The State University of New York (SUNY) at Buffalo
Department of Electrical Engineering

Lab Manual v1.2013

EE 379/578 – Embedded Systems and Applications

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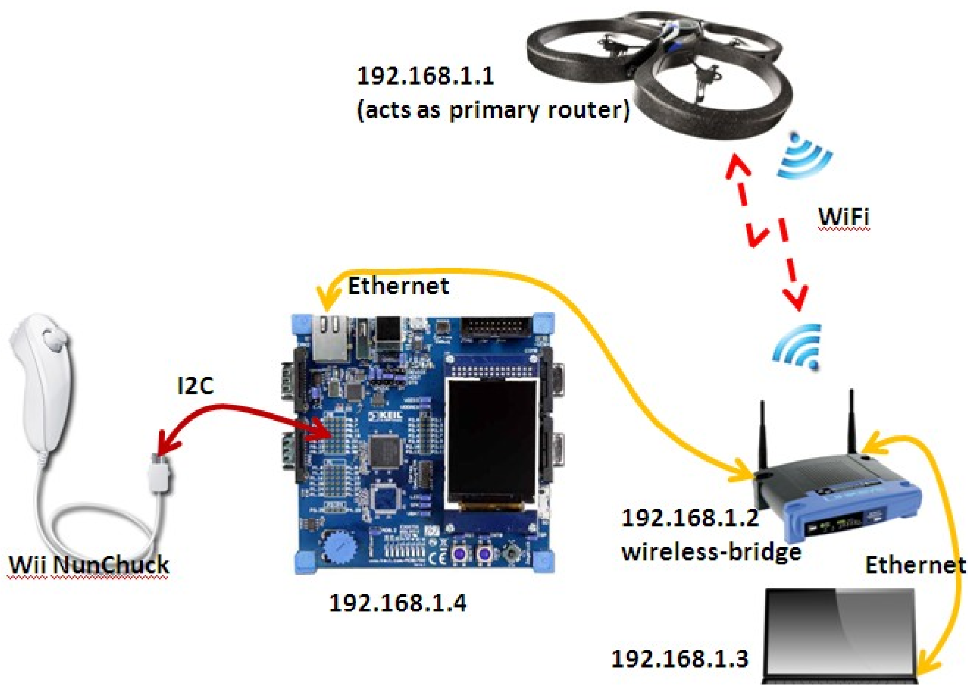

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Lab 1: A “Blinky” Introduction to C and Assembly Programming

1. Objective

The objective of this lab is to give you a “first foot in the door” exposure to the programming in C and assembly of a program, which when executed by the microcontroller (NXP LPC1768, an ARM Cortex-M3) simply blinks LEDs located on the development board. You also learn how to use the ARM Keil uVision IDE to create projects, build and download them to the board (either Keil MCB1700 or Embest EM-LPC1700).

2. Pre-lab Preparation

Optional (but encouraged)
You should plan to work on your own computer at home a lot during this semester. You should install the main software (evaluation version) we will use in this course: the Microcontroller Development Kit (MDK-ARM), which supports software development for and debugging of ARM7, ARM9, Cortex-M, and Cortex-R4 processor-based devices. Download it from ARM’s website [1] and install it on your own computer. This is already installed on the computers in the lab.
MDK combines the ARM RealView compilation tools with the Keil µVision Integrated Development Environment (IDE). The Keil µVision IDE includes: Project Management and Device & Tool Configuration, Source Code Editor Optimized for Embedded Systems, Target Debugging and Flash Programming, Accurate Device Simulation (CPU and Peripheral).

You should read this lab entirely before attending your lab session. Equally important, you should/browse related documents suggested throughout the description of this lab. These documents and pointers are included either in the downloadable archive for this lab or in the list of References. Please allocate significant amount of time for doing this.

3. Lab Description

a. BLINKY 1

Creating a new project

1. First create a new folder called say **EE378_S2013** where you plan to work on the labs of this course. Then, inside it, create a new folder called **lab1**.
2. Launch uVision4, Start->All Programs->Keil uVision4
3. Select Project->New uVision Project… and then select **lab1** as the folder to save in; also type **blinky1** as the File Name.
4. Then, select NXP (founded by Philips) LPC1768 as CPU inside the window that pops-up. Also, click Yes to Copy “startup_LPCxx.s” to Project Folder.
5. Under File Menu select New.
6. Write your code in the and save it as **blinky1.c** in the same project folder. This file (as well as all others discussed in this lab) is included in the downloadable archive from the website of this course. The panel on the left side of the uVision IDE is the Project window. The Project window gives you the hierarchy of Target folder and Source Group folder.

7. Right click on the "Source Group 1" and select "Add files to Source Code".
8. Locate **blinky1.c** and include it to the group folder.
9. Copy **C:\Keil\ARM\Startup\NXP\LPC17xx\system_LPC17xx.c** to lab1 directory and add it as a source file to the project too. Open this file and browse it quickly to see what functions are defined inside it.
10. Click Project menu and then select Build Target.
11. Build Output panel should now show that the program is being compiled and linked. This creates **blinky1.axf** file (in ARM Executable Format), which will be downloaded to the board. To create a **.hex** file (more popular), select Flash->Configure Flash Tools->Output and check mark Create HEX File.
12. Connect the board to two USB ports of the host computer. One connection is to the port J16 of the board (the one that is a Standard-B plug). The second connection is via the ULINK2 debugger/programmer/emulator. These connections are illustrated in Fig.1.
13. Download the program to the Flash of the microcontroller. Select Flash->Download. This loads the **blinky1.axf** file. Then press the RESET push-button of the board.
14. Congratulations! You just programmed your first project. You should notice that the LED P1.29 is blinking. If this is not the case, then you should investigate/debug your project to make it work.

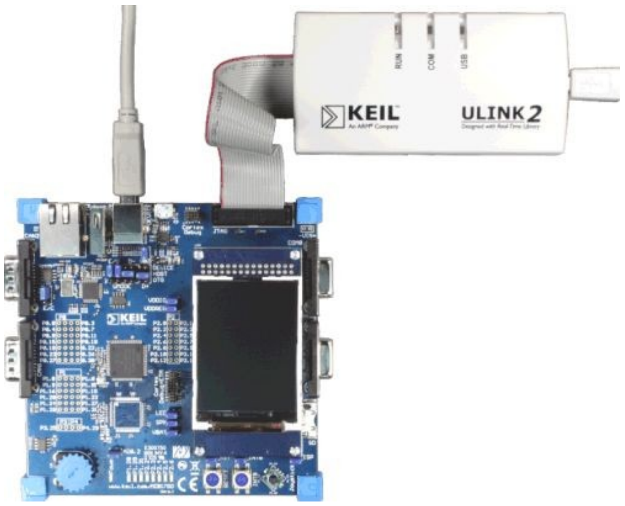
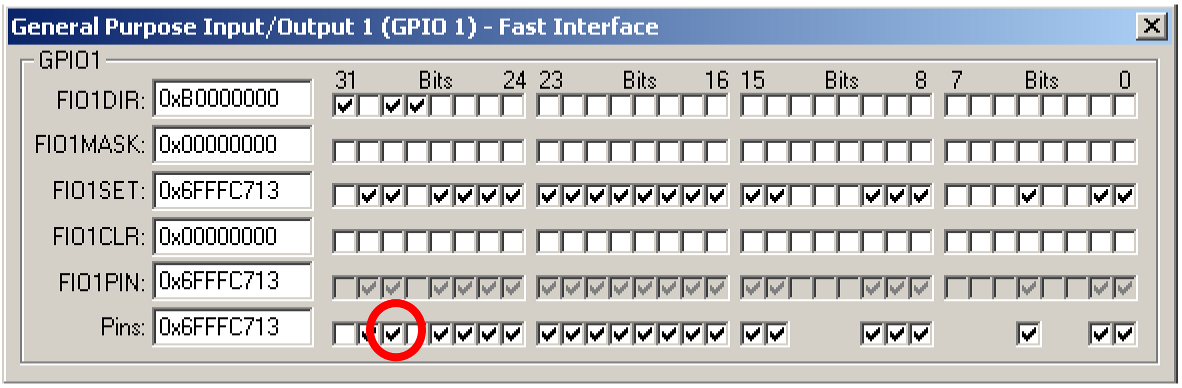


Figure 1 Connection of ULINK2 to the board.

Debugging
If your program has errors (discovered by compiler or linker) or you simply want to debug it to verify its operation, then we can use the debugging capabilities of the uVision tools.

1. Click Debug menu option and select Start/Stop Debug Session. A warning about the fact that this is an evaluation version shows up; click OK.
2. Then, a new window appears where we can see the simulation of the program.
3. This window has several different supportive panels/sub-windows where we can monitor changes during the simulation. The left hand side panel, Registers, provides information regarding the Registers of LPC17xx with which we are working.
4. Again, click on the Debug menu option and select Run. The code starts simulating.
5. It is good practice that before going ahead with the actual hardware implementation to perform a debug/simulation session to make sure that our program behaves according to the design requirements.
6. In our example, we use PORT1.

7. Go to Peripherals menu option then select GPIO Fast Interface followed by Port 1.
8. You should get the window shown in Fig.2 below, where you can see LED P1.29 blinking. To actually observe this you should wait until the simulated time (shown on the bottom-right side of the uVision ISE window) is longer than 1 second. Note that in order to actually simulate 1 second of execution time of the program, the simulator must run much longer. This is expected, as typically simulators require much longer computational runtimes (wallclock time) in order to simulate relatively short execution times of the program under investigation!
9. This is a standard method to check that your program works correctly.
10. The debugger is a very powerful tool. This is only a brief exposure to it; we'll revisit it many times later in this course. Once you are done with the simulation/debug of your program, you can stop it by selecting Start/Stop the Debug Session from the Debug menu option. This stops the show and takes us back to the main uVision window.



FIO1DIR:	0xB0000000
FIO1MASK:	0x00000000
FIO1SET:	0x6FFFC713
FIO1CLR:	0x00000000
FIO1PIN:	0x6FFFC713
Pins:	0x6FFFC713

Figure 2 Pin P1.29 is checked on/off every other second or so.

Taking it further
At this time, you should revisit **blinky1.c** file. Read this file (it has lots of comments) and browse related/included files in order to fully understand what is what and what it does. This is very important.

You should take time to read/browse on your own the user's guide of the board, the user manual and datasheet of LPC17xx microcontrollers as well as other files included in the downloadable archive of this lab [2-5]. Do not attempt to print them as some have >800 pages.
Note that because it is very difficult to cover everything during the lectures and labs, you are expected to proactively engage materials related to this course and take ownership of your learning experience! This is a necessary (but not sufficient) attitude to do well in this course.

b. BLINKY 2

Start uVision and select Project->Open Project, then, browse to open the Blinky project example located at:
C:\Keil460\ARM\Boards\Keil\MCB1700\Blinky
As you noticed, the ARM Kiel software installation contains a folder called **Boards** that contains design examples for a variety of boards. We'll use some of these design examples for the board utilized in this course. However, as we go, you should take a look and play with all these examples; try to understand their code.

Build the project and download to target. Observe operation and comment.

At this time, you should take time to read the .c files of this project, starting with **Blinky.c**. Read it and also browse the other files to gain insights into what and how the code achieves different tasks. At this stage, do not expect to understand everything; however, please make an effort to see as much as you can.

c. BLINKY 3

In this part of the lab, we implement the blinky example by writing a program in assembly language. In this example we'll turn on/off the LED controlled by pin P1.28. Start uVision and create a new project. Add to it the following files:

1. When creating the project say Yes to have added **startup_LPCxx.s** to the project
2. **blinky3.s** (available in the downloadable archive of this lab as well in an ppendix at the end of this lab)
3. **C:\Keil\ARM\Startup\NXP\LPC17xx\system_LPC17xx.c**. This is needed for the SystemInit() function called from within **startup_LPCxx.s**. We could not add this file to the project provided that we comment out the two lines inside **startup_LPCxx.s** that contain SystemInit.

Build the project and download to target. Observe operation and comment.

At this time, you should take time to read the **blinky3.s**. Read it and make sure you understand how the code achieves each task.

4. Lab Assignment

Modify the assembly program blinky3.s to implement the following design description: blink all eight LEDs on the board, one by one from left to right repeatedly.

For each lab with a "Lab Assignment", you must turn-in a lab report in PDF format (font size 11, single spacing), named **lab#_firstname_lastname.pdf** (where "#" is the number of the lab, for example in the case of lab1, "#" must be replaced with 1) which should contain the following sections:

- Lab title, Your name
- Introduction section – a brief description of the problem you solve in this lab assignment, outlining the goal and design requirements.
- Solution section – describe the main technique(s) that you utilized to develop your solution. Include block diagrams, flow graphs, plots, etc. here to aid your explanation.
- Results and Conclusion section – describe your results and any issues you may have faced during the assignment and how you solved them.
- Code listings, assembly or C code that you wrote. Appended at the end of your report. Use smaller font (size 9) to save space.

For full credit, you must demo the correct operation of your assignment to the TA during the next lab. While you are free to hand-write your report (still turned-in as a PDF file), please make sure your report is neat and the presentation is coherent. You will lose points for reports that do not present enough details, are ugly, disorganized, or are hard to follow/read.

5. Credits and references

[1] Software: Microcontroller Development Kit; download from http://www.keil.com/arm/mdk.asp

[2] Hardware: MCB1700 board User's Guide;
http://www.keil.com/support/man/docs/mcb1700/mcb1700_su_connecting.htm
[3] LPC17xx user's manual; http://www.nxp.com/documents/user_manual/UM10360.pdf
[4] NXP LPC17xx datasheet;
http://www.nxp.com/documents/data_sheet/LPC1769_68_67_66_65_64_63.pdf
http://www.keil.com/dd/chip/4868.htm
[5] Cortex-M3 information;
http://www.nxp.com/products/microcontrollers/cortex_m3/
http://www.arm.com/products/processors/cortex-m/cortex-m3.php
[6] Additional resources
--Keil uVision User's Guide
http://www.keil.com/support/man/docs/uv4/
-- Keil uVision4 IDE Getting Started Guide
www.keil.com/product/brochures/uv4.pdf
--ARM Assembler Guide
http://www.keil.com/support/man/docs/armasm/
--ARM Compiler toolchain for uVision. Particularly browse:
ARM Compiler toolchain for uVision, Using the Assembler
ARM Compiler toolchain for µVision, Using the Linker
http://infocenter.arm.com/help/index.jsp?topic=/com.arm.doc.dui0377c/index.html
--Professor J.W. Valvano (UTexas) resources;
http://users.ece.utexas.edu/~valvano/Volume1/uvision/
--UWaterloo ECE254, Keil MCB1700 Hardware Programming Notes
https://ece.uwaterloo.ca/~yqhuang/labs/ece254/doc/MCB1700_Hardware.pdf
----EE 472 Course Note Pack, Univ. of Washington, 2009,
http://abstract.cs.washington.edu/~shwetak/classes/ee472/notes/472_note_pack.pdf (Chapter 6)

APPENDIX A: Some info on LPC1768 peripherals programming

Pins on LPC1768 are divided into 5 ports indexed from 0 to 4. Pin naming convention is Px.y, where x is the port number and y is the pin number. For example, P1.29 means Port 1, Pin 29. Each pin has four operating modes: GPIO (default), first alternate function, second alternate function, and third alternate function. Any pin of ports 0 and 2 can be used to generate an interrupt.

To use any of the LPC1768 peripherals, the general steps to be followed are:
1. Power Up the peripheral to be used
2. Set the Clock Rate for the peripheral
3. Specify the pin operating mode - Connect necessary pins using Pin Connect Block
4. Set direction - Initialize the registers of the peripheral

1. Power Up the peripheral
   Let's assume we are interested in utilizing the pin P1.29 to drive one of the board's LEDs on and off (the blinky1 example). Refer to LPC17xx User's Manual, Chapter 4: Clocking and Power Control. Look for register Power Control for Peripherals register, PCONP. It's on page 63; bit 15 is PGPIO. Setting this bit to 1 should power up the GPIO ports. Note that the default value is 1 anyway, which

means GPIO ports are powered up by default on reset; but the start up code may modify this. Hence, it's good practice to make sure we take care of it. For example, here is how we power up the GPIO:

```
LPC_SC->PCONP |= 1 << 15;
```

2. Set desired clock to the peripheral
   In the same Chapter 4 of the manual, look for Peripheral Clock Selection register, PCLKSEL1; it's on page 57; bits 3:2 set the clock divider for GPIO. In our example, since we're not using interrupts, we won't change the default value. Note that PCLK refers to Peripheral Clock and CCLK refers to CPU Clock. PCLK is obtained by dividing CCLK; see table 42 on page 57 of the manual;

3. Specify the pin operating mode - Connect necessary pins using Pin Connect Block
   To specify the pin operating mode we configure PINSEL registers in the Pin Connect Block(LPC_PINCON macro defined in LPC17xx.h). There are eleven PINSEL registers: PINSEL0, PINSEL1, …, PINSEL10, which are defined as member variables inside the LPC_PINCON_TypeDef C struct. Each one of these eleven registers controls a specific set of pins on a certain port. When the processor powers up or resets, the pins that are connected to the LEDs and joystick are automatically configured as GPIO (default). Hence, in our example, there is no need to change settings in the pin connect block. However, it is a good practice to configure these pins before using them.
   Refer to Section 8.1 of LPC17xx user's manual to see which set of pins are controlled by which PINSEL register. As an example, the five button joystick is connected to pins P1.20, P1.23, P1.24, P1.25 and P1.26. As mentioned earlier, it is a good programming practice to configure it. Refer to page 109, Section 8.5.4, Table 82 in LPC17xx User's Manual for more detailed information.

```
LPC_PINCON->PINSEL3 &= ~((3<< 8)|(3<<14)|(3<<16)|(3<<18)|(3<<20));
// P1.20, P1.23, …, P1.26 are GPIO (Joystick)
```

4. Set direction - Initialize the registers of the peripheral
   In this step of programming of a GPIO pin, we set the I/O direction (i.e., pin to be used as input or output). This is done via FIODIR register (see Chapter 9, page 122 of LPC17xx User's Manual for more info). There are five LPC_GPIOx, where x=0,1,2,3,4, macros defined in LPC17xx.h. The FIODIR is a member variable in LPC_GPIO_TypeDef C struct in LPC17xx.h. To set a pin as input, set the corresponding bit in FIODIR to 0. All I/Os default to input (i.e., all bits in FIODIR are default to logic 0). To set a pin as output, set the corresponding bit in FIODIR to 1. For example, to set pins connected to the joystick as input, we write the following C code:

```
LPC_GPIO1->FIODIR &= ~((1<<20)|(1<<23)|(1<<24)|(1<<25)|(1<<26));
// P1.20, P1.23, ..., P1.26 are input (Joystick)
```

   In our blinky example, we set all pins connected to the 8 LEDs as output. We achieve that via the following C code:

```
LPC_GPIO1->FIODIR |= 0xB0000000; // pins P1.28, P1.29, P1.31 as output
LPC_GPIO2->FIODIR |= 0x0000007C; // pins P2.2, 3, 4, 5, 6 as output
```

   Once a pin is set as output or input it can be utilized in our programs to drive or read logic values.
   a) The pin is set as output

We turn a pin to HIGH/LOW (i.e., digital logic 1/0) by setting the corresponding bit in FIOSET/FIOCLR register. Both FIOSET and FIOCLR are member variables defined in the PC_GPIO_TypeDef C struct. To set a pin to digital 1, set the corresponding bit of LPC_GPIOx->FIOSET to 1. To turn a pin to digital 0, set the corresponding bit of LPC_GPIOx->FIOCLR to 1. Refer to Sections 9.5.2 and 9.5.3 of LPC17xx User's manual for details.
For example, to turn on LED P1.29, the following code can be used:

```
LPC_GPIO1->FIOSET = 1 << 29;
```

In general, to turn any of the 8 LEDs on, one can use the following trick:

```
const U8 led_pos[8] = { 28, 29, 31, 2, 3, 4, 5, 6 };
mask = 1 << led_pos[led];
if (led < 3) { // P1.28,29,31 are part of Port1
    LPC_GPIO1->FIOSET = mask;
} else { // P2.2,3,4,5,6 are part of Port2
    LPC_GPIO2->FIOSET = mask;
}
```

Of course, to turn off a particular LED, just replace FIOSET with FIOCLR in the above code.
Note: we can also set HIGH/LOW a particular output pin via the FIOPIN register. We can write specific bits of the FIOPIN register to set the corresponding pin to the desired logic value. In this way, we bypass the need to use both the FIOSET and FIOCLR registers. However, this is not the recommended method. For example, in the case of the blinky example, we use the following C code:

```
LPC_GPIO1->FIOPIN |= 1 << 29; // make P1.29 high
LPC_GPIO1->FIOPIN &= ~( 1 << 29 ); // make P1.29 low
```

b) The pin is set as input
We read the current pin state from FIOPIN register. The corresponding bit being 1 indicates that the pin is driven high. The corresponding bit being 0 indicates that the pin is driven low. The FIOPIN is a member variable defined in LPC_GPIO_TypeDef C struct. One normally uses bit shift operations to shift the LPC_GPIOx->FIOPIN value to obtain pin value(s). Refer to Section 9.5.4 in the LPC17xx User's manual for details. For example, to read the joystick position, the following code can be used

```
#define KBD_MASK 0x79
uint32_t kbd_val;
kbd_val = (LPC_GPIO1->FIOPIN >> 20) & KBD_MASK;
```

When the joystick buttons are inactive, the bits located at P1.23,24,25,26 are logic 1. When any of the joystick buttons becomes active, the bit corresponding to that pin becomes 0.

APPENDIX B: Listing of blinky3.s

```
; CopyLeft (:-) Cristinel Ababei, SUNY at Buffalo, 2012
; this is one assembly implementation of the infamous blinky example;
; target microcontroler: LPC1768 available on board Keil MCB1700 (or Embest EM-LPC1700 board)
; I tested it first on EM-LPC1700 board as it's cheaper!
;
; Note1: it has lots of comments, as it is intended for the one who
; sees for the first time assembly;
; Note2: some parts of the implementation are written in a more complicated manner
; than necessary for the purpose of illustrating for example different memory
; addressing methods;
; Note3: each project will have to have added to it also system_LPC17xx.s (added
; automatically by Keil uVision when you create your project) and system_LPC17xx.c
; which you can copy from your install directory of Keil IDE (for example,
; C:\Keil\ARM\Startup\NXP\LPC17xx\system_LPC17xx.c)
; Note4: system_LPC17xx.s basically should contain the following elements:
; -- defines the size of the stack
; -- defines the size of the heap
; -- defines the reset vector and all interrupt vectors
; -- the reset handler that jumps to your code
; -- default interrupt service routines that do nothing
; -- defines some functions for enabling and disabling interrupts

        ; Directives
        ; they assist and control the assembly process; directives or "pseudo-ops"
        ; are not part of the instruction set; they change the way the code is assembled;

        ; THUMB directive placed at the top of the file to specify that
        ; code is generated with Thumb instructions;
        THUMB
        ; some directives define where and how the objects (code and variables) are
        ; placed in memory; here is a list with some examples:
        ; AREA, in assembly code, the smallest locatable unit is an AREA
        ; CODE is the place for machine instructions (typically flash ROM)
        ; DATA is the place for global variables (typically RAM)
        ; STACK is the place for the stack (also in RAM)
        ; ALIGN=n modifier starts the area aligned to 2^n bytes
        ; |.text| is used to connect this program with the C code generated by
        ; the compiler, which we need if linking assembly code to C code;
        ; it is also needed for code sections associated with the C library;
        ; NONINT defines a RAM area that is not initialized (normally RAM areas are
        ; initialized to zero); Note: ROM begins at 0x00000000 and RAM begins at
        ; 0x2000000;
        ; EXPORT is a directive in a file where we define an object and
        ; IMPORT directive is used in a file from where we wish to access the object;
        ; Note: we can export a function in an assembly file and call the function
        ; from a C file; also, we can define a function in C file, and IMPORT the function
        ; into an assembly file;
        ; GLOBAL is a synonym for EXPORT
        ; ALIGN directive is used to ensure the next object is aligned properly; for example,
        ; machine instructions must be half-word aligned, 32-bit data accessed with LDR, STR
        ; must be word-aligned; good programmers place an ALIGN at the end of each file so the
        ; start of every file is automatically aligned;
        ; END directive is placed at the end of each file
        ; EQU directive gives a symbolic name to a numeric constant, a register-relative
        ; value or a program-relative value; we'll use EQU to define I/O port addresses;
        AREA    |.text|, CODE, READONLY ; following lines are to be placed in code space
        EXPORT          __main
        ENTRY
        ; EQUates to make the code more readable; to turn LED P1.28 on and off
        ; we will write the bit 28 of the registers FIO1SET (to set HIGH) and FIO1CLR (to set LOW);
        ; refer to page 122 of the LPC17xx user manual to see the adresses of these registers; they are:
FIO1SET         EQU 0x2009C038
FIO1CLR         EQU 0x2009C03C
        ; we will implement a dirty delay by decrementing a large enough
        ; number of times a register;
LEDDELAY EQU 10000000

__main
        ; (1) we want to set as output the direction of the pins that
        ; drive the 8 LEDs; these pins belong to the ports Port 1 and Port 2
        ; and are: P1.28, P1,29, P1.31 and P2.2,...,6
        ; to set them as output, we must set to 1 the corresponding bits in
        ; registers (page 122 of LPC17xx user manual):
        ; FIO1DIR - 0x2009C020
        ; FIO2DIR - 0x2009C040
        ; that is, we'll set to 1 bits 28,29,31 of the register at adress 0x2009C020,
        ; which means writing 0xB0000000 to this location; also, we'll set 1 bits 2,...,6
        ; of the register at address 0x2009C040, which means writing 0x0000007C to
        ; this location;
        MOV R1, #0x0 ; init R1 register to 0 to "build" address
        MOVT R1, #0x2009 ; assign 0x20090000 to R1; MOVT assigns to upper nibble
        MOV R3, #0xC000 ; move 0xC000 into R3
        ADD R1, R1, R3 ; add 0xC000 to R1 to get 0x2009C000
        MOV R4, #0xB0000000 ; place 0xB0000000 (i.e., bits 28,29,31) into R4
        ; now, place contents of R4 (i.e. 0xB0000000) to address
        ; 0x2009C020 (i.e., register FIO1DIR); this sets pins
        ; 28,29,31 as output direction;
        ; Note: address is created by adding the offset 0x20 to R1
        ; Note: the entire complication above could be replaced with
        ; simply loading R1 with =FIO1DIR (but we wanted to experiment with
        ; different flavors of MOV, to upper and lower nibbles); we'll use
        ; the simpler version later;
        STR R4, [R1, #0x20]
        MOV R4, #0x0000007C ; value to go to register of Port 2
        STR R4, [R1, #0x40] ; set output direction for pins of Port 2 by writing to reister FIO2DIR
        ; (2) set HIGH the LED driven by P1.28; to do that we load current
        ; contents of register FIO1SET (i.e., memory address 0x2009C038) to R3,
        ; set to 1 its 28th bit, and then put it back into the location at
        ; memory address 0x2009C038 (i.e., effectively writing into register FIO1SET);
        LDR R1, =FIO1SET ; we'll not touch R1 anymore so that it keeps this address
        LDR R3, [R1]
        ORR R3, #0x10000000 ; set to logic 1 bit 28 of R3
        STR R3, [R1]
        ; (3) some initializations
        LDR R0, =LEDDELAY ; initialize R0 for countdown
        LDR R2, =FIO1CLR ; we'll not touch R2 anymore so that it keeps this address

        ; now, the main thing: turn the LED P1.28 on and off repeatedly;
        ; this is done by setting the bit 28 of registers FIO1CLR and FIO1SET;
        ; Note: one could do this in a simpler way by using a toggling trick:
        ; toggle (could be done using exclusive or with 1) bit 28 of register
        ; FIO1PIN instead (page 122 of LPC17xx user manual) and not use
        ; FIO1CLR and FIO1SET; I do not recommend however this trick as
        ; due to the peculiarities of FIO1PIN;
loop
led_on
        SUBS R0, #1 ; decrement R0; this sets N,Z,V,C status bits
        BNE led_on ; if zero not reached yet, go back and keep decrementing
        LDR R3, [R2] ; recall that R2 stores =FIO1CLR
        ORR R3, #0x10000000 ; set to logic 1 bit 28 of R3
        STR R3, [R2] ; place R3 contents into FIO1CLR, which will put pin on LOW
        LDR R0, =LEDDELAY ; initialize R0 for countdown
led_off
        SUBS R0, #1 ; decrement R0; this sets N,Z,V,C status bits
        BNE led_off ; if zero not reached yet, go back and keep decrementing
        LDR R3, [R1] ; recall that R1 stores =FIO1SET
        ORR R3, #0x10000000 ; set to logic 1 bit 28 of R3
        STR R3, [R1] ; place R3 contents into FIO1SET, which will put pin on HIGH
        LDR R0, =LEDDELAY ; initialize R0 for countdown
        ; now do it again;
        B loop

        ALIGN
        END
```

Lab 2: Using UART

1. Objective

The objective of this lab is to utilize the Universal Asynchronous Receiver/Transmitter (UART) to connect the MCB1700 board to the host computer. Also, we introduce the concept of interrupts briefly. In the example project, we send characters to the microcontroller unit (MCU) of the board by pressing keys on the keyboard. These characters are sent back (i.e., echoed, looped-back) to the host computer by the MCU and are displayed in a hyperterminal window.

2. UART

The most basic method for communication with an embedded processor is asynchronous serial. It is implemented over a symmetric pair of wires connecting two devices (referred as host and target here, though these terms are arbitrary). Whenever the host has data to send to the target, it does so by sending an encoded bit stream over its transmit (TX) wire. This data is received by the target over its receive (RX) wire. The communication is similar in the opposite direction. This simple arrangement is illustrated in Fig.1. This mode of communications is called "asynchronous" because the host and target share no time reference (no clock signal). Instead, temporal properties are encoded in the bit stream by the transmitter and must be decoded by the receiver.

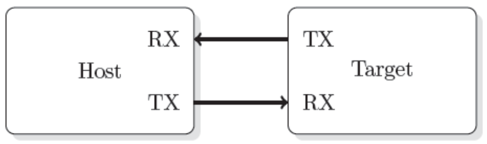


Figure 1 Basic serial communication.

A commonly used device for encoding and decoding such asynchronous bit streams is a Universal Asynchronous Receiver/Transmitter (UART). UART is a circuit that sends parallel data through a serial line. UARTs are frequently used in conjunction with the RS-232 standard (or specification), which specifies the electrical, mechanical, functional, and procedural characteristics of two data communication equipment.

A UART includes a transmitter and a receiver. The transmitter is essentially a special shift register that loads data in parallel and then shifts it out bit by bit at a specific rate. The receiver, on the other hand, shifts in data bit by bit and reassembles the data. The serial line is '1' when it is idle. The transmission starts with a start-bit, which is '0', followed by data-bits and an optional parity-bit, and ends with stop-bits, which are '1'. The number of data-bits can be 6, 7, or 8. The optional parity bit is used for error detection. For odd parity, it is set to '0' when the data bits have an odd number of '1's. For even parity, it is set to '0' when the data-bits have an even number of '1's. The number of stop-bits can be 1, 1.5, or 2. The transmission with 8 data-bits, no parity, and 1 stop-bit is shown in Fig.2 (note that the LSB of the data word is transmitted first).

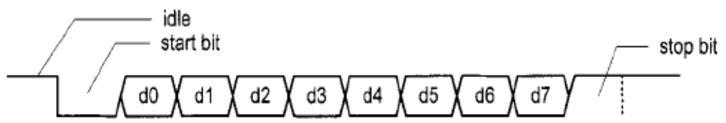


Figure 2 Transmission of a byte.

No clock information is conveyed through the serial line. Before the transmission starts, the transmitter and receiver must agree on a set of parameters in advance, which include the baud-rate (i.e., number of bits per second), the number of data bits and stop bits, and use of parity bit.

To understand how the UART's receiver extracts encoded data, assume it has a clock running at a multiple of the baud rate (e.g., 16x). Starting in the idle state (as shown in Fig.3), the receiver "samples" its RX signal until it detects a high-low transition. Then, it waits 1.5 bit periods (24 clock periods) to sample its RX signal at what it estimates to be the center of data bit 0. The receiver then samples RX at bit-period intervals (16 clock periods) until it has read the remaining 7 data bits and the stop bit. From that point this process is repeated. Successful extraction of the data from a frame requires that, over 10.5 bit periods, the drift of the receiver clock relative to the transmitter clock be less than 0.5 periods in order to correctly detect the stop bit.

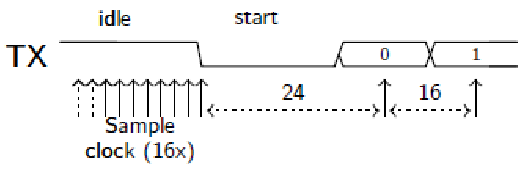


Figure 3 Illustration of signal decoding.

UARTs can be used to interface to a wide variety of other peripherals. For example, widely available GSM/GPRS cell phone modems and Bluetooth modems can be interfaced to a microcontroller UART. Similarly GPS receivers frequently support UART interfaces.

The NXP LPC1768 microcontroller includes four such devices/peripherals called UARTs: UART0/2/3 and UART1. See pages 298 and 318 of the LPC17xx User's Manual [1]. See also page 27 of the Datasheet [2]. UART0 and UART1 of the microcontroller are connected on the MCB1700 board to the ST3232C (IC6), which converts the logic signals to RS-232 voltage levels. This connection is realized from pins {*P0.2/TXD0/AD0.7 and P0.3/RXD0/AD0.6*} and { *P2.0/PWM1.1/TXD1 and P2.1/PWM1.2/RXD1*} of the microcontroller to the pins {*10, 9, 11, and 12*} ST3232C chip. The ST3232C chip drives the two COM0 and COM1 represented by the two *female* DB9 connectors (Note: if you use an Embest LPC1700 board, then, note that these two connectors are *male* DB9 connectors). To see these connections, take a look on pages 1 and 3 of the schematic diagram of the board [3] (included also in the downloadable files of this lab#2).

For more details on UART and RS-232, please read references [1-6].

In this lab we will explore serial communication between the (target) LPC1768 UART and a serial communication port of the host PC.

3. EXAMPLE 1: Microcontroller "echoes" back the characters sent by host computer

(a) <u>Experiment</u>

In the first example of this lab, we'll use an example project that comes with the "LPC1700 code bundle". The LPC1700 Code Bundle is a free software package from NXP that demonstrates the use of the built-in peripherals on the NXP LPC17xx series of microcontrollers. The example software includes a common library, peripheral APIs, and test modules for the APIs.

Download LPC1700 Code Bundle from [7] (http://ics.nxp.com/support/software/code.bundle.lpc17xx.keil/) and save it in your own work directory. Save it with the plan to keep it as we'll revisit some other example in the future. Unzip it to get the **keil_examples** folder created with several examples therein. Take a minute and read **keil_example/readme.txt** now.

Launch Keil uVision4 and then open the project UART from among the example just downloaded. The UART project is a simple program for the NXP LPC17xx microcontrollers using Keil's MCB1700 evaluation board. When sending some characters from a terminal program on the PC at a speed of 57600 Baud to the LPC17xx UART0 or UART1 the LPC17xx will echo those same characters back to the terminal program.

Step 1: Connect the board, ULINK2, and the host computer as shown in Fig.4. Ask the TA for the COM0/1 to Serial Port cable.

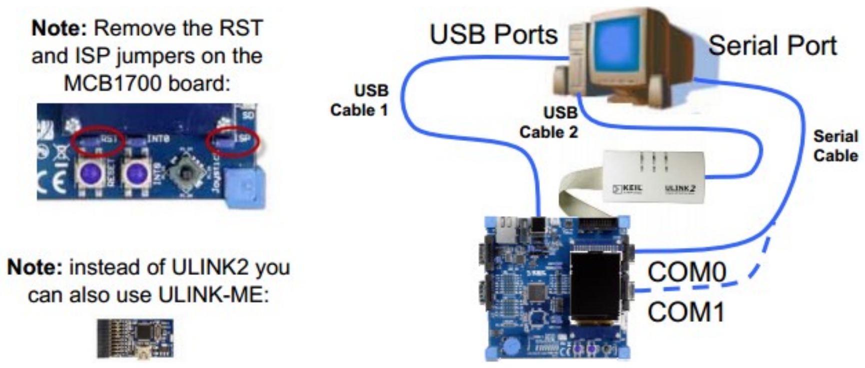

Note: Remove the RST and ISP jumpers on the MCB1700 board:
Note: instead of ULINK2 you can also use ULINK-ME:
USB Ports
Serial Port
USB Cable 1
USB Cable 2
Serial Cable
COM0
COM1

Figure 4 Hardware setup.

Remove the RST and ISP jumpers. Please keep the jumpers safe and place them back when you are done with this lab.
Note: If you are doing this lab using a laptop which does not have a serial port, you can use a USB Serial Converter. I got mine for about $12 from Amazon [8] and it works great.

Step 2: Familiarize yourself with the following files:
--**uart.c**: contains the UART0 / UART1 handlers / driver functions
--**uarttest.c**: contains a small test program utilizing the UART driver
--**system_LPC17xx.c**: Cortex-M3 Device Peripheral Access Layer Source File
--**startup_LPC17xx.s**: CMSIS Cortex-M3 Core Device Startup File
--**Abstract.txt**: Describes what the uarttest.c program does
Change "#include "lpc17xx.h" to "#include <lpc17xx.h>. This is done in order to use the latest Keil's release of the header file (normally located in C:\Keil\ARM\INC\NXP directory).

Step 3: Make sure the uVision4 Target setting is FLASH. Then, build the project by rebuilding all target files. Download to the microcontroller and confirm that download is ok.

Step 4: Establish a Terminal connection
--**Method 1:** If your Windows is XP or older, you can use HyperTerminal:

--Start HyperTerminal by clicking Start - > All Programs -> Accessories -> Communications -> HyperTerminal
--Connect HyperTerminal to the serial port that is connected to the COM0 port of the evaluation board for example. For the HyperTerminal settings you should use: COM1 (double check that it the host's serial port is indeed COM1in your case – you can do that by Start->Control Panel->System->Hardware->Device Manager and click on Ports (COM & LPT); if in your case it's a different port number then use that; for example, in my case as I use the USB to serial adapter with my laptop, the port is COM14), baud rate 57600, 8 data bits, no parity, 1 stop bit, and no flow control.
***--Method 2:** If your Windows is 7 or newer, you first must make sure you download and/or install a serial connection interface (because HyperTerminal is not part of Windows 7 or later). On the machines in the lab, you can use Putty (http://www.putty.org):*
--Start->All Programs->Putty->Putty
--Then, select Connection, Serial and type COM1 (or whatever is in your case; find what it is as described in Method 1), baud rate 57600, 8 data bits, no parity, 1 stop bit, and no flow control.
--Click on Session and choose the type of connection as Serial. Save the session for example as "lab2".
--Finally, click on Open; you should get HyperTerminal like window.
***--Method 3:** You can use other programs such as:*
TeraTerm (http://logmett.com/index.php?/products/teraterm.html) or
HyperSerialPort (http://www.hyperserialport.com/index.html) or
RealTerm (http://realterm.sourceforge.net) or CoolTerm (http://freeware.the-meiers.org), etc.

Step 5: Type some text. It should appear in the HyperTerminal window. This is the result of: First, what you type is sent to the microcontroller via the serial port (that uses a UART). Second, the MCU receives that via its own UART and echoes (sends back) the typed characters using the same UART. The host PC receives the echoed characters that are displayed in the HyperTerminal.
Disconnect the serial cable from COM0 and connect it to COM1 port on the MCB1700 board. The behavior of project should be the same.

***Step 6:** (optional – do **not** do it on computers in the lab): On your own computer only, download and install NXP's FlashMagic tool from here:*
http://www.flashmagictool.com/
Then, follow the steps that describe how to use this tool as presented in the last part of the UART documentation for the code bundle:
http://ics.nxp.com/literature/presentations/microcontrollers/pdf/code.bundle.lpc17xx.keil.uart.pdf (included in the downloadable archive of files for this lab).
Note: With this approach one does not need the ULINK2 programmer/debugger.

(b) Brief program description

Looking at the **main()** function inside the **uarttest.c** file we can see the following main actions:
--UART0 and UART1 are initialized:
```
  UARTInit(0, 57600);   /* baud rate setting */
  UARTInit(1, 57600);   /* baud rate setting */
```
--A while loop which executes indefinitely either for UART0 or for UART1. The instructions executed inside this loop (let's assume the UART0) are:

- Disable Receiver Buffer Register (RBR), which contains the next received character to be read. This is achieved by setting all bits of the Interrupt Enable Register (IER) to ‘0’ except bits THRE and RLS. In this way the LSB (i.e., bit index 0 out of 32 bits) of IER register is set to ‘0’. The role of this bit (as explained in the LPC17xx User’s Manual [1] on page 302) when set to ‘0’ is to disable the Receive Data Available interrupt for UART0.
- Send back to the host the characters from the buffer UART0Buffer. This is done only if there are characters in the buffer (the total buffer size is 40 characters) which have been received so far from the host PC. The number of characters received so far and not yet echoed back is stored and updated in UART0Count.
- Once the transmission of all characters from the buffer is done, reset the counter UART0Count.
- Enable Receiver Buffer Register (RBR). This is achieved by setting to ‘1’ the LSB of IER, which in turn is achieved using the mask IER_RBR.

(c) Source code discussion

Please take your time now to thoroughly browse the source code in files **uart.c** and **uarttest.c** files. Open and read other files as necessary to track the declarations and descriptions of variables and functions.

For example, in **uarttest.c** we see:
--A function call **SystemClockUpdate();**
This is **described** in source file **system_LPC17xx.c** which we locate in the Project panel of the uVision4 IDE. Click on the name of this file to open and search inside it the description of **SystemClockUpdate()**. This function is declared in header file **system_LPC17xx.h**. Open these files and try to understand how this function is implemented; what each of the source code lines do?
--A function call **UARTInit(0, 57600);**
This function is described in source file **uart.c**. The declaration of this function is done inside header file **uart.h**. Open these files and read the whole code; try to understand each line of the code.
--An instruction:
```
LPC_UART0->IER = IER_THRE | IER_RLS;             /* Disable RBR */
```
Based on what’s been studied in lab#1 you should know already that **LPC_UART0** is an address of a memory location – the UART0 peripheral is “mapped” to this memory location. Starting with this memory location, several consecutive memory locations represent “registers” associated with this peripheral/device called UART0. All 14 such registers (or memory locations) are listed on page 300 of the User Manual. Utilizing this peripheral is done through reading/writing into these registers according to their meaning and rules described in the manual. For example, one of the 14 registers associated with UART0 is Interrupt Enable Register (**IER**).
Form a C programming perspective, **LPC_UART0** is declared inside header file **LPC17xx.h**:
```
#define LPC_UART0             ((LPC_UART_TypeDef      *) LPC_UART0_BASE    )
```
Which also declares what **LPC_UART0_BASE** as:
```
#define LPC_UART0_BASE        (LPC_APB0_BASE + 0x0C000)
```
Where **LPC_APB0_BASE** is declared at its turn in the same file:
```
#define LPC_APB0_BASE         (0x40000000UL)
```
This effectively makes **LPC_UART0_BASE** to have value: **0x4000C000**, which not surprisingly coincides with what is reported on page 14 of the LPC17xx User’s Manual!
Furthermore, the Interrupt Enable Register (IER) contains individual interrupt enable bits for the 7 potential UART interrupts. The IER register for UART0 is “mapped” (or associated with) to memory address

0x4000C004 as seen on page 300 of the LPC17xx User's Manual. This fact is captured in the **struct** declaration of **LPC_UART_TypeDef** inside the header file **LPC17xx.h** (open this file and double check it!). As a result, in our C programming, we can refer to the IER register as in the instruction that we are currently discussing: **LPC_UART0->IER**, which basically stores/represents the address **0x4000C004**.
In addition, note that **IER_THRE** and **IER_RLS** are declared inside the header file **uart.h** as:

```
#define IER_THRE  0x02
#define IER_RLS   0x04
```

Which are utilized as masks in our instruction:

```
LPC_UART0->IER = IER_THRE | IER_RLS;            /* Disable RBR */
```

So, finally as we see, the effect of this instruction is simply to turn '1' bit index 1 (the second LSB out of 32 bits) and bit index 2 (the third LSB out of 32 bits) of the IER register! All other bits are set to '0'.
Having bit index 1 of this register set to '1' enables the Transmit Holding Register Empty (THRE) flag for UART0 – see page 302, Table 275 of the LPC17xx User's Manual. Having bit index 2 of this register set to '1' enables the UART0 RX line status interrupts – see page 302, Table 275 of the LPC17xx User's Manual. As already said, all other bits are set therefore via this masking to '0'. This includes the LSB (i.e., bit index 0 out of 32 bits) of IER register, which is set to '0'. The role of this bit (as explained in the LPC17xx User's Manual on page 302) when set to '0' is to disable the Receive Data Available interrupt for UART0.
You should be able now to explain what the following instruction does:

```
LPC_UART0->IER = IER_THRE | IER_RLS | IER_RBR;  /* Re-enable RBR */
```

Summarizing, what the code inside **uarttest.c** does is (as also mentioned in the previous section):
--disable receiving data
--send back data to the PC from the buffer (i.e., array variable UART0Buffer)
--reset counter of characters stored in buffer
--enable receiving data

Note: As mentioned in lab#1, in general one would not need to worry about these details about addresses to which registers are mapped. It would be sufficient to just know of for example the definition and declaration of ***LPC_UART_TypeDef*** *inside the header file* ***LPC17xx.h****. To the C programmer, it is transparent to what exact address the register IER is mapped to for example. However, now at the beginning, it's instructive to track these things so that we get a better global picture of these concepts. It also forces us to get better used with the LPC17xx User's Manual and the datasheets.*

Notice that inside the source file **uart.c** we have these two function descriptions:

```
void UART0_IRQHandler (void) {...}
void UART1_IRQHandler (void) {...}
```

which are not called for example inside **uarttest.c**, but they appear inside **startup_LPC17xx.s**:

```
DCD     UART0_IRQHandler          ; 21: UART0
DCD     UART1_IRQHandler          ; 22: UART1
```

The function **void UART0_IRQHandler (void)** is the UART0 interrupt handler. Its name is **UART0_IRQHandler** because it is named like that by the startup code inside the file **startup_LPC17xx.s**. **DCD** is an assembler directive (or pseudo-op) that defines a 32-bit constant.
To get a better idea about these things, we need to make a parenthesis and discuss a bit about **interrupts** in the next section. For the time being this discussion is enough. We will discuss interrupts in more details in class lectures and in some of the next labs as well.

(d) Interrupts – a 1st encounter

An **interrupt** is the automatic transfer of software execution in response to a hardware event that is **asynchronous** with the current software execution. This hardware event is called a **trigger**. The hardware event can either be a *busy to ready transition* in an external I/O device (i.e., peripheral, like for example the UART input/output) or an internal event (like bus fault, memory fault, or a periodic timer). When the hardware needs service, signified by a busy to ready state transition, it will request an interrupt by setting its trigger flag.
A **thread** is defined as the path of action of software as it executes. The execution of the interrupt service routine (ISR) is called as a background thread, which is created by the hardware interrupt request and is killed when the ISR returns from interrupt (e.g., by executing a **BX LR** in an assembly program). A new thread is created for each interrupt request. In a **multi-threaded** system, threads are normally cooperating to perform an overall task. Consequently, we'll develop ways for threads to communicate (e.g., FIFOs) and synchronize with each other.
A **process** is also defined as the action of software as it executes. Processes do not necessarily cooperate towards a common shared goal. Threads share access to I/O devices, system resources, and global variables, while processes have separate global variables and system resources. Processes do not share I/O devices.

To **arm (disarm)** a device/peripheral means to enable (shut off) the source of interrupts. Each potential interrupting trigger has a separate "arm" bit. One arms (disarms) a trigger if one is (is not) interested in interrupts from this source.
To **enable (disable)** means to allow interrupts at this time (postponing interrupts until a later time). On the ARM Coretx-M3 processor, there is one interrupt enable bit for the entire interrupt system. In particular, to disable interrupts we set the interrupt mask bit, **I**, in **PRIMASK** register.

Note: An interrupt is one of five mechanisms to ***synchronize*** *a microcontroller with an I/O device. The other mechanisms are blind cycle, busy wait, periodic polling, and direct memory access. With an input device, the hardware will request an interrupt when input device has new data. The software interrupt service will read from the input device and save in global RAM. With an output device, the hardware will request an interrupt when the output device is idle. The software interrupt service will get data from a global structure, and write it to the device. Sometimes, we configure the hardware timer to request interrupts on a periodic basis. The software interrupt service will perform a special function; for example, a data acquisition system needs to read the ADC at a regular rate.*

On the ARM Cortex-M3 processor, exceptions include resets, software interrupts, and **hardware interrupts**. Each exception has an associated 32-bit vector that points to the memory location where the **ISR** that handles the exception is located. Vectors are stored in ROM at the beginning of the memory. Here is an example of a few vectors as defined inside **startup_LPC17xx.s**:

```
__Vectors
         DCD     __initial_sp                  ; Top of Stack
         DCD     Reset_Handler                 ; Reset Handler
         DCD     NMI_Handler                   ; NMI Handler
         DCD     HardFault_Handler             ; Hard Fault Handler
         ...
```

```
; External Interrupts
DCD     WDT_IRQHandler                  ; 16: Watchdog Timer
DCD     TIMER0_IRQHandler               ; 17: Timer0
...
DCD     UART0_IRQHandler                ; 21: UART0
...
```

ROM location 0x00000000 has the initial stack pointer and location 0x00000004 contains the initial program counter (PC), which is called the **reset vector**. It points to a function called reset handler, which is the first thing executed following reset.

Interrupts on the Cortex-M3 are controlled by the Nested Vector Interrupt Controller (NVIC). **To activate an "interrupt source" we need to set its priority and enable that source in the NVIC (i.e., activate = set priority + enable source in NVIC).** This activation is in addition to the "arm" and "enable" steps discussed earlier.
Table 50 in the User Manual (page 73) lists the interrupt sources for each **peripheral function**. Table 51 (page 76 in User Manual) summarizes the registers in the NVIC as implemented in the LPC17xx microcontroller. Read the entire Chapter 6 of the User Manual (pages 72-90) and identify the priority and enable registers and their fields of the NVIC. Pay particular attention to (i.e., search/watch for) UART0 in this Chapter. How would you set the priority and enable UART0 as a source of interrupts?

Coming back to our discussion of the function **void UART0_IRQHandler (void)** in **uart.c**, we see a first instruction:

```
IIRValue = LPC_UART0->IIR;
```

What does it do? It simply reads the value of **LPC_UART0->IIR** and assigns it to a variable whose name is IIRValue. **LPC_UART0->IIR** is the value of the register **IIR** (Interrupt IDentification Register - identifies which interrupt(s) are pending), which is one of several (14 of them) registers associated with the UART0 peripheral/device. You can see it as well as the other registers on page 300 of the User Manual. Take a while and read them all. The fields of the interrupt register **IIR** are later described on page 303 in the User Manual. Take another while and read them all on pages 303-304.
Next inside **uart.c** we see:

```
  IIRValue >>= 1;             /* skip pending bit in IIR */
  IIRValue &= 0x07;           /* check bit 1~3, interrupt identification */
```

Which shifts right with one bit IIRValue and then AND's it with 0x07. This effectively "zooms-in" onto the field formed by bits index 1-3 from the original **LPC_UART0->IIR**, bits which are now in the position bits index 0-2 of IIRValue variable.
Going on, we find an "if" instruction with several branches:

```
  if ( IIRValue == IIR_RLS )        /* Receive Line Status */
  {...
  }
  else if ( IIRValue == IIR_RDA )   /* Receive Data Available */
  {...
  }
  else if ( IIRValue == IIR_CTI )   /* Character timeout indicator */
  {...
  }
  else if ( IIRValue == IIR_THRE )  /* THRE, transmit holding register empty */
  {...
  }
```

See in Table 276 on page 303 in the User Manual what is the meaning of the three bits 1-3 from the original IIR register:

```
011 1 - Receive Line Status (RLS).
010 2a - Receive Data Available (RDA).
110 2b - Character Time-out Indicator (CTI).
001 3 - THRE Interrupt
```

For each of these situations, something else is done inside the corresponding branch of the "if" instruction above. In other words, we first identify the interrupt, and for each ID we do something else. If none of the expected IDs is found, we do nothing. **Please take your time now to explain what's done in each of these cases**. Read pages 303-304 in the User Manual for this. This is very important in order to understand the overall operation of the example of this lab.

4. Lab Assignment

1) (not graded and should ***not*** *be discussed in the lab report) Use a Debug session to step through the execution of this program. The scope is for you to better understand its operation. See lab#1 for how to use/run a debug session. See also documentation of the code bundle from NXP [7].*

2) Answer the question: Why did we need to remove the ISP and RST jumpers in Example 1?

3) Describe in less than a page (typed, font size 11, single line spacing) all instructions inside the function **void UART0_IRQHandler (void)** for each of the branches of the main "if" instruction. Include this in your lab report.

4) Modify Example 1 such that the characters typed on the host's keyboard are also displayed on the LCD display on the board. (Hint: re-use code from Blinky2 example of lab#1)

5. Credits and references

[1] LPC17xx user's manual; http://www.nxp.com/documents/user_manual/UM10360.pdf (part of lab#1 files)
[2] NXP LPC17xx Datasheet;
http://www.nxp.com/documents/data_sheet/LPC1769_68_67_66_65_64_63.pdf (part of lab#1 files)
[3] Schematic Diagram of the MCB1700 board; http://www.keil.com/mcb1700/mcb1700-schematics.pdf (part of lab#2 files)
[4] MCB1700 Serial Ports; http://www.keil.com/support/man/docs/mcb1700/mcb1700_to_serial.htm
[5] UART entry on Wikipedia (click also on the references therein for RS-232);
http://en.wikipedia.org/wiki/Universal_asynchronous_receiver/transmitter
[6]
--Jonathan W. Valvano, Embedded Systems: Introduction to Arm Cortex-M3 Microcontrollers, 2012. (Chapters 8,9)
--Pong P. Chu, FPGA Prototyping by VHDL Examples: Xilinx Spartan-3 Version, Wiley 2008. (Chapter 7)
--Lab manual of course http://homes.soic.indiana.edu/geobrown/c335 (Chapter 5)
--EE 472 Course Note Pack, Univ. of Washington, 2009,
http://abstract.cs.washington.edu/~shwetak/classes/ee472/notes/472_note_pack.pdf (Chapter 8)
[7] LPC1700 Code Bundle;
Download: http://ics.nxp.com/support/software/code.bundle.lpc17xx.keil/

Documentation:
http://ics.nxp.com/literature/presentations/microcontrollers/pdf/code.bundle.lpc17xx.keil.uart.pdf
[8] Pluggable USB to RS-232 DB9 Serial Adapter;
Amazon: http://www.amazon.com/Plugable-Adapter-Prolific-PL2303HX-Chipset/dp/B00425S1H8/ref=sr_1_1?ie=UTF8&qid=1359988639&sr=8-1&keywords=plugable+usb+to+serial
Tigerdirect: http://www.tigerdirect.com/applications/SearchTools/item-details.asp?EdpNo=3753055&CatId=464

Lab 3: Debugging and More on Interrupts

1. Objective

The objective of this lab is to learn about the different features of the debugger of uVision. We'll do this by experimenting with several examples. We'll also re-emphasize some aspects about interrupts (UART and Timer) via these examples.

2. uVision Debuger

The µVision Debugger is completely integrated into the µVision IDE. It provides many features, including the following [1]:
--Disassembly of the code on C/C++ source- or assembly-level with program execution in various stepping modes and various view modes, like assembler, text, or mixed mode
--Multiple breakpoint options including access and complex breakpoints
--Review and modify memory, variable, and register values
--List the program call tree including stack variables
--Review the status of on-chip microcontroller peripherals
--Debugging commands or C-like scripting functions
--Code Coverage statistics for safety-critical application testing
--Various analyzing tools to view statistics, record values of variables and peripheral I/O signals, and to display them on a time axis
--Instruction Trace capabilities to view the history of executed instructions

The µVision Debugger offers **two operating modes**:

1) **Simulator Mode** - configures the µVision Debugger as a software-only product that accurately simulates target systems including instructions and most on-chip peripherals (serial port, external I/O, timers, and interrupts; peripheral simulation capabilities vary depending on the device you have selected.). In this mode, you can test your application code before any hardware is available. It gives you serious benefits for rapid development of reliable embedded software.
2) **Target Mode** - connects the µVision Debugger to real hardware. Several target drivers are available that interface to a:
   -ULINK JTAG/OCDS Adapter that connects to on-chip debugging systems
   -Monitor that may be integrated with user hardware or that is available on many evaluation boards
   -Emulator that connects to the microcontroller pins of the target hardware
   -In-System Debugger that is part of the user application program and provides basic test functions
   -ULINKPro Adapter a high-speed debug and trace unit connecting to on-chip debugging systems via JTAG/SWD/SWV, and offering Cortex-M3ETM Instruction Trace capabilities

Debug Menu
The Debug Menu of uVision IDE includes commands that start and stop a debug session, reset the CPU, run and halt the program, and single-step in high-level and assembly code. In addition, commands are available to manage breakpoints, view RTOS Kernel information, and invoke execution profiling. You can modify the memory map and manage debugger functions and settings.

Debug Toolbar
Take a moment and read pages 67-68 of the uV IDE Getting Started Guide [1]. The discussion on these pages present all the icons of the IDE related to the debugger.

Pre-lab preparation
Please take some time now and read fully Chapters 7,8,9 from the uV IDE Getting Started Guide [1].

3. Example 1 – Blinky 1 Revisited

The files necessary for this example are located in **example1** folder as part of the downloadable archive for this lab. As mentioned earlier, the µVision Debugger can be configured as a Simulator or as a Target Debugger. In this example, we'll use the Simulator. Go to the Debug tab of the Options for Target dialog to switch between the two debug modes and to configure each mode. Configure to **Use Simulator**. Before running the simulation, replace the following two lines inside blinky1.c:

```
delay( 1 << 24 );
```

with:

```
delay( 1 << 14 );
```

This is to make the blinking of P1.29 faster inside the simulator; otherwise, we'd need to wait too long to actually see the corresponding bit turning 1 or 0.

Simulation Debug
Open the Blinky1 project that you created in lab#1 or create a new project; use files from **example1** folder.

11. Click Debug menu option and select Start/Stop Debug Session. A warning about the fact that this is an evaluation version shows up; click OK.
12. Then, a new window appears where we can see the simulation of the program.
13. This window has several different supportive panels/sub-windows where we can monitor changes during the simulation. The left hand side panel, Registers, provides information regarding the Registers of LPC17xx with which we are working.
14. Again, click on the Debug menu option and select Run. The code starts simulating.
15. It is good practice that before going ahead with the actual hardware implementation to perform a debug/simulation session to make sure that our program behaves according to the design requirements.
16. In our example, we use PORT1.
17. Go to Peripherals menu option then select GPIO Fast Interface followed by Port 1.
18. You should get the window that shows P1.29 blinking.
19. Stop the simulation: Debug->Stop or hit the Stop icon from the Toolbar.

Breakpoints

1. Let's set two breakpoints on lines:

```
LPC_GPIO1->FIOPIN |= 1 << 29; // make P1.29 high
LPC_GPIO1->FIOPIN &= ~( 1 << 29 ); // make P1.29 low
```

inside **blinky1.c**. To set a breakpoint, right-click on each of these lines, on the left margin of the panel that displays this file and then select Insert/Remove Breakpoint.

2. Go to Peripherals menu option then select GPIO Fast Interface followed by Port 1 to show the GPIO1 Fast Interface.

3. Debug->Run. Notice that the simulation starts and runs till the first breakpoint where it stops. Notice that P1.29 is 0. To continue the simulation click the icon "Step (F11)" once. What happens? P1.29 is turned 1 and we stepped with the simulation to the next instruction inside our program.
4. Step (F11) again more times. Observe what happens each time. While stepping inside the delay() function, observe the value of local variable "i" inside the panel labeled Call Stack + Locals on the bottom right side of the uVision IDE. Notice how "i" is incremented. To get out from within the delay() function click the icon "Step out (Ctrl-F11)".
5. Once you get a hang of it, stop the simulation.

Logic Analyzer
The debugger includes a logic analyzer that will allow you to study the relative timing of various signals and variable changes. It's activated using the button in the debugger. Note that you can only use the logic analyzer when you're running in the simulator, not on the board.
The logic analyzer is mostly self-explanatory. Use the Setup button to add channels. You can use symbolic names such as FIO1PIN to determine what registers or variables to watch, and you can specify a mask value (which is ANDed with the contents of the register or variable) and a right shift value (which is applied after the AND operation). You can view the result as a numeric value ("analog") or as a bit value. At any point you can stop the updating of the screen (and/or stop the simulation itself), and change the resolution to zoom in or out. You can also scroll forward and backward in time using the scrollbar below the logic analyzer window. There are also "prev" and "next" buttons to move quickly from one transition to another.

1. Open the Logic Analyzer by clicking the icon Analysis Windows->Logic Analyzer
2. Click Setup… in the new window of the logic analyzer. Then, click New (Insert) icon and type FIO1PIN. Type in 0x20000000 as "And Mask".
3. Go to Peripherals menu option then select GPIO Fast Interface followed by Port 1 to show the GPIO1 Fast Interface.
4. Run simulation and observe how the signal changes inside the Logic Analyzer window.

4. Example 2 – UART1 sends "Hello World! " Once Only

The files necessary for this example are located in **example2** folder as part of the downloadable archive for this lab. This example is a modified (simplified) version of the example from lab#2. The simplified version uses only UART1 to simply send to the PC the string of characters "Hello World! ".
Please take a moment and read the new files **uart.h**, **uart.c**, and **uarttest.c**. Observe the differences compared to the original example from lab#2. Discuss with your team member the functionality of this new example.

To work with this example, go to your own folder where you have saved **keil_examples/** (this is the code-bundle of lab#2) and copy the whole directory **UART/** to **UART_modified/**. Then, replace the files **uart.h**, **uart.c**, and **uarttest.c** from **UART_modified/** with the ones provided in folder example2 of the downloadable archive of this lab. We make this copy and work inside **keil_examples/** to avoid copying files from **keil_examples/common/** (such as **type.h**).
Launch uVision and open the project from **UART_modified/**. Build the project and download to the board as you did in lab#2. Use a Putty terminal (or a HyperTerminal if you use Windows XP) to see that indeed "Hello World! " is printed out.

Simulation Debug

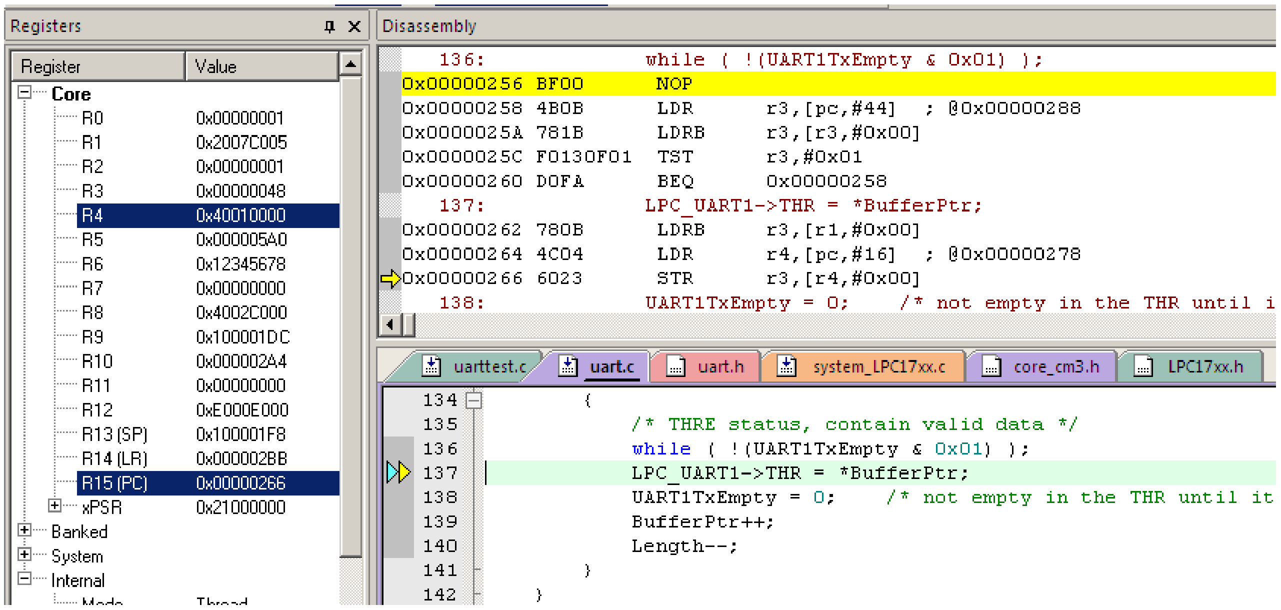
1. Configure the debugger to **Use Simulator**.
2. Click Debug menu option and select Start/Stop Debug Session.
3. Select View->Serial Windows->UART #2. In this window we can see what is sent out from UART1.
4. Select View->Watch Windows->Watch1. Double click on **<Enter expression>** inside the newly opened window and type **UART1TxEmpty**. This will monitor the variable UART1TxEmpty.
5. Run and Step through the program simulation. Observe and comment.

Target Debug

1. Configure the debugger to **ULINK2/ME Cortex Debugger**.
2. Modify the following line inside **uart.c**:
   ```
   volatile uint32_t UART1Count = 1;
   ```

We do this so that UART1 will transmit only one character, which we want to observe during debugging.

3. Build and download.
4. Click Debug menu option and select Start/Stop Debug Session.
5. Run and step through the execution of the program. Observe and comment. Identify the moment when the execution is in the state shown in the figure below. This is the moment when character 'H' (which is 48 in HEX) stored in register R3 is going to be stored to memory location **0x4001000** (stored in register R4), which if you look on page 320 of the user manual, you will see that it is register **LPC_UART1->THR**!



Register	Value
Core	
R0	0x00000001
R1	0x2007C005
R2	0x00000001
R3	0x00000048
R4	0x40010000
R5	0x000005A0
R6	0x12345678
R7	0x00000000
R8	0x4002C000
R9	0x100001DC
R10	0x000002A4
R11	0x00000000
R12	0xE000E000
R13 (SP)	0x100001F8
R14 (LR)	0x000002BB
R15 (PC)	0x00000266
xPSR	0x21000000
Banked	
System	
Internal	

```
    136:            while ( !(UART1TxEmpty & 0x01) );
0x00000256 BF00      NOP
0x00000258 4B0B      LDR      r3,[pc,#44]  ; @0x00000288
0x0000025A 781B      LDRB     r3,[r3,#0x00]
0x0000025C F0130F01  TST      r3,#0x01
0x00000260 D0FA      BEQ      0x00000258
    137:            LPC_UART1->THR = *BufferPtr;
0x00000262 780B      LDRB     r3,[r1,#0x00]
0x00000264 4C04      LDR      r4,[pc,#16]  ; @0x00000278
0x00000266 6023      STR      r3,[r4,#0x00]
    138:            UART1TxEmpty = 0;    /* not empty in the THR until i
```

```
        {
            /* THRE status, contain valid data */
            while ( !(UART1TxEmpty & 0x01) );
            LPC_UART1->THR = *BufferPtr;
            UART1TxEmpty = 0;    /* not empty in the THR until it
            BufferPtr++;
            Length--;
        }
    }
```

Figure 1 Illustration of the moment when 'H' is placed into register 0x40010000

5. Example 3 – Blink LED using Timer 0 Interrupt

The file necessary for this example is located in **example3** folder as part of the downloadable archive for this lab. We discussed this example in class (see lecture notes #9).

First, create a new uVision project and use the provided source file, **blink1_lec09.**c. Build and download. Observe operation and comment. Also, take some time and read the file to remember anything that it does.

Target Debug

1. Configure the debugger to **ULINK2/ME Cortex Debugger**.
2. Click Debug menu option and select Start/Stop Debug Session.
3. Open the Logic Analyzer by clicking the icon Analysis Windows->Logic Analyzer
4. Click Setup… in the new window of the logic analyzer. Then, click New (Insert) icon and type FIO1PIN. Type in 0x20000000 as "And Mask".
5. Go to Peripherals menu option then select GPIO Fast Interface followed by Port 1 to show the GPIO1 Fast Interface.
6. Run simulation and step through the execution of the program. Observe how the signal changes inside the Logic Analyzer window as well as inside the peripheral monitoring window. Comment.

6. Example 4 – Drawing circles on the 320x240 pixels LCD display of the MCB1700 board

You are given two versions of this example: Version 1 files are located in **lab3_circles1** and Version 2 files are located in **lab3_circles2**. Both versions do the same thing: plot randomly sized circles at random locations and of random colors on the 320x240 LCD display of the board. Create two different uVision projects for each version of this example. Create these projects inside the **keil_examples/** directory with all the examples of the code-bundle used in lab#2 so that you will not need to copy standard header files from **common**/. Build and download each of the projects. Observe their operation. You should observe a simplified (in that circles are not filled) operation of the one shown in Fig.2 below.

Read and compare the source code from **main_circles1.c** and **main_circles2.c**. Which version do you think is better and why? Is there anything that you would change to make this example more efficient?

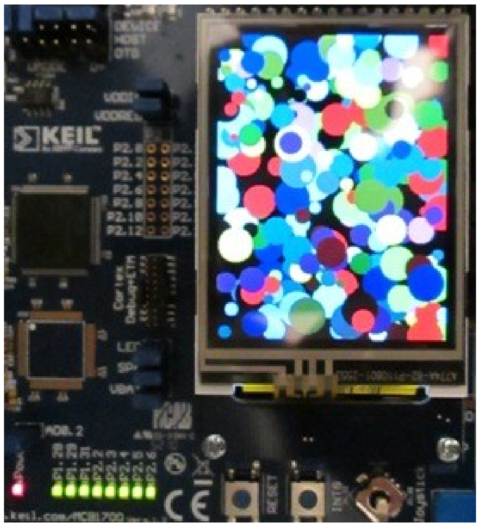


Figure 2 Plotting circles on the LCD display of MCB1700 board.

7. Lab Assignment

Write a program that uses the LCD screen of the MCB1700 board to display a smiley face ☺ in the center of the screen. In your program, you should use the Timer 0 Interrupt to trigger the change of color for the smiley face every other second. The smiley face's color should alternate between yellow and red. The size of the face should be approximately the size of a dime. The background can be any other color different from yellow and red.
Hint: Start with modifying any of the projects from Example 4 above. This example has already functions for drawing empty circles and lines. I have included already place holders for functions that you would need to describe/write (inside **CRIS_UTILS.c** and **CRIS_UTILS.h**). Then, you also need only to implement the logic of the main program by changing the main() function. The timer 0 interrupt is already set up in the Example 4 for you.

8. Credits and references

[1] Keil ARM, Getting Started, Creating Applications with µVision; http://www.keil.com/product/brochures/uv4.pdf (included in lab#1 files too)
[2] uVision IDE and Debugger; http://www.keil.com/uvision/debug.asp
[3] Lab Manual for ECE455 https://ece.uwaterloo.ca/~ece455/lab_manual.pdf

APPENDIX A: More on Interrupts (based in part on [3])

The LPC1768 microprocessor can have many sources of interrupts. All the internal peripherals are capable of generating interrupts. The specific conditions that produce interrupts can be set individually for each peripheral. The individual interrupts can be enabled or disabled using a set of registers (think of memory locations in the "memory space").

Selected GPIO pins can also be set to generate interrupts. The push button INT0 is connected to pin P2.10 of the LPC1768 microprocessor. This pin can be a source of external interrupts to the MCU. The table below shows different functionalities that can be assigned to P2.10 pin.
If you plan to use P2.10 as GPIO, then you should also enable this source of interrupt as described in section 9.5.6 of the LPC17xx user manual. Note that you can set the P2.10 pin to be sensitive to either the rising edge or the falling edge. More information on clearing the interrupt pending bit can be found in table 123 in section 9.5.6.1, page 139 of the user manual.

Table E.1 – Pin functions for P2.10

Bits 21:20 of **PINSEL4**	**Function**	**Value after reset**
00	GPIO P2.10 pin (default)	00
01	$\overline{EINT0}$	
10	NMI	
11	Reserved	

To write an **interrupt handler** in C we need to describe/create a function with an appropriate name and it will automatically be used (it will be called automatically via the pointers stored inside the **vector table**). The name of this function consists of the prefix from the table below plus the keyword “**Handler**” appended (e.g., **TIMER0_IRQHandler**).

```
-------------------------------------------------------------------------------------
Int#   Prefix              Description
-------------------------------------------------------------------------------------
0      WDT_IRQ             Watchdog timer
1      TIMER0_IRQ          Timer 0
2      TIMER1_IRQ          Timer 1
3      TIMER2_IRQ          Timer 2
4      TIMER3_IRQ          Timer 3
5      UART0_IRQ           UART 0
6      UART1_IRQ           UART 1
7      UART2_IRQ           UART 2
8      UART3_IRQ           UART 3
9      PWM1_IRQ            PWM 1 (not used on MCB1700)
10     I2C0_IRQ            I2C 0 (not used on MCB1700)
11     I2C1_IRQ            I2C 1 (not used on MCB1700)
12     I2C2_IRQ            I2C 2 (not used on MCB1700)
13     SPI_IRQ             SPI (used for communicating with LCD display)
14     SSP0_IRQ            SSP 0 (not used on MCB1700)
15     SSP1_IRQ            SSP 1 (not used on MCB1700)
16     PLL0_IRQ            PLL 0 (interrupts not used by our labs)
17     RTC_IRQ             Real-time clock
18     EINT0_IRQ           External interrupt 0
19     EINT1_IRQ           External interrupt 1 (not used on MCB1700)
20     EINT2_IRQ           External interrupt 2 (not used on MCB1700)
21     EINT3_IRQ           External interrupt 3 (not used on MCB1700) & GPIO interrupt
22     ADC_IRQ             ADC end of conversion
23     BOD_IRQ             Brown-out detected (not used)
24     USB_IRQ             USB
25     CAN_IRQ             CAN
26     DMA_IRQ             DMA
27     I2S_IRQ             I2S (not used on MCB1700)
28     ENET_IRQ            Ethernet
29     RIT_IRQ             Repetitive-interrupt timer
30     MCPWM_IRQ           Motor control PWM
31     QEI_IRQ             Quadrature encoder
32     PLL1_IRQ            USB phase-locked loop
33     USBActivity_IRQ     USB activity
34     CANActivity_IRQ     CAN activity
```

A particular peripheral can generate its interrupts for a variety of reasons, which are configured within that peripheral. For example, timers can be configured to generate interrupts either on match or on capture. The priorities of the interrupts can be set individually. See sections 6.5.11 to 6.5.19 of the user manual for details.

A set of functions is available for enabling and disabling specific interrupts, setting their priority, and controlling their pending status (find them inside **core_cm3.**h file, which is the so called CMSIS Cortex-M3 Core Peripheral Access Layer Header File):

```
void NVIC_EnableIRQ(IRQn_Type IRQn)
void NVIC_DisableIRQ(IRQn_Type IRQn)
void NVIC_SetPriority(IRQn_Type IRQn, int32_t priority)
uint32_t NVIC_GetPriority(IRQn_Type IRQn)
void NVIC_SetPendingIRQ(IRQn_Type IRQn)
void NVIC_ClearPendingIRQ(IRQn_Type IRQn)
IRQn_Type NVIC_GetPendingIRQ(IRQn_Type IRQn)
```

The IRQn names are just the prefix from the table above with an "n" appended (e.g., TIME0_IRQn).
We can also enable or disable interrupts altogether using `__disable_irq()` and `__enable_irq()`.

We can also trigger any interrupt in software (inside our C programs) by writing the interrupt number to the **NVIC->STIR** register (values up to 111 are permitted). We must clear interrupt conditions in the interrupt handler. This is done in different ways, depending on what caused the interrupt. For example, if we have **INT0** configured to generate an interrupt, you would clear it by setting the low-order bit of the **LPC_SC->EXTINT** register.

For detailed descriptions of all interrupts, you should read Chapter 6 of the NXP LPC17xxx User Manual.

APPENDIX B: Listing of source file blink1_lec09.c used in Example 3 of this lab

```
//
// this is a simple example, which turns one of the MCB1700 board's LEDs
// on/off; it uses a Timer 0 interrupt; we discussed it in lecture#9 in
// class;
//

#include "LPC17xx.h"

int main (void)
{
    // (1) Timer 0 configuration (see page 490 of user manual)
    LPC_SC->PCONP |= 1 << 1; // Power up Timer 0 (see page 63 of user manual)
    LPC_SC->PCLKSEL0 |= 1 << 2; // Clock for timer = CCLK, i.e., CPU Clock (page 56 user manual)

    // MR0 is "Match Register 0". MR0 can be enabled through the MCR to reset
    // the Timer/Counter (TC), stop both the TC and PC, and/or generate an interrupt
    // every time MR0 matches the TC. (see page 492 and 496 of user manual)
    LPC_TIM0->MR0 = 1 << 23; // Give a value suitable for the LED blinking
```

```
                         // frequency based on the clock frequency

    // MCR is "Match Control Register". The MCR is used to control if an
    // interrupt is generated and if the TC is reset when a Match occurs.
    // (see page 492 and 496 of user manual)
    LPC_TIM0->MCR |= 1 << 0; // Interrupt on Match 0 compare
    LPC_TIM0->MCR |= 1 << 1; // Reset timer on Match 0

    // TCR is "Timer Control Register". The TCR is used to control the Timer
    // Counter functions. The Timer Counter can be disabled or reset
    // through the TCR. (see page 492 and 494 of user manual)
    LPC_TIM0->TCR |= 1 << 1; // Manually Reset Timer 0 (forced);
    LPC_TIM0->TCR &= ~(1 << 1); // Stop resetting the timer

    // (2) Enable timer interrupt;
    // TIMER0_IRQn is 1, see lpc17xx.h and page 73 of user manual
    NVIC_EnableIRQ(TIMER0_IRQn); // see core_cm3.h header file

    // (3) Some more one-time set-up's;
    LPC_TIM0->TCR |= 1 << 0; // Start timer (see page 492 and 494 of user manual)
    LPC_SC->PCONP |= ( 1 << 15 ); // Power up GPIO (see lab1)
    LPC_GPIO1->FIODIR |= 1 << 29; // Put P1.29 into output mode. LED is connected to P1.29

    // (4) infinite loop;
    while (1) // Why do we need this?
    {
        // do nothing
    }

    return 0;
}

// Here, we describe what should be done when the interrupt on Timer 0 is handled;
// We do that by writing this function, whose address is “recorded” in the vector table
// from file startup_LPC17xx.s under the name TIMER0_IRQHandler;
void TIMER0_IRQHandler(void)
{
    // IR is "Interrupt Register". The IR can be written to clear interrupts. The IR
    // can be read to identify which of eight possible interrupt sources are
    // pending. (see page 492 and 493 of user manual)
    if ( (LPC_TIM0->IR & 0x01) == 0x01 ) // if MR0 interrupt (this is a sanity check);
    {
        LPC_TIM0->IR |= 1 << 0; // Clear MR0 interrupt flag (see page 492 and 493 of user manual)
        LPC_GPIO1->FIOPIN ^= 1 << 29; // Toggle the LED (see lab1)
    }
}
```

Lab 4: CAN and I2C

1. Objective

The objective of this lab is to learn about Controller Area Network (CAN). We'll do this by experimenting with an example that on board A converts (ADC) the value of the potentiometer and sends it via CAN to board B where the LEDs will be turned on/off by the received value. The transmitted and received data are displayed on the LCD screens of both boards. We'll also study I2C communication protocol and use a Wii NunChuck to control a moving circle on the LCD display.

2. CAN Introduction

This discussion is based on Chapter 16 of the LPC17xx user manual [1]. Please take time to read the aforementioned chapter completely.

CAN Controllers

Controller Area Network (CAN) is the definition of a high performance communication protocol for serial data communication. The CAN Controller of the LPC1768 microcontroller (supports 2 CAN controllers and buses; 11-bit identifier as well as 29-bit identifier) is designed to provide a full implementation of the CAN-Protocol according to the CAN Specification Version 2.0B. Microcontrollers with this on-chip CAN controller are used to build powerful local networks by supporting distributed real-time control with a very high level of security. The applications are automotive, industrial environments, and high speed networks as well as low cost multiplex wiring. The result is a strongly reduced wiring harness and enhanced diagnostic and supervisory capabilities.

The CAN block is intended to support multiple CAN buses simultaneously, allowing the device to be used as a gateway, switch, or router among a number of CAN buses in various applications. The CAN module consists of two elements: the controller and the Acceptance Filter. All registers and the RAM are accessed as 32-bit words.

CAN Controller Architecture

The CAN Controller is a complete serial interface with both Transmit and Receive Buffers but without Acceptance Filter. CAN Identifier filtering is done for all CAN channels in a separate block (Acceptance Filter). Except for message buffering and acceptance filtering the functionality is similar to the PeliCAN concept.
The CAN Controller Block includes interfaces to the following blocks (see Fig.1):
--APB Interface
--Acceptance Filter
--Nested Vectored Interrupt Controller (NVIC)
--CAN Transceiver (a separate chip on the MCB1700 board, shown in Fig.2)
--Common Status Registers

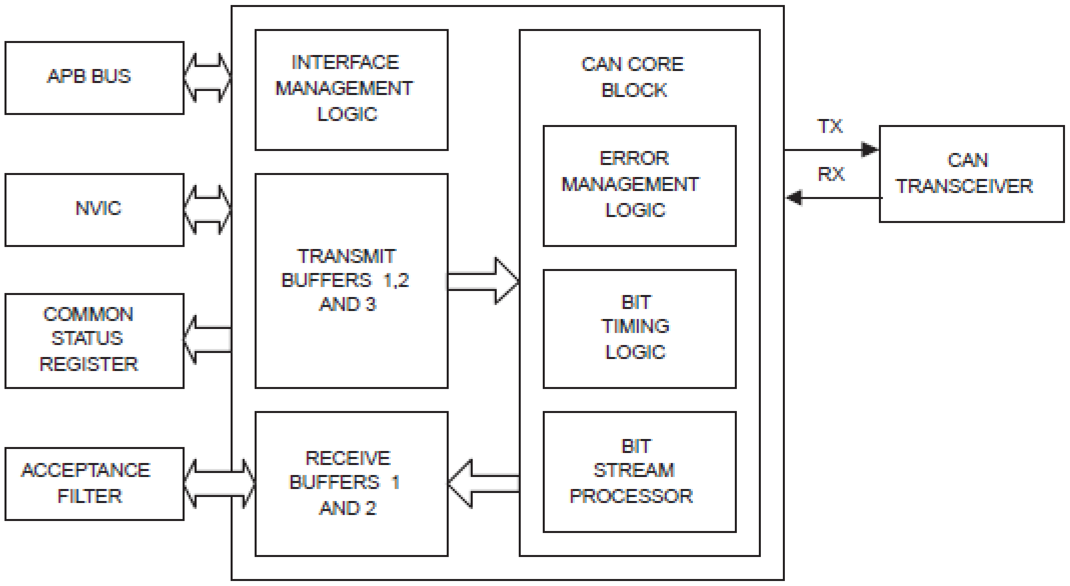


Figure 3 CAN controller block diagram [1]

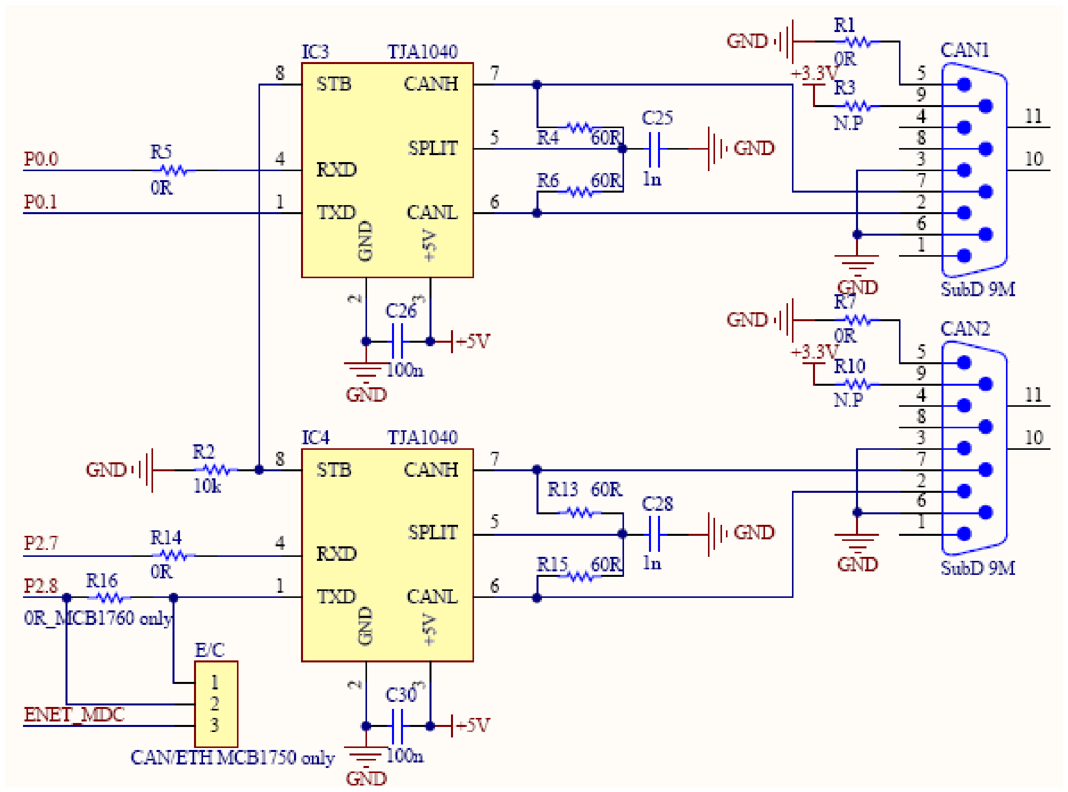


Figure 1 Portion of the schematic diagram of MCB1700 board that shows the CAN1,2 connections [2]

Please read through the pointers suggested [3] to learn more about CAN. Also, take a look at the datasheet of the NXP's TJA1040 High speed CAN transceiver integrated circuit (included in the downloadable archive of this lab) [4].

3. Example 1 – CAN2 – CAN1 loopback on the same board

The files necessary for this example are located in **CAN_Keil470/** folder as part of the downloadable archive for this lab. This is actually the whole uVision project directory. Just copy it to **keil_examples/** (this is the code-bundle of lab#2). Then clean and re-build the project. Download to the board. Connect the serial cable as shown in Fig.3 using the **adaptor from your TA**. Observe operation and comment.

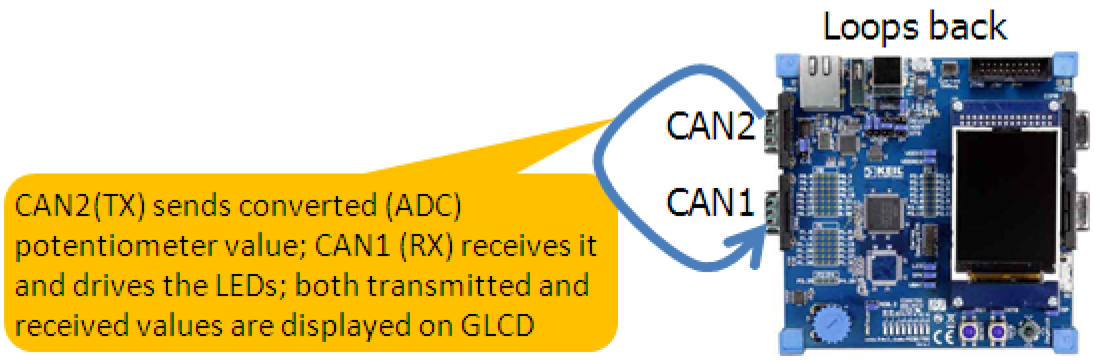

Loops back
CAN2
CAN1
CAN2(TX) sends converted (ADC) potentiometer value; CAN1 (RX) receives it and drives the LEDs; both transmitted and received values are displayed on GLCD

Figure 2 Block diagram of example 1.

4. Example 2 – CAN2 of board A sends to CAN1 of board B

This is basically the same example as in the previous section. You do not need to create another uVision project. To do this example, work with your neighboring team to realize the configuration shown in Fig.4. Use the serial cable to connect CAN2 of the transmitter board (board A) to the CAN1 of the receiver board (board B). Tune the potentiometer of board A and observe that it's received by board B, which drives its 8 LEDs and also displays the data on the LCD.

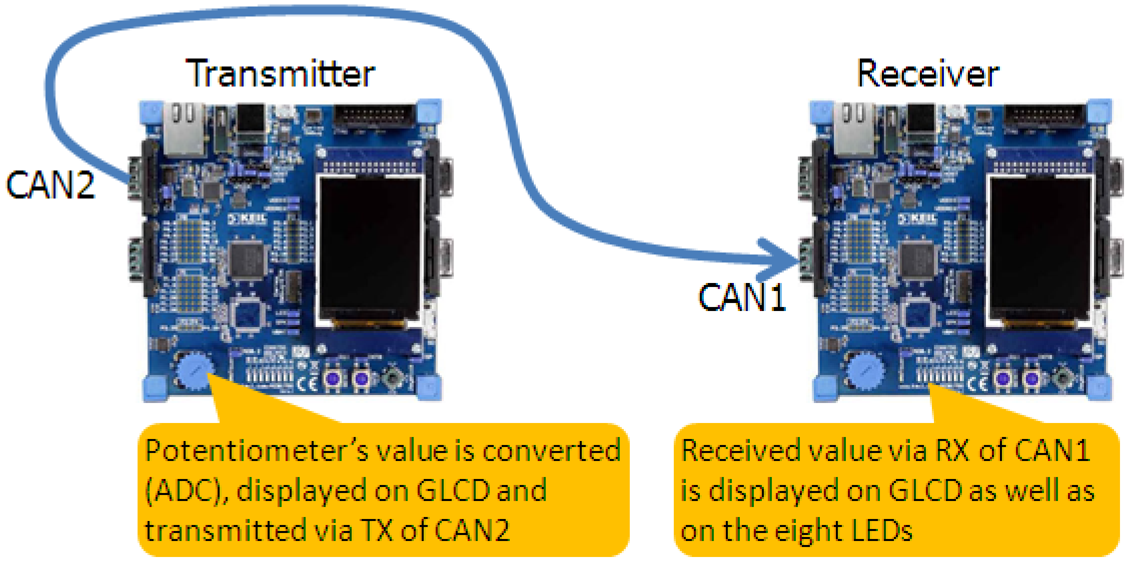

Transmitter
Receiver
CAN2
CAN1
Potentiometer's value is converted (ADC), displayed on GLCD and transmitted via TX of CAN2
Received value via RX of CAN1 is displayed on GLCD as well as on the eight LEDs

Figure 3 Block diagram of example 2.

5. I2C Introduction

I2C (inter-integrated circuit) is a two wire protocol used to connect one or more “masters” with one or more “slaves”. The case of a single master (the LPC1768) communicating with two slave devices is illustrated in Fig.5. In this configuration, a single master (LPCxxxx) communicates with two slaves over the pair of signal wires SCL (serial clock line) and SDA (serial data/address). Example slave devices include temperature, humidity, and motion sensors as well as serial EEPROMs, serial RAMs, LCDs, tone generators, other microcontrollers, etc.

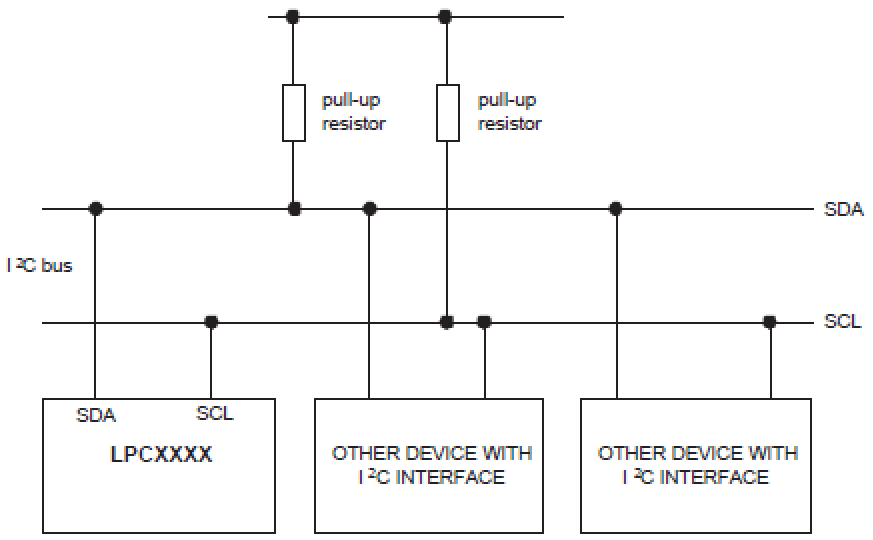

pull-up resistor
pull-up resistor
SDA
I²C bus
SCL
SDA
SCL
LPCXXXX
OTHER DEVICE WITH I²C INTERFACE
OTHER DEVICE WITH I²C INTERFACE

Figure 4 I2C bus configuration.

Electrically, the value of the two signal wires is “high” unless one of the connected devices pulls the signal “low”. The two pull-up resistors in Fig.5 force the default value of the two bus wires to VCC (typically 3.3V). Any device on the bus may safely force either wire low (to GND) at any time because the resistors limit the current draw; however, the communication protocol constrains when this should occur. To communicate, a master drives a clock signal on SCL while driving, or allowing a slave to drive SDA. Therefore, the bit-rate of a transfer is determined by the master.

The I2C Physical Protocol:

Communication between a master and a slave consists of a sequence of transactions where the master utilizes the SCL as a clock for serial data driven by the master or a slave on SDA as shown in Fig.6. When the master wishes to talk to a slave, it begins by issuing a start sequence on the I2C bus. A start sequence is one of two special sequences defined for the I2C bus, the other being the stop sequence. These are also referred to as Start condition (S) and Stop condition (P).

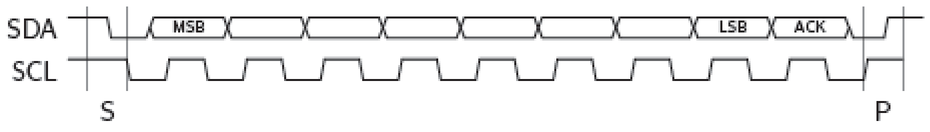


Figure 5 I2C physical protocol.

A transaction consists of a sequence of bytes. Each byte is sent as a sequence of 8 bits. The bits of each byte of data are placed on the SDA line starting with the MSB. The SCL line is then pulsed high, then low. For every 8 bits transferred, the device receiving the data sends back an acknowledge bit, so there are actually 9 SCL clock pulses to transfer each 8 bit byte of data. If the receiving device sends back a low ACK bit, then it has received the data and is ready to accept another byte. If it sends back a high (Not Acknowledge, NACK) then it is indicating it cannot accept any further data and the master should terminate the transfer by sending a stop sequence.

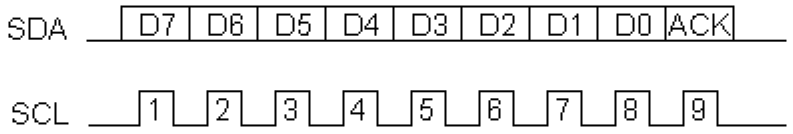


Figure 6 Illustration of sending of 1 byte of data.

The data may be sent by either the slave or the master, as the protocol dictates, and the ACK or NACK is generated by the receiver of the data. Start (S) and Stop (P) conditions are always generated by the master. A high to low transition on SDA while SCL is high defines a Start. A low to high transition on SDA while SCL is high defines a Stop.

There are three **types of transactions** on the I2C bus, all of which are initiated by the master. These are: write, read - depending on the state of the direction bit (R/W), and combined transactions. The first two of these (illustrated in Fig.8) are:

(1) Write transaction - Data transfer from a master transmitter to a slave receiver. The first byte transmitted by the master is the slave address. Next follows a number of data bytes. The slave returns an acknowledge bit after each received byte, unless the slave device is unable to accept more data.

(2) Read transaction - Data transfer from a slave transmitter to a master receiver. The first byte (the slave address) is transmitted by the master. The slave then returns an acknowledge bit. Next follows the data bytes transmitted by the slave to the master. The master returns an acknowledge bit after all received bytes other than the last byte. At the end of the last received byte, a “not acknowledge” is returned. The master device generates all of the serial clock pulses and the START and STOP conditions. A transfer is ended with a STOP condition or with a repeated START condition. Since a repeated START condition is also the beginning of the next serial transfer, the I2C-bus will not be released.

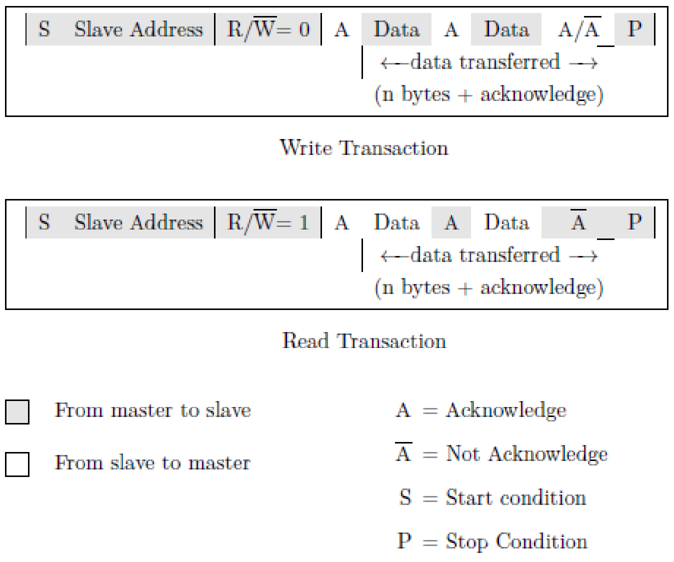


Figure 7 I2C write and read transactions.

The LPC17xx I2C interfaces are byte oriented and have four **operating modes**: master transmitter mode, master receiver mode, slave transmitter mode, and slave receiver mode. Please read Chapter 19 of the LPC17xx user manual for details on each of these operating modes [5]. Also, please read NXP I2C-bus specification and user manual for even more details [6].

I2C Device Addressing:
All I2C addresses are either 7 bits or 10 bits. The use of 10 bit addresses is rare. Most common chips use 7 bit addresses - we can have up to 128 devices on the I2C bus. When sending out the 7 bit address, we still always send 8 bits. The extra bit is used to inform the slave if the master is writing to it or reading from it. If the bit is zero the master is writing to the slave. If the bit is 1 the master is reading from the slave. The 7 bit address is placed in the upper 7 bits of the byte and the Read/Write (R/W) bit is in the LSB.

6. Wii NunChuck

The Wii NunChuk is an input device with a joystick, two buttons, and a three-axis accelerometer as illustrated in Fig.9,10. The three axes X, Y, and Z correspond to the data produced by the accelerometer, joystick. X is right/left, Y is forward/backwards, and Z is up/down (accelerometer only).

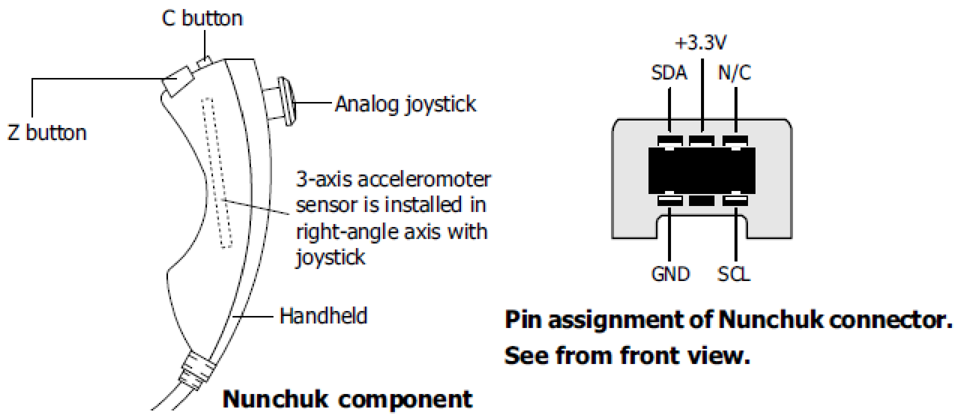

C button
Z button
Analog joystick
3-axis accelerometer sensor is installed in right-angle axis with joystick
Handheld
Nunchuk component
+3.3V
SDA
N/C
GND
SCL
Pin assignment of Nunchuk connector.
See from front view.

Figure 8 NunChuck basic information.

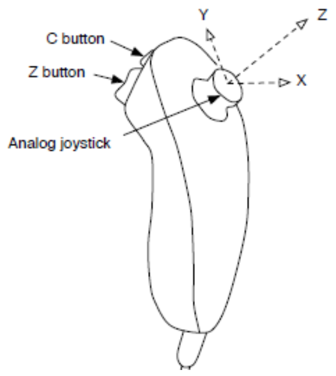


Figure 9 NunChuck X,Y,Z.

The NunChuck communicate via I2C. We'll hook the NunChuck to the I2C1 bus of the LPC1768 microcontroller on the MCB1700 board. We'll initialize the Nunchuk to a known state and then to regularly “poll” its state. The data are read from the NunChuck in a six-byte read transaction. These data are formatted as illustrated in Fig.11 and are read beginning with byte 0x0 (little-endian). The only complication with this format is that the 10-bit/axis accelerometer data are split.

	7	6	5	4	3	2	1	0
0x00	Joystick JX							
0x01	Joystick JY							
0x02	Accelerometer AX[9:2]							
0x03	Accelerometer AY[9:2]							
0x04	Accelerometer AZ[9:2]							
0x05	AZ[1:0]		AY[1:0]		AX[1:0]		C	Z

Figure 10 Formatting of data from NunChuck.

The NunChuck is a slave I2C bus device. It has 2 slave IDs for writing (0xA4) and reading (0xA5) data which is shown in Fig.12.

1	0	1	0	0	1	0	R/$\overline{W}$

Figure 11 Slave IDs.

Communication with the NunChuk consists of two phases – an initialization phase (executed once) in which specific data are written to NunChuk and a repeated read phase in which the six data bytes are read. Each read phase consists of two transactions – a write transaction which sets the read address to zero, and a read transaction.

<u>Initialize start NunChuk command</u>

The initialization consists of two write transactions, each of which writes a single byte to a register internal to the I2C slave: reg[0xf0]=0x55, reg[0xfb]= 0x00. Normally this done once only.

START	0xA4	Device Ack.	0xF0	Device Ack.	0x55	Device Ack.	STOP
START	0xA4	Device Ack.	0xFB	Device Ack.	0x00	Device Ack.	STOP

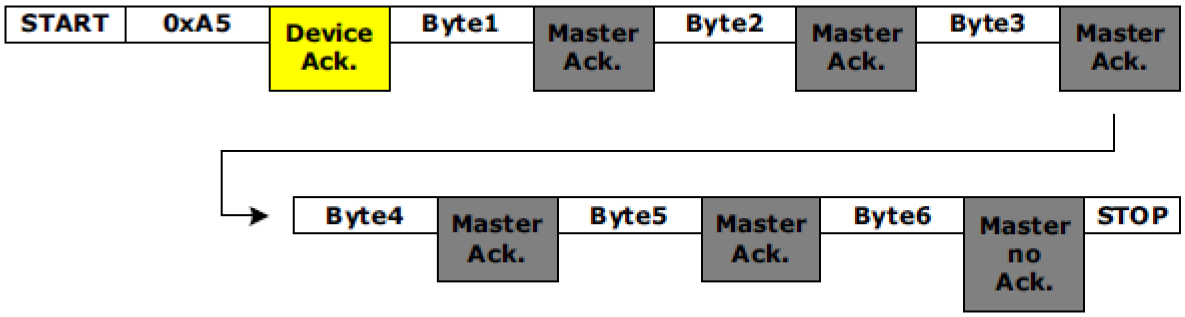
The read process consists of writing a 0 and then reading 6 bytes of data.

<u>Conversion command (0x00)</u>

Send this command to get all sensor data and store into the 6-byte register within Nunchuk controller. This must be executes before reading data from the Nunchuk.

START	0xA4	Device Ack.	0x00	Device Ack.	STOP

Data read command
Send the slave ID for reading (0xA5) and wait for the stream data 6-byte from the Nunchuk.



The joystick data are in the range 0..255 roughly centered at 128. The dynamic range is somewhat less than the full range (approximately 30-220).
The accelerometer data are in the range 0..1023 where 0 corresponds to -2g and 1023 corresponds to +2g. The accelerometer can be used both to detect motion (acceleration), but also as a "tilt sensor" when it is not in motion because we can use the earth's gravitational field as a reference. Suppose we have measured values of gravity in three dimensions, Gx, Gy, Gz. Then:

$$G_x^2 + G_y^2 + G_z^2 = 1g^2$$

From this, it is possible to compute "pitch" (rotation around the X axis), "roll" (rotation around the Y axis) and "yaw" (rotation around the Z axis). For joystick replacement, it is sufficient to compute (after range conversion to -512..511).

$$pitch = atan\left(\frac{AX}{\sqrt{AY^2 + AZ^2}}\right)$$

$$roll = atan\left(\frac{AY}{\sqrt{AX^2 + AZ^2}}\right)$$

Remember that this is for 360 degrees and a reasonable of motion to measure is perhaps 90 degrees.

Please read more about NunChuck hacking in the cited references [10] and on the Internet.

7. Example 3 – NunChuck data & moving circle (according to joystick) displayed on LCD display of the MCB1700 board

Note: Because I have only one NunChuck and a single NunChuck-adaptor, and because this example requires some wiring, you will not actually do this example in the lab. I will demonstrate it in each of the lab sessions or in class. However, you should read and study the source code to get familiar with this example and how it uses I2C.

In this example, we use the I2C to connect the NunChuck to the board. We'll display the data read from the NunChuck on the 320x240 pixels display and we'll use this data to move around a circle drawn on the display.

The files necessary for this example are located in **I2C_NunChuck/** folder as part of the downloadable archive for this lab. This is actually the whole uVision project directory. Just copy it to **keil_examples/** (this is the code-bundle of lab#2). Then clean and re-build the project. Download to the board. Connect the NunChuck as shown as shown in Fig.13 using the **wires provided by your instructor**. Observe operation and comment.

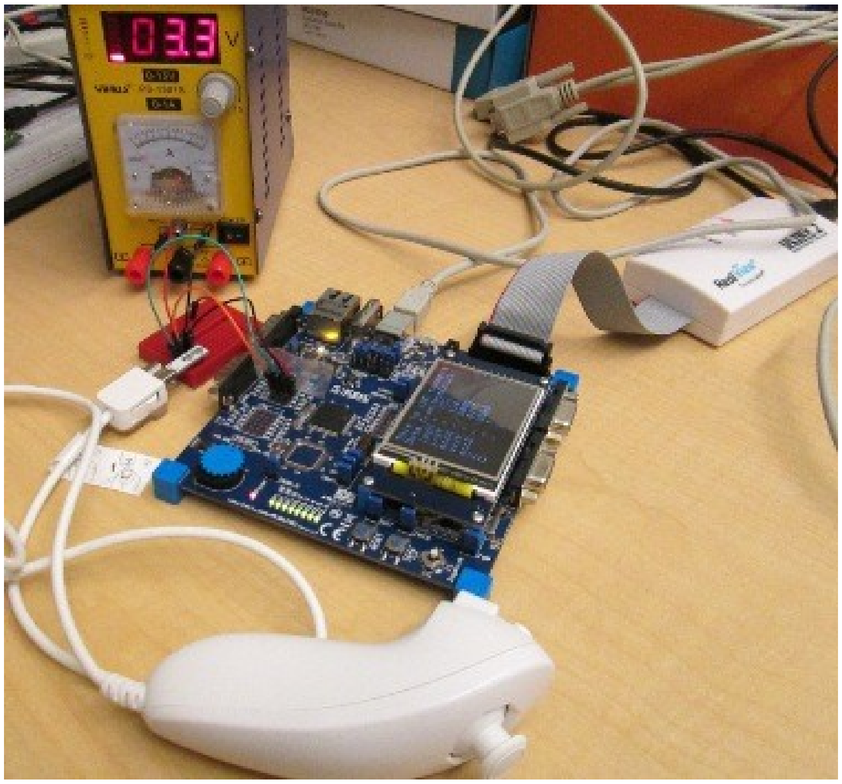


Figure 12 NunChuck connected to MCB1700 board. Data from NunChuck controls the movement of a circle on the LCD display.

8. Lab Assignment

Pre-lab report *(worth 8 points out of 20 points for this whole lab)*:
Write the pre-lab report and explain line by line of code the following functions from inside **can.c** file of example 1:

```
      void CAN_setup (uint32_t ctrl) { ... }
      void CAN_start (uint32_t ctrl) { ... }
      void CAN_waitReady (uint32_t ctrl) { ... }
      void CAN_wrMsg (uint32_t ctrl, CAN_msg *msg) { ... }
      void CAN_rdMsg (uint32_t ctrl, CAN_msg *msg) { ... }
      void CAN_IRQHandler (void) { ... }
```

Lab assignment project *(demo worth 6 points, final report worth 6 points):*

Modify example 1 as follows: remove the part related to the ADC and add instead the part related to the UART1 from the example studied in lab#2. In fact, from the UART1 source code you should add only the part that sends characters typed on the keyboard of the host PC to the board. You can remove from the UART1 code the part that sends the characters back to the host PC (which we used to display in the Putty terminal). Here, in this modified example, we want to send character by character via CAN: send out via CAN2 Tx and receive in via CAN1 Rx. The transmitted and received character should be displayed on the LCD instead of the old ADC value. The received character should also drive the 8 LEDs as in example 1.

9. Credits and references

[0] Textbook, Sections 18.4,5.

References on CAN:
[1] LPC17xx user manual (Chapter 16);
http://www.nxp.com/documents/user_manual/UM10360.pdf
[2] Schematic Diagram of the MCB1700 board; http://www.keil.com/mcb1700/mcb1700-schematics.pdf
[3] Pointers on CAN related information:
-- Keil CAN Primer; http://www.keil.com/download/files/canprimer_v2.pdf
-- CAN Introduction; http://www.esd-electronics-usa.com/Controller-Area-Network-CAN-Introduction.html
-- CAN Information; http://hem.bredband.net/stafni/developer/CAN.htm
-- CAN Primer; http://www.dgtech.com/images/primer.pdf
-- CAN Tutorial; http://www.computer-solutions.co.uk/info/Embedded_tutorials/can_tutorial.htm
-- Jonathan W. Valvano’s lecture 15; http://users.ece.utexas.edu/~valvano/EE345M/view15_CAN.pdf
(Note: his lectures are based on Stellaris MCU’s; however, the basics about CAN are the same)
-- Entry on Wikipedia; http://en.wikipedia.org/wiki/CAN_bus
-- CAN Specification, Version 2.0, 1991; http://esd.cs.ucr.edu/webres/can20.pdf
-- NXP’s Bosch CAN, protocol standard;
http://www.freescale.com/files/microcontrollers/doc/data_sheet/BCANPSV2.pdf
-- CAN Bus Description;
http://www.interfacebus.com/CAN-Bus-Description-Vendors-Canbus-Protocol.html
-- Marco Di Natale, Understanding and using the Controller Area Network, 2008;
http://www-inst.eecs.berkeley.edu/~ee249/fa08/Lectures/handout_canbus2.pdf
-- CAN PPT presentation at CMU; http://www.ece.cmu.edu/~ece649/lectures/11_can.pdf
[4] NXP's TJA1040 High speed CAN transceiver integrated circuit;
http://www.nxp.com/documents/data_sheet/TJA1040.pdf

References of I2C:
[5] LPC17xx user manual (Chapter 19);
http://www.nxp.com/documents/user_manual/UM10360.pdf
[6] Pointers on I2C related information:
--NXP I2C-bus specification and user manual; http://www.nxp.com/documents/user_manual/UM10204.pdf
-- tutorial 1; http://www.best-microcontroller-projects.com/i2c-tutorial.html
-- tutotial 2; http://www.robot-electronics.co.uk/acatalog/I2C_Tutorial.html
-- tutorial 3; http://embedded-lab.com/blog/?p=2583
-- Wikipedia entry; http://en.wikipedia.org/wiki/I%C2%B2C

[7] Lab manual of course http://homes.soic.indiana.edu/geobrown/c335 (Chapter 9).
[8] http://www.i2c-bus.org/addressing/
[9] I2C vs. SPI; http://www.byteparadigm.com/applications/introduction-to-i2c-and-spi-protocols/
[10] Pointers on NunChuck:
--Robotshop; http://www.robotshop.com/ca/content/PDF/inex-zx-nunchuck-datasheet.pdf
--Chad Philips. Read wii nunchuck data into arduino; http://www.windmeadow.com/node/42
--Wikipedia. Wii remote. http://en.wikipedia.org/wiki/Wii_Remote
--Wiibrew, Wiimote/Extension Controllers; http://wiibrew.org/wiki/Wiimote/Extension_Controllers
--Dangerousprototype, http://dangerousprototypes.com/docs/Wii_Nunchuck_quick_guide
--Freescale Semiconductor, Tilt sensing using linear accelerometers, 2012.
[11] Wii NunChuck adaptor; https://www.sparkfun.com/products/9281

APENDIX A: Listing of the main source code file for example 3

```
#include <stdio.h>
#include <stdlib.h>
#include "lpc17xx.h"
#include "type.h"
#include "i2c.h"
#include "GLCD.h"
#include "CRIS_UTILS.h"

void NunChuck_translate_data(void);
void NunChuck_print_data_init(void);
void NunChuck_print_data(void);
void search_for_i2c_devices(void);

#define __FI 1 // Use font index 16x24

#define PORT_USED 1

#define NUNCHUK_ADDRESS_SLAVE1 0xA4
#define NUNCHUK_ADDRESS_SLAVE2 0xA5

volatile int joy_x_axis;
volatile int joy_y_axis;
volatile int accel_x_axis;
volatile int accel_y_axis;
volatile int accel_z_axis;
volatile int z_button = 0;
volatile int c_button = 0;

extern volatile uint8_t I2CMasterBuffer[I2C_PORT_NUM][BUFSIZE]; // BUFSIZE=64
extern volatile uint8_t I2CSlaveBuffer[I2C_PORT_NUM][BUFSIZE];
extern volatile uint32_t I2CReadLength[I2C_PORT_NUM];
extern volatile uint32_t I2CWriteLength[I2C_PORT_NUM];

char text_buffer[8];
volatile uint8_t ack_received, ack_sent; // debugging only


// we'll use delay_dirty() as a software delay function; it should produce
// about a second when del=(1 << 24) or so of delay depending on CCLK;
volatile uint32_t temp;
void delay_dirty( uint32_t del)
```

```
{
        uint32_t i;
        for ( i=0; i<del; i++) { temp = i; }
}

// Communication with the Nunchuk consists of two phases:
// -->phase 1: initialization phase (executed once) in which specific data
// are written to the Nunchuk;
// Essentially initialization consists of two write transactions,
// each of which writes a single byte to a register internal to
// the I2C slave ( reg[0xf0] = 0x55, reg[0xfb] = 0x00 ).
// -->phase 2: repeated read phase in which six data bytes are read
// again and again; each read phase consists of two transactions -
// a write transaction which sets the read address to zero, and a
// read transaction.
// NOTES:
// -- I2C0 only supports 'fast mode' that the NunChuck uses!
// -- When I2C0 is used the pin connections are: SDA=P0.27, SCL=P0.28
// -- When I2C1 is used the pin connections are: SDA=P0.19, SCL=P0.20
void NunChuck_phase1_init(void)
{
    // this function should be called once only;
    uint32_t i;

    I2CWriteLength[PORT_USED] = 3; // write 3 bytes
    I2CReadLength[PORT_USED] = 0; // read 0 bytes
    I2CMasterBuffer[PORT_USED][0] = NUNCHUK_ADDRESS_SLAVE1;
    I2CMasterBuffer[PORT_USED][1] = 0xF0; // at adress 0xF0 of NunChuck write:
    I2CMasterBuffer[PORT_USED][2] = 0x55; // data 0x55
    I2CEngine( PORT_USED );

    // should I introduce a delay? people say it's useful when debugging;
    delay_dirty( 0x100000 );

    I2CWriteLength[PORT_USED] = 3; // write 3 bytes
    I2CReadLength[PORT_USED] = 0; // read 0 bytes
    I2CMasterBuffer[PORT_USED][0] = NUNCHUK_ADDRESS_SLAVE1;
    I2CMasterBuffer[PORT_USED][1] = 0xFB; // at adress 0xFB of NunChuck write:
    I2CMasterBuffer[PORT_USED][2] = 0x00; // data 0x00
    I2CEngine( PORT_USED );
}

void NunChuck_phase2_read(void)
{
    // this is called repeatedly to realize continued polling of NunChuck
    uint32_t i;

    I2CWriteLength[PORT_USED] = 2; // write 2 bytes
    I2CReadLength[PORT_USED] = 0; // read 6 bytes;
    I2CMasterBuffer[PORT_USED][0] = NUNCHUK_ADDRESS_SLAVE1;
    I2CMasterBuffer[PORT_USED][1] = 0x00; // address
    I2CEngine( PORT_USED );

    delay_dirty( 0x10000 );

    I2CWriteLength[PORT_USED] = 1; // write 1 bytes
    I2CReadLength[PORT_USED] = 6; // read 6 bytes;
    I2CMasterBuffer[PORT_USED][0] = NUNCHUK_ADDRESS_SLAVE2;
    I2CEngine( PORT_USED );
    // when I2CEngine() is executed, 6 bytes will be read and placed
    // into I2CSlaveBuffer[][]
```

```
}


int main(void)
{
    uint32_t i;
    uint32_t x_prev=160, y_prev=120;
    uint32_t x_new=160, y_new=120;
    uint32_t dx=4, dy=4, delta=5, radius=16;

    // (1) Initializations of GLCD and SER;
    GLCD_Init();
    GLCD_SetTextColor(Yellow);
    CRIS_draw_circle(160,120, radius);

    NunChuck_print_data_init();

    // (2) SystemClockUpdate() updates the SystemFrequency variable
    SystemClockUpdate();

    // (3) Init I2C devices; though we'll use only I2C1
    I2C0Init( );
    I2C1Init( );
    I2C2Init( );

    // (4)
    LPC_SC->PCONP |= ( 1 << 15 );
    LPC_GPIO0->FIODIR |= (1 << 21) | (1 << 22);
    LPC_GPIO0->FIOCLR |= 1 << 21;
    LPC_GPIO0->FIOSET |= 1 << 22;

    // (5) NunChuck phase 1
    //search_for_i2c_devices(); // debug only purposes;
    NunChuck_phase1_init();

    // Note: Be careful with dirty fixed delays realized with for loops
    // From device to device, or even same device with different write length,
    // or various I2C clocks, such delay may need to be changed;
    // however, it's good to have a break point between phases;
    // (6)  for ever loop
    while( 1 ) {

        // (a) reset stuff
        for ( i = 0; i < BUFSIZE; i++ ) {
            I2CSlaveBuffer[PORT_USED][i] = 0x00;
        }

        // (b) NunChuck phase 2
        NunChuck_phase2_read();
        NunChuck_translate_data();
        NunChuck_print_data();

        // (c) re-draw the circle to mimic movement if necessary;
        // Note: joy_x_axis, joy_y_axis have values in range: 30..230
        // with mid-range value of about 130 when the joystick rests;
        // implement the simplest method to move the circle around:
        // ->whenever joy_x_axis=190..230 (upper values in its range)
        // keep shifting the circle to the right;
        // ->whenever joy_x_axis=30..70 (lower values in its range)
        // keep shifting the circle to the left;
        // ->whenever joy_x_axis is in the mid-range do not move circle
        // apply same logic for joy_x_axis
        // TODO (assignments): move the circle based on the rotations
        // i.e., do not use joystick; use buttons Z and C to increase
        // or decrease the radius of the circle displayed on LCD;
        if (joy_x_axis > 190) {
            dx = delta;
        } else if (joy_x_axis < 90) {
            dx = -delta;
        } else {
            dx = 0;
        }
        x_new = x_prev + dx;
        if (x_new > 320 - radius) x_new = 320 - radius;
        if (x_new < 0 + radius) x_new = radius;
        if (joy_y_axis > 190) {
            dy = -delta;
        } else if (joy_y_axis < 90) {
            dy = delta;
        } else {
            dy = 0;
        }
        y_new = y_prev + dy;
        if (y_new > 240 - radius) y_new = 240 - radius;
        if (y_new < 0 + radius) y_new = radius;

        if ( (x_new != x_prev) || (y_new != y_prev)) { // must move circle;
            // first erase the circle at previous location;
            GLCD_SetTextColor(Black);
            CRIS_draw_circle(x_prev,y_prev, radius);
            // then re-draw at new location;
            GLCD_SetTextColor(Yellow);
            CRIS_draw_circle(x_new,y_new, radius);
        }
        x_prev = x_new;
        y_prev = y_new;

        // (d) long delay such that I have enough time to release joystick
        // and have the circle stay at new location; this is a hack
        // and should be modified to work nicely and to use rotations;
        delay_dirty( 0x10000 );
    }

}


void NunChuck_translate_data(void)
{
    int byte5 = I2CSlaveBuffer[PORT_USED][5];
    joy_x_axis = I2CSlaveBuffer[PORT_USED][0];
    joy_y_axis = I2CSlaveBuffer[PORT_USED][1];
    accel_x_axis = (I2CSlaveBuffer[PORT_USED][2] << 2);
    accel_y_axis = (I2CSlaveBuffer[PORT_USED][3] << 2);
    accel_z_axis = (I2CSlaveBuffer[PORT_USED][4] << 2);
    z_button = 0;
    c_button = 0;

    // byte I2CSlaveBuffer[PORT_USED][5] contains bits for z and c buttons
    // it also contains the least significant bits for the accelerometer data
    if ((byte5 >> 0) & 1)
        z_button = 1;
    if ((byte5 >> 1) & 1)
```

```
        c_button = 1;
    accel_x_axis += (byte5 >> 2) & 0x03;
    accel_y_axis += (byte5 >> 4) & 0x03;
    accel_z_axis += (byte5 >> 6) & 0x03;
}

void NunChuck_print_data_init(void)
{
    // this should be called once only;

    GLCD_SetTextColor(White);

    GLCD_Clear(Black); // clear graphical LCD display; set all pixels to Black
    GLCD_SetBackColor(Black); // set background color for when characters/text is printed
    GLCD_SetTextColor(White);
    GLCD_DisplayString(0, 0, __FI, " This is I2C example");
    GLCD_DisplayString(1, 0, __FI, " Data from NunChuck:");

    GLCD_DisplayString(2, 2, __FI, "joyX =");
    GLCD_DisplayString(3, 2, __FI, "joyY =");
    GLCD_DisplayString(4, 2, __FI, "accX =");
    GLCD_DisplayString(5, 2, __FI, "accY =");
    GLCD_DisplayString(6, 2, __FI, "accZ =");
    GLCD_DisplayString(7, 2, __FI, "Z    =");
    GLCD_DisplayString(8, 2, __FI, "C    =");
}

void NunChuck_print_data(void)
{
    // this is called as many times as reads from the NunChuck;

    GLCD_SetTextColor(White);

    sprintf(text_buffer, "%03d", joy_x_axis);
    GLCD_DisplayString(2, 10, __FI, (uint8_t*)text_buffer);
    sprintf(text_buffer, "%03d", joy_y_axis);
    GLCD_DisplayString(3, 10, __FI, (uint8_t*)text_buffer);
    sprintf(text_buffer, "%04d", accel_x_axis);
    GLCD_DisplayString(4, 10, __FI, (uint8_t*)text_buffer);
    sprintf(text_buffer, "%04d", accel_y_axis);
    GLCD_DisplayString(5, 10, __FI, (uint8_t*)text_buffer);
    sprintf(text_buffer, "%04d", accel_z_axis);
    GLCD_DisplayString(6, 10, __FI, (uint8_t*)text_buffer);
    sprintf(text_buffer, "%01d", z_button);
    GLCD_DisplayString(7, 10, __FI, (uint8_t*)text_buffer);
    sprintf(text_buffer, "%01d", c_button);
    GLCD_DisplayString(8, 10, __FI, (uint8_t*)text_buffer);
}
```

Lab 5: USB audio, Stepper Motor

1. Objective

The objective of this lab is to learn through examples about:

- USB: play a youtube song through the speaker available on the MCB1700 board and control its volume via the potentiometer also available on the board.
- Control of a simple stepper motor using four GPIOs and the joystick of MCB1700 board to set the direction of the rotation.

2. USB Introduction

USB was developed (in the mid-1990s) by Compaq, Intel, Microsoft, and NEC, joined later by Hewlett-Packard, Lucent and Philips. The USB was developed as a new means to connect a large number of devices to the PC, and eventually to replace the "legacy" ports (serial ports, parallel ports, keyboard and mouse connections, joystick ports, midi ports, etc.). The USB is based on a "tiered star topology" in which there is a single host controller and up to 127 "slave" devices. The host controller is connected to a hub, integrated within the PC, which allows a number of attachment points (referred to as ports). This is illustrated in the figure below.

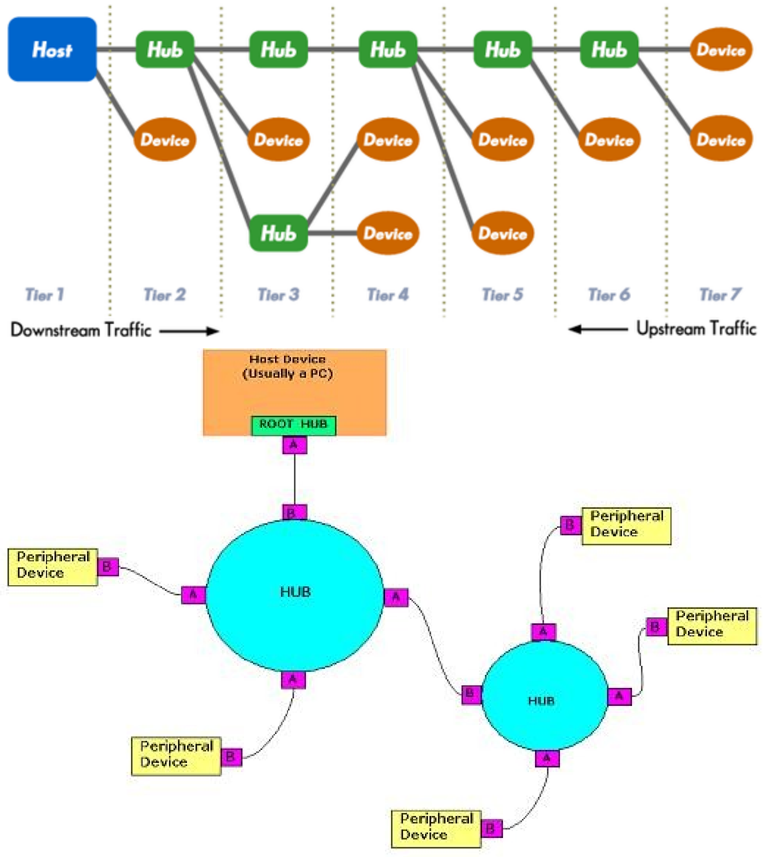


Figure 1 USB "tiered star topology".

USB is intended as a bus for devices near to the PC (up to 5 m). For applications requiring distance from the PC, another form of connection is needed, such as Ethernet.

USB is a four-wire bus (requires a shielded cable containing 4 wires) that supports communication between a host and one or more (up to 127) peripherals. The host controller allocates the USB bandwidth to attached devices through a *token-based protocol*. The bus supports hot plugging and dynamic configuration of the devices. All transactions are initiated by the host controller.
The host schedules transactions in 1 ms frames. Each frame contains a Start-Of-Frame (SOF) marker and transactions that transfer data to or from device endpoints. Each device can have a maximum of 16 logical or 32 physical endpoints. There are four types of transfers defined for the endpoints.

- Control transfers are used to configure the device.
- Interrupt transfers are used for periodic data transfer.
- Bulk transfers are used when the rate of transfer is not critical.
- Isochronous transfers have guaranteed delivery time but no error correction.

LPC1768 has a USB 2.0 interface that can be configured as:

- **Host**
- **Device**
- **OTG**: USB On-The-Go, often abbreviated USB OTG or just OTG, is a specification that allows USB devices such as digital audio players or mobile phones to act as a host, allowing other USB devices like a USB flash drive, mouse, or keyboard to be attached to them.

The USB device controller on the LPC17xx enables full-speed (12 Mb/s) data exchange with a USB host controller. A simplified block diagram of the three USB connectors of the MCB1700 board is shown in the figure below (see also the schematic diagram of the MCB1700 board; file available in archive of lab2).

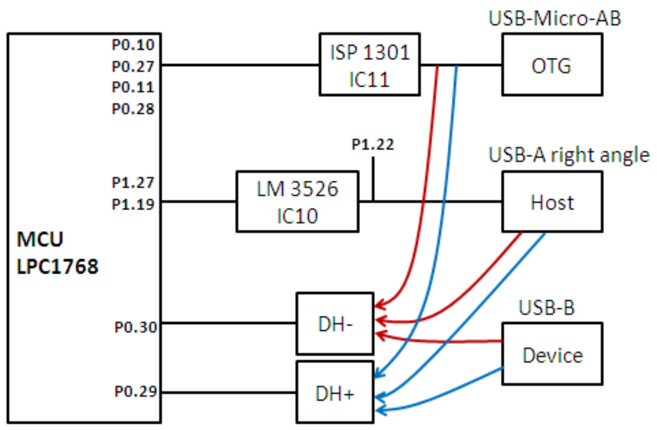


Figure 2 The three USB connectors on MCB1700 board.

Some of the most popular types of USB connectors are shown in figure below:

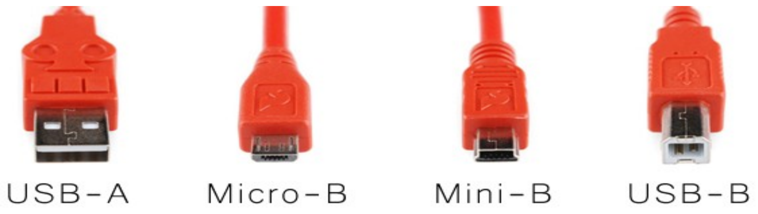


Figure 3 Common USB connectors.

There is a lot of online information describing the USB. ***As a start, please read the first pointer from the references suggested in [2].*** Also, take a look at Chapters 11,12,13 of the LPC17xx user manual.

3. Example 1: Play audio to speaker of MCB1700

The Audio project example is a demo program for the KeilMCB1700 Board using the NXP LPC17xx Microcontroller. It demonstrates an USB Audio Device – Speaker. The USB Audio Device is recognized by the host PC running Windows which will load a generic Audio driver and add a speaker which can be used for sound playback on the PC. Potentiometer on the board is used for setting the Volume.

The files of this example are in **keil_example/USBAudio/**. Launch uVision and open the project; clean and re-build. Download to the board. Now, start a web browser and play the clip from:
http://www.youtube.com/watch?v=Tj75Arhq5ho
Te audio should play on the speaker of the MCB1700 board. Tune the potentiometer, listen, and enjoy. Observe operation and comment.

This is not an easy project example. However, take some time to read the source code and try to get a birds-eye-view understanding of it. Start with **usbmain.c** and backtrack the function calls. Only with a thorough understanding of the USB theory this source code would be easier to digest.

Optional: Study the USBHID example too.

4. Stepper Motor Introduction

A stepper motor (also referred to as step or stepping motor) is an electromechanical device achieving mechanical movements through conversion of electrical pulses. Stepping motors can be viewed as electric motors without commutators. Typically, all windings in the motor are part of the stator, and the rotor is either a permanent magnet or, in the case of variable reluctance motors, a toothed block of some magnetically soft material. All of the commutation must be handled externally by the motor controller, and typically, the motors and controllers are designed so that the motor may be held in any fixed position as well as being rotated one way or the other.

Stepper motors are driven by digital pulses rather than by a continuous applied voltage. Unlike conventional electric motors which rotate continuously, stepper motors rotate or step in fixed angular increments. A stepper motor is most commonly used for position control. With a stepper motor/driver/controller system design, it is assumed the stepper motor will follow digital instructions. Most steppers can be stepped at audio frequencies, allowing them to spin quite quickly, and with an appropriate controller, they may be started and stopped at controlled orientations.

For some applications, there is a choice between using servomotors and stepping motors. Both types of motors offer similar opportunities for precise positioning, but they differ in a number of ways. Servomotors require analog feedback control systems of some type. Typically, this involves a potentiometer to provide feedback about the rotor position, and some mix of circuitry to drive a current through the motor inversely proportional to the difference between the desired position and the current position.

In making a choice between steppers and servos, a number of issues must be considered; which of these will matter depends on the application. For example, the repeatability of positioning done with a stepping motor depends on the geometry of the motor rotor, while the repeatability of positioning done with a servomotor generally depends on the stability of the potentiometer and other analog components in the feedback circuit.

Stepping motors can be used in simple open-loop control systems; these are generally adequate for systems that operate at low accelerations with static loads, but closed loop control may be essential for high accelerations, particularly if they involve variable loads. If a stepper in an open-loop control system is overtorqued, all knowledge of rotor position is lost and the system must be reinitialized; servomotors are not subject to this problem.

In this lab, we'll use a so called "five wire stepper" shown in the figure below. This 28BYJ48 stepper motor is driven via a driver board that contains 4 Darlington drivers (ULN2003) and 4 LEDs.

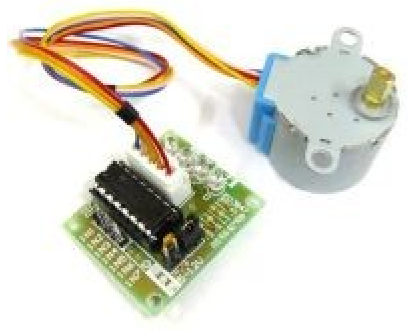


Figure 4 Stepper motor with driver board.

The diagram below shows the 5 wires connected to the motor, which must be plugged into the driver board. The connections between the MCB1700 (read the source code of the example in the next section) and the ULN2003 driver board are:

- 5V+ connect to +(5..12)V
- 5V- connect to 0V (Ground)
- IN1: to MCB1700 pin P0.0
- IN2: to MCB1700 pin P0.1
- IN3: to MCB1700 pin P0.2
- IN4: to MCB1700 pin P0.3

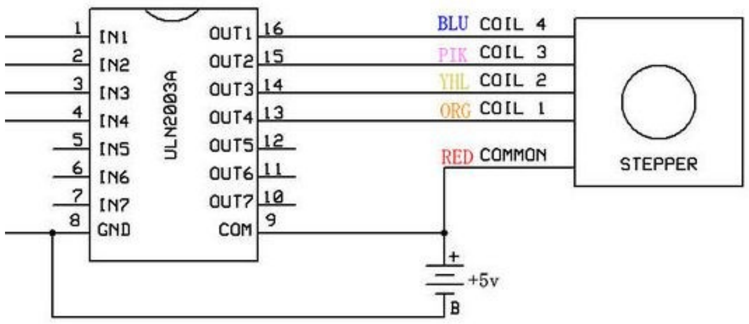


Figure 5 Connections between drive board and stepper.

Figure below shows a closer look at the connections of the stepper motor.

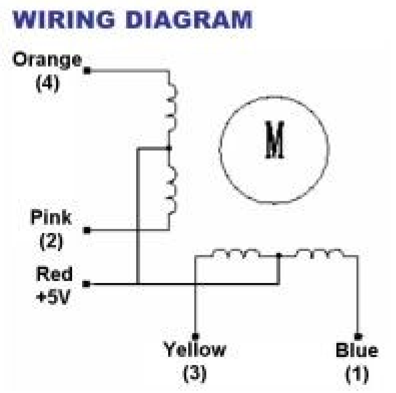
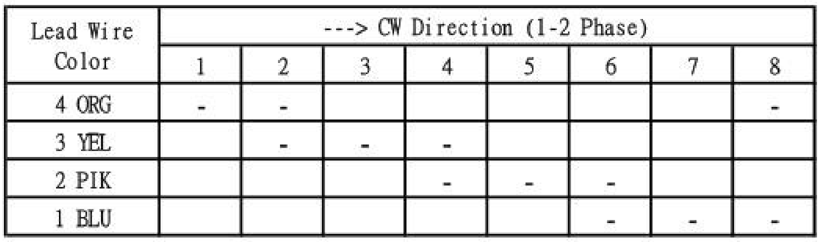


Figure 6 Wiring of the stepper motor.

To drive the motor we set to logic high/low the pins of the MCU in an 8-phase order as shown in the figure below (clockwise movement):
Drive IN4 only
Drive IN4 and IN3
Drive IN3 only
Drive IN3 and IN2
…



Lead Wire Color	---> CW Direction (1-2 Phase)							
	1	2	3	4	5	6	7	8
4 ORG	-	-						-
3 YEL		-	-	-				
2 PIK				-	-	-		
1 BLU						-	-	-

Figure 7 Order of driving the first four wires of the stepper.

For more details on stepper motors take a look at the suggested references [3] and search on the Internet.

5. Example 2: Control of a stepper motor

In this example, we control the rotation of the 28BYJ48 stepper motor via the joystick on the MCB1700 board. If the joystick is pressed to the left the rotation is clockwise and if the joystick is pressed to the right the rotation is anti-clockwise.

The files necessary for this example are located in **lab5_stepper/** folder as part of the downloadable archive for this lab. This is actually the whole uVision project directory. Just copy it to **keil_examples/** (this is the code-bundle directory of lab#2). Then clean and re-build the project. Download to the board. Connect the stepper motor and the driver board as shown in the figure below using the **power supply and the wires provided by your TA**. Observe operation and comment.

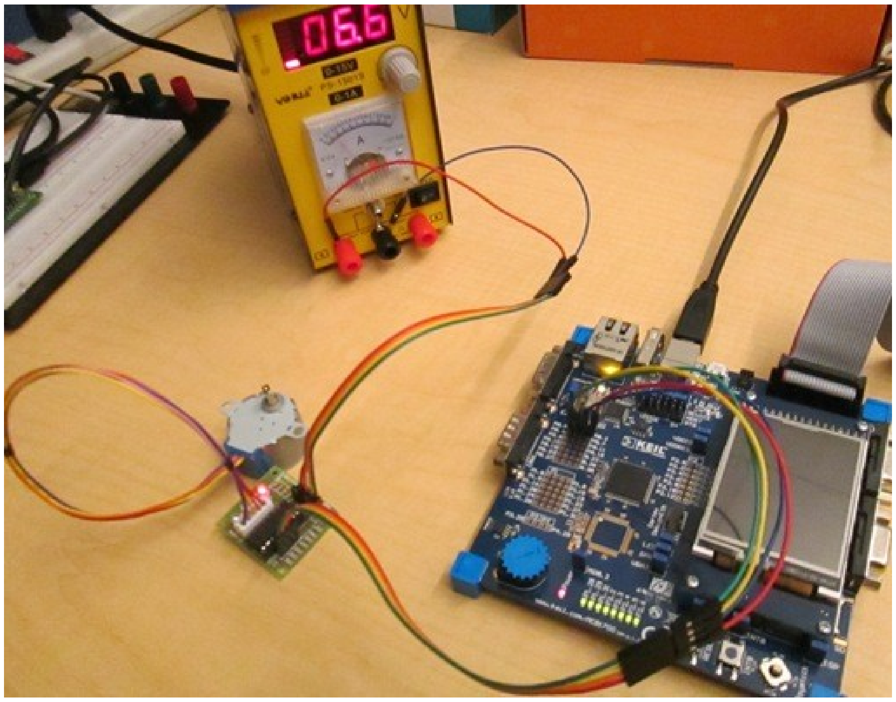


Figure 8 Stepper motor setup.

6. Lab Assignment

This lab has no lab assignment (no pre-lab report, no final lab report). Instead you should use the extra lab-time to work on your projects and on the HW assignment #4.

7. Credits and references

[1] Micro SD(HC) cards:
[2] USB:
--USB Made Simple (excellent read): http://www.usbmadesimple.co.uk/index.html
--USB Background; http://www.totalphase.com/support/kb/10047/
--USB Home: http://www.usb.org/home
-- http://www.keil.com/rl-arm/rl-usbhost.asp

--USB on-the-go (OTG) basics; http://www.maximintegrated.com/app-notes/index.mvp/id/1822
-- http://en.wikipedia.org/wiki/Universal_Serial_Bus
--LUFA; http://www.fourwalledcubicle.com/LUFA.php
[3] Stepper motors:
--Control of stepping motors, a tutorial; http://homepage.cs.uiowa.edu/~jones/step/
--Sparkfun tutorial; https://www.sparkfun.com/tutorials/400
--More tutorials; http://www.stepperworld.com/pgTutorials.htm
--Even more tutorials; http://www.epanorama.net/links/motorcontrol.html#stepper
--Stepper Motor 5V 4-Phase 5-Wire & ULN2003 Driver Board (includes detailed specs); http://www.geeetech.com/wiki/index.php/Stepper_Motor_5V_4-Phase_5-Wire_%26_ULN2003_Driver_Board_for_Arduino
Buy it for $2.02 (amazing price) on Amazon: http://www.amazon.com/28BYJ-48-28BYJ48-4-Phase-Arduino-Stepper/dp/B0089JV2OM/ref=pd_sim_sbs_vg_1

Lab 5: Supplemental Material – SPI and SD cards

1. Objective

The objective of this lecture is to learn about Serial Peripheral Interface (SPI) and micro SD memory cards.

2. SPI Introduction

Serial Peripheral Interface (SPI) communication was used to connect devices such as printers, cameras, scanners, etc. to a desktop computer; but it has largely been replaced by USB. SPI is still utilized as a communication means for some applications using displays, memory cards, sensors, etc. SPI runs using a master/slave set-up and can run in full duplex mode (i.e., signals can be transmitted between the master and the slave simultaneously). When multiple slaves are present, SPI requires no addressing to differentiate between these slaves. There is no standard communication protocol for SPI.

SPI is used to control peripheral devices and has some advantages over I2C. Because of its simplicity and generality, it is being incorporated in various peripheral ICs. The number of signals of SPI, three or four wires, is larger than I2C's two wires, but the transfer rate can rise up to 20 Mbps or higher depends on device's ability (5 - 50 times faster than I2C). Therefore, often it is used in applications (ADC, DAC or communication between ICs) that require high data transfer rates.

The SPI communication method is illustrated in Fig.1 below. The master IC and the slave IC are tied with three signal lines, **SCLK** (Serial Clock), **MISO** (Master-In Slave-Out) and **MOSI** (Master-Out Slave-In). The contents of both 8-bit shift registers are exchanged with the shift clock driven by master IC. An additional fourth signal, **SS** (Slave Select), is utilized to synchronize the start of packet or byte boundary and to facilitate working with multiple slave devices simultaneously. Most slave ICs utilize different pin names (e.g., DI, DO, SCK and CS) to the SPI interface. For one-way transfer devices, such as DAC and single channel ADC, either of data lines may be omitted. The data bits are shifted in MSB first.

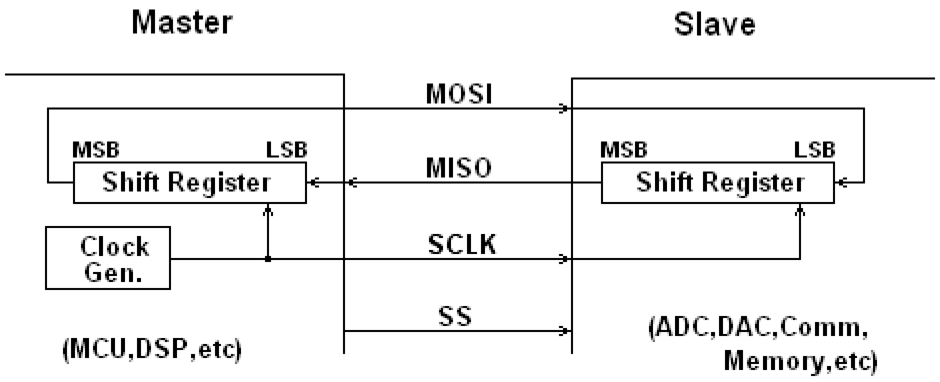


Figure 1 SPI communication method.

When additional slaves are attached to the SPI bus, they are attached in parallel and an individual SS signal must be connected from the master to each of the slaves (as shown in Fig.2). The data output of the slave IC is enabled when the corresponding SS signal is set; the data output is disconnected from the MISO line when the slave device is deselected.

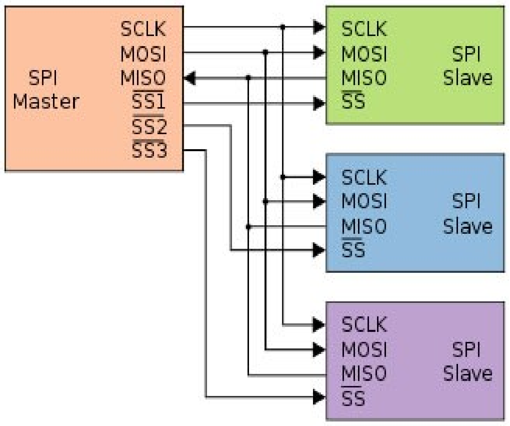


Figure 2 Single master multiple slaves configuration.

In SPI, data shift and data latch are done on opposite clock edges. Consequently, the four different operation modes (as a result of the combination of clock polarity and clock phase) that the master IC can configure its SPI interface are shown in Fig.3 below.

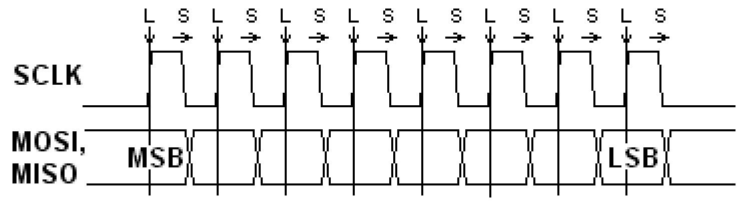
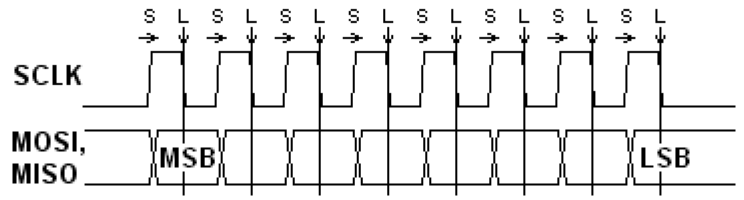
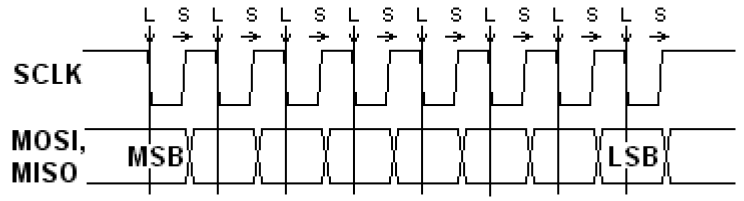
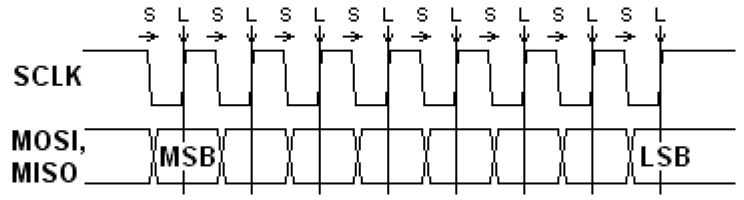
SPI Mode	Timing Diagram
Mode 0 Positive Pulse. Latch, then Shift. (CPHA=0, CPOL=0)	 L S L S L S L S L S L S L S L S SCLK MOSI, MISO MSB LSB
Mode 1 Positive Pulse. Shift, then Latch.	 S L S L S L S L S L S L S L S L SCLK MOSI, MISO MSB LSB
Mode 2 Negative Pulse. Latch, then Shift.	 L S L S L S L S L S L S L S L S SCLK MOSI, MISO MSB LSB
Mode 3 Negative Pulse. Shift, then Latch.	 S L S L S L S L S L S L S L S L SCLK MOSI, MISO MSB LSB

Figure 3 The four different operation modes of SPI.

There is a lot of online information on SPI. You should search and read some for more details. Good starting points are the references suggested in [1] from where most of the above material has been adopted. Also, read Chapter 17 of the LPC17xx User Manual for details on the SPI interface available on the LPC1768 MCU that we use in this course.

3. MMC and SDC Cards

A) Background

The Secure Digital Memory Card (SDC) is the de facto standard memory card for mobile devices. The SDC was developed as upper-compatible to Multi Media Card (MMC). SDC compliant equipment can also use MMCs in most cases. These cards have basically a flash memory array and a (micro)controller inside. The flash memory controls (erasing, reading, writing, error controls, and wearleveling) are completed inside the memory card. The data is transferred between the memory card and the host controller as data blocks in units of 512 bytes; therefore, these cards can be seen as generic hard disk drives from the view point of upper level layers. The currently defined file system for the memory card is FAT12/16 with FDISK petitioning rule. The FAT32 is defined for only high capacity (>= 4G) cards.

Please take a while and read the following very popular webpage that describes the use of MMC and SDC cards: http://elm-chan.org/docs/mmc/mmc_e.html
A lot of the concepts described in the aforementioned webpage apply also to working with micro SD cards, which we'll use in the examples studied later on in this lecture.

A block diagram of the SD card is shown in Fig.4. It consists of a 9-pin interface, a card controller, a memory interface and a memory core. The 9-pin interface allows the exchange of data between a connected system and the card controller. The controller can read/write data from/to the memory core using the memory core interface. In addition, several internal registers store the state of the card. The controller responds to two types of user requests: control and data. Control requests set up the operation of the controller and allow access to the SD card registers. Data requests are used to either read data from or write data to the memory core.

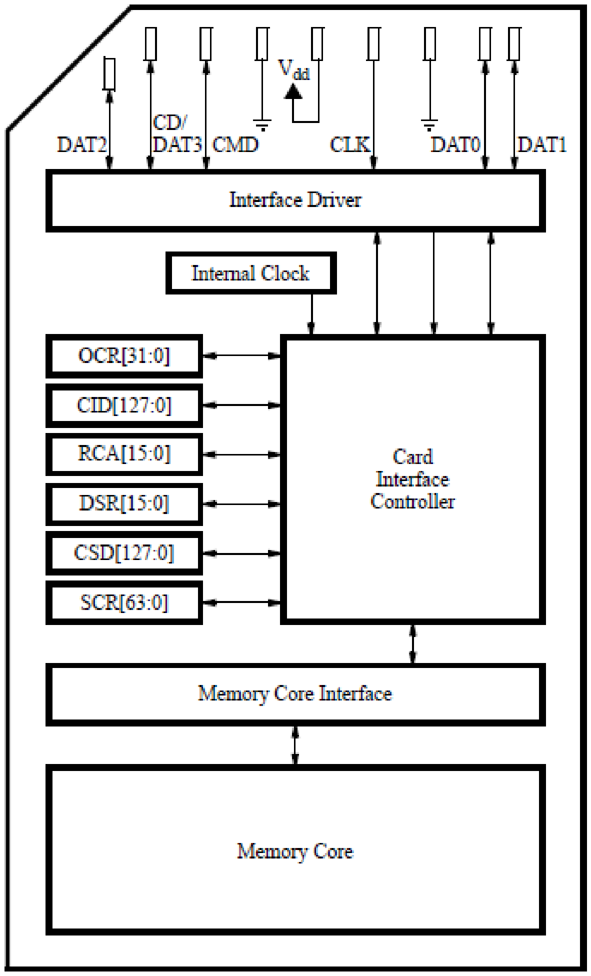


Figure 4 Block diagram of an SD card.

B) ***<u>Communication with SD cards</u>***
Communication with an SD card can be done in one of two modes: the SD mode or the SPI mode. By default, the SD card operates in the SD mode. However, we'll work with the SPI mode and communicate with it using the SPI protocol.

Communication with the SD card is performed by sending commands to it and receiving responses from it. A valid SD card command consists of 48 bits as shown in Fig.5. The leftmost two bits are the start bits which we set to (01). They are followed by a 6-bit **command number** and a 32-bit argument where additional information may be provided. Next, there are 7 bits containing a Cyclic Redundancy Check (CRC) code, followed by a single stop bit (1).

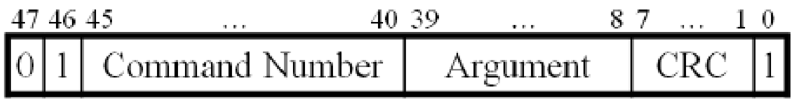


Figure 5 Format of the 48-bit command for an SD card.

The CRC code is used by the SD card to verify the integrity of a command it receives. By default, the SD card ignores the CRC bits for most commands (except CMD8) unless a user requests that CRC bits be checked upon receiving every message.

Sending a command to the SD card is performed in serial fashion. By default, the MOSI line is set to 1 to indicate that no message is being sent. The process of sending a message begins with placing its most-significant bit on the MOSI line and then toggling the SD CLK signal from 0 to 1 and then back from 1 to 0. Then, the second bit is placed on the MOSI line and again the SD CLK signal is toggled twice. Repeating this procedure for each bit allows the SD card to receive a complete command.

Once the SD card receives a command it will begin processing it. To respond to a command, the SD card requires the SD CLK signal to toggle for at least 8 cycles. Your program will have to toggle the SD CLK signal and maintain the MOSI line high while waiting for a response. The length of a response message varies depending on the command. Most of the commands get a response mostly in the form of 8-bit messages, with two exceptions where the response consists of 40 bits.

To ensure the proper operation of the SD card, the SD CLK signal should have a frequency in the range of 100 to 400 kHz.

To communicate with the SD card, your program has to place the SD card into the SPI mode. To do this, set the MOSI and CS lines to logic value 1 and toggle SD CLK for at least 74 cycles. After the 74 cycles (or more) have occurred, your program should set the CS line to 0 and send the command CMD0:

01 000000 00000000 00000000 00000000 00000000 1001010 1

This is the reset command, which puts the SD card into the SPI mode if executed when the CS line is low. The SD card will respond to the reset command by sending a basic 8-bit response on the MISO line. The structure of this response is shown in Fig.6. The first bit is always a 0, while the other bits specify any errors that may have occured when processing the last message. If the command you sent was successfully received, then you will receive the message $(00000001)_2$.

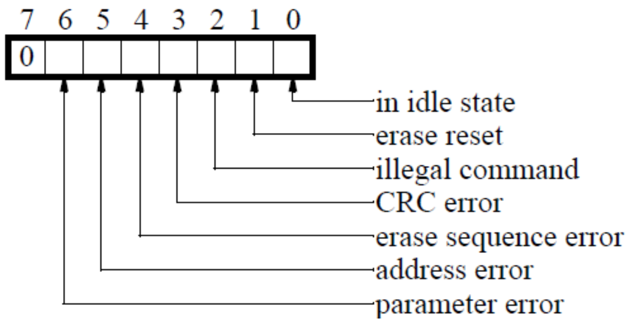


Figure 6 Format of a basic 8-bit Response to every command in SPI mode.

To receive this message, your program should continuously toggle the SD CLK signal and observe the MISO line for data, while keeping the MOSI line high and the CS line low. Your program can detect the message, because every message begins with a 0 bit, and when the SD card sends no data it keeps the MISO line high. Note that the response to each command is sent by the card a few SD CLK cycles later. If the expected response is not received within 16 clock cycles after sending the reset command, the reset command has to be sent again.

Following a successful reset, test if your system can successfully communicate with the SD card by sending a different command. For example, send one of the following commands, while keeping the CS at value 0:

(i) Command CMD8

01 001000 00000000 00000000 00000001 10101010 0000111 1

This command is only available in the latest cards, compatible with SD card Specifications version 2.0. For most older cards this command should fail and cause the SD card to respond with a message that this command is illegal.

(ii) Command CMD58

01 111010 00000000 00000000 00000000 00000000 0111010 1

This command requests the contents of the operating conditions register for the connected card.

A response to these commands consists of 40 bits (see Fig.7), where the first 8 bits are identical to the basic 8-bit response, while the remaining 32 bits contain specific information about the SD card. Although the actual contents of the remaining 32 bits are not important for this discussion, a valid response indicates that your command was transmitted and processed successfully. If successful, the first 8 bits of the response will be either 00000001or 00000101 depending on the version of your SD card.

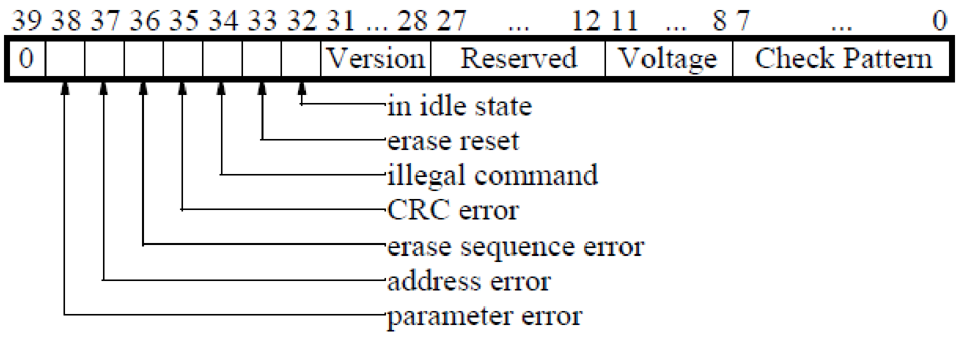


Figure 7 The format of the 40-bit Response.

The steps necessary to complete the SD card initialization are shown in the flowchart in Fig.8. The flowchart consists of boxes in which a command number is specified. Starting at the top of the flowchart, each command has to be sent to the SD card, and a response has to be received. In some cases, a response from the card needs to be processed to decide the next course of action, as indicated by the diamond-shaped decision boxes.

This is just one example of such an initialization sequence (credit: ftp://ftp.altera.com/up/pub/Altera_Material/12.0/Laboratory_Exercises/Embedded_Systems/DE2/embed_lab9.pdf, from where portions of this discussion are adopted). It's possible that it may work or not depending on the type of card you use and on its manufacturer. Other similar such flowcharts exist; for example: http://elm-chan.org/docs/mmc/sdinit.png. Most of the times, you will have to try to implement several of them until you will get it to work; unless you use a known card and an already written program for that card.

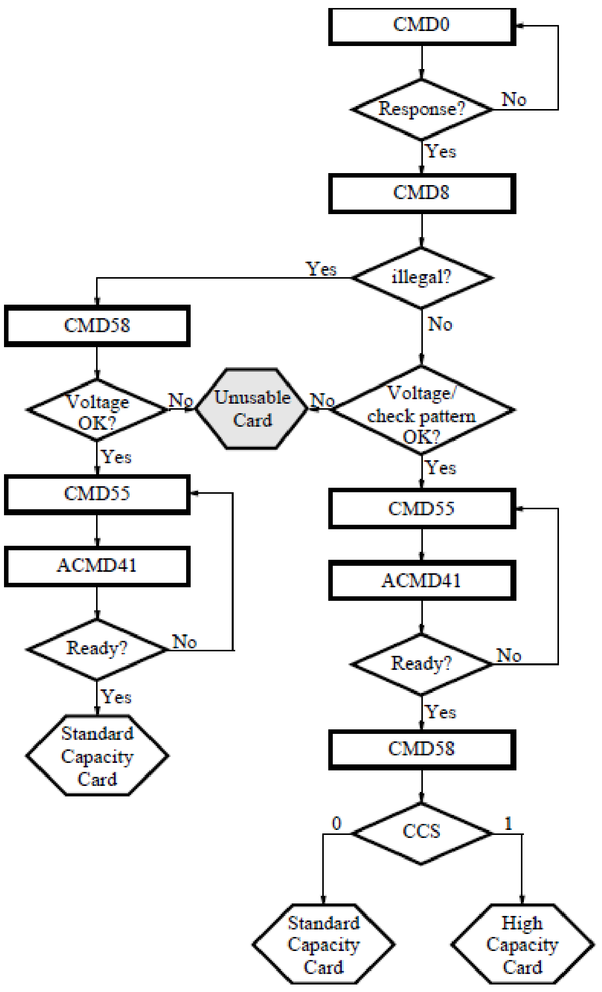


Figure 8 Flowchart of a generic SD card initialization routine in SPI mode.

C) __FAT File system basics__

Microcontrollers are relatively memory constrained, e.g., 512K bytes flash, which limits the ability to store large quantities of data either as inputs to or outputs from an embedded program. For example, in a game application it might be desirable to access sound and graphic files or in a data logging application, to store extended amounts of data. In addition, accessing the contents of the flash requires a special interface and software. In such applications it is desirable to provide external storage which the MCU can access while running and the user/programmer can easily access at other times. SD cards provide a cost effective solution which can be accessed by both the processor and user. In practice, these cards have **file systems** (typically FAT) and can be inserted in commonly available adaptors. Furthermore, the physical interface of most SD cards has a SPI mode (described in the previous section and which is demonstrated with an actual implementation in Example 1 in the next section) which is accessible.

Communicating with an SD memory card is relatively simple using some SPI driver like the one described in the previous section. However, controlling the card and interpreting the data communicated requires significant additional software. Such software practically elevates the level of access to the card to a higher level of abstraction as illustrated in Fig.9 (user or application space).

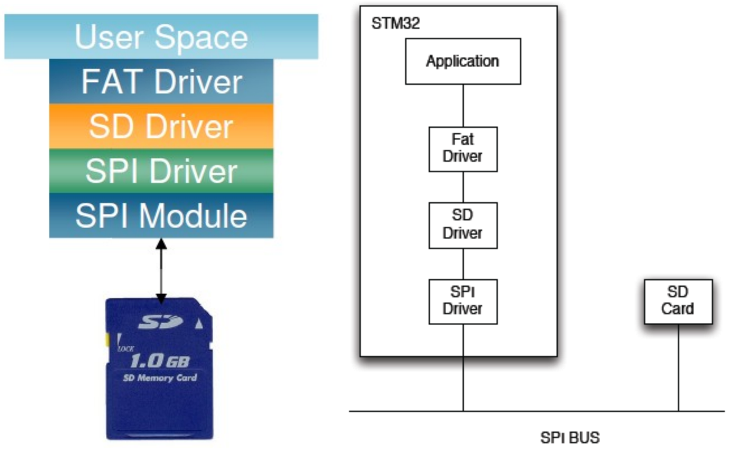
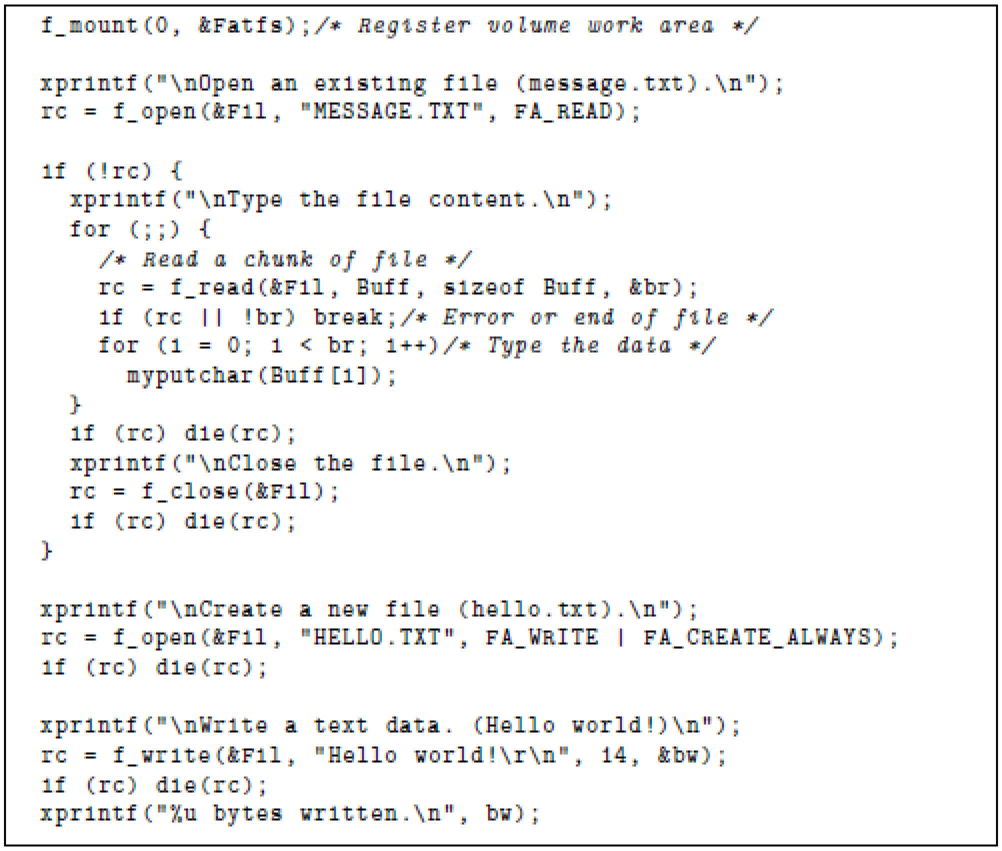


Figure 9 SD card software stack.

The aforementioned software is typically what is referred as a **FAT file system driver**. One such example is the available widely used FatFs module, which with some amount of porting could be utilized with our SPI driver. Note that Keil offers a similar module too, but it's not free; if you tried to compile for example the **SD_File/** project, you will get an error as you would need an RL license...

The data on an SD card is organized as a file system – cards below 2GB are typically formatted as FAT16 file systems. In a FAT file system, the first several storage blocks are used to maintain data about the file system – for example allocation tables – while the remaining blocks are used to store the contents of files and directories.
An application, which wishes to access data stored on an SD Card, utilizes file level commands such as open, read, and write to access specific files within the SD card file system. These commands are provided by a FAT file system driver. The FAT file system issues commands at the level of block reads and writes without any knowledge of how these commands are implemented. A separate SD driver implements these commands. Finally, the SD driver utilizes the SPI interface to communicate with the SD Card.

Fortunately, it is not necessary to write all of this software. One can use of the FatFs generic file system (or use licensed ones but for pay, like the one from Keil). This open source package provides most of the components required including a "generic" SD driver that is relatively easily modified to utilize with any typical SPI driver.
To understand how an application interacts with FatFs, consider the example derived from the FatFs sample distribution illustrated in Fig.10 (credit: http://homes.soic.indiana.edu/geobrown/c335 from where portions of this description have been adopted too). This example fragment assumes it is communicating with an SD card formatted with a fat file system which contains file in the root directory called MESSAGE.TXT. The program reads this file, and creates another called HELLO.TXT. Notice the use of relatively standard file system commands.

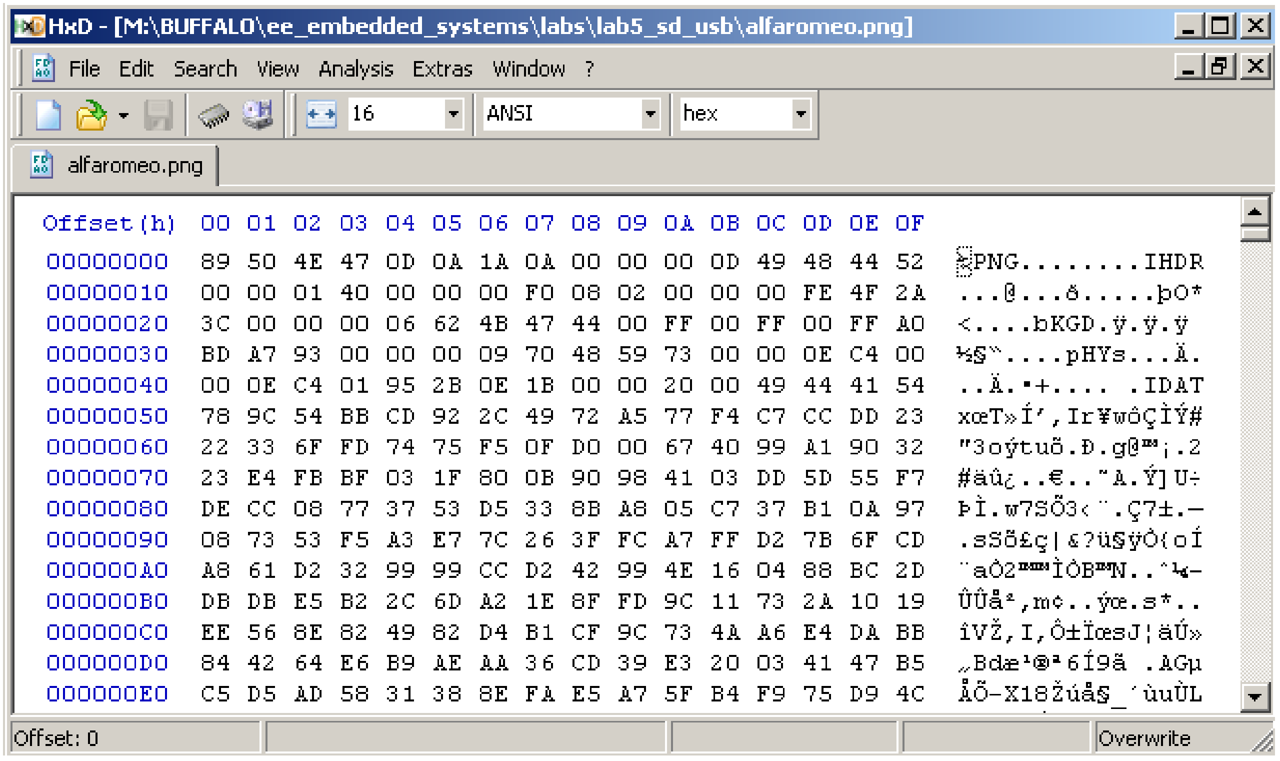


```
f_mount(0, &Fatfs);/* Register volume work area */

xprintf("\nOpen an existing file (message.txt).\n");
rc = f_open(&Fil, "MESSAGE.TXT", FA_READ);

if (!rc) {
  xprintf("\nType the file content.\n");
  for (;;) {
    /* Read a chunk of file */
    rc = f_read(&Fil, Buff, sizeof Buff, &br);
    if (rc || !br) break;/* Error or end of file */
    for (i = 0; i < br; i++)/* Type the data */
      myputchar(Buff[i]);
  }
  if (rc) die(rc);
  xprintf("\nClose the file.\n");
  rc = f_close(&Fil);
  if (rc) die(rc);
}

xprintf("\nCreate a new file (hello.txt).\n");
rc = f_open(&Fil, "HELLO.TXT", FA_WRITE | FA_CREATE_ALWAYS);
if (rc) die(rc);

xprintf("\nWrite a text data. (Hello world!)\n");
rc = f_write(&Fil, "Hello world!\r\n", 14, &bw);
if (rc) die(rc);
xprintf("%u bytes written.\n", bw);
```

Figure 10 FatFs example.

4. Example 1: Reading from a micro SD card (1GB) raw data from fixed physical addresses

In this example, I simply read raw data from a fixed physical address on the micro SD memory card. The SD card has only one file, which is a small .png image **alfaromeo.png** with size 320x240 pixels. Using the free HxD hexadecimal editor, I first found that the physical address where the file is stored inside the memory is **0x00040000**. This is a neat editor, which also shows the contents of the file as in figure below:

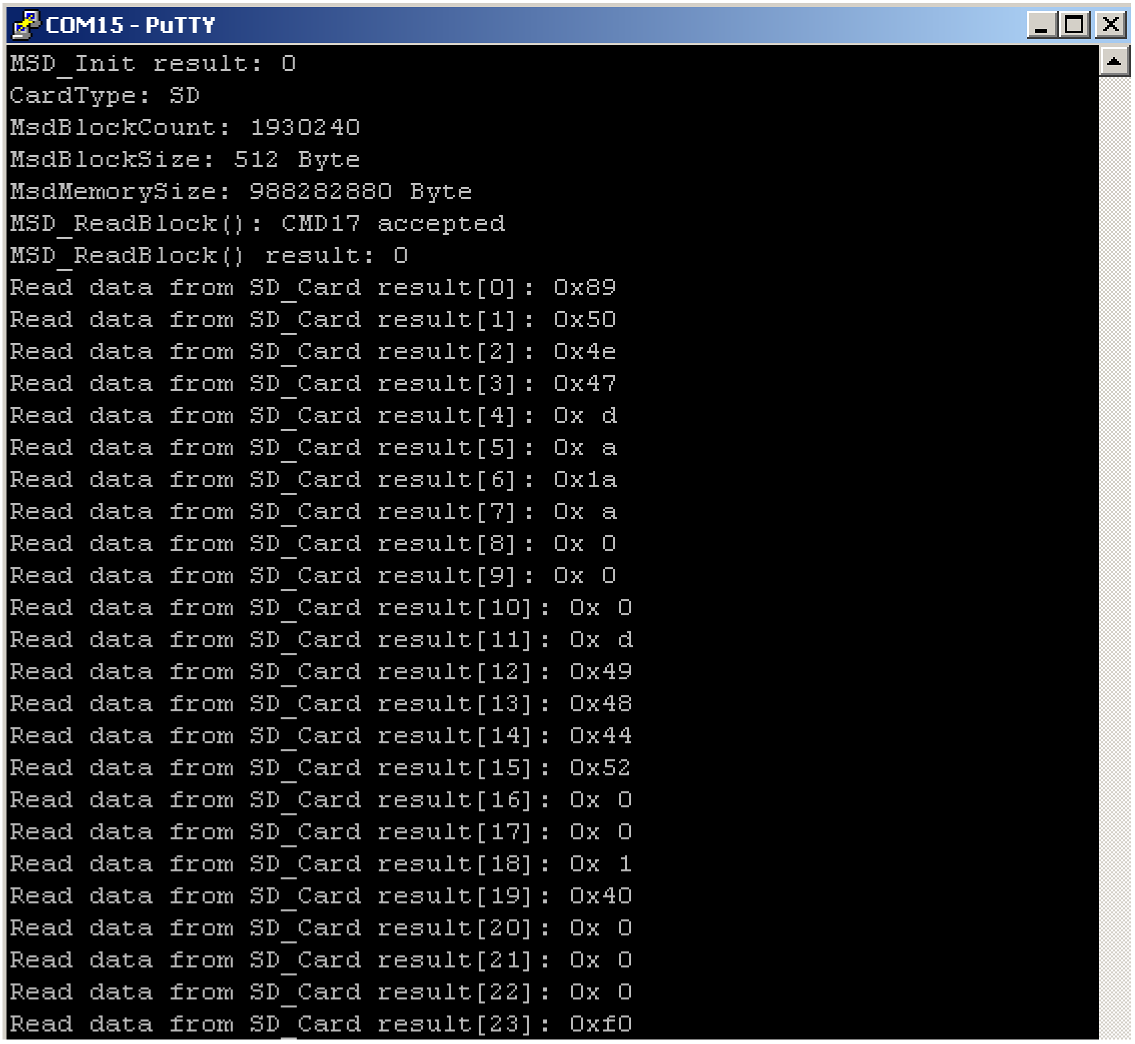

HxD - [M:\BUFFALO\ee_embedded_systems\labs\lab5_sd_usb\alfaromeo.png]
File Edit Search View Analysis Extras Window ?
16
ANSI
hex
alfaromeo.png
Offset: 0
Overwrite

```
Offset(h) 00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F

00000000  89 50 4E 47 0D 0A 1A 0A 00 00 00 0D 49 48 44 52  ‰PNG........IHDR
00000010  00 00 01 40 00 00 00 F0 08 02 00 00 00 FE 4F 2A  ...@...ð.....þO*
00000020  3C 00 00 00 06 62 4B 47 44 00 FF 00 FF 00 FF A0  <....bKGD.ÿ.ÿ.ÿ 
00000030  BD A7 93 00 00 00 09 70 48 59 73 00 00 0E C4 00  ½§"....pHYs...Ä.
00000040  00 0E C4 01 95 2B 0E 1B 00 00 20 00 49 44 41 54  ..Ä.•+.... .IDAT
00000050  78 9C 54 BB CD 92 2C 49 72 A5 77 F4 C7 CC DD 23  xœT»Í',Ir¥wôÇÌÝ#
00000060  22 33 6F FD 74 75 F5 0F D0 00 67 40 99 A1 90 32  "3oýtuõ.Ð.g@™¡.2
00000070  23 E4 FB BF 03 1F 80 0B 90 98 41 03 DD 5D 55 F7  #äû¿..€..˜A.Ý]U÷
00000080  DE CC 08 77 37 53 D5 33 8B A8 05 C7 37 B1 0A 97  ÞÌ.w7SÕ3‹¨.Ç7±.—
00000090  08 73 53 F5 A3 E7 7C 26 3F FC A7 FF D2 7B 6F CD  .sSõ£ç|&?ü§ÿÒ{oÍ
000000A0  A8 61 D2 32 99 99 CC D2 42 99 4E 16 04 88 BC 2D  ¨aÒ2™™ÌÒB™N..ˆ¼-
000000B0  DB DB E5 B2 2C 6D A2 1E 8F FD 9C 11 73 2A 10 19  ÛÛå²,m¢..ýœ.s*..
000000C0  EE 56 8E 82 49 82 D4 B1 CF 9C 73 4A A6 E4 DA BB  îVŽ‚I‚Ô±ÏœsJ¦äÚ»
000000D0  84 42 64 E6 B9 AE AA 36 CD 39 E3 20 03 41 47 B5  „Bdæ¹®ª6Í9ã .AGµ
000000E0  C5 D5 AD 58 31 38 8E FA E5 A7 5F B4 F9 75 D9 4C  ÅÕX18Žúå§_´ùuÙL
```

Figure 11 Contents of .png file displayed using HxD editor.

The program in this example (found as the entire uVision project **lab5_sd_dbg/** inside the downloadable archive of lab#5) simply: 1) initializes the SPI and the SD card and 2) reads data from the SD card starting at address **0x00040000** and then prints byte by byte to the putty terminal of the host PC. This relatively simple set-up is very useful for debugging purposes and for investigating micro SD cards (which working with is kind of painful as a lot of times SD cards do not behave as theoretically described on sdcard.org or for example in SanDisk's ambiguous documentation…).

Use the provided uVision project **lab5_sd_dbg/**. Clean and build, then download to the MCB1700 board. Observe operation and comment. Study the source code. The putty terminal should print useful information as in the figure below. Note that the data read from the SD card matches the data shown using the HxD editor.



```
MSD_Init result: 0
CardType: SD
MsdBlockCount: 1930240
MsdBlockSize: 512 Byte
MsdMemorySize: 988282880 Byte
MSD_ReadBlock(): CMD17 accepted
MSD_ReadBlock() result: 0
Read data from SD_Card result[0]: 0x89
Read data from SD_Card result[1]: 0x50
Read data from SD_Card result[2]: 0x4e
Read data from SD_Card result[3]: 0x47
Read data from SD_Card result[4]: 0x d
Read data from SD_Card result[5]: 0x a
Read data from SD_Card result[6]: 0x1a
Read data from SD_Card result[7]: 0x a
Read data from SD_Card result[8]: 0x 0
Read data from SD_Card result[9]: 0x 0
Read data from SD_Card result[10]: 0x 0
Read data from SD_Card result[11]: 0x d
Read data from SD_Card result[12]: 0x49
Read data from SD_Card result[13]: 0x48
Read data from SD_Card result[14]: 0x44
Read data from SD_Card result[15]: 0x52
Read data from SD_Card result[16]: 0x 0
Read data from SD_Card result[17]: 0x 0
Read data from SD_Card result[18]: 0x 1
Read data from SD_Card result[19]: 0x40
Read data from SD_Card result[20]: 0x 0
Read data from SD_Card result[21]: 0x 0
Read data from SD_Card result[22]: 0x 0
Read data from SD_Card result[23]: 0xf0
```

Figure 12 Output of Putty terminal connected to the MCB170 board.

5. Example 2: Read picture from micro SD card and display on the 320x240 LCD display of the MCB1700 board

This example is an improved version of the previous example. Here, I simply read the small .bmp (TODO: make it work with .png format too) image, **alfaromeo.bmp**, and display it on the 320x240 LCD screen of the MCB1700 board. The program in this example can be found inside the uVision project **lab5_sd_lcd/** inside the downloadable archive of lab#5.

Clean and build, then download to the MCB1700 board. Observe operation and comment. Study the source code. You should see the image displayed on the LCD screen as shown below (use the micro SD card from the TA).

Figure 13 Cris' Alfaromeo sports-car shown on the LCD display of the MCB1700 board. ☺

6. Example 3: Manipulate files on the SD card using the FatFs file system

The program in this example can be found inside the uVision project **lab5_sd_fat/** inside the downloadable archive of lab#5. Clean and build, then download to the MCB1700 board. Observe operation and comment. Study the source code.

7. References, credits

[1] SPI related references:
--About SPI; http://elm-chan.org/docs/spi_e.html
--SPI bus (see also the references and external links therein!);
http://en.wikipedia.org/wiki/Serial_Peripheral_Interface_Bus
[2] SD memory cards related references:
--How to use MMC/SDC cards (very popular reference!); http://elm-chan.org/docs/mmc/mmc_e.html
--Modified version of the above: http://users.ece.utexas.edu/~valvano/EE345M/view12_SPI_SDC.pdf
--Lab manual; http://homes.soic.indiana.edu/geobrown/c335
--Application note; http://alumni.cs.ucr.edu/~amitra/sdcard/Additional/sdcard_appnote_foust.pdf
--https://www.sdcard.org/home/
--SDCARD Physical Layer Simplified Specification;
https://www.sdcard.org/downloads/pls/simplified_specs/archive/part1_101.pdf
--Toshiba SD Card specification;
http://embdev.net/attachment/39390/TOSHIBA_SD_Card_Specification.pdf
--MultiMediaCard (MMC); http://en.wikipedia.org/wiki/MultiMediaCard
--Secure Digital (SD) Card; http://en.wikipedia.org/wiki/Secure_Digital_card
--FatFs - Generic FAT File System Module; http://elm-chan.org/fsw/ff/00index_e.html
[3] PNG and BMP formats:
-- http://en.wikipedia.org/wiki/Portable_Network_Graphics
-- http://en.wikipedia.org/wiki/BMP_file_format

Lab 6: Introduction to RTX Real-Time Operating System (RTOS)

1. Objective

The objective of this lab is to learn how to write simple applications using RTX (ARM Keil's real time operating system, RTOS). These simple examples involve flashing LEDs, counting, and displaying on the board's LCD display a "simulation" of how to drive a step-motor. In addition, we'll look at FreeRTOS too.

Note: A lot of the discussion in this lab is based on ARM's online information.

2. RTOS

Simple embedded systems typically use a *Super-Loop* concept where the application executes each function in a fixed order. Interrupt Service Routines (ISR) are used for time-critical program portions. This approach is well suited for small systems but has limitations for more complex applications. These limitations include the following disadvantages:

- Time-critical operations must be processed within interrupts (ISR)
  - ISR functions become complex and require long execution times
  - ISR nesting may create unpredictable execution time and stack requirements
- Data exchange between *Super-Loop* and ISR is via global shared variables
  - Application programmer must ensure data consistency
- A *Super-Loop* can be easily synchronized with the System timer, but:
  - If a system requires several different cycle times, it is hard to implement
  - Split of time-consuming functions that exceed Super-Loop cycle
  - Creates software overhead and application program is hard to understand
- *Super-Loop* applications become complex and therefore hard to extend
  - A simple change may have unpredictable side effects; such side effects are time consuming to analyze.

These disadvantages of the *Super-Loop* concept are solved by using a **Real-Time Operating System (RTOS)**.

A RTOS separates the program functions into self-contained tasks and implements an on-demand scheduling of their execution. An advanced RTOS, such as the Keil RTX, delivers many benefits including:

- **Task scheduling** - tasks are called when needed ensuring better program flow and event response
- **Multitasking** - task scheduling gives the illusion of executing a number of tasks simultaneously
- **Deterministic behavior** - events and interrupts are handled within a defined time
- **Shorter ISRs** - enables more deterministic interrupt behavior
- **Inter-task communication** - manages the sharing of data, memory, and hardware resources among multiple tasks
- **Defined stack usage** - each task is allocated a defined stack space, enabling predictable memory usage
- **System management** - allows you to focus on application development rather than resource management (housekeeping)

3. RL-RTX

The Keil RTX (Real Time eXecutive) is a royalty-free deterministic RTOS designed for ARM and Cortex-M devices. It is one of the components of RL-ARM, the RealView Real-Time Library (RL-ARM). RTX and its source code are available in all MDK-ARM Editions [1].

RTX allows one to create programs that simultaneously perform multiple functions (or tasks, statically created processes) and helps to create applications which are better structured and more easily maintained. Tasks can be assigned execution priorities. The RTX kernel uses the execution priorities to select the next task to run (preemptive scheduling). It provides additional functions for inter-task communication, memory management and peripheral management.

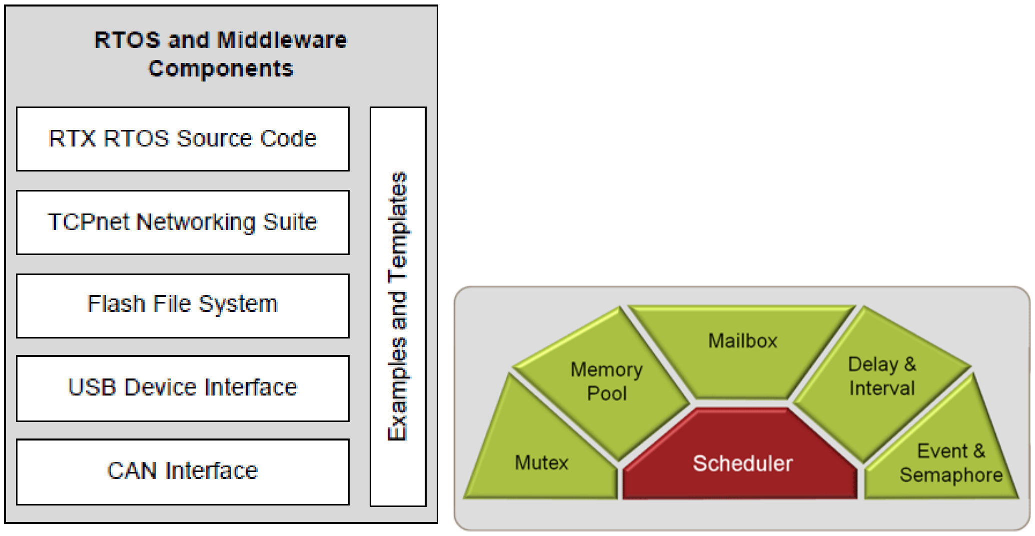


Figure 1 RL-ARM Real-Time Library and RTX Real-Time Operating System diagrams.

The main features of RTX include:

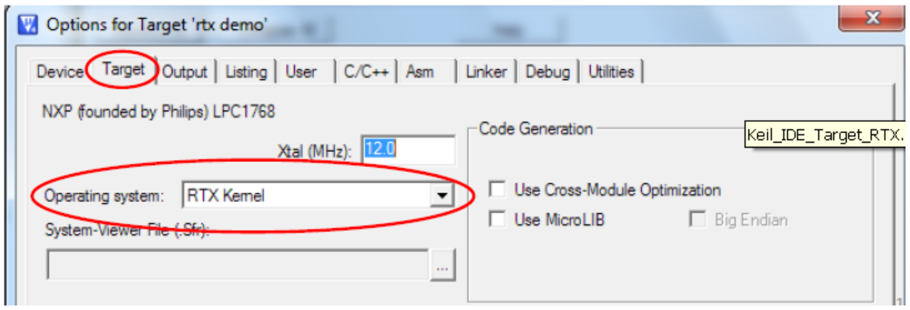
- Royalty-free, deterministic RTOS with source code
- Flexible Scheduling: round-robin, pre-emptive, and collaborative
- High-Speed real-time operation with low interrupt latency
- Small footprint for resource constrained systems
- Unlimited number of tasks each with 254 priority levels
- Unlimited number of mailboxes, semaphores, mutex, and timers
- Support for multithreading and thread-safe operation
- Kernel aware debug support in MDK-ARM
- Dialog-based setup using µVision Configuration Wizard

4. Example 1: Creating an RL-RTX Application

RTX programs are written using standard C constructs and compiled with the RealView Compiler. The header file `RTL.h` defines the RTX functions and macros that allow you to easily declare tasks and access all RTOS features.

The following are the basic steps (in the context of this course) to create an application that uses RL-RTX library:

1. Create a new project and use NXP LPC1768 as the target processor.
2. Copy the `RTX_Conf_CM.c` (C:\Keil\ARM\RL\RTX\Config) to the project folder and add it to your project.
   Note: Examples that come with the Keil's uVision installation contain in their own project folders local copies of the `RTX_Conf_CM.c`, which may be different from the one in C:\Keil\ARM\RL\RTX\Config due to their different time-stamps…
3. Open the `RTX_Conf_CM.c` under the Configuration Wizard and set the CPU to 100000000. You need to set the total number of tasks the system can manage. The default value is 6 and normally is sufficient.
4. Open up the Target Option window and activate the "Target" tab. Choose "RTX Kernel" as the operating system (default is set to None). Click Use MicroLIB in the code- generation window.



NXP (founded by Philips) LPC1768

Xtal (MHz): 12.0

Operating system: RTX Kernel

5. Now you can start to develop an RTX application. Start with the `os_tsk_*()` function reference which is within the µVision Help File.

Let's now create a simple example project called **lab6_ex1_4tasks** and place it in a new folder called **lab6_ex1_4tasks/**. The entire uVision project folder is included in the downloadable archive for this lab. The **main_4tasks.c** is also listed in Appendix A of this document. This is a simple RTX application that lights up the first LED when it starts and then displays the "Hello World!" string on the LCD screen. Then the system creates an initialization task named `init` which spawns four tasks `task1, task2, task3`, and `task4`. `task1` counts and displays digits 0-9 in a round robin fashion. `task2` makes a LED blinks every one second. `task3` keeps incrementing a global counter. `task4` keeps decrementing a global counter.

All these tasks are created with the same priority. Tasks of equal priority will be run in *Round Robin* when they enter the ready state. Higher priority tasks will preempt (or interrupt) a running task. Lower priority tasks will not run. Note that, it might have been more intuitive if Round Robin Timeout had been called Round Robin Task Switching Time. If no tasks are ready to run then RTX will execute its *idle demon*. This is located in the file **RTX_Conf_CM.c**. One can insert user code to run during this idle time.

Configure the project to use "RTX Kernel" as the operating system. Also, remember to configure the CPU speed to 100 MHz by means of the `RTX_Conf_CM.c` configuration wizard. Compile, and download to the board. Observe operation and comment.

Now, run a simulation debug session and use the following debug features of uVision:

- **RTX Tasks and System Window**
  Click Debug -> OS Support -> RTX Tasks and Systems. This window updates as the RTX runs. You can watch task switching and various system and task related information in this window.
- **RTX Event Viewer**
  Click Debug -> OS Support -> Event Viewer. Event Viewer provides a graphical representation of how long and when individual tasks run.

For more details on the above, please take some time to read entirely the “Keil RTX RTOS: The Easy Way” tutorial [2]. Please read especially section 7, which describes other ways to switch tasks aside from the aforementioned *Round Robin*.

5. Example 2: Simulating a stepper-motor driver

a) <u>Semaphores: MUTEX</u>

There are several types of semaphores (the basic idea behind each type is the same):

- Binary
- Counting
- Mutex

Semaphores are typically used in one of two ways:

1) To control access to a shared device between tasks. A printer is a good example. You don't want 2 tasks sending to the printer at once, so you create a binary semaphore to control printer access. When a device wishes to print, it attempts to "take" the semaphore. If the semaphore is available, the task gets to print. If the semaphore is not available, the task will have to wait for the printer.
2) Task synchronization. By tasks taking and giving the same semaphore, you can force them to perform operations in a desired order.

Counting semaphores are used when you might have multiple devices (like 3 printers or multiple memory buffers).
Binary semaphores are used to gain exclusive access to a single resource (like the serial port, a non-reentrant library routine, or a hard disk drive). A counting semaphore that has a maximum value of 1 is equivalent to a binary semaphore (because the semaphore's value can only be 0 or 1).
Mutex semaphores are optimized for use in controlling mutually exclusive access to a resource. There are several implementations of this type of semaphore.

Mutex stands for “**Mutual Exclusion**” and is a specialized version of a semaphore. Like a semaphore, a Mutex is a container for tokens. The difference is that a Mutex is initialized with one token. Additional Mutex tokens cannot be created by tasks. The main use of a Mutex is to control access to a chip resource such as a peripheral. For this reason, a Mutex token is binary and bounded. Apart from this, it really works in the same way as a semaphore. First, we must declare the Mutex container and initialize the Mutex:

```
os_mut_init (OS_ID mutex);
```

Then any task needing to access the peripheral must first acquire the Mutex token:

```
os_mut_wait (OS_ID mutex, U16 timeout);
```

Finally, when we are finished with the peripheral, the Mutex must be released:

```
os_mut_release (OS_ID mutex);
```

Mutex use is much more rigid than semaphore use, but is a much safer mechanism when controlling absolute access to underlying chip registers.

Take some time to read more on:

- Mutex management routines in RTX: http://www.keil.com/support/man/docs/rlarm/rlarm_ar_mut_mgmt_funcs.htm
- Building Applications with RL-ARM, Getting Started (included also in the lab files): http://www.keil.com/product/brochures/rl-arm_gs.pdf

b) RTX_Blinky Example

This is the RTX_Blinky example that comes bundled with the Keil uVision software installation. You can find it in **C:\Keil\ARM\Boards\Keil\MCB1700\RTX_Blinky** or inside the downloadable archive with the files of this lab.

In this example, four LEDs are blinking simulating the activation of the four output driver stages phase A,B,C,D. This is also displayed on the LCD display of the MCB1700 board. Compile, and download to the board. Observe operation and comment.

Take some time and read the source code from **blinky.c** in order to get a good understanding of what's happening. See how a mutex is utilized to control the access to the LCD display. If you want to see how some of the `os_*` functions are implemented, read the RTX source code from **C:\Keil\ARM\RL\RTX/**.

There is also an abundance of information on ARM's website. For example, here is the description of `os_mut_wait`:
http://infocenter.arm.com/help/index.jsp?topic=/com.arm.doc.kui0062a/rlarm_os_mut_wait.htm

6. Lab assignment

*This is optional and **available only to undergraduates** in this course. If done correctly, you may get up to 3% of the final grade.*

Create a new uVision project and write a program using the Super-Loop approach discussed in this lab to implement Example 2. You should not use RTX at all but your program should achieve the same behavior as RTX_Blinky example. Develop your program using only the programming techniques that we used earlier in this course. This exercise is to outline the differences between RTX and Super-Loop embedded programming approaches.

7. Credits and references

[0] Building Applications with RL-ARM, Getting Started (included also in the lab files): http://www.keil.com/product/brochures/rl-arm_gs.pdf
[1] RTX Real-Time Operating System;
-- http://www.keil.com/arm/selector.asp
-- http://www.keil.com/rtos/
-- http://www.keil.com/rl-arm/rtx_rtosadv.asp
-- http://www.keil.com/rl-arm/kernel.asp
-- http://infocenter.arm.com/help/index.jsp?topic=/com.arm.doc.kui0062a/rlarm_ar_your_first_app.htm
-- http://www.keil.com/support/man/docs/rlarm/rlarm_ar_svc_func.htm

[2] Robert Boys, Keil RTX RTOS: The Easy Way V0.4. 2012;
http://www.sase.com.ar/2012/files/2012/09/RLarmSteps.pdf
[3] Irene Huang, ECE-254 Labs; https://ece.uwaterloo.ca/~yqhuang/labs/ece254/document.html
[4] On mutexes;
-- RL-ARM, Getting Started (Chapter 2): http://www.keil.com/product/brochures/rl-arm_gs.pdf
-- Daniel Robbins, Common threads: POSIX threads explained - The little things called mutexes;
http://www.ibm.com/developerworks/library/l-posix2/
-- A.D. Mashall, Programming in C, UNIX System Calls and Subroutines using C, 2005 (Chapter on Mutual Exclusion Locks);
http://www.cs.cf.ac.uk/Dave/C/node31.html#SECTION003110000000000000000
-- M. Mitchell, J. Oldham, and A. Samuel. Advanced linux programming, 2001 (Chapter 4);
http://advancedlinuxprogramming.com/alp-folder/alp-ch04-threads.pdf
-- Multithreaded Programming (POSIX pthreads Tutorial); http://randu.org/tutorials/threads/
-- MSDN Introduction to Mutex Objects; http://msdn.microsoft.com/en-us/library/windows/hardware/ff548097(v=vs.85).aspx
-- Lock-free programming; http://preshing.com/20120612/an-introduction-to-lock-free-programming

APPENDIX A: Listing of main_4tasks.c of Example 1 project

```
// simple RL-RTX application to blink an LED and
// to display 0-9 in a round robin fashion on LCD
// display of MCB1700 board
// this is meant to be a "hello world" example for
// RTX application development;

#include <stdio.h>
#include <LPC17xx.h>
#include <RTL.h>
#include "GLCD.h"
#include "LED.h"

#define __FI 1 // Use font index 16x24

// global counters will count 60 seconds up and down;
int g_counter1 = 0, g_counter2 = 60;
char text_buffer[8];

// displays 0-9 in a round robin fashion
__task void task1(void)
{
    int i = 0;
    GLCD_DisplayString(3, 0, 1, "Task 1:");

    for (;;i++) {
        GLCD_DisplayChar(3, 7, 1, i+'0');
        os_dly_wait(100);
        // Note1: The Delay function pauses the calling task by the amount
        // of ticks passed as the argument. Control will switch to the
        // next task ready else passes to the idle demon. After the
        // specified number of ticks has expired, the calling task will
        // be placed in the ready state. The delay does not use up
        // processing time with a loop.
        if (i == 9) {
            i = -1;
        }
    }
}

// toggles LED #7 at P2.6 every second
__task void task2(void)
{
    GLCD_DisplayString(4, 0, 1, "Task 2:LED");
    for (;;) {
        LED_on(7);
        os_dly_wait(60);
        LED_off(7);
        os_dly_wait(40);
    }
}

// task that keeps incrementing a global counter
__task void task3(void)
{
    GLCD_DisplayString(5, 0, 1, "Task 3:");
    for (;;) {
        g_counter1++;
        if (g_counter1 == 60) g_counter1 = 0; // reset;
        os_dly_wait(100);
        sprintf(text_buffer, "%d", g_counter1);
        GLCD_DisplayString(5, 7, __FI, (uint8_t*)text_buffer);
    }
}

// task that keeps decrementing a global counter
__task void task4(void)
{
    GLCD_DisplayString(6, 0, 1, "Task 4:");
    for (;;) {
        g_counter2--;
        if (g_counter2 == 0) g_counter2 = 60; // reset;
        os_dly_wait(100);
        sprintf(text_buffer, "%d", g_counter2);
        GLCD_DisplayString(6, 7, __FI, (uint8_t*)text_buffer);
    }
}

// initialization task that spawns all other tasks
__task void init(void)
{
    os_tsk_create(task1, 1);  // task 1 at priority 1
    os_tsk_create(task2, 1);  // task 2 at priority 1
    os_tsk_create(task3, 1);  // task 3 at priority 1
    os_tsk_create(task4, 1);  // task 4 at priority 1
    os_tsk_delete_self();     // task must delete itself before exiting
}
```

```
int main(void)
{
    // (1) initialize the LPC17xx MCU;
    SystemInit();

    // (2) initialize GLCD and LED;
    LED_init();
    GLCD_Init();
    LED_on(0); // turn on LED #0 at P1.28

    GLCD_Clear(Yellow);
    GLCD_DisplayString(0, 0, 1, "RTX Hello World! :-)");

    // (3) initilize the OS and start the first task
    os_sys_init( init);
}
```

Lab 7: Introduction to Ethernet

1. Objective

The objective of this lab is to introduce you to Ethernet. We also study the EMAC EasyWEB example (from Keil) which illustrates a simple web server hosted on the MCB1700 board.

Note: This presentation has been adapted from various references listed at the end of this lab.

2. Ethernet

Ethernet is now the world's most pervasive networking technology.

History
In 1973 Xerox Corporation's Palo Alto Research Center began the development of a bus topology LAN (local area network). In 1976 Xerox built a 2.94 Mbps network to connect over 100 personal workstations on a 1 km cable. This network was called the **Ethernet**, named after the **ether**, the single coaxial cable used to connect the machines. Xerox Ethernet was so successful, that in 1980 Digital Equipment Corporation, Intel Corporation, and Xerox had released a de facto standard for a 10 Mbps Ethernet, informally called DIX Ethernet (from the initials of the 3 companies). This Ethernet Specification defined Ethernet II and was used as a basis for the IEEE 802.3 specification in 1985. Strictly, "Ethernet" refers to a product which predates the IEEE 802.3 Standard. However nowadays any 802.3 compliant network is referred to as an Ethernet. Ethernet has largely replaced competing wired LAN technologies.

Over the years Ethernet has continued to evolve, with 10Base5 using thick coaxial cable approved in 1986, 10Base2 using cheaper thin coaxial cable approved in 1986. Twisted pair wiring was used in 10BaseT, approved in 1991 and fiber optic in 10BaseF, approved in 1994-95. In 1995, 100Mbps Ethernet was released, increasing the speed of Ethernet, which has since been further increased with the release of Gigabit Ethernet in 1998-99. In 2002, 100 Gigabit was published and recently 100 Gigabit Ethernet (or 100GbE) and 40 Gigabit Ethernet (or 40GbE) emerged and were first defined by the IEEE 802.3ba-2010 standard. In the future, Ethernet will continue to increase in speed.

Broadcast Network Operation
Ethernet is a Broadcast Network: hosts are connected to a network through a single shared medium. This has the advantage that messages don't have to be routed to their destination, as all hosts are present on the shared medium, but it does incur another set of problems. The main problem which needs to be addressed is that of Media Access Control (MAC) or giving fair access to multiple nodes on a shared medium.

Collisions: When a number of nodes are connected to a single shared medium, one of the issues is the possibility of two or more nodes trying to broadcast at the same time. This is called a **collision** and prevents any information passing along the network because the multiple messages would corrupt each other, destroying both. There are two main methods for reducing the effect of collisions 1) **Collision Avoidance** and 2) **Collision Resolution**. Collision Avoidance involves systems which prevent any collisions occurring in the first place, such as polling or token passing. Collision Resolution or Contention MAC Strategies rely on the fact that collisions will occur, and try to cope with them as well as possible. Ethernet uses Collision Resolution. Below, we discuss some collision resolution techniques.

ALOHA: The most basic form of Collision Resolution is to simply allow any station to send a message (or packet) whenever it is ready to send one. This form of transmission was first used in a prototype packet radio network, ALOHANET, commissioned in Hawaii in 1970, and has been known ever since as unslotted ALOHA. In Pure ALOHA, packets contain some form of error detection which is verified by the receiver. If the packet is received correctly, the destination returns an acknowledgment. If a collision occurs and the message is destroyed or corrupted, then no acknowledgment will be sent. If the sender does not receive an acknowledgment after a certain delay, it will re-send the message.

Carrier Sense Multiple Access (CSMA): The next stage in Collision Resolution after ALOHA was to add the ability for devices to detect whether the shared medium is idle or not. This is called "Carrier Sense Multiple Access" or CSMA. This, however, does not completely eliminate collisions, since two devices could detect the medium as idle, then attempt to send at approximately the same time.
CSMA is actually a family of protocols which vary by the method which they wait for the medium to become idle, known as the persistence strategy. Here is a list of two major strategies:

- **1-Persistent CSMA** - In this strategy, when a device wants to send a message, it first listens to the medium. If it is idle the message is sent immediately, however, if it is busy the device continues to listen to the medium until it becomes idle and then sends the message immediately. The problem is that if a number of devices attempt to send during a busy period, then they shall all send as soon as the medium becomes idle, leading to a collision.
- **nonpersistent CSMA** - This strategy attempts to reduce the greediness of 1-Persistent CSMA. It again first listens to the medium to see if it is idle, if so it sends immediately. If the medium is busy, instead of continuing to listen for the medium to become idle and transmitting immediately, it waits a random period, then, it tries again. This means that in high load situations, there is less chance of collisions occurring.

Collision Window: A collision occurs when two devices send at approximately the same time. But how long does a device have to wait until it knows that its message has not been corrupted by a collision? Messages take a certain amount of time to travel from the device to the end of the signaling medium, which is known as the **propagation delay**. It would seem that a device only needs to wait for one propagation delay, until the message reaches the last receiver, to know if a collision has occurred. This, however, is not the case. Take for example the following situation. A device sends a message, which takes 1 propagation delay to reach the last device on the medium. This last device on the medium could then send a message just before the original message reaches it (i.e., just before 1 propagation delay). This new message would take an additional propagation delay to reach the original device, which means that this device would not know that a collision had occurred until after 2 propagation delays.

Collision Detection: Knowing how long is needed to wait to discover if a collision has occurred, we can use this to increase the effectiveness of CSMA. CSMA behaves inefficiently when a collision occurs, since both stations continue to send their full packet, even though it will be corrupted. A simple enhancement to CSMA is the addition of Collision Detection (**CSMA/CD**). A simple check is made to make sure that the signal present on the medium is the same as the outgoing message. If it isn't, then, a collision is occurring, and the message can be aborted. This means that the time spent sending the doomed messages can utilized for something else.

Ethernet Protocol

The Ethernet protocol is made up of a number of components:

a) Ethernet frames
b) Physical Layer
c) MAC operation.

a) Frame Structure:

Information is sent around an Ethernet network in discreet messages known as frames. The frame structure consists of the following fields:

- **Preamble** - This consists of seven bytes, all of the form "10101010". This allows the receiver's clock to be synchronized with the sender's.
- **Start Frame Delimiter** - This is a single byte ("10101011") which is used to indicate the start of a frame.
- **Destination Address** - This is the address of the intended recipient of the frame. The addresses in 802.3 use globally unique hardwired 48 bit addresses.
- **Source Address** - This is the address of the source, in the same form as above.
- **Length** - This is the length of the data in the Ethernet frame, which can be anything from 0 to 1500 bytes.
- Data - This is the information being sent by the frame.
- **Pad** - 802.3 frame must be at least 64 bytes long, so if the data is shorter than 46 bytes, the pad field must compensate. The reason for the minimum length lies with the collision detection mechanism. In CSMA/CD the sender must wait at least two times the maximum propagation delay before it knows that no collision has occurred. If a station sends a very short message, then it might release the ether without knowing that the frame has been corrupted. 802.3 sets an upper limit on the propagation delay, and the minimum frame size is set at the amount of data which can be sent in twice this figure.
- **CRC**: Cyclic Redundancy Check to detect errors that occur during transmission (DIX version of FCS). **or FCS**: Frame Check Sequence to detect errors that occur during transmission (802.3 version of CRC). This 32 bit code has an algorithm applied to it which will give the same result as the other end of the link, provided that the frame was transmitted successfully.

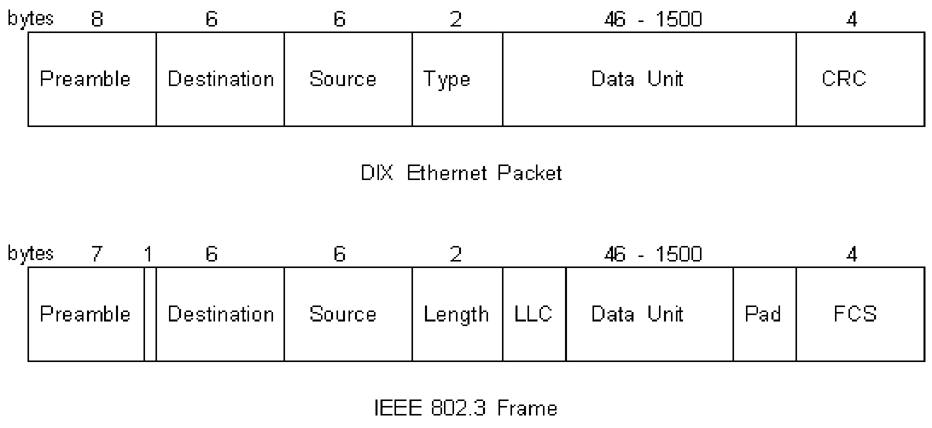


Figure 1 Structure of an Ethernet frame.

Ethernet vs. 802.3: Although the Ethernet and 802.3 standards are effectively the same thing, there are some subtle differences between Ethernet II and 802.3. The IEEE 802.3 standard was part of a bigger standard, 802. This contains a number of different network technologies, such as token ring, and token bus, as well as Ethernet. These technologies are brought together by a layer on top of these MAC Layers called Logical Link Control (LLC) as shown in the figure below. Ethernet II, however, does not use this LLC layer.

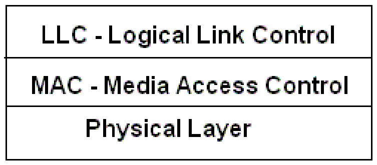


Figure 2 Illustration of LLC layer.

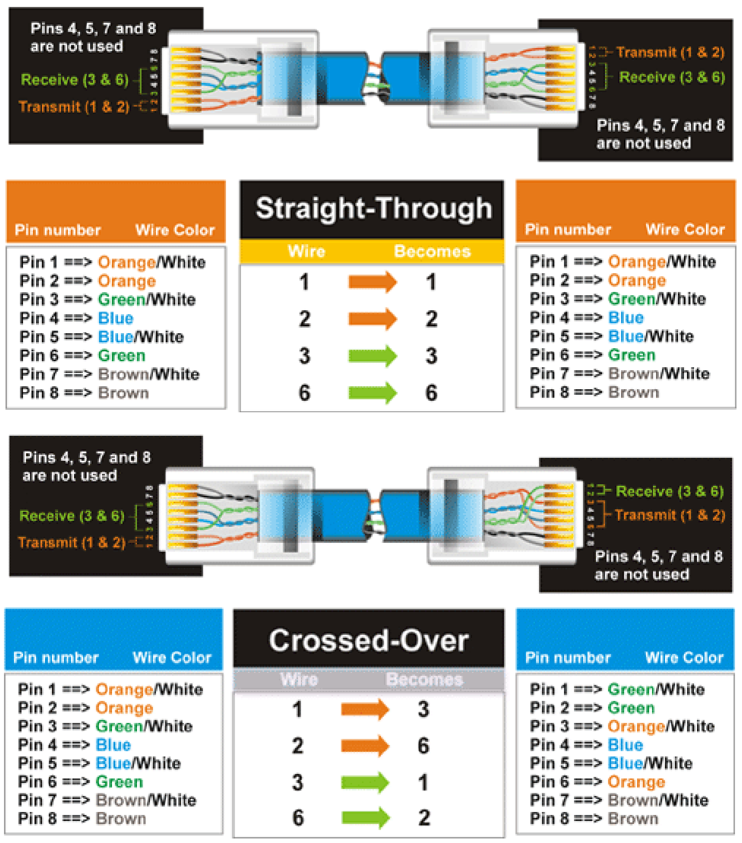
b) Physical Layer:

The Physical Layer is concerned with the low level electronic way in which the signals are transmitted. In Ethernet, signals are transmitted using Manchester Phase Encoding (MPE) – **see Appendix A**. This encoding is used to ensure that clocking data is sent along with the data, so that the sending and receiving device clocks are in sync. The logic levels are transmitted along the medium using voltage levels of ±0.85V.

The table below lists some of the cable types utilized by Ethernet networks.

Cable type	**Max speed**	**Max Length**	**Operating Frequency**
CAT5	100 Mbps	100 m	100 MHz
CAT5e	1 Gbps	100 m	100 MHz
CAT6	10 Gbps	50 m	250 MHz
CAT6a	10 Gbps	100 m	500 MHz

The structure of a typical Ethernet cable is shown in the figure below.



Pins 4, 5, 7 and 8 are not used
Receive (3 & 6)
Transmit (1 & 2)
Transmit (1 & 2)
Receive (3 & 6)
Pins 4, 5, 7 and 8 are not used

Straight-Through

Pin number	Wire Color
Pin 1 ==>	Orange/White
Pin 2 ==>	Orange
Pin 3 ==>	Green/White
Pin 4 ==>	Blue
Pin 5 ==>	Blue/White
Pin 6 ==>	Green
Pin 7 ==>	Brown/White
Pin 8 ==>	Brown

Wire	Becomes
1	1
2	2
3	3
6	6

Pin number	Wire Color
Pin 1 ==>	Orange/White
Pin 2 ==>	Orange
Pin 3 ==>	Green/White
Pin 4 ==>	Blue
Pin 5 ==>	Blue/White
Pin 6 ==>	Green
Pin 7 ==>	Brown/White
Pin 8 ==>	Brown

Pins 4, 5, 7 and 8 are not used
Receive (3 & 6)
Transmit (1 & 2)
Receive (3 & 6)
Transmit (1 & 2)
Pins 4, 5, 7 and 8 are not used

Crossed-Over

Pin number	Wire Color
Pin 1 ==>	Orange/White
Pin 2 ==>	Orange
Pin 3 ==>	Green/White
Pin 4 ==>	Blue
Pin 5 ==>	Blue/White
Pin 6 ==>	Green
Pin 7 ==>	Brown/White
Pin 8 ==>	Brown

Wire	Becomes
1	3
2	6
3	1
6	2

Pin number	Wire Color
Pin 1 ==>	Green/White
Pin 2 ==>	Green
Pin 3 ==>	Orange/White
Pin 4 ==>	Blue
Pin 5 ==>	Blue/White
Pin 6 ==>	Orange
Pin 7 ==>	Brown/White
Pin 8 ==>	Brown

Figure 3 Ethernet cable structure.

c) Media Access Control (MAC) Operation:
Ethernet is a CSMA/CD (Carrier Sense Multiple Access/Collision Detection) network. To send a frame, a station on an 802.3 network first listens to check if the medium is busy. If it is, then, the station uses the 1-persistent strategy, and transmits after only a short fixed delay (the inter-frame gap) after the medium becomes idle. If there is no collision, then this message will be sent normally. If the device detects a collision however, the frame transmission stops and the station sends a jamming signal to alert other stations of the situation. The station then decides how long to wait before re-sending using a truncated binary exponential backoff algorithm. The station waits for some multiple of 51.2us slots. The station first waits for either 0 or 1 slots, then transmits. If there is another collision, then the station waits for 0,1,2 or 3 slots before transmitting. This continues with the station choosing to wait a random number of slots from 0 to 2^k - 1 if there have been k collisions in the current transmission, until k=10 where the number of slots chosen from stops growing. After 16 continuous collisions, the MAC layer gives up and reports a failure to the layer above.

Many companies offer Ethernet MAC (EMAC) Controllers as SW or HW cores.

3. Open Systems Interconnection (OSI) Model

The Open Systems Interconnection (OSI) model is a prescription of characterizing and standardizing the functions of a communications system in terms of abstraction layers. Similar communication functions are grouped into logical layers. A layer serves the layer above it and is served by the layer below it.

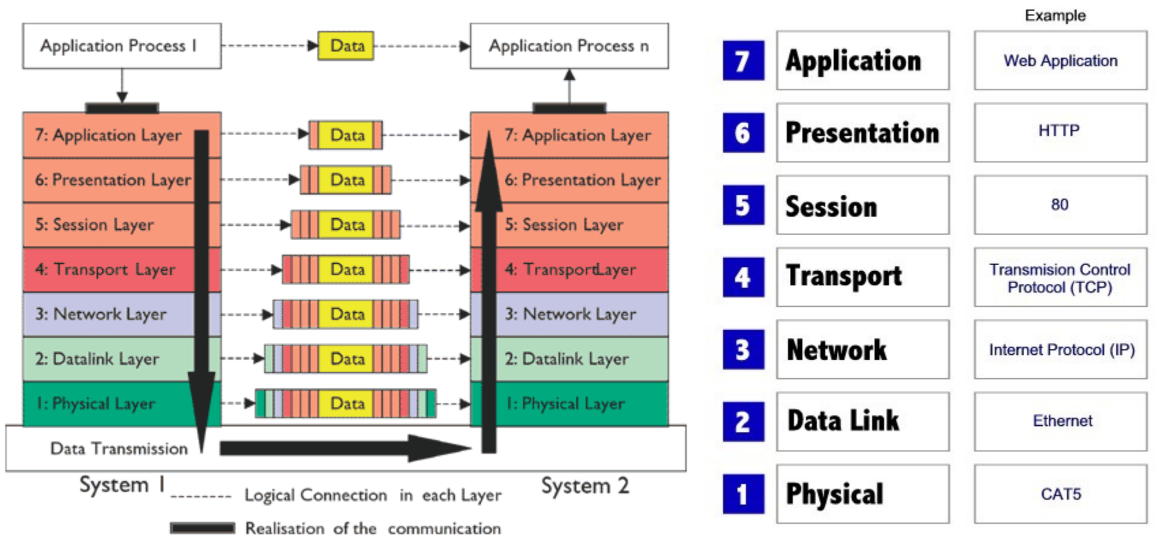


Figure 4 Illustration of the 7 layers of the OSI model. An example.

A brief explanation of each of these seven layers follows:

7. Application layer: The top-most layer of the OSI model. The primary role of the application layer is that it checks resource usability and synchronization with the remote partner. The application layer is the closest to the end user, which means that both the OSI application layer and the user interact directly with the software application.

6. Presentation layer: The function of this layer is very critical as it provides encryption services. Other services apart from encryption include decryption, data compression, and decompression.

5. Session layer: The session layer controls the dialogues (connections) between computers. It establishes, manages and terminates the connections between the local and remote application. It provides for full-duplex, half-duplex, or simplex operation, and establishes checkpointing, adjournment, termination, and restart procedures. This layer also separates the data of different applications from each other.

4. Transport layer: The transport layer provides transparent transfer of data between end users, providing reliable data transfer services to the upper layers. The transport layer controls the reliability of a given link through flow control, segmentation/desegmentation, and error control. The transport layer is responsible basically for **segmentation and reassembly** (S&R).The data from upper layer is combined together and sent as a single data stream. The Transmission Control Protocol (**TCP**) and the User Datagram Protocol (**UDP**) of the Internet Protocol Suite are commonly categorized as layer-4 protocols within OSI.

3. Network layer: The network layer provides the functional and procedural means of transferring variable length data sequences from a source host on one network to a destination host on a different network (in contrast to the data link layer which connects hosts within the same network), while maintaining the quality of service requested by the transport layer. This layer basically is used for routing. It tracks location of devices. Data travels organized as **packets** - data packets and route-update packets.

2. Data Link Layer (DLL): The data link layer provides the functional and procedural means to transfer data between network entities and to detect and possibly correct errors that may occur in the physical layer. This layer is usually divided into 2 sublayers – 1) the upper one is LLC (Logical Link Control) and the lower one is **MAC (Medium Access Control)**. The DLL deals with the movement of data on Local Area Networks (LANs). The data movement is in the form of **frames** and forwarded on the basis of hardware address called the MAC address.

1. **Physical layer**: The physical layer defines electrical and physical specifications for devices. It defines the relationship between a device and a transmission medium, such as a copper or fiber optical cable. This includes the layout of pins, voltages, line impedance, cable specifications, signal timing, hubs, repeaters, network adapters, etc. Data travels in form of digital signals, e.g., 01110001000. The real transmission takes place here, i.e., traveling through a medium like cable, fiber optic, or air.

4. The Internet Protocol (a.k.a. TCP/IP Protocol)

The Internet Protocol suite is the set of communications protocols used for the Internet and similar networks. It is generally the most popular protocol stack for wide area networks. It is **commonly known as TCP/IP**, because of its most important protocols: Transmission Control Protocol (TCP) and Internet Protocol (IP), which were the first networking protocols defined in this standard. It is also referred to as the DoD model - due to the foundational influence of the ARPANET in the 1970s (operated by DARPA, an agency of the United States Department of Defense).

TCP/IP provides end-to-end connectivity specifying how data should be formatted, addressed, transmitted, routed and received at the destination. It has **four abstraction layers** (see figure below) which are used to sort all Internet protocols according to the scope of networking involved. From lowest to highest, the layers are:

1. **Link layer**: contains communication technologies for a local network.
2. **Internet layer (IP)**: connects local networks, thus establishing internetworking.
3. **Transport layer**: handles host-to-host communication.
4. **Application layer**: contains all protocols for specific data communications services on a process-to-process level. It focuses more on network services, APIs, utilities, and operating system environments. For example, HTTP specifies the web browser communication with a web server. See **Appendix B** for more info.

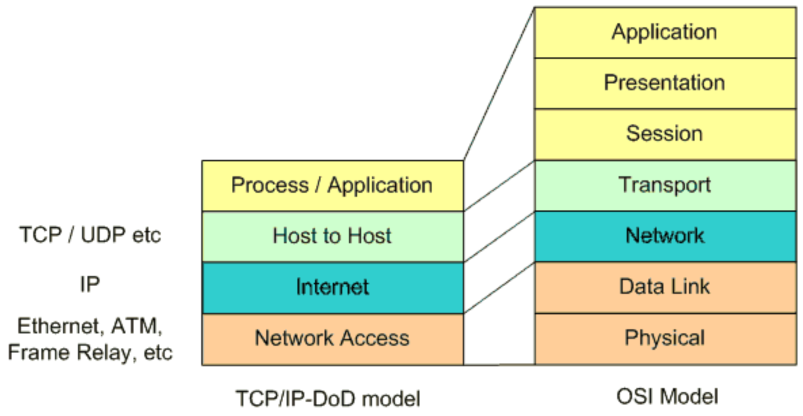


Figure 5 Comparison of TCP/IP and OSI layer stacks.

***<u>Note 1</u>:** Sometimes, people mix or are not aware of the meaning and differences between Ethernet and TCP/IP. Generally speaking, they are different levels or layers of a network. Ethernet covers the physical medium plus some low level things like message collision detection. TCP/IP worries about getting a message to where it is going.*
TCP/IP is usually found on Ethernet based networks, but it can be used on other networks as well. Also, you can have Ethernet without TCP/IP, and in fact a lot of proprietary industrial networks do exactly that. In addition, you can also run TCP/IP in parallel with other things like UDP on the same Ethernet connection.

Note 2: *In the seven-layer OSI model of computer networking, "****packet****" strictly refers to a data unit at layer 3, the Network Layer. At this layer, a packet is also commonly called a "****datagram****". The correct term for a data unit at the Data Link Layer - Layer 2 of the seven-layer OSI model - is a "****frame****", and at Layer 4, the Transport Layer, the correct term is a "****segment****". Hence, e.g., a* ***TCP segment*** *is carried in one or more* ***IP Layer datagrams (or packets)****, which are each carried in one or more* ***Ethernet frames*** *- though the mapping of TCP, IP, and Ethernet, to the layers of the OSI model is not exact (as we'll discuss in the next section).*

Some prefer to refer to all these simply as (network) packets. ***Network packets*** *are described like Russian dolls (a.k.a. Matroishka). An IP-packet resides within an Ethernet-packet. A TCP-packet resides within an IP-packet. A HTTP-packet resides within a TCP-packet. See figure below for an illustration of this point.*

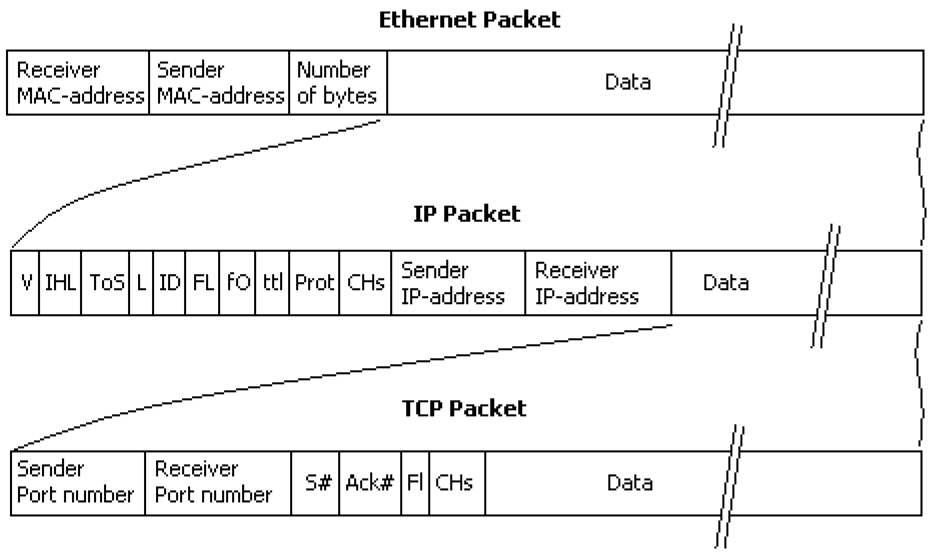


Figure 6 TCP packet (or segment) vs. IP datagram (or packet) vs. Ethernet packet (or frame).

A network packet is nothing more than a chunk of data that an application wants to deliver to another system on the network. This chunk of data has information added to the front and back that contains instructions for where the data needs to go and what the destination system should do with it once it arrives. The addition of this routing and usage information is called **encapsulation**.

The figure below illustrates the process. We start with a chunk of **application data**, to which we add a header. We take that data (application data plus application header) and package it up as a series of **TCP segments** by adding TCP headers. We then add an IP header to each TCP segment, making **IP datagram**. Finally, we add Ethernet headers and trailers to the IP datagrams, making an **Ethernet frame** that we can send over the wire. Each layer has its own function: TCP (the transport layer) makes sure data gets from point A to point B reliably and in order; IP (the network layer) handles routing, based on IP addresses and should be familiar to you; and Ethernet (the link layer) adds low-level MAC (media access control) addresses that specify actual physical devices. It's also important to note that there are several choices at each layer of the model: at the transport layer, you can see either TCP, UDP, or ICMP. Each layer of the network stack is unaware of the layers above and below. The information coming from the layers above are simply treated as data to be encapsulated. Many application protocols can be packed into TCP. When the packet is received at its final destination, the same process is repeated in reverse. The packet is de-encapsulated and the headers stripped off when it is received by the intended target.

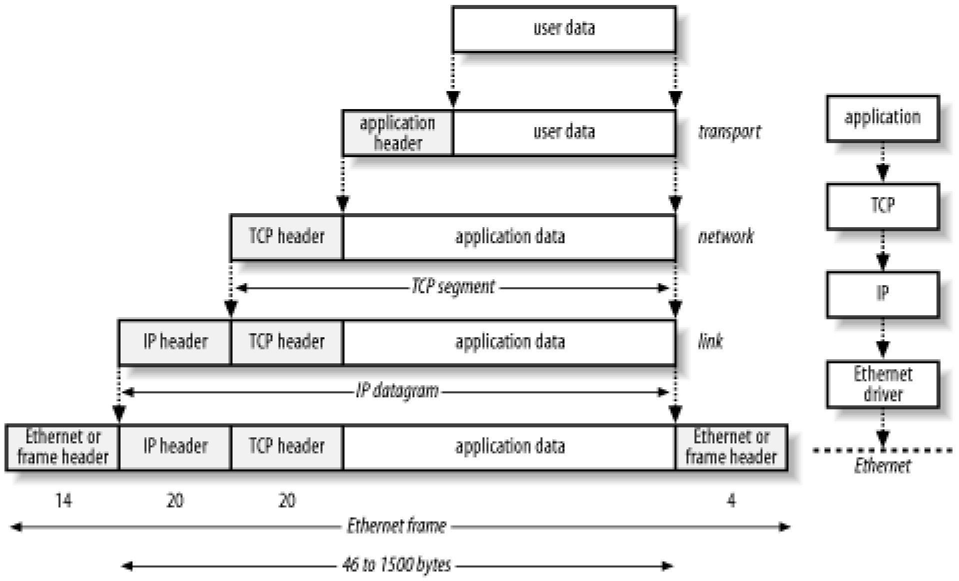


Figure 7 Illustration of encapsulation.

5. The Internet

The Internet is a global system of interconnected computer networks that use the standard Internet Protocol suite (**TCP/IP**) to serve billions of users worldwide. It is a **network of networks** that consists of millions of private, public, academic, business, and government networks, of local to global scope, that are linked by a broad array of electronic, wireless and optical networking technologies. The Internet carries an extensive range of information resources and services, such as the inter-linked hypertext documents of the World Wide Web (WWW) and the infrastructure to support email.
A simplified architecture of the Internet network is shown in the figure below.

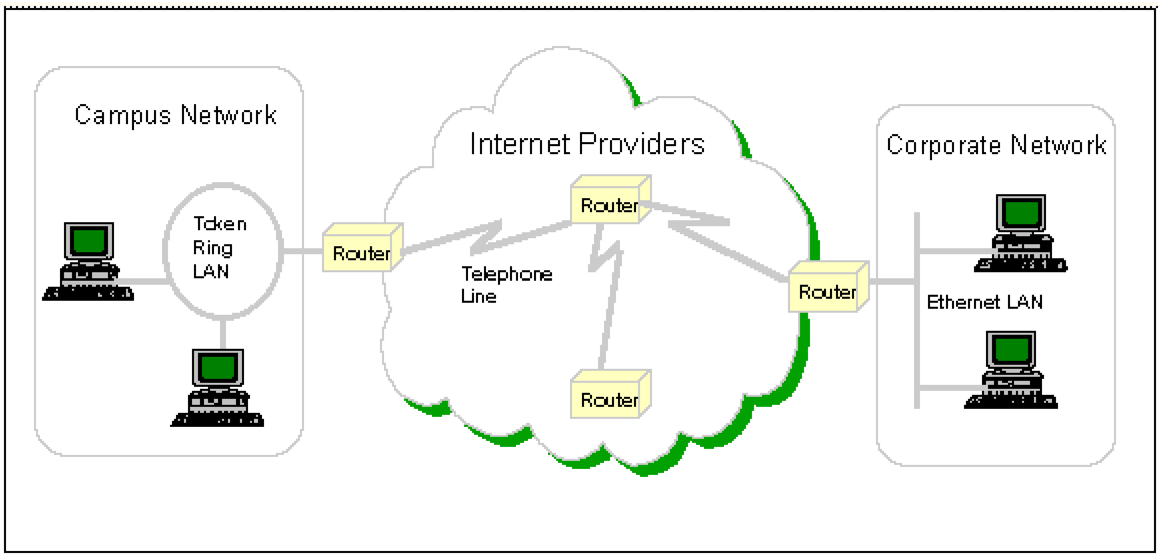


Figure 8 Simplified Internet architecture.

Another view of the Internet, that illustrates various components at different hierarchy levels, is shown in figure below.

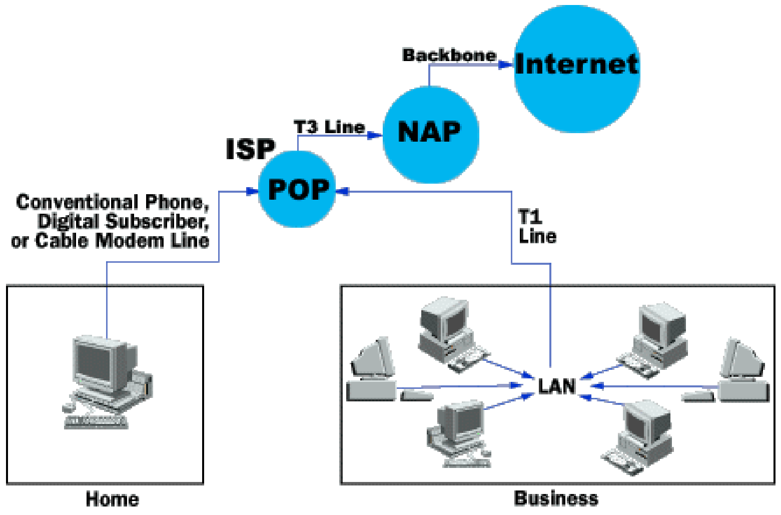


Figure 9 Illustration of the hierarchy of the Internet.

6. Ethernet Block of LPC1768

The Ethernet block contains a full featured 10 Mbps or 100 Mbps Ethernet MAC (**Media Access Controller**) designed to provide optimized performance through the use of DMA hardware acceleration. Features include a generous suite of control registers, half or full duplex operation, flow control, control frames, hardware acceleration for transmit retry, receive packet filtering and wake-up on LAN activity. Automatic frame transmission and reception with Scatter-Gather DMA off-loads many operations from the CPU.

The Ethernet block is an AHB master that drives the AHB bus matrix. Through the matrix, it has access to all on-chip RAM memories. A recommended use of RAM by the Ethernet is to use one of the RAM blocks exclusively for Ethernet traffic. That RAM would then be accessed only by the Ethernet and the CPU, and possibly the GPDMA, giving maximum bandwidth to the Ethernet function.

The Ethernet block interfaces between an off-chip Ethernet PHY using the RMII (Reduced Media Independent Interface) protocol and the on-chip MIIM (Media Independent Interface Management) serial bus, also referred to as MDIO (Management Data Input/Output).

The block diagram of the Ethernet block - shown in the figure below - consists of:

- The host registers module containing the registers in the software view and handling AHB accesses to the Ethernet block. The host registers connect to the transmit and receive data path as well as the MAC.
- The DMA to AHB interface. This provides an AHB master connection that allows the Ethernet block to access on-chip SRAM for reading of descriptors, writing of status, and reading and writing data buffers.
- The Ethernet MAC, which interfaces to the off-chip PHY via an RMII interface.
- The transmit data path, including:
  – The transmit DMA manager which reads descriptors and data from memory and writes status to memory.
  – The transmit retry module handling Ethernet retry and abort situations.

– The transmit flow control module which can insert Ethernet pause frames.

- The receive data path, including:
  – The receive DMA manager which reads descriptors from memory and writes data and status to memory.
  – The Ethernet MAC which detects frame types by parsing part of the frame header.
  – The receive filter which can filter out certain Ethernet frames by applying different filtering schemes.
  – The receive buffer implementing a delay for receive frames to allow the filter to filter out certain frames before storing them to memory.

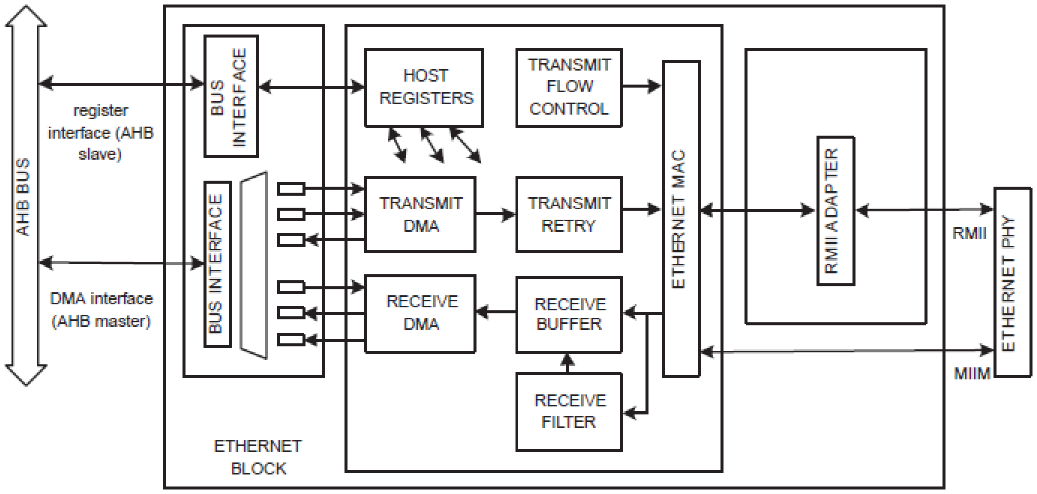


Figure 10 Block diagram of the Ethernet block of LPC17xx microcontrollers.

The fields of the Ethernet packet are as shown in the figure below.

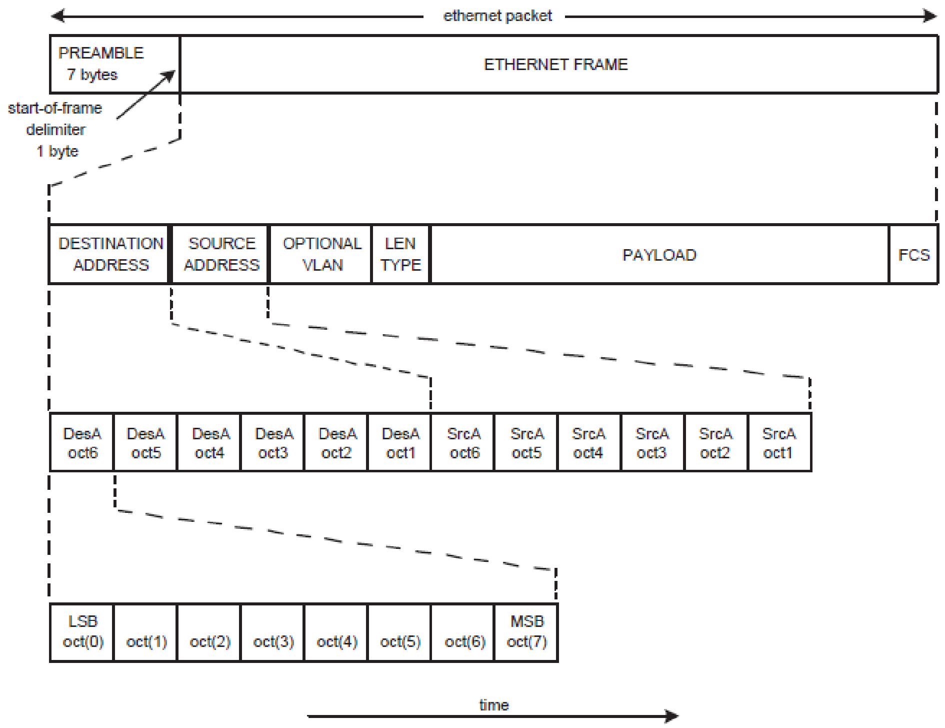


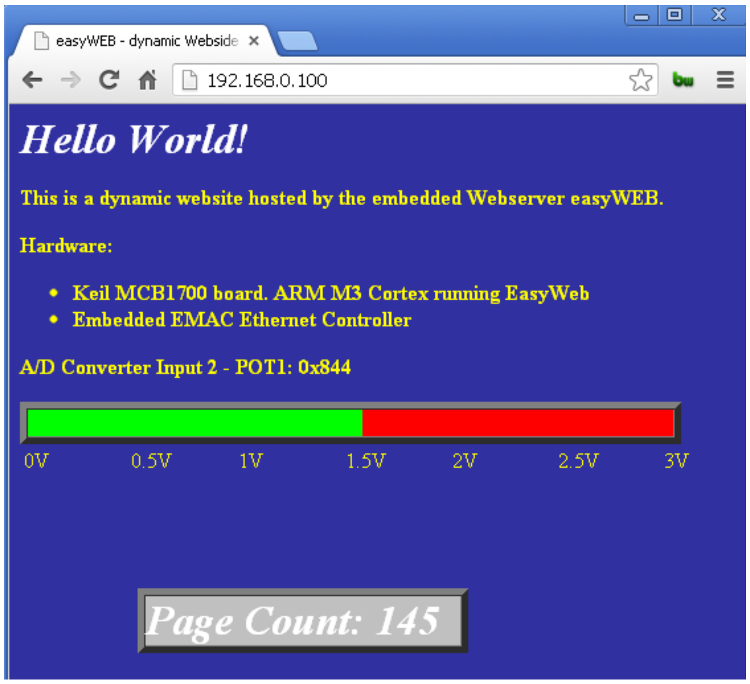
Figure 11 Fields of the Ethernet packet.

7. Example 1: EasyWEB

This is the EasyWEB example that comes as part of the code bundle from NXP. You can also find it inside the downloadable archive with the files of this lab.

The EMAC project is a simple embedded web server for the NXP LPC17xx microcontrollers also known as "EasyWEB". This tiny web server was taken from the "Design & Elektronik" magazine extra issue "Embedded Internet". This software was adapted to work with a Keil MCB1700 board and the ARM RealView C-Compiler with as few modifications as possible. The served web page shows the value of one analog input (AN2) which can be controlled via the blue potentiometer on the MCB1700 board.
Please read the **1_code.bundle.lpc17xx.keil.emac.pdf** file (included in the downloadable archive for this lab) to see how to set-up and run this example (use the CAT 5E cable from your TA). Compile, and download to the board. Observe operation and comment. When up and running you should see the webpage shown in the figure below.

Take some time and read the source code in order to get a good understanding of what's happening.



Hello World!

This is a dynamic website hosted by the embedded Webserver easyWEB.

Hardware:

- Keil MCB1700 board. ARM M3 Cortex running EasyWeb
- Embedded EMAC Ethernet Controller

A/D Converter Input 2 - POT1: 0x844

Page Count: 145

Figure 12 Webpage that shows the value of the ADC value of the MCB1700 board.

8. Lab assignment

This is optional. If done correctly, you may get up to 2% of the final grade.

Create a new uVision project and write a program that uses Ethernet to connect two boards and transmit the value of the ADC from one board to the other, where it is displayed on the LCD screen.

9. Credits and references

[1]
--Ethernet Introduction, Ross MCIlroy, 2004; http://www.dcs.gla.ac.uk/~ross/Ethernet/index.htm
--Data Network Resource, Rhys Haden, 2013; http://www.rhyshaden.com/eth_intr.htm
--OSI Model, Wikipedia entry; http://en.wikipedia.org/wiki/OSI_model
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--Internet: "The Big Picture"; http://navigators.com/internet_architecture.html
--Internet Technical Resources; http://www.cs.columbia.edu/~hgs/internet/
--Internet; Wikipedia entry; http://en.wikipedia.org/wiki/Internet
[2] LPC17xx user manual, 2010; http://www.nxp.com/documents/user_manual/UM10360.pdf

APPENDIX A: Manchester Phase Encoding (MPE)

802.3 Ethernet uses Manchester Phase Encoding (MPE). A data bit '1' from the level-encoded signal (i.e., that from the digital circuitry in the host machine sending data) is represented by a full cycle of the inverted signal from the master clock which matches with the '0' to '1' rise of the phase-encoded signal (linked to the phase of the carrier signal which goes out on the wire). i.e., -V in the first half of the signal and +V in the second half.

The data bit '0' from the level-encoded signal is represented by a full normal cycle of the master clock which gives the '1' to '0' fall of the phase-encoded signal. i.e., +V in the first half of the signal and -V in the second half.

The following diagram shows graphically how MPE operates. The example at the bottom of the diagram indicates how the digital bit stream **10110** is encoded.

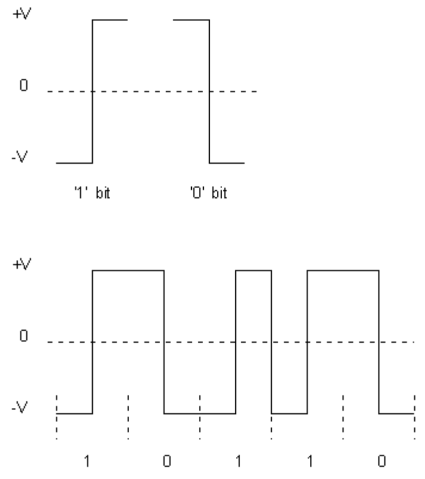


Figure 13 Illustration of MPE operation.

A transition in the middle of each bit makes it possible to synchronize the sender and receiver. At any instant the ether can be in one of three states: transmitting a 0 bit (-0.85v), transmitting a 1 bit (0.85v) or idle (0 volts). Having a normal clock signal as well as an inverted clock signal leads to regular transitions which means that synchronization of clocks is easily achieved even if there are a series of '0's or '1's. This results in highly reliable data transmission. The master clock speed for Manchester encoding always matches the data speed and this determines the carrier signal frequency, so for 10Mbps Ethernet the carrier is 10MHz.

APPENDIX B: How the Application Layer of TCP/IP layer stack model works

One may ask why an Application Layer is needed for TCP/IP, since the Transport Layer handles a lot of interfacing between network and applications. While this is true, the Application Layer focuses more on network services, APIs, utilities, and operating system environments.

By breaking the TCP/IP Application Layer into three separate layers, we can better understand what responsibilities the Application Layer actually has.

The OSI Equivalent of the TCP/IP Application Layer:

1. **Application Layer -** The seventh OSI model layer (which shouldn’t be confused with the TCP/IP stack’s Application Layer). It supports network access, as well as provides services for user applications.
2. **Presentation Layer -** The Sixth OSI model layer is the Presentation Layer. It translates data into a format that can be read by many platforms. With all the different operating systems, programs, and protocols floating around, this is a good feature to have. It also has support for security encryption and data compression.
3. **Session Layer -** The fifth layer of the OSI model is the Session Layer. It manages communication between applications on a network, and is usually used particularly for streaming media or using web conferencing.

To better see the concepts of the Application Layer, let’s take a look at a few examples of the Application Layer in action:

Application Layer APIs

A good example of an API is DirectX. If you’ve ever run a multimedia application and used Windows at the same time, odds are you have come into contact with DirectX. DirectX is made up of many different components that allow programmers to create multimedia applications (such as video games).

There are many types of APIs. You may have heard of NetBIOS, Winsock, or WinAPI among others. The world of APIs has also extended to web services. You may have heard of a Google API, for instance. In this case Google allows developers to use its internal functions, yet also keeps Google’s internal code safe.

Network Services

The Application Layer handles network services; most notably file and printing, name resolution, and redirector services.

Name resolution is the process of mapping an IP address to a human-readable name. You may be familiar with the name Google more so than the IP address of Google. Without name resolution, we would have to remember four octets of numbers for each website we wanted to visit…

A redirector, otherwise known as a requester, is a service that is largely taken for granted. It is a handy service that looks at requests a user may make: if it can be fulfilled locally, it is done so. If the request requires a redirection to another computer, then the request is forwarded onto another machine. This enables users to access network resources just like they were an integral part of the local system. A user could browse files on another computer just like they were located on the local computer.

Lastly we have file and print services. If a computer needs to access a file server or a printer, these services will allow the computer to do so. While fairly self-explanatory it's worth reviewing...

Network Utilities

This is where most people have experience - within the network utilities section of the Application Layer. Every time you use a Ping, Arp, or Traceroute command, you are taking full advantage of the Application Layer.

It's quite convenient that the Application Layer is located on the top of the TCP/IP stack. We can send a Ping and, if successful, can verify that the TCP/IP stack is successfully functioning. It's a good idea to commit each utility to memory, as they are very useful for maintaining, configuring, and troubleshooting networks.

Listed below are seven of the most used utilities.

1. **ARP** - Arp stands for Address Resolution Protocol. It is used to map an IP address to a physical address found on your NIC card. Using this command can tell us what physical address belongs to which IP address.
2. **Netstat** - Netstat is a tool that displays local and remote connections to the computer. It displays IP addresses, ports, protocol being used, and the status of the connection.
3. **Ping** - Ping is a simple diagnostic tool that can check for connectivity between two points on a network. It is one of the most used TCP/IP utilities when setting up a network or changing network settings.
4. **TraceRT** - Tracert, or traceroute, is a command that shows the path that packets of data take while being sent. It's handy for checking to see where a possible network failure lies, or even for ensuring that data packets are taking the fastest route possible on a network.
5. **FTP/TFTP** - FTP and TFTP are both used for transferring files. It is important to note that FTP is a TCP utility, while TFTP is a UDP utility. TFTP tends to be less secure than FTP, and is generally only used for transferring non-confidential files over a network when speed is concerned.
6. **Hostname** - Hostname is a simple command that displays the hostname of the current computer: simple yet effective.
7. **Whois** - Whois information is just like an online phonebook. It shows the contact information for owners of a particular domain. By using a Whois search, you will find that Google is based in California ☺.

APPENDIX C: Key Features of TCP/IP

Five of the most important features of TCP/IP are:

a) Application support

b) Error and flow control
c) Logical Addressing
d) Routing
e) Name resolution

a) Application Support
Assume you are multitasking - you are uploading files to your website, sending an email, streaming music, and watching video all at the same time. How does the computer know where to send each packet of data if multiple applications are running? We sure wouldn't want to use our email program to watch video, and vice versa!

This problem is addressed by using channels called **ports**. These numbered ports each correspond to a certain action. For example, the email is likely using port 25 for operation. Files you upload to your website use the FTP port, which is usually port 20 and 21. Browsing a webpage uses a specific port - the HTTP port 80.

In total, there are 65,535 ports for controlling the flow of information.

b) Error and Flow Control
TCP/IP is considered a connection-oriented protocol suite. This means that if data isn't received correctly, a request to resend the data is made. This is compared to User Datagram Protocol (UDP), which is connectionless. UDP is a suite of protocols just like TCP/IP, with a few notable differences. UDP is great for broadcasting data - such as streaming radio music. If part of the data was lost, we wouldn't want to go back and retrieve it - it would waste bandwidth, and would create collisions or noise in our signal. With UDP, the lost data might be represented as a silent spot.

c) Logical Addressing
Most computers today come standard with Network Interface Cards (NICs). These cards are the actual hardware used to communicate to other computers. Each card has a **unique physical address** that is set at the factory, and can't be changed. Essentially this is an identifier for the computer it is installed on.

Networks rely on the physical address of a computer for data delivery, but we have a problem. The NIC card is constantly looking for transmissions that are addressed to it - what if the network was very large in size? To put it into perspective, imagine your computer looking at every single bit of data on the internet to see if any of the millions of data packets are addressed to it.

This is where **logical addressing** comes in. You are probably more familiar with the term **IP address**, however. These IP addresses can be subnetted on a network to divide a large network into tiny pieces. Instead of looking at every bit of data on the internet, logical addressing allows for computers to just look at data on a home network or subnet.

d) Routing
A router is a device used to read logical addressing information, and to direct the data to the appropriate destination. Routers are commonly used to separate networks into portions - this greatly reduces network traffic if done correctly.

TCP/IP includes protocols that tell routers how to find a path through the network. This is a vital feature of the TCP/IP suite that enables massive LAN connections to be created.

e) Name Resolution

Finally, we have name resolution. If you wanted to conduct a search on the internet, you would probably just type Google's URL into your address bar. What you probably didn't know is that you aren't necessarily connecting to "google.com", but rather an **IP address**. Instead of having to remember an IP address, name resolution allows you to remember Google's name.

It might not be so bad if IP addresses were not so lengthy in size. Which is easier to remember http://74.125.224.72/ or google? This handy service is accomplished on name servers, which are just computers that store tables that translate domain names to and from IP addresses.

Lab 7: Supplemental Material – AR.Drone Control

1. Objective

The objective of this (supplemental) lab is to use the MCB1700 board, a WRT54GL wireless router, and a Wii NunChuck to control a Parrot AR.Drone. The overall set-up of this project is shown in the figure below.

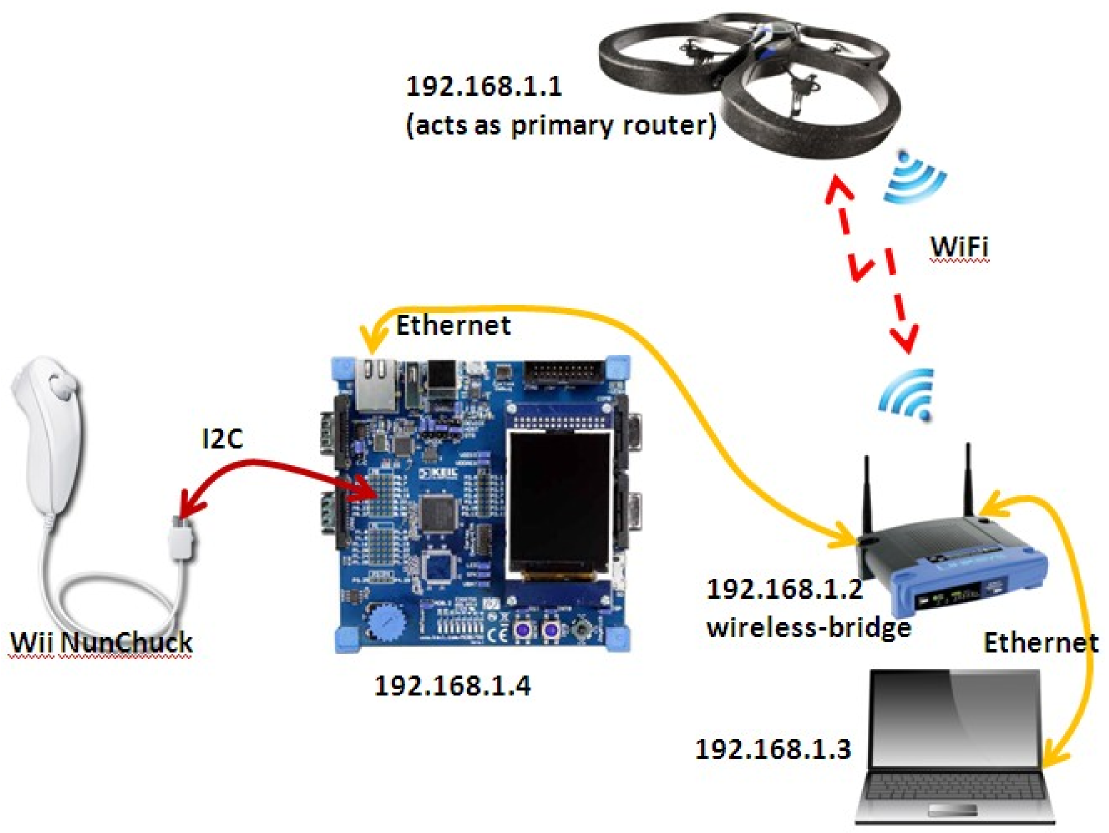


Figure 1 Overview of the project developed in this lab.

2. AR.Drone

AR.Drone is a sophisticated Linux-based WiFi-enabled flying embedded system. It’s a neat toy and much more!

The Parrot AR.Drone was revealed at the International CES 2010 in Las Vegas. At the same time, Parrot also demonstrated the iOS applications used to control it. Along with AR.Freeflight, the application designed for free operation of the drone, Parrot also released AR.Race, allowing users to participate in solo games, or interact with other drones in combat simulations.

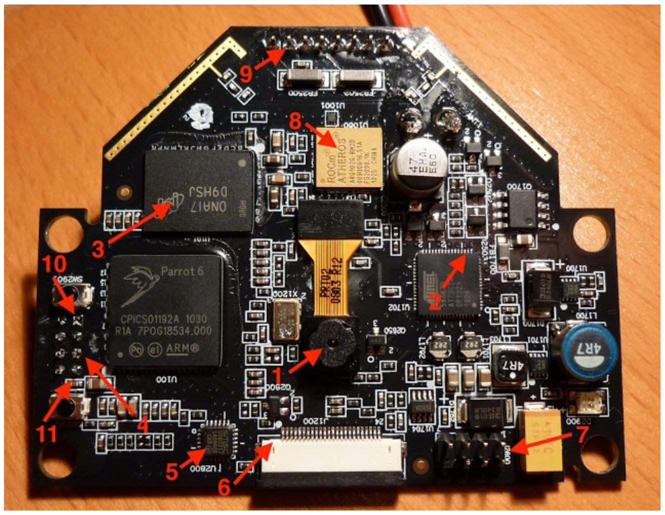


Figure 2 AR.Drone and its main board.

The AR.drone can be piloted by an iPod app, making it usable with any WiFi-enabled iDevice. Android-based apps have emerged too. The drone has two video cameras, one front facing and the other down facing, plus an accelerometer, two gyrometers, and an ultrasonic altimeter. It is all controlled by an ARM-based processor running Linux. Both the iOS-based app and the Linux-based embedded system are hackable. Parrot provides an SDK and encourages developers to use it as an application platform. Cool things can be developed with it – imagine virtual reality.

I controlled my AR.drone with:
1) my iPod,
2) laptop-based application via the laptop's wireless card,
3) same laptop-based application via a Wireless-G router, WRT54GL, which is connected to the laptop via an Ethernet cable; the router is programmed to work as a "wireless bridge"; also, the laptop's own wireless card is shut-off in this case, and
4) MCB1700 board (has an LPC1768 microcontroller) connected to the WRT54GL router (again set-up as a wireless bridge) and a Wii NunChuck.

In this supplemental lab, we'll study the number 4) aforementioned scenario.

Some technical specifications of the AR.Drone include (of the first model):
- CPU: 468MHz ARM9 embedded microcontroller
- RAM: 128MB
- Interfaces: USB and Wi-Fi 802.11b/g
- Front camera: VGA sensor with 93º lens
- Vertical camera: 64º lens, recording up to 60fps

A closer look at the motherboard is shown in Fig.1, which points out some of the main elements:
1: Camera, I2C bus 0 address 5d
2: I2C connectors for I2C Bus 0 arrive here
3: DRAM cache
4: Connector to navigation board, at least one serial port

5: USB driver SMSC USB3317
6: Connector to front camera, probably not an I2C device
7: External connection port with TTYS0 serial port and USB port
8: ROCm Atheros AR6102G-BM2D wireless
9: Power supply for the engines
10: Ground
11: VCC +5V

Read more details about AR.Drone here:
--Parrot AR.Drone official website; http://ardrone2.parrot.com/usa/
--AR.Drone open API platform; https://projects.ardrone.org/
--AR.Drone Developer Guide SDK 1.7; http://www.ardrone-flyers.com/wiki/Version_SDK-1.7
--AR.Drone mainboard overview (Fig.1 right taken from here); http://awesome-drone.blogspot.com/
--Hacking the AR-DRONE Parrot; http://www.libcrack.so/2012/10/13/hacking-the-ar-drone-parrot/
--Chip Overclock's dissection (6 parts, so far);
http://coverclock.blogspot.com/2011/02/deconstructing-ardrone.html
http://coverclock.blogspot.com/2011/02/deconstructing-ardrone-part-2.html
http://coverclock.blogspot.com/search/label/AR.drone
--Shwetak N. Patel, Univ. of Washington; http://abstract.cs.washington.edu/~shwetak/classes/ee472/
--Buy it for about $300 at Amazon; http://www.amazon.com/Parrot-AR-Drone-Quadricopter-Controlled-Android/dp/B007HZLLOK/ref=sr_1_1?ie=UTF8&qid=1367113226&sr=8-1&keywords=ar+drone

3. Linksys Wireless-G WRT54GL router

This is already a somewhat old router but it's still very popular and with a lot of online support. It can be utilized as an access-point to extend your wireless LAN but also as a wireless-bridge to further extend your network. A nice thing is that it can be utilized as a "wireless card" for a laptop/PC which does not have one; not to mention its Linux compatibility.

The Linksys Wireless-G Broadband Router is really three devices in one box. First, there's the Wireless Access Point, which lets you connect both screaming fast Wireless-G (802.11g at 54Mbps) and Wireless-B (802.11b at 11Mbps) devices to the network. There's also a built-in 4-port full-duplex 10/100 Switch to connect your wired-Ethernet devices together. Connect four PCs directly, or attach more hubs and switches to create as big a network as you need. Finally, the Router function ties it all together and lets your whole network share a high-speed cable or DSL Internet connection.

Figure 3 Wireless-G WRT54GL router.

We’ll this router to connect to and control the AR.Drone. To do that, we need to set it to work as a **“wireless bridge”**. But before that, we must update its firmware with Tomato.

The drone itself acts as a router, that’s why it can't connect to another router like a wrt54gl. With factory software is can't function as a client of another router, but routers can be reconfigured to relay the drones signal and extend the range. The drone emits a standard wifi signal for clients to connect to, so you have to configure your router to act as the client. With the wrt54gl routers, one can use Tomato’s firmware: http://www.polarcloud.com/tomato
Tomato is a simple replacement firmware for Linksys' WRT54G/GL/GS, Buffalo WHR-G54S/WHR-HP-G54 and other Broadcom-based routers. It features an easy to use GUI, a new bandwidth usage monitor, more advanced QOS and access restrictions, enables new wireless features such as WDS and wireless client modes, raises the limits on maximum connections for P2P, allows you to run your custom scripts or telnet/ssh in and do all sorts of things like re-program the SES/AOSS button, adds wireless site survey to see your wifi neighbors, and more.

So, download the Tomato’s firmware and save it on your computer (you will need only WRT54G_WRT54GL.bin).
Then, open the original Linksys GUI in your browser. The default URL is http://192.168.1.1/.
Leave user name as blank and type “admin” as password.
Select Upgrade Firmware and use Tomato’s WRT54G_WRT54GL.bin.

After, a few minutes the upgrade will be done.
Next, we do a so called **Hard Reset** (a.k.a. 30/30/30 reset) of the router. The following procedure will clear out the NVRAM and set dd-wrt back to default values:

- With the unit powered on, press and hold the reset button on back of unit for 30 seconds
- Without releasing the reset button, unplug the unit and hold reset for another 30 seconds
- Plug the unit back while STILL holding the reset button a final 30 seconds

Note: *This procedure should be done BEFORE and AFTER every firmware upgrade/downgrade.*
Open the new Tomato GUI in your browser. The default URL is http://192.168.1.1/.
User “root” as user and “admin” as password.
Then, Navigate to Basic–>Network. There are a few settings to toggle in this section.
Within the Network sub-menu do the following settings:

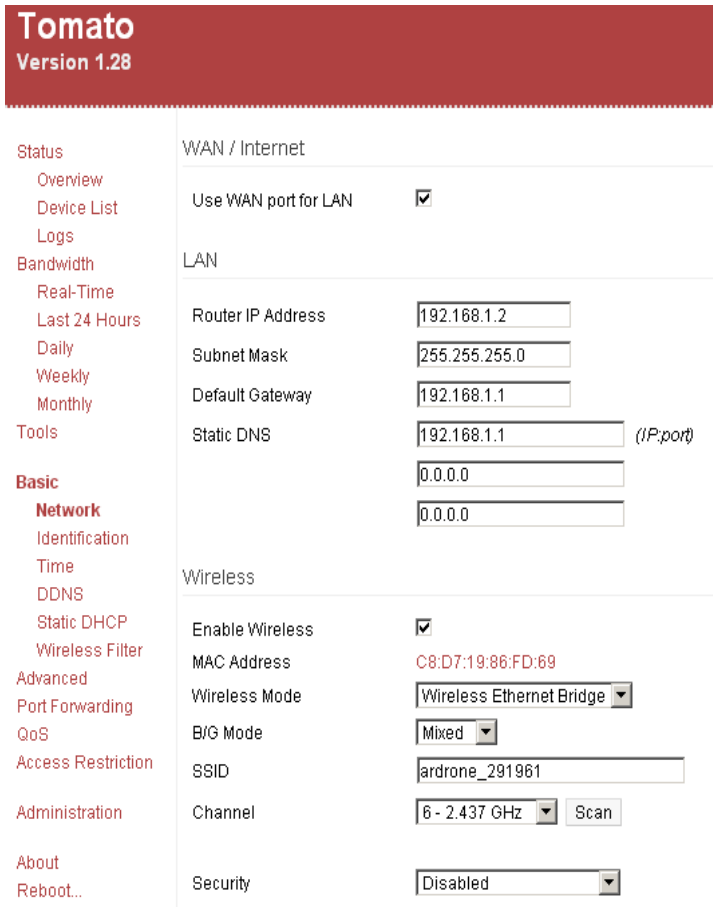
- First, toggle the WAN / Internet to Disabled.
- Second, change the values in the LAN section to the following:
    - Router IP Address: 192.168.1.2 (presumes that the Primary Router IP is 192.168.1.1 – that will be the AR.Drone)
    - Subnet Mask: 255.255.255.0
    - Default Gateway: 192.168.1.1 (the IP of the Primary Router, i.e., the AR.Drone)
    - Static DNS: 191.168.1.1
    - DCHP Server: Unchecked

In the Wireless section of the Network sub-menu, configure the following settings:

- Enable Wireless: Checked.
- Wireless Mode: Wireless Ethernet Bridge
- Wireless Network Mode: Mixed

- SSID: ardrone_291961. This is the name SSID of the network whose Primary Router is the AR.Drone. In my case it's ardrone_291961; you can check what yours is by looking up for wireless networks with your laptop, after you power-up the drone.
- Channel: The channel of the Primary Router, i.e., 6 – 2.437.
- Security: Disabled

After the above changes, your Tomato's GUI should look like in the figure below:



WAN / Internet

Use WAN port for LAN ✓

LAN

Router IP Address	192.168.1.2
Subnet Mask	255.255.255.0
Default Gateway	192.168.1.1
Static DNS	192.168.1.1 (IP:port)
	0.0.0.0
	0.0.0.0

Wireless

Enable Wireless	✓
MAC Address	C8:D7:19:86:FD:69
Wireless Mode	Wireless Ethernet Bridge
B/G Mode	Mixed
SSID	ardrone_291961
Channel	6 - 2.437 GHz Scan
Security	Disabled

Figure 4 Setting up the router as wireless-bridge.

Note: *For some reason, each time I need to log-in and set-up the router, I need to do the 30/30/30 hard-reset described above, which is becoming annoying. An alternative to Tomato is DD-WRT firmware (http://www.dd-wrt.com/site/index). I have not tried it yet though.*

Read more details about WRT54GL wireless router and more here:
--How To Turn An Old Router Into A Wireless Bridge; http://www.makeuseof.com/tag/how-to-turn-an-old-router-into-a-wireless-bridge/
--How To Extend Your Wi-Fi Network With Simple Access Points; http://www.howtogeek.com/104469/how-to-extend-your-wi-fi-network-with-simple-access-points/
--How To Extend Your Wireless Network with Tomato-Powered Routers; http://www.howtogeek.com/104007/how-to-extend-your-wireless-network-with-tomato-powered-routers/
--Turn Your Old Router into a Range-Boosting Wi-Fi Repeater; http://lifehacker.com/5563196/turn-your-old-router-into-a-range+boosting-wi+fi-repeater

--Buy a used WRT54GL for about $25 here; http://www.amazon.com/Cisco-Linksys-WRT54GL-Wireless-G-Broadband-Router/dp/B000BTL0OA

4. Wii NunChuck

The Wii NunChuk is an input device with a joystick, two buttons, and a three-axis accelerometer as illustrated in the figure below. The three axes X, Y, and Z correspond to the data produced by the accelerometer, joystick. X is right/left, Y is forward/backwards, and Z is up/down (accelerometer only).

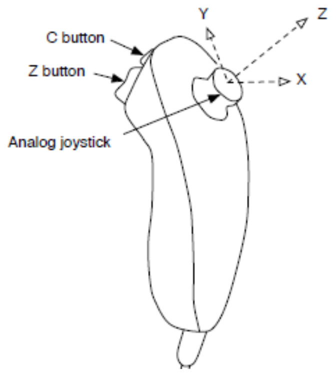


Figure 5 Wii NunChuck.

The NunChuck communicates via I2C. We'll hook the NunChuck to the I2C1 bus of the LPC1768 microcontroller on the MCB1700 board. We'll initialize the Nunchuk to a known state and then regularly "poll" its state.

We've already discussed this in lab#4. Please re-visit lab#4 as we'll utilize much of it to put together the project herein.

5. uIP – A Light Weight TCP/IP Stack

The AR.Drone can be controlled via UDP packets. We'll do that by utilizing a popular TCP/IP stack: micro IP (a.k.a., uIP).

The uIP was an open source TCP/IP stack capable of being used with tiny 8- and 16-bit microcontrollers. It was initially developed by Adam Dunkels (http://dunkels.com/adam/) of the "Networked Embedded Systems" group at the Swedish Institute of Computer Science, licensed under a BSD style license, and further developed by a wide group of developers. uIP can be very useful in embedded systems because it requires very small amounts of code and RAM. It has been ported to several platforms, including DSP platforms.

The uIP implementation is designed to have only the absolute minimal set of features needed for a full TCP/IP stack. It can only handle a single network interface and contains only a rudimentary UDP implementation, but focuses on the IP, ICMP and TCP protocols. uIP is written in the C programming language.

Download and read more details about UIP here:
--uIP downloads; https://github.com/adamdunkels/uip/tags
--uIP (micro IP); http://en.wikipedia.org/wiki/UIP_(micro_IP)
-- The uIP TCP/IP stack; http://www.gaisler.com/doc/net/uip-0.9/doc/html/main.html
--Some documentation; http://ucapps.de/midibox_ng/doxygen/group__uip.html

6. Example 1: Simple Controls of AR.Drone

The files necessary for this example are located in downloadable archive for this lab. This is actually the whole uVision project directory. Just copy it, then clean and re-build the project. Download to the board.

Make all the necessary connections as illustrated in Fig.1.

- Power-up the AR.Drone and place on the floor.
- Connect MCB1700 board to the WRT54GL wireless router using an Ethernet cable.
- Connect the NunChuck as done in lab#4 using the NunChuck adaptor, additional wires, and power supply provided by your instructor. Use the button "C" for take-off and button "Z" to land. Use the joystick to move the drone. Read the source code, which has comments explaining these controls.

Observe operation and comment.

7. TODOs

Lab assignments:
--Change the source code to implement more complex controls.
--Read also the data provided by the AR.Drone and do something about it, e.g., display text and/or video data on the LCD screen of the board, etc.
--Propose something creative and implement it!

Lab 8: Streaming Video from CMOS Camera

This lab is under development.

Notes on Using MCB1700 Board

These notes are meant to help you in deciding whether to adopt MCB1700 board for an undergraduate lab. After one semester of using this board (124 students using the boards on a daily basis), I have decided not to utilize it anymore in a teaching lab for the following reasons:

- The board does not have its own power supply. It does not have a power switch either. You will have to attach it to your computer via USB for power.
- It's fragile; not sturdy. Particularly the COM and CAN ports are weakly attached to the board. A few of these ports fell off within a few weeks. Pushing and pulling serial cables into the COM ports weakened them very quickly.
- The LCD display is relatively slow. While particular MCB1700 samples have a touch-screen LCD display, there is almost no information on it; no examples on how to use the touch screen either.
- The board does not have a protective transparent cover (like for example many of Altera's FPGA boards). Objects can easily fall off and break the LCD display. It happened with two boards in my lab. In one instance, an iPhone fell on the LCD display; the display broke, the iPhone was perfectly fine ☺.
- The board does not have simple header connectors (like for example Arduino's stackable connectors) for access to general purpose IOs. Instead it has simple prototyping area directly on the board.
- The price of $240 (academic price) without the ULINK2 programmer (which is an additional $150) is high.

Please do not get me wrong, MCB1700 is a beautiful board. It has lots of nice peripheral devices and features. However, its construction makes it more appropriate for personal use when you would handle it gently and with care; it's not designed for daily (ab)use in a teaching lab.

For the aforementioned reasons, I will most like use the Land Tiger next time.