a

Name: Soleil Demick

Collaborators: ______

Thayer School of Engineering • DARTMOUTH

ENGS 28, W26

Lab 3 — Driving large loads

Due: Tuesday January 27, 2026 2:15 PM

Contents

1 Overview . . . 3
1.1 Place in course . . . 3
1.2 Learning Objectives . . . 3

2 Prelab . . . 3
2.1 What is required to drive large loads . . . 3
2.2 Introduction to Transistors . . . 4
2.2.1 BJT Operation . . . 4
2.2.2 Analyzing the low side NPN driver . . . 5
2.2.3 MOSFET operation . . . 6
2.2.4 Analyzing a high side PFET driver . . . 7

3 Procedure . . . 8
3.1 Examine the solenoid . . . 8
3.2 Construct an NPN low side driver. . . . 9
3.3 Construct a PFET high side high voltage driver. . . . 11
3.4 Coding Challenge . . . 12

4 Postlab . . . 13

A Example Layout . . . 14
A.1 NPN Low Side Driver . . . 14
A.2 PFET High Side Driver . . . 15

Deliverables

1 Prelab (2 points) . . . 3
2 Current Required (3 points) . . . 4
3 Bipolar Datasheets (2 points) . . . 5
4 High Side PNP (3 points) . . . 6
5 MOSFET Datasheets (2 points) . . . 7
6 Heater Voltage (1 points) . . . 8
7 Solenoid Characteristics (3 points.) . . . 9
8 Current Limit Calculation (2 points) . . . 10
9 Current through the solenoid (1 points) . . . 11

1 Overview

1.1 Place in course

Up to this point, we have used our microcontroller to receive input from a button and to produce output on a few actuators (a UART/Terminal and an LED). Today we will look at a few circuits that will allow us to control much larger devices. In fact we will learn how to control devices that operate at much higher voltages and currents than the chip can deliver by itself.

1.2 Learning Objectives

- Learn about the operation of a solenoid.
- Evaluate several techniques to control a high voltage and/or high current device.
- Construct and demonstrate several types of circuit to control large loads.

2 Prelab

2.1 What is required to drive large loads

When considering how to control an external actuator, there are two fundamental electrical characteristics to consider. Unsurprisingly, these are the *Voltage* and *Current* required to enable the device.

In our case, we are somewhat limited in our ability to supply both of these.

Examine the **Electrical Characteristics** section of the STM32C031 datasheet linked from this Lab's Assignment page on Canvas. Answer the questions below assuming V_{cc} is $3.3V$.

The third and fourth questions requires you to look at the **Power Supply and Connections** section of the User's Manual for the Nucleo board (also on Canvas).

Deliverable 1: Prelab *(2 points)*

- What is the maximum current an I/O pin can deliver? 20mA
- What is the minimum guaranteed *HIGH* voltage (called V_{OH})provided by an I/O pin? 2.0V
- What is the maximum current we can pull from the $3.3V$ supply on the board? 500mA
- What is the maximum current we can pull from the $5V$ supply on the board? 500mA

If the actuator you are driving has requirements that exceed *either* of these limitations, you must devise an auxiliary circuit to make up for the deficiencies.

As a simple example, suppose you have a 10Ω resistive heating element. You are asked to use your Nucleo to turn the heater on and produce at least 1.0W of heat to keep an (exceedingly small) cup of coffee warm. Can you do it directly from the Nucleo?

Using Ohm's Law (1) and the Power Rule (2) answer the following questions.

$$V = IR \qquad \text{Ohm's Law (1)}$$
$$P = IV \qquad \text{Power Rule (2)}$$

Deliverable 2: Current Required *(3 points)*

- Using the value for V_{OH} from above, how much current would be required to produce 1.0W in the heater? 500mA
- Can the Nucleo power supply provide this? Yes, barely
- Can a Nucleo IO pin provide this? No
- Using V_{OH} and the maximum current from Deliverable 1 what is the actual maximum heat you could produce without external circuits? 1.0W

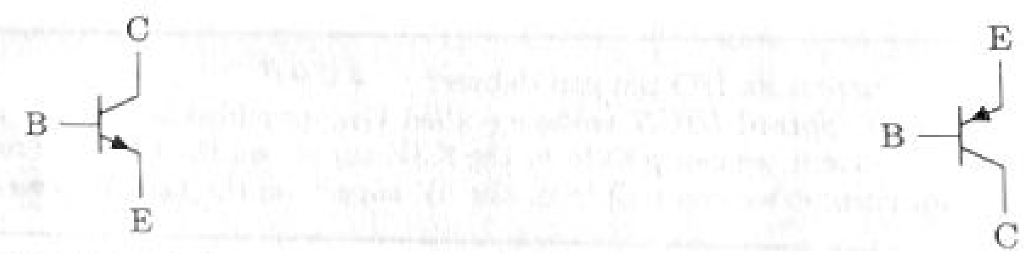
2.2 Introduction to Transistors

There are two main families of transistors. They are the bipolar junction transistor (BJT or bipolar) and the metal oxide field effect transistor (MOSFET or FET). Within each of these families are two subcategories. Bipolar transistors are either PNP (P-type) or NPN (N-type) and mosfets are either P-channel (PFET or PMOS) or N-Channel (NFET or NMOS). In all cases, the name provides a bit of detail about exactly how the device is constructed, but more importantly, it provides a mneumonic which helps to remember how we will use the devices[1].

In this lab, we will be using these devices as switches, specifically to connect an actuator to either a positive supply voltage (high side drive) or ground (low side drive). If you associate **P** (as in PNP or PFET), with **Postive** voltage and **N** (as in NPN or NFET) with **Negative** (ground) voltage, you will be assured of using the correct type of device for a given problem.

2.2.1 BJT Operation

An NPN transistor (Fig 1a) has three terminals called the Collector, Base, and Emitter. The PNP variant (Fig 1b) has the same terminals. We are going to be using these transistors in a regime called *saturation*.



(a) NPN Terminals

(b) PNP Terminals

Figure 1: Bipolar Schematic Symbols

When operated in saturation (as a switch), there are only a few parameters of interest to the designer. They are listed below.

- β also called h_{FE}: The current gain.
- V_{BE}: The voltage required across the base-emitter terminals to begin operating.

[1] We are using these devices in a very constrained manner. As such, we will only be scratching the surface of their capabilities. If you want to understand more, consider taking ES32 and ES61, which cover their use in much greater depth or ES60 which explores their construction and the physics that allows them to work. ES31 will teach you how to use MOSFETs to create digital logic gates.

Deliverable 3: Bipolar Datasheets *(2 points)*

Examine the BJT data sheets on Canvas and fill in the table below with your findings.

Part Number	Type (NPN or PNP)	β (h_{FE})	Max collector current
KSC2073	NPN	75	1.5A
TIP42	NPN	75	6A
2N3906	PNP	100	-200mA
2N3904	NPN	100	200mA

To first order, the BJT in saturation can be modelled by (3), where β is the current gain of the device and ranges from about 20 for very large devices to 200 for very small devices. We will generally be using devices in the "large" category.

$$I_C = \beta I_B \tag{3}$$

As depicted in the circuit symbol, there is a diode between the base and the emitter. The device's output current (I_C) flows between the collector and the emitter. It is governed by the base current (I_B) flowing between the base and the emitter.

As soon as there is enough voltage between the base and emitter (V_{BE}) current will start to flow. The voltage required is the forward bias voltage of the diode and is generally around $0.7V$. For a PNP device, the base must be $0.7V$ below the emitter, which is typically tied to the highest voltage in the system.

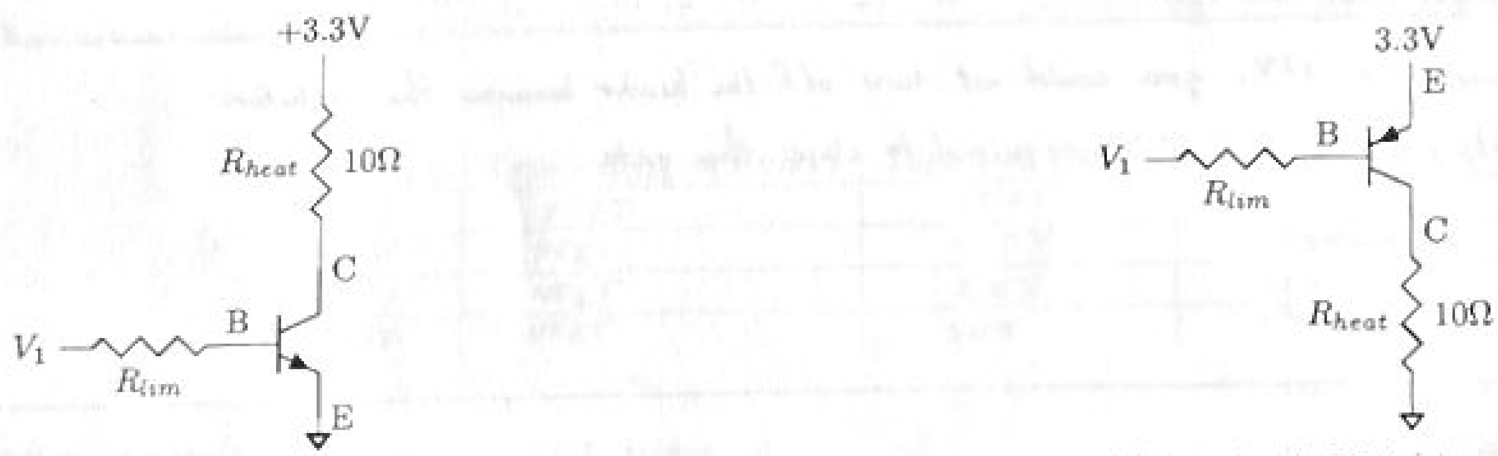
Once a base current (I_B) has been established, (3) governs the behavior of the collector current (I_C).

Because the base-emitter drops a fixed voltage, we must take care to ensure that we *limit* the amount of current flowing into the base terminal. This usually comes in the form of a series resistance. The example in section 2.2.2 will make this more clear.

2.2.2 Analyzing the low side NPN driver

Returning to our heater example, Figure 2a shows a complete circuit to control our heater. The heater is represented here as a resistor (R_{heat}) and the controller output pin produces a voltage on V_1. (Note this voltage is V_{OH} as determined in Deliverable1).

For this example, assume we are using a KSC2073 as the transistor.



(a) A low side NPN driver

(b) A high side PNP driver

Figure 2: Bipolar Load Drivers

R_{lim} is used to control the amount of current flowing through the base-emitter path. How do we determine a reasonable value for R_{lim}?

Start by determining how much current we need to pass through the R_{heat} to generate the required minimum heat of $1.0W$. (Note - for this analysis, we assume that the voltage between the collector and emitter (V_{CE}) is zero. This is a reasonable approximation for a device in saturation).

1. Determine the required collector current.
   (a) Use KVL to find $V_{heat} = 3.3V - V_{CE} = 3.3V$
   (b) From (2) this means we need $1.0/3.3V = 300mA$
2. Determine the base current required.
   (a) From (3): $I_B = I_C/\beta$
   (b) From the KSC2073 datasheet: $I_B = I_C/40 = 7.5mA$
3. Now determine the proper resistance.
   (a) Use KVL to show that $V_{lim} = V_{OH} - V_{BE} = 2.9V - 0.7V = 2.2V$
   (b) Calculate R_{lim} from (1): $R_{lim} = V_{lim}/I_B = 2.2V/7.5mA = 293\Omega$

In this example a 293Ω resistor and a transistor with exactly $\beta = 40$ will provide *exactly* the right amount of current. In practice all of these values have temperature and manufacturing variations and cannot be relied on to be *exactly* correct at all times. In order to provide some *design margin* we want to ensure that the NPN device can provide *at least* enough current. Generally a factor of two is plenty for this type of circuit, so we would choose a limiting resistor around 150Ω.

For completeness, a high side bipolar driver is shown in Figure 2b. The analysis of this circuit proceeds along the same lines as the low side version. The main difference is where the base and emitter are connected.

Deliverable 4: High Side PNP *(3 points)*

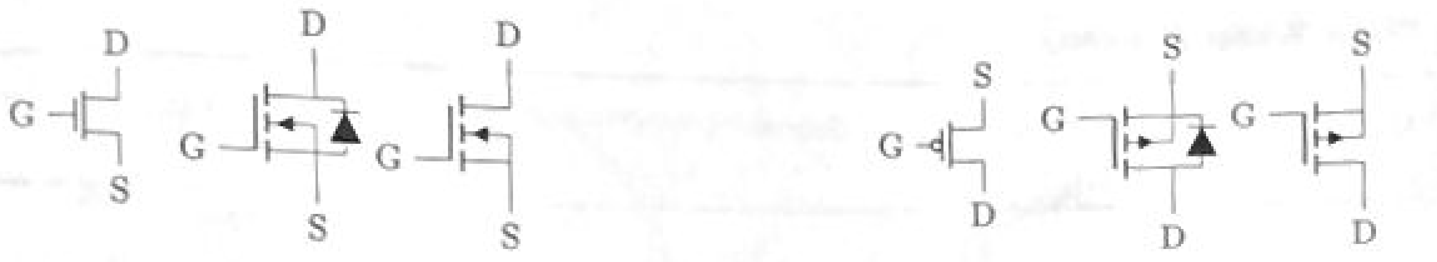
Examine the high side driver circuit (Figure 2b) and determine whether a HIGH ($3.3V$) or LOW ($0V$) output from the controller will activate the heater.
If the supply voltage for the heater was changed to 12V and the controller remained on a 3.3V supply, would this circuit still work? (Could you turn OFF the heater?)
Briefly explain your reasoning in the space below.

A LOW output from the controller activates the heater, as then $V_{BE} > 0.7V$.
If the supply was 12V, you could not turn off the heater because the controller could not provide the 11.3V required to close the gate.

2.2.3 MOSFET operation

Like the bipolar devices, the MOSFETs (Fig 3a and 3b) have three terminals. They are the Gate, the Drain, and the Source. Like BJTs, the controlling terminal (the Gate in this case) is used to modulate the amount of current that can flow between the other two terminals (Source and Drain).

For our purposes, there are 3 main differences between FETs and BJTs.



(a) NFET Terminals

(b) PFET Terminals

Figure 3: MOSFET Schematic Symbols

1. The FET is controlled by the voltage on the gate, not the current into it. (In fact, the current into the gate is zero!)
2. Current can flow in either direction between the source and drain.
3. FETs can *easily* be destroyed by Electrostatic Discharge (ESD).

Note!

Whenever you handle an FET, be sure to discharge any static electricity before touching the device. The easiest way to do this is to touch a large metal object prior to picking up the FET.

It is sometimes instructive to think of a MOSFET as a voltage controlled resistor. A voltage applied between the gate and the source (V_{GS}) controls the resistance between the drain and source (R_{DS}).

The main parameter associated with a MOSFET is its threshold voltage (V_t). This is somewhat like the diode voltage in the BJT, except that it is much more varied. As with the BJT, we will be using FETs in *saturation*. Saturation occurs when the gate-source voltage (V_{GS}) is much greater than the threshold voltage. When this occurs the resistance between the drain and source (R_{DS}) goes essentially to zero. For our purposes, a MOSFET obeys (4) and (5).

$$R_{DS} = 0 \qquad \text{if } |V_{GS}| \gg |V_t| \tag{4}$$

$$R_{DS} = \infty \qquad \text{if } |V_{GS}| \ll |V_t| \tag{5}$$

Deliverable 5: MOSFET Datasheets *(2 points)*

Fill in the table below with values from the datasheets.

Part Number	Type (NFET or PFET)	Threshold Voltage	Max drain current
IRF9Z24	PFET	-2.0V	-12A
BS250P	PFET	-1.0V	-230mA
IRFZ24	NFET	2.0V	12A
BS107P	NFET	1.0V	120mA

2.2.4 Analyzing a high side PFET driver

It is often the case that your actuator will require more voltage than your controller can withstand. For example, what if our heater was 144Ω? If we were still tasked with extracting 1.0W from it, we'd have no choice but to raise the voltage applied to it.

Deliverable 6: Heater Voltage *(1 points)*

> Use Ohm's law and the power law ((1) and (2)) to determine what voltage you would need to apply to the new heater to extract the same 1.0W. 12 V

This voltage is appreciably higher than the maximum voltage the controller can handle. To solve this problem, we will use a high-side MOSFET driver.

To understand the operation of the high side driver shown in Fig 4 begin by assuming V_{in} is low. This means that $V_{GS} \ll V_t$ and (5) governs the operation of N1.

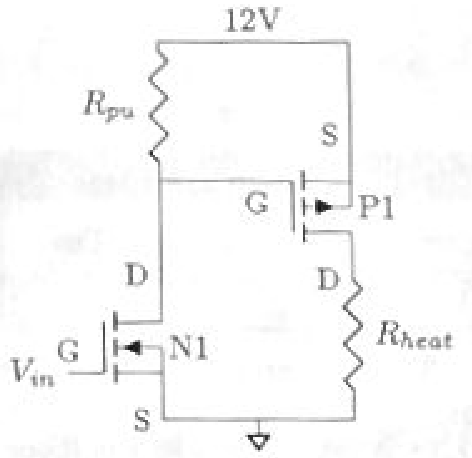


Figure 4: A high side MOSFET driver

With $N1$ *off*, the Gate of $P1$ is connected to the positive supply ($12V$) through the pullup resistor R_{pu}. As mentioned earlier, no current flows into the gate of a MOSFET. R_{DS} for $N1$ is infinite, so no current flow there either. By KCL, I_{pu} is zero, so V_{pu} is also zero. KVL now tells us the the voltage on the Gate of $P1$ is $12V$ and therefore, V_{GS} for $P1$ is also zero and the current through the PFET is zero. The heater is off.

Now, look at the other case, when V_{in} is high ($3.3V$). Now, (4) governs $N1$. R_{DS} of $N1$ is now zero, so the gate of $P1$ is at $0V$ and V_{GS} is $-12V$. Again, (4) holds, and R_{DS} for $P1$ is also 0. Now, the heater has the full $12V$ across it and produces the required 1.0W of heat.

What about R_{pu} (the pullup resistor)? How big should it be? Its only job is to ensure that when $N1$ is off, the gate of $P1$ is pulled all the way up to V_{CC} ($12V$ in this case). The resistance should be large enough that $N1$ doesn't need to provide too much current when it is turned on. Generally a value of $1K\Omega$ to $10K\Omega$ is fine here.

If you are curious, R_{pu} can be constrained by determining the capacitance of the Gate node of $P1$ (this *node* also contains the Drain of $N1$). The size of the pullup governs how quickly the PFET will turn off. When it is on, $V_G = 0V$. The voltage when the NFET turns off will be governed by a saturating exponential $V_G = 12(1 - e^{-t/RC})$. One can solve this equation to find the time at which $V_G = V_{cc} - V_t$ in terms of R. R can be adjusted as needed to set the *turn off* time of the circuit. Once R_{pu} is known, $N1$ could be chosen to provide a comparable *turn on* time. In practice, this level of detail is seldom required.

3 Procedure

3.1 Examine the solenoid

A solenoid[2], pictured in Fig 5 is fundamentally a coil of wire wound around a hollow core. Maxwell's equations tell us that anytime charges move, a magnetic field is induced. Thus, if we run a current through the solenoid, a magnetic field will develop. The right hand rule can be used to determine the orientation of the magnetic field. (Note - because it is more fun, we are actually using a solenoid actuated cabinet lock shown in Figure 6)

[2] From www.electricsolenoidvalves.com

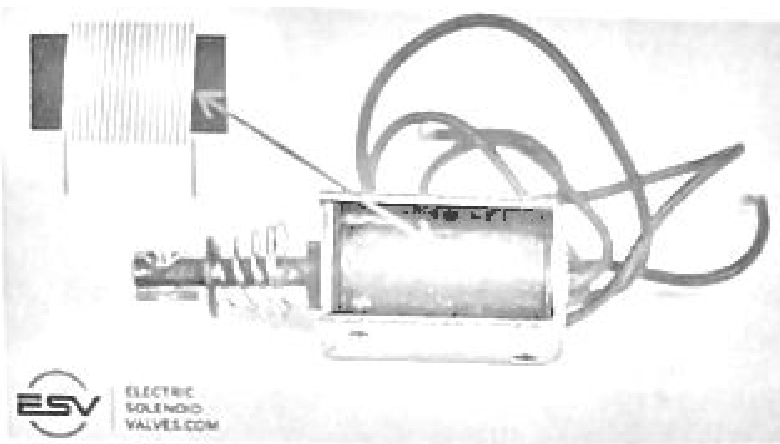


Figure 5: A solenoid

Figure 6: A solenoid

In our case, the magnetic field is directed along the long axis of the solenoid. Inside the core of the solenoid, we find a ferromagnetic rod (typically steel) attached to the solenoid housing with a spring. When enough current is applied to the solenoid, the magnetic force attracting the rod will overpower the spring and the rod will move.

When the current is removed, the magnetic field collapses and the spring takes over, returning the rod to its resting position. This is one way we can convert electrical energy into linear motion.

Deliverable 7: Solenoid Characteristics *(3 points.)*

- Use your multimeter to measure the resistance between the two leads on the solenoid.
- The solenoid requires 300mA to actuate. Given the resistance you have measured, what is the minimum voltage required across the solenoid?
- Can the Nucleo drive this solenoid directly? Briefly explain why or why not in the space below.

$R = 26.1\Omega$

$V = (300mA)(26.1\Omega) = 7.83V$

No, as the Nucleo can provide at most 5 V.

3.2 Construct an NPN low side driver.

Because your Nucleo can only provide 3.3V to drive the solenoid, we will need to use the power brick in your kit.

For these circuits, we will use a barrel jack adapter shown in Figure 7 to connect directly to the breadboard. You will use the pin labelled VIN for these cicuits. This will allow the full 9V from your adapter to power to solenoid.

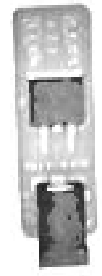


Figure 7: Adapter Board

Note!

Remove the 3.3V connection between your Nucleo and your breadboards before proceeding.

Construct the circuit shown in Figure 9. Using values obtained earlier from the data sheets, calculate a reasonable value for R_{lim}. Be sure to include it in your circuit or you will run the risk of burning out your Nucleo. The transistor we are using is a KSC2073TU. Its data sheet is available in the assignment page on Canvas. The device is pictured in Fig 8. Be sure to note which terminal is which when wiring it up.

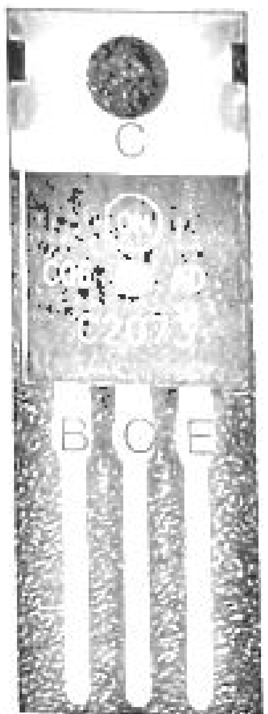


Figure 8: KSC2073

$$I_B = \frac{300mA}{\beta} = \frac{300mA}{40} = 7.5mA$$

$$R = \frac{V_{OH} - V_{BE}}{I_B} = \frac{2.0V - 0.7V}{7.5mA} = 173\,\Omega$$

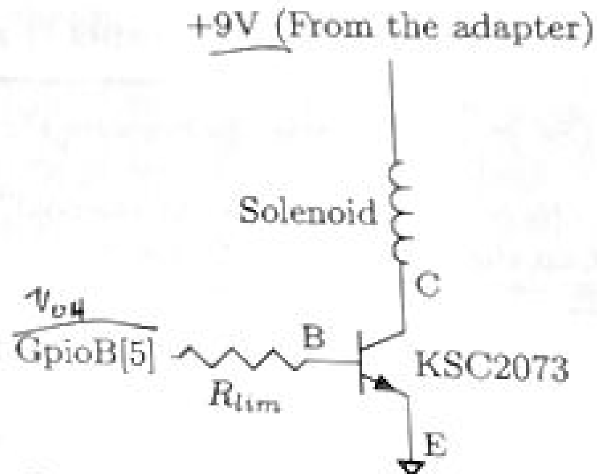


Figure 9: A low side solenoid driver

Deliverable 8: Current Limit Calculation *(2 points)*

What value did you calculate for R_{lim}? Show your reasoning for partial credit. Check with an instructor or a TA before energizing this circuit.

173Ω

Doc Rev: 0x4d3f

Note!

When the solenoid turns off, the magnetic field collapses and creates a very large *induced* voltage on the two wires. To prevent the voltage from doing any damage, there is a diode in place across the two leads. To function properly, the **RED** lead must be connected to the more positive voltage, and the **BLACK** lead must be connected to the more negative voltage.

Connect your push button (with a debouncing capacitor!) to a GPIO on your controller. You can use the same configuration as last week's lab if you wish.

Using your code from last week as a starting point, program your controller so that when the button is pushed, the solenoid will fire, opening the lock. When the button is released, the solenoid should return to its resting (locked) position.

The full circuit is shown in Figure 13 in Appendix A.1

Deliverable 9: Current through the solenoid *(1 points)*

Measure the voltage across R_{lim}. How much current is the Nucleo IO pin providing? 2.5V, I=10.5mA
Measure the voltage across the solenoid. How much current is it consuming? V = 8.77V, I = 0.32mA

You have just demonstrated the use of a small current to control a much larger current!

3.3 Construct a PFET high side high voltage driver.

Now we will take a look at a highside FET driver.

Note!

Be very careful when handling MOSFETs. The gate oxide is very thin (on the order of $5x10^{-10}m$). Any static electricity accumulated on your body can easily destroy the device.

Before you touch either of these transistors, be sure to discharge any accumulated static by touching a large conductive object (a table leg will generally suffice). It is also a good idea to grab all three legs of the device at the same time. This ensures that all 3 terminals are at the same potential and no current can flow.

Construct the circuit shown in Figure 12. In this circuit, there are two very different transistors. The larger *power* transistor is a IRF9Z24. The smaller *signal* transistor is a BS107P. The smaller transistor (an NFET) doesn't need to provide any significant current and is therefore much smaller (and cheaper) than the larger PFET.

You can use the same switch configuration for this section as for the last.

Confirm that this circuit is also capable of driving the solenoid.

Deliverable 10: I_{off} *(1 points)*

Measure the voltage across R_{pu} when the solenoid is off. 0 V
How much current is flowing through the resistor? 0 A

This is another useful way to control a large load. The main difference with this circuit when compared with the NPN version is that this circuit requires no current from the Nucleo once the NFET is turned on (or off).

The full circuit is shown in Figure 14 in Appendix A.2.

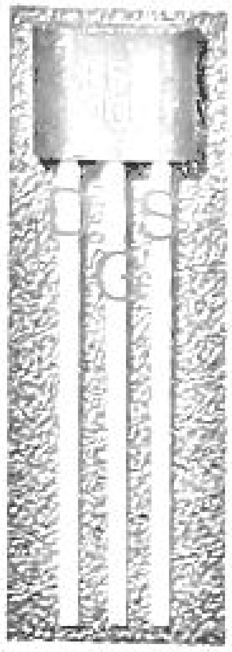


Figure 10: BS107P

Figure 11: IRF9Z24

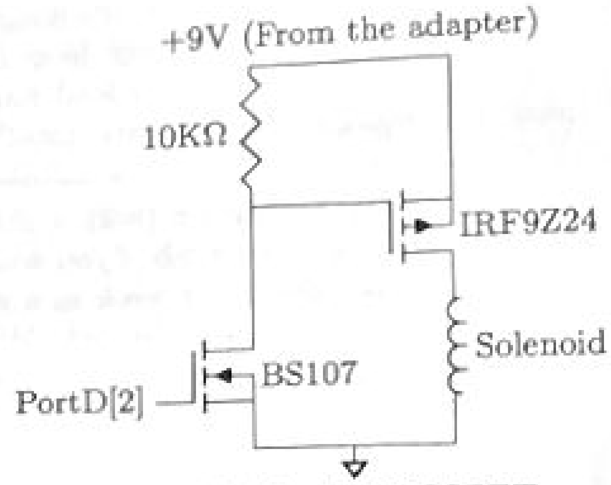


Figure 12: A high side MOSFET driver

V_{IN}	Solenoid
0	0
1	1

3.4 Coding Challenge

For this final exercise, you will implement two commands that can be issued from CoolTerm which will replace the functionality provided by the button.

Imagine that the solenoid controls a door latch. When the solenoid is energized (retracts), the door is open. When it is not energized, the door is closed (and latched).

For this exercise, you will check the uart (`uart2_read()`) looking for either of the following commands.

1. "O": Open the door. Opens the door (energizes the solenoid), equivalent to pressing the button. The door remains open until a close command is issued.
2. "C": Close the door. Closes the door (de-energizes the solenoid), equivalent to releasing the button.

A word about the code

When writing this code, think about separating the various components into small, self contained blocks. You should have two distinct sections. One to process any commands, and one to change the state of the lock if required.

This practice clearly separates the sensors and actuators and allows easy modification of either part of the system.

Have fun!

Deliverable 11: Remote Locking *(5 pts)*

Demonstrate your working code to a TA or Instructor.

TA or Instructor Signature