EECS 3100 Embedded Systems

Lab 7 - Traffic Light Controller

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Preparation (*to be completed prior to the lab session*)

- This is a team project.
- Read the **Lab07-PreLabReading.docx** document.
- Review the material on "**C Struct Type – A Tutorial**" for reference.
- Read this entire project assignment document carefully.
- Compile/Link/Simulate the sample project in **TrafficLight** folder.
- Complete Parts A through E of the **Procedure** section of this document prior to your lab demo session.
- Print and fill out the required information in **Lab07-DemoRecord** sheet and bring it to the lab session.
- Keil project template is in the folder entitled **…\Project Templates\Lab7_TrafficLight**

Purpose

This lab has the following major objective:

> *The study of real-time synchronization by designing a finite state machine controller and implementing it in embedded software using appropriate data structures.*

Software skills you will learn include advanced indexed addressing, linked data structures, creating fixed time delays using the SysTick timer, and debugging real-time systems.

Note: The Lab 7 starter file has the appropriate connections to the Lab 7 simulator extension/grader (EECS3100Lab7.dll). Also note that the call to TExaS_Init in the template code will activate the 80 MHz PLL.

Design Overview

Consider a two-street intersection as shown below. There are two one-way streets, labeled ***South*** and ***West*** for southbound and westbound cars to travel on.

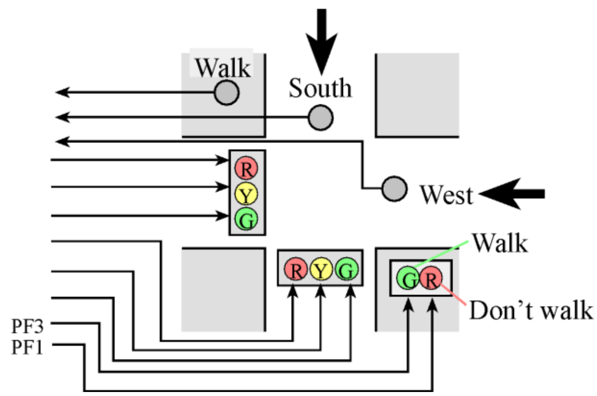


Figure 7.1. Traffic Light Intersection (3 inputs and 8 outputs).

- Inputs - there are 3 inputs to the system as follows:
    1. ***South Sensor****:* This sensor is to be activated (set to logic 1), if one or more cars are near the intersection on the South road. You will interface an on-off binary switch that will generate the activation signal for a simulated sensor. Pressing the switch will simulate sensor activation.
    2. ***West Sensor****:* Same as south sensor but for westbound traffic.
    3. ***Walk Button:*** Will be pushed by a pedestrian when he or she wishes to cross in any direction. A hardware switch will implement this button functionality. Closing or pressing the switch will simulate the button press effect.

- Outputs – you will use 8 outputs from your microcontroller to control the traffic lights.

    1. ***(6 LEDs) South & West, R/Y/G Lights***: You will have to interface a total of 6 LED’s for the South and West’s red, yellow and green lights.

    2. ***(1 LED) Walk light:*** This will be the green LED (PF3) on the LaunchPad, and will be turned on when pedestrians are allowed to cross. To request a walk, a pedestrian must push and hold the walk button for at least 2 seconds, after which a person can release the button, and the walk request should be serviced eventually. If the user does not hold down the button for 2 seconds this document does not specify what will happen, you may either go to the walking state(s) or not. We leave this decision up to the engineers designing the FSM. Your engineering decisions need to be documented as part of your project report.

       The walk sequence should be realistic, showing three separate conditions:
        1. ***Walk:*** Your walk light should be on signifying the pedestrians may cross. You may decide how long you want to allow pedestrians to cross. The two traffic signals will be red in this state.
        2. ***Warning***: Flash your “don't walk” LED signifying that pedestrians need to hurry up. You may decide how long you want to flash it.
        3. ***Don’t Walk:*** Your “don't walk” LED should be on and constant. The two traffic signals must change allowing the normal traffic flow.

3. ***(1 LED) Don't Walk light:*** This will be the red LED (PF1) on the LaunchPad.
    a. When the "don't walk" condition flashes (and the two traffic signals are red), pedestrians should hurry up and finish crossing in any direction.
    b. When the "don't walk" condition is on steady, pedestrians should not enter the intersection.

Procedure

The basic approach to this lab will be to first develop and debug your system using the simulator and then interface with actual lights and switches on a physical TM4C123. As you have experienced, the simulator requires different amount of actual time as compared to simulated time. On the other hand, the correct simulation time is maintained in the SysTick timer, which is decremented every cycle. The simulator speed depends on the amount of information it needs to update into the windows and the speed of your personal computer. Because we do not want to wait the minutes required for an actual intersection, the cars in this traffic intersection travel much faster than real cars. In other words, you are encouraged to adjust the timing so that the operation of your machine is convenient for you to debug and for the TA to observe during demonstration.

Part A - Pin/Port Selection

Decide which port pins you will use for the inputs and outputs. Avoid the pins with hardware already connected. Table 4.1 in the book lists the pins to avoid. Run the starter code in the simulator to see which ports are available for the lights and switches; these choices are listed in Tables 7.1 and 7.2. The "don't walk" and "walk" lights must be PF1 and PF3 respectively, but you have some flexibility when deciding where to attach the remaining signals. In particular, Table 7.1 shows you two possibilities for how you can connect the six LEDs that form the traffic lights. Table 7.2 shows you two possibilities for how you can connect the three positive logic switches that constitute the input sensors. Obviously, you will not connect both inputs and outputs to the same pin. Please note that the possibilities listed in Tables 7.1 and 7.2 are not the only possibilities.

Stoplight Signal	**Option 1**	**Option 2**
Red south	PA7	PE5
Yellow south	PA6	PE4
Green south	PA5	PE3
Red west	PA4	PE2
Yellow west	PA3	PE1
Green west	PA2	PE0

Table 7.1. Possible ports to interface the traffic lights (PF1=red don't walk, PF3=green walk).

Stoplight Sensor	Option 1	Option 2
Walk sensor	PA4	PE2
South sensor	PA3	PE1
West sensor	PA2	PE0

Table 7.2. Possible ports to interface the sensors.

Please note the following complications if you do not use the above options in Tables 7.1 and 7.2:

If you are using PD0, PD1, PB7, PB6, PB1 or PB0, make sure R9, R10, R25, and R29 are removed from your TM4C123 LaunchPad. The TM4C123 LaunchPads may not have R25 and R29 soldered on; in that case just remove R9 and R10. The R9 and R10 jumpers are only needed for some MSP430 booster packs running on the TM4C123, so there is little chance you will ever need R9 and R10.

Part B - FSM Design

Design a finite state machine that implements a traffic light system. Include a picture of your finite state machine in the deliverables clearly showing the various states, inputs, outputs, wait times and transitions. It is advisable that you consult with your TA to verify your FSM design before continuing to code. You must draw and generate the FSM diagram using a computer tool.

Note: It may be helpful to look at the "Engineering Questions" and also the "Tips and Tricks" Sections below for guidance.

Part C - Debug C Code in Simulation

Write and debug the C code that implements the traffic light control system.

Develop a comprehensive testing scenario to be employed for verification of the correctness of your design. Refer to Part E for reference.

In simulation mode, capture logic analyzer screen shots showing the operation of your traffic lights when cars are present on both roads.

Note: Automatic grader score will not be considered as part of your actual grade.

Part D - Construct and Test Circuit

Caution: Do not place or remove wires on the proto-board while the power is on.

After you have debugged your system in simulation mode, you will implement it on the real board. Use the same ports you used during simulation. **EECS3100_TM4C123_Artist.sch** is a starter file you should use to draw your hardware circuit diagram using the PCB Artist.

The first step is to interface three push-button switches for the sensors. You should implement positive logic switches. Build the switch circuits and test the voltages using a voltmeter. You can also use the debugger to observe the input pin to verify the proper operation of the interface.

The next step is to build six LED output circuits. Build the system physically in a shape that matches a traffic intersection, so the TA (or an observer) can better visualize the operation of the system.

Part E - Testing on Real Hardware

Debug your combined hardware/software system on the actual TM4C123 board. Then test the following scenarios, take a picture of the outputs for each.

Walk Behavior:

- The green LED is turned on when pedestrians are allowed to cross.
- System accounts for pedestrian pressing and releasing button after 2 seconds.
- System eventually processes walk request.

The walk sequence should be realistic, showing three separate conditions:

- ***Walk:*** Walk light should be on signifying the pedestrians may cross.
- ***Warning***: The “don't walk” LED flashes signifying that pedestrians need to hurry.
- ***Don’t Walk:*** The “don't walk” LED should be on and constant.

Don’t Walk Behavior

- The “don’t walk” LED flashes when the two traffic signals are red.
- The “don’t walk” LED is steadily on, while traffic signals process non-pedestrian traffic.

Traffic Behavior

- The traffic signals should facilitate traffic flow only when there are no pending pedestrian requests.
- The traffic signals behave according to expected patterns, including transitioning between stop, warning, and go states.
- There is a delay on the warning (yellow) states.
- Traffic in one direction is not in go state until traffic in other direction is in stop state.

Demonstration

During the demonstration, you will need to show both the simulated and actual TM4C123 systems to the TA. The TAs will expect you to know how the **`SysTick_Wait`** function works, and know how to add more input signals and/or output signals. Questions that may be asked during demonstration is:

1. How can you experimentally prove your system works? In other words, what data should be collected and how would you collect it?
2. What type of FSM do you have?
3. How many states does it have?

4. In general, how many next-state arrows are there?
5. How is the linked data structure used to implement the FSM?
6. What does it mean for the C compiler to align objects in memory?
7. Why does the compiler perform alignment?
8. What are some general qualities that would characterize a good FSM?
9. If you were to write software that delays 1 second without using the timer, how would you prove the delay will be 1 second?

Engineering Questions

There are many engineering questions that students ask. How you choose to answer these questions will determine how good an engineer you are, but will not affect your grade on this lab. For each question, there are many possible answers, and you are free to choose how you want to answer it. It is reasonable however for the TA to ask how you would have implemented other answers to these engineering questions using the same FSM structure.

1. How long should I wait in each state? *Possible answer*: 5+ seconds of real TA time.
2. What happens if I push 2 or 3 buttons at a time? *Possible answer*: cycle through the requests servicing them in a round robin fashion (service one, then another)
3. What if I push the walk button, but release it before 2 seconds are up? *Possible answer*: service it or ignore it depending on exactly when it occurred.
4. What if I push a car button, but release it before it is serviced? *Possible answer*: ignore the request as if it never happened (e.g., car came to a red light, came to a full stop, and then made a legal turn). *Possible answer*: service the request or ignore it depending on when it occurred.
5. Assume there are no cars and the light is green on the North, what if a car now comes on the East? Do I have to recognize a new input right away or wait until the end of the wait time? *Possible answer:* no, just wait until the end of the current wait, then service it. *Possible answer*: yes; break states with long waits into multiple states with same output but shorter waits.
6. What if the walk button is pushed while the “do not walk” light is flashing? *Possible answer*: ignore it, go to a green light state and if the walk button is still pushed, then go to walk state again. *Possible answer:* if no cars are waiting, go back to the walk state. *Possible answer*: remember that the button was pushed, and go to a walk state after the next green light state.
7. Does the walk occur on just one street or both? *Possible answer*: stop all cars and let people walk across either or both streets.
8. How do I signify a walk condition? *Answer*: You must use the on board green LED for walk, and on board red LED as the “do not walk”.

In real products that we market to consumers, we put the executable instructions and the finite state machine linked data structure into the nonvolatile memory such as Flash. A good implementation will allow minor changes to the finite machine (adding states, modifying times, removing states, moving transition arrows, changing the initial state) simply by changing the linked data structure, without changing the executable instructions. Making changes to executable code requires you to debug/verify the system again. If there is a 1-1 mapping from FSM to linked data structure, then if we just change the state graph and follow the 1-1 mapping, we can be confident our new system will operate the new FSM properly. Obviously, if we add another input sensor or output light, it may be necessary to update the executable part of the software, re-assemble or re-compile and retest the system.

Deliverables

Please submit a written project report: refer to the **Lab07-GradingChart** document to prepare your lab report and include the following as attachments:

1. Logic analyzer screenshot while in simulation mode, when cars are present on both roads and pedestrians interact with the controller system.
2. Circuit diagram (with your name and date) using the PCB Artist.
3. Pictures of each use-case testing scenarios as elaborated in Part E.
4. Drawing of the finite state machine done on computer (must be neat, organized and professionally presentable).
5. Copy of C source code which must be commented, organized and presentable. Use 10 point font size and landscape page orientation for printing your source code.
6. A narrative for detailed description of team member contributions to all aspects of the project including hardware prototyping design and test, code development, software test and debugging, and report preparation and authoring.

Grading Requirements

This lab was written in a manner intended to give you a great deal of flexibility in how you draw the FSM graph, while at the same time require very specific boundaries on how the FSM controller must be written. This flexibility causes students to question "when am I done?" or "is this enough for an A?" To clarify the distinction between computer engineering, and civil engineering, we re-state the computer engineering requirements. In particular do these 9 requirements well and you can get a good grade on this lab.

1. *Input Dependence:*
   This means each state has 8 arrows such that the next state depends on the current state and the input. This means you cannot solve the problem by simply cycling through all the states regardless of the input. You should not implement a Mealy machine.

2. *1-1 Mapping:*
   There must be a 1-1 mapping between state graph and data structure. For a Moore machine, this means each state in the graph has an output, a time to wait, and 8 next state arrows (one for each input). The data structure has exactly these components: an output, a time to wait, and 8 next state pointers (one for each input). There is no more or no less information in the data structure then the information in the state graph. In other words what you have down on your state graph is exactly mapped to your data structures in the code.

3. *No Conditional Branches:*

There can be no conditional branches (do-while, while-loop, if-then, or for-loops) in your system, other than in `SysTick_Wait` and in `SysTick_Wait10ms`. See the Example 6.4 in the book. You will have an unconditional while-loop in the main program that runs the FSM controller.

4. *Clear State Graph:*
   The state graph defines exactly what the system does in a clear and unambiguous fashion.

5. *Consistent State Format:*
   Each state has the same format as every other state. This means every state has exactly 8 bits of output, one time to wait, and 8 next pointers.

6. *Naming Convention:*
   Please use good names (easy to understand and easy to change). Examples of bad state names are **S0** and **S1**.

7. *No Accidents:*
   Do not allow cars to crash into each other. Do not allow pedestrians to walk in one direction while any cars are allowed to go. Engineers do not want people to get hurt. i.e., there should not be only a green or only a yellow LED on one road at the same time there is only a green or only a yellow LED on the other road.

8. *State Count Requirement:*
   There should be approximately 10 to 30 states with a Moore finite state machine. Usually students with less than 10 states did not flash the do not walk light, or they flashed the lights using a counter. Counters and variables violate the "no conditional branch" requirement. If your machine has more than 30 states you have made it more complicated than absolutely necessary and you should consider revising your design.

9. *"2 Second Walk" Button Timing:*
   If the pedestrian pushes the walk button for 2 or more seconds, eventually a walk light must occur. If the pedestrian pushed the walk button for less than 2 seconds, it is up to you to decide what happens.

Tips and Tricks

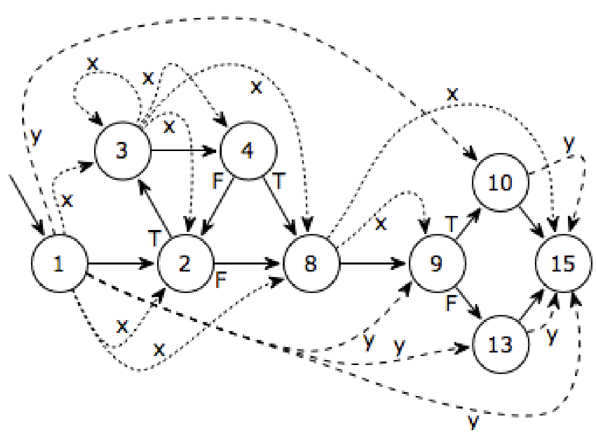
- When a car sensor is released or deactivated (set to logic 0), it means no cars are waiting to enter the intersection: i.e. when you are not pressing the button no cars are on the road.
- You should exercise common sense when assigning the length of time that the traffic light will spend in each state; so that the system changes at a speed convenient for the TA (stuff changes fast enough so the TA doesn't get bored, but not so fast that the TA can't see what is happening).
- There is no single, "best" way to implement your system. However, your scheme must use a linked data structure stored in ROM. There should be a 1-1 mapping from the FSM states and the linked elements. An example solution will have about 10 to 30 states in the finite state machine, and provides for input dependence.

- Try not to focus on the civil engineering issues. I.e., the machine does not have to maximize traffic flow or minimize waiting. On the other hand if there are multiple requests, the system should cycle through, servicing them all. Build a quality computer engineering solution that is easy to understand and easy to change.

Handling the 2 Second Walk

- One way to handle the 2-second walk button requirement is to have a simplified state graph centered around a "center home" or "check all" state. The idea is that you have one state that you can always come back to that controls what your state graph is doing. Initially when thinking about this problem you can identify that servicing traffic on the east or west road or servicing the pedestrians can be thought of a set sequence of events that have to start and end somewhere. So just make them start and end at the "check all" state. This approach may make sense to some of you. If not, there is another approach mentioned next.
- Another way to handle the 2-second walk button requirement is to add a duplicate set of states. The first set of states means the walk button is not pressed. The second set of states means the walk operation is requested. Go from the first set to the second set whenever the walk is pushed. Go from the second back to the first, whenever the walk condition is output. The two sets of states allow you to remember that a walk has been requested; in this way the request is serviced when appropriate.

  *Aside: If your FSM starts to look like the image below, you may want to go to a TA for advice on cleaning it up. We mention this to reinforce point 4 of the grading requirements which is to have a **Clear State Graph.***



Drawing your FSM

- Because we have three inputs, there will be 8 next state arrows. One way to draw the FSM graph to make it easier to read is to use X to signify don't care. For example, compare the Figure 7.7 in the pre lab reading document to the FSM graph in Figure 7.3 below. Drawing two arrows labeled **01** and **11** is the same as drawing one arrow with the label **X1**. When we implement the data structure, we will expand the shorthand and explicitly list all possible next states.

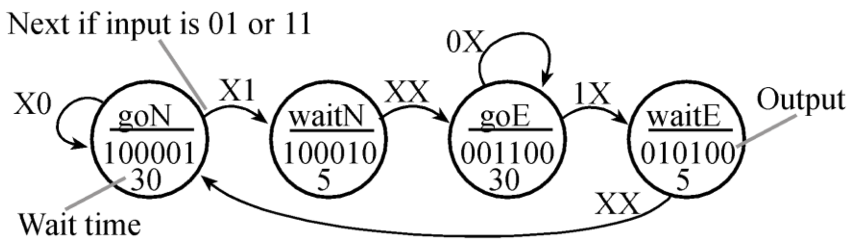
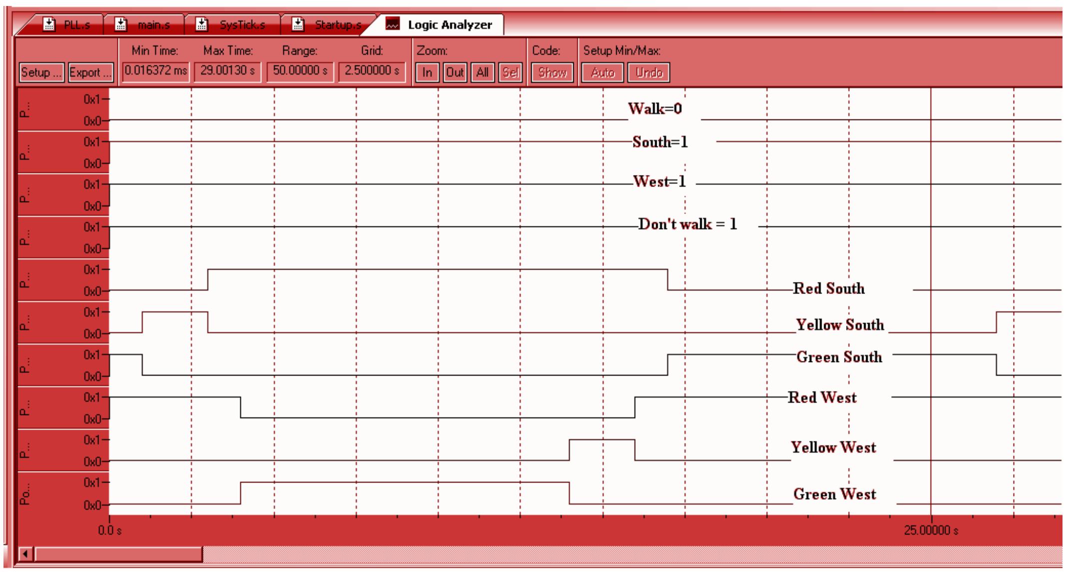


Figure 7.3. FSM from the book Figure 6.9 redrawn with a shorthand format.

Example Logic Analyzer Windows

Your version will not be red, and also your I/O window may look slightly different from these examples (e.g., you are free to assign signals to different port bits.)



Simulation showing cars on both South and West

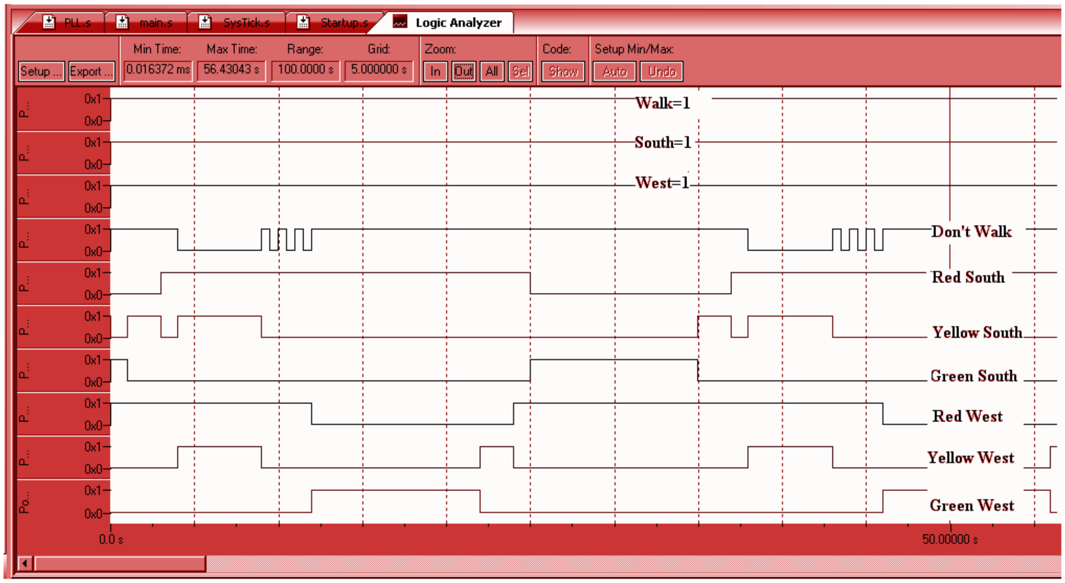


Figure 7.5. Simulation showing walk pushed, and cars on both South and West

FAQ

1. *Is the walk signal for a certain direction?*

   No, the walk signal will be pushed by a pedestrian when he or she wishes to cross in any direction.

2. *We are getting an error when we compile, saying that the file TM4C123GH6PM.h cannot be opened because it cannot be found. Where can we find this file?*

   If you still have your EECS3100 folder, you could copy paste it into your folder that lists includes your lab 7. It should be in the "inc" folder:

   C:\Keil\EECS3100\inc\TM4C123GH6PM.h

3. *The lab manual mentions "SysTick_Wait" and "SysTick_Wait10ms" subroutines. Are we supposed to program these, or are they included somewhere?*

   These files are found in the TrafficLight folder provided with this assignment. You can copy and paste the SysTick.c and .h files into your working directory, then add them to your project by right clicking the source folder in the Keil project explorer on the left side and selecting "Add existing files...". Make sure to include the #include "SysTick.h" in your main.c to get the function prototypes for SysTick_Init and SysTick_Wait. SysTick.c will be in C, so no worries of assembly there. You can call assembly functions from C, but it would be easier to just stick with the C file in this case.

4. *Is #define GPIO_PORTF_OUT (*((volatile uint32_t *)0x40025028)) the correct code to set bits 1 and 3 of Port F so that I can change the lights on them? I got this number by adding x20 and x08 to x4002.5000 which is the start memory map in peripherals in one of the data sheets.*

   It looks like that address will allow you to read/write to PF1 and PF3 without affecting the other pins on Port F

5. *Are there limitations to SysTick_Wait that we should know about? It seems that when we call this subroutine to wait for 2 seconds, it gets stuck in an infinite loop.*

   Make sure to call SysTick_Init

6. *When I try to build my files I get this error:*

   linking...
   .\Lab7.axf: error: L6002U: Could not open file --ro-base: No such file or directory ".\Lab7.axf" - 1 Errors, 0 Warning(s).
   Target not created

   Someone asked how to fix this in the lab 5 FAQ where some TAs offered an interim solution in reference to assembly files. Is there a formal solution yet?

   Try uninstalling and reinstalling Keil, re-download the project templates, and make sure your launchpad drivers are up to date.

7. *What is a possible source of error to the warning "_____ macro redefined"? This occurs whenever I try to do a:*

   #define GPIO_PORTE_DIR_R (((volatile unsigned long *)0x40024400))*

   This macro is defined in the "tm4c123gh6pm.h" file. There is no need to redefine this macro since you should be including this file in your "TableTrafficLight.c" file.

8. *How do we do a NOP properly in C? We keep getting an error saying that Port A doesn't have a clock set.*

   Instead of using SYSCTL_RCGCGPIO_R to set clock, use the following instead:

   ```
   SYSCTL_RCGC2_R |= 0x32;     // 1) enable clock for ports F, E, and B
   delay = SYSCTL_RCGC2_R;     //    and wait for a while
   ```

The second line is just wasting a few clock cycles before modifying the port registers to allow the clock to settle.

9. *I don't know why there should be 8 next states? I don't see how there could be 8 other states.*

   Since you have three different inputs buttons, you have 8 different combinations of inputs that you need to account for. This is a maximum however, there are many states where you will progress to another state regardless of what the other switches are (like when you are blinking the walk LED to signify it is almost done. Even if another button is pressed, you should finish blinking before handling that request). Your next states will have many duplicates typically, but you will need to have 8 to account for each input combination in every state.

10. *How would you show the Tiva board's LED lights on PCB Artist? Do you have to show it at all?*

    The circuit is already embedded in the board, so I would only worry about showing pinouts and external hardware interfaces for the LEDs, switches, etc.

11. *I know we cannot use conditional branches, but switches were not listed as something we were not allowed to use in the lab manual. Will points be deducted if we implement a switch?*

    The reason we prohibit branches is because the logic of which next state to go to for each state should be specified in your FSM data, not in your engine. The only thing your engine should do is find the next state in the data, using the current state as an index or pointer (whichever you used in your design). This way, you should have no need to use switches or conditional branches.

12. *Do we need pull down resistors for the LEDs on the board? PF3 and PF1?*

    You only need to use the PDR and PUR registers when configuring the onboard switches. For the LEDs, you don't need to worry about them.

13. *What's a good way of reading if the pedestrian button has been pressed for 2 seconds or more? I'm confused on this. Can we just continue to check the input value over and over again until the No of cycles x 12.5ns equals 2 seconds and then check the final input value? If at any moment within those two seconds it hasn't been pressed we can assume they let it go?*

    Try to think of time in terms of states instead of clock cycles for this lab. The state machine reads inputs at the end of state before it transitions. So one idea is to make each state last 1 or 2 seconds so each button being pressed gets read.

14. *When we run the program in our simulation, the appropriate lights turn on, but then do not turn off when they are supposed to. Such as the walk warning light does not blink. Is anyone else having this problem?*

    This sounds like a problem with your state machine. Double check your outputs in your state machine making sure you set pins equal to zero. Also, if you are using Port D for your lights, the signals will not be processed correctly since Port D was designed for special cases/uses.

15. *I am not able to have lasting color changes on their logic analyzers?*

    Select a color to change the pin to, click OK to close the palette, then click "close" on the setup analyzer window. Repeat for all pins. It's tedious that you have to do it for each pin individually, but it worked for me.

16. *Why are we disabling and then enabling interrupts?*

    Typically, global interrupts rather than individual functions are disabled during "critical sections". Consider what would happen if you were initializing a timer or some other function when another interrupt fired? Or if you were reading or writing to a piece of data when an interrupt fired that modified the data at the same address? When you start using interrupts more in your labs in the upcoming weeks it'll become more of something to think about.