ENGG1000

Electrical Stream 2018

Week 5 - Motors and Drive Circuits

Never Stand Still | Faculty of Engineering | School of Electrical Engineering and Telecommunications

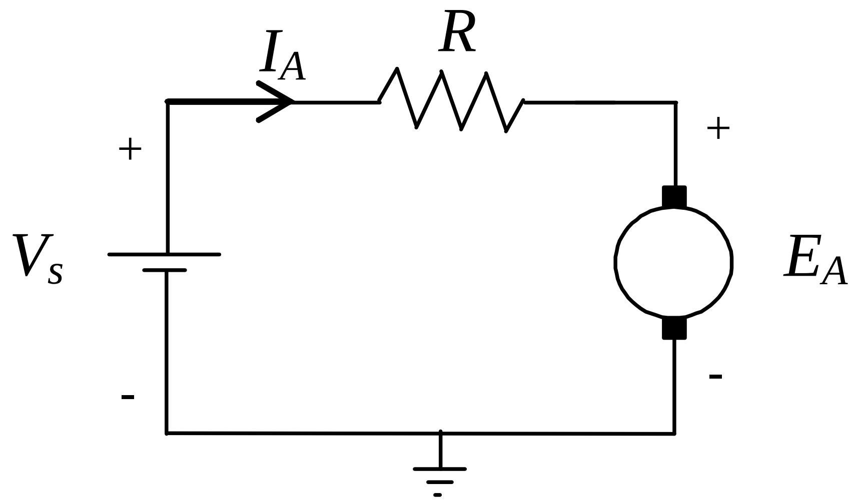
DC motors

- DC is an acronym for direct current
  – Has a fixed value for all time
  – As opposed to alternating current (AC), which varies with time
- There are many different types of DC and AC motors

source: http://www.inverter-china.com/ru-blog/catalog.asp?cate=10&page=2

The permanent magnet DC motor

- Circuit model



  - V_s is supply voltage
  - R is armature resistance
  - E_A, I_A armature voltage, current

$$V_s = E_A + I_A R$$

The permanent magnet DC motor

- Speed proportional to armature voltage (back EMF)

$$E_A = K_E \omega$$

- Torque proportional to armature current

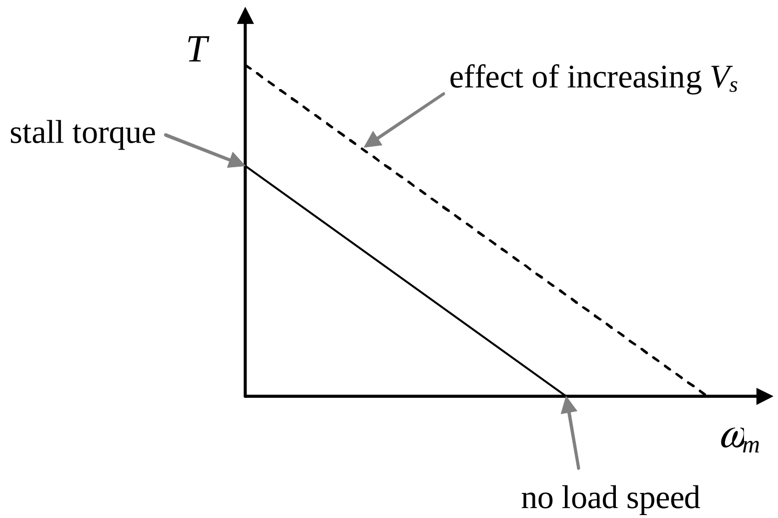
$$T_M = K_T I_A$$

So

$$T_M = K_T I_A = K_T \frac{V_s - E_A}{R} = K_T \frac{V_s - K_E \omega}{R}$$

Torque-speed characteristics

- Rearranging: $$\omega = \frac{1}{K_E}\left(V_s - \frac{R}{K_T}T_M\right)$$



Also: motor will not start turning without a small current: "stall current"

$\Rightarrow$ Need to design E_A, I_A to achieve a particular torque/speed operating point

The DC motor - Load

- If we apply a voltage and a current to a DC motor, what determines what speed it will run at?
- Mechanical Power supplied: $P_{load} = T_M \omega$
- At steady state, approximate the motor torque to be linearly-proportional to current:

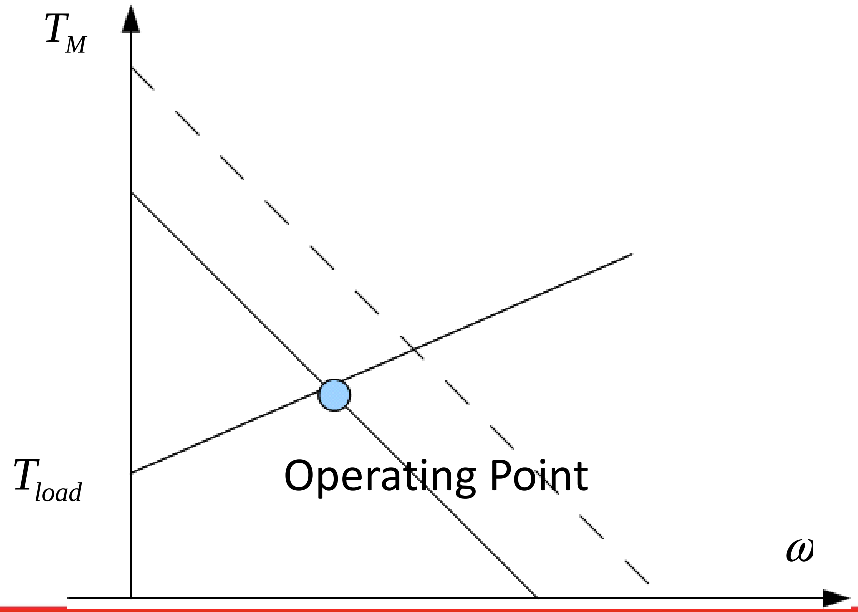
$$T_{load} = T_M - J\dot{\omega} - B\omega$$

$$T_{load} = T_M - B\omega$$

B is a frictional constant.

The DC motor – Load Lines

- Plot both Mechanical torque-speed and Electrical torque-speed curves
- Where they meet is the operating point (in the steady state, ie. constant speed)



The DC motor – Load Lines

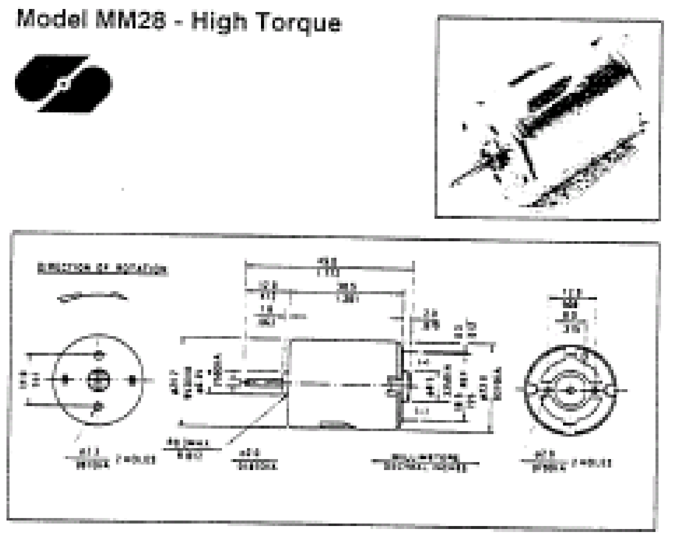
- Varying supply voltage will move operating point
- Optimal operating point:
  - Maximum power transfer to the load

$$T_M = \tfrac{1}{2} T_{stall} \qquad \omega = \tfrac{1}{2}\omega_{\text{no load}}$$

- Power transferred is the area under the torque-speed graph

The DC motor

- Be careful to observe the maximum current and voltage ratings of the motor
- See data sheets:



Model MM28 - High Torque

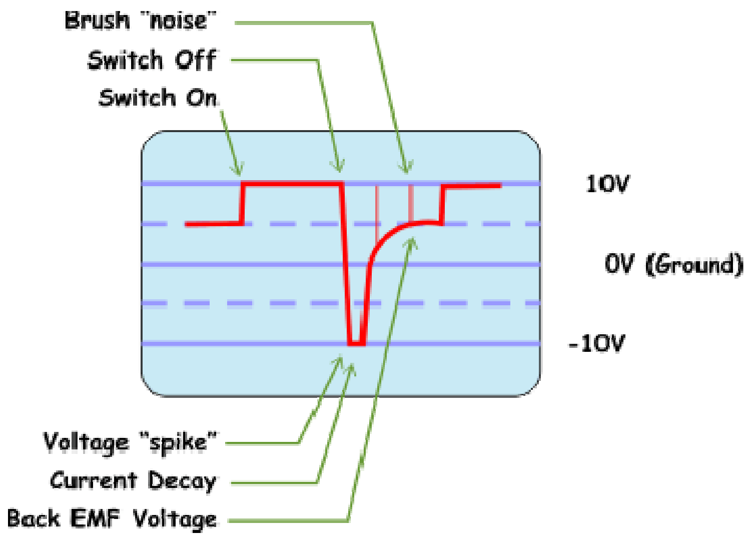
Order Code	Model	Operating Range	Approx Weight
450-020	MM28	3.0-6.0V	42 g

NOMINAL	NO LOAD		AT MAXIMUM EFFICIENCY					
Constant Volts	Speed rpm	Current A	Speed rpm	Current A	Torque g-cm	Output W	Efficiency %	Stall Torque g-cm
3.0V	9600	0.220	8000	0.99	20.0	1.64	56.2	112

Motor Inductance

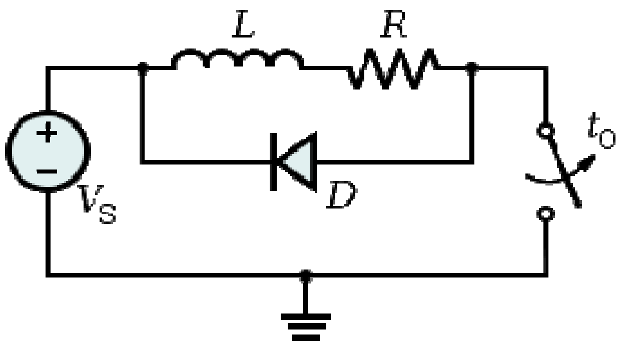
- Motor modelled with an inductive element
- Resistor in series with an inductor
- Captures transient behaviour
- Change motor current produces voltage spikes

$$V = L\frac{di}{dt}$$



Motor Inductance

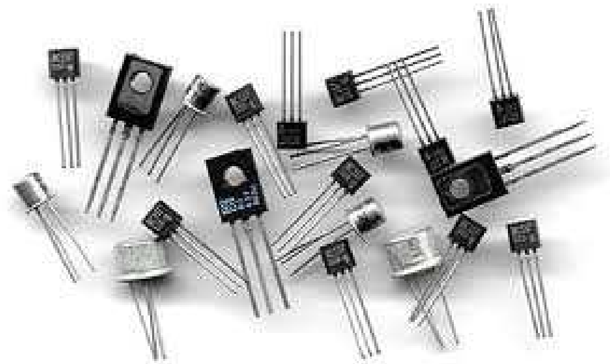
- Large negative voltage spikes can cause problems
  - Particularly if switched by transistors
- Fly-back diode (also called free-willing diode)
  - Limits voltage surge to 1.1V (diode conducting voltage drop)



source: http://en.wikipedia.org/wiki/Flyback_diode

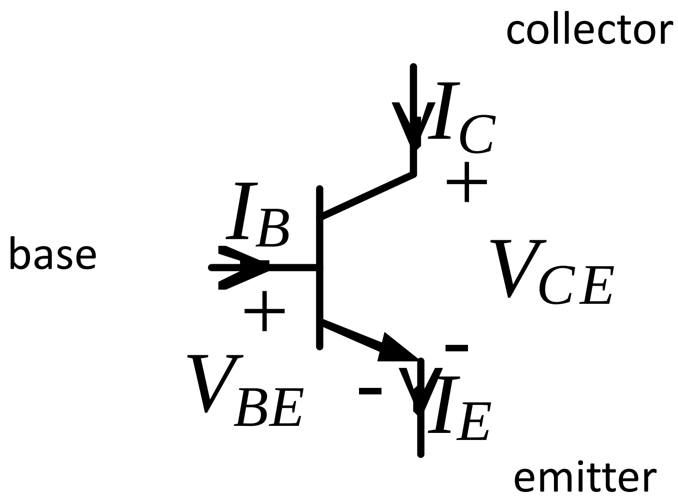
DC motor circuits

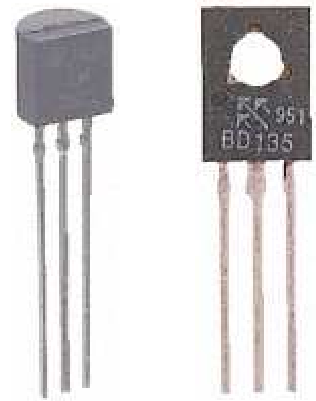
- We'll consider two popular motor drive circuits
  - H-bridge
  - PWM
- But first we must discuss transistors...



The Bipolar Junction Transistor (BJT)

- Nonlinear device with three terminals:



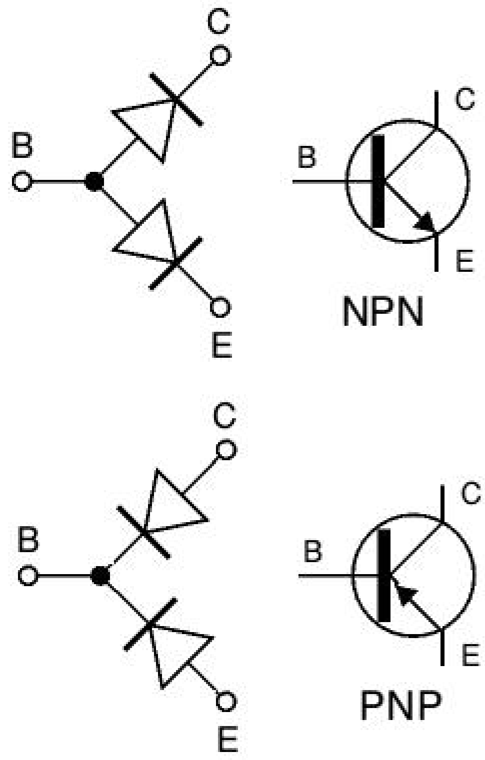


- Has several operating modes
  - $V_{BE} > 0.7$V, $V_{CE} > 0.3$ V $\Rightarrow$ forward active mode

source: http://australia.rs-online.com

Transistor as Two Diodes

- Two types – NPN and PNP
- Effectively a diode as C-B and B-E (two back to back PN junctions)
- PNP transistor has the N and P regions reversed
- Work the same way, but all polarities are the opposite for a PNP (versus an NPN)



source: http://www.mobileelectronics.com.au/forums/index.php?/topic/58571-blown-jay-car-amp-help/page__st__15

Transistor – Forward Active Mode

Most circuits aim to bias the transistor so it is in forward-active mode -> straight-forward to analyse

- VC > VE, and BE junction forward-biased (CE junction reverse-biased)
- When conducting, VB – VE ≈ 0.6-0.8V (forward-bias voltage)
- If the above is true, the current CE will be proportional to the BE current…

Transistor Current Gain

- In forward active mode

$$I_C = \beta I_B$$

  - β (or H_{FE} or h_{FE}) is the current gain
    - Typically large, e.g. 50 to 200
  - A small input current (I_B) can be used to control a large output current (I_C or I_E)
  - Also

$$I_E = I_B + I_C = (\beta + 1) I_B = \frac{(\beta + 1)}{\beta} I_C$$

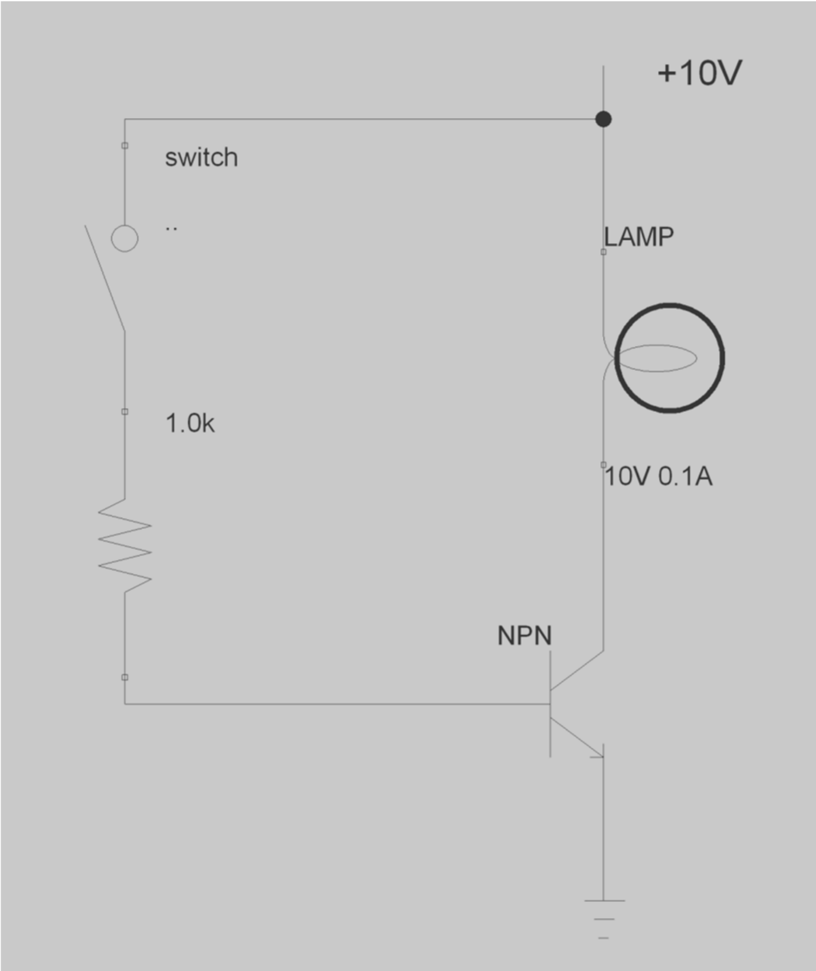
    - Most current is going from collector $\rightarrow$ emitter

Transistor – Limitations

Practical limitations of forward-active mode

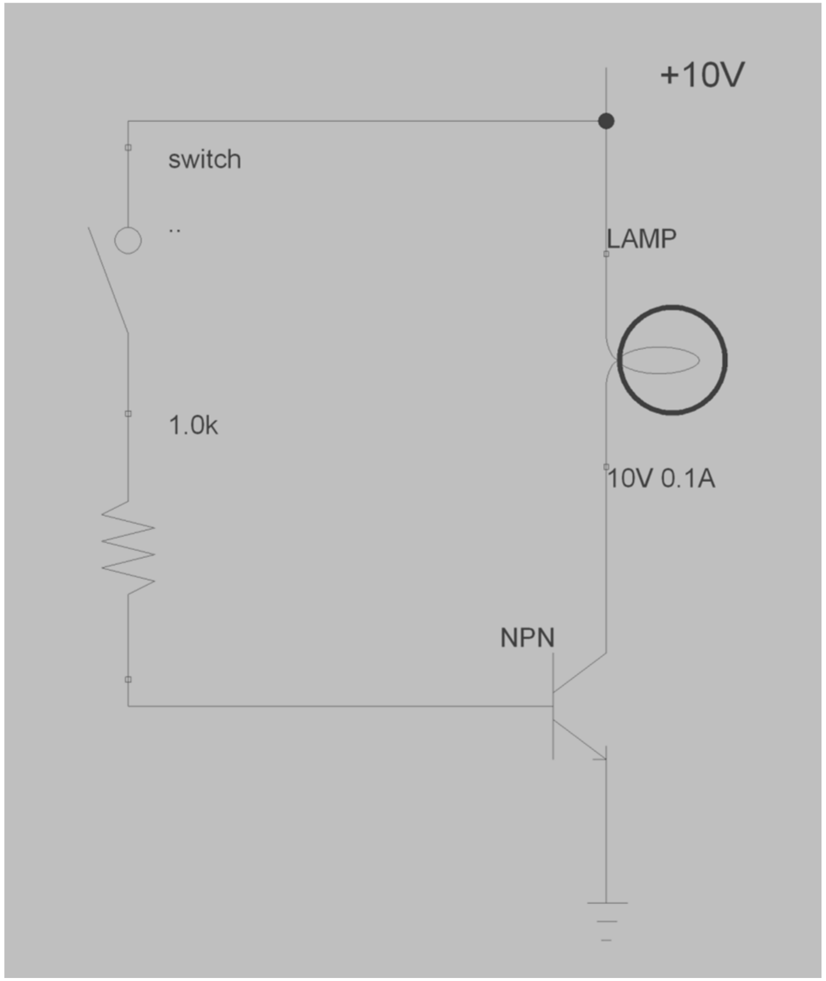
- A transistor has maximum values of I_C, I_E, and V_CE that it can handle
- The power dissipation is limited (I_C*V_CE)
- The properties depend heavily on temperature
- The current gain, β, varies substantially within models -> don't build circuits that depend on this parameter
- Always limit the base current (since is a forward-biased diode BE)

Transistor Switch



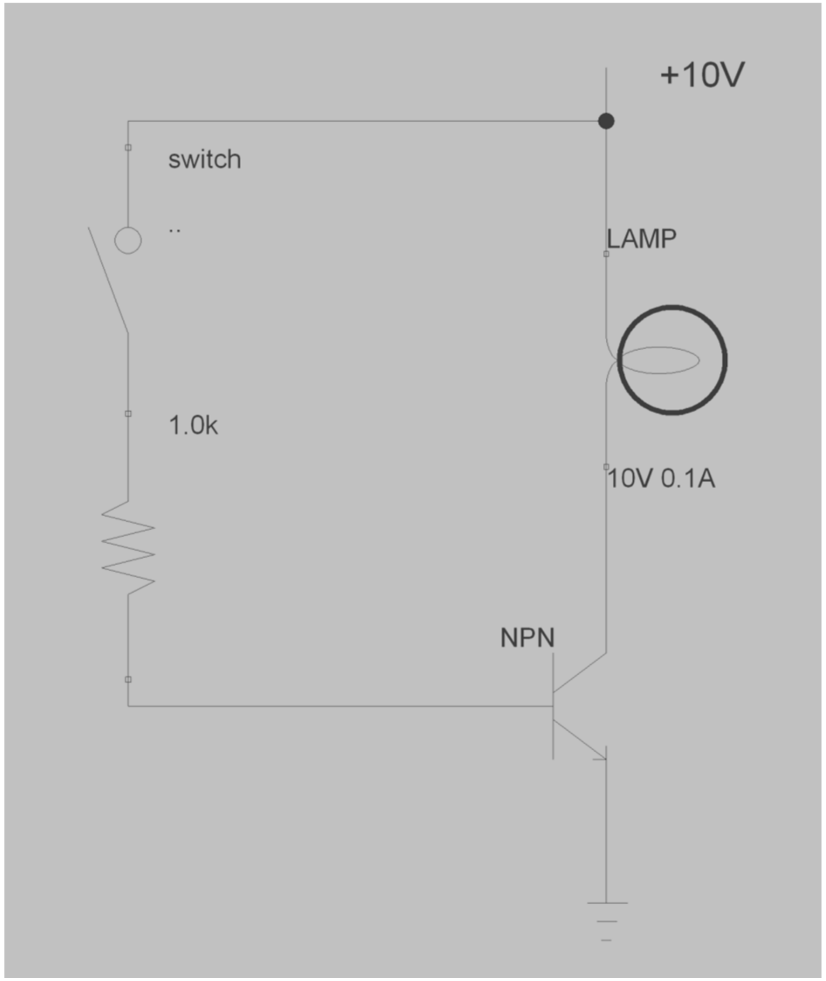
- When switch is open, I_B = 0, so I_CE = 0 -> lamp is off
- When switch is closed, how do we analyse this circuit?
- Assume the transistor is in forward-active mode
  - BE junction is conducting

Transistor Switch



- $V_{BE} = 0.6V$
- $I_B = 9.4mA$
- If say, $\beta = 100$, then $I_C = 940mA$!
- But then $V_C < 0$ -> so transistor is not operating in the forward-active region
- Transistor here saturates

Transistor Saturation

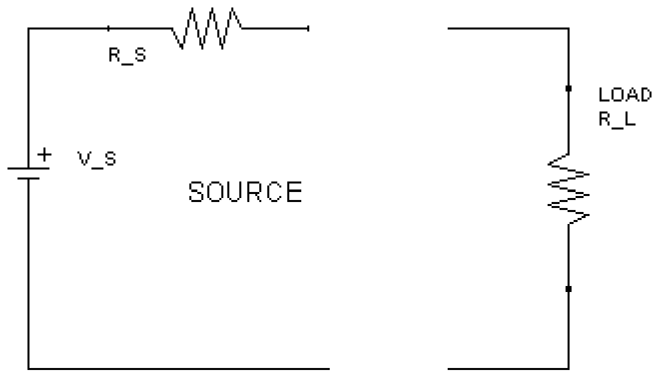


- Here, V_CE is forced as close to zero as it can go
  - Typical saturation voltages 0.05-0.2V
- Approx. 10V across the lamp, so I_C = 100mA
- Note here – a small current (9.4mA) controls a large current (100mA)

Voltage Sources

- Real voltage sources have internal resistance
- When a load is connected, the supplied voltage is really

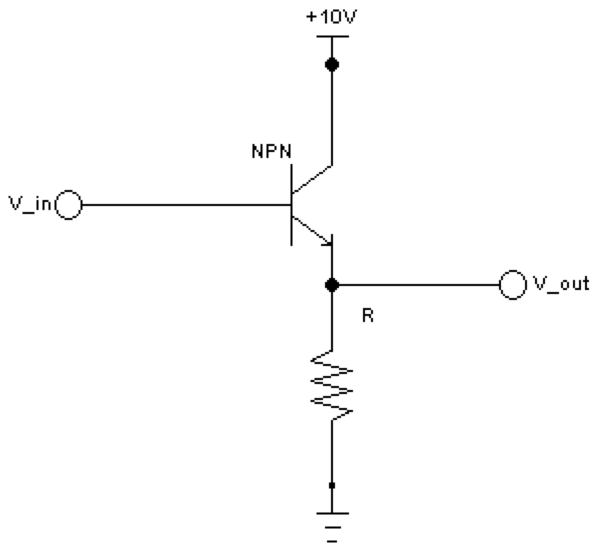
$$V_O = \frac{R_L}{R_S + R_L} V_S$$



- The ideal is $R_L >> R_S$
- Important to realise this when you drive one circuit by another – may not always be possible!

Emitter Follower

- A simple transistor buffer circuit to connect between circuits to overcome the voltage-divider problem



- For input voltage

  0.6V < V_in < 10V

- Transistor in the forward-active region

$$V_{out} = V_{in} - 0.6\mathrm{V}$$

- So, what's the point?

Emitter Follower

- The point is that the output impedance is significantly reduced -> $R_L >> R_S$
  - If you are going to connect something to the output, this external circuit sees a reduced source resistance
- Equivalently, the input impedance is significantly increased
  - If you think of V_out as the load, and you driving this with a circuit -> that external supply circuit sees a much larger R_L

Emitter Follower

- Input resistance is $R_{in} = \dfrac{\Delta V_B}{\Delta I_B}$
- Output resistance is $R_{out} = \dfrac{\Delta V_E}{\Delta I_E}$

Analysis:

- Since $\Delta V_B = \Delta V_E$ and $R = \dfrac{\Delta V_E}{\Delta I_E}$
- For the transistor in the forward-active region:

$$\Delta I_E = (\beta + 1)\Delta I_B$$

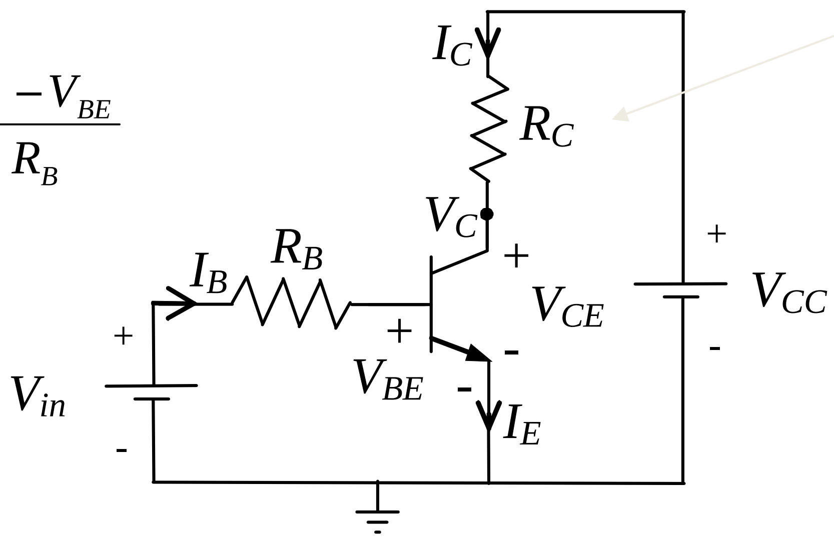
- Therefore, $R_{in} = (\beta + 1)R_{out}$
- If we though the resistance seen by a load connected at V_out, when driven by a source of R_s at V_in

$$R_{out} = \frac{1}{(\beta + 1)} R_s$$

Transistor circuit analysis

- Common-emitter configuration

$$I_C = \beta I_B = \beta \frac{V_{in} - V_{BE}}{R_B}$$



in many applications, R_C is the load

directly controlled by I_B

constant

device constants

$$V_C = V_{CC} - R_C I_C = V_{CC} - \beta R_C \frac{V_{in} - V_{BE}}{R_B}$$

output

constant, determined by design

Transistors as switches

- Common-emitter configuration

  V_{in} large -> saturation

  $\Rightarrow I_B$ large

  $\Rightarrow I_C$ large

  $\Rightarrow R_C I_C$ large

  $\Rightarrow V_C$ small

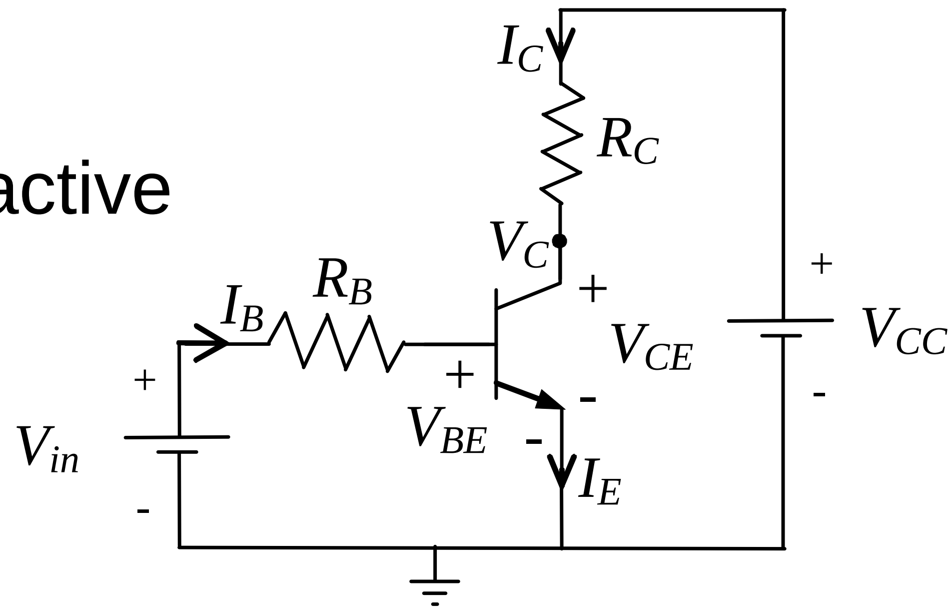
  V_{in} small -> forward-active

  $\Rightarrow I_B$ small

  $\Rightarrow I_C$ small

  $\Rightarrow R_C I_C$ small

  $\Rightarrow V_C$ large

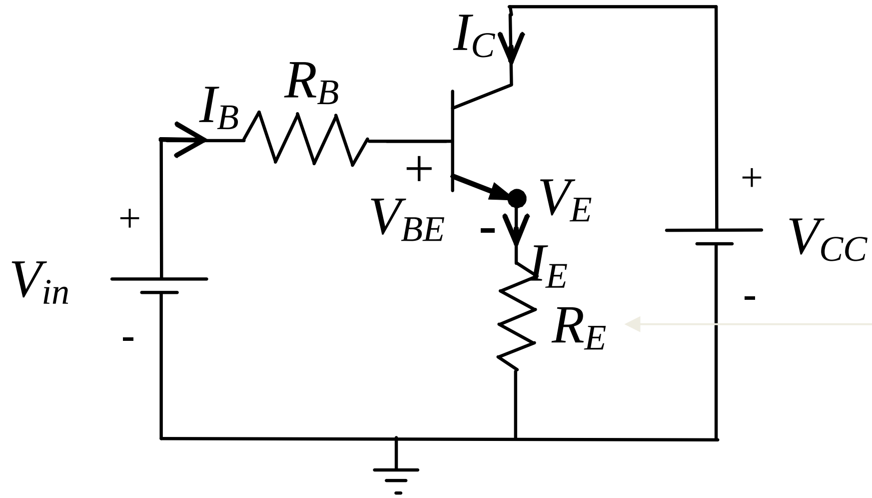


Transistors as switches

- If V_{in} is large and R_C is chosen large enough, then the output $V_C \approx 0$
  - "high" input $\rightarrow$ "low" output
- If V_{in} is so small that $V_{in} \leq V_{BE}$, then the output $V_C = V_{CC}$
  - "low" input $\rightarrow$ "high" output
    - Note: if $V_{in} < V_{BE}$, actually the transistor is no longer in the forward active mode, and no current flows

Transistor circuit analysis

- Common-collector configuration



in some applications, R_E is the load

directly controlled by V_{in} constant   design   device constant

$$V_E = V_{in} - V_{R_B} - V_{BE}$$

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

Transistor amplifiers

- Transistors also allow linear control of voltage/current
  - Providing (common-emitter configuration)
    - $V_C < V_{CC}$ ($V_C = V_{CC}$ is known as cut-off) and
    - $V_C >$ about 0.2V ($V_C <$ 0.2V is known as saturation)

  then

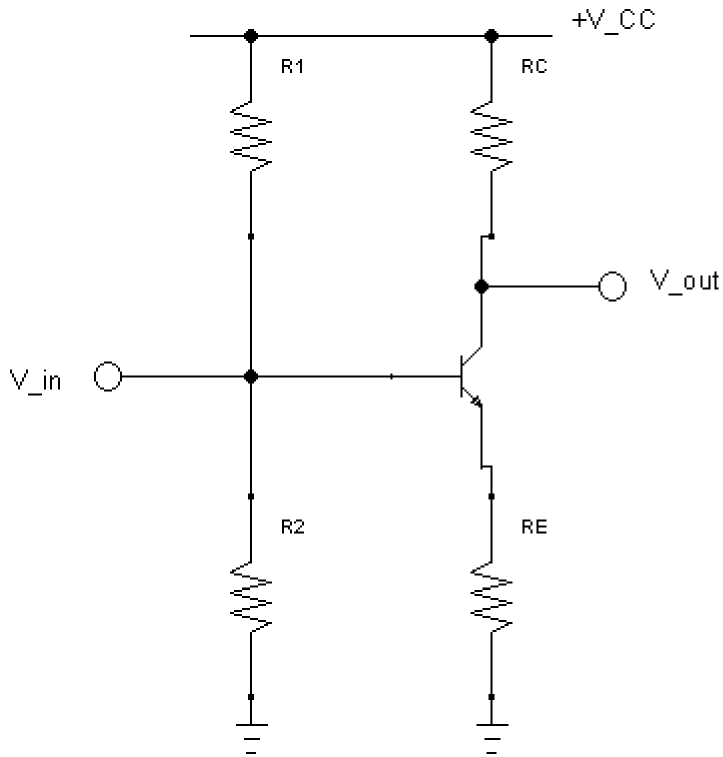
$$V_C = V_{CC} - \beta R_C \frac{V_{in} - V_{BE}}{R_B}$$

$$I_C = \beta \frac{V_{in} - V_{BE}}{R_B}$$

- Since $V_C > V_{in}$, this is called amplification

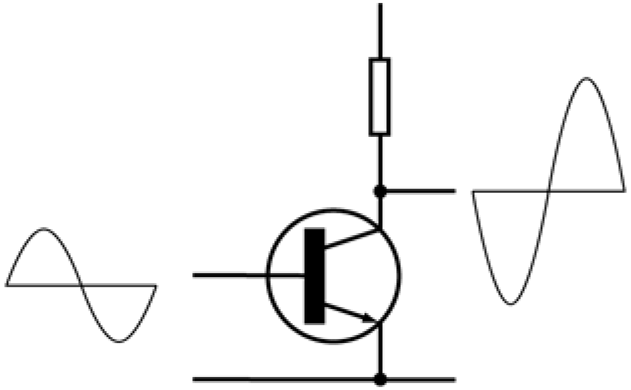
Transistor amplifiers

- Common Emitter Amplifier
  - The classic basic single transistor amplifier

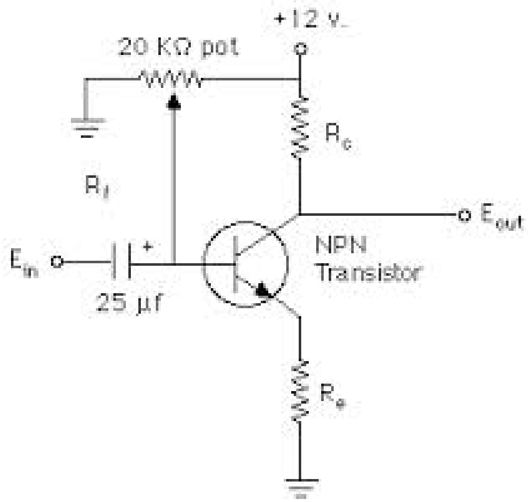


Mixed Signals

- DC source/current used to establish the operating point
- Input signal amplified is a time-varying signal (AC, or information carrying…)

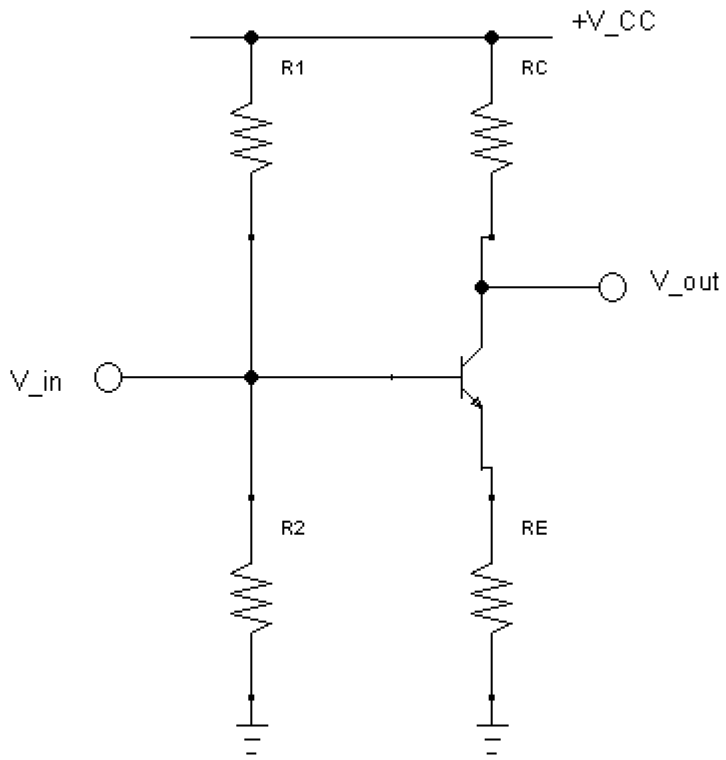


Source: http://en.wikipedia.org/wiki/Amplifier



Source: http://terpconnect.umd.edu/~toh/Chem498C/Transistor.html

Transistor amplifiers



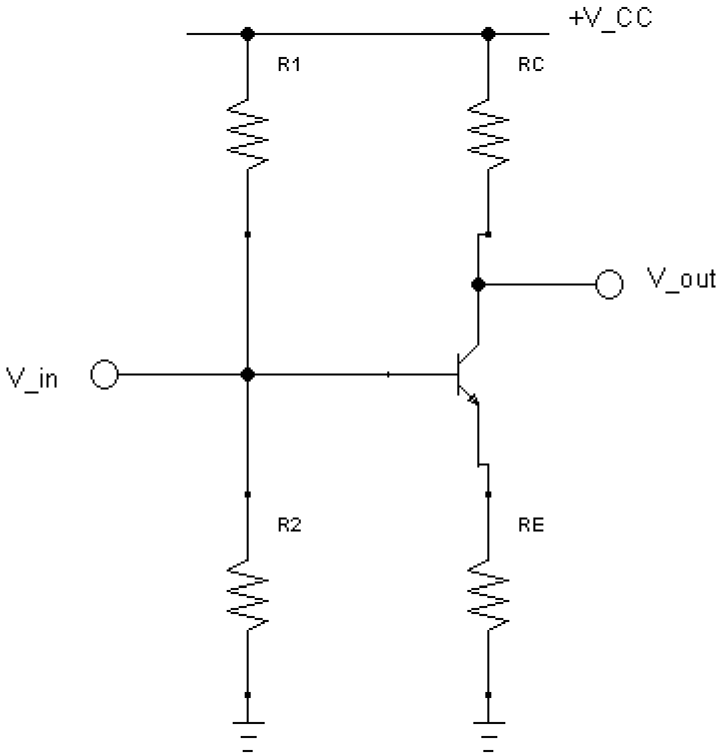
- AC amplifier
- In forward-active mode (DC biasing circuit): $\Delta v_B = \Delta v_E$
- Emitter current is:

$$i_E = \Delta v_E / R_E = \Delta v_B / R_E$$

- Collector current changes by the same amount.
- Collector voltage change:

$$\Delta v_C = -i_C R_C = -\Delta v_B \left(R_C / R_E \right)$$

Transistor amplifiers



- Output voltage change related to input voltage change (effectively the AC input/output)
- Gain: $\dfrac{v_{out}}{v_{in}} = \dfrac{\Delta v_C}{\Delta v_B} = -\dfrac{R_C}{R_E}$
- Inverting amplifier
- High input impedance, low output impedance

Why a Transistor?

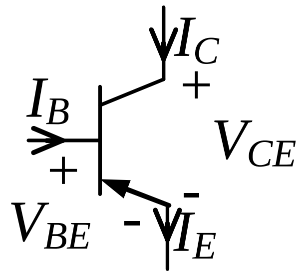
- Why do we need all this just to turn something on and off? or to control something using V_{in}?
  - Many outputs, e.g. loudspeaker, require a large output current
  - Many circuits begin with a small current, e.g. a sensor of some kind
  - Often we want to drive an output based on a small input current

$$I_C = \beta I_B$$

- Transistors can act as a current source
  - I_C depends only on I_B, *not on load*

Practical considerations

- PNP transistors
  - So far, we have only looked at the NPN transistor
  - The PNP is identical but complementary



  - Currents I_B, I_C and I_E as shown are negative

Practical considerations

- Transistors are not all the same
  - Have different current gains

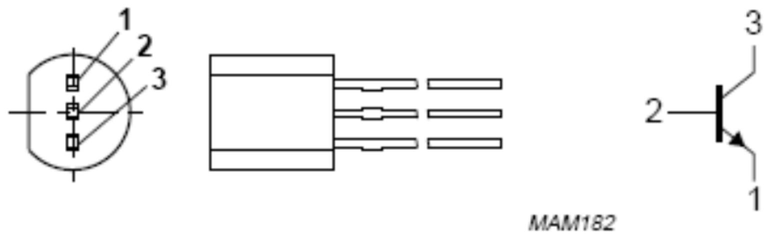
h_{FE}	DC current gain	I_C = 2 mA; V_{CE} = 5 V	200	800	

  - Have different power ratings

I_{CM}	peak collector current		–	200	mA

  - Have different pin layouts

- See data sheets!

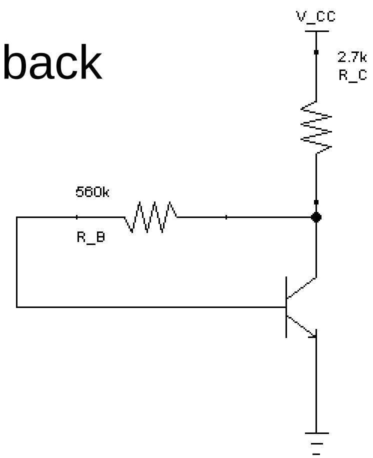


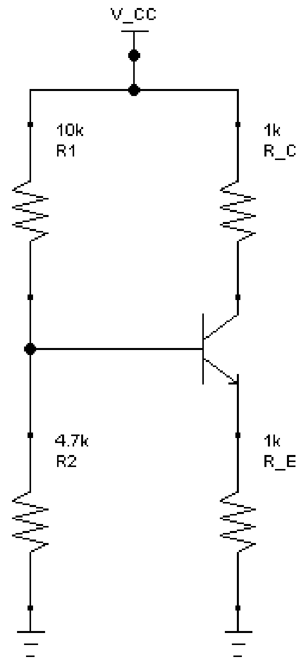
source: http://engg1000.ee.unsw.edu.au/datasheets/Transistors/BC549-datasheet.pdf

Transistor Biasing

- It important for reliable circuit design that the behaviour is independent of the transistor gain β
- β is a highly variable quantity
  - Between identical models; with temperature
- Make sure the operating point is independent of β -> good biasing

Collector-feedback biasing

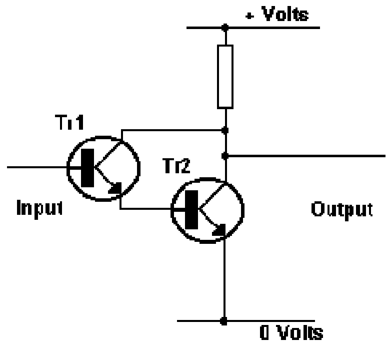




Voltage-divider biasing

Special transistors

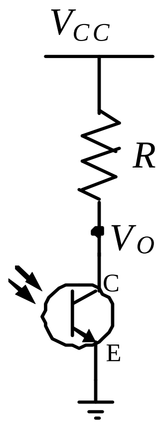
- Darlington pair
  - Very high current gain



- Phototransistors
  - Like a photodiode, except with internal gain
  - Current ↑ when exposed to light

E

C

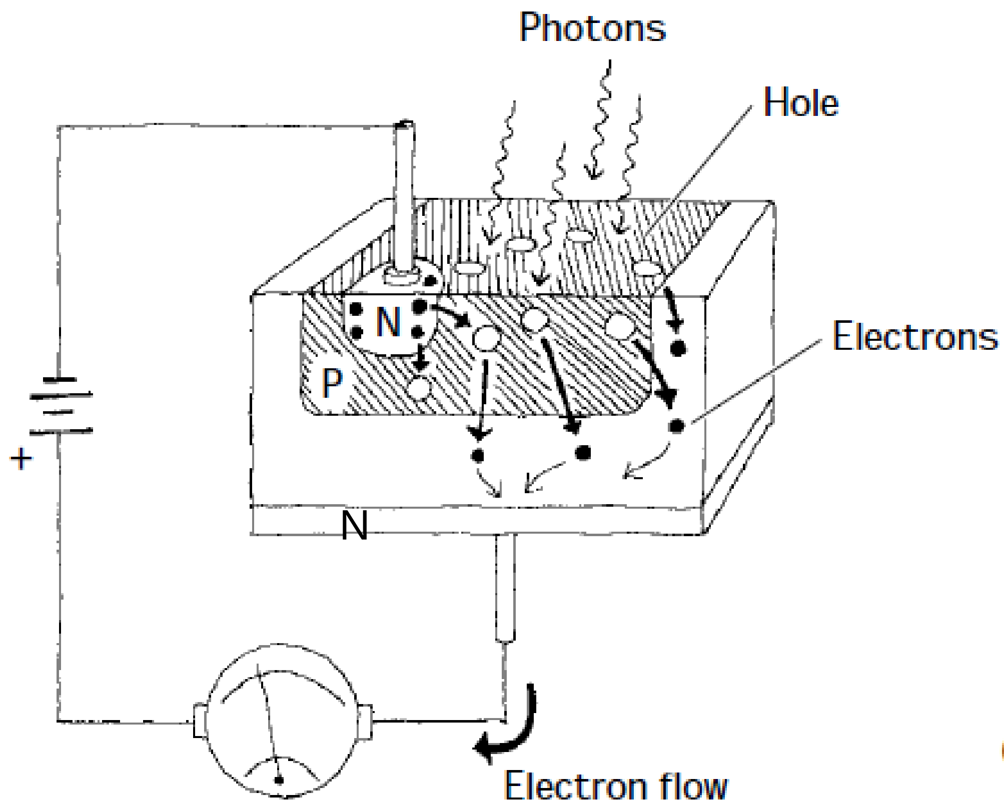


Design R so that

$$I = \frac{V_{CC} - V_O}{R}$$

is ~ few mA or as given in data sheet, V_O is breakdown voltage

Phototransistor

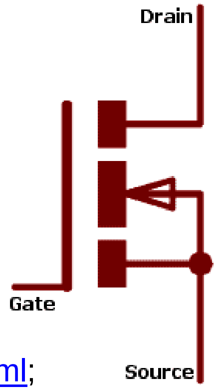


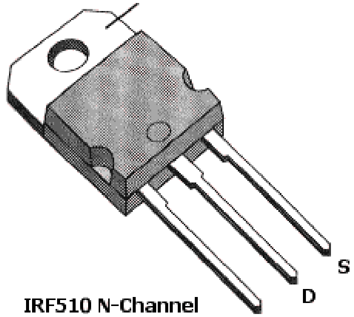
source: Scherz, 20000

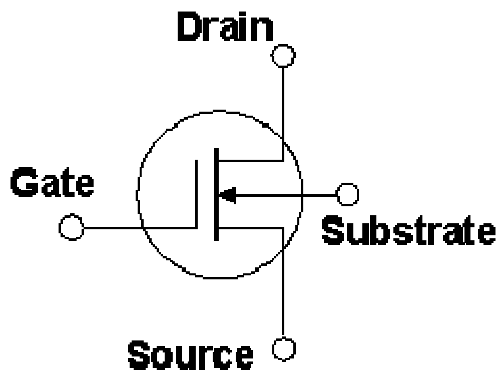
- – Photons hitting P layer give electrons energy to jump to lower N layer
- – Then electrons from upper N layer pass into P layer to combine with the holes
- – Exposed base – light provides the base current

Field Effect Transistors

- FETs – the most common form of transistor
- N-channel MOSFET is similar to an npn BJT
  - Voltage at the Gate (~base) controls the current flow between the Drain (~collector) and the Source (~emitter)
  - For current flow, V_G > V_S
  - Gate current is essentially zero -> very high input impedance







n-Channel MOSFET

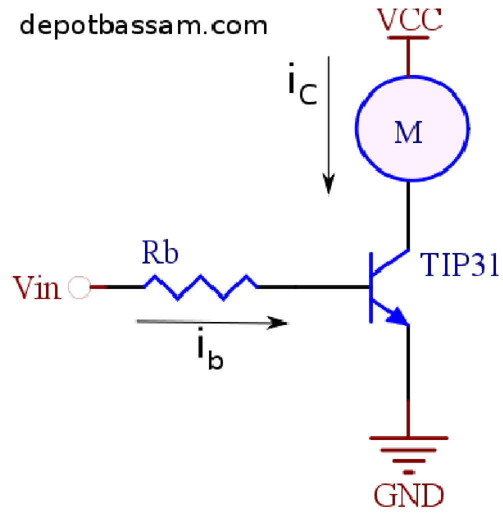
Source: http://transistor-man.com/lampfade.html; http://macao.communications.museum/eng/exhibition/secondfloor/moreinfo/2_10_4_howfetworks.html

Power Dissipation

- Note: MOSFETs sensitive to static discharge
- Have lower bias-voltages, so in general will not waste so much power
- BJT, with 3A going CE, with voltage drop of 0.7V, will dissipate power at 2.1W
- Some transistors come in special packages to dissipate high levels of heat:
  - Eg. TO-3 package – 3W
  - Larger powers may require heat sink

Electrical drive circuits

- Speed control
  - Common-emitter amplifier, with motor as load R_C
  - Voltage across load R_C is given by



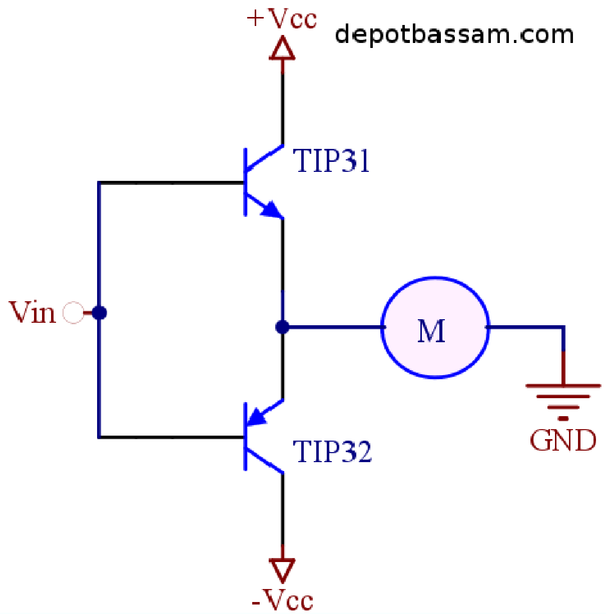
$$V_{CC} - V_C = \beta R_C \frac{V_{in} - V_{BE}}{R_B}$$

i.e. linearly controlled by V_{in}

  - Similar for common-collector, other transistor amplifier circuits
  - Take care with transistor heat dissipation

Electric drive circuits

- Direction control
  - Just swap polarity of supply voltage V_s
- Speed and direction control
  - Push-pull amplifier



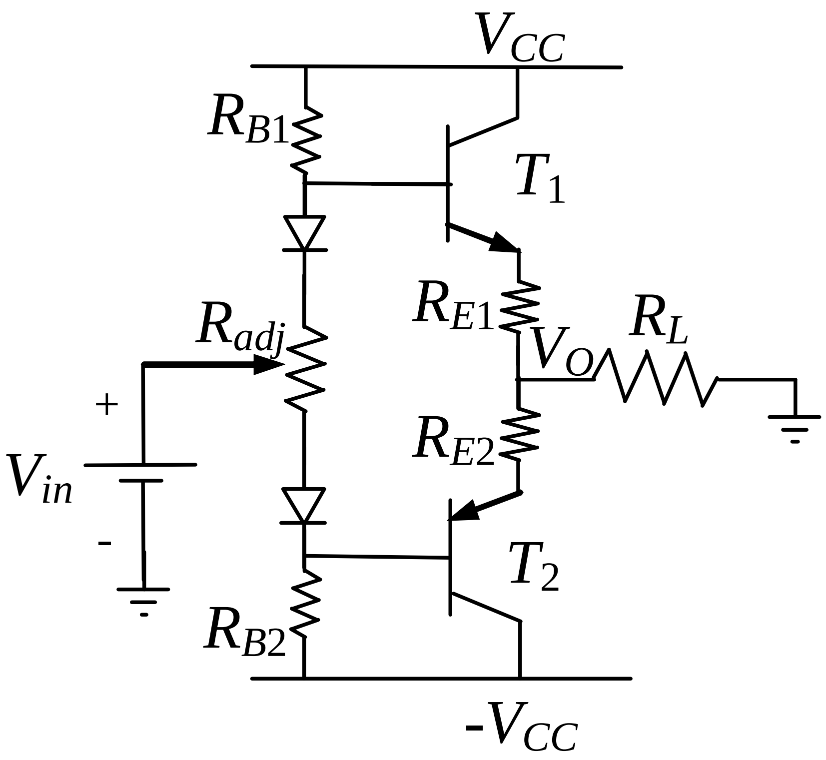
$V_{in} > V_{BE}$: T_1 is on, T_2 is off

Current flows from V_{CC} through R_L to ground. $V_O = V_{in} - V_{BE} > 0$

$V_{in} < -V_{BE}$: T_1 is off, T_2 is on
Current flows from $-V_{CC}$ through R_L to ground. $V_O = V_{in} + V_{BE} < 0$

Electric drive circuits

- A more sophisticated push-pull amplifier

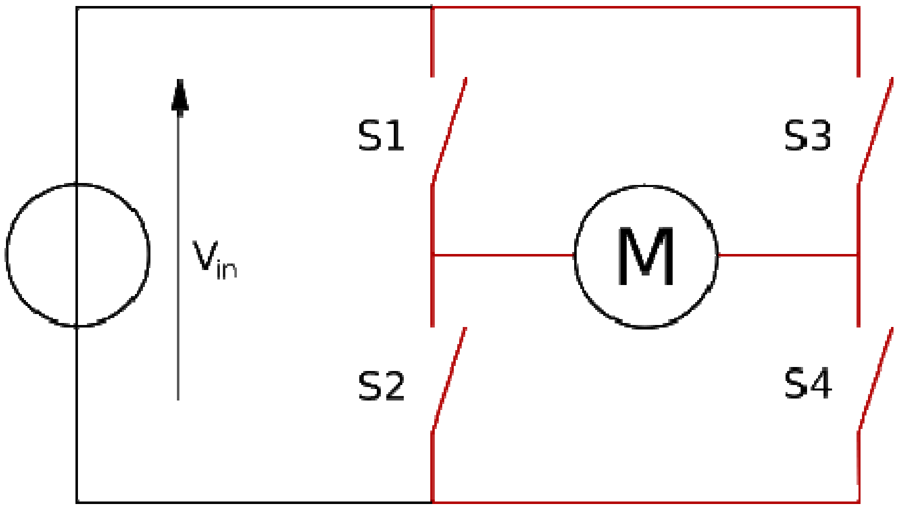


- Removes dead zone $-V_{BE} \leq V_{in} \leq V_{BE}$
- Choose R_{B1}, R_{B2} large
  – Small enough to allow a forward bias current in diodes
- Choose $R_{adj} << R_{B1}$, R_{B2}, to give voltage drop of just greater than $2V_{BE}$ between the bases of T_1 and T_2
- R_{E1}, R_{E2} are small ~ 1Ω

Input voltage waveform could be PWM

H-bridge

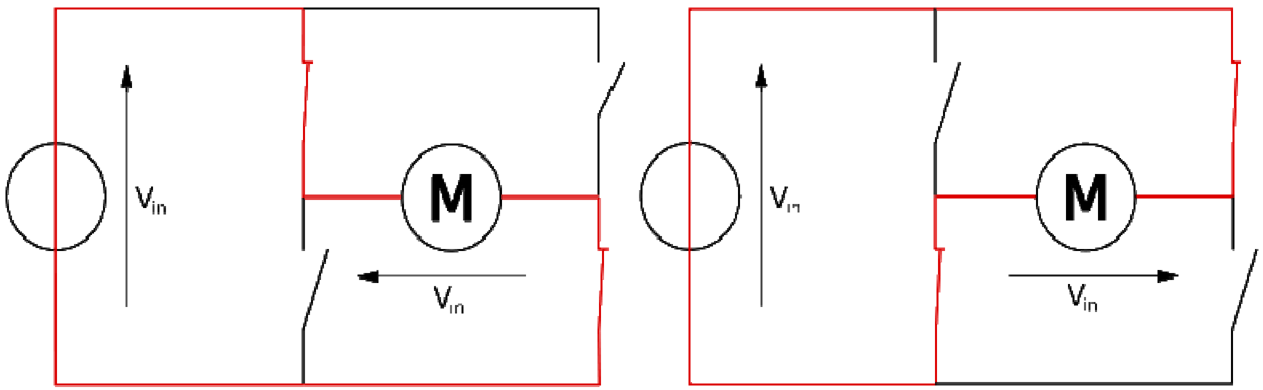
- Popular and sophisticated motor control circuit
- Can be used in conjunction with PWM
- Used with a single-sided supply



Source: http://en.wikipedia.org/wiki/File:H_bridge.svg

H-bridge - principle

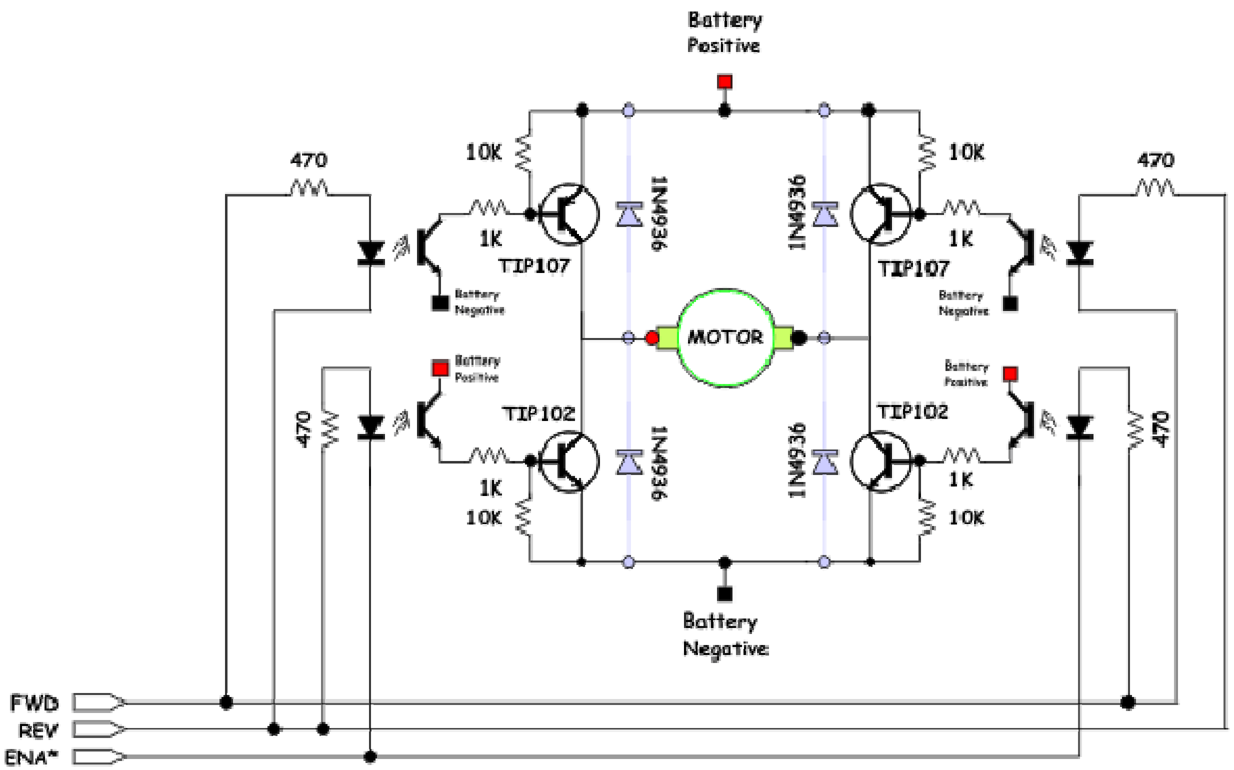
- Opposite pairs of switches control motor direction



- Braking – both upper switches or lower switches on together
  - -> back EMF will bring motor to halt

H-bridge - Example

- Example circuit for H-bridge motor control
- To be driven by logic circuit or microcontroller



Source: http://www.mcmanis.com/chuck/robotics/tutorial/h-bridge/bjt-circuit.html]

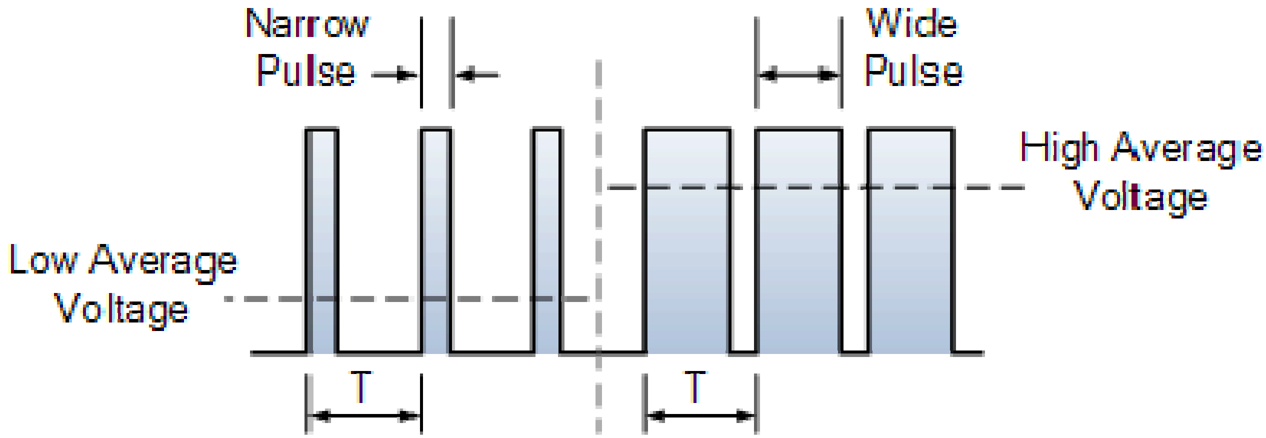
H-bridge – Example Logic

FWD	REV	ENA*	Description
1	0	0	go forward
1	0	1	PWM forward control
1	1	0	Braking
1	1	1	PWM controlled braking
0	1	0	Go backwards
0	1	1	PWM reverse control
0	0	0	Coast – power off
0	0	1	Coast – power off

- Note use of opto-isolators at inputs
- Transistors come with "fly-back diodes" internal to package
    - Protect against voltage surges

Source: http://www.mcmanis.com/chuck/robotics/tutorial/h-bridge/bjt-circuit.html]

Pulse Width Modulation



- Able to achieve find control of motor speed
- Adjust the Duty Cycle
- Use dedicated ICs (555 Timer), or most microcontrollers have PWM output
  - Eg. the Arduino

Coming Up

- Lab Openings during Mid-session break
  - Thursday 1-5pm (5th April)
  - Friday 1-4pm (6th April)
  - Lab EEG14
- Week 6 Labs Open (EEG14 & EE214)
  - Monday 2-6pm
  - Thursday 2-6pm
- Circuit Quiz coming up in Week 7
  - Enrolment available on Moodle during Week 6