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MICROELECTRONIC ENGINEERING

BJT IC Design

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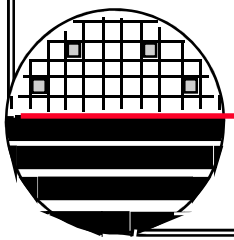
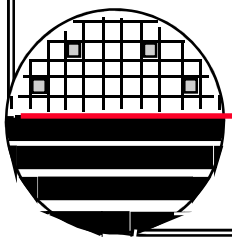
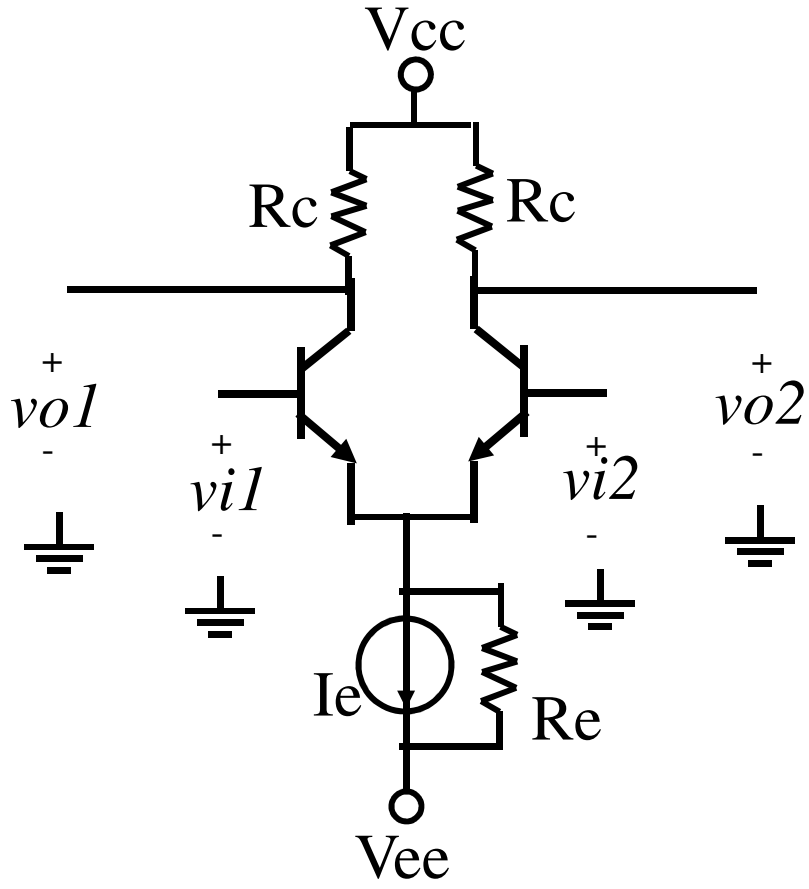


OUTLINE

Differential Amplifier
Biasing, Current Sources, Mirrors
Output Stages
Operational Amplifiers
References
Homework Questions

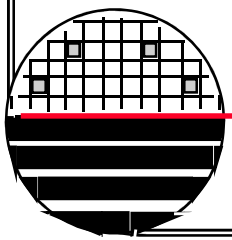


DIFFERENTIAL AMPLIFIER

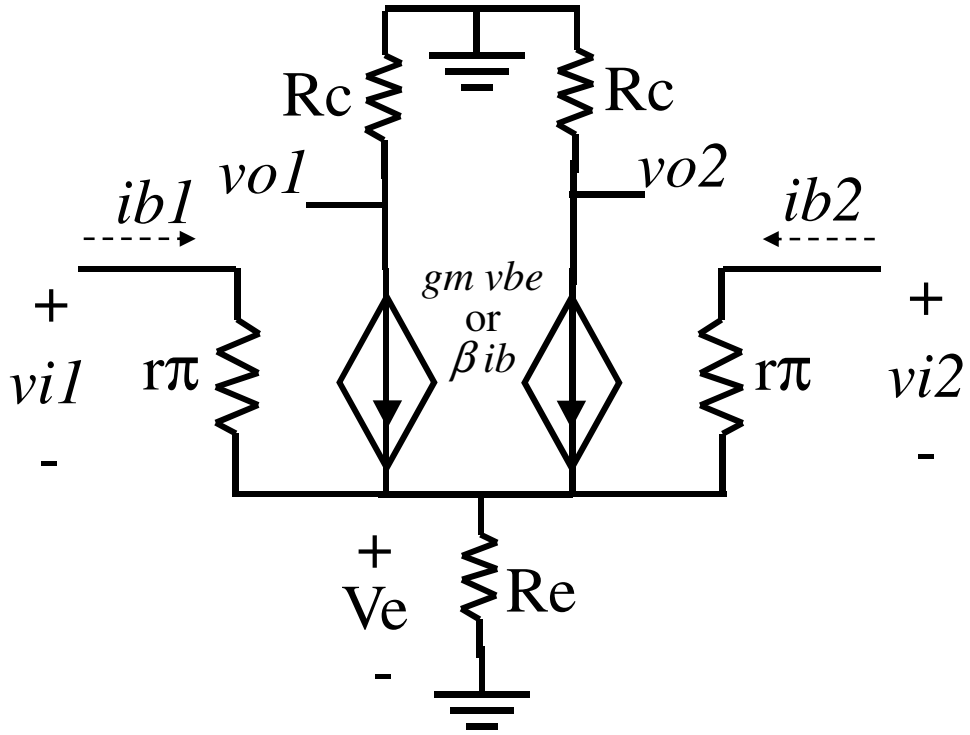


DC Analysis – assume:
Identical transistors,
Re=infinite, vin1=vin2=0

Then
Ic1=Ic2=Ie/2
Vo1=Vo2=Vcc-Rc Ie/2



SMALL SIGNAL ANALYSIS



Lets define:

Differential input voltage

$vid = vi1 - vi2$

Common input voltage

$vic = (vi1 + vi2)/2$

Differential Output Voltage

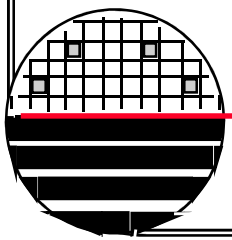
$Vod = Vo1 - Vo2$

Common output voltage

$Voc = (Vo1 + Vo2)/2$

Single sided output voltage

$Voss = Vo1 \text{ or } Vo2$



VOLTAGE GAINS: Avd, Avc, CMRR

Differential mode voltage gain, Avd = *Vod / vid*

Let $vin1 = vid/2 + \overset{0}{vic}$ and $vin2 = -vid/2 + \overset{0}{vic}$

$Ib1 = (vin1 - Ve) / r\pi$ $\qquad$ $Ib2 = (vin2 - Ve) / r\pi$

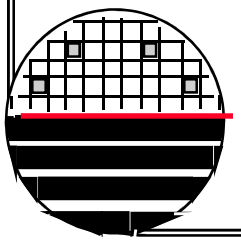
$Ib1 = (vid/2 - Ve) / r\pi$ $\qquad$ $Ib2 = (-vid/2 - Ve) / r\pi$

$Vo1 = - \beta\ ib1\ Rc$ $\qquad$ $Vo2 = - \beta\ ib2\ Rc$

$Vod = Vo1 - Vo2 = - \beta\ ib1\ Rc - - \beta\ ib2\ Rc$

$Vod = (\beta\ Rc / r\pi)\ (vid/2 + vid/2)$

$$Avd = - \frac{\beta\ Rc}{r\pi}$$



VOLTAGE GAINS: Avd, Avc, CMRR

Common Mode Voltage Gain Avc = Voc/Vic = $\dfrac{(Vo1 + Vo2)/2}{(vin1 + vin2)/2}$

Let Vid = 0 thus vin1 = vin2 = Vic

$Ve = 2\,Re\,(\beta + 1)\,ib$

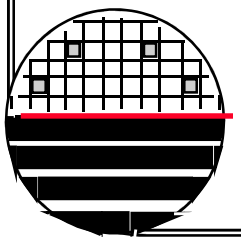
$ib = (Vic - Ve) / r\pi$

$ib = \dfrac{Vic - 2\,Re\,(\beta+1)ib}{r\pi}$ Rearranging; $ib = \dfrac{Vic}{2\,Re\,(\beta+1) + r\pi}$

$Voc = \dfrac{-\beta\,ib1\,Rc + -\beta\,ib2\,Rc}{2}$ and ib1 = ib2

Thus $Voc = -\beta\,Rc\,ib = \dfrac{-\beta\,Rc\,Vic}{2Re\,(\beta+1) + r\pi}$

$$Avc = \frac{Voc}{Vic} = \frac{-\beta\,Rc}{2Re\,(\beta+1) + r\pi}$$



OTHER RESULTS

Single Sided Output Differential Voltage Gain:

$$\frac{Voss}{Vid} = 1/2 \; \frac{-\beta \, Rc}{r\pi}$$

note: half

Single Sided Output Common Mode Voltage Gain:

$$\frac{Voss}{Vic} = \frac{-\beta \, Rc}{2Re\,(\beta+1) + r\pi}$$

note: same

Common Mode Rejection Ratio: CMRR is a figure of merit used to compare differential amplifiers

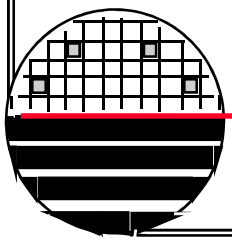
$$CMRR = \frac{Avd}{Avc}$$

Differential Mode Input Resistance:

$$Rid = 2\, r\pi$$

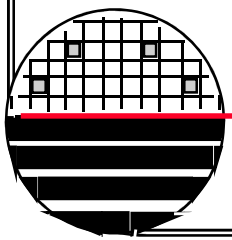
Common Mode Input Resistance:

$$Ric = r\pi + (\beta+1)\, 2\, Re$$



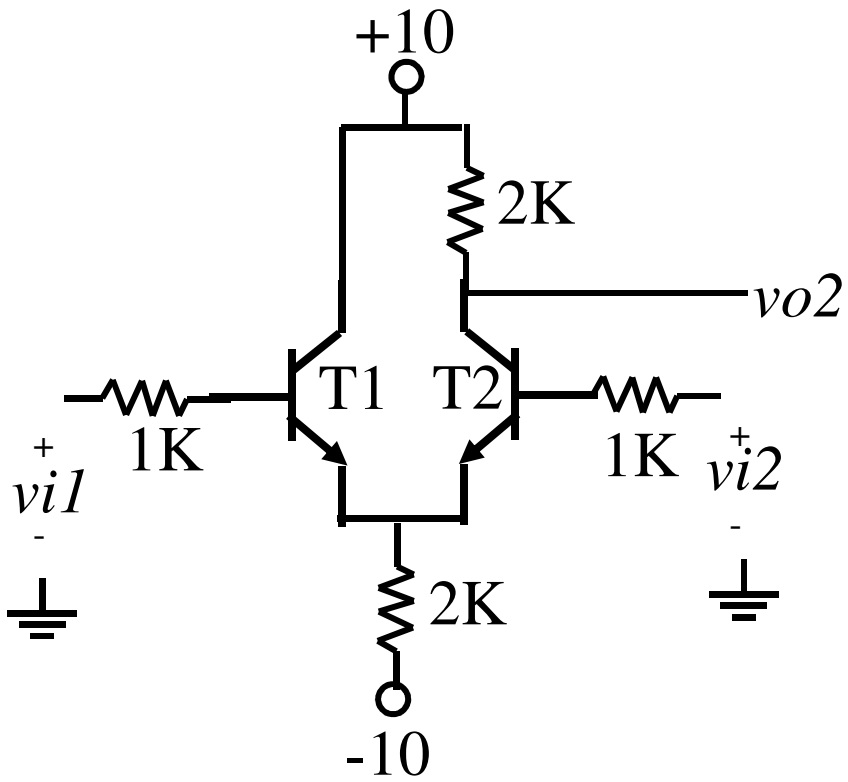
VARIATIONS

Variations:
1. Resistor between emitter and –Vee rather than current source
2. Series base resistors
3. Emitter resistors
4. Various types of current sources
5. Darlington configuration
6. FET's
7. Single sided outputs
8. Active loads
9. unbalanced or non symmetrical circuits



EXAMPLE DIFFERENTIAL AMPLIFIER

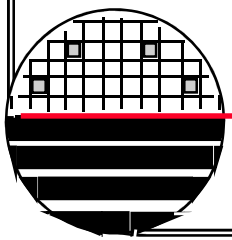
Analyze the following differential amplifier, β=200



SOLUTION TO EXAMPLE ON PREVIOUS PAGE

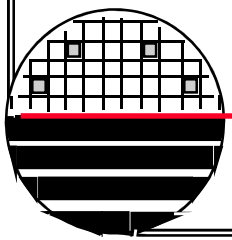
DC Analysis:

Small Signal Analysis:

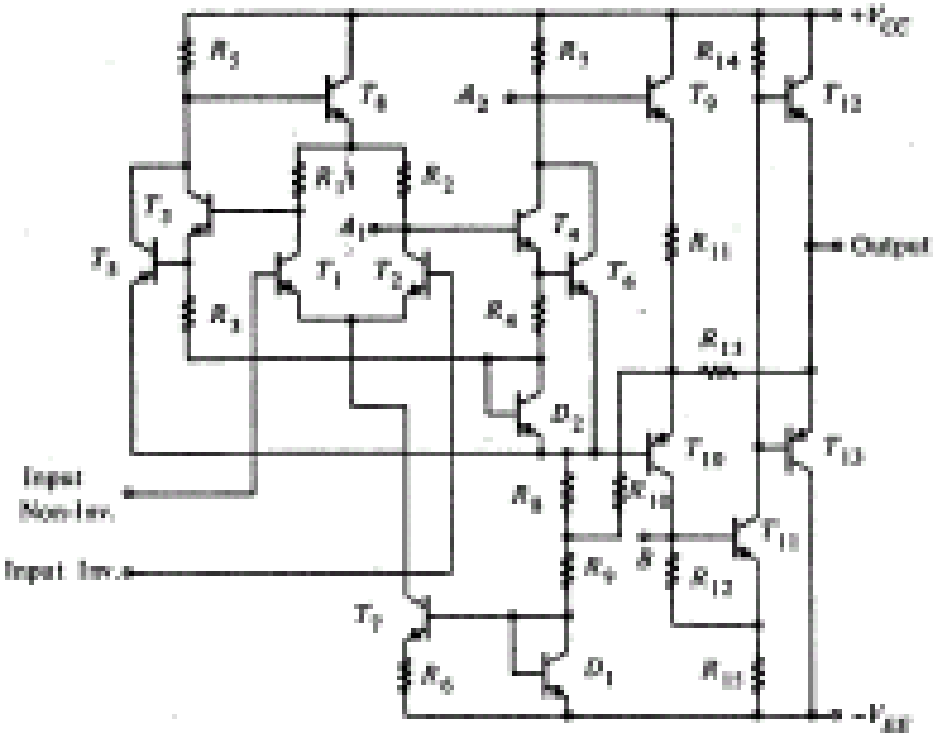


SUMMARY

1. The differential amplifier should amplify the difference between the two input voltages.
2. The differential amplifier should suppress signals that are common to both inputs.
3. The differential amplifier with a constant current source is superior to the differential amplifier with just a resistor.
4. The common mode rejection ratio is used as a figure of merit for comparison.
5. The differential amplifier is a dc amplifier as well as an ac amplifier.



709 OPERATIONAL AMPLIFIER



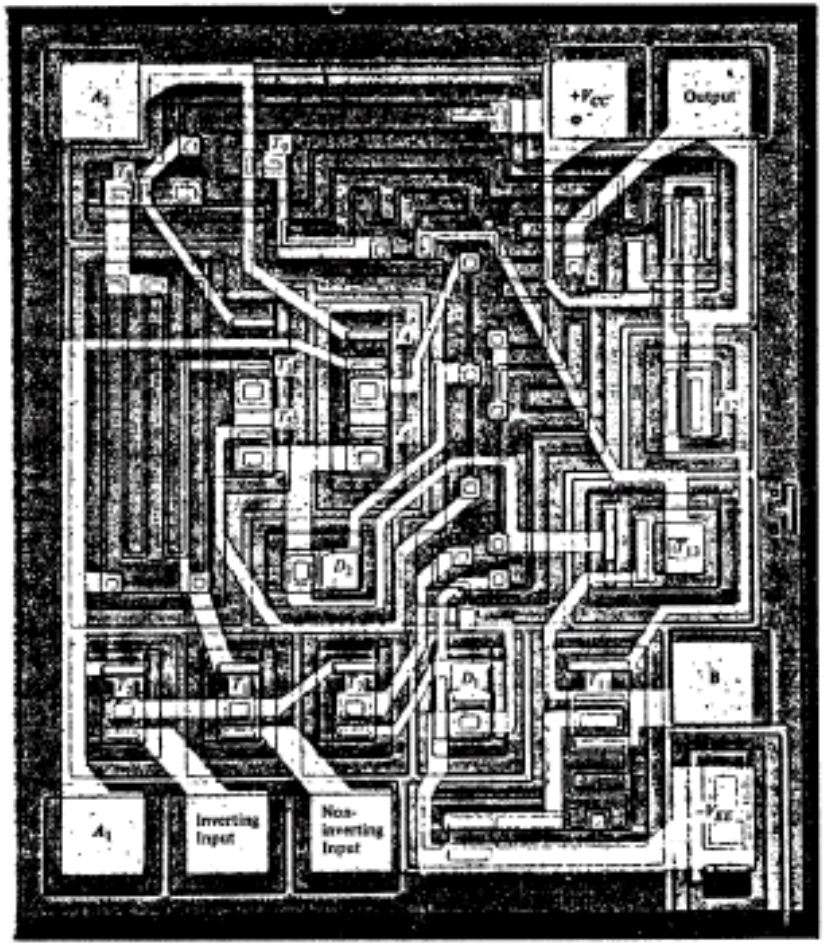
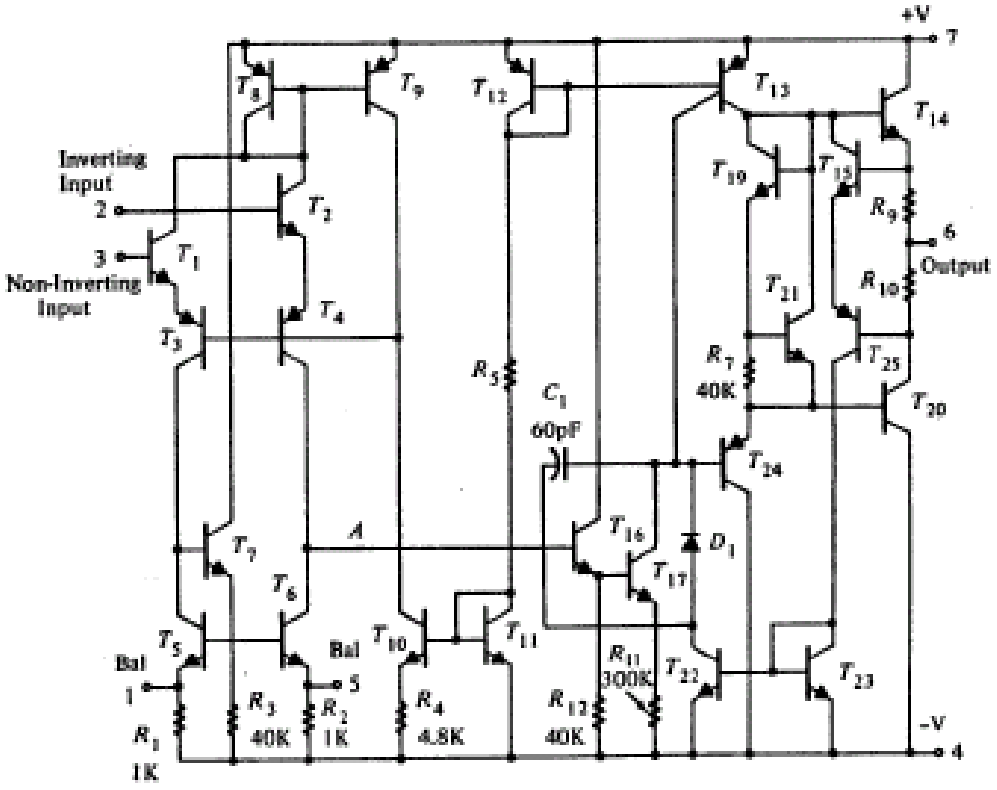
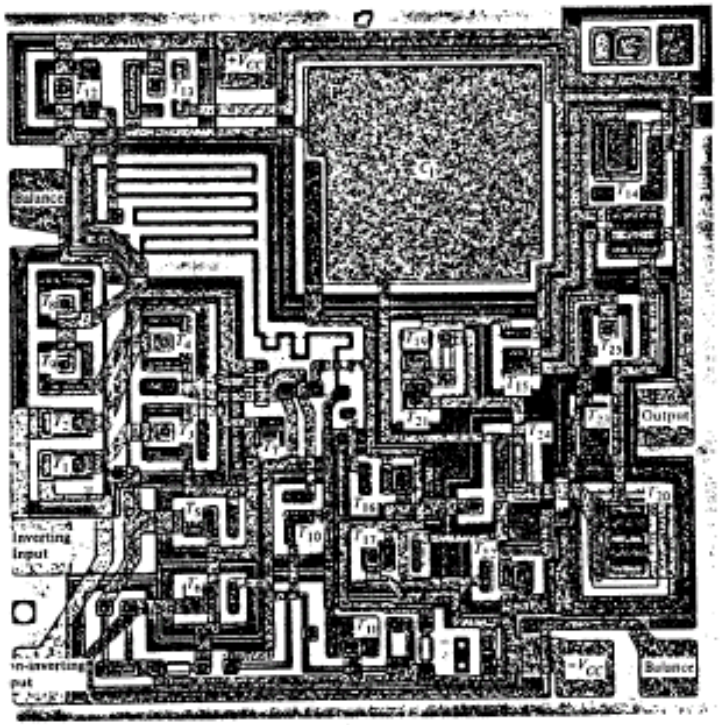


Figure 5.21 Circuit layout for the 709 operational amplifier. (*Photo: Fairchild.*)

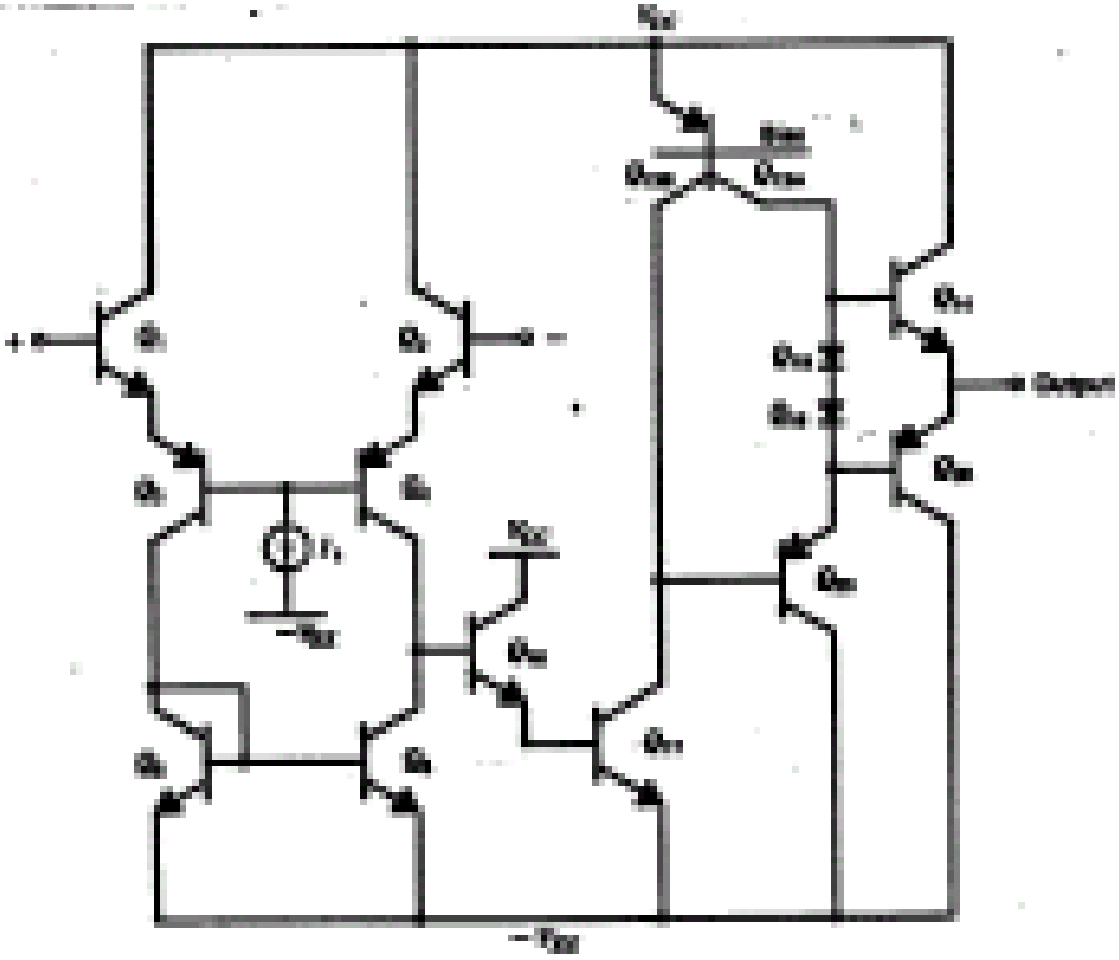
741 OPERATIONAL AMPLIFIER





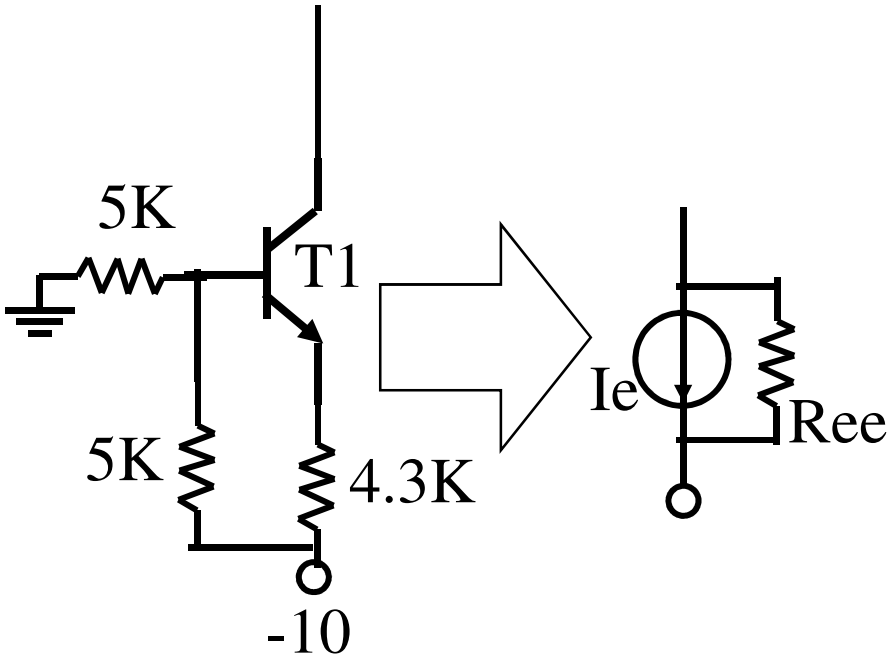
ure 5.23 Photomicrograph of the 741 operational amplifier. Die size: 56 mils are. (*Photo: Fairchild.*)

SIMPLIFIED 741 OP AMP SCHEMATIC

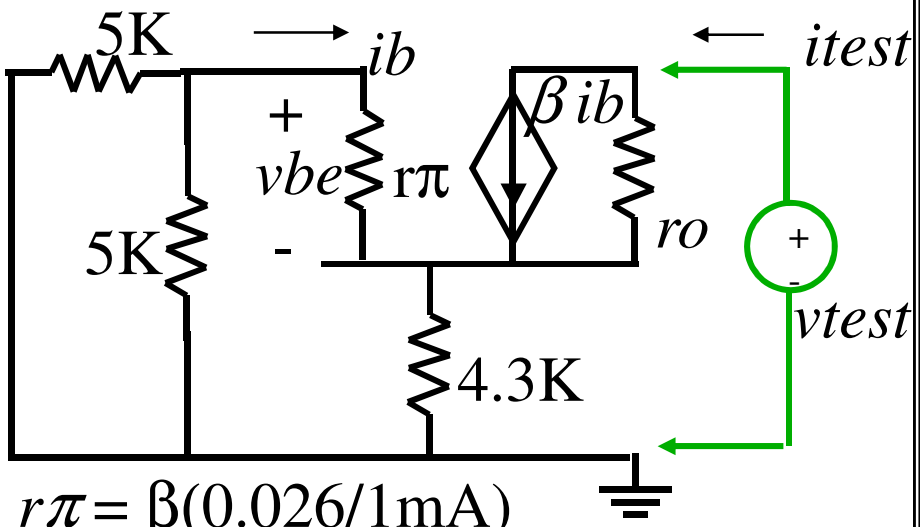


CURRENT SOURCE

There are many types of current sources. Consider the following:



What is Ie? (Ans: 1mA)

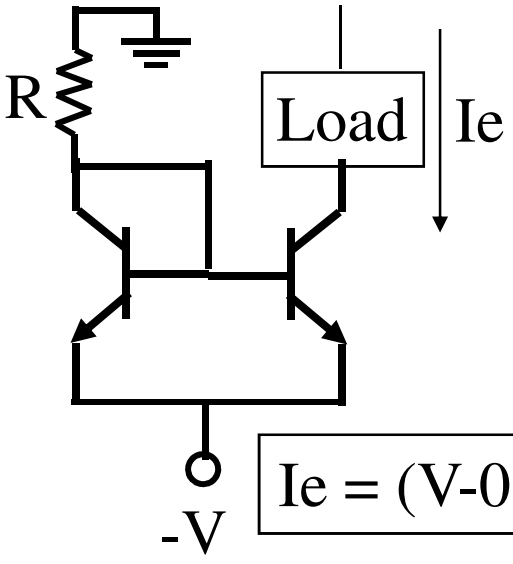


$r\pi = \beta(0.026/1mA)$
$= 100\ (26) = 2.6K$

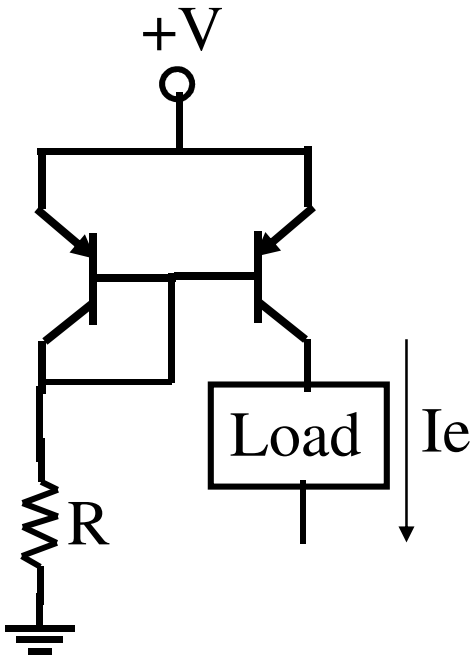
Ree = infinity if ro = zero

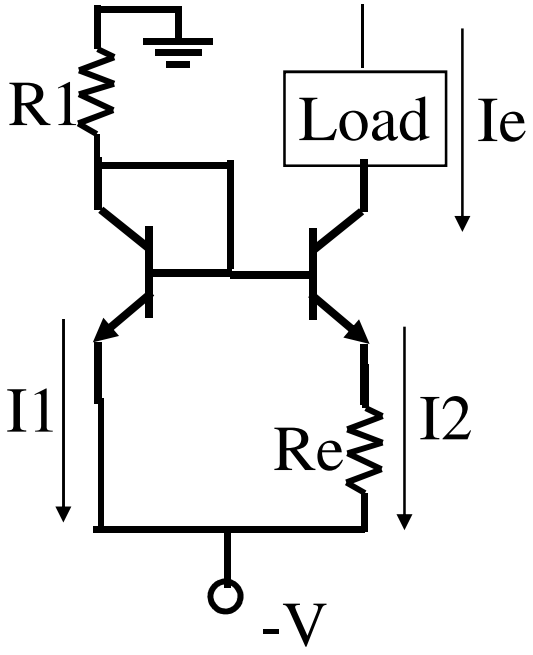
Ree in this example is 4.68 Meg if β = 100 and *ro* = 100K

CURRENT SOURCES, SINKS and MIRRORS



$$Ie = (V-0.7)/R$$





$$Vbe1 = Vbe2 + I2Re$$

$$KT/q \ln I1/Is = KT/q \ln I2/Is + I2Re$$

$$KT/q \ln(I1/I2) = I2Re$$

note: I2 is always smaller than I1

EXAMPLES FOR CURRENT SOURCE

Example 1: suppose I1 = 1 mA and I2 is 10 uA find Re

$$KT/q \ln(I1/I2) = I2Re$$

$$0.026 \ln (1mA/10uA) = 10uA\ Re$$

$$0.1197 = 10uA\ Re$$

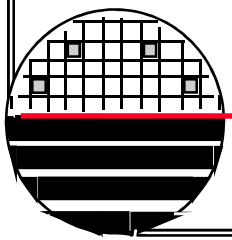
$$Re = 11.97K$$

Example 2: suppose I1 = 1 mA and Re = 20K find I2

$$KT/q \ln(I1/I2) = I2Re$$

$$0.026\frac{\ln(1mA/I2)}{I2} = 20K$$

Try I2 =	Left Side =
1uA	179K
5uA	27.6K
6uA	22.2K
7uA	18.4K
Etc.	



MORE CURRENT SOURCES

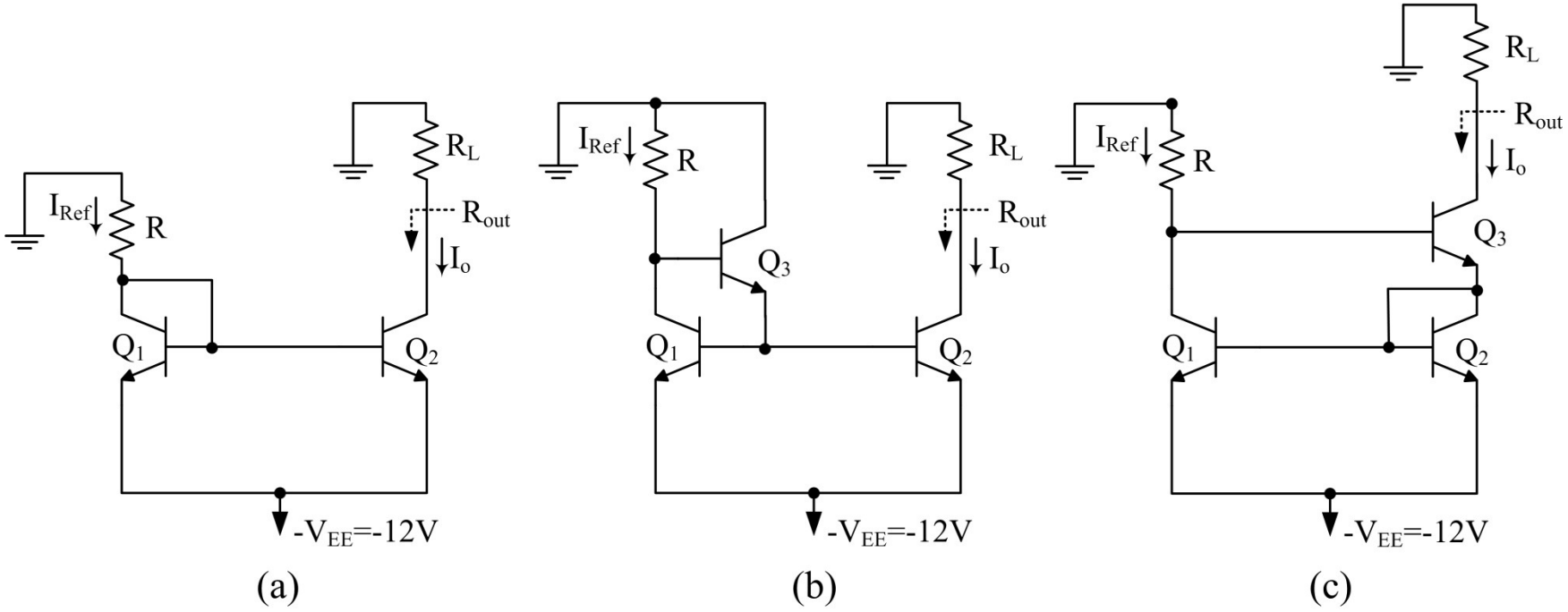
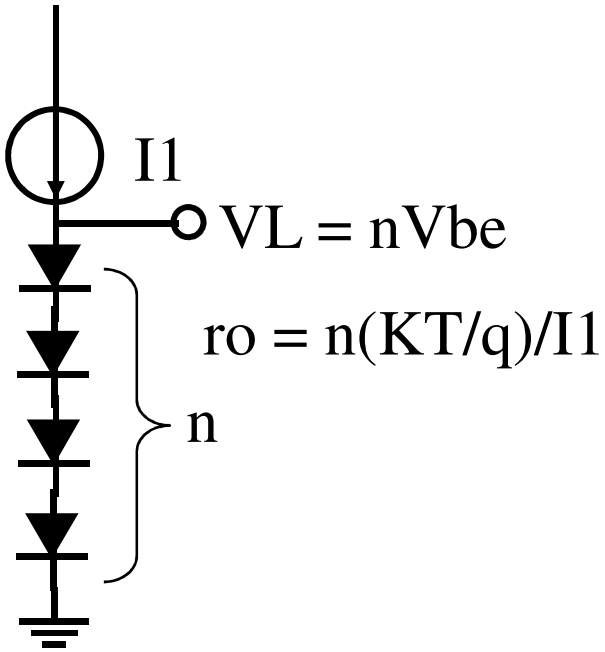


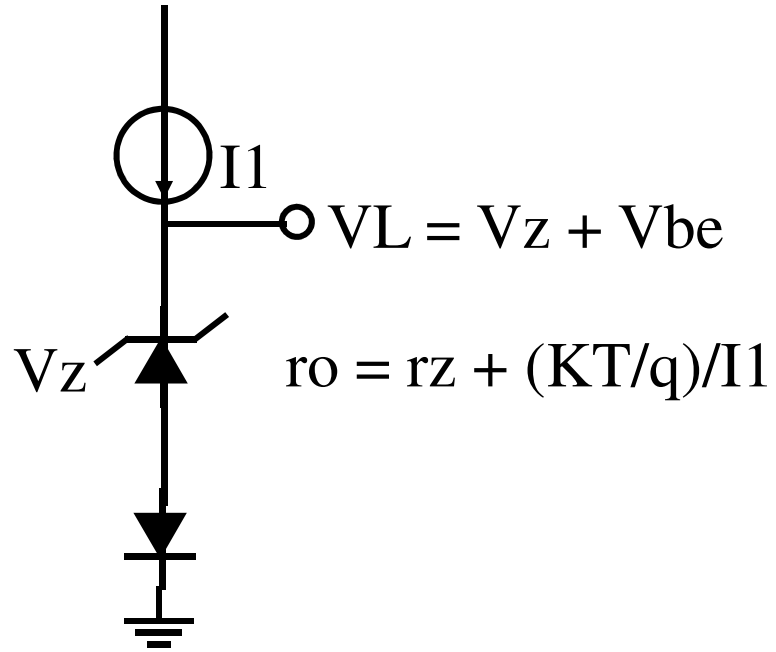
Figure 1. (a) Basic, (b) Current-buffered, and (c) Wilson current sources.

$$I_o = I_s e^{(qV_{BE}/kT)}\left(1+\frac{V_{CE}}{|V_A|}\right)$$

VOLTAGE SOURCES / REFERENCES

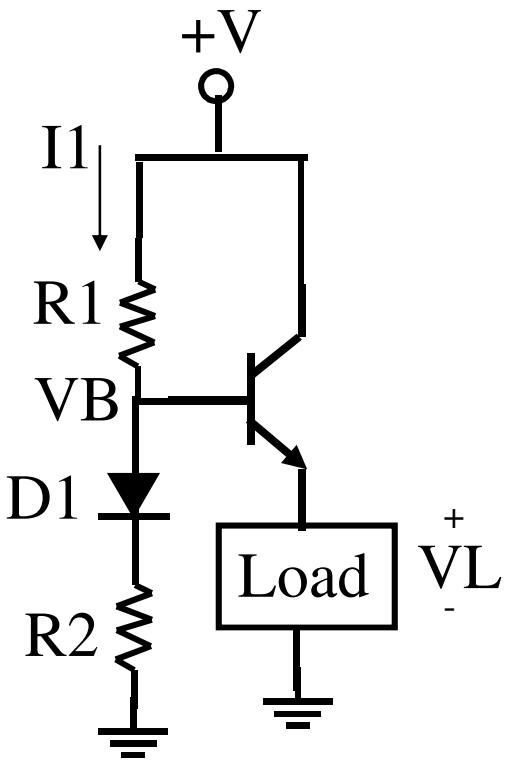
Voltage sources should have constant voltage and zero source resistance.





dVL/dT = dVz/dT +dVbe/dT

VOLTAGE SOURCES



Assume Ib is small compared to I1

$VL = VB - 0.7$

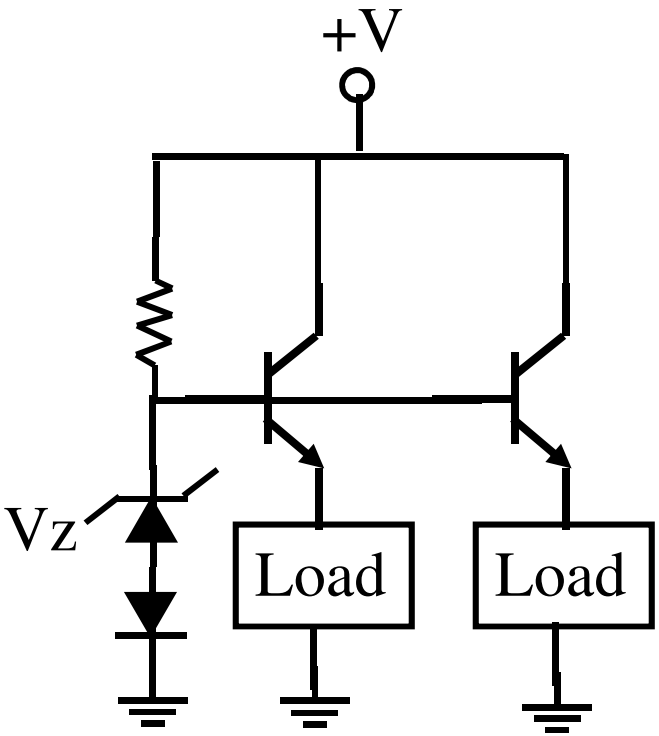
$VB - 0.7 = (V-0.7)\, R2/(R1+R2)$

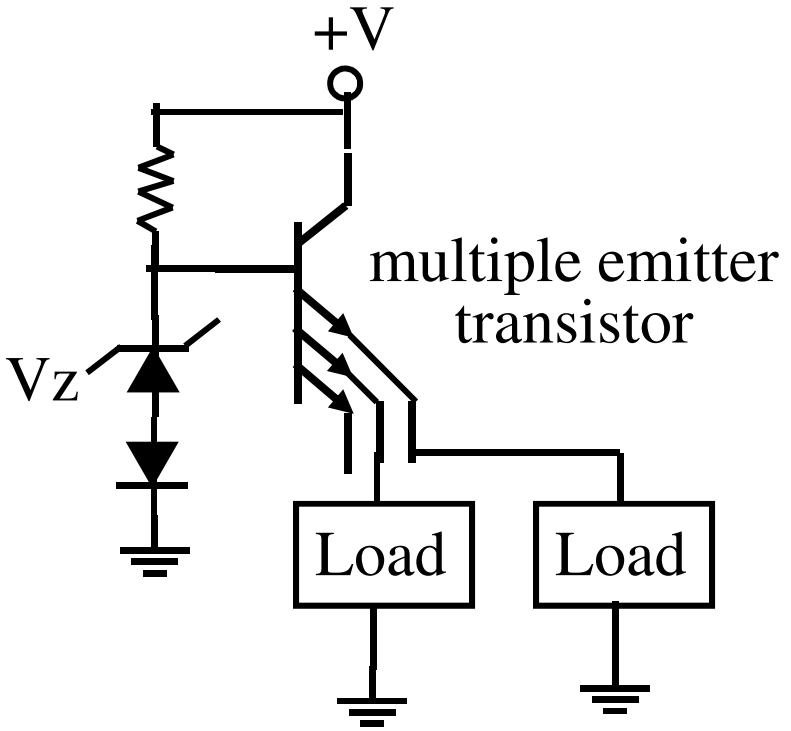
Therefore: $\boxed{VL = (V-0.7)\, R2/(R1+R2)}$

$$\boxed{ro = r\pi + \frac{R1//R2}{(\beta+1)}}$$ Note: small

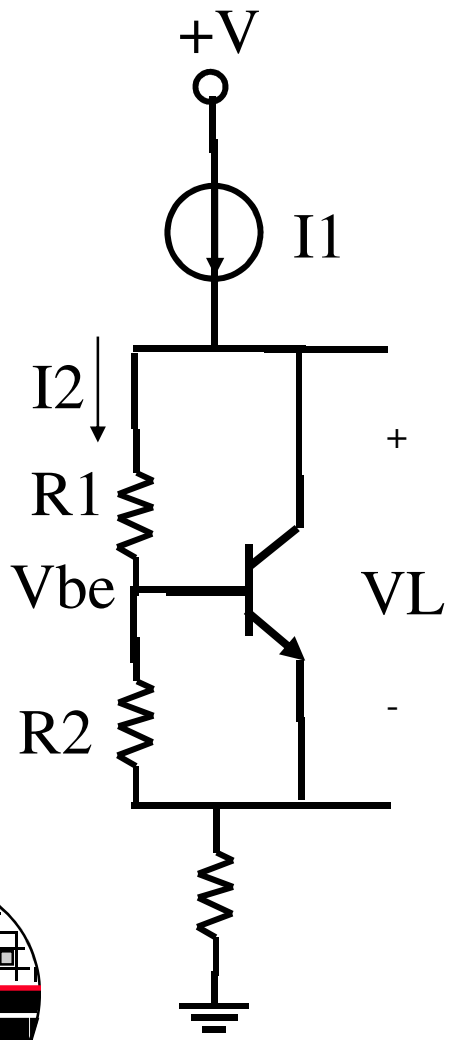
What is the purpose of D1?
(answer: reduces the change in VL with temperature)

VOLTAGE MIRROR





LEVEL SHIFTING

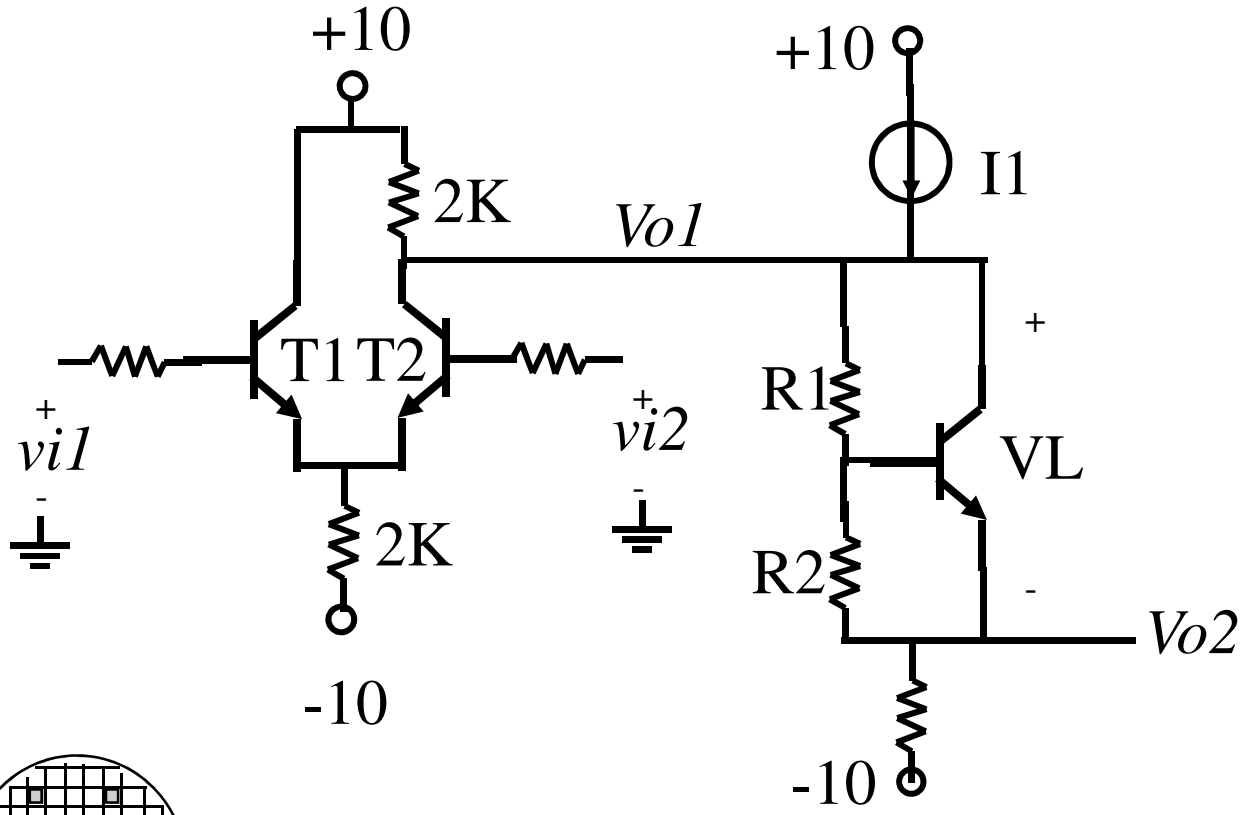


$$I2 = Vbe/R2$$

$$VL = Vbe\ (1 + R1/R2)$$

LEVEL SHIFTING

It would be nice to have zero volts out when we have zero volts in. By adding a level shifting stage we can achieve this.



for $vi1 = vi2 = 0$

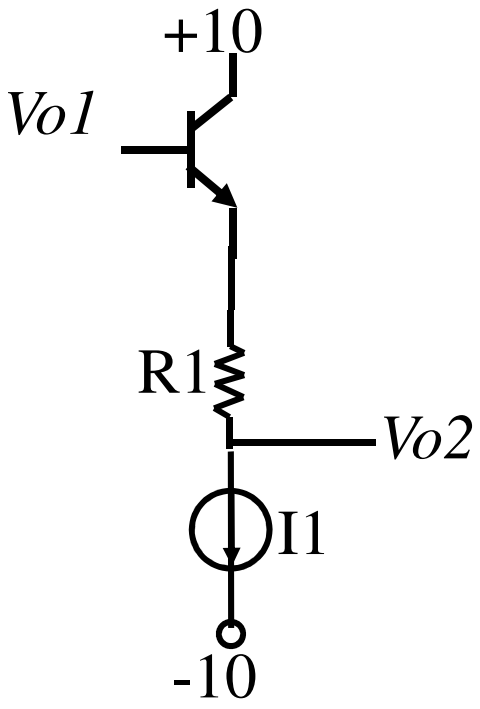
$Vo1 = 5.35$

and $Vo2 = 0$

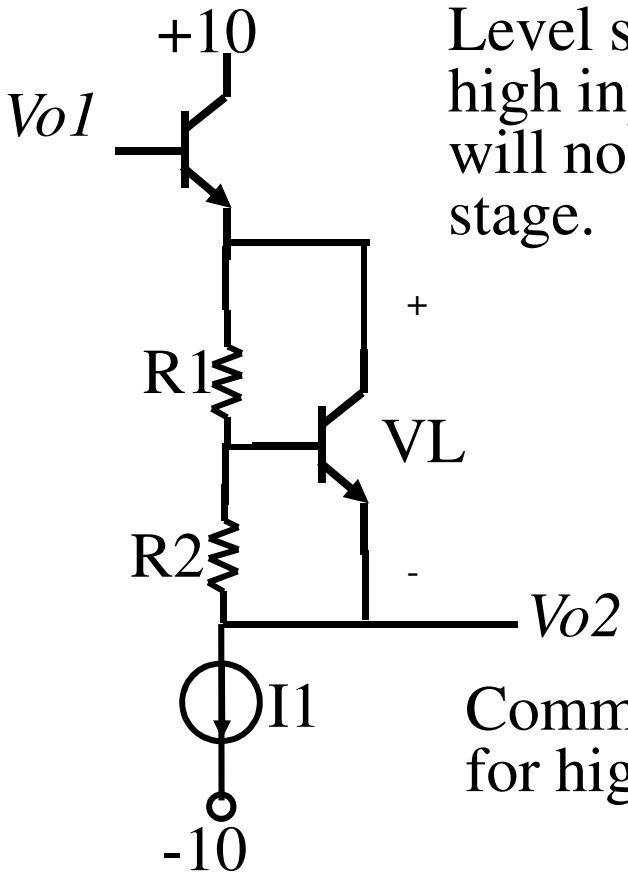
if Vbe=0.67

and R1/R2 = 7

LEVEL SHIFTING



Simple resistor level shifter



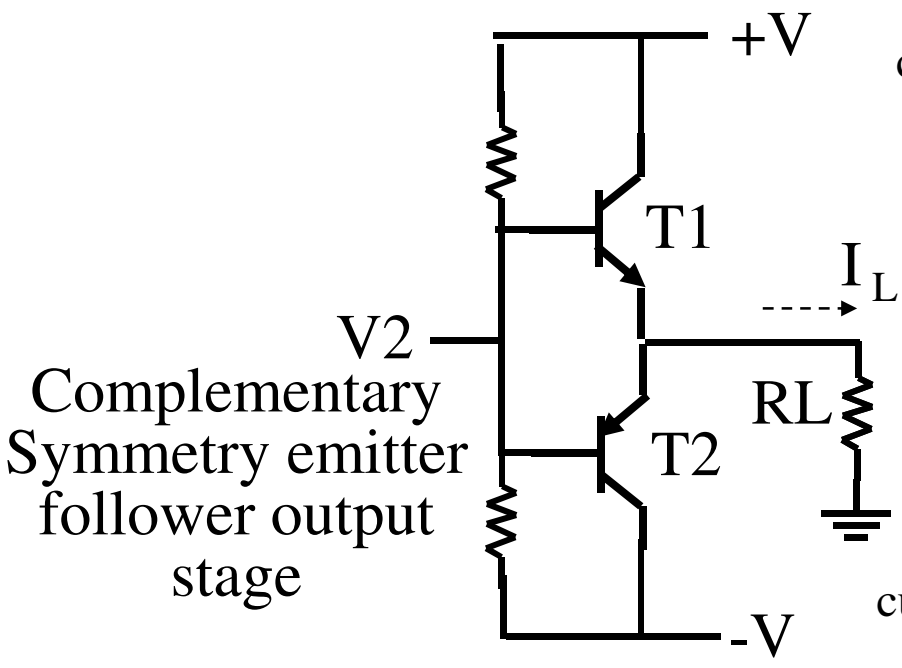
Vbe Multiplier level shifter

Level shifting should have high input resistance so it will not "load" the previous stage.

Common collector input for high input resistance.

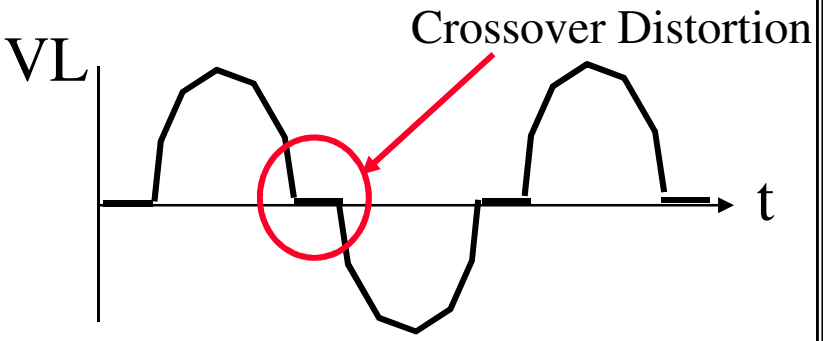
OUTPUT STAGES

An output stage is needed to provide the capability of sourcing or sinking "large" currents to the load



Complementary Symmetry emitter follower output stage

For V2 > 0.7 T1 is on and current flows from +V thru T1 and RL to Gnd. T2 is off.

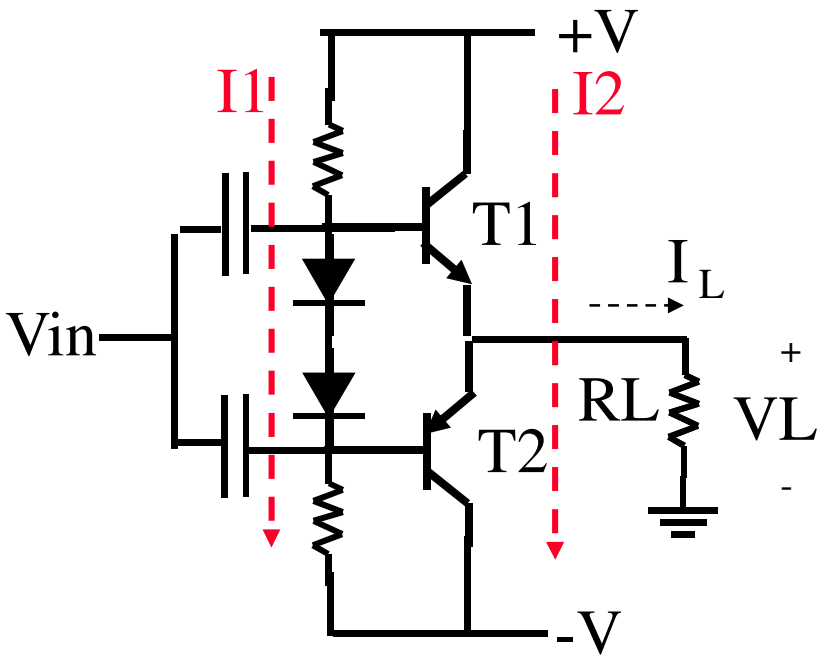


For V2 < 0.7 T2 is on and current flows from Gnd thru RL and T2 to -V. T1 is off.

With no signal in the transistors T1 and T2 are biased in an off state. This is called a class B amplifier.

OUTPUT STAGES

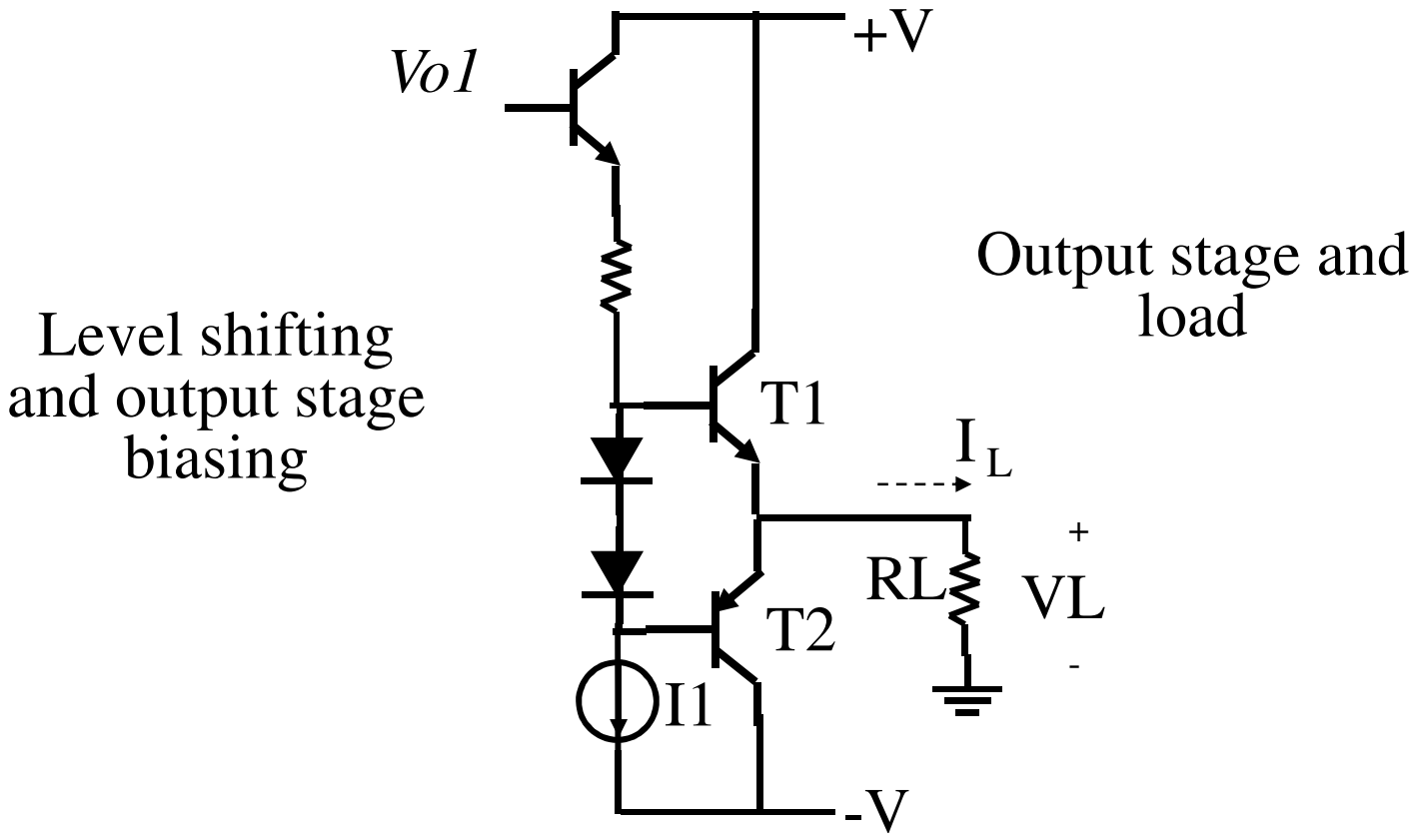
To eliminate the crossover distortion we can bias the transistors T1 and T2 so that they are just ready to conduct (ie Vbe ~ 0.65)



Note: D1 and D2 are probably transistors identical to T1 and T2 with Base and Collector shorted. Thus I1 = I2 and is called the idle current. I1 = (2 V -1.4)/2R

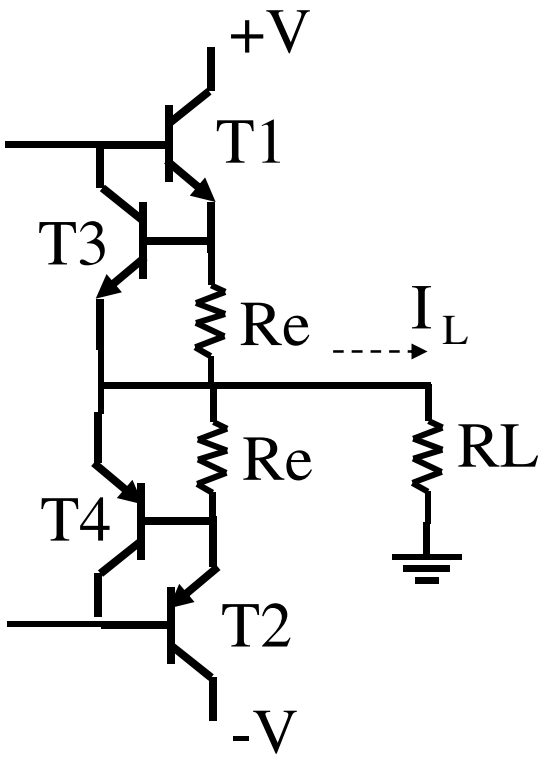
Note: We can eliminate the capacitors if we use a properly designed level shifting stage as show on the following pages

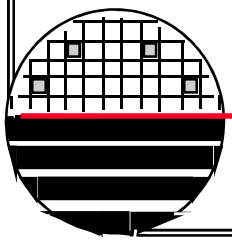
OUTPUT STAGES



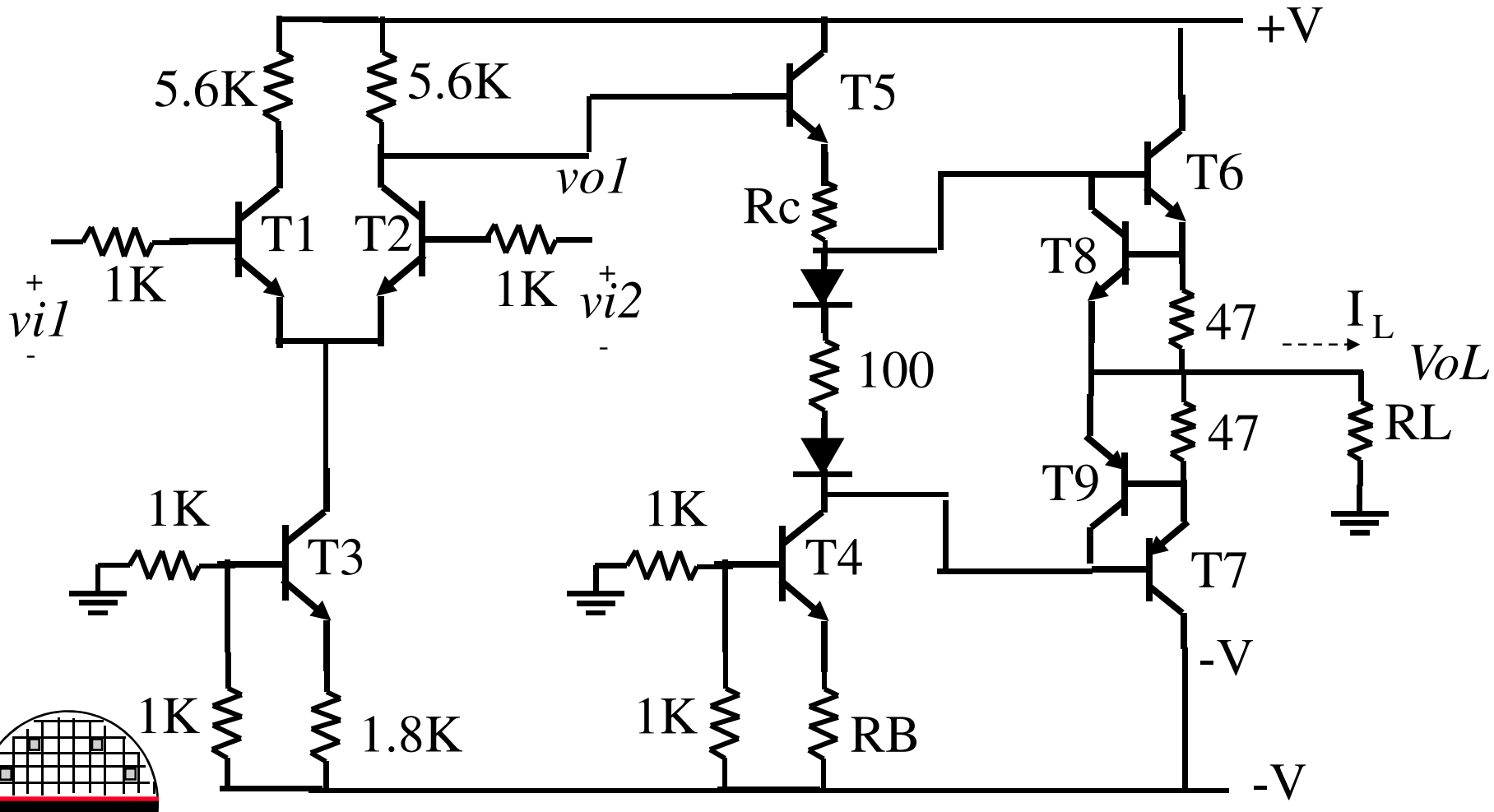
OUTPUT STAGE WITH CURRENT LIMITING

When T1 is on IL flows from +V thru T1, Re and Rl to Gnd. If RL accidently went to zero IL would only go to 0.7/Re because at that value of IL T3 would turn on which would remove the base drive from T1 thus IL would be limited to 0.7/Re. Similar for T2.

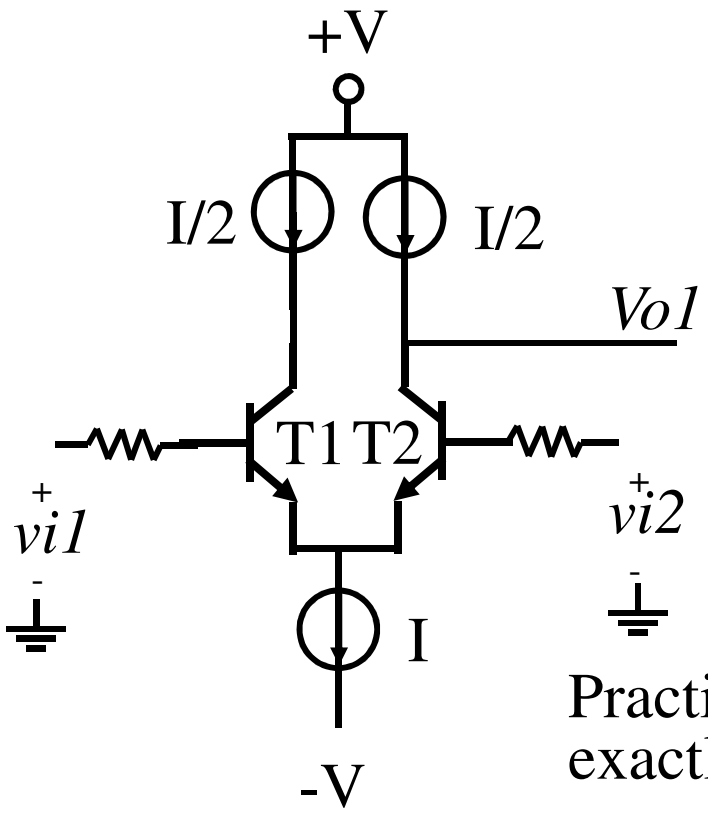




SIMPLE OPERATIONAL AMPLIFIER



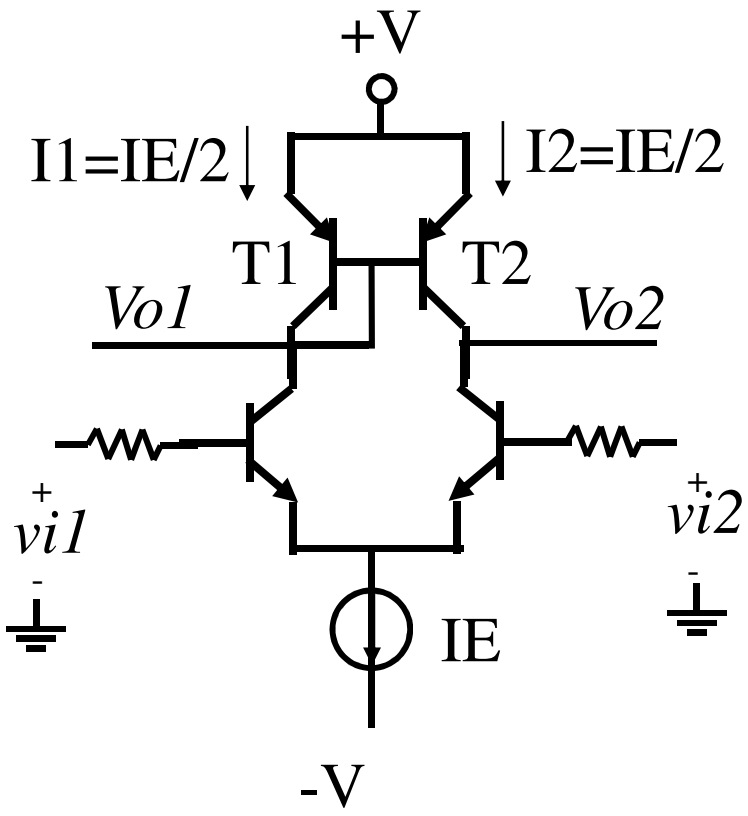
ACTIVE LOADS



Replacing some of the resistors with current sources requires less space and enables higher differential voltage gain and lower common mode gain.

Practically: I/2 sources can not be made exactly correct.

ACTIVE LOADS – CURRENT MIRROR



DC Analysis:
1. IE is constant current.
2. I1 = I2 = IE/2

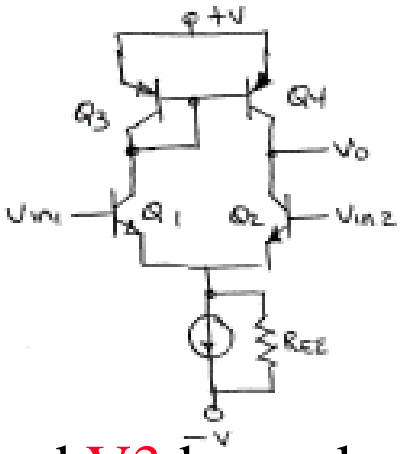
3. Vo1 = V -0.7
actually Vo1 = V – KT/q ln I1/IS

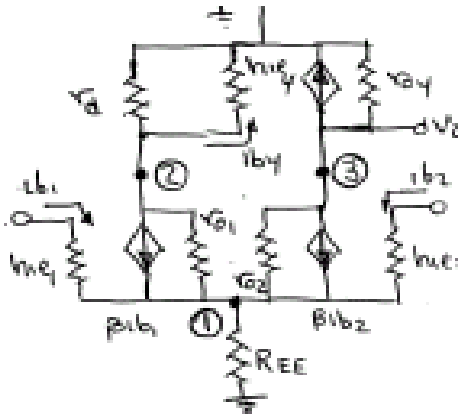
4. Vo2 = V – VEB1-VBC2
Vo2 = V – KT/q ln I1/Is – VBC2

When Vin1=Vin2=zero and I1=I2=IE/2 we have everything balanced and VBC2=VBC1=0 thus Vo2=V-0.7

5. When Vin1 > Vin2 then I1 > I2 and Vo2 rises toward +V
Note: p-p signal swing is about 1 volt

SMALL SIGNAL ANALYSIS OF DIFF AMP WITH ACTIVE LOAD





hie = rπ

Let V1,V2 and V3 be node voltages at node 1,2 and 3 summing currents

at node1

$(Vin1-V1)(\beta+1)/r\pi1 + (V2-V1)/ro1 + (V3-V1)/ro2 + (\beta+1)(Vin2-V1)/r\pi2 - V1/REE = 0$

at node2

$V2/Rd + V2/r\pi4 + (V2-V1)/ro1 + \beta(Vin1-V1)/r\pi1 = 0$

at node3

$\beta V2/r\pi4 + V3/ro4 + (V3-V1)/ro2 + \beta(Vin2-V1)/r\pi2 = 0$

SMALL SIGNAL ANALYSIS OF DIFF AMP WITH ACTIVE LOAD

Rearranging:

at 1 $[-1/REE-(\beta+1)/r\pi1-1/ro1-1/ro2-(\beta+1)/r\pi2]V1+[1/ro1]V2+[1/ro3]V3 = RHS$

$a1$

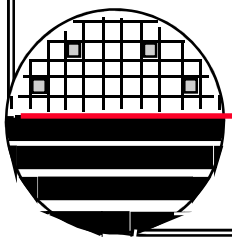
$RHS = -Vin2(\beta+1)/r\pi2 - Vin1(\beta+1)/r\pi1$

at 2 $[-1/ro1-\beta/r\pi1]V1 +[1/Rd+1/r\pi4+1/ro1]V2+ 0\ V3= -\beta Vin1/r\pi1$

$a2$ $a3$

at 3 $[-\beta/r\pi2-1/ro2]V1+\beta/r\pi4V2 + [1/ro4+1/ro2]V3 = -\beta Vin2/r\pi2$

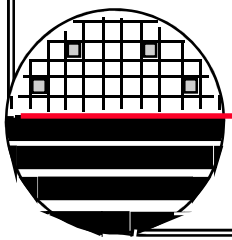
$a4$ $a5$



SMALL SIGNAL ANALYSIS OF DIFF AMP WITH ACTIVE LOAD

Using Cramer's rule and determinants

$$V3 = \frac{\begin{vmatrix} a1 & 1/ro1 & [-Vin2(\beta+1)/r\pi 2 - Vin1(\beta+1)/r\pi 1] \\ a2 & a3 & -\beta Vin1/r\pi 1 \\ a4 & \beta/r\pi 4 & -\beta Vin2/r\pi 2 \end{vmatrix}}{\begin{vmatrix} a1 & 1/ro1 & 1/ro3 \\ a2 & a3 & 0 \\ a4 & \beta/r\pi 4 & a5 \end{vmatrix}}$$



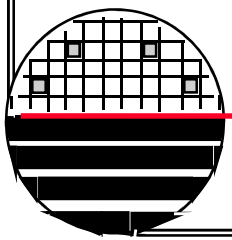
SMALL SIGNAL ANALYSIS OF DIFF AMP WITH ACTIVE LOAD

Example: let ro1= ro2 = ro3 = 50K
$r\pi 1 = r\pi 2 = r\pi 3 = 2K$
β =100, rd =20, REE = infinite

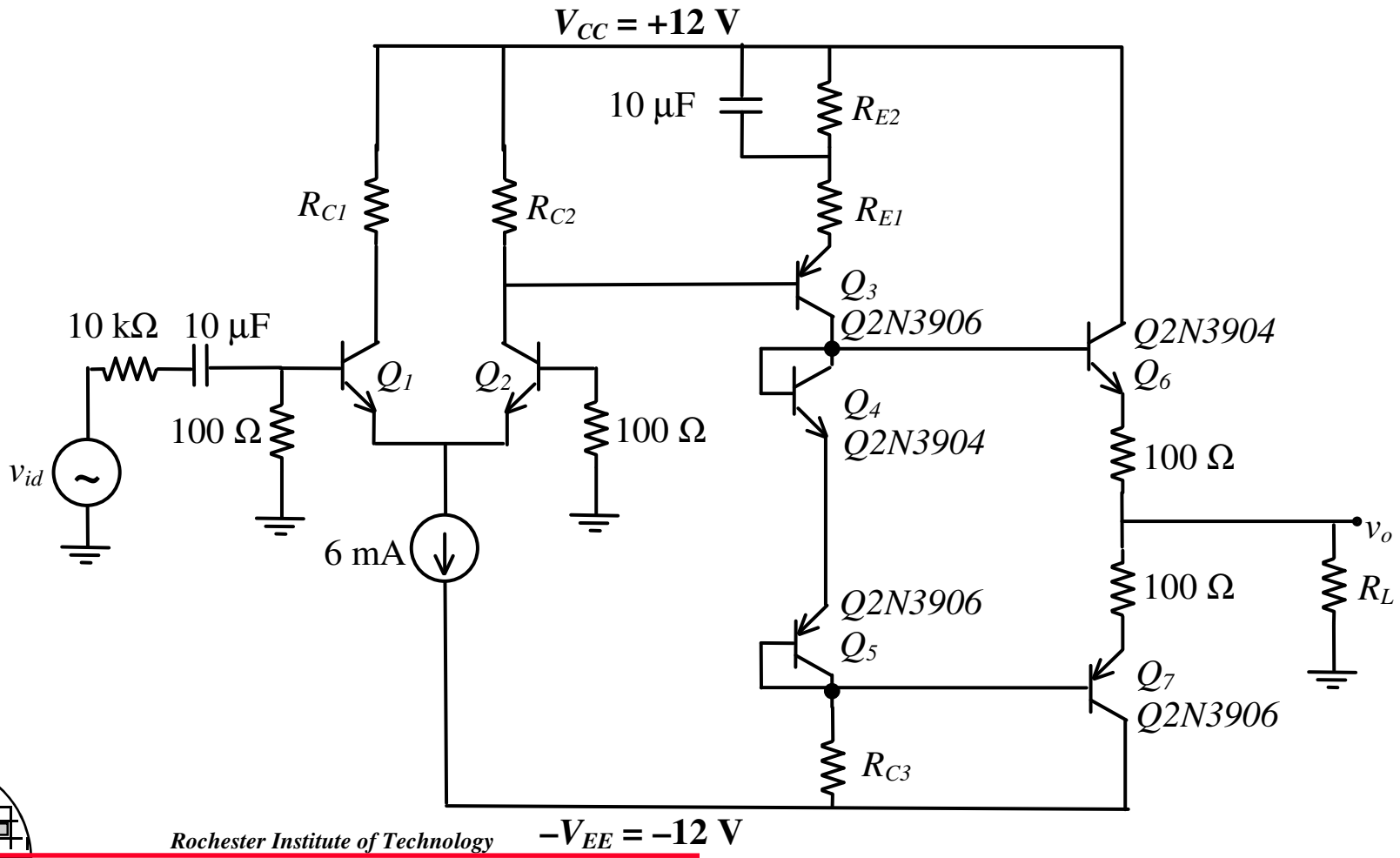
a) If Vin1=1/2 volt and Vin2= -1/2 volt
Find V3 = 1246
Therefore Avd = 1246

b) If Vin1=1 volt and Vin2= 1 volt
Find V3 = 0.00005108
Therefore Avc = 0.00005108

c) CMMR = 1246/0.00005108 = 2.44e7



EXAMPLE FROM LAB



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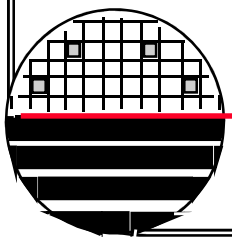
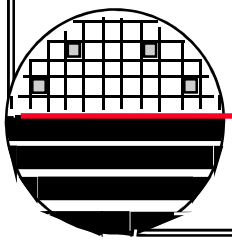
2. Device Electronics for Integrated Circuits, 2nd Edition, Kamins and Muller, John Wiley and Sons, 1986.
3. The Bipolar Junction Transistor, 2nd Edition, Gerald Neudeck, Addison-Wesley, 1989.
4. Analog Integrated Circuits, Gray and Meyers



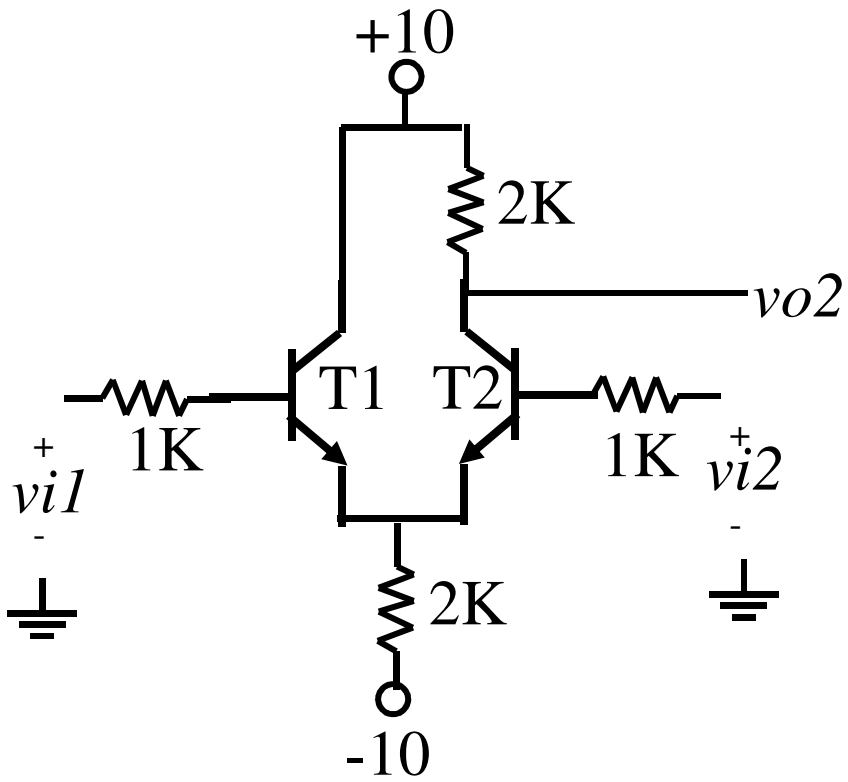
HOMEWORK – BIPOLAR IC DESIGN

1. Derive the exact value of Ree for the current source on page 15.
2. Design a 100 μA current source.
3. For the simple op amp shown on page 29
    a. let vin1 = vin2 = zero. Select values for Rc and Rb such that Vout = zero.
    b. What is the maximum load current before current limiting?
    c. Calculate the small signal differential voltage gain.
4. Do a SPICE analysis of the simple op amp on page 29
5. Do a SPICE analysis of the differential amplifier using active loads shown on page 32.



SOLUTION TO EXAMPLE ON PAGE 9

Analyze the following differential amplifier, β=200



SOLUTION TO EXAMPLE ON PAGE 9

DC analysis: if Vin1 = Vin2 = zero, IC1 = IC2 and IB1=IB2

KVL: $IB\ 1K + 0.7 + 2(\beta+1)IB\ 2K - 10 = 0$

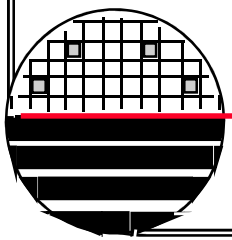
$IB = 9.3 / (1K+2(200+1)\ 2K = 11.6uA$

$IC = 200\ IB = 2.32\ mA$

$VCE1 = 10 - -\ IB\ 1K - -\ 0.7 = 10.7$

$VCE2 = 10 - IC\ 2K - -\ 0.7 = 6.06$

$r\pi = \beta VT / IC = 200\ (0.026V)/2.32\ mA = 2.24K$



SOLUTION TO EXAMPLE ON PAGE 9

AC analysis:

$$\frac{Voss}{Vid} = 1/2 \; \frac{-\beta \, Rc}{(R\pi + 1K)} = - \tfrac{1}{2} (200) \; 2K \; / \; (1K+2.24K) = -61.7$$

$$\frac{Voss}{Vic} = \frac{-\beta \, Rc}{2Re \; (\beta+1) + (r\pi + 1K)} = -400K \; / \; (4K(201)+3.24K) = 0.496$$

$$CMMR = 61.7 \; / \; .496 = 125$$