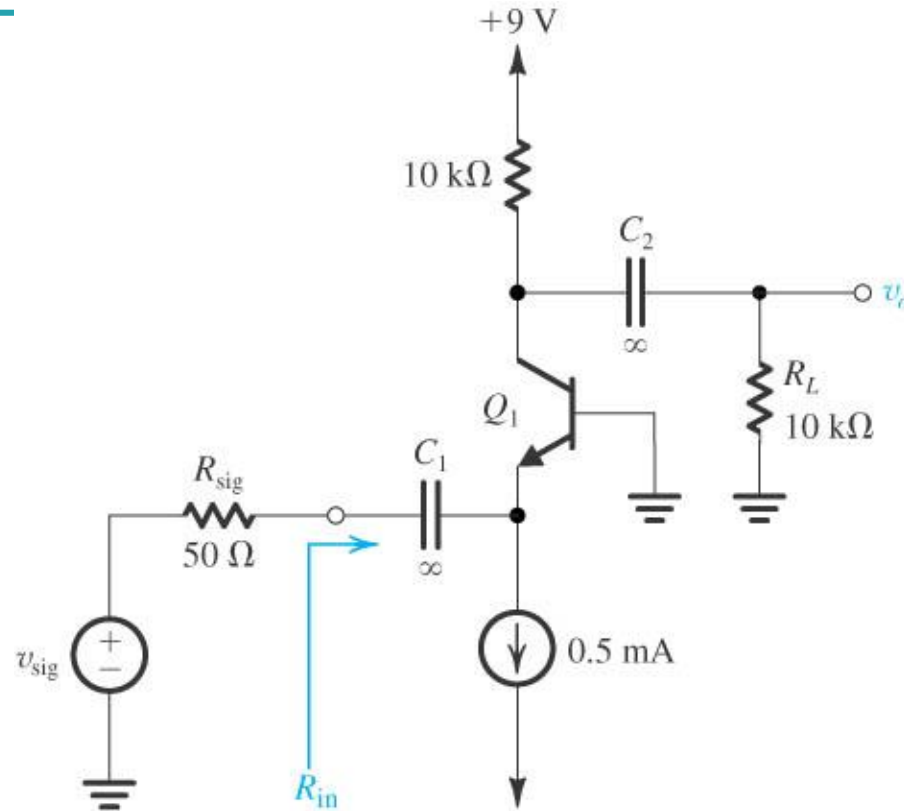


Figure P5.115

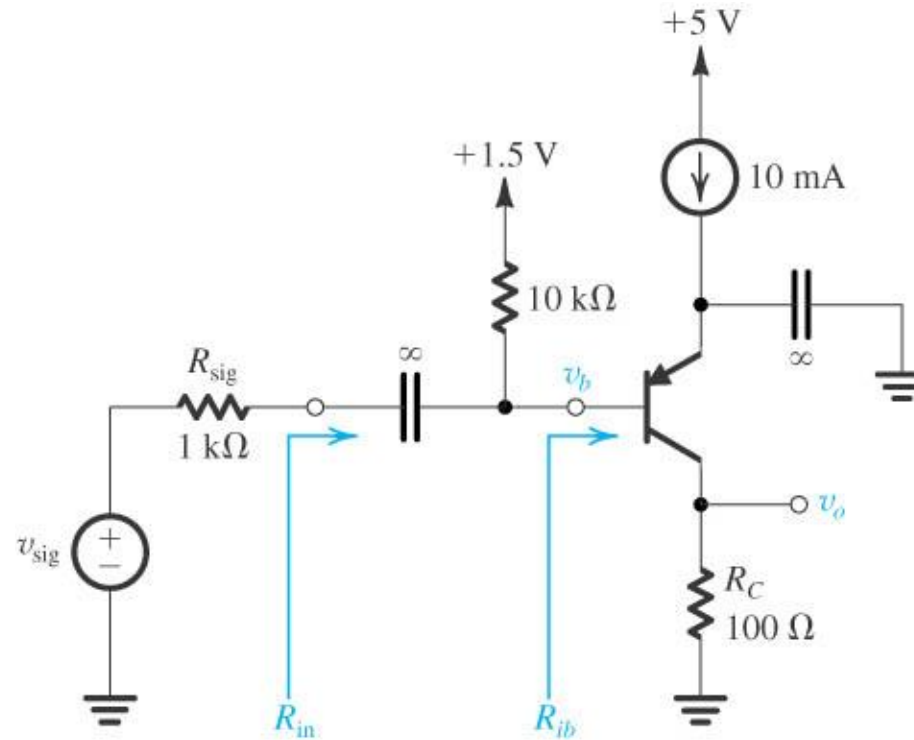


Figure P5.116

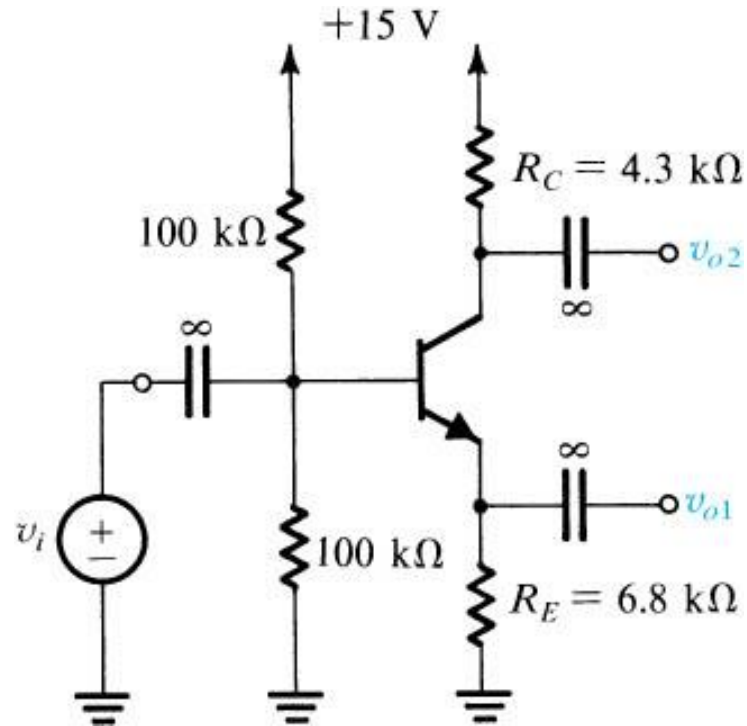


Figure P5.124

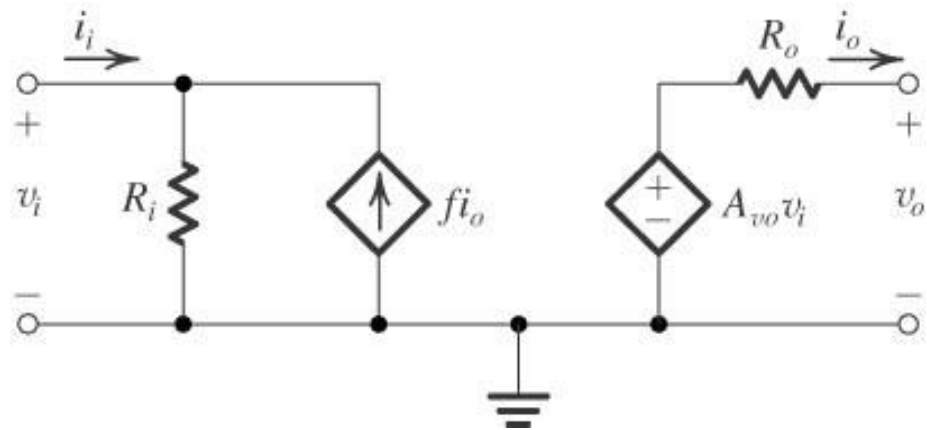


Figure P5.126

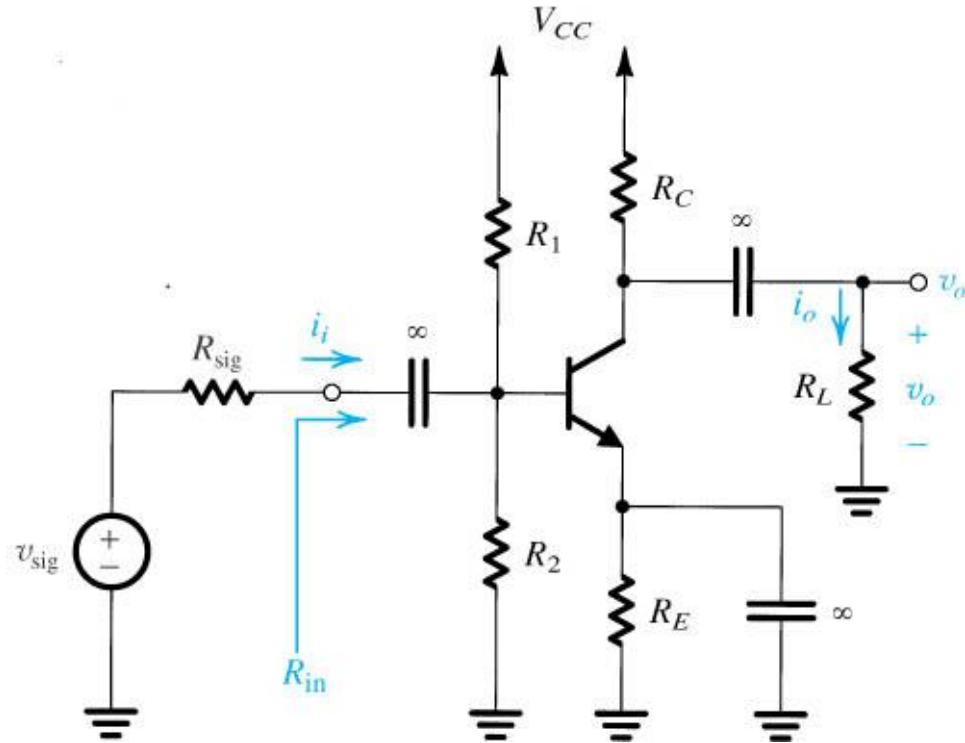


Figure P5.130

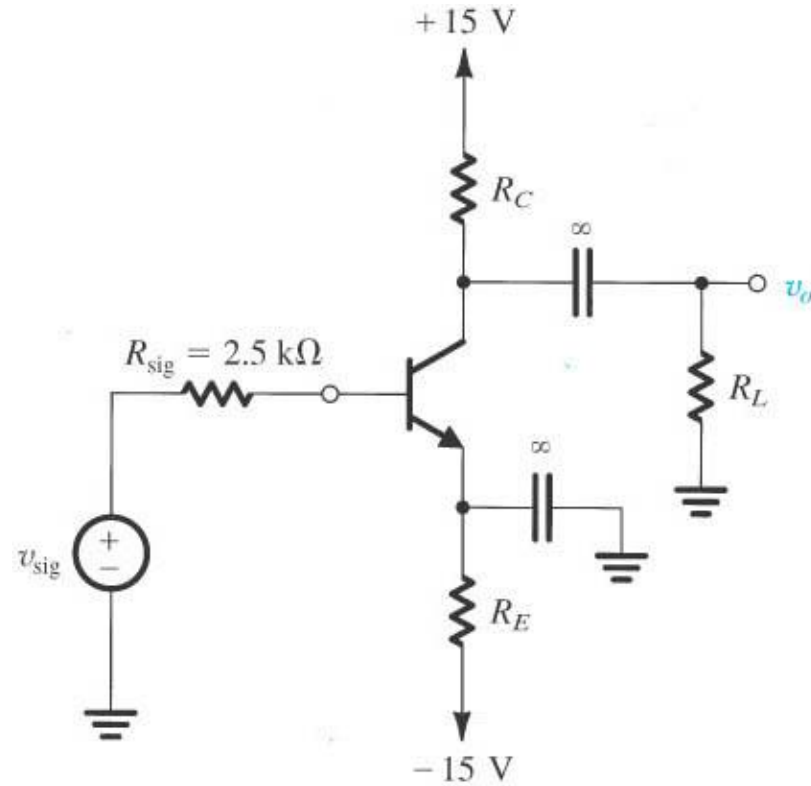


Figure P5.134

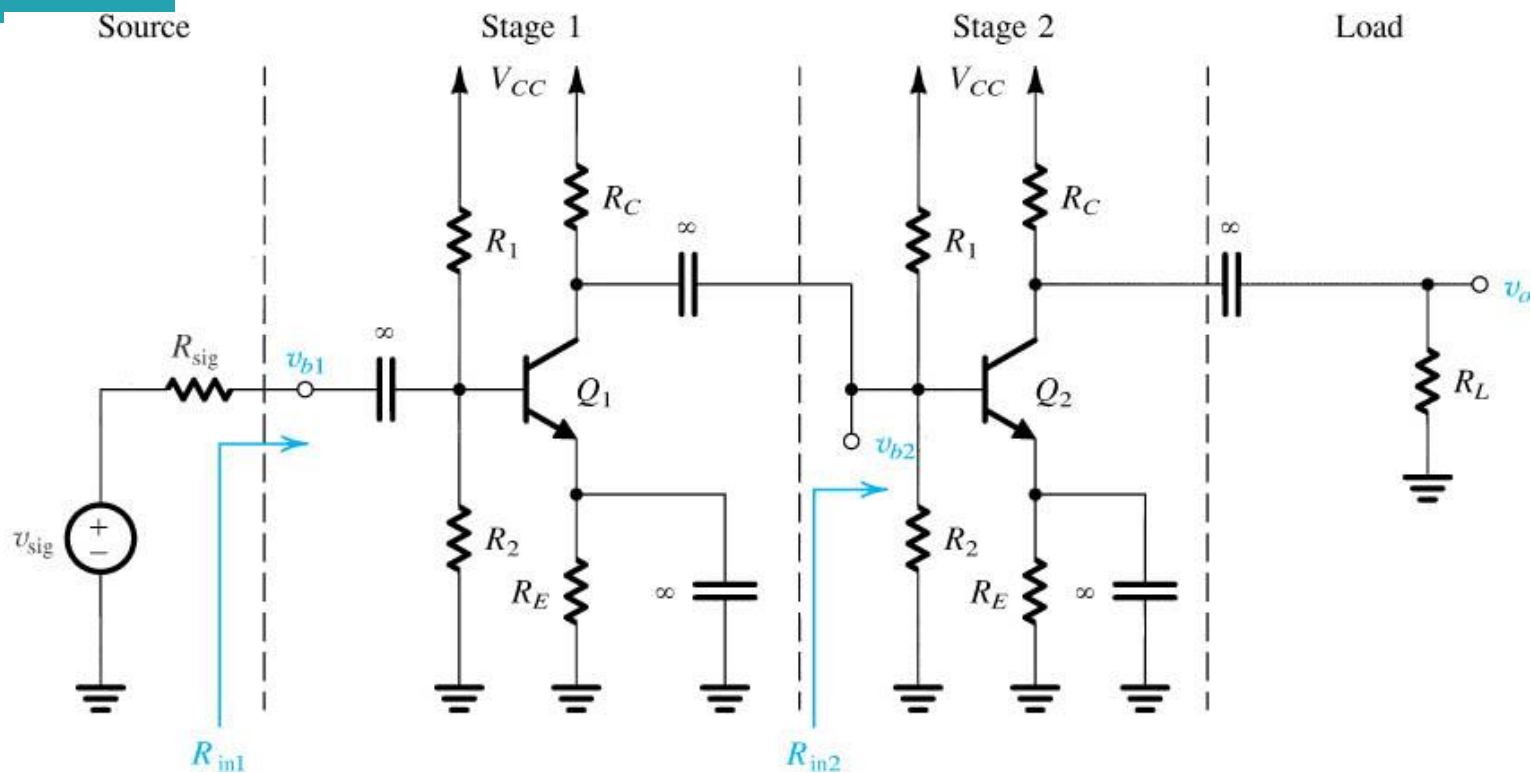


Figure P5.135

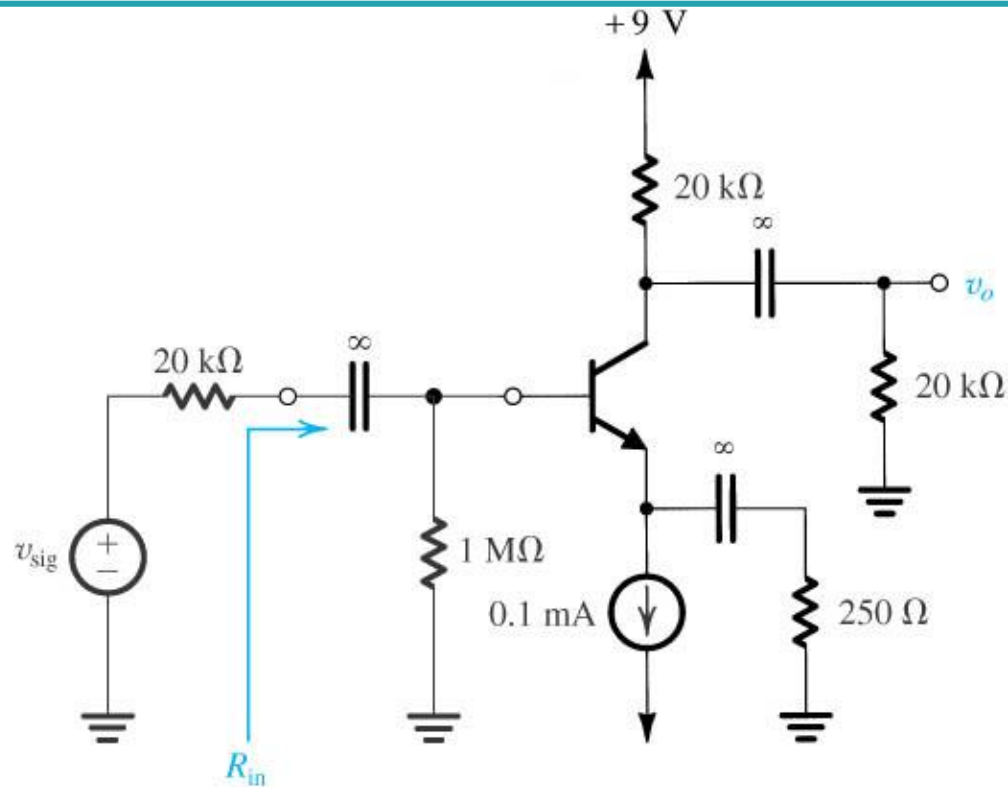


Figure P5.136

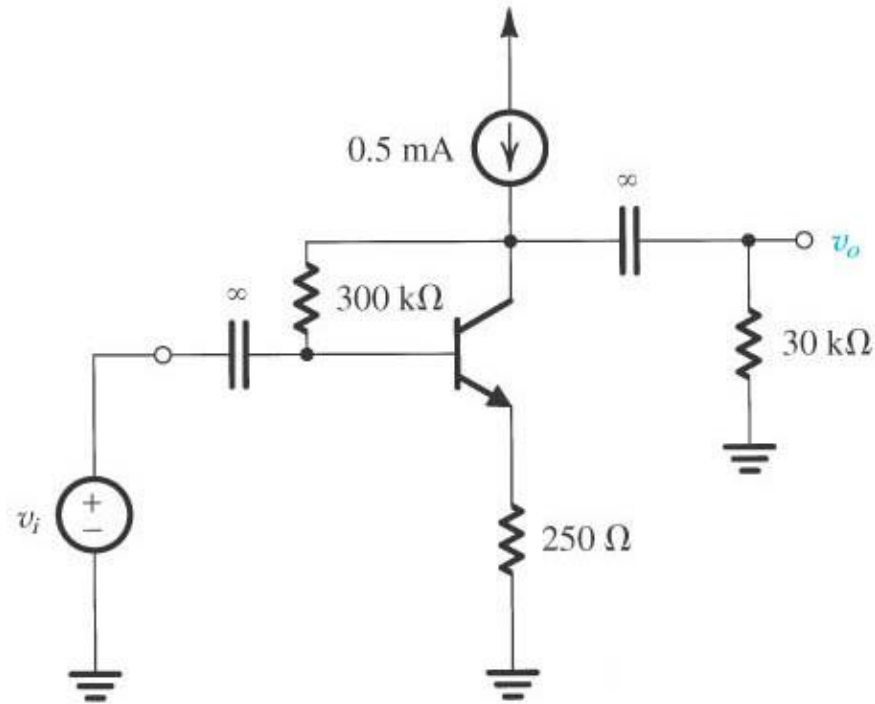


Figure P5.137

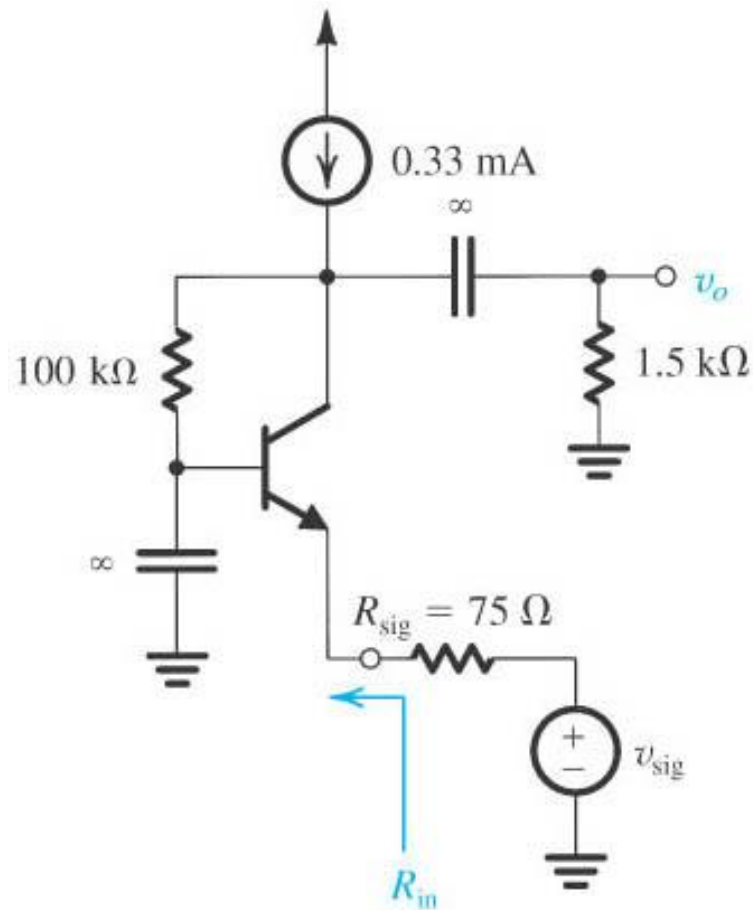


Figure P5.141

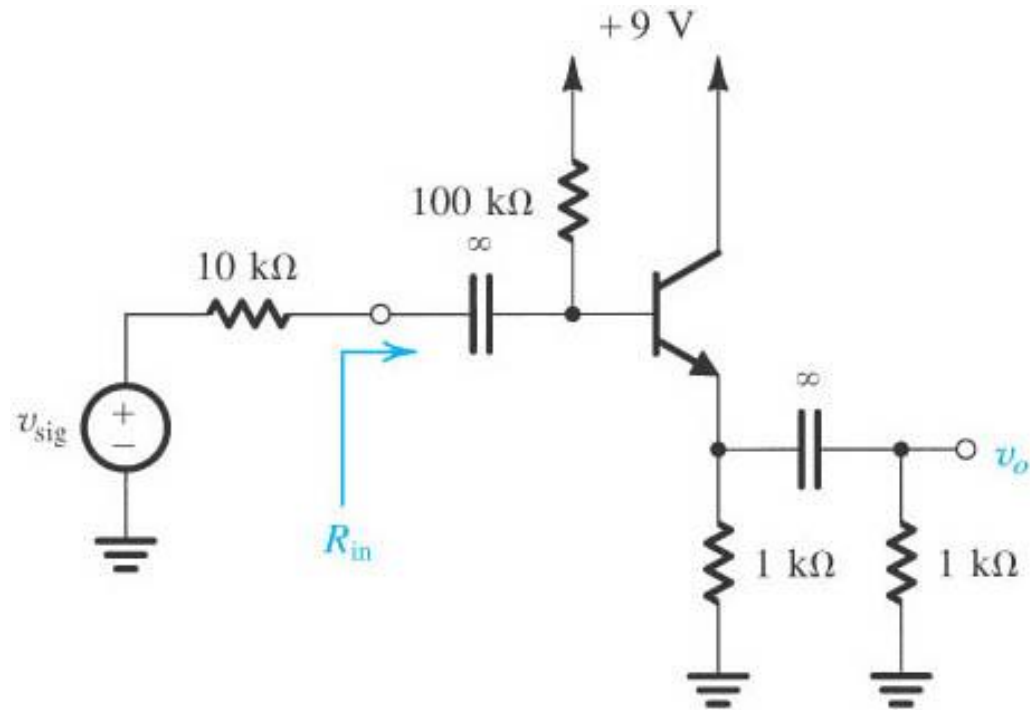


Figure P5.143

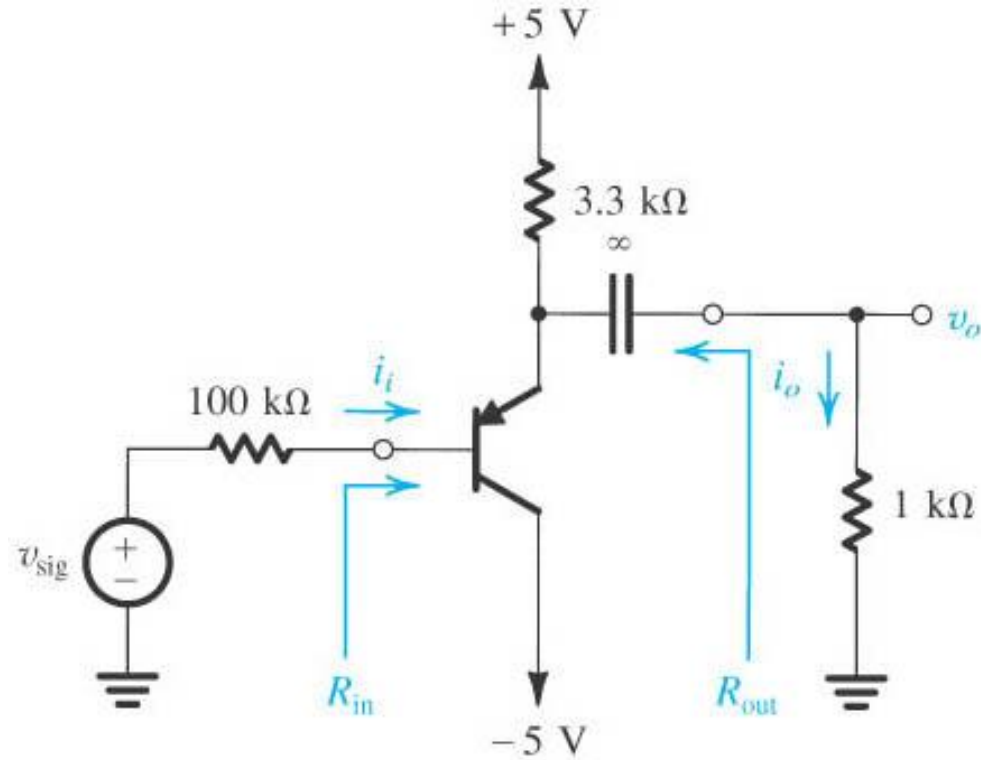


Figure P5.144

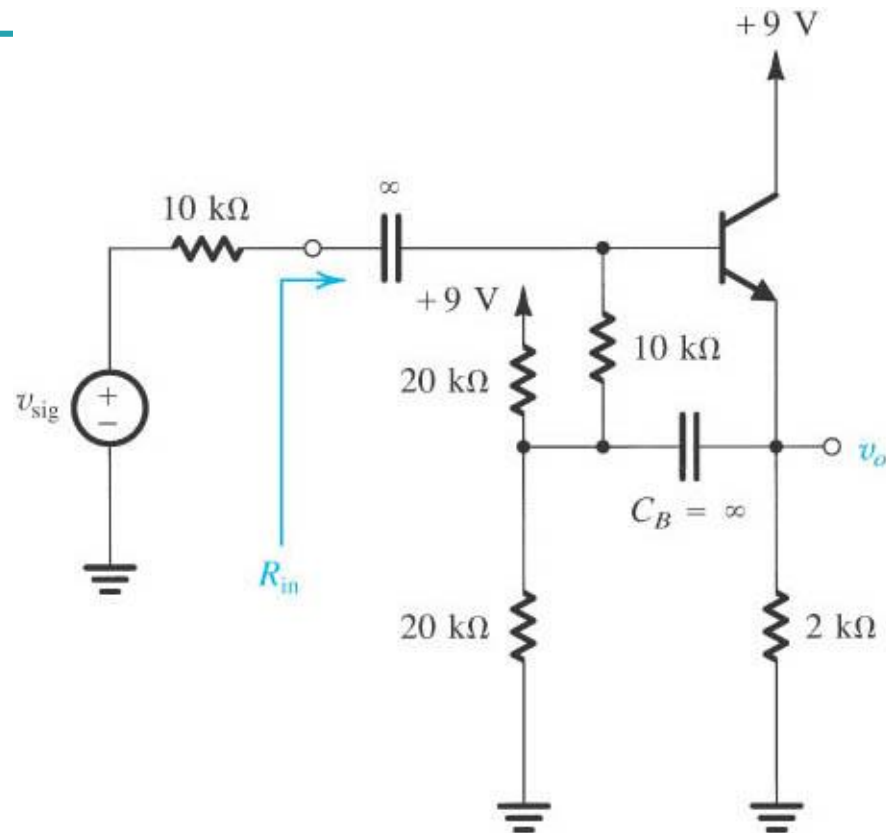


Figure P5.147

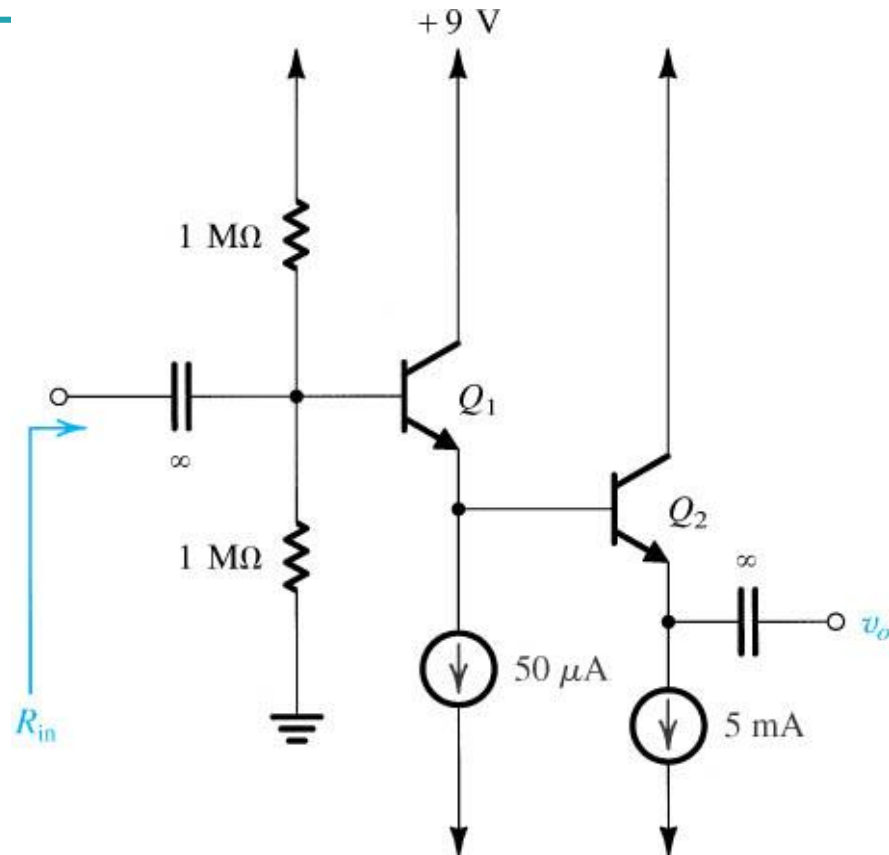


Figure P5.148

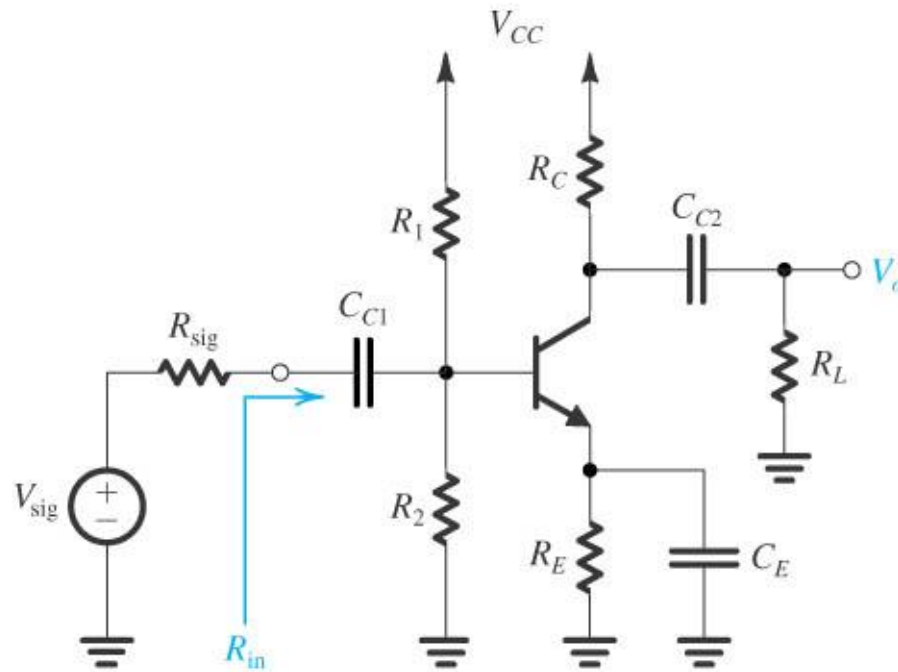


Figure P5.159

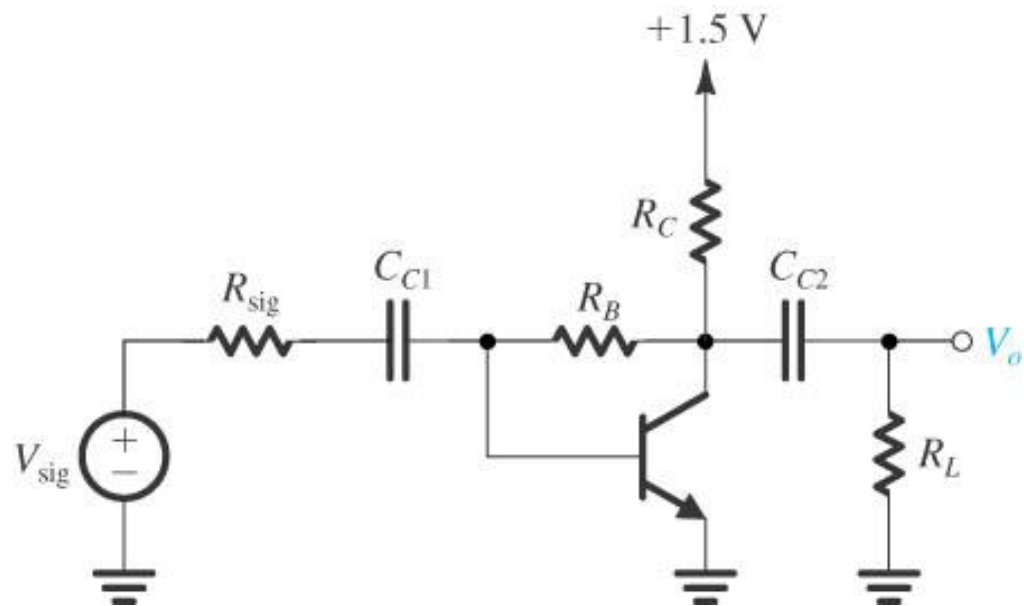


Figure P5.161

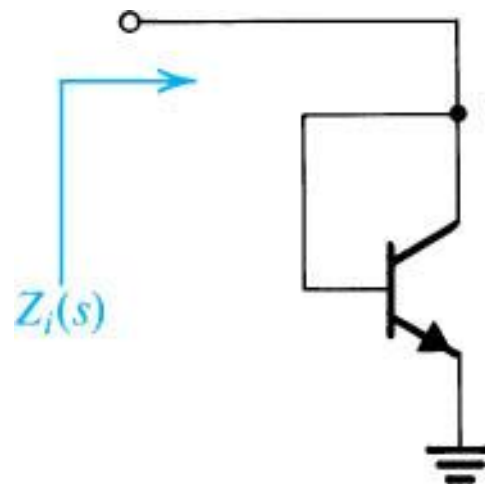


Figure P5.162

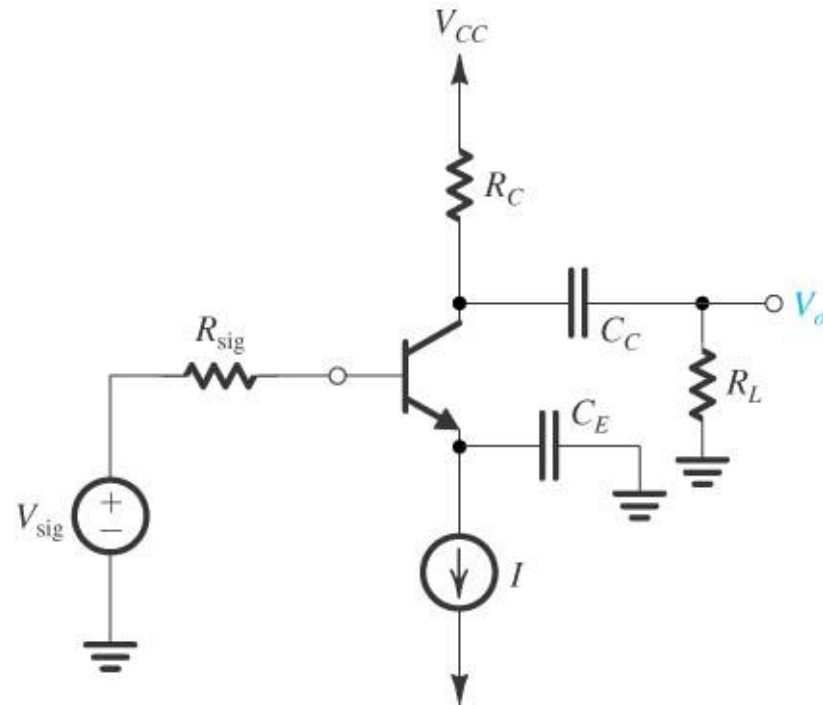


Figure P5.166

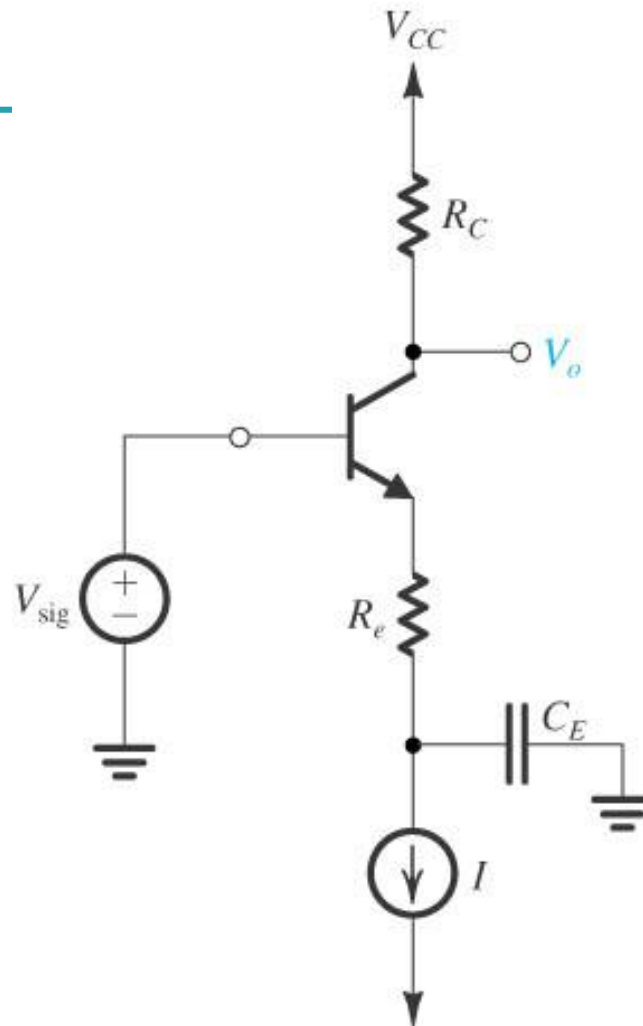


Figure P5.167

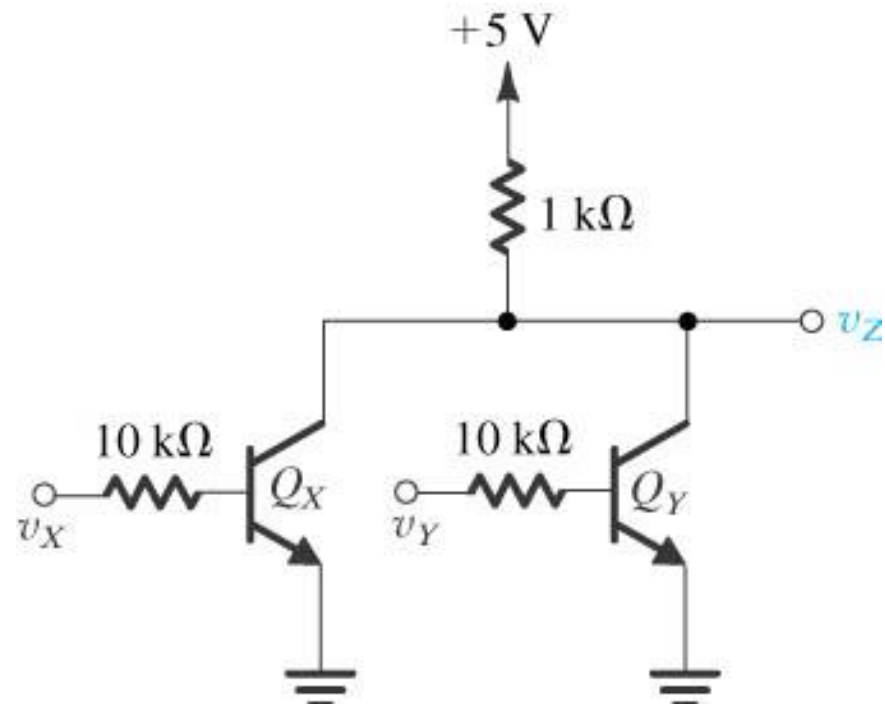


Figure P5.171