2| Power

Power Amplifiers

- Amplifiers that produce voltage amplification or current amplification also produce power amplification
- However, the term **power amplifier** is normally reserved for circuits whose main function is to deliver large amounts of power
- These can be produced using FETs or bipolar transistors, or using special purpose devices such as **thyristors**.

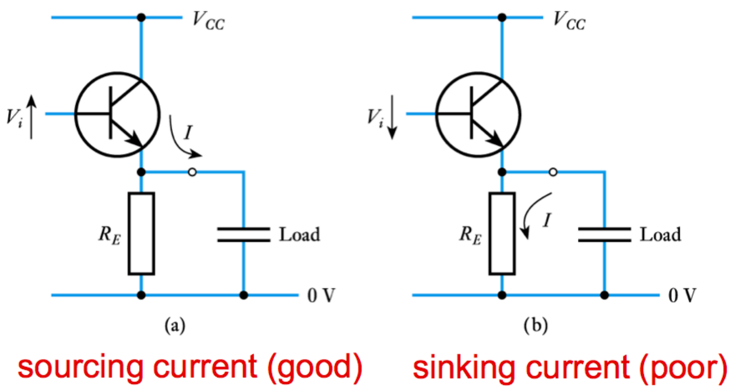
BIPOLAR TRANSISTOR POWER AMPLIFIERS

When designing a power amplifier we normally require a low output resistance so that the circuit can deliver a high output current

- we often use an **emitter-follower** (i.e. buffer amplifier)
- this does not produce voltage gain but has a **low output resistance**, $r_o \approx r_e \approx 25\Omega$
- in many cases the load applied to a power amplifier is not simply **resistive** but also has an **inductive** or **capacitive** element

CURRENT SOURCES AND LOADS

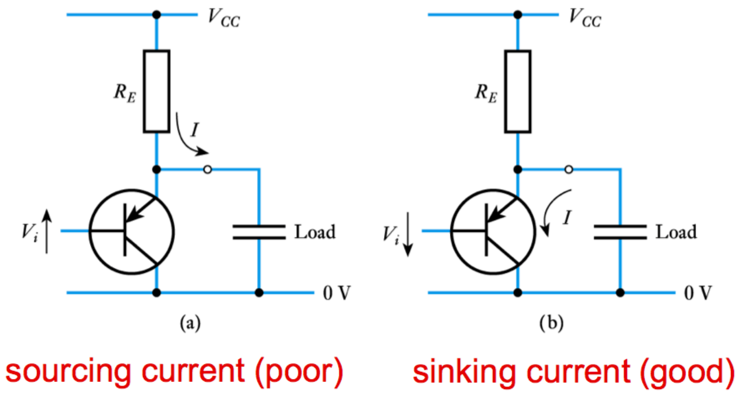
- When driving a reactive load, we need to supply current at some times (the output acts as a **current source**)
- At other times we need to absorb current (the output acts as a **current sink**)



This circuit is a **good current source** but, the one on the right has a **poor current sink** (since the stored charge must be removed by R_E).

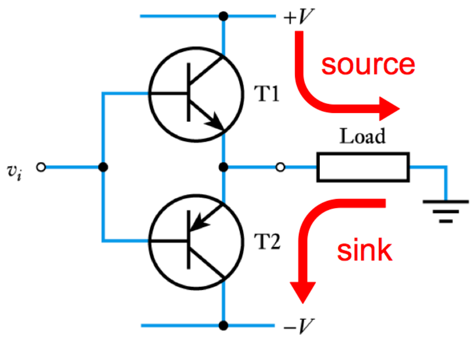
Resistors need to be avoided as they consume a lot of power and take up a lot of space.

An alternative circuit using ***pnp*** transistors is a **good current sink**, but a **poor current source,** as it uses R_E. The gain is about 1.

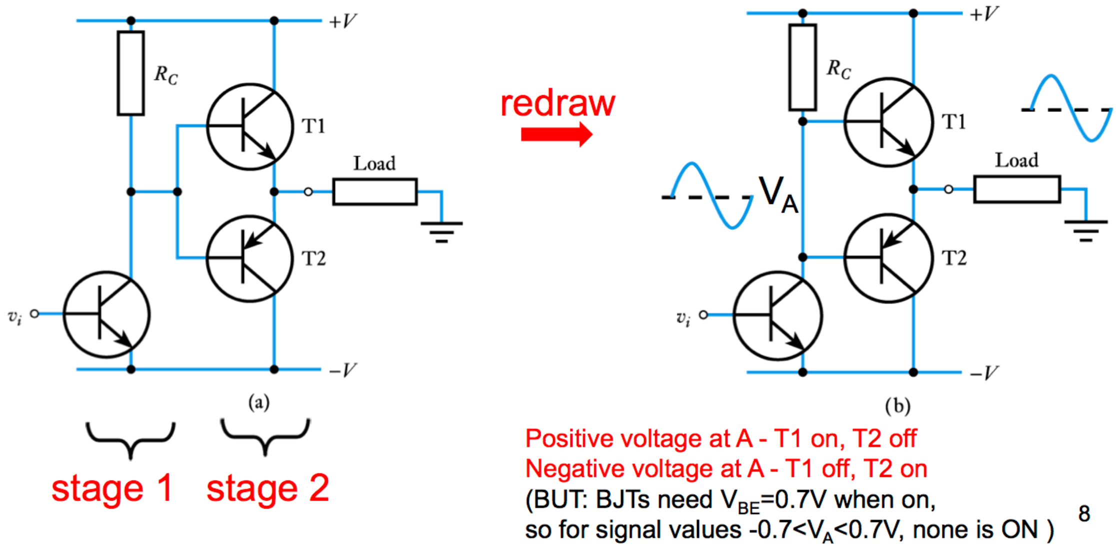


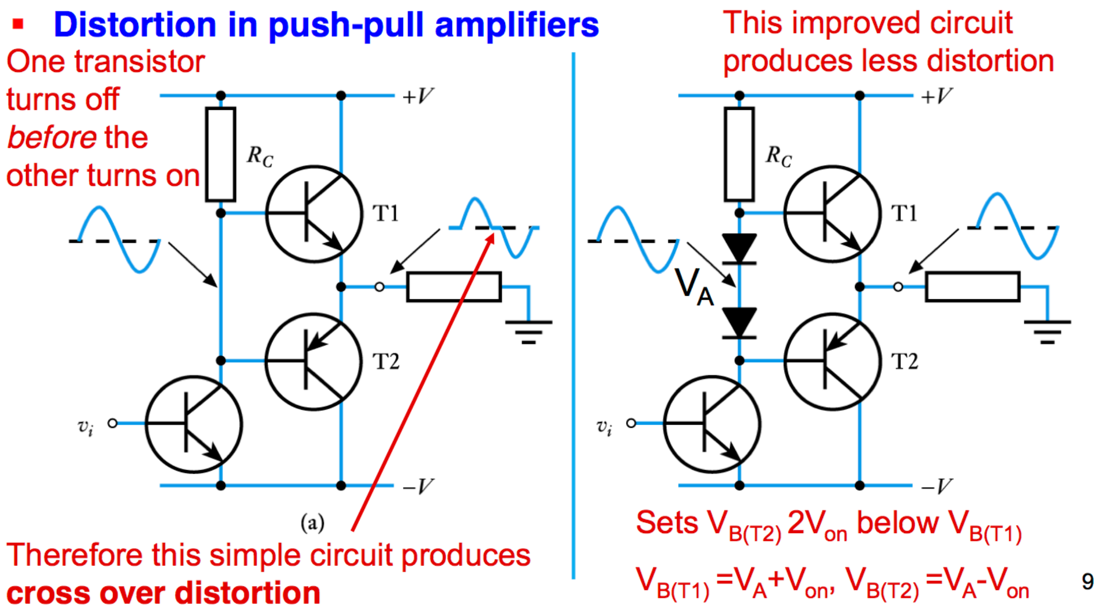
Push-Pull Amplifiers

- Combining these circuits can produce an arrangement that is both a good current source and a good current sink. This is called a **push-pull amplifier**.
- This has a low output resistance when both sourcing and sinking current
- Only one transistor is turned-on at a time.

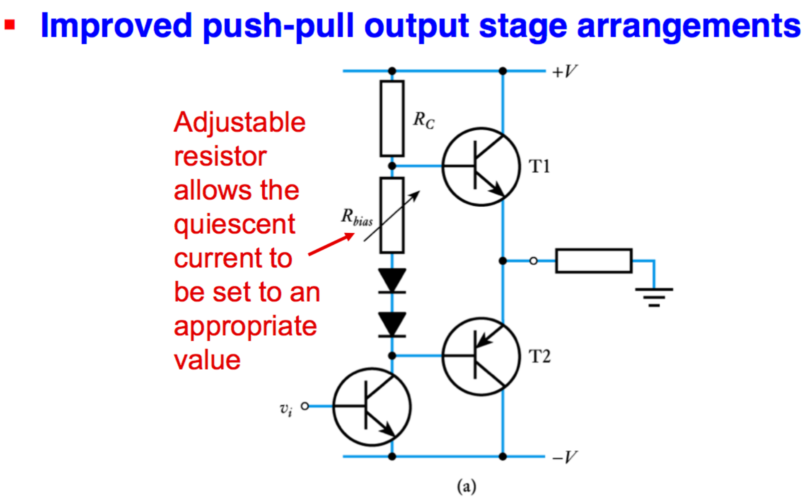


PUSH-PULL STAGE





- Although the inclusion of diodes **reduces the distortion**, it does not remove it all together.
- The current through the transistors is greater than that through the diodes, and therefore the turn-on voltage across each diode is slightly less than the V_{BE} of each transistor.
- Therefore, some distortion still remains.



AMPLIFIER EFFICIENCY

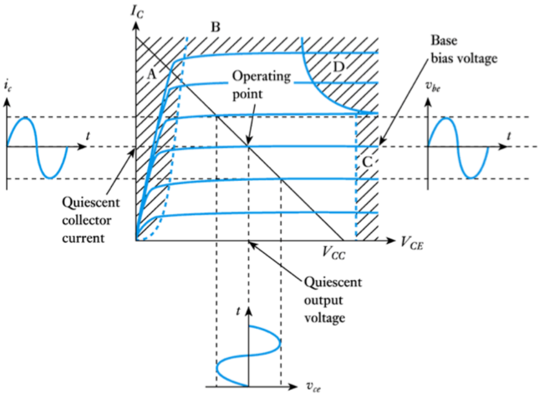
An important consideration in the design of power amplifiers is efficiency

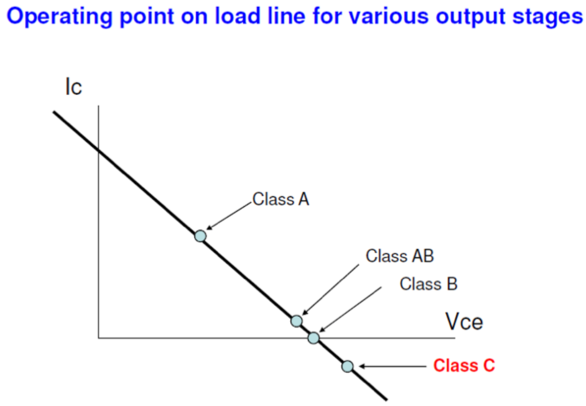
$$\text{Efficiency} = \frac{\text{Power Dissipated in the Load}}{\text{Power Absorbed from the Supply}}$$

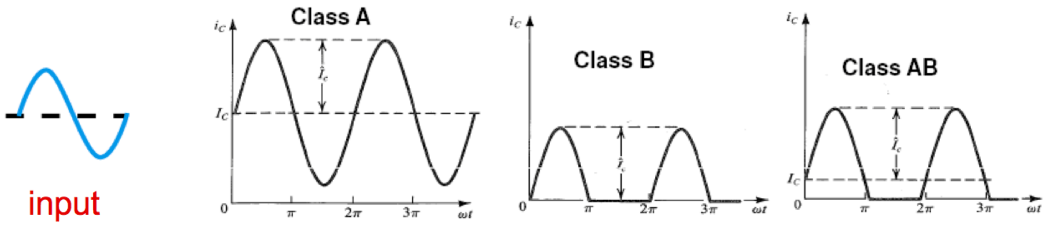
Efficiency determines the power dissipated in the amplifier itself.

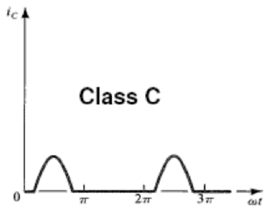
Power dissipation is important because it determines the amount of waste heat produced. (Excess heat may require heat sinks, cooling fans etc.).

Classes of Amplifiers





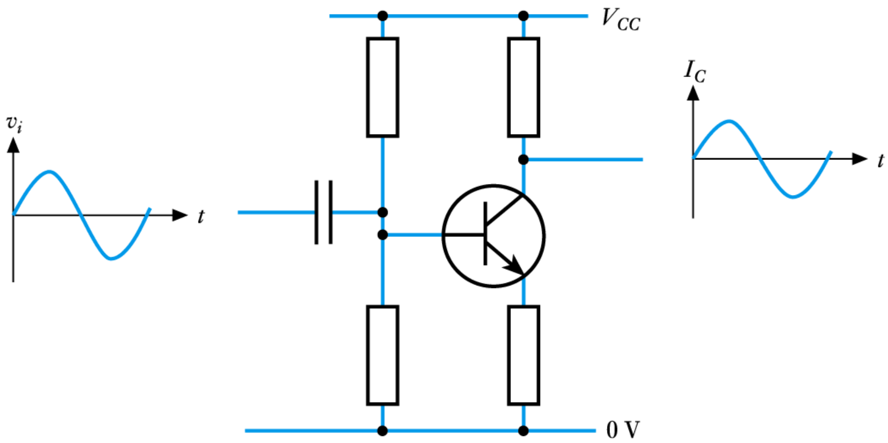




Amplifier	Maximum Efficiency, η_{max}
Class A	25%
Class B	78.5%
Class C	99%

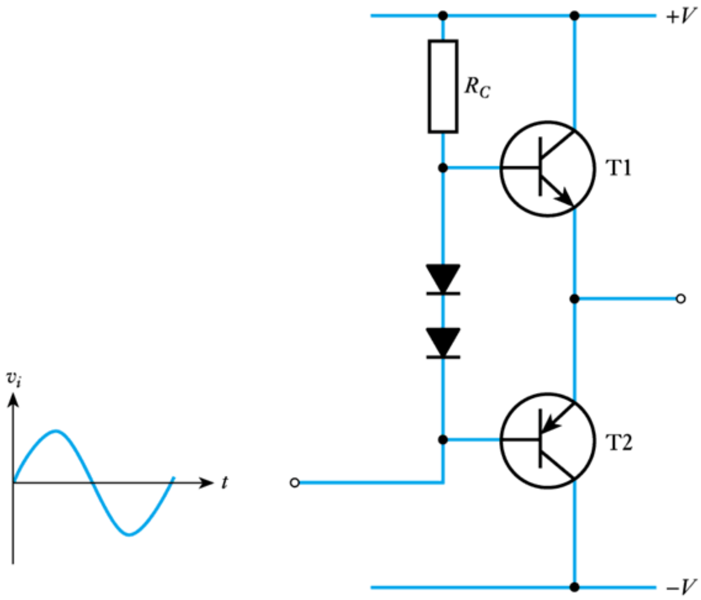
CLASS A

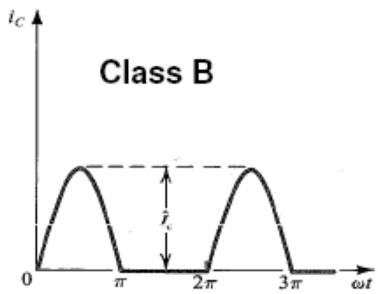
- Active device conducts for complete cycle of input signal
- Example shown here with input stage
- Poor efficiency (normally less than 25%)
- Low distortion



CLASS B

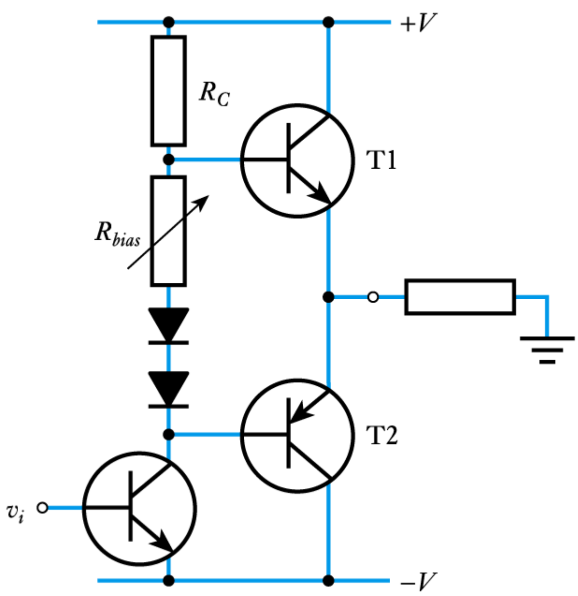
- Active devices conducts for half of the complete cycle of input signal (operating point is at the edge)
- Good efficiency (up to 78%)
- Quiescent current is zero
- Considerable distortion

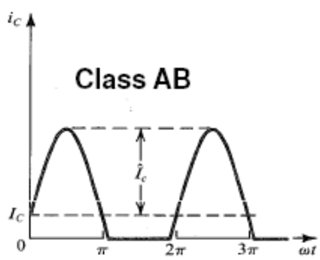




CLASS AB

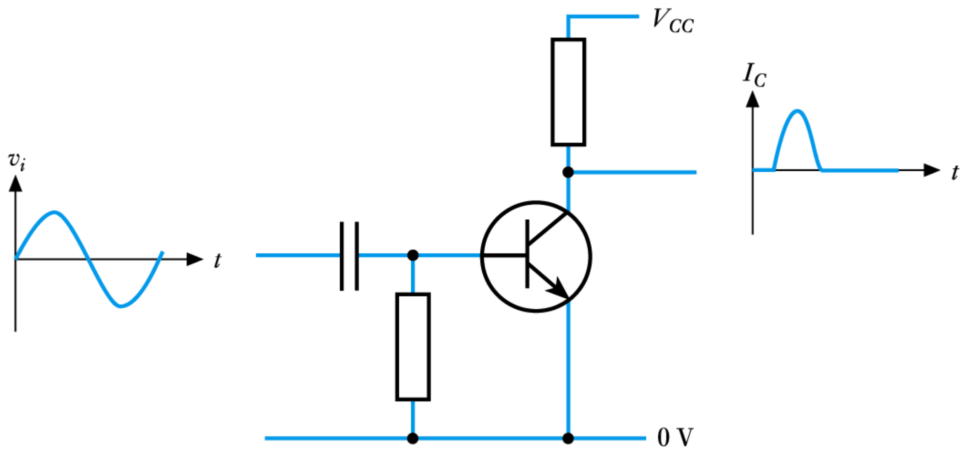
- Active devices conducts for more than half but less than the complete cycle of input signal.
- Example shown here (with appropriate R_{bias})
- Efficiency depends on bias
- Distortion depends on bias





CLASS C

- Active devices conducts for less than half the complete cycle of input signal
- Operating point is adjusted accordingly
- Example shown here
- High efficiency (approaching 100%)
- Gross distortion

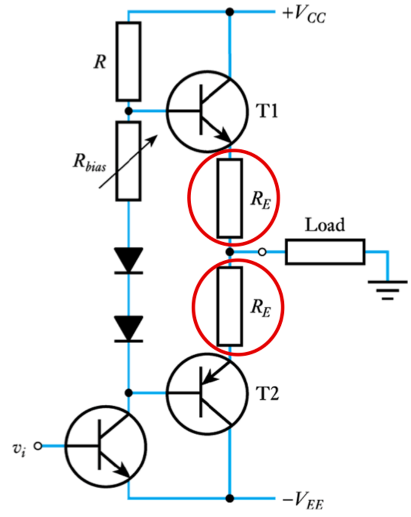


Design Techniques

OUT STAGE TECHNIQUES

Back to our amplifier:

- **Insert feedback resistors**
  - The stability of the earlier circuit can be improved by adding small emitter resistors
    - These provide negative feedback
    - Stabilises the quiescent current
    - R_{bias} is adjusted to compensate

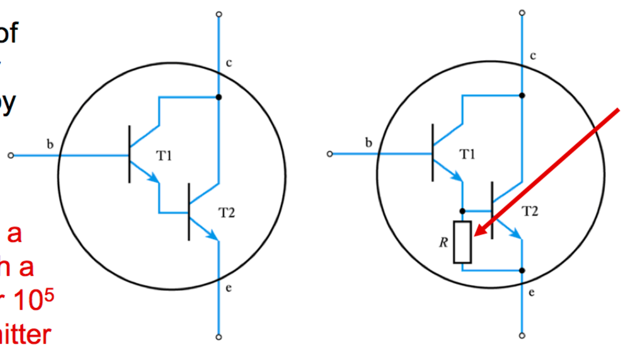


DARLINGTON TRANSISTORS

Current gain of first transistor is multiplied by that of the second

Can produce a transistor with a gain of 10^4 or 10^5 (common-emitter configuration)

Base-emitter voltage is about 1.4 V



(a) (b)

Often a resistor *R* is added to improve the turn-off time – typically this is a few kilo-ohms and does not affect the basic operation of the circuit

- A high input resistance buffer amplifier
- Example: For the circuit indicated:

Quiescent output voltage

$$V_B \approx V_{CC}\frac{R_2}{R_1+R_2} = 10 \times \frac{18\ \text{M}\Omega}{10\ \text{M}\Omega + 18\ \text{M}\Omega} = 6.4\ \text{V}$$

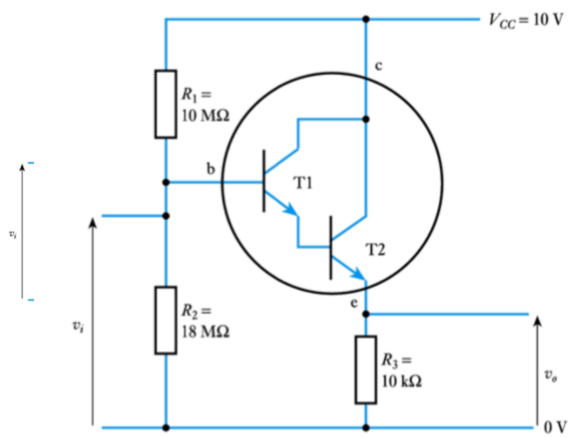
$$V_{o(\text{quiescent})} = V_E = V_B - V_{BE} = 6.4 - 1.4 = 5.0\ \text{V}$$

Small signal voltage gain

Small signal voltage gain $\approx$ 1 (Common Collector)

Small signal input resistance

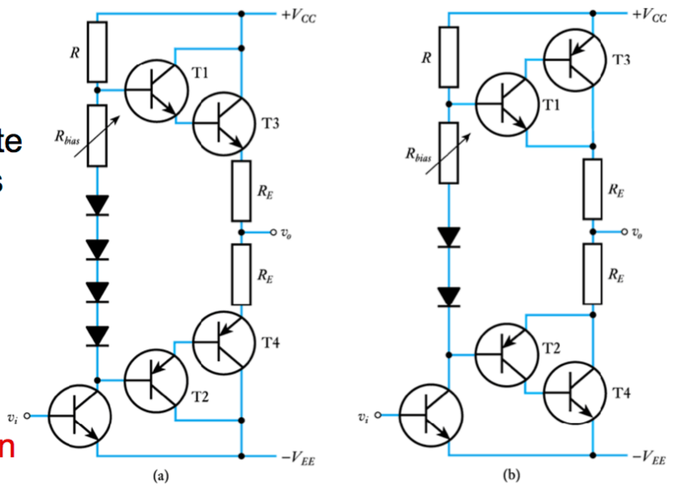
$$R_i \approx R_1 // R_2 = 10\ \text{M}\Omega\ //18\ \text{M}\Omega = 6.4\ \text{M}\Omega$$



- A common application of Darlington and complementary Darlington transistors is in the production of power transistors.
- Conventional high-power transistors have a relatively low gain, perhaps 10 - 60
- A typical Darlington power transistor would have a much higher gain – Perhaps a minimum gain of 1000 at 10 A

OUTPUT STAGE TECHNIQUES

- **Insert Darlington transistors**
  - Since the gain of power transistors is normally quite low, Darlington transistors are sometimes used
  - The offset between the bases is adjusted to suit
  - Darlington pairs provide high input impedance
  - Complementary Darlington pairs provide even larger input impedance and almost 100% negative feedback

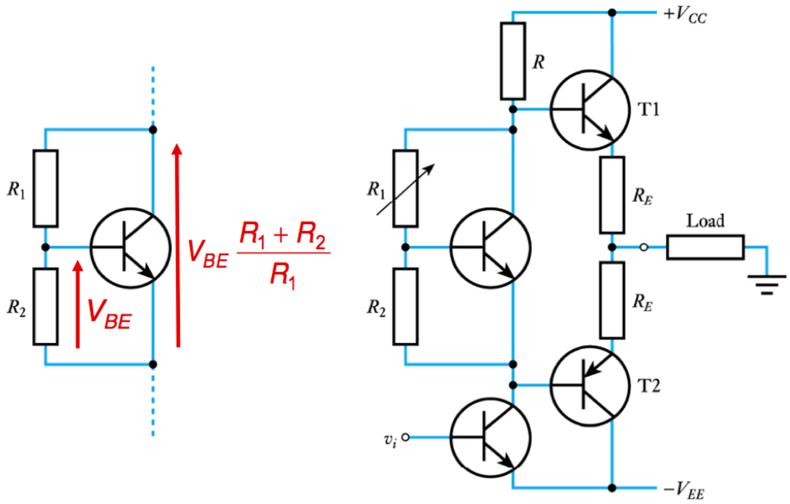


Use of Darlington pairs

Use of complementary Darlington pairs

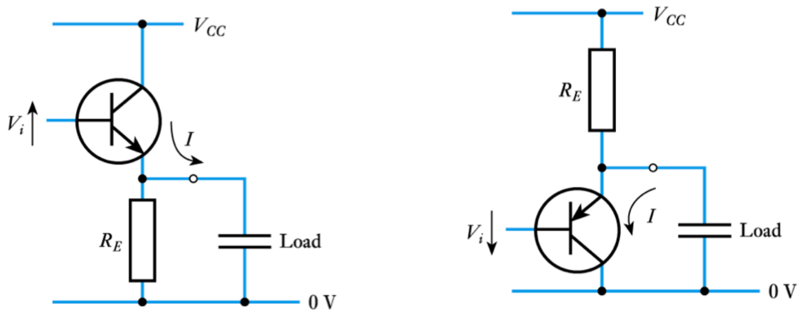
25

- **V_{BE} multiplier**
  - A V_{BE} multiplier arrangement allows the offset voltage between the bases to be set using a single transistor and two resistors

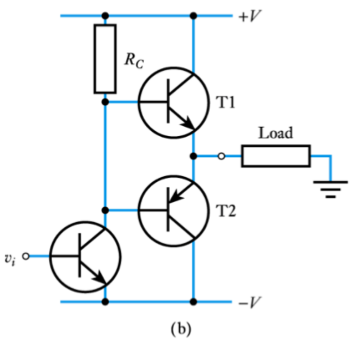


(a) A V_{BE} multiplier (b) An output stage using a V_{BE} multiplier

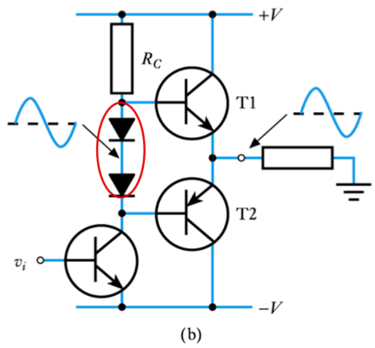
Power Amplifier Design Stages



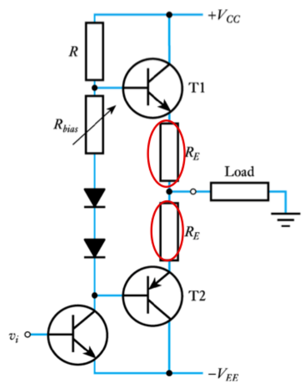
Started with the good current source/sink configurations



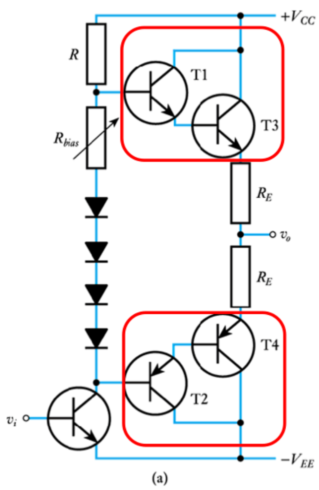
(1) Simple push-pull amplifier



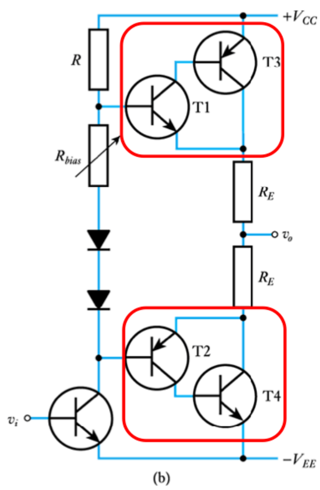
(2) Add diodes to eliminate distortion



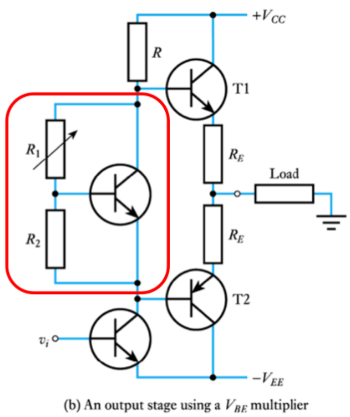
(3) Add resistances for negative feedback



(4a) Add Darlington transistors



(4b) Complimentary Darlington transistors

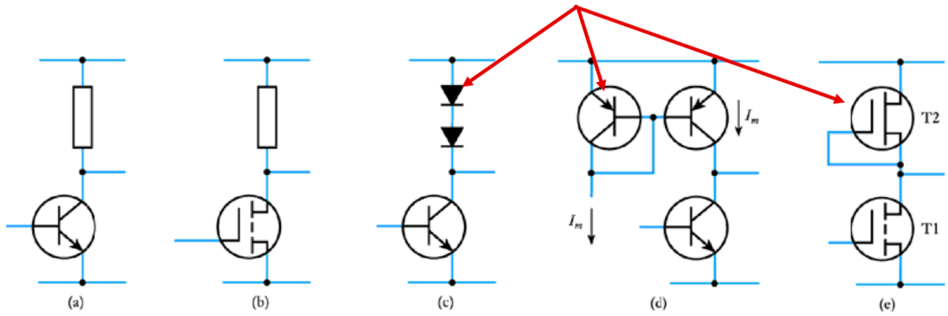


(5) Replace diodes with V_{BE} multiplier

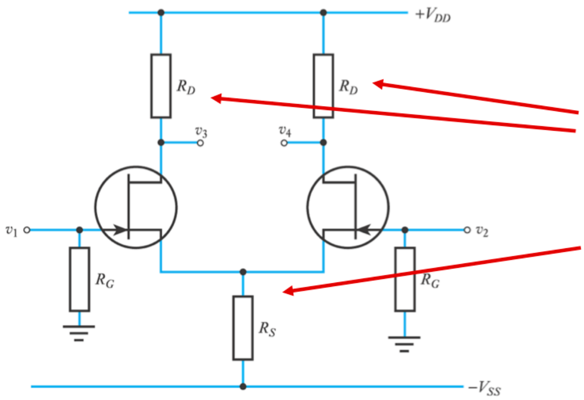
Another example on how to remove resistances

- When producing integrated circuits, resistors are to be avoided
- A range of **active load** arrangements are used

These devices are smaller than resistors within ICs



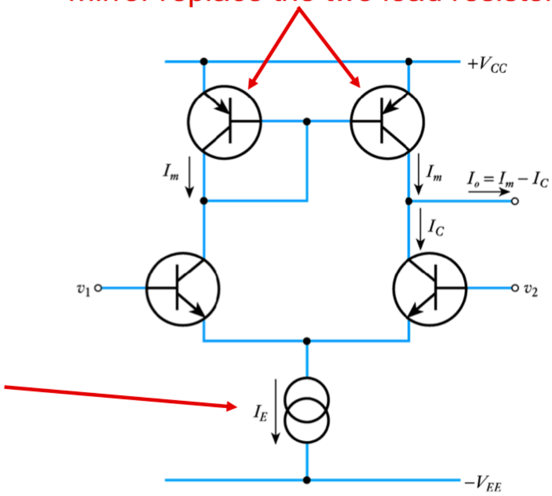
- Earlier we studied the differential amplifier



Uses resistances that take space on the IC and dissipate power

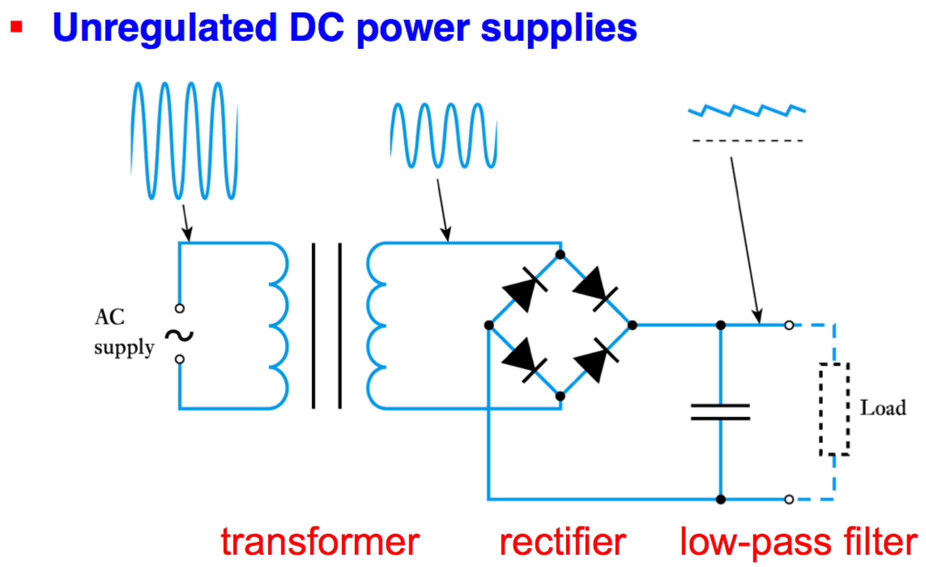
- a long-tailed pair amplifier with a current-mirror load

Here the two halves of the current mirror replace the two load resistors



We noted earlier that a current mirror could also be used here as a constant current source

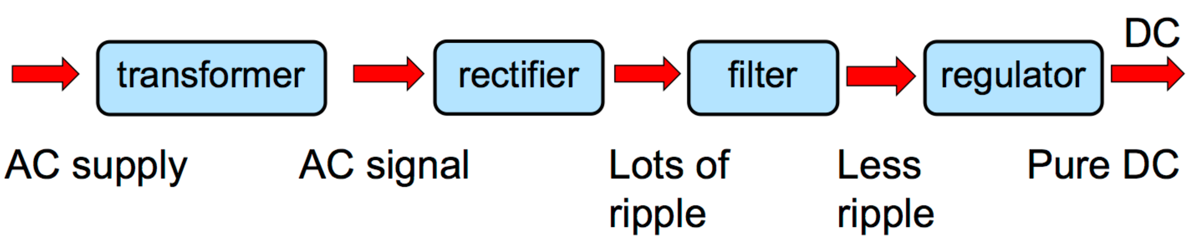
Power Supply Basics



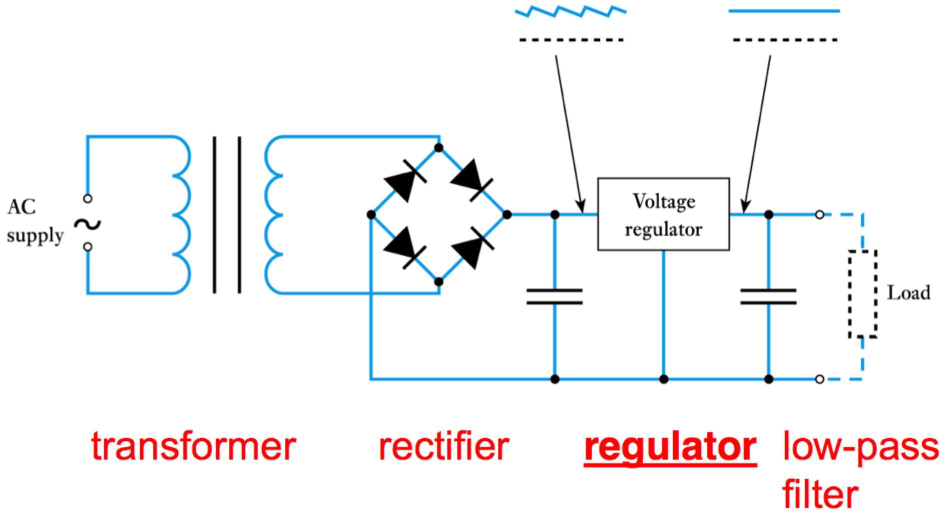
NEED FOR REGULATORS

- A simple power supply consisting of only transformer, rectifier, reservoir and low pass filter however, does have some drawbacks.
- The output voltage of the power supply unit (PSU) tends to fall as more current is drawn from the output. This is due to:
    - The reservoir capacitor being discharged more on each cycle.
    - Greater voltage drop across the resistor.
- These problems can be largely overcome by **including a regulator stage** at the power supply output. The regulator transforms the voltage and takes away any ripple.
- The basic power supply circuits described here are commonly used in DC adaptors supplied with many electronics products.

DC POWER SUPPLY DESIGN - MAIN STAGES OF SIGNAL CONVERSION

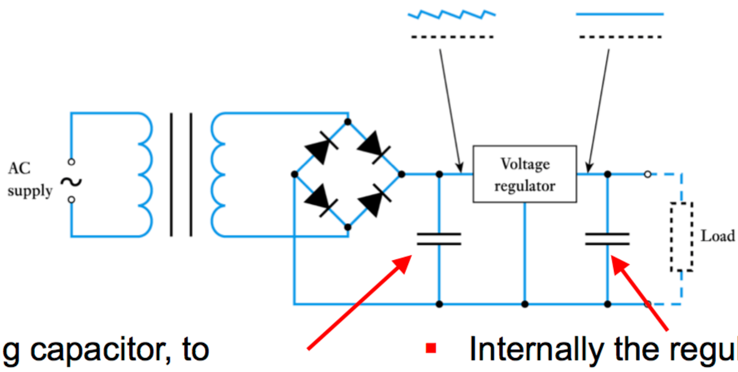


REGULATED DC POWER SUPPLIES



ROLE OF CAPACITORS IN REGULATORS

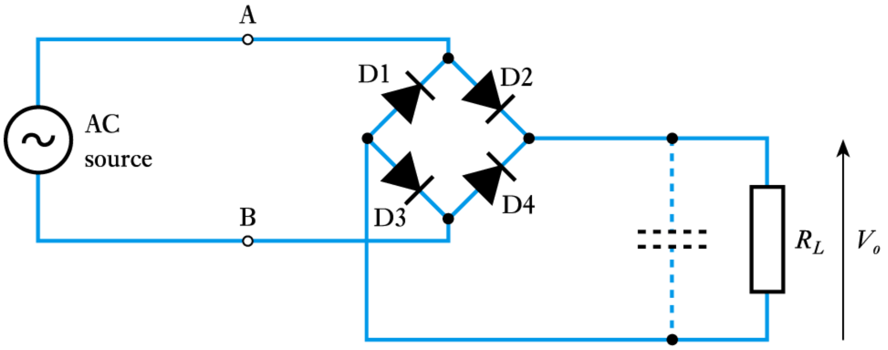
- **Modern day regulators require two capacitors (may/may-not be integrated within the regulator)**

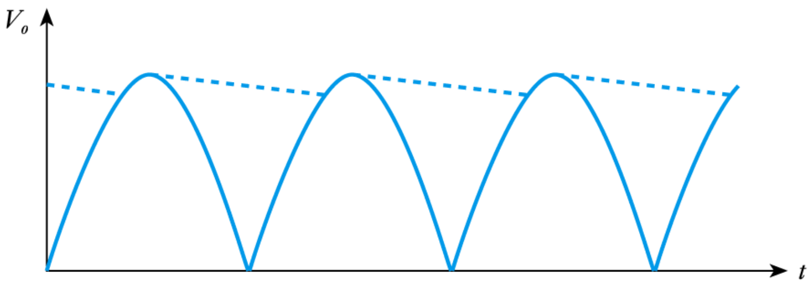


- Decoupling capacitor, to remove high-frequency noise that may be present on the input , (or smooth the ac signal after the bridge)
- Internally the regulator uses a feedback loop to stabilize the output voltage. The second capacitor ensures that the feedback loop is stable

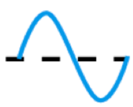
Full Wave Rectifier – Bridge

Use of a diode bridge reduces the time for which the capacitor has to maintain the output voltage and thus reduces the ripple voltage;

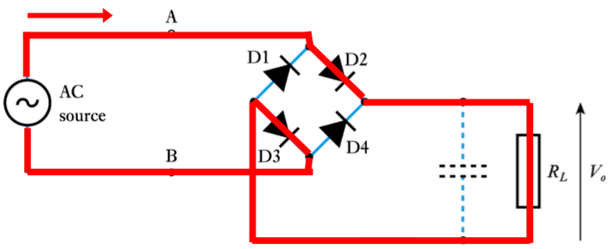




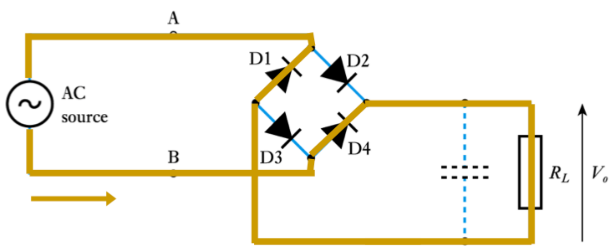
- Positive half cycle
- D2, D3 conducting



input



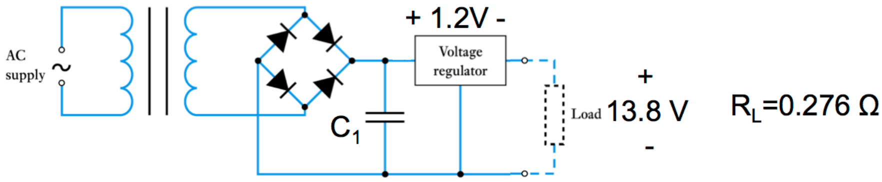
- Negative half cycle
- D1, D4 conducting

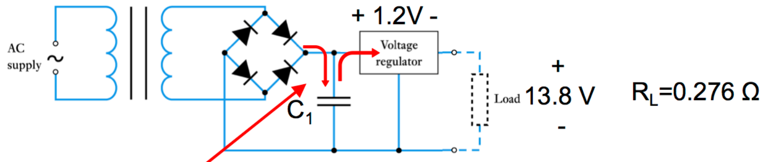


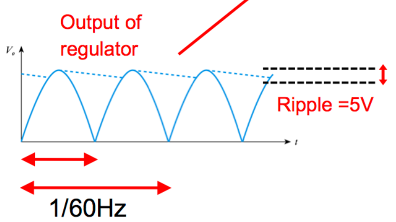
Example: Assume a power supply using a bridge rectifier connected to a 60Hz input. The output should be $V_{out} = 13.8\text{V}$ across a load resistance of 0.276Ω. A voltage regulator is in series with the bridge, and requires a minimum of 1.2V.

a) Determine the value of the filter capacitor C which produces a maximum voltage ripple at the input of the regulator of 5V.

b) Determine the rms voltage of the secondary winding of the transformer







1. Current lows in C_1 during charging
2. Current i_C flows out of C1 after the peak of the cycle, and continues for half period (approximately)
3. The current needs to be constant, to keep the voltage on the load constant

- **Solution (part a): The capacitor supplies current into the load for half period to keep its voltage constant. Only 5V drop in the C_1 voltage is allowed**

The current needed in the load is: (supplied by C_1) $\quad i_c = i_R = \dfrac{V_R}{R} = \dfrac{13.8V}{0.276} = 50A$

The current in/out of the capacitor is: $i_c \approx -C\dfrac{\Delta v_C}{\Delta t}$ thus $C \approx -i_c\dfrac{\Delta t}{\Delta v_C}$

The period of the signal out of the bridge is: $\Delta t = \dfrac{1}{2 \text{ x } 60Hz} = 8.33ms$

Since $\Delta v_C = 5V \qquad C \approx i_c\dfrac{\Delta t}{\Delta v_C} = 50A\dfrac{8.33 \text{ x } 10^{-3}s}{5V} = 83.3mF$

1

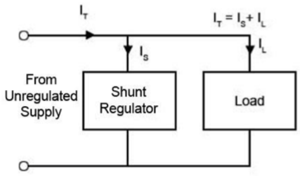
- **Solution (part b):**

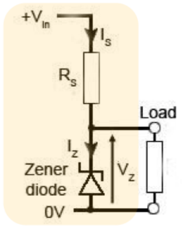
Need to identify the peak voltage, so add all voltage drops:
Remember: The on-voltage for each diode is V_{on}~0.7V
The bridge has two diodes switched *on* at a time

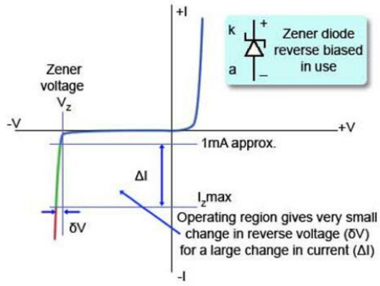
Therefore
$$V_p = V_{out} + V_{reg.} + V_{ripple} + V_{D1} + V_{D2}$$
$$= 13.8 + 1.2 + 5 + 0.7 + 0.7 = 21.4V$$

and
$$V_{rms} = \frac{V_p}{\sqrt{2}} = 15.13V$$

Shunt Regulator (Voltage Reference)







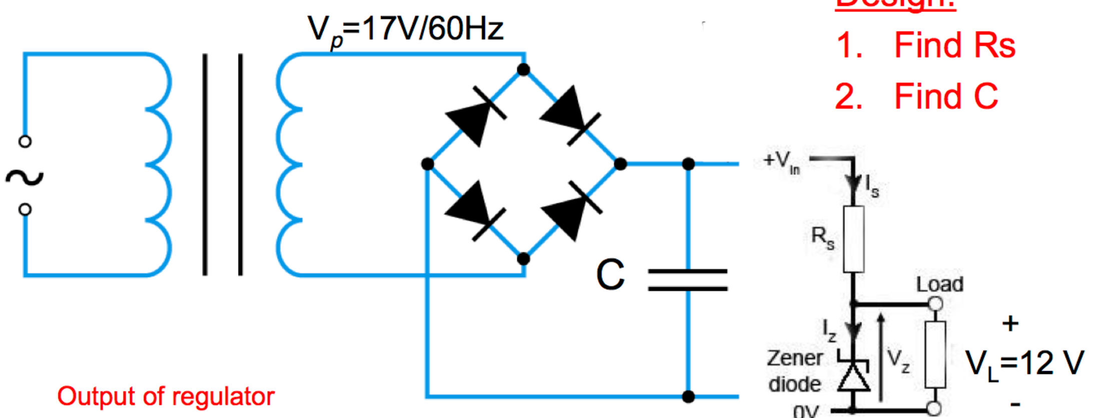
- **Shunt regulator**
  - Ensures a stable voltage across the load at all times.
  - Achieved by regulating the current.

- **Zener diode in reverse breakdown**
  - The extra current goes through the diode, rather than the load.
  - Limitations: small currents/voltages, as much as the diode can handle.

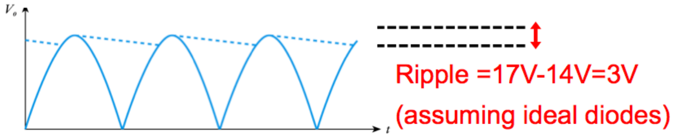
- **Example:** Consider the output of a bridge rectifier. Assume the ac voltage supplying the bridge rectifier has a peak voltage V=17V and a 60Hz frequency. Design the rest of the power supply using a Zener diode in the regulator section. The output should be V_{out}=12V and the maximum output current should be 50mA. Assume the Zener diode can handle 1.2W and that the minimum current flow required through the Zener is appr. ~ 1mA.
  a) What is the maximum current that the Zener can handle?
  b) Determine the value of C such that the voltage does not drop below 14V
  c) Determine the value of the series resistance
  d) Determine the maximum power dissipation in the resistance

- **Explain the problem:**

Design:
1. Find Rs
2. Find C



Output of regulator



Solution (assuming ideal diodes):

a) $P = v \text{ x } i$ and therefore $i_{\max} = \frac{P}{v} = \frac{1.2W}{12} = 0.1A = 100mA$

b) Assuming the diodes are ideal:

$$C \approx -i_c \frac{\Delta t}{\Delta v_C} = 0.05 \frac{1/(2 \text{ x } 60Hz)}{17V - 14V} = \frac{0.00833s}{3V} = 139\mu F$$

For C pick something larger (even 5x) to ensure more current can be supplied (Zener current is not constant)

c) Series resistance: $R_S = \frac{\Delta V_{Rs}}{i} = \frac{14V - 12V}{0.05A} = 40\Omega$

Design for lowest voltage (14V) – worst case scenario

For Rs pick something a bit smaller to ensure always at least 12V on output

d) $P_{\max} = \Delta V_{\max}^2 / R_S = \left(V_{\max}^{in} - V_{out}\right)^2 / R_S = (17V - 12V) / 40\Omega = 0.625W$

Solution (assuming non-ideal diodes):

b) Assuming non-ideal, the capacitance will be larger:

$$C \approx -i_c \frac{\Delta t}{\Delta v_C} = 0.05 \frac{1/(2 \text{ x } 60Hz)}{(17V - 2 \text{ x } 0.7V) - 14V} = \frac{0.00833s}{1.6V} = 260\mu F$$

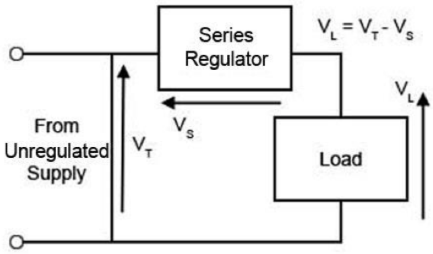
c) Series resistance: $R = \frac{\Delta V}{i} = \frac{14V - 12V}{0.05A} = 40\Omega$

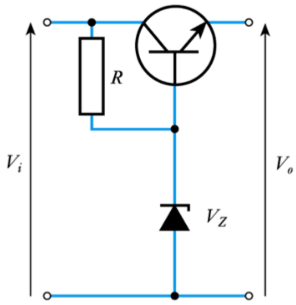
d) $P_{\max} = \Delta V_{\max}^2 / R = \left(V_{\max}^{in} - 2 \text{ x } V_{on} - V_{out}\right)^2 / R$

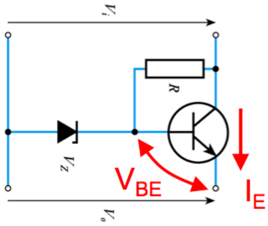
$= (17V - 2 \text{ x } 0.7V - 12V)^2 / 40\Omega = 0.324W$

Note: Now the rest of the power is dissipated in the bridge diodes

Series Regulator





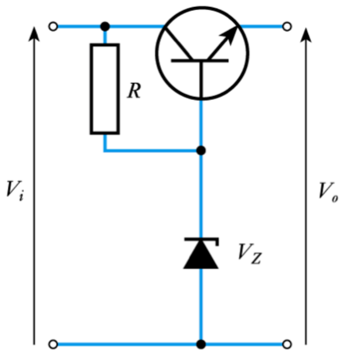


See better if rotated

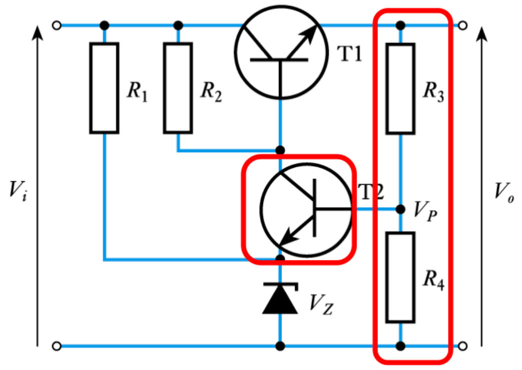
- **Series regulator**
  - Ensures a stable voltage across the load at all times.
  - Achieved by <u>regulating the voltage drop</u> across it using a negative feedback system.

- Stable voltage reference at the base of the power transistor TR by V_Z
  - $V_{out}+V_{BE}=V_z$ therefore $V_{out}=V_z-V_{BE}$
  - If $V_{out}=V_E$ drops, V_{BE} increases, I_E increases, and V_{out} increases again.
  - If $V_{out}=V_E$ increases, V_{BE} drops, I_E decreases, and V_{out} decreases again

- **Voltage regulators**



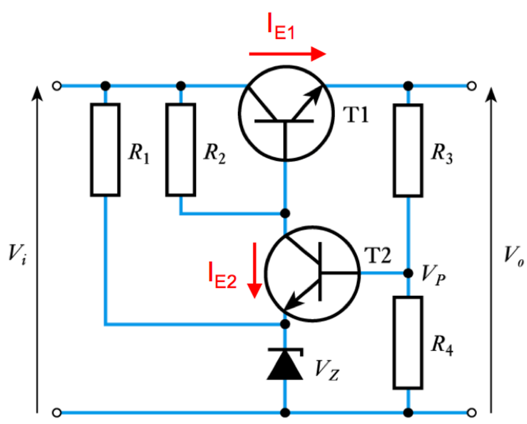
(a)



(b)

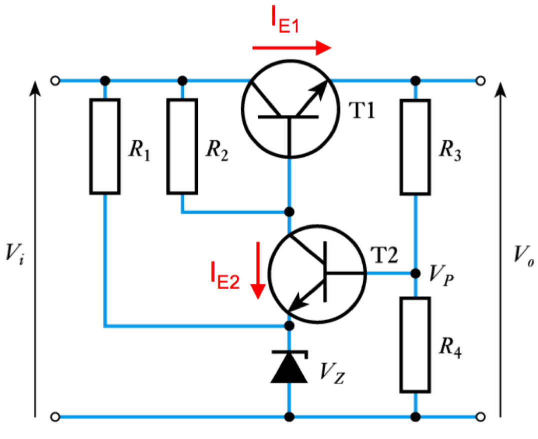
- <u>Feedback using T2</u>

  If V_{out} drops:
  - V_P drops,
  - V_{BE2} drops (since V_Z is const.
  - I_{E2} drops,
  - current through R_2 drops
  - the potential difference across R_2 drops,
  - $V_{C2}=V_{B1}$ increases (since Vi remains the same),
  - V_{BE1} increases,
  - I_{E1} increases, and
  - V_{out} increases again.



(b)

- <u>Feedback using T2</u>
  If V_{out} increases:
  - V_P increases,
  - V_{BE2} increases (V_Z is const.)
  - I_{E2} increases,
  - current through R_2 increases
  - the potential difference across R_2 increases,
  - $V_{C2} = V_{B1}$ drops,
  - V_{BE1} drops,
  - I_{E1} drops, and
  - V_{out} drops again.

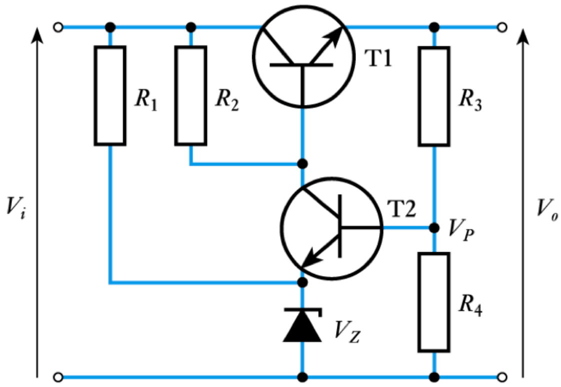


(b)

<u>The role of the Zener diode</u>

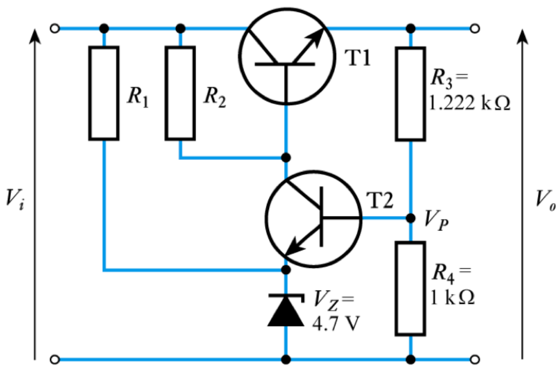
- The emitter voltage is held constant by the Zener diode

- Thus the circuit stabilises at a point where the voltage at the midpoint of the potential divide (Vp) is approximately equal to + 0.7V



(b)

- **Example:** Determine the output voltage of the following regulator (assuming that the input voltage is sufficiently high to allow normal operation).



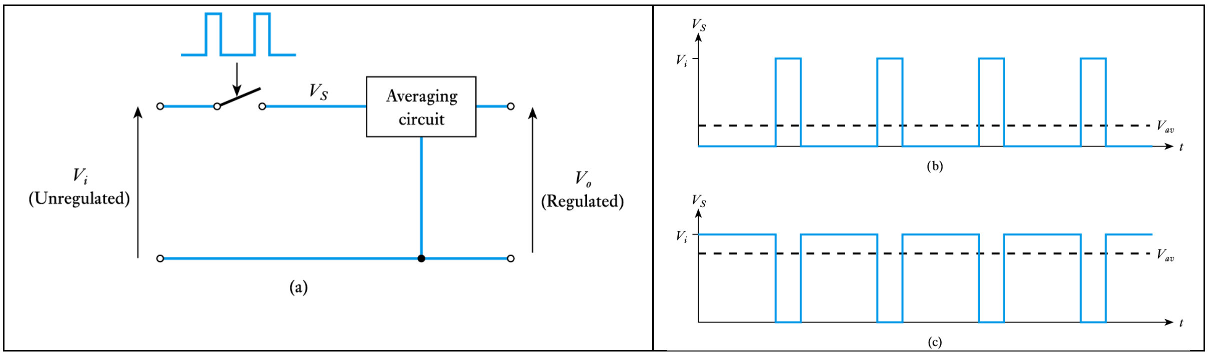
$V_P = V_Z + 0.7V$, therefore;

$$V_o = (V_Z + 0.7V)\frac{R_3 + R_4}{R_4} = (4.7 + 0.7V)\frac{1.222\text{ k}\Omega + 1\text{ k}\Omega}{1\text{ k}\Omega}$$

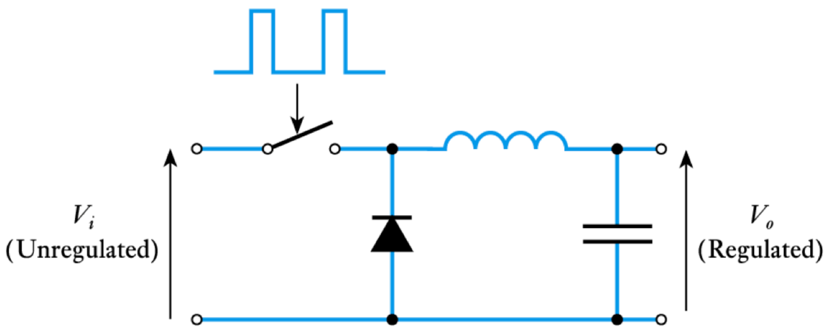
$$v_o = 12.0\ V$$

Switch Mode Power Supplies

– Uses a switching regulator
– Output voltage is controlled by the duty-cycle of the switch
– Uses an averaging circuit to 'smooth' output

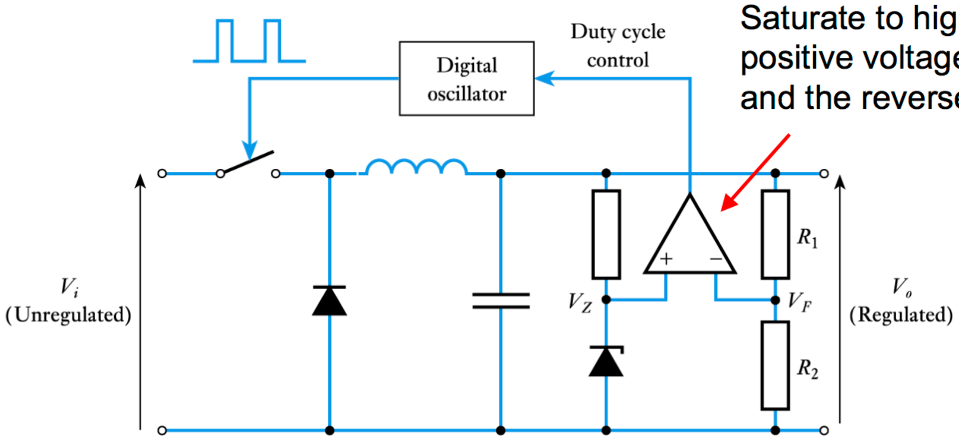


AN LC AVERAGING CIRCUIT



- When switch closed current flows through the inductor and into the capacitor (diode passes no current)
- Although, time current is stored in the inductor
- When switch opens, current is supplied by the inductor
- This forward biases the diode
- Current is taken from the capacitor by the load and the voltage drops (ripple)

- **Using feedback in a switching regulator**



Comparator:
When V+>V-,
Saturate to highest positive voltage,
and the reverse

- The voltage V_F is formed from R_1 and R_2.
- This is compared to the Zener output (V_z)
- The output from the comparator is used to vary the duty cycle.
- Thus the output is maintained that V_F equals V_z

$$V_F = V_o \frac{R_2}{R_1 + R_2} = V_Z$$

therefore;

$$V_O = V_Z \frac{R_1 + R_2}{R_2}$$