UiT The Arctic University of Norway

Project 1: Boot-Up Mechanism

Loading a kernel and switching to 32-bit mode

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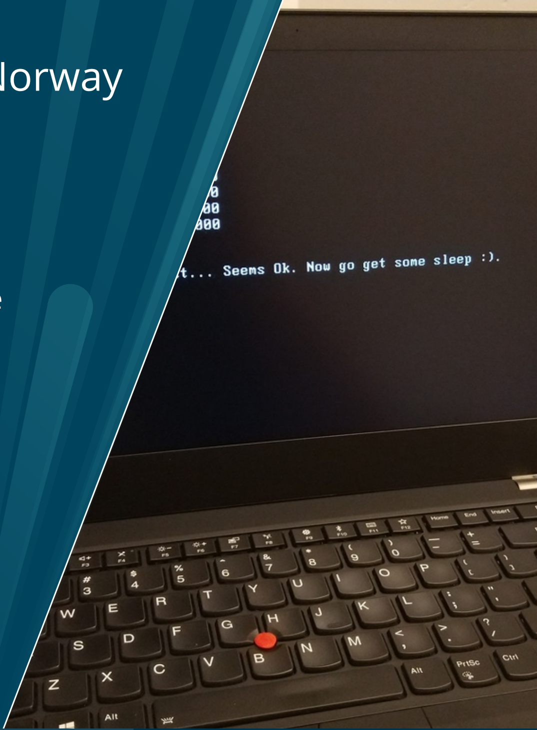


Project 1

Project 1 is a demo

- You do not have to turn anything in
- Get the code. Build it. Run it.
- Set up your build environment
- Familiarize yourself with the code and the tools

We will be building an OS

- Each project will build on the previous
- Project 1: We give you a “hello world”
- Project 2: You start building a kernel
- Projects 3-6: You add more and more features

Project 1: “Hello World”

The code contains

- Bootloader
- “Hello world” kernel
- Utility to create a bootable disk image

The image

1. Boots
2. Loads the kernel
3. Prints a hello message

Architecture

- We’re going back to the 90s: 32-bit Intel x86 (aka i386)
- The OS can boot on some old hardware, but it’s getting harder
- We will develop primarily in an x86 emulator: Bochs

Project 1

What happens when a PC boots?

First steps

1. CPU: starts executing at 0xfffffff0 (*reset vector*)
2. Motherboard: makes sure there's something to execute: a jump to 0xf0000
3. BIOS ROM: starts at 0xf0000

BIOS: Basic Input Output System

- Firmware in ROM
- Knows how to talk to disks, keyboard, display
- Knows how to look for a bootable disk
- Provides interface for software to talk to disks, keyboard, display

Next steps

4. BIOS: looks for a bootable disk
5. BIOS: loads bootloader from disk
6. Bootloader: loads kernel from disk
7. Kernel: starts

UEFI is the New BIOS

UEFI: Unified Extensible Firmware Interface

- Began around 1998
- Replacement for BIOS
- Much more sophisticated

For example, the bootloader:

- BIOS:
  - Reads first 512 bytes of disk
  - Those 512 bytes contain simple partition table and bootloader code
  - First bootloader typically needs to load a *second stage* bootloader that understands the filesystems and can find the kernel
- UEFI:
  - Understands filesystems and executable file formats
  - Loads bootloader like an OS would load a normal program

We Don't Use UEFI

UEFI BIOS Compatibility

- UEFI replaced BIOS, but it kept *Compatibility Mode Support* (CSM) . . . until ~2020
- New computers are UEFI-only

Our OS still uses the old BIOS boot system

- This is why it's getting harder to boot our OS on real PCs
- This is why we're giving you this code instead of making you write it
- Writing a BIOS bootloader requires knowledge of obsolete hardware modes

Project 1

x86 Family History

Year	CPU	Regs	Addresses	Hottest feature
1978	Intel 8086	16-bit	20-bit (1 MiB)	Segmented addressing
1982	Intel 286	16-bit	24-bit (16 MiB)	Memory protection
1985	Intel 386	32-bit	32-bit (4 GiB)	Virtual memory paging
...				
2003	AMD Opteron	64-bit	52-bit (4 PiB)	64 bits!

Note the shifting bottlenecks

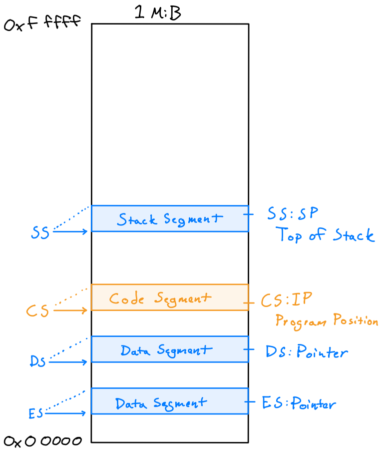
- 16-bit CPUs: registers. Harder to make wider registers than more memory
- 32-bit CPUs: memory, then regs. 4 GiB of RAM was a lot ... until it wasn't
- 64-bit CPUs: memory again. 4 PiB of RAM is a lot

Why is History Important?

Because every boot is a walk through history

- x86 CPUs are aggressively backwards compatible
- Even new CPUs act like an 8086 at boot, just in case
- Software must start with 16-bit code and bootstrap its way to 32- or 64-bit
  - BIOS-style: bootloader and OS must do this (our OS does this)
  - UEFI-style: firmware does this before handing off
- Understanding history helps you understand the present

i8086 Segmented Memory Addressing

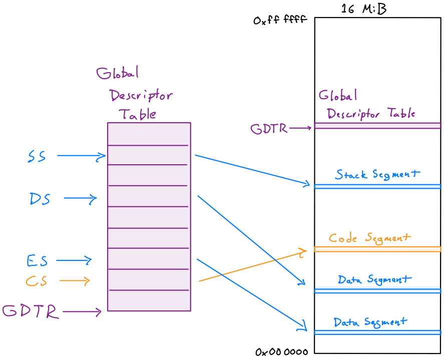


Segmented addressing

Address Space	Registers
20-bit (1 MiB)	16-bit (64 KiB)

- Divide memory into 64 KiB *segments*
  - Instruction pointer (IP) $\rightarrow$ Code Segment (CS)
  - Stack pointer (SP) $\rightarrow$ Stack Segment (SS)
  - Data pointers $\rightarrow$ Data Segments (DS, ES, FS, GS)
- CS, SS, DS, ES, FS, GS are 16-bit segment registers
  - Specificy base of segment (shift by 4)
  - CS 0x1234 $\rightarrow$ Address 0x12340
  - IP 0x5678 $\rightarrow$ Address 0x12340 + 0x5678 = 0x179B8

i286 Protected Mode Addressing

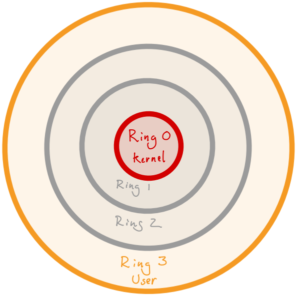


Protected mode addressing

Address Space	Registers
24-bit (16 MiB)	16-bit (64 KiB)

- Add a layer of indirection
  - Move segment information into memory
  - Set up a table of 8-byte *segment descriptors*
- 8-byte segment descriptor in memory
  - 24-bit base address
  - 16-bit limit (end of segment)
  - various flags, including privilege level
- 16-bit segment register
  - 13 bit index into descriptor table
  - 3 bits for flags

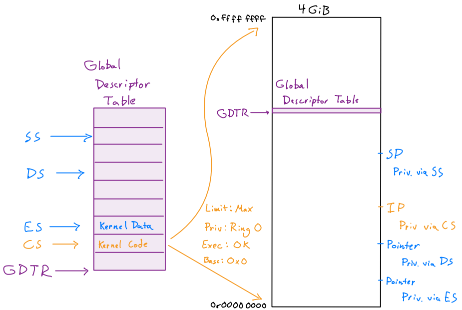
Protected Mode Privilege Levels



Privilege levels

- 2 bits for privilege level $\rightarrow$ 4 privilege levels
  - Ring 0 (innermost): operating system kernel
  - Rings 1 & 2: intended for device drivers
  - Ring 3 (outermost): user applications
- Segment descriptor determines current priv level
  - CS register selects descriptor
  - Descriptor priv level determines current priv level
  - Certain operations can only be executed with priv 0
  - Attempts to change CS are checked against current priv level vs requested priv level
- In practice, most operating systems use only kernel and user

i386 Flat Memory Model



Flat addressing

Address Space	Registers
32-bit (4 GiB)	32-bit (4 GiB)

- Do we still need segment descriptors?
  1. To reach whole address space? — Not needed
  2. To mark off protected regions of memory? — No, paging is better
  3. To set current privilege level? — Still used
- Vestigial descriptor table
  1. Kernel-level code: priv 0, executable
  2. Kernel-level data: priv 0, no-execute
  3. User-level code: priv 3, executable
  4. User-level data: priv 0, no-execute

x86-64 Canonical Addressing

Address Space	Registers
52-bit (4 PiB)	64-bit (16 EiB)

- Pointers can address more memory than we can make RAM for
  - CPU designs don't bother having 64 address lines
  - Only 52 lines, which can address up to 4 PiB
- Canonical address form
  - High bits must be all 0 or all 1

```
0xFFF0 0000 0000 0000 -- 0xFFFF FFFF FFFF FFFF
0x0000 0000 0000 0000 -- 0x000F FFFF FFFF FFFF
```

  - This prevents software from trying to use unused bits for other purposes

Moving Through History on Boot

- CPU starts in 16-bit *Real Mode* (8086-style)
- To get to 32-bit *Protected Mode* (386-style)
  1. Create a Global Descriptor Table (GDT) in memory
  2. Set the Global Descriptor Table Register (GDTR)
  3. Enable the A20 line
  4. Enable Protected Mode
  5. Jump into 32-bit code

  $\rightarrow$ Our OS gets to here $\leftarrow$
- To get to 64-bit *Long Mode* (x86-64)
  1. Set up paging data structures in memory
  2. Set the appropriate paging registers
  3. Enable Long Mode
  4. Jump into 64-bit code

  $\rightarrow$ UEFI gets here before handing off $\leftarrow$

Side Note: AMD and x86-64

Why was it AMD who had the first 64-bit x86 system?

Because they developed the architecture

Intel Itanium and Intel Architecture 64 (IA-64)

- All-new architecture, not backwards compatible
- Based on *Very Long Instruction Word (VLIW)* concept
- Backwards compatibility with x86 through emulation layer, very slow
- Commercial flop. Tech press called it "The Itanic".
- AMD extended the x86 architecture instead. That's what stuck.
- Side-side note: UEFI was developed for Itanium

Project 1

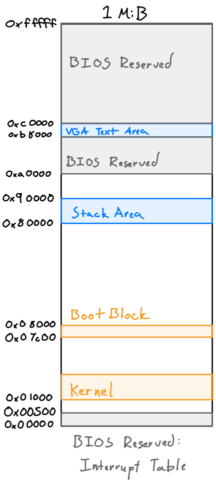
BIOS Memory Map

- 1 MiB, divided into sixteen 64 KiB blocks

Addr	Block	Desc
`0xf0000`	F block	System ROM BIOS
`0xe0000`	E block	PCjr cartridges
`0xd0000`	D block	PCjr cartridges
`0xc0000`	C block	ROM expansion
`0xb0000`	B block	CGA memory
`0xa0000`	A block	EGA memory
`0x00000`	0-9 block	“conventional memory” / “low memory”

- Blocks 0-9: 640 KiB, this is the origin of the classic 640k limit

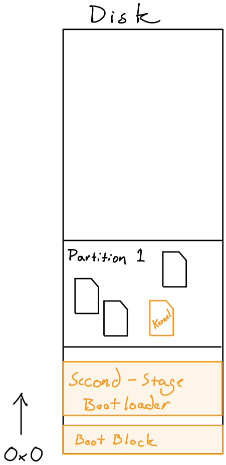
Where to Load Our OS



P1 memory map

- 0xa0000: Reserved: High memory
  - 0xb8000: VGA text buffer
- 0x80000: Stack
- 0x07c00: Boot block
- 0x01000: Kernel
- 0x00000: Reserved: Interrupt vector table

Disk Image: Normal OS for BIOS-Based System



Typical OS disk

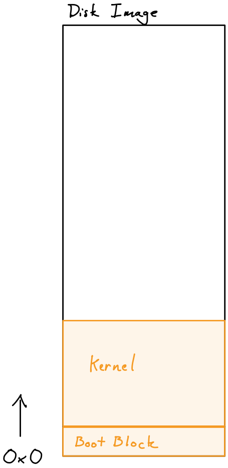
Disk

- First 512 bytes: bootloader code + partition table
- Rest of disk is divided into partitions
- Partitions have filesystems
- Executables are ELF files

Boot

1. BIOS loads bootblock
2. Bootloader loads second-stage bootloader
3. Second-stage bootloader loads kernel ELF

Disk Image: Our OS



Our OS disk image

Disk

- First 512 bytes: bootloader code (no partition table)
- Rest of disk is raw kernel data

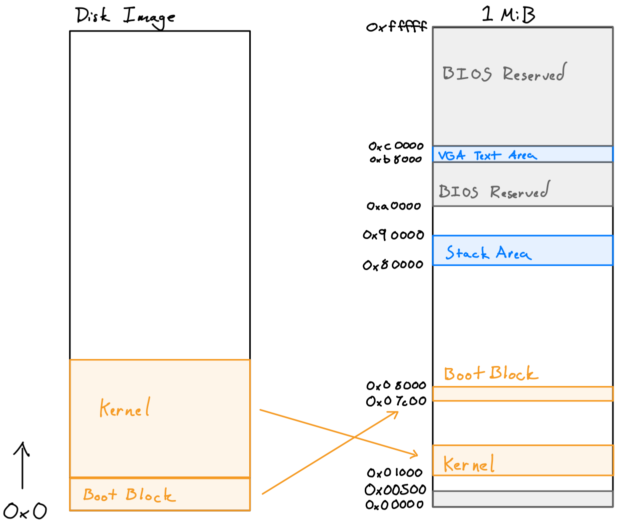
Boot

1. BIOS loads bootloader
2. Bootloader loads kernel

`createimage` program

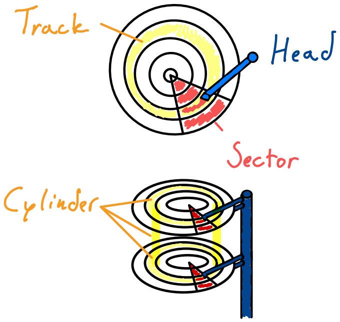
- Read the kernel ELF file at build time
- Copy to image instead of memory

Disk Image to Memory



Loading boot block and kernel from disk to memory

Reading a Disk, BIOS Style: CHS Addressing



Spinning disk platters

- CHS: Cylinder / Head / Sector
- Floppy disks
  - Move arm to select *track*
  - Select one of two read *heads*, one per side
  - Time read to rotation to select a *sector*
- Spinning hard disks
  - Stack of disk platters
  - Move arm to select *cylinder* of stacked tracks
  - Select head to select platter and side
- Mapping blocks $\leftrightarrow$ CHS
  - Block 0 $\leftrightarrow$ CHS 0/0/1
  - No circuitry in floppy controller for mapping
  - Software must do the mapping
  - Even solid-state drives provide CHS emulation

Project 1

OS Source Code

Repository tree

```
.
|-- src
|    |-- boot     Bootloader source
|    |-- kernel   Kernel source
|    `-- lib      Libraries source
|-- host          Output directory for host machine (your computer)
|-- target        Output directory for target machine (x86-32)
`-- thirdparty    BIOS images for emulator
```

Build process

```
1. Compile src/lib/**            -> target/lib/lib*.a
2. Compile src/boot/**           -> target/boot/bootblock
3. Compile src/kernel/**         -> target/kernel/kernel
4. Compile src/createimage.c     -> host/createimage
5. Run host/createimage          -> image
```

Make

Make Commands

```
make                # Default, equivalent to 'make image test'
docker-run make     # Run the same command in a Docker container
```

Makefiles

```
Makefile            # Main Makefile, delegates to host or target Makefiles
host/Makefile       # Rules for compiling for host machine
target/Makefile     # Rules for compiling for target machine
src/Makefile.common # Common rules, included by host and target Makefiles
```

Host System (Your Computer)

- x86-64 architecture
- Recommend Ubuntu 22.04 LTS (Jammy Jellyfish)
  - Other Linuxes should work, but may have GCC version issues
  - Windows Subsystem for Linux might work
  - Mac ???
- Can also use Docker
  - `Dockerfile` describes the system
  - `docker-run` script spins up a container and runs a command

```
docker-run make
```

Emulator: Bochs

- Supported emulator: Bochs
  - x86 emulator that focuses on accuracy over speed
  - Sorry, no QEMU (yet)
- Bochs built-in debugger
  - Similar to GDB, but a little clunky
  - Advantage: 16-bit code (bootloader)
  - Install `bochs` from `apt`: configured for built-in debugger
- Connect Bochs to GDB (recommended)
  - Much more powerful
  - Weakness: 16-bit code (because GDB assumes flat memory model)
  - Requires building Bochs from source

Project 1

Suggested Tasks

- Build: get code, set up environment, build OS
- Step through with a debugger
  - Bochs debugger? Step through bootloader (breakpoint: 0x7c00)
  - Bochs + GDB? Step through 32-bit code (breakpoint: `_start32`)
  - Get a feel for x86 ASM and how C maps to it
- Read code
  - Can you follow the bootblock ASM?
  - Can you follow the kernel C code?
  - Can you follow the C library code?
- Look at docs
  - `doc/x86`: x86 architecture and ASM programming
  - `doc/abi`: System V ABI docs (C calling convention, ELF format, etc.)
  - Download and flip through Intel manuals
  - Download and flip through AMD manuals (AMD may be easier to read)

Ask for Help

- The OS course is challenging
  - But it's supposed to be a fun challenge
- We're here to help
  - Ask questions on Discord (and please ask in the open chats)
  - Talk to your TA
  - Come to the colloquium sessions
- We also need feedback
  - The course is in transition, there will be hiccups
  - The code is in transition, there will be bugs
  - Let us know what is working and what is not