A TUTORIAL ON MOBILE EMBEDDED SYSTEMS

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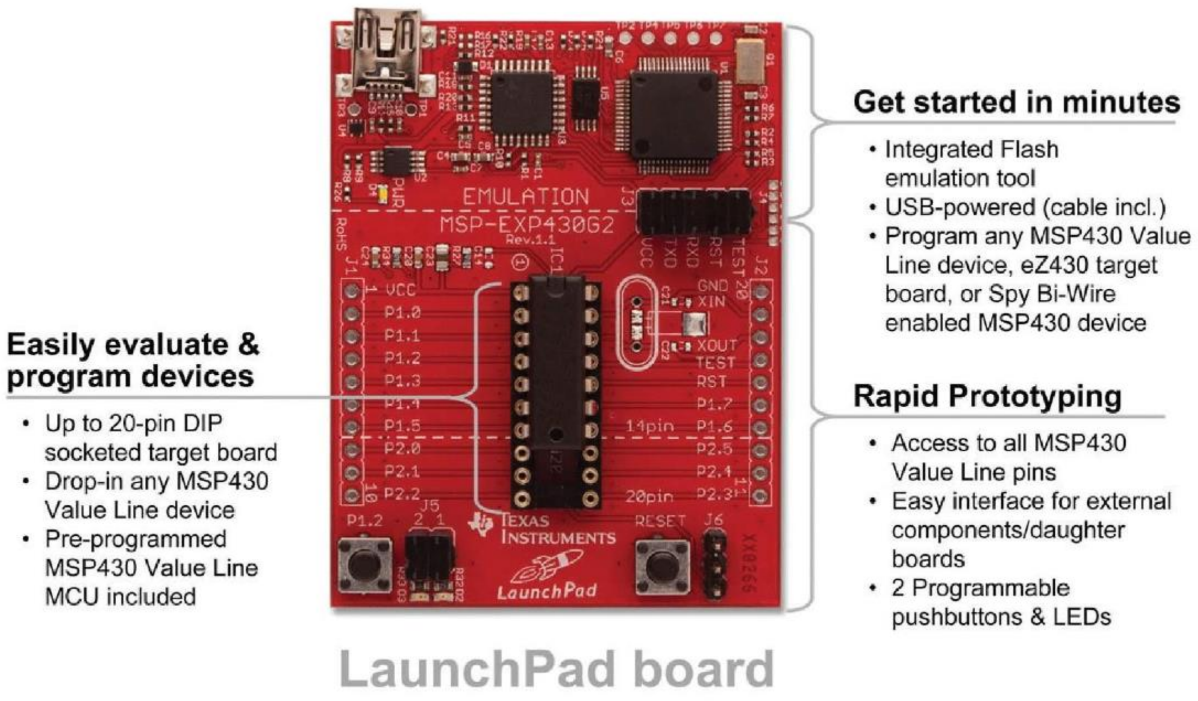
Getting Started with a Microcontroller

This tutorial document is meant to be a primer for working with microcontrollers to realize some simple applications based on this versatile embedded system. The subsequent sections of the document will go over the necessary theoretical background and concepts. However, in this section, we describe how to practically get started using one of these devices. The reason we do this first is to allow the reader to be able to try out the various example programs found in the document, and also to motivate the reader to continually program a microcontroller and try out new concepts as and when they are learned through progression in this tutorial.

Specifically, we will explain how to get started with the Texas Instruments Launchpad board that houses the microcontroller designated MSP430G2553. As shown in the image below, the Launchpad houses the MSP430 board along with several other peripherals in a setup that makes it very simple to program and test. A given application can be executed by the microcontroller by simply downloading the corresponding code onto it using the mini-USB interface.


Get started in minutes
• Integrated Flash emulation tool
• USB-powered (cable incl.)
• Program any MSP430 Value Line device, eZ430 target board, or Spy Bi-Wire enabled MSP430 device
Easily evaluate & program devices
• Up to 20-pin DIP socketed target board
• Drop-in any MSP430 Value Line device
• Pre-programmed MSP430 Value Line MCU included
Rapid Prototyping
• Access to all MSP430 Value Line pins
• Easy interface for external components/daughter boards
• 2 Programmable pushbuttons & LEDs
LaunchPad board
EMULATION
MSP-EXP430G2
Texas Instruments
LaunchPad

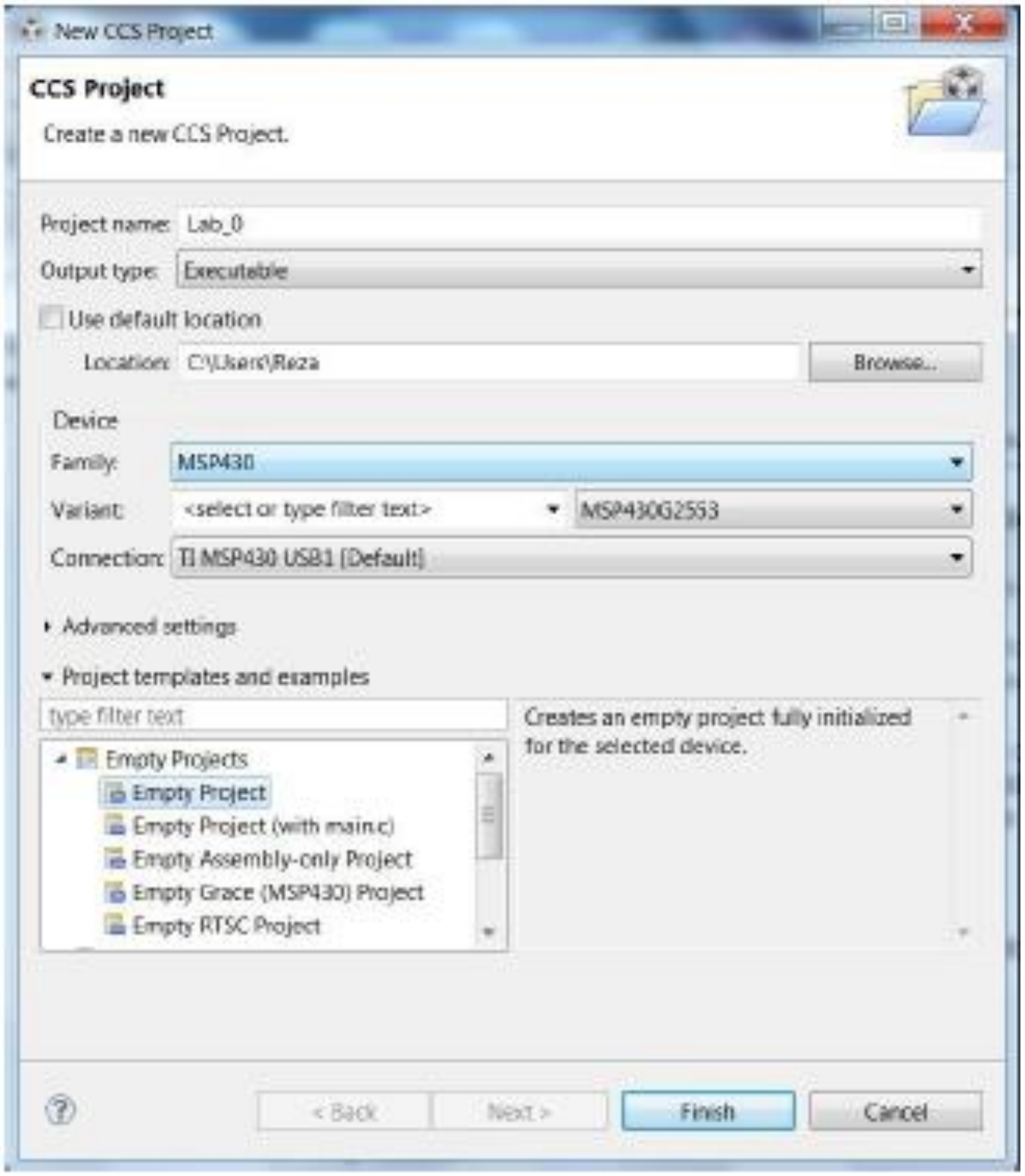
The PC application that will be used to download code onto the MSP430 board is called Code Composer Studio (CCS). This is the integrated development environment (IDE) for TI's DSPs, microcontrollers and application processors. It includes compilers for the MSP430 low power 16-bit microcontroller device families, source code editor, project build environment, debugger, profiler, simulators and many other features. This section describes how to make a new project and set the target configurations for downloading applications onto the MSP430 LaunchPad board.

Note: These instructions are written for Code Composer v5.3, but should be largely similar for newer versions as well.

First, complete the following steps:

- Open CCSv5.3
- Click on *File --> New --> CCS Project*
- In the *Project name* field choose a name and a location for the project
- In the Device section select Family as 'MSP430'
- Select MSP430Gvxx Family and MSP430G2553 as Variant
- Select connection type TI MSP430 USB1[Default]
- Select 'Empty Project' and click 'Finish'

Here is what the screen should look like after choosing all the settings:



CCS Project

Create a new CCS Project.

Project name: Lab_0

Output type: Executable

Use default location

Location: C:\Users\Reza

Device

Family: MSP430

Variant: <select or type filter text> MSP430G2553

Connection: TI MSP430 USB1 [Default]

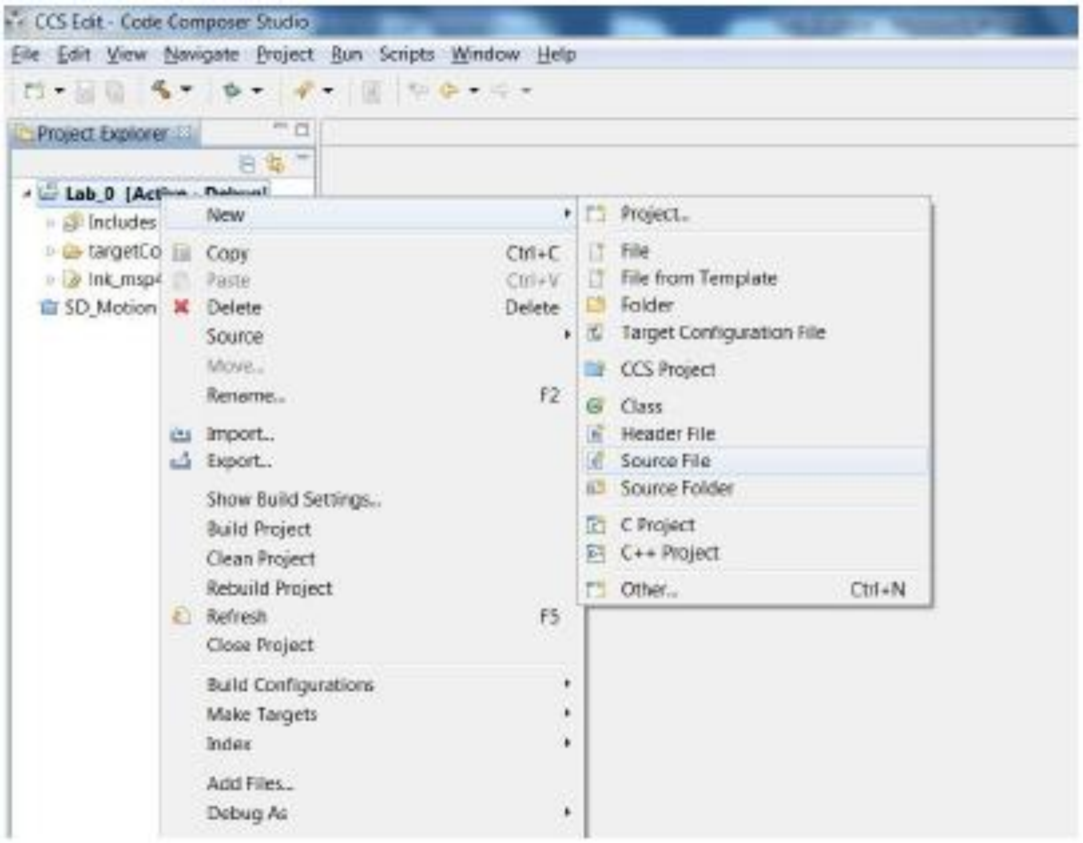
Advanced settings

Project templates and examples

Empty Projects
- Empty Project
- Empty Project (with main.c)
- Empty Assembly-only Project
- Empty Grace (MSP430) Project
- Empty RTSC Project

Creates an empty project fully initialized for the selected device.

An empty project is created. You can create source or header files and add them to the project by selecting *Project Explorer* on the left side of main view and then right-click and select *New.*

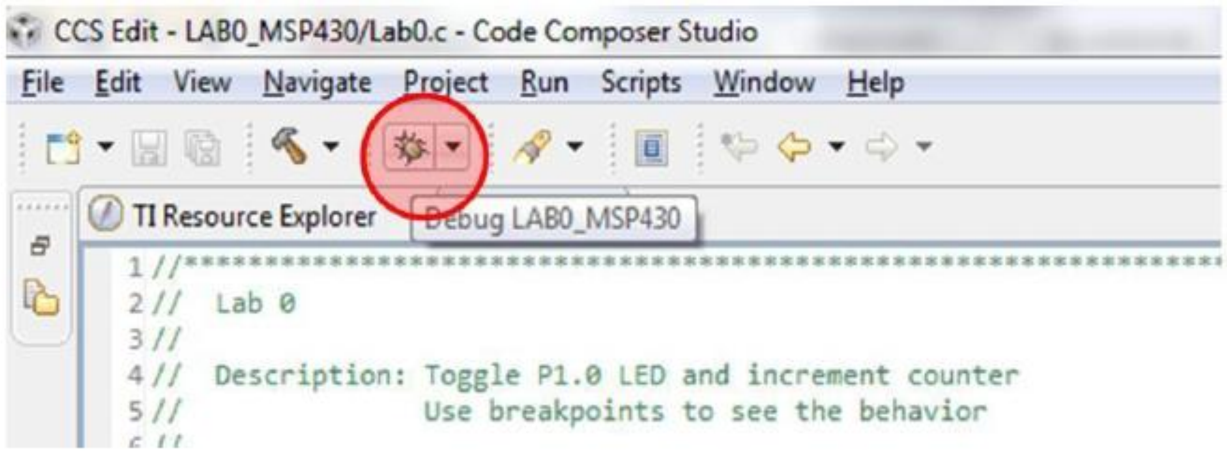


Alternately, instead of creating a new file here, you could add an existing file or set of files. Right-click on your project in the *Project Explorer* and select *Add Files* or go to *Project --> Add Files*. To get started, copy and paste the code below into a blank file onto your computer, give it a name like 'Example_Launchpad' and save it as a '.c' file type:

```
#include "msp430g2553.h"
void main(void)
{
  WDTCTL = WDTPW + WDTHOLD;                  // Stop WDT - Watchdog Timer

  // Configure LED at P1.0 as Output
  P1DIR |= BIT0;                             // P1.0 output

  // Loops Forever
  while(1)
  {
       P1OUT ^= BIT0;     // Toggle P1.0
       // Add some delay so we can see the LED change
         __delay_cycles(200000);
  }
}
```

Once this file has been created, you can choose it when going through the process to add an existing file to your project. When adding the file, CCS will ask whether you want to 'Copy Files' or 'Link to Files'. The first option will create a copy of your file and place it in your chosen CCS workspace, whereas the latter option will create a link to the original file.

For this example project, this C file alone is enough to execute a simple application that toggles the LED on the board. You can now compile and debug the project by pressing the F11 key or clicking on the green bug icon shown in the screenshot below. Before this step, make sure the Launchpad is connected to your PC via the provided USB cable (the power LED should be on).



```
//*****************************************************************
//  Lab 0
//
//  Description: Toggle P1.0 LED and increment counter
//               Use breakpoints to see the behavior
```

If the hardware setup is correct and there are no errors in the code (ignore compiler warnings) the debugger will start and the screen changes to the debug perspective. Press F8 or the green 'Play' button on the toolbar at the top to start code execution. You should see the LED start blinking.

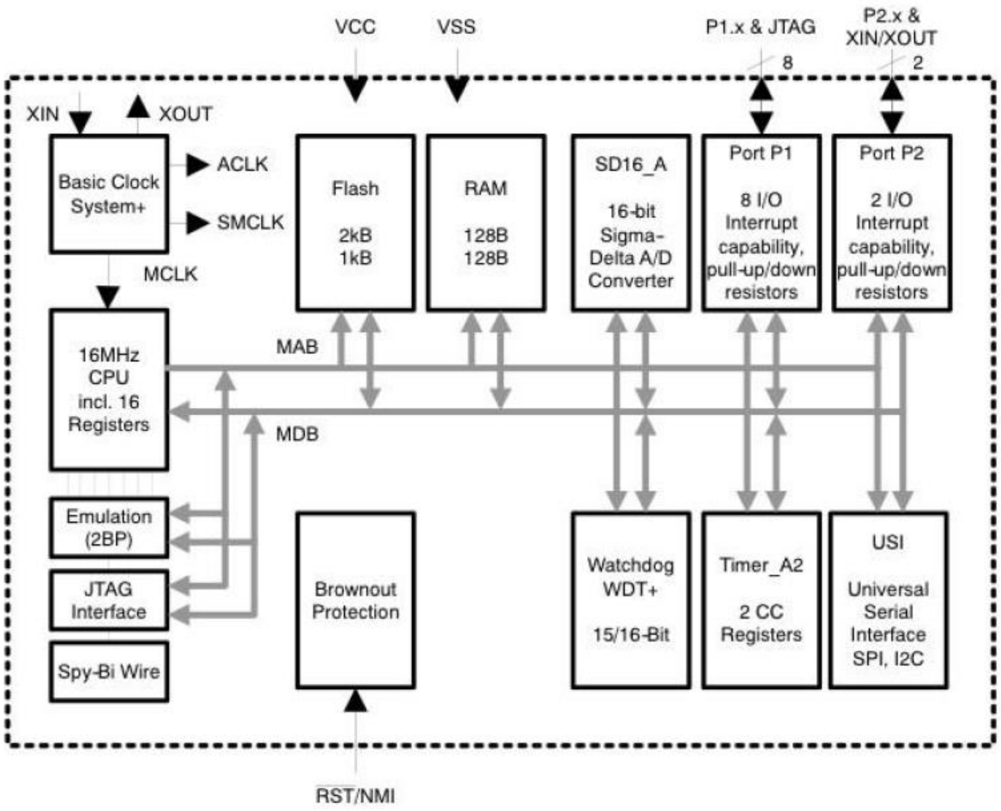
As you learn more concepts you will be able to write your own programs and test them out using the same procedure. Furthermore, all the code snippets in the exercise problems of the subsequent sections are compatible with this Launchpad board and can be downloaded in the same way. The debugging window can also be used to step through the program, monitor any variables and troubleshoot issues.

Microcontroller

General Description

A microcontroller is a low power, low resource processor used in embedded systems. The microcontroller typically acts as the central hub that is used to control and communicate with external devices and peripherals, and also manage memory on an embedded system. Often it is also used to perform computations for relatively simple applications.

When compared to traditional microprocessors in PCs, microcontrollers are typically cheaper, have much lower power consumption and also have lower amount of memory to use. Another key difference is that microcontrollers have not only a CPU, but also several peripherals on a single chip. A functional block diagram for the TI MSP430F2013 microcontroller is shown below:


VCC
VSS
P1.x & JTAG
8
P2.x & XIN/XOUT
2
XIN
XOUT
Basic Clock System+
ACLK
SMCLK
MCLK
Flash 2kB 1kB
RAM 128B 128B
SD16_A 16-bit Sigma-Delta A/D Converter
Port P1 8 I/O Interrupt capability, pull-up/down resistors
Port P2 2 I/O Interrupt capability, pull-up/down resistors
16MHz CPU incl. 16 Registers
MAB
MDB
Emulation (2BP)
JTAG Interface
Spy-Bi Wire
Brownout Protection
Watchdog WDT+ 15/16-Bit
Timer_A2 2 CC Registers
USI Universal Serial Interface SPI, I2C
RST/NMI

Apart from the 16MHz CPU, we can also see peripherals for communication, analog-to-digital conversion and timers. There are also general purpose digital pins which can also be utilized for interaction with external devices. This tutorial will subsequently go over each of the above mentioned components and more.

A user can program a microcontroller to define the actions it needs to perform to meet the desired functionality. This is typically done by writing the program in C code, having a compiler (such as the one included in CCS) convert that to machine readable code and then downloading it onto some form of non-volatile memory on the microcontroller, such as flash memory. Such a program is generally referred to as 'firmware'; when the microcontroller is powered on subsequently, it reads the program from memory and executes the instructions in order.

Instruction Set Architecture (ISA)

The Instruction Set Architecture (ISA) defines the different commands that can be processed by the microcontroller. It is essentially the "contract" between the architects of the device hardware and the programmers of the device firmware. The C code that the user writes is converted to assembly code, and each possible assembly instruction is defined by the ISA. An ISA that supports a high number of instructions could provide added functionality for the user and also possibly allow the microcontroller to complete certain actions quicker if there are specialized instructions for it. However, having too many instructions could also mean the hardware becomes needlessly complicated to support the interpretation and execution of all the instructions. Moreover, the user might find the architecture too clunky to effectively learn and use.

The design of the ISA would thus depend on the device and its intended use. Microcontrollers are typically meant to be lightweight, low power solutions and hence the ISA is relatively small compared to something like a PC. This dichotomy is borne out by two prominent architecture types: Complex Instruction Set Computing (CISC) and Reduced Instruction Set Computing (RISC).

CISC, as the name suggests, included complex instructions that encapsulated multiple basic actions. This led to programs that were shorter and easier to write, but each instruction took longer to execute under the hood due to the complexity. PCs typically use CISC-like architectures. Microcontrollers on the other hand, use RISC. RISC consists of simplified, uniform instructions that only completed basic tasks. It led to longer programs for equivalent tasks, but the time to execute each instruction was lower, the program flow was more predictable, and the hardware required to support the instruction set was simpler.

The ISA also defines, among other things, the size of individual instructions and the ways in which memory can be addressed. C is the programming language of choice for most microcontrollers; it is 'high level' enough to be easily readable and usable compared to 'lower level' assembly or machine code, and at the same time it is sufficiently 'low level' to allow for efficient coding and use of the device hardware.

Clocks

Microcontrollers have one or more clock signals that are used as the basis for any activities that require timing. The clock signals usually constitute square waves oscillating at a given frequency, and these can be generated in a few different ways. One popular and intuitive way to generate a regular clock signal is sourcing an oscillating crystal. This leads to very accurate clock signals with very little error and drift build-up over time; however the drawback is that this is a relatively expensive solution, both in terms of monetary cost and power consumption. Another popular alternative is generating a signal using a custom circuit loop, such as in the case of a digitally controlled oscillator (DCO). This solution is relatively inexpensive and power-conscious, but is prone to higher rates of error with respect to the true expected frequency, especially when compared to a corresponding clock signal generated by a crystal. Thus, the sources of the clock signals have several trade-offs, and care must be taken to choose the right option taking into account the needs of the application.

In terms of applications, an obvious one for clocks would be the timing of external events and generation of periodic signals. There are in fact specialized hardware modules to fully utilize the clocks in this way and these will be described in further detail in the section on 'Timers'. If we take a more fundamental look, the execution of code on the microcontroller itself is a synchronous activity; typically a clock is used to time the execution of successive instructions, with a faster clock resulting in a higher processing speed but also higher power consumption. Another important application domain for clocks in the context of microcontrollers is in communication. As we will see in further detail in future sections, certain types of digital communication require a shared clock between the communicating devices to synchronize the sending and receiving of data. Finally, these clock signals can also be sent to any external peripherals that do not have a suitable clock source of their own to function.

In the specific case of the MSP430 microcontroller, there are three clock signals available: the Master Clock (MCLK), Sub-Main Clock (SMCLK) and the Auxiliary Clock (ACLK). These three signals can be configured to source their signal from an internal crystal, DCO loop or any other suitable external clock source. Moreover, there are divider circuits in place so that the clock signal can oscillate at certain fractions of the given clock source frequency.

The MCLK is used to synchronize the execution of instructions by the central processor and hence fundamentally defines the timing of the microcontroller's performance. It can also however, be piped out and used as a clock signal for other applications in parallel. In general, a higher MCLK speed means higher performance and more power consumption. The SMCLK and the ACLK can both be used for all of the other applications of clock signals as mentioned before. The key difference is that the SMCLK typically supports higher frequencies on the order of MHz, whereas the ACLK is designed to be used for low frequency clocking applications on the order of a few KHz as necessary.

For more information on the details of the various available clock sources and clock speeds, please refer to the specific datasheet of the microcontroller. The datasheet for the MSP430G2553 is provided in the Appendix section at the end of this document.

Low Power Modes

One of the key features of an embedded system is energy efficiency, and the microcontroller can help to save power through customizable low power modes. There are typically multiple levels of low power modes, with each level increasingly powering down more components of the system to save power. For example, on the TI MSP430F5438 microcontroller the various power modes, with approximate current consumption in parentheses, are described as follows:

Active Mode (AM): CPU, all clocks, and enabled modules are active (≈300 μA)

Low Power Mode 0 (LPM0): CPU and MCLK are disabled, SMCLK and ACLK remain active (≈85 μA)

Low Power Mode 3 (LPM3): CPU, MCLK, SMCLK, and DCO are disabled; only ACLK remains active (≈1 μA)

Low Power Mode 4 (LPM4): CPU and all clocks disabled, RAM is retained (≈0.1 μA)

As can be seen, in all low power modes the CPU is disabled so there will be no more computations and no more code executing. The choice of low power mode depends on which components the user wants to retain while the CPU is disabled. Low power modes are useful when the system only needs to be fully active in response to sporadic external events, or if the system only needs to be active for a brief amount of time in a periodic fashion. In either case the system can be brought back to active mode with the use of interrupts, which are described in the following section.

Interrupts

Interrupts can break the flow of execution of code on a microcontroller to perform a given task in response to an aperiodic external event or a scheduled internal event. Interrupts are typically high priority events that require immediate response. For example, if the user presses a button to turn on a light the system needs to respond immediately to the button press so the user interface remains viable. The interrupt mechanism enables this by allowing the microcontroller to break out of its current routine, perform the required actions related to the interrupt, and return back to the previous state to continue executing the code it was before. Alternatively, interrupts can also work well with low power modes to reduce energy consumption; for example the device can go into low power mode with no code executing, and a button press can trigger an interrupt that wakes up the device from low power mode to perform the required action and then return to sleep if desired. This is in contrast to 'polling', wherein the CPU is fully powered on but is idle waiting for the event to happen. Thus, it is almost always preferable to use interrupts instead of polling if the CPU is not required to be active while the next event is pending.

The configurable sources of interrupts can vary, depending on the specific microcontroller and the hardware available. Some common sources of interrupts include:

1. **General Purpose Input/Output (GPIO) pins:** These are simply generic digital logic lines that connect the microcontroller to one or more peripherals. The microcontroller can be configured such that a transition in logic level triggers an interrupt. For example, the circuit can be designed in such a way that a button press triggers a logic level '1' on a specific GPIO pin that is configured for interrupts so that the microcontroller can respond to the button press.
2. **Timers:** Timers will be described in more detail in the following section, but essentially they are internal components that can be set up to count to a specific value and trigger an interrupt; this allows the user to trigger interrupts after known time intervals. They can also be configured to repeat this process so that the interrupts are periodic.
3. **Analog-to-Digital Converter (ADC):** The ADC of the microcontroller can trigger an interrupt when a conversion is complete and the new digitized sample is ready.

Once an interrupt is triggered, the microcontroller begins executing the code in the corresponding interrupt service routine (ISR). If the microcontroller was previously actively executing code and was in the middle of an instruction, it completes that instruction alone, saves the state and jumps immediately to the ISR. Otherwise, if the microcontroller was sleeping in a low power mode, it returns to active mode after the interrupt and starts executing the code in the ISR.

Each source of interrupt has its own entry in an interrupt vector table, and each ISR has a unique identifier corresponding to an entry in this table so that the correct one is executed when an interrupt occurs. By default, the ISRs over which the user has control are left blank without code so that the user can fill it in and dictate the appropriate response to the interrupt.

When multiple sources of interrupt are triggered concurrently, interrupt priority is used to determine the order of execution of the ISRs. Typically for a given microcontroller this priority is predetermined and fixed for the different sources of interrupts. It is a good rule of thumb to keep the code in ISRs to a minimum to avoid unexpected interruptions or missed interrupts when there are multiple sources of interrupt enabled. The programmer must also be careful to write the ISR in such a way that there are no errors caused when the interrupted code is resumed.

There are also two classes of interrupts: maskable and non-maskable. Maskable interrupts can be enabled and disabled by the user at any time with the appropriate commands in the code. Whereas non-maskable interrupts cannot be disabled by the user and typically have a priority higher than the maskable ones since they occur as the result of critical events. An example of an event that causes a non-maskable interrupt is the corruption of the on-board memory.

For reference, the interrupt vectors for the MSP430x2xx class of microcontrollers is shown below:

INTERRUPT SOURCE	INTERRUPT FLAG	SYSTEM INTERRUPT	ADDRESS	SECTION	PRIORITY
Power-up External reset Watchdog	PORIFG RSTIFG WDTIFG	Reset	0xFFFE	.reset	15, highest
NMI Oscillator fault Flash memory violation	NMIIFG OFIFG ACCDVIFG	Non-maskable	0xFFFC	.int14	14
Timer_B3	TBCCR0 CCIFG	Maskable	0xFFFA	.int13	13
Timer_B3	TBCCR1 CCIFG TBCCR2 CCIFG, TBIFG	Maskable	0xFFF8	.int12	12
			0xFFF6	.int11	11
Watchdog Timer	WDTIFG	Maskable	0xFFF4	.int10	10
Timer_A3	TACCR0 CCIFG	Maskable	0xFFF2	.int09	9
Timer_A3	TACCR1 CCIFG, TACCR2 CCIFG, TAIFG	Maskable	0xFFF0	.int08	8
USCI_A0/USCI_B0 Rx	UCA0RXIFG, USB0RXIFG	Maskable	0xFFEE	.int07	7
USCI_Z0/USCI_B0 Tx	UCA0TXIFG, UCB0TXIFG	Maskable	0xFFEC	.int06	6
ADC10	ADC10IFG	Maskable	0xFFEA	.int05	5
			0xFFE8	.int04	4
I/O Port P2	P2IFG.0 – P2IFG.7	Maskable	0xFFE6	.int03	3
I/O Port P1	P1IFG.0 – P1IFG.7	Maskable	0xFFE4	.int02	2
			0xFFE2	.int01	1
			0xFFE0	.int00	0

Exercise Module

The following code snippet taken from the TI MSP430ware example code set for the MSP430G2553 microcontroller shows the use of interrupts. The code sets up interrupts on GPIO pin 1.4 and provides an ISR that is called when there is a high-to-low transition on that pin. Apart from the time the interrupt is handled, the microcontroller is in LPM4. Modify the code such that the microcontroller exits the low power mode once 10 high-to-low transitions on P1.4 have taken place:

```
#include <msp430.h>
int main(void)
{
  WDTCTL = WDTPW + WDTHOLD;                  // Stop watchdog timer
  P1OUT =  0x10;                             // P1.4 set
  P1REN |= 0x10;                             // P1.4 pullup
  P1IE |= 0x10;                              // P1.4 interrupt enabled
  P1IES |= 0x10;                             // P1.4 Hi/lo edge
  P1IFG &= ~0x10;                            // P1.4 IFG cleared
__bis_SR_register(LPM4_bits + GIE);}        // Enter LPM4 w/interrupt
// Port 1 interrupt service routine
```

```
#pragma vector=PORT1_VECTOR

__interrupt void Port_1(void)

{

  P1IFG &= ~0x10;                           // P1.4 IFG cleared

}
```

Timers

Timers are basically counters that count at a fixed speed based on the local clock on the embedded device. The timers can be used in two different modes based on their intended use:

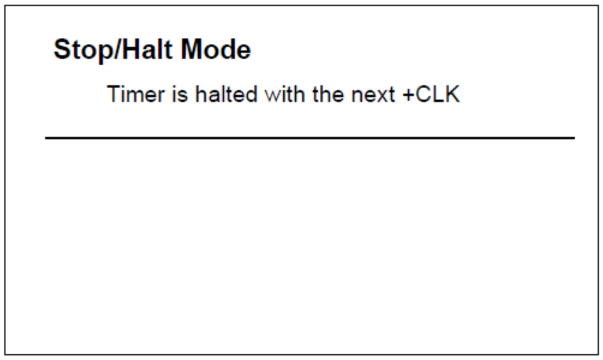
Compare Mode

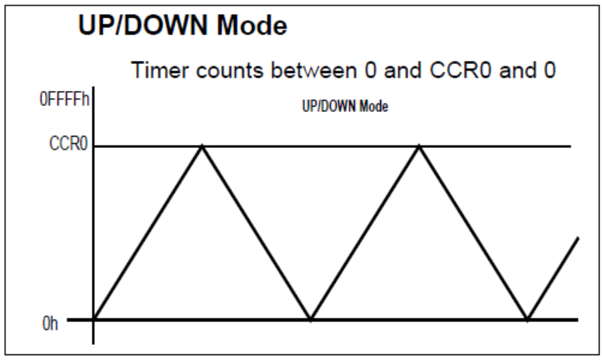
In this mode a specific fixed count, known as the ‘compare value’ can be set up in a register by the user and the timer count is continually compared with this number. As the timer counts up, whenever the timer value matches the ‘compare value’ an interrupt is generated. In this way, interrupts can be generated after a known amount of time or at repeated periodic intervals. This allows the system to perform actions at scheduled regular intervals.

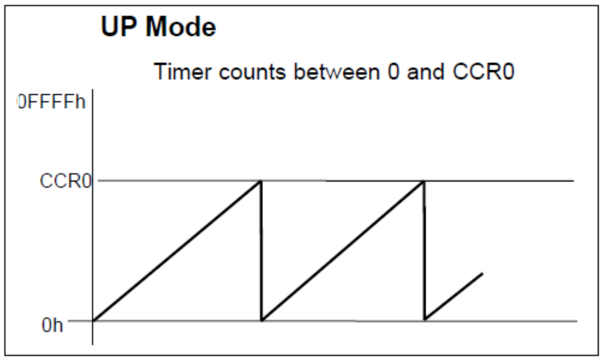
Often, the specific method of counting up and interrupt generation can also be configured. On the MSP430 for example, there are 4 modes:

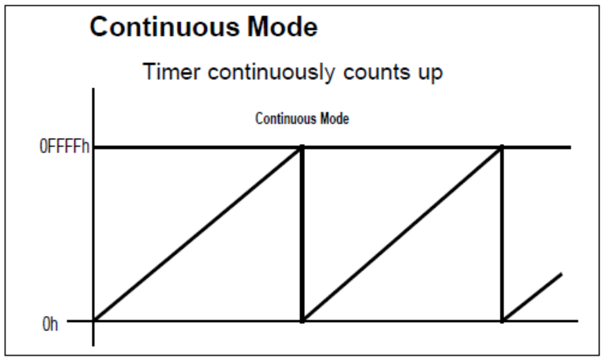
1. **Stop/Halt Mode:** The counter counts up to the designated value at the given clock speed and then stops counting altogether.
2. **Up/Down Mode:** The timer counts up to the ‘compare value’, which is stored in a capture compare register (CCR). Once this value is reached, the timer counts back down to zero at the same rate, and then starts counting up again once zero is reached.
3. **Up Mode:** The timer counts up to the ‘compare value’ stored in the designated CCR register and then instantaneously drops down to zero, before counting up again.
4. **Continuous Mode:** In this mode there is no ‘compare value’ and the timer simply counts up to the maximum possible value, rolls over back to zero, and repeats the process continuously.

The 4 modes are illustrated in the figure below:









To add further functionality, there can be multiple CCR registers active at the same time, so the timer can generate interrupts at multiple custom time intervals within a larger period.

Exercise Module

The following code snippet uses the timer in compare mode and initializes it to count in continuous mode. The microcontroller goes to low power mode and it wakes up to execute the ISR in the code snippet and toggles P1.0 every time the timer reaches the maximum value, in this case 0xFFFF. Suppose we want P1.0 to toggle every 50000 timer counts instead. Show how the code should be modified to accomplish this in each of three counting modes: a) continuous mode, b) up mode c) up/down mode.

```
#include <msp430.h>

int main(void)

{

  WDTCTL = WDTPW + WDTHOLD;                   // Stop WDT

  P1DIR |= 0x01;                              // P1.0 output

  CCTL0 = CCIE;                               // CCR0 interrupt enabled

  CCR0 = 50000;

  TACTL = TASSEL_2 + MC_2;                    // SMCLK, contmode

  __bis_SR_register(LPM0_bits + GIE);         // Enter LPM0 w/ interrupt

}
```

```
// Timer A0 interrupt service routine

#pragma vector=TIMER0_A0_VECTOR

__interrupt void Timer_A (void)

{

  P1OUT ^= 0x01;                            // Toggle P1.0

}
```

Capture Mode

In this mode the timer is continually counting up, and whenever a specific external event occurs the timer count at that time is stored. In this way, the timing of external events can be captured. For example, the time difference between two consecutive button presses can be measured by capturing the timer count for each button press event and calculating the difference.

There is also a specialized timer on some microcontrollers called the Real-Time Clock (RTC). As the name suggests, the purpose of this timer is to count out real world time; it supports registers for every common time interval from a year, to a second and can also generate interrupts at intervals defined by real time.

There is sometimes another specialized timer that plays an important role; on the MSP430 this timer is called the 'Watchdog Timer'. The role of this timer is to help the system reset if there is a catastrophic error from which it cannot recover. A common scenario would be if the firmware flow left the processor deadlocked in an unexpected state from which it cannot proceed. The watchdog timer can be set up to expire after a pre-selected period to act as a fail-safe and reset the system in such situations. Programmers must be aware that the timer could potentially be pre-configured with a default countdown value which could cause unintended resets of the program if not dealt with. If the watchdog functionality is not necessary, the timer can be disabled; it can then be potentially reconfigured to act as a regular timer for general timing applications.

Exercise Module

In the following code snippet, Timer A0 is used for input capture to measure the duty cycle of a signal generated by Timer A1. Assume that the output of Timer A1 (on pin 2.1) is connected externally to the input capture pin for Timer A0 (pin 1.2) to facilitate such a measurement. Gain an understanding of how the code does this, and then modify it so that Timer A0 now only captures rising edges and uses this to measure the period of the signal from Timer A1 instead.

```
#include <msp430.h>



unsigned char Count, First_Time;
unsigned int REdge1, REdge2, FEdge;


int main(void)
{
  unsigned int Period, ON_Period;
  unsigned char DutyCycle;

  WDTCTL = WDTPW + WDTHOLD;                  // Stop watchdog timer

  P1DIR |= BIT0;                             // P1.0/LED Output
  P1OUT &= ~BIT0;                            // LED off
  if (CALBC1_8MHZ==0xFF)                    // If calibration constant erased
  {
    while(1);                                // do not load, trap CPU!!
  }
  DCOCTL = 0;                                // Select lowest DCOx and MODx settings
  BCSCTL1 = CALBC1_8MHZ;                     // Set DCO to 8MHz
  DCOCTL = CALDCO_8MHZ;

  // Configure Port Pins
  P2DIR |= BIT1;                             // P2.1/TA1.1 Output
  P2SEL |= BIT1;                             // TA1.1 Option select
  P1DIR &= ~BIT2;                            // P1.1/TA0.1 Input Capture
  P1SEL |= BIT2;                             // TA0.1 option select

 // Configure TA1.1 to output PWM signal
 // Period = 82/32khz = 2.5ms ~ 400Hz Freq
  TA1CCR0 = 82-1;                           // Period Register
  TA1CCR1 = 21;                             // TA1.1 25% dutycycle
  TA1CCTL1 |= OUTMOD_7;                     // TA1CCR1, Reset/Set
  TA1CTL = TASSEL_1 + MC_1 + TACLR;         // ACLK, upmode, clear TAR
 // Configure the TA0CCR1 to do input capture
 // TA0CCR1 Capture mode; CCI1A; Both Rising and Falling Edge; interrupt enable
  TA0CCTL1 = CAP + CM_3 + CCIE + SCS + CCIS_0;

// SMCLK, Cont Mode; start timer
 TA0CTL |= TASSEL_2 + MC_2 + TACLR;

  // Variable Initialization
  Count = 0x0;
  First_Time = 0x01;

  while(1)
  {
      __bis_SR_register(LPM0_bits + GIE);   // Enter LPM0
      __no_operation();                     // For debugger
      // On exiting LPM0
      if (TA0CCTL1 & COV)                   // Check for Capture Overflow
          while(1);                         // Loop Forever
      Period = REdge2 - REdge1;             // Calculate Period
      ON_Period = FEdge-REdge1;             // On period
      DutyCycle = ((unsigned long)ON_Period*100/Period);
      if(DutyCycle!= 25)
      {
          P1OUT |= BIT0;
      }



      else
      {
          P1OUT &= ~BIT0;
      }
  }
}


// TA0_A1 Interrupt vector
#pragma vector = TIMER0_A1_VECTOR
__interrupt void TIMER0_A1_ISR (void)
{
  switch(__even_in_range(TA0IV,0x0A))
  {
      case  TA0IV_NONE: break;              // Vector  0:  No interrupt
      case  TA0IV_TACCR1:                   // Vector  2:  TACCR1 CCIFG
        if (TA0CCTL1 & CCI)                 // Capture Input Pin Status
        {
            // Rising Edge was captured
            if (!Count)
            {
                REdge1 = TA0CCR1;
                Count++;
            }
            else
            {
                REdge2 = TA0CCR1;
                Count=0x0;
          __bic_SR_register_on_exit(LPM0_bits + GIE);  // Exit LPM0 on return to main
            }



            if (First_Time)
                First_Time = 0x0;
        }
        else
        {
            // Falling Edge was captured
            if(!First_Time)
            {
                FEdge = TA0CCR1;
            }
        }
        break;
      case TA0IV_TACCR2: break;             // Vector  4:  TACCR2 CCIFG
      case TA0IV_6: break;                  // Vector  6:  Reserved CCIFG
      case TA0IV_8: break;                  // Vector  8:  Reserved CCIFG
      case TA0IV_TAIFG: break;              // Vector 10:  TAIFG
      default:     break;
  }
}
```

Interfacing, IO and AFE

In this section we describe the various ways the microcontroller can interact with external devices.

Digital Input/Output (GPIO)

General Purpose Input/Output (GPIO) ports are versatile digital pins that can be used to configure external peripherals or take as input digital signals from these devices. They can also be reconfigured to be used for communication. They are simply digital logic lines whose voltage can be pulled high for a logic ‘1’ and pulled low for a logic ‘0’. In other words, when the voltage on a GPIO pin exceeds a certain threshold it is interpreted as a binary logic value of ‘high, ‘1’ or ‘true’, and it is ‘low’, ‘0’ or ‘false’ otherwise. When configured as outputs, these pins can be used to signal or otherwise configure other external devices. When configured as inputs they can receive digital signals from external devices; a useful feature when configured as inputs is that they can also be configured to trigger interrupts when a given transition (high-to-low or low-to-high) happens on the corresponding digital line. If we look back at the example application described in the ‘Interrupts’ section wherein a button press triggers an interrupt, it can be readily seen that a GPIO pin is ideal to be set up as in input to signal the button press in this scenario. However, that is just one example use of these pins and it is likely a given project will use them in many other ways as well. They are effectively the pathways for the microcontroller to interact with devices and peripherals that are off-chip.

Exercise Module

Assume that pin 1.4 of the microcontroller is connected to an external peripheral and meant to be used as an input for signals from that peripheral. The peripheral will attempt to pull 1.4 ‘low’ whenever it signals, and the microcontroller should in response briefly flash an LED connected to pin 1.0. Fill in the code snippet below to achieve this functionality.

Hint: You will need to set P1.4 to be pulled up by default, and enable high-to-low transition interrupts for that pin so that the microcontroller can correspondingly toggle P1.0 in the ISR.

```
#include <msp430.h>

int main(void)

{

  WDTCTL = WDTPW + WDTHOLD;                  // Stop watchdog timer

  P1DIR = 0x01;                       // P1.0 output, others pins on Port 1 are inputs

//Code to set up P1.4 and associated interrupts goes here

  __bis_SR_register(LPM4_bits + GIE);       // Enter LPM4 w/interrupt

}


// Port 1 interrupt service routine

#pragma vector=PORT1_VECTOR

__interrupt void Port_1(void)

{

  //Code to flash LED on P1.0 goes here

  P1IFG &= ~0x10;                            // P1.4 IFG cleared

}
```

Analog Input (AFE)

The Analog Front End represents the entire sub-system that is used to take as input analog signals from the outside world using designated GPIO pins, process and digitize them. Typically, the microcontroller can configure several aspects of the AFE such as the sampling rate of the ADC, on which pin the analog input is expected, the expected range of the signal and so on. The microcontroller can then enable interrupts and set a specific bit in a register to have the ADC start converting whatever it receives on the designated pin. When analog-to-digital conversion for a single sample is complete, the results are stored in a data register and an interrupt is triggered so that the microcontroller becomes aware that a digitized sample is ready to be read. This process continues for all subsequent samples until the ADC is disabled.

Exercise Module

In the following code snippet, the ADC is configured to sample inputs on port 1.7 (designated as A7). Timer A0 is set up with CCR1 and CCR0 in up mode and every time the timer ISR fires (once every 32

ACLK cycles) the ADC is enabled and configured to measure a sample. Then when the sample is ready, the ADC ISR is executed; however in the current version of the code the ISR does nothing except disable the ADC before the next timer interrupt enables it again. In other words, the converted sample is left unused. You have two tasks:

1. Explain exactly the configurations of the ADC, specifically the significance of the assignments to the registers ADC10CTL0 and ADC10CTL1.
2. Modify the code so that the ADC converted sample is checked to see if the input voltage is greater than 0.75V and if yes, turns on an LED (assumed to be connected to P1.0)

```
#include <msp430.h>

int main(void)

{

  WDTCTL = WDTPW + WDTHOLD;                    // Stop WDT


  ADC10CTL1 = INCH_7 + SHS_1;                  // P1.7, TA1 trigger sample start

  ADC10AE0 = 0x80;                             // P1.7 ADC10 option select

  TACCTL0 = CCIE;                              // Enable interrupt

  TACCR0 = 32-1;                               // PWM Period

  TACCTL1 = OUTMOD_3;                          // TACCR1 set/reset

  TACCR1 = 2;                                  // TACCR1 PWM Duty Cycle

  TACTL = TASSEL_1 + MC_1;                     // ACLK, up mode

  __bis_SR_register(LPM3_bits + GIE);          // Enter LPM3, enable interrupts

}


// ADC10 interrupt service routine

#pragma vector=ADC10_VECTOR

__interrupt void ADC10_ISR(void)

{

  ADC10CTL0 &= ~ENC;                           // ADC10 disabled

  ADC10CTL0 = 0;                               // ADC10, Vref disabled completely

}


// Timer A0 interrupt service routine

#pragma vector=TIMER0_A0_VECTOR
```

```
__interrupt void Timer_A(void)

{

  ADC10CTL0 = SREF_1 + ADC10SHT_2 + REFON + ADC10ON + ADC10IE;

  ADC10CTL0 |= ENC;                         // ADC10 enable set

}
```

Analog Output (DAC)

The Digital to Analog Converter (DAC) can be used to reverse the process of the ADC and allow the microcontroller to feed it appropriate signals digitally and have them converted to corresponding analog voltages to be transmitted out. This can be used to drive devices such as a microphone which require an analog input.

Communication

Communication protocols on a microcontroller can be broadly divided into two categories: synchronous and asynchronous.

Synchronous Communication

This class of communication protocols is characterized by the presence of a shared digital clock signal between the two communicating devices in addition to the lines used for communicating data. The clock signal is typically used to ensure that the receiving device samples the transmitted data at the appropriate time instances for correct interpretation. The two most commonly used synchronous protocols are described below:

Serial Peripheral Interface (SPI)

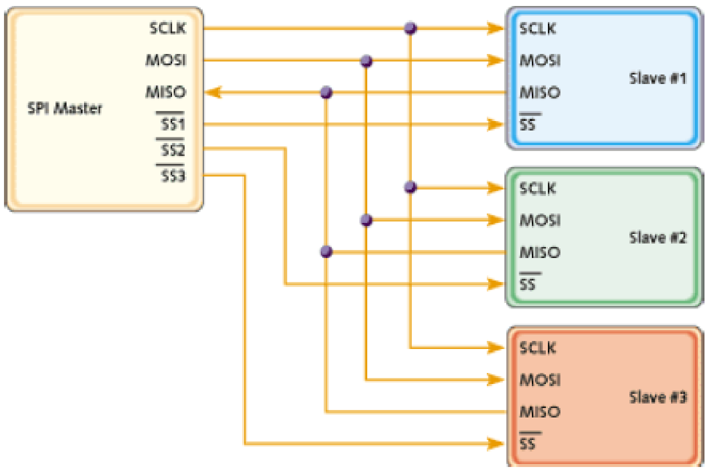
Serial Peripheral Interface (SPI) involves communication between one master and one or more slave devices. The devices can be comprised of any number of embedded microcontrollers or analog front ends, with the designation of master and slave depending on the expected roles of each device. When two or more devices are communicating using SPI, four hardware connections are required between each master-slave pair; their names and functions are listed below:

1. Master Output Slave Input (MOSI) – Used to transmit bytes from master device to slave device
2. Master Input Slave Output (MISO) – Used to transmit bytes from slave device to master device
3. Serial Clock (SCLK) – Clock signal supplied by the master along with each transmitted byte to synchronize slave's sampling of each bit in the byte
4. Slave Select (SS) – When this line is pulled low, then the slave connected to this line is enabled to actively communicate with the master.

These connections are in parallel with corresponding ports on the master and slave connected together, *i.e.*, MOSI of master connected to MOSI of slave, MISO of master connected to MISO of slave and so on. Since the functionality of the SS line is to choose the active slave, the hardware configuration varies depending on the purpose. There are two commonly used configurations:

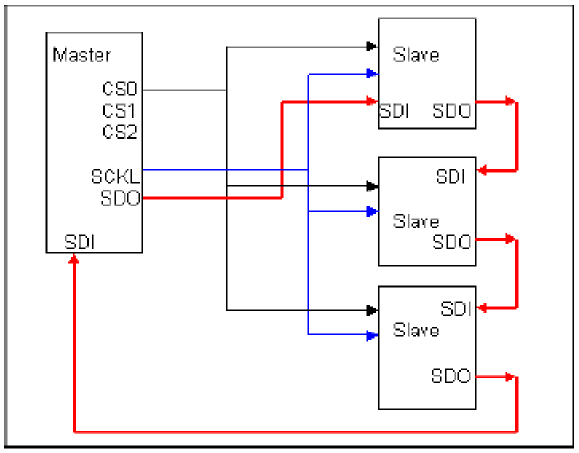
Independent Slaves:

As shown in the figure, this involves connecting the MOSI, MISO and SCLK lines of the master to the corresponding pins of each slave. The master then has separate slave select pins for each slave to activate or deactivate them at will.



Daisy Chain:

An alternate configuration involves chaining the slaves such that the output of the first slave feeds into the input of the next as shown in the figure. In this way, only one SS line is required on the master, and each intermediate slave has the responsibility of shifting on the data to the target slave. In effect the entire chain acts as a shift register with the master controlling the amount of shift.



SPI is implemented such that the MOSI and MISO lines conceptually form a ring buffer, with the master initiating all data transfers in either direction. As and when a byte is written on to the MOSI line, a byte gets shifted back in through the MISO line. The data that gets transmitted out by the master is whatever data was placed in the SPI Transmit register by the user’s program, and the data that gets received is whatever was put on the transmit register of the slave by the program on that device.

In effect, this means that if the master wants to only write to the slave then the master proceeds to write byte by byte and simply ignores the bytes returned by the slave. Conversely, if only read is required, the master writes dummy bytes into the MOSI line that prompt a shifting in of the data available for transmit on the slave side.

Along with each transmitted byte the master also sends clock signal that toggles at a previously fixed frequency that corresponds to the time between successive bits in the byte that is to be transmitted. The slave uses this clock signal to sample each bit of the byte on the rising edge or falling edge of the clock depending on how the SPI connection was initialized in the program.

The biggest drawback of SPI is that the complexity of implementing the required hardware scales up significantly as more and more peripherals are connected. However, it is relatively simple to implement in software and is generally capable of relatively high speeds due to the simplicity of the protocol.

Exercise Module:

The two code snippets below set up SPI communication for a master and slave device respectively. The ports are initialized for SPI communication, and both devices have an ISR that is called when data is received. Currently, the master just sends one byte and then all communication stops. Modify the code such that:

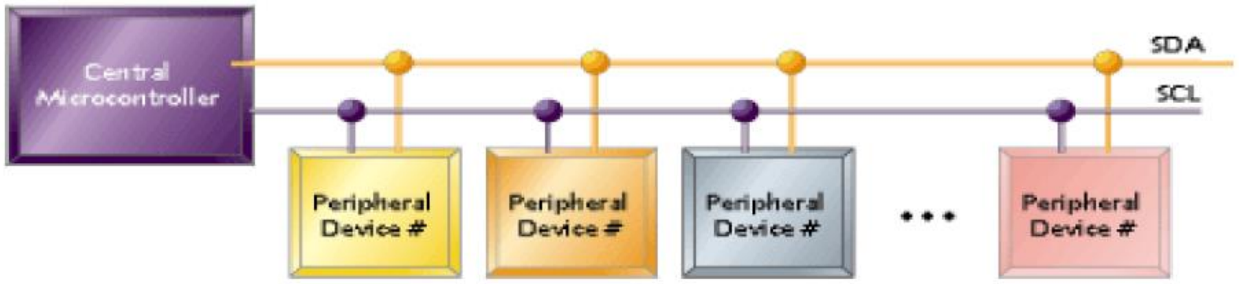
1) The master sends the value ‘0x01’
2) The slave receives the value and echoes it back to the master
3) The master verifies that the echoed value is the same as the one that was sent. If yes, set P1.0 high and if no, set P1.0 low.
4) The master then increments the value to be sent to ‘0x02’ and the process is repeated. This continues indefinitely.

```
//Master device SPI code

#include <msp430.h>

unsigned char MST_Data, SLV_Data;

int main(void)

{

  volatile unsigned int i;

  WDTCTL = WDTPW + WDTHOLD;                  // Stop watchdog timer

  P1OUT = 0x00;                              // P1 setup for LED & reset output

  P1DIR |= BIT0 + BIT5;                      //

  P1SEL = BIT1 + BIT2 + BIT4;

  P1SEL2 = BIT1 + BIT2 + BIT4;

  UCA0CTL0 |= UCCKPL + UCMSB + UCMST + UCSYNC;  // 3-pin, 8-bit SPI master

  UCA0CTL1 |= UCSSEL_2;                      // SMCLK
  UCA0BR0 |= 0x02;                          // /2
  UCA0BR1 = 0;                              //
  UCA0MCTL = 0;                             // No modulation
  UCA0CTL1 &= ~UCSWRST;                     // **Initialize USCI state machine**
  IE2 |= UCA0RXIE;                          // Enable USCI0 RX interrupt
  P1OUT &= ~BIT5;                           // Now with SPI signals initialized,
  P1OUT |= BIT5;                            // reset slave
  __delay_cycles(75);                 // Wait for slave to initialize

  MST_Data = 0x01;                          // Initialize data values
  SLV_Data = 0x00;

  UCA0TXBUF = MST_Data;                     // Transmit first character
  __bis_SR_register(LPM0_bits + GIE);       // CPU off, enable interrupts
}

// Master RX ISR
#pragma vector=USCIAB0RX_VECTOR
__interrupt void USCIA0RX_ISR(void)
{
  while (!(IFG2 & UCA0TXIFG));      // USCI_A0 TX buffer ready for next transmission?
//Code for Master TX goes here
 __delay_cycles(50); // Add time between transmissions to make sure slave can keep up
}









//Slave SPI code
```

```
#include <msp430.h>
int main(void)
{
  WDTCTL = WDTPW + WDTHOLD;                 // Stop watchdog timer
  // If clock sig from mstr stays low, it is not yet in SPI mode
  while (!(P1IN & BIT4));
  P1SEL = BIT1 + BIT2 + BIT4;
  P1SEL2 = BIT1 + BIT2 + BIT4;
  UCA0CTL1 = UCSWRST;                       // **Put state machine in reset**
  UCA0CTL0 |= UCCKPL + UCMSB + UCSYNC;      // 3-pin, 8-bit SPI master
  UCA0CTL1 &= ~UCSWRST;                     // **Initialize USCI state machine**
  IE2 |= UCA0RXIE;                          // Enable USCI0 RX interrupt
  __bis_SR_register(LPM4_bits + GIE);       // Enter LPM4, enable interrupts
}
// Slave RX ISR
#pragma vector=USCIAB0RX_VECTOR
__interrupt void USCI0RX_ISR (void)
{
  while (!(IFG2 & UCA0TXIFG));              // USCI_A0 TX buffer ready?
}
```

Inter-Integrated Circuit (I^2C)

This protocol involves the devices sharing a so-called 'I^2C bus' of digital lines for communication. This mode of communication is also based on designations of master and slave like the SPI, but there are some key differences. Firstly, multiple masters and slaves can be physically connected to the same I^2C bus. Each slave is individually addressable by the master(s). Only one master can control the shared bus at a time, and the control is decided by pre-defined arbitration procedures. However, we will not discuss the multi-master scenario in further detail in this tutorial as it is assumed the scenario is a microcontroller playing the role of the master while using I^2C to communicate with various slave peripheral devices.



The bus consists of two digital lines denoted SDA (serial data) and SCL (serial clock). The clock line SCL is used to synchronize the writing and reading of data, and is controlled by the master. The speed of the clock defines the speed of communication. Addressing, transmission and reception of data is done through the SDA line. In most protocols, these lines are pulled to a logic 'high' using resistors when the communication is idle. When communication is to be initiated, the procedure is as follows:

1. The master forces a high-to-low transition on the SDA line while SCL is high; this constitutes a 'start condition'.
2. After this start bit, the next 7 bits are used to refer to a unique address that identifies the slave for this transmission.
3. The master then sends 1 bit that denotes whether this transmission is going to be a 'read' (slave transmitter to master receiver) or a 'write' (master transmitter to slave receiver).
4. The receiver then acknowledges this with an 'ACK' signal, which involves pulling the SDA line low.
5. The transmitter transmits one byte of data on the SDA line. The SCL line is toggled in sync with the bits of the data packet such that each new bit is valid to be read when SCL is high, and a transition between bits occurs while SCL is low.
6. The receiver sends an 'ACK' signal to acknowledge the receipt of the transmitted byte from the previous step.
7. Steps 5 and 6 are repeated as necessary to transmit the required number of bytes.
8. The end of the data transmission can occur in one of two ways:
    a. If this was a 'write' transaction, at the end of the last byte of data the master issues a 'stop' signal. This involves a low-to-high transition of the SDA line while SCL is high.
    b. For a 'read' transaction the master does not ACK the final received byte, and simply issues a 'stop' signal instead to indicate to the receiver that enough bytes have been read.

There may be situations where the slave receiver needs more time to process a given bit in the middle of a byte packet. In these instances, I^2C allows for "clock stretching"; the slave can pull the SCL line low, and the master will wait until the SCL line is released before sending the next bit. Another useful feature is that the master is capable of sending a general broadcast to all slaves connected to the same bus, as opposed to addressing them one at a time.

The biggest advantage of I^2C is that the cost and complexity of the hardware does not scale up with the number of peripherals being used, since they can all share the same bus. However, the software routines to implement the protocol can be relatively more complex compared to those of other communication methods.

Asynchronous Communication

Asynchronous communication protocols do not require a shared clock signal between the two communicating devices. The most widespread mode of asynchronous communication is the Universal Asynchronous Receiver/Transmitter (UART) protocol which is described below.

Universal Asynchronous Receiver/Transmitter (UART) Protocol

In the UART protocol each data packet is a fixed size of one byte, and this byte is bracketed by a start bit and a stop bit so that the receiving device knows when to read the data. Since there is no shared clock to guide the reading of each data bit, the interpretation of the received data is based on previously agreed upon communication speeds between the two devices. This speed of course is calculated by each device based on its own local clock; so the expectation is that the relative error between the two clocks is not so large that the receiving device interprets the data incorrectly. The communication speed is typically reported as a 'baud rate'. A 'baud' is a general term for a symbol in communication, and in this context it refers to a single bit. Therefore a baud rate of 115200, means the UART communication will transmit data at the rate of 115,200 bits every second.

UART requires only two connections between the two communicating devices. Each device has two designated UART pins: a transmitting (TX) output port and a receiving (RX) input port. The TX port of Device 1 is connected to the RX port of Device 2, and this is used for Device 1 to transmit data to Device 2. Similarly, the TX port of Device 2 is connected to the RX port of Device 1. Regardless of the nature of either device, there is no designation of 'master' or 'slave' in terms of the communication as was the case for SPI and I^2C. In other words, both devices have equal control over the communication.

Both the UART lines are held high by default when communication is idle. Communication begins with a 'start' bit, which is merely pulling the sender's TX line low. Data is then transmitted one byte at a time from the sender's transmit register at the agreed baud rate, and is received by the receiver on its RX line and stored in a receive register.

The main advantage of UART is the simplicity of the hardware necessary: just two digital lines to communicate between devices. It is also relatively simple to implement in firmware and there are several existing solutions to convert UART to Bluetooth or USB protocol for other applications. The main drawback is that it cannot really be used by one microcontroller to talk to multiple peripherals without unduly complicating the hardware. Moreover, because of the lack of synchronizing clock, it is susceptible to errors if there is a clock mismatch between devices. As one can imagine, this also means that the UART is typically precluded from operating at very high speeds as the probability of error increases as the time between successive bits reduces.

Exercise Module

The following code snippet initializes the microcontroller for UART communication at a baud rate of 115200, using the SMCLK as a 1MHz clock source. After UART is initialized, the microcontroller goes to sleep and waits for a received character, which triggers the RX interrupt. The ISR then echoes back the received character on the UART TX line. Modify the code to have the UART use a baud rate of 9600 with the ACLK as the clock source instead. Assume that the ACLK speed is 32768Hz.

```
#include <msp430.h>

int main(void)

{

  WDTCTL = WDTPW + WDTHOLD;                    // Stop WDT

  if (CALBC1_1MHZ==0xFF)                               // If calibration constant
erased

  {

    while(1);                                  // do not load, trap CPU!!

  }

  DCOCTL = 0;                                  // Select lowest DCOx and MODx settings

  BCSCTL1 = CALBC1_1MHZ;                       // Set DCO

  DCOCTL = CALDCO_1MHZ;

  P1SEL = BIT1 + BIT2 ;                        // P1.1 = RXD, P1.2=TXD

  P1SEL2 = BIT1 + BIT2;

  UCA0CTL1 |= UCSSEL_2;                        // SMCLK

  UCA0BR0 = 8;                                 // 1MHz 115200

  UCA0BR1 = 0;                                 // 1MHz 115200

  UCA0MCTL = UCBRS2 + UCBRS0;                  // Modulation UCBRSx = 5

  UCA0CTL1 &= ~UCSWRST;                        // **Initialize USCI state machine**

  IE2 |= UCA0RXIE;                             // Enable USCI_A0 RX interrupt


  __bis_SR_register(LPM0_bits + GIE);          // Enter LPM0, interrupts enabled

}

// Echo back RXed character, confirm TX buffer is ready first

#pragma vector=USCIAB0RX_VECTOR

__interrupt void USCI0RX_ISR(void)

{

  while (!(IFG2&UCA0TXIFG));                   // USCI_A0 TX buffer ready?

  UCA0TXBUF = UCA0RXBUF;                       // TX -> RXed character

}
```

Data Transmission and Storage

Transmission to External Device

Certain applications require transmitting data to an external device such as a PC. We will go over two commonly used options for accomplishing this here:

Bluetooth Serial Link

The microcontroller can communicate the data to a Bluetooth chip which would then wirelessly transmit to a PC using the standard Bluetooth protocol. On the receiving PC side it is interpreted as standard serial data transmitted at the given baud rate just like UART. Moreover, the communication between the microcontroller and the Bluetooth chip is also done using UART. In other words, these Bluetooth modules have in-built firmware of their own that can convert incoming UART data into packets that conform to the standard Bluetooth protocol; in the other direction, the Bluetooth module also converts any incoming Bluetooth data into UART to be sent to the microcontroller. Therefore, as far as programmers on the microcontroller and PC are concerned, this is in effect a UART connection between the microcontroller and the PC at the designated baud rate. The Bluetooth module merely acts as a go-between to make the connection wireless, which could be very useful for applications that require untethered sensors.

Bluetooth modules available on the market commonly come with firmware pre-loaded for some basic functionality. The default expected UART baud rate is usually set to 115200. The module is set up such that as soon as it is powered on, it acts as a slave device and begins ‘advertising’; this means it is waiting for a master device such as a PC to establish a connection. Once the module is advertising, the user can usually use the PC to discover it as a new Bluetooth device and pair with it. After this process is complete, the user has the info on which COM port# the module was assigned to on the PC. As mentioned before, this is just like a serial connection to that COM port on the PC and can be used to write a program on the PC for receiving data on that port. Although this is a common mode of operation for these Bluetooth serial links, it is best to read the documentation of the specific module in question to find details on the default start-up routine.

There is expected to be a hardware connection along the UART lines between the Bluetooth module and the microcontroller. Just as was described in the previous section on UART, the TX line of the module is connected to the RX line of the microcontroller and vice versa. Most likely, the same board that houses the microcontroller and powers it will also be used to supply the requisite power to the Bluetooth module.

It is also usually possible to interact with the Bluetooth module using the microcontroller to change some settings on the module. For example, one common reason for change of the default firmware is to change the baud rate. Most Bluetooth modules will document a specialized set of commands that can be sent to it along the UART lines to have it make the appropriate changes to its firmware.

A specific example of such a Bluetooth module that can be used for quick prototyping is the Sparkfun Bluetooth Mate Silver found here: https://www.sparkfun.com/products/12576

The board has a Bluetooth chip with pin-outs to supply power and two pins for UART TX and RX. Once power is supplied to the board, the Bluetooth chip begins advertising and is discoverable by a PC. The PC can pair with it and assign a COM port to it. The two UART pins can be connected to the UART pins of a

microcontroller. With the appropriate code on the microcontroller and PC, this simple hardware setup is sufficient for the MSP430 to communicate wirelessly to the PC at a baud rate of 115200. A more detailed step-by-step tutorial with documentation can be found here:
https://learn.sparkfun.com/tutorials/using-the-bluesmirf?_ga=1.172744867.1641870786.1462054224

Connecting the Bluetooth Mate to the MSP430 Launchpad

Here are step-by-step instructions for the hardware and firmware setup for a simple UART echo application using the MSP430 Launchpad board and the Sparkfun Bluetooth Mate Silver BT module:

1. Flash the MSP430 Launchpad board using CCS (as described in the introductory section) and download a suitable UART firmware.
2. You can use the example code given in the exercise problem of the previous 'UART' section in this doc. This will set up UART on pins 1.1 (RX) and 1.2 (TX) of the Launchpad board with a baud rate of 115200. The code will make the microcontroller echo back any character received by the Launchpad.
3. Unplug the Launchpad (*i.e.* power it off) before completing the subsequent hardware connections for safety. Use temporary jumper cables or solder wires to complete the connections in steps 4 through 7.
4. Connect the 'RX-I' pin of the BT module to pin 1.2 of the Launchpad board.
5. Connect the 'TX-O' pin of the BT module to pin 1.1 of the Launchpad board.
6. Connect the VCC pin of the BT module to any available VCC pin on the Launchpad board
7. Connect the VCC pin of the BT module to any available VCC pin on the Launchpad board
8. Now plug in the Launchpad board to the PC using the mini-USB cable and it should power on both the Launchpad as well as the BT module. A red LED on the BT module should be blinking to indicate that it is advertising and waiting for a connection from the PC.
9. Follow the instructions in the SparkFun tutorial under the section 'Connecting to the Modem in Windows' to pair your BT module with your PC (Link to tutorial: https://learn.sparkfun.com/tutorials/using-the-bluesmirf?_ga=1.172744867.1641870786.1462054224)
10. Once the BT module is paired to the PC it will be associated with a COM port on that PC for all future serial links. Find the COM port number by going to 'Devices and Printers', right-clicking on your BT module's name and looking at the Hardware Properties.
11. On the PC open PuTTY (download and install this free software if unavailable on your computer). Set up a 'Serial' connection at a baud rate of 115200 with the COM port # identified earlier.
12. After entering these settings on the main PuTTY screen, also go to the 'Serial' section of the PuTTY window (located on the left) and change the 'Flow Control' setting to 'None' if it is not already.
13. Click 'Open' and this should open the connection on the PuTTY window with a blank terminal screen. The LED on the BT module should also be a solid green indicating a successful connection
14. Now any character you type on the keyboard will be sent to the MSP430 via Bluetooth, and it will be echoed back to your screen on the terminal window.

Data Storage

While by no means comparable in size to the memory available on a PC, microcontrollers typically do have a certain amount of non-volatile memory, *i.e.,* memory that will still be available even after the device has been power cycled (turned off and back on). For example, the MSP430G2553 microcontroller that is on the Launchpad board has 16kB of flash memory. Typical uses of this memory would be to store a relatively small amount of data, or certain numerical constants that are used in the program itself. For example, if a physiological monitoring device has been calibrated according to certain physical parameters of the subject, these parameters can be stored in the flash memory for easy retrieval in the future.

There are a few things to keep in mind when working with flash memory. Typically, flash memory is partitioned into segments. On the MSP430, these segments of main memory are of size 512 bytes, meaning the MSP430G2553 has 32 such segments to give a total main memory of 16kB. Due to the hardware architecture of flash memory, writing to and deleting from memory work differently. The programmer can write can typically write anything from one bit (the smallest unit), a byte or even one word (2 bytes, in the case of this microcontroller) at a time. However, erasing from memory can only be done in segments. In other words, in order to erase even 1 byte of memory, the entire corresponding 512-byte segment needs to be erased. Therefore if less than 1 segment needs to be erased, the remaining data needs to be written temporarily into a different part of memory in order to save it and write it back after the erase.

The programmer needs to be well aware of the organization and size of the flash memory being used, and also needs to be comfortable coding using pointers to flash memory. An important thing to keep in mind is that the code to be executed by the microcontroller is also stored in the same flash memory, thus reducing the effective size available for data storage, as well as increasing the risk of unintended memory corruption. However, once the programmer becomes familiar with Flash memory, it can be a useful tool for several applications.

Exercise Problem

The following code snippet initializes the flash memory, and then continually writes an increasing value to each byte address of Segment C. On each iteration a new value is to be written, the previously stored values in Segment C are erased. Write code that adds another function that, when called, would copy the contents of Segment C to Segment D, and then erase the contents of Segment C.

```
#include <msp430.h>

char  value;                                // 8-bit value to write to segment A


// Function prototype

void write_SegC (char value);


int main(void)
```

```
{
  WDTCTL = WDTPW + WDTHOLD;                  // Stop watchdog timer
  if (CALBC1_1MHZ==0xFF)                      // If calibration constant erased
  {
    while(1);                                // do not load, trap CPU!!
  }
  DCOCTL = 0;                                // Select lowest DCOx and MODx settings
  BCSCTL1 = CALBC1_1MHZ;                     // Set DCO to 1MHz
  DCOCTL = CALDCO_1MHZ;
  FCTL2 = FWKEY + FSSEL0 + FN1;              // MCLK/3 for Flash Timing Generator
  value = 0;                                 // initialize value

  while(1)                                   // Repeat forever
  {
    write_SegC(value++);                     // Write segment C, increment value
    __no_operation();                        // SET BREAKPOINT HERE
  }
}

void write_SegC (char value)
{
  char *Flash_ptr;                           // Flash pointer
  unsigned int i;

  Flash_ptr = (char *) 0x1040;               // Initialize Flash pointer to Segment C
  FCTL1 = FWKEY + ERASE;                     // Set Erase bit
  FCTL3 = FWKEY;                             // Clear Lock bit
  *Flash_ptr = 0;                            // Dummy write to erase Flash segment

  FCTL1 = FWKEY + WRT;                       // Set WRT bit for write operation
  for (i=0; i<64; i++)
  {
    *Flash_ptr++ = value;                     // Write value to flash
  }

  FCTL1 = FWKEY;                              // Clear WRT bit
  FCTL3 = FWKEY + LOCK;                       // Set LOCK bit
}
```

Appendix: Useful Resources

The following documents are useful references for details on the various concepts and devices discussed in the tutorial:

- Code Composer Studio User's Guide: More details on how to use the various features of Code Composer for downloading and debugging your code.
- MSP430G2553 Datasheet: Electrical characteristics and other detailed information of the MSP430 chip itself, including its various peripherals
- MSP430G2553 User's Guide: User's Guide for the MSP430x2xx family of microcontrollers, with descriptions of the various peripherals including the register maps.
- MSP-EXP430G2 Quick Start Guide for the Launchpad board
- MSP-EXP430G2 User's Guide: User's Guide for the entire integrated Launchpad board