Learning Goals

In this lecture, we will see:

• How UNIX and C were designed together
• How C compilers work
• How package managers work
• How Python has taken over UNIX scripting
Outline

1. The C Language
2. Compilation
3. Package Management
4. Python
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4. Python
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• C is used everywhere, and has inspired:
  • Every major operating system
  • Every mainstream programming language
• Even if you never write C, you indirectly use it every day.
Nowadays, C is considered a weird, old (and sometimes scary!) language.

This is the “hello, world!” program in B (the language before C):

```c
main( ) {
    extern a, b, c;
    putchar(a); putchar(b); putchar(c); putchar('!*n');
    a 'hell';
    b 'o, w';
    c 'orld';
}
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Early C

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```

The C programming language was used to implement most of UNIX’s kernel and userspace.
Problems with K&R C

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- If you didn't tell the compiler what data type a variable was, it just assumed it was an integer.
- It had no memory protection or error detection, so even minor bugs would cause your program to crash.

Some OS-specific functions, like `printf`, had to come from somewhere. This meant the machine code had to be “linked” to a C “standard library” which came with the OS.
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Here's the “hello, world” program, rewritten in modern C:

```c
#include <stdio.h>

int main(int argc, char **argv) {
    printf("hello, world\n");
}
```
1. The C Language
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How source code becomes machine code

The modern C-style process of compilation can be broken into three steps:

1. A COMPILER turns C code into assembly code (cc).
2. An ASSEMBLER turns assembly code into machine code (as).
3. A LINKER takes many different pieces of machine code (often from different source code files) and weaves them into a single program (ld).
How source code becomes machine code

The modern C-style process of compilation can be broken into three steps:

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Modern C compilers let you do all of these steps with a single command, but they still do each step separately behind the scenes.
A COMPILER reads source code, like this:

```c
#include <stdio.h>
int main(int argc, char **argv) {
    printf("hello, world\n");
}
```

This is meant to be human-readable and portable. The same code would work on Linux on an Intel CPU or macOS on an ARM CPU.

We can compile this by running `cc -S hello.c -o hello.s` to get an assembly file called `hello.s`. 
A COMPILER writes assembly code, like this:

```assembly
.file "hello.c"
.text
<section .rodata
.LC0:
.string "hello, world"
.text
.globl main
.type main, @function
main:
.LFB0:
.cfi_startproc
pushq  %rbp
.cfi_def_cfa_offset 16
.cfi_offset 6, -16
movq  %rsp, %rbp
leaq .LC0(%rip), %rax
movq  %rax, %rdi
call puts@PLT
movl  $0, %eax
leave
.cfi_def_cfa 7, 8
ret
.LFE0:
.size main, .-main
.ident "GCC: (GNU) 12.2.1 20230111"
.section .note.GNU-stack,"",@progbits
```

This is technically still considered human-readable!
An ASSEMBLER reads assembly code, like this:

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    pushq %rbp
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    .cfi_offset 6, -16
    movq %rsi, -16(%rbp)
    leaq .LC0(%rip), %rax
    movq %rax, %rdi
    call puts@PLT
    movl $0, %eax
    leave
    .cfi_def_cfa_register 6
    .cfi_endproc
.LFE0:
    .size main, .-main
    .ident "GCC: (GNU) 12.2.1 20230111"
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```

We can assemble this by running `as -c hello.s -o hello.o` to get an object file called “hello.o”.
Assembler Output

An ASSEMBLER writes machine code, which is not human-readable, but the disassembly looks like this:

Disassembly of section .text:

```
0000000000000000 <main>:
  0: 55 push %rbp
  1: 48 89 e5 mov %rsp,%rbp
  4: 48 83 ec 10 sub $0x10,%rsp
  8: 89 7d fc mov %edi,-0x4(%rbp)
 b: 48 89 75 f0 mov %rsi,-0x10(%rbp)
f: 48 8d 05 00 00 00 00 00 lea 0x0(%rip),%rax # 16 <main+0x16>
 16: 48 89 c7 mov %rax,%rdi
 19: e8 00 00 00 00 call 1e <main+0x1e>
 1e: b8 00 00 00 00 mov $0x0,%eax
 23: c9 leave
 24: c3 ret
```

The call to `printf` is missing because the assembler doesn't know where it is! This incomplete machine code is called an OBJECT FILE.
An LINTER reads incomplete machine code in object files:

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We could theoretically link this using ld to get an executable, but the exact command is complicated and system-dependent. Instead, we'll ask cc to do it:

```
cc hello.o -o hello
```
A LINKER writes complete machine code as an executable binary; once again, let's look at the disassembly:

Now the call to printf is fixed (actually called puts because of a compiler optimization). This is because the program is now "linked" to the system C library, libc, which has a definition of printf/puts.
We can compile C into a shared object, which is a library any program can use.

On Linux, these files end with .so; on macOS, they sometimes end with .dylib instead. The Windows equivalent ends with .dll.

cc -shared test.c -o test.so creates a shared object file containing all the functions from test.c.

These "shared objects" are linked at runtime by a dynamic linker, which is part of the OS.

These .so files are usually in /usr/lib/.

The environment variable $LD_LIBRARY_PATH can add more locations.

The ldd command tells you which shared libraries a program requires to run; if they're not installed, the program will give an error and exit.
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So why does anyone use C?

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- It's required: UNIX is defined in terms of C. A UNIX-based OS must have a C compiler. All the interfaces to ask the OS for anything are designed for C programs.
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Without a dependency manager of some sort, you get annoying errors like this:
Solutions

One solution is **STATIC LINKING**.

- This means every dependency of a program must be *compiled into* that program's binary file.
- This is common nowadays; the iOS and Android app stores (more or less) use this.

Another solution is **PACKAGING** programs.

- This means every program comes with a *list* of dependencies which are automatically downloaded/installed alongside it.
- This is more widespread; UNIX uses it by default, as do programming language-specific tools like *pip*. 
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Local package managers have the downside that they may do redundant work; different programs may get duplicate copies of the same library.
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Python

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• Python is compatible with C.

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Python looks a lot more friendly than C:

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#!/usr/bin/env python3
print("Hello, World!")
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- Note the shebang line, like a shell script, but calling `python3` instead of `bash`. 
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- Note the shebang line, like a shell script, but calling `python3` instead of `bash`.
- There are two incompatible versions of Python; `python` is usually Python 2, but `python3` is Python 3. Use `python3` for anything new you write.
Creating a new Python Project

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- If you're writing a more complicated program, you probably want to create a new project.
- As far as Python knows, a project is just a directory, so we can create a new Python project with `mkdir`.
Dependencies

- Much like C programs, we sometimes want our Python program to depend on code someone else wrote.

We can install programs with the Python package manager, `pip` (or more accurately, `pip3`). However, we generally don't want to copy the C approach of installing libraries globally, since then we could only have one version of a library installed for all our Python scripts. Instead, we create a virtual environment and install our required dependencies in there.
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Let's practice this! First, create a directory named `python-test`; then create and activate an environment named `myenv` inside it!
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- Now, let's install the `numpy` package, which lets us do vector math: `pip3 install numpy`.

We can now launch a Python Read-Eval-Print-Loop (REPL) by running `python3`. This lets us type Python commands and have them immediately executed, just like the shell!

Inside the REPL, run `import numpy` to import the `numpy` library we just installed.

Try running `numpy.array([1, 2, 3]) + numpy.array([4, 5, 6])`.
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- Try running `numpy.array([1, 2, 3]) + numpy.array([4, 5, 6])`. 
Let's write a Python script.

In fact, let's translate a shell script we wrote in Lecture 4—my_folder.sh—into Python!

Create a new file called my_folder.py and open it in your favorite editor.
#!/usr/bin/env python3

import os
import sys

def make_my_folder(folder_name, file_name):
    os.mkdir(folder_name)
    os.chdir(folder_name)
    with open(file_name, 'a'):
        pass

make_my_folder(sys.argv[1], sys.argv[2])
Let's write a Python script that uses a dependency, `vector_norm.py`.

```bash
akshay@akshays-thinkpad ~ % python vector_norm.py 1 2 3
```

```python
#!/usr/bin/env python3
import numpy as np
import sys

vector = np.array(sys.argv[1:])
print(np.linalg.norm(vector))
```
Packaging a Virtual Environment

The virtual environment you created is customized to your computer, so what do we do if we want to send a Python project to someone else?

1. Create a `requirements.txt` file by running `pip3 freeze > requirements.txt`.
2. Send your Python files (`.py`) and `requirements.txt` to someone else.
3. Have the other person create a virtual environment and run `pip3 install -r requirements.txt` inside it to install all the requirements.
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2. Send your Python files (*.py) and requirements.txt to someone else.
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1. Create a `requirements.txt` file by running `pip3 freeze > requirements.txt`.

2. Send your Python files (*.py) and `requirements.txt` to someone else.

3. Have the other person create a virtual environment and run `pip3 install -r requirements.txt` inside it to install all the requirements.
What's so great about Python?

Source: xkcd 353
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Python scripts can link against C shared object files. The entire C software ecosystem is usable from inside Python.
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```c
int add(int a, int b) { return a + b; }
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Python-C Foreign Function Interface

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We can compile it into `add.so`:

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c -shared add.c -o add.so
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We can compile it into `add.so`:

```bash
cc -shared add.c -o add.so
```

We can use it from Python:

```python
import ctypes
lib = ctypes.CDLL("./add.so")
print(lib.add(1, 2))
```