

Electrical and Computer Engineering (ECE) Operating Systems and System Programming ECE254 Laboratory Manual

by

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Preface

Two operating systems are used in laboratories. One is the general purpose operating system Linux that supports Intel processors on personal computers. The second is the ARM RL-RTX that supports ARM Cortex-M3 processors on Keil MCB1700 boards.

The Linux computing environment is for practising system programming aspect of the course. The ARM RL-RTX, a real-time operating system library, is for practising the operating system kernel programming aspect of the course.

The first purpose of this document is to provide the descriptions of each laboratory project. The second purpose of this document is a quick reference guide of the relevant development tools for completing laboratory projects.

Who Should Read This Lab Manual?

This lab manual is written for students who are taking Electrical and Computer Engineering (ECE) Operating Systems and System programming course ECE254 in the University of Waterloo.

What is in This Lab Manual?

This manual is divided into three parts.

Part I describes the lab administration policies

Part II is a set of course laboratory projects as follows.

- Lab0A: Introduction to Linux system programming
- Lab0B: Introduction to ARM RL-RTX kernel and application programming
- Lab1: Task management in ARM RL-RTX

- Lab2: Inter-process communication by message passing
- Lab3: Concurrency control

Part III is the reference guide of the development tools for Linux and ARM RL-RTX. The main topics are as follows.

- Software Development Tools on Linux
 - Linux hardware environment
 - Editors
 - Compiler
 - Debugger
 - Utility to automate build
 - Utility for version control
- Keil MCB1700 Development Hardware Environment and Software Tools
 - Keil MCB1700 hardware environment
 - Keil MCB1700 software development Tools
 - Programming MCB1700 with ARM RL-RTX
 - * Building an RTX application
 - * Building a customized ARM RL-RTX library
 - * Creating an application with customized ARM RL-RTX library
 - Programming MCB1700

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We would like to sincerely thank our students who took ECE254 and MTE241 ¹ courses in the past two years. They provided constructive feedback every term to make the manual more useful to address problems that students would encounter when working on each lab assignment.

Special thank goes to Dr. Thomas Reidemeister who shared his prototyping work in SE350 ² course project on Keil MCB1700 boards with us.

¹MTE241 is the course number for Introduction to Real-time Systems in the University of Waterloo Mechatronics Engineering program.

²SE350 is the course number for Operating Systems in the University of Waterloo Software Engineering Program.

We are grateful to teaching assistants Bo Zhu, Dr. Nabil Drawil, Pei Wang, Shasha Zhu, Zheng Wu and Zack Newsham who provided valuable feedback and improved lab tutorials.

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The project and manual won't be possible without lab facilities. Thank Roger Sanderson for providing us with lab tools and resources. Our gratitude also goes out to Eric Praetzel who sets up the Keil boards in lab and maintains the Keil software on Nexus machines; Laura Winger who managed to customize the boards so that we have the neat plastic cover to protect our hardware. We appreciate that Bernie Roehl and Rasoul Keshavarzi-Valdani have shared their valuable Keil board experiences with us. Bob Boy from ARM always answers our questions in a detailed and timely manner. Thank everyone who has helped.

Part I

Lab Administration

Lab Administration Policy

Group Lab Policy

- **Group Size.** All labs are done in a group of *two*. A size of three is only considered in a lab section that has an odd number of students and only one group is allowed to have a size of three. All group of three requests are processed on a first-come first-served basis. A group size of one is not permitted except that your group is split up. There is no workload reduction if you do the labs individually. Everyone in the group normally gets the same mark. The Learn at URL <http://learn.uwaterloo.ca> is used to signup for groups. *The lab group signup is due by 4:30pm on the First Friday of the academic term.* Late group sign-up incurs a 5% per day final lab mark deduction.
- **Group Split-up.** If you notice workload imbalance, try to solve it as soon as possible within your group or split-up the group as the last resort. Group split-up is only allowed once. You are allowed to join a one member group after the split-up. But you are not allowed to split up from the newly formed group again. There is one grace day deduction penalty to be applied to each member in the old group. We highly recommend everyone to stay with your group members as much as possible, for the ability to do team work will be an important skill in your future career. Please choose your lab partners carefully. A copy of the code and documentation completed before the group split-up will be given to each individual in the group.
- **Group Split-up Deadline.** To split from your group for a particular lab, you need to notify the lab instructor in writing and sign the group split-up form (see Appendix). Lab n ($n=1,2,3,4$) group split-up form needs to be submitted to the lab instructor by 4:30pm Thursday in the week that Lab n has scheduled lab sessions. If you are late to submit the split-up form, then you need to finish Lab n as a group and submit your split-up form during the week where Lab $(n+1)$ has scheduled sessions and split starting from Lab $(n+1)$.

Deliverable	Weight	Due Date	File Name
Group Sign-up		4:30pm May. 9th	
LAB1	2%	11:59pm May. 13th	LAB1_Gid.zip
LAB2	2%	11:59pm May. 27th	LAB2_Gid.zip
LAB3	6%	11:59am Jun. 26th	LAB3_Gid.zip
LAB4	4%	11:59pm Jul. 8th	LAB4_Gid.zip
LAB5	6%	11:59pm Jul. 22nd	LAB5_Gid.zip

Table 1: Project Deliverable Weight of the Course Grade and Deadlines. Replace the “id” in “Gid” with the two digit group ID

Lab Assignments Grading and Deadline Policy

Labs are graded by lab TAs based on the rubric listed in each lab. The weight of each lab towards your final course grade is listed in Table 1.

- **Lab Assignment Preparation and Due Dates.** Students are required to prepare the lab well before they come to the scheduled lab session. *Pre-lab deliverable for each lab is due before the scheduled lab session starts.* During the scheduled lab session, we either provide in lab help or conduct lab assignment evaluation or do both at the same time. Table 1 lists the Post-lab deliverable deadlines. *Please be advised that lab sessions during the midterm week are cancelled.*
- **Lab Assignment Late Submissions.** There are five grace days ³ that can be used for some Post-lab deliverables late submissions. A Post-lab deliverable that does not accept a late submission will be clearly stated in the lab assignment description. Normally grace days are for lab reports. Labs whose evaluation involves demonstrations do not accept late submissions of the code. A group split-up will consume one grace day. After all grace days are consumed, your late submission will automatically get a grade of zero.

Lab Assignments Solution Internet Policy

It is not permitted to post your lab assignment solution source code or lab report on the internet freely for public to access. For example, it is not acceptable to host a public repository on GitHub that contains your lab assignment solutions. A warning with instructions

³Grace days are calendar days. Days in weekends are counted.

to take the lab assignment solutions off the internet will be sent out upon the first offence. If the no action is taken from the offender within twenty-four hours, then a lab grade zero will automatically be assigned to the offender.

Seeking Help Outside Scheduled Lab Hours

- **Discussion Forum.** We recommend students to use the Learn discussion forum to ask the teaching team questions instead of sending individual emails to lab teaching staff. For questions related to lab projects, our target response time is one business day before the deadline of the particular lab in question. ⁴. *After the deadline, there is no guarantee on the response time.*
- **Office Hours.** During weeks where there are no scheduled labs, lab teaching staff hold bi-weekly office hours. The Learn system calendar gives the office hour details.
- **Appointments.** Students can also make appointments with lab teaching staff should their problems are not resolved by discussion forum or during office hours. When you request an appointment, please specify three preferred times and roughly how long you would like the appointment to be. On average, an appointment is fifteen minutes per project group.

Lab Facility After Hour Access Policy

After hour access to the lab will be given to the class when we start to use the Keil boards in lab. However please be advised that the after hour access is a privilege. Students are required to keep the lab equipment and furniture in good conditions to maintain this privilege.

No food or drink is allowed in the lab (water is permitted). Please be informed that you may share the lab with other classes. When resources become too tight, certain cooperation is required such as taking turns to use the stations in the lab.

⁴Our past experiences show that the number of questions spike when deadline is close. The teaching staff will not be able to guarantee one business day response time when workload is above average, though we always try our best to provide timely response.

Part II

Lab Projects

Chapter 1

Lab1: Introduction to Linux System Programming

1.1 Objective

This lab is to introduce the general Linux Development Environment at ECE department and basic Linux system programming procedures to students. After finishing this lab, students will have a good understanding of the following:

- How to use the `gcc` compiler on Linux.
- How to use the `make` utility on Linux.
- How to use the `ddd` debugger on Linux.
- How to read Linux manual page.
- How to write a C program to obtain file attributes.

1.2 Starter Files

The starter file is on GitHub at <http://github.com/yqh/ECE254/> under directory `lab1/starter`. It contains three sub-directories where we have example source code to help you started:

- the `cmd_arg` demonstrates how to capture command line input arguments;

- the `ls` demonstrates how to list all files under a directory and obtain owner permission and file types; and
- the `pointer` demonstrates how to use pointers to access C structure.

Using the code in the starter files is permitted and will not be considered as plagiarism.

1.3 Pre-lab Preparation

Read Chapter 6.

1.4 Warm-up Exercises

This exercise is to practice a few basic UNIX commands on Linux.

1. Use the SSH Secure Shell Client to login onto `ecelinux.uwaterloo.ca`. You are now inside the Linux shell.
2. Use the `ls` command to list all files in your current working directory.
3. Read the online manual of the `ls` command by issuing `man ls` command to the shell.
 - Which option of `ls` produces output in long listing format, which includes the file type, permission, ownership, group ownership, size, time of the last modification and file name?
 - What does `-a` option do?
 - What does `-lau` option do?
 - What does `-lac` option do?
4. Create a directory as the work space of ECE254 labs. Name the newly created directory as `ece254`. Read the man page of the command `mkdir` to see how to do it.
5. Change directory to the newly create directory of `ece254`. The command is `cd`. Read the man page to find out the exact syntax of the command.
6. Clone the entire repository by using the command:
`git clone https://github.com/yqh/ECE254.git`

1.5 Lab1 Assignment

This assignment is to program a command called `myls`, which is a simplified version of the Linux `ls` command. You should use the `stat`, `lstat` and `fstat` family of system calls to obtain file attributes. To use `system` or `exec` family system calls to execute the `ls` command directly from C code is not an accepted solution to this programming assignment.

1.5.1 Man Page

Name

`myls` - list directory contents

Synopsis

`myls` OPTION DIRECTORY

Description

List information of files in `DIRECTORY`. The order of the files are listed is not specified. The command will show file type ¹, permissions, ownership, group ownership, size in bytes, time stamp and the file name. The time stamp shown depends on the value of the `OPTION`:

- u: last access time.
- c: last change time.
- l: last modification time.

Exit status is 0 if OK, 1 if problem.

Expected Output Format

The output format is similar to `ls -l` except that the command does not print the number of hard links of a file, which is the second column of the `ls -l` output. To be more specific, the `myls` `OPTION` `DIRECTORY` will output eight columns and they are:

¹we only require the program to identify directory, regular file and symbolic link types.

- column 1: standard ten character string to show file type and permissions. For example `drwx-----` means the file is a directory, user has read, write and execute permissions, and group or others have no permissions;
- column 2: owner user name;
- column 3: group name;
- column 4: size in bytes;
- column 5: abbreviated month name of the time stamp;
- column 6: the day of the month as a decimal number of the time stamp with leading zeros removed;
- column 7: the hour and minute of the time stamp in 24 hour format if the file is created in the current year; or the year in decimal number (four digits) if the year of the time stamp is older than the current year;
- column 8: file name. For a symbolic link, the file name should be followed by “ -> ” and the file the symbolic link points to.

Each column is separated by white space(s) ².

A Sample Program Run

```
[ecelinux1:]myls -u ./
lrwxrwxrwx  yqhuang  users      8 May  6 16:14 main.c -> ls_GNU.c
-rw-----  yqhuang  users    441 May  6 14:25 Makefile
-rw-----  yqhuang  users  4852 Dec 13  2013 ls_GNU.c
lrwxrwxrwx  yqhuang  users    18 May 12 16:12 mybin -> /home/yqhuang/bin/
drwx-----  yqhuang  users   4096 Dec 13  2013 ..
-rw-----  yqhuang  users  10264 May  6 16:14 main.o
drwx-----  yqhuang  users   4096 Dec 13  2013 .
-rw-----  yqhuang  users   4930 May  6 16:16 myls.c
-rwx-----  yqhuang  users  14375 May  6 16:14 main.out
-rwx-----  yqhuang  users  15156 May  6 16:16 myls
-rw-----  yqhuang  users  11008 May  6 16:16 myls.o
drwx-----  yqhuang  users   4096 May  6 22:37 test_dir
```

²It will be nicer to align each column by padding extra spaces, though this is not a requirement.

1.5.2 Hints

- From the OS point of view, a directory is a file. But it is a special file. Read the man page of `opendir()`, `readdir()`, `closedir()`. Can `open()/close()` system call open/close a directory? Can you read a directory file by the `read()` system call? Read the man page of `perror(3)`, which prints a system error message. Use `perror()` to print out system error when a call fails is a good programming practice.
- The `stat()`, `fstat()` and `lstat()` system calls can be used to obtain file attribute information. Read the man page (section 2) of these system calls. Which one of these system calls gives information about a symbolic link file?
- Execute the Linux “`ls -lau /bin`”, “`ls -lac /bin`”, “`ls -la /bin`”, and “`stat <filename>`” commands and see the output.
- Study `ls_fname.c`, `ls_ftype.c` and `ls_fperm.c` starter files. The example files show how command line arguments are passed to the `main` function and how to interpret the `st_mode` value in the system defined `struct stat` by using system defined macros.
- Study the man pages of `strcmp(3)`, `strcat(3)`, `strlen(3)`, `sprintf(3)`, `readlink(2)`, `getpwuid(3)`, `getgrgid(3)`, `localtime(3)`, `strftime(3)` and `ctime(3)`.

1.6 Deliverables

1.6.1 Pre-lab Deliverables

There is no pre-lab deliverable.

1.6.2 Post-lab Deliverables

Here are the steps to create your post-lab deliverable submission.

- Create a directory and name it `lab1`.
- Put the entire source code with a Makefile under the directory `lab1`. We expect that typing `make` in `lab1` directory will generate the executable file with name `mys`. We expect that by typing `make clean`, all object code and `mys` file are removed.
- Use `zip` command to zip up the contents of `lab1` directory and name it `lab1.zip`

Submit the `lab1.zip` file to Lab1 Dropbox in Learn.

1.7 Marking Rubric

TA will test your source code on one of the ecelinux machines. Total mark is 10. You will get full mark is all required file attributes are displayed correctly. Partial mark will be given based on the portion of the correctly displayed file attributes if not all required attributes are displayed correctly.

Chapter 2

Lab2: Introduction to ARM RL-RTX Kernel and Application Programming

2.1 Objective

This Lab is to introduce the Keil μ Vision4 IDE and ARM RL-RTX development. Students will build the ARM RL-RTX from source. After this lab, students will have a good understanding of the following:

- How to create a μ Vision RTX project;
- How to build an RL-RTX library from source;
- How to create an application with self-built RTX Library;
- How to use SVC as the gateway to program OS functions.

2.2 Starter Files

In <https://github.com/yqh/ECE254> GitHub repository, the `lab2/starter/` directory contains the following:

- `Startup/`: frequently used source code; and
- `HelloWorld/`: a μ Vision project that prints “Hello World!” to UART0.

2.3 Pre-lab Preparation

- Read Chapters 7 and Section 8.5.

2.4 Warm-up Exercises

Change to the directory where you have the ece254 lab repository. Use "git pull" command to fetch any newly updated files from <https://github.com/yqh/ECE254>.

Notes

- The Keil IDE does not tolerate space(s) in the path name on Nexus. For example, a project in a directory which contains **My Documents** as part of the path name sometimes will give you error saying certain files could not be created.

2.4.1 Build and Run the HelloWorld Application

This exercise is to familiarize you with the simulator target and in-memory execution target executions. When you open the provided HelloWorld project, you will see the following two targets as shown in figure 2.1.

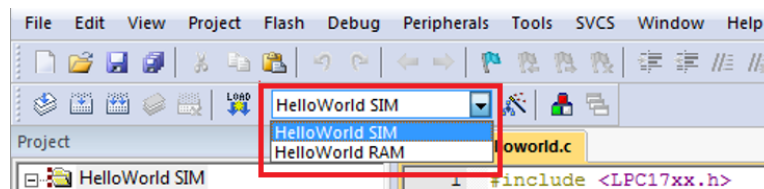


Figure 2.1: Keil IDE: List of Targets

- The **HelloWorld SIM** target is to use simulator to debug the target with the default memory map.
- The **HelloWorld RAM** target is to use the hardware ULINK/ME Cortex debugger to debug the target. The memory map is reconfigured (see 7.2.3) to relocate everything to RAM and a debugger initialization file (see 7.1) is required.

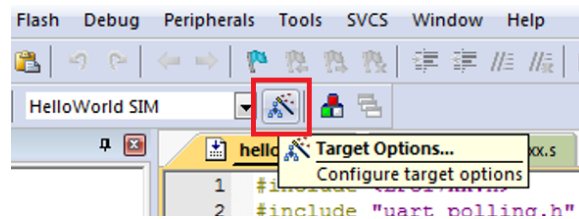


Figure 2.2: Keil IDE: Target Option Button

Execution of the HelloWorld SIM Target

Open the HelloWorld application and follow the steps listed below.

1. Click the Target Option button (see figure 2.2) to verify the following:
 - the default memory map is used (see figure2.3); and

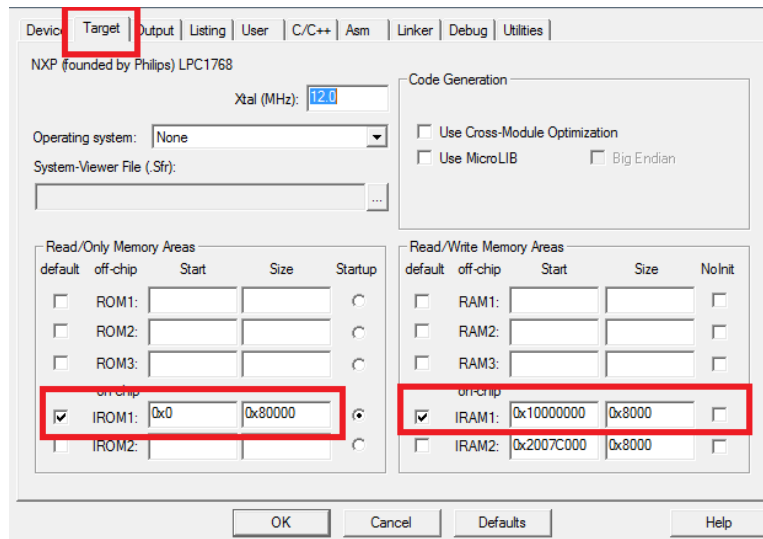


Figure 2.3: Keil IDE: Target Default Memory Map Configuration

- the simulator is used (see figure 2.4).
2. Build the HelloWorld SIM Target by pressing the Build button or F7 (see Figure 2.5).
 3. Click the Start/Stop Debug Session button or press Ctrl-F5 to enter the simulator (see Figure 2.6).

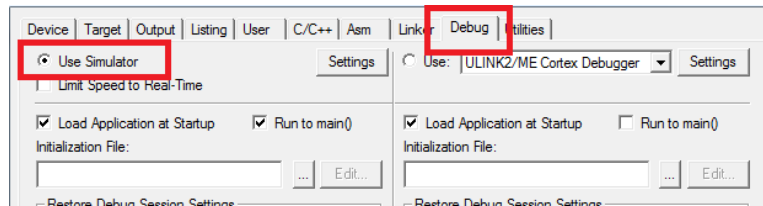


Figure 2.4: Keil IDE: Simulator Debugger Configuration

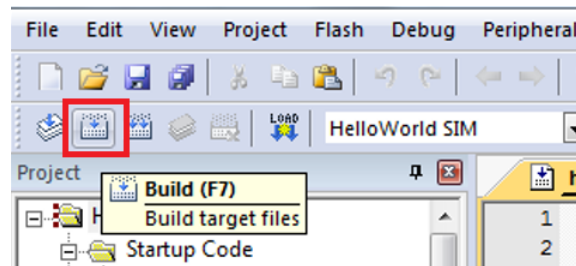


Figure 2.5: Keil IDE: Build Button

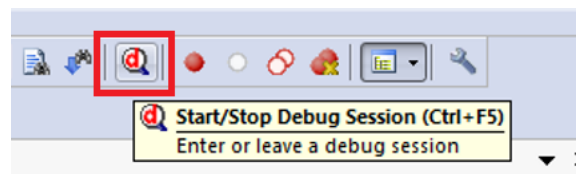


Figure 2.6: Keil IDE: Start/Stop Debug Session Button

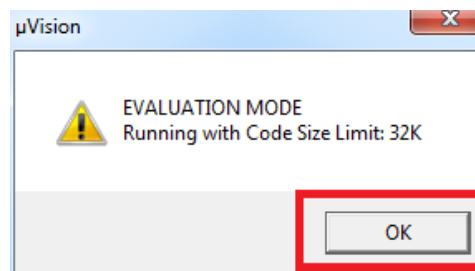


Figure 2.7: Keil IDE: Evaluation Mode Code Size Warning Dialog Box

4. Click OK when you are prompt with the code size limit of 32K in evaluation mode warning dialogue box (see Figure 2.7).
5. Choose UART#1 from the Serial Windows button (see Figure 2.8). You will see the UART#1 window shown up at the bottom right part of the screen (see Figure 2.9).
6. Click the Run button or press F5 key to execute the program under simulator (see

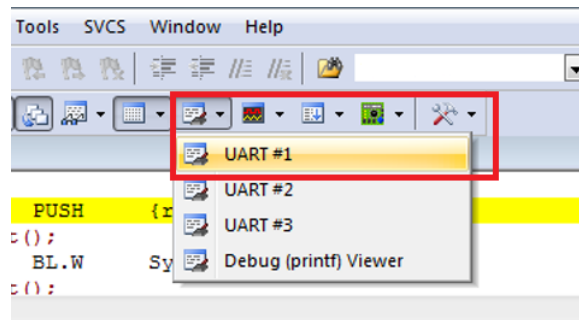


Figure 2.8: Keil IDE: Enable UART Window View

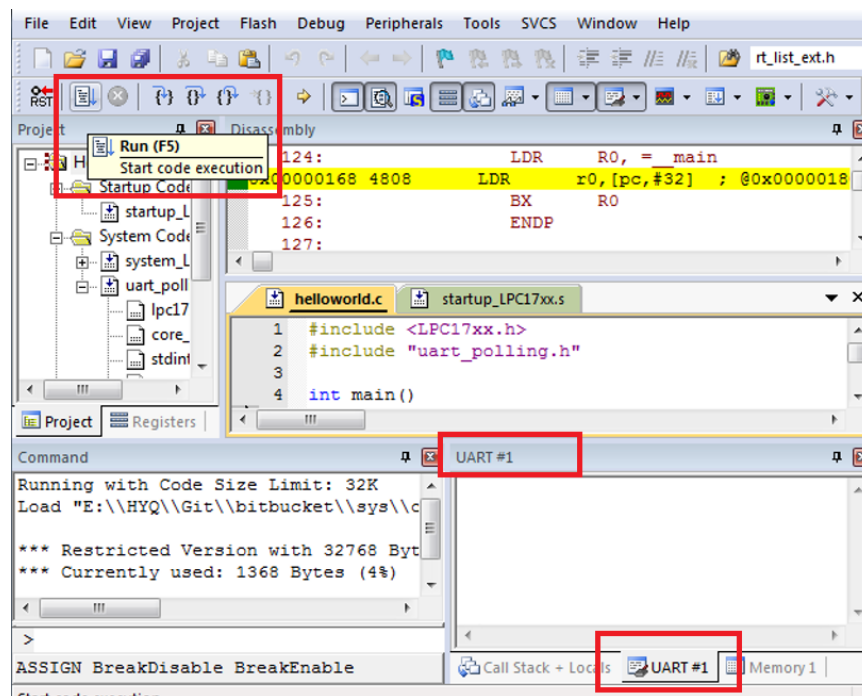


Figure 2.9: Keil IDE: UART Window View and Run Button

Figure 2.9). You will see "Hello World!" appearing in the UART#1 window in the simulator.

7. Click the Start/Stop Debug Session button or press Ctrl-F5 to exit from the simulator (see Figure 2.6).

Execution of the HelloWorld RAM Target

Open the HelloWorld application and follow the steps listed below.

1. Click the Target Option button (see figure 2.2) to verify the following:
 - the in-memory execution memory map is used (see figure 2.10); and

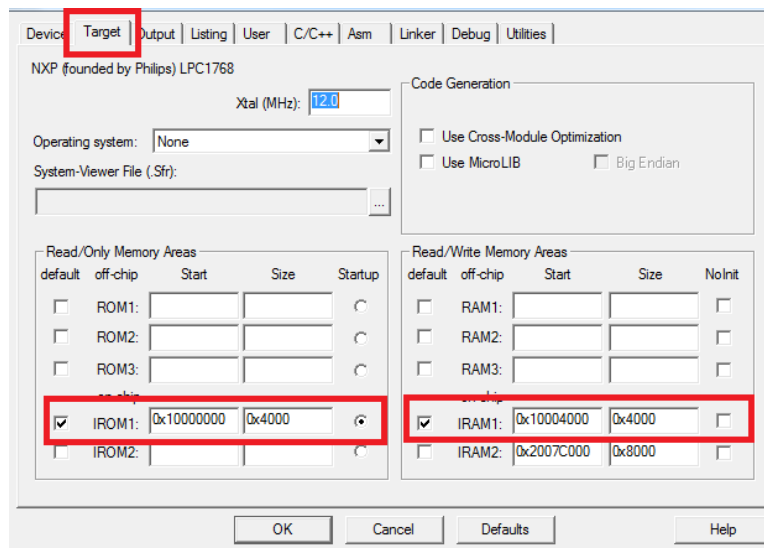


Figure 2.10: Keil IDE: Target In-Memory Execution Memory Map Configuration

- the ULINK2/ME Cortex Debugger is selected with a valid initialization file (see figure 2.11).

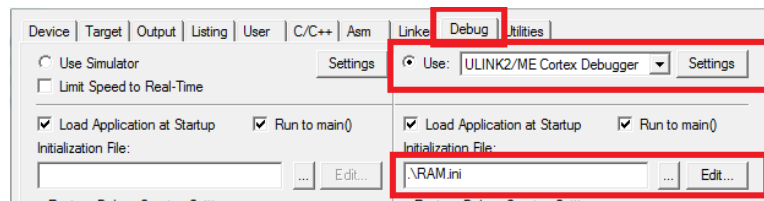
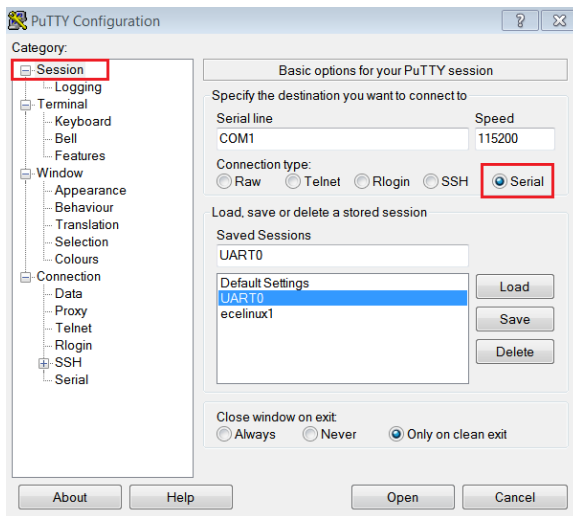


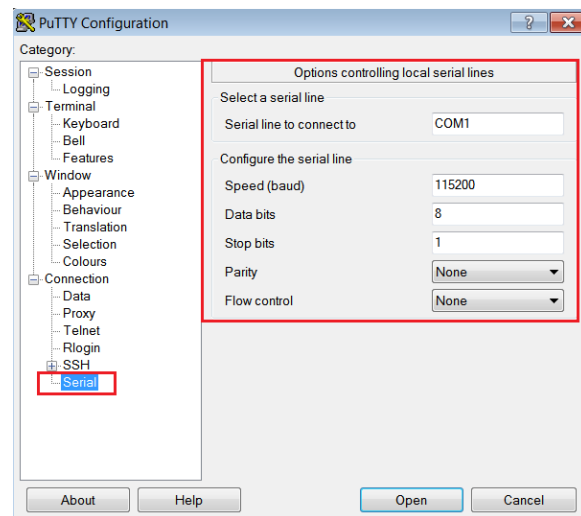
Figure 2.11: Keil IDE: ULINK2/ME Cortex Debugger Configuration

2. Build the HelloWorld RAM Target by pressing the Build button or F7 (see Figure 2.5).

3. Click the Start/Stop Debug Session button or press Ctrl-F5 to enter a debug session (see Figure 2.6). This target uses the hardware ULINK2/ME Cortex Debugger. Note you should not click the Download button to load the code to the board. When you start a debug session, the debugger initialization file (i.e. `RAM.ini`) will execute the `LOAD` command to load the code to the board.
4. Click OK when you are prompt with the code size limit of 32K in evaluation mode warning dialogue box (see Figure 2.7).
5. Start a PuTTY terminal and make sure you have the correct configuration as shown in Figures 2.12(a) and 2.12(b).



(a) PuTTY Session for Serial Port Communication



(b) PuTTY Serial Port Configuration

6. Click the Run button or press F5 key to execute the program on the board and you should see “Hello World!” displayed on PuTTY. Note that nothing will appear in the `UART#1` window because we are not using the simulator to debug.
7. Click the Start/Stop Debug Session button or press Ctrl-F5 to exit from the debug session (see Figure 2.6).

2.5 Real-time Executive Exercises

The Keil MDK-ARM contains the RealView Real-Time Library (RL-ARM), which has a Real-time Executive (RTX) named RL-RTX. The RTX kernel is a real time operating

system (RTOS) that enables one to create applications that simultaneously perform multiple functions or tasks (statically created processes). 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.

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

2.5.1 Manual of RL-RTX

The manual of the RL-RTX is accessible through the Keil MDK-ARM Help (see Figure 2.12). The highlighted sections are highly recommended to read through.

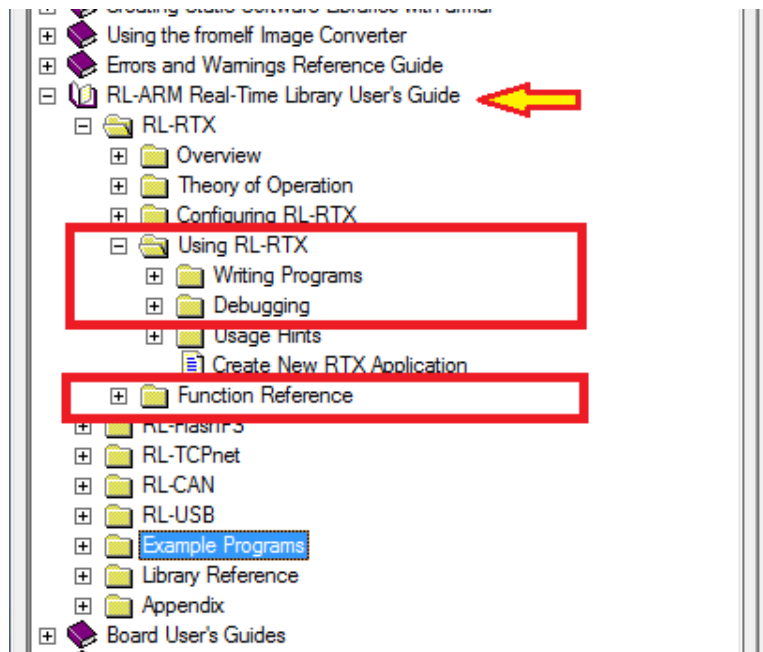


Figure 2.12: Keil IDE: RL-RTX Manual

2.5.2 Creating a Real-time Executive Application

Overview

Our goal is to create an application that simultaneously run two tasks which output to UART. The first task displays the value of a loop variable `i` every one second. The second task displays “Task2: Hellow World!” every three seconds. By using the task management and time management functions provided by RL-RTX, we could create such an application very easily.

Listing 2.1 shows the source code of the modified `helloworld.c` which now calls RTX API functions. Two tasks are defined. A task is a function whose prototype starts with the keyword `__task`. A task function normally never terminates. If a task function needs to terminate, then `os_tsk_delete_self()` is required to be called. Otherwise undefined behaviour will happen and will cost lots of your time to debug without any clue.

```
/**
 * @file: helloworld.c
 * @brief: Two simple tasks running pseduo-parallelly
 */

#include <LPC17xx.h>
#include <RTL.h>
#include <stdio.h>
#include "uart_polling.h"

__task void task1()
{
    unsigned int i = 0;

    for(;; i++)
    {
        printf("Task1: %d\n", i);
        os_dly_wait(100);
    }
}

__task void task2()
{
    while(1)
    {
```



```

    printf("Task2: HelloWorld!\n");
    os_dly_wait(300);
}
}

__task void init(void)
{
    os_tsk_create(task1, 1); // task1 at priority 1
    os_tsk_create(task2, 1); // task2 at priority 2
    os_tsk_delete_self(); // must delete itself before exiting
}

int main ()
{
    SystemInit();
    uart0_init();
    os_sys_init(init);
}

```

Listing 2.1: RTX HelloWorld C Source Code

Detailed Steps

To create an RL-RTX application for MCB1700 boards, first you need to follow the same steps as you create a regular μ Vision application. We already have a HelloWorld application from the warm-up exercises. So this step is done. Next you will need to do three extra steps to make the application an RTX application and the steps are:

1. To include the RTX Library header file `RTL.h` in the source code.

All the RTX kernel APIs are listed in `RTL.h` file which is by default located at `ARM\RV31\INC\` under the Keil software installation directory. You will need to include this file in your C file before you can call any RL-RTX API functions. Adding the following line in your source code `helloworld.c` after the `#include <LPC17xx.h>` line:

```
#include <RTL.h>
```

2. To tell the linker to link with the RTX library.

The RL-RTX kernel comes in the form of a pre-compiled library, which by default is located at `ARM\RV31\LIB\` under the Keil software installation directory. In order to use the functions in this library, one needs to link the application with RTX kernel library. This is achieved by specifying “RTX kernel” under Operating system in the target option setting (see Figure 2.13).

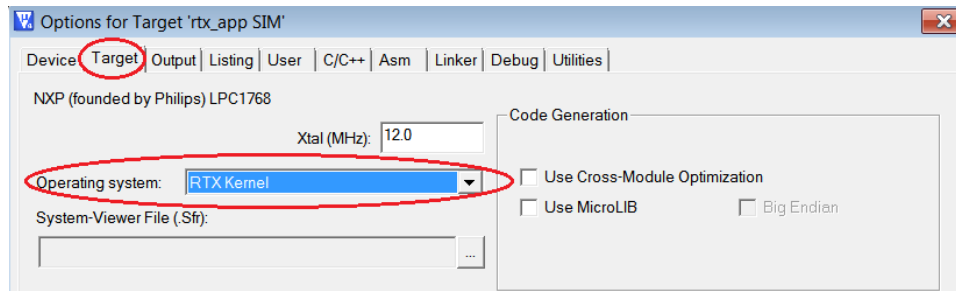


Figure 2.13: Keil IDE: Using RTX Kernel

3. To configure the RTX kernel by modifying source code of `RTX_Conf_CM.c`.
Figure 2.14 is the HelloWorld RTX project setup. Comparing it with the non-RTX μ Vision HelloWorld application used in the warm-up exercises, `RTX_Conf_CM.c` and `Retarget.c`¹ are two new files added to the project.

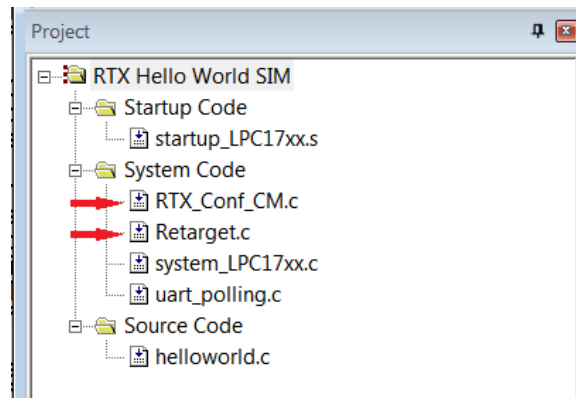


Figure 2.14: Keil IDE: RTX HelloWorld Project Files

The `RTX_Conf_CM.c` is for RTX kernel configuration such as how big the stack a task needs, how long the time slice should be and what is the CPU frequency et. al.. The configuration is at source code level through the Configuration Wizard in the μ Vision editing window (see Figure 2.15). Special attention should be paid to the following setting to avoid hard to debug problems:

¹These two files are located in the lab2 starter directory on GitHub.

- Do remember to configure the CPU speed to 100 MHz through the `RTX_Conf_CM.c` configuration wizard. Otherwise you will get wrong timing result.
- The default stack size is 200 bytes. Using `printf()` family functions such as `sprintf()` can easily cause a stack overflow. Normally 512B would be sufficient. If you are not tight on memory, 1 KB is safer.
- The number of concurrent running tasks is the maximum active tasks the application is allowed to have. If the code has more active tasks than this number, your application will run into undefined hard to debug behaviour.

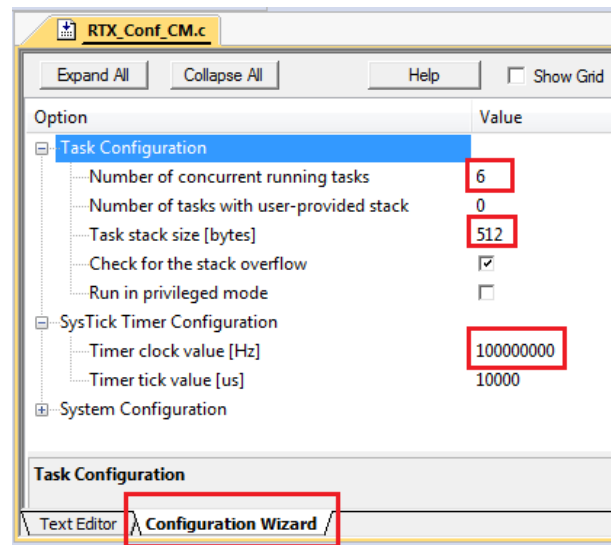


Figure 2.15: Configuring RTX Kernel

The `Retarget.c` is not RTX application specific. This file implements the low-level I/O functions that higher level I/O functions in C library such as `printf()` needs. With this file, your RTX task can call C library functions such as `printf()` and the output will appear in UART0.

Build the project and execute it both inside the simulator and on the actual board.

2.5.3 Building an RL-RTX Library for Cortex-M3

The ARM RL-RTX kernel comes with source code. You can modify the source code and build your own modified ARM RL-RTX Library. The simplest way to do this is to make a copy of the existing RTX library project for Cortex-M processors and then start to make modifications. Here are detailed steps:

1. Create a folder to hold your RTX Cortex-M3 library project. Let's name the folder RTX_CM3.
2. Go to ARM\RL\RTX under the Keil software installation directory and copy the following items to your RTX Cortex-M3 library project folder of RTX_CM3. Note you need to preserve the original directory structure when you make the copy of all the files listed below.
 - RTX_Lib_CM.uvopt
 - RTX_Lib_CM.uvproj
 - SRC\CM

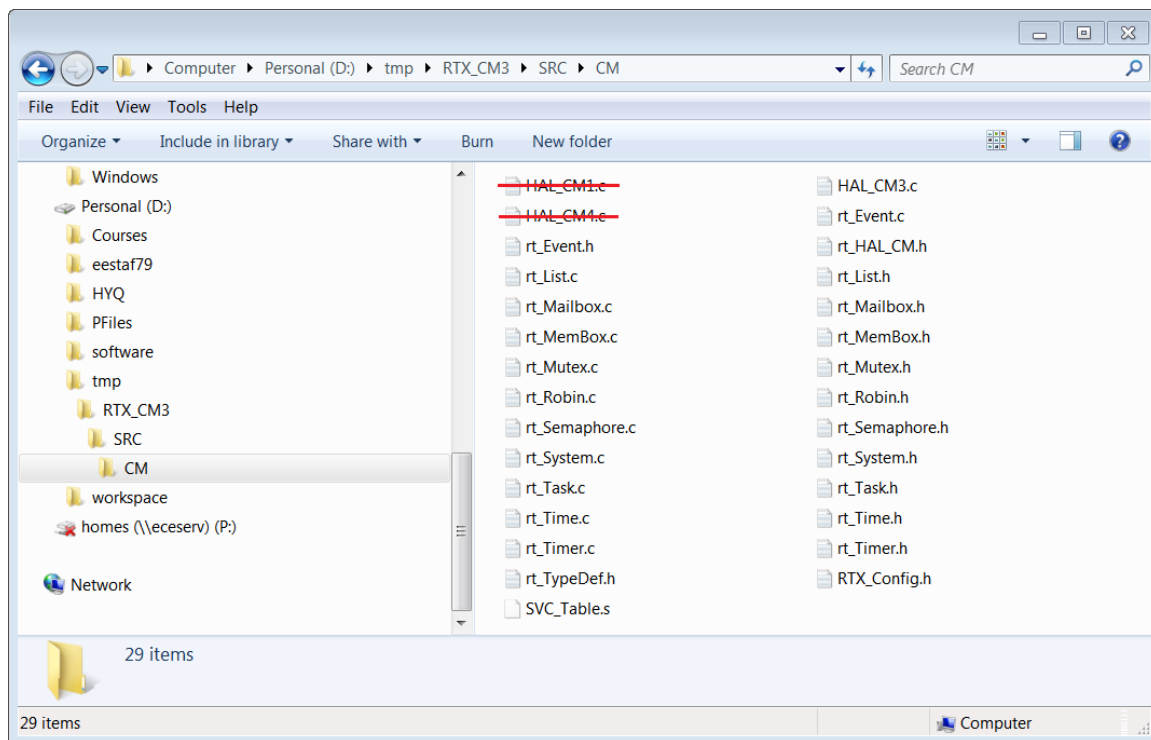


Figure 2.16: RTX Library Source Files for Cortex-M3

3. Start working on your own copy of the RTX library from now on. Remove HAL_CM1.c and HAL_CM4.c files that are under RTX_CM3\SRC\CM directory (see figure 2.16). These two files are for Cortex-M1 and Cortex-M4 processors which is not the hardware in the lab.
4. Open RTX_Lib_CM.uvproj under your RTX_CM3 directory that you newly created. Right click the CM3_LE target under the project window to bring up the menu and

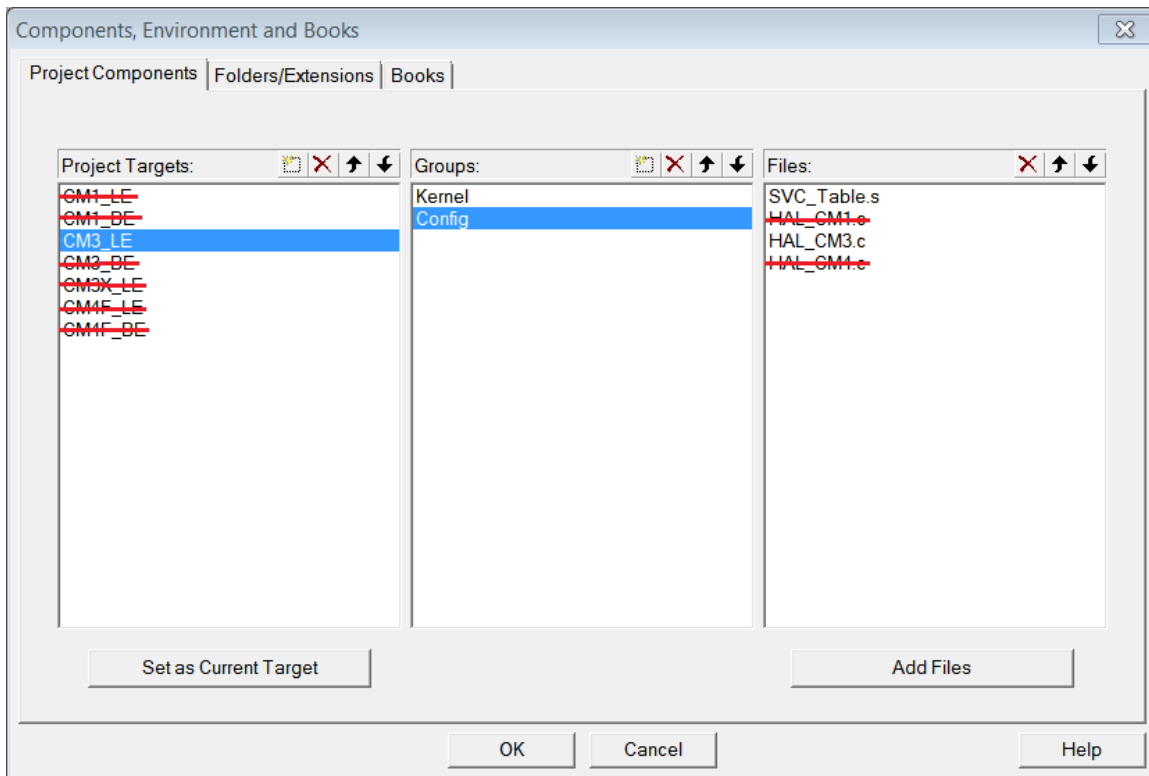


Figure 2.17: RTX Library Project Components for Cortex-M3

click “Manage Components”. You will only need the `CM3_LE` target, which supports NXP1768 on MCB1700 boards. Remove all other targets in the Project Targets window. You also need to remove the `HAL_CM1.c` and `HAL_CM4.c` files in the Files window (see Figure 2.17).

5. Click the Build button to build the library. You will notice a `.lib` file is created under `CM3_LE` folder and this is the RTX library for Cortex-M3 processor you just built. The RTX library you just build cannot be executed because it is only a library file. You will need to create an RTX Application which calls some of the functions inside the RTX library file in order to see the effect of the library. We will further discuss how to do this in Section 2.5.5.

2.5.4 Creating a Multi-project Workspace

We now have two RTX related projects. One is the RTX HelloWorld application that uses the RL-RTX built by ARM. The second is the self built RTX library for Cortex-M3

processors. We would like to create a workspace so that we can work on these two projects in the same IDE window. The steps are as follows.

1. Put the HelloWorld RTX application and the self-built RTX library for Cortex-M3 project in the same folder.
2. Click Project → New Multi-Project Workspace (see Figure 2.18). A new window appears to ask you to give a name for the multi-project workspace and let's call it `helloworld_rtxlib.uvmpw` (see Figure 2.19) and press the Save button.

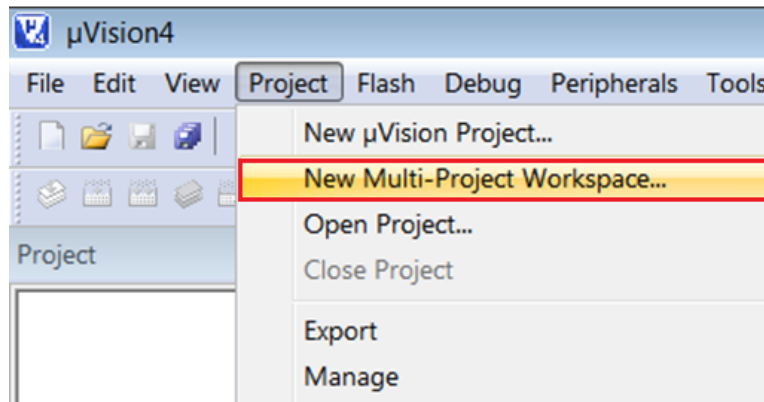


Figure 2.18: Keil IDE: Create New Multi-Project Workspace

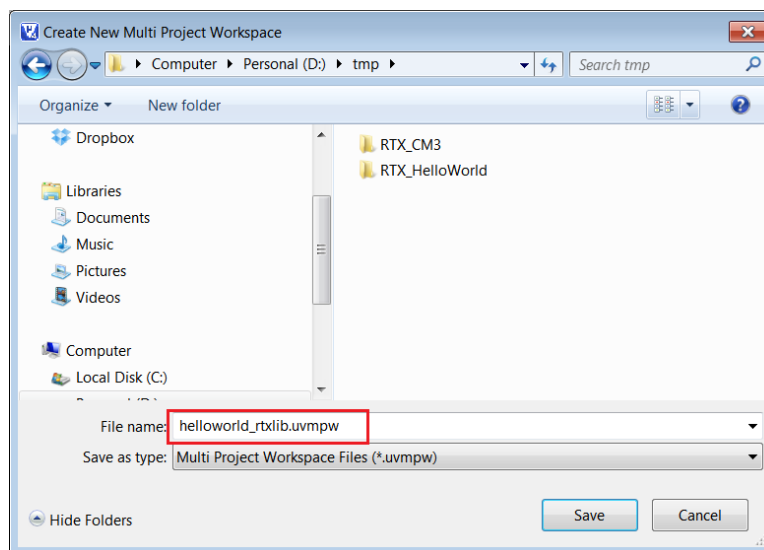


Figure 2.19: Keil IDE: Naming a New Multi-Project Workspace

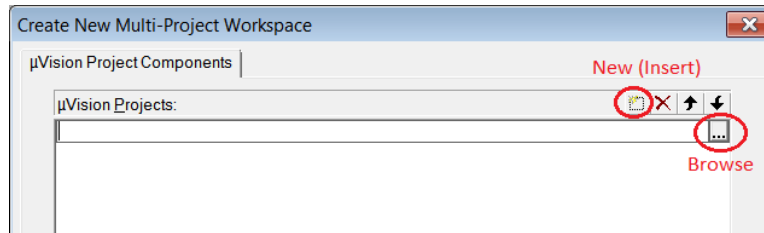


Figure 2.20: Keil IDE: Adding a μ Vision Project into Worksapce

3. A new dialogue box will pop up to ask you add μ Vision projects into the workspace. Click the New button to start adding a project and click the Browse button to select a project file (see Figure 2.20). Let's first add the RTX_CM_Lib.uvproj (see Figure 2.21). Similarly, add RTX>HelloWorld.uvproj to the workspace. Click the OK button to finish adding projects into the workspace.

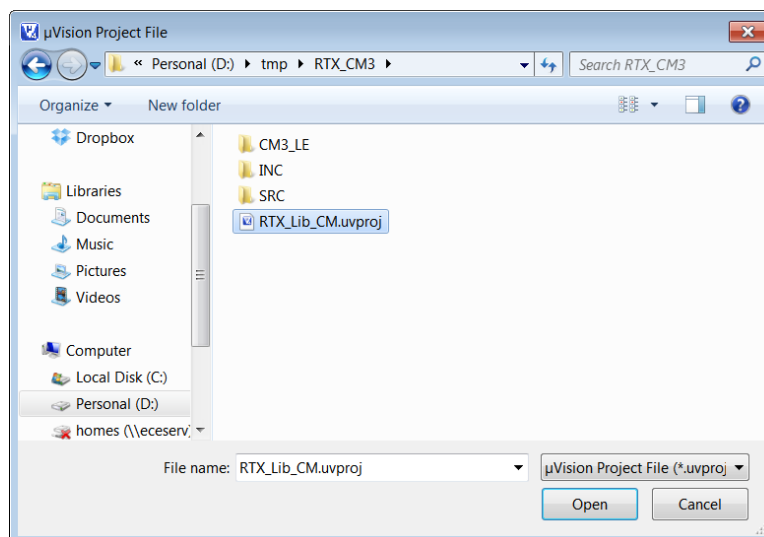


Figure 2.21: Keil IDE: Adding RTX_CM_Lib.uvproj into Worksapce

4. Two projects appear under the Project Window (see Figure 2.22. Click the Batch Build button (see Figure 2.22 to bring up the Batch Build window. Select all the targets you want to build in a batch (see Figure 2.23). By setting up batch build, multiple targets can be built by a single click of the Build button inside the batch build dialogue box.

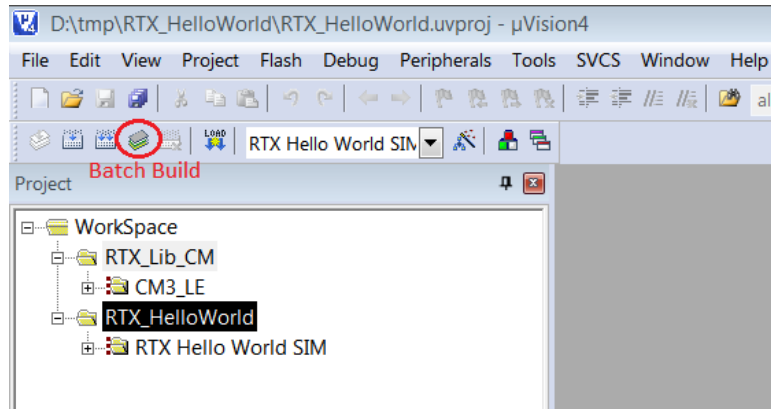


Figure 2.22: Keil IDE: Workspace with Two Projects

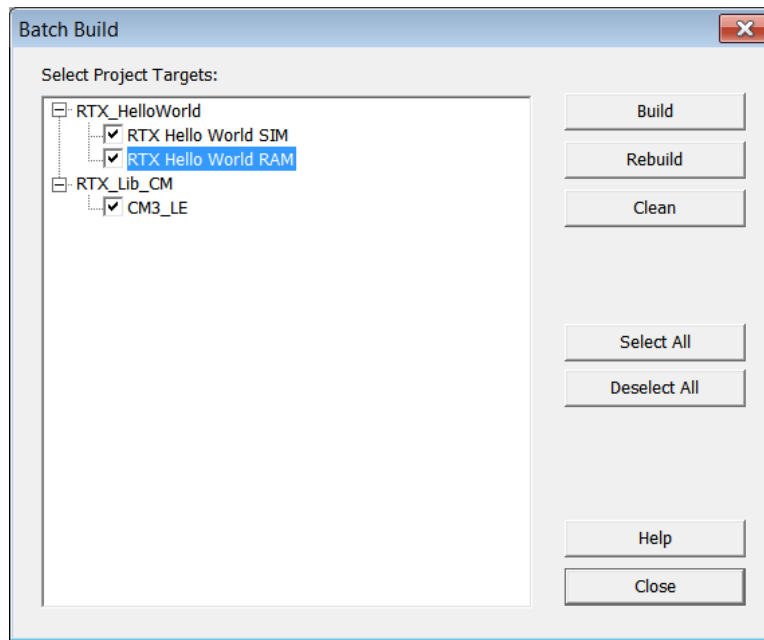


Figure 2.23: Keil IDE: Batch Build

2.5.5 Making an RTX Application with a Self-built RTX Library

Having finished the workspace setup, we now start to modify the RTX HelloWorld application so that it links with the self-built RTX Library instead of the pre-built RTX library provided by ARM. The steps are as follows.

1. Activate the RTX_HelloWorld project by highlighting the project name and right click. Then click the Set as Active Project (see Figure 2.24).

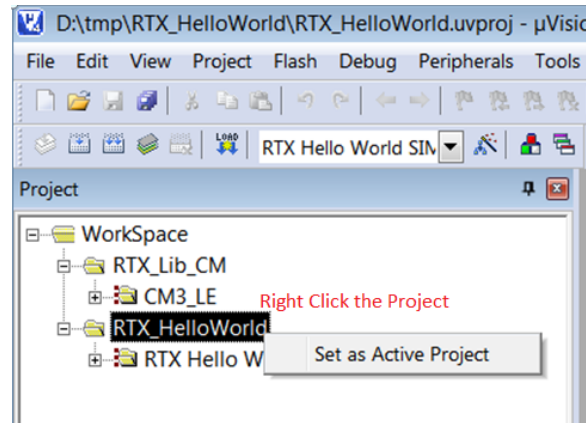


Figure 2.24: Keil IDE: Set an Active Project

2. Remove the pre-built RTX library by ARM from the target option setting (see Figure 2.25).

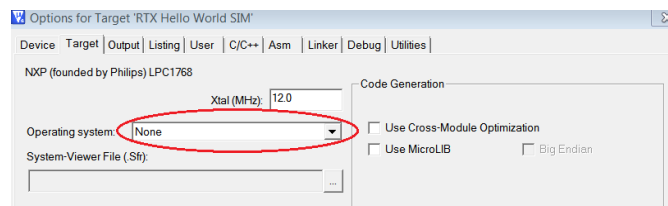


Figure 2.25: Keil IDE: Removing Linkage with Stocked RTX Library

3. Add the RTX library we built (i.e. RTX_CM3.lib) to the project (see Figure 2.26).

Build and download the updated HelloWorld RTX application. Verify it works both under simulator and on the board.

2.6 Lab2 Assignment

2.6.1 Questions

1. The RTX_lib.c is located at ARM\RV31\INC under the default Keil installation directory. What does os_active_TCB array in RTX_lib.c contain?
2. Is the TCB of os_idle_task an element in the os_active_TCB?

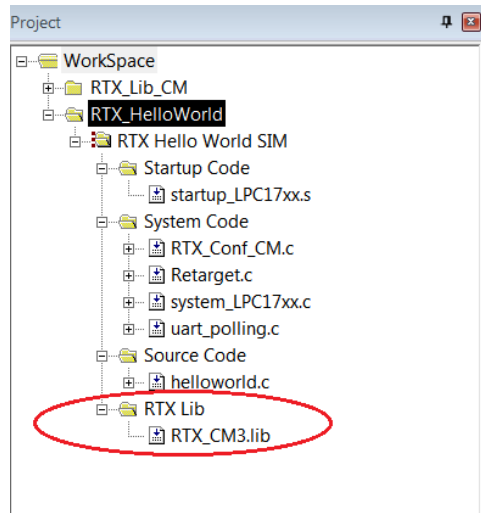


Figure 2.26: Keil IDE: Adding Your Own RTX Library

3. For a task with task ID n , what is the index of this task's TCB in the `os_active_TCB` array?

2.6.2 Programming Project Description

1. Add a function to RL-RTX API to return the number of active tasks in the system. A task is considered active when its state is not set to INACTIVE in the TCB. Note that the os idle task is a valid task that you should check the state as well.

```
int os_tsk_count_get (void);
```

Note that you need to use the SVC as the gateway to access the kernel data structure.

2. Write five simple tasks. One of the tasks calls the `os_tsk_count_get` function to test the number of active tasks in the system returned by the function.

2.6.3 Adding a New Function to the RTX Library

The self-built RTX library for Cortex-M3 for now provides the same functionality as the pre-built RTX Library provided by ARM for Cortex-M3 processors. In this lab programming project, you are asked to add one new function to the RTX Library. This means you need to modify the source code of the RTX library project.

The default `RTL.h` file is the RTX user interface. When a new RTX API function is added to the RTX, the corresponding user level interface of the function needs to be added to this file. However to make the newly added function easy to view, we instead will create a new `RTL_ext.h` file which contains the user level interface of the newly added functions. A good place to put this new header file will be in the directory where the `RTX_CM3` library project is resided. Let's create a directory and name it `INC`. Inside this directory, create a file named `RTL_ext.h`. Listing 2.2 gives the user interface of the required new function.

```
#ifndef __RTL_EXT_H__
#define __RTL_EXT_H__

#ifdef __cplusplus
extern "C" {
#endif

typedef unsigned int U32;

#if !(__TARGET_ARCH_6S_M || __TARGET_ARCH_7_M || __TARGET_ARCH_7E_M)
/*-----
 *      Functions ARM
 *-----*/
#else
/*-----
 *      Functions Cortex-M
 *-----*/
#define __SVC_0      __svc_indirect(0)

/* ECE254 Comment: added for lab2 */
extern int rt_tsk_count_get(void);
#define os_tsk_count_get() _os_tsk_get((U32)rt_tsk_count_get)
extern int _os_tsk_get (U32 p) __SVC_0;

#ifdef __cplusplus
}
#endif
#endif
#endif
/* end of file */
```

Listing 2.2: The `RTL_ext.h` C Source Code

Then we need to create the corresponding kernel functions which does the actual work of calculating how many tasks are not INACTIVE. Since this function is related to task management, it is natural to think to add the kernel function `rt_tsk_count_get()` implementation in the file `rt_Task.h` and `rt_Task.c` files. However, for the same reason for easy to view the changes we will make to the kernel. We will create two new kernel source code files and name them as `rt_Task_ext.h` (see Listing 2.3) and `rt_Task_ext.c` (see Listing 2.4). The `rt_Task_ext.c` should be added to the RTX library project under the `kernel` Group.

```
/**
 * @file:  rt_Task_ext.h
 */

extern int rt_tsk_count_get (void);

/* end of file */
```

Listing 2.3: The `rt_Task_ext.h` C Source Code

```
/**
 * @file:  rt_Task_ext.c
 */

#include "rt_TypeDef.h"
#include "RTX_Config.h"
#include "rt_System.h"
#include "rt_Task.h"
#include "rt_List.h"
#include "rt_MemBox.h"
#include "rt_Robin.h"
#include "rt_HAL_CM.h"
#include "rt_Task_ext.h"

int rt_tsk_count_get (void) {
    /* add your own code here */
    /* change the following line to return the number of active tasks */
    return 0;
}

/* end of file */
```

Listing 2.4: The `rt_Task_ext.c` Template C Source Code

2.6.4 Using the Newly Created RTX Function

To use the newly created function, you will need to include the newly created `RTL_ext.h` header file in the C source code. Assume that you have put the `RTL_ext.h` under the directory of `../../RTX_CM3/INC`, then you will add the following line:

```
#include "../../INC/RTX_CM3/RTL_ext.h"
```

Then a task can call this function to obtain the number of tasks that are not in INACTIVE state in the system. The following is an example code excerpt.

```
__task void task1() {  
    int num;  
    while (1) {  
        // ...  
        num = os_tsk_count_get();  
        printf("number of tasks:\n", num);  
        // ...  
    }  
}
```

2.7 Deliverables

2.7.1 Pre-lab Deliverables

There is no pre-lab deliverable.

2.7.2 Post-lab Deliverables

Submit a compressed archive file that contains the following:

1. Answers to questions in Section 2.6.1.
2. Source code and a README (any useful instructions for evaluation TA) of the programming project in Section 2.6.2.

Name the file `lab2_Gid.zip`, where `id` is your two digit Group ID, and submit it to Lab2 Dropbox in Learn.

Points	Description
3	Answers to lab assignment questions
2	Building a multi-project workspace that contains self-built RTX and an application that links with this RTX
3	Implementation of <code>os_tsk_count_get</code>
2	Implementation of testing tasks to test <code>os_tsk_count_get()</code>

Table 2.1: Lab2 Marking Rubric

2.8 Marking Rubric

Table 2.1 shows the rubric for marking the lab.

Chapter 3

Lab3: Task Management in RL-RTX

3.1 Objective

This lab is to learn about, and gain practical experience in ARM RL-RTX kernel programming. In particular, you will add three functions to ARM RL-RTX library.

After this lab, students will have a good understanding of:

- how to program an RTX function to read kernel task control block related data structure;
- how to block and unblock a task by using context switching related kernel functions.

Chapter 4

Lab4: Inter-process Communication by Message Passing

4.1 Objective

This lab is to learn about, and gain practical experience in message passing for the purpose of inter-process communication. In particular, you will use the POSIX message queue facility in a general Linux environment and the mailbox APIs in RL-RTX on the Keil LPC1768 board.

After this lab, students will have a good understanding of, and ability to program with

- the `fork()` and `exec()` system calls, and their use for creating a new child process on the Linux platform;
- the `wait()` family system calls, and their use to obtain the status-change information of a child process;
- the POSIX message queue facility (`<mqueue.h>`) on the Linux platform for inter-process communication.

Chapter 5

Lab5: Thread Concurrency Control

5.1 Objective

This lab is to learn about, and gain practical experience in concurrency control for the purpose of inter-thread communication by shared memory and compare its performance with inter-process/task communication by message passing. In particular, you will use the POSIX pthread library in a general Linux environment and RL-RTX on the Keil LPC1768 board.

Sharing data among threads in a general Linux environment is straight forward because threads share the same memory [4]. For the Keil RL-RTX tasks, they share the same addressing space, hence behave similar as threads.

The challenging part of sharing memory is to avoid race conditions. In a general Linux environment, pthread semaphore and mutex library calls are to be used for thread mutual exclusion. In RL-RTX, semaphore and mutex management functions are to be used for task communication mutual exclusion.

After this lab, students will have a good understanding of, and ability to program with

- the pthread `pthread_create()` and `pthread_join()` to create and join threads,
- the pthread `sem_int()`, `sem_post()` and `sem_wait()` library calls for inter-thread communication concurrency control in a general Linux environment.

Part III

Development Environment Quick Reference Guide

Chapter 6

Introduction to ECE Linux Programming Environment

6.1 Linux Hardware Environment

There are ten Linux servers that are open to ECE undergraduate students. They are `ecelinux1.uwaterloo.ca` - `ecelinux4.uwaterloo.ca` and `ecelinux6.uwaterloo.ca` - `ecelinux11.uwaterloo.ca`. The `ecelinux1-4` can be accessed off-campus as well as on campus. The rest of these machines are only accessible on-campus and consoles are located at E5-5038 whose door code is printed in the welcome message when you login onto any one of the Linux workstations. Linux CentOS is installed on all these machines.

6.2 How to Connect to Linux Servers

The servers are accessed by remote login. You will need to have a terminal client that supports secure shell (ssh) installed before you can log onto one of the `ecelinux` servers. Two popular terminal clients are:

- Windows secure shell client and
- PuTTY .

Both terminal clients are installed on ECE Nexus machines. Use your WatIAM credential to login onto these machines.

To use the SSH Secure shell windows client, click Start → All Programs → Internet Tools → **Secure shell client**. Figure 6.1(a) is a screen shot taken on a Nexus computer.

To use the PuTTY, click Start → All Programs → Portable PuTTY → **PuTTY**. Figure 6.1(b) is a screen shot taken on a Nexus computer.

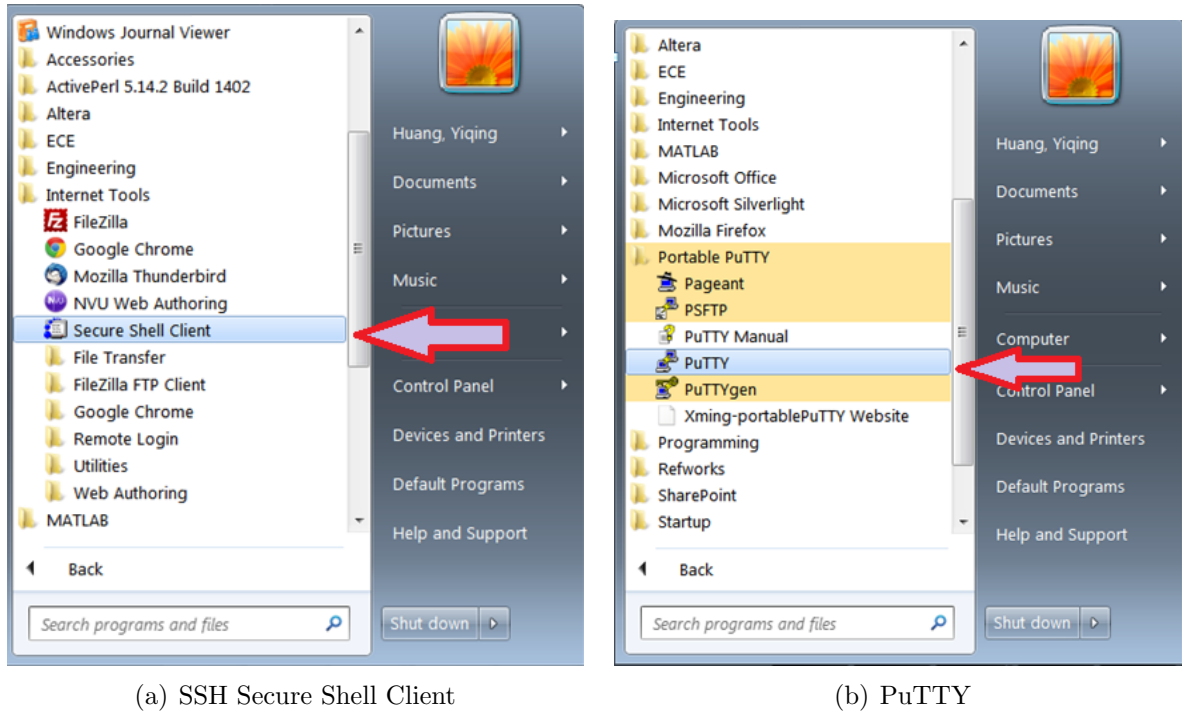


Figure 6.1: Invoking Terminal Clients on an ECE Nexus PC

6.3 Work Environment Setup

6.3.1 Setting up Remote Linux Graphic Support

After you login, you will notice that you are in a command line shell environment, one where GUI applications cannot be run. For example the `ddd` debugger is an important GUI application you will most likely want to use. You will need to configure your environment to support GUI application to be able to display graphics on your terminal.

First start the X server on your local machine. Xming is a popular and free X server which is installed on ECE Nexus computers. Start Xming by clicking All Programs → Xming (see Figure 6.2).

The second step is to configure the terminal client so that X11 forwarding is enabled.

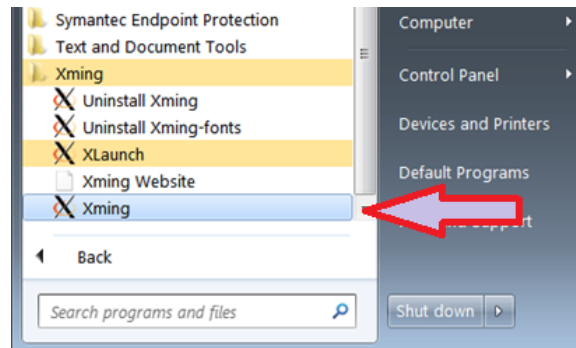
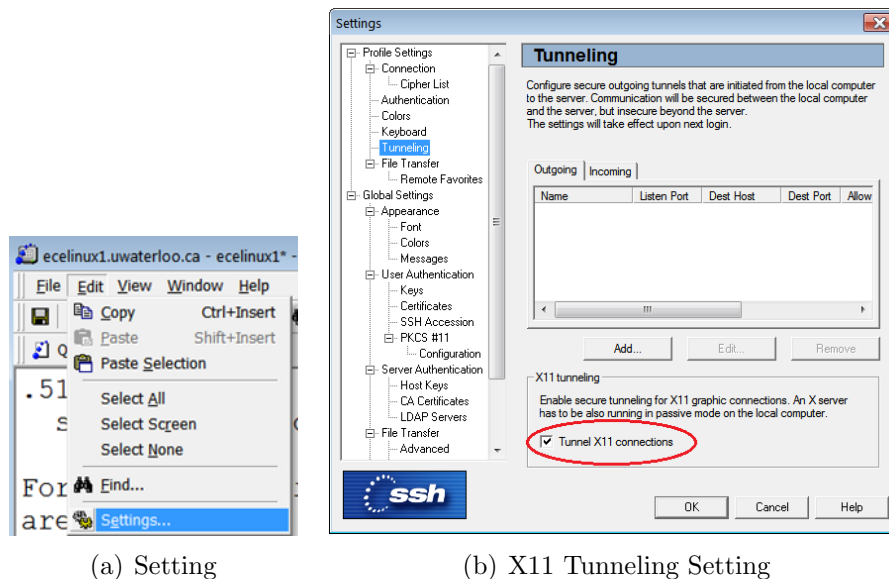


Figure 6.2: Invoking Xming on an ECE Nexus Computer



(a) Setting

(b) X11 Tunneling Setting

Figure 6.3: SSH Secure Shell Client X11 Setting

For SSH secure shell client, select Edit → Settings to bring up the setting dialog window (see Figure 6.3(a)). Go to Profile Settings → Tunneling and put a check mark beside the Tunnel X11 connection item (see Figure 6.3(b)).

For PuTTY, go to Connection → SSH → X11 and put a check mark beside the Enable X11 forwarding item (see Figure 6.4).

6.3.2 Mapping Linux Account on Nexus

Your ECE Linux files can be access through network drive mapping on Nexus machines. Open My Computer → Tools → Map Network Drive (see Figure 6.5(a)). Under Driver,

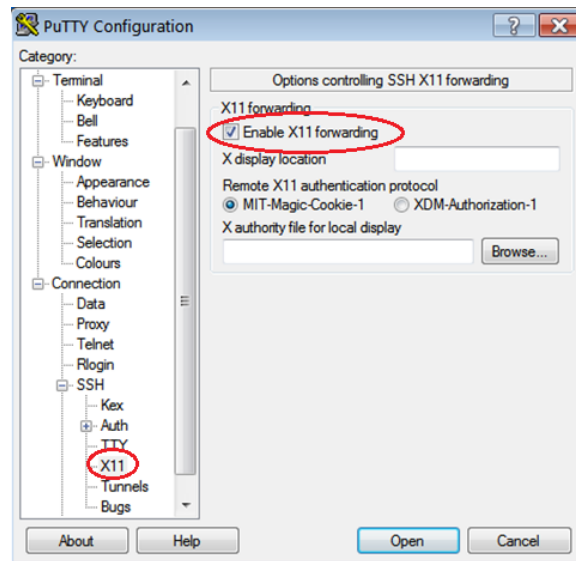
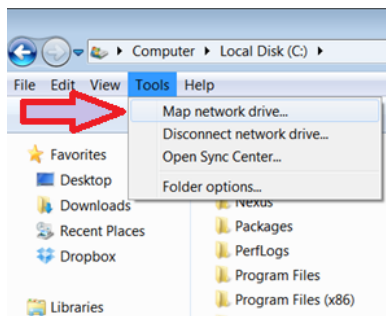
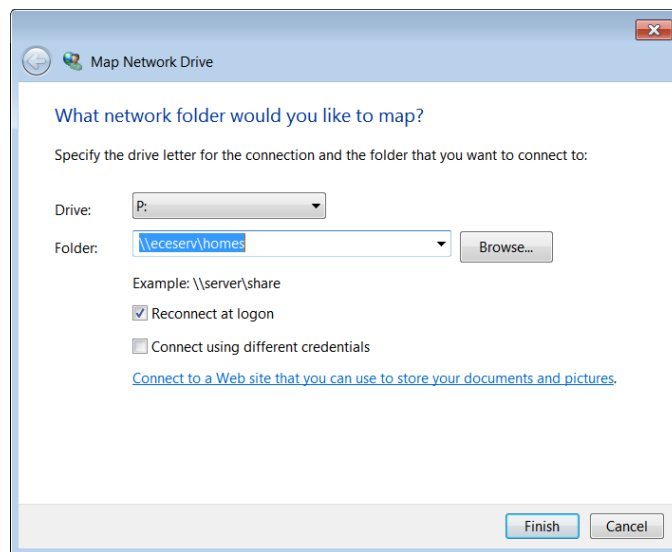


Figure 6.4: PuTTY X11 Forwarding Setting

pick a drive letter, say P. Under Folder, type `\\eceserv\homes`. Put a check mark beside Reconnect at logon item and click Finish (see Figure 6.5(b)). You will use your WatIAM credential to authenticate yourself.



(a) Prepare to Map a Network Drive



(b) Configuring Network Drive Mapping

Figure 6.5: SSH Secure Shell Client X11 Setting

6.4 Basic Software Development Tools

To develop a program, there are three important steps. First, a program is started from source code written by programmers. Second, the source code is then compiled into object code, which is a binary. Non-trivial project normally contains more than one source file. Each source file is compiled into one object code and the linker would finally link all the object code to generate the final target, which is the executable that runs. People refer to compiling and linking as building a target. It is very rare that the target will run perfectly the first time it is built. Most of time you need to fix defects and bugs in your code and this is the third step. The debugger is a tool to help you identify the bug and fix it. Table 6.1 shows the key steps in programming work flow, the corresponding tools are needed and some example tools provided by a general purpose Linux operating system.

Task	Tool	Examples
Editing the source code	Editor	vi, emacs
Compiling the source code	Compiler	gcc
Debugging the program	Debugger	gdb, ddd

Table 6.1: Programming Steps and Tools

At each development step, you will have a choice of tools to get the work done. Most of you probably are more familiar with a certain Integrated Development Environment (IDE) which integrates all these tools into a single environment. For example Eclipse and Visual Studio. However another choice is that you pick your favorite tool in each programming step and build your own tool chain. Many seasoned Linux programmers build their own tool chains. A few popular tools are introduced in the following subsections.

6.4.1 Editor

Some editors are designed to better suit programmers' needs than others. The *vi* (*vim* and *gvim* belong to the vi family) and *emacs* (*xemacs* belongs to emacs family) are the two most popular editors for programming purposes.

Two simple notepad editors *pico* and *nano* are also available for a simple editing job. These editors are not designed for serious programming activity. To use one of them to write your first *Hello World* program is fine though.

After you finish editing the C source code, give the file name an extension of *.c*. Listing 6.1 is the source code of printing "Hello World!" to the screen.

```

#include <stdio.h>
#include <stdlib.h>

int main()
{
    printf("Hello World!\n");
    exit(0);
}

```

Listing 6.1: HelloWorld C source Code

Next we will compile and execute the program.

6.4.2 C Compiler

The executable *gcc* is the GNU project C and C++ compiler. To compile the HelloWorld source code in Listing 6.1, type the following command at the prompt:

```
gcc helloworld.c
```

You will notice that a new file named `a.out` is generated. This is the executable generated from the source code. To run it, type the following command at the prompt and hit Enter.

```
./a.out
```

The result is “Hello World!” appearing on the screen.

You can also instruct the compiler to name the executable another name instead of the default `a.out`. The `-o` option in *gcc* allows one to name the executable a name. For example, the following command will generate an executable named “`helloworld.out`”.

```
gcc helloworld.c -o helloworld.out
```

although there is no requirement that the name ends in `.out`.

6.4.3 Debugger

The GNU debugger *gdb* is a command line debugger. Many GUI debugger uses *gdb* as the back-end engine. One GNU GUI debugger is *ddd*. It has a powerful data display functionality.

GDB needs to read debugging information from the binary in order to be able to help one to debug the code. The `-g` option in `gcc` tells the compiler to produce such debugging information in the generated executable. In order to use `gdb` to debug our simple HelloWorld program, we need to compile it with the following command:

```
gcc -g helloworld.c -o helloworld.out
```

The following command calls `gdb` to debug the `helloworld.out`

```
gdb helloworld.out
```

This starts a `gdb` session. At the `(gdb)` prompt, you can issue `gdb` command such as `b main` to set up a break point at the entry point of `main` function. The `l` lists source code. The `n` steps to the next statement in the same function. The `s` steps into a function. The `p` prints a variable value provided you supply the name of the variable. Type `h` to see more `gdb` commands.

Compared to `gdb` command line interface, the `ddd` GUI interface is more user friendly and easy to use. To start a `ddd` session, type the command

```
ddd
```

and click `File → Open Program` to open an executable such as `helloworld.out`. You will then see `gdb` console in the bottom window with the source window on top of the `gdb` console window. You could see the value of variables of the program through the data window, which is on top of the source code window. Select `View →` to toggle all these three windows.

6.5 More on Development Tools

For any non-trivial software project, it normally contains multiple source code files. Developers need tools to manage the project build process. Also project normally are done by several developers. A version control tool is also needed.

6.5.1 How to Automate Build

`Make` is an utility to automate the build process. Compilation is a cpu-intensive job and one only wants to re-compile the file that has been changed when you build a target instead of re-compile all source file regardless. The **make** utility uses a Makefile to specify

the dependency of object files and automatically recompile files that has been modified after the last target is built.

In a Makefile, one specifies the targets to be built, what prerequisites the target depends on and what commands are used to build the target given these prerequisites. These are the *rules* contained in Makefile. The Makefile has its own syntax and is a good reference on Make. The general form of a Makefile rule is:

```
target ...: prerequisites ...
    recipe
    ...
    ...
```

One important note is that each recipe line starts with a TAB key rather than white spaces.

Listing 6.2 is our first attempt to write a very simple Makefile.

```
helloworld.out: helloworld.c
    gcc -o helloworld.out helloworld.c
```

Listing 6.2: Hello World Makefile: First Attempt

Our second attempt is to break the single line gcc command into two steps. First is to *compile* the source code into object code .o file. Second is to *link* the object code to one final executable binary. Listing 6.3 is our second attempted version of Makefile.

```
helloworld.out: helloworld.o
    gcc -o helloworld.out helloworld.o

helloworld.o: helloworld.c
    gcc -c helloworld.c
```

Listing 6.3: Hello World Makefile: Second Attempt

When a project contains multiple files, separating object code compilation and linking stages would give a clear dependency relationship among code. Assume that we now need to build a project that contains two source files **src1.c** and **src2.c** and we want the final executable to be named as **app.out**. Listing 6.4 is a typical example Makefile that is closer to what you will see in the real world.

```
all: app.out

app.out: src1.o src2.o
    gcc -o app.out src1.o src2.o

src1.o: src1.c
    gcc -c src1.c
```

```

src2.o: src2.c
    gcc -c src2.c

clean:
    rm *.o app.out

```

Listing 6.4: A More Real Makefile: First Attempt

We also have added a target named *clean* so that `make clean` will clean the build.

So far we have seen the Makefile contains *explicit rules*. Makefile can also contain *implicit rules*, *variable definitions*, *directives* and *comments*. Listing 6.5 is a Makefile that is used in the real world.

```

1 # Makefile to build app.out
2 CC=gcc
3 CFLAGS=-Wall -g
4 LD=gcc
5 LDFLAGS=-g
6
7 OBJS=src1.o src2.o
8
9 all: app.out
10 app.out: $(OBJS)
11     $(LD) $(CFLAGS) $(LDFLAGS) -o $@ $(OBJS)
12 .c.o:
13     $(CC) $(CFLAGS) -c $<
14 .PHONY: clean
15 clean:
16     rm -f *.o *.out

```

Listing 6.5: A Real World Makefile

Line 1 is a comment. Lines 2 – 7 are variable definitions. Line 12 is an implicit rule to generate .o file for each .c file. See <http://www.gnu.org/software/make/manual/make.html> if you want to explore more of makefile.

6.5.2 Version Control Software

ECE Linux has the following version control software installed.

- CVS
- SVN
- Git

Choose your favourite one. Any one of them will be able to help you manage ECE254 code repository. Git is getting more and more popularity these days. If you decide to use GitHub to host your repository, please make sure it is a private one. Go to <http://github.com/edu> to see how to obtain five private repositories for two years on GitHub for free.

6.5.3 Integrated Development Environment

Eclipse with C/C++ Plug-in has been installed on all ECE Linux servers. You will need to first set up the X Window support properly (see section 6.3.1, then type the following command to bring up the eclipse frontend.

```
/opt/eclipse64/eclipse
```

This eclipse is not the same as the default eclipse under `/usr/bin` directory. You may find running eclipse over network performs poorly at home though. It depends on how fast your network speed is.

If you have Linux operating system installed on your own personal computer, then you can download the eclipse with C/C++ plugin from the eclipse web site and then run it from your own local computer. However you should always make sure the program will also work on ecelinux machines, which is the environment TAs would be using to test your code.

6.6 Man Page

Linux provides manual pages. You can use the command `man` followed by the specific command or function you are interested in to obtain detailed information.

Man pages are grouped into sections. We list frequently used sections here:

- Section 1 contains user commands.
- Section 2 contains system calls
- Section 3 contains library functions
- Section 7 covers conventions and miscellany.

To specify which section you want to see, provide the section number after the `man` command. For example,

```
man 2 stat
```

shows the system call `stat` man page. If you omit the 2 in the command, then it will return the command `stat` man page.

You can also use `man -k` or `apropos` followed by a string to obtain a list of man pages that contain the string. The Whatis database is searched and now run `man whatis` to see more details of `Whatis`.

Chapter 7

Keil Software Development Tools

The Keil MDK-ARM development tools are used for MCB1700 boards in our lab. The tools include

- μ Vision4 IDE which combines the project manager, source code editor and program debugger into one environment;
- ARM compiler, assembler, linker and utilities;
- Real-Time Library which includes an RTX Real-Time Kernel with source code;
- ULINK USB-JTAG Adapter which allows you to debug the embedded programs running on the board.

The MDK-Lite is the evaluation version and does not require a license. However it has a code size limit of 32KB, which is adequate for your course projects. The MDK-Lite version 4.60.0.0 ¹ is installed on all lab computers. If you want to install the software on your own computer, Appendix B gives detailed instruction.

7.1 Creating an Application in μ Vision4 IDE

To get started with the Keil IDE, the MDK-ARM Primer

[http : //www.keil.com/support/man/docs/gsac/](http://www.keil.com/support/man/docs/gsac/)

¹The latest version is 5.1.0.0 We have not fully tested the supplied sample code with this version. This manual is based on version 4.60.0.0.

is a good place to start. We will walk you through the IDE by developing a simple HelloWorld application which displays Hello World through the UART0 that is connected to the lab PC. Note the HelloWorld example uses polling rather than interrupt.

7.1.1 Create a New Project

1. Create a folder named “HelloWorld” on your computer ².
2. Copy the following files to “HelloWorld” folder:
 - manual_code\Startup\uart_polling.h
 - manual_code\Startup\uart_polling.c
 - manual_code\Startup\system.LPC17xx.c
3. Create a new μ Vision project by click
 - Project \rightarrow New μ Vision Project (See Figure 7.1)

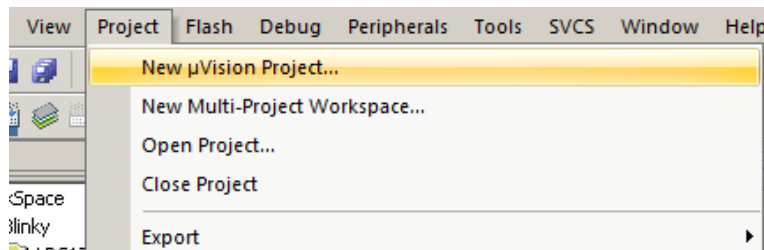


Figure 7.1: Keil IDE: Create a New Project

- Choose NXP(Founded by Philips) \rightarrow LPC1768 (See Figure 7.2(a) and Figure 7.2(b))
- Answer “Yes” to copy the startup code (See Figure 7.3).

7.1.2 Managing Project Components

You just finished creating a new project. On the left side of the IDE is the Project window and expand all objects, you will see the default project setup as shown in Figure 7.4.

²The folder path name should not contain spaces on Nexus computers.

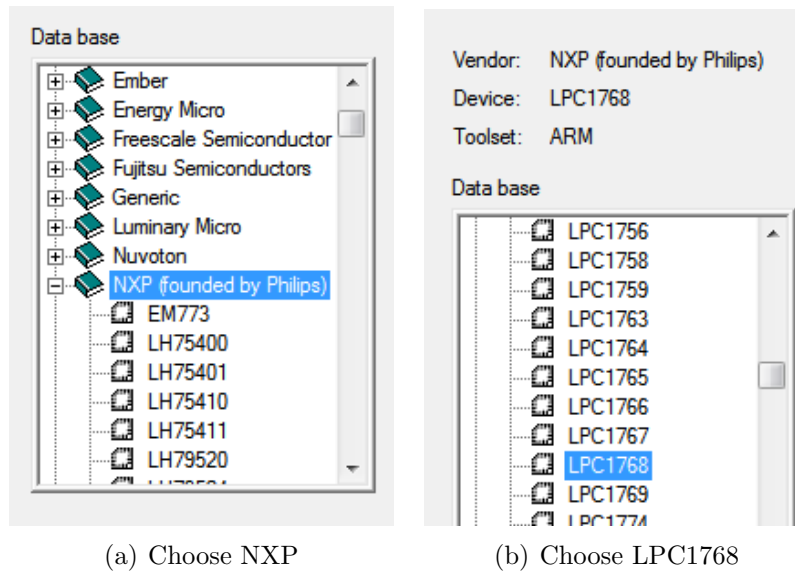


Figure 7.2: Keil IDE: Choose MCU

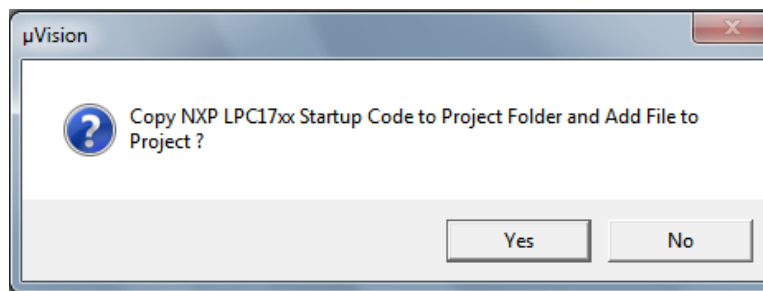


Figure 7.3: Keil IDE: Copy Startup Code

1. Rename the Target

The “Target 1” is the default name of the project build target and you can rename it by clicking the target name to highlight it and then click the highlighted name to input a new target name, say “HelloWorld SIM”

2. Rename the Source Group

The IDE allows you to group source files to different groups to better manage the source code. By default “Source Group 1” is created and the startup code “startup_LPC17xx.s” is put under this source group. You can rename the source group by clicking the source group name to highlight it and then click again to input a new name, say “Startup Code”.

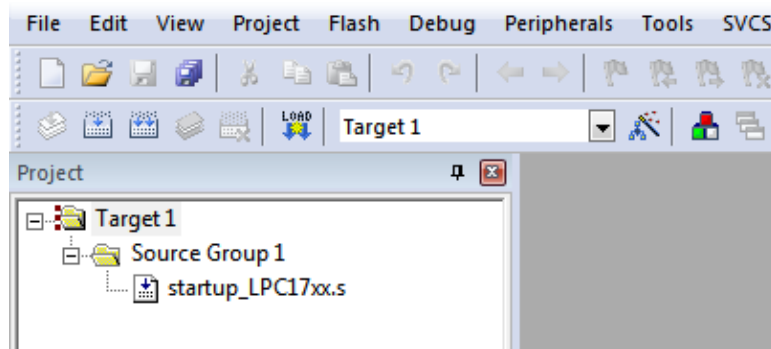


Figure 7.4: Keil IDE: A default new project

3. Add a New Source Group

You can add new source groups to your project. Click “Project → Manage” → “Components, Environment, Books...” (See Figure 7.5 You can now add new source

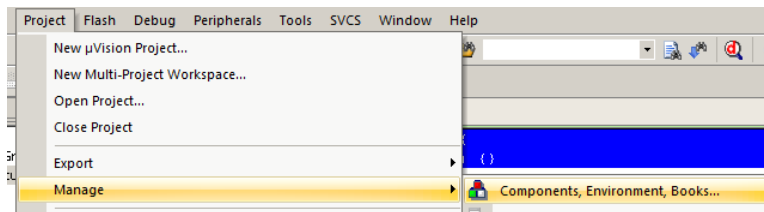


Figure 7.5: Keil IDE: Manage Project Components

groups to the project. Let’s add “System Code” and “Source Code” source groups to the project (See Figure 7.6. Your project will now look like Figure 7.7

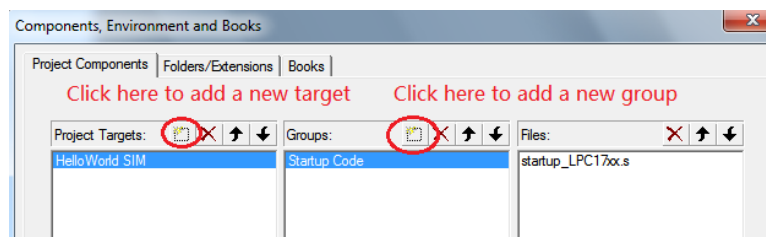


Figure 7.6: Keil IDE: Manage Components Window

4. Add Source Code to a Source Group

Now add “system_LPC17xx.c” to “System Code” group by double clicking the source group and choose the file from the file window. Double clicking the file name will add

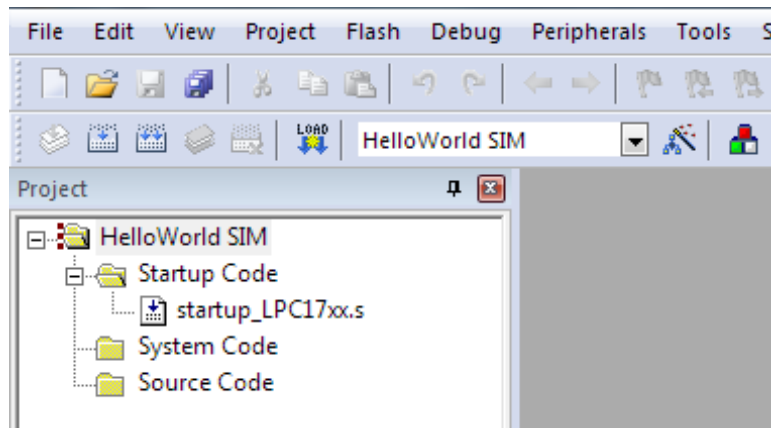


Figure 7.7: Keil IDE: Updated Project Profile

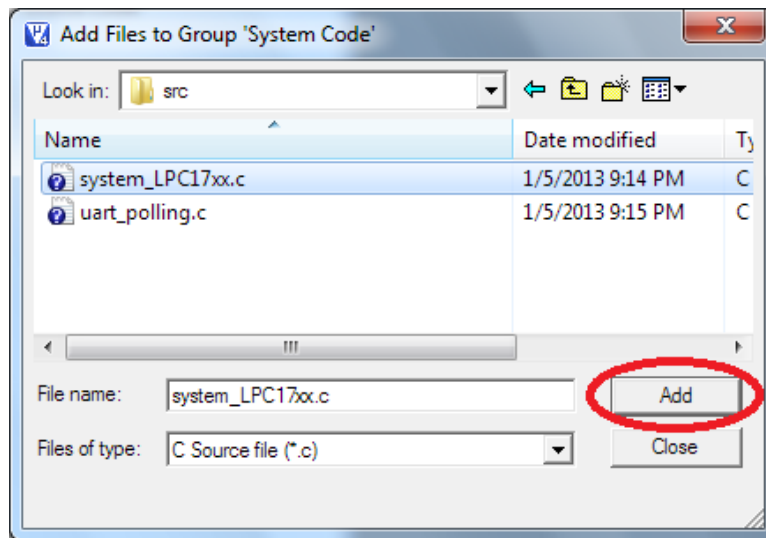


Figure 7.8: Keil IDE: Add Source File to Source Group

the file to the source group. Or you can select the file and click the “Add” button at the lower right corner of the window (See Figure 7.8).

Similarly, add “uart_polling.c” to “Source Code” group. Your project will now look like Figure 7.9.

5. Create a new source file

The project does not have a main function yet. We now create a new file by clicking the “New” button (See Figure 7.10). Before typing anything to the file, save the file and name it “main.c”. Put the following code to the main.c file:

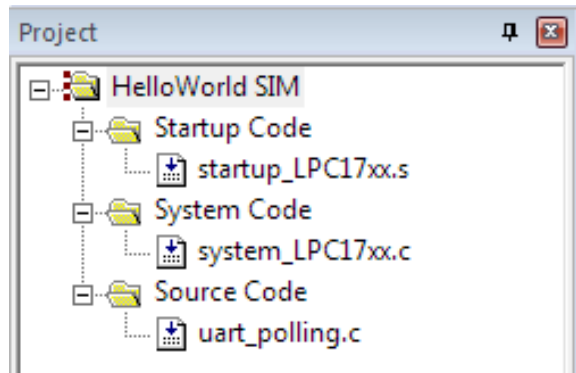


Figure 7.9: Keil IDE: Updated Project Profile

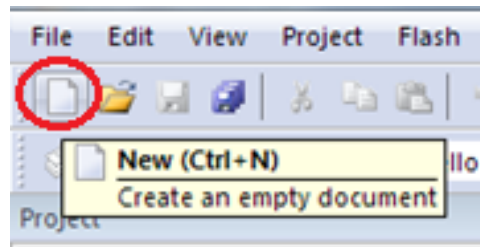


Figure 7.10: Keil IDE: Create New File

```
#include <LPC17xx.h>
#include "uart_polling.h"
int main() {
    SystemInit();
    uart0_init();
    uart0_put_string("Hello World!\n\r");
    return 0;
}
```

Then add main.c to the “Source Code” group. Your final project would look like the screen shot in Figure 7.11.

7.1.3 Build and Download

To build the target, click the “Build” button (see Figure 7.12). If nothing is wrong, the build output window at the bottom of the IDE will show a log similar like the one shown in Figure 7.13

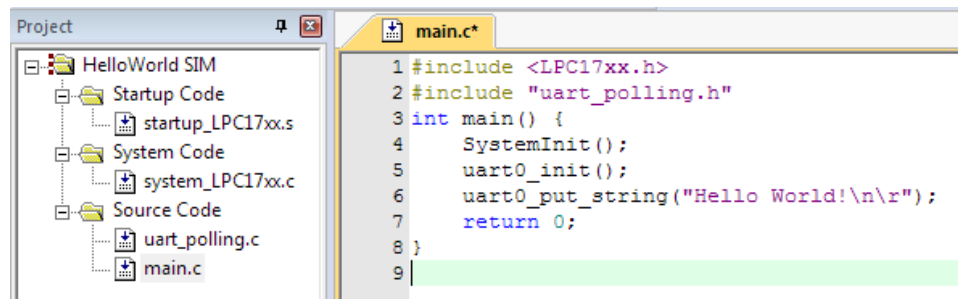


Figure 7.11: Keil IDE: Final Project Setting

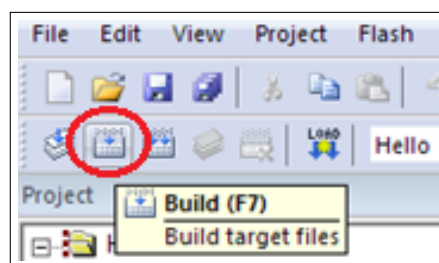


Figure 7.12: Keil IDE: Build Target

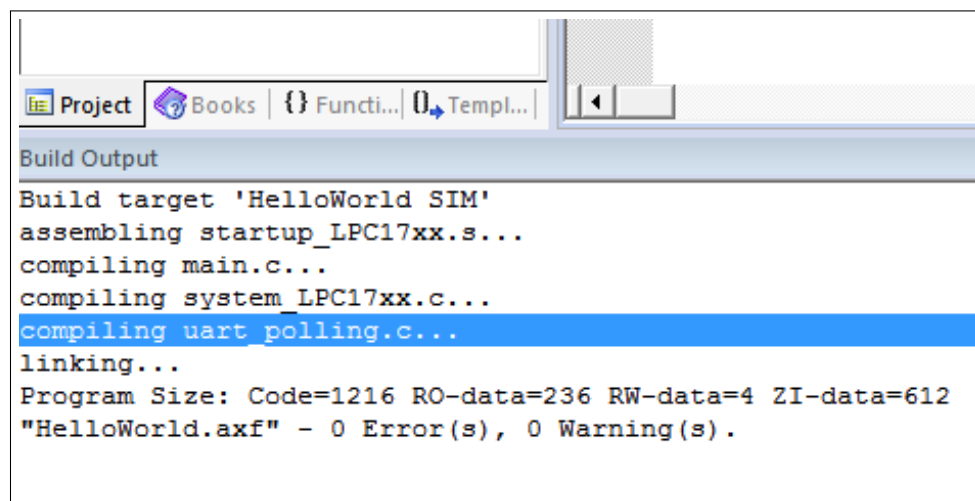


Figure 7.13: Keil IDE: Build Target

To download the code to the board, click the “Load” button (see Figure 7.14). The download is through the Ulink-Me.

You will need a terminal emulator such as PuTTY that talks directly to COM ports in order to see output of the serial port. Open up the PuTTY on your PC and choose COM1. An example PuTTY Serial configuration is shown in Figures 7.15(a) and 7.15(b). Press

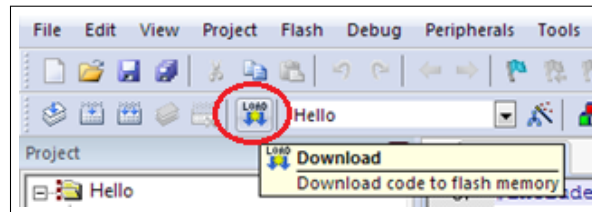
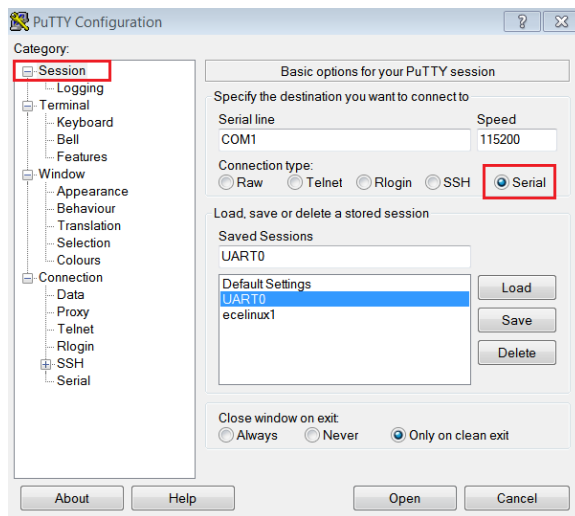
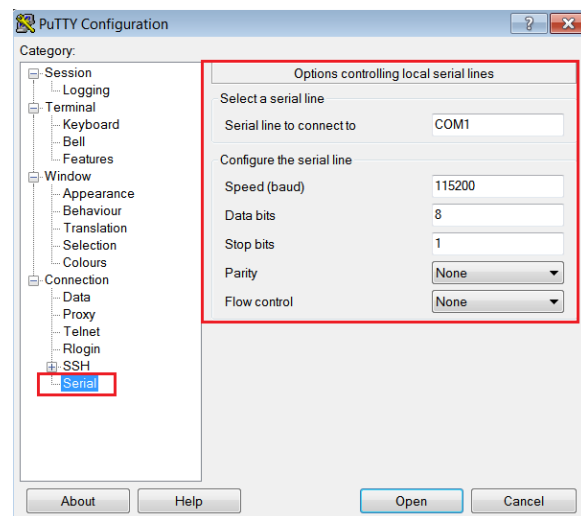


Figure 7.14: Keil IDE: Download Target to Flash

the Reset button on the board and you should see “Hello World!” displayed on PuTTY.



(a) PuTTY Session for Serial Port Communication



(b) PuTTY Serial Port Configuration

7.2 Debugging

You can use either the simulator within the IDE or the ULINK Cortex Debugger to debug your program. To start a debug session, click Debug→Start/Stop Debug Session from the IDE menu bar or press Ctrl+F5. Figure 7.15 shows the a typical debug session interface.

As any other GUI debugger, the IDE allows you to set up break points and step through your source code. It also shows the registers, which is very helpful for debugging low level code. Click View, Debug and Peripherals from the IDE menu bar and explore the functionality of the debugger.

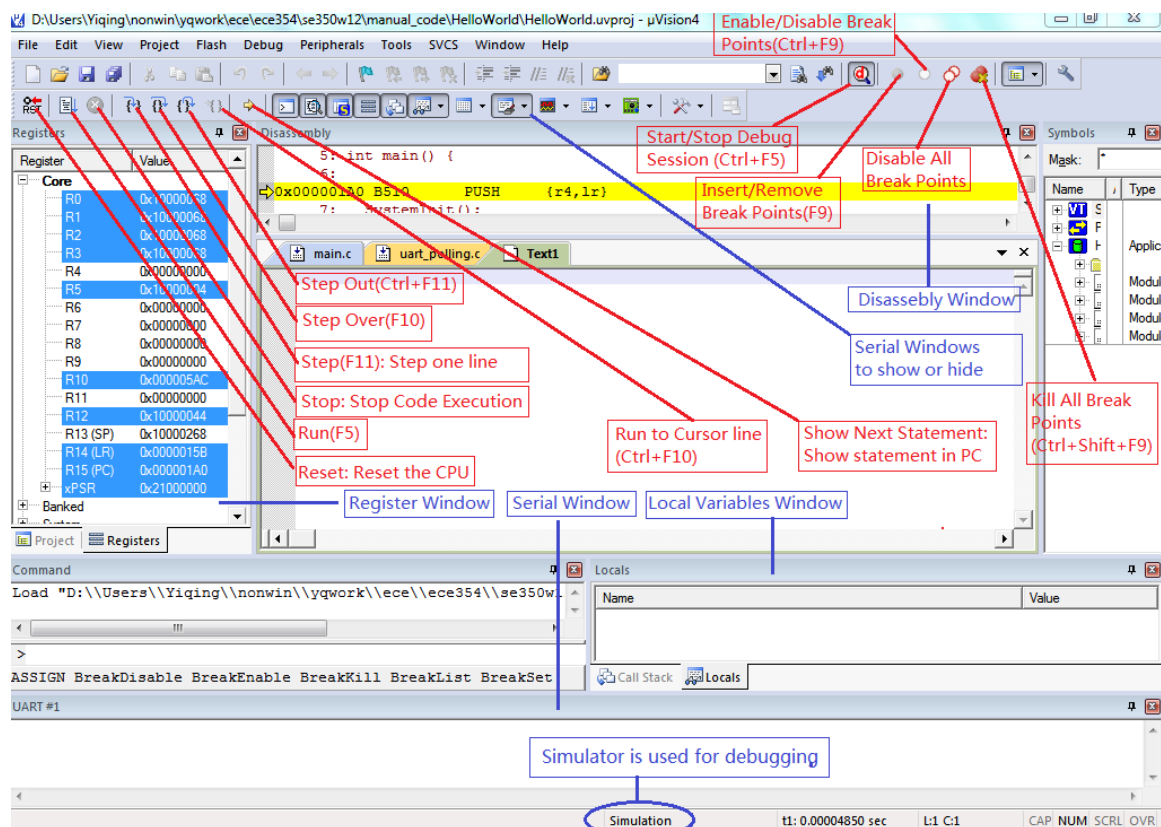


Figure 7.15: Keil IDE: Debugging

7.2.1 Disabling CRP

In order to avoid stealing firmware, the LPC1768 provides Code Read Protection (CRP) that allows fine-grain control about which areas of the memory can be read. A detailed description is found in Section 32.6 of [3]. In essence if the Assembler Directive NO_CRP is not present, the hardware is initialized to only make the firmware read-only (see Figure 7.16)

```

110      IF      :LNOT::DEF:NO_CRP
111      AREA    |.ARM.__at_0x02FC|, CODE, READONLY
112      CRP_Key DCD      0xFFFFFFFF
113      ENDIF
114
115
116      AREA    |.text|, CODE, READONLY

```

Figure 7.16: startup_LPC17xx.s excerpt

Since it is advisable to change values on the fly when debugging, the CRP should be

disabled during prototyping. Open up the target option window and click the Asm tab. Put “NO_CRP” as shown in Figure 7.17

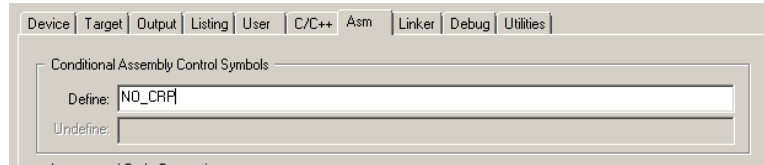


Figure 7.17: Keil IDE: Using Simulator for Debugging

7.2.2 Simulation

Most of the development normally is done under the simulation mode. The default setting of the project uses the simulator to debug as shown in the target option (see Figure 7.18). Instead of load the program to the board for execution, you can run the code using the

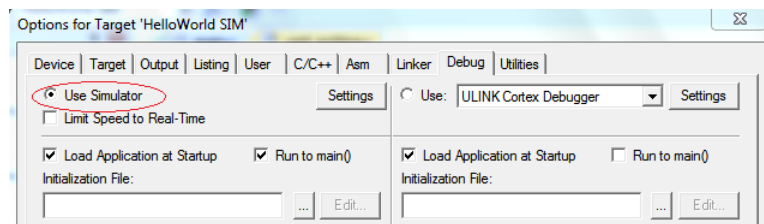


Figure 7.18: Keil IDE: Using Simulator for Debugging

debugger under simulation mode.

7.2.3 Configure In-Memory Execution Using ULINK Cortex Debugger

When you debug hardware related problems, you most likely will find the ULINK Cortex Debugger is helpful. You need to configure the debugger as shown in Figure 7.19.

The default image memory map setting is that the code is executed from the ROM (see Figure 7.20(a)). Since the ROM portion of the code needs to be flashed in order to be executed on the board, this incurs wear-and-tear on the on-chip flash of the LPC1768. Since most attempts to write a functioning RTX will eventually require some more or less elaborate debugging, the flash memory might wear out quickly. Unlike the flash memory stick file systems where the wear is aimed to be uniformly distributed across the memory portion, this flash memory will get used over and over again in the same portion.

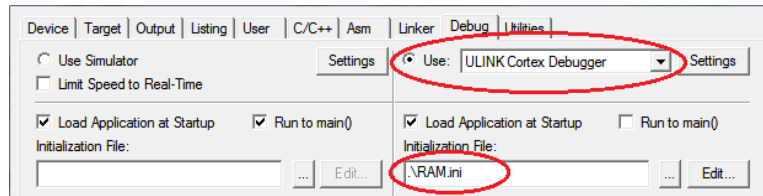
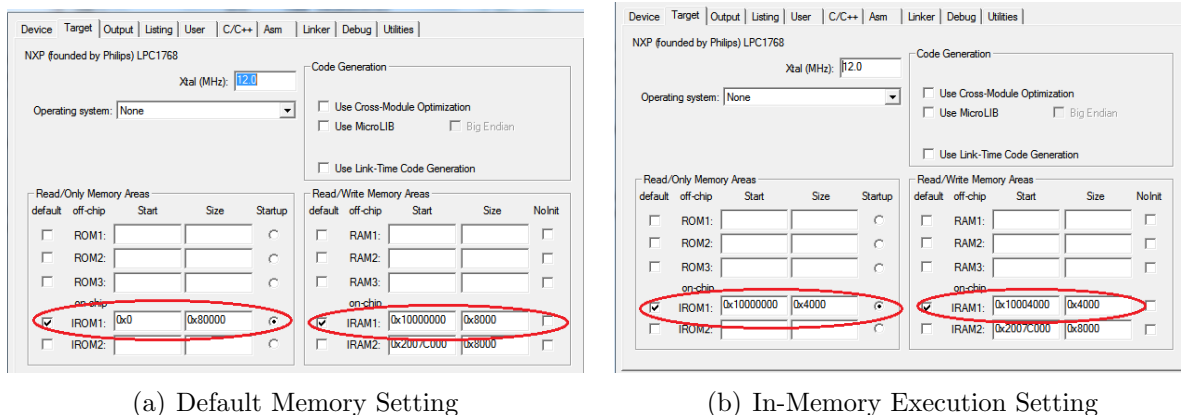


Figure 7.19: Keil IDE: Using ULINK Cortex Debugger

The ARM compiler can be configured to have a different starting address. We can create a RAM target where the code starting address is in RAM (see Figure 7.20(b)). An initialization file `RAM.ini` (see Listing 7.1) is needed to do the proper setting of SP, PC and vector table offset register.



(a) Default Memory Setting

(b) In-Memory Execution Setting

Figure 7.20: Keil IDE: Configure for In-Memory Execution

```

FUNC void Setup (void) {
    SP = _RDWORD(0x10000000);           // Setup Stack Pointer
    PC = _RDWORD(0x10000004);           // Setup Program Counter
    _WDWORD(0xE000ED08, 0x10000000);    // Setup Vector Table
    Offset Register
}
// You need to provide the path of the .axf file here
LOAD build\RAM\HelloWorld.axf INCREMENTAL // Download
Setup();                                  // Setup for Running
g, main

```

Listing 7.1: The RAM.ini file

To download the code to the board, one should not use the download button. Instead,

the debug button is used to initiate a debug session and the `RAM.ini` file will load the code to the board.

Chapter 8

Programming MCB1700

8.1 The Thumb-2 Instruction Set Architecture

The Cortex-M3 supports only the Thumb-2 (and traditional Thumb) instruction set. With support for both 16-bit and 32-bit instructions in the Thumb-2 instruction set, there is no need to switch the processor between Thumb state (16-bit instructions) and ARM state (32-bit instructions).

In the RTOS lab, you will need to program a little bit in the assembler language. We introduce a few assembly instructions that you most likely need to use in your project in this section.

The general formatting of the assembler code is as follows:

```
label
    opcode operand1, operand2, ... ; Comments
```

The `label` is optional. Normally the first operand is the destination of the operation (note `STR` is one exception).

Table 8.1 lists some assembly instructions that the RTX project may use. For complete instruction set reference, we refer the reader to Section 34.2 (ARM Cortex-M3 User Guide: Instruction Set) in [3].

8.2 ARM Architecture Procedure Call Standard (AAPCS)

The AAPCS (ARM Architecture Procedure Call Standard) defines how subroutines can be separately written, separately compiled, and separately assembled to work together. The

Mnemonic	Operands/Examples	Description
LDR	<i>Rt</i> , [<i>Rn</i> , # <i>offset</i>] LDR R1, [R0, #24]	Load Register with word Load word value from an memory address R0+24 into R1
LDM	<i>Rn</i> {!}, <i>reglist</i> LDM R4, {R0 – R1}	Load Multiple registers Load word value from memory address R4 to R0, increment the address, load the value from the updated address to R1.
STR	<i>Rt</i> , [<i>Rn</i> , # <i>offset</i>] STR R3, [R2, R6] STR R1, [SP, #20]	Store Register word Store word in R3 to memory address R2+R6 Store word in R1 to memory address SP+20
MRS	<i>Rd</i> , <i>spec_reg</i> MRS R0, MSP MRS R0, PSP	Move from special register to general register Read MSP into R0 Read PSP into R0
MSR	<i>spec_reg</i> , <i>Rm</i> MSR MSP, R0 MSR PSP, R0	Move from general register to special register Write R0 to MSP Write R0 to PSP
PUSH	<i>reglist</i> PUSH {R4 – R11, LR}	Push registers onto stack push in order of decreasing the register numbers
POP	<i>reglist</i> POP {R4 – R11, PC}	Pop registers from stack pop in order of increasing the register numbers
BL	<i>label</i> BL funC	Branch with Link Branch to address labeled by funC, return address stored in LR
BLX	<i>Rm</i> BLX R12	Branch indirect with link Branch with link and exchange (Call) to an address stored in R12
BX	<i>Rm</i> BX LR	Branch indirect Branch to address in LR, normally for function call return

Table 8.1: Assembler instruction examples

C compiler follows the AAPCS to generate the assembly code. Table 8.2 lists registers used by the AAPCS.

Register	Synonym	Special	Role in the procedure call standard
r15		PC	The Program Counter.
r14		LR	The Link Register.
r13		SP	The Stack Pointer (full descending stack).
r12		IP	The Intra-Procedure-call scratch register.
r11	v8		Variable-register 8.
r10	v7		Variable-register 7.
r9		v6	Platform register.
		SB	The meaning of this register is defined by platform standard.
		TR	
r8	v5		Variable-register 5.
r7	v4		Variable-register 4.
r6	v3		Variable-register 3.
r5	v2		Variable-register 2.
r4	v1		Variable-register 1.
r3	a4		argument / scratch register 4
r2	a3		argument / scratch register 3
r1	a2		argument / result / scratch register 2
r0	a1		argument / result / scratch register 1

Table 8.2: Core Registers and AAPCS Usage

Registers R0-R3 are used to pass parameters to a function and they are not preserved. The compiler does not generate assembler code to preserve the values of these registers. R0 is also used for return value of a function.

Registers R4-R11 are preserved by the called function. If the compiler generated assembler code uses registers in R4-R11, then the compiler generate assembler code to automatically push/pop the used registers in R4-R11 upon entering and exiting the function.

R12-R15 are special purpose registers. A function that has the `__svc_indirect` keyword makes the compiler put the first parameter in the function to R12 followed by an `SVC` instruction. R13 is the stack pointer (SP). R14 is the link register (LR), which normally is used to save the return address of a function. R15 is the program counter (PC).

Note that the exception stack frame automatically backs up R0-R3, R12, LR and PC together with the xPSR. This allows the possibility of writing the exception handler in purely C language without the need of having a small piece of assembly code to save/restore R0-R3, LR and PC upon entering/exiting an exception handler routine.

8.3 Cortex Microcontroller Software Interface Standard (CMSIS)

The Cortex Microcontroller Software Interface Standard (CMSIS) was developed by ARM. It provides a standardized access interface for embedded software products (see Figure 8.1). This improves software portability and re-usability. It enables software solution suppliers to develop products that can work seamlessly with device libraries from various silicon vendors [1].

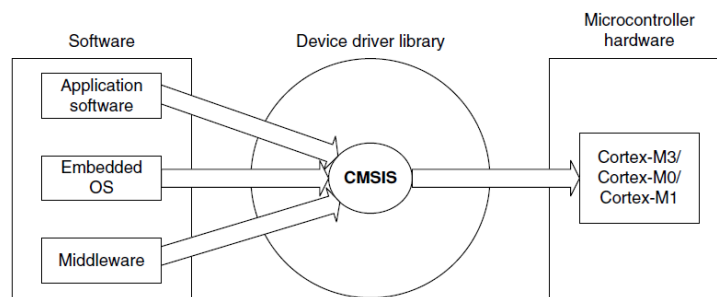


Figure 8.1: Role of CMSIS[5]

The CMSIS uses standardized methods to organize header files that makes it easy to learn new Cortex-M microcontroller products and improve software portability. With the `<device>.h` (e.g. `LPC17xx.h`) and system startup code files (e.g., `startup_LPC17xx.s`), your program has a common way to access

- **Cortex-M processor core registers** with standardized definitions for NVIC, SysTick, MPU registers, System Control Block registers, and their core access functions (see `core_cm*.ch` files).
- **system exceptions** with standardized exception number and handler names to allow RTOS and middleware components to utilize system exceptions without having compatibility issues.
- **intrinsic functions with standardized name** to produce instructions that cannot be generated by IEC/ISO C.
- **system initialization** by common methods for each MCU. For example, the standardized `SystemInit()` function to configure clock.
- **system clock frequency** with standardized variable named as `SystemFrequency` defined in the device driver.

- **vendor peripherals** with standardized C structure.

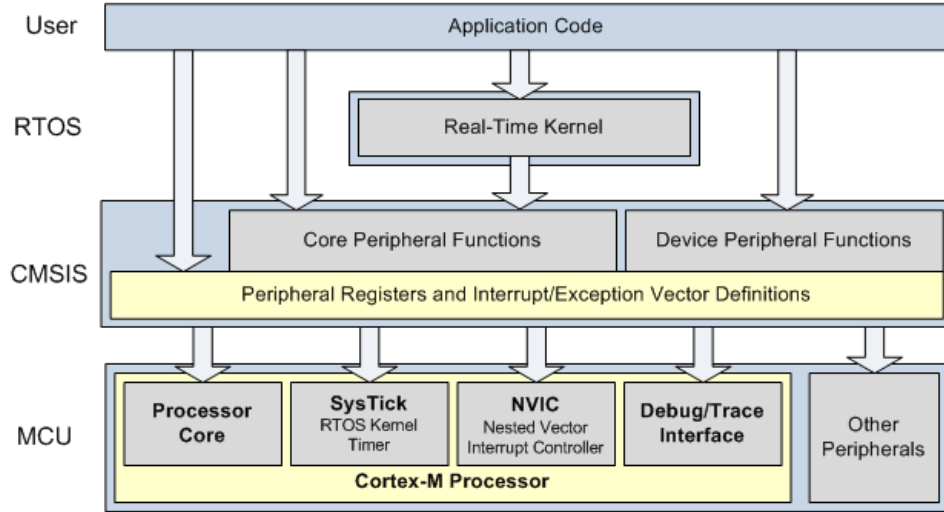


Figure 8.2: CMSIS Organization[1]

8.3.1 CMSIS files

The CMSIS is divided into multiple layers (See Figure 8.2). For each device, the MCU vendor provides a device header file `<device>.h` (e.g., `LPC17xx.h`) which pulls in additional header files required by the device driver library and the Core Peripheral Access Layer (see Figure 8.3).

By including the `<device>.h` (e.g., `LPC17xx.h`) file into your code file. The first step to initialize the system can be done by calling the CMSIS function as shown in Listing 8.1.

```
SystemInit(); // Initialize the MCU clock
```

Listing 8.1: CMSIS SystemInit()

The CMSIS compliant device drivers also contain a startup code (e.g., `startup_LPC17xx.s`), which include the vector table with standardized exception handler names (See Section 8.3.3).

8.3.2 Cortex-M Core Peripherals

We only introduce the NVIC programming in this section. The Nested Vectored Interrupt Controller (NVIC) can be accessed by using CMSIS functions (see Figure 8.4). As an

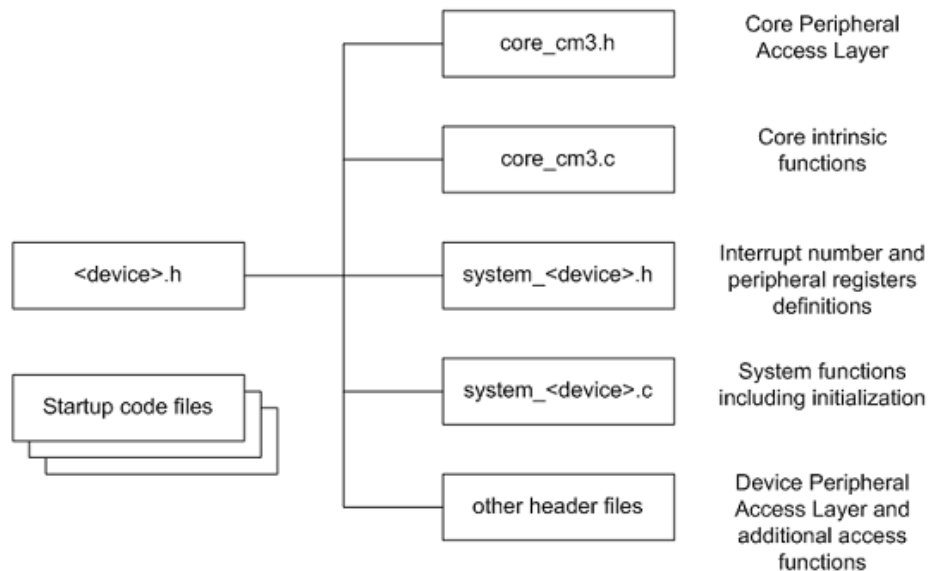


Figure 8.3: CMSIS Organization[1]

	Function definition	Description
void	NVIC_SystemReset (void)	Resets the whole system including peripherals.
void	NVIC_SetPriorityGrouping (uint32_t priority_grouping)	Sets the priority grouping.
uint32_t	NVIC_GetPriorityGrouping (void)	Returns the value of the current priority grouping.
void	NVIC_EnableIRQ (IRQn_Type IRQn)	Enables the interrupt IRQn.
void	NVIC_DisableIRQ (IRQn_Type IRQn)	Disables the interrupt IRQn.
void	NVIC_SetPriority (IRQn_Type IRQn, int32_t priority)	Sets the priority for the interrupt IRQn.
uint32_t	NVIC_GetPriority (IRQn_Type IRQn)	Returns the priority for the specified interrupt.
void	NVIC_SetPendingIRQ (IRQn_Type IRQn)	Sets the interrupt IRQn pending.
IRQn_Type	NVIC_GetPendingIRQ (IRQn_Type IRQn)	Returns the pending status of the interrupt IRQn.
void	NVIC_ClearPendingIRQ (IRQn_Type IRQn)	Clears the pending status of the interrupt IRQn, if it is not already running or active.
IRQn_Type	NVIC_GetActive (IRQn_Type IRQn)	Returns the active status for the interrupt IRQn.

Figure 8.4: CMSIS NVIC Functions[1]

example, the following code enables the UART0 and TIMER0 interrupt

```

NVIC_EnableIRQ(UART0_IRQn); // UART0_IRQn is defined in LPC17xx.h
NVIC_EnableIRQ(TIMER0_IRQn); // TIMER0_IRQn is defined in LPC17xx.h

```

8.3.3 System Exceptions

Writing an exception handler becomes very easy. One just defines a function that takes no input parameter and returns void. The function takes the name of the standardized exception handler name as defined in the startup code (e.g., `startup_LPC17xx.s`). The following listing shows an example to write the UART0 interrupt handler entirely in C.

```
void UART0_Handler (void)
{
    // write your IRQ here
}
```

Another way is to use the embedded assembly code:

```
__asm void UART0_Handler(void)
{
    ; do some asm instructions here
    BL __cpp(a_c_function) ; a_c_function is a regular C function
    ; do some asm instructions here,
}
```

8.3.4 Intrinsic Functions

ANSI cannot directly access some Cortex-M3 instructions. The CMSIS provides intrinsic functions that can generate these instructions. The CMSIS also provides a number of functions for accessing the special registers using `MRS` and `MSR` instructions. The intrinsic functions are provided by the RealView Compiler. Table 8.3 lists some intrinsic functions that your RTOS project most likely will need to use. We refer the reader to Tables 613 and 614 one page 650 in Section 34.2.2 of [3] for the complete list of intrinsic functions.

8.3.5 Vendor Peripherals

All vendor peripherals are organized as C structure in the `<device>.h` file (e.g., `LPC17xx.h`). For example, to read a character received in the RBR of UART0, we can use the following code.

```
unsigned char ch;
ch = LPC_UART0->RBR; // read UART0 RBR and save it in ch
```


Instruction		CMSIS Intrinsic Function
CPSIE I		<code>void __enable_irq(void)</code>
CPSID I		<code>void __disable_irq(void)</code>
Special Register	Access	CMSIS Function
CONTROL	Read	<code>uint32_t __get_CONTROL(void)</code>
	Write	<code>void __set_CONTROL(uint32_t value)</code>
MSP	Read	<code>uint32_t __get_MSP(void)</code>
	Write	<code>void __set_MSP(uint32_t value)</code>
PSP	Read	<code>uint32_t __get_PSP(void)</code>
	Write	<code>void __set_PSP(uint32_t value)</code>

Table 8.3: CMSIS intrinsic functions defined in `core_cmFunc.h`

8.4 Accessing C Symbols from Assembly

Only embedded assembly is support in Cortex-M3 (i.e. inline assembly is not supported). To write an embedded assembly function, you need to use the `__asm` keyword. For example the the function “`embedded_asm_function`” in Listing 8.2 is an embedded assembly function. You can only put assembly instructions inside this function. Note that inline assembly is not supported in Cortex-M3.

The `__cpp` keyword allows one to access C compile-time constant expressions, including the addresses of data or functions with external linkage, from the assembly code. The expression inside the `__cpp` can be one of the followings:

- A global variable defined in C

```
typedef struct pcb {
    struct * mp_next;
    uint32_t m_sp;
    //.....
} pcb_t;

pcb_t g_pcb;
uint32_t g_var;

__asm embedded_asm_function(void) {
    LDR R3, =__cpp(&g_pcb) ; load R3 with the address of g_pcb
    LDM R3, {R1, R2}      ; load R1 with g_pcb.mp_next
                          ; load R2 with g_pcb.m_sp
    LDR R4, =__cpp(g_var) ; load R4 with the value of g_var
```

```
}
```

Listing 8.2: Example of accessing global variable from assembly

- A C function

```
extern void a_c_function(void);  
...  
__asm embedded_asm_function(void) {  
    ;.....  
    BL __cpp(a_c_function) ; a_c_function is regular C function  
    ;.....  
}
```

- A constant expression in the range of 0 – 255 defined in C.

```
uint8_t const g_flag;  
  
__asm embedded_asm_function(void) {  
    ;.....  
    MOV R4, #_cpp(g_flag) ; load g_flag value to R4  
    ;.....  
}
```

Note the MOV instruction only applies to immediate constant value in the range of 0 – 255.

You can also use the IMPORT directive to import a C symbol in the embedded assembly function and then start to use the imported symbol just as a regular assembly symbol. For example

```
void a_c_function (void) {  
    // do something  
}  
  
__asm embedded_asm_add(void) {  
    IMPORT a_c_function ; a_c_function is a regular C function  
    BL a_c_function    ; branch with link to a_c_function  
}
```

Names in the `__cpp` expression are looked up in the C context of the `__asm` function. Any names in the result of the `__cpp` expression are mangled as required and automatically have `IMPORT` statements generated from them.

8.5 SVC Programming: Writing an RTX API Function

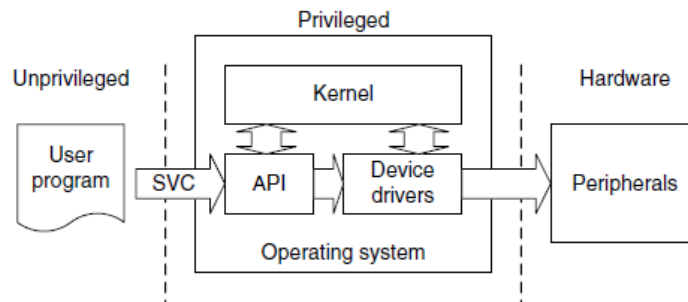


Figure 8.5: SVC as a Gateway for OS Functions [5]

A function in RTX API requires a service from the operating system. It needs to be implemented through the proper gateway by *trapping* from the user level into the kernel level. On Cortex-M3, the `SVC` instruction is used to achieve this purpose.

The basic idea is that when a function in RTX API is called from the user level, this function will trigger an `SVC` instruction. The `SVC_Handler`, which is the CMSIS standardized exception handler for `SVC` exception will then invoke the a kernel function that provide the actual service (see Figure 8.5). Effectively, the RTX API function is a wrapper that invokes `SVC` exception handler and passes corresponding kernel service operation information to the `SVC` handler.

To generate an `SVC` instruction, there are two methods. One is a direct method and the other one is an indirect method.

The direct method is to program at assembly instruction level. We can use the embedded assembly mechanism and write `SVC` assembly instruction inside the embedded assembly function. The ARM RL-RTX API functions that are not started with the `os_` prefix are implemented in this way. Examples are `_alloc_box` and `_free_box` defined in `HAL_CM3.c`. Listing 8.3 shows the code snippet of the `_alloc_box`.

```
__asm void *_alloc_box(void *box_mem) {
    LDR R12,=__cpp(rt_alloc_box)
```

```

; privileged mode code handling omitted for brevity reason
SVC 0
BX LR
ALIGN
}

```

Listing 8.3: Code Snippet of `_alloc_box`

The corresponding kernel function is the C function `rt_alloc_box` defined in `rt_MemBox.c`. This function entry point is loaded to `r12`. Then `SVC 0` causes an SVC exception with immediate number 0. In the SVC exception handler, we can then branch with link and exchange to the address stored in `r12`. Listing 8.4 is an excerpt of the `SVC_handler` in `HAL_CM3.c` from the ARM RL-RTX source code.

```

__asm void SVC_Handler(void) {
    MRS R0, PSP

    ;Extract SVC number, if SVC 0, then do the following

    LDM R0, {R0-R3, R12}; Read R0-R3, R12 from stack
    BLX R12 ; R12 contains the kernel function entry point

    ;Code to handle context switching is omitted

    MVN LR, #:NOT:0xFFFFFFFF; set EXC_RETURN, thread mode, PSP
    BX LR

    ;User SVC code is omitted
}

```

Listing 8.4: Code Snippet of `SVC_Handler`

The indirect method is to ask the compiler to generate the `SVC` instruction from C code. The ARM compiler provides an intrinsic keyword named `__svc_indirect` which passes an operation code to the SVC handler in `r12[2]`. This keyword is a function qualifier. The two input we need to provide to the compiler is

- `svc_num`, the immediate value used in the `SVC` instruction and
- `op_num`, the value passed in `r12` to the handler to determine the function to perform. The following is the syntax of an indirect `SVC`.

```
__svc_indirect(int svc_num)
    return_type function_name(int op_num[, argument-list]);
```

The system handler must make use of the `r12` value to select the required operation. For example The RL-RTX provide the following user level function to terminate a task:

```
#include <rtl.h>
OS_RESULT os_tsk_delete (OS_TID taskid)
```

In `RTL.h`, the following code is revelent to the implementation of the function.

```
#define __SVC_0 __svc_indirect(0)
extern OS_RESULT rt_tsk_delete(OS_TID task_id);
#define os_tsk_delete(task_id) _os_task_delete ((U32) rt_tsk_delete,
    task_id)
extern OS_RESULT _os_tsk_delete (U32 p, OS_TID task_id) __SVC_0;
```

The compiler generates two assembly instructions

```
LDR.W r12, [pc, #offset]; Load rt_tsk_delete in r12
SVC 0x00
```

The `SVC_handler` in Listing 8.4 then can be used to handle the `SVC 0` exception.

Appendix A

Forms

Lab administration related forms are given in this appendix.

ECE254 Request to Leave a Project Group Form

Name:	
Quest ID:	
Student ID:	
Lab Assignment ID	
Group ID:	
Name of Other Group Members:	

Provide the reason for leaving the project group here:

Signature _____

Date _____

Appendix B

MDK-ARM Installation

There is only a windows port for the Keil MDK-ARM for now. The MDK-ARM V4.60.0.0 direct download link is inside the Learn (<http://learn.uwaterloo.ca>) ¹.

During the process of the installation of the MDK-ARM, you will be asked to add example code. Choose Keil(NXP) MCB1xxx Boards example projects (see Figure B.1).

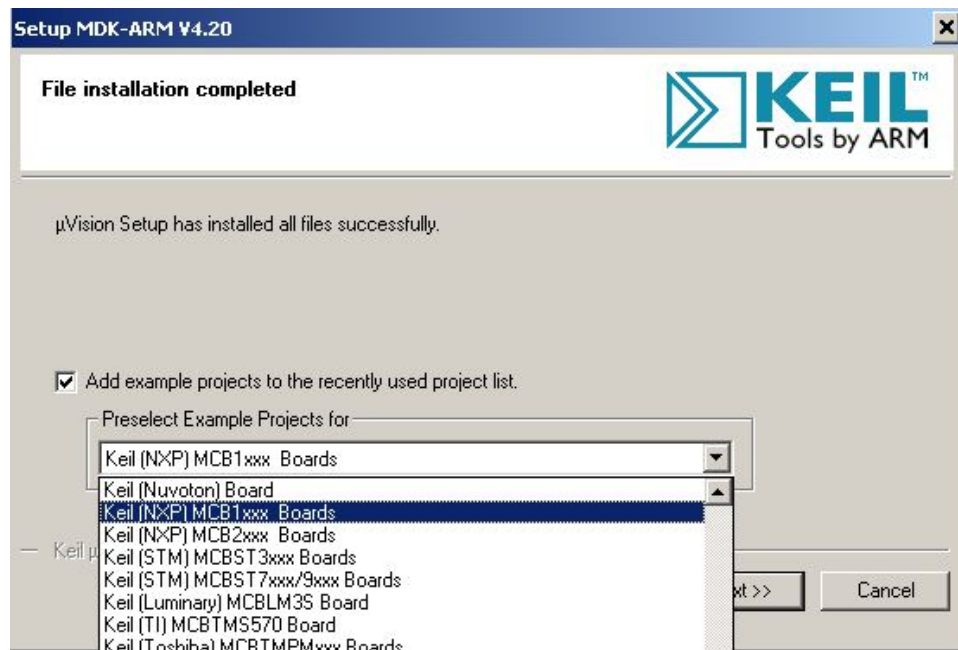


Figure B.1: MDK-ARM Installation Steps: Choose Example Projects

¹The latest version of MDK-ARM is at Keil website <http://www.keil.com/download/product/>. However the lab manual is written for V4.60.0.0. We haven't tested the latest version.

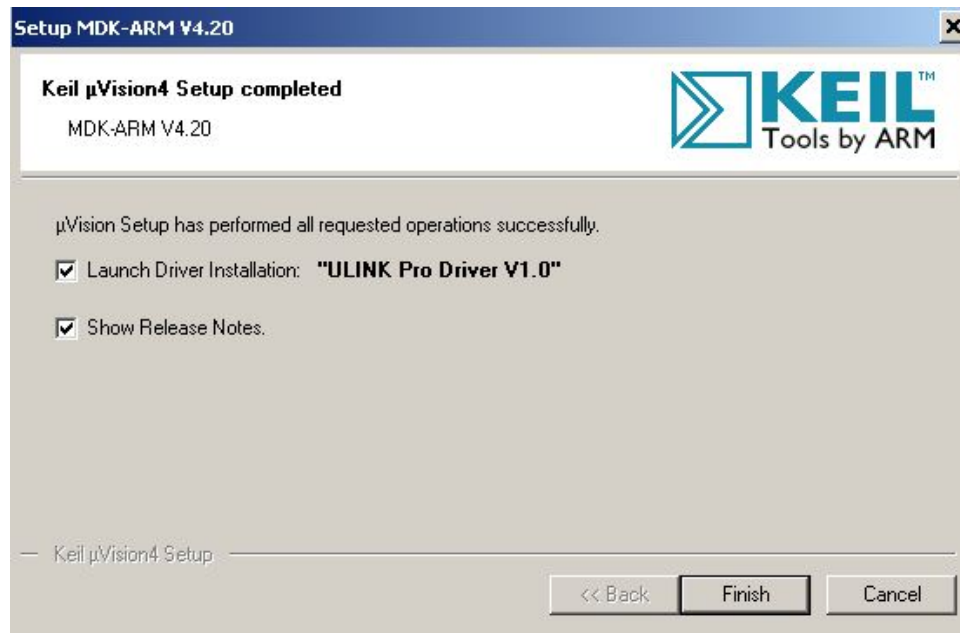


Figure B.2: MDK-ARM Installation Steps: Finish

At the last step of MDK-ARM installation, be sure that the launch the “ULINK Pro Driver



Figure B.3: MDK-ARM Installation Steps: ULINK Pro Driver

V1.0” driver installation check box is checked (see Figure B.2. Once you click “Finish” button, the ULINK Pro Driver installation starts. Click “Install” button to install the driver (see Figure B.3).

Bibliography

- [1] MDK Primer. <http://www.keil.com/support/man/docs/gsac>. 65, 66, 67
- [2] Realview compilation tools version 4.0: Compiler reference guide, 2007-2010. 72
- [3] LPC17xx User Manual, Rev2.0, 2010. 58, 62, 68
- [4] M. Mitchell, J. Oldham, and A. Samuel. Advanced linux programming. *Available on-line at <http://advancedlinuxprogramming.com>*, 2001. 37
- [5] J. Yiu. *The Definitive Guide to the ARM Cortex-M3*. Newnes, 2009. ix, 65, 71