



UiT The Arctic University of Norway

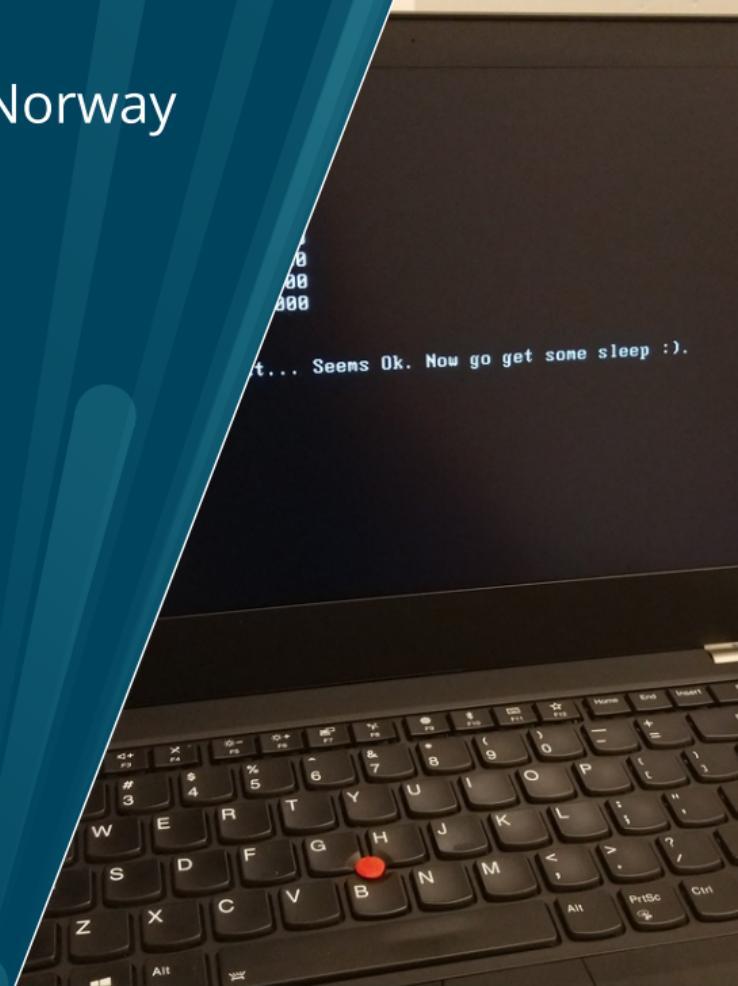
Project 1

Loading Programs

Mike Murphy

UiT INF-2203

Spring 2026



Introduction

Projects General

Project 1

Background

Target: i386

Coding without a Standard Library

Building and Booting

Provided Precode

Conclusion

Project 1

Hello, World!

Mike Murphy

- ▶ Michael **Mike**
- ▶ Not as scary as I look
- ▶ American (sorry)
- ▶ Æ kan norsk men engelsk e lettere

Aging into a Unix Greybeard

- ▶ Gen AI bad
- ▶ Open source good
- ▶ Linux rules!
- ▶ Windows? Haven't used it since 2006

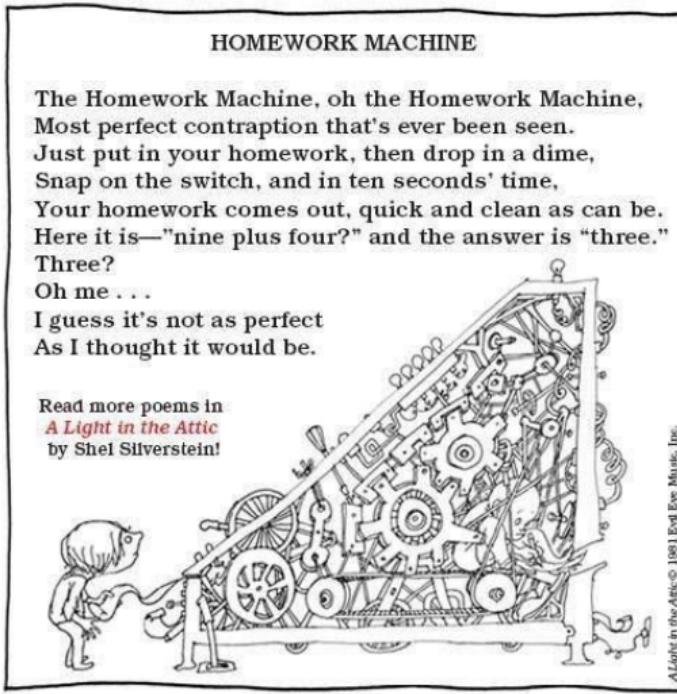
No AI!

Sarah Connor watching you
use AI for everything



Linda Hamilton in *Terminator 2: Judgment Day*, judging you¹

¹Photo from *Terminator 2: Judgment Day* (1991, dir. James Cameron), meme text origin unknown



"The Homework Machine" by Shel Silverstein²

²Poem and illustration from *A Light in the Attic*, 1981

Projects Overview

Build an OS from Scratch(-ish)

Munix — Munin/Micro Unix

- ▶ P1: Running a program
- ▶ P2: Protection
- ▶ P3: Multitasking
- ▶ P4: Inter-Process Communication

Basic format

- ▶ We provide a basic skeleton (“precode”)
- ▶ You fill in the important bits
- ▶ Time ~3–4 weeks
- ▶ Continuation options: yours or ours

Work in Pairs or Alone

- ▶ Projects: Groups of 1–2
- ▶ Work *together*. Do not divide work.
- ▶ Oral exams: Assignment group

Deliverables

- ▶ Midpoint design review
- ▶ **Hand-in: Code, Report**
- ▶ Possible postmortem

Challenging Projects

Challenge

- ▶ Was challenging as a 20-ECTS course
- ▶ Will be challenging at 10-ECTS
- ▶ Tough but rewarding
- ▶ Tough but *fun*³

Get Your Hands Dirty

- ▶ The projects are to give you *experience*
- ▶ Do the work → easy exam

Recommended Prereqs⁴

- ▶ INF-1101 Data Structures and Algorithms
- ▶ INF-2200 Architecture

Important Concepts

- ▶ C language
- ▶ Assembly language
- ▶ Unix command line
- ▶ Git

³Fun might be in the Dwarf Fortress sense

⁴See UiT course info: <https://uit.no/utdanning/emner/emne/906652/inf-2203>

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Machine View

```
info    : boot_mb2.c: tag: framebuffer: addr=0xb8000, pitch=160, width=80, height=25, bp
p=16, type=2
info    : boot_mb2.c: tag: type 14 (size   28)
info    : boot_mb2.c: tag: end
info    : [OK] vfs_file.c: registered device driver: major #4 = ramdisk
info    : [OK] vfs_file.c: registered device driver: major #3 = tty
info    : [OK] vfs_fs.c: registered filesystem driver: fstypeid #3 = cpiofs
info    : [OK] kernel.c: get initrd info provided by bootloader
info    : [OK] ramdisk.c: create ramdisk device for initrd at 0x11e000, size 0x2e00
info    : [OK] vfs_fs.c: mount device 1024 on /
info    : [OK] tty.c: init tty 1 on serial 1
munix v2026-P1 kshell tty1
> s
bin/
bin/hello-raw
bin/noop-raw
bin/plane-raw
> hello-raw
info    : elf.c: ELF class=1(32-bit) data=1(LE) v1 abi=0(sysv),v0
info    : elf.c: entry point 0x50008d
info    : elf.c: 1 segments, entry size 32 bytes
info    : elf.c: seg 0: type=1(LOAD) offset=0 vaddr=0x500000 filesz=0x122 memsz=0x122 fl
ags=0x5 align=0x1000
info    : process.c: hello-raw: calling to 0x50008d to start ...
Hello, world!
This is the hello-raw program speaking!
info    : process.c: hello-raw: returned 0
> █
```

Project 1 in QEMU (serial I/O): running a “hello world” program

Finish Boot, Load Programs

We Provide

- ▶ Build system
- ▶ Bootloader (GRUB)
- ▶ Skeleton kernel
- ▶ Basic I/O
- ▶ Test programs

Your Tasks

1. Finish reading boot info
2. Read and load executable files

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1. Finish reading boot info
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- ▶ Less than 100 lines of code

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 - ▶ Hard part: getting ready to write it

Finish Boot, Load Programs

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- ▶ Build system
- ▶ Bootloader (GRUB)
- ▶ Skeleton kernel
- ▶ Basic I/O
- ▶ Test programs

Task Zero

- ▶ Set up build environment
- ▶ Understand precode organization
- ▶ Understand build system
- ▶ Understand kernel startup
- ▶ Understand how GRUB passes data
- ▶ Understand ELF format
- ▶ Brush up on weak spots

Your Tasks

1. Finish reading boot info
 2. Read and load executable files
- ▶ Less than 100 lines of code
 - ▶ Hard part: getting ready to write it

Finish Boot, Load Programs

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- ▶ Build system
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Lots of Background

Let's get into it ...

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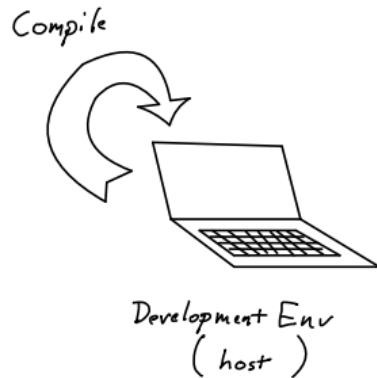
Project 1

A Brief History of x86

Year	CPU	Regs	Addresses	Hot Feature
1978	Intel 8086	16-bit	20-bit (1 MiB)	16-bit!
1982	Intel 286	16-bit	24-bit (16 MiB)	Protection
1985	Intel 386	32-bit	32-bit (4 GiB)	Virtual Memory
...				
2003	AMD Opteron	64-bit	52-bit (4 PiB)	64-bit!

- ▶ All backwards compatible
- ▶ Modern CPU boots up in 8086 16-bit mode
- ▶ Same basic instruction set, just extended
- ▶ We are targeting the 386 (aka generic 32-bit x86)
- ▶ Emulator: QEMU (qemu-system-i386)

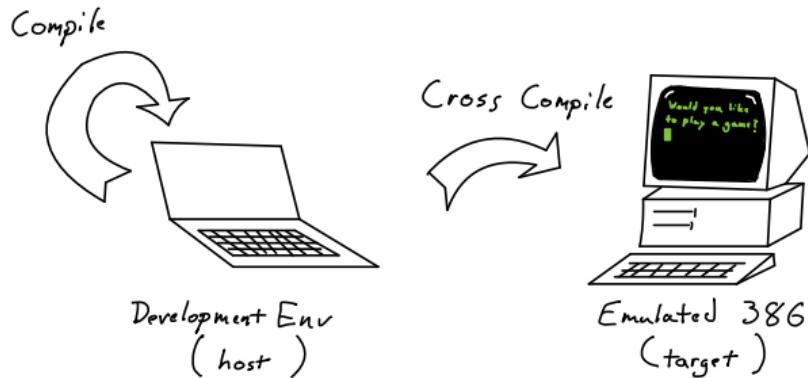
Cross Compiler



Normal Compiler

- ▶ Runs on *host*
- ▶ Compiles for host
- ▶ Invoke as normal:
`gcc hello.c`

Cross Compiler



Normal Compiler

- ▶ Runs on *host*
- ▶ Compiles for *host*
- ▶ Invoke as normal:
`gcc hello.c`

Cross Compiler

- ▶ Runs on *host*
- ▶ Compiles for *target*
- ▶ Invoke with prefix:
`i386-elf-gcc hello.c`

Installing a Cross Compiler

- ▶ Do I really need a cross compiler?
 - ▶ Yes
 - ▶ Even on x86_64, you have a different OS
 - ▶ We need to compile for generic ELF-based system, not Linux specifically
- ▶ Installing a cross compiler:
 1. Start with Linux/Unix environment
 2. Install regular compiler
 3. Download GNU source code:
 - ▶ **binutils**: assembler, readelf, objdump, etc.
 - ▶ **gcc**: GNU Compiler Collection
 4. Configure with --target=i386-elf
 5. Build from source
- ▶ Instruction docs in precode repository

Linux/Unix is the Base

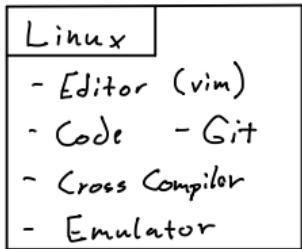
- ▶ This code is developed under Linux
 - ▶ Build uses common command-line tools:
make, shell scripts, etc.
- ▶ We will assume you have a Linux/Unix development environment:
 - ▶ Ubuntu 22.04 is the reference
 - ▶ Other Linux distros should work
 - ▶ Mac should also work
(MacOS is Unix under the hood)
 - ▶ Windows + WSL2 should work
- ▶ You are responsible for your development environment
- ▶ Know thy tools



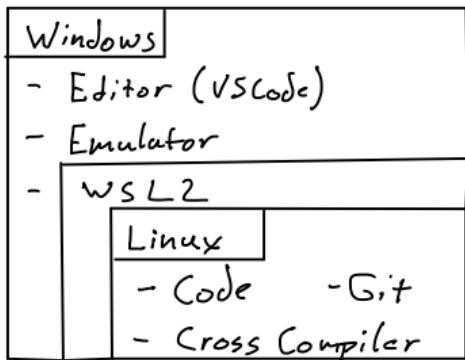
"It's a Unix System. I know this."⁵

Ariana Richards in *Jurassic Park* (1993, dir: Steven Spielberg)

About Windows



Linux Environment



Windows Environment (I think)

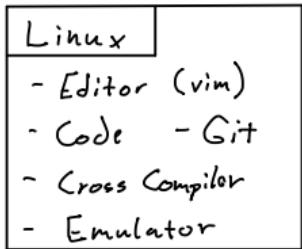
If You Use WSL

- ▶ Be aware of the layers
 - ▶ What is inside WSL
 - ▶ What is outside
- ▶ Use Git *inside WSL* to get precode
- ▶ Windows's Git will mangle the files/permissions

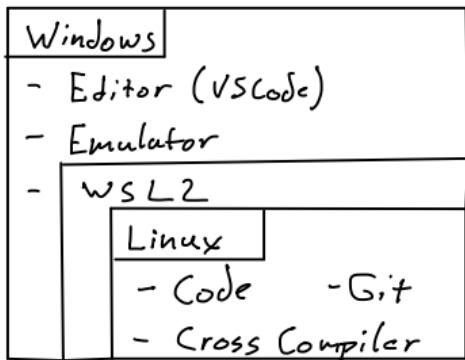
Beware of Microsoft

- ▶ WSL + VSCode

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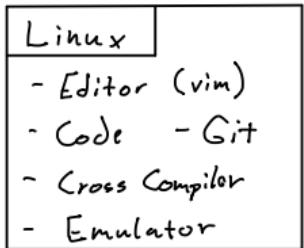
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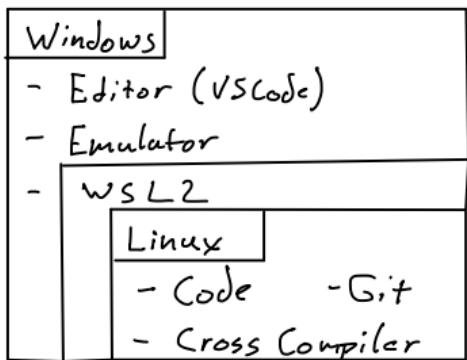
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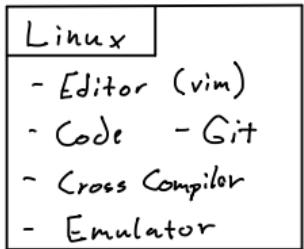
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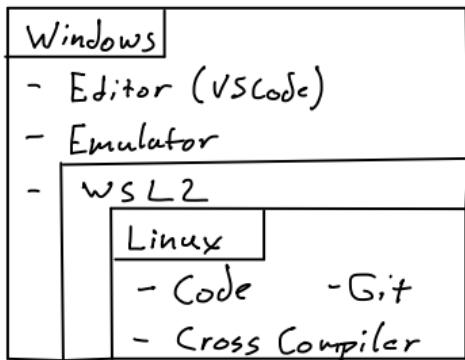
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- ▶ WSL + VSCode + GitHub
- ▶ Suddenly the de-facto dev suite

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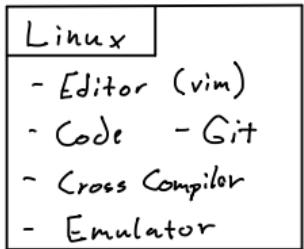
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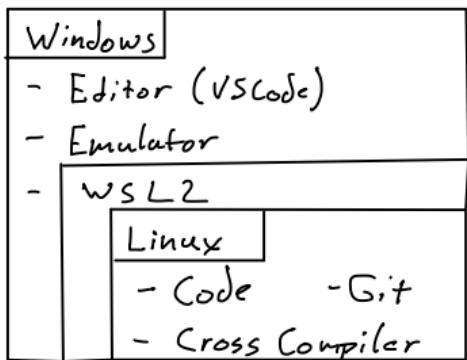
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- ▶ True goal: profit

About Windows



Linux Environment



Windows Environment (I think)

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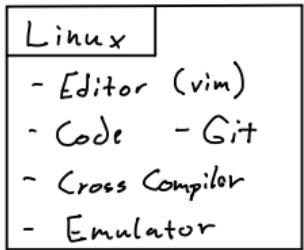
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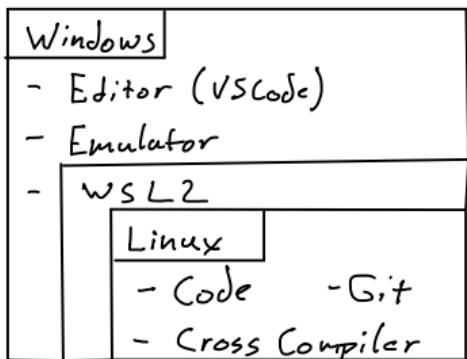
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"Embrace and Extend"

About Windows



Linux Environment



Windows Environment (I think)

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- ▶ WSL + VSCode + GitHub
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"Embrace and Extend" Extinguish

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Classic C Hello World

C source (hello.c)

```
#include <stdio.h>

int main(int argc, char *argv[])
{
    printf("Hello, world!\n");
    return 0;
}
```

Compiled x86-64 assembly (hello.s)

```
.section    .rodata
.LC0:
    .string "Hello, world!"

.text
.globl main
main:
    endbr64
    pushq   %rbp
    movq    %rsp, %rbp
    subq    $16, %rsp
    movl    %edi, -4(%rbp)
    movq    %rsi, -16(%rbp)
    leaq    .LC0(%rip), %rax
    movq    %rax, %rdi
    call    puts@PLT
    movl    $0, %eax
    leave
    ret
```

Example commands

```
gcc hello.c -o hello.s -S \
-fno-asynchronous-unwind-tables

gcc hello.c -o hello
./hello
objdump -d hello | less
```

C Standard Library: Hosted vs Freestanding

Provided by libc

- ▶ printf
- ▶ strcpy
- ▶ memcpy
- ▶ open
- ▶ ...

- ▶ Basics like printf are provided by C Standard Library, aka libc

C Standard Library: Hosted vs Freestanding

Provided by libc	Provided by OS
<ul style="list-style-type: none">▶ printf▶ strcpy▶ memcpy▶ open▶ ...	<ul style="list-style-type: none">▶ System services▶ Hardware access▶ Actual I/O▶ ...

- ▶ Basics like printf are provided by C Standard Library, aka libc
- ▶ C library is an *interface* to OS services

C Standard Library: Hosted vs Freestanding

Provided by Compiler

- ▶ Basic operations
- ▶ Number type/limits
- ▶ `size_t`
- ▶ `stdarg`
- ▶ ...

Provided by libc

- ▶ `printf`
- ▶ `strcpy`
- ▶ `memcpy`
- ▶ `open`
- ▶ ...

Provided by OS

- ▶ System services
- ▶ Hardware access
- ▶ Actual I/O
- ▶ ...

- ▶ Basics like `printf` are provided by C Standard Library, aka libc
- ▶ C library is an *interface* to OS services
- ▶ Core parts of C library come from compiler itself

C Standard Library: Hosted vs Freestanding

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- ▶ Basic operations
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- ▶ ...

Provided by libc

- ▶ `printf`
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- ▶ `memcpy`
- ▶ `open`
- ▶ ...

Provided by OS

- ▶ System services
- ▶ Hardware access
- ▶ Actual I/O
- ▶ ...

- ▶ Basics like `printf` are provided by C Standard Library, aka `libc`
- ▶ C library is an *interface* to OS services
- ▶ Core parts of C library come from compiler itself
- ▶ We will start with only that core *freestanding* C environment

Freestanding C

- ▶ Program starts at `_start`, not `main`
- ▶ Only basic headers available, such as:

header	purpose	example
<code><stddef.h></code>	Important defs	<code>NULL, size_t, ptrdiff_t</code>
<code><stdint.h></code>	Fixed-width ints	<code>uint8_t, uint32_t</code>
<code><limits.h></code>	Integer limits	<code>INT_MIN, INT_MAX</code>
<code><float.h></code>	Float limits	<code>FLT_MIN, FLT_MAX</code>
<code><stdarg.h></code>	Argument lists	<code>va_list, va_start</code>

- ▶ No `printf`. No I/O.

"Raw" Test Programs Included in Precode

process/noop-raw.c

```
int _start(void) { return 0; }
```

process/hello-raw.c

- ▶ A freestanding "hello world"
- ▶ Writes to serial port
- ▶ Includes minimal serial port code

process/plane-raw.c

- ▶ Fly a plane across the screen
- ▶ Writes to screen
- ▶ Includes minimal screen driver code

Simplified cross-compiler commands

```
i386-elf-gcc -ffreestanding -c -o hello-raw.o hello-raw.c
i386-elf-gcc -static -nostartfiles -nolibc hello-raw.o -o hello-raw
```

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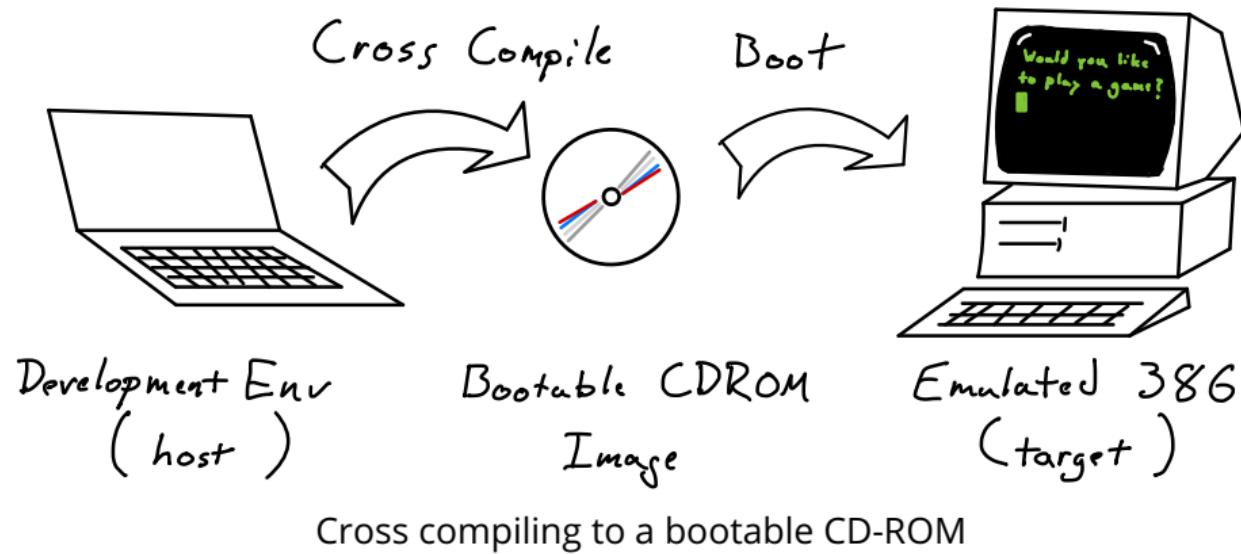
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Bootable CD Image



Building the Boot Image

1. Kernel

- ▶ Sources in `src/kernel/*.c`
- ▶ Combine to make kernel

2. Programs

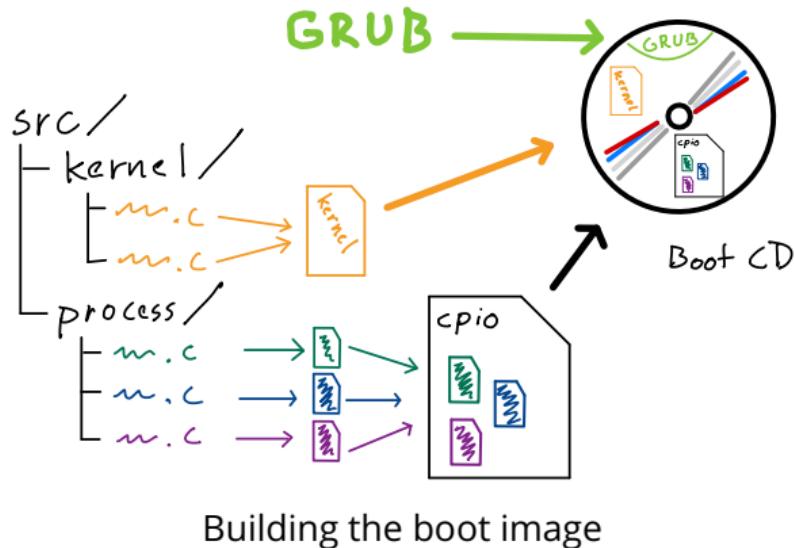
- ▶ Sources in `src/process/*.c`
- ▶ Each file is one program
- ▶ "Zip" into cpio archive (*initrd: initial ramdisk*)

3. Boot filesystem

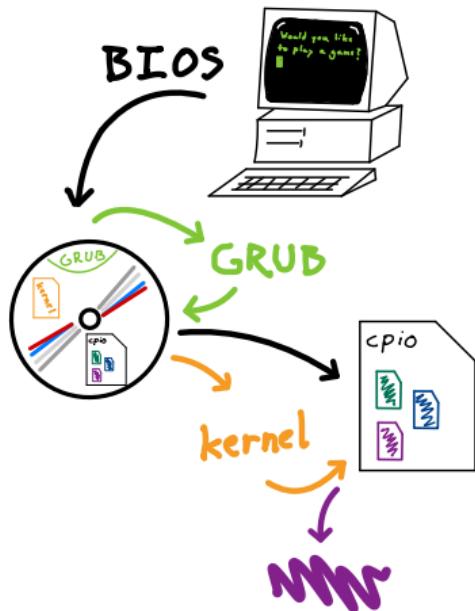
- ▶ Kernel
- ▶ cpio archive

4. Boot image

- ▶ GRUB adds boot info and bootloader



Booting the Boot Image



Booting the boot image

1. BIOS (firmware) loads and runs GRUB
2. GRUB loads kernel and initrd
3. GRUB runs kernel
4. Kernel reads archive and loads programs
 - 4.1 Gets archive location from GRUB
 - 4.2 Treats archive as filesystem
 - 4.3 Reads program file from inside archive
 - 4.4 Loads and runs program

Build Files/Process

Top-level Makefile:

```
make image
```

```
munix/
|-- Makefile
|-- src/
|   |-- configure
|   `-- Makefile.template
|
`-- out/
    `-- i386-elf/
        '-- Makefile
```

1. Creates `out/i386-elf/` output directory
2. Runs `configure` script
 - ▶ Generates `out/i386-elf/Makefile` with i386 variables
3. Uses `out/i386-elf/Makefile: make image`
 - ▶ Includes `src/Makfile.template` for common rules
 - ▶ Builds image

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Source

```
munix/
`-- src/
    |-- kernel/
    |   |-- kernel.[ch]
    |   |-- kshell.[ch]
    |   `-- process.[ch]
    |-- lib/
    `-- process/
        |-- noop-raw.c
        |-- hello-raw.c
        `-- plane-raw.c
```

Kernel

- ▶ Built from `src/kernel/*.c` plus libraries
- ▶ `kernel.[ch]` = kernel main
- ▶ `kshell.[ch]` = kernel shell
- ▶ `process.[ch]` = loading processes

Programs

- ▶ Each C file in `process/*.c` is one program
- ▶ “-raw” ending = raw code. No libraries

Libraries

libcore

- ▶ Essential utilities
- ▶ No I/O: no `fprintf`, only `sprintf`

libarch

```
munix/  
`-- src/  
    `-- lib/  
        |-- core/  
        |-- arch/i386/  
        |-- drivers/  
        `-- oss/
```

- ▶ Architecture-specific code
- ▶ How to use CPU: I/O ports, halt, startup

libdrivers

- ▶ Code to talk to hardware devices
- ▶ e.g. serial port, screen, etc.

oss/

- ▶ Open-source headers (Multiboot, ELF)

“Everything is a File”

- ▶ Core tenet of the Unix Philosophy
- ▶ Files are sequences of bytes
 - ▶ Everything is just a sequence of bytes, really
 - ▶ So let's read and write to devices as if they were files
 - ▶ Serial port? File
 - ▶ Terminal interface? File
 - ▶ Disk partition? File!
 - ▶ File? Oh you better believe that's a file
- ▶ Virtual Filesystem
 - ▶ Not C:\ or D:\
 - ▶ Everything is *mounted* into one unified hierarchy
 - ▶ Hierarchy starts with *root*, represented by a slash /
 - ▶ By convention
 - ▶ /dev/ = Devices
 - ▶ /bin/ = Binaries (programs)
 - ▶ ...

Drivers

```
munix/src/lib/drivers/  
|-- chrdev/  
| |-- ramdisk.c  
| |-- serial.c  
| |-- tty.c  
|-- fileformat/  
| |-- ascii.h  
| |-- elf.c  
| |-- elf.h  
|-- fs/  
| |-- cpiofs.c  
|-- devices.h  
|-- log.c  
|-- log.h  
|-- vfs_file.c  
|-- vfs_fs.c  
`-- vfs.h
```

Interfaces

- ▶ `vfs.h` = Common file and filesystem interfaces
- ▶ `devices.h` = Header for devices
- ▶ `log.h` = Macros to write to a file as a kernel log

chrdev/ = Character Devices

- ▶ Devices as files
- ▶ Serial port
- ▶ TTY: wraps another file to add terminal features
- ▶ Ramdisk: treat bytes in memory like a file/device

fs/ = Filesystems

- ▶ `cpiofs`: Treat a `cpio` archive as a filesystem
- ▶ Ramdisk + `cpiofs` → Read files from initrd

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Project 1

Task Zero

- ▶ Get your environment set up
- ▶ Explore and learn the code
- ▶ Suggestion: run kernel in debugger and step through startup
- ▶ Brush up on your weak spots

Design Reviews

- ▶ TAs will schedule *design reviews* about halfway through project time
- ▶ Meet with TA
- ▶ Present your plan for the assignment

Main tasks

1. Finish reading boot info and find ramdisk location
 2. Read, load, and run a program file
- ▶ Not a lot of code
 - ▶ But a lot to understand first

Hand-in

- ▶ Code and report
- ▶ Zip (or tarball) and upload to Canvas

Report

- ▶ Tell us what you did and why
- ▶ Four pages is a good length

More on i386

x86 Registers

Eight General Purpose Registers: AX, BX, CX, DX, SI, DI, SP, BP

- ▶ *General Purpose*: can load/store, do math, etc.
- ▶ But may have special talent (like Stack Pointer)
- ▶ Named for talent/conventional use

Data

- ▶ **AX**: Accumulator
- ▶ **DX**: Data
- ▶ **BX**: Base

String operations

- ▶ **SI**: Source Index
- ▶ **DI**: Destination Index
- ▶ **CX**: Counter

Stack

- ▶ **SP**: Stack Pointer
- ▶ **BP**: Base Pointer

Control Registers

- ▶ **IP**: Instruction Pointer
- ▶ **FLAGS**: Condition bits
- ▶ (and more)

Intel Registers: Prefixes

