

HIGH PERFORMANCE PROGRAMMING
UPPSALA UNIVERSITY
SPRING 2022
LAB 1: LINUX & C BASICS

The aim of this lab is to familiarise students with the Linux/Unix environment, the build process, and those aspects of C that are the most usual source of confusion and bugs. Before the next lab, you should feel comfortable executing the tasks in this lab, understand the steps of the build process, and have some experience in understanding and manipulating C code.

Before you start! Search on the web for a Linux/Unix quick reference. There are many to choose from — find one you like!

Another thing before you start! It may be tempting to copy+paste some of the commands from these lab instructions into your terminal window. However, sometimes it happens that some characters are not copied correctly when copying from a pdf. Make sure that you learn how to type the special characters needed, like the at-sign (@) and the tilde (~), directly using the keyboard.

1. GETTING STARTED

Log into a system and download the lab tar-ball `Lab01_Linux.tar.gz` from the Module page in Studium. Save it to your desktop.

Open a terminal. You'll see a bash prompt (a.k.a. shell) like

```
username@hostname: ~ $
```

where **username** is your username and **hostname** is the name of the computer you are logged in to.

You can type commands at the prompt, and bash will attempt to execute them. It does this by looking through your `PATH` until it finds the right program. `PATH` is an *environment variable* that lets the system find the things you need, no matter where they might be found.

Important: Linux is case-sensitive. That means that there's a difference between `PATH`, `Path`, and `path`.

Type `echo HEJ hej` to see how the `echo` command works — simply echoing back the thing you gave it as input.

Type `echo $PATH` to see what `PATH` expands into — a colon-delimited list of directories.

Type `which echo` to see where the `echo` command is located.

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A single dot, ".", denotes the current working directory, where you're located right now (which should be your home directory). Similarly, ".." denotes the parent directory.

Type `pwd` to see your current working directory.

Type `ls` to see the contents of your current working directory.

Type `cd ..` to change directory to the parent directory.

Type `cd -` to return to the previous directory.

Create a directory for the course: Type `mkdir HPP` and `cd` into it (`cd HPP`).

Create a directory for this lab, `cd` into it.

Move the lab file to this directory (note that `~` always denotes your home directory):

```
mv ~/Desktop/Lab01_Linux.tar.gz ./
```

Decompress the tar-ball with the following command:

`tar -xvzf L<TAB>`, where `<TAB>` is the "tab" button. After you hit TAB, the command should read `tar -xvzf Lab01_Linux.tar.gz`.

That's right, hitting the TAB button autocompletes directories and filenames, so you don't have to type everything and, *even more importantly*, avoid typos. *Always use tab completion as you navigate directories and write file names. This will save your life!*

`tar` is an archiving program. The cryptic-looking string of letters `-xvzf` are known as *flags*. Flags control what the program is going to do.

Use the command `man tar` to look at the manual page for `tar` and read about what each flag does. Note that 'q' quits the man, space scrolls down a page, and typing e.g. `/Word` searches for 'Word' in the text. You can also use arrow keys to scroll up/down, or d/u keys to scroll a whole page at a time.

Many programs also take the `--help` option, which usually prints out a shorter, more understandable summary of the command than man.

The `tar` command can also be used to create a tar-ball (this is how the `Lab01_Linux.tar.gz` file was created). Use `man tar` to figure out how this is done, and create your own tar-ball package from some files or directories. Hint: the `-c` and `-f` options can be useful (and `-z` if you want to use gzip compression).

The `tar` command will be useful later when you are going to submit code and/or reports for the assignments in this course. Then you will be asked to package your submission into a single `.tar.gz` and submit that in Studium.

By convention, a tar file (a.k.a. tarball) created without compression is given the extension `.tar` while a file created with compression is given the extension `.tar.gz` or `.tgz`.

2. THE BUILD PROCESS

The process of transforming a written program into an executable in Linux/Unix takes 4 distinct steps, see Figure 2.1. For convenience, some or all of these steps can be performed with a single command. First, we will look at how to compile a simple program with a single command, and then we will look at each build step individually.

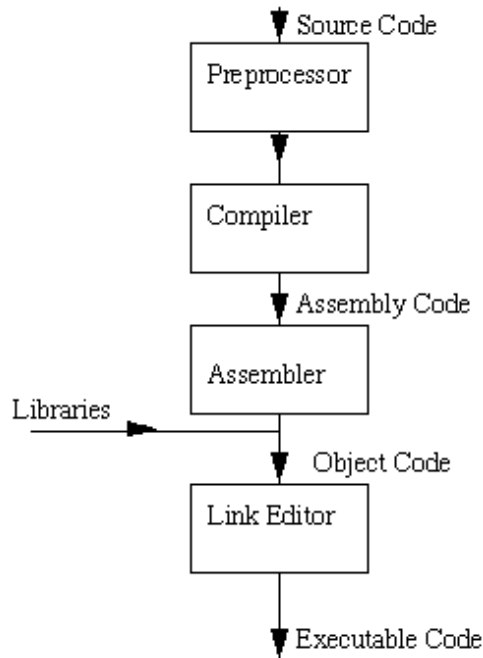


FIGURE 2.1. An overview of the build process. The “Link Editor” that converts object code to executable code is often simply called a “Linker”

Task 1: Cd into the Task-1 directory. Compile the first program with the following command:

```
gcc -o first first.c
```

Here, we are using the gcc compiler. The “-o first” flag tells the compiler to call the output file “first”. The compiler then recognises the .c file ending, denoting a C source file, which it puts through the entire build process.

You can run the program by typing `./first`.

Now compile again giving another name, e.g. “-o haha” instead of “-o first”. Run the new “haha” and check that it works in the same way as “first”. You can also skip the -o flag and simply compile like this:

```
gcc first.c
```

What happens then? Use `ls` to see if any file was created. Can you run it? (The somewhat boring name `a.out` is usually the default executable name, if `-o` is not specified.)

2.1. Preprocessing. The preprocessor takes your C code as input and generates another C code as output. Preprocessing is used to combine different source files together, introduce code from an external source (e.g. a library), and to customise a code so it suits system or user requirements.

A list of common preprocessor directives:

- **#include** inserts code into a file. Typically, a C program code is separated into two sets of files. Header files (ending in `.h`) contain function prototypes, and source files (ending in `.c`) contain the function definitions (more on function prototypes and definitions in Section 2.2). In `first.c`, the `include` directive is used to include the function definitions from the standard library for I/O (input/output).
- **#define** defines a macro. Macros can be used to store predefined constants like `#define PI 3.14` or short code snippets like `#define SQR(x) ((x)*(x))`. The preprocessor will then look for `PI` or `SQR(...)` and replace those tokens with `3.14` or `((...)*(...))`, respectively.
- **#if**, **#ifdef**, **#ifndef**, **#endif** are used to add or remove code depending either on a boolean condition or whether a keyword is defined.

Task 2:

Cd into the Task-2 directory, type `gcc -E -o preprocess.i preprocess.c` in the terminal and compare the output file with the `.c` and `.h` files.

Useful predefined macros, handy for debug prints or to annotate output:

- `__LINE__` Line of the current file
- `__FILE__` Name of the current file
- `__DATE__` Current date
- `__TIME__` Current time

2.2. Compilation. The compiler takes C code as input and generates assembly code as output.

If we want, we can examine the assembly code to see what the program is *actually* doing. For example, this can be useful if we suspect that the compiler has a bug in it. Later in the course, being able to look at the assembly code will be useful when we want to check if and how the compiler has optimized the code.

You can ask `gcc` to generate assembly code with `gcc -S *.c`, and it will output a `.s` file for every `.c` file.

The compiler does the bulk of the work when building a program. The compiler therefore gives you a wealth of options to tweak its behaviour, a few of which are listed below. Read the `man` page or the option summary online at gcc.gnu.org/onlinedocs/gcc/Option-Summary.html for more details.

2.2.1. *Useful basic compiler options, warnings, etc.*

- `-Imyincludedir` Add myincludedir to search path for include files.
- `-Wall` Turn on all warnings. Make this one a habit!
- `-g` Produce debugging information that a debugger (like `gdb`) can use.
- `-O` Optimisation settings.
 - `-O0` Turn off all optimisation (default). Use this when debugging!
 - `-O` or `-O1` Turn on optimisations to reduce code size and execution time that don't take much compilation time.
 - `-O2` Optimize even more. Perform nearly all optimisations that don't involve a space-speed tradeoff.
 - `-O3` Turn on maximum optimisation. You'll experiment with these optimisation levels in the next lab.
 - `-Os` Optimise for size.

2.3. Assembly. The assembler takes assembly code as input and generates object files as output. Object files are binary files that can either be linked with start-up code or wrapped into a library. Each source file will typically result in a `.o` file.

You can tell `gcc` to stop at the assembly step with the `-c` flag. This is commonly done in projects when you want explicit control over the linking step. Cd into the Task-3 directory and compile all the `.c` files with the command `gcc -c *.c`.

2.4. Linking. The linker combines object files and external libraries and generates an executable or library as output. There are two types of libraries: *static* and *dynamic*.

The static library is just an archive of `.o` files. You use it by linking it into your executable in the same way as your own `.o` files. The linker only loads the functions of the library that your code references. This moderately increases the size of the executable, but the running process will be small.

The dynamic library is prepared differently. When you link to a dynamic library, the linker just puts references in the executable, which results in a small executable file. When the running executable encounters function that is linked in from a dynamic library, the function loads dynamically (hence the name). The dynamic linker tends to load a large portion of the library, even if only a few functions are used, which increases the memory footprint of the running process.

Task 3:

We are going to create libraries for the add and subtract functions of the calculator program.

Create a static library from the `.o` files by writing

```
ar crs libstaticfunction.a add.o subtract.o
```

Now generate a new executable file using the static library and the calculator.o file:

```
gcc -o static_calculator calculator.o -L. -lstaticfunction
```

The `-L` flag tells the linker in which directory to look for libraries. The `-lname` flag tells the linker to link with static libraries with the name `libname.a` or dynamic libraries with the name `libname.so`.

Create a dynamic library with these commands:

```
gcc -o libdynfunction.so -shared add.o subtract.o
```

And link a corresponding executable:

```
gcc -o dyn_calculator calculator.o -L. -ldynfunction
```

If you get an error that the system cannot find `libdynfunction.so` when running `dyn_calculator`, you have to update the search path for dynamic libraries:

```
export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:.
```

Tip: Use `ldd dyn_calculator` to ask the executable which dynamic libraries it is linked to.

(note) – The intrepid student can read about performance issues of dynamic libraries in Section 14.11 in *Optimizing software in C++*.

3. MAKEFILES

When working with multiple compilation units (`.c` files), compiler flags, library paths, and so much more, it becomes necessary to make the build process repeatable and smooth. This is done with `make`. This program reads in and executes *makefiles*.

A makefile can contain a number of rules, defined like so:

```
target: dependency1 dependency2
<TAB>command-to-create-target
```

White space is important. There must be a TAB in front of the command. When `make` creates a target, it first looks at the specified dependencies. If the dependencies are files, then it only executes the command if any of those files have changed or the target is not present. If the dependencies are other targets, then it attempts to create those targets before continuing.

Task 4: Cd into Task-4 and type `make` to build the `sorting` executable. By default, `make` will run the file called `makefile` (or `Makefile`) and build the first target (and therefore also any other targets that are dependencies of the first target). Type `make clean` to delete all the `.o` files in preparation for the next step.

Read `makefile` and understand how it works.

The `-w` flag turns off warnings. This is not good. Instead we want to turn on all warnings (`-Wall`), but you'll notice that this makefile does not make this super-easy. Each time we want to change compiler flags we have to make changes to 3 or 4 lines of code.

The file `makefile-1` is more useful to us. By using variables to collect common elements in the commands, we can make changing the build process much more efficient.

Turn on all warnings by editing the `CFLAGS` variable in `makefile-1`.

Type `make -f makefile-1` to build the program again. (Do you get compiler warnings now?)

In practice, one usually does not write a makefile from scratch. We highly recommend that you save `makefile-1` to an easy-to-remember directory and use it as a template in the future.

4. USING SSH AND SCP

The `ssh` command can be used to login to another computer. The `scp` command allows us to transfer files to/from another computer. (On Windows you can install OpenSSH or PuTTY for remote login and file transfer.)

In this course, `ssh` and `scp` are useful for us since using those commands we can copy our code to another computer and login and to test runs there, making it easy to test our code on different kinds of computers, with different CPU models etc.

Task 5:

At <http://www.it.uu.se/datordrift/maskinpark/linux/> you can find a list of Linux computers that are available for students to login to and use. You can use any of the computers listed under “**Students**” there, i.e. from `arrhenius.it.uu.se` down to `vitsippa.it.uu.se`.

To login to one of them, use the `ssh` command like this:

```
ssh user123@arrhenius.it.uu.se
```

where `user123` is your username (the same username that you use to login to the computers in the lab rooms).

The first time you login to a computer, you will probably see a message about “authenticity of host” and a question “Are you sure you want to continue connecting (yes/no)?” – you need to type “yes” to continue.

Pick one of the computers in the list at

<http://www.it.uu.se/datordrift/maskinpark/linux/> and login there using `ssh` as described above. To verify that you are really logged in to a different computer, you can use the `hostname` command, that simply prints the name of the computer you are currently logged in to:

```
hostname
```

To logout from the remote system, type “`exit`”. Then run the `hostname` command again to verify that you have really logged out.

Two other commands that are useful in this context are `who` and `whoami` (“who am I”). The `who` command shows the list of users currently logged in to a computer, and the `whoami` command shows your own username; the username you used to login. Note that your username on a remote system could be different from the username on your local computer. Try the `who` and `whoami` commands both locally and when logged in to a remote computer.

Note that it can be convenient to use several terminal windows when using `ssh` to login to different remote computers. For example, you could have one terminal window for your local computer, another window where you login to remote computer A and a third window where you login to remote computer B. Then, if you want to do something locally you do not need to do “`exit`” from the remote computer, you can simply use another terminal window instead.

Cd into the **Task-5** directory, and use `ls` to look at the contents of that directory. There should be a file called `hej.txt` with a little text inside it. Next, we will look at how you can copy that file to a remote computer using the `scp` command.

The `scp` command (secure copy) works in a similar way as the regular `cp` command (copy), with the difference that `scp` allows the source file or the destination file to be on a remote system.

To copy the `hej.txt` file to the other computer, you can use `scp` like this:

```
scp hej.txt user123@arrhenius.it.uu.se:.
```

The second argument in the above command has the following form: username, then “`@`”, then hostname, then “`:`”, then file path (the dot means your top directory, for subdirectories specify `./mysubdir/`). So, the example above tells `scp` that the local file `hej.txt` should be copied to `arrhenius.it.uu.se` and that the file created (the destination) should be in your login directory.

To check that your copying worked, use `ssh` to login to the other computer and then “`ls -lrt`” to check that your file is really there. Then do “`exit`” to logout again.

You can also use `scp` to copy a file in the other direction, from a remote computer to the local computer:

```
scp user123@arrhenius.it.uu.se:./hej.txt hej2.txt
```

Try that, and then use “`ls`” to check that the file was really copied. Does it work? What happens if you do:

```
scp user123@arrhenius.it.uu.se:./hej.txt .
```

Do some experiments of your own using `ssh` and `scp`, to make sure you understand how those commands work. You should be able to copy files from your local computer to a remote system, login to that system and work with the files there, and also copy files back from the remote system to your local computer.

5. MONITORING A PROGRAM WHILE IT IS RUNNING

The `top` command can be useful for checking if a program is running and how much CPU time it is using.

Task 6:

Cd into the Task-6 directory.

Compile and run the small test code there. Change the value of `N` in the code so that it takes ~ 10 -20 seconds to run.

Run it, and while it is running, run the `top` command in another terminal window. Do you see your program running? The “%CPU” column shows how much CPU time each process is currently using. A single-threaded program running by itself on one core would get 100% while a threaded program running e.g. 3 threads on 3 cores would get 300%. In `top`, use `q` to quit.

6. DEBUGGING

Finding bugs in C programs in Linux without an IDE usually involves four things (remember to use `-Wall` as well):

- (1) Good design. A careful program design with clearly defined and well documented/commented parts helps a lot
- (2) Using `assert` statements
- (3) Using `printf` statements
- (4) Using the `gdb` debugger and other tools

Task 7: Cd into the Task-7 directory. In this directory you have two programs with errors, `prime.c` and `trace.c`. The program for prime computations is easier to debug and has only 4 errors. The trace program is supposed to add the diagonal elements of a square matrix, if you are new to C programming this task may be difficult. Then leave it and don't try to find the errors, you will learn more about C programming during the next lectures and labs. Do your best now, and then you can go back and look at this task again after the C lectures. Your task is to debug the programs. Turn on warnings. Or don't, if you want more of a challenge.

Use `assert` statements, `assert(bug_condition && "Description of error")`, to trap for bugs. For example, if at a certain point in the code you want to verify that the variable `q` has a positive value, you could use a line like this:

```
assert( q > 0 && "checking that q is positive");
```

or simply

```
assert( q > 0 );
```

Keep in mind that asserts are used to help finding programming errors during development, *not* for error-checking in a final release version of a code, so they are not the way to handle issues like bad user input.

All `assert` statements can be disabled by defining a macro with the name `NDEBUG` at some point before including `assert.h`. So, for a final release version of a program you can add a line like `#define NDEBUG` before `assert.h` is included and then all `assert` statements will be skipped by the compiler (it is a predefined macro removing all asserts). This is a convenient way of making sure the release version of the code will not be slowed down by any `assert` statements.

If you want to follow the program's execution with print statements, you can distribute a few `printf("%s: %d n=%d\n", __FILE__, __LINE__, n)` in the code using copy-and-paste. Then you will see the value of the variable `n` in the different lines.

Use GDB to locate segmentation fault bugs: First, compile with the `-g` flag to save debug info within the executable. Then, initialize the debugger with the `trace` executable inside by typing `gdb ./trace`. Type `run` or just `r` to start the program. `q` will exit gdb. The gdb debugger and other tools for debugging will be covered more in later labs.