Lecture 4

Henry Lau (2020)

Topic

Electrically operated switch

- Relay
- BJT
- MOSFET

Relay

Henry

Electrical operated switch

The definition of a electrically operated switch is a switch that is operated by electricity.

The difference between electrically operated switch and mechanical switch is that one is controlled by current/voltage. The another one is controlled through physical means, like flipping a switch with your hand.

Types

Covered in this ppt:

- Relay
- Bipolar junction transistors (BJT)
- Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

Will not be covered (go google if you want to learn more)

- Solids-State Relay
- IGBT
- Thyristor

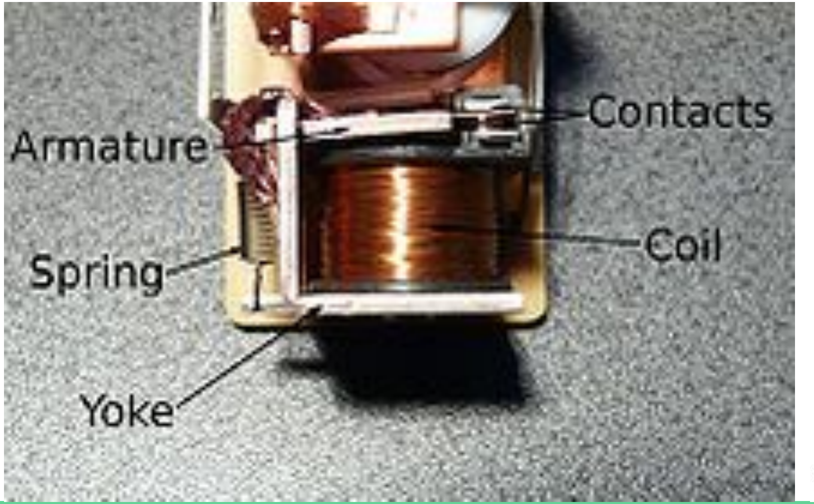
Relay

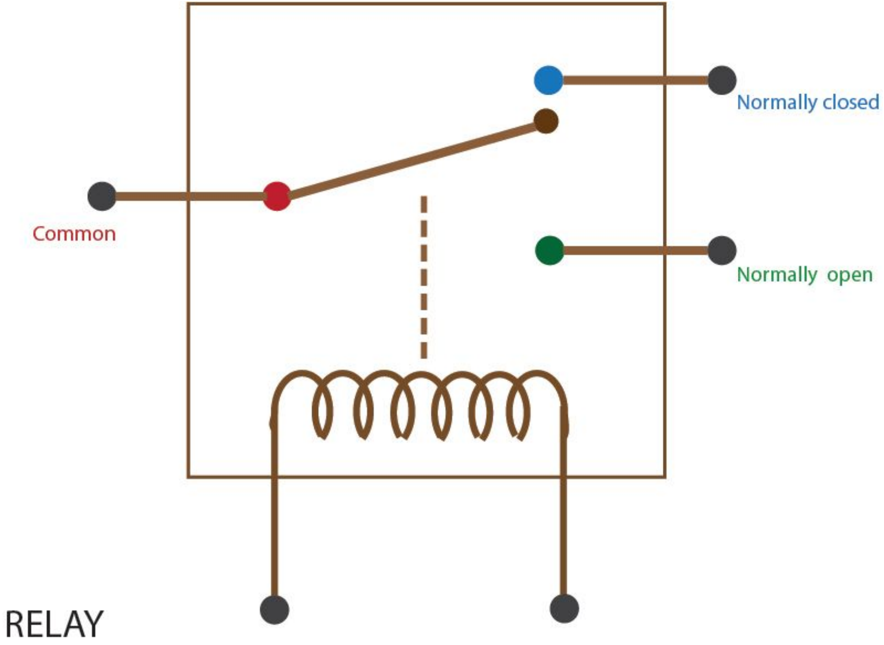
Relay is quite easy to use

We will focus on mechanical relay (there are different type of relays)

Structure

The mechanical relay consist of a coil, 2 contacts points (normal open (NO) and normal close (NC) for the armature and a spring. Normally there are 5 pins in a relay module.



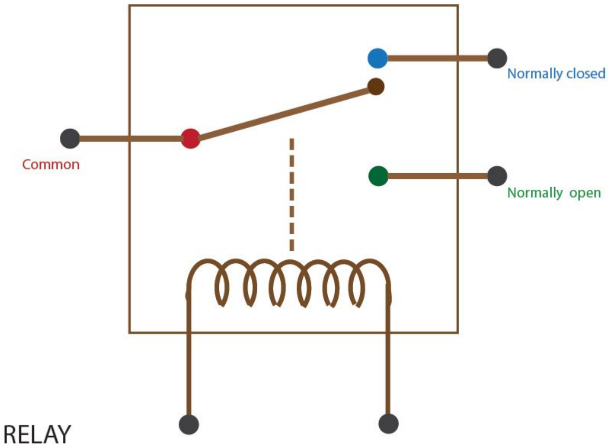


Relay

Common Pin, NO, NC, and 2 pin for powering the coil.

When there is:

- No current going through the coil: common in contact with normal close
- Current going through the coil: common in contact with normal open



Operation

When there are no current passing through the coil of the relay, the spring will keep the armature in contact with Normal Close. Hence the name “Normal Close” (close circuit is turned off state”. The Normal Open pin is opened in this state.

The coil is formed by wrapping copper wires around a metal core. It has high inductance. (inductors are made from coiled wires too).

Operation

When there is current conducting through the coil, it will generate a magnetic field. The force generated by the magnetic field is stronger than the spring and pull the armature in contact with normal open.

In short: no current in coil = armature in contact with normal close. Have current in coil = armature in contact with normal open.

This is why it is an electrically operated switch, the current flow through the switch is being controlled through another current.

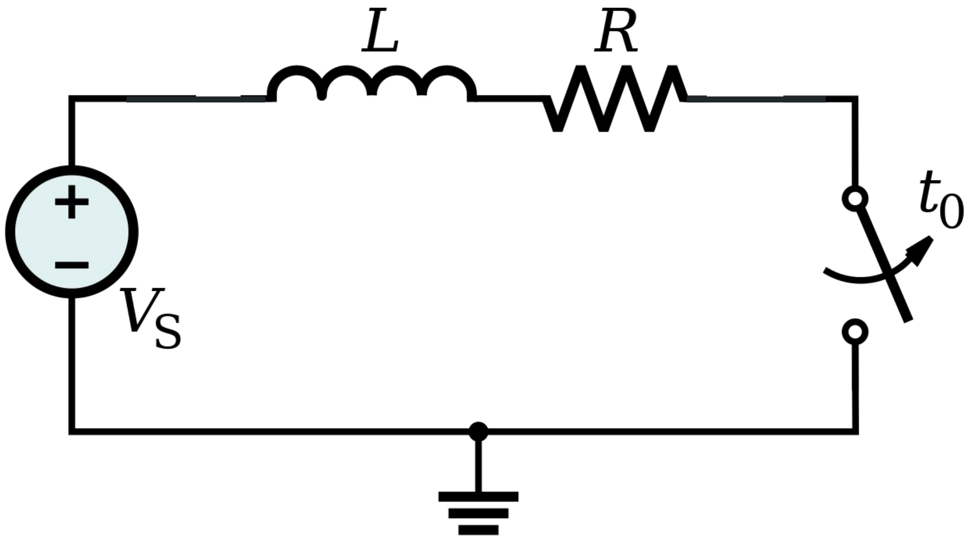
Usage

Usually used in operation that does not need fast switching. As the response time are usually slower when compared to other electronic switches.

Remember $V = L * (di/dt)$. Switching on and off the relay will generate voltage spike. In the moment that the relay is being switched off, the sudden current change (from on to off in a short time) = di/dt. The voltage spike could damage different components along the power rail (including the relay).

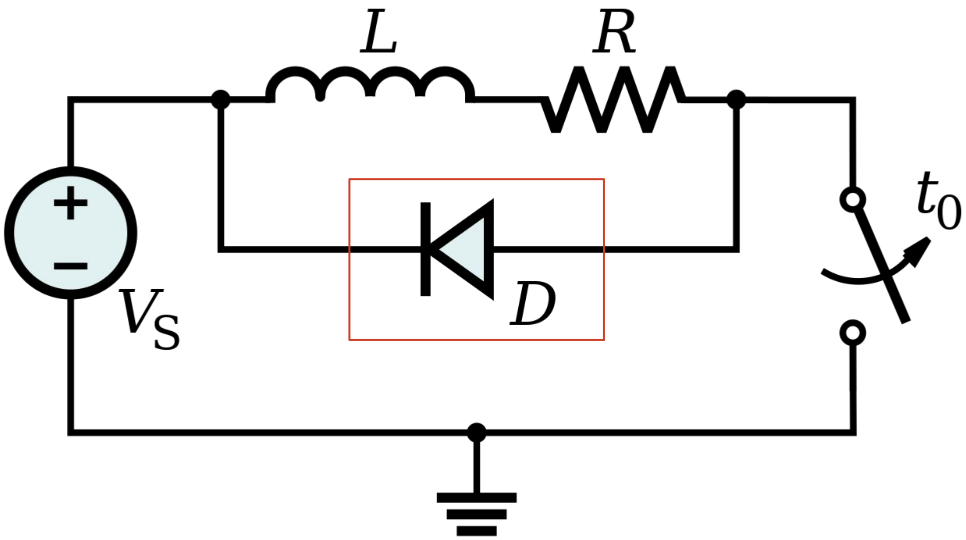
Usage (High Side vs Low Side Switch)

In Robocon 2018, Jacky Ng has designed a circuit involving a relay. And it exploded spectacularly. Where is the problem?



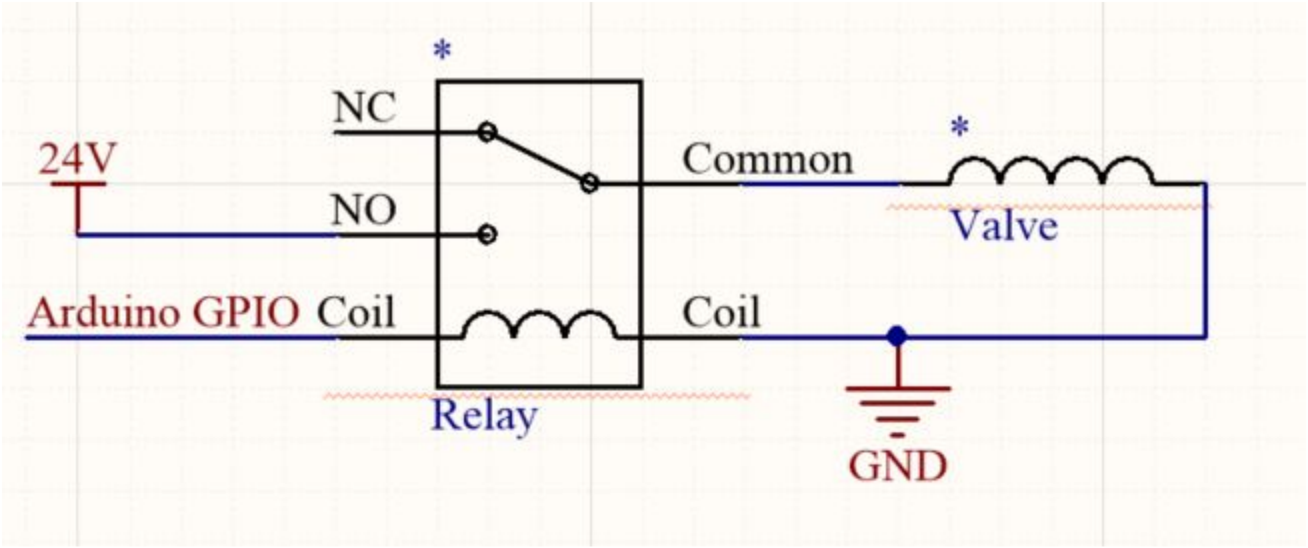
Protection circuit

To protect the relay and the surrounding components. We could use a flyback diode to protect it., or just place it as high side switch



Driving Valve with Relay

The relay should be placed as high side switch



Problem with using Relay

Typical relay contains mechanical components, usually mechanical components has shorter lifespan than electronic components

BJT

Skipped

Bipolar Junction Transistor

It is not commonly used in the competition

Just for your interest

Google if you want to know more about it.

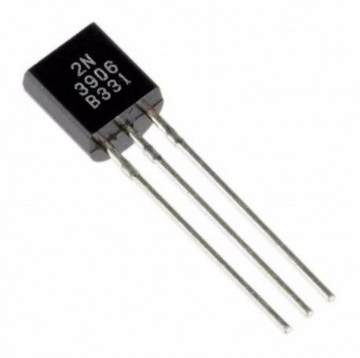
Bipolar Junction Transistor

It is a type of transistor.

The name explains the structure of this kind of transistor which has junction formed by P type semiconductors and N type semiconductors.

2 types: NPN and PNP, which have opposite structures.

They can be used to amplify current.



Pins

Each transistor has 3 terminals: Base (B), Collector (C), Emitter (E).

The symbols of NPN 

and PNP 

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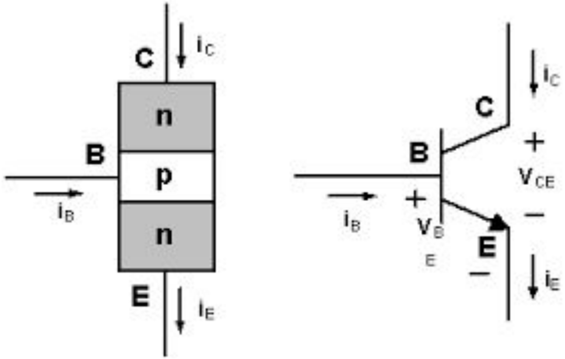
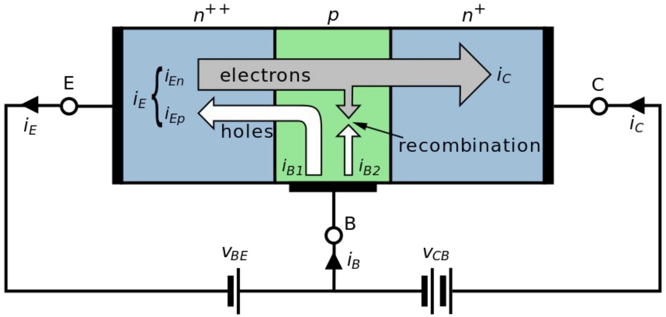


No matter which one, the terminal with an arrow is the Emitter.

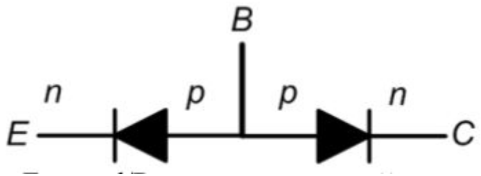
By looking at the direction of the arrow, you can distinguish NPN and PNP.

Structure - NPN



Take NPN as an example, there are:

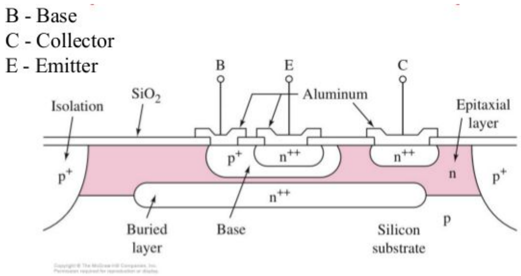
- Lightly n-doped layer connecting C
- Thin Moderately p-doped layer connecting B
- Heavily n-doped layer connecting E



Can be seen as 2 diodes connected back-to-back.

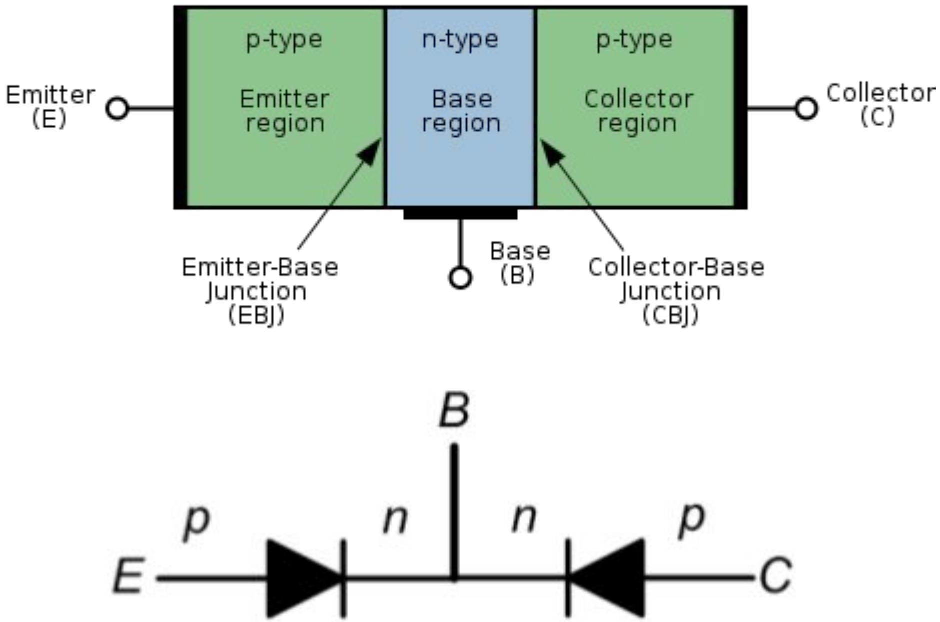
- However, the “diodes” can be either forward or reverse biased.

Actually a NPN BJT look like this:



Structure - PNP

For PNP, the structure is opposite:



Operation

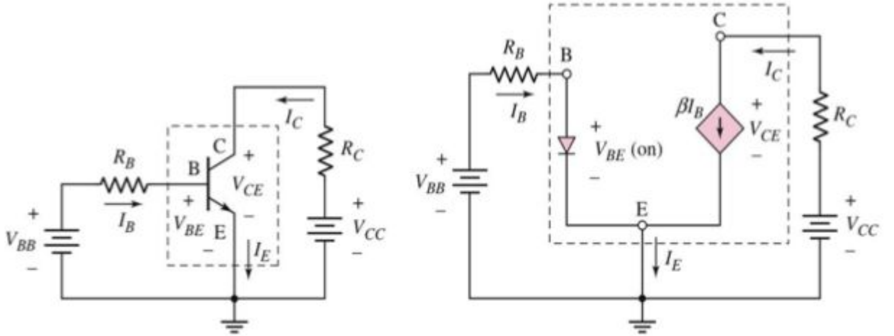
4 modes base on the voltage level on different terminals:

	Voltage		**B-C junction**	**B-E junction**
	NPN	**PNP**		
Forward-active	C>B>E	E>B>C	Reverse biased	Forward biased
Saturation	B>C, B>E	C>B, E>B	Forward	Forward
Cut-off	C>B, E>B	B>C, B>E	Reverse	Reverse
Reverse-active	E>B>C	C>B>E	Forward	Reverse

Operation

Forward-active

- usually the mode that we care
- always follows $\mathbf{I_C = \beta I_B}$, where β is common emitter current gain which is dependent on the specification of the BJT
- that's why we called BJT a **"current-dependent current source"**
- Equivalent circuit when in forward-active mode:



Operation

Saturation

- $\mathbf{I_C} < \boldsymbol{\beta}\mathbf{I_B}$

Cut-off

- BJT is **shut down**, almost no current

Reverse-active

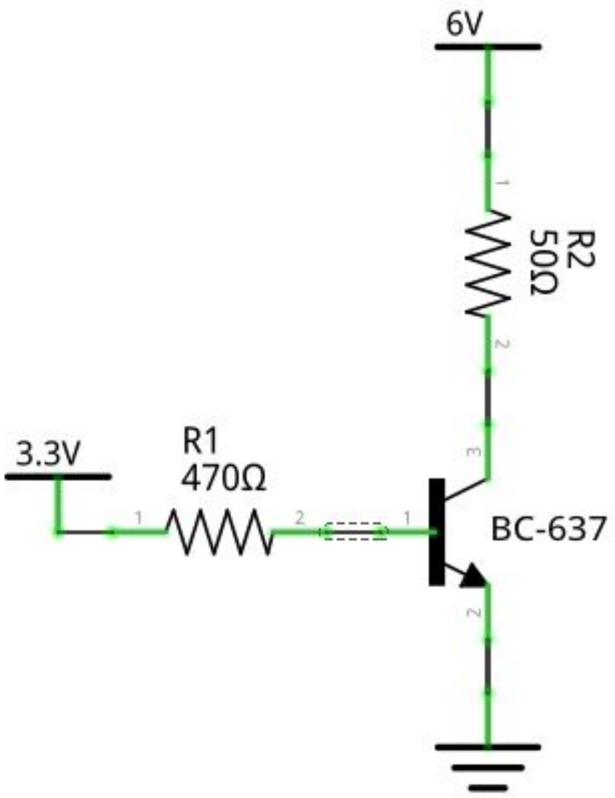
- roles of the emitter and collector regions are switched
- usually BJT not optimized to do that, current gain β is much smaller

Usage - NPN - Low Side Driver

Remember driving a motor using L298N? Actually it can be driven using a single BJT.

To make things simpler, Let assume the motor is a 50 Ω resistor (R_2) and is connected to the Collector of a NPN.

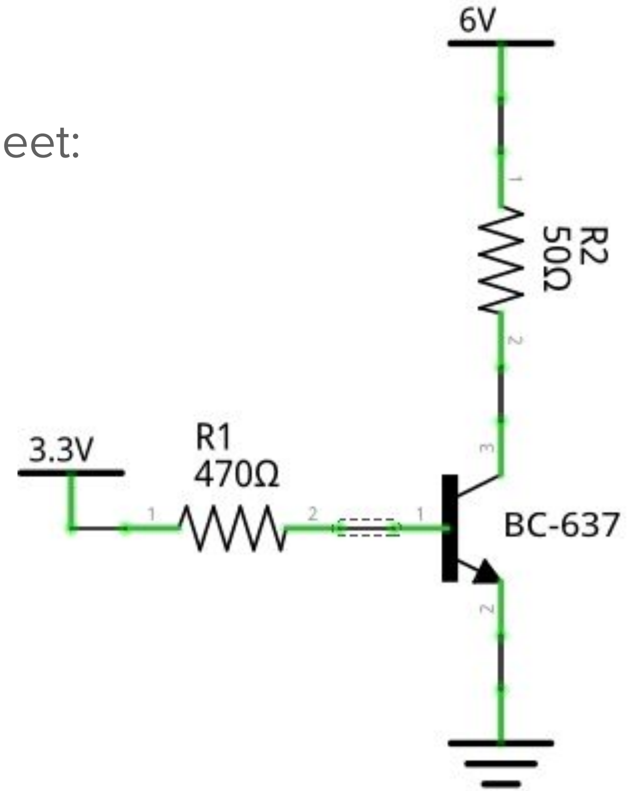
Arduino is connected to the Base with a current limiting resistor (R_1).



Usage - NPN - Low Side Driver

There are 2 items that you can find on BC-637 datasheet:
http://www.mouser.com/ds/2/149/BC637-888529.pdf

- DC Current Gain (β) = 25
- Base-Emitter On Voltage ($V_{BE(on)}$) = 1 V



Usage - NPN - Low Side Driver

Using KVL along the blue path (from B to E):

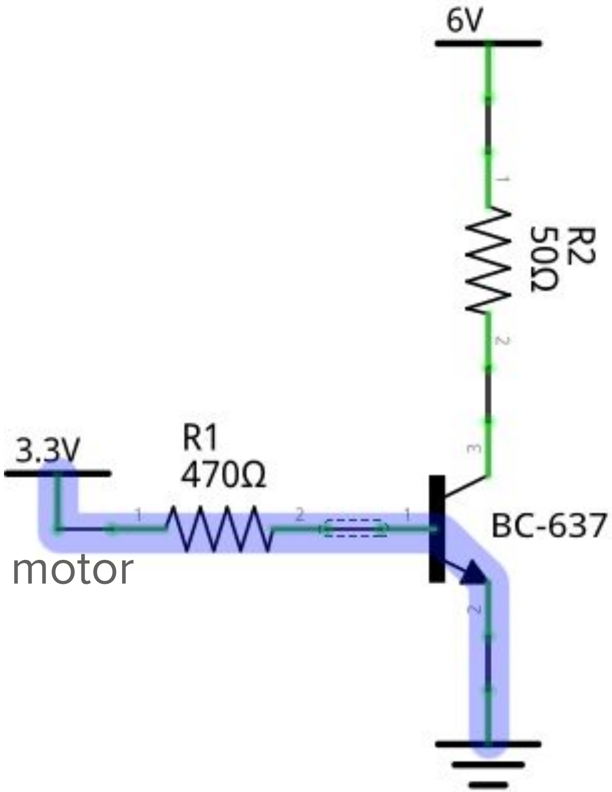
$3.3V = \text{voltage across R1} + \text{voltage across B-E}$

$3.3V = I_B \times R_1 + V_{BE(on)}$

$3.3V = I_B \times 470\Omega + 1$

$I_B = (3.3 - 1) \div 470 = 0.00489\ A = 4.89\ mA$

$I_c = \beta\, I_B = 122\ mA$, which is the current across the motor



Usage - NPN - Low Side Driver

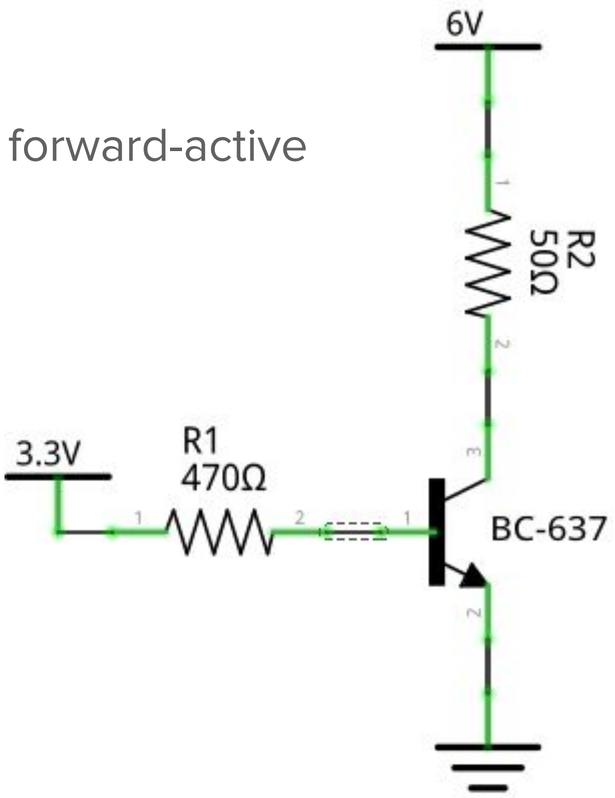
All the way along we have assumed that the NPN is in forward-active state, but is it true?

At C:

$$V_C = 6 - \text{voltage across the motor}$$
$$V_C = 6 - I_C \times R_2 = 6 - 122\text{ mA} \times 50\ \Omega = -0.117\text{ V}$$

Oh crap, it is even lower than the Base! So it's must not be in forward-active

Let's change the value of R_1 than.



Usage - NPN - Low Side Driver

From B to E:

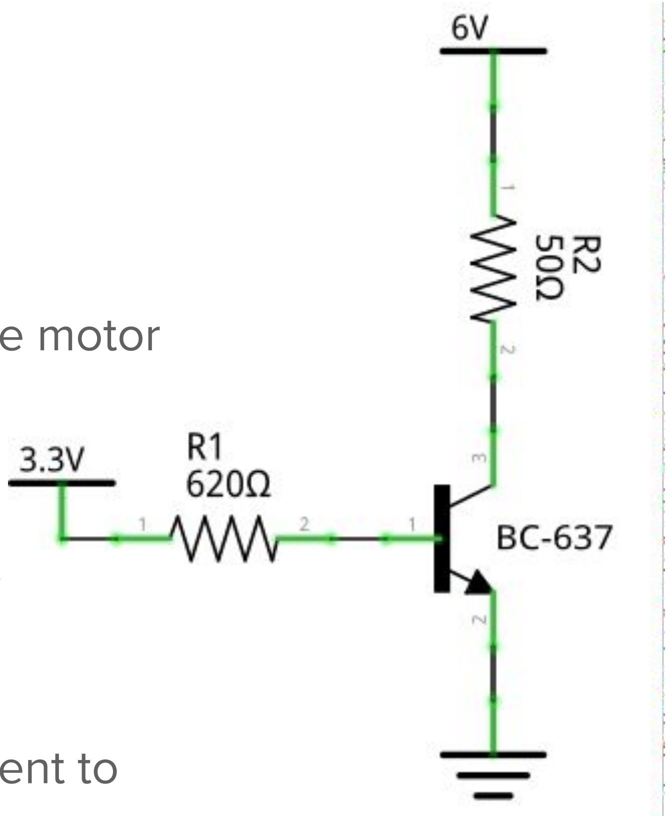
$I_B = (3.3 - 1) \div 620 = 0.00371\ \text{A} = 3.71\ \text{mA}$
$I_C = \beta\ I_B = 92.7\ \text{mA}$, which is the current across the motor

At C:

$V_C = 6 - I_C \times R_2 = 6 - 92.7\ \text{mA} \times 50\ \Omega = 1.36\ \text{V} > V_B$

Great! The BJT is really in forward-active!

When the output from Arduino is 0V, there is not current to the Base and the BJT is cut-off.

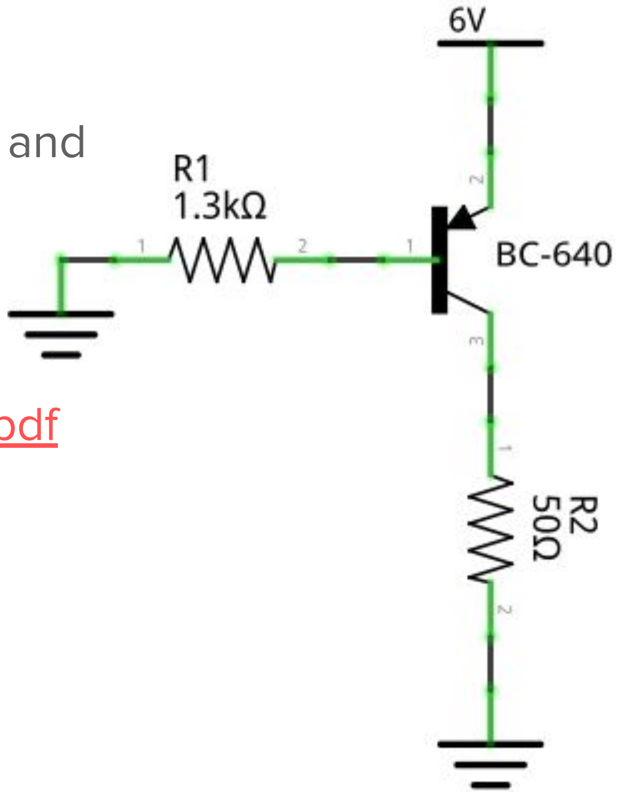


Usage - PNP - High Side Driver

Now the BJT is connected to the anode of the motor, and the output signal from Arduino is 0V.

Characteristics of BC-640:

- http://www.mouser.com/ds/2/149/BC640-30759.pdf
- DC Current Gain β = 25
- Base-Emitter On Voltage ($V_{BE(on)}$) = -1 V



Usage - PNP - High Side Driver

Using similar technique:

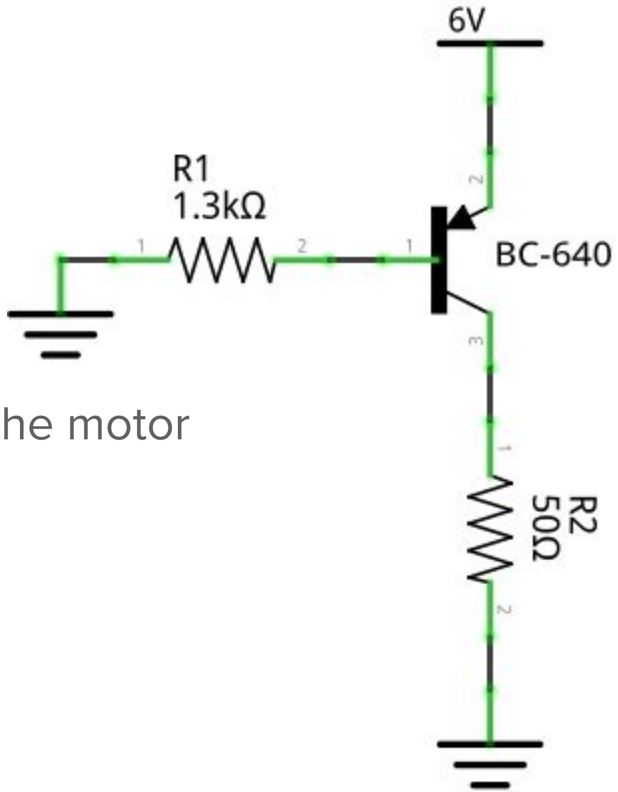
From C to B:

$$I_B = (6 - 1) \div 1300 = 0.00385 \text{ A} = 3.85 \text{ mA}$$

$I_C = \beta\, I_B = 96.2$ mA, which is the current through the motor

At C:

$$V_C = I_C \times R_2 = 96.2 \text{ mA} \times 50\ \Omega = 4.81 \text{ V} < V_B$$



Tutorial

1. Explain the working principle of flyback diode.
2. Explain the working principle of solid state relay.
3. Why mechanical relay could not be switch in high frequency?
4. Please design a relay with flyback diode.

Tutorial

1. What is a push-pull config of BJT?
2. What is a open collector config of BJT?
3. What will happen if the voltage across collector and emitter is higher than rated?
4. What is the power efficiency of the High Side Driver on the last page?
5. Is there a way to turn off the motor on the last page? If yes, how? If no, why not?

MOSFET

Henry Lau (2018)
Jacky Ng (2018)

Keywords for googling

N-channel / P-channel MOSFETS

Rds(on), Vds, Vgs, Id

Conduction power loss, switching power loss

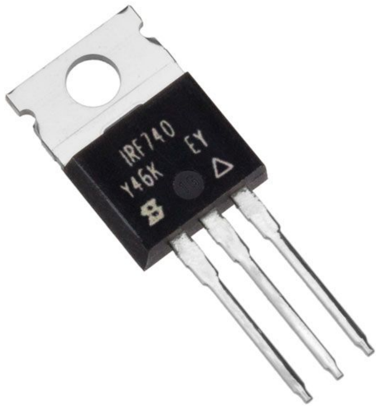
Input capacitance (https://toshiba.semicon-storage.com/info/docget.jsp?did=13415)

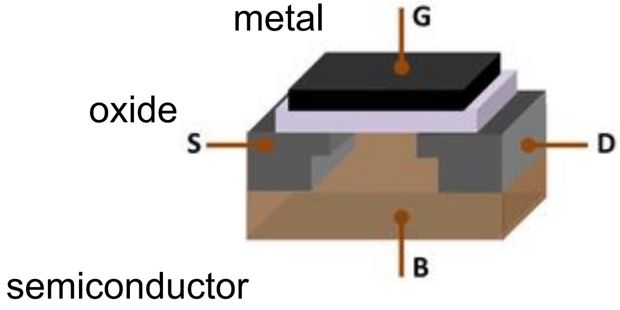
Metal-Oxide-Semiconductor Field-Effect Transistor

It is a type of transistor.

The name explains the structure of this kind of transistors, which is made with metal, oxide and semiconductor.

They are voltage driven which made them very easy to drive on and off as electronic switches.





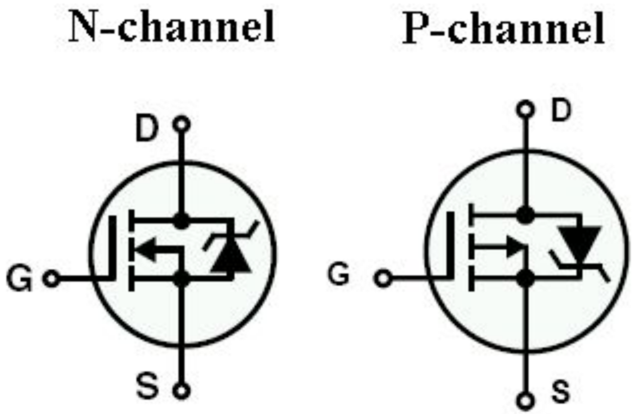
Types

- n-Channel Enhancement-Mode MOSFET
- p-Channel Enhancement-Mode MOSFET
- n-Channel Depletion-Mode MOSFET (uncommon)
- p-Channel Depletion-Mode MOSFET (uncommon)

When we talks about nMOSFET and pMOSFET, we are usually referring to n-Channel and p-Channel Enhancement-Mode MOSFET.

Pins

Each MOSFET has 3 terminals: Gate (G), Drain (D), Source (S).



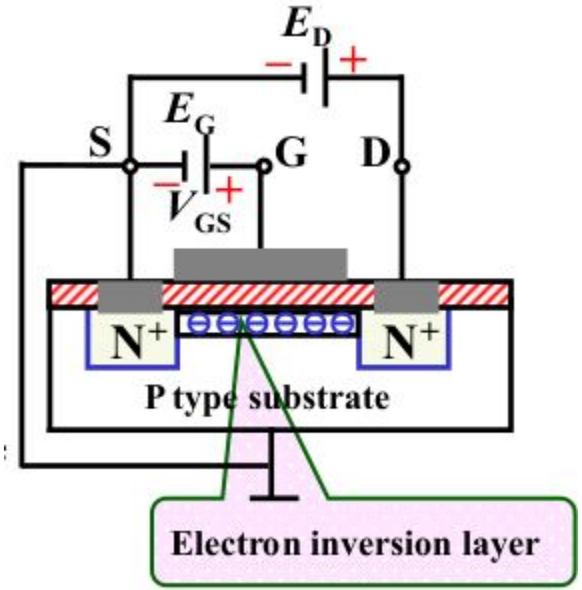
No matter which one, the terminal drawn with an arrow is the Source.

By looking at the direction of the arrow, you can distinguish nMOSFET and pMOSFET. (pointing in is N-MOSFET)

Structure - nMOSFET

Take n-Channel Enhancement-Mode MOSFET as an example, there are:

- **Gate (G)** connected to the metal, which is electrically insulated with the semiconductor
- **Drain (D)** and **Source (S)** connected to n-doped substrates, which are separated by a p-doped layer

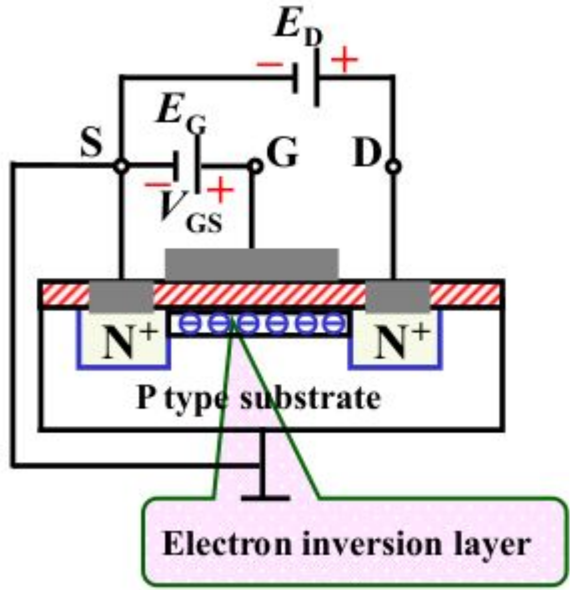


Structure - nMOSFET

When **positive** voltage is applied to the Gate, it generates an electric field which repel **holes** in the **p-doped** layer and creates a electron inversion layer, an moves between Drain and Source.

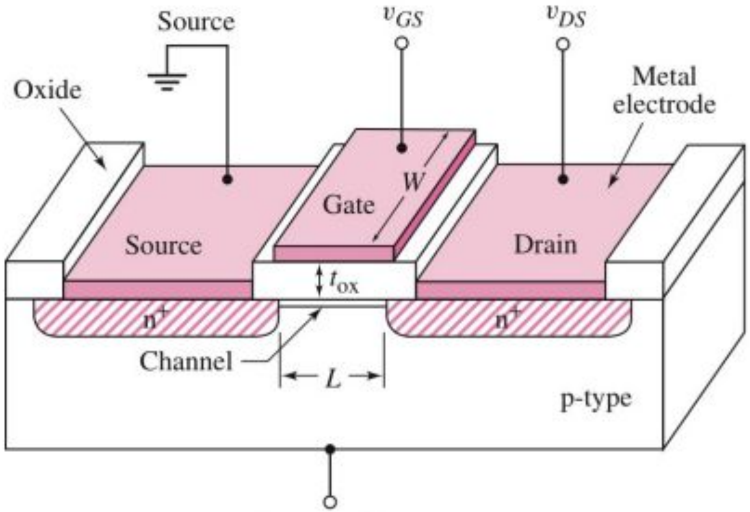
Unlike the base in BJT, there is **no current** into the **Gate** In MOSFET, current only passes through the Drain and The Source.

I.e. $\mathbf{I_D = I_S}$



Structure - nMOSFET

Actually a n-Channel Enhancement-Mode MOSFET look like this:

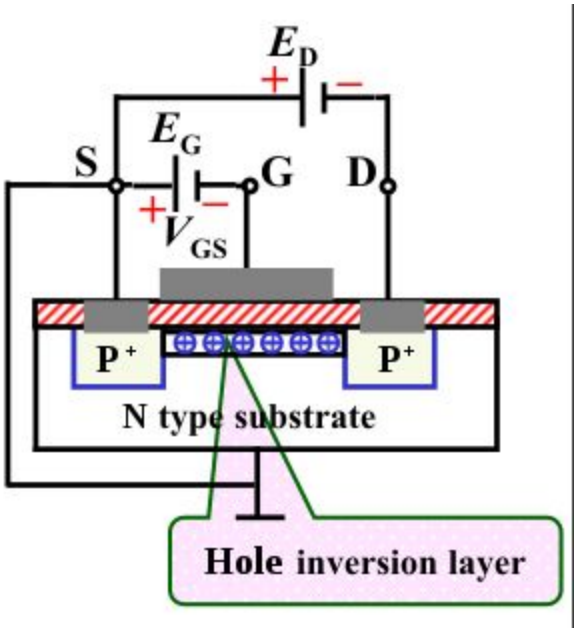


Structure - pMOSFET

For a p-Channel Enhancement-Mode MOSFET:

- **Drain (D)** and **Source (S)** connected to p-doped substrates, which are separated by a n-doped layer

When **negative** voltage is applied to the Gate, it generates an electric field which repel **electrons** in the **n-doped** layer and creates a **hole** inversion layer, and hence **holes** can moves between Drain and Source.



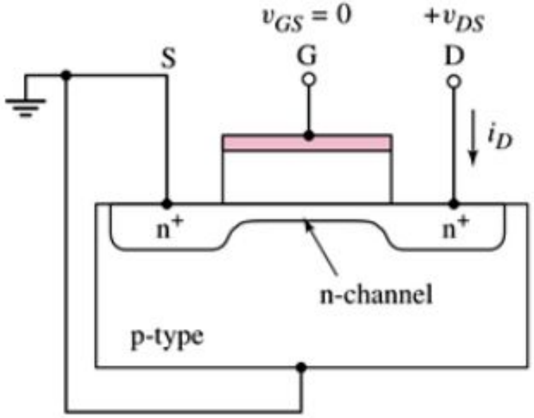
Structure - Depletion-Mode MOSFET

Take n-Channel Depletion-Mode MOSFET as an example:

N-type impurities is introduced under oxide layer, so inversion layer exists even when there is no voltage applied on the gate

Hence n-Channel Depletion-Mode MOSFET are **normally-on**

In order to turn it off, negative gate voltage should be applied

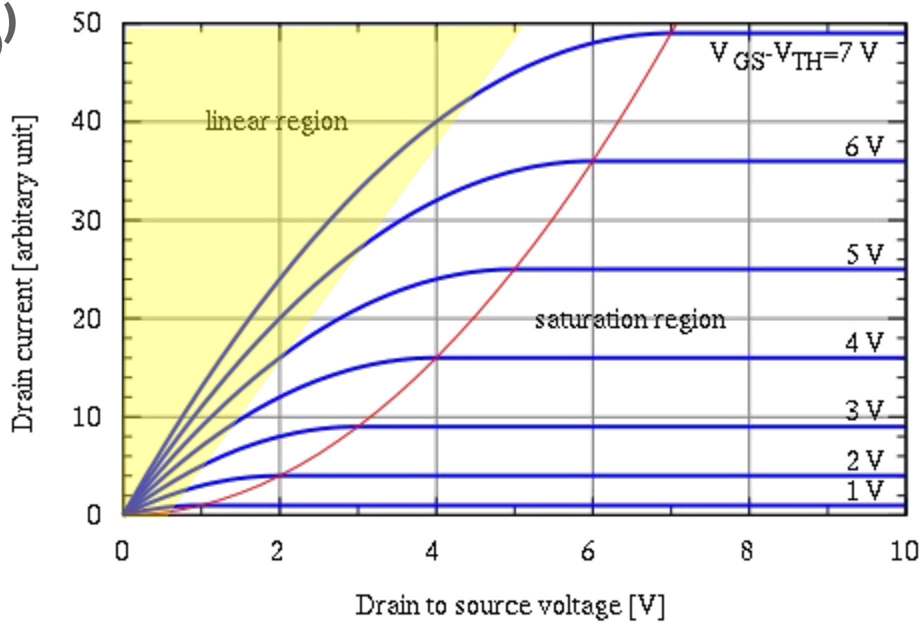


Operation

- Each MOSFET has its own **threshold voltage (V_{TH})**
- When the V_{GS} is lower than V_{TH} (nMOSFET) / V_{SG} is higher than V_{TH} (pMOSFET), the MOSFET is **shut down**, and there is almost no current between Drain and Source
- For Enhancement-Mode nMOSFET, $\mathbf{V_{TH}} > 0$,
  For Enhancement-Mode pMOSFET, $\mathbf{V_{TH}} < 0$
  - Hence Enhancement-Mode MOSFET are normally off
- For Depletion-Mode nMOSFET, $\mathbf{V_{TH}} < 0$,
  For Depletion-Mode pMOSFET, $\mathbf{V_{TH}} > 0$
  - Hence Depletion-Mode MOSFET are normally on

Operation

- I_D increases linearly with $\mathbf{V_{DS}}$ when V_{DS} is low (highlighted area), hence can be treated as a resistor with a particular **Drain-to-Source On-Resistance ($R_{DS(on)}$)**
- $R_{DS(on)}$ varies with different V_{GS} , which can be seen on the datasheet of a MOSFET

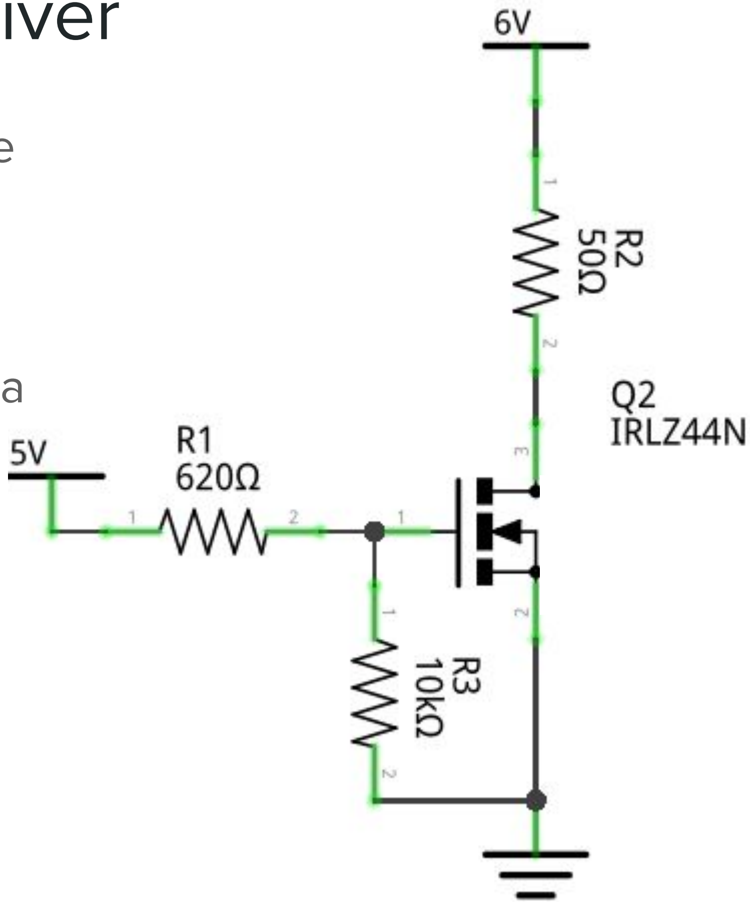


Remember V = IR

Usage - nMOSFET - Low Side Driver

Let's have a low side driver similar to the one in the chapter of BJT.

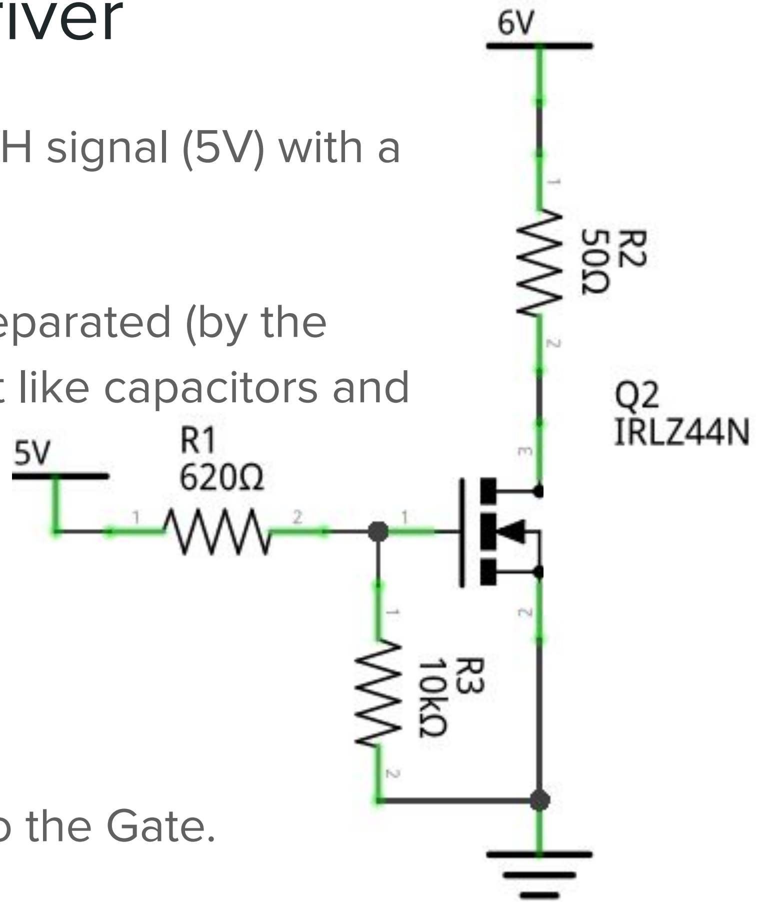
To make things simpler, Let assume the motor is a 50 Ω resistor (R_2) and is connected to the Drain of a nMOSFET.



Usage - nMOSFET - Low Side Driver

Arduino is connected to the Gate outputting a HIGH signal (5V) with a current limiting resistor (R_1).

- As the terminals of MOSFET are electrically separated (by the oxide layer and the depletion region), they act like capacitors and hence MOSFET has a relatively high parasitic capacitance.
- If R_1 does not exists, there will be a surge in current during switching and damage the MOSFET.

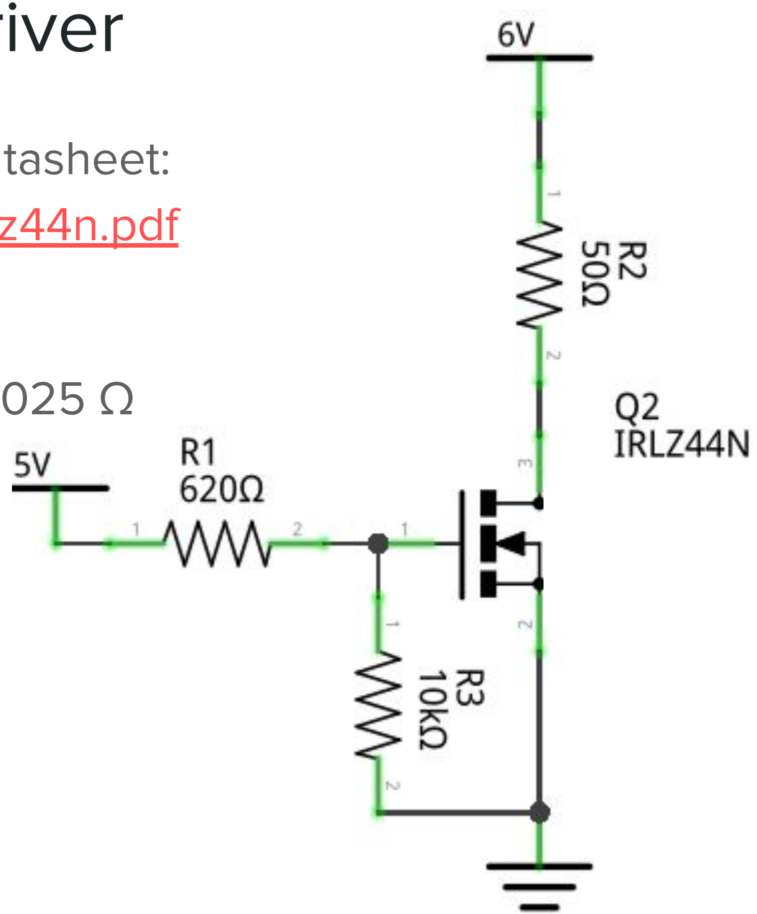


There is also a pull-down resistor (R_3) connected to the Gate.

Usage - nMOSFET - Low Side Driver

There are 2 items that you can find on IRLZ44N datasheet: http://www.irf.com/product-info/datasheets/data/irlz44n.pdf

- Gate Threshold Voltage ($V_{GS(th)}$) = 2.0 V
- Drain-Source On-State Resistance ($R_{DS(on)}$) = 0.025 Ω



Usage - nMOSFET - Low Side Driver

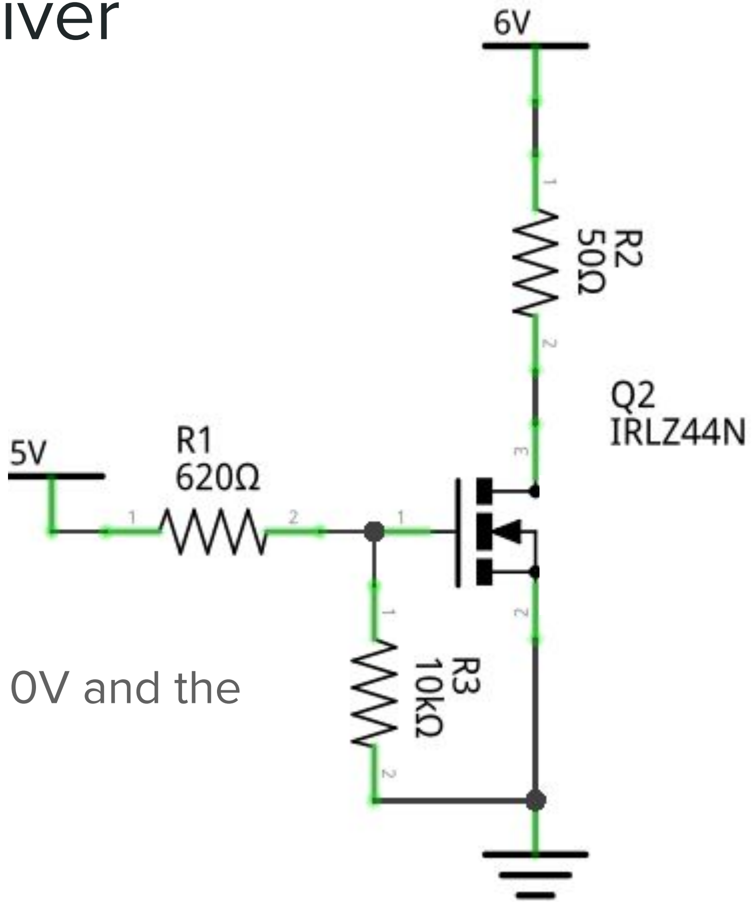
As $V_{GS} > V_{TH}$,the MOSFET is turned on.

V = IR

$6V = I_D \times (50 + R_{DS(on)})$

$I_D = 119.9$ mA

When the output from Arduino is 0V, there is V_{GS} = 0V and the MOSFET is cut-off.



Altium Lab section

Choose N-channel MOSFET to operate pneumatic valve and electromagnets.

Choosing MOSFET with current rating and threshold voltage that even 3.3V logc could activate it

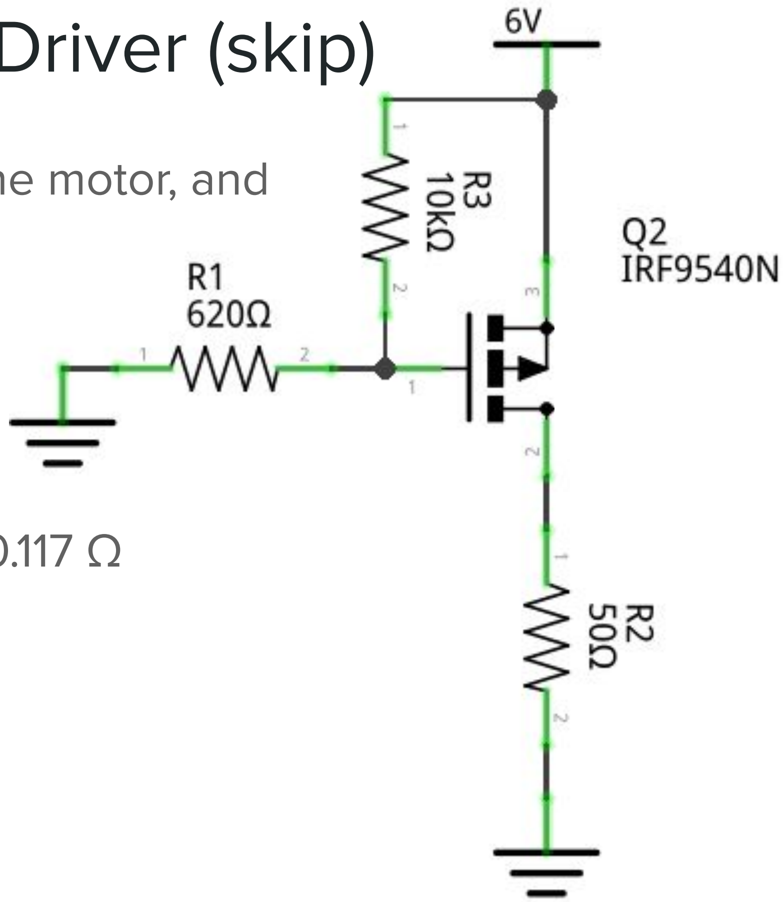
Usage - pMOSFET - HIGH Side Driver (skip)

Now the MOSFET is connected to the anode of the motor, and the output signal from Arduino is 0V.

- Characterics of IRF9540 datasheet: https://www.infineon.com/dgdl/irf9540n.pdf
- Gate Threshold Voltage ($V_{GS(th)}$) = -2.0 V
- Drain-Source On-State Resistance ($R_{DS(on)}$) = 0.117 Ω

Using similar technique:

$I_D = 6 \div (50 + R_{DS(on)})$ 119.7 mA



Usage

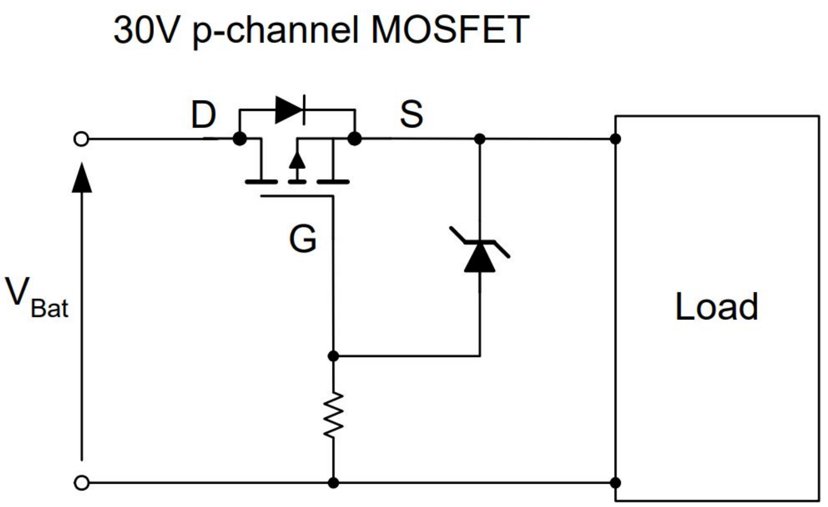
- Reverse polarity protection
- OR-ing operations
- Buck converters (with IC)
- OV/UV protection (with IC)

Reverse Polarity Protection

- P-MOSFET could be used on the high side to block reverse current

- It is more expensive than using diode, but the efficiency is better

https://www.infineon.com/dgdl/Reverse-Batery-Protection-Rev2.pdf?fileId=db3a304412b407950112b41887722615



OR-ing FET operation

As stated before, we can use diodes to implement a OR-ing circuit.

But diode has large voltage drop and will generate a lot of heat.

The solution is to replace them with MOSFET.

Using MOSFETs will require some external circuits to control the on/off state of the MOSFET.

For the implementation of OR-ing MOSFET in real life, refer to the datasheet of lm5050 and the schematic of power board in M2.

OR-ing Operation with LM5050

By using other ICs like LM5050, a redundant power supply could be created.

https://www.ti.com/lit/ds/symlink/lm5050-2.pdf?ts=1625557523783&ref_url=https%253A%252F%252Fwww.google.com%252F

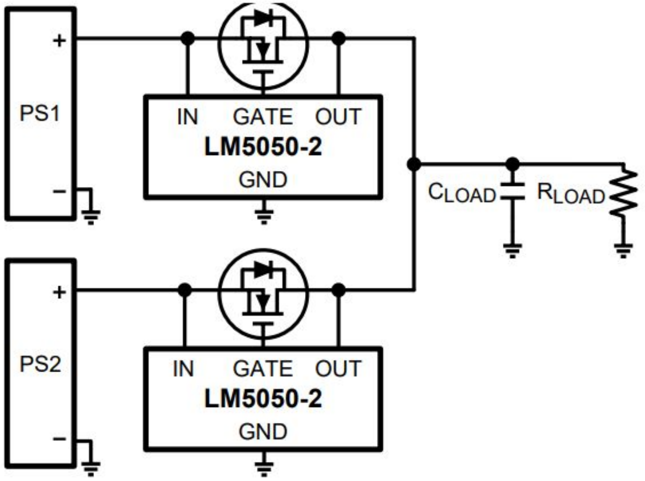


Figure 2. Typical Redundant Supply Configuration

Altium Lab

Replace the diode with p-channel MOSFET for reverse voltage protection

Check out lm5050 for ORing MOSFET instead of Diode

Power Loss in MOSFET

2 types of power loss in MOSFET: Switching loss and conduction loss.

Conduction loss

It is the power loss that occurs when mosfet conducts current, the loss = I^2 R

Usually we just use I(out)^2 x Rds(on) x Duty cycle as power loss, as the ripple current is much smaller than the continuous DC current, so we just calculate the conduction loss due to current loss.

$$P_{CON} = R_{DS(on)} \times I^2_{QSW(RMS)}$$
$$= R_{DS(on)} \times \frac{V_{OUT}}{V_{IN}} \times \left(I^2_{OUT} + \frac{I^2_{RIPPLE}}{12} \right)$$

Switching loss

Switching loss is related to input voltage (Vin), Current (I), rise time, fall time of the MOSFET and its switching frequency

P(loss) = Vin x I x (rise time + fall time) x frequency

Switching loss is proportional to the frequency

Choose MOSFET with lower rise and fall time for high frequency usage

TI’s NEXFET series have low rise and fall time

Power loss

The power loss of MOSFET is affected by these 2 things.

When choosing a MOSFET for your operation, perform calculations for its heat generation and allocate enough copper plane/heatsink to dissipate the heat.

Power loss in different application

In OR-ing FET operating. The dominant power loss is conduction loss of the MOSFET since the MOSFET stayed turn on for all the time.

In Buck Converter, both switching loss and conduction loss are major factors.

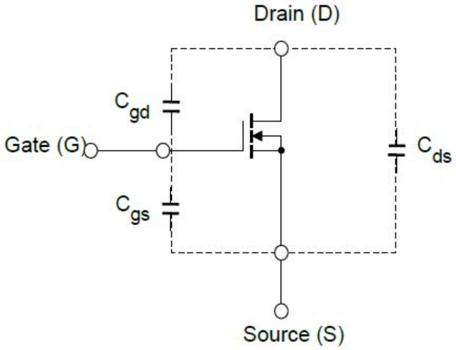
Current limiting resistor

Since MOSFETs got input capacitance, you need a resistor to form a RC circuit.

Higher resistance is required when the driving source (e.g. IO of MCU) has low current output

The capacitor needs to be fully charged before the MOSFET is turned on or off

Input capacitance affects the switching frequency of MOSFET.



Input capacitance $(C_{iss}) = C_{gd} + C_{gs}$

Output capacitance $(C_{oss}) = C_{ds} + C_{gd}$

Reverse transfer capacitance $(C_{rss}) = C_{gd}$

Input capacitance

SISA96DN-T3, The input capacitance is known as Ciss, driving the mosfet is similar to driving a RC circuit.

Forward transconductance [b]	g_{fs}	V_{DS} = 15 V, I_D = 10 A	-	70	-	S
Dynamic [b]						
Input capacitance	C_{iss}	V_{DS} = 15 V, V_{GS} = 0 V, f = 1 MHz	-	1385	-	pF
Output capacitance	C_{oss}		-	478	-	
Reverse transfer capacitance	C_{rss}		-	37	-	
		V_{DS} = 15 V, V_{GS} = 10 V, I_D = 10 A	-	20.5	31	

Input capacitance

Time to charge/discharge the capacitor is 4 tau (tau = RC)

Current draw from MCU when the capacitor is fully discharged: I = V/R. Voltage is voltage of MCU, resistor is the resistance of current limiting resistor.

E.g. Arduino GPIO can source 5V @ 50mA at most, so the current limiting resistor should be 5V/0.05 = 100 ohm resistor. The maximum switch on delay is 4RC = 0.54 micro seconds

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Rise and time

Rise and fall time of the MOSFET relates to the switching power loss of it

Turn-on delay time	$t_{d(on)}$	V_{DD} = 15 V, R_L = 1.5 Ω, $I_D \cong$ 10 A, V_{GEN} = 10 V, R_g = 1 Ω	-	8	16	ns
Rise time	t_r		-	25	50	
Turn-off delay time	$t_{d(off)}$		-	13	26	
Fall time	t_f		-	9	18	
Turn-on delay time	$t_{d(on)}$	V_{DD} = 15 V, R_L = 1.5 Ω, $I_D \cong$ 10 A, V_{GEN} = 4.5 V, R_g = 1 Ω	-	12	24	
Rise time	t_r		-	47	94	
Turn-off delay time	$t_{d(off)}$		-	15	30	
Fall time	t_f		-	25	50	

Tutorial

1. What is the power efficiency of the High Side Driver on the last page?
2. Which driver circuit is better, BJT or MOSFET in low voltage (under 48V)? Why?
3. If you have an Arduino, is it possible to modify the circuit to turn off the MOSFET? If yes please draw the circuit diagram, if no please explain.
4. How does temperature affects the on resistance of MOSFET?
5. Are there other kinds of power loss besides of conduction loss with using MOSFET as motor drivers?

Tutorial

https://www.vishay.com/docs/75285/sisa96dn.pdf

1. Try to describe the Rds(on) on this MOSFET when Vgs = 3V, 5V and 10V
2. Can you describe how temperature affects the Rds(on)
3. Can you describe how Vgs affects Rds(on)
4. Can you describe how Vgs affects Id
5. Could you turn it on with Arduino's digital output pin? Please explain your answer. (the HIGH voltage of arduino is 5V)
6. Could you turn it on with STM32's digital output pin? (the HIGH voltage of STM32 is 3.3V)
7. What is the input capacitance of the MOSFET? Assume STM32 could only source 20mA, what value should you use for the current limiting resistor?

Reference

- ELEC3346 Electronic Circuits Ch 4
  - https://drive.google.com/file/d/15c0fw_T6di7eX5oreYZRqWRI4SW0mEs5/view
- Electronic Basics #23: Transistor (MOSFET) as a Switch
  - https://www.youtube.com/watch?v=o4_NeqlJgOs
- TI SLVA771 application notes
  - http://www.ti.com/lit/an/slva771/slva771.pdf
- TI SLYT664 application notes
  - http://www.ti.com/lit/an/slyt664/slyt664.pdf