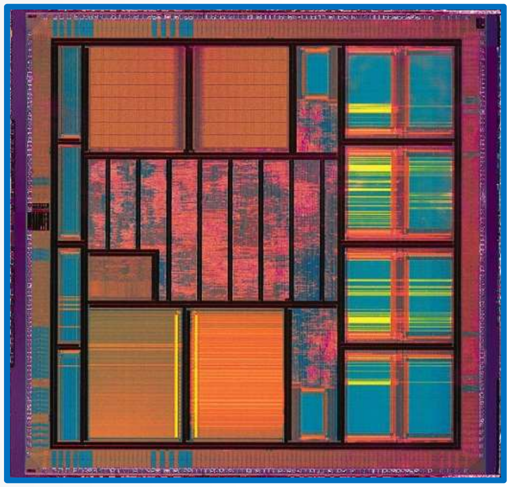
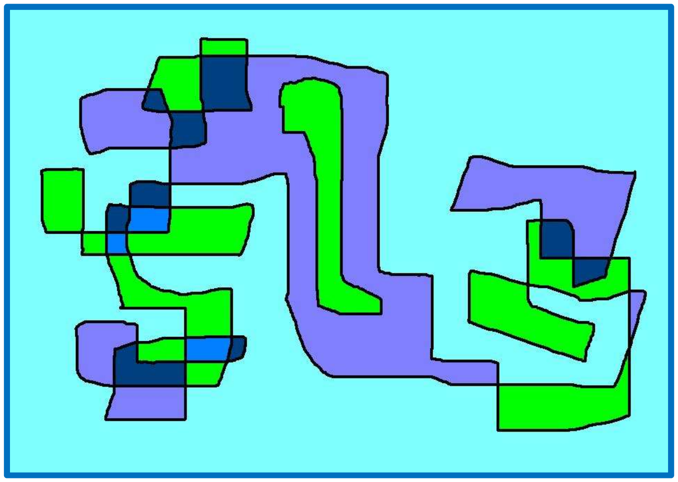
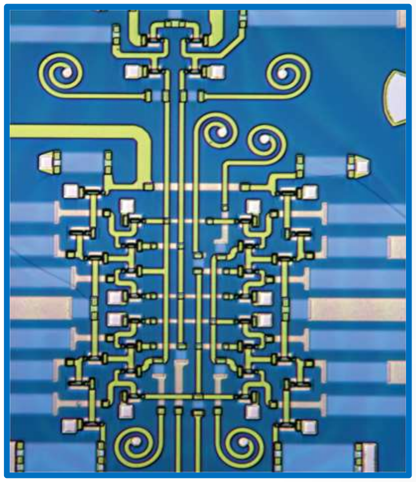




ENE/EIE 211: Electronic Devices and Circuit Design II

Lecture 6: 741 Op Amp

Outline

- Brief History
- Stages
- DC Bias Point Analysis
- Small Signal Analysis
- Concluding Remarks

Brief History

1964 – Bob Widlar designs the first op-amp: the 702.

- Using only 9 transistors, it attains a gain of over 1000
- Highly expensive: $300 per op-amp

1965 – Bob Widlar designs the 709 op-amp which more closely resembles the current uA741

- This op-amp achieves an open-loop gain of around 60,000.
- The 709's largest flaw was its lack of short circuit protection.

Brief History (cont)

After Widlar left Fairchild, Dave Fullagar continued op-amp design and came up with the uA741 which is the most popular operational amplifier of all time.

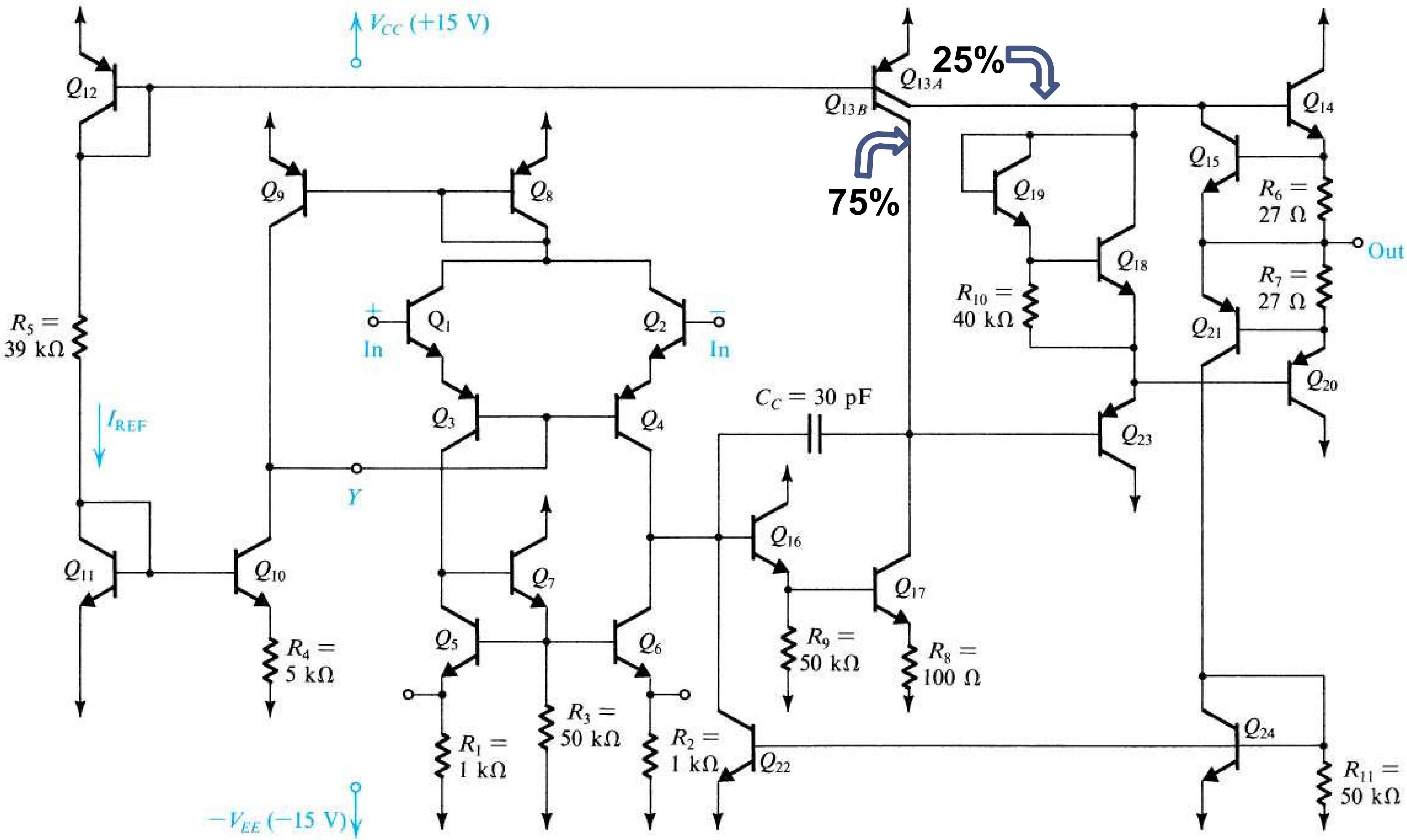
- This design's basic architecture is almost identical to Widlar's 309 op-amp with one major difference: the inclusion of a fixed internal compensation capacitor.

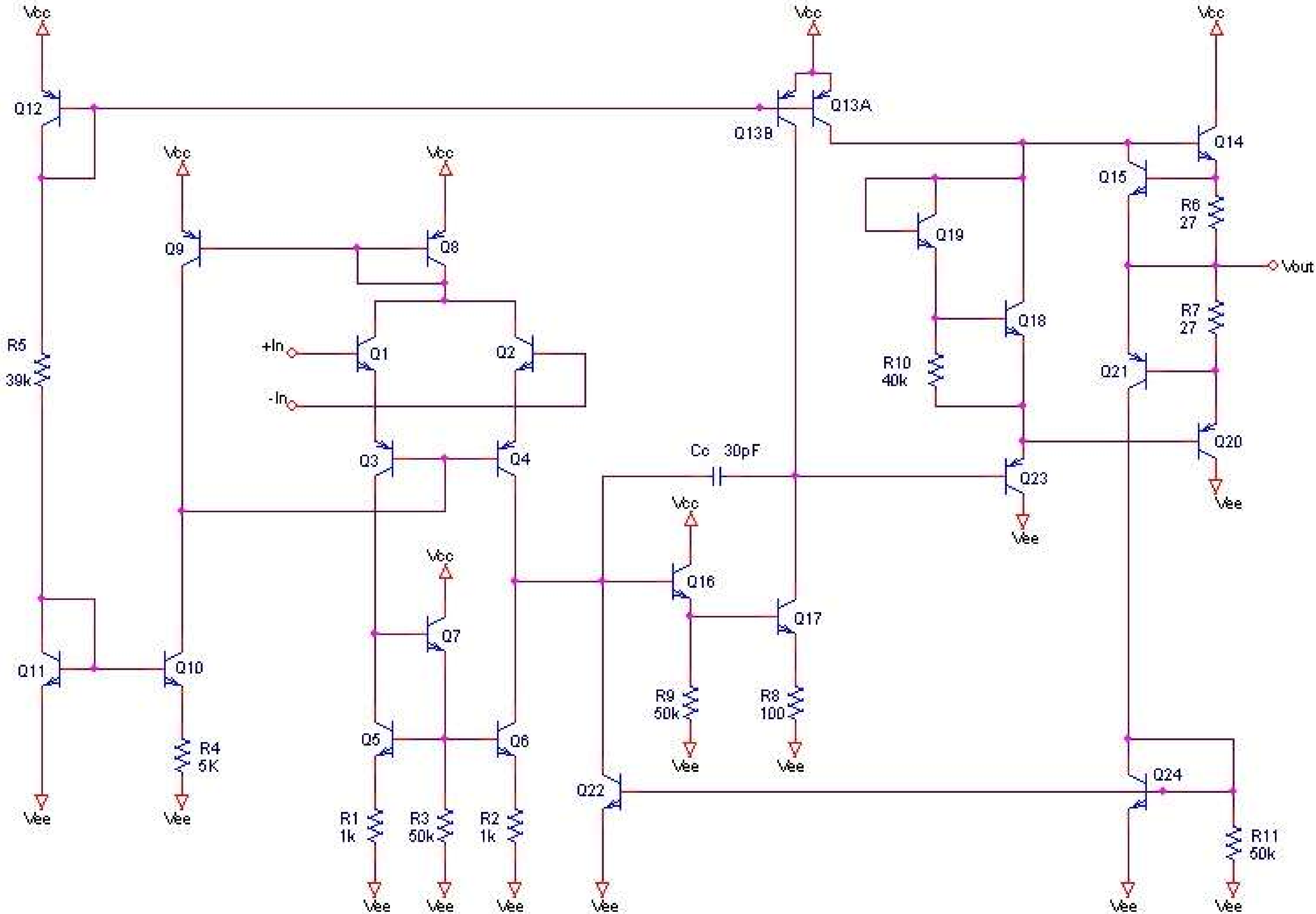
  This capacitor allows the uA741 to be used without any additional, external circuitry, unlike its predecessors.

-The other main difference is the addition of extra transistors for short circuit protection.

-This op-amp has a gain of around 250,000

Schematic (Screamatic)




Vcc
Q12
Q13B
Q13A
Q14
Vcc
Vcc
Q9
Q8
Q15
R6
27
Q19
Vout
Q1
Q2
+In
-In
Q18
R7
27
R5
39k
R10
40k
Q21
Q3
Q4
Cc 30pF
Q20
Q23
Vee
Vcc
Q16
Q17
Q7
Q11
Q10
R9
50k
R8
100
R4
5K
Q5
Q6
Q22
Q24
R1
1k
R3
50k
R2
1k
R11
50k
Vee

Stages

- Input Differential Stage
- Intermediate Single-Ended High-Gain Stage
- Output Buffering Stage
- Current Source / Short Circuit Protection

Device Parameters

For standard npn and pnp transistors, the following parameters will be used:

npn: $I_S = 10^{-14}$ A, $\beta = 200$, $V_A = 125$ V

pnp: $I_S = 10^{-14}$ A, $\beta = 50$, $V_A = 50$ V

The nonstandard devices are Q13, Q14 and Q20. Transistor Q13 is assumed to be equivalent to 2 transistors Q13A and Q13B, with parallel base-emitter junctions and having the following I_S's:

$I_{SA} = 0.25 \times 10^{-14}$ A $\qquad$ $I_{SB} = 0.75 \times 10^{-14}$ A

Q14 and Q20 have area 3x that of a standard device.

Output transistors usually have large areas, to be able to supply large load currents and dissipate relatively large amounts of power with only a moderate increase in device temperature.

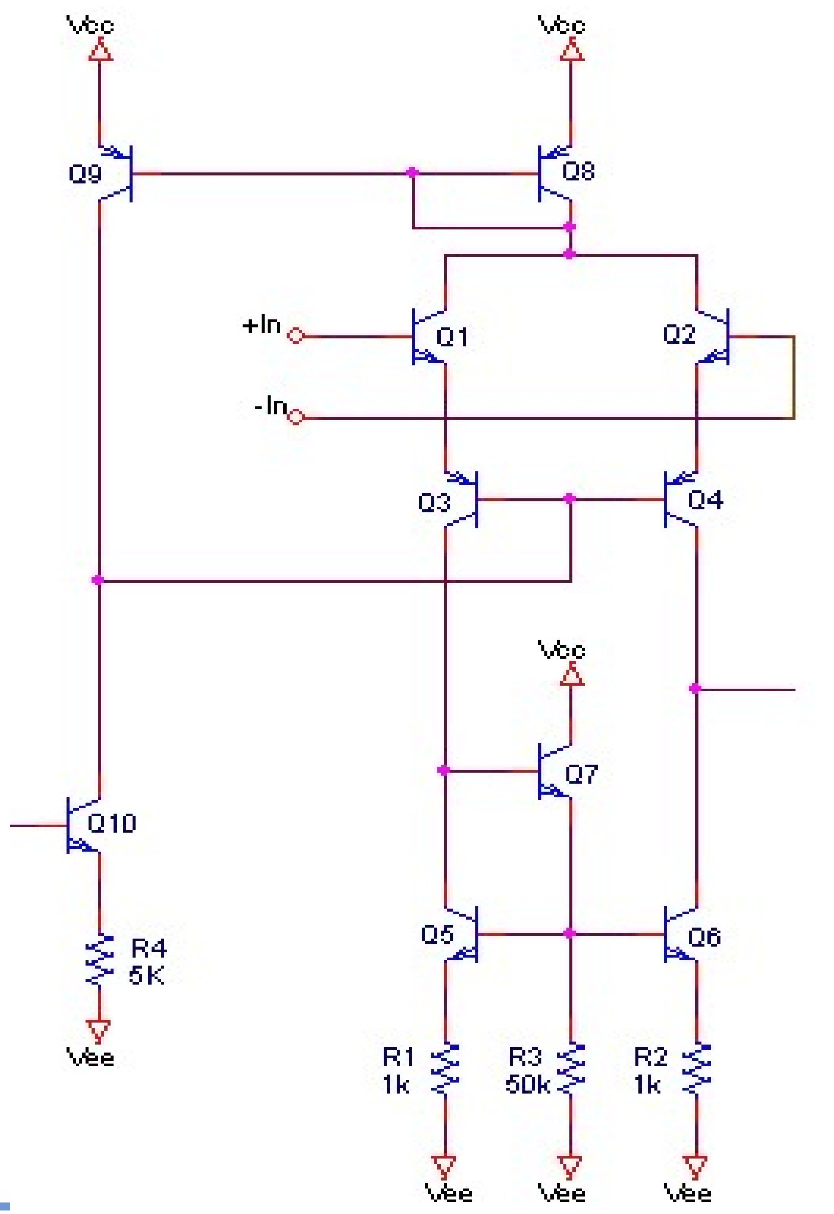
Input Differential Stage

The input stage consists of the transistors Q1 through Q7 with biasing performed by Q8, Q9, and Q10.

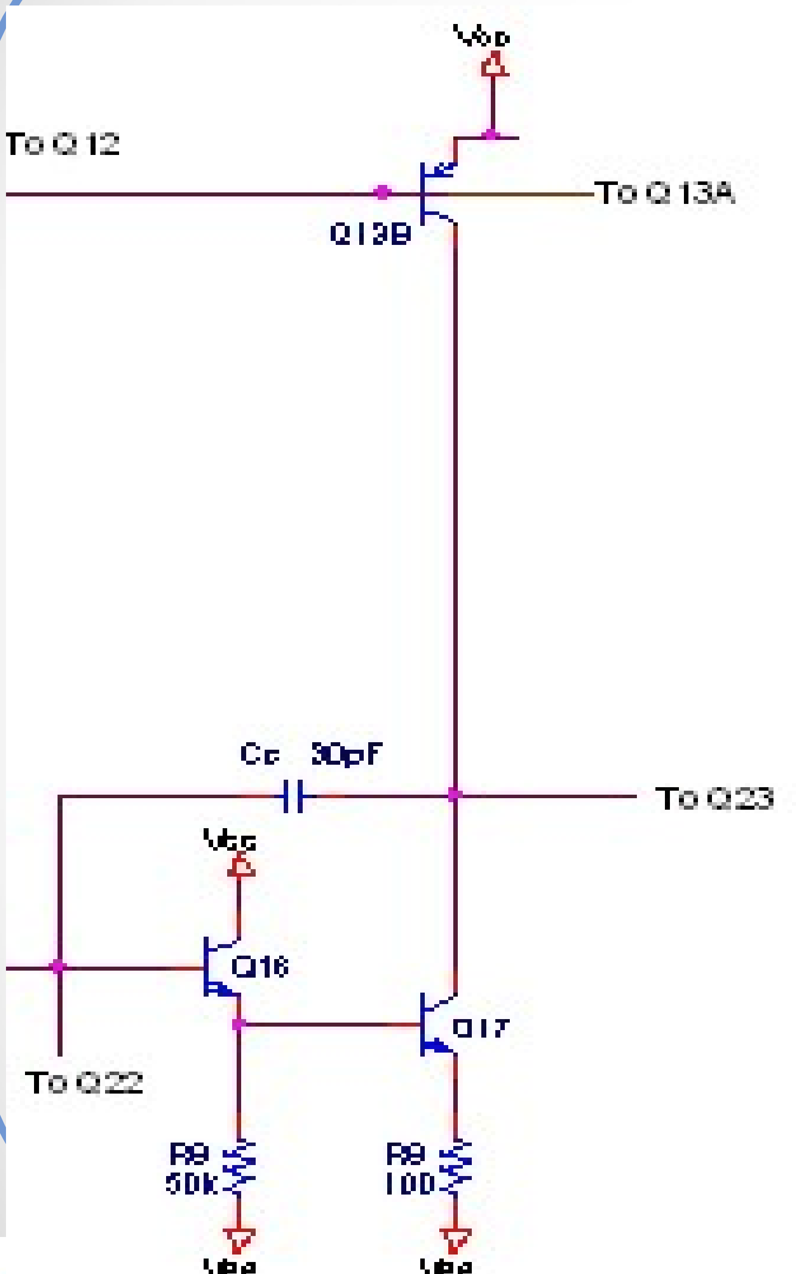
Transistors Q1 and Q2 are emitter followers which causes input resistance to be high and deliver the differential input signal to the common base amplifier formed by Q3 and Q4.

Transistors Q5, Q6, and Q7, and resistors R1, R2, and R3 form the load circuit of the input stage. This portion of the circuit provides a high resistance load.

Transistors Q3 and Q4 also serve as protection for Q1 and Q2. The emitter-base junction of Q1 and Q2 breaks down at around 7V but the pnp transistors have breakdown voltages around 50V. So, having them in series with Q1 and Q2 protects Q1 and Q2 from an accidental connection between the input terminals.



Intermediate Single-Ended High-Gain Stage



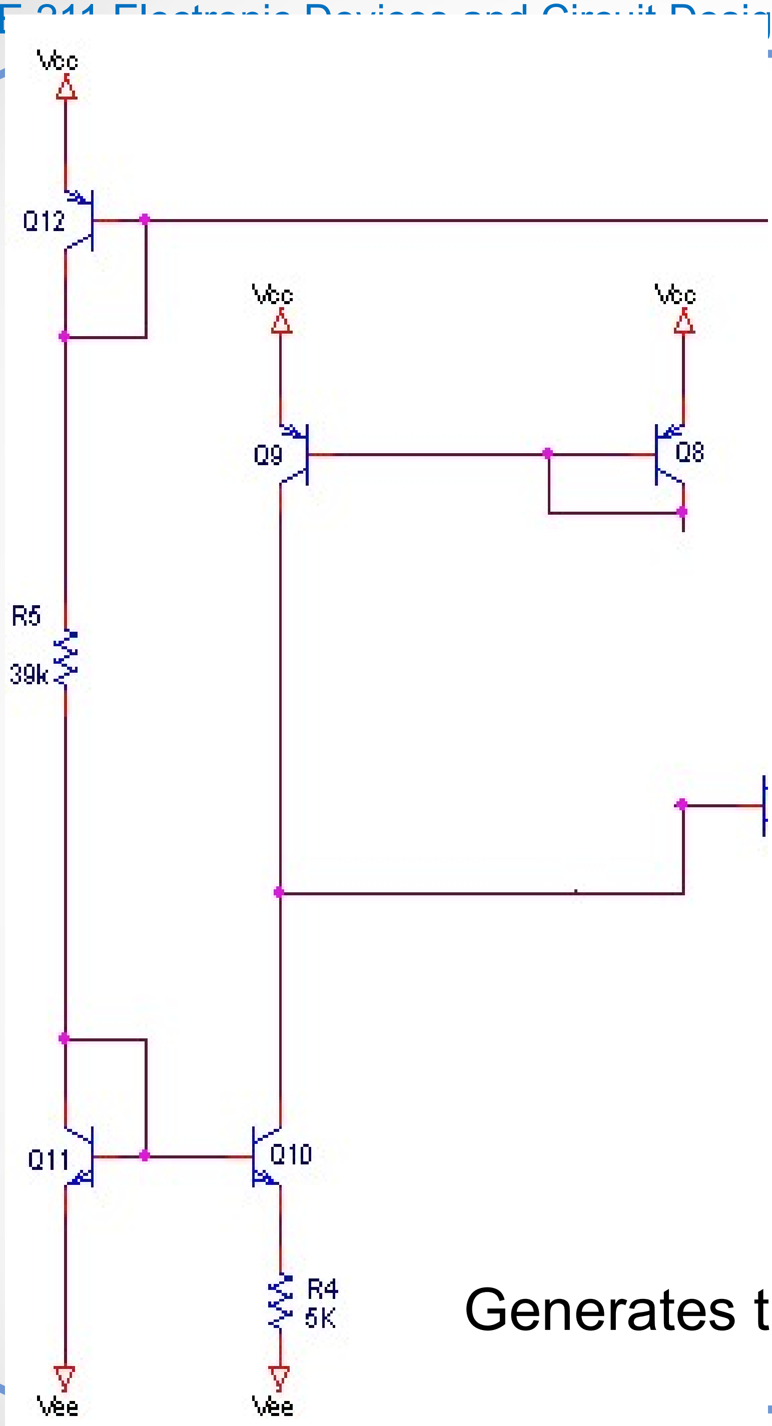
The second stage is composed of Q16, Q17, Q13B, and the resistors R8 and R9.

Transistor Q16 acts as an emitter follower giving the second stage a high input resistance.

Transistor Q17 is a common-emitter amplifier with a 100-Ω resistor in the emitter. The load of this amplifier is composed of the output resistance of Q13B. This use of a transistor as a load resistance is called *active load*.

The output of this amplifier (the collector of Q17) has a feedback loop through Cc. This capacitor causes the op-amp to have a pole at about 4Hz.

Biasing Current Sources



Generates the reference bias current through R5

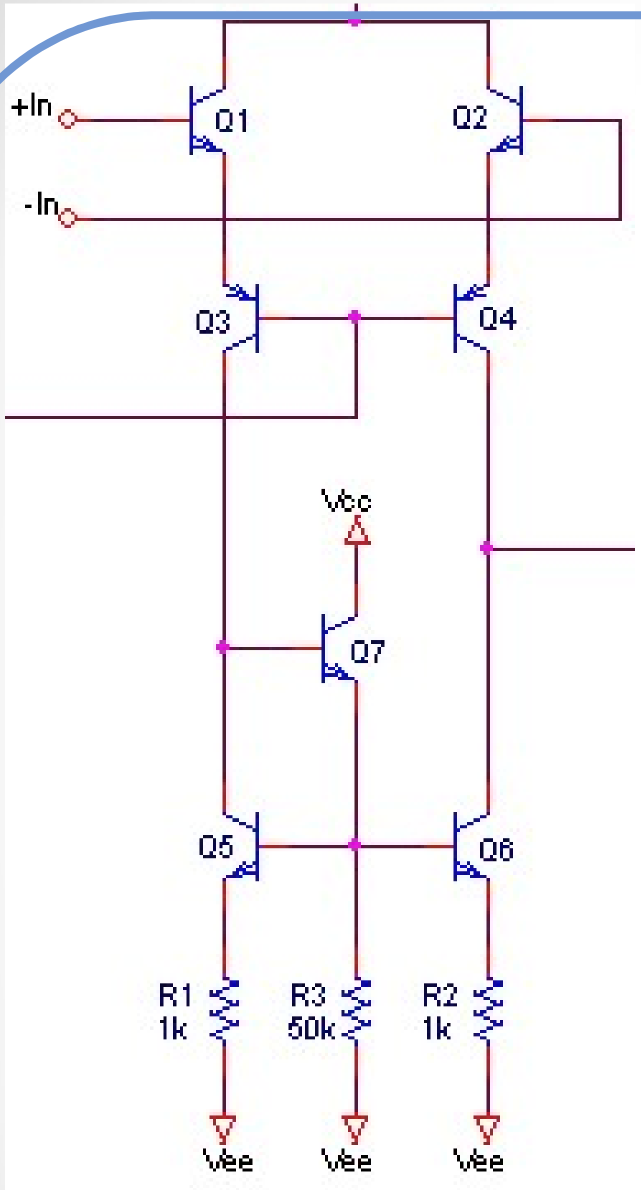
Biasing Current Sources: DC Analysis

- The opAmp reference current is given by:

$$I_{ref} = \frac{V_{CC} - V_{EB12} - V_{BE11} - (-V_{EE})}{R_5}$$

- For V_{cc}=V_{ee}=15V and V_{BE11}=V_{BE12}=0.7V, we have I_{REF}=0.73mA

Input Stage



- The differential pair, Q1 and Q2 provide the main input
- Transistors Q5-Q7 provide an active load for the input

Input Stage: DC Analysis - 1

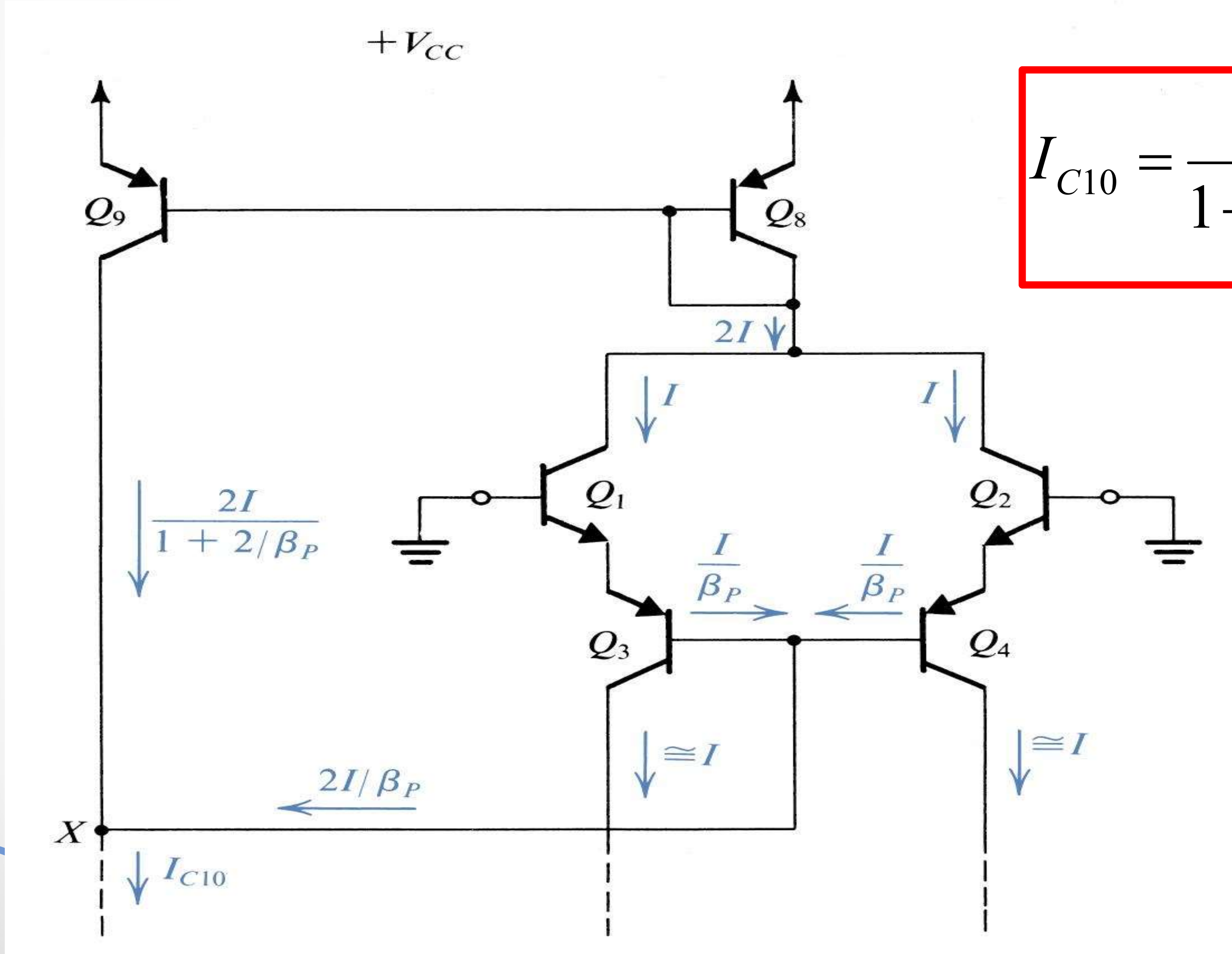
- Assuming that Q10 and Q11 are matched, we can write the equation from the Widlar current source:

$$V_T \cdot \ln\left(\frac{I_{REF}}{I_{C10}}\right) = I_{C10} \cdot R_4$$

- Using trial and error, we can solve for I_{C10}, and we get: $I_{C10} = 19\ \mu A$

Input Stage:
DC Analysis -2

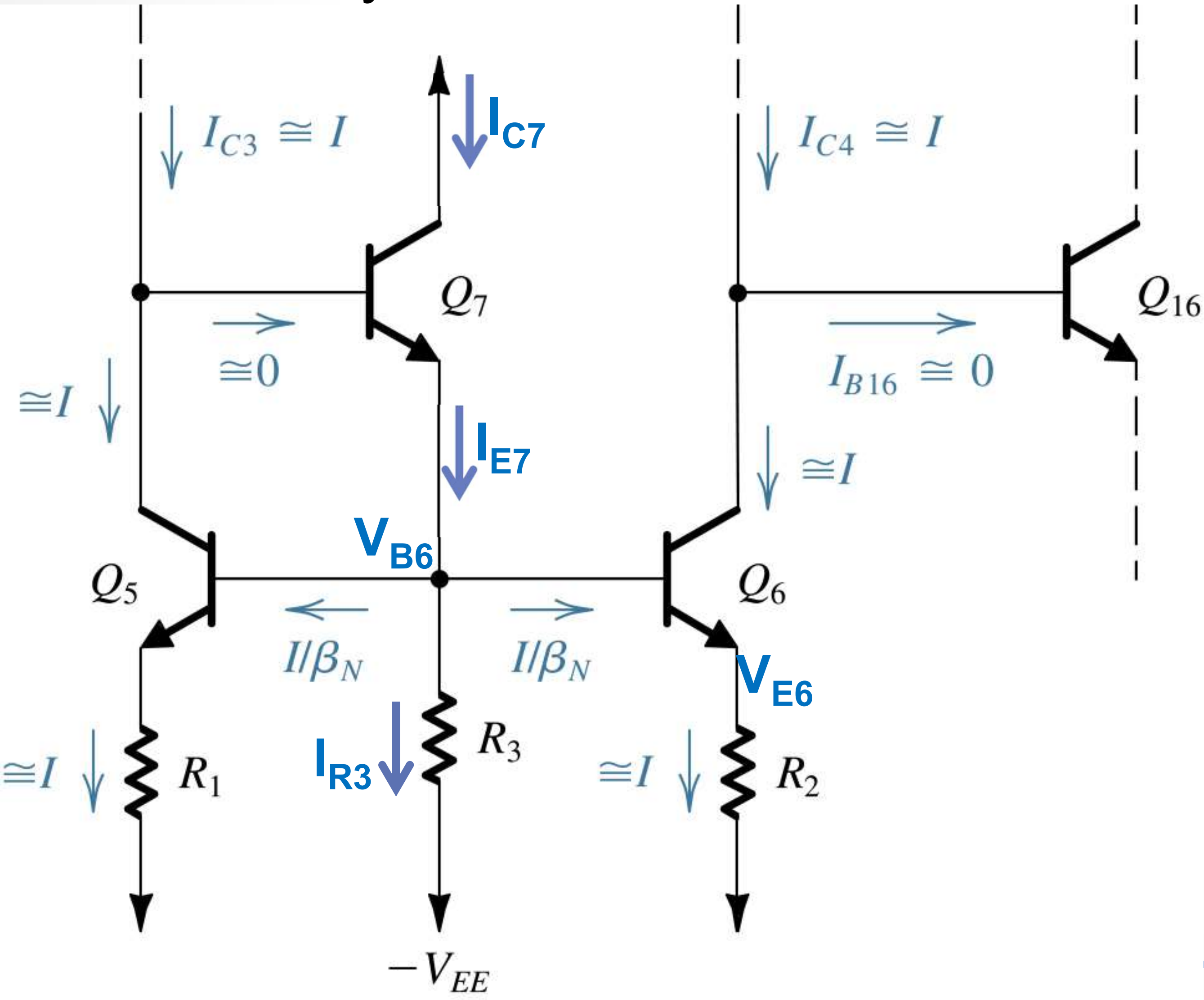
- From symmetry we see that $I_{C1}=I_{C2}=I$, and if the *npn* β is large, then $I_{E3}=I_{E4}=I$



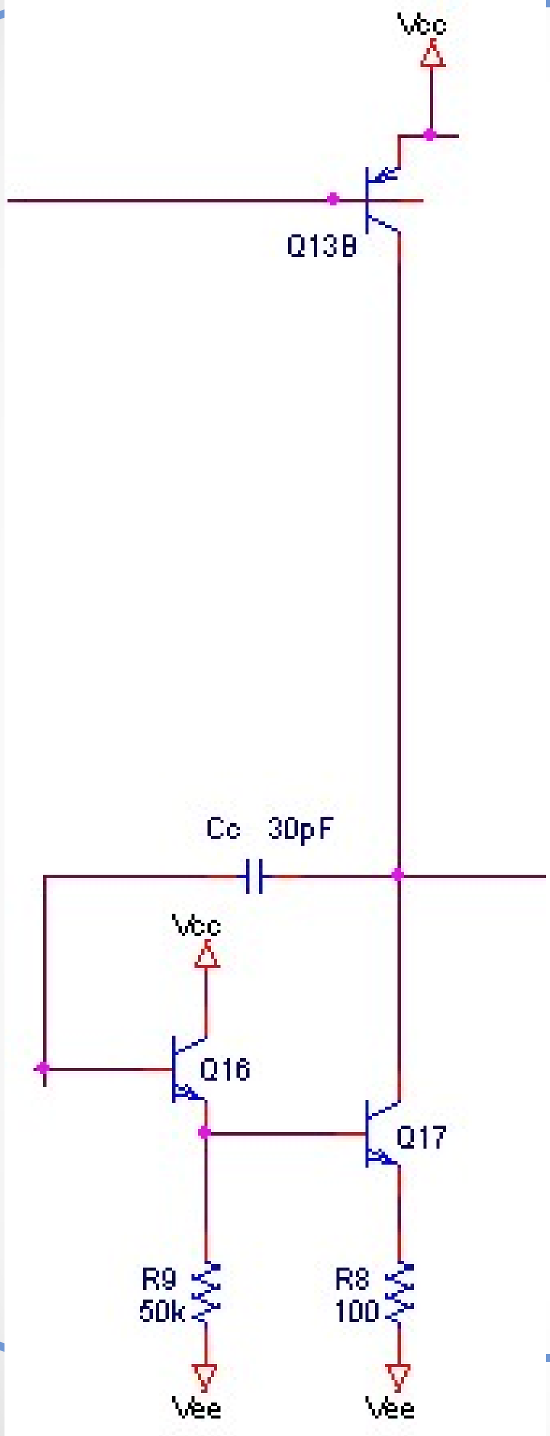
$$I_{C10}=\frac{2I}{1+2/\beta_p}+\frac{2I}{\beta_p}$$

Input Stage:
DC Analysis -3

- Analysis of the active load:



$$V_{E6} = IR_2 + (-V_{EE})$$
$$V_{B6} = V_{E6} + V_{BE6}$$
$$I_{R3} = \frac{V_{B6} - (-V_{EE})}{R_3}$$
$$I_{E7} = \frac{2I}{\beta_N} + I_{R3}$$
$$I_{C7} = \alpha I_{E7}$$



Second (Intermediate) Stage

- Transistor Q16 acts as an emitter-follower giving this stage a high input resistance
- Capacitor Cc provides frequency compensation using the Miller compensation technique

Second Stage: DC Analysis

- Neglecting the base current of Q23, I_{C17} is equal to the current supplied by Q13b
- I_{C13b}=0.75I_{REF} where β_P >> 1
- Thus: I_{C13b}= 0.75 x 730mA = 547.5mA ≈ 550mA ☺ = I_{C17}
- Then we can also write:

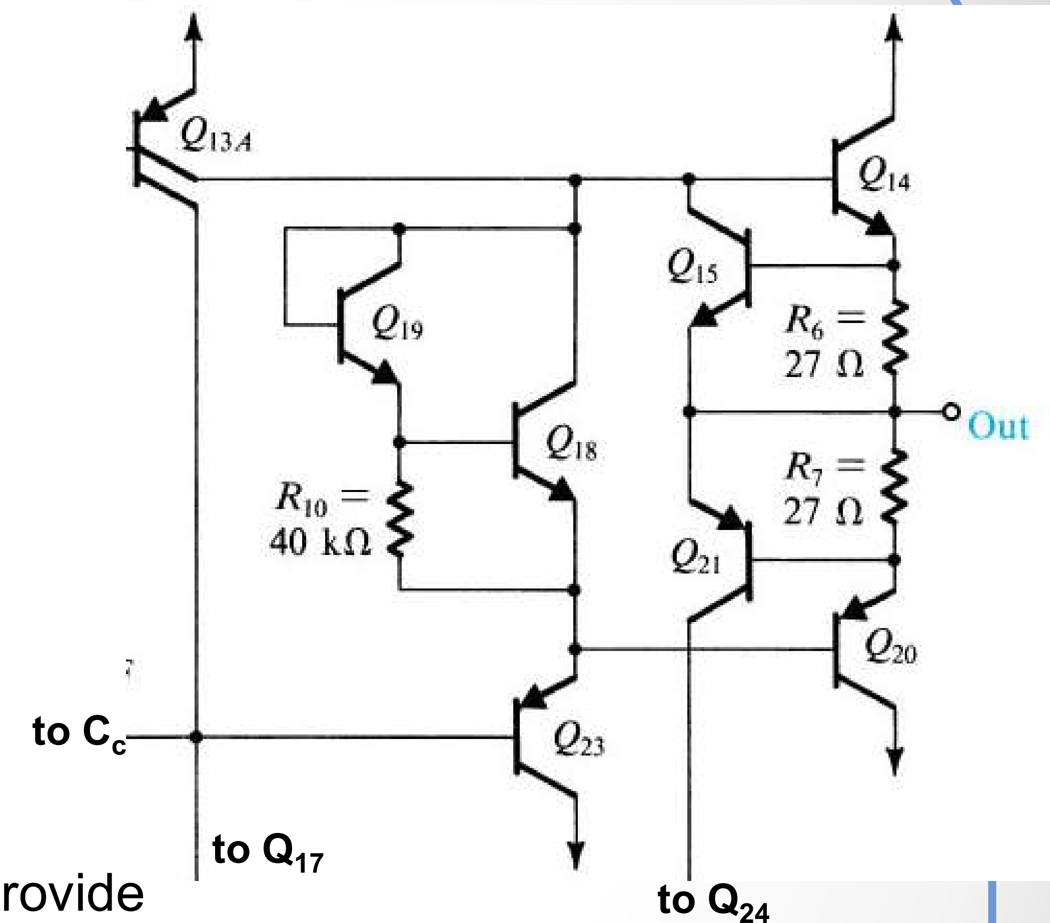
$$V_{BE17} = V_T \cdot \ln\left(\frac{I_{C17}}{I_S}\right) = 618mV$$

$$I_{C16} = I_{E16} = I_{B17} + \frac{I_{E17} \cdot R_8 + V_{BE17}}{R_9} = 16.2\mu A$$

Output Buffering Stage

The Output Stage consists of the complimentary pair Q14 and Q20, a class AB output stage.

- Q18 and Q19 are fed by current source Q13A and provide bias to the transistors Q14 and Q20.
- Q15 and Q21 give short circuit protection (described later) and Q13A supplies current to the output stage.
- Q23 acts as an emitter follower, thus minimizing the loading effect of the output stage on the second stage.



The purpose of the Output Stage is to provide the amplifier with a low Rout. Another requirement of the Output Stage is the ability to dissipate large load currents without dissipating large quantities of power.

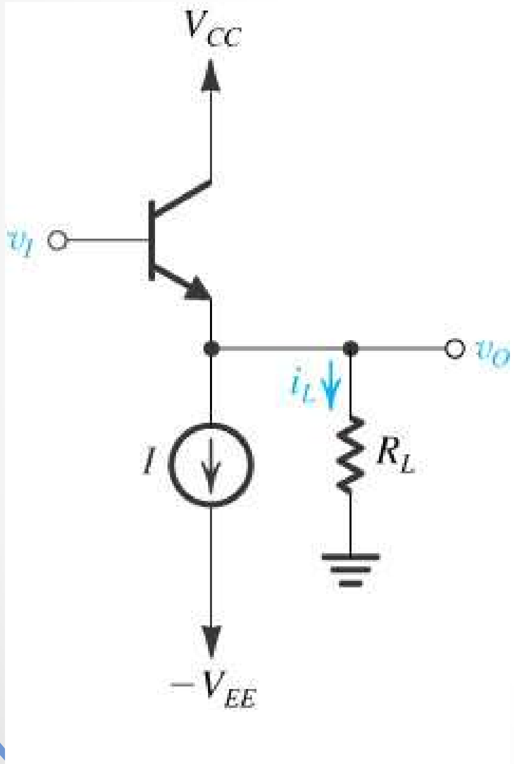
Output Stage: DC Analysis

- Q13a delivers a current of $0.25I_{REF}$, so we can say: $I_{C23}=I_{E23}=0.25I_{REF}= 0.25 \times 730mA = 182.5mA \approx 180mA$ ☺ Assuming $V_{BE18} = 0.6V$, then $I_{R10}=15mA$, $I_{E18}=180-15=165mA$ and $I_{C18}=I_{E18}=165mA$

- $I_{C19}=I_{E19}=I_{B18}+I_{R10}= \dfrac{I_{C18}}{\beta} +I_{R10} = 15.8mA$

The Output Stage

The purpose of the output stage is to provide the amplifier with a low Rout. In addition, it should be able to supply relatively large load currents without dissipating an unduly large amount of power in the IC. There are gazillion operation classes: class A, class B, class AB, class C, class D and etc. Since class C and beyond are rather specialized classes, they will not be covered here.



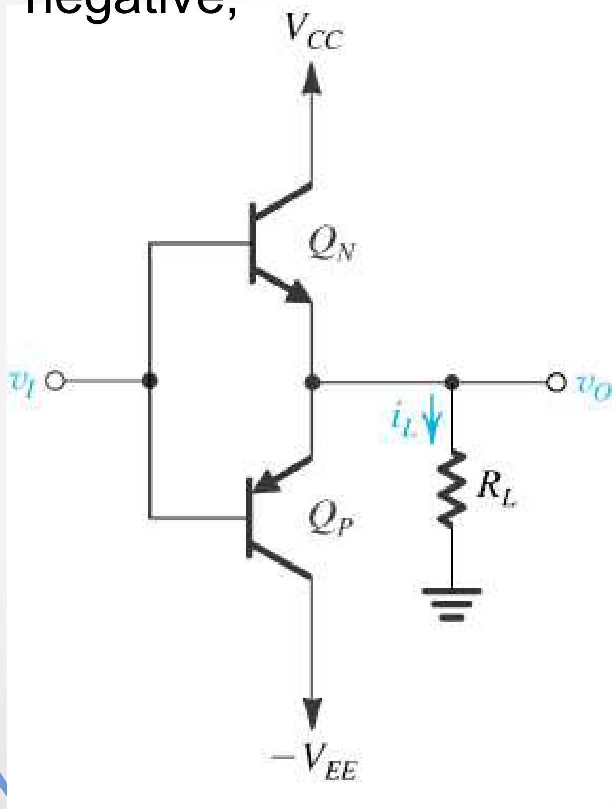
(a)

Class A: an emitter follower biased with a constant current source I. To keep the emitter –follower transistor conducting at all times and thus ensure the low Rout, the bias current I must be greater than the largest I_L.

The drawback is the large power dissipation in the transistor.

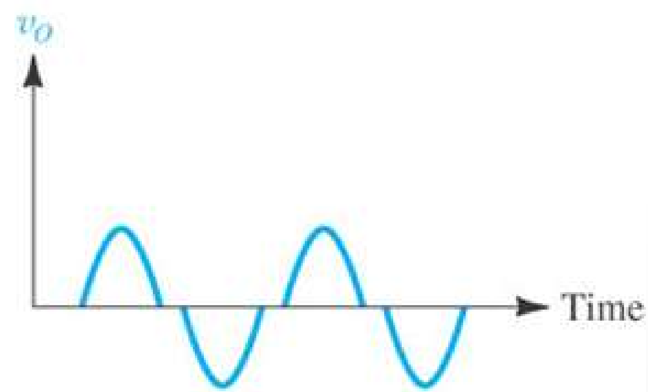
Class B: The power dissipation is reduced since the transistor is on only when an input signal is applied. The npn transistor will source output current while the pnp will sink the output current. Both transistors will be off when Vi = 0.

When Vi goes positive, Q_N conducts while Q_P remains off. When Vi goes negative, the transistors reverse roles.



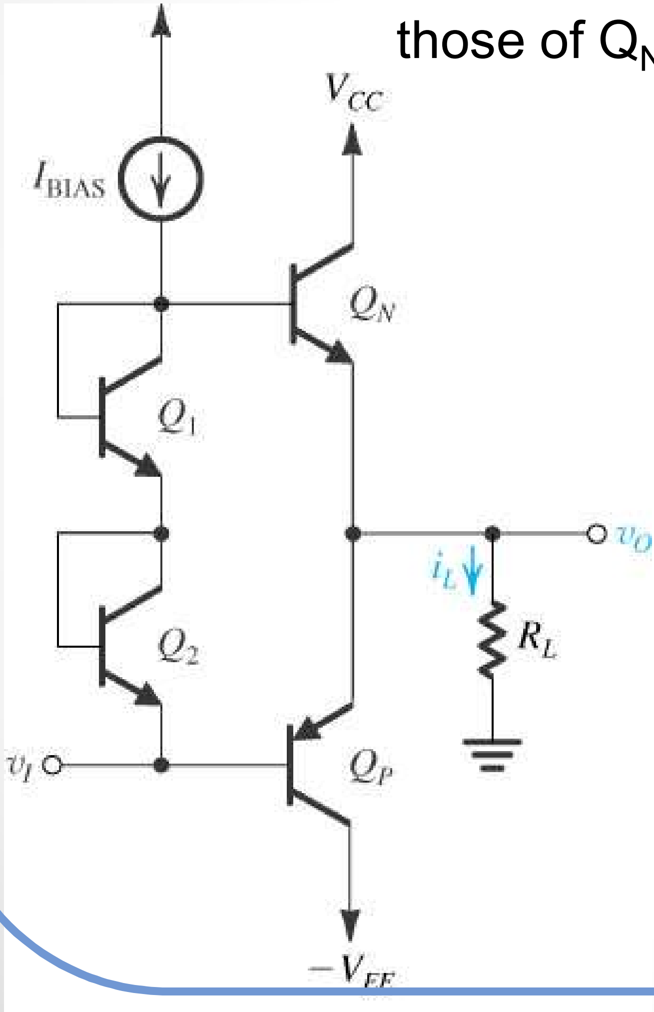
(b)

Although efficient in terms of power dissipation, it suffers from a crossover distortion. Because for |Vi| less than 0.5 V, neither of them conducts and Vo = 0.



Class AB: Crossover distortion can be reduced by biasing the output stage transistors at a low current. This ensures that the output transistors Q_N and Q_P will remain conducting when Vi is small.

- One way to bias the transistors is thru the use of 2 diode-connected transistors Q1 and Q2 with junction areas much smaller than those of Q_N and Q_P.

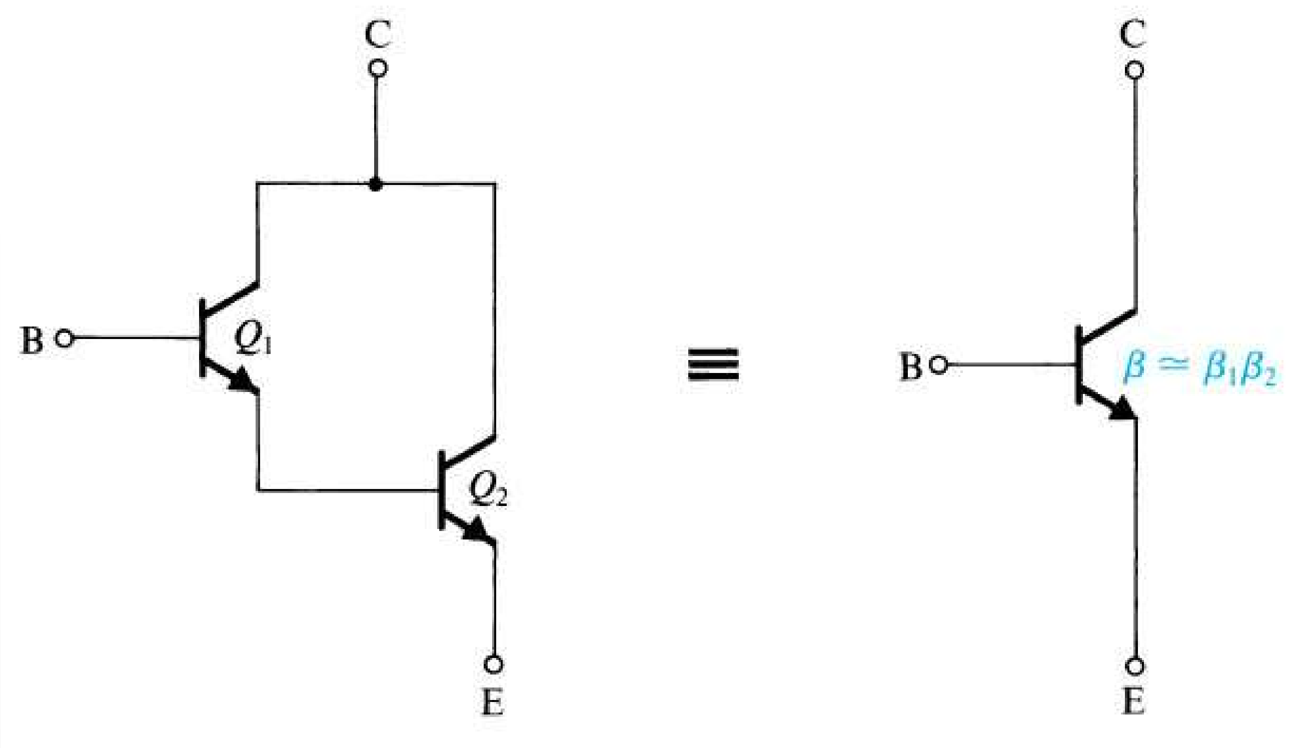


(d)

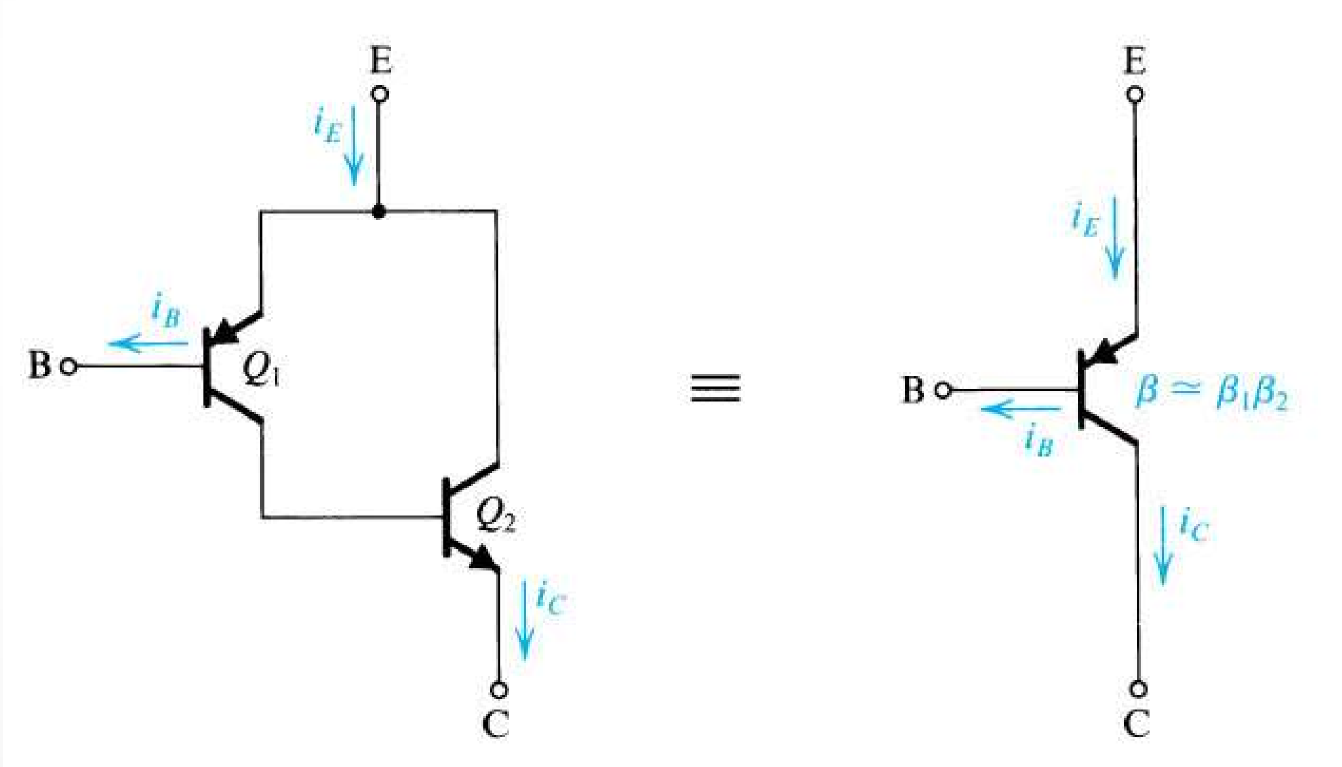
Darlington configuration

A cascade connection of 2 common-collector transistors. It is used to implement a high-performance voltage follower. In output stage, it increases the current gain of the output stage transistors, and thus reduces the required base current drive.

This is equivalent to a single npn transistor having $\boxed{\beta = \beta_1\beta_2}$ and $\boxed{V_{BE} = V_{BE1} + V_{BE2}}$



It can also be used for pnp transistors and this is done in discrete-circuit design. In IC design, however, the lack of good-quality pnp transistors prompted the use of the alternative compound configuration shown below.



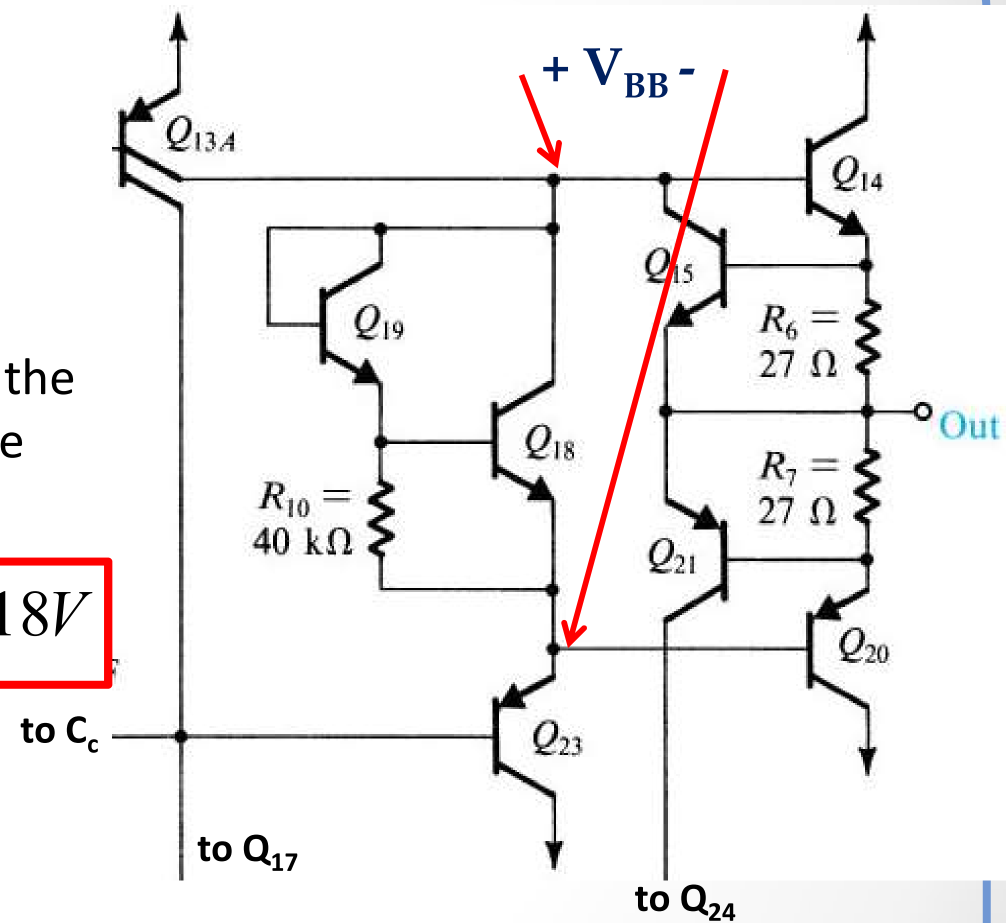
Output-stage Biasing Currents

The voltage drop across the base-emitter junction of Q19 is

$$\boxed{V_{BE19} = V_T \ln(\frac{I_{C19}}{I_S}) = 530mV}$$

The purpose of the Q18-Q19 network is to establish 2xV_{BE} drops between the bases of the output transistors Q14 and Q20. This voltage drop, V_{BB}, can be now calculated as

$$\boxed{V_{BB} = V_{BE18} + V_{BE19} = 588 + 530 = 1.118V}$$



Output-stage Biasing Currents

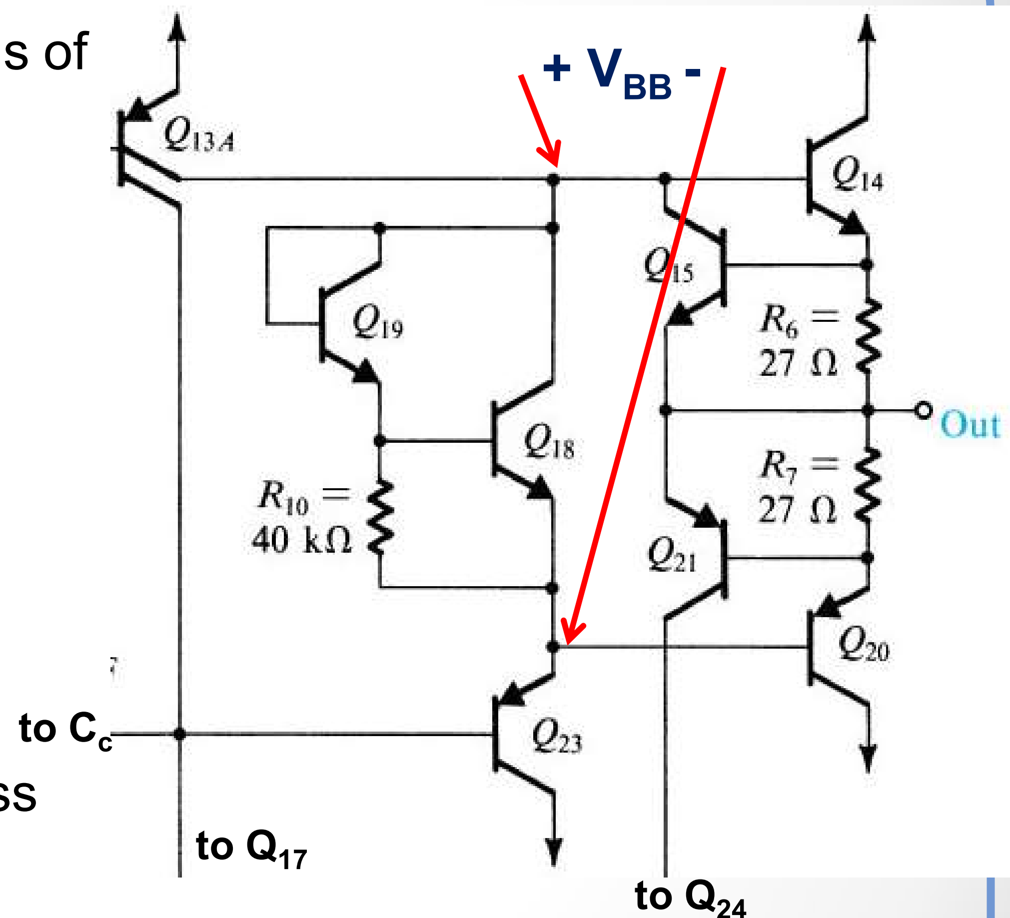
Since V_{BB} appears across the series combination of the base-emitter junctions of Q14 and Q20, we can write

$$\boxed{V_{BB} = V_T \ln\left(\frac{I_{C14}}{I_{S14}}\right) + V_T \ln\left(\frac{I_{C20}}{I_{S20}}\right)}$$

Using the calculated value of V_{BB} and substituting $I_{S14} = I_{S20} = 3\times10^{-14}$ A, we can find

$$\boxed{I_{C14} = I_{C20} = 154\mu A}$$

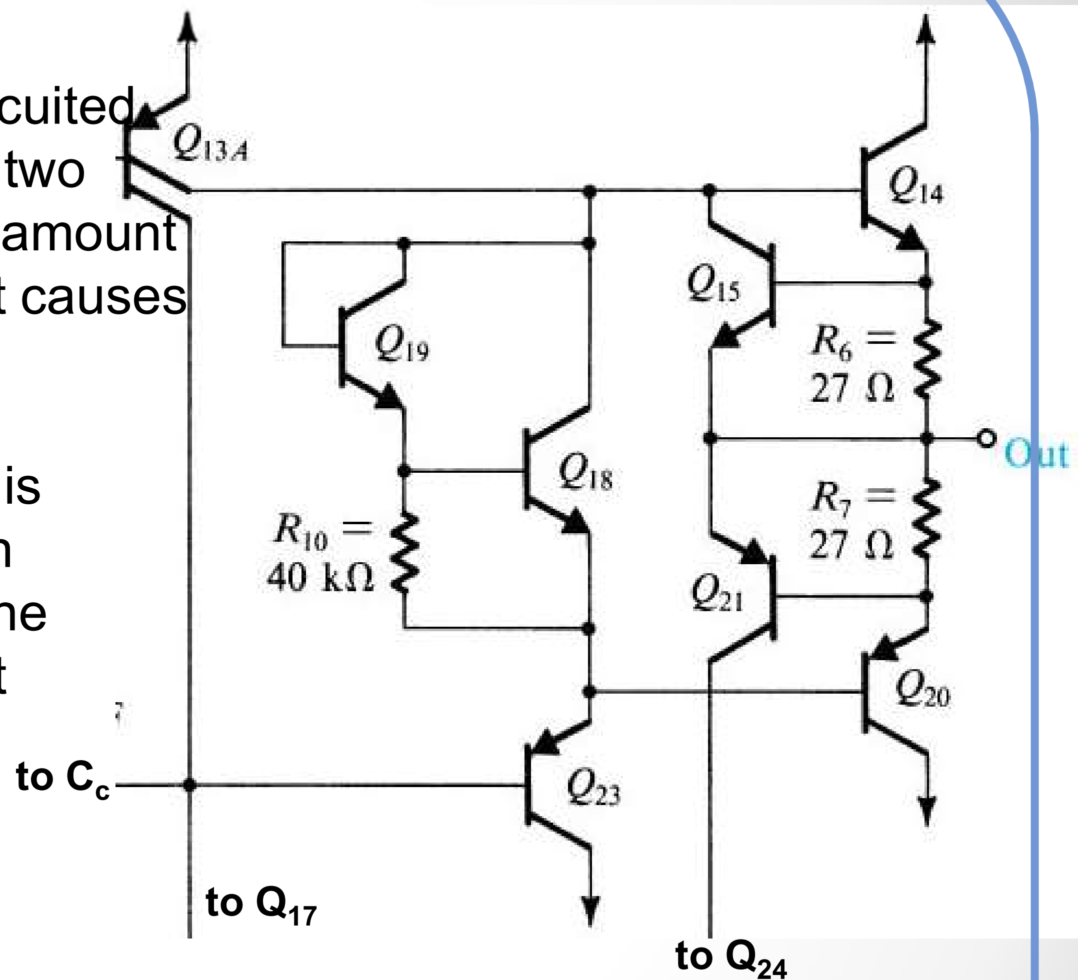
This is the small current at which the class AB output stage is biased.



Output Short Circuit Protection

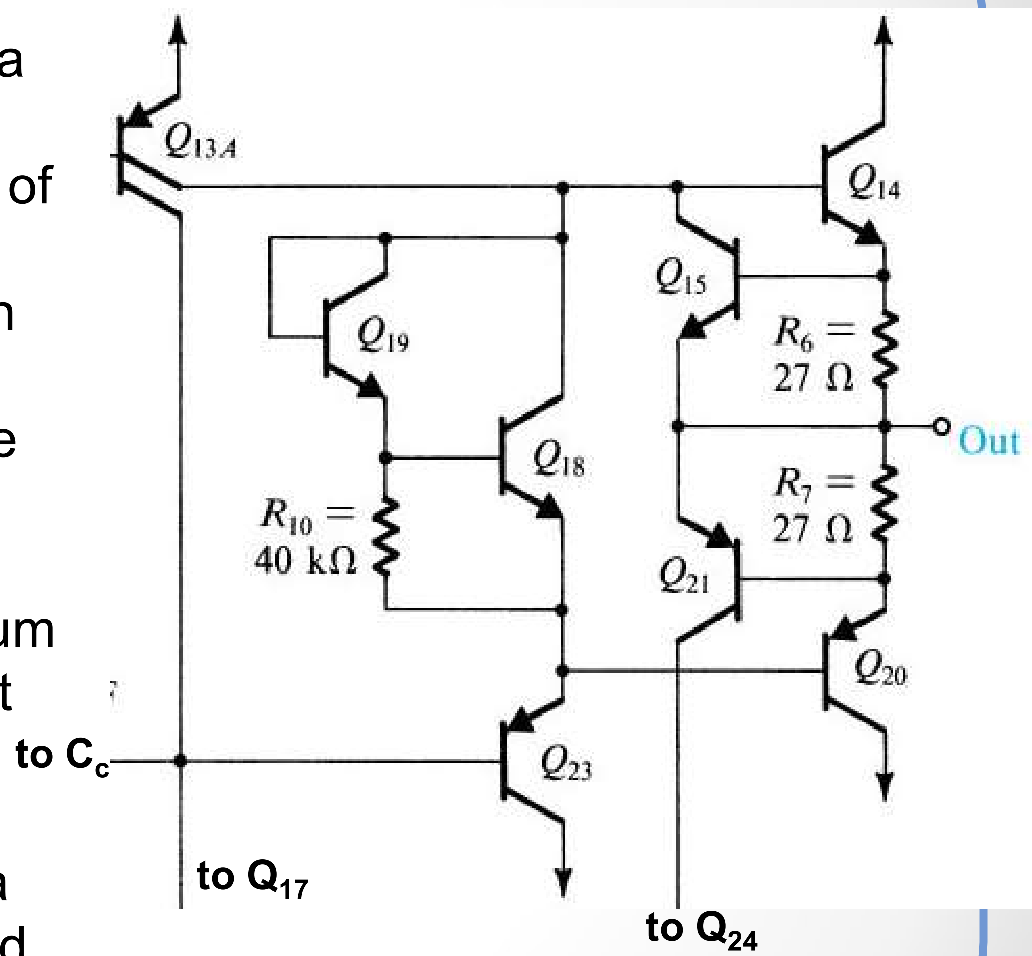
If the op amp output terminal is short-circuited to one of the power supplies, one of the two output transistors could conduct a large amount of current. This can result in heating that causes burnout of the IC.

To prevent this mishap, the 741 op amp is equipped with the short-circuit protection whose function is to limit the current in the output transistors in the event of a short circuit.



Output Short Circuit Protection

- R6, together with Q15, limits the current that would flow out of Q14 in the event of a short circuit.
- Specifically, if the current in the emitter of Q14 exceeds about 20mA, the voltage drop across R6 exceeds 540 mV, which turns Q15 on.
- As A15 turns on, its collector robs some of the current supplied by Q13A, thus reducing the base current of Q14.
- This mechanism thus limits the maximum current the op amp can source to about 20 mA.
- Limiting of the max current that the op amp can sink through Q20 is done by a similar mechanism to the one discussed above.



Output Short Circuit Protection

- These transistors are normally off
- They only conduct in the event that a large current is drawn from the output terminal (i.e. a short circuit)

DC Analysis Summary

Table of Results

Below is a table that lists all of the transistors and their collector currents.

		DC Collector Currents of the 741 op-amp (uA)					
Q1	9.5	Q8	19	Q13B	550	Q19	15.8
Q2	9.5	Q9	19	Q14	154	Q20	154
Q3	9.5	Q10	19	Q15	0	Q21	0
Q4	9.5	Q11	730	Q16	16.2	Q22	0
Q5	9.5	Q23	730	Q17	550	Q23	180
Q6	9.5	Q13A	180	Q18	165	Q24	0
Q7	10.5						

Concluding Remarks

The uA741 operational amplifier is a versatile circuit that is not adversely affected by outside interference.

- Changes in beta, resistor values, and temperature have little effect on the op-amp.
- This shows how well the uA741 was designed.

However, as technology continues to improve, CMOS amplifiers are beginning to become more popular than their BJT cousins.

References

Microelectronic Circuits by Adel S. Sedra & Kenneth C. Smith. Saunders College Publishing

μA741 General Purpose Operational Amplifies by Texas Instruments

The 741 Op Amp: DC and Small Signal Analysis by Jeremy Andrus and Paulo Ribeiro, Calvin College, Michigan, USA

Operational Amplifier by Wikipedia.org


WATCH
FOR
ICE
UNFORTUNATELY,
polar bears can't read.