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College of Engineering and Petroleum

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ME319 MECHATRONICS

Part II: The Cells – Electronic Circuits

Lecture 2: Switching Semiconductors

Spring 2021

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Lesson Objectives

- Review the basic operation of Bipolar Junction Transistors (BJT)
- Review the basic operation of MOSFETs
- Practice designing a BJT and MOSFET circuits
- Choosing between BJTs and MOSFETs

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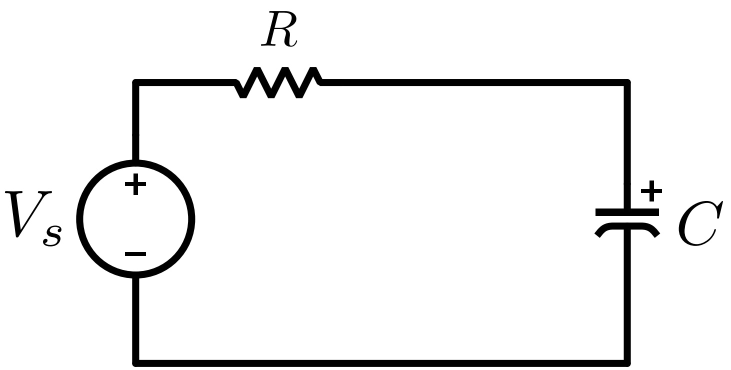
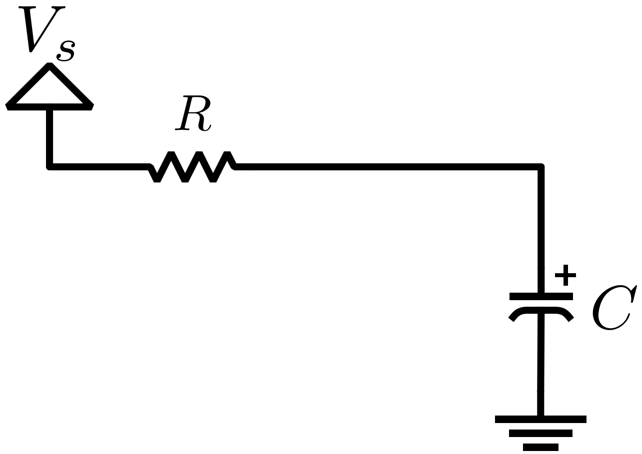
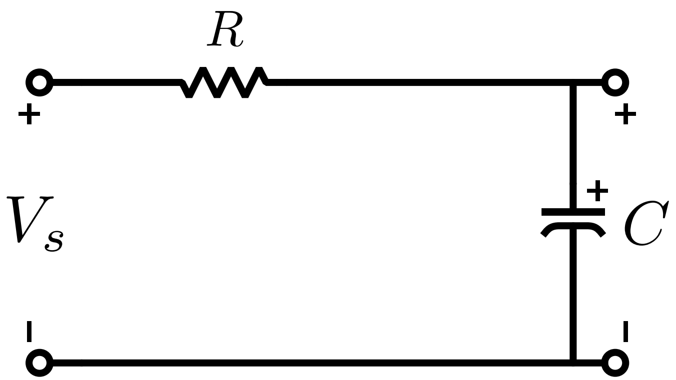
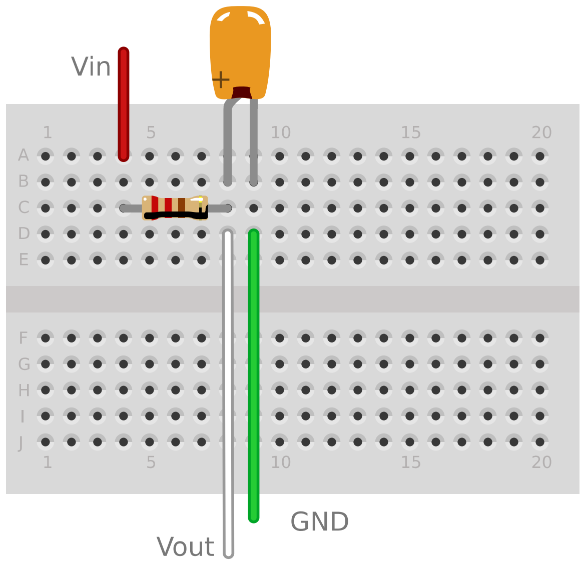
- Remember that these are equivalent

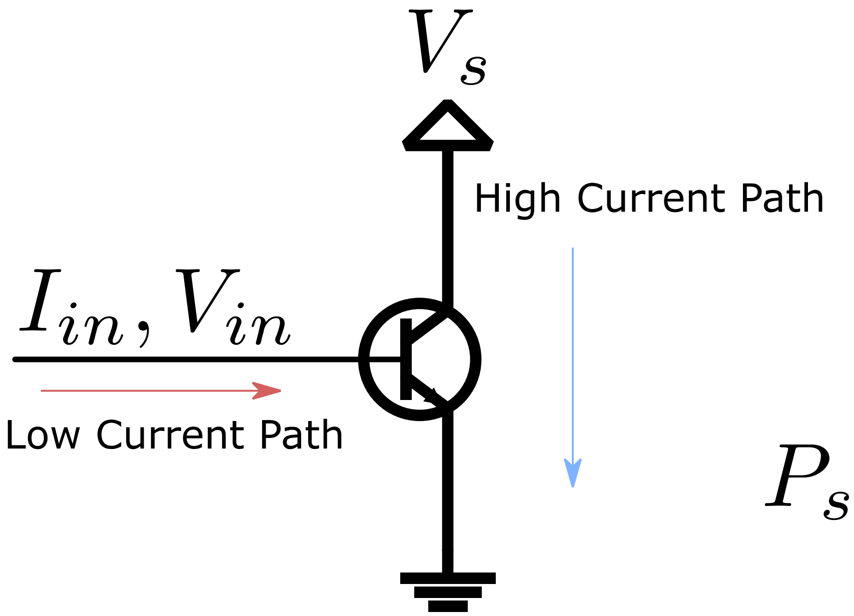


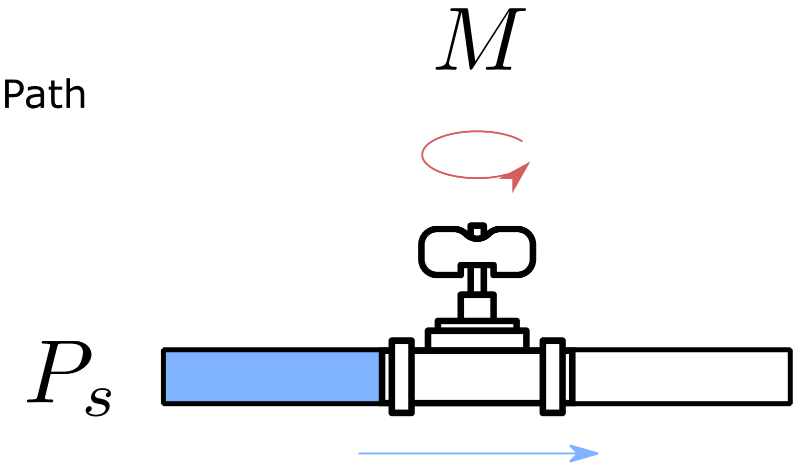




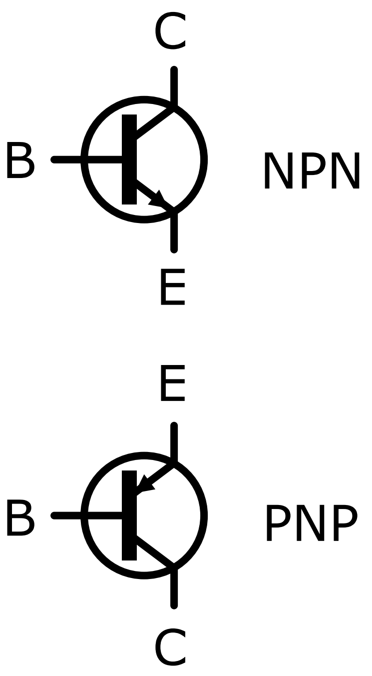


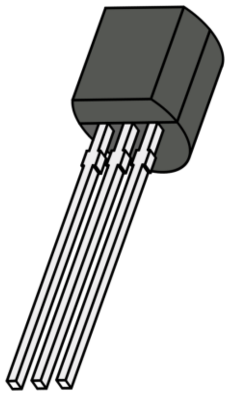
- Microcontrollers and digital logic devices can only provide limited current
- On STM32F401x MCUs, a GPIO pin can provide a $I_{max} = 25mA$. Only enough to power small status LEDs and other basic logic circuits.
- Switching devices can act like a pipe valve.
- Relatively low current is required to turn the switch on/off allowing a high current path to open/close.



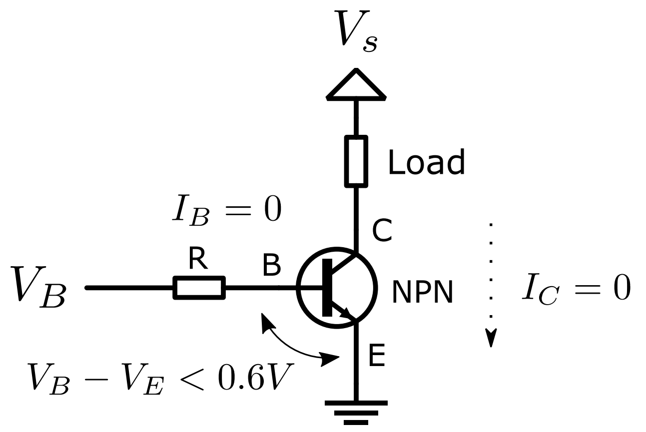


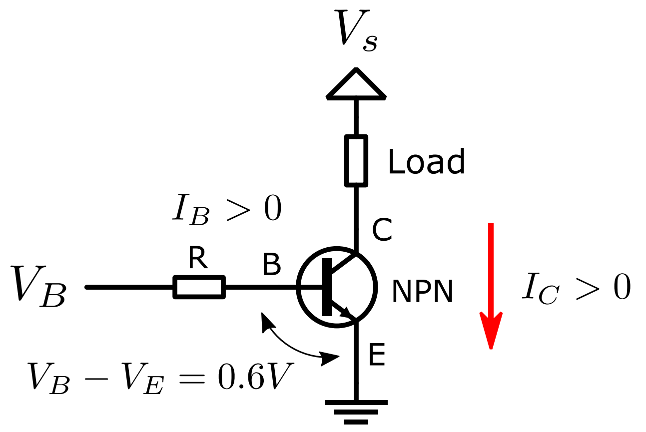
- Bipolar Junction Transistors (BJT's) are common circuit elements used primarily for switching
- B: Base, E: Emitter, C: Collector
- BJT is a **current controlled** device, where amount of current supplied at B determines current flow from C to E
- Small base current allows much larger current to flow from collector to emitter
  - Strength of BJT
- On/Off State
- When On: Saturation/Linear Region





- When a BJT is connected **downstream** of a load, it's termed a **low side switch**. Usually a (NPN)
- Sufficient current must be supplied at **base** to close the circuit (activate switch: on state)
  - This current value is dependent upon load current.
  - As a rule of thumb, the voltage between B and E must at least be $0.6V$
  - For a low side switch where E is connected to GND, this means the signal voltage at B must be higher than $0.6V$
  - If the signal is provided by a MCU, it can surely provide the $0.6V$





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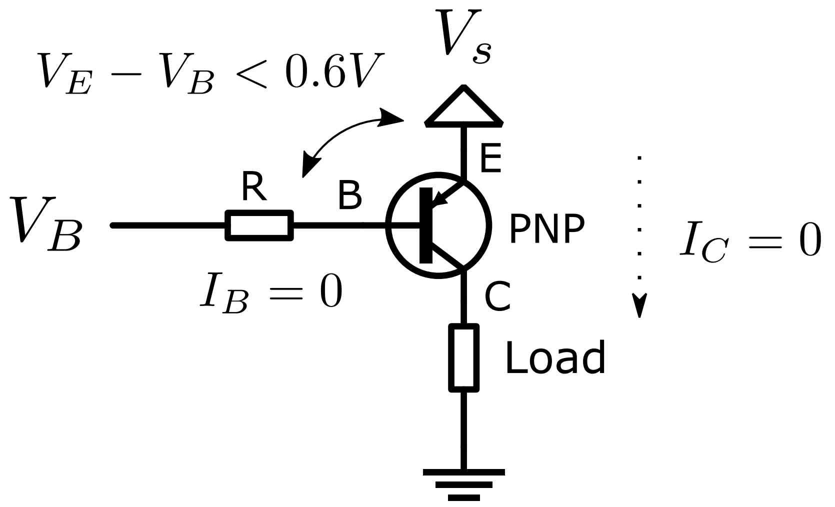
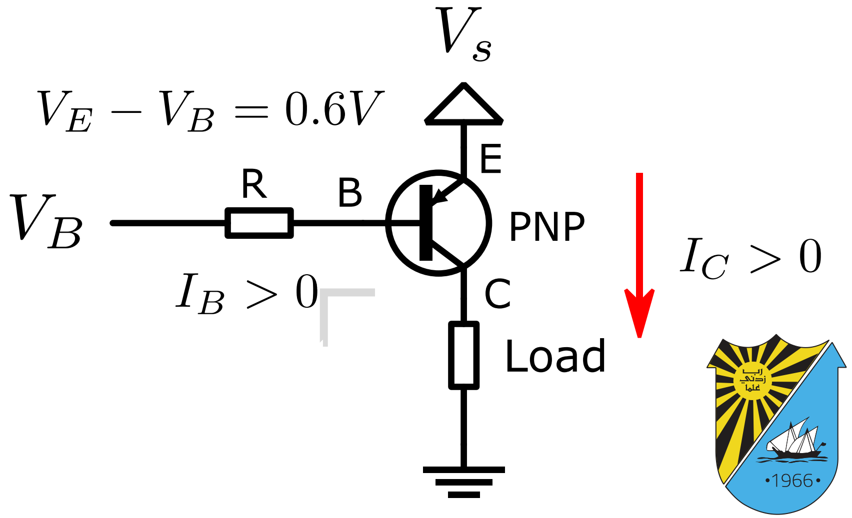
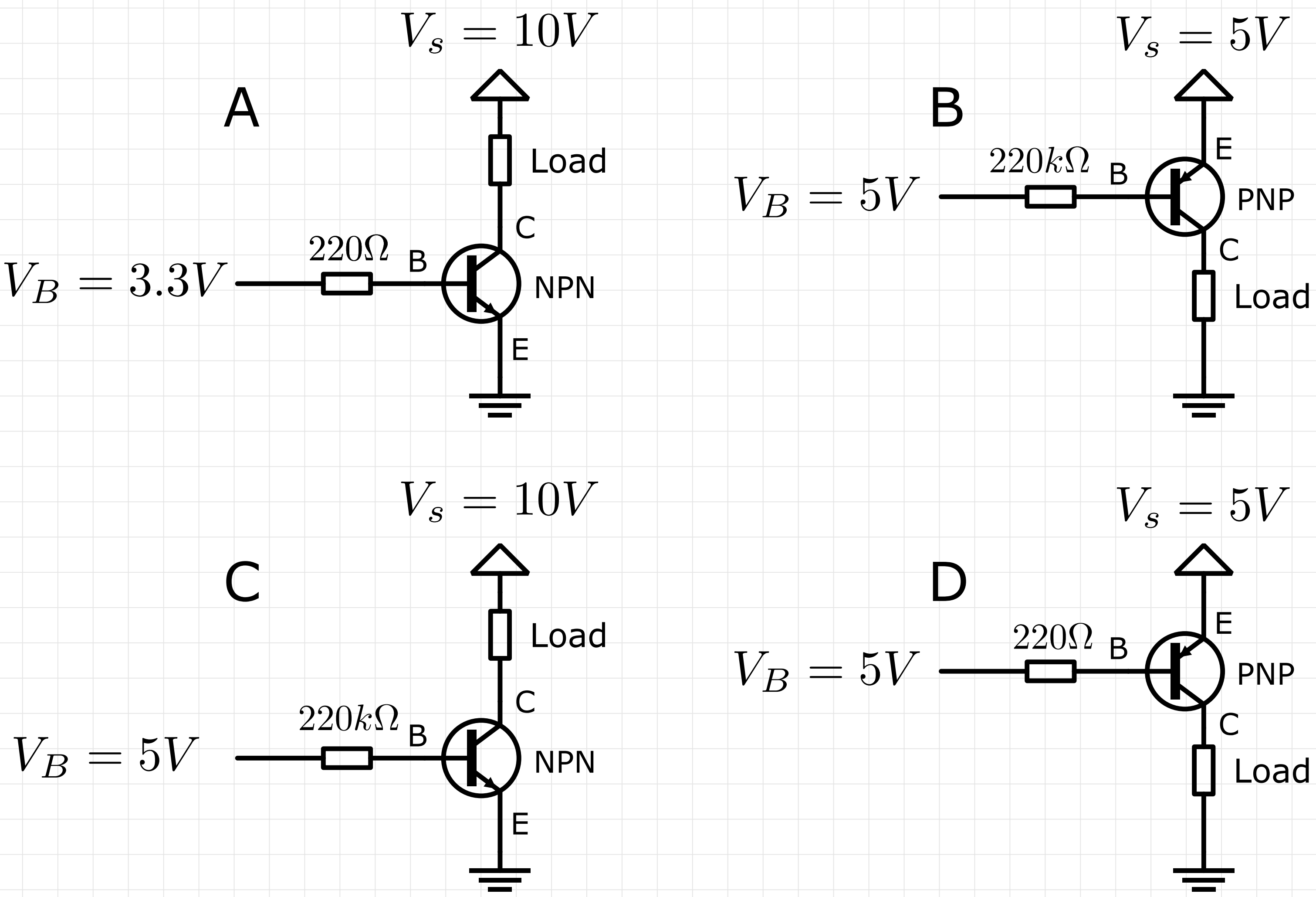
- When a BJT is connected **upstream** of a load, it's termed a **high side switch**. Usually a (PNP)
- Sufficient current must be supplied at **base** to open the circuit (deactivate the switch)
- As a rule of thumb, the voltage between E and B must at least be $0.6V$
- For a high side switch where E is connected to V_s, this means the signal voltage at B must be higher than $V_s - 0.6V$, to open the switch (deactivate switch)
- If the signal is provided by a MCU, it has to provide a voltage close to V_s
  - Otherwise, the BJT will remain activated



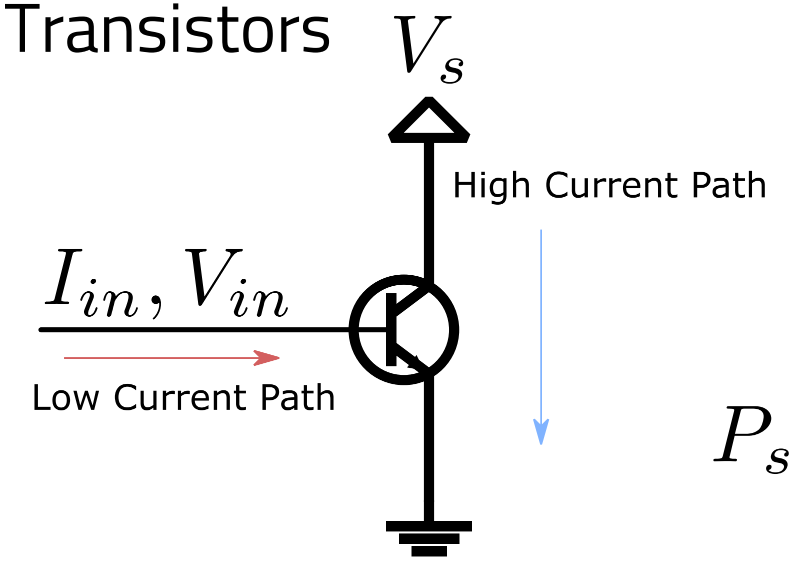


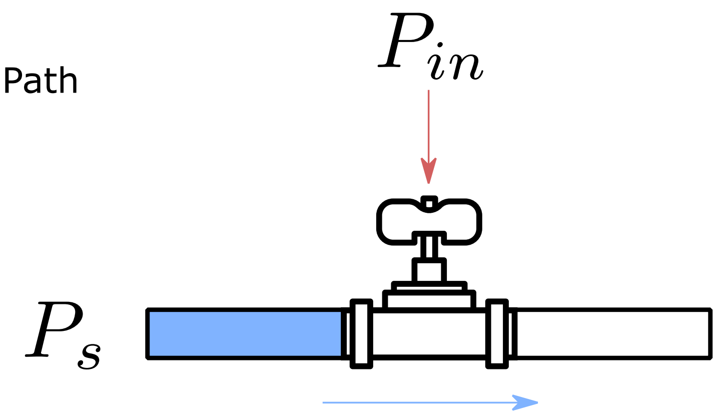
For each of the following configurations, determine if the switch is activated or not. Calculate I_B for each case.



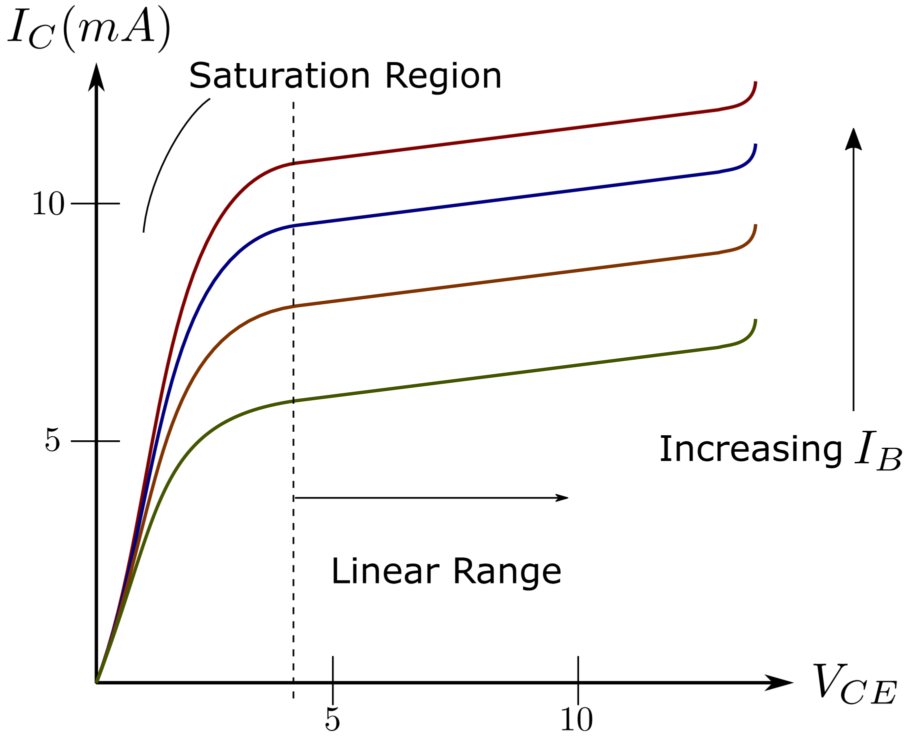
BJT Efficiency and Voltage Drop – Mechanical Analogy

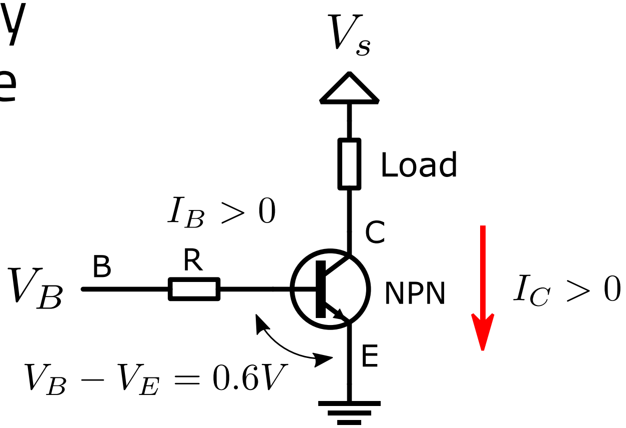
- Imagine the valve of a pipe is spring loaded
- You can push lightly P_{in}, and water will flow, but the valve will not be fully open:
  - *Higher pressure losses and lower water flow*
- When you push with P_{in} to open the valve all the way, you clear the water path:
  - *Minimal pressure losses, maximum flow rate*
- Further increase in pressure P_{in} doesn't improve the flow
- Applies to BJT Transistors
  - $P_{in} \Leftrightarrow I_{in}$





- Lower voltage drop across the transistor (V_{CE}), means more voltage supplied to the load.
- To achieve lower V_{CE} in a BJT, the transistor must operate in the **Saturation Region**
- As a rule of thumb, the saturated voltage drop $V_{CE(sat)} = 0.2V$
  - This can be achieved by having the collector to base current ratio to be between 10-20
  - $I_C : I_B = 10 - 20$
- So, while lower base current I_B (high $I_C : I_B$ ratio) may be sufficient to activate the transistor, it will operate in the linear region (not efficient).
- A high than necessary base current I_B ($I_C : I_B < 10$) does not add any value.





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Example 2

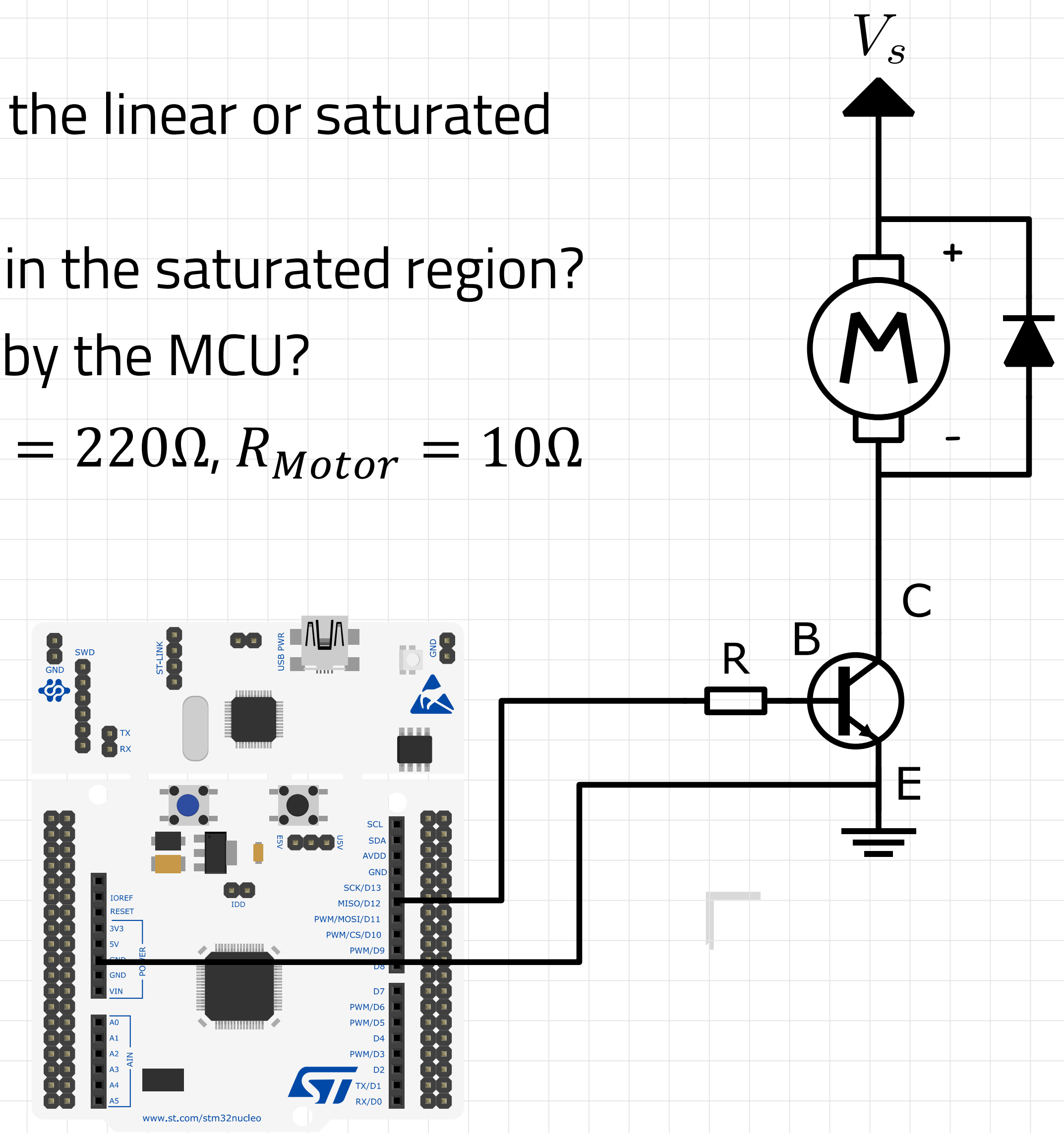
We want to control a unidirectional motor using a BJT transistor. If we use the STM32F401x MCU GPIO output connected to the base of the BJT transistor.

Is the motor turned on? If so, is the BJT operating in the linear or saturated region?

What value of R is required to have the BJT operate in the saturated region?

Can the required current for saturation, be supplied by the MCU?

GPIO Logic Pin: $V = 3.3V$, $\mathrm{I_{max}} = 25\mathrm{mA}$, $V_s = 6V$, $R = 220\Omega$, $R_{Motor} = 10\Omega$



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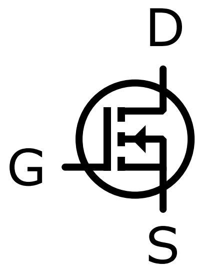
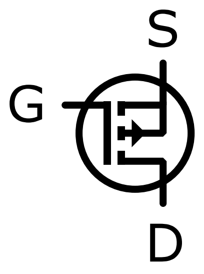
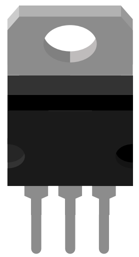
- MOSFET: Metal-Oxide Semiconductor Field Effect Transistor
- Another type of transistor that can be used as a switching device.
- Similar to BJT's they can be configured as a **low side switch** (usually N-MOSFET, or N-Channel, or N-FET), or a **high side switch** (usually P-FET)
- Unlike BJT's, they are **voltage controlled**, not current controlled.
- Note the terminal names are different
- G: Gate, S: Source, D: Drain
- There is a fourth terminal called the body, but it's usually connected to the source.
- The terminal names are based on electron current (flows in the opposite direction of conventional current)







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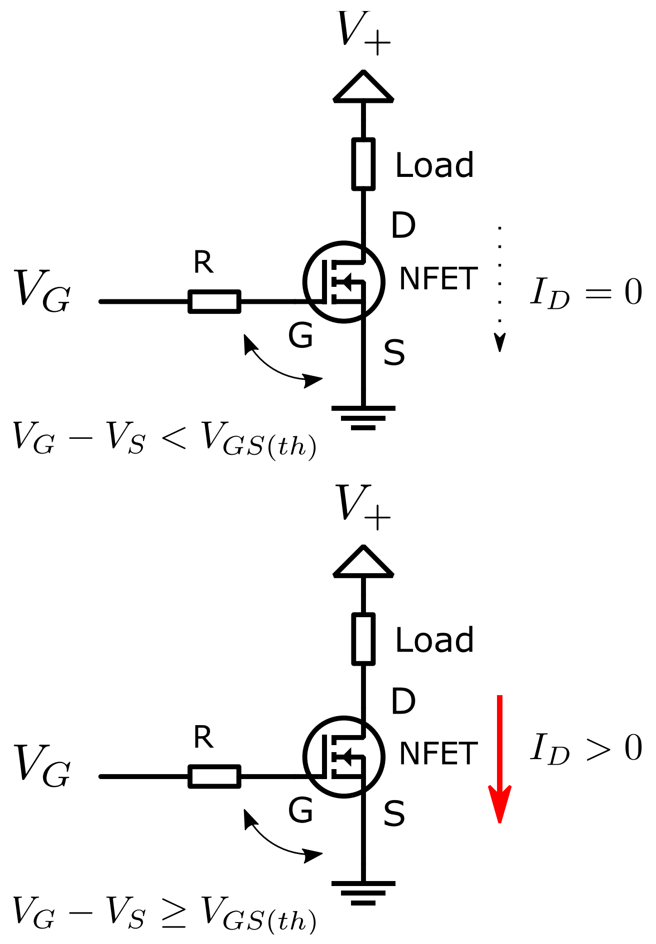
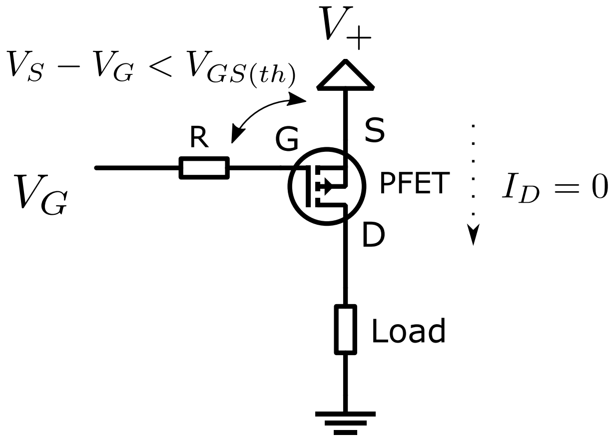
MOSFET (NFET) as a Low Side Switch

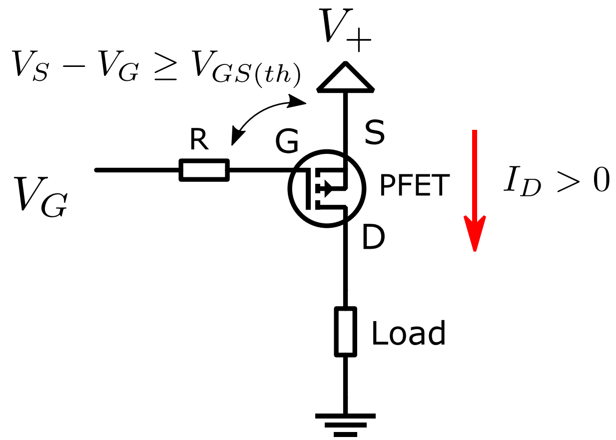
- When a MOSFET is connected downstream of a load, it's termed a low side switch. Usually an N-Channel MOSFET (N-FET)
- Sufficient **voltage** must be supplied at **Gate** to close the circuit (activate switch)
  - $V_G - V_S \geq V_{GS(threshold)}$
  - For logic-level MOSFETS, $V_{GS(threshold)} \approx 1.1V - 3V$
    - Since many logic devices operate at $3.3V$
  - If the Source terminal of the NFET is connected to GND, then $V_G \geq V_{GS(threshold)}$ to activate the switch.
- A low side switch is a convenient and simple switch configuration. No need to take V_+ value into account.



MOSFET (PFET) as High Side Switch

- When a MOSFET is connected upstream of a load, it's termed a high side switch. Usually a P-Channel MOSFET (P-FET)
- Sufficient **voltage** must be supplied at **Gate** to open the circuit (**deactivate** switch)
  - $V_G - V_S \geq V_{GS(threshold)}$: to deactivate the switch
  - If the Source terminal of the NFET is connected to V_+, then $V_+ - V_G \geq V_{GS(threshold)}$ to deactivate the switch.
- A low side NFET switch is more efficient and simple to control. Good for switching components on/off
- A high side PFET switch is safer, since the load is connected to ground. Good for supplying external power to circuit system.
- Implementing a high side switch requires certainty about value of V_+





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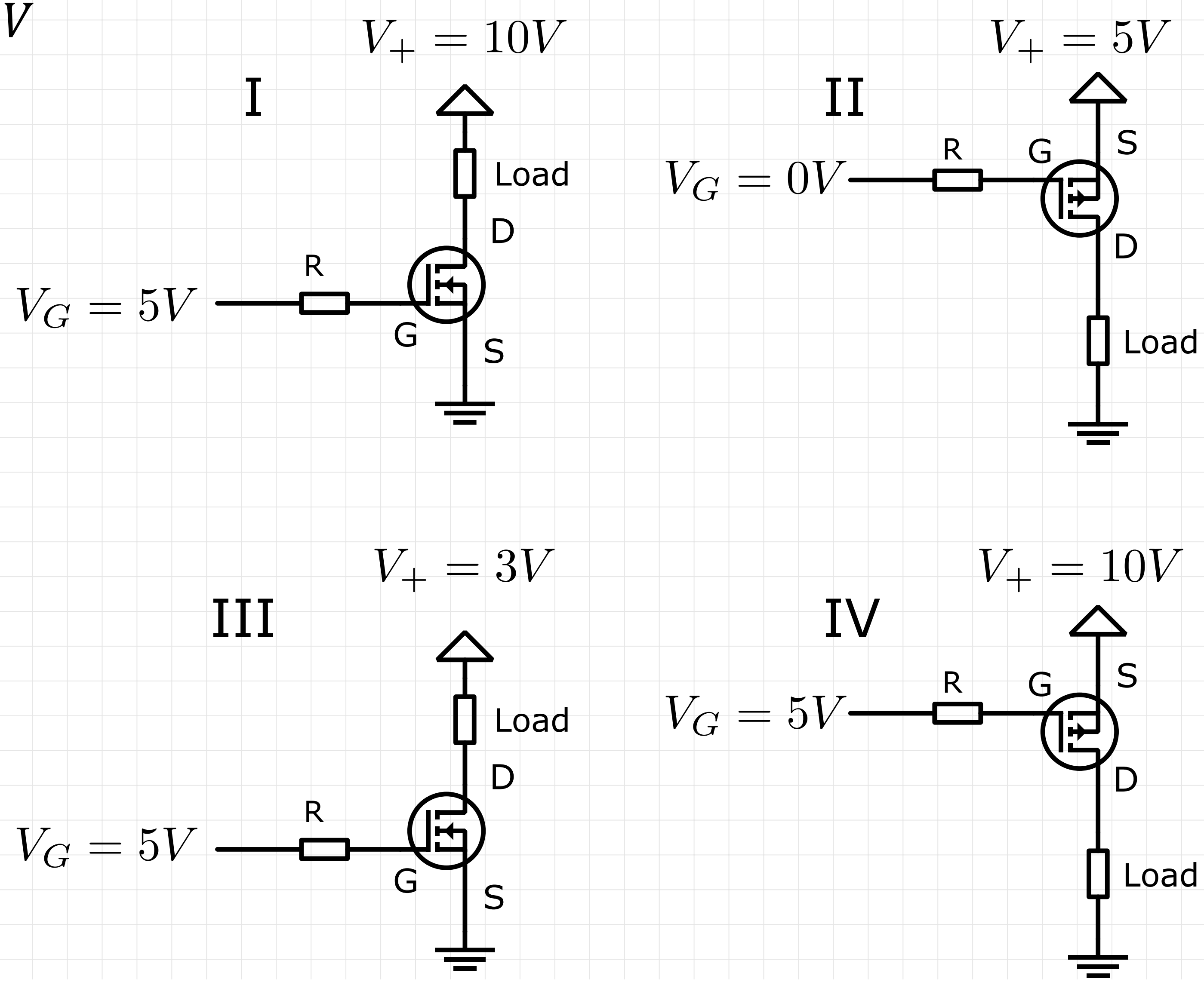
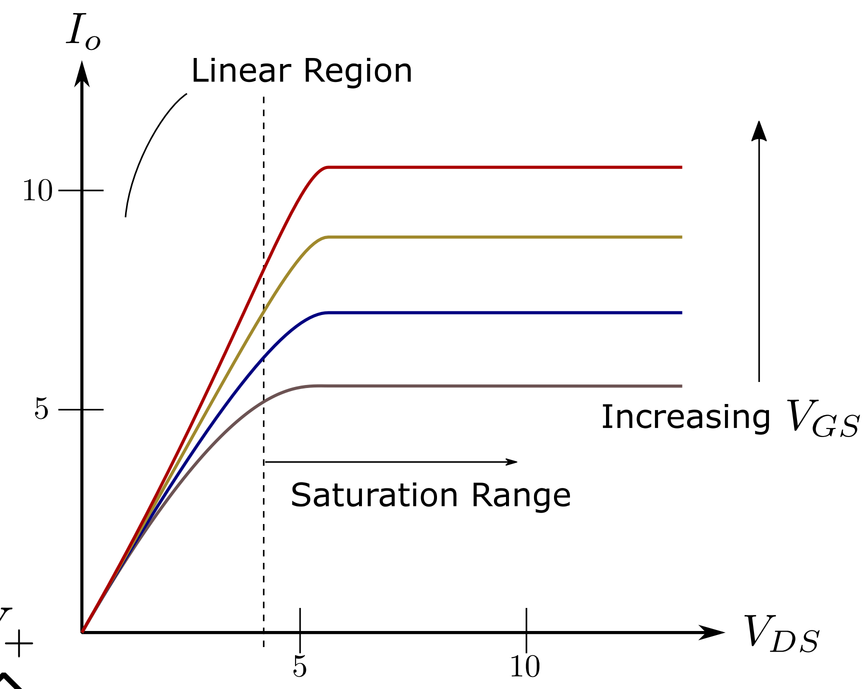
For each of the following configurations, determine if the switch is activated or not.

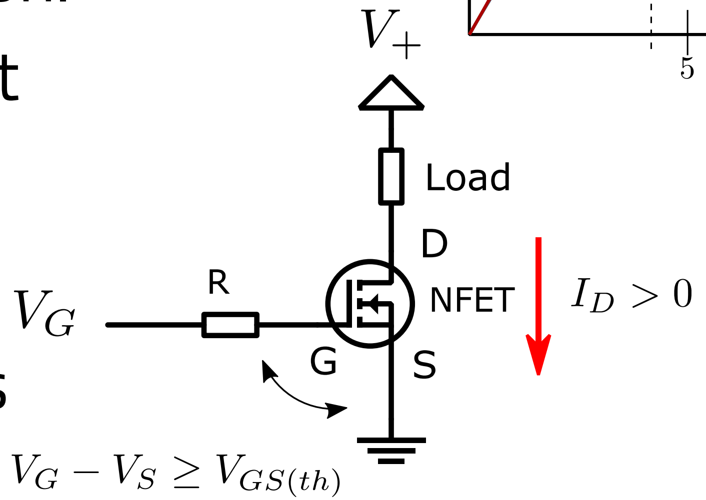
Assume $V_{GS(th)} = 1.8V$

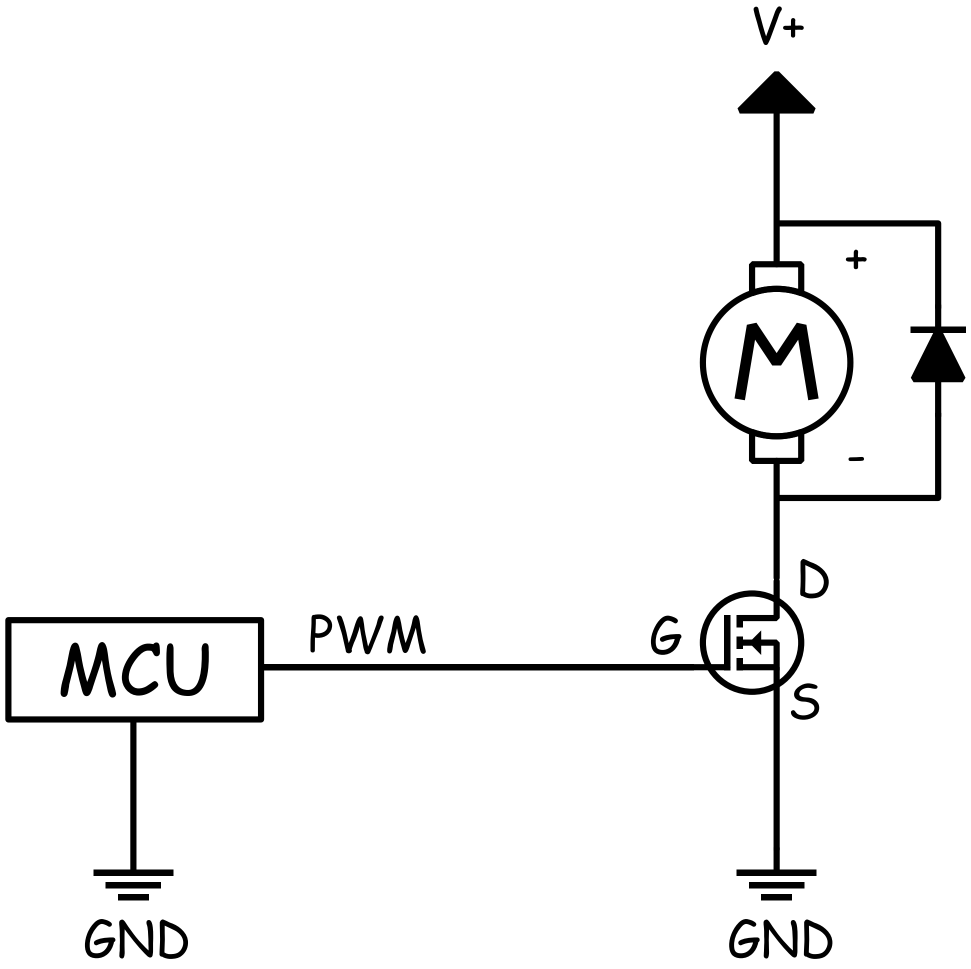


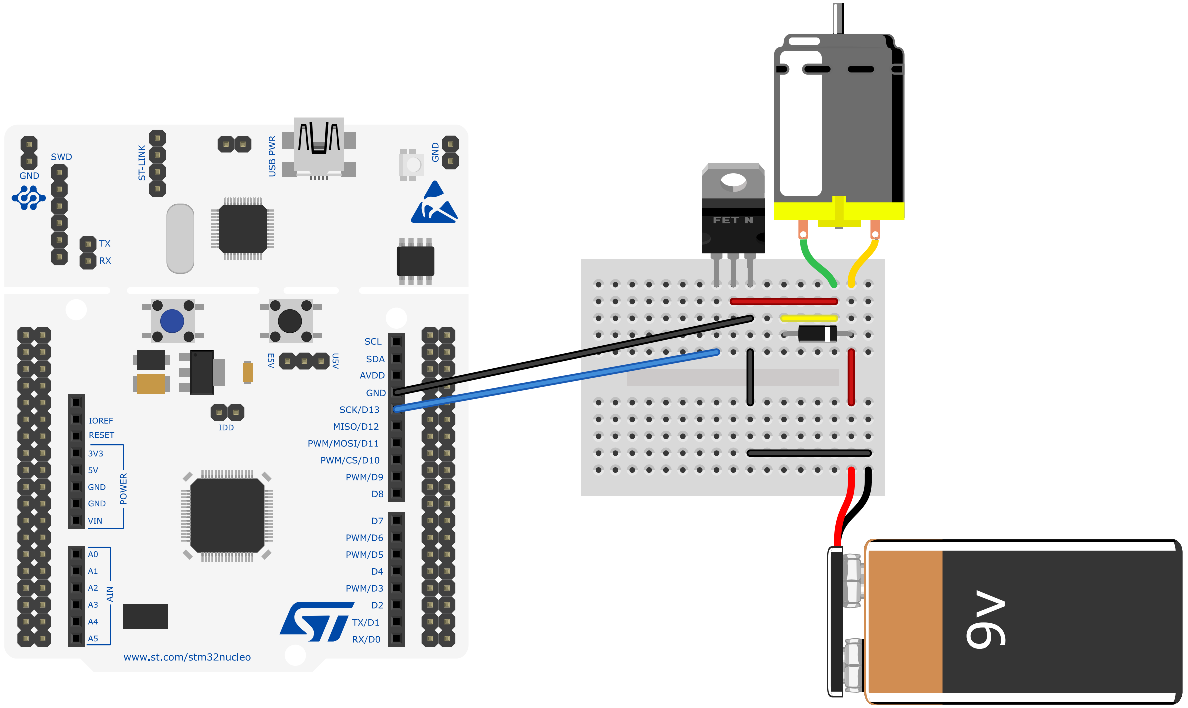
MOSFET Efficiency

- Similar to BJT, the MOSFET efficiency varies based on the region of operation.
- Unlike BJTs, MOSFETs are more efficient in the **linear** region, when the voltage across the MOSFET is minimized (small V_{DS})
  - Higher V_{GS} would push the operation toward the linear, more efficient, region.
  - Higher $V_{GS} \Rightarrow$ Lower V_{DS}, up to a point
- MOSFET have a specific resistance $R_{DS(on)}$ when activated.
- Less voltage drop across MOSFET means higher voltage available to load.









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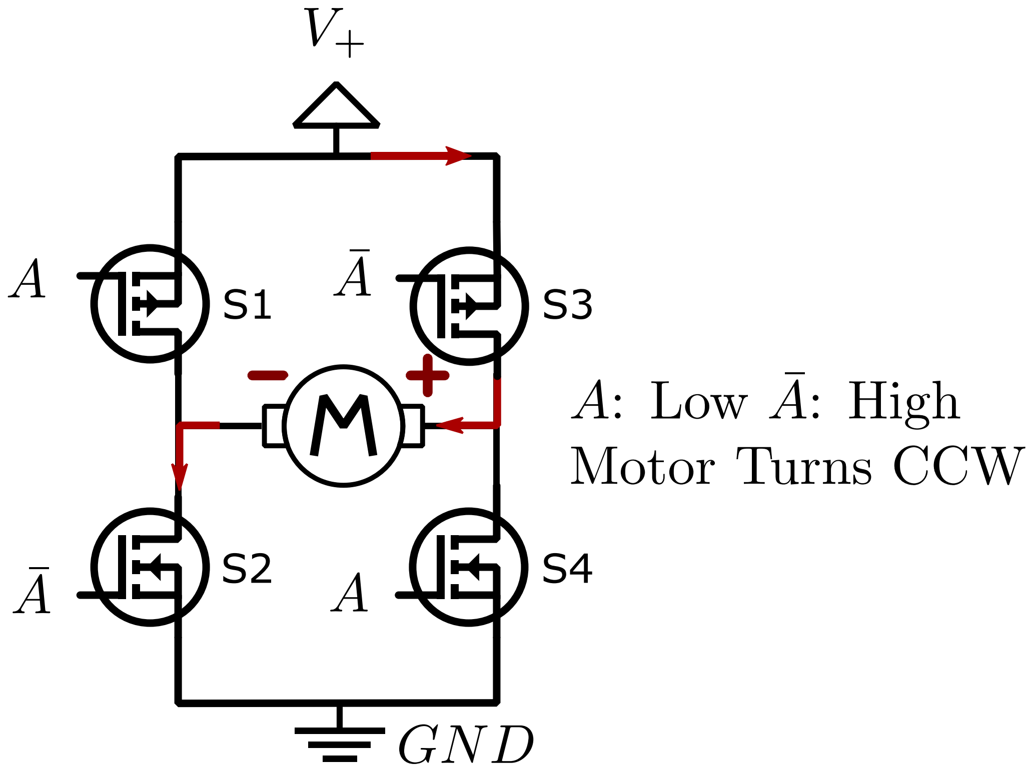
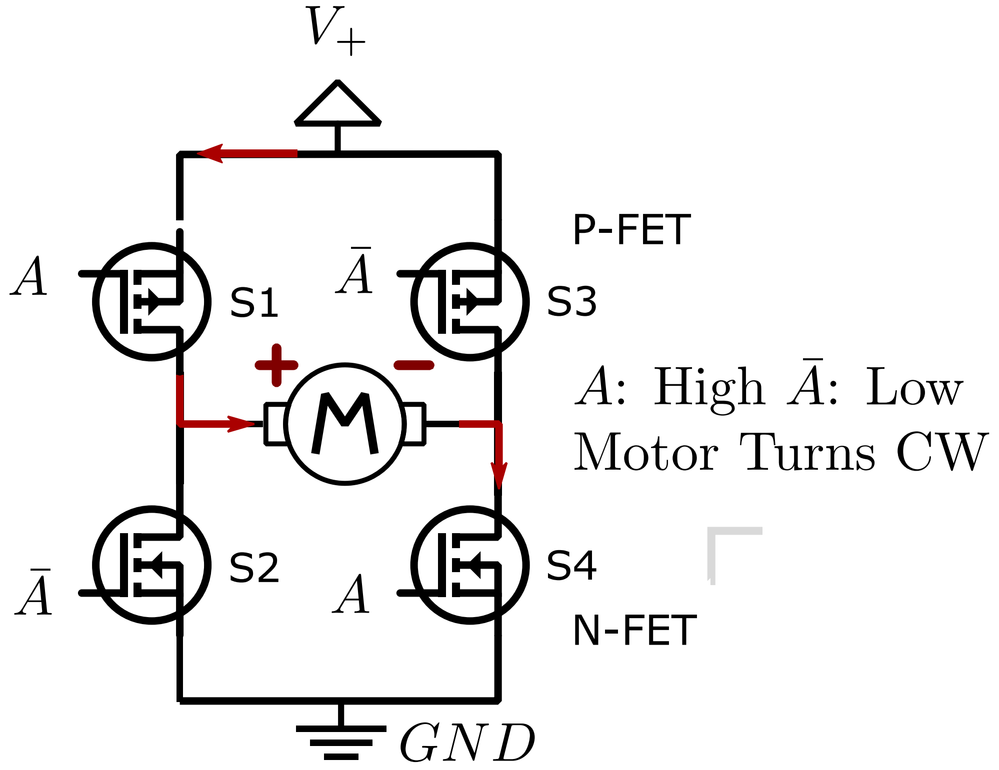
- What if we wanted to control a bidirectional motor.
- In a previous example we discussed a unidirectional control.
- For bi-directional control we need to **flip the polarity** of the voltage
- We can achieve this via an H-Bridge Circuit





Choosing BJTs vs MOSFETs

BJT

(+) Can activate on low voltage across BE

(+) Can tolerate higher switching voltage V_s

(+) Less expensive

(-) Less Efficient (Higher voltage drop, higher V_{CE})

(-) Requires a base resistor

MOSFET

(+) More efficient (lower V_{DS})

(+) Simple setup

(+) Comes in logic level gate voltage

(-) More Expensive

(-) Needs a higher switching voltage (higher V_{GS})

MOSFETs are the current choice of switching, as they keep improving in their capabilities.

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Reading a MOSFET Datasheet

- There are thousands of MOSFET devices available on the market.
  - New ones introduced frequently.
- MOSFET technical datasheets are loaded with information. Need to know what's applicable/useful for you in your application.
- In most mechatronic applications, we care about:
  - Threshold gate voltage $V_{GS(th)}$
  - Efficiency of MOSFET and at which V_{GS} voltage.
  - Maximum Current Rating
  - Maximum Switching Voltage Rating
  - How does it behave under pulsed operation (PWM signal)

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Example 4

If $V_G = 3.3V$, calculate the current passing through the load and the power dissipated in the MOSFET. Assume $T_C = 25^oC$