Lab 2-3. Breathing LED (Switch and LED Interfacing)

Preparation

1. Read Sections 1.17, 2.4.2, 2.7.2, 2.7.4 and 3.3
2. Look at Canvas for starter file download information from Git

Purpose

The purpose of this lab is to learn how to interface a switch and an LED and to program the LED to operate at a variable duty-cycle determined by the switch. The last 10% of the lab grade is for making the LED "breathe". You will also perform explicit measurements on the circuits in order to verify they are operational and to improve your understanding of how they work.

System Requirements

The primary task of the lab is to make an LED toggle at 8 Hz with varying duty-cycle.

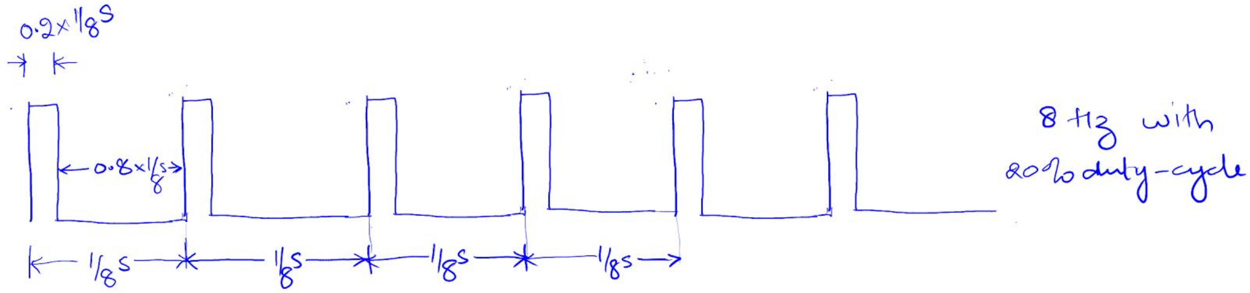
The external hardware for the lab includes, One button, one LED and associated components needed to interface them. In addition the internal (on-board) switch on PF4(SW1) is also used:

- PE1 is positive-logic Button input (1 means pressed, 0 means not pressed)
- PE0 is positive-logic LED output (1 activates external9 LED on protoboard)
- PF4 is negative-logic on-board button SW1 on Launchpad (0 means pressed, 1 means not pressed)

Overall functionality of this system is to operate as follows:

1. Make PE0 an output and make PE1 and PF4 inputs.

2. The system starts with the the LED toggling at 8Hz, which is 8 times per second with a duty-cycle of 20%. Therefore, the LED is ON for (0.2*1/8)th of a second and OFF for (0.8*1/8)th of a second.



3. When the button on (PE1) is pressed-and-released increase the duty cycle by 20% (modulo 100%). Therefore for each press-and-release the duty cycle changes from 20% to 40% to 60% to 80% to 100%(ON) to 0%(Off) to 20% to 40% so on.
4. Implement a "breathing LED" when SW1 (PF4) on the Launchpad is pressed:
   a. Be creative and play around with what "breathing" means. An example of "breathing" is most computers power LED in sleep mode (e.g., https://www.youtube.com/watch?v=ZT6siXyIjvQ).
   b. When (PF4) is released while in breathing mode, resume blinking at 8Hz. The duty cycle can either match the most recent duty-cycle or reset to 20%.

Procedure

Back in Lab 0, you developed and debugged your system using the simulator, however the code you developed could also be run on the real board (try it). In this lab you will build and test your hardware for the real-board but for software debugging purposes it may be useful to run in simulation mode.

To run the simulator, you must do two things. First, execute Project->Options and select the Debug tab. The debug parameter field must include **-dEE319KLab3**. Second, the **EE319KLab3.dll** file must be present in your Keil\ARM\BIN folder (already installed during the EE319Kware install step you performed for Lab0).

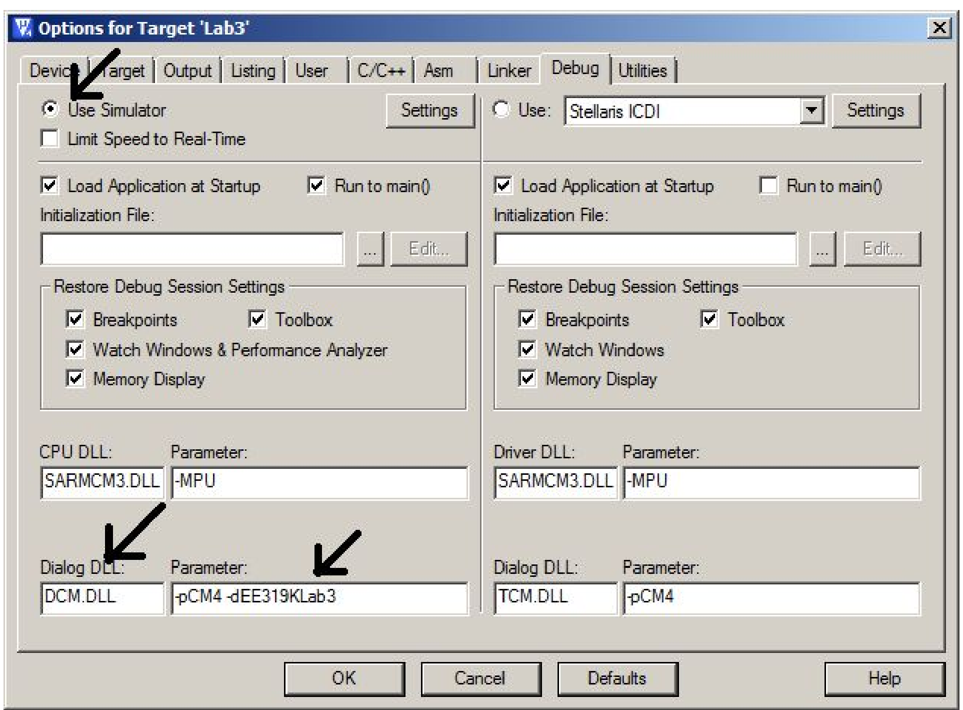


Figure 3.1a. Using TExaS to debug your software in simulation mode (DCM.DLL -pCM4 -dEE319KLab3).

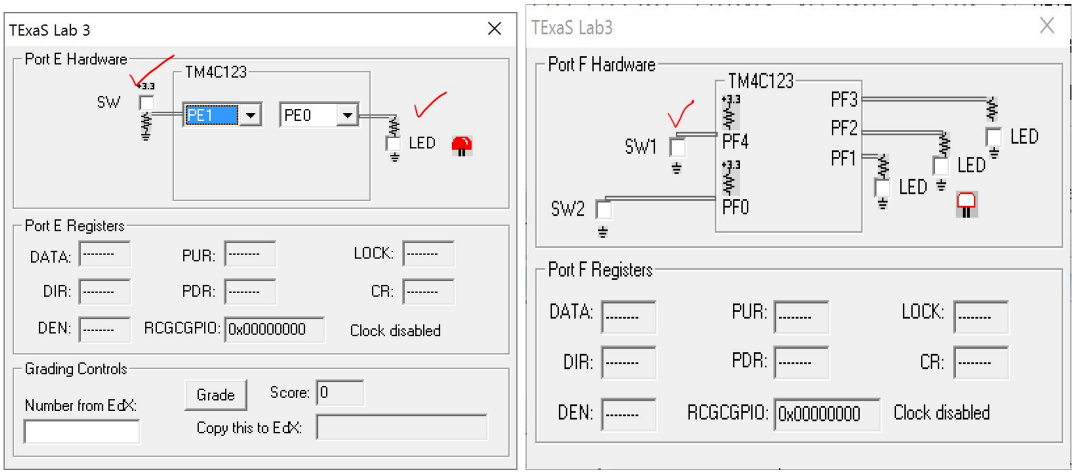


Figure 3.1b. Simulation of Ports E and F

Part a - Develop Incrementally

The best approach to time delay will be to use a hardware timer, which we will learn to use in Lab 4. In this lab we do not expect you to use the hardware timer. Again, use the logic analyzer on the simulator to verify the software operates properly.

Whenever we call **TExaS_Init**, we activate the phase lock loop (PLL) and run at 80 MHz.

Time is very important to embedded systems. One of the simplest ways in which we manage time is by determining how long it takes to run our software. One method we use to measure time in our embedded systems is to measure the time each instruction takes to execute. There are two ways to determine how long each instruction takes to execute.
The first method uses the ARM data sheet. For example, the following is a page from the Cortex-M4 Technical Reference Manual. E.g., see pages 34-38 of
http://users.ece.utexas.edu/~valvano/EE345L/Labs/Fall2011/CortexM4_TRM_r0p1.pdf

Load	Word	`LDR Rd, [Rn, <op2>]`	2^b
	To PC	`LDR PC, [Rn, <op2>]`	$2^b + P$
	Halfword	`LDRH Rd, [Rn, <op2>]`	2^b
	Byte	`LDRB Rd, [Rn, <op2>]`	2^b
	Signed halfword	`LDRSH Rd, [Rn, <op2>]`	2^b
	Signed byte	`LDRSB Rd, [Rn, <op2>]`	2^b
	PC relative	`LDR Rd,[PC, #<imm>]`	2^b

On the TM4C123 the default bus clock is 16 MHz ±1%. However using Texas_Init engages the Phase-Lock-loop (PLL) and runs the TM4C123 at 80MHz. At 80MHz one clock-cycle takes $1/80*10^6$seconds or 12.5nanoseconds. The following is a portion of a listing file (diss-assembly) with a simple delay loop. The SUBS and BNE instructions are executed 800 times. The SUBS takes 1 cycle and the BNE takes (1+P) where P can vary between 1 and 3 cycles. In simulation P is 2 making the wait loop be of 4 cycles. On the real-board P can vary because of optimization using a pipeline. The minimum time to execute this code is 800*(1+(1+1))*12.5 ns = 30 μs. The maximum time to execute this code is 800*(1+(1+3))*12.5 ns = 50 μs. Since it is impossible to get an accurate time value using the cycle counting method, we will need another way to estimate execution speed.

```
0x00000158 F44F7016        MOV R0,#800
0x0000015C 3801      wait  SUBS R0,R0,#0x01
0x0000015E D1FD            BNE  wait
```

*(note: the **BNE** instruction executes in 3 cycles on the simulator, but an indeterminate number of cycles on the real board)*

An accurate method to measure time uses a logic analyzer or oscilloscope. In the simulator, we will use a simulated logic analyzer, and on the real board we will use an oscilloscope. To measure execution time, we cause rising and falling edges on a digital output pin that occur at known places within the software execution. We can use the logic analyzer or oscilloscope to measure the elapsed time between the rising and falling edges. In this lab we will measure the time between edges PE0.

We suggest developing the code in stages:
Stage1: Write a simple main loop that toggles an LED(PE0) at 8Hz with a 50% duty-cycle calling a delay subroutine. This should be simple:

```
Loop
    Delay for 1/16th of a second
    Toggle PE0
     B   Loop
```

Stage2: Rewrite code in Stage1 so you can program a target duty-cycle (say 20%). Verify in simulator using the Logic Analyzer that you indeed have a 8Hz signal with the target duty-cycle.
Stage3: Introduce the switch(PE1) into the logic and use it to modify the duty-cycle. Note that the duty-cycle change has to happen on the press followed by a release. Therefore the change takes effect on the release. Test in simulator and verify function using the Logic Analyzer (https://youtu.be/5fD71LdAXZs).
Stage4: Build the circuit (see figure below) and check twice to make sure you have it correct. If in doubt take it to a TA during their office hours. Connect the real-board and flash it with the code you wrote in Stage3. You will see a flashing LED and the effect of changes in the duty-cycle are visible to the naked eye. Note at this point that the Logic Analyzer in Keil no longer is available as a tool as it only works in Simulation. To verify the timing of the LED's toggling you can use an external Oscilloscope or TexasDisplay (https://youtu.be/3Gi5e4iljuE).
Stage5: At this point you implemented 90% of the requirement of this lab. Now you will add the breathing feature which is enabled when PF4 (SW1) is pressed and disabled when released. We want you to be creative in devising a solution to implement this feature. However, here are some ideas:

- A breathing LED increases in brightness gradually and once it reaches its full brightness it decreases it brightness gradually till it reaches zero brightness. At which point it again repeats the increase.
- A frequency of 8Hz is low enough to be visible to the naked eye. We need the toggle the LED at a higher frequency (say 80Hz) to be able to see the desired effect of duty-cycle impacting brightness.
- Varying brightness is achieved by varying duty-cycle. You may need more than 5 levels of duty-cycle for better breathing feel.
- Consider changing the duty-cycle at a programmable rate. That is, if your current duty-cycle is x%, stay at this duty-cycle for N iterations before changing to (x ± d)%.
- Remember, you can play with both the frequency and the duty-cycle.

Part b - Read Data Sheets

Engineers must be able to read datasheets during the design, implementation and debugging phases of their projects. During the design phase, datasheets allow us to evaluate alternatives, selecting devices that balance cost, package size, power, and performance. For example, we could have used other IC chips like the 7405, 74LS05, or 74HC05 to interface the LED to the TM4C123. In particular, we chose the 7406 or 74LS06 because it has a large output current

(I_{OL} = 40 mA), 6 drivers, and is very inexpensive (59¢). During the implementation phase, the datasheet helps us identify which pins are which. During the debugging phase, the datasheet specifies input/output parameters that we can test. Download the 7406 and LED datasheets, [7406.pdf]() and [LED_red.pdf](), and find the two pictures as shown in Figure 3.5. Next, hold your actual 7406 chip and identify the location of pin 1. Find in the datasheet the specification that says the output low voltage (V_{OL}) will be 0.4V when the output low current (I_{OL}) is 16 mA (this is close to the operating point we will be using for the LED interface).

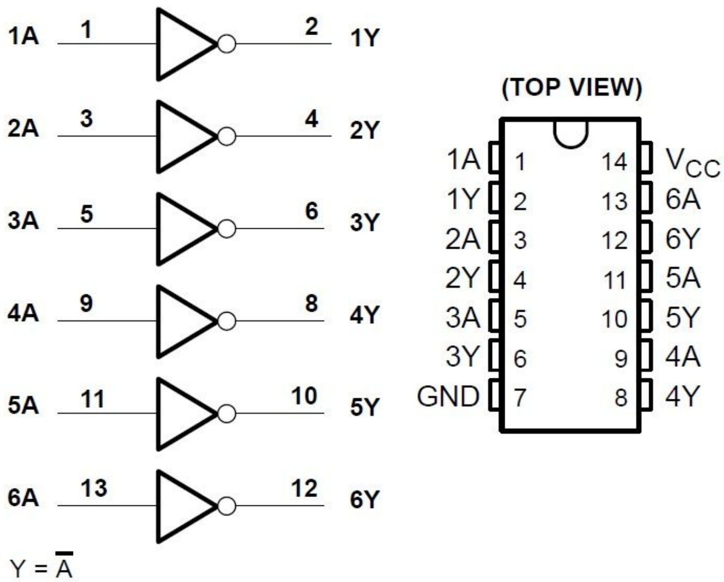


Figure 3.5. Connection diagram and physical package diagram for the 7406.

Using the data sheet, hold an LED and identify which pin is the anode and which is the cathode.

Sometimes we are asked to interface a device without a data sheet. Notice the switch has 4 pins in a rectangular shape, as shown in Figure 3.6. Each button is a single-pole single-throw normally-open switch. All four pins are connected to the switch. Using your ohmmeter determine which pairs of pins are internally connected (having a very small resistance), and across which pair of pins is the switch itself. In particular, draw the internal connections of the switch, started in Figure 3.6, showing how the four pins are connected to the switch.

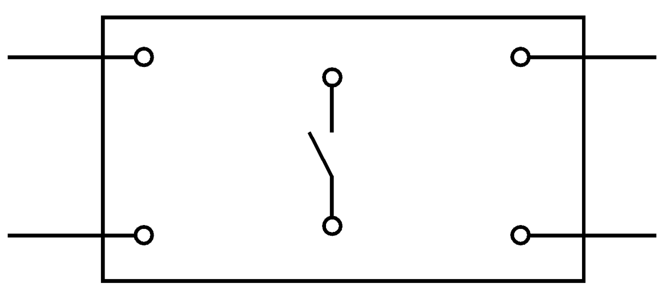


Figure 3.6. Connection diagram for the normally open switch.

To build circuits, we'll use a solderless breadboard, also referred to as a protoboard. The holes in the protoboard are internally connected in a systematic manner, as shown in Figure 3.7. The long rows of of 50 holes along the outer sides of the protoboard are electrically connected. Some protoboards like the one in Figure 3.7 have four long rows (two on each side), while others have just two long rows (one on each side). We refer to the long rows as power buses. If your protoboard has only two long rows (one on each side), we will connect one row to +3.3V and another row to ground. If your protoboard has two long rows on each side, then two rows will be ground, one row will be +3.3V and the last row will be +5V (from VBUS). Use a black marker and label the voltage on each row. In the middle of the protoboard, you'll find two groups of holes placed in a 0.1 inch grid. Each adjacent row of five pins is electrically connected. We usually insert components into these holes. IC chips are placed on the protoboard, such that the two rows of pins straddle the center valley.

To make connections to the TM4C123 we can run male-male solid wire from the bottom of the microcontroller board to the protoboard. For example, assume we wish to connect TM4C123 PE1 output to the 7406 input pin 1. First, cut a 24 gauge solid wire long enough to reach from PE1 and pin 1 of the 7406. Next, strip about 0.25 inch off each end. Place one end of the wire in the hole for the PE1 and the other end in one of the four remaining of the 7406 pin 1.

If you are unsure about the wiring, please show it to your TA before plugging in the USB cable. I like to place my voltmeter on the +3.3V power when I first power up a new circuit. If the +3.3V line doesn't immediately jump to +3.3V, I quickly disconnect the USB cable. Alternatively, you can monitor the +3.3V line with the green led in the upper portion of the launchpad near the usb connectors. If this led does not turn on when you think you are applying power, you might have a short circuit.

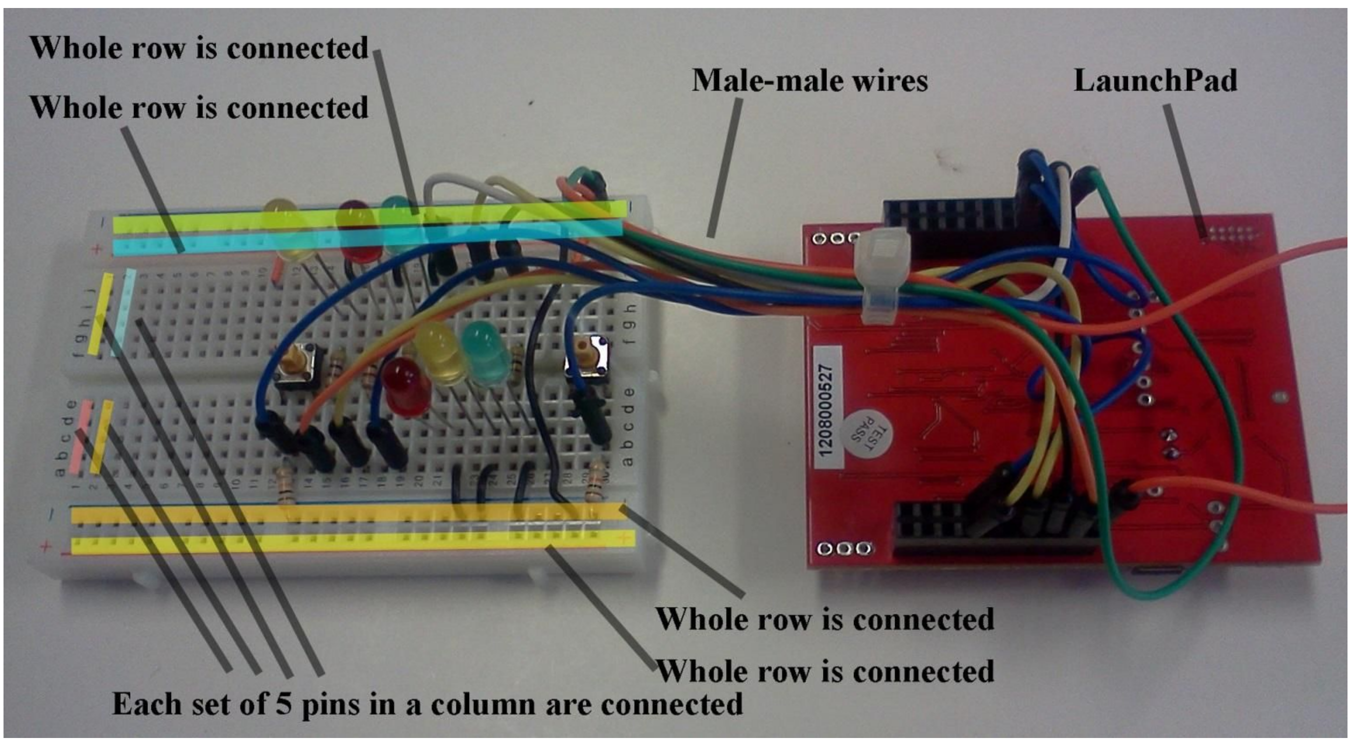


Figure 3.7. All the pins on each of the four long rows are connected. The 5 pins in each short column are connected. Use male-male wires to connect signals on the LaunchPad to devices on the protoboard. Make sure ground wire connected between the LaunchPad and your circuit. The +3.3V and VBUS (+5V) power can be wired from the LaunchPad to your circuit. I like to connect the two dark blue rows to ground, one red row to +3.3V and the other red row to VBUS(+5V).

Part c - Construct Circuit

After the software has been debugged on the simulator, you will build the hardware on the real board. Please get your design checked by the TA before you apply power (plug in the USB cable). *Do not place or remove wires on the protoboard while the power is on.* The circuit diagram for this lab is given in Figure 3.8.

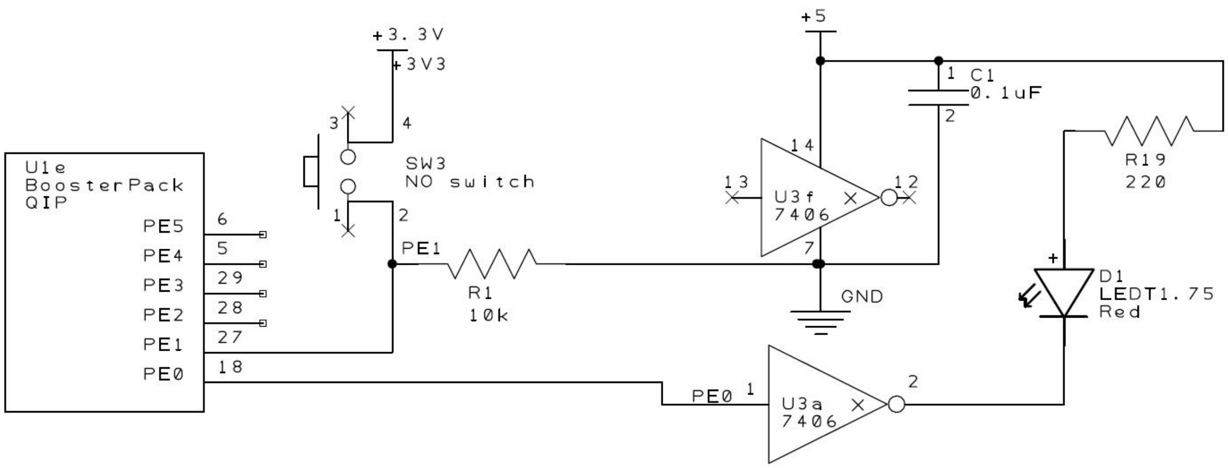


Figure 3.8. PCB Artist drawing showing Port E, 3.3V power, a 10kΩ resistor, a switch, one 7406 gate, an LED, a 220Ω resistor, a 0.1 μF capacitor, +5V power and ground.

Before connecting the switch to the microcontroller, please take the measurements in Table 3.1 using your digital multimeter. The input voltage (V_{PE1}) is the signal that will eventually be connected to **PE1**. With a positive logic switch interface, the resistor current will be V_{PE1}/10kΩ. The voltages should be near +3.3 V or near 0 V and the currents will be less than 1 mA. The goal is to verify the V_{PE1} voltage is low when the switch is not pressed and high when the switch is pressed.

Parameter	Value	Units	Conditions
Resistance of the 10kΩ resistor, R1		ohms	with power off and disconnected from circuit (measured with ohmmeter)
Supply Voltage, $V_{+3.3}$		volts	Powered (measured with voltmeter)
Input Voltage, V_{PE1}		volts	Powered, but with switch not pressed (measured with voltmeter)
			Powered, but switch not pressed

Resistor current		mA	$I=V_{PE1}/R1$ (calculated and measured with an ammeter)
Input Voltage, V_{PE1}		volts	Powered and with switch pressed (measured with voltmeter)
Resistor current		mA	Powered and switch pressed $I=V_{PE1}/R1$ (calculated and measured with an ammeter)

Table 3.1. Switch measurements.

Next, you can connect the input voltage to **PE1** and use the debugger to observe the input pin to verify the proper operation of the switch interface. You will have to single step through the code that initializes Port E, and PE1. You then execute the **Peripherals->TEXaS Port E** command. As you single step you should see the actual input as controlled by the switch you have interfaced, see Figure 3.8.

The next step is to build the LED output circuit. LEDs emit light when an electric current passes through them, as shown in Figure 3.9. LEDs have polarity, meaning current must pass from anode to cathode to activate. The anode is labeled **a** or **+** , and cathode is labeled **k** or **-**. The cathode is the short lead and there may be a slight flat spot on the body of round LEDs. Thus, the anode is the longer lead. LEDs are not usually damaged by heat when soldering. Furthermore, LEDs will not be damaged if you plug it in backwards. However, LEDs won't work plugged in backwards. Look up the pin assignments in the 7406 data sheet. Be sure to connect +5V power to pin 14 and ground to pin 7. The 0.1 μF capacitor from +5V to ground filters the power line. Every digital chip (e.g., 7406) should have a filter capacitor from its power line (i.e., pin 14 V_{CC}) to ground. The capacitor in your kit is ceramic, which is not polarized, meaning it can be connected in either direction.

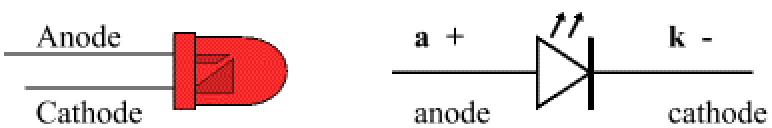


Figure 3.9. Left: a side view of an LED with leads labeled; Right: the corresponding circuit diagram

Take the measurements as described in Table 3.2. The R19 measurement occurs before R19 is inserted into the circuit. Single step your software to make **PE0** to output. Initially **PE0** will be low. So take four measurements with **PE0** low, rows 2,3,4,5 in Table 3.2. Then, single step some more until **PE0** is high and measure the three voltages (rows 8,9,10 in Table 3.2). When active, the LED voltage should be about 2 V, and the LED current should be about 10 mA. The remaining rows are calculated values, based on these 8 measurements. The LED current (row 12) can be determined by calculation or by direct measurement using the ammeter function. You should perform both ways to get LED current.

Warning: NEVER INSERT/REMOVE WIRES/CHIPS WHEN THE POWER IS ON.

Row	Parameter	Value	Units	Conditions
1	Resistance of the 220Ω resistor, R19		ohms	with power off and disconnected from circuit

				(measured with ohmmeter)
2	+5 V power supply V_{+5}		volts	(measured with voltmeter relative to ground, *notice that the +5V power is not exactly +5 volts*)
3	TM4C123 Output, V_{PE0} input to 7406		volts	with **PE0** = 0 (measured with voltmeter relative to ground)
4	7406 Output, V_{k-} LED k-		volts	with **PE0** = 0 (measured with voltmeter relative to ground)
5	LED a+, V_{a+} Bottom side of R19		volts	with **PE0** = 0 (measured with voltmeter relative to ground)
6	LED voltage		volts	calculated as $V_{a+} - V_{k-}$
7	LED current		mA	calculated as $(V_{+5} - V_{a+})$/R19 and measured with an ammeter
8	TM4C123 Output, V_{PE0} input to 7406		volts	with **PE0** = 1 (measured with voltmeter relative to ground)
9	7406 Output, V_{k-} LED k-		volts	with **PE0** = 1 (measured with voltmeter relative to ground)
10	LED a+, V_{a+} Bottom side of R19		volts	with **PE0** = 1 (measured with voltmeter relative to ground)
11	LED voltage		volts	calculated as $V_{a+} - V_{k-}$
12	LED current		mA	calculated as $(V_{+5} - V_{a+})$/R19 and

				measured with an ammeter

Table 3.2. LED measurements (assuming the 220 Ω resistor is labeled R19).

Part d - Debug Hardware + Software

Debug your combined hardware and software system on the real-board.

Demonstration

(both partners must be present, and demonstration grades for partners may be different)

You will show the TA your program operation on the actual TM4C123 board. The TA may look at your data and expect you to understand how the data was collected and how the switch and LEDs work. Also be prepared to explain how your software works and to discuss other ways the problem could have been solved. Why the 7406 was used to interface the LED? I.e., why did we not connect the LED directly to the TM4C123. Why do you think you need the capacitor for 7406 chip? What would the flashing LED “look” like if the delay were 1ms? How would you modify the software to change the rate at which LED flickers? What operating point (voltage, current) exists when the LED is on? Sketch the approximate current versus voltage curve of the LED. Explain how you use the resistor value to select the operating point. What is the difference between a positive logic and negative logic interface for the switch or the LED? We may test to see if you can measure voltage, current and/or resistance with your meter (so bring your meter to the demonstration).

Deliverables

(Items 2, 3, 4, 5, and 6 are one pdf file uploaded to Git , have this file open during demo.)

1. Lab 2-3 grading sheet (TA prints). You fill out the information at the top.
2. Circuit diagram (hand-drawn or optionally using PCB Artist)
3. Screenshots like Figure 3.10a,b showing your debugging in the simulator
4. Switch measurements (Table 3.1)
5. LED measurements (Table 3.2)
6. Assembly source code of your final program
7. Optional Feedback : http://goo.gl/forms/rBsP9NTxSy

Precautions to avoid damaging your system

1. Do not attach or remove wires on the protoboard when power is on. Always shut power off when making hardware changes to the system.
2. Touch a grounded object before handling CMOS electronics. Try not to touch any exposed wires.
3. Do not plug or unplug the modules into the LaunchPad while the system is powered.
4. Do not use the TM4C123 with any external power sources, other than the USB cable. In particular, avoid connecting signals to the TM4C123 that are not within the 0 to +5V range. Voltages less than 0V or greater than +5V will damage the microcontroller.
5. Do not use PC3,PC2,PC1,PC0. These are needed for the debugger.
6. You can’t use PA1 PA0 PD4 and PD5. These are connected to the serial port and USB.
7. If you use both PD0 and PB6, remove R9 from your board. If you use both PD1 and PB7, remove R10 from your board.

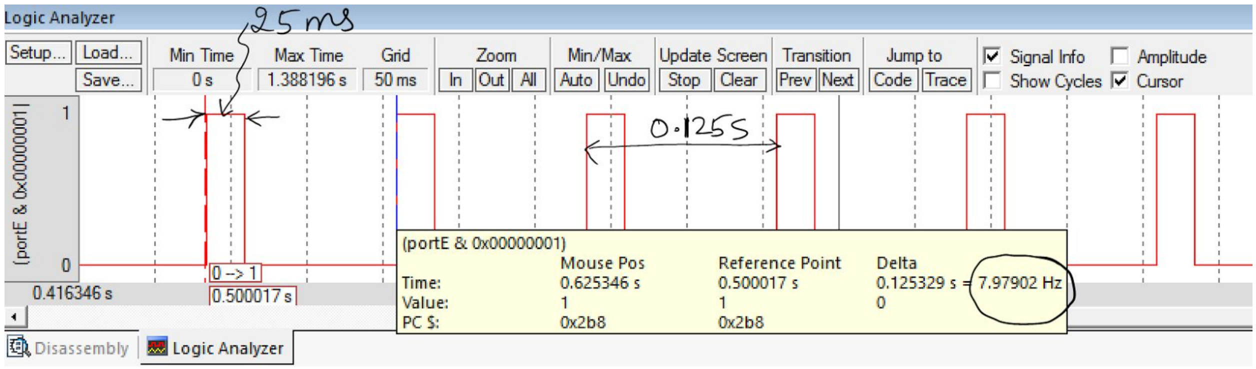


Figure 3.10a. Simulation of Lab 3, showing PE0 output toggling at 8 Hz with 20% duty-cycle.

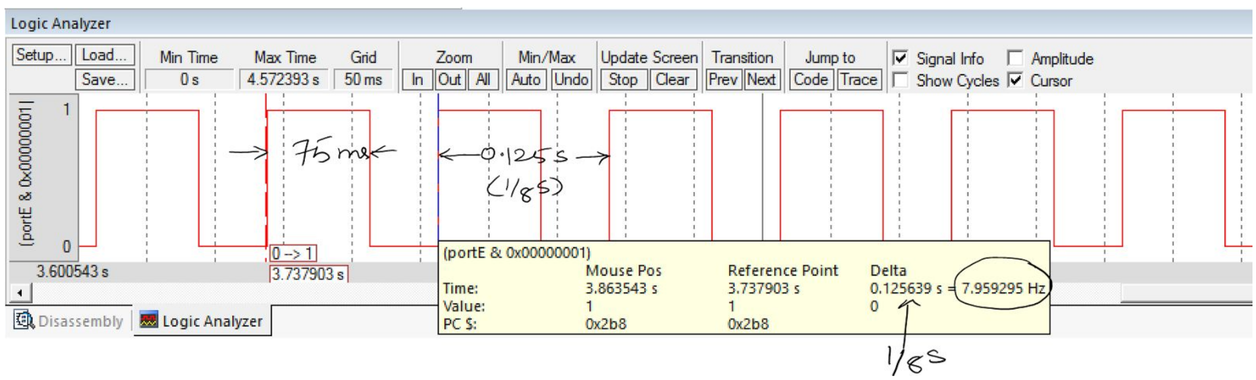


Figure 3.10b. Simulation of Lab 3, showing PE0 output toggling at 8 Hz with 60% duty-cycle.

FAQ

The list of FAQ below are populated from Piazza over the semesters (thanks to the contributions of all past TAs and students). More questions may be posted so please check back regularly.

1. For my 1/8s (125 ms) delay, I'm having trouble getting the delay up to the right number of ms. I've tried combining multiple delay subroutines to increase the delay, but i'm still quite a ways from 125ms. Can anyone share a smart way of increasing the delay?

   Notice that the clock for this lab is running at 80MHz instead. Your calculation in writing your delay loop count must account for this speed which implies each cycle is 12.5ns.

2. How are we supposed to determine which pair of pins has the switch across them using the ohmmeter? Each pair has the exact same resistance between them when I measure it.

   Were you measuring the resistance with the switch pressed? If so, all of the pins will be connected together and have the same, albeit small, resistance. Otherwise, if you were measuring with the switch not pressed, you should be measuring different resistances between different pairs. If you are absolutely sure this is not the case, it is possible that you could have a broken switch.

   The size of the resistance might also provide a hint as to what is going on (think about when the resistance should be very large and when it should be very small, assuming the switch is working correctly).

3. How do we measure current through a resistor?

You put the multimeter in series with the resistor. Or you can kind of "cheat" and measure the voltage, then calculate the current. You should understand how to do both ways though.

4. What is the bottom side of a resistor?

   The lab manual is sort of confusing when it says 'bottom side of R19', but what it wants is the voltage of the LED anode side. It refers to the part of the circuit 'below' the 220 resistor and 'above' the LED.

5. How do we measure stepwise data for rows 8 -10 on the table? I'm reading fluctuating data on the multimeter.

   With Keil you can debug your circuit in real time. If you click under Projects --> Options for Target --> Debug and use the stellaris ICDI instead of the simulator you can the press debug and actually step through your code and watch how it affects your circuit. Think about when in your program should PE1 be set to zero and jump to it. You can now measure these elements knowing that PE1 is supplying no voltage. The values can be expected to vary slightly.

6. After thoroughly checking my hardware wiring, I tried implementing it with the software and couldn't even get the LED to turn on. Are there any possible explanations for why this could be happening?

   Before moving on to circuits, make sure your program work first on the simulator. Once that is checked, make sure everything is connected securely. Circuit problems come from crappy wires most of the time.. are you using your own wires or wires from the check out desks? A multimeter will be your best friend when it comes to debugging a circuit.

7. Do we actually need to add a capacitor? What impact will it have to our system?

   The capacitor acts as a filter for the system's 5V power line. We are using the 5V line to power the 7406 buffer, which is being used as the current sink for our LED. When we are toggling it, and due to a ton of other random factors, we will see current and voltage fluctuations (typically pretty small in this type of system). The capacitor across the power line and ground will act as a sort of dampener/filter, resisting changes in voltage. This is to keep the 5V as close to 5V as possible amid voltage fluctuations. You circuit will likely work fine most of the time, but as your circuits become larger, more complex, and more dynamic, you may see certain systems drop below their necessary minimum Vcc and not function properly. You can think of the capacitor as a large water reservoir. Excess voltage will fill the tank, while a deficit will be countered by the excess "water" in the tank flowing out.

8. My logic analyzer no longer is showing the ports on the side. When I run it the analyzer is completely blank. Any idea on how to get the values of the ports back on the logic analyzer?