SEMICONDUCTOR DIODES AND TRANSISTORS

PROGRAMED INSTRUCTION

TEKTRONIX

MANUFACTURERS OF CATHODE-RAY OSCILLOSCOPES

VOLUME 5
CIRCUITS 2

TEKTRONIX PUBLICATION 062-0217-00

SEMICONDUCTOR DIODES AND TRANSISTORS

VOLUME 5

CIRCUITS 2

TEKTRONIX, INC.
P. O. BOX 500
BEAVERTON, OREGON

STOP. PLEASE READ.

In Volume 5 we will discuss high frequency and temperature considerations in linear transistor circuits. We also include a review of the characteristics of transistor switching circuits.

The prerequisites for taking this volume are Volumes 1-4 of Semiconductor Diodes and Transistors, or the equivalent.

The objectives for each set on the following page can also be used as a table of contents. That is, objective 1 will indicate the material in set 1, etc.

OBJECTIVES

1. Recall the component parts of a high frequency equivalent circuit.

2. Recall the two primary limitations of high frequency performance of a transistor common emitter circuit.

3. Recall the methods of minimizing the high frequency limitations on a common emitter circuit.

4. Recall the high frequency limitations on a common emitter circuit and methods of minimizing these limitations.

5. Recall the high frequency advantage of a cascoded amplifier stage and be able to determine the approximate gain.

6. Recall the high frequency limitations on a common collector circuit and methods of minimizing these limitations.

7. Recall the characteristics of current mode and saturated mode switching.

8. Recall the effects of temperature change in the base emitter junction of a transistor.

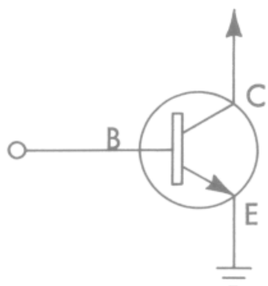
9. Recall the method of stabilizing a transistor circuit against changes in ambient temperature.

10. Recall the output distortion from a push-pull circuit due to changes in power dissipated by the transistors.

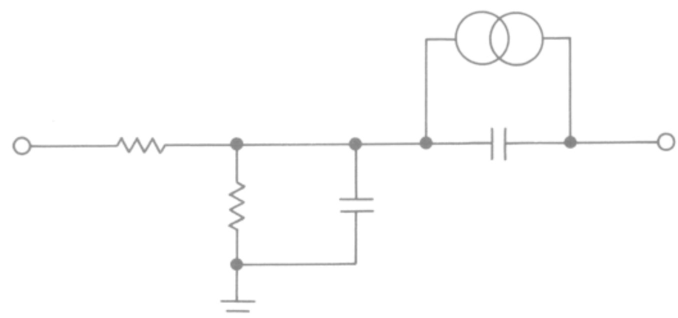
11. Recall the point at which a transistor operates to be thermally balanced.

12. Recall the method of adding components to a push-pull circuit to obtain thermal balance.

1.0 Label the component parts in the transistor high frequency equivalent circuit below.

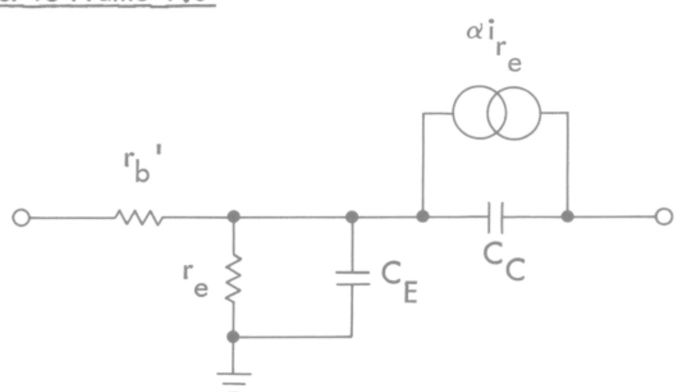


Transistor



High Frequency Equivalent

Answer to Frame 1.0



r_b' - base resistance

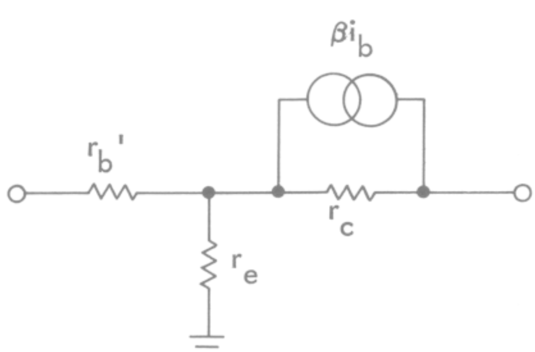
αi_{r_e} - Alpha times the current through r_e

C_c - Collector Base Junction Capacitance

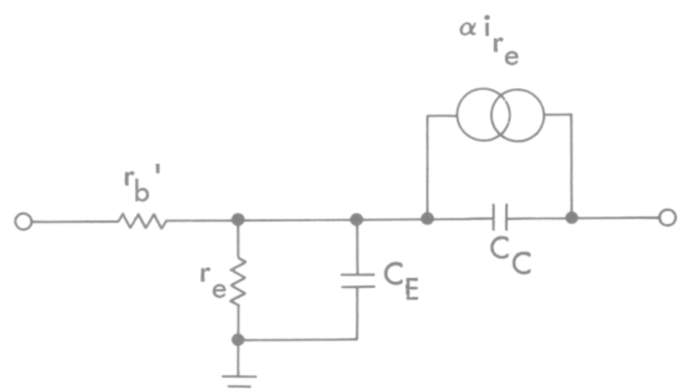
C_E - Emitter Base Junction Capacitance

r_e - AC emitter resistance $(\frac{26}{I_E})$

We have adapted the transistor equivalent circuit used in Volume 4 to a high frequency equivalent circuit. (Both are common emitter circuits.)



Low Frequency Equivalent



High Frequency Equivalent

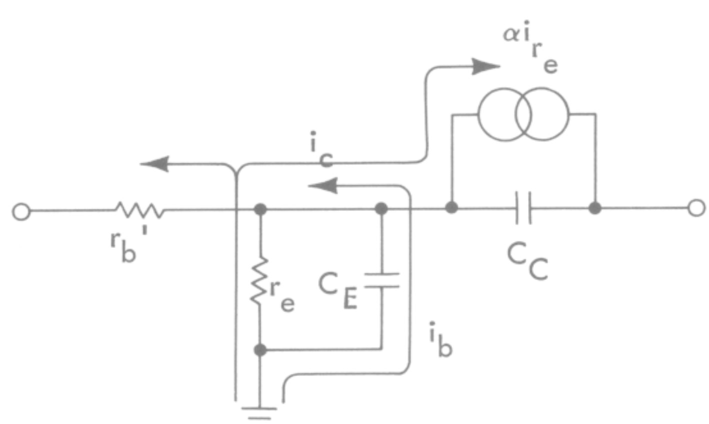
The transistor high frequency equivalent circuit has three changes from the low frequency equivalent circuit.

The changes are:

1. Add C_E; C_E represents the capacitance across the emitter base junction.

2. Add C_C and omit r_c; C_C represents the capacitance across the collector base junction. The reverse biased collector base resistance (r_c) has been omitted because X_{c_c} at high frequencies is much less than r_c.

3. αi_{r_e}, the current generator amplitude has been changed from βi_b. In the low frequency equivalent circuit we assumed that all the emitter current was flowing through r_e. Under these circumstances we could consider the amplitude of the collector current generator to be βi_b or αi_e (βi_b and αi_e are equal). However, no part of the emitter current flowing through C_E, the emitter capacitance, is conducted through the collector current generator. Current through C_E constitutes moving charges in and out of the base. No electrons actually cross the emitter base junction. Therefore we must stipulate that only α times the emitter current through r_e will be conducted in the collector current generator. As the signal frequency is increased, a larger percentage of i_e will flow through C_E. Therefore as signal frequency is increased, for a constant emitter amplitude, the collector current amplitude will decrease.



1.1 Across each junction in a transistor, there is _______________ which must be considered at high frequencies.

---

capacitance

1.2 There is capacitance across the ______________ base junction and the _____________ base junction.

---

emitter
collector

1.3 Because it is forward biased, the depletion region is narrower and the capacitance is larger across the ________________ base junction.

---

emitter

1.4 At higher frequencies the capacitive reactance of C_C becomes low enough that we may ignore the resistance of ____________________.

---

r_c (collector resistance)

1.5 The portion of the base current that flows through the emitter capacitance C_E, ____________ (is/is not) multiplied by the current generator.

---

is not

1.6 The current generator, then, will multiply only the portion of the base current that flows through ________________________.

---

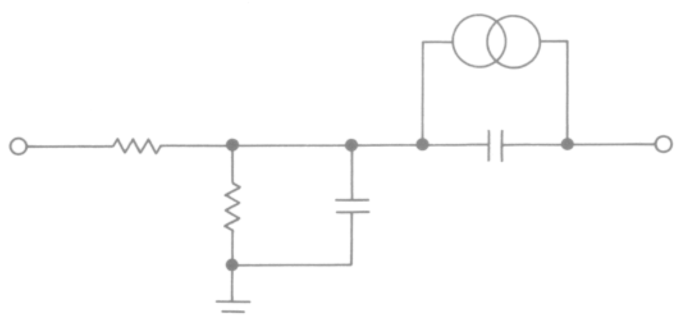
r_e (emitter resistance)

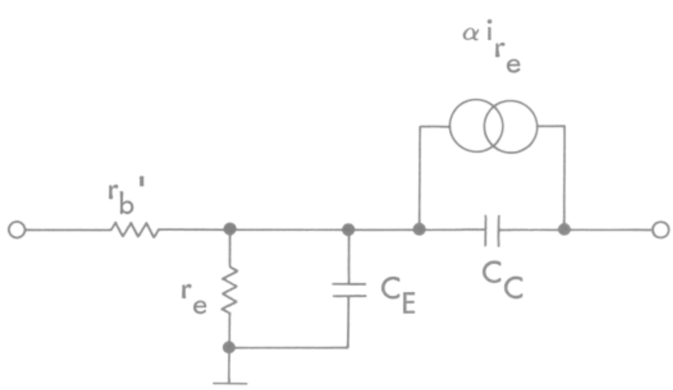
1.7 The amplitude of the current generator output is then α times only the portion of emitter current through ________________.

---

r_e (emitter resistance)

1.8 Label all the parts of the high frequency equivalent circuit below.

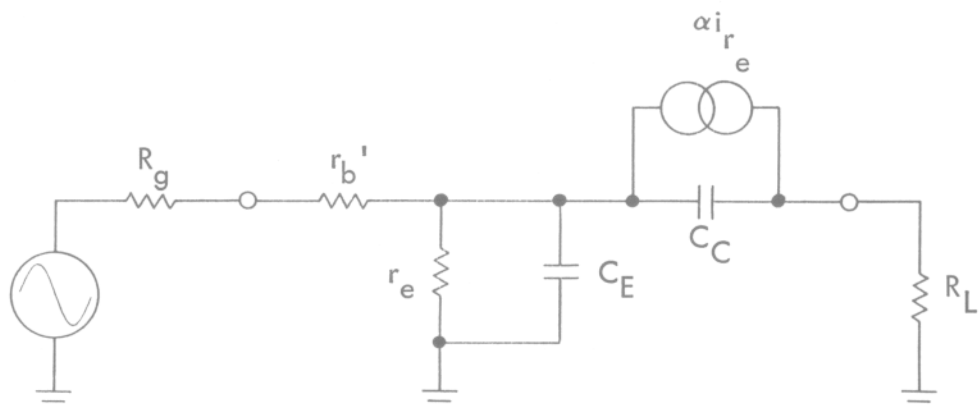




2.0 The two primary limitations that determine the high frequency response of a transistor in a common emitter configuration are:

1. The high frequency at which the collector signal current is .707 of the collector low frequency signal current. This frequency is the frequency at which X_{C_E} is equal to ________________.

2. The time constant involving the components________, _________, _________ and _________.



Answer to Frame 2.0:

βr_e

C_C

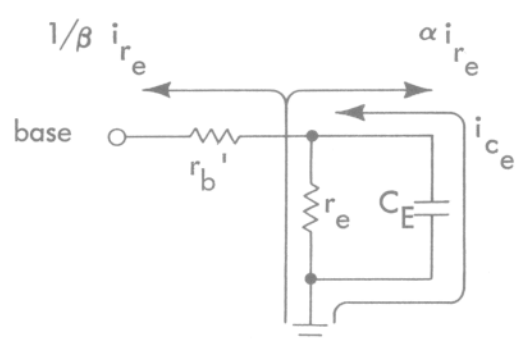
R_g

r_b

R_L

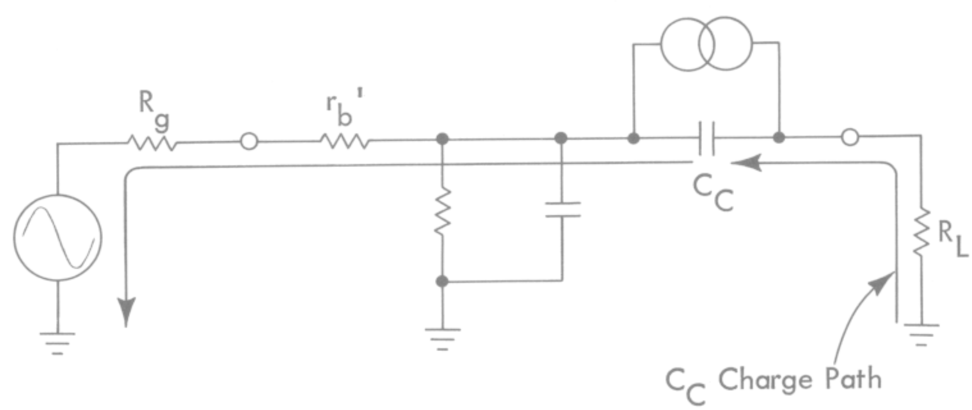
The two primary limitations that determine the high frequency response of a transistor in the common emitter configuration are:

1. The frequency at which the capacitive reactance of C_E (X_{C_E}) is equal to β times r_e. The key to understanding this is to remember we are driving the base of the transistor. From the base r_e looks β times as large as it is because only $1/\beta$ of the current through r_e flows to the base. However, all the current through C_E flows to the base so it will be seen from the base as its actual value.



At the frequency where X_{C_E} equals βr_e only .707 of the total emitter current will be flowing through r_e to the collector. The voltage gain of the stage will be 30% down due to this consideration alone.

2. The other limitation in the common emitter configuration is the time constant of C_C times the voltage gain of the stage $(A_V + 1)$ (Miller effect) and the series resistance of R_g, r_b', and R_L.



2.1 At the frequency where X_{C_E} is equal to $\beta r_e'$, .707 of the base current will flow through ________________.

---

r_e or C_E

2.2 At this frequency the collector signal current will be only .707 of the ____________ frequency collector signal current.

---

low

2.3 If the collector signal current is down to .707 of the low frequency signal current the voltage gain of the stage must be down to ________________ of the low frequency voltage gain.

.707

2.4 Due to the Miller effect, the collector base capacitance (C_C) will be seen from the base as ________________ times as large as its actual value.

$(A_V + 1)$

2.5 This capacitance $\left[(A_V + 1)\, C_C\right]$ will have to charge through the three resistors ________________, ________________, and ________________.

R_g

r_b'

R_L

2.6 The fastest change available at the collector of the transistor is, then, limited by R_g, r_b', R_L and collector ____________________.

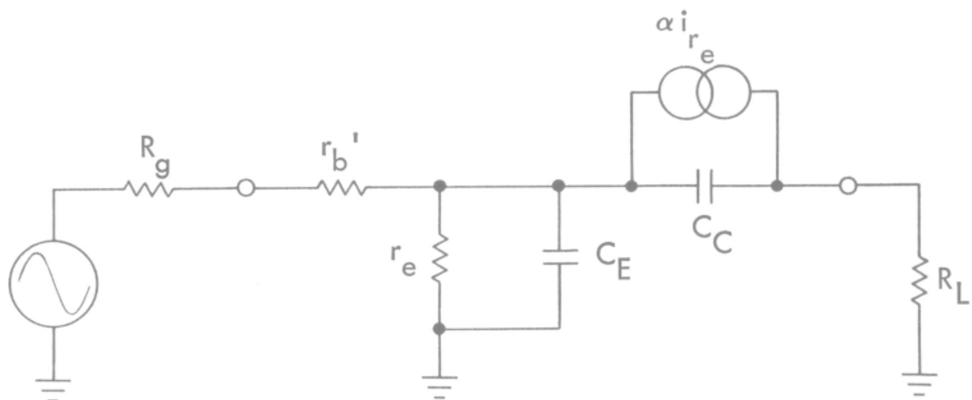
---

capacitance

2.7 The high frequency performance of a transistor in the common emitter configuration is then limited by:

1. The frequency at which the reactance of the emitter junction ____________ is equal to the emitter ______________ x ______________.

2. The time constant including the ___________ capacitance and the resistances _____________, ______________ and ______________.

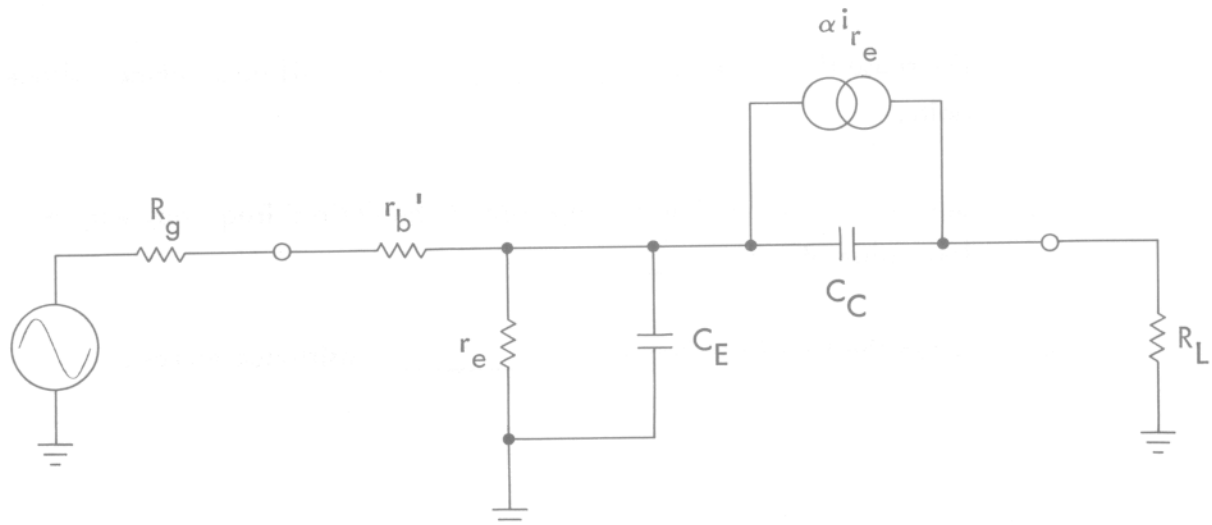


C_E
resistance or r_e
β
Collector or Miller
R_g
r_b'
R_L

3.0 To increase the frequency at which X_{C_E} is equal to βr_e we can increase emitter ________________.

To reduce the time constant of $(A_V + 1)\, C_C \times (R_g + r_b' + R_L)$ we can:

1. Increase ____________ to base voltage to reduce the value of C_C.
2. Decrease the value of ____________ which will also reduce voltage gain.
3. Select a transistor that will operate at the desired frequency with a low value of ____________.
4. Drive the transistor from a ____________ resistance source.



αi r e
R g
r b '
C C
r e
C E
R L

Answer to Frame 3.0:

current
collector
R_L
r_b'
low

In attaining high frequency performance from a transistor in the common emitter configuration there are a number of tradeoffs that must be made.

The first is in the selection of the transistor. One of the methods of attaining high frequency operation from a transistor is to make the base thinner. When the base is made thinner r_b' will increase. The first tradeoff, then, is in the selection of a transistor. It must operate at the desired frequency yet r_b' must be kept small to decrease the time constant involving C_C, r_b', R_g and R_L.

The next tradeoff is in the selection of R_L. As we decrease R_L to decrease the time constant of C_C, r_b', R_g and R_L, we decrease the voltage gain of the stage.

Another tradeoff is the operating transistor V_{cb}. The larger V_{cb} the smaller the collector capacitance C_C, but the more power dissipated by the collector.

The value of R_g should also be kept to a minimum. This may be at the expense of voltage gain in the previous stage or require an additional emitter follower stage.

These are four tradeoffs we can make to increase high frequency performance by reducing the time constant of C_C, r_b', R_g and R_L.

The other high frequency limitation is the frequency at which $X_{C_E} = \beta r_e$. By increasing emitter current we reduce r_e ($r_e \approx \frac{26}{I_E\ (mA)}$). A higher frequency will be required to bring X_{C_E} down to the lower value. By increasing emitter current we also increase the power dissipated by the transistor, another tradeoff.

3.1 In selecting a transistor for a high frequency circuit it is desirable to have the base resistance r_b' as ____________ as possible.

---

small

3.2 By operating the transistor at a high V_{cb}, we reduce the value of ____________ but increase the ____________ dissipated by the transistor.

---

collector capacitance (C_C)
power

3.3 We sacrifice voltage gain to improve the high frequency performance of a common emitter transistor circuit by reducing ______________.

R_L

3.4 For high frequency performance it is desirable to drive a transistor in the common emitter configuration from a ______________ resistance source.

---

low

3.5 We can improve high frequency performance by increasing I_E, which will reduce ______________.

---

r_e

3.6 For high frequency performance, we operate a transistor with a ________ (large/small) V_{cb} and a ________ (large/small) I_E which will increase the ______________ dissipated by the transistor.

To further enhance the performance of a transistor in the common emitter configuration, we select a transistor with a ______________ value r_b', reduce the value of R_L at the expense of ______________ gain and drive the transistor from a ______________ resistance source.

---

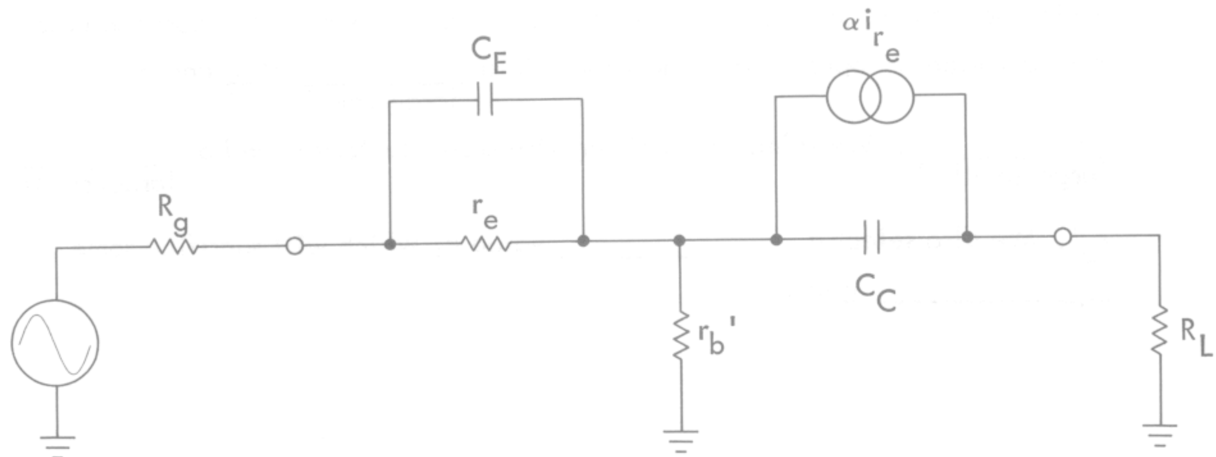
large
large
power
low
voltage
low

4.0 The two primary limitations on the high frequency performance of a transistor in the common base configuration are:

1. The frequency at which X_{C_E} is equal to ______________.

2. The time constant of _____________, ______________ and ______________.

To increase the high frequency performance of a transistor in the common base configuration we operate the transistor with a __________ (large/small) V_{cb} and a __________ (large/small) I_E. We select a transistor with a satisfactory f_t and a __________ (large/small) r_b'. We also select a ______________ value R_L which will sacrifice some ______________ gain.



R g
C E
r e
α i r e
C C
r b '
R L

Answer to Gating Frame 4.0

r_e

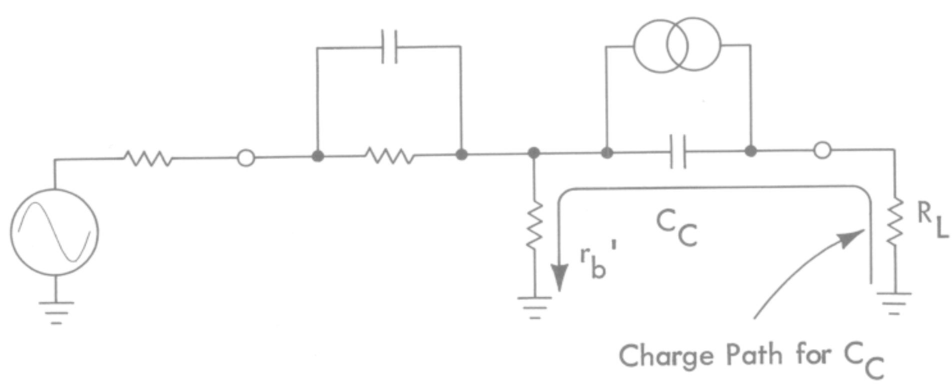
R_L

C_c

r_b'

large
large
small
low
voltage

The two primary high frequency limitations of a transistor in the common base configuration are essentially the same as in the common emitter configuration. There is the frequency at which the signal current through r_e is only 70% of the emitter signal current. However, in the common base configuration we are diriving the emitter therefore r_e is not multiplied by β. The frequency at which I_{r_e} is 70% of I_e is the frequency at which X_{c_e} is equal to r_e. The other limitation is the time constant involving C_c and r_b' in the transistor and the collector load R_L.



The common base configuration is able to operate at a higher frequency than the common emitter configuration for two reasons:

1. The generator resistance has been removed from the time constant of C_C, r_b', and R_L.

2. r_e is not amplified β times therefore the frequency must be much higher before X_{c_e} is equal to r_e.

The means of improving high frequency performance of a transistor in the common base configuration are similar to those used in the common emitter configuration. A transistor is selected with an acceptable f_t and a low r_b'. The transistor is operated at a high V_{cb} to reduce C_C and a high I_E to reduce r_e.

The collector load is again kept small to improve high frequency, but again at the expense of voltage gain.

4.1 One high frequency limitation on a transistor in the common base configuration is the frequency at which X_{C_E} is equal to ______________.

---

r_e

4.2 Another high frequency limitation on a transistor in the common base configuration is the time constant involving ______________, ______________ and ______________.

C_C
r_b'
R_L

4.3 A transistor that is selected for a high frequency common base circuit should have an acceptable f_t and a small ______________.

---

r_b'

4.4 Assuming all other factors equal, a transistor in the common base configuration with 10 mA of quiescent current would have a ____________ (lower/higher) frequency response than one conducting 1 mA of quiescent current.

---

higher

4.5 Assuming all other factors equal, a common base transistor with 2 volts quiescent V_{CB} would have a ____________ (lower/higher) frequency response than one with 5 volts quiescent V_{CB}.

---

lower

4.6 Assuming all other factors equal, a common base transistor with an R_L of 1 kΩ would have a ____________ (lower/higher) frequency response than one with an R_L of 100Ω.

---

lower

4.7 In a transistor in the common base configuration, the collector signal current will be 70% of its low frequency value when the signal frequency is high enough so that X_{c_e} is equal to ______________. Another limitation on the common base configuration is the time constant involving __________, ___________, and ______________.

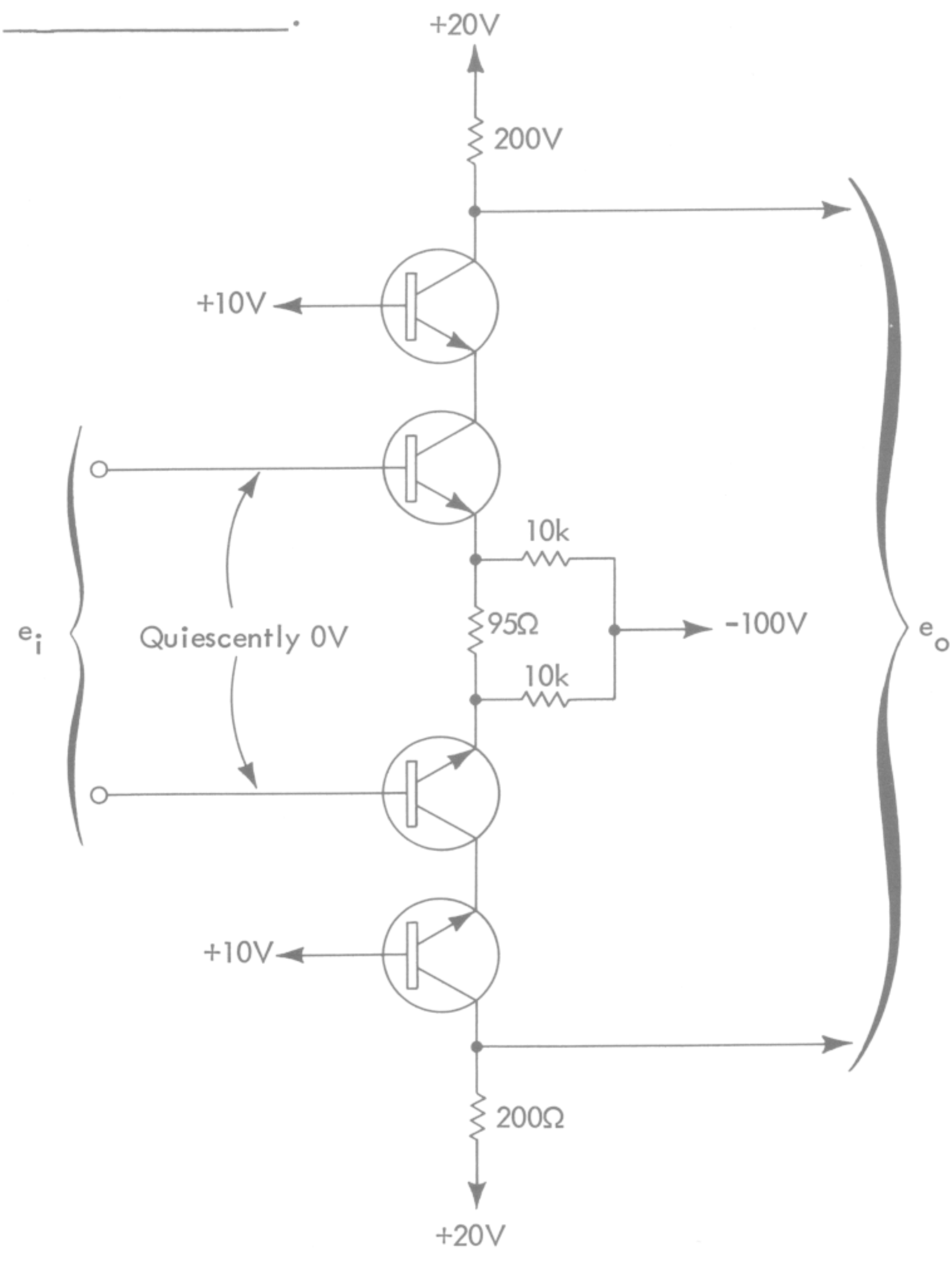
A transistor with an acceptable f_t with a low value ____________ should be selected for a high frequency common base circuit. To improve the high frequency response the common base transistor should be operated with a _______ (low/high) V_{CB} and a _______ (low/high) I_E. The collector load resistor (R_L) should be kept _________ (small/large).

---

r_e
C_C
r_b'
R_L
r_b'
high
high
small

5.0 Determine the approximate A_v in the circuit below.

$A_v \approx$ ________________.



The advantage of a cascoded amplifier stage from a high frequency standpoint is that ________________ ________________ is almost eliminated in the common emitter section.

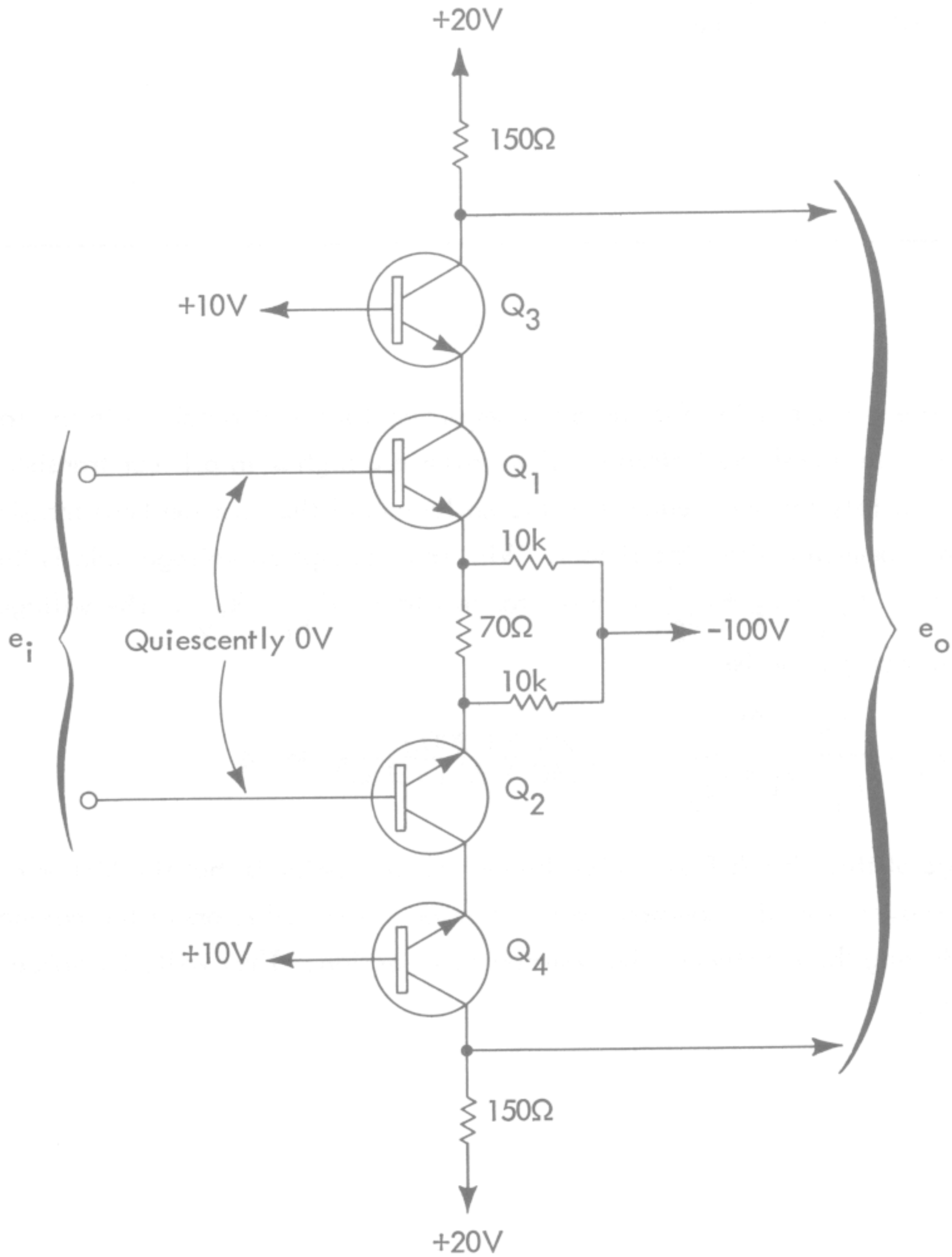
Answer to Frame 5.0:

$A_v \approx 4$
Miller capacitance

The approximate voltage gain of a cascoded amplifier stage is determined in the same way as the voltage gain in a push-pull circuit. If we assume a high β in all four transistors, we can assume approximately the same current in the collectors of the common base transistor as in the emitters of the common emitter transistors. With this assumption voltage gain is the ratio of emitter resistance ($r_{e_1} + R_E + r_{e_2}$) to collector resistance ($R_{L_1} + R_{L_2}$). The voltage gain in the circuit on the facing page is:

$$A_v \approx \frac{R_{L_1} + R_{L_2}}{r_{e_1} + R_E + r_{e_2}} = \frac{200\Omega + 200\Omega}{2.6\Omega + 95\Omega + 2.6\Omega} \approx 4$$

The advantage of this circuit from a high frequency standpoint is that the Miller capacitance is essentially removed from the common emitter section. The collectors of the common emitter section are driving the emitters of the common base section. They will, therefore, only move a few millivolts.


+20V
150Ω
+10V
Q3
Q1
10k
e_i
Quiescently 0V
70Ω
-100V
e_o
10k
Q2
+10V
Q4
150Ω
+20V

5.1 When an input signal is applied to the circuit on the facing page, the collectors of Q_1 and Q_2 will have a signal amplitude of a few ___________ .
μV/mV/volts

---

millivolts

5.2 By keeping the collectors of Q_1 and Q_2 nearly constant we have nearly eliminated the _________________ capacitance effect.

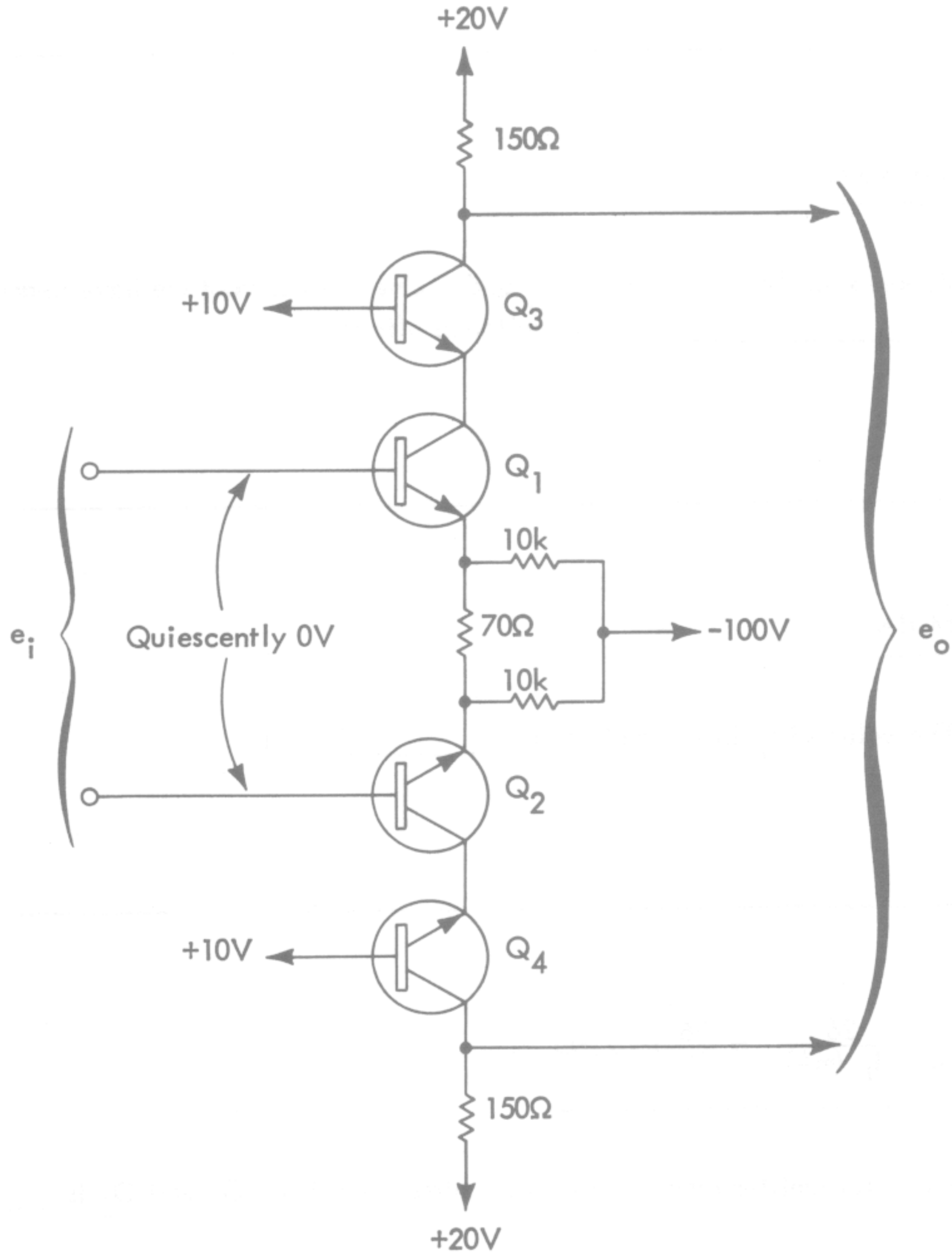
Miller

5.3 The value of r_e in Q_1 and Q_2 is _________Ω each.

$$r_e = \frac{26}{I_E\ (mA)} = \frac{26}{10} = 2.6\Omega$$

5.4 The total emitter resistance in the emitter circuit of Q_1 and Q_2 is __________Ω.

$2.6\Omega + 70\Omega + 2.6\Omega = 75.2\Omega$

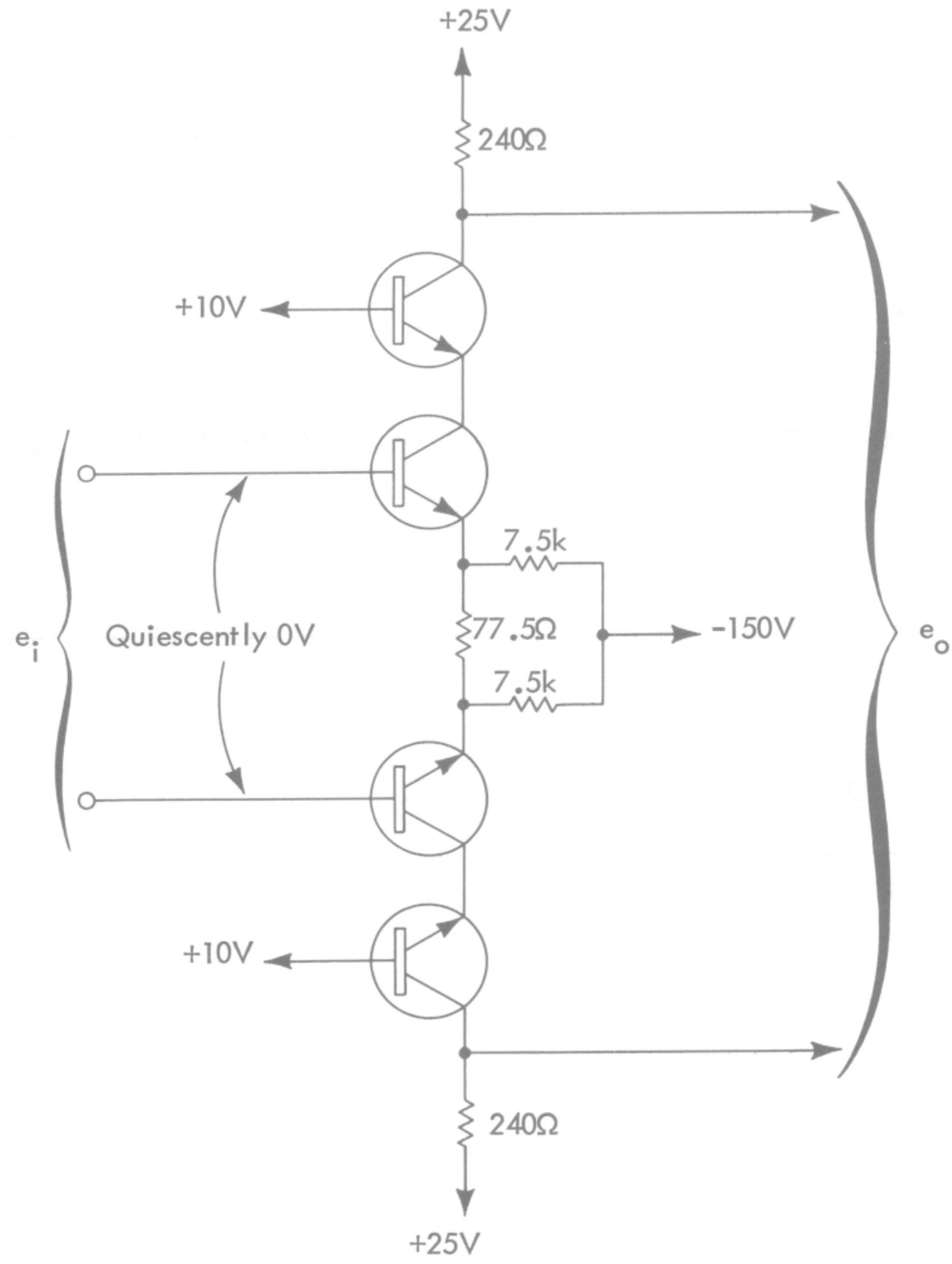

+20V
150Ω
+10V
Q3
Q1
10k
70Ω
-100V
10k
e_i
Quiescently 0V
e_o
Q2
+10V
Q4
150Ω
+20V

5.5 The sum of the collector load resistors on Q_3 and Q_4 is ________ Ω.

300Ω

5.6 The approximate voltage gain of the circuit on the facing page is ____________.

$$A_v \approx \frac{300\Omega}{75\Omega} = 4$$


+25V
240Ω
+10V
7.5k
e_i
Quiescently 0V
77.5Ω
-150V
e_o
7.5k
+10V
240Ω
+25V

5.7 The high frequency advantage of a cascoded stage is that ______________ ______________ is effectively removed from the common emitter section. The voltage gain of the cascoded amplifier on the facing page is ______________.

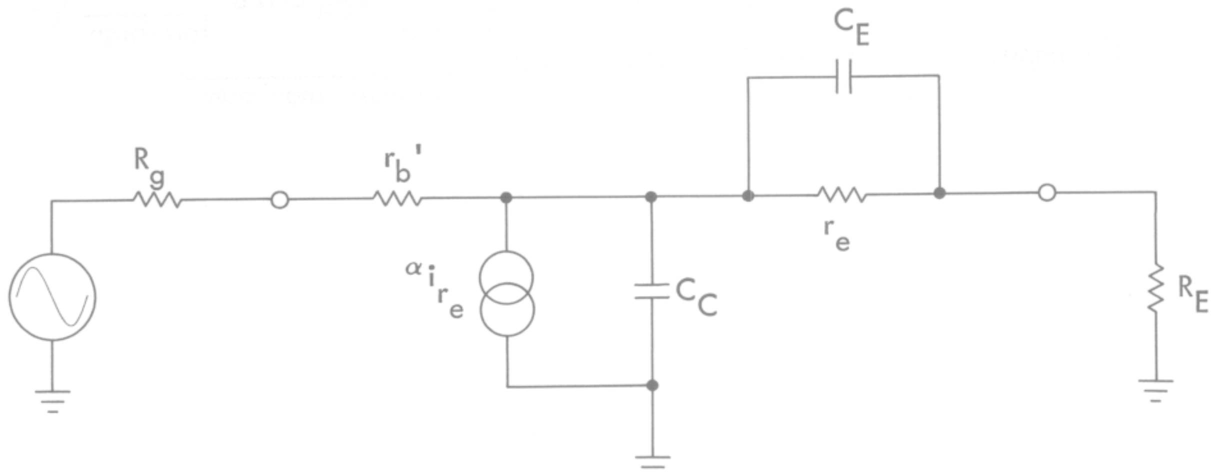
Miller capacitance
6

6.0 The two primary limitations on a common collector transistor circuit are:

1. The frequency at which X_{C_E} is equal to ______________.

2. The frequency at which X_{C_C} is equal to ______________ and ____________.

To minimize these limitations a transistor with an acceptable f_t and a low __________ is selected. The transistor is operated at a ________ (low/high) V_{CB} and a ________ (low/high) I_E. The impedance of the signal source is kept at a ______________ (minimum/maximum).



C_E
R_g
r_b'
r_e
αi_{r_e}
C_C
R_E

Answer to Frame 6.0:

βr_e
r_b'
R_g
r_b'
high
high
minimum

The high frequency limitations of the common collector configurations are attributed to primarily the same factors that limited the common emitter and common base configurations.

1. The frequency at which X_{C_E} is equal to βr_e the emitter signal current will be down to 70% of the low frequency signal current. As in the common emitter configuration r_e looks β times its value when driven from the base.

2. At the frequency where X_{C_C} is equal to $r_b' + R_g$, the signal amplitude at r_e is attenuated to 70% its actual value by the voltage divider action of $r_b' + R_g$ to C_c.

To reduce the effects of these limitations, the same techniques as were used in the common emitter and common base circuits are used. A transistor is selected for an acceptable f_t and a low r_b'. The transistor is operated at a high V_{CB} to reduce the value of C_c and at a high I_E to reduce the value of r_e. The signal source impedance (R_g) is kept to a low value.

6.1 At the frequency where X_{C_E} is equal to βr_e in a common collector circuit, the emitter signal current will be ______% of its low frequency signal current.

70%

6.2 As the input frequency to a transistor in the common collector configuration is increased, the signal to r_e will be attenuated by the voltage divider action of __________ + __________ and __________.

---

r_b'
R_g
X_c or X_{C_C}

6.3 A transistor to be used in a high frequency common collector circuit is selected for an acceptable f_t and a low value ____________.

---

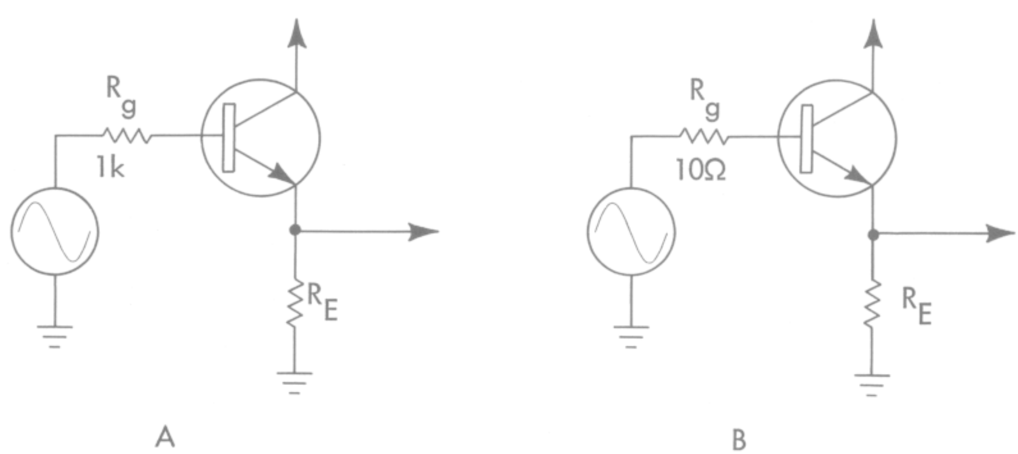
r_b'

6.4 All other factors being equal, a transistor in the common collector configuration that is conducting 1 mA quiescently will have a ___________ (lower/higher) frequency response than one conducting 20 mA.

---

lower

6.5 All other factors being equal, circuit __________ below will have the higher frequency response.



B

6.6 All other factors being equal a transistor in the common collector configuration with a V_{CB} of 10V will have a ___________ (lower/higher) frequency response than one with a V_{CB} of 1V.

---

higher

6.7 Two high frequency limitations on a common collector circuit are:

1. The frequency at which X_{C_E} is ________ times as large as r_e.

2. The frequency at which $R_g + r_b'$ is equal to ____________.

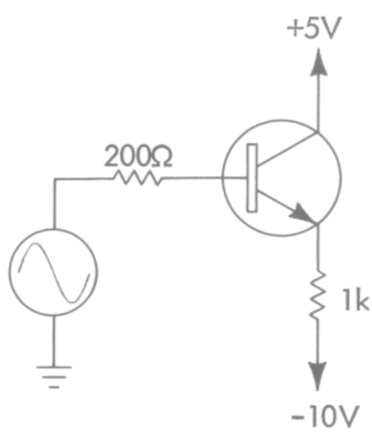
We would choose transistor __________ for use in a 50 MHz common collector circuit.

Transistor A – f_t = 200 MHz $r_b' = 50\Omega$

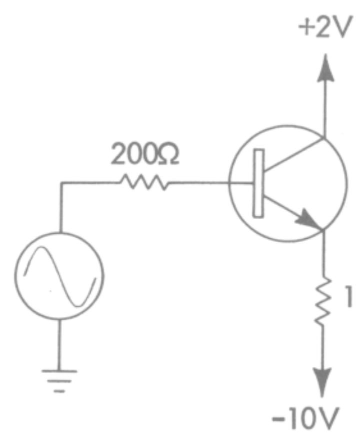
Transistor B – f_t = 250 MHz $r_b' = 100\Omega$

Select the circuit in each pair that would have the best high frequency response.

Circuit _________ will have the best high frequency response.

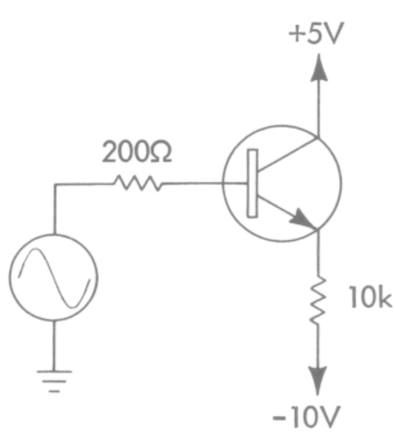


A

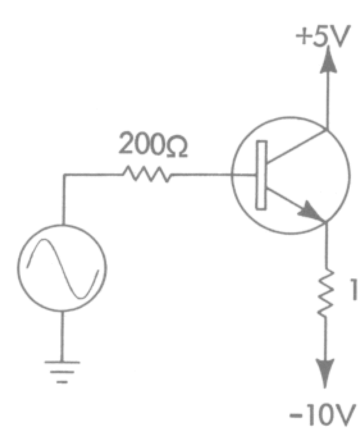


B

Circuit ________ will have the best high frequency response.

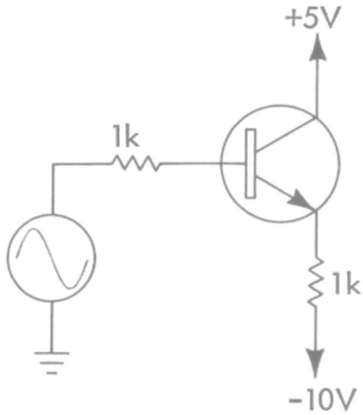


A

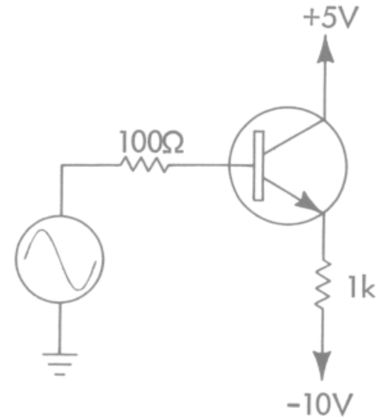


B.

Circuit ____________ will have the best high frequency response.



A

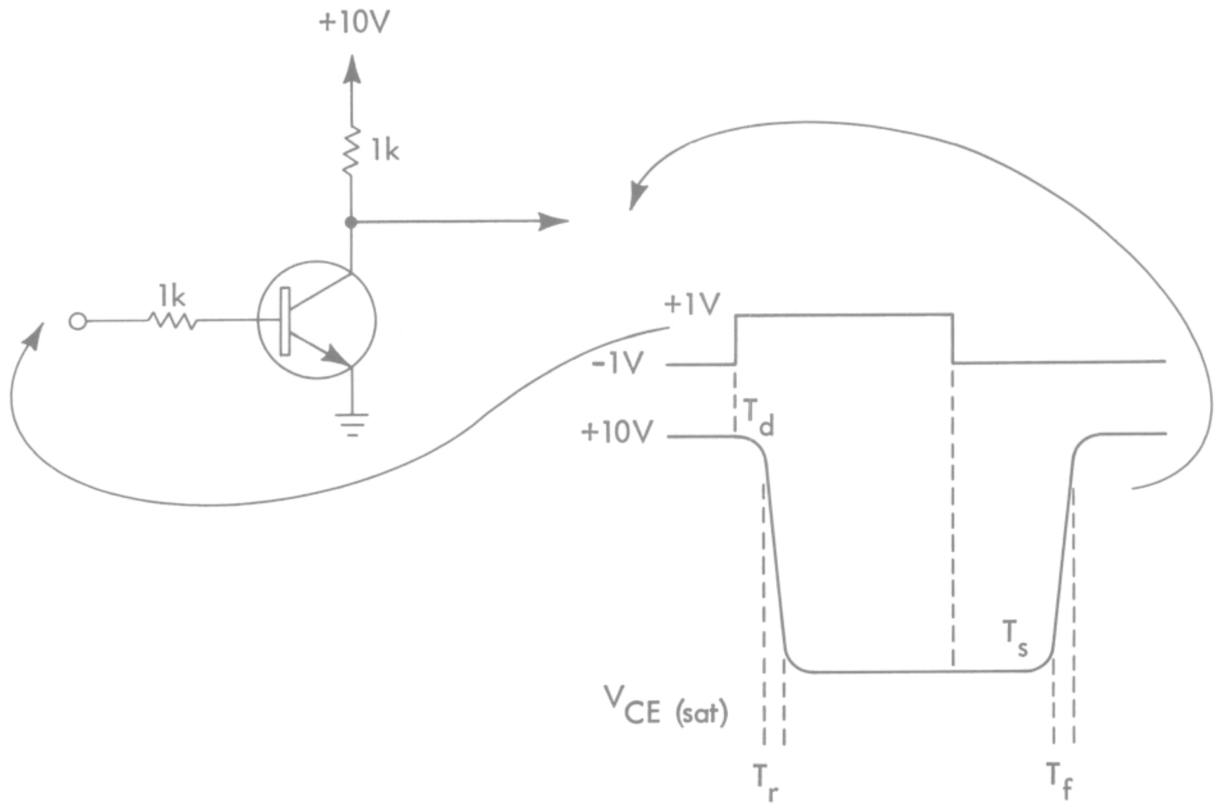


B

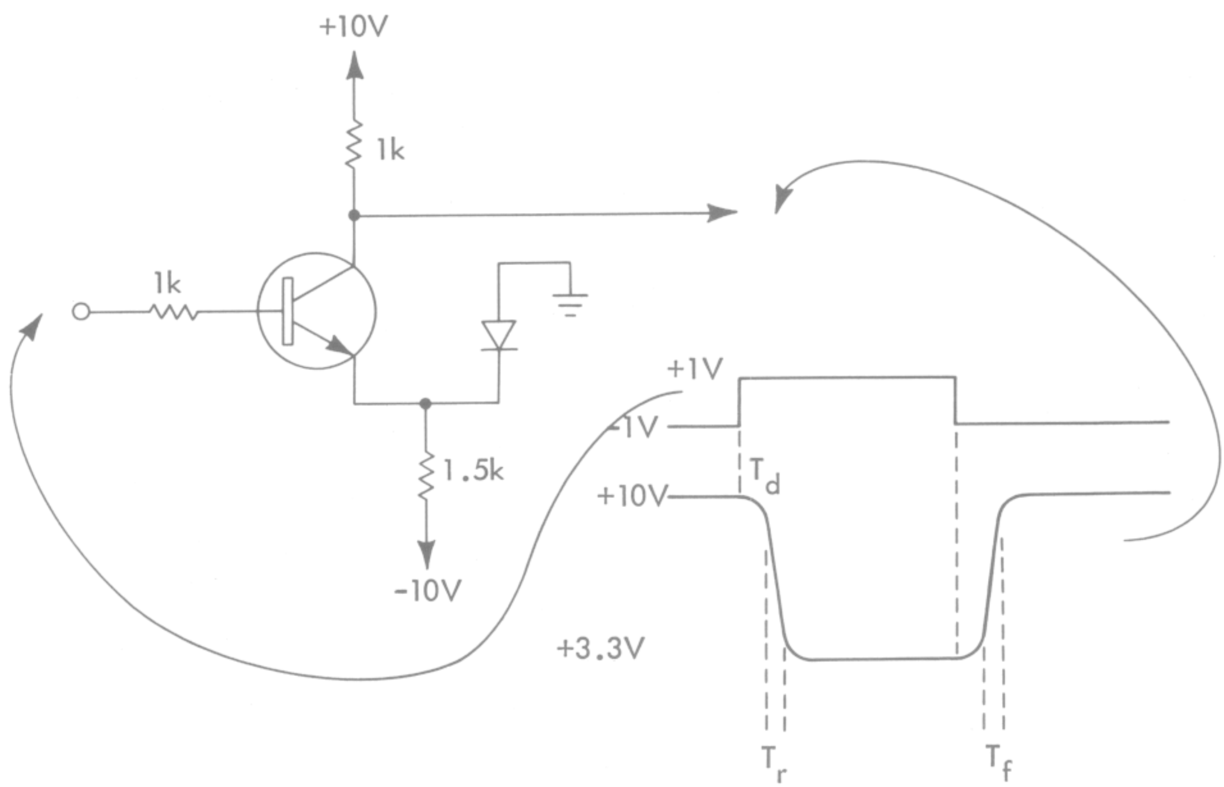
β
X_{C_C}
Transistor A
Circuit A
Circuit B
Circuit B

7.0 Circuit A is an example of ________________ mode switching. Circuit B is an example of ____________ mode switching.

With the same square wave in, the transistor in circuit ___________ will dissipate the most power. The circuit that will respond to the highest repetition rate input is circuit ___________. When in the "on" mode, the collector voltage of circuit __________ will be closest to ground potential. The collector voltage at this time is labeled __________________.


+10V
1k
1k
+1V
-1V
T_d
+10V
T_s
$V_{CE\ (sat)}$
T_r
T_f

A


+10V
1k
1k
1.5k
-10V
+1V
-1V
T_d
+10V
+3.3V
T_r
T_f

B

Answer to Frame 7.0:

saturated
current
B
B
A
$V_{CE\ (sat)}$

Circuit A is an example of saturated mode switching. The transistor is allowed to go into saturation. A transistor is in saturation when the collector base junction is forward biased. This circuit is used in programing where the transistor, in its on state, must simulate a closed switch. For this reason the saturated voltage $V_{CE\ (sat)}$ is an important transistor switching characteristic. The transistor in circuit A will dissipate very little power because it will operate in either cutoff or saturation. By allowing the transistor to saturate, storage time becomes significant, especially at high repetition rates. Storage time is a limiting factor on how high a repetition rate this circuit can operate.

Circuit B is an example of current mode switching. When the transistor is off, the diode will clamp the transistor emitter to $\approx -.7V$. When the transistor is turned on, the current is switched from the diode to the transistor. The size of the emitter resistor and collector resistor are selected so the transistor is not allowed to go into saturation. This effectively removes storage time from the switching time so this circuit is able to operate at a higher repetition rate than the saturated mode circuit (A).

The transistor in circuit B will dissipate more power than in circuit A because the transistor does not simulate a closed switch in the "on" cycle so this circuit isn't usually used in programming. It is used primarily where a high repetition rate is desired.

7.1 More power is dissipated by a transistor in a ________________ mode switching circuit.

---

current

7.2 The highest repetition rate is available in a ________________ mode switching circuit because ________________ time is effectively removed from the switching time.

---

current
storage

7.3 In a circuit that demands performance that very closely approximates a switch, ________________ mode switching would be used.

---

saturated

7.4 How closely a transistor approximates a closed switch is the transistor characteristic ______________.

$V_{CE\ (sat)}$

7.5 A limiting factor of switching repetition rate in a saturated mode circuit is ______________ time.

---

storage

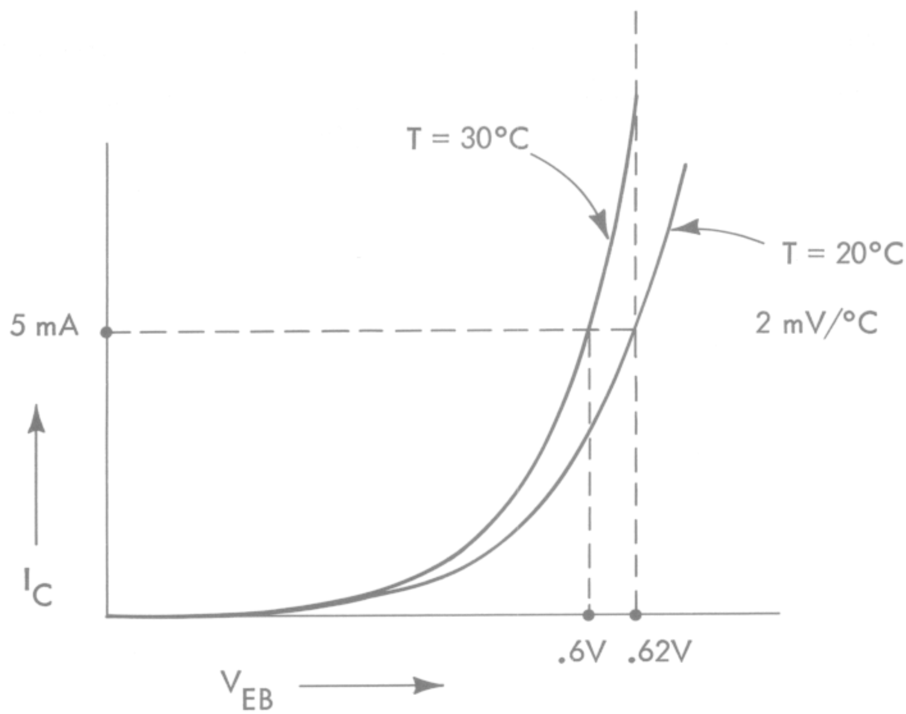
7.6 The transistor characteristic $V_{CE\ (sat)}$ is important when the transistor is to be used in a ______________ mode switching circuit.

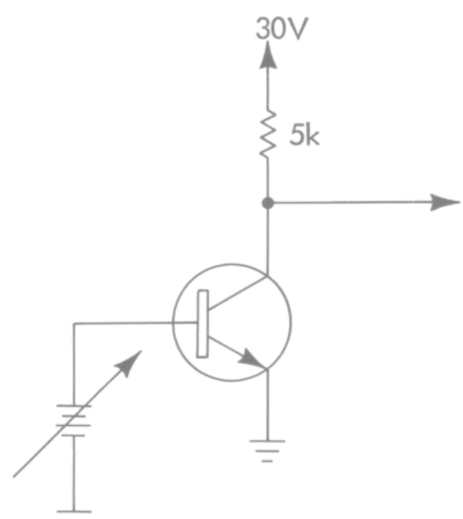
The transistor in a current mode switching circuit will dissipate _________ (less/more) power than one in a saturated mode switching circuit. The switching rate in a saturated mode circuit is limited by _____________ time. The current mode switching circuit has a ___________ (lower/higher) switching rate capability than the saturated mode switching circuit.

---

saturated
more
storage
higher

8.0 As temperature in a transistor increases, the base to emitter voltage required for a given collector current ______________ (decreases/increases) approximately __________ mV/°C.


T = 30°C
T = 20°C
5 mA
2 mV/°C
I
C
.6V
.62V
V
EB


30V
5k

Answer to Frame 8.0:

decreases
≈ 2

The junctions in a transistor have a negative temperature coefficient. That is, for an increase in temperature the emitter base voltage required for a given collector current is reduced. For every °C increase in junction temperature, the emitter base voltage required for a given collector current is reduced ≈ 2 mV. This is an approximation that applies to both silicon and germanium transistors.

On the facing page is an example to illustrate this point. It takes .62V from base to emitter to maintain 5 mA collector current at a temperature of 20°C. However, at 30°C it only takes a V_{EB} of .6V to maintain an I_c of 5 mA. If V_{EB} is not reduced to .6V, a reduction of 20 mV, then I_c will increase sharply with the increase in temperature.

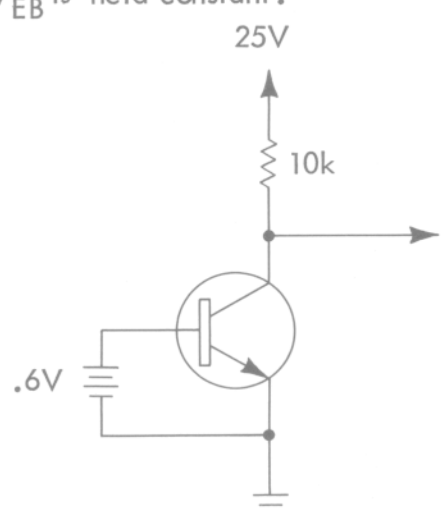
8.1 As temperature increases in a transistor the V_{EB} required for a given collector current ________________.
decreases/increases

<u>decreases</u>

8.2 A transistor, then, is said to have a ________________ temperature coefficient.

<u>negative</u>

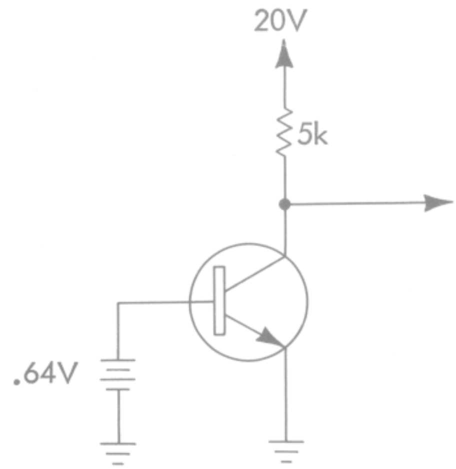
8.3 In the circuit below the collector voltage will ________________ as temperature
decrease/increase
increases, assuming V_{EB} is held constant.



<u>decrease (T increases, V_{EB} constant, $\therefore$ I_c increases causing V_c to decrease)</u>

8.4 In the circuit below, as the temperature in decreased 5°C, the V_{EB} must

_______________ to ________V to maintain a V_c of 5V.
decrease/increase

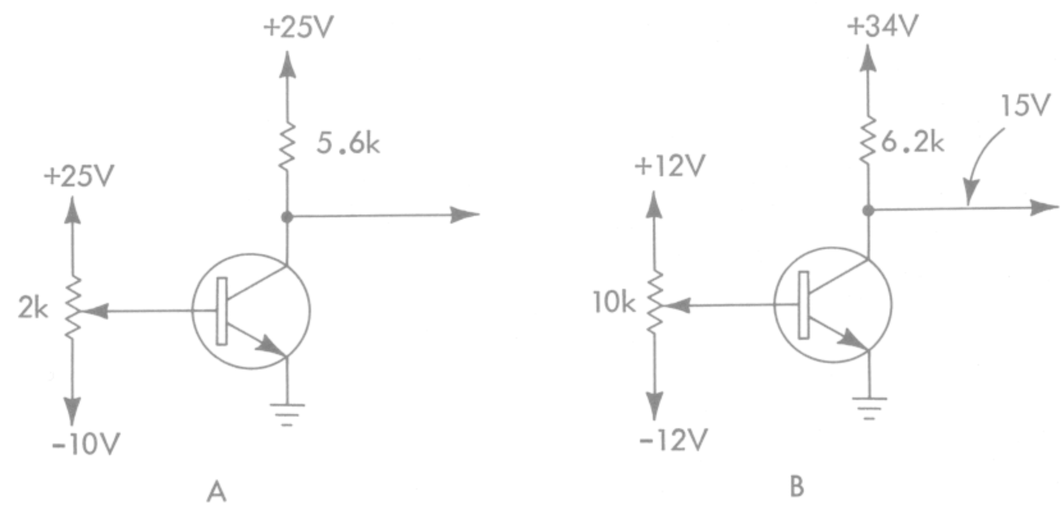


---

increase
.65V (5°C requires 10 mV change in V_{EB})

<u>Note:</u> In Set 8 we have introduced a problem in transistor circuits caused by changes in transistor temperature. The change in transistor temperature may be caused by a change in ambient temperature or a change in power dissipated by the transistor. In the following sets we will discuss methods of minimizing these temperature problems.

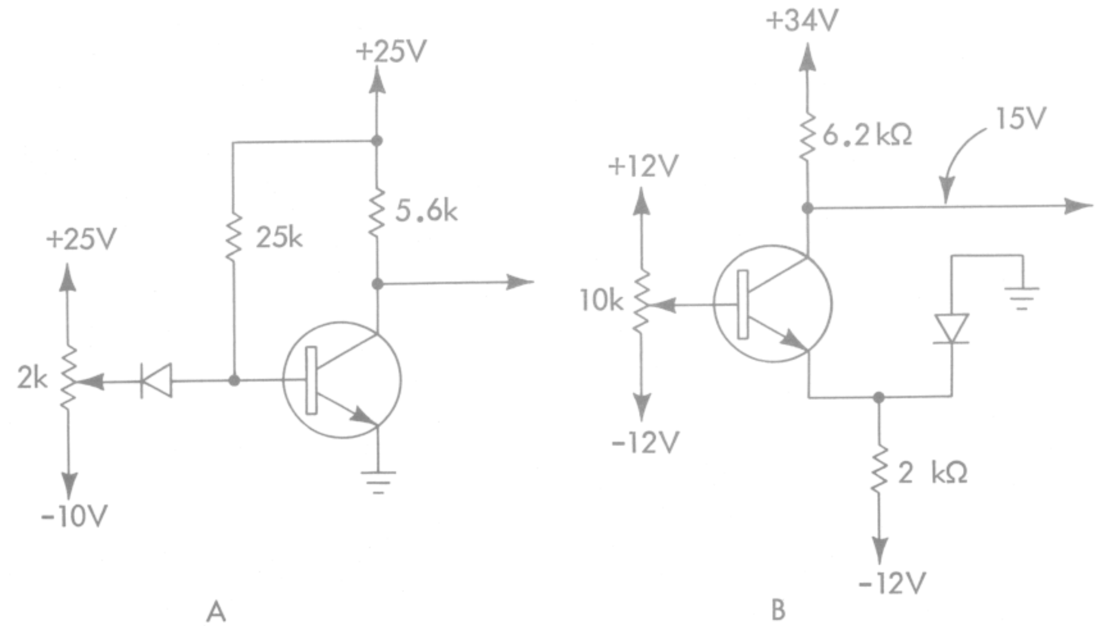
9.0 Temperature stabilize the transistor in circuit A against changes in ambient temperature by properly adding a diode to the base circuit. Temperature stabilize the transistor in circuit B against changes in ambient temperature by properly adding a diode to the emitter circuit.



Circuit A

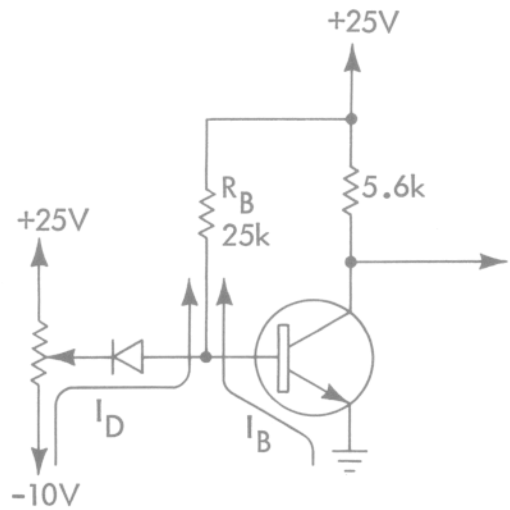
Circuit B

Answer to Frame 9.0:



A forward biased semiconductor diode has approximately the same temperature coefficient as the emitter base junction in a transistor; i.e., for a 1°C increase in temperature, the junction voltage across the diode will decrease by ≈2 mV.

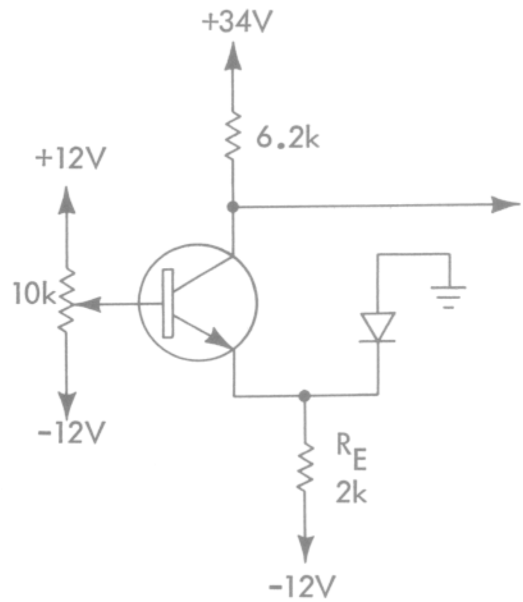
By connecting the diode in parallel with the emitter base junction, we can compensate for the ΔV_{EB} due to temperature change.



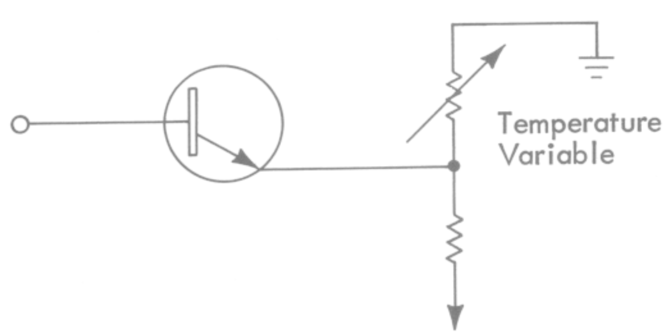
In the circuit above we adjust the variable resistor for the desired collector output voltage. As temperature increases or decreases the V_{EB} required for a given I_c will decrease or increase.

The diode, having approximately the same temperature coefficient as the transistor, will provide the decreased or increased base voltage. The collector current will remain constant and, as a result, collector voltage will remain constant.

The resistance value of R_B is not critical. Some circuits select R_B to draw ≈1 mA of current; others select it to draw more.



In the circuit above the variable resistor is again adjusted for the desired collector output voltage. As temperature increases or decreases, the V_{EB} required for a given I_c will decrease or increase. The diode will act as a temperature variable resistor and provide the decreased or increased emitter voltage (see circuit below). The collector current will remain constant and as a result, collector voltage will remain constant. The emitter resistor, R_E, can be connected to an available negative supply, in our example -12V, R_e is then selected to provide the same amount of current to the diode as is being provided to the transistor. The diode is then operating at the same point on its response curve as the emitter base junction of the transistor. In this way, the diode voltage is able to follow the emitter-base junction voltage better.



9.1 The emitter base junction of a transistor and a semiconductor diode have _______________ temperature coefficient.
the same/a different

---

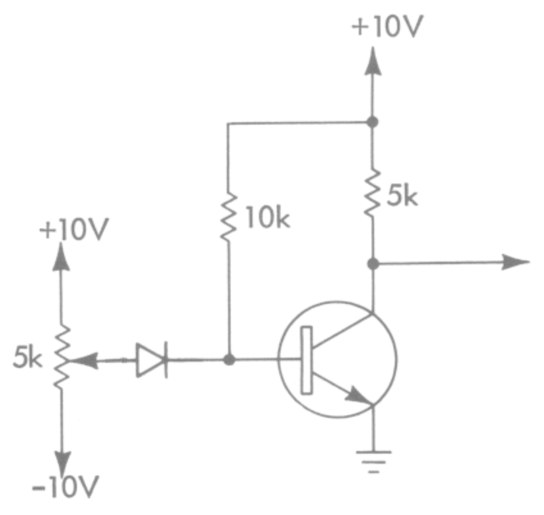
the same

9.2 To temperature stablize a transistor with a semiconductor diode, the diode should be connected in _______________ with the _______________ to base junction of the transistor.
series/parallel

---

parallel
emitter

9.3 Correct the circuit below for proper temperature stabilization, if there are any errors.

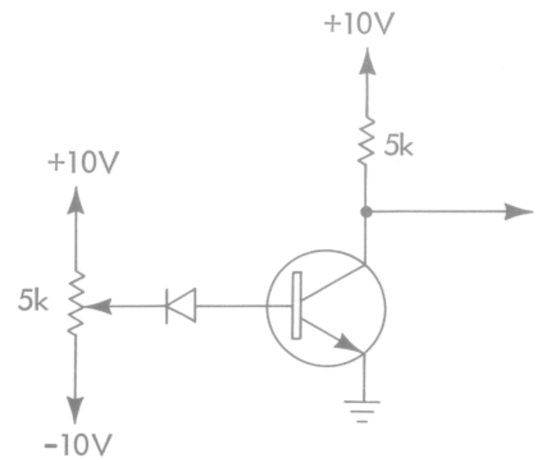


---

answer on next page

The anode and cathode leads of the diode should be reversed.

9.4 Correct the circuit below for proper temperature stabilization if there are any errors.

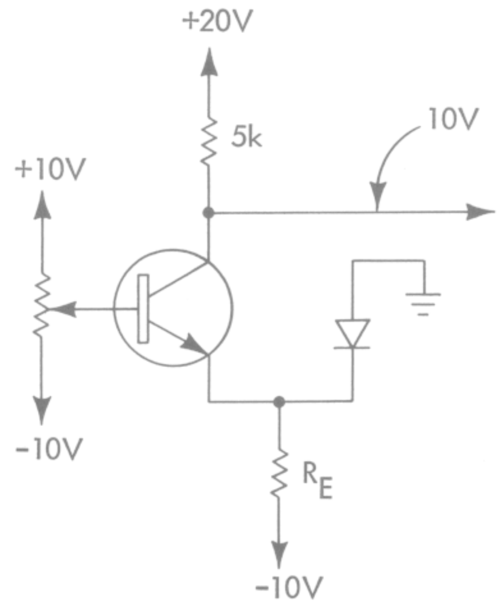


add a resistor of ≈10 kΩ from the base to +10V

9.5 When the diode for temperature stabilization is in the emitter circuit, the diode should be conducting the same amount of current as the ____________________.

transistor

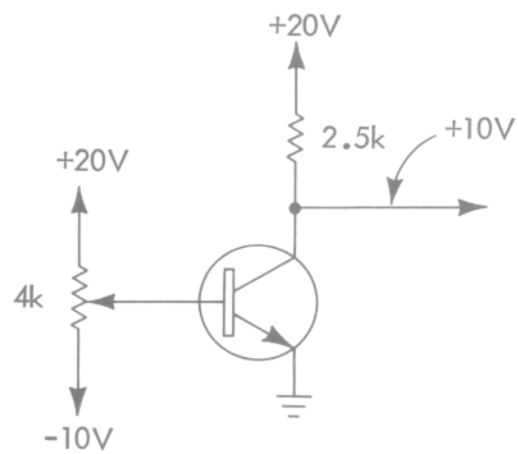
9.6 Determine the size of R_E.



answer on next page

The value of R_E is 2.5 kΩ ($\frac{10V}{4\ mA}$ = 2.5 kΩ) (2.33k if .7V V_{EB} is considered).

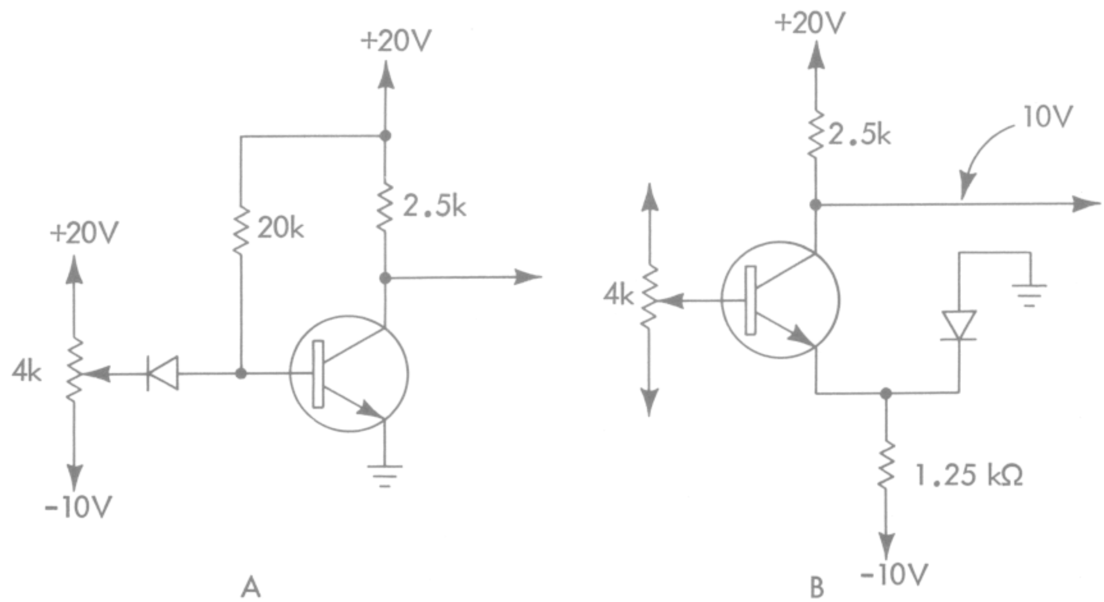
9.7 Temperature stabilize the circuit below using a diode first in the base circuit and then in the emitter circuit. Include the component sizes selected.



A B

answer on next page

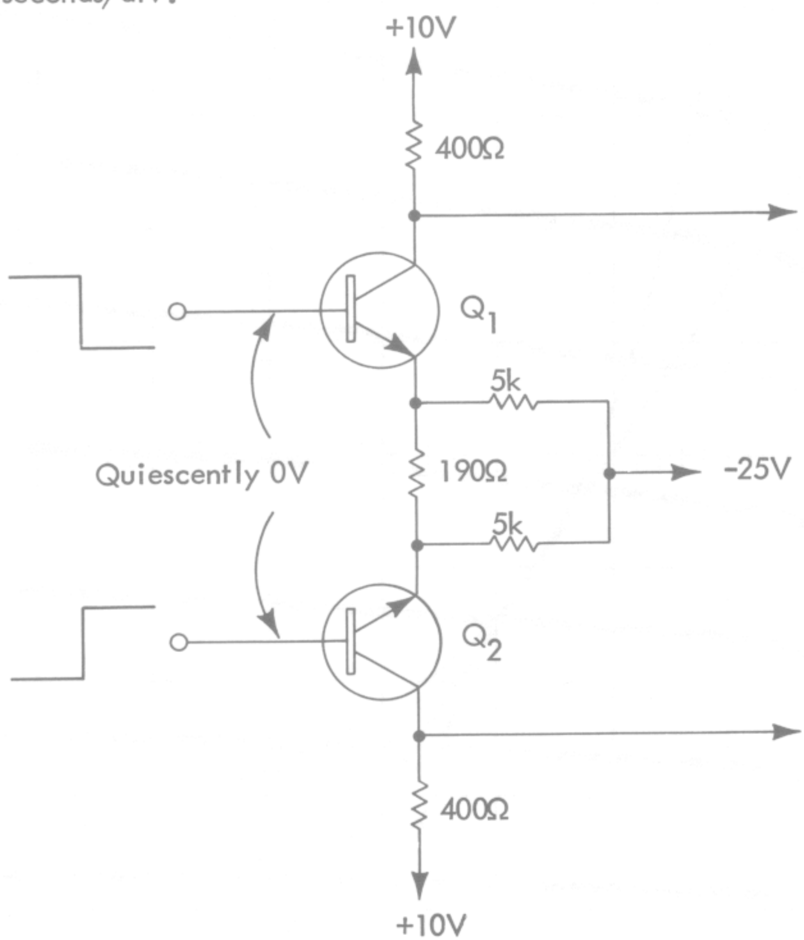
Answer to 9.7:

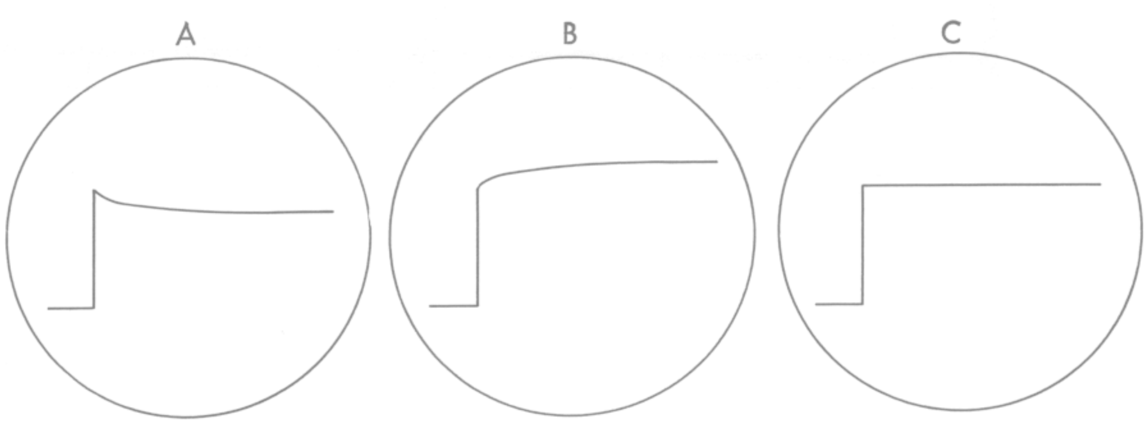


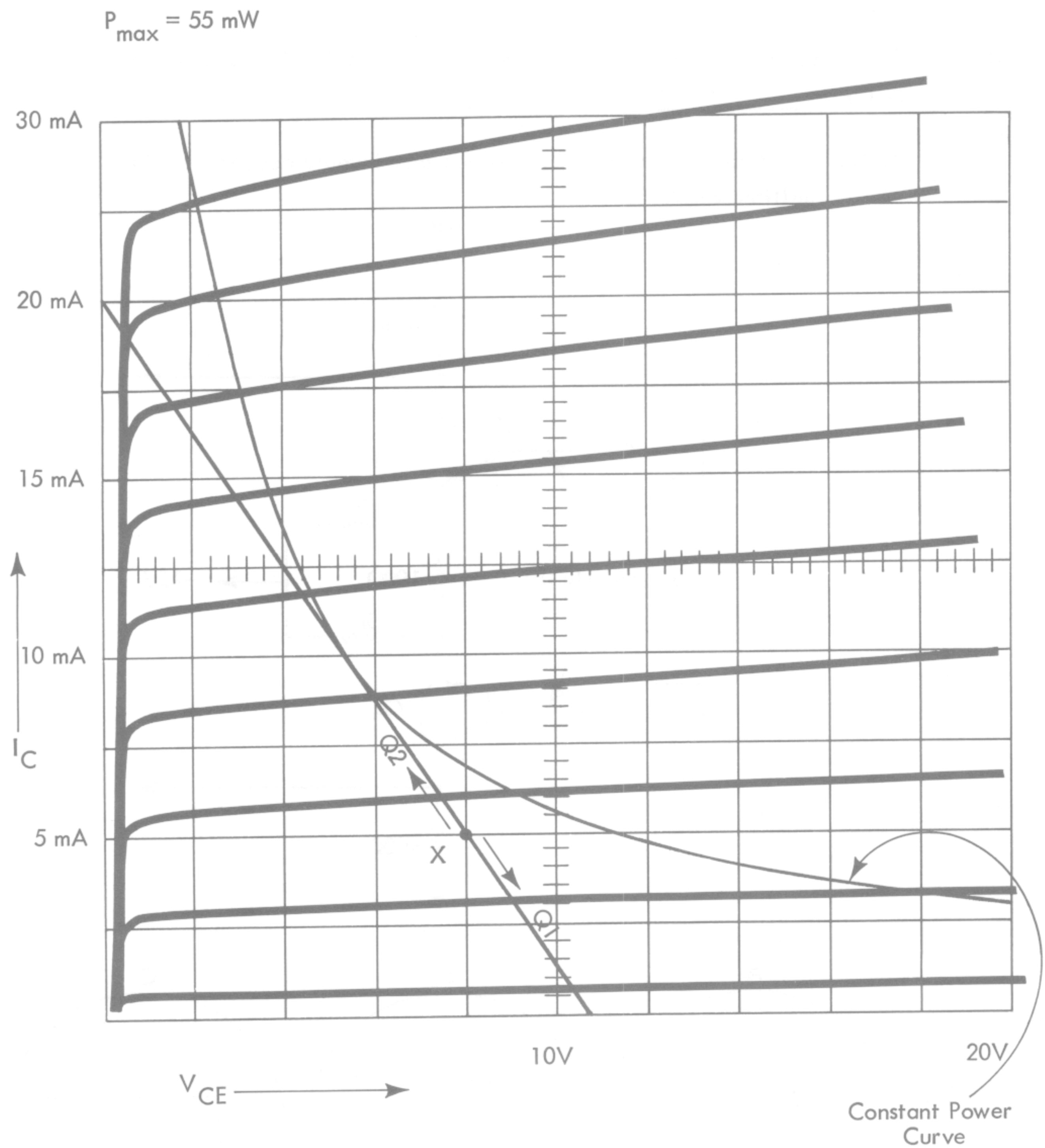
In the following set we will discuss the distortion on the output waveform of a push-pull circuit caused by a change in power dissipated by the transistors. The following sets will analyze the problem and finally arrive at a method for minimizing distortion due to thermal effects.

10.0 The output from the circuit below would present a CRT display like display A, B or C? ____________.

NOTE: To obtain the "display" the sweep speed would have to be a few milliseconds/div.





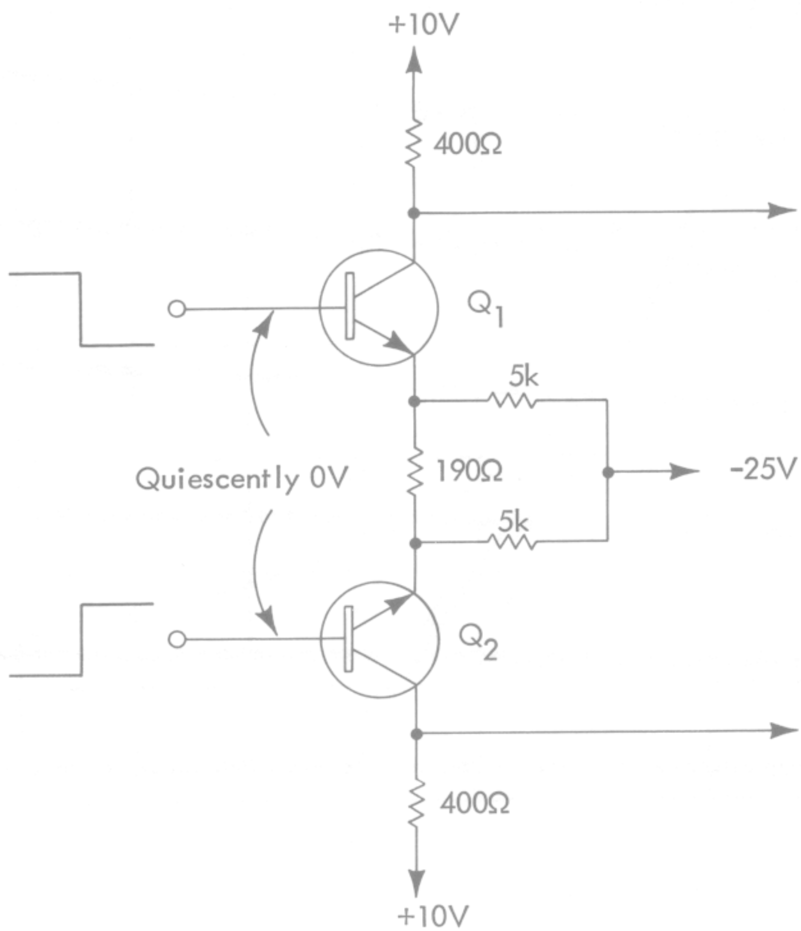


P$_{max}$ = 55 mW
30 mA
20 mA
15 mA
10 mA
5 mA
I$_C$
Q2
X
Q1
10V
20V
V$_{CE}$
Constant Power Curve

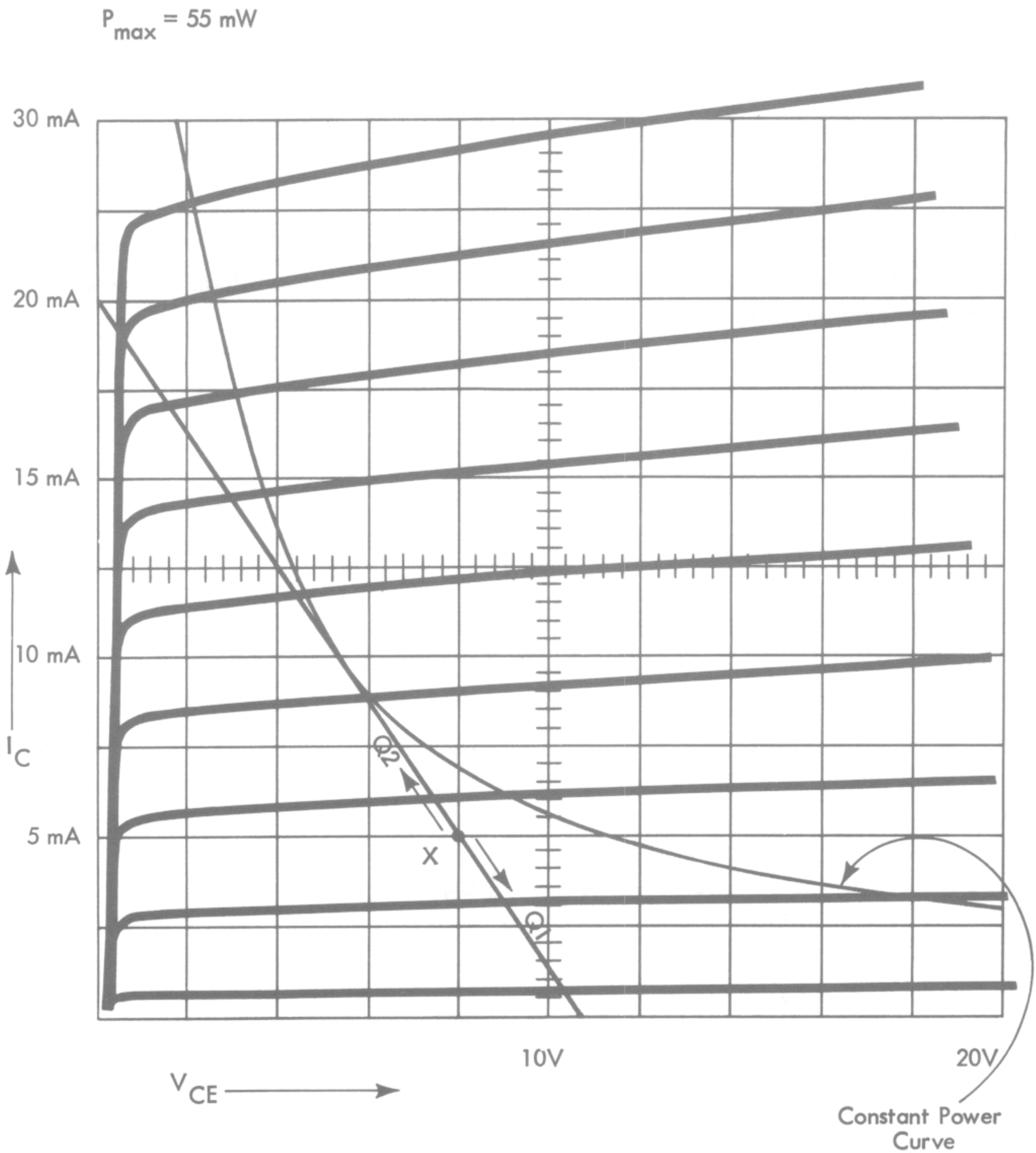
Answer to Frame 10.0:

B

Distortion in transistor circuits can be caused by a change in power dissipated by the transistors. The first step in determining how the distortion will affect the output waveform is to determine the quiescent operating point for each transistor.

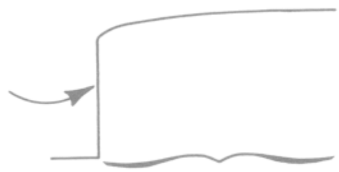


With the base of each transistor in the circuit above quiescently at 0V, there will be ≈5 mA I_E in each transistor. With a good β, each transistor I_c will also be ≈5 mA. 5 mA through the 400Ω collector load resistors will drop 2V. The V_c of each transistor will therefore be 8V. The transistor will, then, be operating at 8V V_c and 5 mA I_c which is point X on the facing page curves.


P$_{max}$ = 55 mW
30 mA
20 mA
15 mA
10 mA
5 mA
I$_C$
Q2
X
Q1
10V
20V
V$_{CE}$
Constant Power Curve

By applying a negative going signal to the base of Q_1 the collector will go positive. From the curves on the facing page we can see that the operating point has moved away from the constant power curve or has decreased transistor power dissipation. If we look at the output from Q_1, it would look as below.

Original Step

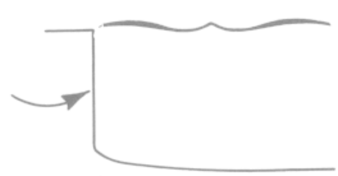


As the transistor dissipates less power the temperature decreases and the V_{EB} required to maintain a constant I_c increases (Set 8). However, the V_{EB} in this case remains constant, therefore, I_c will decrease. As I_c decreases V_c will increase resulting in this waveform.

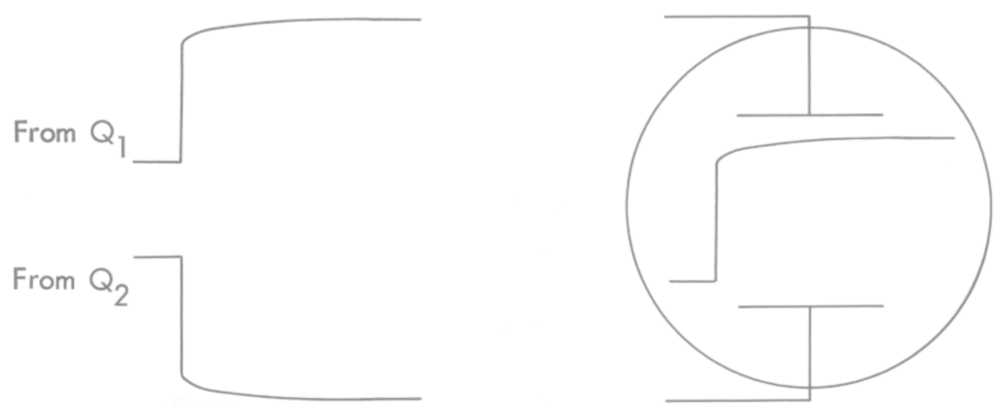
By applying a positive going signal to the base of Q_2 the collector will go negative. From the curves on the facing page we can see that the operating point has approached the constant power curve or has increased transistor power. If we look at the output from Q_2 it would look as below.

As the transistor dissipates more power the temperature increases and the V_{EB} required to maintain a constant I_c decreases. However, the V_{EB} in this case remains constant, therefore I_c will increase. As I_c increases V_c will decrease resulting in this waveform.

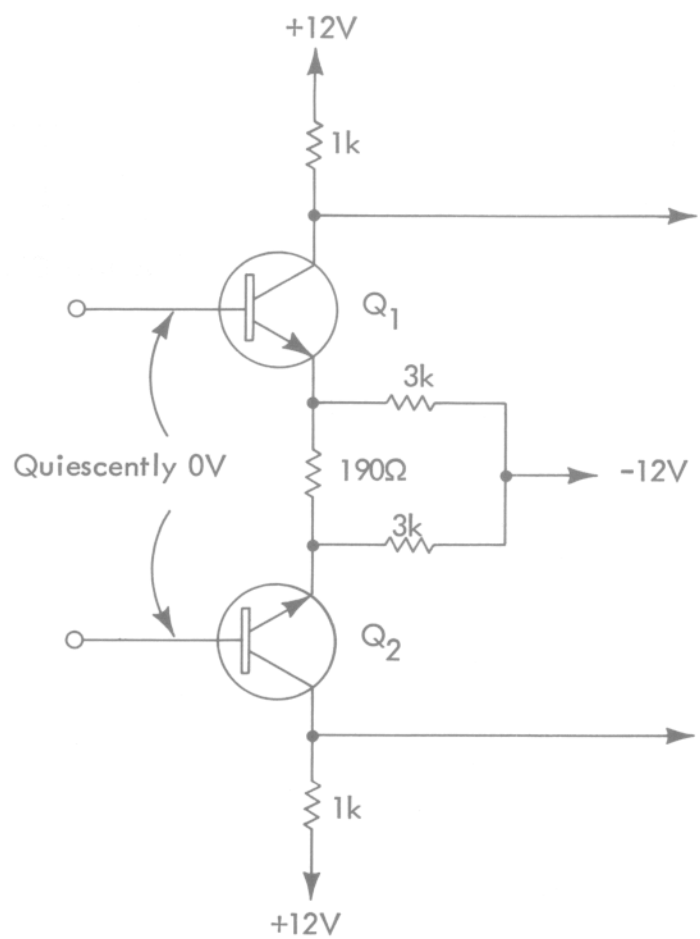
Original Step



If we use the output from this circuit to drive the vertical plates of a CRT, the display would look as below.



Resultant CRT Display


+12V
1k
Q1
Quiescently 0V
3k
190Ω
-12V
3k
Q2
1k
+12V

10.1 As power dissipation in a transistor increases the V_{EB} required to maintain a constant I_c will ________________ (decrease/increase).

---

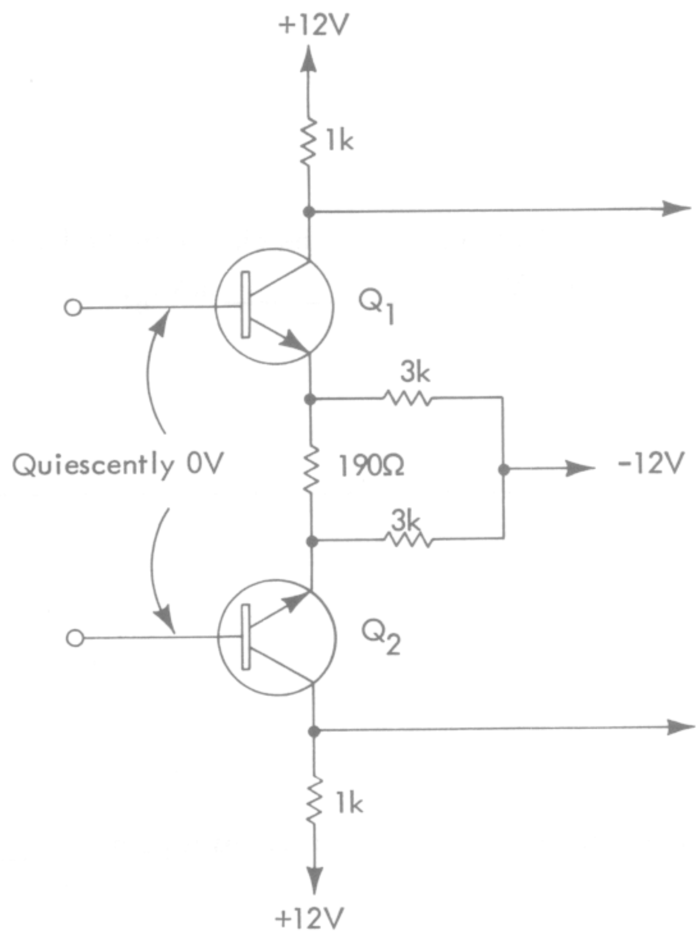
decrease

10.2 The operating point for the transistors in the circuit on the facing page is ________________ volts V_c and ____________ mA I_c.

$V_c \approx 8V$
$I_c \approx 4$ mA

10.3 The operating point on the set of transistor curves is point ____________.

C


+12V
1k
Q1
3k
Quiescently 0V
190Ω
-12V
3k
Q2
1k
+12V

10.4 If a step were applied so that the current through Q_1 would decrease by 1 mA and the current through Q_2 would increase by 1 mA, the power dissipated by Q_1 would ______________ (increase/decrease) and the power dissipated by Q_2 would ______________ (increase/decrease).

---

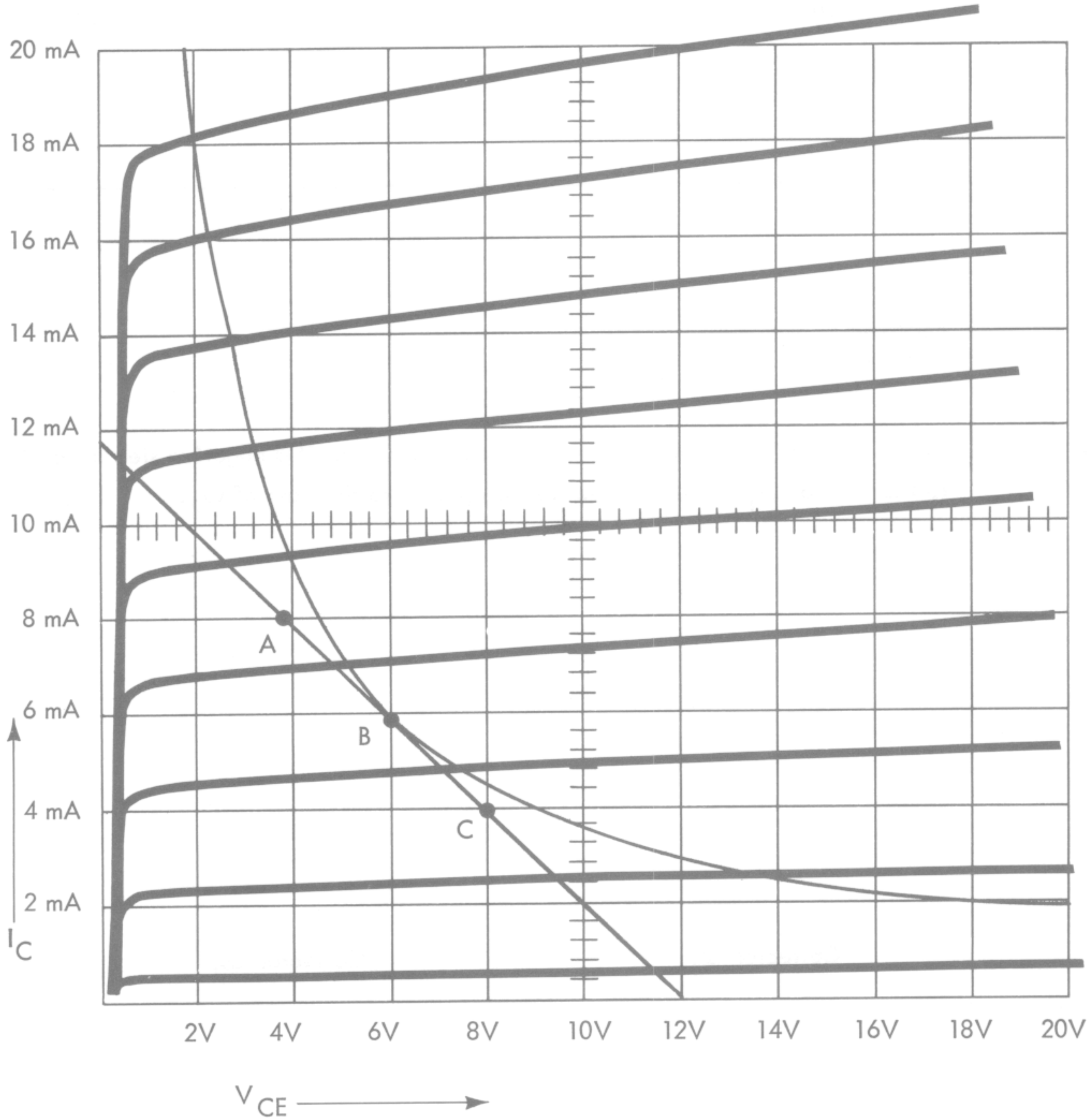
decrease
increase

10.5 Draw the resulting output waveform for each transistor if a negative step is applied to the base of Q_1 and a positive step is applied to the base of Q_2.

Collector Q_1 Collector Q_2

---

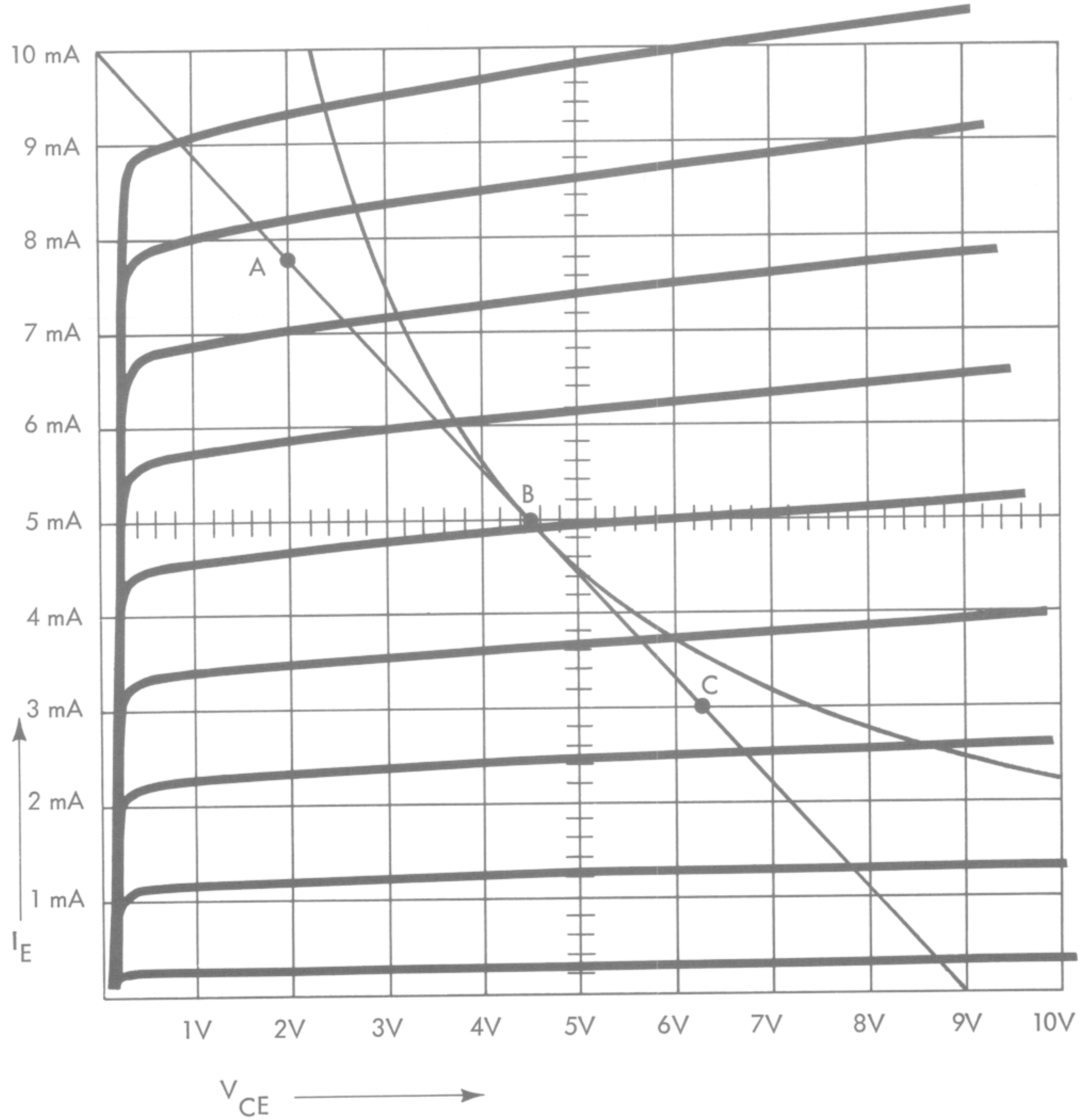
answer on next page



20 mA
18 mA
16 mA
14 mA
12 mA
10 mA
8 mA
6 mA
4 mA
2 mA
I
C
A
B
C
2V
4V
6V
8V
10V
12V
14V
16V
18V
20V
V
CE

Collector Q_1

Collector Q_2

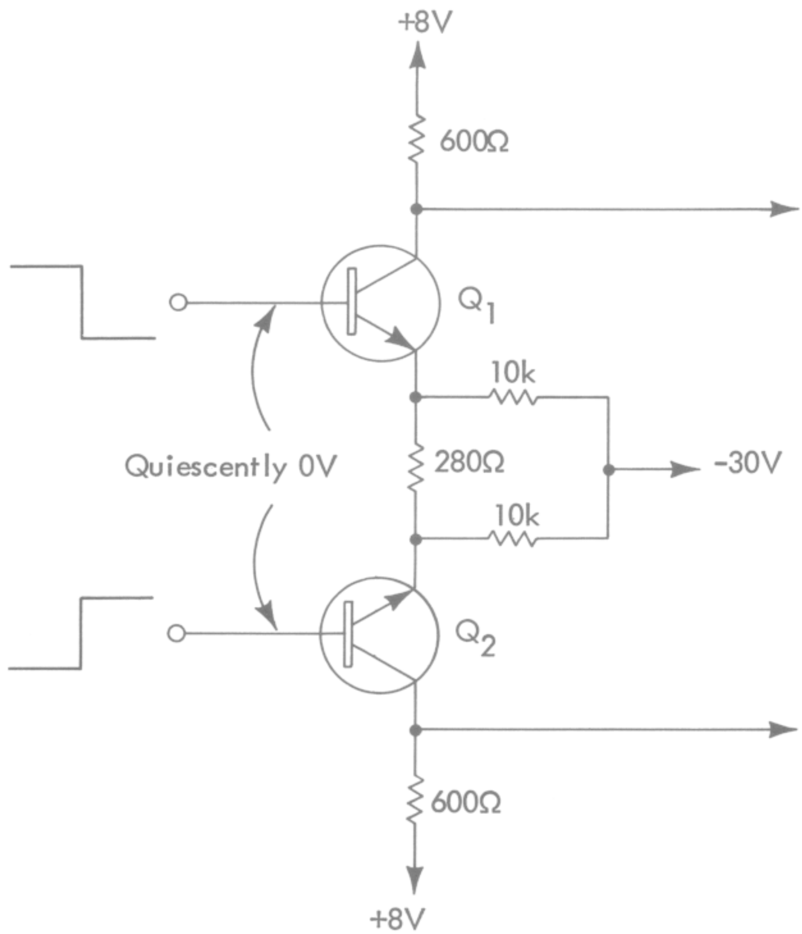

10 mA
9 mA
8 mA
7 mA
6 mA
5 mA
4 mA
3 mA
2 mA
1 mA
I_E
A
B
C
1V
2V
3V
4V
5V
6V
7V
8V
9V
10V
V_{CE}

10.6 Determine the quiescent V_c and I_c and determine the operating point on the curves on the facing page for the circuit below. Draw the output waveform at each collector.

$V_c \approx$ ____________V

$I_c \approx$ ____________mA

Operating at Point ____________



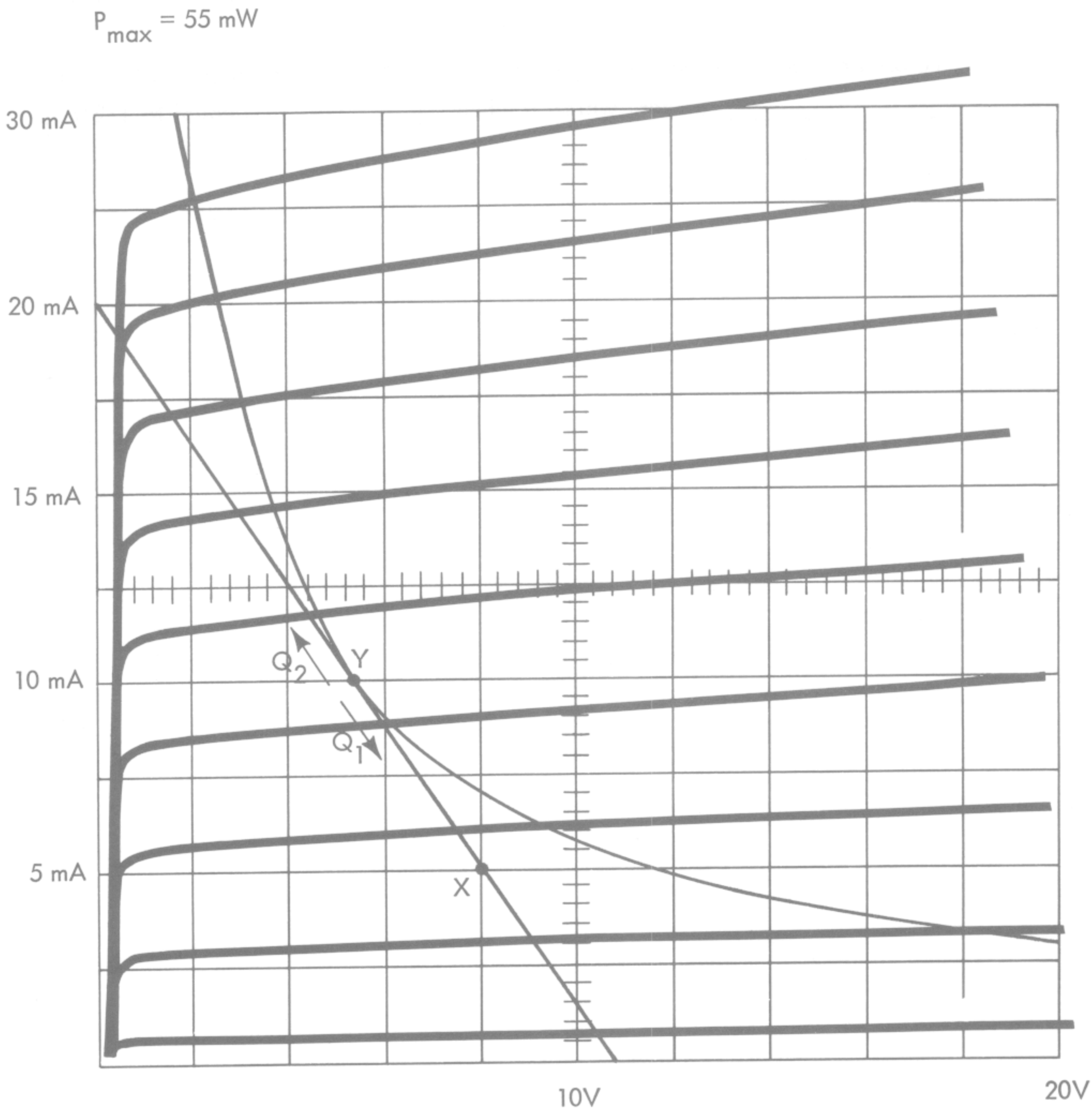
Collector Q_1 Collector Q_2

---

answer on next page

$V_c \approx 6.2V$
$I_c \approx 3\ mA$
Operating at Point C

11.0 To obtain thermal balance we operate the transistors in a push-pull circuit at _______________ power, which is when ____________ is equal to $1/2 V_{CC}$.



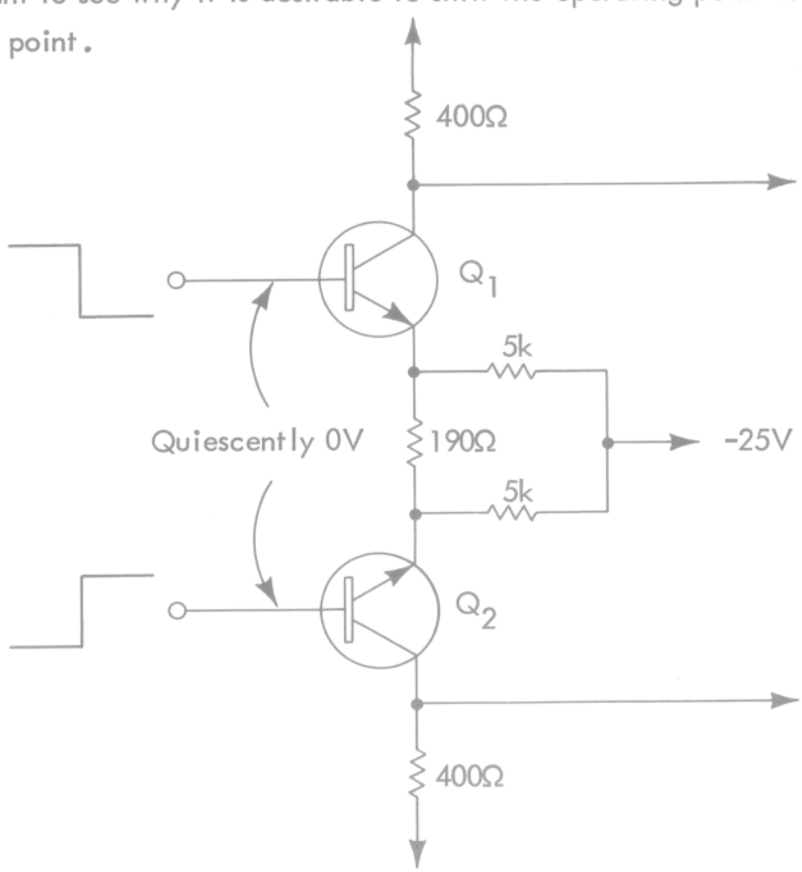
P$_{max}$ = 55 mW
30 mA
20 mA
15 mA
10 mA
5 mA
Y
X
Q$_2$
Q$_1$
10V
20V

Answer to Frame 11.0:

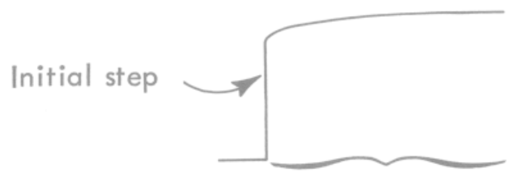
maximum
V_{CE}

Let's assume that the operating point for the transistors in the circuit below is point Y on the facing page curves rather than point X as we had in Set 10.

Note: In the next set we will determine how we shift the operating point. In this set we want to see why it is desirable to shift the operating point to the maximum power point.



If we apply a negative step to the base of Q_1, the operating point moves to a higher V_{CE} and a lower power. The collector waveform will look as below.

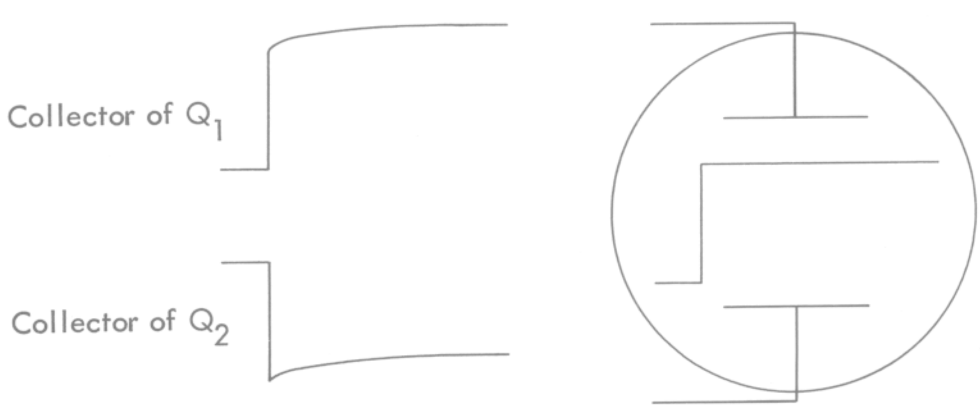


As the transistor cools, I_c will decrease because V_{EB} is held constant. V_c will increase and this waveform will result.

At the same time we apply a positive step to the base of Q_2. The operating point moves to a lower V_{CE} and again a lower power. The collector output waveform will look as below.

As the transistor cools I_c will again decrease because V_{EB} is held constant. V_c will increase and this waveform will result.

If we take the output from the circuit now the drift due to thermal effects will cancel one another. The circuit is said to be thermally balanced.



For any circuit, that transistor will always be dissipating maximum power for that circuit when the V_{CE} of the transistor is 1/2 the collector supply voltage, V_{CC}. To be thermally balanced the transistors in a push-pull circuit must have a V_{CE} of $1/2V_{CC}$ when balanced.

11.1 To be thermally balanced, the transistors in a push-pull circuit must be operating at ______________ circuit power.

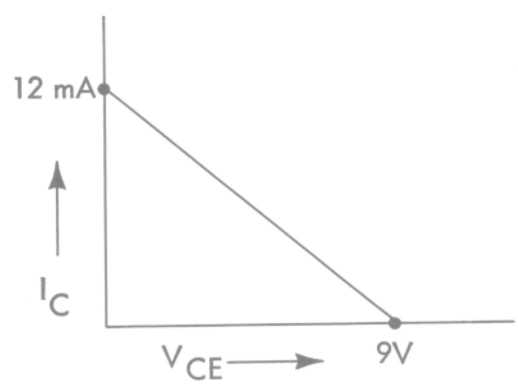
---

maximum

11.2 To operate at maximum power the V_{CE} of the transistors must be _________% of V_{CC} in a balanced condition.

50%

11.3 If the load line below was the load line for transistors in a push-pull circuit and the transistors were thermally balanced, the transistor operating point would be __________ volts V_{CE}.

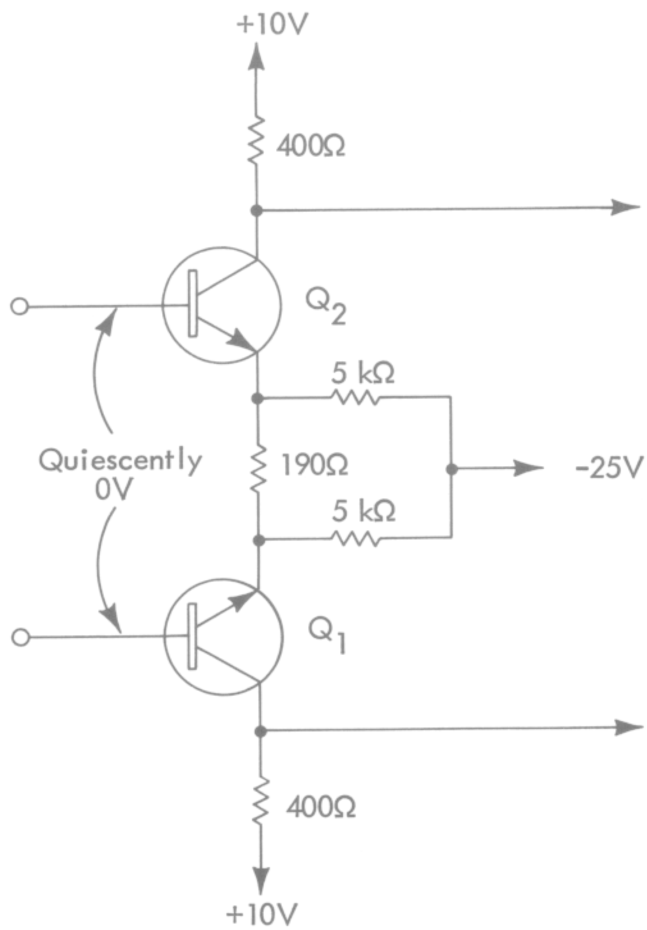


$V_{CE} = 4.5V$

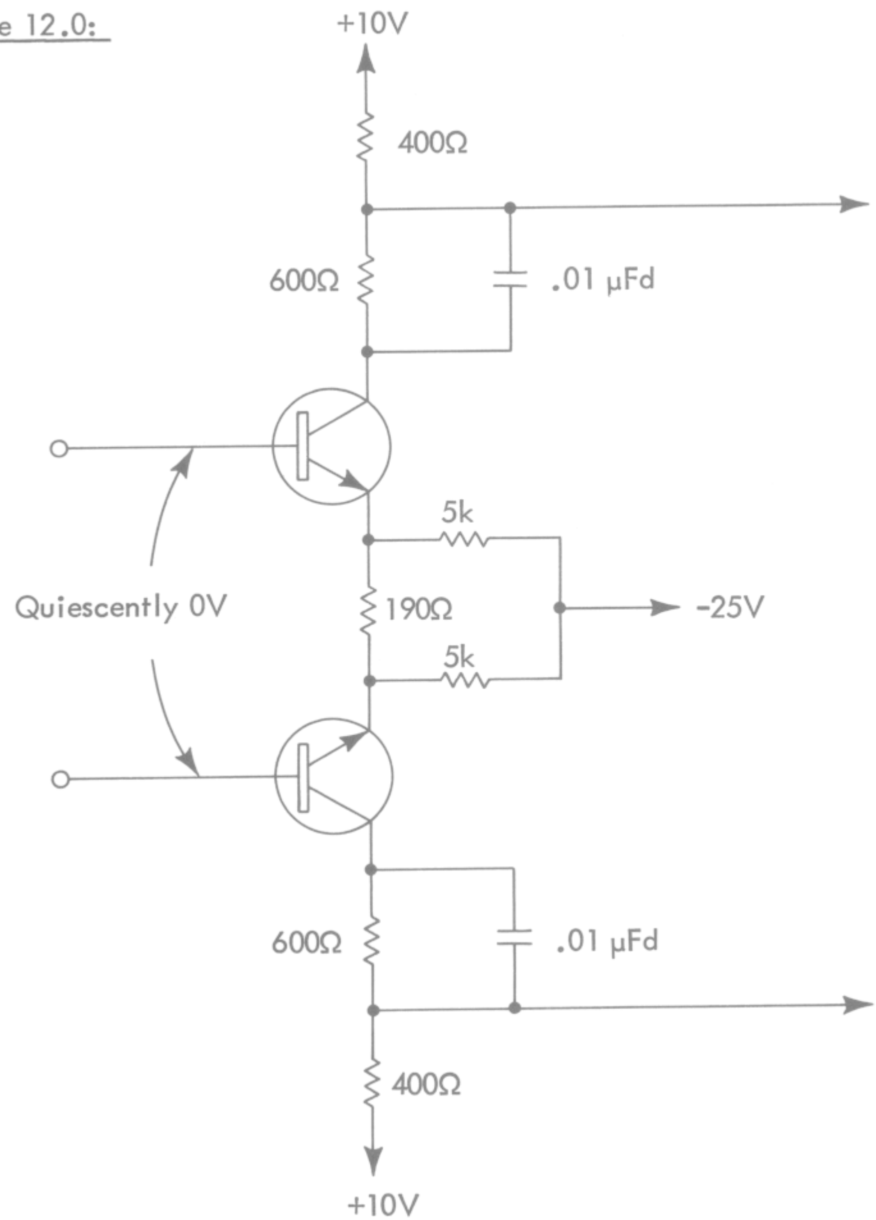
11.4 Assume that the V_{CC} to the transistors in a push-pull circuit is 14V, to operate the transistors at maximum power, we will operate at a V_{CE} of ________ volts. To be thermally balanced we will operate the transistors at a V_{CE} of ________ volts.

7V
7V

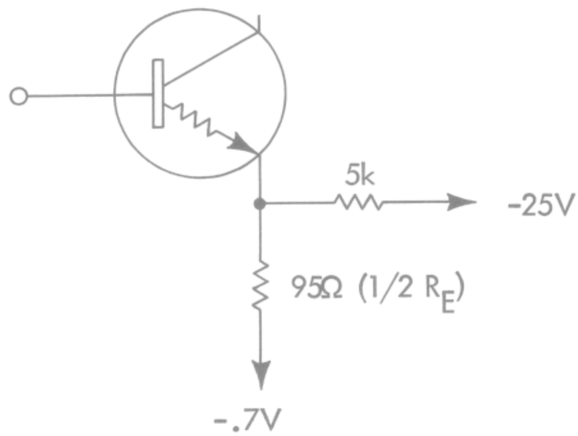
12.0 Thermally balance the transistors in the circuit below.



Answer to Frame 12.0:

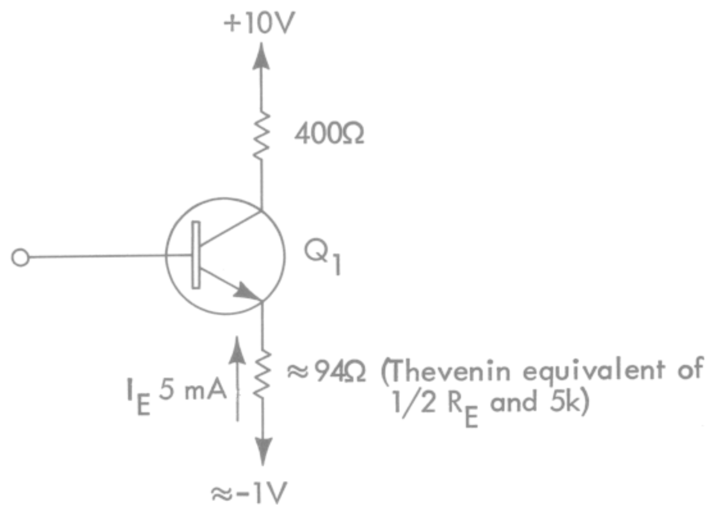


The first step in determining the value of the thermal balance resistor is to determine the V_{CC} to the circuit. The collector voltage of +10V is easily observed. The emitter voltage is not so obvious. To determine the emitter voltage we must remember that in a push-pull circuit each transistor is driven by the same amplitude signal but 180° out of phase. One end of R_E (190Ω) will move positive by the same amount; the other end moves negative. The center of the resistor is at an effective AC ground. With this in mind we can redraw the emitter circuit of Q_1 (see next page).



We are concerned with setting V_{CE} to 1/2 V_{CC} when the push-pull circuit is in a balanced state. In a balanced state there is no DC current through R_E. Therefore, the effective ground at the center of R_E will be at the same DC potential as the emitter of Q_1. If we have silicon transistors this will be -.7V since the base is at 0V.

At this point we can Thevenize the emitter circuit and simplify the circuit for Q_1 as below.



The V_{CC} of the circuit for Q_1 is then 11V.

The emitter current for Q_1 will remain 5 mA because it is conducting through the relatively large resistance of 5 kΩ (see facing page).

If the transistor is to drop 1/2 V_{CC} (5.5V), then the series resistance must drop the other 5.5V. From Ohm's Law the series resistance must be:

$$R = \frac{5.5V}{5\ mA} = 1.1\ k\Omega$$

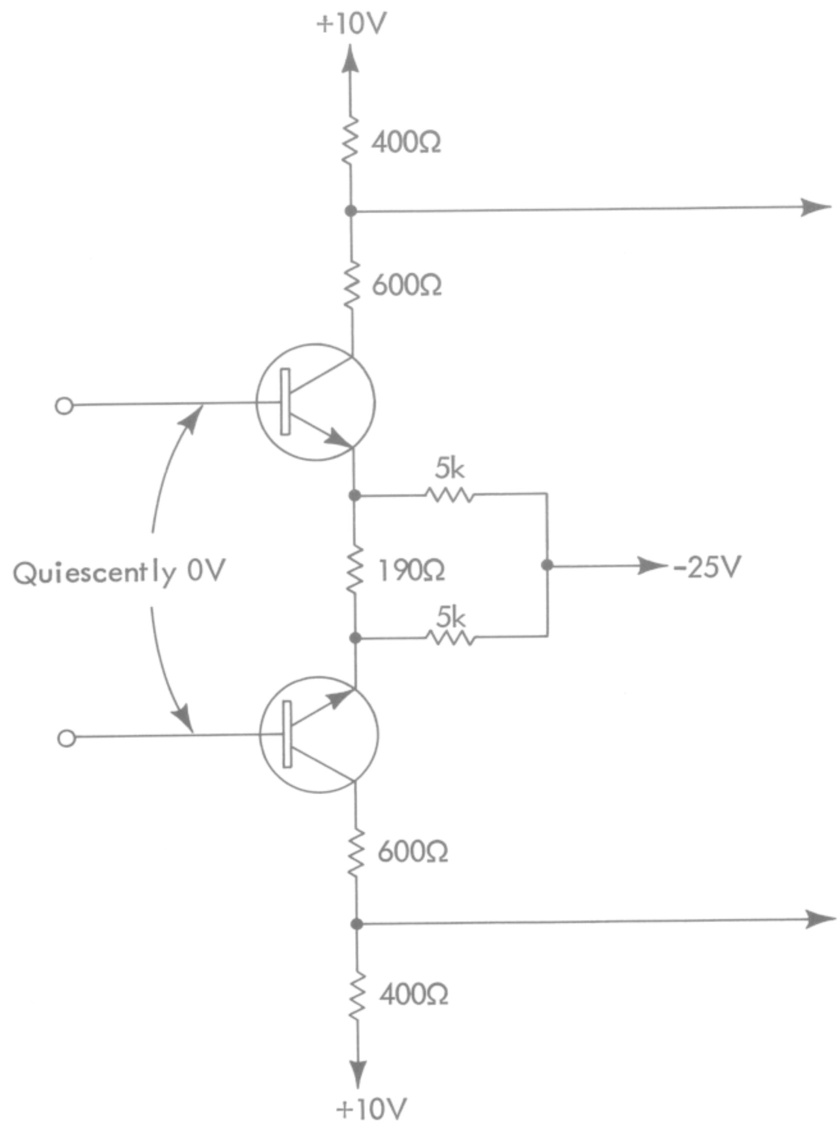
$R_L = 400\Omega$; $R_E = 94\Omega$. The thermal resistance must make up the difference.

$$R = 1.1\ k\Omega$$

$$R_L + R_E = 494\Omega$$

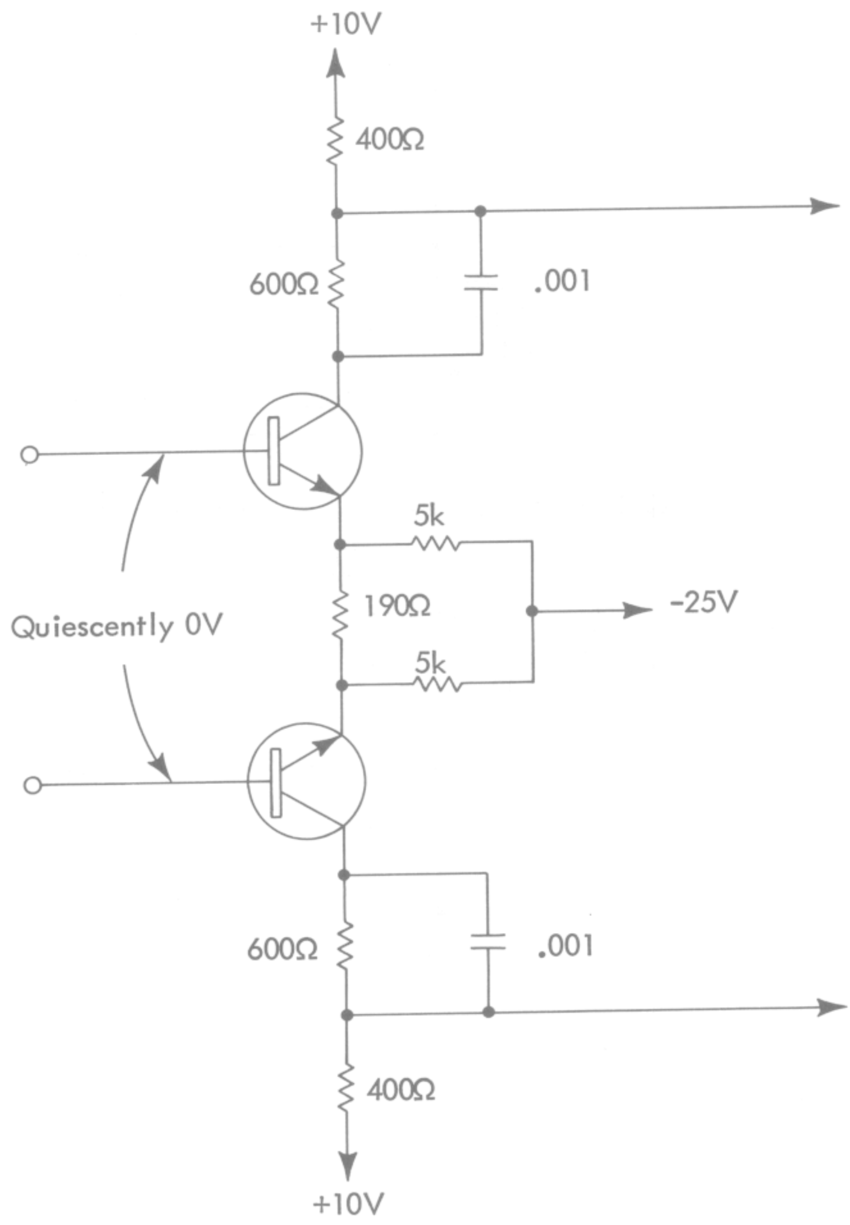
$$R_{Thermal} = 606\Omega \text{ or } \approx 600\Omega.$$

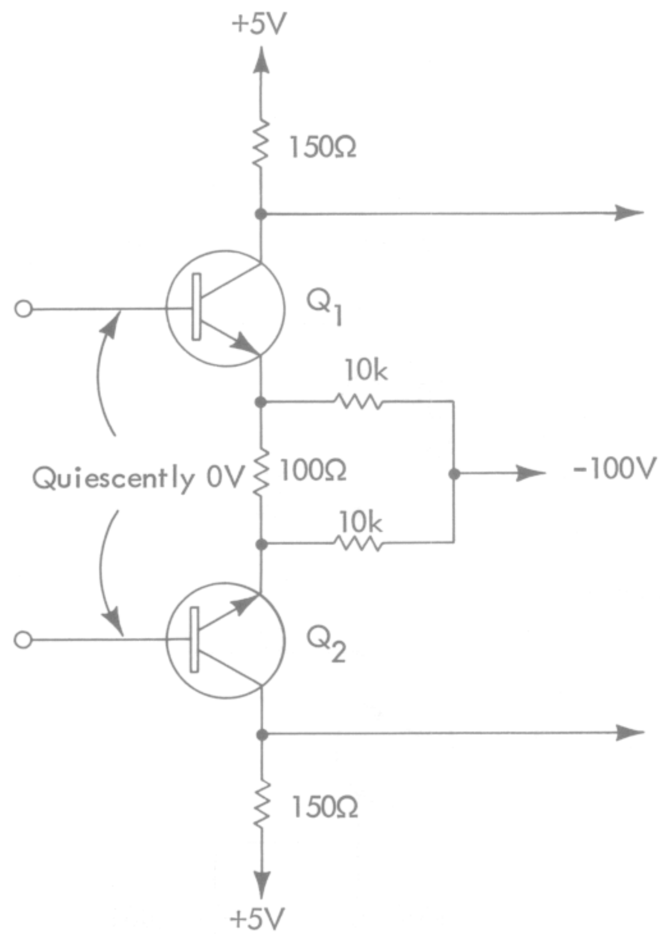
Since the circuit for Q_2 is the same as for Q_1, we also add a 600Ω resistor to the collector circuit of Q_2. The circuit now looks as below.



The voltage gain of the stage is the same because the output is developed across only the 400Ω collector resistors. The voltage gain at the collectors of the transistors has more than doubled however. This doesn't affect the low frequency operation of the circuit but the high frequency performance will be impaired because of increased Miller effect.

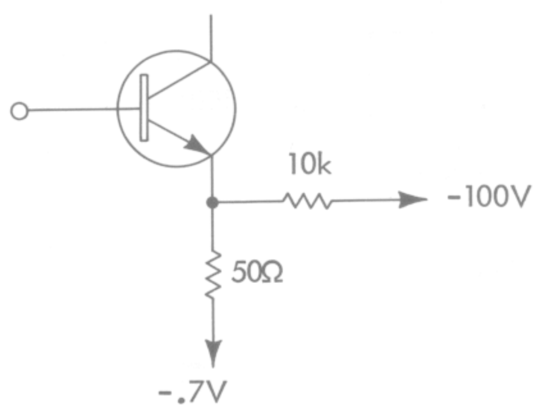
We therefore supply an AC bypass capacitor (.001 μFd) around the thermal balance resistor and have the final circuit as below.





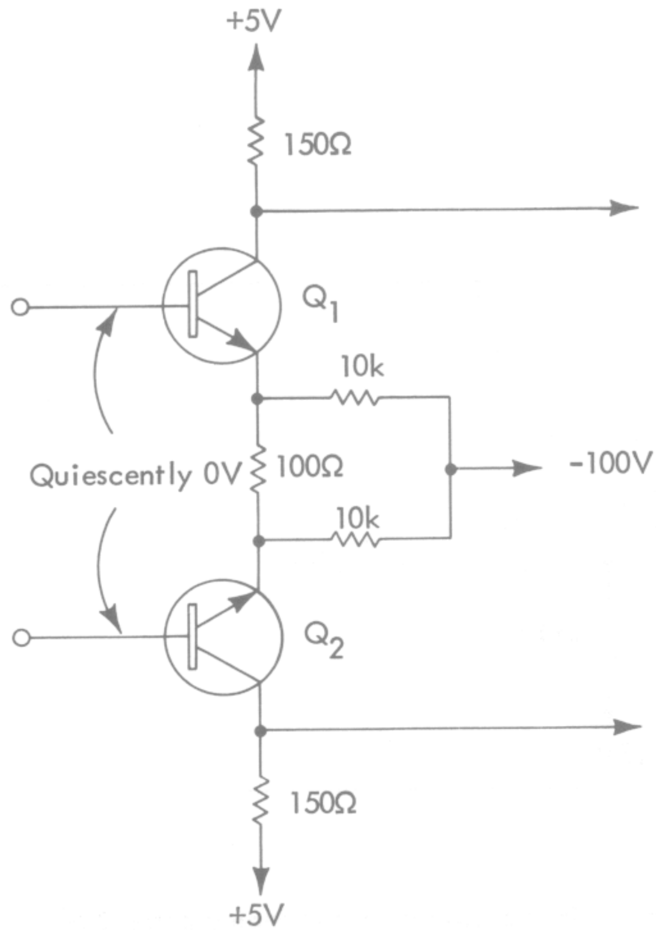
+5V
150Ω
Q1
10k
Quiescently 0V
100Ω
-100V
10k
Q2
150Ω
+5V

12.1 Draw the emitter circuit for Q_1 in the circuit on the facing page, assuming Q_1 is a silicon transistor



12.2 The V_{CC} for Q_1 in the circuit on the facing page is ≈________ volts.

≈6 volts


+5V
150Ω
Q_1
10k
Quiescently 0V
100Ω
-100V
10k
Q_2
150Ω
+5V

12.3 The emitter current through Q_1 is ________ mA.

---

10 mA

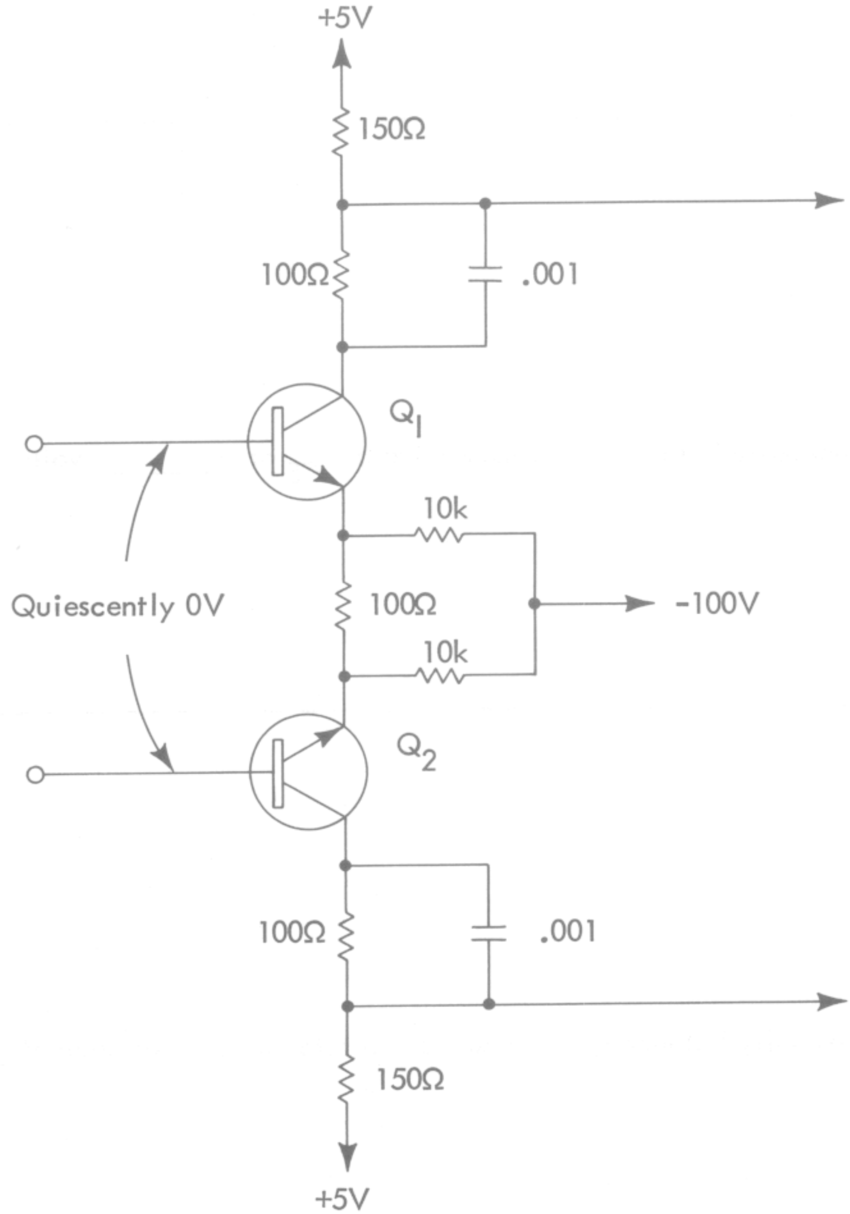
12.4 To be thermally balanced, Q_1 must have a V_{CE} of ________ volts.

---

3 volts

12.5 To be thermally balanced, Q_1 must have a total series resistance of ____________ ohms.

$$R_{Total} = \frac{3V}{10\ mA} = 300\Omega$$


+5V
150Ω
100Ω
.001
Q1
10k
Quiescently 0V
100Ω
-100V
10k
Q2
100Ω
.001
150Ω
+5V

12.6 To thermally balance Q_1, then, we must add a resistor between the collector and the 150Ω R_L of ________ ohms.

300Ω - 200Ω (sum or R_E (50Ω) and R_L (150Ω) = 100Ω

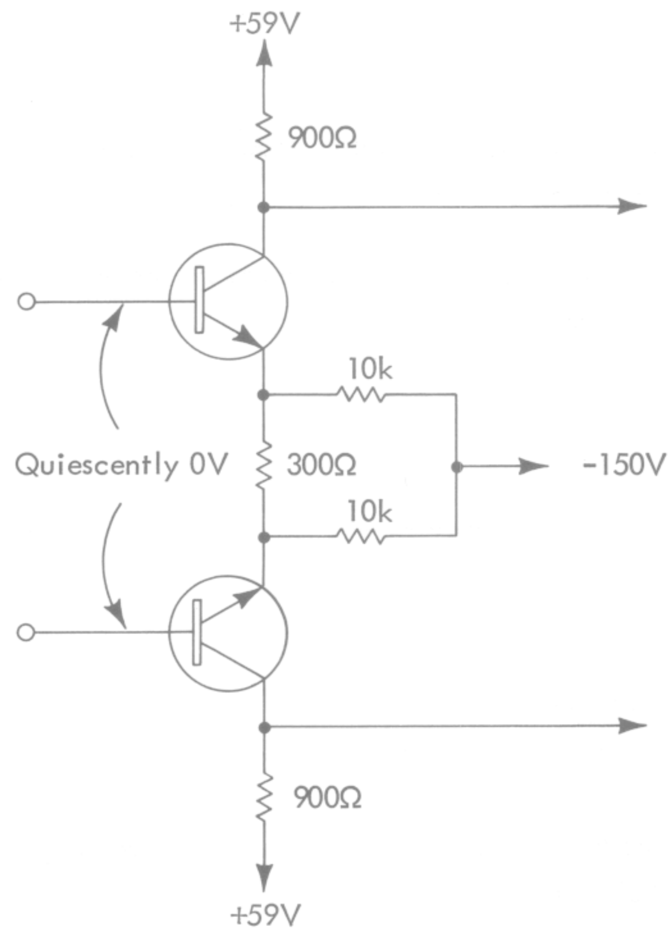
12.7 To thermally balance Q_2 we must add a resistor between the collector and the 150Ω R_L of ________ ohms.

100Ω (it has the same circuit as Q_1)

12.8 To improve the high frequency performance we place a ____________ in shunt with the thermal balance resistor.

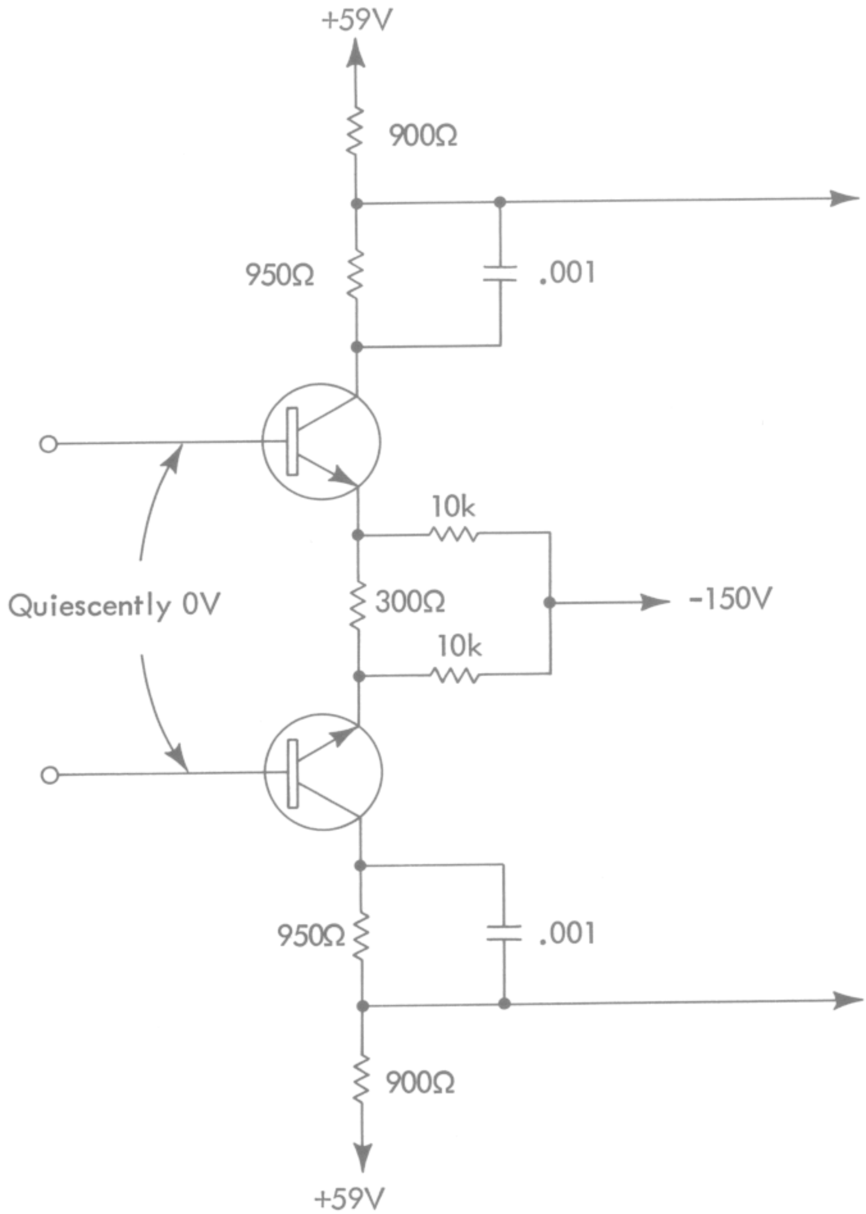
---

capacitor


+59V
900Ω
10k
Quiescently 0V
300Ω
-150V
10k
900Ω
+59V

12.9 Redraw the circuit on the facing page with the thermal balance components added.

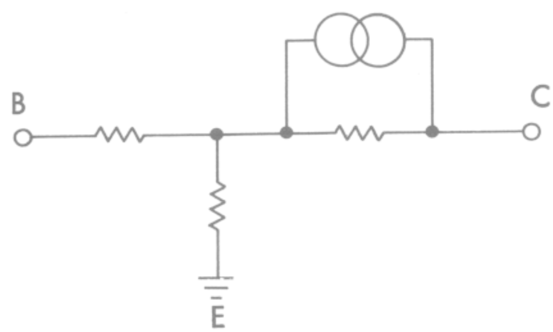
answer on next page



+59V
900Ω
950Ω
.001
10k
Quiescently 0V
300Ω
-150V
10k
950Ω
.001
900Ω
+59V

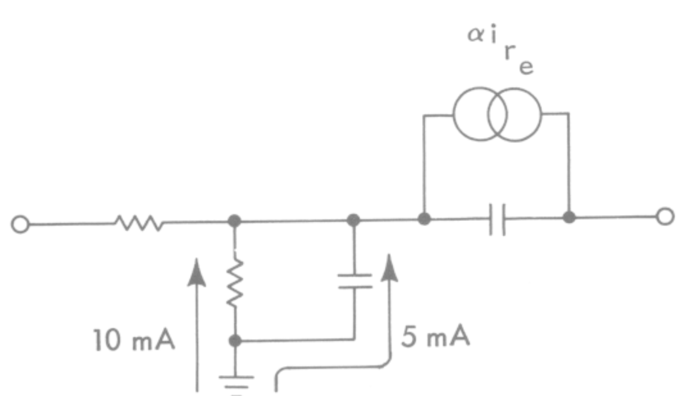
POST TEST

1. Change the transistor low frequency equivalent circuit below to a high frequency equivalent circuit and label the parts.



2. In the manufacturing of a transistor, improving f_T will usually result in an increase in ______________________.

3. If we assume an α of .98 in the transistor below, the current in the collector current generator, αi_{r_e}, is ____________ mA.



4. As the resistance of the signal source to a common emitter transistor circuit is increased, the high frequency performance of that circuit will

______________________.
increase/decrease/remain the same

5. As the collector load resistor (R_L) is increased, the gain of a common emitter circuit will ______________________ and the high
increase/decrease/remain the same

frequency performance will ______________________.
increase/decrease/remain the same

6. To reduce collector capacitance (C_c), we would ____________ base to
increase/decrease

____________ voltage.

7. By increasing emitter current we improve the high frequency performance because ______________ is reduced.

8. Even though the f_t of one transistor is higher than that of another, the high frequency performance may be poorer because of a substantially increased

________________.

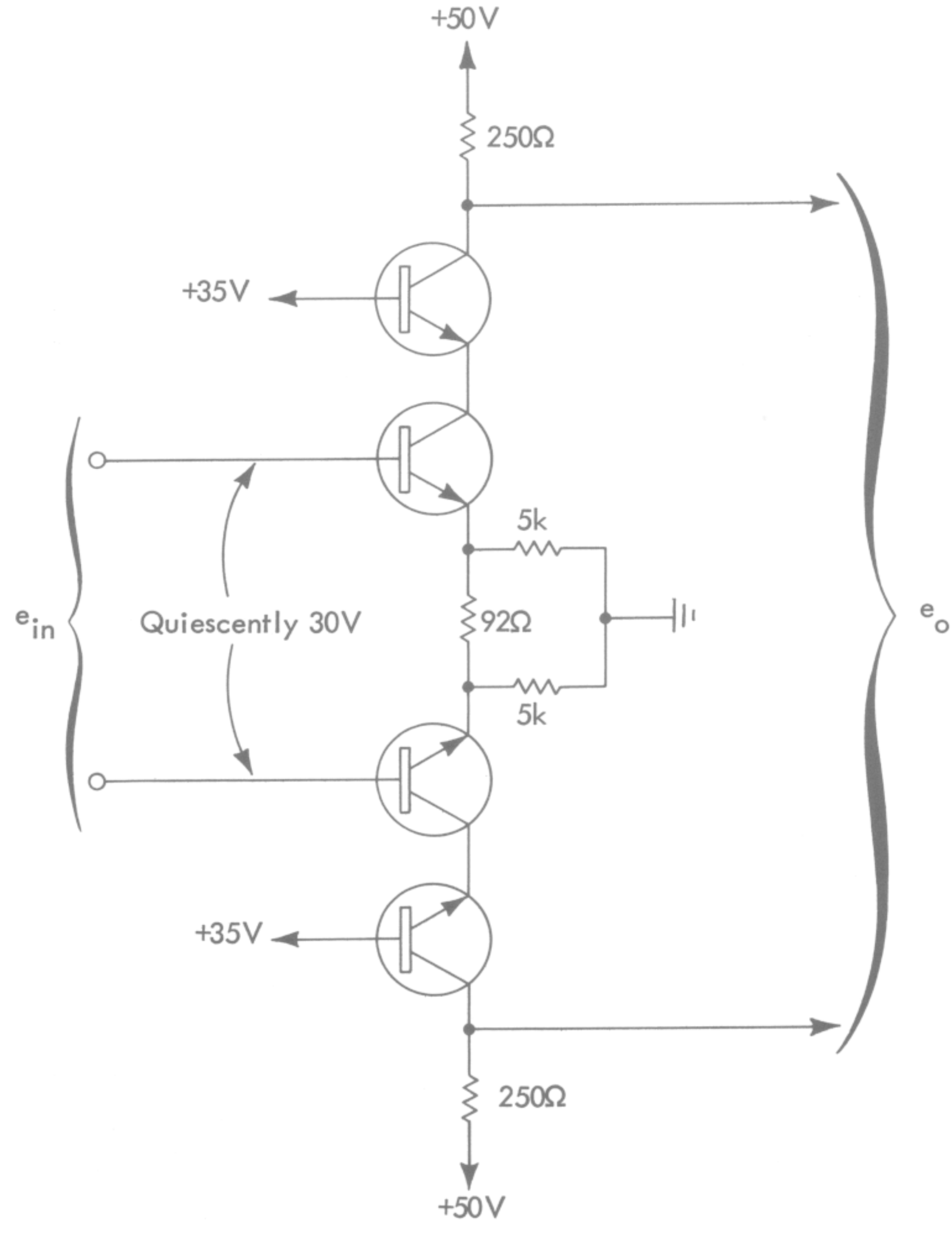
9. The common base configuration has ______________________ high
better/poorer/about the same

frequency performance than/as the common emitter configuration.

10. An advantage of a cascoded push-pull amplifier stage over a common emitter push-pull amplifier stage is better high frequency performance. This is because it eliminates nearly all the ____________ ______________ from the common emitter section.

11. Determine the voltage gain in the cascoded amplifier stage below.

$A_v \approx$ ____________________



12. The high frequency performance of the common collector circuit, like the common emitter circuit, is limited by the higher input impedance. From the input the emitter base resistance (r_e) is seen as ______________ times its actual value.

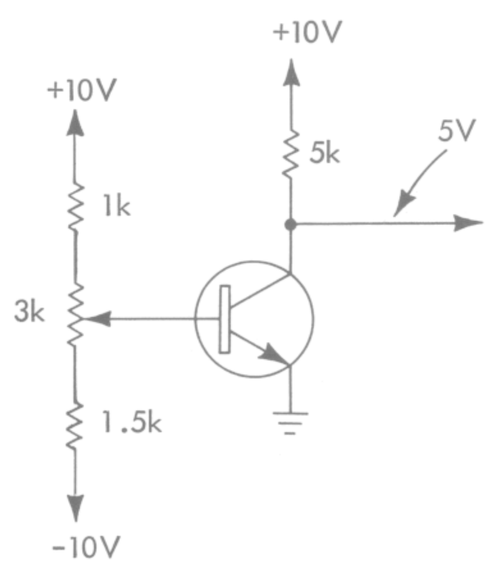
13. In all three transistor configurations, the high frequency performance is improved by operating the transistor at a ____________ V_{CB} and a ____________ I_E.
large/small   large/small

14. A minimum amount of power is dissipated by a transistory when operated in a ________________ mode switching circuit.

15. The maximum switching rate of a switching circuit is increased if the transistors are operated in a ____________________ mode switching circuitt because ________________ time is removed from the switching time.

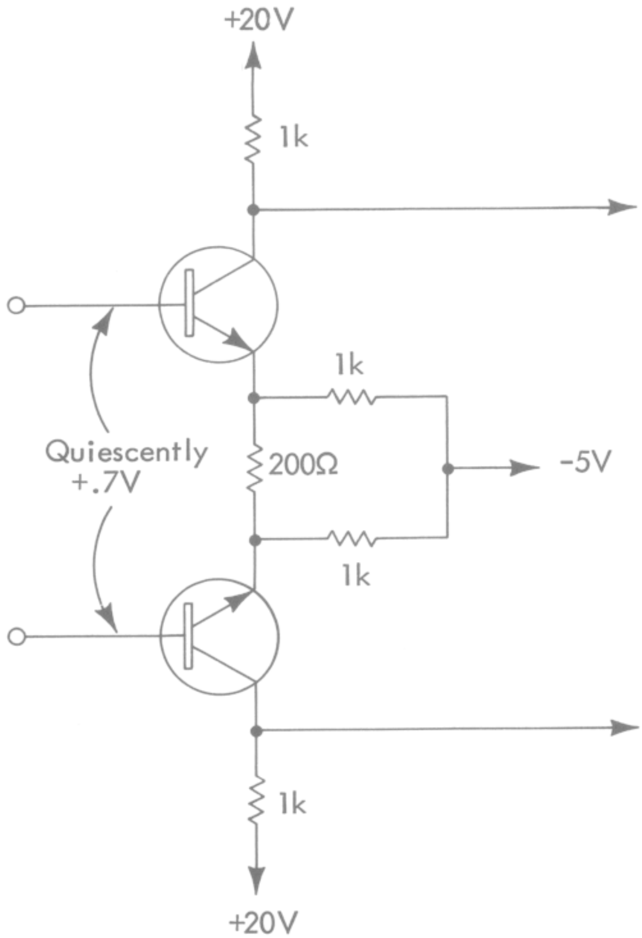
16. $V_{CE\ (sat)}$ is an important transistor parameter in a ____________________ mode switching circuit.

17. Add components to the circuit below that will stabilize the DC output voltage against ambient temperature changes.



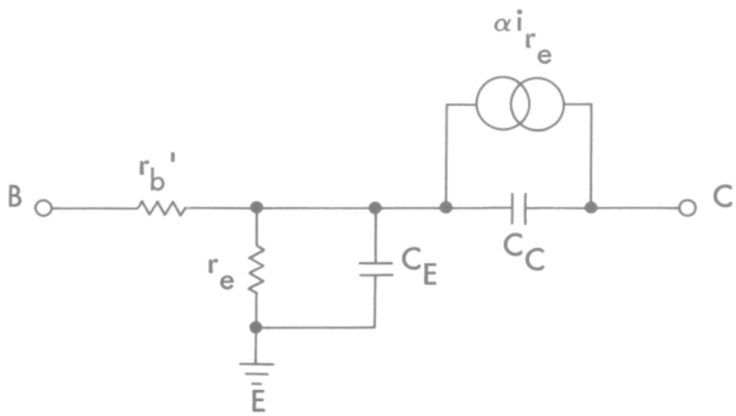
18. To thermally balance a push-pull transistor circuit, the transistor ________________ is one-half V_{CC}.

19. Thermally balance the push-pull transistor circuit below.



POST TEST ANSWERS

1.



2. r_b'

3. 9.8 mA

4. decrease

5. increase
   decrease

6. increase
   collector

7. r_e $\left(\downarrow r_e = \frac{26}{I_E \uparrow}\right)$

8. r_b'

9. better

10. Miller capacitance

11. $A_v \approx 5$

12. β

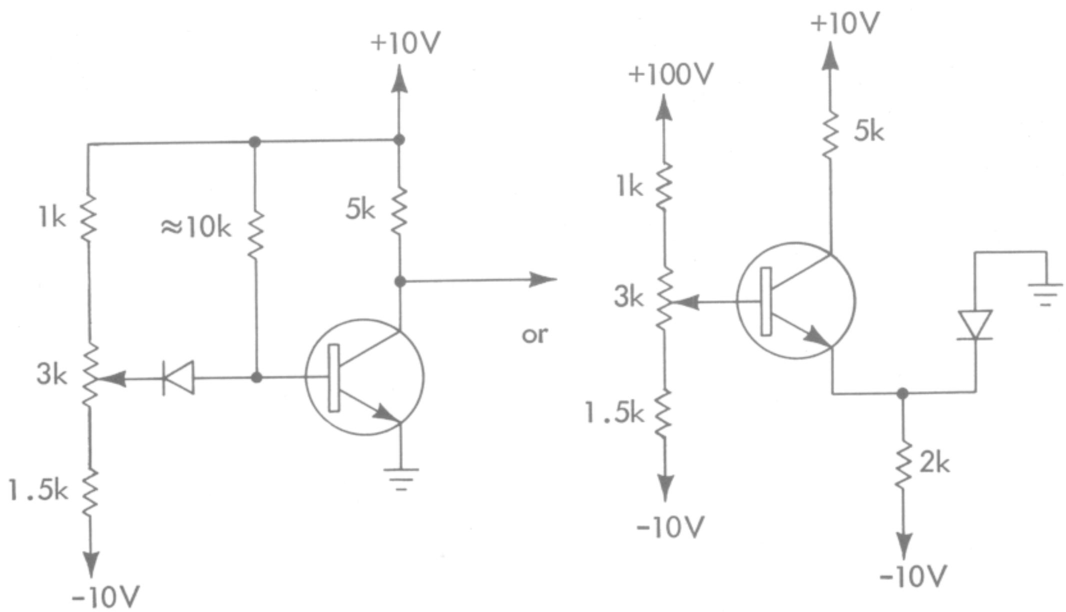
13. large
large

14. saturated

15. current
storage

16. saturated

17.



18. V_{CE}

19.