Lab 2

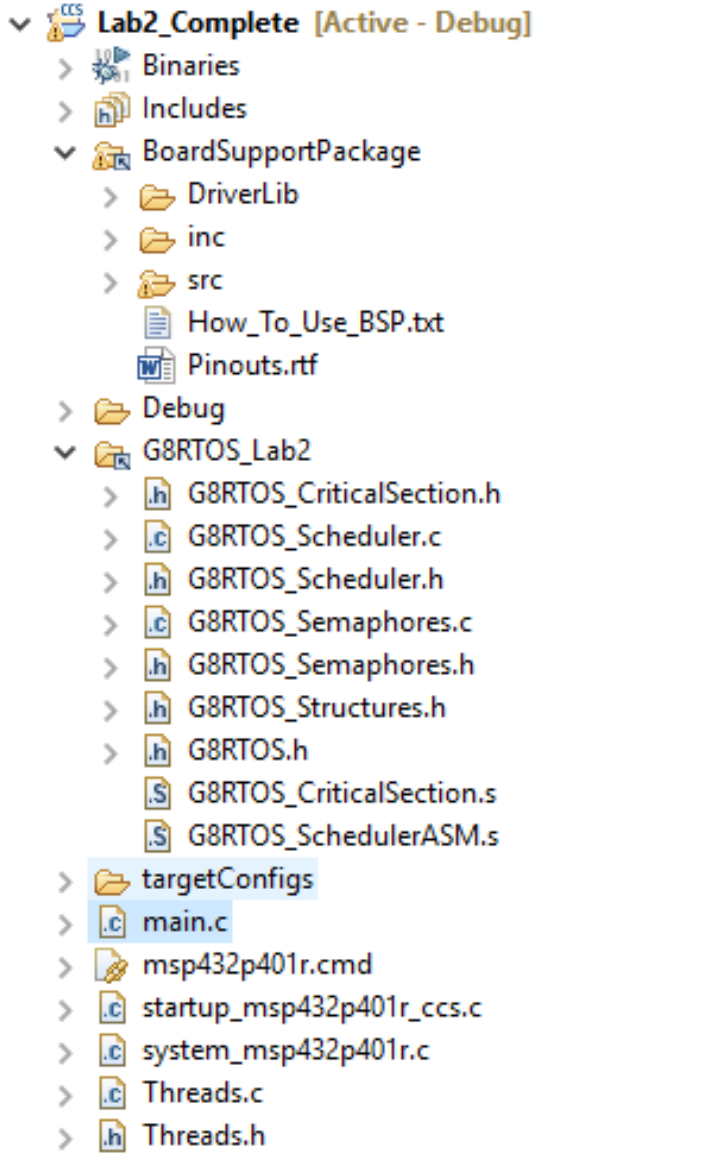
G8RTOS IMPLEMENTATION

Overview

- Implement a basic RTOS on your board.
- You have to implement:
  - OS Structures (Thread Control Block)
  - OS Initialization functions (SysTick and Structures)
  - A Round-Robin Scheduler
  - Context Switching (PendSV handler)
  - Thread related function (Add thread)
  - Launch and start your RTOS

Board Support Package

- You will be given a boardsupportpackage with a bunch of useful functionality
- Create a new CCS Project
- Follow the instructions in Lab 1 and add the new BSP

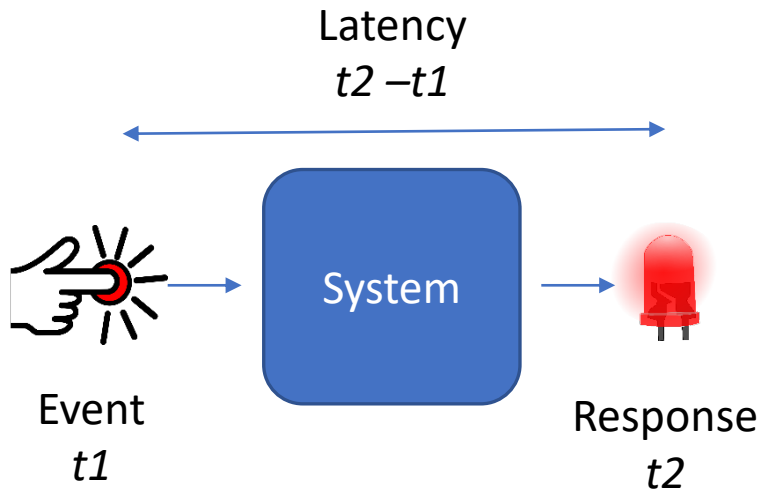


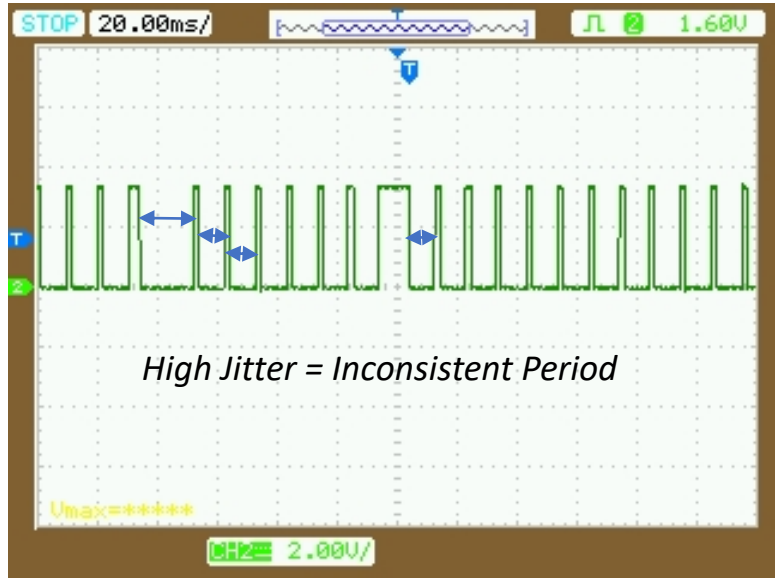
Integrate the LED Library

- Integrate the LED library you created in Lab1 into the BSP
- Add the LED .c file into `src` and the LED library .h file into `inc` folders of the BSP
- Add an #include “yourLEDLibrary.h” in `BSP.h`
- Add a call to the LEDinit function in your library to the `_initBoard` function in the `BSP.c` file.

RTOS

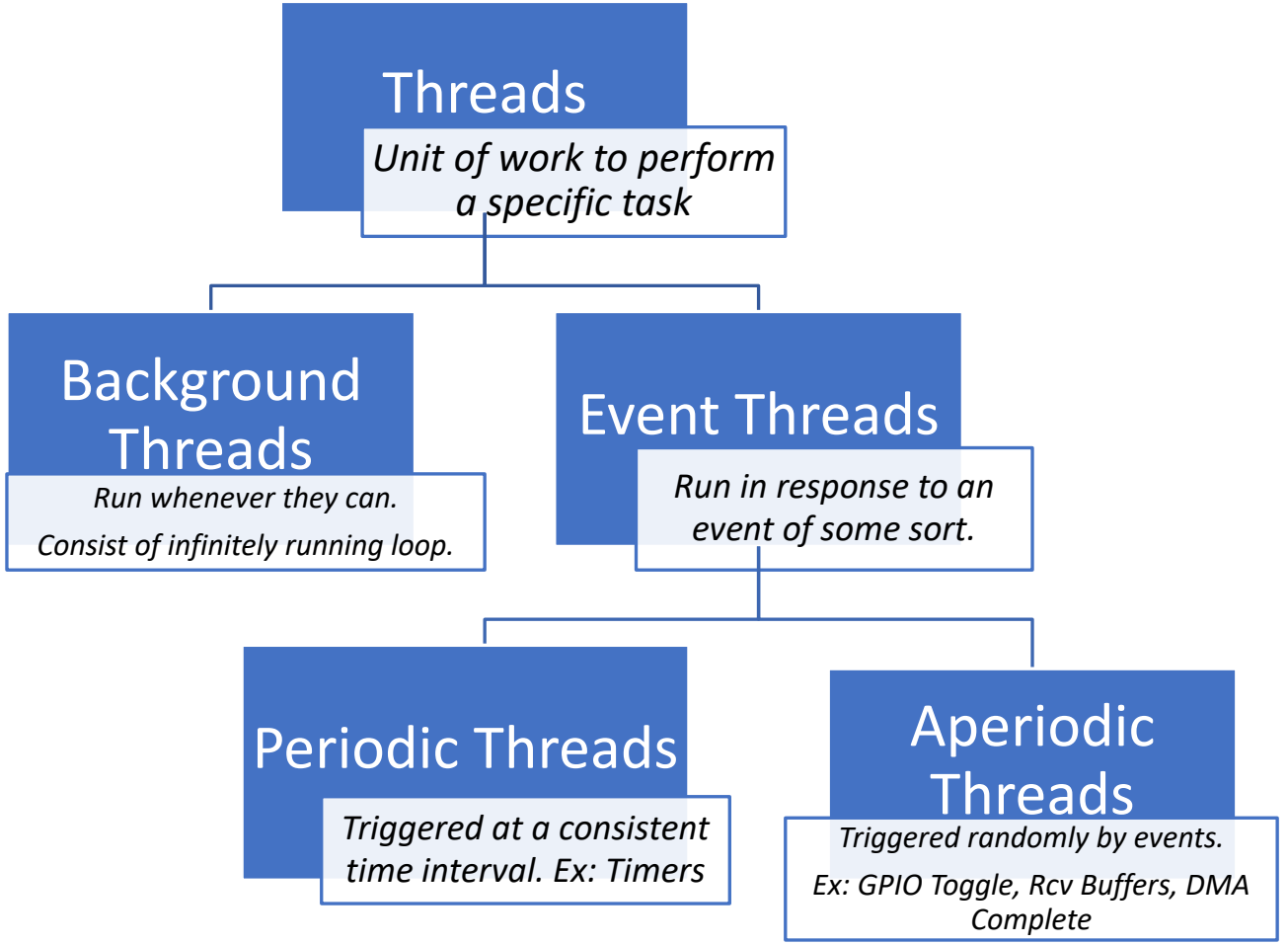
- Why an OS? Multi-**tasking** and resource sharing
- **Real-Time** OS: OS where tasks have deadlines. If the deadline is missed the plant blows up.
- We want to reduce **latency**
- We want to reduce **Jitter**





RTOS: Threads

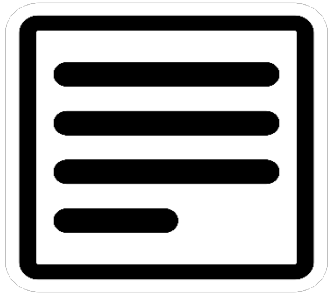
- We have Multiple tasks one CPU -> Time-multiplexed system
- Tasks -> **Threads** . We run one thread at the time.
- The **scheduler** will decide which task gets to run at the moment.



RTOS: Threads

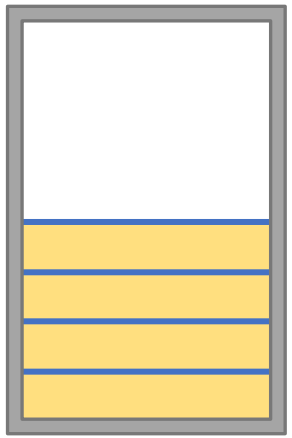
- Implementing threads?
- The components of a thread

Code



CPU Registers/Context

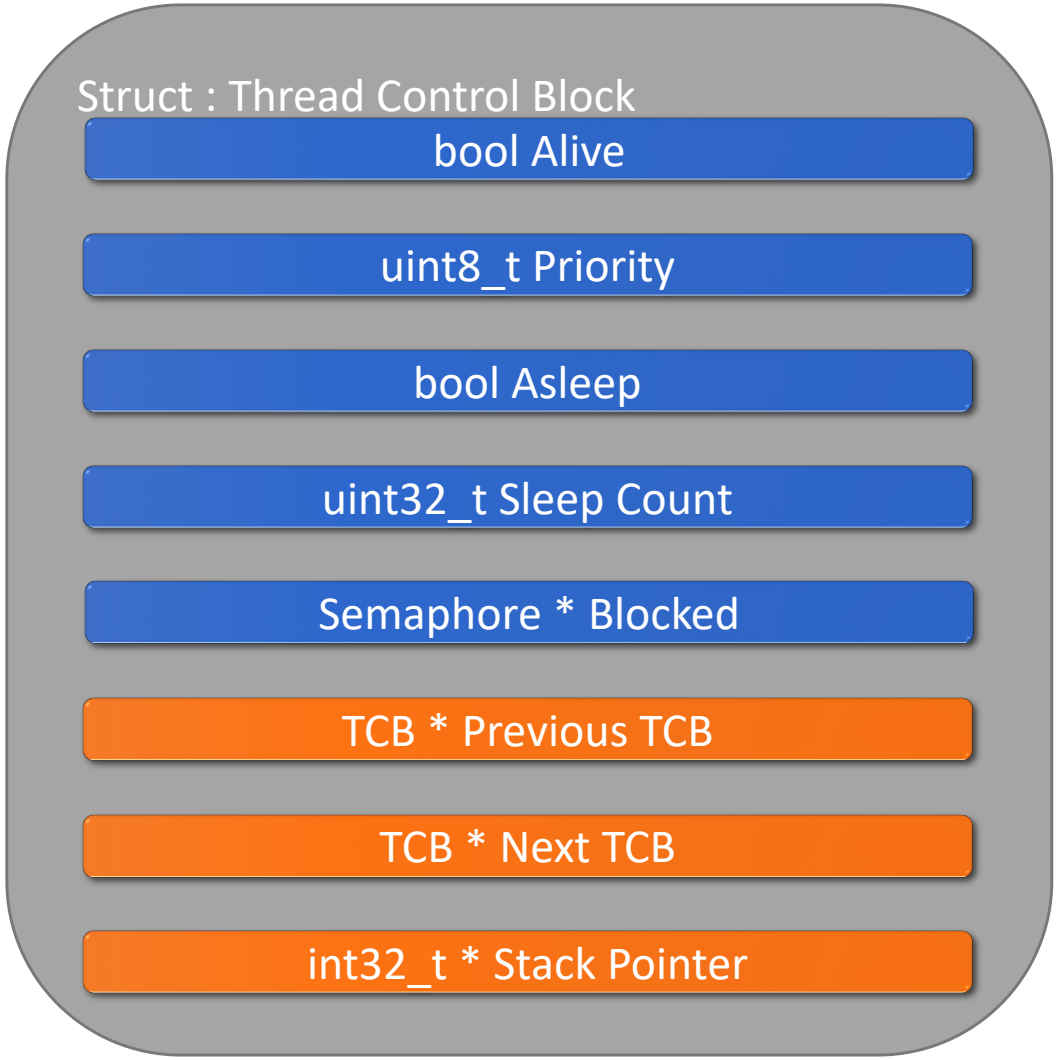
All of the Thread's memory including its stack



- We want to be able to stop a thread. Leave it aside. And then pick it up later. What is the minimum components we need for this?

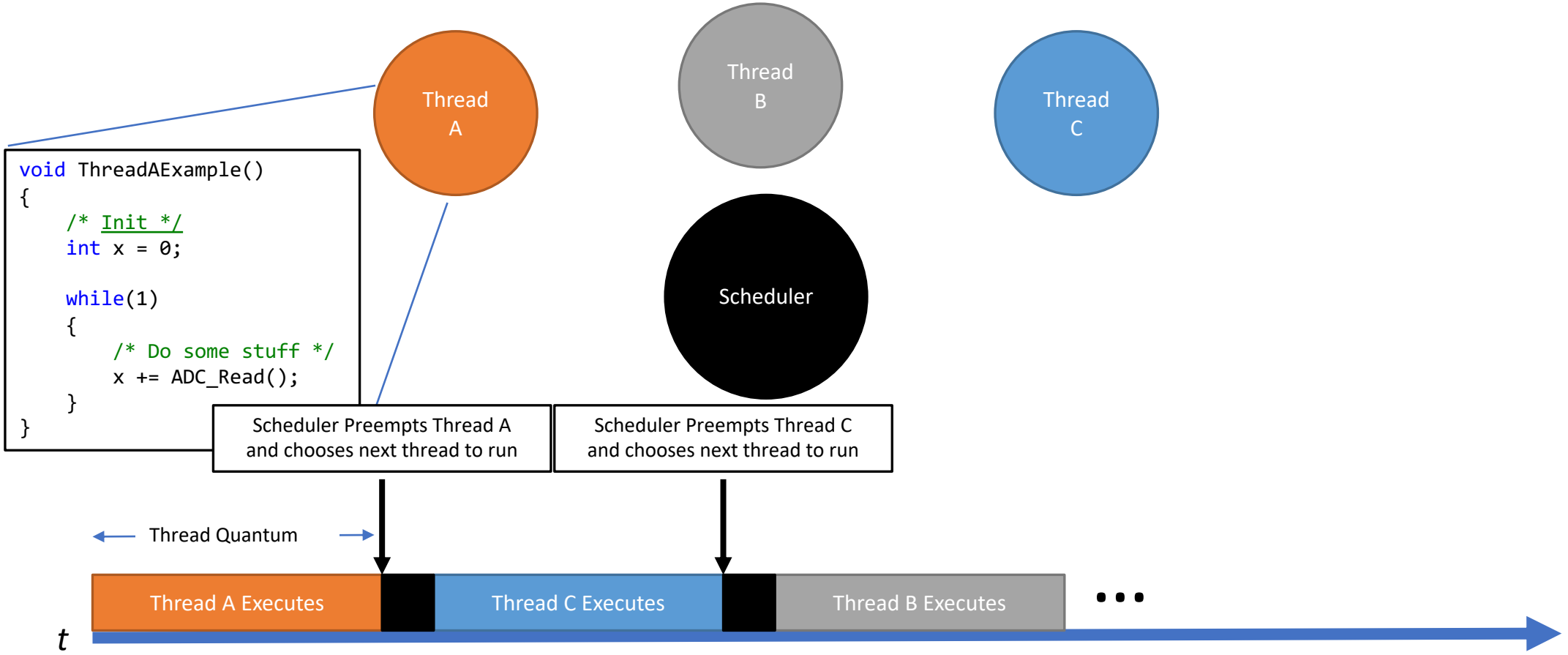
RTOS: Thread-control-block (TCB)

- Thread-control-block (TCB): a data-structure for storing the thread information. This is what you need to develop in Part1.
- For Lab2 this looks like the following.
- Create a `struct` and `typedef` it for easy access.



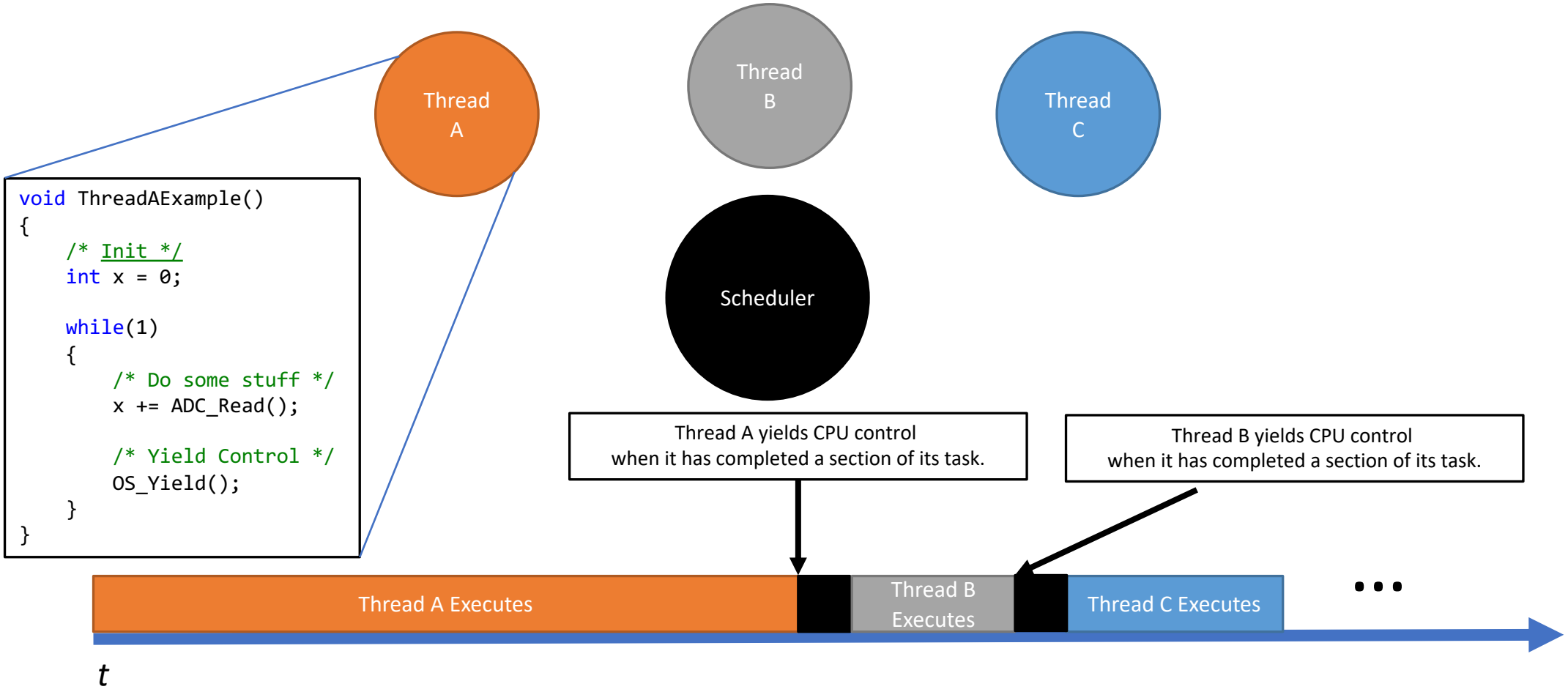
RTOS: Scheduler

- Preemptive Thread Scheduling where the scheduler jumps in and stops one thread and replaces it with another (preempts the thread).



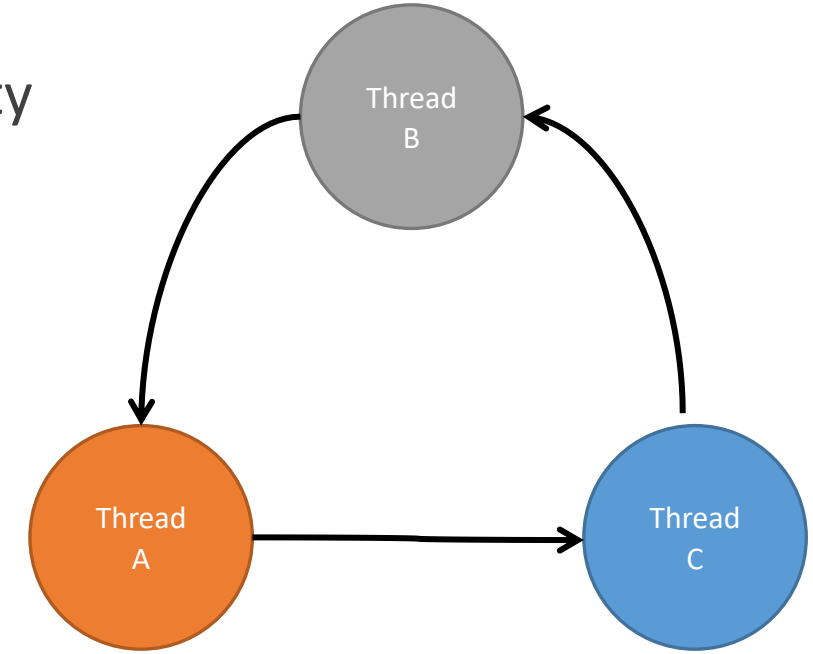
RTOS: Scheduler

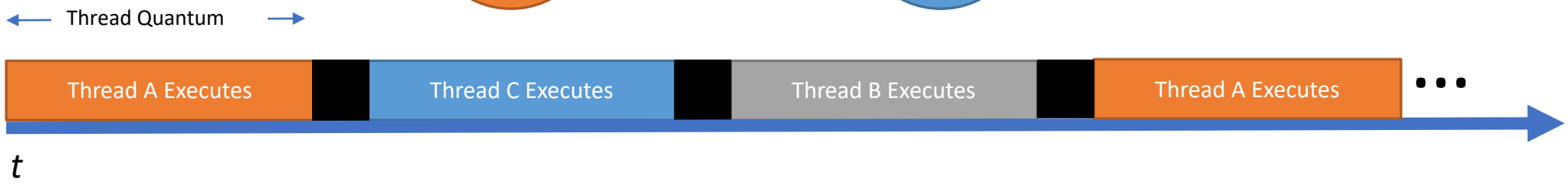
- Cooperative Thread Scheduling where the threads themselves yield the CPU to one another



RTOS: Scheduler

- We are looking for a **round-robin** scheduler in Lab2. Goes through a list and executes each thread for a given time and then moves to the next one.
- Guarantees fairness.
- No concept of priority





RTOS: Context Switching

- How to switch from one thread to another given that we have their two TCBs?
- Save the important stuff, switch to the new thread, later pick up the important stuff.
- Important stuff: The set of all registers a thread needs saved in order to correctly resume execution at a later time is known as it's **execution context.**
- For the ARM Cortex M4 (when not using floating point), a thread's context consists of the **Status Register, Program Counter, Link Register and Registers R0-R12**.
- In order to use multiple threads on a single CPU, we must be able to save the state if one thread and restore the state of another, this is known as a **context switch.**
- We need to interrupt the current thread's execution to perform a context switch either voluntarily (cooperative) or nonvoluntarily (preemptive).

RTOS: Context Switching

- In Lab2 we use the following two interrupts for scheduling and context switching

Systick Interrupt

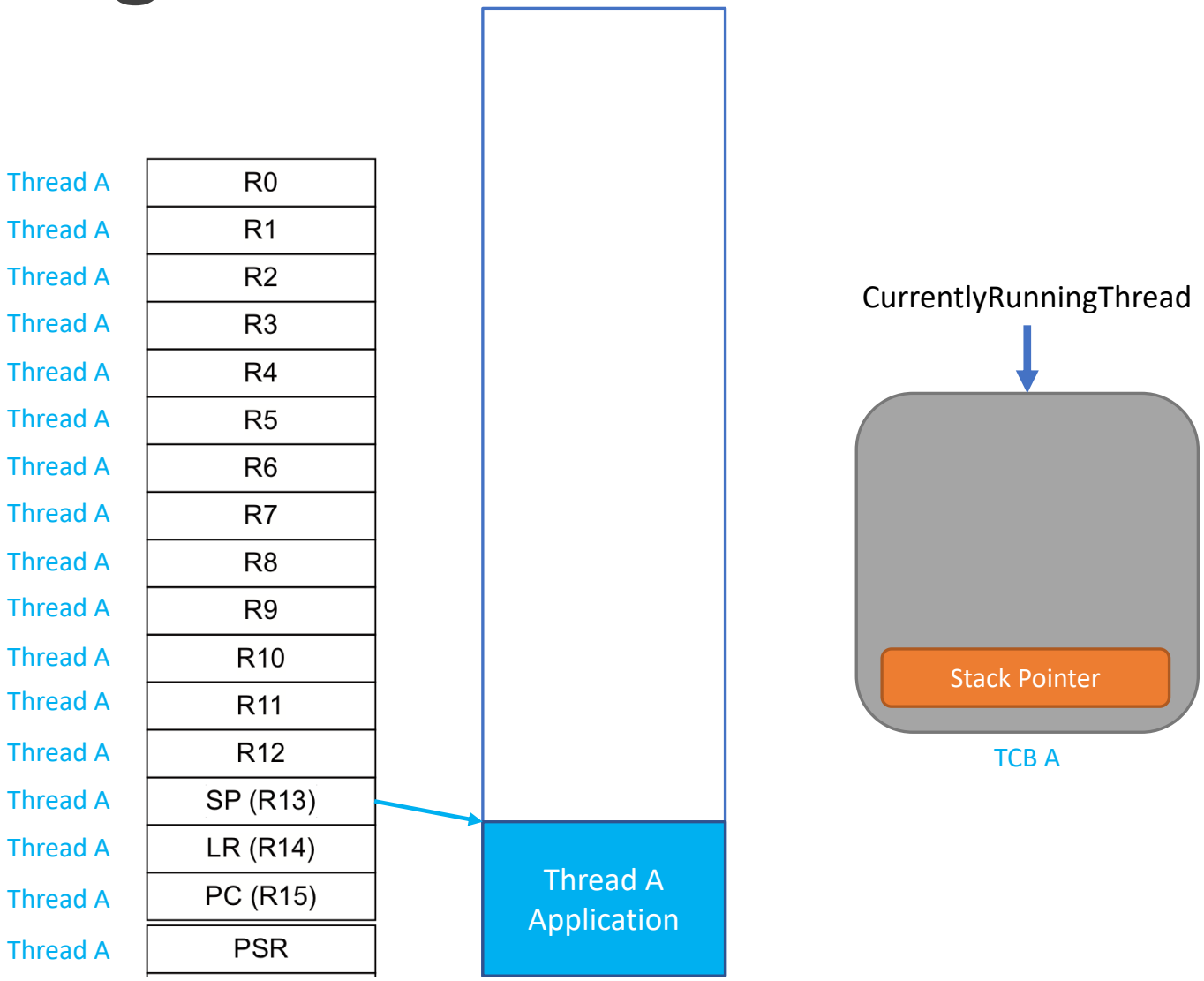
- Caused by Systick Timer reaching zero
- For our OS, it will interrupt every 1 millisecond.
- Increments a system time variable.
- Triggers the context switch interrupt.
- In the future, it will have more responsibilities such as modifying TCBs and running Periodic Events.

PendSV Interrupt

- Request for system-level service.
- Specifically created by ARM for performing context switches in an OS setting.
- Will be used for our context switch.
- Since we will be modifying CPU register, the ISR will need to be written primarily in Assembly.

RTOS: Context Switching

- Context-switch done by



RTOS: Context Switching

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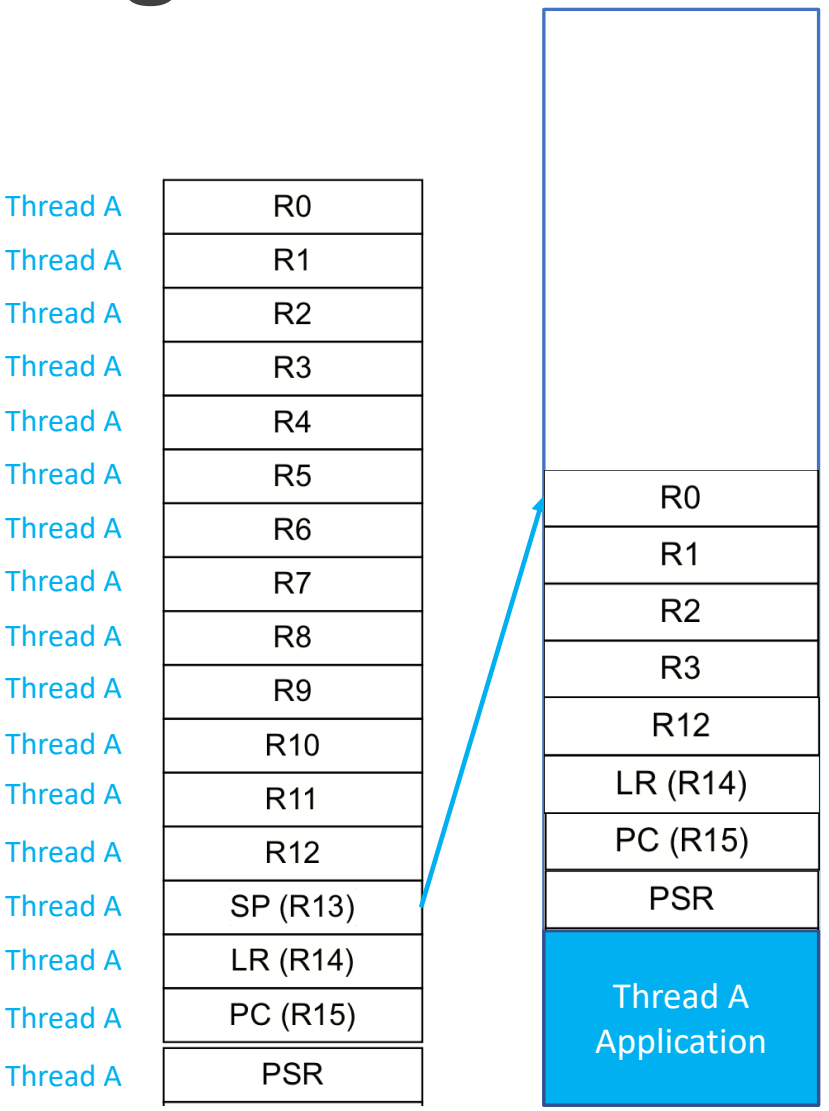

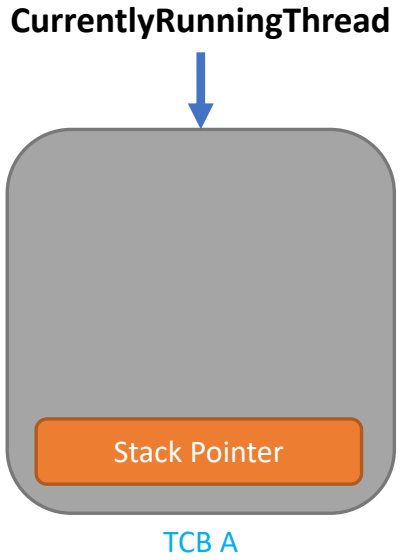

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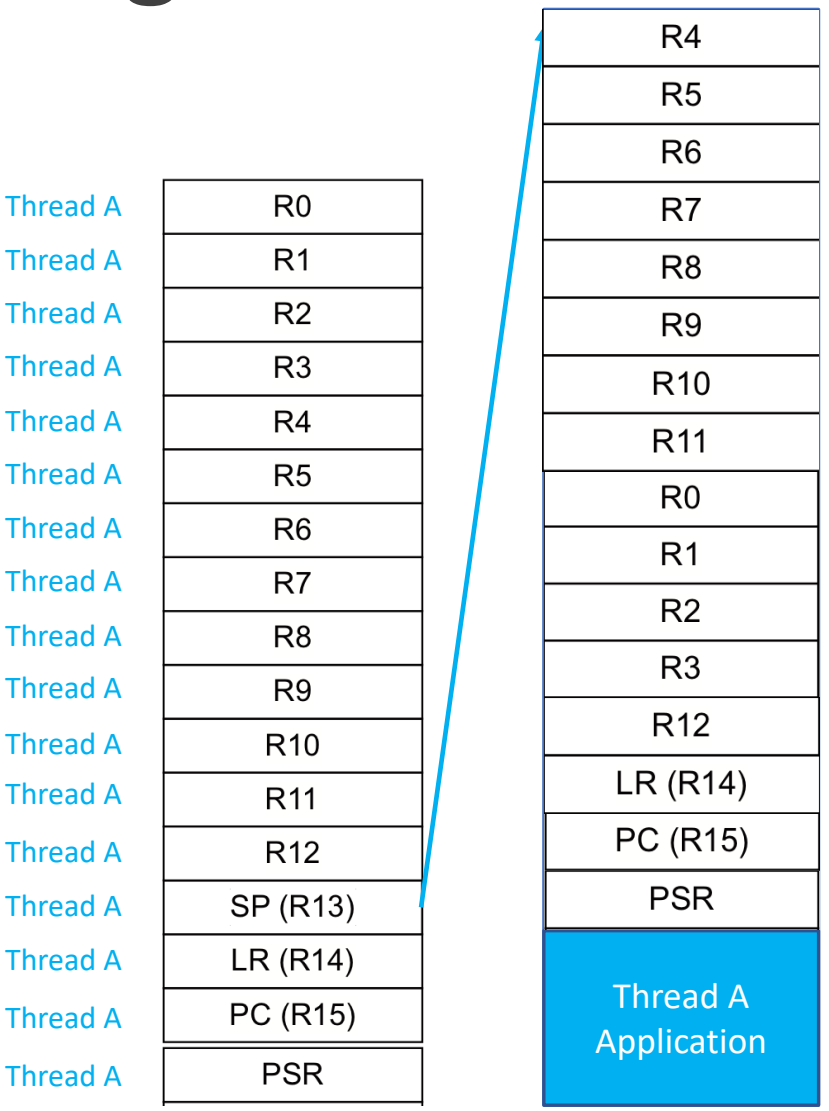

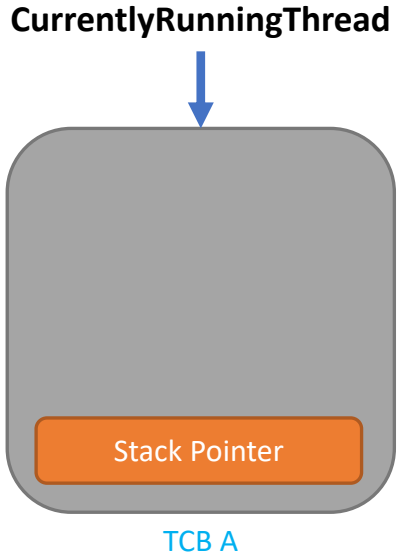

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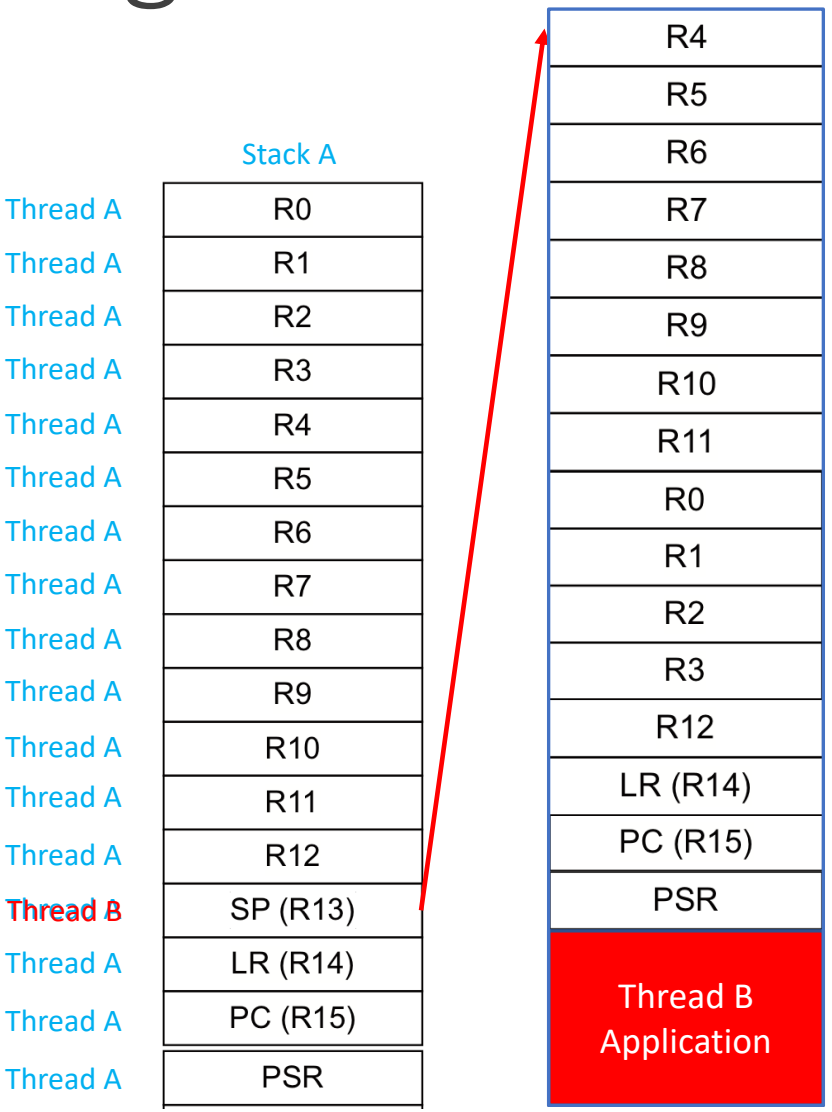
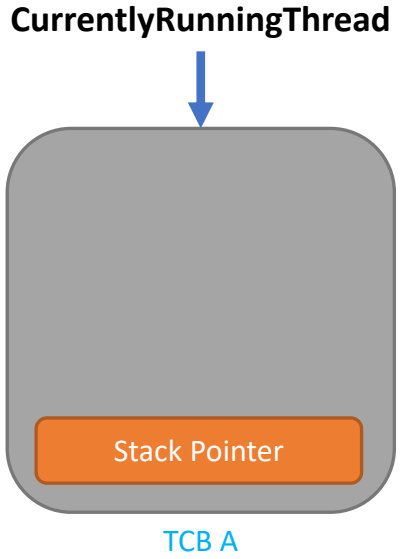
  - Call the scheduler to update CurrentlyRunningThread.
  - Load the new-thread's (Thread-B's) stack pointer. This should point to the top of Thread-B's context.





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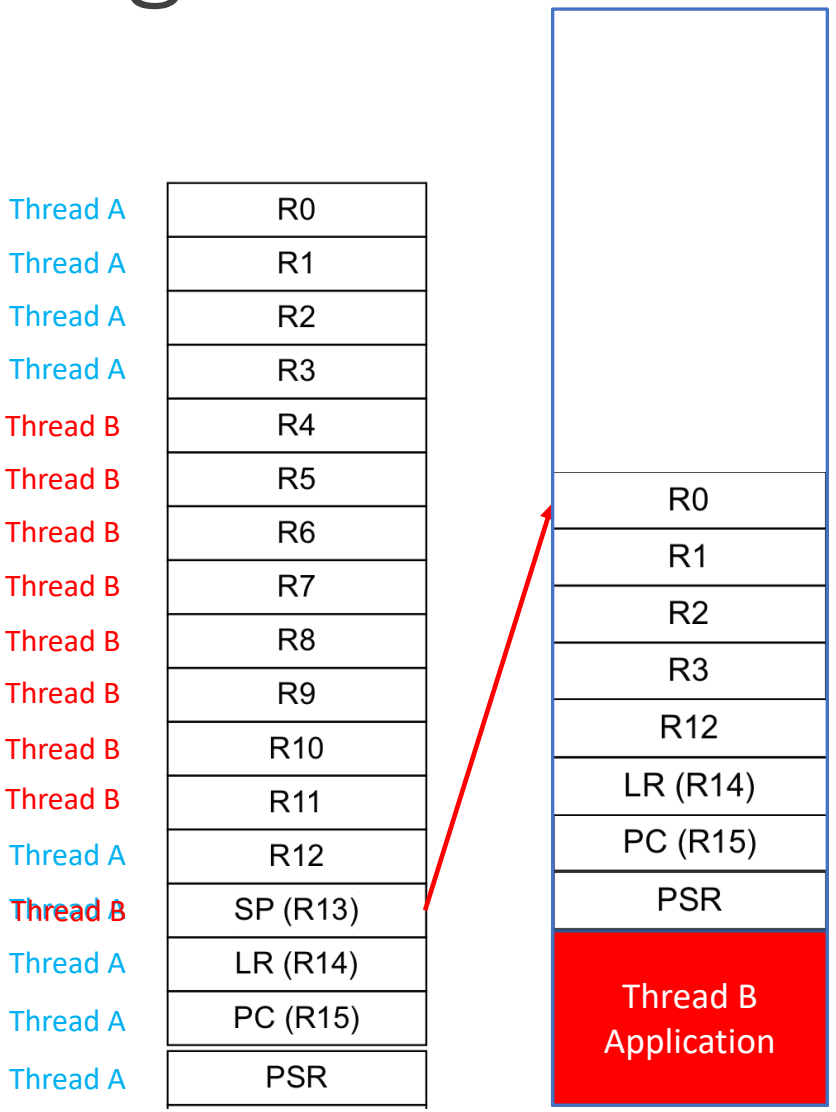
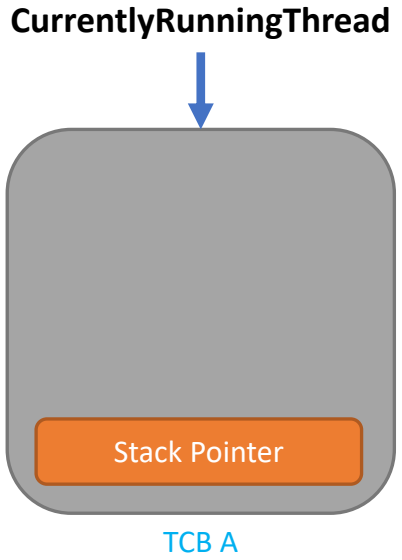
  - Call the scheduler to update CurrentlyRunningThread.
  - Load the new-thread's (Thread-B's) stack pointer. This should point to the top of Thread-B's context.
  - Pop Thread-B's R4-R11 (they were pushed during the context-save of Thread-B).





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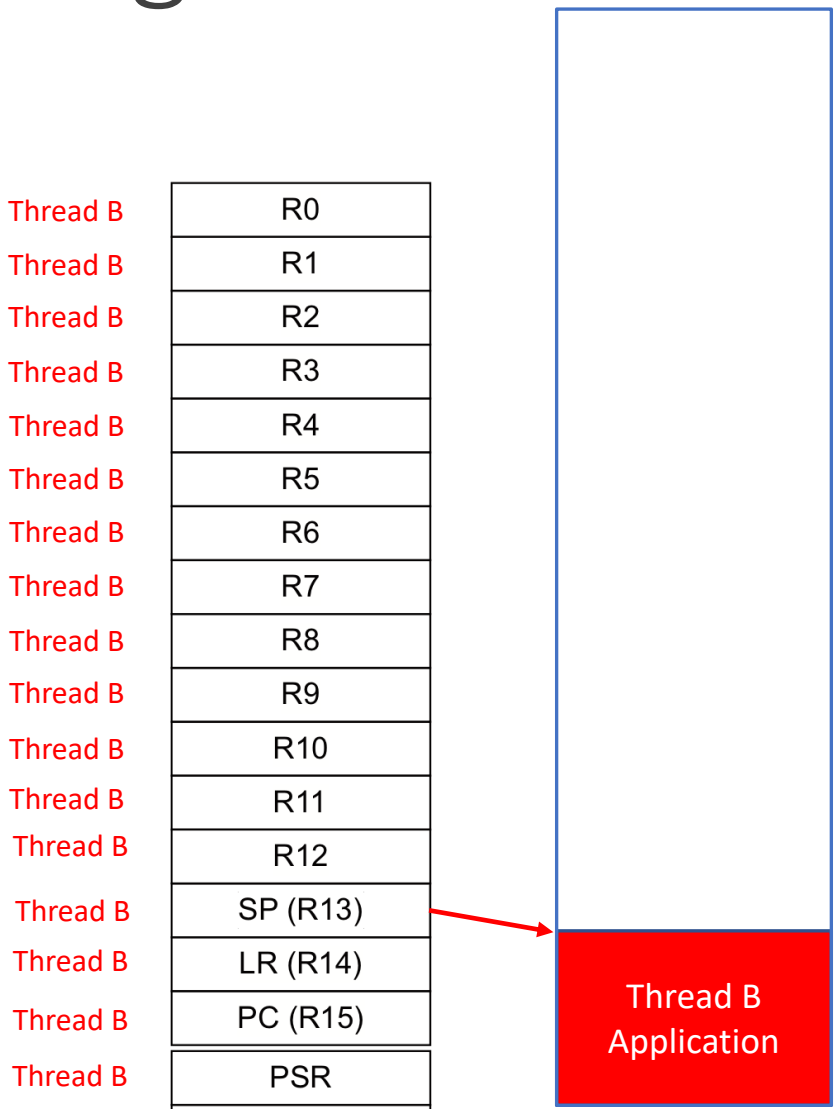
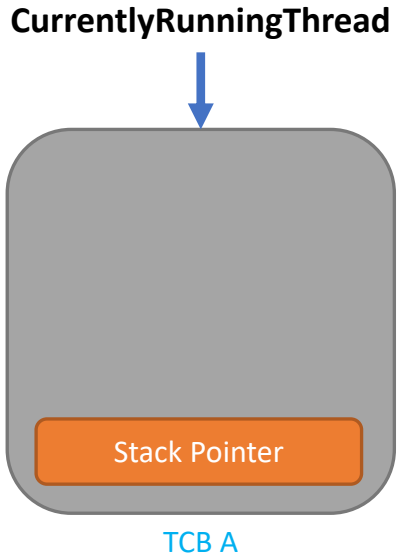
  - Call the scheduler to update CurrentlyRunningThread.
  - Load the new-thread's (Thread-B's) stack pointer. This should point to the top of Thread-B's context.
  - Pop Thread-B's R4-R11 (the ones we pushed during context save).
  - Returning from PendSV will pop the remaining registers for Thread-B. Thread-B should have all of its context now.





RTOS: Context Switching

- ASM skeleton will be provided to you:

```
; Functions Defined
.def G8RTOS_Start, PendSV_Handler

; Dependencies
.ref CurrentlyRunningThread, G8RTOS_Scheduler

.thumb; Set to thumb mode
.align 2; Align by 2 bytes (thumb mode uses
allignment by 2 or 4)
.text; Text section

; Need to have the address defined in file
; (label needs to be close enough to asm code to
be reached with PC relative addressing)
RunningPtr: .field CurrentlyRunningThread, 32
```

```
; PendSV_Handler
; - Performs a context switch in G8RTOS
; - Saves remaining registers into thread stack
;- Saves current stack pointer to tcb
;- Calls G8RTOS_Scheduler to get new tcb
;- Set stack pointer to new stack pointer from new tcb
;- Pops registers from thread stack
PendSV_Handler:

.asmfunc
;Implement this
.endasmfunc

; end of the asm file
.align
.end
```

RTOS: Critical Section

- In multi-threading, multiple threads need access to the same device or shared memory
- This causes threads to fight over the resource resulting in errors
  - Ex. 1. Two threads writing to an LCD, the second thread interrupting the first
  - Ex. 2. Two threads initializing a port differently. The order the threads are run in will determine the final state of the port
- Critical section: the part of the program where shared memory is accessed
- Consequences of not handling critical sections are race conditions and flawed results
- The above context switching code especially the saving and loading of registers should be in a critical section.

RTOS: Critical Section

- The Lab2 skeleton includes some assembly code and its relative C declarations for entering and exiting critical sections.

```
; Functions Defined
.def StartCriticalSection, EndCriticalSection

.thumb; Set to thumb mode
.align 2; Align by 2 bytes (thumb mode uses
allignment by 2 or 4)
.text; Text section
```

```
; Starts a critical section
; - Saves the state of the current PRIMASK (I-bit)
; - Disables interrupts
; Returns: The current PRIMASK State
StartCriticalSection:
.asmfunc

MRS R0, PRIMASK; Save PRIMASK to R0 (Return Register)
CPSID I; Disable Interrupts
BX LR; Return

.endasmfunc
```

```
; Ends a critical Section
; - Restores the state of the PRIMASK given an input
; Param R0: PRIMASK State to update
EndCriticalSection:
.asmfunc

MSR PRIMASK, R0; Save R0 (Param) to PRIMASK
BX LR; Return

.endasmfunc
```

RTOS: Add-Thread Function

- Before launching our operating system, we must initialize our threads and put them in the scheduler.
- In Lab2, you will be creating a function `Add_Thread` that will initialize a thread and place it in the scheduler given a Void-Void Function pointer.
- The first step to adding a thread is to check if there are any available empty threads in the operating system.
- In order to keep our thread addition fast and deterministic, our TCBs and thread stacks will be statically allocated. Therefore these is a limited number of TCBs and accompanying stacks available.
- The operating system keeps track of the number of threads currently in the scheduler with a `NumThreads` Variable. To check if we are at our limit, we will check if `NumThreads` is equal to our limit. If it is, the function will return an error code instead of adding a thread.
- If there is available space in the thread list the function will add a new TCB to the list. Set the next and prev pointers.

RTOS: Add-Thread Function

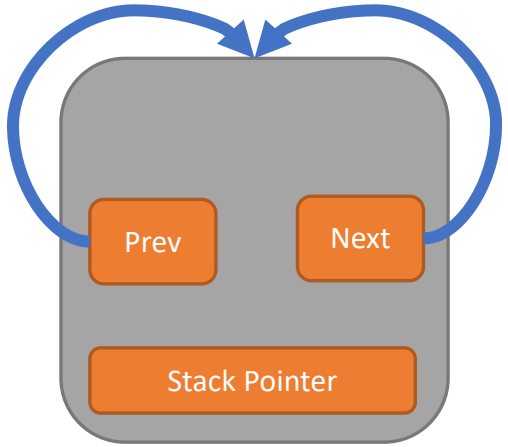
- The `threadStacks` is a static array that holds all the stack areas in memory.

```
/* Thread Stacks */
static int32_t threadStacks[MAX_THREADS][STACKSIZE];
```

- `STACKSIZE` is set to 1024.
- When initializing a thread *we have to note that when the first context-switch arrives and picks up our thread it expects a full execution context (R0-R15, PC, PSR). Simply focus on how you implemented the context-switch and what it expects from the stack.* For the context switch described earlier the thread initialization looks like this:
  - R0-R15 to dummy values.
  - PC to the thread's function pointer (the void-void function pointer that the Add_Thread function receives)
  - PSR to some default value that has the thumb-bit set.
  - The stack-pointer in the TCB struct should point to the top of all of these (`&threadStacks[threadnum][STACKSIZE-16]` because the stack grows from high addresses to low ones).

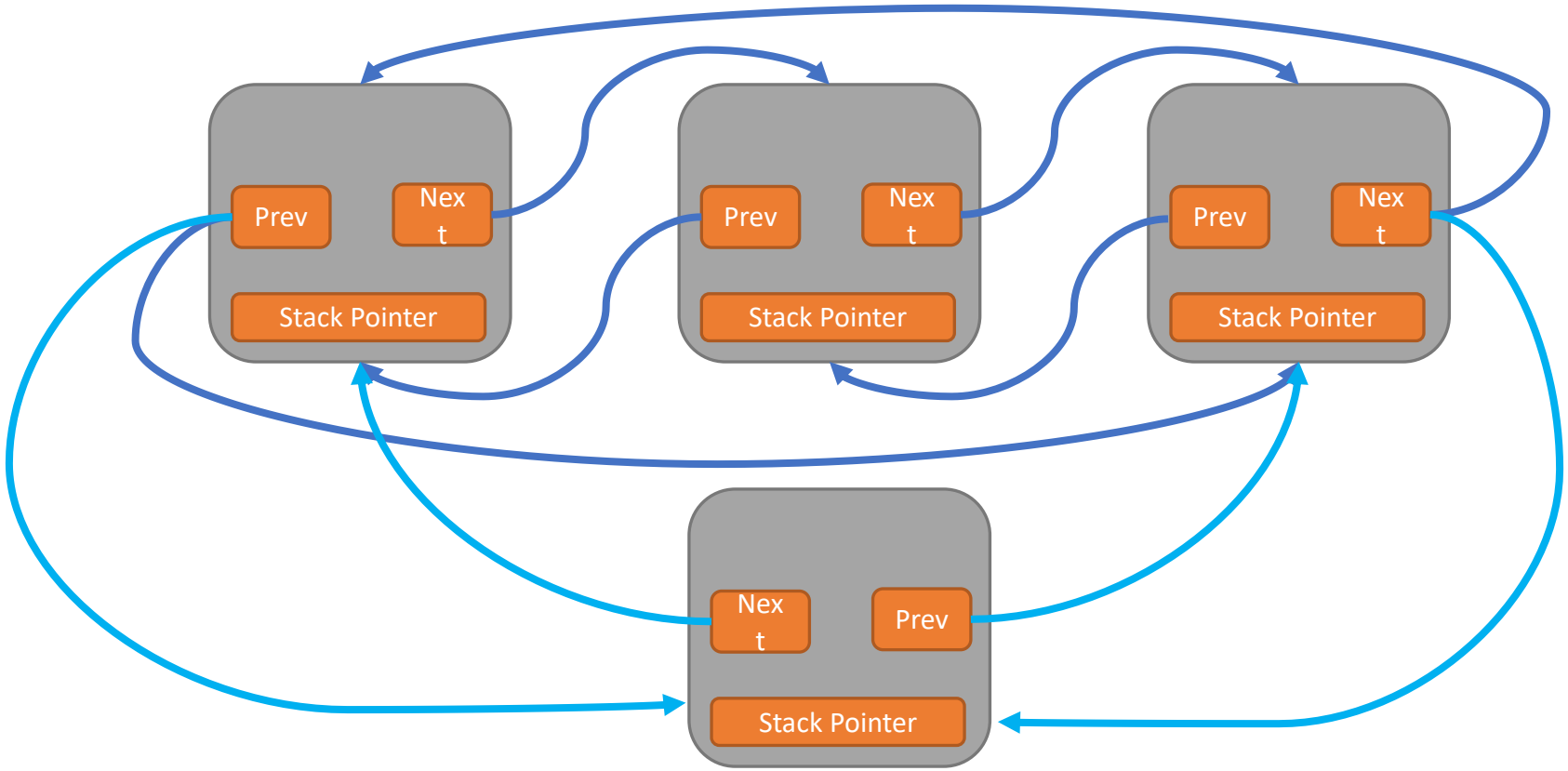
RTOS: Add-Thread

First thread to be added



TCB

Multiple threads in a round-robin scheduler



TCB

RTOS final steps

- The assembly context-switch function calls the C scheduler function which picks the next thread to run. In Lab2 this function simply picks the next thread using the next-pointer in the TCB.
- When you have finished configuring G8RTOS, your OS is now ready to launch. To start the OS, you must arm the SysTick and PendSV exceptions, set the `CurrentlyRunningThread` to the first thread in the scheduler, load the context of said thread into the CPU, and enable interrupts. This task will be split into two functions:
  - `G8RTOS_Launch:`

  This C function will be called from main and will accomplish the following:
    - Set CurrentlyRunningThread
    - Initialize SysTick
    - Set the priorities of PendSV and SysTick to the lowest priority
    - Call G8RTOS_Start
  - `G8RTOS_Start:`

  This assembly function will accomplish the following:
    - Loads the currently running thread's context into the CPU
    - Enable interrupts

RTOS final steps

- The assembly context-switch function calls the C scheduler function which picks the next thread to run. In Lab2 this function simply picks the next thread using the next-pointer in the TCB.
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  This C function will be called from main and will accomplish the following:
    - Set CurrentlyRunningThread
    - Initialize SysTick
    - Set the priorities of PendSV and SysTick to the lowest priority
    - Call G8RTOS_Start
  - `G8RTOS_Start:`

  This assembly function will accomplish the following:
    - Loads the currently running thread's context into the CPU
    - Enable interrupts
    - Jump to first thread somehow

You can test all of this by using a couple of threads to increment counters or play with LEDs.

RTOS: Semaphores

- Historically semaphores were first turn signals
- Generally speaking are indicators of intent
- In computer context, a semaphore is a type of flag
- Two uses of semaphores
  - Mutual exclusion – Only one thread should be accessing a shared resource at a time
  - Synchronization – Threads A should start doing something only when Thread B signals it to do so
- Make flag more informative: counter
- Mutex vs. Semaphore
  - A mutex is a lock with only one state – locked/unlocked. A mutex can only be released by the thread that acquired it
    - Similar to a binary semaphore, but cannot be signaled by another thread i.e. LCD
  - A semaphore can have a value greater than 1 and can be signaled by any other thread
    - i.e. 4K buffer split into 4 1K buffers

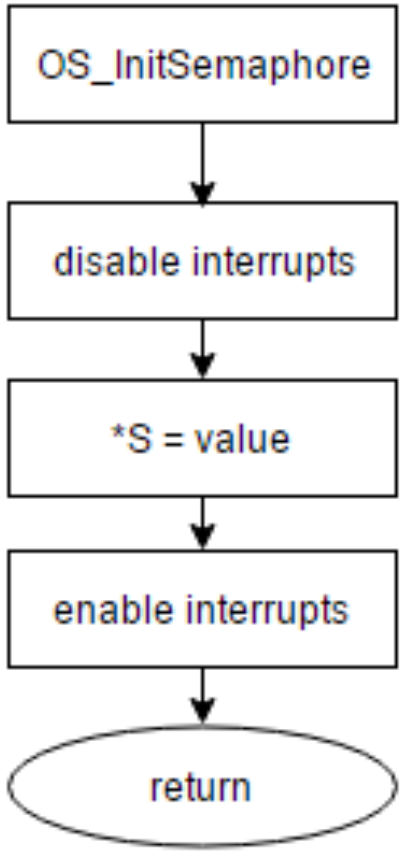
RTOS: Semaphores

- Semaphore is a counter with three functions:
  - `G8RTOS_InitSemaphore(*SEMAPHORE_NAME, SEMAPHORE_VALUE)`
  - `G8RTOS_WaitSemaphore(*SEMAPHORE_NAME)`
  - `G8RTOS_SignalSemaphore(*SEMAPHORE_NAME)`

- In G8RTOS_Semaphores.h, you should create a new type of:
  - `typedef int32_t semaphore_t`

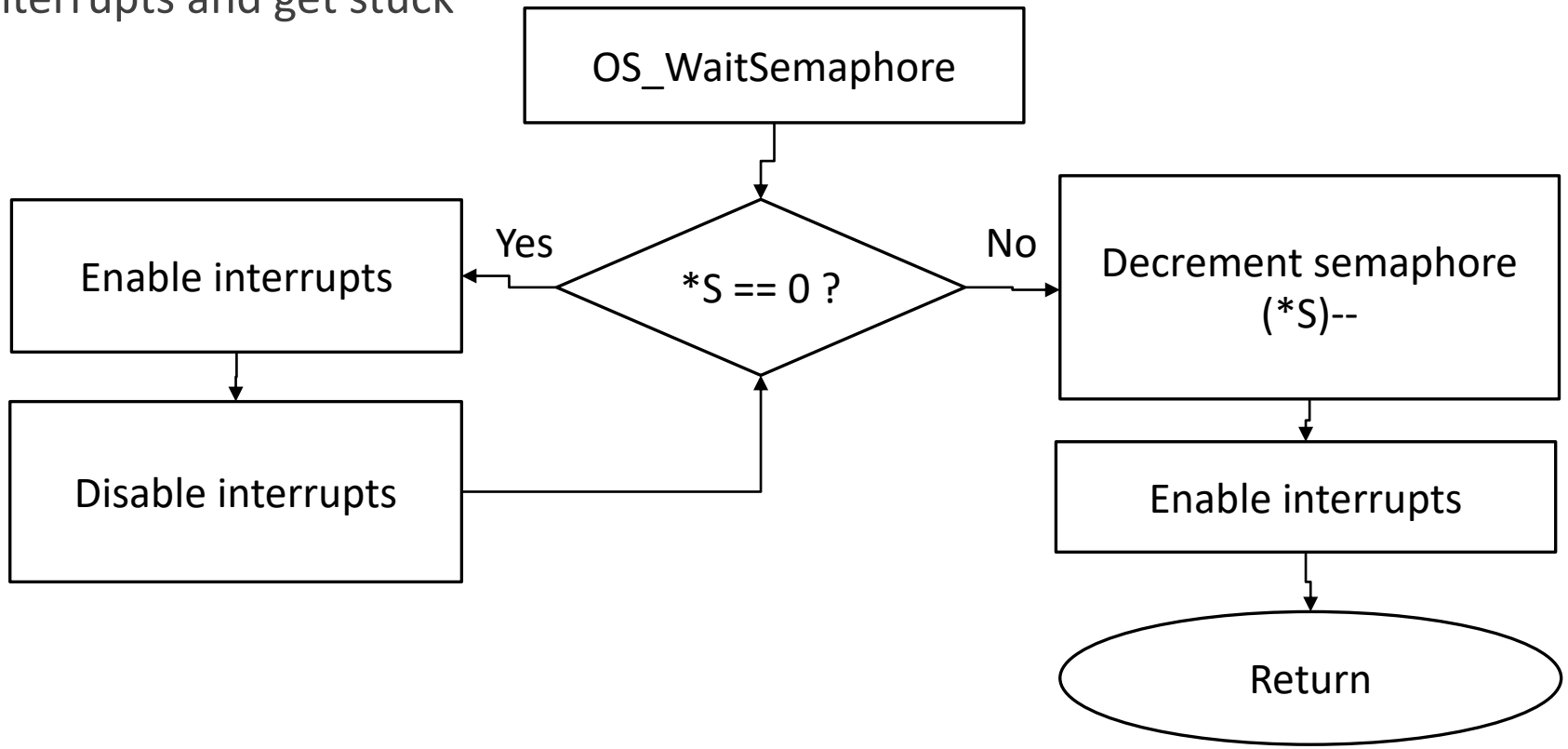
`G8RTOS_InitSemaphore(semaphore_t *S, int32_t value)`

- Enter a critical section and initialize the semaphore in it.
- Pass the pointer to the semaphore around so that its value can be modified



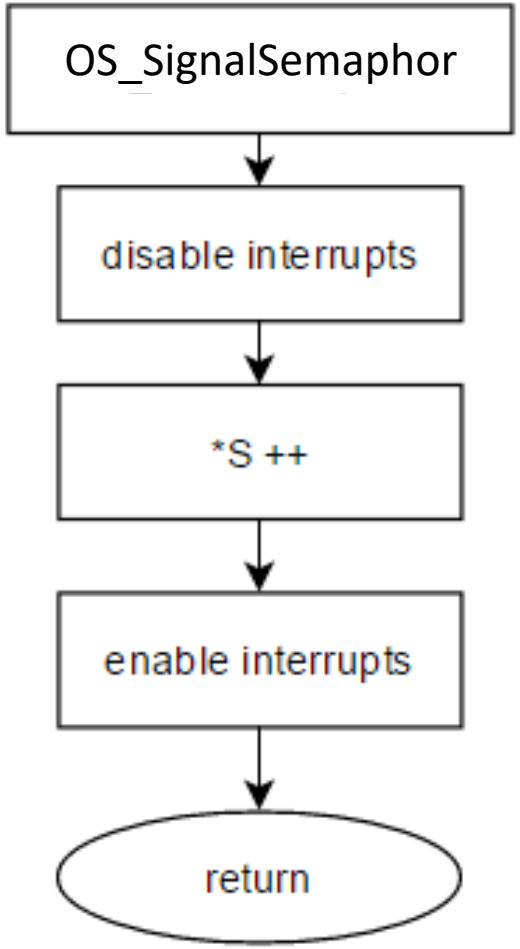
G8RTOS_WaitSemaphore(semaphore_t *S)

- Wait for semaphore to become non-zero.
- While waiting enter and exit the critical section so that we won't miss all the interrupts and get stuck in the loop forever.



G8RTOS_SignalSemaphore(semaphore_t *S)

- Enter critical section.
- Increment the semaphore.
- Make sure to increment the semaphore itself not its pointer (*S)++;



Mutual Exclusion

- An example use of semaphores for mutually exclusive tasks.

```
G8RTOS_InitSemaphore(&LCDReady,1);

void Task0{

    G8RTOS_WaitSemaphore(&LCDReady);
    LCD_Write("Coming to you live from task 0");
    G8RTOS_SignalSemaphore(&LCDReady);
}

void Task1{

    G8RTOS_WaitSemaphore(&LCDReady);
    LCD_Write("Coming to you live from task 1");
    G8RTOS_SignalSemaphore(&LCDReady);
}
```

Synchronization

- Enter critical section.
- Increment the semaphore.
- Make sure to increment the semaphore it self not its pointer (*S)++;

```
uint32_t ADCData;
G8RTOS_InitSemaphore(&ADCReady,0);

void TaskADC{

    ADCData = ADC_Read();
    G8RTOS_SignalSemaphore(&ADCReady);
}

void TaskLCD{

    G8RTOS_WaitSemaphore(&ADCReady);
    LCD_Write(ADCData);
}
```

RTOS: Threads

- Implement the above semaphore functions in Lab2. Now we can add threads to the RTOS and synchronize them using semaphore.
- We will use two semaphore to make sure the access to the LED I2C interface and the sensors I2C interface is exclusive.
- You developed functions for writing to LEDs in Lab1. They should be included in the BSP.
- Functions for reading sensor data are available in the BSP.

```
/* reading X location from accelerometer. Initialization is done
in the BSP initialization function*/
#include <BSP.h>
int16_t accelerometerX;
while(bmi160_read_accel_x(&accelerometerX));
```

```
/* reading Light sensor data. */
uint16_t lightData;
while(!sensorOpt3001Read(&lightData));
```

```
/* reading Light sensor data. */
int16_t gyroZ;
while(bmi160_read_gyro_z(&gyroZ));
```

RTOS: Threads

- You need the following three threads:
  - Thread 0:
    - waits for the sensor I2C semaphore.
    - Reads accelerometer's x-axis and saves it.
    - Releases the sensor I2C semaphore.
    - Waits for the LED I2C semaphore. Once available output data to red LEDs as shown in the Lab manual. And then releases it.
  - Thread 1:
    - waits for the I2C semaphore.
    - Reads the light sensor and save to local variable.
    - Releases the I2C semaphore.
    - Wait for the I2C semaphore. Once available output data to green LEDs as shown in the Lab manual.
  - Thread 2:
    - waits for the I2C semaphore.
    - Reads from the z-axis of the gyro and save into local variable
    - Releases the I2C semaphore.
    - Wait for the I2C semaphore. Once available output data to blue LEDs as shown in the Lab manual. Don't forget to release the semaphore by signaling it (signal function).

RTOS: Threads

- Write all the threads in a `Threads.c` file with a header file `Threads.h` as well.
- Initialize the RTOS. Add the threads to the RTOS.
- Start the RTOS using the launch and start functions.