Lecture 13

Transistors

Stuff

- Vote on Piazza poll for waldo music. Poll closes Tuesday.

Party Rock anthem by LMFAO
https://www.youtube.com/watch?v=KQ6zr6kCPj8

Black Sheep by Metric
https://www.youtube.com/watch?v=USfoTGFGARE

How Dare You Want More by Bleachers
https://www.youtube.com/watch?v=gu-Ctqe4DPU

Hello by OMFG
https://www.youtube.com/watch?v=ih2xubMaZWI
https://www.youtube.com/watch?v=Jx4N-AP-ItI

ABBA **dancing queen**
https://www.youtube.com/watch?v=xFrGuyw1V8s
https://www.youtube.com/watch?v=Bla98LPpJT8

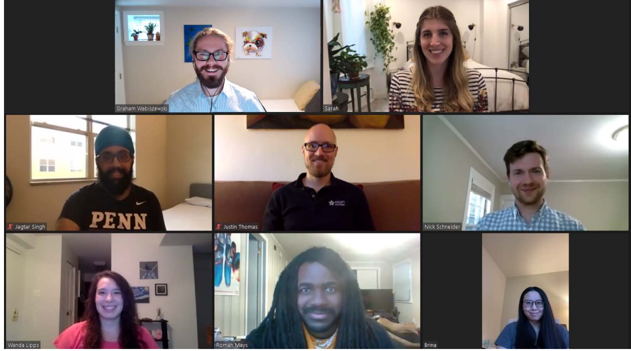
Gimme! Gimme! Gimme! by Abba!
https://www.youtube.com/watch?v=XEjLoHdbVeE
https://www.youtube.com/watch?v=BhrFOIobXZ0

Feel It Still by Portugal. The Man
https://www.youtube.com/watch?v=pBkHHoOIIn8
https://www.youtube.com/watch?v=932n5qEyOsk

Uptown Funk
https://www.youtube.com/watch?v=OPf0YbXqDm0
https://www.youtube.com/watch?v=5zKAAjQgETk

Single Ladies (mix)
https://www.youtube.com/watch?v=MIyiu-RWwcE

MEAM DEI Scholarship



MEAM is proud to have a diverse and strong community. To support that diversity and promote an inclusive culture that works to overcome bias and discrimination, we have launched a new program: *MEAM's Diversity, Equity, and Inclusion Scholarship.*

This opportunity is open to MEAM undergraduate students, graduate students, and postdoctoral scholars.

Applicants must propose an idea to work on during the academic year to build community and enact change in support of DE&I in MEAM. Winners will conduct that work (for at least 1 hr/week) and attend bi-weekly MEAM DEI Task Force meetings (1 hr/2 weeks).

How to apply:

1. Go to https://www.me.upenn.edu/diversity-equity-inclusion/
2. Under the *About* tab, click on Diversity, Equity and Inclusion.
3. Links to the DEI Scholarship info, and the DEI Scholarship Application are under "MEAM DEI Resources & Opportunities".

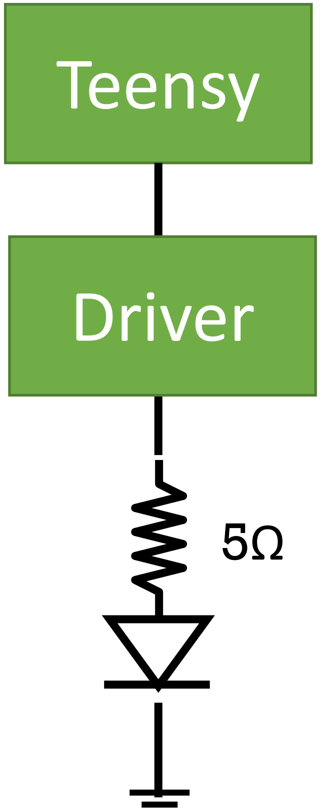
Deadline: November 5th , 2021

Agenda

- Bipolar Junction Transistors
- MOSFET and output drivers
- BJT vs MOSFET

When will we use Transistors in 510?

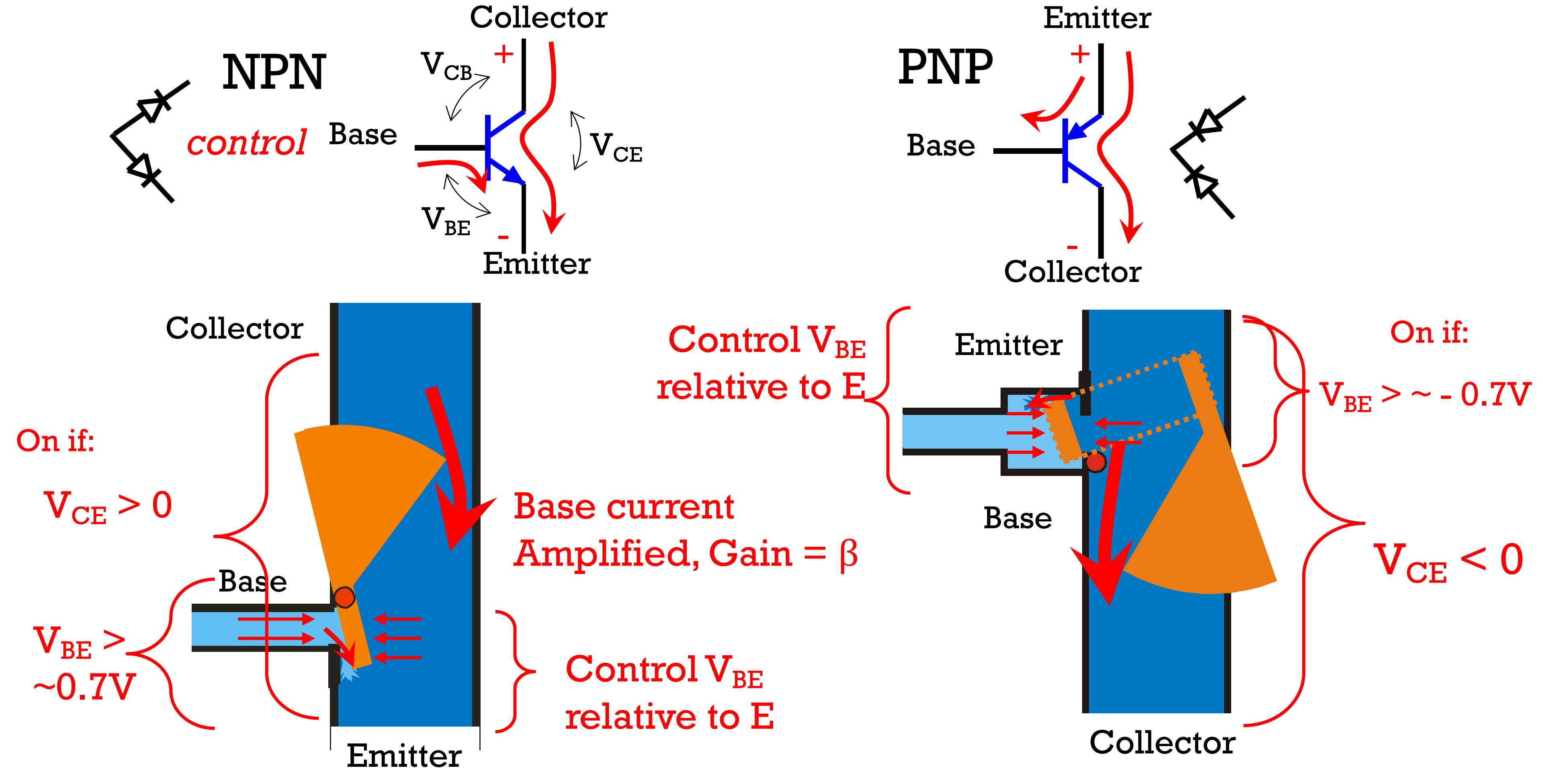
- Anyplace we need a switch, but in particular:
- What do we do if we want to turn on a motor that needs 500mA? (Teensy outputs can only drive 40mA)
- Or make 100 LED's blink together?
- Or one really bright LED that takes 1A?
- We can use **transistors** as large current drivers



01

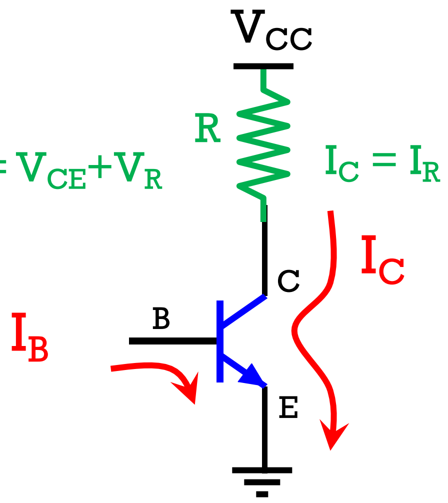
Bipolar Junction Transistors (BJT)

Bipolar Junction Transistors (BJT)

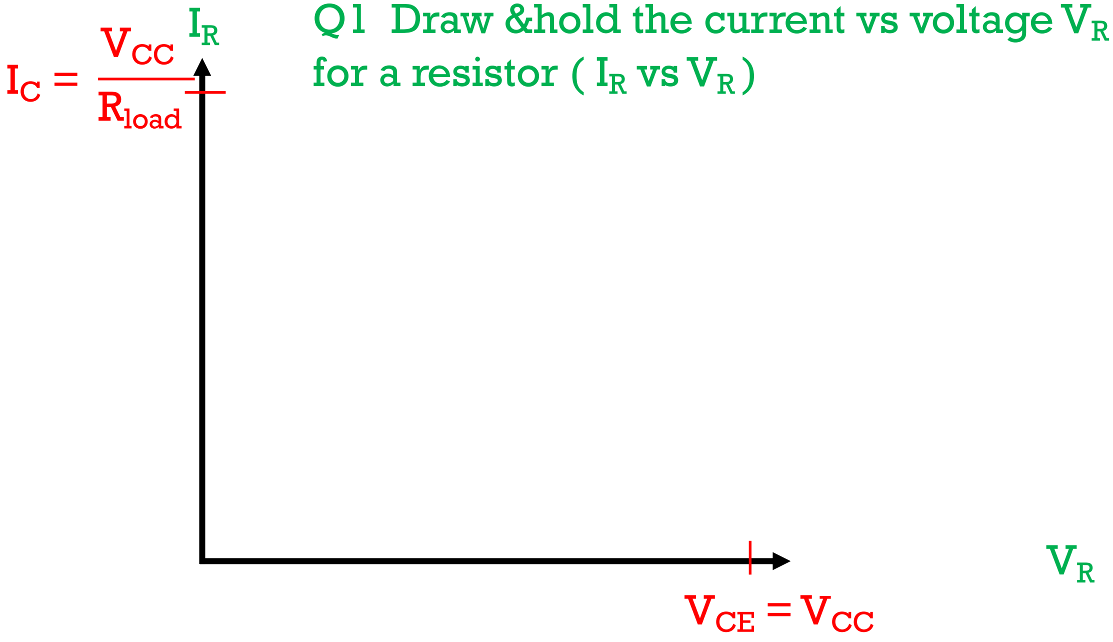


Example BJT Transistor behavior (recall phototransistor)

$V_{CC} = V_{CE} + V_R$



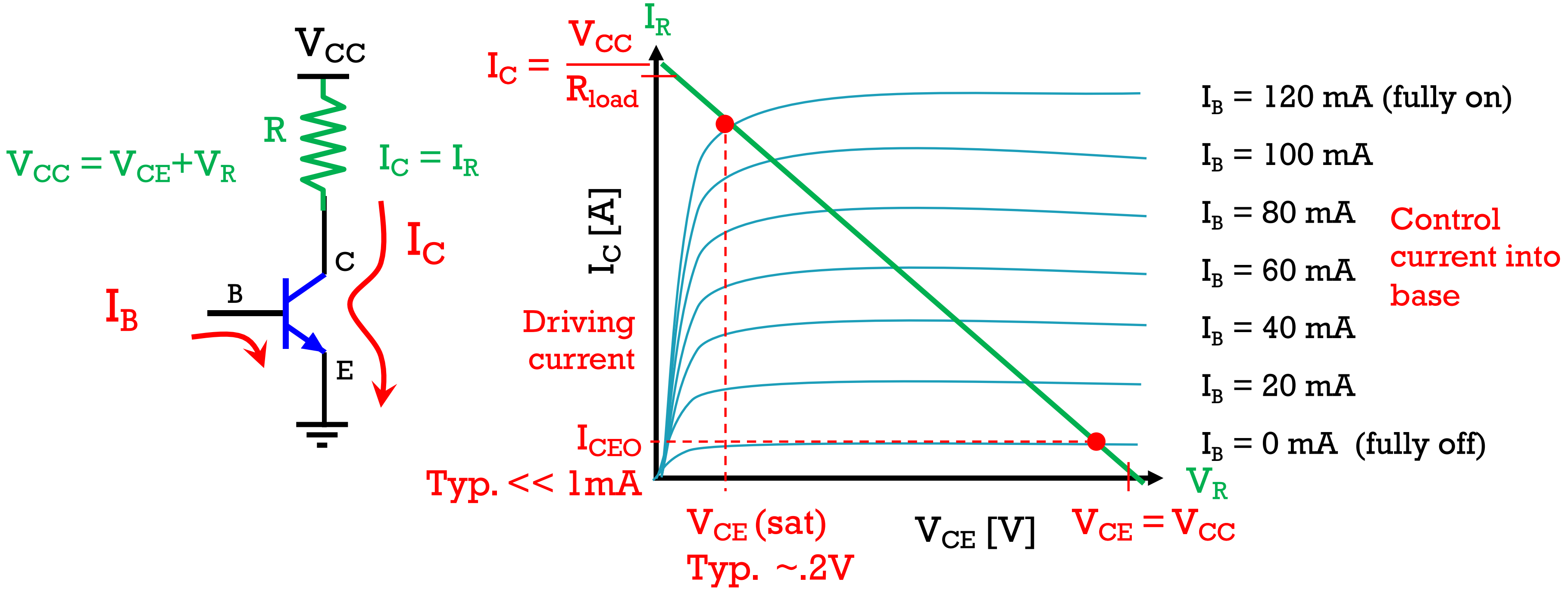
Q1 Draw &hold the current vs voltage V_R curve for a resistor (I_R vs V_R)



Q2 Draw &hold the current vs voltage curve for the (I_R vs V_{CE}) where V_{CC} is contant and we vary V_{CE}

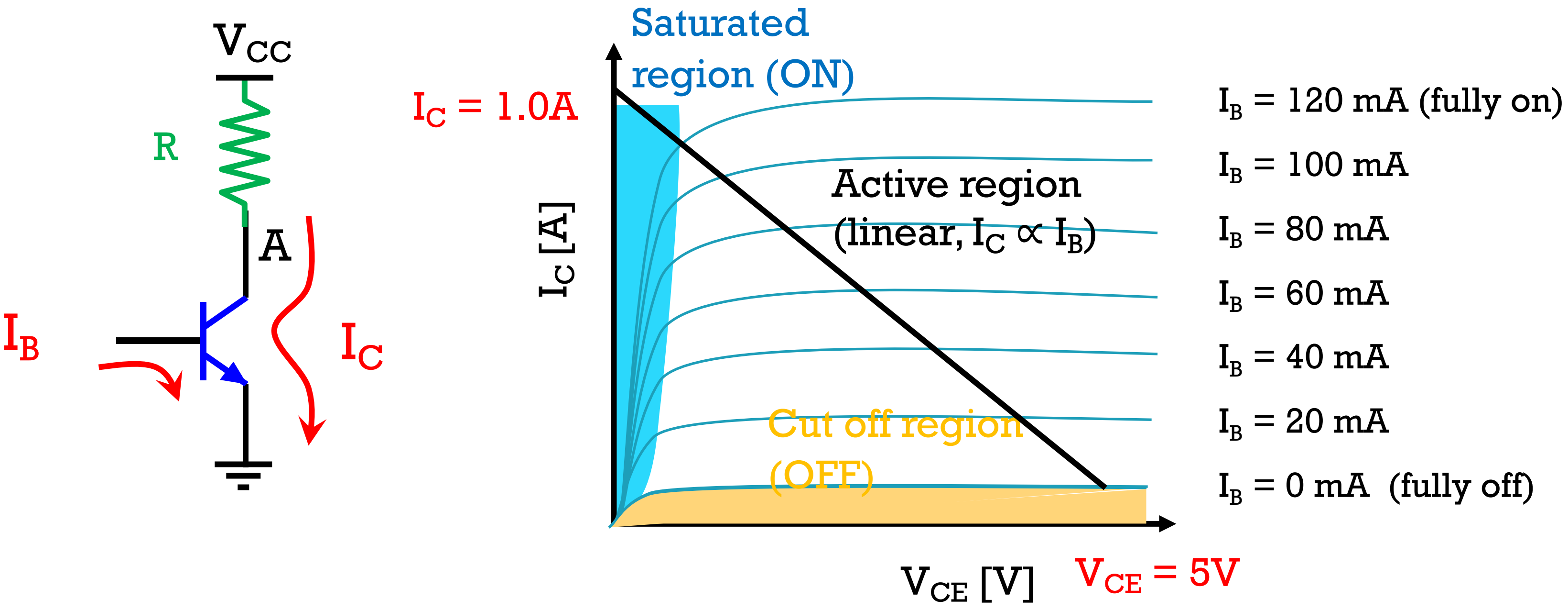
https://www.electronics-tutorials.ws/transistor/tran_4.html

Example BJT Transistor behavior (recall phototransistor)



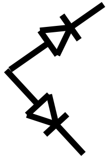
https://www.electronics-tutorials.ws/transistor/tran_4.html

BJT Transistor as a switch

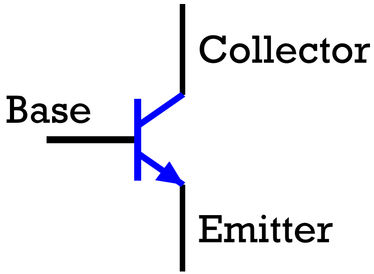


https://www.electronics-tutorials.ws/transistor/tran_4.html

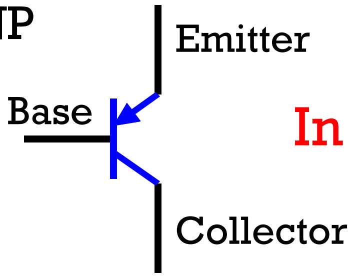
Bipolar Junction Transistors used as switches



NPN



PNP



In Saturation

How do we get them turned on?

Forward bias the Base:Emitter Junction

$V_{BE} > \sim 0.7V$

Supply current to base

How much current?

In saturation, gain ~= 10
(different than β)

~1/10th as much as desired Collector:Emitter current

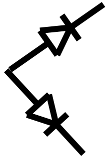
How do we know if transistor is in saturation?

V_{CE} will drop to about 0.2V

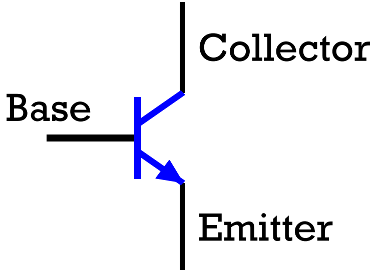
If nothing else limits voltage

Thus Base:Collector junction also forward biased

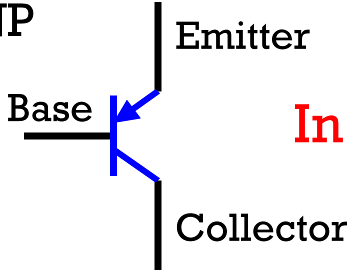
Bipolar Junction Transistors used as switches



NPN



PNP



In OFF region

How do we get them turned OFF?

Reverse bias the Base:Emitter Junction

$V_{BE} < \sim 0.7V$

(e.g. set $V_{Base} = V_{Emitter} = 0V$)

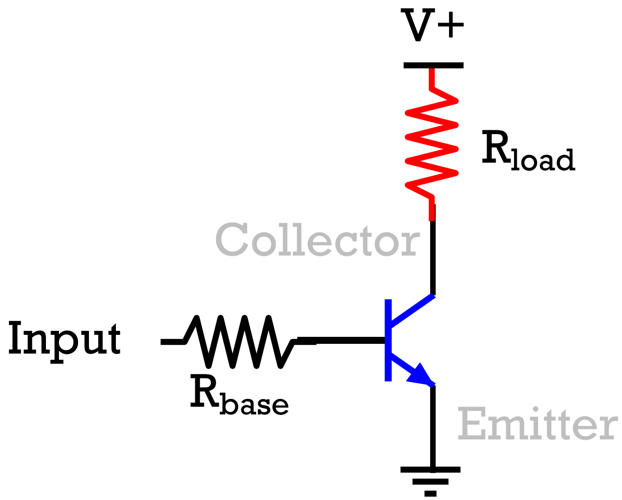
No current will flow ($I_C = 0$)

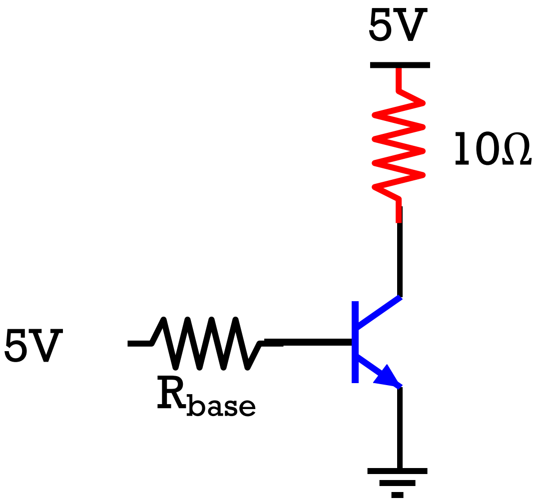
How do we know if transistor is OFF?

V_{CE} will act as open switch infinite resistance

Example NPN

- Open collector (simplest switching transistor configuration)





For TIP31C:
Typical

$V_{CE(sat)} = 0.1V$

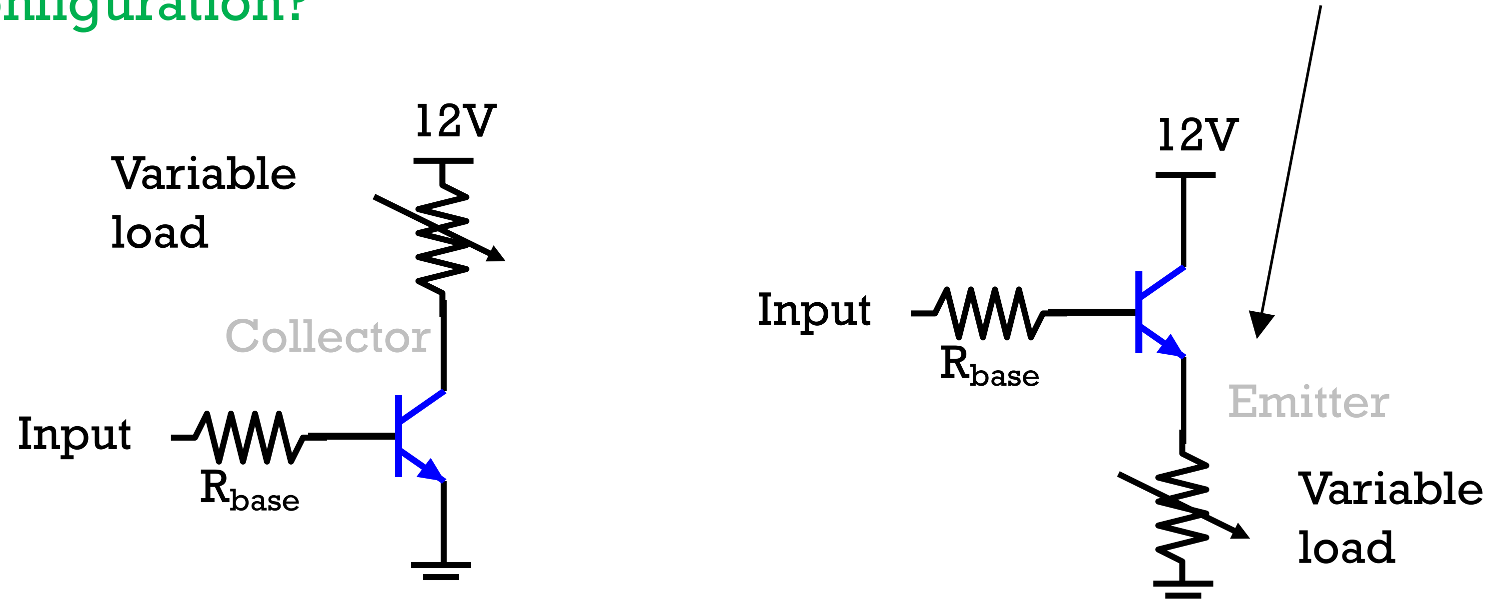
$V_{BE(sat)} = 0.7V$

Q3 Find the value for R_{base} that will ensure the transistor is ON

Q4 If we don't have that value. Do we want larger or smaller Ω to be ON?

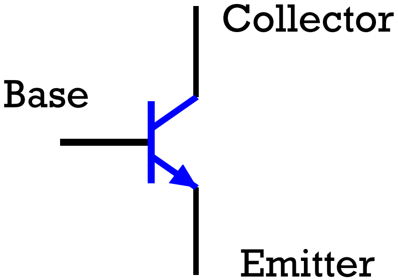
V_{BE} emitter reference

Q5 What is the *disadvantage* of using the open emitter configuration?



BJT Quiz:

NPN

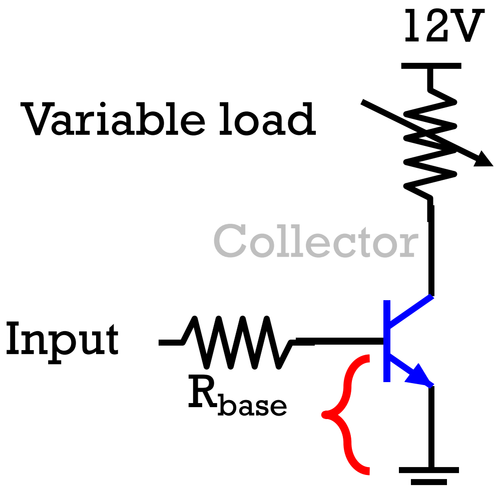


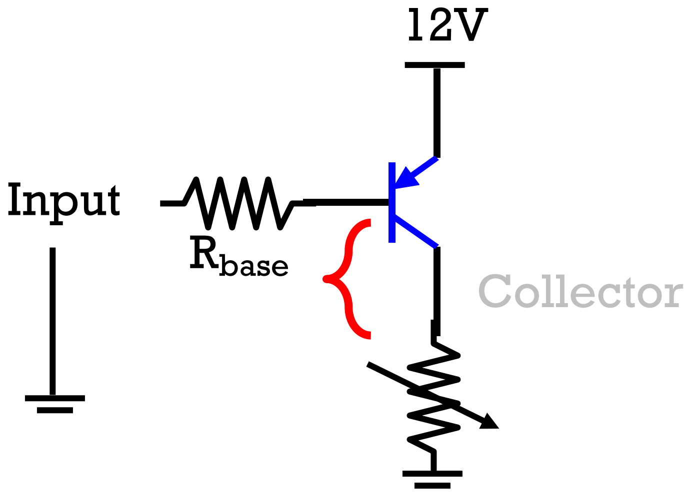
- If the voltage at the emitter is 5V what voltage do we need at the base to turn the transistor on?
  A. 6V
  B. 5V
  C. 0V
- If the voltage at the collector is 5V what voltage do we need at the base to turn on the NPN transistor?
  A. 6V
  B. 0V
  C. Not enough info.
- How much current will flow if on?
  A. About 1x current into base
  B. About 10x current into base
  C. About 100x current into base

V_{BE} emitter reference

- What is the disadvantage of using the open emitter configuration?

If you need to need a **high side drive**, use PNP!



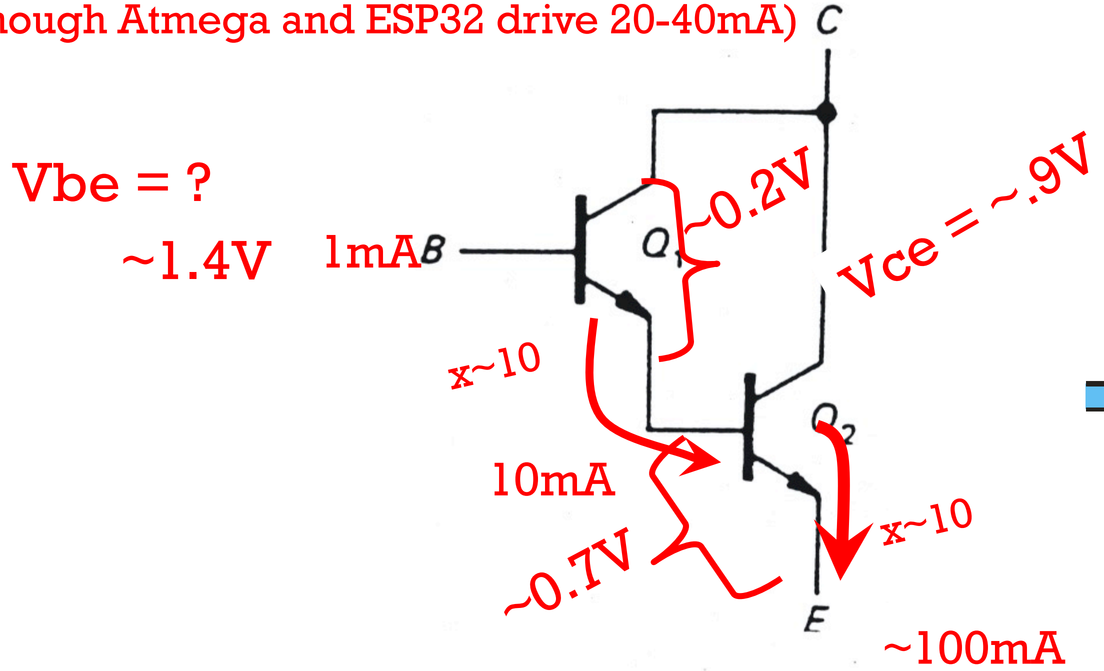


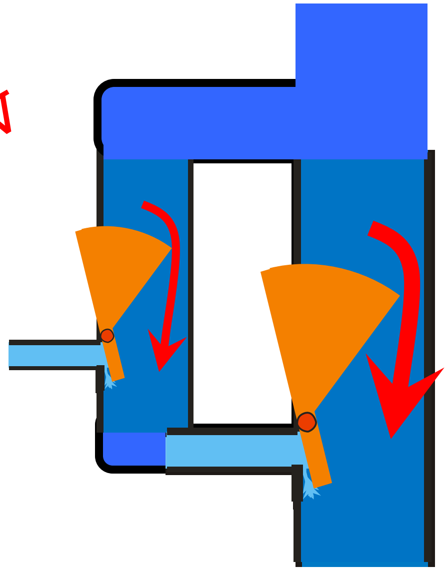
V_{BE} better if relative to same reference as input voltage (e.g. ground)

High gain outputs

Logic outputs typically drive <10mA
(though Atmega and ESP32 drive 20-40mA)

Darlington Pair (cascaded transistors)



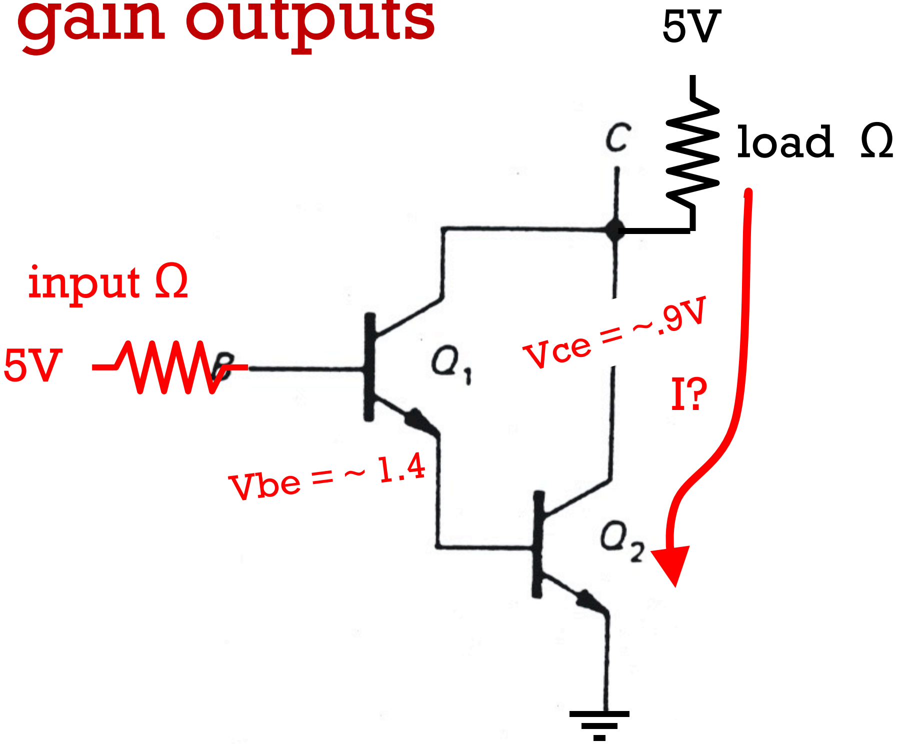


Typ. Gain in saturation >100

note: Vce may increase some with I_C

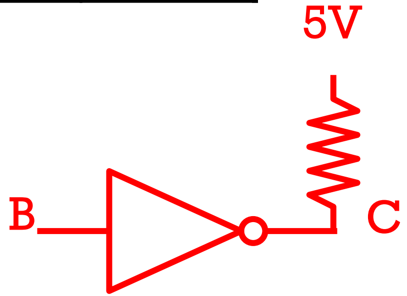
High gain outputs

The Darlington



Q6

V_B	V_C?
5V	
0V	



Think of it like an O.C inverter, except output doesn't go down to 0V

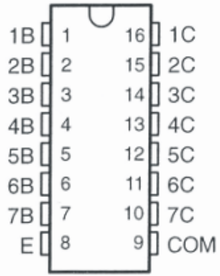
7 Darlingtons

SLRS027 – D2624, DECEMBER 1976 – REVISED APRIL 1993

HIGH-VOLTAGE HIGH-CURRENT DARLINGTON TRANSISTOR ARRAYS

- 500-mA Rated Collector Current (Single Output)
- High-Voltage Outputs . . . 50 V
- Output Clamp Diodes
- Inputs Compatible With Various Types of Logic
- Relay Driver Applications
- Designed to Be Interchangeable With Sprague ULN2001A Series

D OR N PACKAGE
(TOP VIEW)



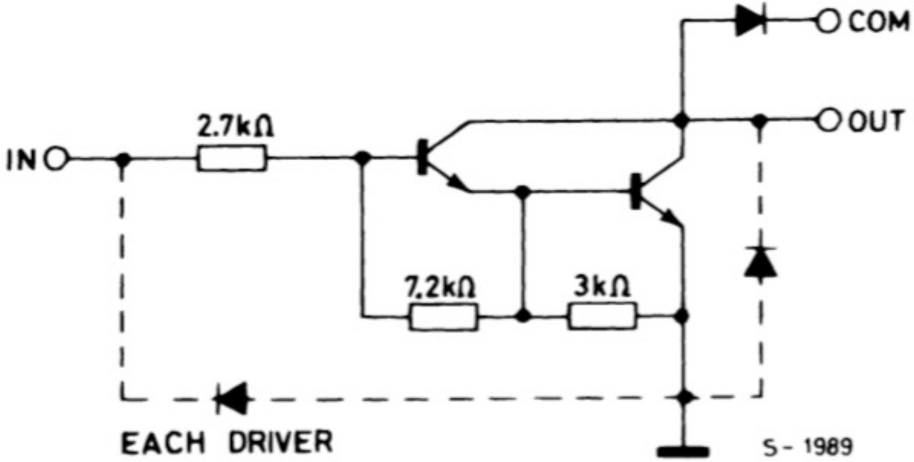
description

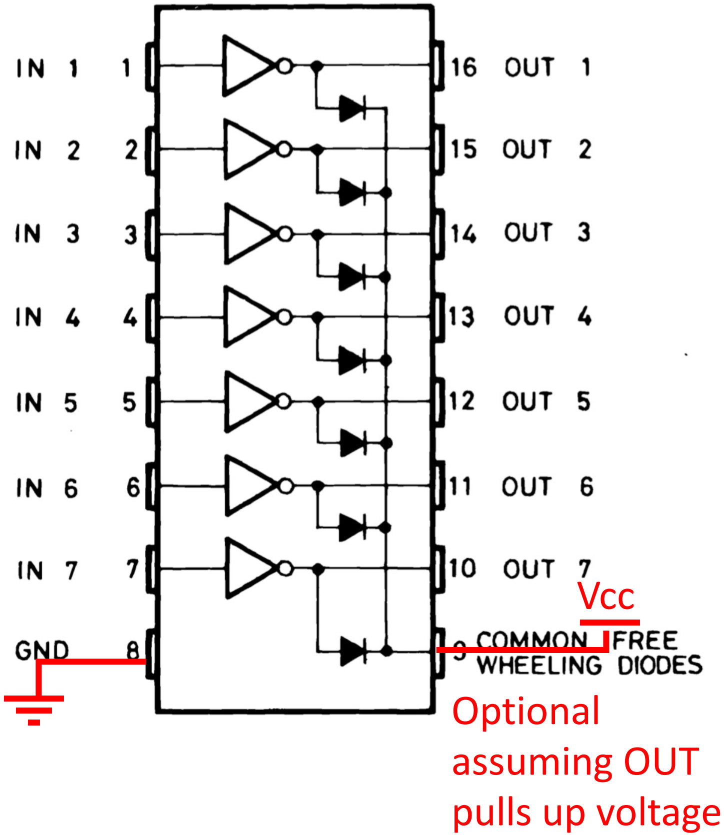
The ULN2001A, ULN2002A, ULN2003A, and ULN2004A are monolithic high-voltage, high-current Darlington transistor arrays. Each consists of seven npn Darlington pairs that feature high-voltage outputs with common-cathode clamp diodes for switching inductive loads. The collector-current rating of a single Darlington pair is 500 mA. The Darlington pairs may be paralleled for higher current capability. Applications include relay drivers, hammer drivers, lamp drivers, display drivers (LED and gas discharge), line drivers, and logic buffers. For 100-V (otherwise interchangeable) versions, see the SN75465 through SN75469.

The ULN2001A is a general-purpose array and can be used with TTL, P-MOS, CMOS, and other MOS technologies. The ULN2002A is specifically designed for use with 14- to 25-V P-MOS devices. Each input of this device has a zener diode and resistor in series to control the input current to a safe limit. The ULN2003A has a 2.7-kΩ series base resistor for each Darlington pair for operation directly with TTL or 5-V CMOS devices. The ULN2004A has a 10.5-kΩ series base resistor to allow its operation directly from CMOS or P-MOS devices that use supply voltages of 6 to 15 V. The required input current of the ULN2004A is below that of the ULN2003A, and the required voltage is less than that required by the ULN2002A.

ULN2003A (in ministore)

- We can choose Vcc (e.g., 5 or 12V)
- You can drive inputs with TTL (e.g., 5V)
- Open collector outputs (COM) is optional for protection – need pullup on output

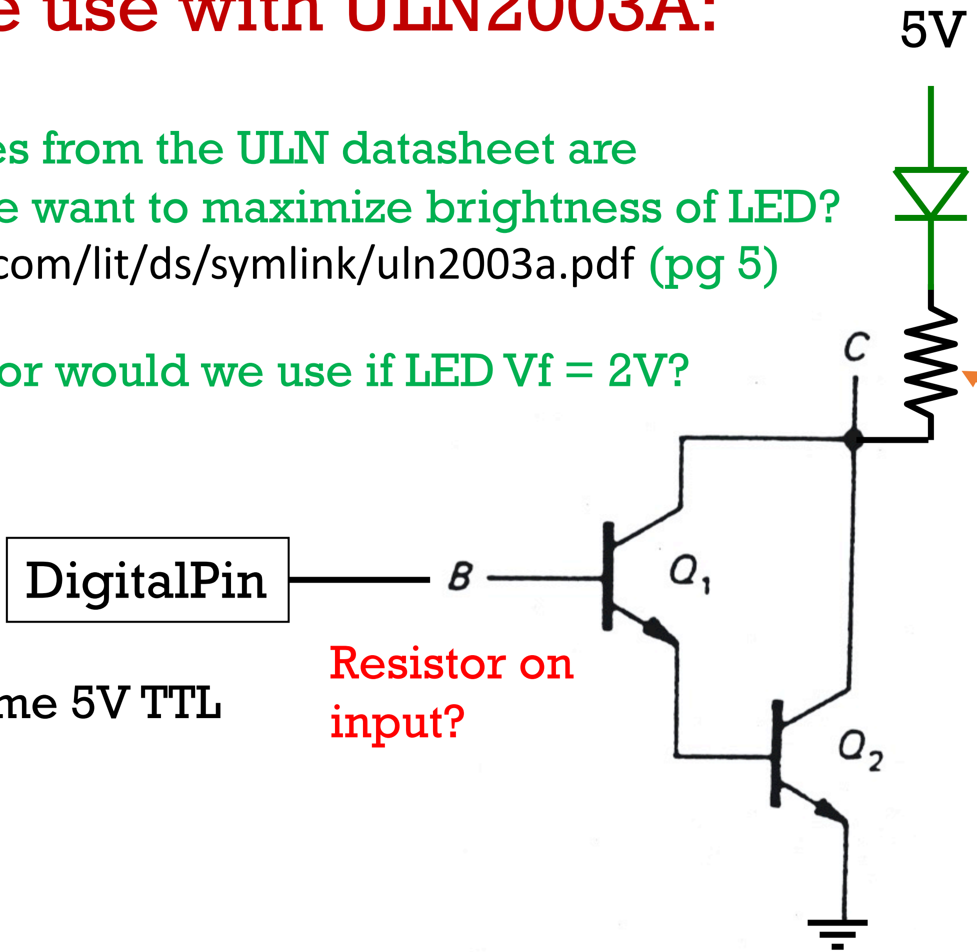




Sample use with ULN2003A:

Q7 What values from the ULN datasheet are important if we want to maximize brightness of LED?
https://www.ti.com/lit/ds/symlink/uln2003a.pdf (pg 5)

Q8 What resistor would we use if LED Vf = 2V?



Could be LED or Motor or Solenoid

We want to set the load resistor if we want 500mA through LED?

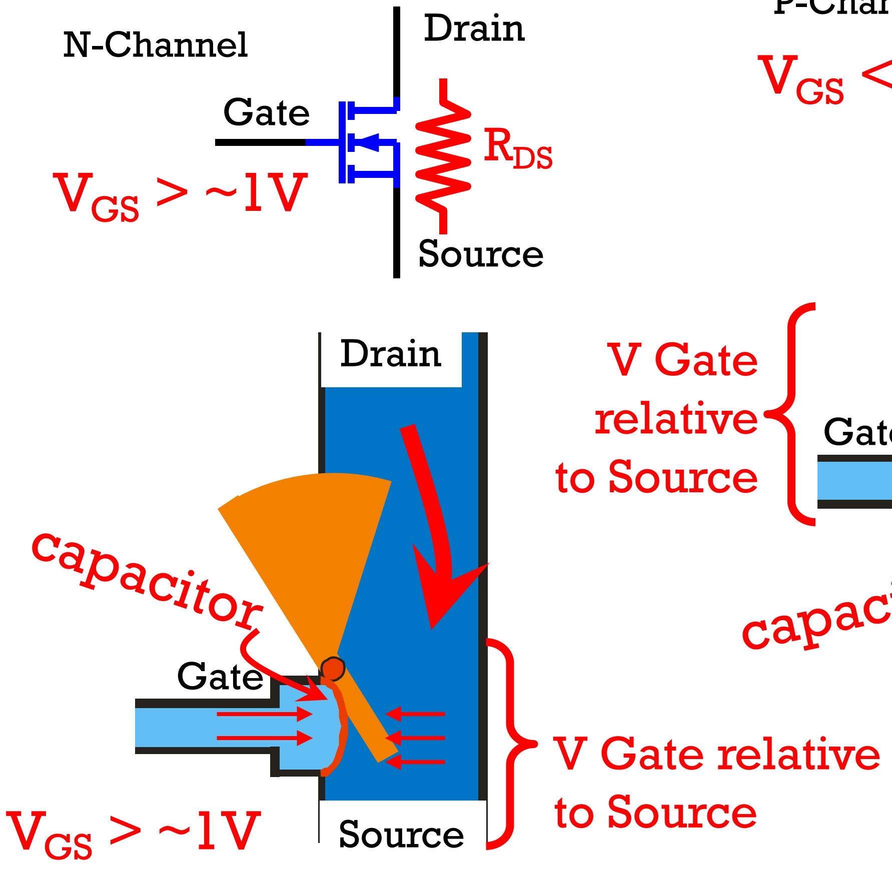
Resistor on input?

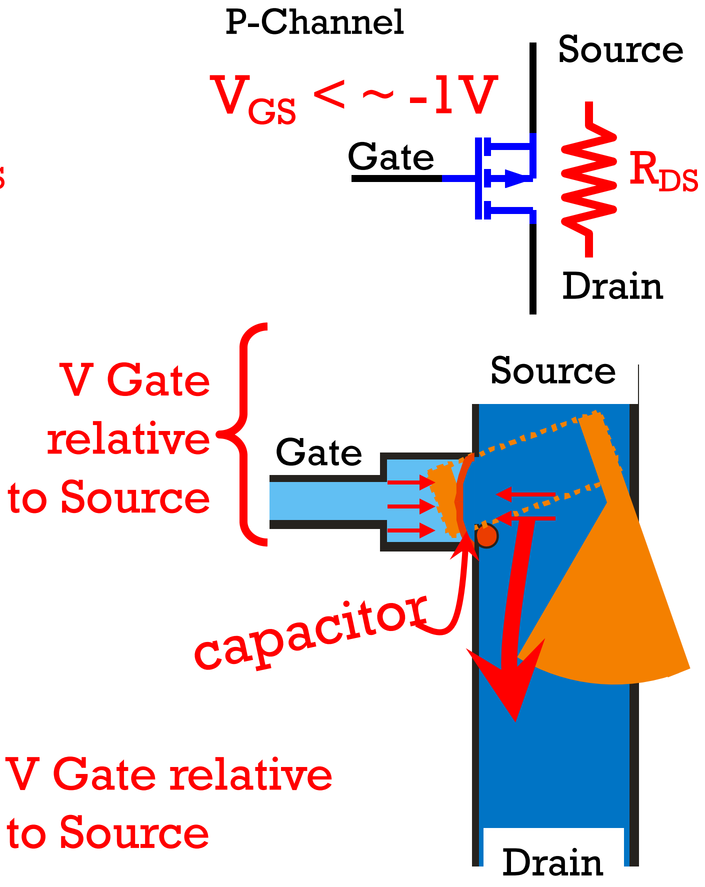
Assume 5V TTL

02

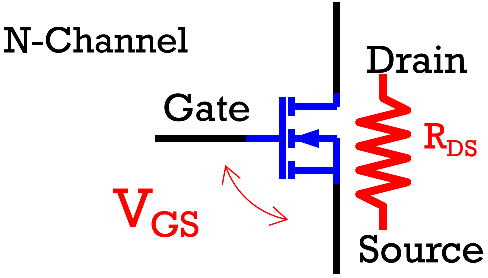
MOSFET and output drivers

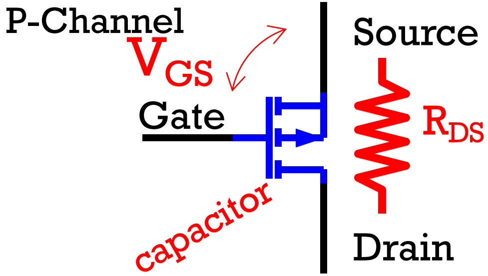
MOSFETs (Metal Oxide Semiconductor Field Effect Transistor) (enhancement mode)





MOSFETs (Metal Oxide Semiconductor Field Effect Transistor) used as Switches ON





How do we get them turned ON?

Ranges 1-8V

$|V_{GS}| >$ Threshold N-Channel: positive, P-Channel: negative

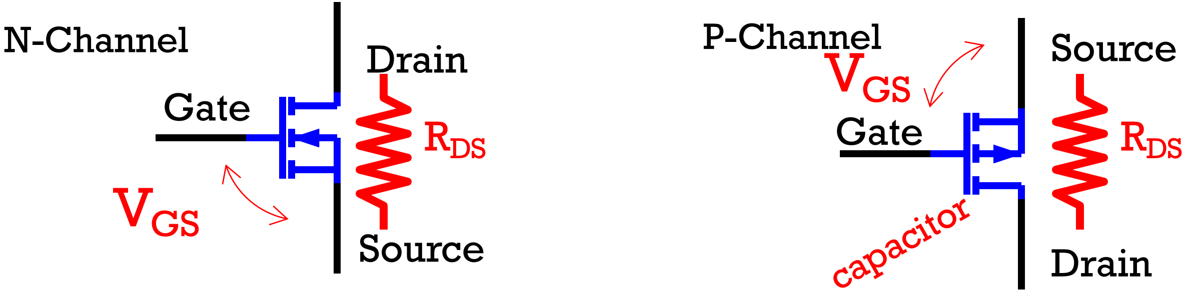
Note, very little current flows through the gate, but capacitance at gate must be charged (or drained) which takes time

How do we know if we have been successful?

R_{DS} will drop to a low value

Can be << 1 ohm

MOSFETs (Metal Oxide Semiconductor Field Effect Transistor) used as Switches OFF



How do we get them turned OFF?

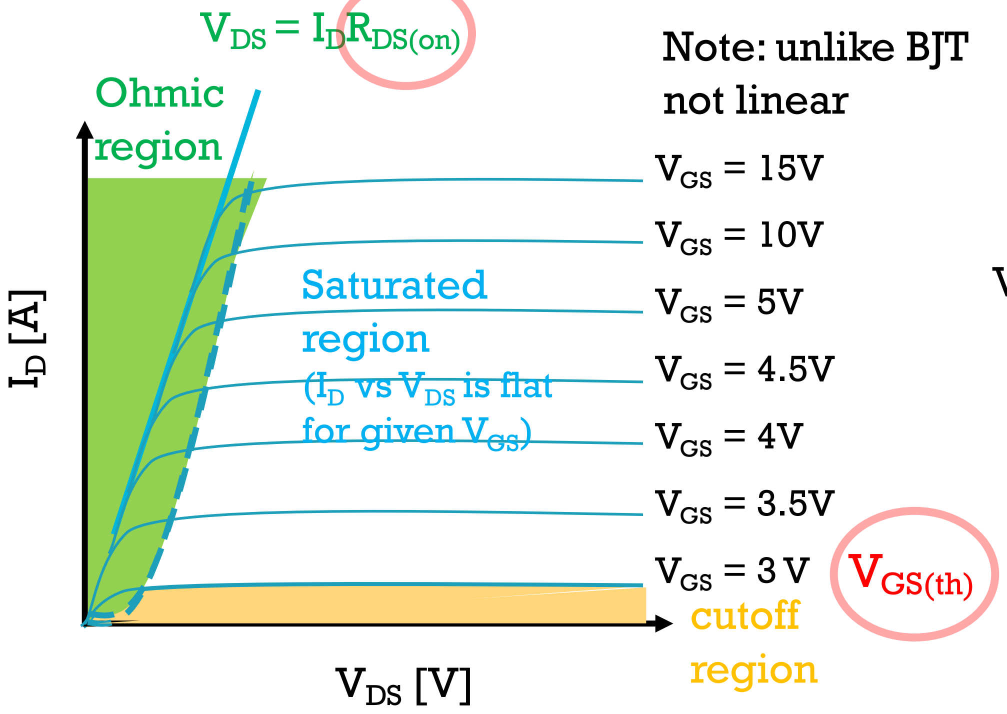
$|V_{GS}|$ < Threshold e.g. N-Channel: G = S, P-Channel G = S

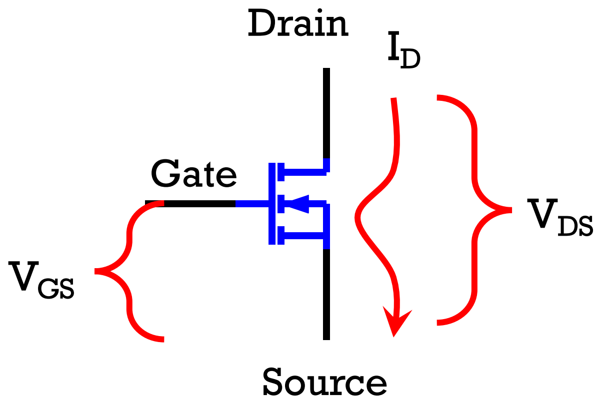
$R_{DS(off)}$ very high -> open circuit

How do we know if we have been successful?

R_{DS} will be like open circuit

N-Channel MOSFET I-V behavior





Depending on V_{DS}

MOSFET acts as a resistor

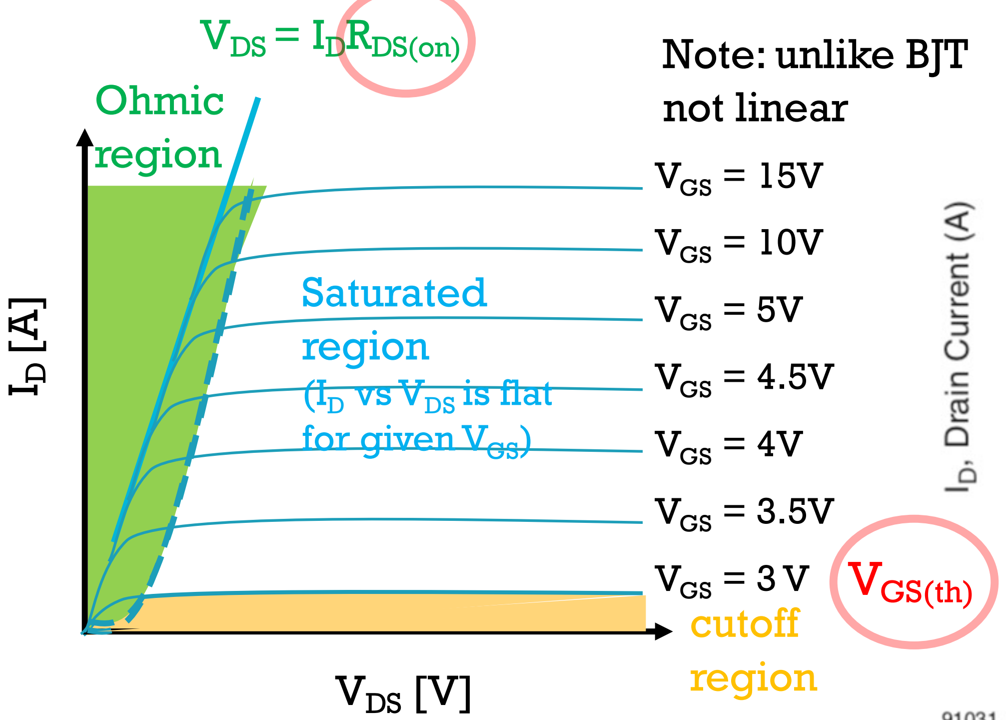
I_D depends on V_{DS}

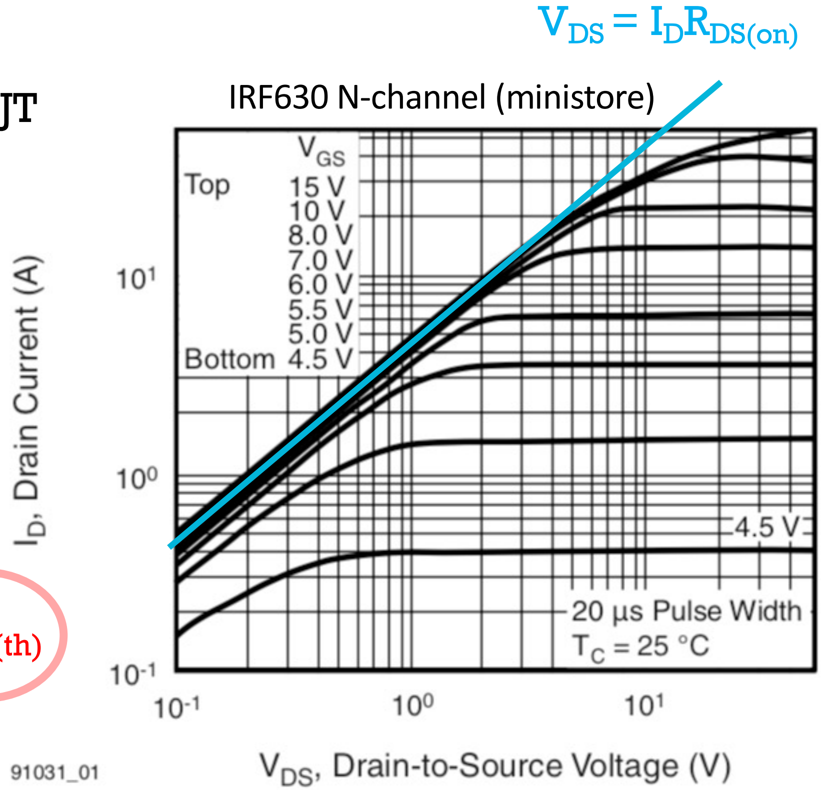
MOSFET acts as a switch

I_D depends on V at Gate

N-Channel MOSFET I-V behavior

Note: unlike BJT not linear

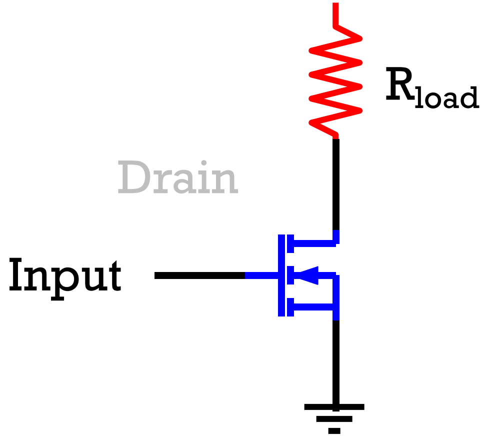


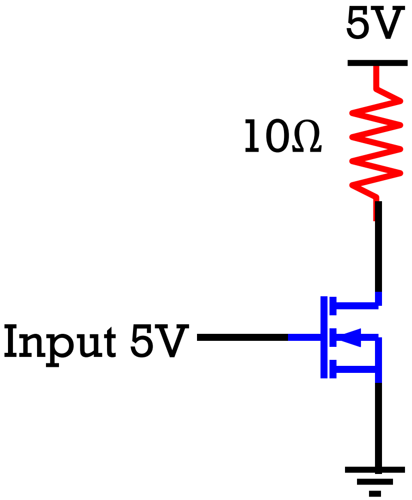


Note graph is Log/Log

Example MOSFET

- Open drain (simplest switching transistor configuration)



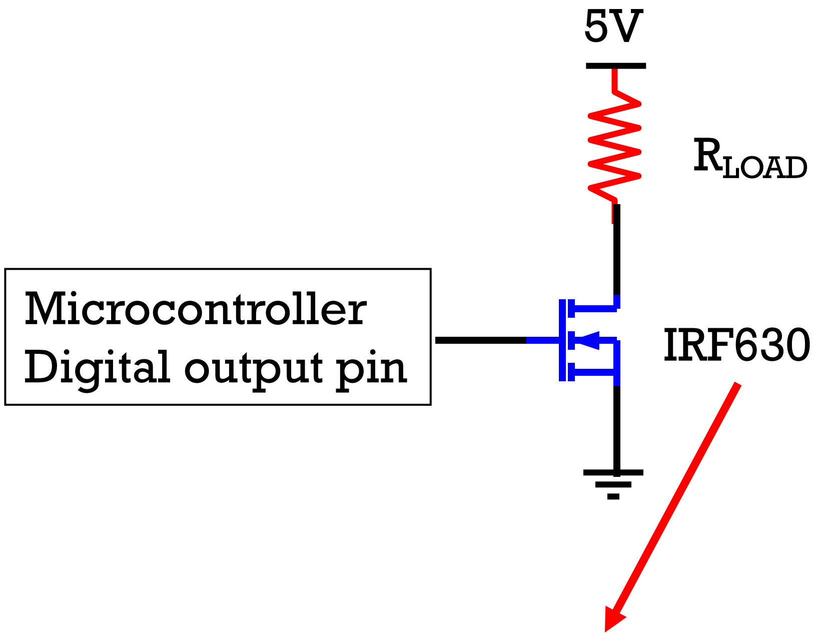


Q9: Why don't we need a resistor on the input as we did on BJT?

Interfacing with microcontrollers

Q10: (yes/no) Will this circuit work with a microcontroller that has

- A) 3.3V logic like the ESP32
- B) HCT logic like the Teensy
- C) TTL logic

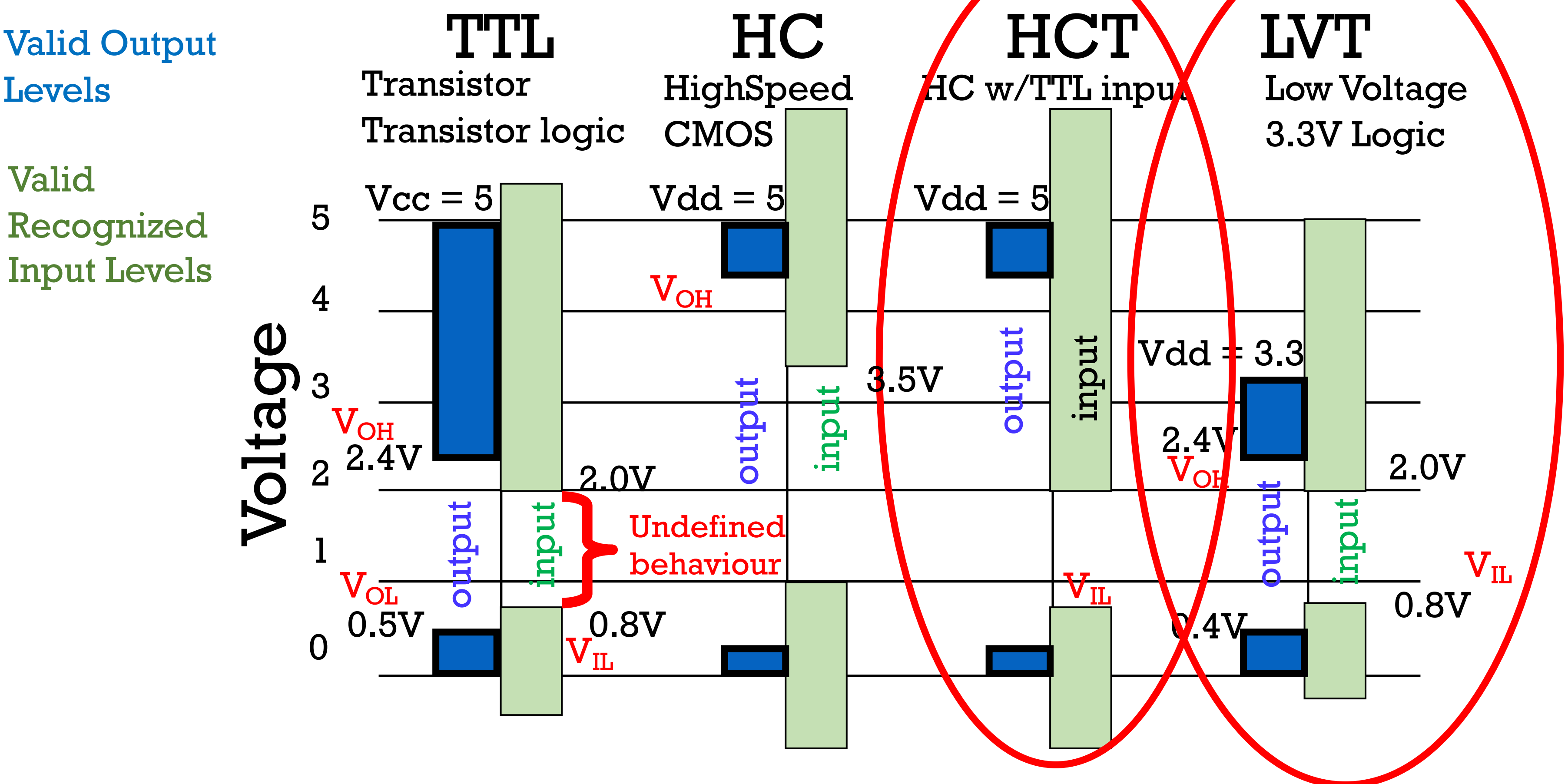


https://rocelec.widen.net/view/pdf/rfuyavpoxc/HRISD017-4-316.pdf
(pg 3 or 5)

From Lecture 4
Logic Levels

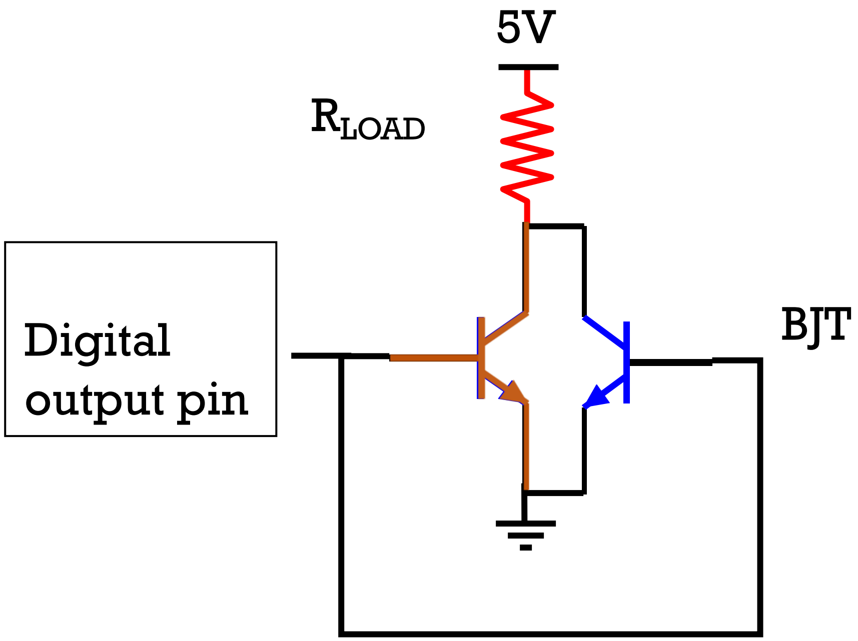
Teensy @ 5V is LVTTL close to this

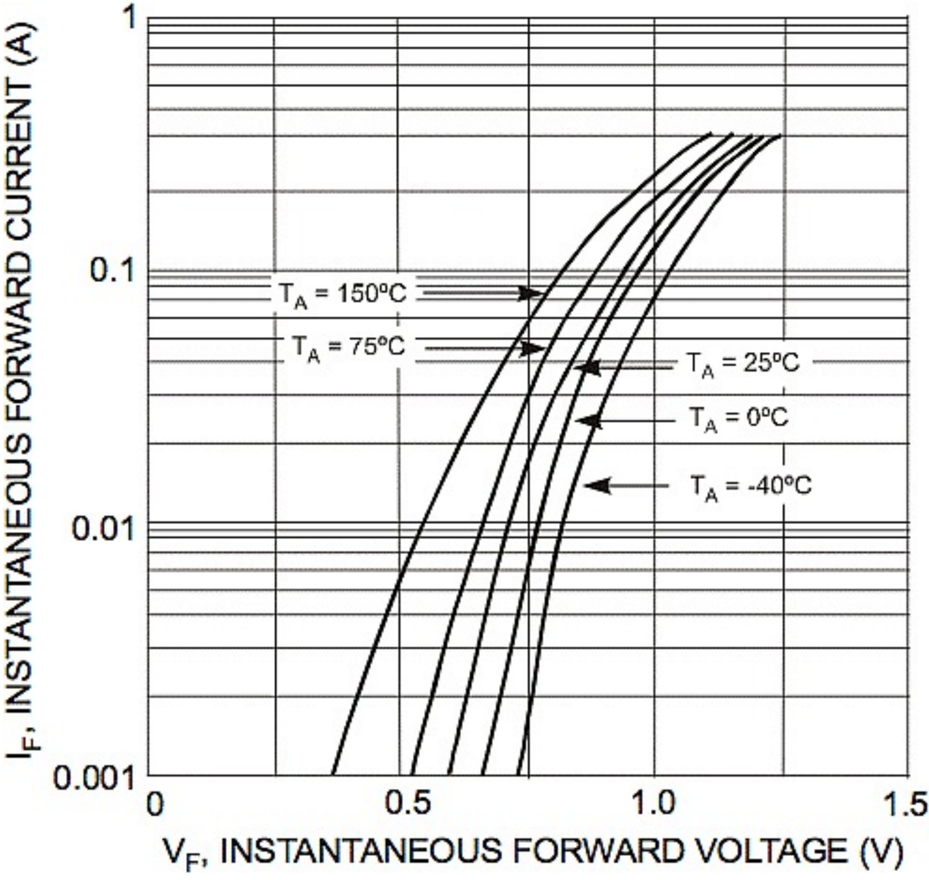
ESP32



Temperature Effects on Driving Currents

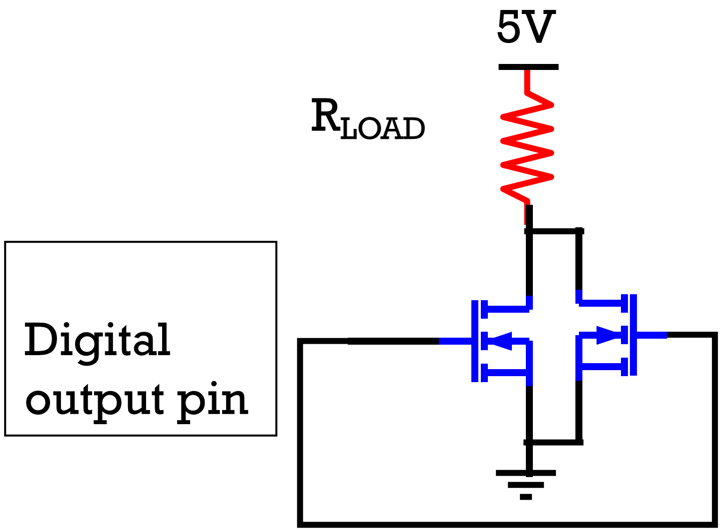
- Thermal runaway. Parallel silicon devices don't share equally.





Positive $R_{DS(on)}$ Temperature Coefficient

- As Temperature goes up, what happens to $R_{DS(on)}$?
- The main failure mode for drivers is getting too hot.



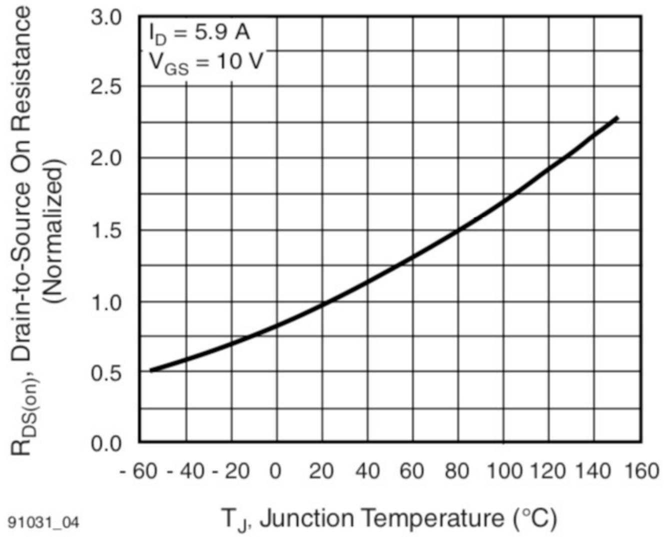


Fig. 4 - Normalized On-Resistance vs. Temperature

Caveat, not true for low V_{GS}, Depends on MOSFET

For IRF630, @ V_{GS}=4.5V, Temp coeff is negative!

For VGS= 8,10,15V, ID falls with higher temp, but VGS=4.5 and 5V ID goes UP!

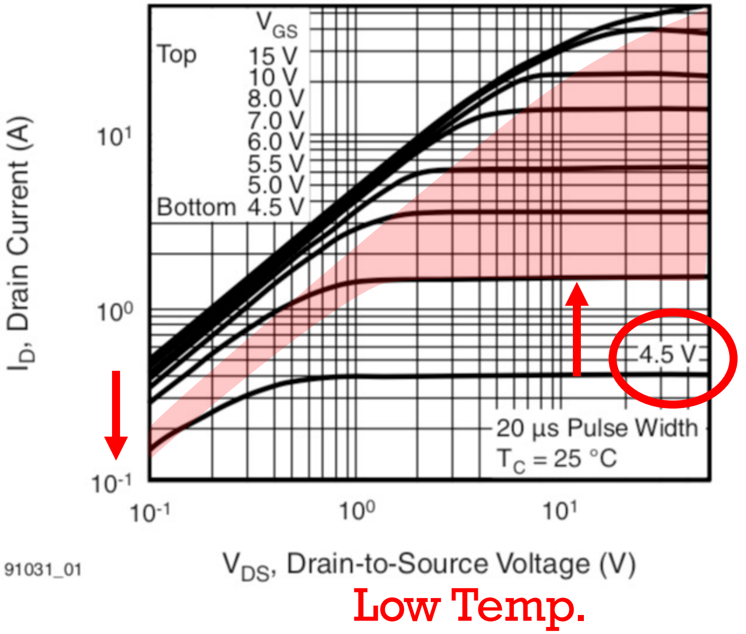


Fig. 1 - Typical Output Characteristics, T_C = 25 °C

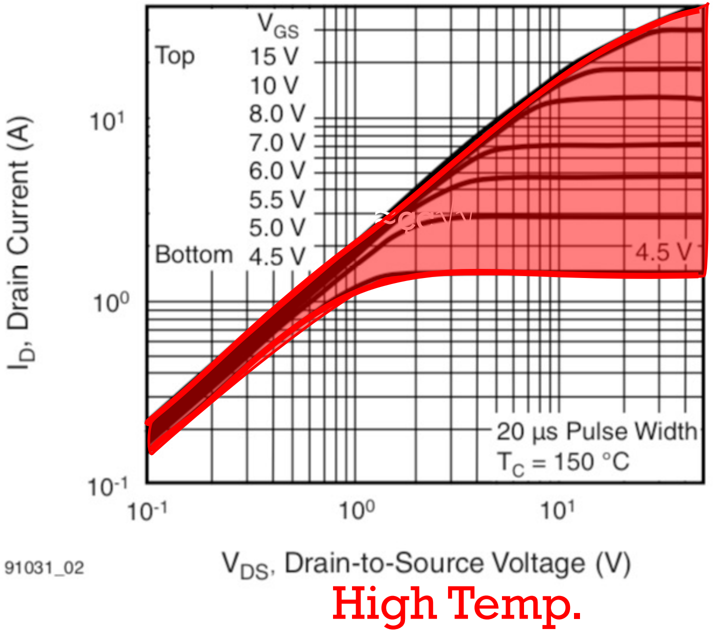
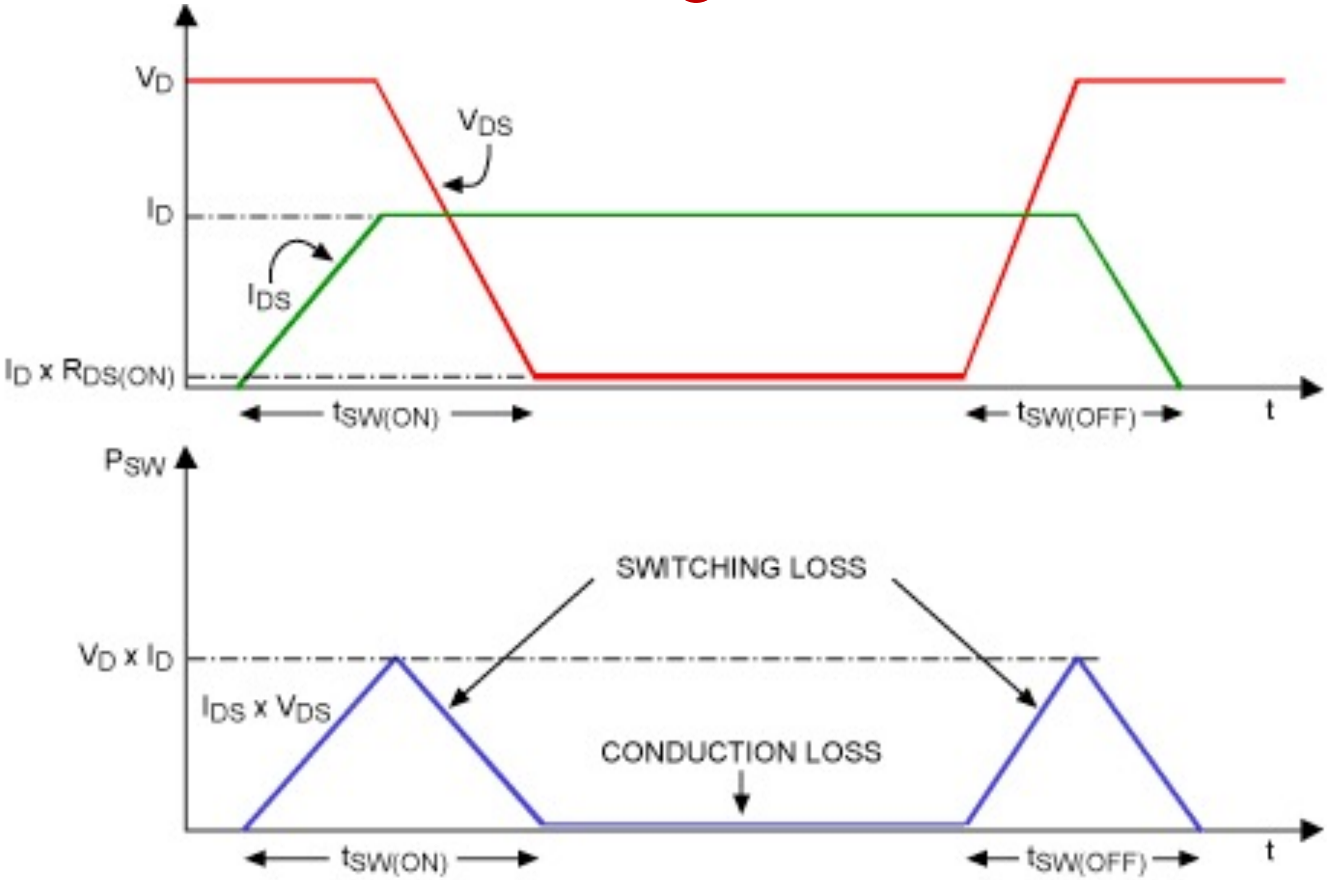


Fig. 2 -Typical Output Characteristics, T_C = 150 °C

Ministore MOSFETs

IRLB8721	25A	N-channel MOSFET
IRF9520	6.8A	P-Channel MOSFET
FQP8P10	4A	P-Channel MOSFET
2N7000	75mA	N-Channel MOSFET
IRF630	5.9A	N-Channel MOSFET

Power lost to heat through MOSFET



https://www.maximintegrated.com/en/app-notes/index.mvp/id/4266

Choosing MOSFET drivers (for this class)

Output Specifications

- $R_{DS(on)}$ sets current capability (assuming you can heatsink device)
  - Can also look at continuous drain current

Driving Specifications

- $V_{GS(th)}$ Voltage required to turn on.
  - Older power MOSFETS require voltages larger than micro's normally supply $> 5V$ (not compatible)
- Q_G Total Gate Charge, don't want this to be too large otherwise may run into heating issues when using PWM
  - e.g., <20nC may be ok for this class (use slower PWM freq)

03

MOSFET vs BJT

BJT vs MOSFET

Driving

- BJT's are driven by current in base
- BJT's require Vbe ~0.7V to start conducting

- MOSFETS require $V_{GS(th)}$ to start (varies: 1-8V)
- MOSFETS are driven by voltage, Vgs

Outputs

- BJT limited by Vce

- MOSFETS limited by Rds_on
- MOSFETS can combine in parallel

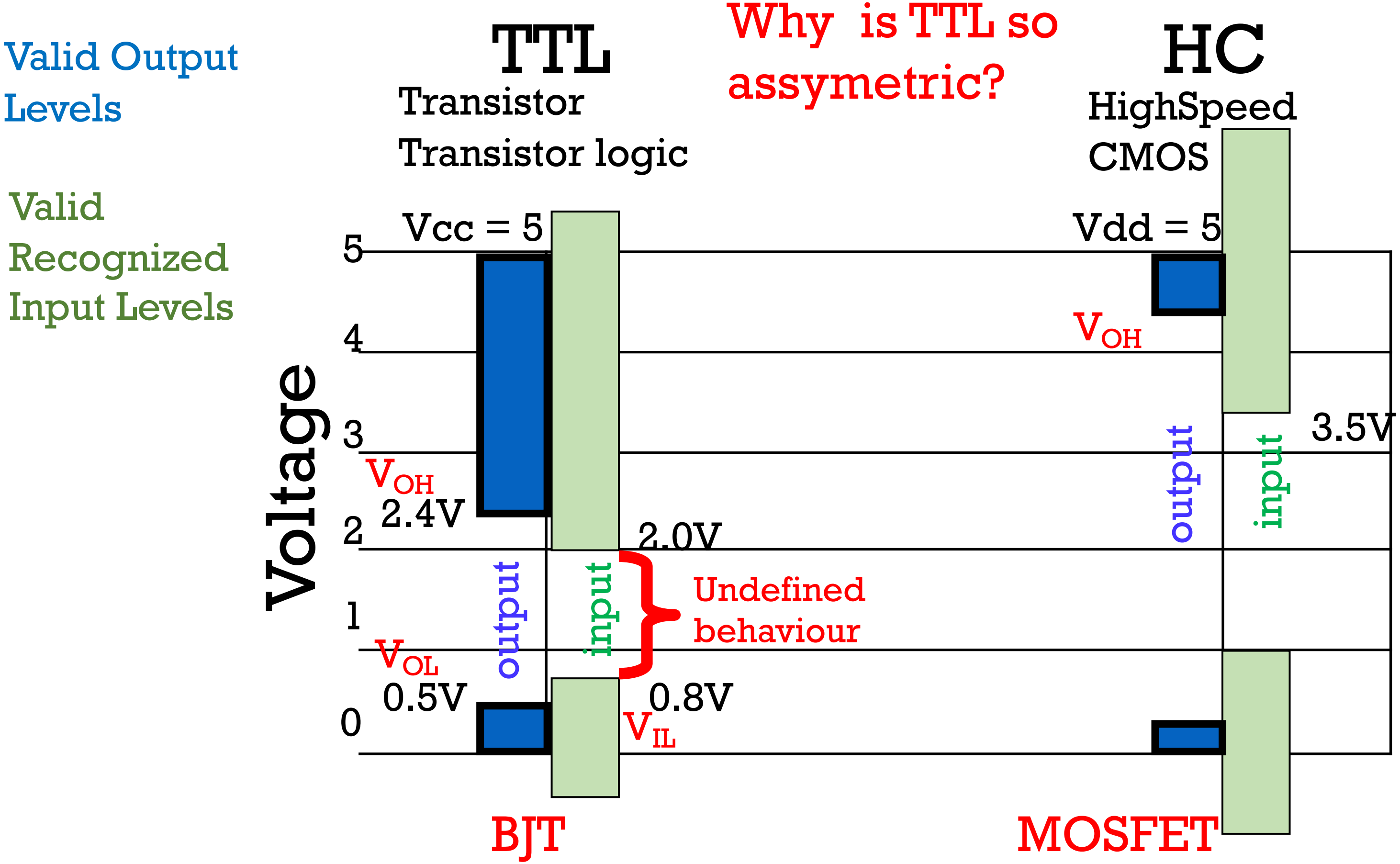
Costs

- BJT's are cheaper for switching small currents e.g., I_C ~200mA

- MOSFETS are smaller and cheaper more efficient for switching larger currents e.g., I_D>~5A

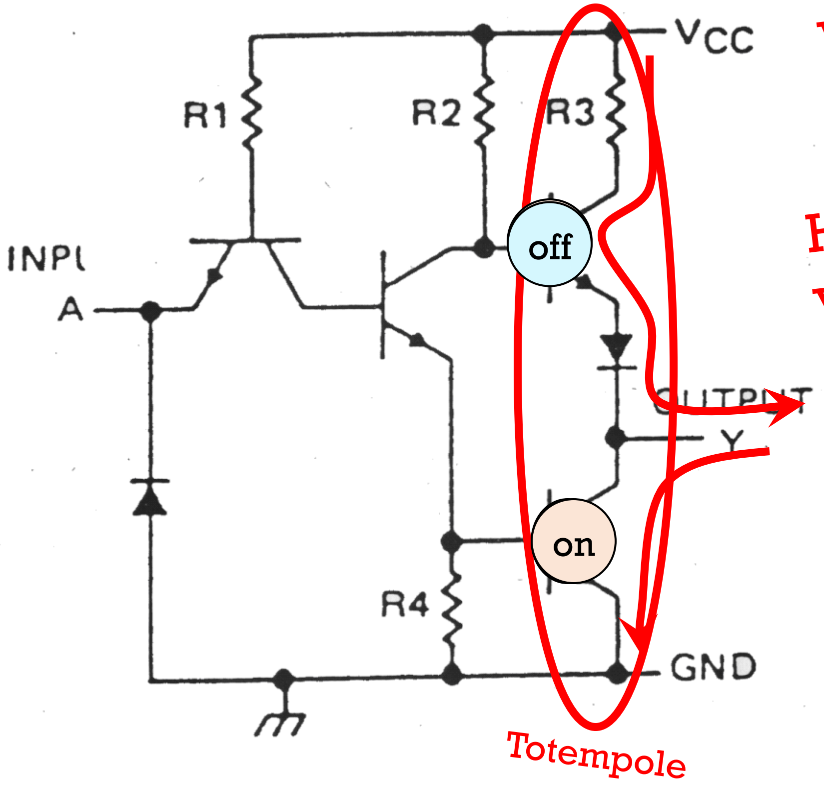
From Lecture 4 Logic Levels

Why is TTL so assymetric?



Digital Logic: Bipolar TTL output

TTL
Inverter



What is typical voltage at Y when ON?

High voltage is

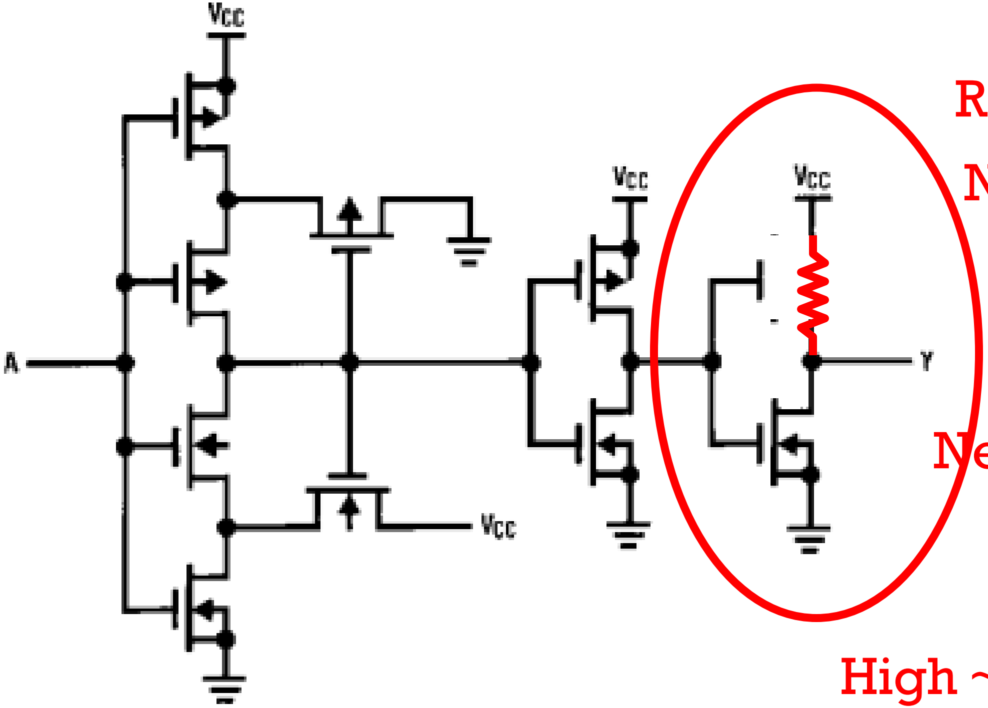
$V_{OH} = V_{CC} - V_F - V_{CE}(sat) - V_{R3}$

What is typical voltage at Y when OFF?

$V_{OL} = V_{CE}(sat)$

Digital Logic: CMOS totem pole

CMOS
Inverter



Resistor = R_{DSON}

No diodes

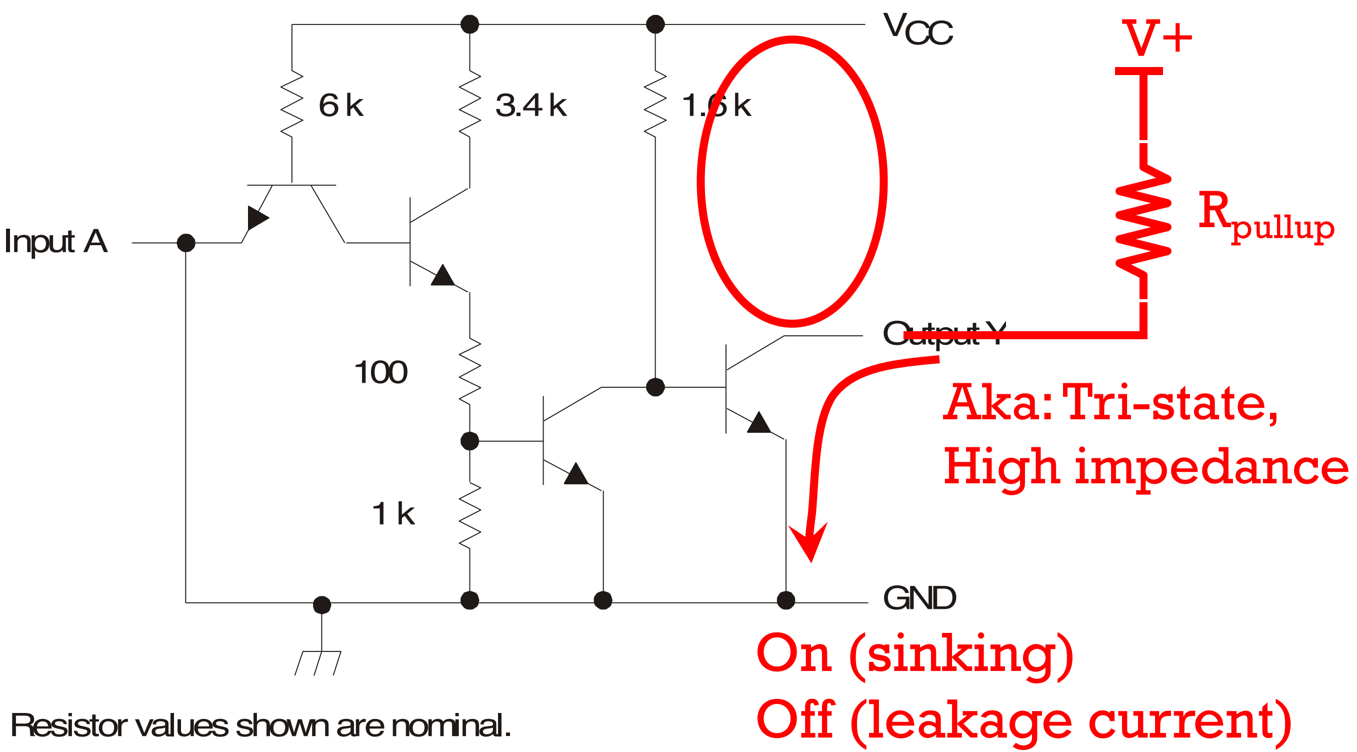
Nearly rail-to-rail

High ~ >4.9V

Low ~<0.05V

Digital Logic: Open Collector

(Open drain for CMOS)



Summary

- BJT are current controlled (ULN2003 is Darlington pair of BJT's)
- MOSFETs are voltage controlled
- MOSFETs are the trend for large current control
- Be sure to understand V_{GS} characterstics of MOSFETs for your application

Answer in Chat

Answer how you feel about each topic below with:

1. I don't understand this topic at all
2. I don't know now, but know what to do to get by
3. I understand some, but expect to get the rest later
4. I understand completely already

A. Transistor function (BJT)

B. Transistor function(MOSFET)

C. Using Transistors

04 (if time)

Extra stuff

Aside – on coding (all valid);

Which is better?

A:

```
int steps=1, bumpedflag=FALSE;
```

or

B:

```
int steps=1, bumpedflag;
```

or

C:

```
int steps=1;
bool bumpedflag;
```

Gobal variables are all initialized to 0 (not true for local variables). But explicitly assigning to 0 doesn't hurt and indicates intention

To use `bool` you must `#include <stdbool.h>`

Aside – on coding;

Which is better?

```
TCCR1B = (1<<CS10) | (1<<CS12);
```

Slightly faster and shorter
(smart compiler will join into one command)

vs

```
set(TCCRIB,CS10);
set(TCCRIB,CS12);
```

Is a little clearer,
(won't get confused with | or &)

Aside – on coding 2;

From /usr/local/CrossPack-AVR/avr/include/**avr/sfr_defs.h** (on mac)

```
#define bit_is_set(sfr, bit) (_SFR_BYTE(sfr) & _BV(bit))
#define _BV(bit) (1 << (bit))
#define _SFR_BYTE(sfr) _MMIO_BYTE(_SFR_ADDR(sfr))
#define _MMIO_BYTE(mem_addr) (*(volatile uint8_t *)(mem_addr))
->
bit_is_set(sfr, bit)    ((*(volatile uint8_t *)(sfr)) & (1 << (bit)))
[mostly, skipping the part about casting the address pointer]

#define bit_is_set(sfr, bit) (_SFR_BYTE(sfr) & _BV(bit))
#define bit_is_clear(sfr, bit) (!(_SFR_BYTE(sfr) & _BV(bit)))
#define loop_until_bit_is_set(sfr, bit) do { } while (bit_is_clear(sfr, bit))
#define loop_until_bit_is_clear(sfr, bit) do { } while (bit_is_set(sfr, bit))
```

For C Casting tutorial see https://www.tutorialspoint.com/cprogramming/c_type_casting.htm