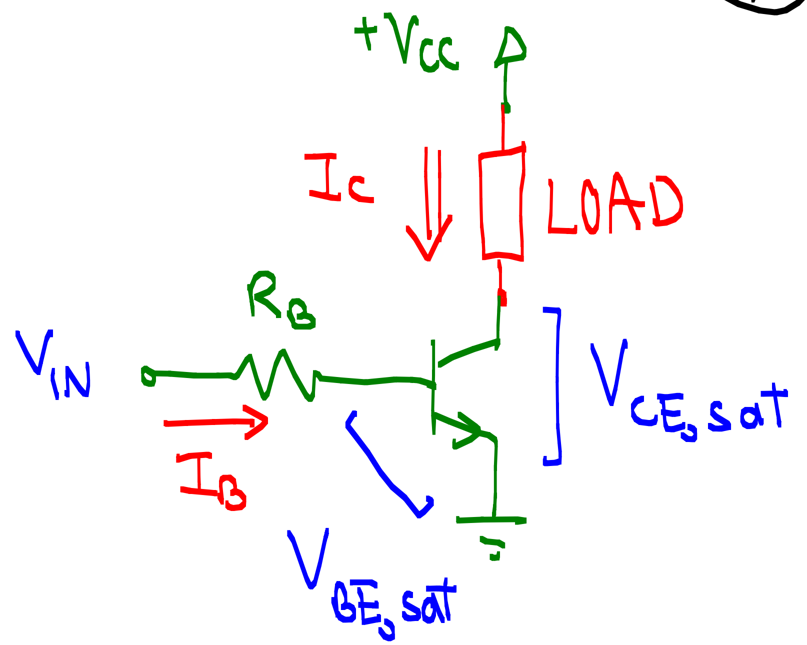
Lecture 9: MOSFET Switches

0. Review
1. MOSFET Intro
2. MOSFET Switch Analysis
3. MOSFET Switch Design

- PreLab 4 due Thu
- HW4 due Fri (Oct 25)
- Exam 1 re-do (counts as HW) due next Tue (Oct 29)
- Lab3 report due Nov 4 (Mon)

Textbook Reading: 12-4 Enhancement Mode MOSFET
5 Ohmic region
8 Power FETs
9 High-side MOSFET load switches

0. Review



Step 1 Know your load: $\underbrace{\text{Current}}_{\star}$, voltage, etc

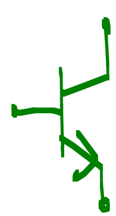
Step 2 Wisely choose the transistor

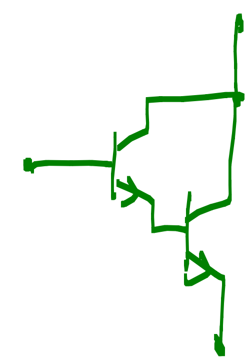
↳ Check max I_c, max V_{CE}, T_J

Step 3 Properly saturate the transistor

(A) $V_{CE} = V_{CE,sat}$

(B) $\underbrace{I_B \approx \dfrac{I_c}{10}}_{\text{single BJT}}$ or $\underbrace{I_B \approx \dfrac{I_c}{250}}_{\text{Darlington}}$





1. MOSFET Intro

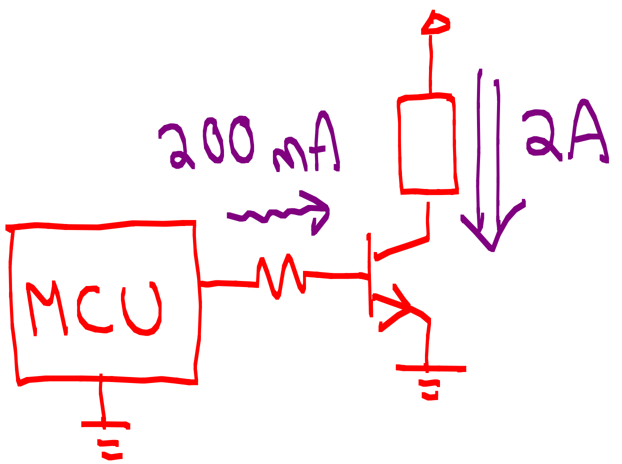
- BJT switches are very useful, but some issues to consider:

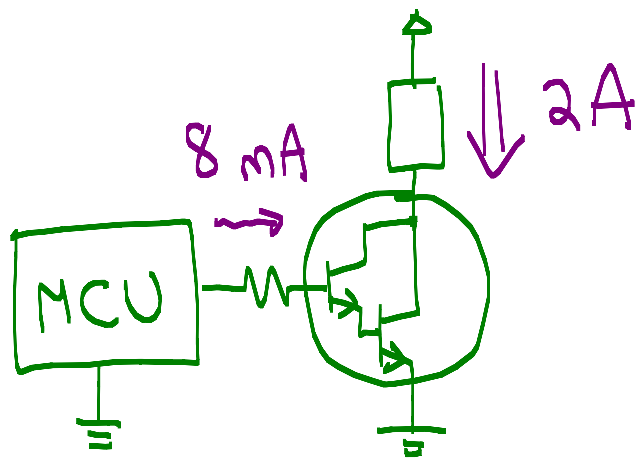
① Base Current

When I_c is large ($>1A$)

$\Rightarrow I_B \sim \frac{1}{10} I_c > 100\,mA$

Arduino will burn out! ☹

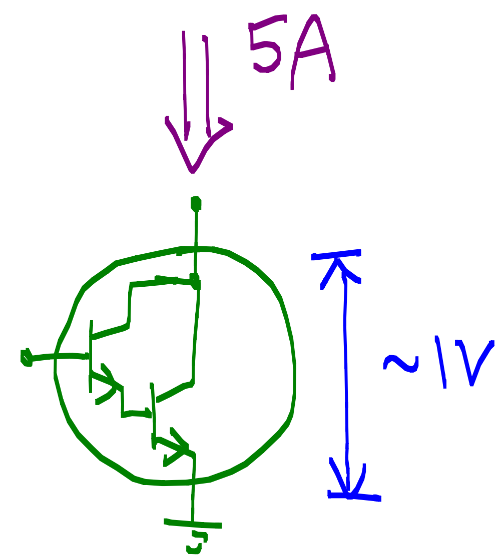




☆ Darlington is good choice for $I_c \sim$ several amps

② Power Dissipation

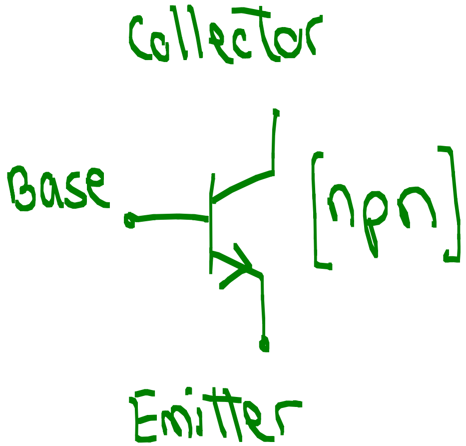
$$P = I_B V_{BE} + I_c \underbrace{V_{CE}}_{\text{Can be } \sim 1V}$$

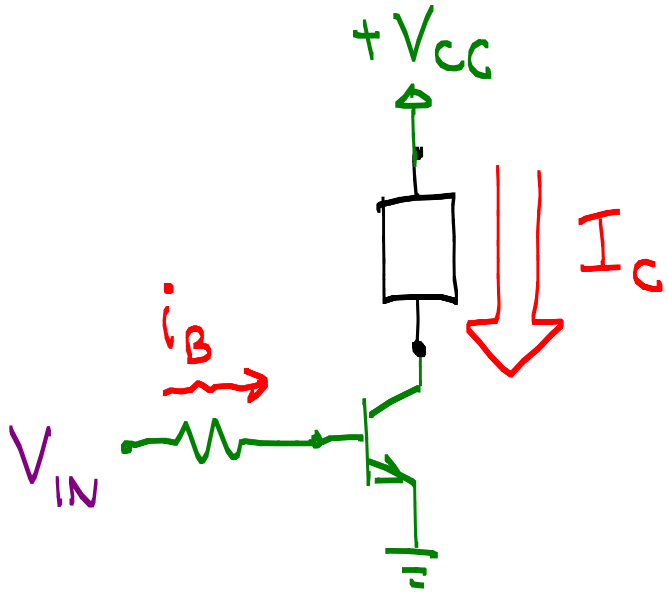


$P \sim \underline{\underline{5W}}$

BJT gets HOT!

BJT: Bipolar Junction Transistor





- $\boxed{\text{Control}}$

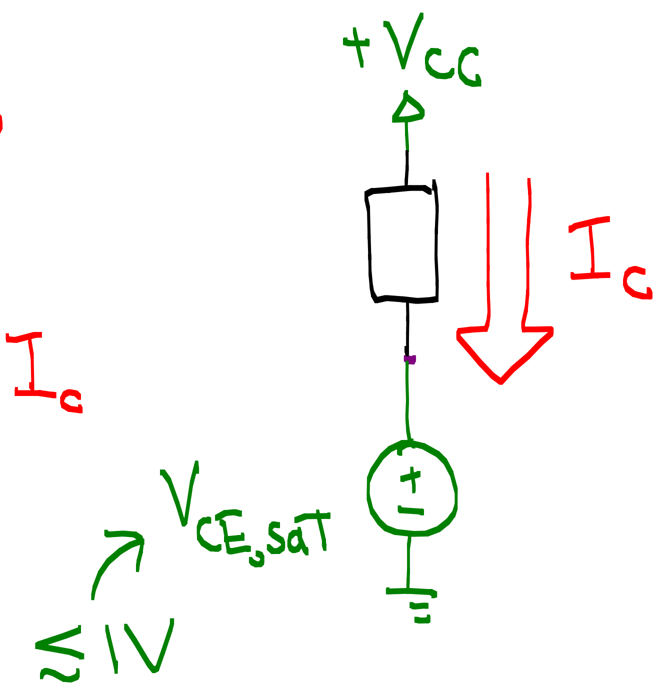
  Base current i_B

- $\boxed{\text{Load}}$

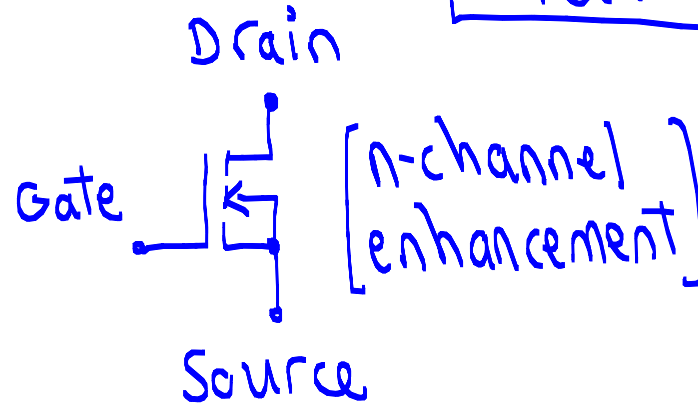
  Collector current I_C

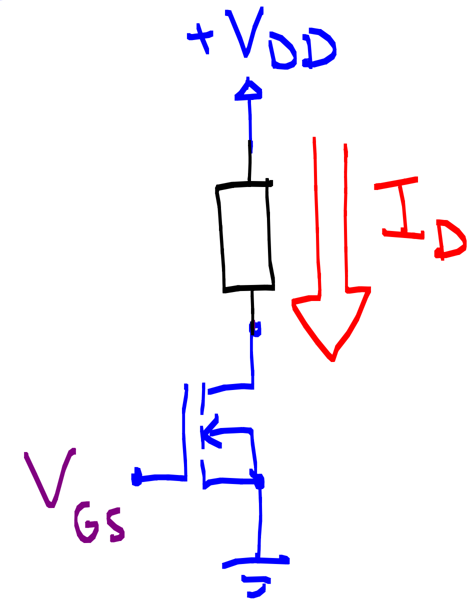
- $\boxed{\text{Mode}}$

  Saturation



MOSFET: Metal Oxide Semiconductor Field Effect Transistor





ZERO DC gate current!

- $\boxed{\text{Control}}$

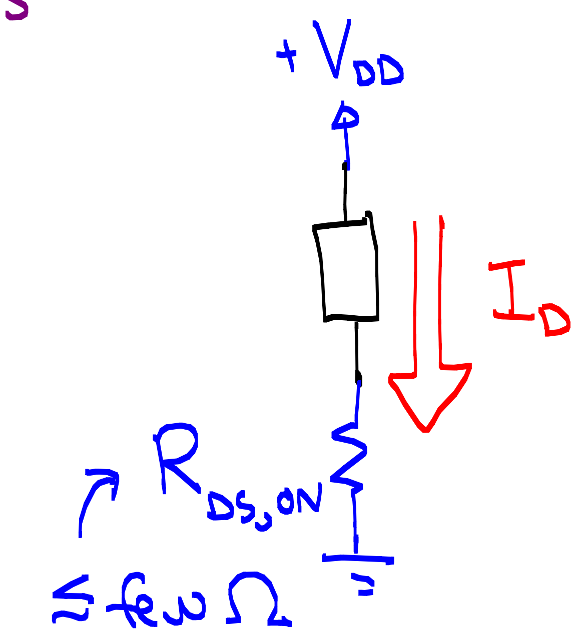
  Gate Source voltage V_{GS}

- $\boxed{\text{Load}}$

  Drain current I_D

- $\boxed{\text{Mode}}$

  Ohmic (linear) region

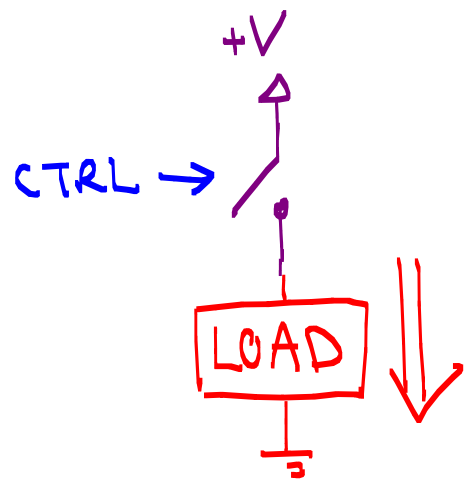


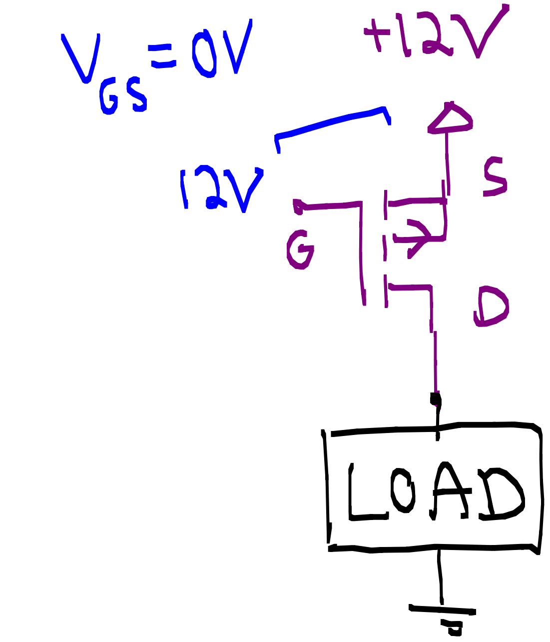
Low-side vs. High-side Switch

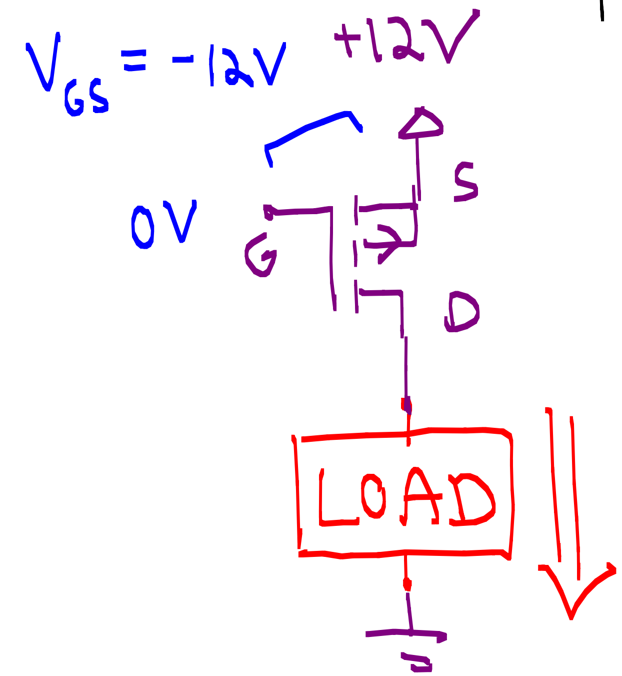
High-side (p-ch)

ON when

V_{GS} is negative



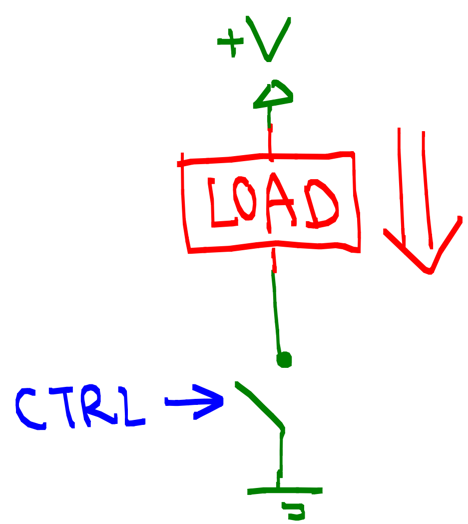


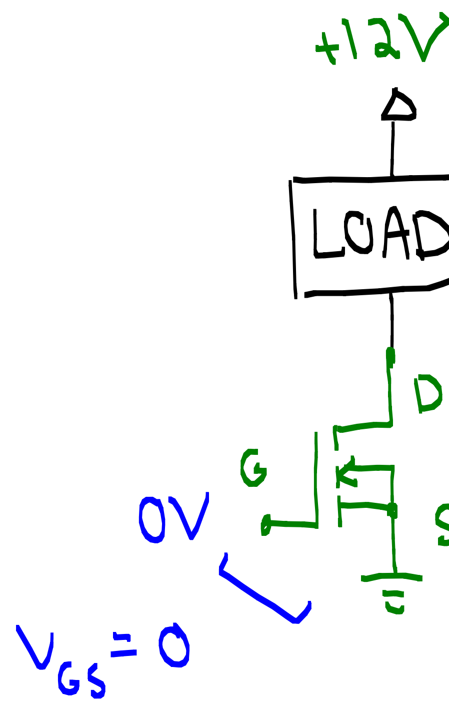


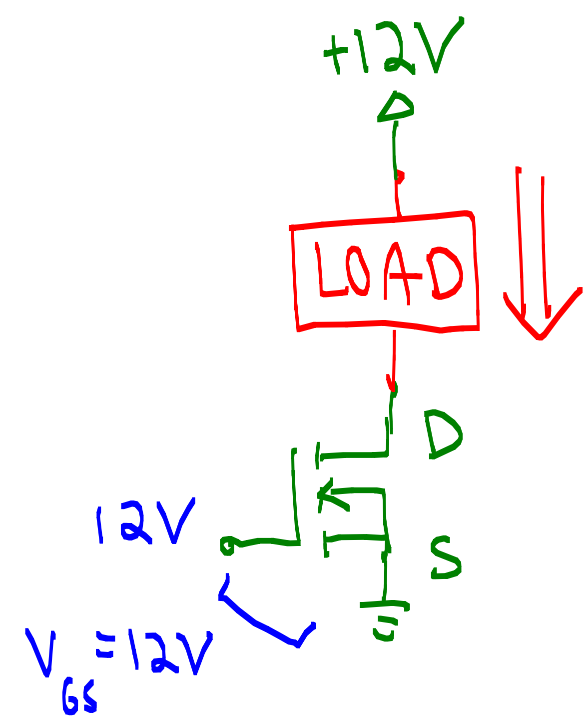
Low-side (n-ch)

ON when

V_{GS} is positive







• MOSFET Properties: 2 major ones

① V_{GS}: Gate-source voltage

☆ Threshold: $V_{GS} \gg V_{GS,TH}$ (ON)

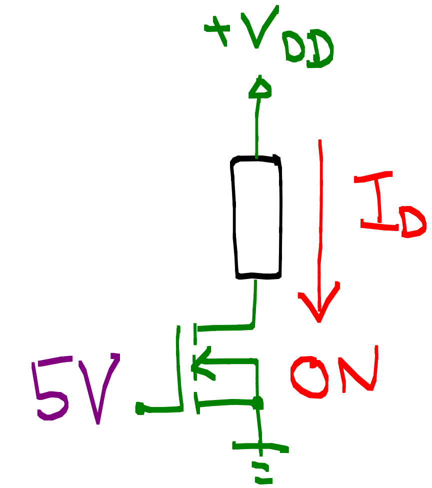
$V_{GS} \approx V_{GS,TH}$ (Barely on)

$V_{GS} < V_{GS,TH}$ (OFF)

Small signal MOSFET

e.g. 2N7000

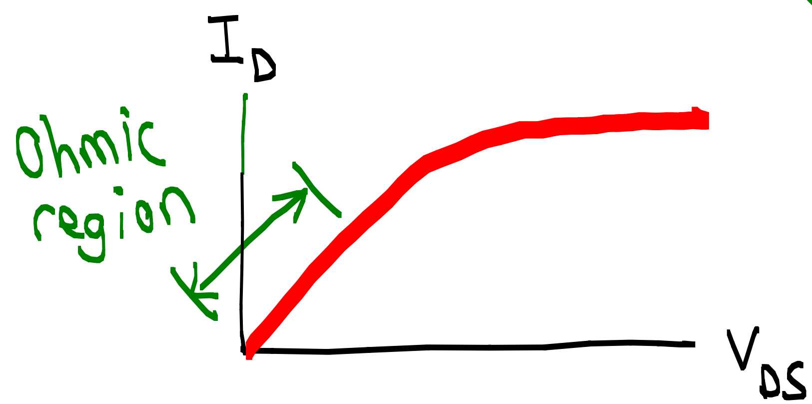
$V_{GS,TH} \sim 2V$



② $R_{DS,ON}$: Drain-Source on-resistance

→ Requires operation in ohmic region

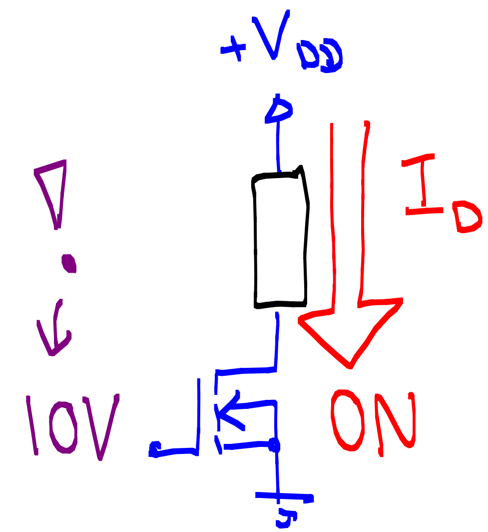
(I_D cannot be too large!)



Power MOSFET

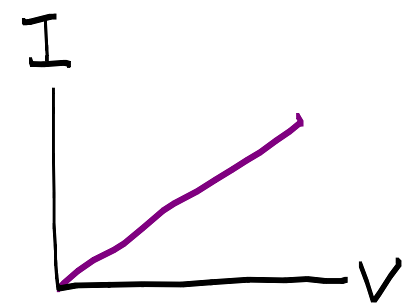
e.g. IRF510

$V_{GS,TH} \sim 5V$



Resistor

$I = \frac{1}{R} V$



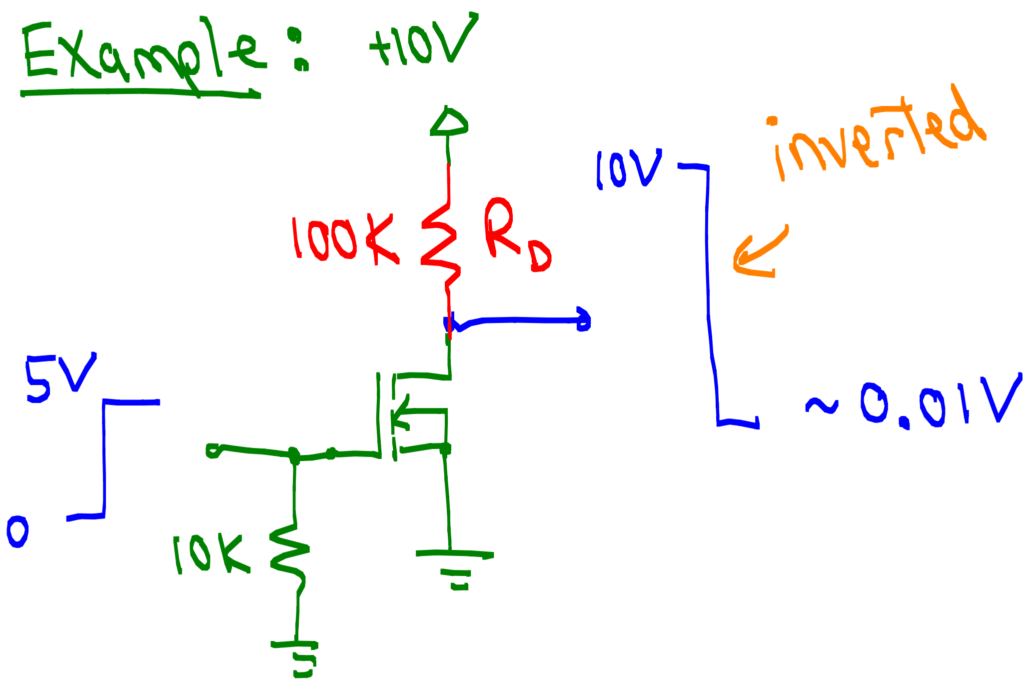
Q: How to convert 0-5V logic to higher voltage (e.g. 10V)?

A: Make a <u>logic level shifter</u> using...

$$V_{GS} = \begin{cases} 0 & \text{(OFF)} \\ -10V & \text{(ON)} \end{cases}$$

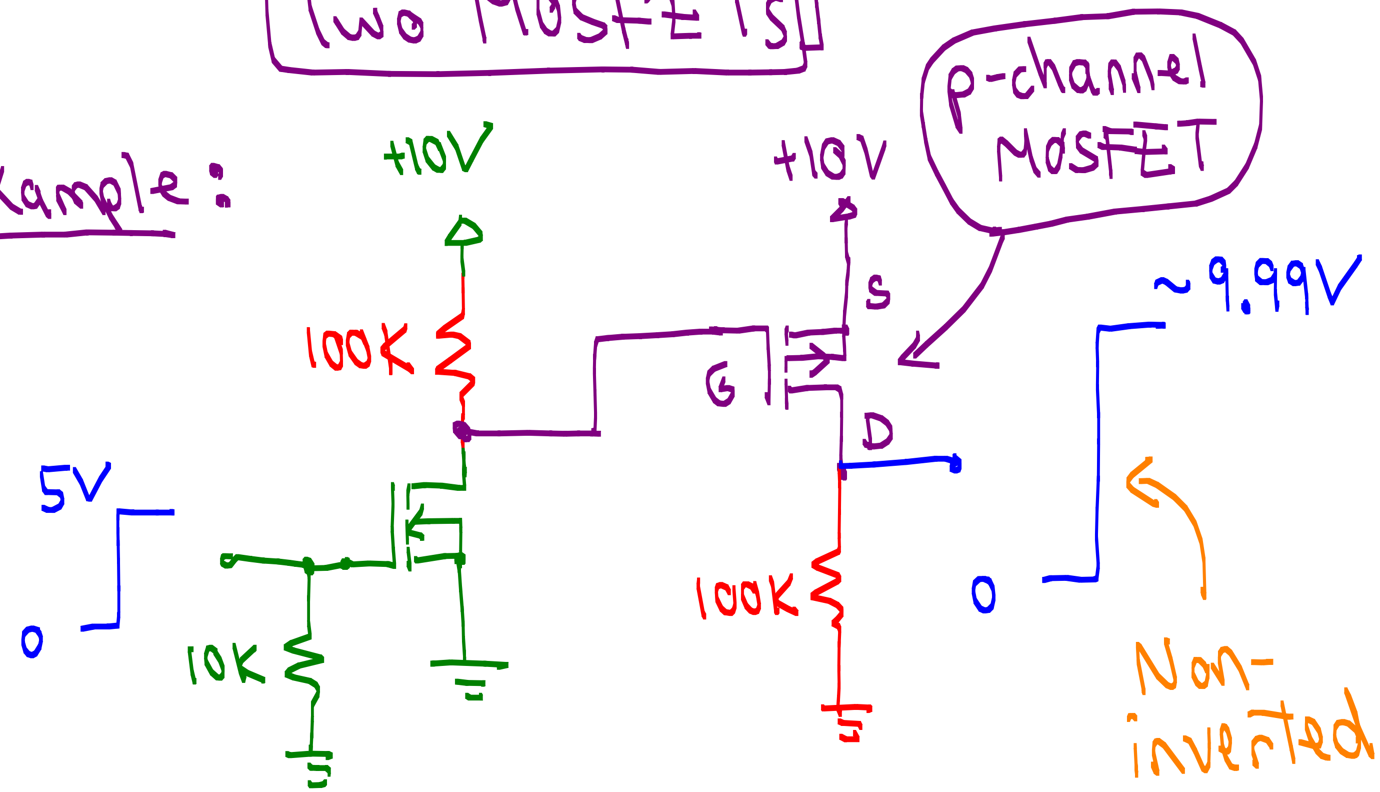
One MOSFET

Example:



Two MOSFETs

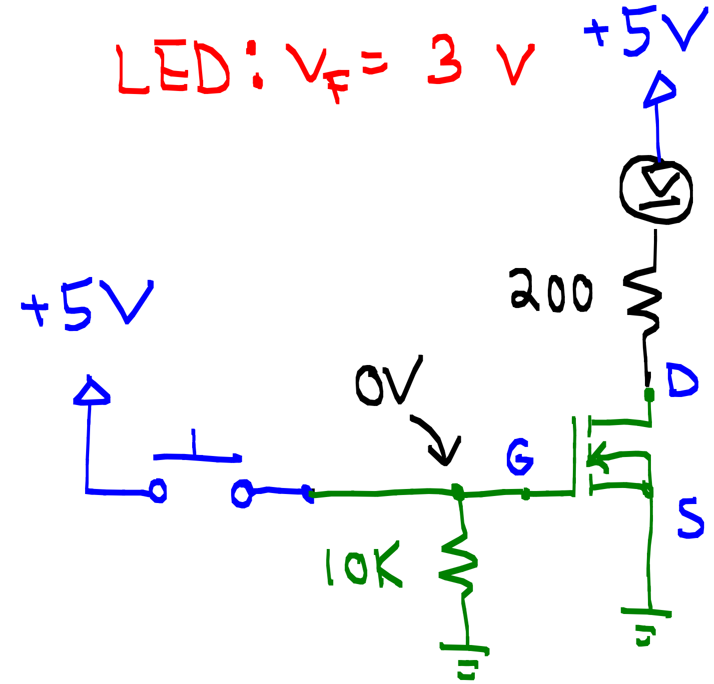
Example:



✱ R_D value:	100K	10K	1K
Power dissipation:	Low	Med	High
Speed:	SLOW (~100μs)	MED (~10μs)	FAST (~1μs)

2. MOSFET Switch Analysis ECE248 Style

LED: $V_F = 3$ V



- **Example: LED Driver**

MOSFET Properties: $V_{GS,TH} = 2.4V$, $R_{DS,ON} = 3\Omega$ $\left\{ \begin{array}{l} V_{GS} = 5V \\ I_{D,ON} = 250mA \end{array} \right.$

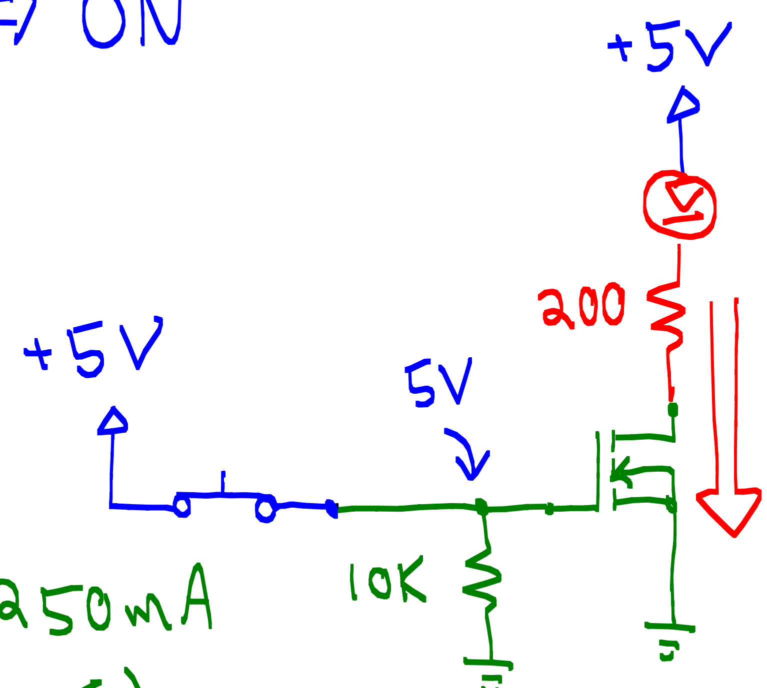
- open push button: $V_{GS} = 0V < 2.4V \Rightarrow$ OFF
- Closed push button: $V_{GS} = 5V > 2.4V \Rightarrow$ ON

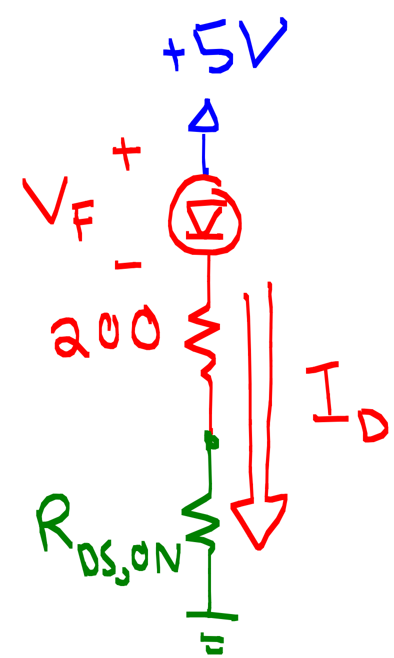
KVL: $5 - \overset{3\,V}{\boxed{V_F}} - I_D \times 200 - I_D \times \underset{3\Omega}{\boxed{R_{DS,ON}}} = 0$

$$\rightarrow I_D = \frac{5 - 3\,V}{200 + 3\Omega} = .0099A$$

$$= 9.9\,mA < 250mA$$

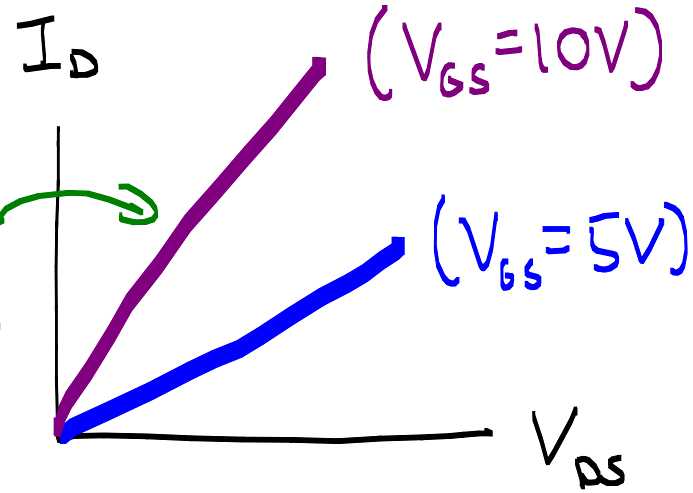
(ohmic ✓)



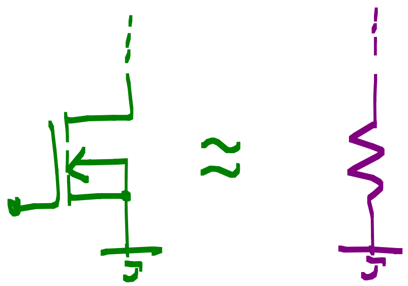


ECE 363 style analysis

- $R_{DS,ON}$ depends on V_{GS}!

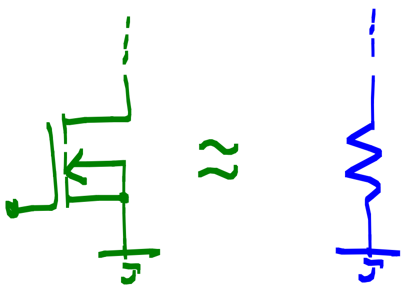


$R_{DS,ON} = \frac{1}{\text{slope}}$

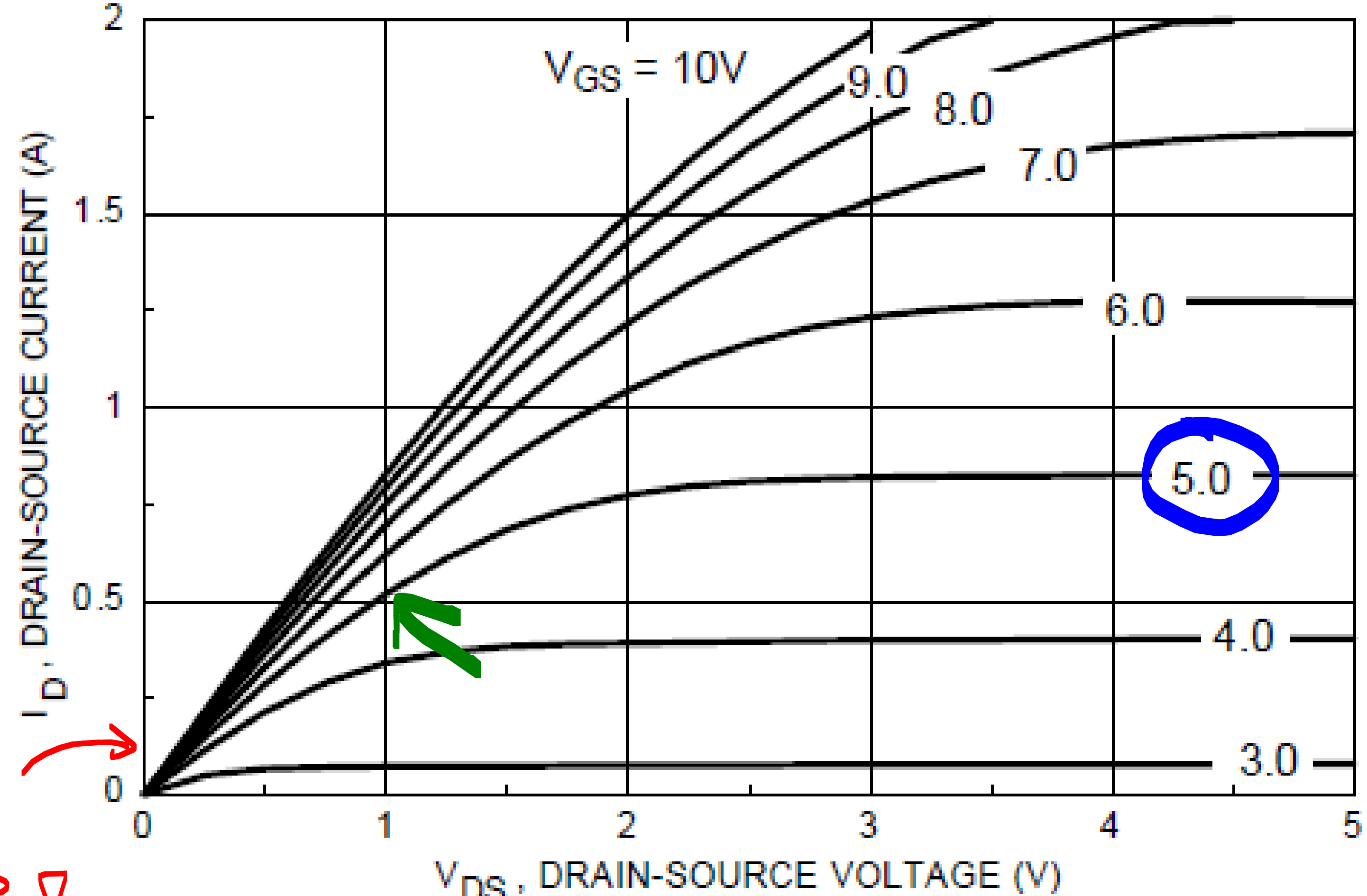
10V  $\approx$ 1.2Ω

.010A is down here!

(ohmic region ✓)

5V  $\approx$ 2Ω

- MOSFET data sheet has a plot like this:



I-V curve for $V_{GS}=5V$

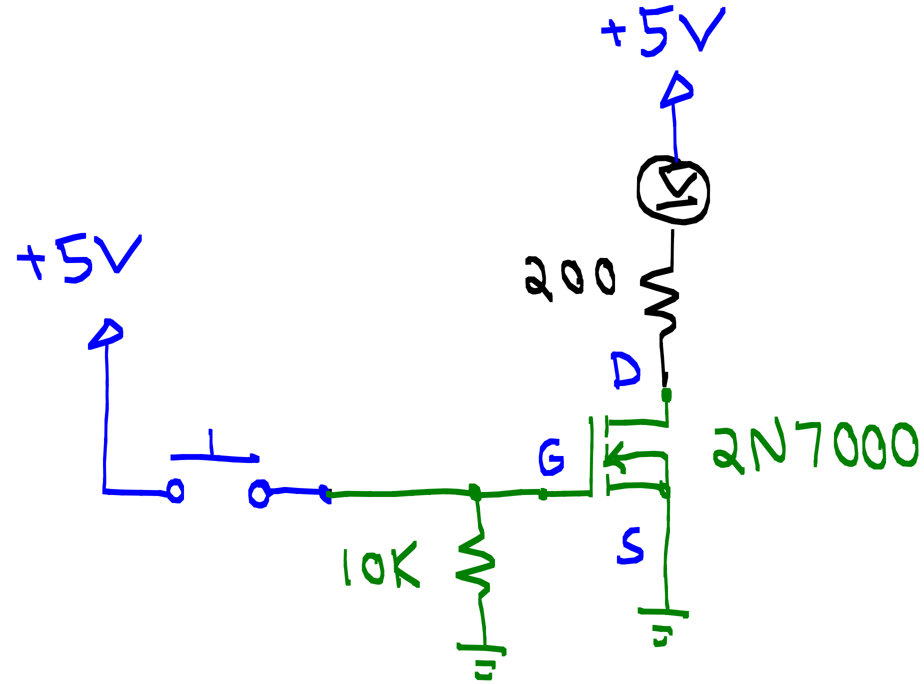
Figure 1. On-Region Characteristics

$$R_{DS,ON} = \frac{1}{\text{slope}} \approx \frac{1}{.5A/1V} = \underline{\underline{2\Omega}}$$

- From data sheet:

$V_{GS,TH} = 2.1\ V$, $R_{DS,ON} = 2\ \Omega$

10mA is in ohmic region ✓



- Push button open:

$V_{GS} = 0V < 2.1V$ OFF

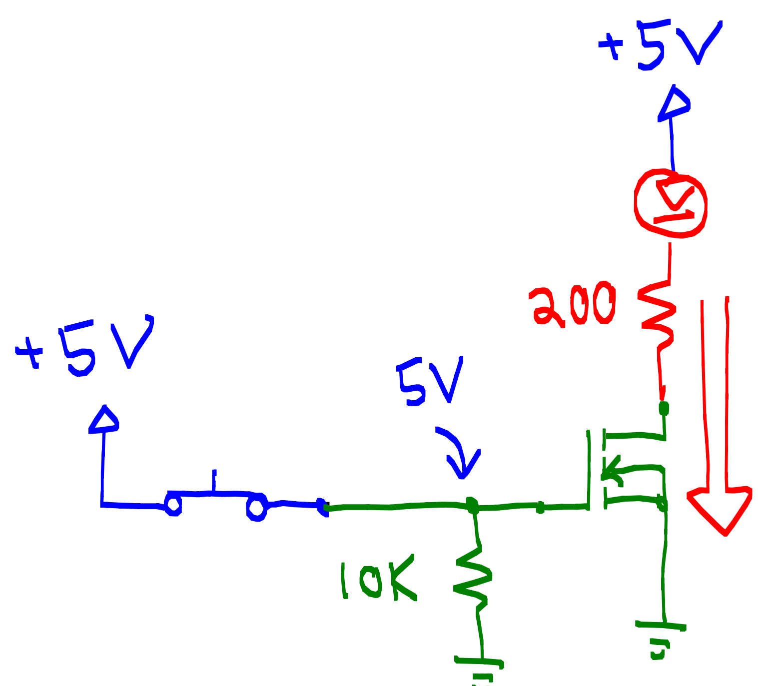
- Push button closed:

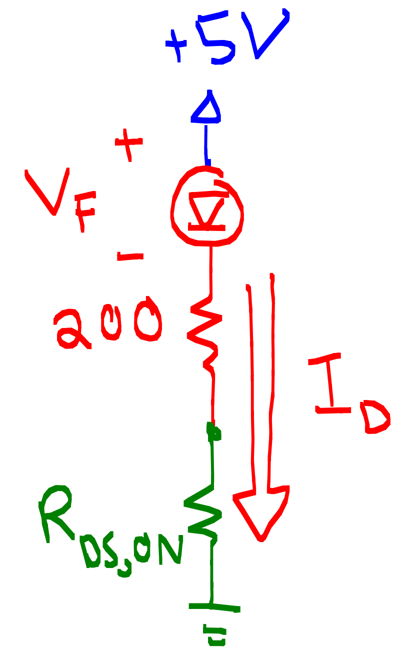
$5 - \boxed{V_F} - I_D \cdot 200 - I_D \cdot 2 = 0$

3 V

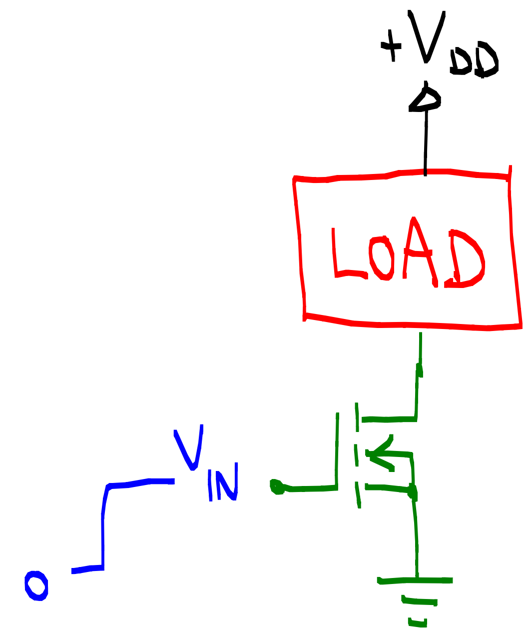
$$I_D = \frac{5-3\ V}{200+2} = .099\ A$$

$$= \boxed{9.9\ mA}$$





3. MOSFET switch design



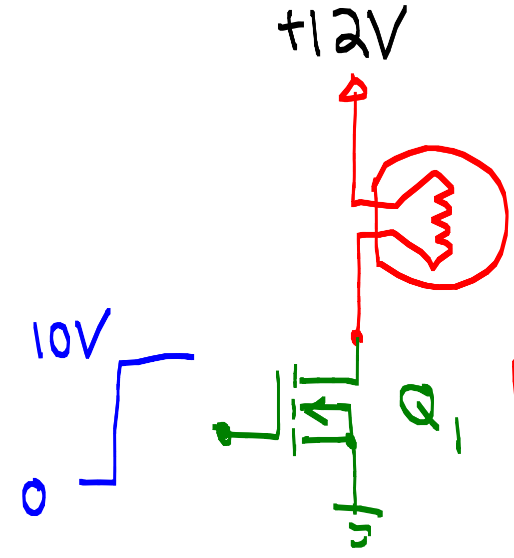
STEP 1 Know your load → Voltage, Current

STEP 2 Wisely choose the MOSFET

1. Max I_D, max V_{DS}, max V_{GS}
2. V_{GS} and $R_{DS,ON}$ are OK
3. Max T_J is OK

STEP 3 When MOSFET is on, load is properly working

- **Design example using typical properties:**



[within 5% of rated power]

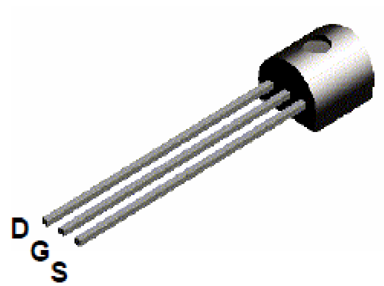
$\boxed{\text{STEP 1}}$ Load properties

$$I = \frac{6W}{12V} = 0.5A \xrightarrow{\times 2} 1A \text{ rating}$$

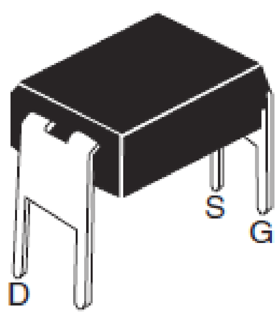
$$R = (12V)^2/6W = 24\Omega$$

$\boxed{\text{STEP 2}}$ Choose MOSFETs

Q_1:



TO-92
2N7000



	Max I_D	V_{GS}	V_{DS}	Rated P (no HS)	Rated P (w/HS)
2N7000	200mA	±20V	60V	0.4W	
IRFD120	1.3A	±20V	100V	1.3W	

• Threshold V_{GS}:

SPECIFICATIONS (T_J = 25 °C, unless otherwise noted)						
PARAMETER	**SYMBOL**	**TEST CONDITIONS**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
Static						
Drain-Source Breakdown Voltage	V_{DS}	V_{GS} = 0 V, I_D = 250 μA	100	-	-	V
V_{DS} Temperature Coefficient	$\Delta V_{DS}/T_J$	Reference to 25 °C, I_D = 1 mA	-	0.13	-	V/°C
Gate-Source Threshold Voltage	$V_{GS(th)}$	V_{DS} = V_{GS}, I_D = 250 μA	2.0	-	4.0	V
Gate-Source Leakage	I_{GSS}	V_{GS} = ± 20 V	-	-	± 100	nA
Zero Gate Voltage Drain Current	I_{DSS}	V_{DS} = 100 V, V_{GS} = 0 V	-	-	25	μA
		V_{DS} = 80 V, V_{GS} = 0 V, T_J = 150 °C	-	-	250	
Drain-Source On-State Resistance	$R_{DS(on)}$	V_{GS} = 10 V, I_D = 0.78 A[b]	-	-	0.27	Ω

* Clearly, $V_{GS} = 10V \gg V_{GS,Th}$ ✓

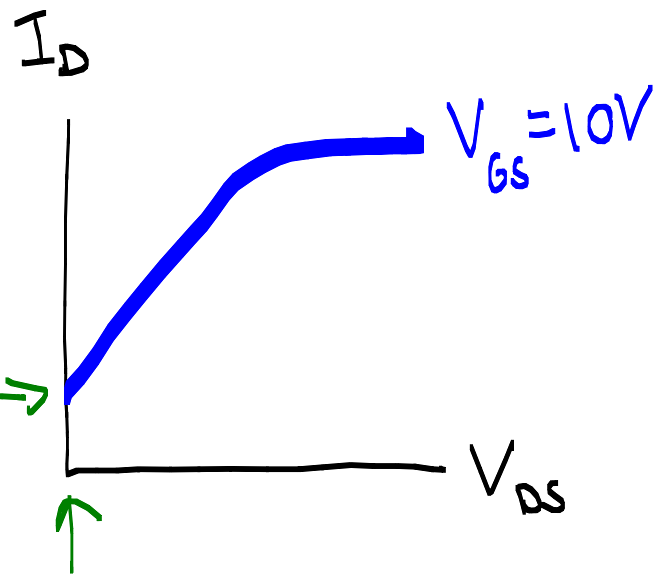
Worst case values

Max $V_{GS,TH} = 4V$

Max $R_{DS,ON} = 0.27\Omega$

Typical $R_{DS,ON}$?

Typical $R_{DS,ON}$ @ $V_{GS}=10V$:



Typical $R_{DS,ON} \approx \dfrac{0.1V}{0.5A} = \underline{\underline{0.2\Omega}}$

- Ohmic region?

Clearly in ohmic region :)

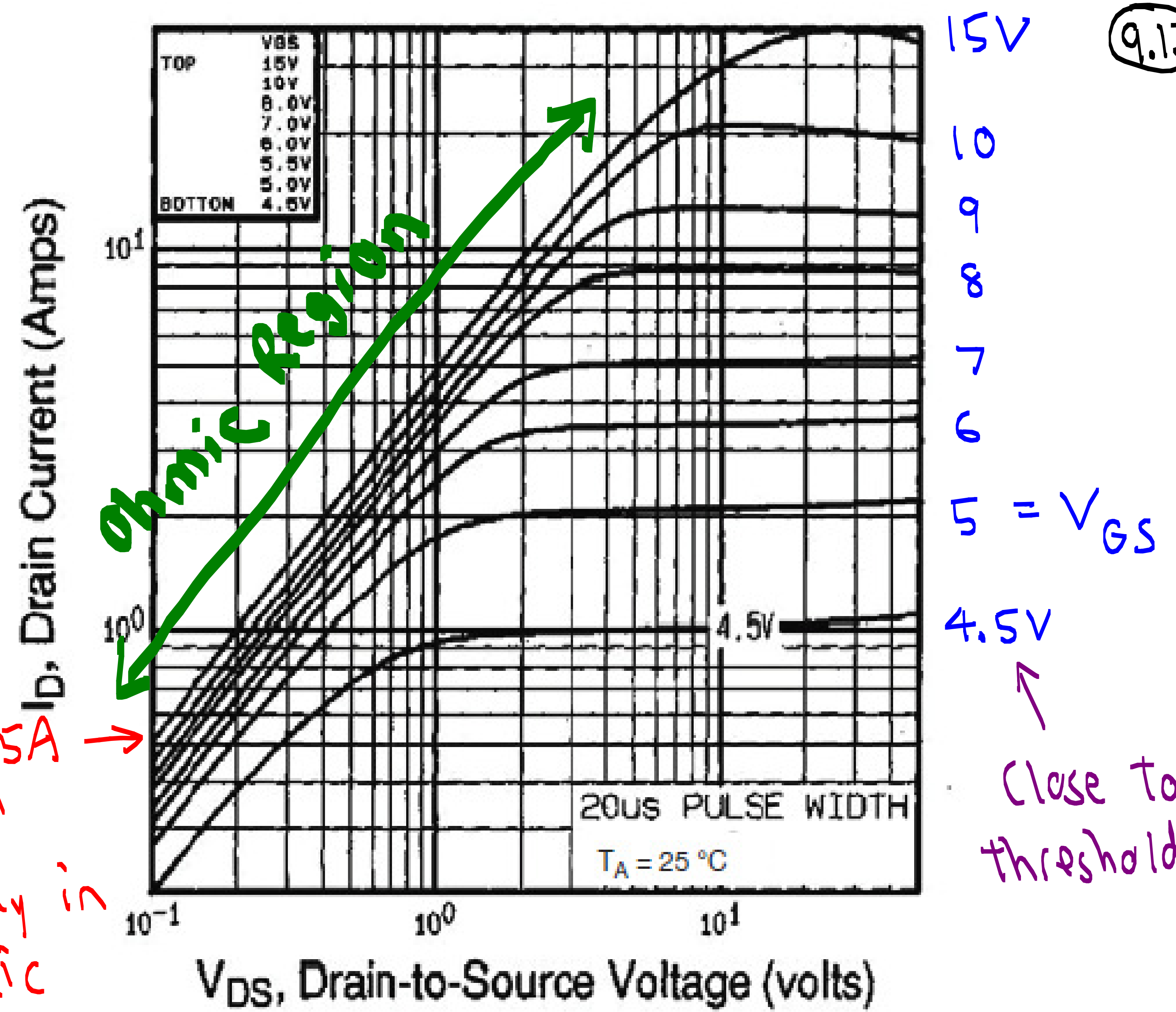


Fig. 1 - Typical Output Characteristics, $T_A = 25\ ^\circ C$

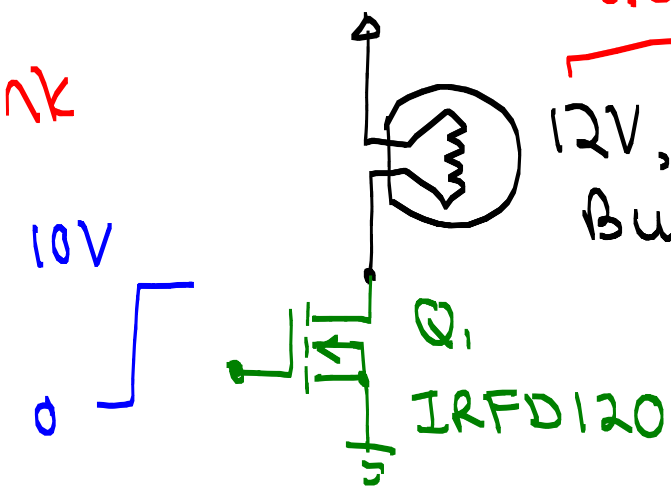
• $V_{GS} = 10V \rightarrow Q_1$ is ON

$I_D = \dfrac{\cancel{12-0V}}{24 + .2\Omega} = 0.496A$

$P = (.496A)^2 .2\Omega = \underline{\underline{.049W}} \xrightarrow{\times 2} 0.1W$

No heat sink needed.

$T_J = 25°C + (.0492W)\, 120°C/W = 31°C < 85°C$



(175°C max)

☆ NOTE: MOSFETs can handle higher T_J than BJTs!

(150°C max)

$\boxed{\text{STEP 3}}$ Confirm operation

Bulb current: $I_D = \underline{\underline{.496A}}$

Bulb power: $P = (.496A)^2 (24\Omega) = \underline{\underline{5.9W}}$ (< ~2% of rated power) ✓