ECE 4750 Computer Architecture, Fall 2024
Tutorial 1: Linux Development Environment

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1. Introduction

All the lab assignments for this course are designed assuming you will be using a Linux (or UNIX-like) operating system for development. Basic Linux knowledge is essential to successfully complete these lab assignments and a more in-depth understanding enhances productivity. This tutorial covers the computing resources to be used in the course and offers a brisk introduction to the Linux operating system for first time users including some details specific to this course.

To follow along with the tutorial, type the commands without the `%` character. In addition to working through the commands in the tutorial, you should also try the more open-ended tasks marked with the ★ symbol.

2. ECE Computing Resources

We will be using `ecelinux` workstations and servers for all of the laboratory assignments. The `ecelinux` machines all run the Red Hat Enterprise Linux 7 operating system, and they all use an identical setup. You do not need to do anything special to create an `ecelinux` account. You will be using your NetID and Cornell password to login, and an `ecelinux` account will be automatically created for you when you first login. Any student enrolled in any ECE class should automatically be granted access to the `ecelinxu` workstations and servers. Having said this, if you cannot login to *either* the `ecelinux` workstations or the `ecelinux` servers, you should email the COE/CIS sysadmins at `itcoecis-help@cornell.edu`.

There are three ways you can get access to the `ecelinux` workstations and servers: you can use the `ecelinux` workstations in 314 Phillips, you can remotely login to the `ecelinux` servers from the CIT Windows Computing Lab in 318 Phillips Hall, or you can remotely login to the `ecelinux` servers from your own personal workstation. Since we use open-source tools in this course, it should also be possible for you to directly work locally on your own workstation without logging into the `ecelinux` servers. This would require you to setup your own local development environment, so we cannot really provide too much support for this option.

2.1. The `ecelinux` Workstations in 314 Phillips Hall

You can use the 24 brand new `ecelinux` workstations in 314 Phillips Hall to work on your lab assignments. The `ecelinux` workstations are fast and have generous 27″ monitors. You should be able to access the lab using your keycard, although you might need to try swiping your card a few times. You can login to the workstations using your NetID and Cornell password. Once you have logged into an `ecelinux` workstation, you can open a terminal by choosing *Applications* > *Favorites* > *Terminal* from the menu at the top of the desktop.

2.2. The `ecelinux` Servers

The department has a cluster of `ecelinux` servers dedicated for ECE instructional use. These servers are setup in the exact same way as the `ecelinux` workstations in 314 Phillips Hall. There are two servers named as follows:

- `ecelinux-01.ece.cornell.edu`
- `ecelinux-02.ece.cornell.edu`

If one of the two servers seems slow, students may want to try logging into the other server. Note that there are actually two other servers named `ecelinux-03` and `ecelinux-04`, and there is also a load-balancer named `ecelinux`. We do not recommend students use any of these servers. The

`ecelinux-01` and `ecelinux-02` servers are significantly faster, which can make a big difference when running long simulations and CAD tools. Students should always explicitly login to either `ecelinux-01` or `ecelinux-02`, unless these two faster servers are down.

2.3. Remote Login from CIT Windows Computing Lab in 318 Phillips Hall

Students can also use the 45 Windows workstations in 318 Phillips Hall to login to an `ecelinux` server remotely. You should be able to access the lab using your keycard, and you can use your NetID and Cornell password to login to the workstations. You can then use MobaXterm to login to an `ecelinux` server. To start MobaXterm choose *All Programs* > *Class Files* > *MobaXterm Personal Edition* > *MobaXterm Personal Edition* from the start menu. Once MobaXterm has loaded you will see it has started a local terminal. Use the following command at the local terminal prompt to login to an `ecelinux` server:

```
% ssh -X <netid>@ecelinux-01.ece.cornell.edu
```

Replace `<netid>` with your Cornell NetID in the command above, and feel free to use `ecelinux-02` instead of `ecelinux-01`. Do not type the `%` character. We use the `%` character to indicate what commands we should enter on the command line. Executing the command will prompt you to enter your Cornell password, and then you should be connected to the `ecelinux` server. The `-X` command line option enables X11 forwarding so that we can start a GUI application like `gtkwave` on the server yet have the actual GUI displayed on our local machine.

After logging into an `ecelinux` server you will notice that a sidebar appears on the left that shows you the files in your home directory. You can drag files to/from the sidebar and the desktop to easily move files to/from the Windows workstation and an `ecelinux` server. To hide the sidebar choose *View* > *Show/hide sidebar* from the menu.

2.4. Remote Login from Personal Windows Laptop/Workstation

You can also login to an `ecelinux` server from your own personal Windows workstation. You will need to install MobaXterm on your workstation. Download the installer from here:

- `http://mobaxterm.mobatek.net/MobaXterm_Setup_9.4.msi`

Run the installer, click *next* to start the installation, agree to the EULA and click *next*, click *next* to install in the default location, click *install* to start the installation, and click *finish* to finish the installation. Then start MobaXterm by choosing *All Programs* > *MobaXterm Personal Edition* > *MobaXterm Personal Edition* from the start menu. You should agree if Windows asks to grant any additional security permissions to MobaXterm. Then follow the directions in Section 2.3. Note that if your connection to an `ecelinux` server seems to be dropping, you may need to set the SSH "keep alive signal". Choose *Settings* > *Configuration* and check the option to send a keep alive signal every 60 seconds.

2.5. Remote Login from Personal Mac Laptop/Workstation

To start, you need to open a local terminal by typing "terminal" into Spotlight. By default your connection to an `ecelinux` server will be dropped if you are inactive for a certain amount of time. To prevent this, you need to add some configuration information to a specific file. We will learn more about the `echo` command and command output redirection later in the tutorial, but for now carefully enter the following commands in the terminal.

```
% echo "Host *.ece.cornell.edu"    >> ~/.ssh/config
% echo "  ServerAliveInterval 180" >> ~/.ssh/config
```

Do not type the % character. We use the % character to indicate what commands we should enter on the command line. You will need to install X11, although some older versions of Mac OS X have X11 installed by default, or you may have previously installed X11. To see if you have X11 installed, enter the following command in the terminal.

```
% xclock
```

Again, do not type the % character. If your system cannot find `xclock` then you need to install X11. The specific X11 window system you will want to use is called XQuartz, and it is available from here:

- `http://xquartz.macosforge.org/landing`

Use the DMG to install XQuartz and then try running `xclock` again. Once `xclock` works locally, then use SSH to login to an `ecelinux` server as follows:

```
% ssh -X <netid>@ecelinux-01.ece.cornell.edu
```

Replace `<netid>` with your Cornell NetID in the command above and do not type the % character. Feel free to use `ecelinux-02` instead of `ecelinux-01`.

2.6. Remote Login from Personal Linux Laptop/Workstation

If you are using Linux you will likely know how to open a local terminal. By default your connection to the an `ecelinux` server will be dropped if you are inactive for a certain amount of time. To prevent this, you need to add some configuration information to a specific file. We will learn more about the `echo` command and command output redirection later in the tutorial, but for now carefully enter the following commands in the terminal.

```
% echo "Host *.ece.cornell.edu"    >> ~/.ssh/config
% echo "  ServerAliveInterval 180" >> ~/.ssh/config
```

Then use SSH as follows:

```
% ssh -X <netid>@ecelinux-01.ece.cornell.edu
```

As mentioned above, replace `<netid>` with your Cornell NetID in the command above and do not type the % character. Feel free to use `ecelinux-02` instead of `ecelinux-01`.

2.7. Remote Login from Off-Campus Using the Cornell VPN

Logging in remotely from your own personal laptop/workstation will work fine if you are connected to the wired or wireless (e.g., RedRover) campus network. If you are off-campus, then you will need to use the Cornell virtual private network (VPN) to access an `ecelinux` server. Simply follow the instructions at the following link to install the Cisco VPN software for the appropriate operating system running on your laptop/workstation.

- `https://it.cornell.edu/cuvpn`
- `https://it.cornell.edu/landing-page-kba/2605/5273`

Then follow the instructions at the following link to connect to the Cornell VPN using the Cisco VPN software for the appropriate operating system running on your laptop/workstation.

- `https://it.cornell.edu/cuvpn`
- `https://it.cornell.edu/landing-page-kba/2605/823`

After connecting to the VPN, you can follow the above instructions to SSH into an `ecelinux` server.

2.8. Testing X11 After Remote Login

After remotely logging into an `ecelinux` server remotely using any of the above approaches, you can verify that a GUI application (e.g., `gtkwave`) will work by running the following command.

```
% xclock
```

Just to be very explicit, you want to execute the `xclock` command *remotely* after logging into an `ecelinux` server via SSH (i.e., not locally on your Mac/Linux laptop/workstation). If you cannot see the analog clock, there there is likely an issue with your X11 setup. You can also try the more interesting `xeyes`.

```
% xeyes
```

2.9. Personal Computing Resources

While we strongly encourage students to use the `ecelinux` workstations and servers, more advanced students are welcome to work directly on their own workstations without logging into an `ecelinux` server. This is not too much work if your are using a UNIX-like system (e.g., Mac OS X, Linux). It will require the student to install the PyMTL hardware modeling framework and `gtkave`. For some laboratory assignments, students might have to install the RISC-V cross-compiler as well. More information about installing these tools is available at the following links:

- `http://gtkwave.sourceforge.net`
- `https://github.com/cornell-brg/pymtl`
- `https://github.com/riscv/riscv-tools` (follow instructions for GCC/Newlib toolchain)

The course staff cannot offer too much support for this, and please remember that all lab submissions must work on the `ecelinux` workstations and servers, since that is where the course staff will be doing the assessment.

3. The Linux Command Line

In this section, we introduce the basics of working at the Linux command line. Please note that this Linux tutorial is obviously not comprehensive and cannot replace the extensive amount of documentation available online or elsewhere. The goal is to get you comfortable with commands required to complete the lab assignments. Before trying the commands listed in this section, you will need to get access to the ECE computing resources as described in the previous section.

The shell is the original Linux user interface which is a text-based command-line interpreter. The default shell on the `ecelinux` machines is Bash. While there are other shells such as `sh`, `csh`, and `tcsh`, for this course we will always be assuming you are using Bash. As mentioned above, we use the `%` character to indicate commands that should be entered at the Linux command line, but you should not include the actual % character when typing in the commands on your own. To make it

easier to cut-and-paste commands from this tutorial document onto the command line, you can tell Bash to ignore the '%' character using the following command:

```
% alias %=""
```

Now you can cut-and-paste a sequence of commands from this tutorial document and Bash will not get confused by the '%' character which begins each line.

3.1. Hello World

We begin with the ubiquitous "Hello, World" example. To display the message "Hello, World" we will use the `echo` command. The `echo` command simply "echos" its input to the console.

```
% echo "Hello, World"
```

The string we provide to the `echo` command is called a *command line argument*. We use command line arguments to tell commands what they should operate on. Although simple, the `echo` command can very useful for creating simple text files, displaying environment variables, and general debugging.

★ *To-Do On Your Own:* Experiment with using the `echo` command to display different messages.

3.2. Manual Pages

You can learn more about any Linux command by using the `man` command. Try using this to learn more about the `echo` command.

```
% man echo
```

You can use the up/down keys to scroll the manual one line at a time, the space bar to scroll down one page at a time, and the `q` key to quit viewing the manual. You can even learn about the `man` command itself by using `man man`. As you follow the tutorial, feel free to use the `man` command to learn more about the commands we cover.

★ *To-Do On Your Own:* Use the `man` command to learn more about the `cat` command.

3.3. Create, View, and List Files

We can use the `echo` command and a feature called *command output redirection* to create simple text files. We will discuss command output redirection in more detail later in the tutorial. Command output redirection uses the > operator to take the output from one command and "redirect" it to a file. The following commands will create a new file named `ece4750-tut1.txt` that simply contains the text "Computer Architecture".

```
% echo "Computer Architecture" > ece4750-tut1.txt
```

We can use the `cat` command to quickly display the contents of a file.

```
% cat ece4750-tut1.txt
```

For larger files, `cat` will output the entire file to the console so it may be hard to read the file as it streams past. We can use the `less` command to show one screen-full of text at a time. You can use the up/down keys to scroll the file one line at a time, the space bar to scroll down one page at a time, and the `q` key to quit viewing the file.

```
% less ece4750-tut1.txt
```

You can use the `ls` command to list the filenames of the files you have created.

```
% ls
```

We can provide *command line options* to the `ls` command to modify the command's behavior. For example, we can use the `-1` (i.e., a dash followed by the number one) command line option to list one file per line, and we can we can use the `-l` (i.e., a dash followed by the letter l) command line option to provide a longer listing with more information about each file.

```
% ls -1
% ls -l
```

You should see the newly created `ece4750-tut1.txt` file along with some additional directories or folders. We will discuss directories in the next section. Use the following commands to create a few more files using the `echo` command and command output redirection, and then list the files again.

```
% echo "Application" > ece4750-tut1-layer1.txt
% echo "Algorithm"   > ece4750-tut1-layer2.txt
% ls -1
```

★ *To-Do On Your Own:* Create a new file named `ece4750-tut1-layer3.txt` which contains the third layer in the computing systems stack (i.e., programming language). Use `cat` and `less` to verify the file contents.

3.4. Create, Change, and List Directories

Obviously, having all files in a single location would be hard to manage effectively. We can use *directories* (also called folders) to logically organize our files, just like one can use physical folders to organize physical pieces of paper. The mechanism for organizing files and directories is called the *file system*. When you first login to an `ecelinux` machine, you will be in your *home directory*. This is your own private space on the server that you can use to work on the lab assignments and store your files. You can use the `pwd` command to print the directory in which you are currently working, which is known as the *current working directory*.

```
% pwd
/home/<netid>
```

You should see output similar to what is shown above, but instead of `<netid>` it should show your actual NetID. The `pwd` command shows a *directory path*. A directory path is a list of nested directory names; it describes a "path" to get to a specific file or directory. So the above path indicates that there is a toplevel directory named `home` that contains a directory named `<netid>`. This is the directory path to your home directory. As an aside, notice that Linux uses a forward slash (/) to separate directories, while Windows uses a back slash (\) for the same purpose.

We can use the `mkdir` command to make new directories. The following command will make a new directory named `ece4750` within your home directory.

```
% mkdir ece4750
```

We can use the `cd` command to change our current working directory. The following command will change the current working directory to be the newly created `ece4750` directory, before displaying the current working directory with the `pwd` command.

```
% cd ece4750
% pwd
/home/<netid>/ece4750
```

Use the `mkdir`, `cd`, and `pwd` commands to make another directory.

```
% mkdir tut1
% cd tut1
% pwd
/home/<netid>/ece4750/tut1
```

We sometimes say that `tut1` is a subdirectory or a child directory of the `ece4750` directory. We might also say that the `ece4750` directory is the parent directory of the `tut1` directory.

There are some important shortcuts that we can use with the `cd` command to simplify navigating the file system. The special directory named `.` (i.e., one dot) always refers to the current working directory. The special directory named `..` (i.e., two dots) always refers to the parent of the current working directory. The special directory named `~` (i.e., a tilde character) always refers to your home directory. The special directory named `/` (e.g., single forward slash) always refers to the highest-level root directory. The following commands illustrate how to navigate up and down the directory hierarchy we have just created.

```
% pwd
/home/<netid>/ece4750/tut1
% cd .
% pwd
/home/<netid>/ece4750/tut1
% cd ..
% pwd
/home/<netid>/ece4750
% cd ..
% pwd
/home/<netid>
% cd ece4750/tut1
% pwd
/home/<netid>/ece4750/tut1
% cd
% pwd
/home/<netid>
% cd /
% pwd
/
```

```
% cd ~/ece4750
% pwd
/home/<netid>/ece4750
```

Notice how we can use the `cd` command to change the working directory to another arbitrary directory by simply using a directory path (e.g., `ece4750/tut1`). These are called *relative paths* because the path is relative to your current working directory. You can also use an *absolute path* which always starts with the *root directory* to concretely specify a directory irrespective of the current working directory. A relative path is analogous to directions to reach a destination from your current location (e.g., How do I get to the coffee shop from my current location?), while an absolute path is analogous to directions to reach a destination from a centralized location (e.g., How do I get to the coffee shop from the center of town?).

```
% pwd
/home/<netid>/ece4750
% cd /home/<netid>/ece4750/tut1
% pwd
/home/<netid>/ece4750/tut1
% cd
% pwd
/home/<netid>
```

This example illustrates one more useful shortcut. The `cd` command with no command line arguments always changes the current working directory to your home directory. We can use the `ls` command to list files as well as directories. Use the following commands to create a new file and directory in the `ece4750/tut1` subdirectory, and then list the file and directory.

```
% cd ~/ece4750/tut1
% echo "Computer Architecture" > ece4750-tut1.txt
% mkdir dirA
% ls -1
```

You should see both the `dirA` subdirectory and the newly created `ece4750-tut1.txt` file listed. Feel free to use the `cat` command to verify the file contents of the newly created file. We can use the `tree` command to recursively list the contents of a directory. The following commands create a few more directories before displaying the directory hierarchy.

```
% cd ~/ece4750/tut1
% mkdir -p dirB/dirB_1
% mkdir -p dirB/dirB_2
% mkdir -p dirC/dirC_1
% cd ~/ece4750/tut1
% tree
.
+-- dirA
+-- dirB
|   |-- dirB_1
|   `-- dirB_2
|-- dirC
|   `-- dirC_1
```

```
‘-- ece4750-tut1.txt
```

Note that we are using the `-p` command line option with the `mkdir` command to make multiple nested directories in a single step.

★ *To-Do On Your Own:* Experiment with creating additional directories and files within the `ece4750/tut1` subdirectory. Try creating deeper hierarchies with three or even four levels of nesting using the `-p` option to the `mkdir` command. Experiment with using the `.` and `..` special directories. Use the `tree` command to display your newly created directory hierarchy.

3.5. Copy, Move, and Remove Files and Directories

We can use the `cp` command to copy files. The first argument is the name of the file you want to copy, and the second argument is the new name to give to the copy. The following commands will make two copies of the files we created in the previous section.

```
% cd ~/ece4750/tut1
% cp ece4750-tut1.txt ece4750-tut1-a.txt
% cp ece4750-tut1.txt ece4750-tut1-b.txt
% ls -1
```

We can also copy one or more files into a subdirectory by using multiple source files and a final destination directory as the arguments to the `cp` command.

```
% cd ~/ece4750/tut1
% cp ece4750-tut1.txt dirA
% cp ece4750-tut1-a.txt ece4750-tut1-b.txt dirA
% tree
```

We can use the `-r` command line option to enable the `cp` command to recursively copy an entire directory.

```
% cd ~/ece4750/tut1
% tree
% cp -r dirA dirD
% tree
```

If we want to move a file or directory, we can use the `mv` command. As with the `cp` command, the first argument is the name of the file you want to move and the second argument is the new name of the file.

```
% cd ~/ece4750/tut1
% mv ece4750-tut1.txt ece4750-tut1-c.txt
% ls -1
```

Again, similar to the `cp` command, we can also move one or more files into a subdirectory by using multiple source files and a final destination directory as the arguments to the `mv` command.

```
% cd ~/ece4750/tut1
% tree
```

```
% mv ece4750-tut1-a.txt dirB
% mv ece4750-tut1-b.txt ece4750-tut1-c.txt dirB
% tree
```

We do not need to use the `-r` command line option to move an entire directory at once.

```
% cd ~/ece4750/tut1
% tree
% mv dirD dirE
% tree
```

The following example illustrates how we can use the special `.` directory to move files from a subdirectory into the current working directory.

```
% cd ~/ece4750/tut1
% tree
% mv dirE/ece4750-tut1.txt .
% tree
```

We can use the `rm` command to remove files. The following command removes a file from within the `ece4750/tut1` subdirectory.

```
% cd ~/ece4750/tut1
% ls -1
% rm ece4750-tut1.txt
% ls -1
```

To clean up, we might want to remove the files we created in your home directory earlier in this tutorial.

```
% cd
% rm ece4750-tut1.txt
% rm ece4750-tut1-layer1.txt
% rm ece4750-tut1-layer2.txt
% rm ece4750-tut1-layer3.txt
```

We can use the `-r` command line option with the `rm` command to remove entire directories, but please be careful because it is relatively easy to permanently delete many files at once. See Section 6.3 for a useful command that you might want to use instead of the `rm` command to avoid accidentally deleting important work.

```
% cd ~/ece4750/tut1
% ls -1
% rm -r dirA dirB dirC dirE
% ls -1
```

★ *To-Do On Your Own:* Creating additional directories and files within the `ece4750/tut1` subdirectory, and then use the `cp`, `mv`, and `rm` commands to copy, move, and remove the newly created directories and files. Use the `ls` and `tree` commands to display your file and directory organization.

3.6. Using `wget` to Download Files

We can use the `wget` command to download files from the internet. For now, this is a useful way to retrieve a text file that we can use in the following examples.

```
% cd ~/ece4750/tut1
% wget http://www.csl.cornell.edu/courses/ece4750/overview.txt
% cat overview.txt
```

3.7. Using `grep` to Search Files

We can use the `grep` command to search and display lines of a file that contain a particular pattern. The `grep` command can be useful for quickly searching the contents of the source files in your lab assignment. The command takes the pattern and the files to search as command line arguments. The following command searches for the word "memories" in the `overview.txt` file downloaded in the previous section.

```
% cd ~/ece4750/tut1
% grep "memories" overview.txt
```

You should see just the three lines within the `overview.txt` file that contain the word "memories". We can use the `--line-number` and `--color` command line options with the `grep` command to display the line number of each match and to highlight the matched word.

```
% cd ~/ece4750/tut1
% grep --line-number --color "memories" overview.txt
```

We can use the `-r` command line option to recursively search all files within a given directory hierarchy. In the following example, we create a subdirectory, copy the `overview.txt` file, and illustrate how we can use the `grep` command to recursively search for the word "memories".

```
% cd ~/ece4750/tut1
% mkdir dirA
% cp overview.txt dirA
% grep -r --line-number --color "memories" .
```

Notice how we specify a directory as a command line argument (in this case the special `.` directory) to search the current working directory. You should see the three lines from both copies of the `overview.txt` file. The `grep` command also shows which file contains the match.

As another example, we will search two special files named `/proc/cpuinfo` and `proc/meminfo`. These files are present on every modern Linux system, and they contain information about the processor and memory hardware in that system. The following command first uses the `less` command so you can browse the file, and then uses the `grep` command to search for `processor` in the `/proc/cpuinfo` file. Recall that with the `less` command, we use the up/down keys to scroll the file one line at a time, the space bar to scroll down one page at a time, and the `q` key to quit viewing the file.

```
% cd ~/ece4750/tut1
% less /proc/cpuinfo
% grep "processor" /proc/cpuinfo
```

It should be pretty clear that you are using a multicore processor! You can also search to find out which company makes the processors and what clock frequency they are running at:

```
% cd ~/ece4750/tut1
% grep "vendor_id" /proc/cpuinfo
% grep "cpu MHz" /proc/cpuinfo
```

We can find out how much DRAM is in the system by searching for `MemTotal` in the `/proc/meminfo` file.

```
% cd ~/ece4750/tut1
% grep "MemTotal" /proc/meminfo
```

★ *To-Do On Your Own:* Try using `grep` to search for the words "processor" and "network" in the `overview.txt` file.

3.8. Using `find` to Find Files

We can use the `find` command to recursively search a directory hierarchy for files or directories that match a specified criteria. While the `grep` command is useful for searching file contents, the `find` command is useful for quickly searching the file and directory names in your lab assignments. The `find` command is very powerful, so we will just show a very simple example. First, we create a few new files and directories.

```
% cd ~/ece4750/tut1
% mkdir -p dirB/dirB_1
% mkdir -p dirB/dirB_2
% mkdir -p dirC/dirC_1
% echo "test" > dirA/file0.txt
% echo "test" > dirA/file1.txt
% echo "test" > dirB/dirB_1/file0.txt
% echo "test" > dirB/dirB_1/file1.txt
% echo "test" > dirB/dirB_2/file0.txt
% tree
```

We will now use the `find` command to find all files named `"file0.txt"`. The `find` command takes one command line argument to specify where we should search and a series of command line options to describe what files and directories we are trying to find. We can also use command line options to describe what action we would like to take when we find the desired files and directories. In this example, we use the `--name` command line option to specify that we are searching for files with a specific name. We can also use more complicated patterns to search for all files with a specific filename prefix or extension.

```
% cd ~/ece4750/tut1
% find . -name "file0.txt"
```

Notice that we are using the special . directory to tell the `find` command to search the current working directory and all subdirectories. The `find` command always searches recursively.

★ *To-Do On Your Own:* Create additional files named `"file2.txt"` in some of the subdirectories we have already created. Use the `"find"` command to search for files named `"file2.txt"`.

3.9. Using `tar` to Archive Files

We can use the `tar` command to "pack" files and directories into a simple compressed *archive*, and also to "unpack" these files and directories from the archive. This kind of archive is sometimes called a *tarball*. Most open-source software is distributed in this compressed form. It makes it easy to distribute code among collaborators and it is also useful to create backups of files. We can use the following command to create an archive of our tutorial directory and then remove the tutorial directory.

```
% cd ~/ece4750
% tar -czvf tut1.tgz tut1
% rm -r tut1
% ls -l
```

Several command line options listed together as a single option (`-czvf`), where `c` specifies we want to create an archive, `z` specifies we should use "gzip" compression, `v` specifies verbose mode, and `f` specifies we will provide filenames to archive. The first command line argument is the name of the archive to create, and the second command line argument is the directory to archive. We can now extract the contents of the archive to recreate the tutorial directory. We also remove the archive.

```
% cd ~/ece4750
% tar -xzvf tut1.tgz
% rm tut1.tgz
% tree tut1
```

Note that we use the `x` command line option with the `tar` command to specify that we intend to extract the archive.

★ *To-Do On Your Own:* Create an example directory within the `ece4750/tut1` subdirectory. Copy the `overview.txt` file and rename it to add example files to your new directory. Use the `tar` command to create and extract an archive of just this one new directory.

3.10. Using `top` to View Running Processes

You can use the `top` command to view what commands are currently running on the Linux system in realtime. This can be useful to see if there are many commands running which are causing the system to be sluggish. When finished you can use the `q` character to quit.

```
% top
```

The first line of the `top` display shows the number of users currently logged into the system, and the *load average*. The load average indicates how "overloaded" the system was over the last one, five, and

15 minutes. If the load average is greater than the number of processors in the system, it means your system will probably be sluggish. You can always try logging into a different server in the cluster.

3.11. Environment Variables

In the previous sections, we have been using the Bash shell to run various commands, but the Bash shell is actually a full-featured programming language. One aspect of the shell that is similar in spirit to popular programming languages, is the ability to write and read *environment variables*. The following commands illustrate how to write an environment variable named `ece4750_tut1_layer1`, and how to read this environment variable using the `echo` command.

```
% ece4750_tut1_layer1="application"
% echo ${ece4750_tut1_layer1}
```

Keep in mind that the names of environment variables can only contain letters, numbers, and underscores. Notice how we use the `${}` syntax to read an environment variable. There are a few built-in environment variables that might be useful:

```
% echo ${HOSTNAME}
% echo ${HOME}
% echo ${PWD}
```

We often use the `HOME` environment variable in directory paths like this:

```
% cd ${HOME}/ece4750
```

The `PWD` environment variable always holds the current working directory. We can use environment variables as options to commands other than `echo`. A common example is to use an environment variable to "remember" a specific directory location, which we can quickly return to with the `cd` command like this:

```
% cd ${HOME}/ece4750/tut1
% TUT1=${PWD}
% cd
% pwd
/home/<netid>
% cd ${TUT1}
% pwd
/home/<netid>/ece4750/tut1
```

★ *To-Do On Your Own:* Create a new environment variable named `ece4750_tut1_layer2` and write it with the second layer in the computer systems stack (i.e., algorithm). Use the `echo` command to display this environment variable. Experiment with creating a new subdirectory within `ece4750/tut1` and then using an environment variable to "remember" that location.

3.12. Command Output Redirection

We have already seen using the `echo` command and command output redirection to create simple text files. Here is another example:

```
% cd ${HOME}/ece4750/tut1
% echo "Application" > computing-stack.txt
% cat computing-stack.txt
```

The > operator tells the Bash shell to take the output from the command on the left and overwrite the file named on the right. We can use any command on the left. For example, we can save the output from the `pwd` command or the `man` command to a file for future reference.

```
% cd ${HOME}/ece4750/tut1
% pwd > cmd-output.txt
% cat cmd-output.txt
% man pwd > cmd-output.txt
% cat cmd-output.txt
```

We can also use the >> operator which tells the Bash shell to take the output from the command on the left and append the file named on the right. We can use this to create multiline text files:

```
% cd ${HOME}/ece4750/tut1
% echo "Algorithm"             > computing-stack.txt
% echo "Programming Language" >> computing-stack.txt
% echo "Operating System"     >> computing-stack.txt
% cat computing-stack.txt
```

★ *To-Do On Your Own:* Add the remaining levels of the computing stack (i.e., gate-level, circuits, devices, technology) to the `computing-stack.txt` text file. Use the `cat` command to verify that the file contents.

3.13. Command Chaining

We can use the `&&` operator to specify two commands that we want to chaining together. The second command will only execute if the first command succeeds. Below is an example.

```
% cd ${HOME}/ece4750/tut1 && cat computing-stack.txt
```

★ *To-Do On Your Own:* Create a single-line command that combines creating a new directory with the `mkdir` command and then immediately changes into the directory using the `cd` command.

3.14. Command Pipelining

The Bash shell allows you to run multiple commands simultaneously, with the output of one command becoming the input to the next command. We can use this to assemble "pipelines"; we "pipe" the output of one command to another command for further actions using the | operator.

The following example uses the `grep` command to search the special `proc/cpuinfo` file for lines containing the word "processor" and then pipes the result to the `wc` command. The `wc` command counts the number of characters, words, or lines of its input. We use the `-l` command line option with the `wc` command to count the number of lines.

```
% grep processor /proc/cpuinfo | wc -l
```

This is a great example of the Linux philosophy of providing many simple commands that can be combined to create more powerful functionality. Essentially the pipeline we have created is a command that tells us the number of processors in our system.

As another example, we will pipe the output of the `last` command to the `grep` command. The `last` command lists the names of all of the users that have logged into the system since the system was rebooted. We can use `grep` to search for your NetID and thus quickly see how when you previously have logged into this system.

```
% last | grep <netid>
```

We can create even longer pipelines. The following pipeline will report the number of times you have logged into the system since it was rebooted.

```
% last | grep <netid> | wc -l
```

★ *To-Do On Your Own:* Use the `cat` command with the `overview.txt` file and pipe the output to the `grep` command to search for the word "memories". While this is not as fast as using `grep` directly on the file, it does illustrate how many commands (e.g., `grep`) can take their input specified as a command line argument or through a pipe.

3.15. Aliases, Wildcards, Command History, and Tab Completion

In this section, we describe some miscellaneous features of the Bash shell which can potentially be quite useful in increasing your productivity.

Aliases are a way to create short names for command sequences to make it easier to quickly execute those command sequences in the future. For example, assume that you frequently want to change to a specific directory. We can create an alias to make this process take just two keystrokes.

```
% alias ct="cd ${HOME}/ece4750/tut1"
% ct
% pwd
/home/academic/<netid>/ece4750/tut1
```

If you always want this alias to be available whenever you login to the system, you can save it in your `.bashrc` file. The `.bashrc` is a special Bash script that is run on every invocation of a Bash shell.

```
% echo "alias ct=\"cd ${HOME}/ece4750/tut1\"" >> ${HOME}/.bashrc
```

The reason we have to use a back slash (\) in front of the double quotes is to make sure the `echo` command sees this command line argument as one complete string.

Wildcards make it easy to manipulate many files and directories at once. Whenever we specify a file or directory on the command line, we can often use a wildcard instead. In a wildcard, the asterisk (`*`) will match any sequence of characters. The following example illustrates how to list all files that end in the suffix `.txt` and then copies all files that match the wildcard from one directory to another.

```
% cd ${HOME}/ece4750/tut1
```

```
% ls *.txt
% cp dirA/file*.txt dirB
% tree
```

The Bash shell keeps a history of everything you do at the command line. You can display the history with the `history` command. To rerun a previous command, you can use the `!` operator and the corresponding command number shown with the `history` command.

```
% history
```

You can pipe the output of the `history` command to the `grep` command to see how you might have done something in the past.

```
% history | grep wc
```

If you press the up arrow key at the command line, the Bash shell will show you the previous command you used. Continuing to press the up/down keys will enable you to step through your history. It is very useful to press the up arrow key once to rerun your last command.

The Bash shell supports tab completion. When you press the tab key twice after entering the beginning of a filename or directory name, Bash will try to automatically complete the filename or directory name. If there is more than one match, Bash will show you all of these matches so you can continue narrowing your search.

4. Linux Text Editors

You will need to use a text editor to edit source files in Linux. There are two kinds of text editors: graphical and non-graphical. The non-graphical text editors work by opening files through the command line and then using the keyboard to navigate files, execute commands, etc. The graphical text editors work by providing a GUI so that the user can use a mouse to interact with the editor.

4.1. Nano

Nano is a very simple non-graphical text editor installed on the `ecelinux` machines. The editor is easy to learn and use. You can start Nano by typing the command `nano` in the terminal and optionally specifying the filename you want to view and edit.

```
% cd ${HOME}
% nano ~/ece4750/tut1/overview.txt
```

Use the arrow keys to move the cursor position. Notice that the editor specifies most of the useful commands at the bottom of the terminal screen. The symbol ^ indicates the `CONTROL` key. To type any text you want, just move the cursor to the required position and use the keyboard. To save your changes press `CONTROL+O` and press the `<ENTER>` key after specifying the filename you want to save to. You can exit by pressing `CONTROL+X`.

★ *To-Do On Your Own:* Use Nano to make some changes to the `overview.txt` text file and then save your edits to your home directory. View the new file using the `cat` command from the command line and then delete the file using the `rm` command.

4.2. Emacs and Vim

While the `nano` editor is easy to learn, students that anticipate using Linux in the future beyond this course might want to use a more powerful editor such as `emacs` or `vim`. Both also have GUI equivalents. By default `emacs` will start the GUI, while using the `-nw` command line option will enable non-graphical mode. `vim` is purely non-graphical, but `gvim` is the graphical equivalent. It is beyond the scope of this tutorial to teach you the usage of these editors, but most advanced Linux users use one of these more powerful text editors for development.

4.3. MobaTextEditor

If you are using MobaXterm, you can simply right click on a file in the integrated MobaXterm file browser and choose "Open with Default Text Editor" to open the file with the embedded MobaTextEditor. Unlike the other text editors mentioned in this section, the MobaTextEditor actually runs locally on your Windows workstation. MobaXterm ensures that any changes you make to a file through the MobaTextEditor are automatically uploaded to the `ecelinux` servers. You might need to experiment to determine the most productive setup.

5. The Two-Window Linux Workflow

Some students use a *one-window workflow*. They use various commands at the command line and whenever they want to edit a file they launch a text editor, edit and save the file, exit the text editor, and then return to working at the command line. This can be a tedious process and involve many keystrokes and/or mouse clicks to simply edit a file and see the corresponding effect.

We strongly encourage students to use a *two-window workflow* regardless of how they are accessing the ECE computing resources and which text editor they are using. A two-window workflow involves always having two windows side-by-side. The window on the left will be a terminal at the command line, while the window on the right will be a text editor. The student should be able to switch back-and-forth between the two windows using the keyboard although this is not strictly necessary. By using two windows, the student can work at the command line, quickly switch to edit/save a file, and then quickly switch back to see the corresponding effect.

Figure 1 illustrates an example two-window workflow on the workstations in the ECE Linux Computing Lab in 314 Phillips Hall. A terminal is on the left and a text editor is on the right. Notice that the generous 27" monitors in 314 Phillips Hall enable using a side-by-side split within a text editor such that a terminal and two files are all visible at the same time. You can use the ALT-TAB keyboard combination to quickly switch back-and-forth between the two windows. Figure 2 illustrates an example two-window workflow on the workstations in the CIT Windows Computing Lab in 318 Phillips Hall. MobaXterm is on the left and a text editor is on the right. Again, you can use the ALT-TAB keyboard combination to quickly switch back-and-forth between the two windows. Both RHEL7 and Windows have nice features where if you drag a window off the left or right side of the screen it will automatically make the window fill just the left or right half of the screen. The key is to be able to be able to see the command line and your text editor at the same time, and to also be able to quickly switch back-and-forward between the command line and your text editor.

6. Course-Specific Linux Commands

In this section, we describe various aspects of the development environment that are specific to the severs used in the course.

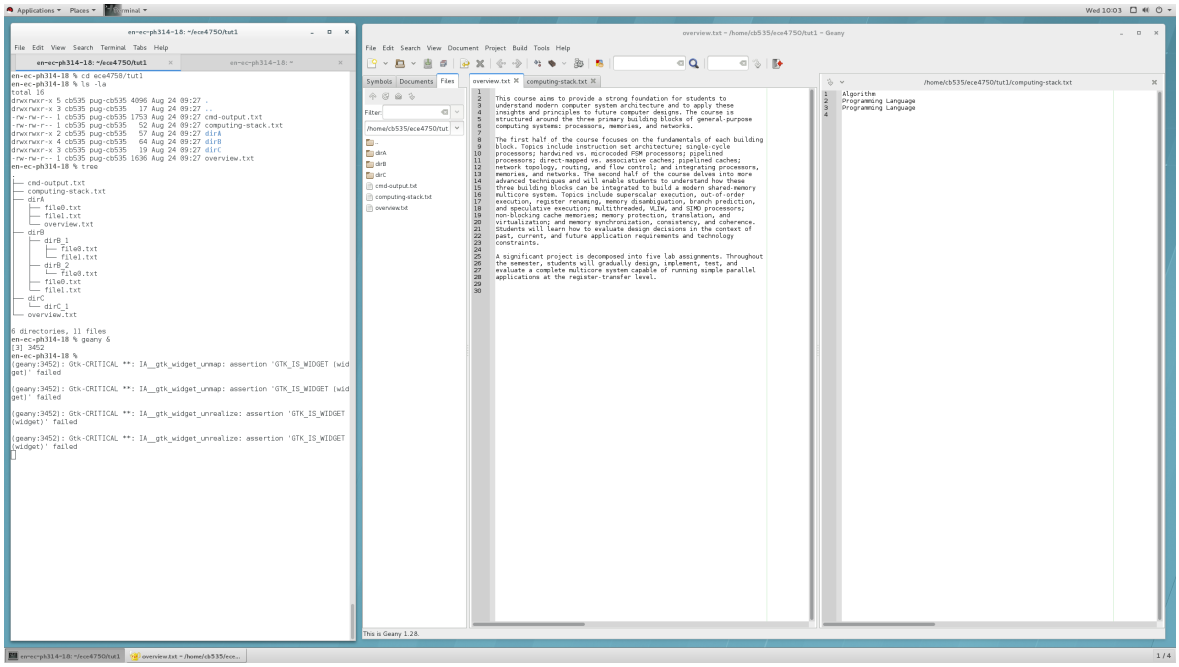

Figure 1: Recommended Two-Window Workflow for Linux

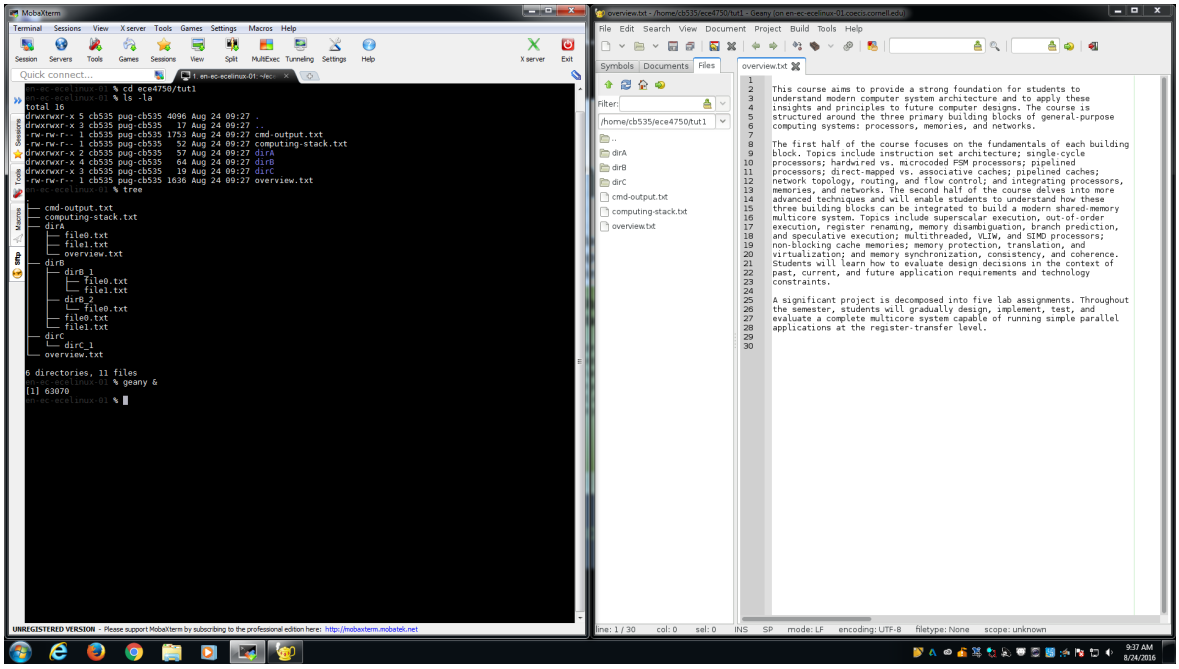

Figure 2: Recommended Two-Window Workflow for Windows

6.1. Course Setup Script

Once you are logged into an `ecelinux` machine, as explained in Section 2, you will need to setup the working environment with the following command in order to work on the course lab assignments.

```
% source setup-ece4750.sh
```

The `source` command executes the commands in the given file. Running the command will display some information about what the setup script is doing. Since we always need to source the setup script, we can add this to our `.bashrc` file as follows.

```
% echo "source setup-ece4750.sh -q" >> ${HOME}/.bashrc
```

The extra `-q` command line option prevents the script from displaying its output every time we login to an `ecelinux` machine. With these modifications to our `.bashrc`, we know that the environment will be correctly setup every time we login.

If for any reason running the setup script prevents you from using tools for another course, you will need to run the setup script manually every time you want to work on a course lab assignment.

6.2. Using `quota` to Check Your Space Usage

Students are allocated 10GB of storage on the servers. You can use the following command to show much space you are using:

```
% quota
```

The `blocks` column is how much data you are using, and the `quota` column is your quota. If you have exceed the 10GB quota, you can browse your home directory and list the size of files and the contents of directories with the `du` command:

```
% cd ${HOME}
% du -sh *
```

By recursively changing directories and examining the sizes of files and directories you can figure out what you need to delete. We can pipe the output of `du` to the `sort` and `head` commands to find the top 20 largest files and directories like this:

```
% cd ${HOME}
% du -xak . | sort -nr | head --lines=20
```

Or just use the following to generate a human readable summary of the size of files/directories in the current working directory. Note that it can take 20–30 seconds for this command to finish, so please be patient.

6.3. Using `trash` to Safely Remove Files

We have installed a simple program called `trash` which moves files you wish to delete into a special subdirectory of your home directory located at `${HOME}/tmp/trash`. The following commands create a file and then deletes it using `trash`.

```
% cd ${HOME}
% echo "This file will be deleted." > testing.txt
```

```
% trash testing.txt
% echo "This file will also be deleted." > testing.txt
% trash testing.txt
% ls ${HOME}/tmp/trash
```

If you look in `${HOME}/tmp/trash` you will see subdirectories organized by date. Look in the subdirectory with today's date and you should two files corresponding to the two files you deleted. We highly recommend always using the `trash` command instead of `rm` since this avoids accidentally deleting your work.

7. Conclusion

This tutorial hopefully helped you become familiar with Linux and how to use it for working on the labs. You have gained some experience working at the command line and also working with either a graphical or non-graphical text editor. We have introduced the two-window Linux workflow and some Linux commands specific to the course. There are many more resources online for learning Linux, and keep in mind that learning to work productively using the Linux operating system can pay dividends in many other contexts besides this course.

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