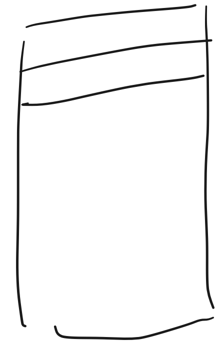
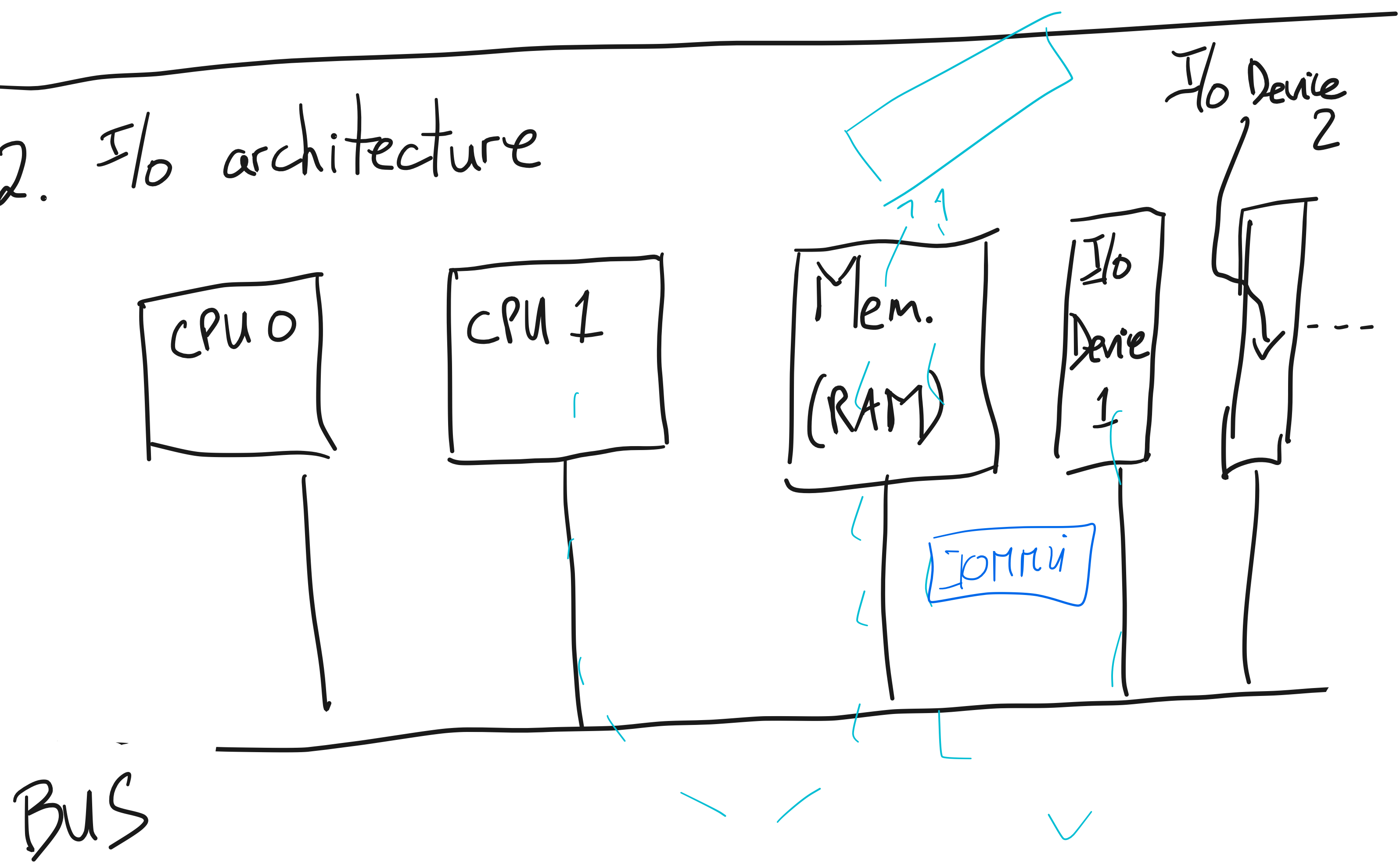
1. Last time
2. I/o architecture
3. CPU/device interaction
   - Mechanics
   - Polling vs. interrupts
   - DMA vs. programmed I/o
4. Software architecture: device drivers
5. Synchronous vs. asynchronous I/o
6. Context switches (WeensyOS)

x86_64_pagetable*



2. I/o architecture



3. CPU/Device interaction

A. Mechanics of communication

(a) explicit I/O instructions

outb, inb, outw, inw, . . .

outb(addr in I/o space , byte)

byte ← inb(addr in I/o space)

examples:

(i) boot.c

(ii) keyboard_read

(iii) console_show_cursor

(b) memory-mapped I/O

example:

console_putc()

(c) interrupts

(d) via physical memory

B. Polling vs. interrupts (vs. busy waiting)

Tradeoff ---

C. DMA vs. programmed I/O

programmed I/O: what we have seen so far

DMA: device directly reads from (or writes to) memory; initial CPU ↔ device coordination is required.

4 possibilities:

{DMA, programmed I/O} × {polling, interrupts}

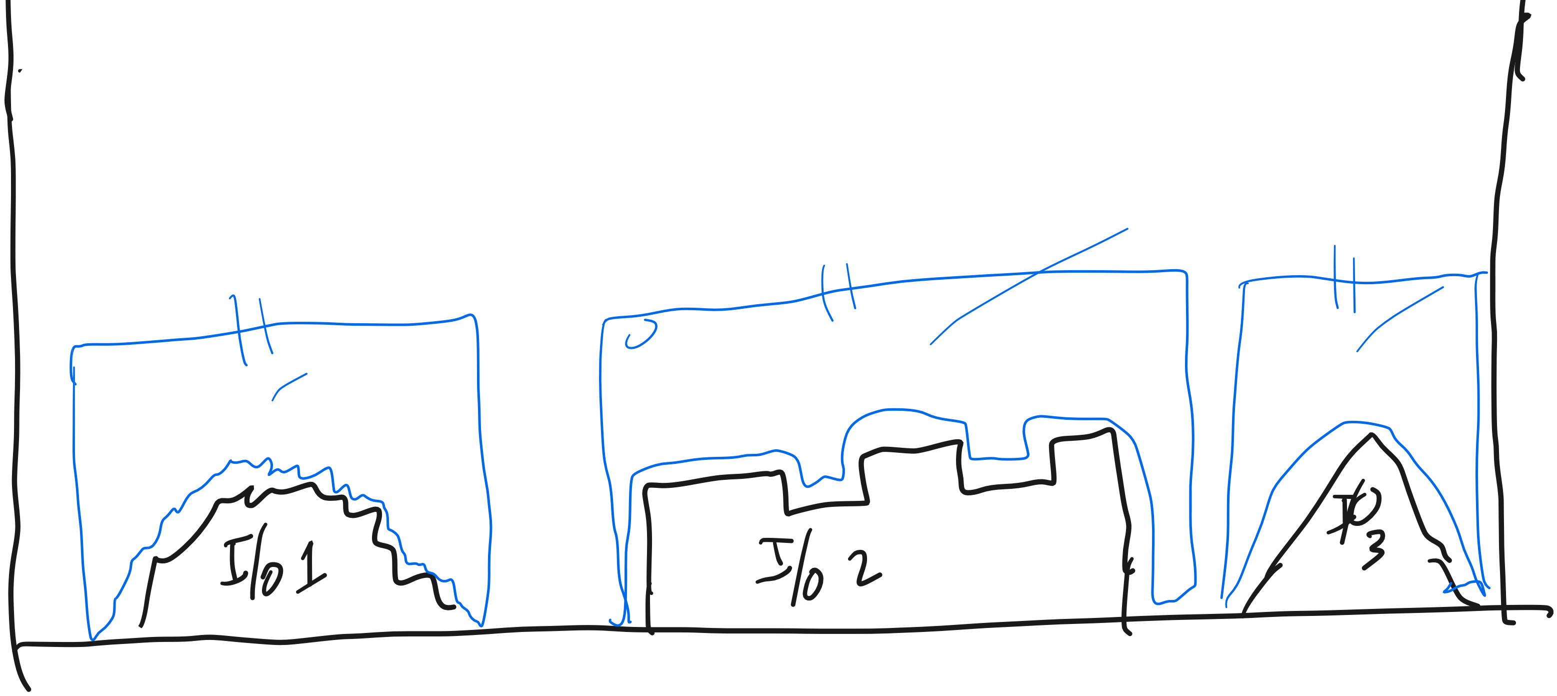
(DMA, polling)

(prog_I/O, polling)

...

---

4. Device drivers



stuxnet

5. Synchronous vs. asynchronous I/O

blocking == synchronous

non-blocking == asynchronous

NOTE: kernel never blocks when issuing I/O (in items 2-4 today).

S… vs. async is about the interface

Sync vs. asyn

presented to user-level processes.

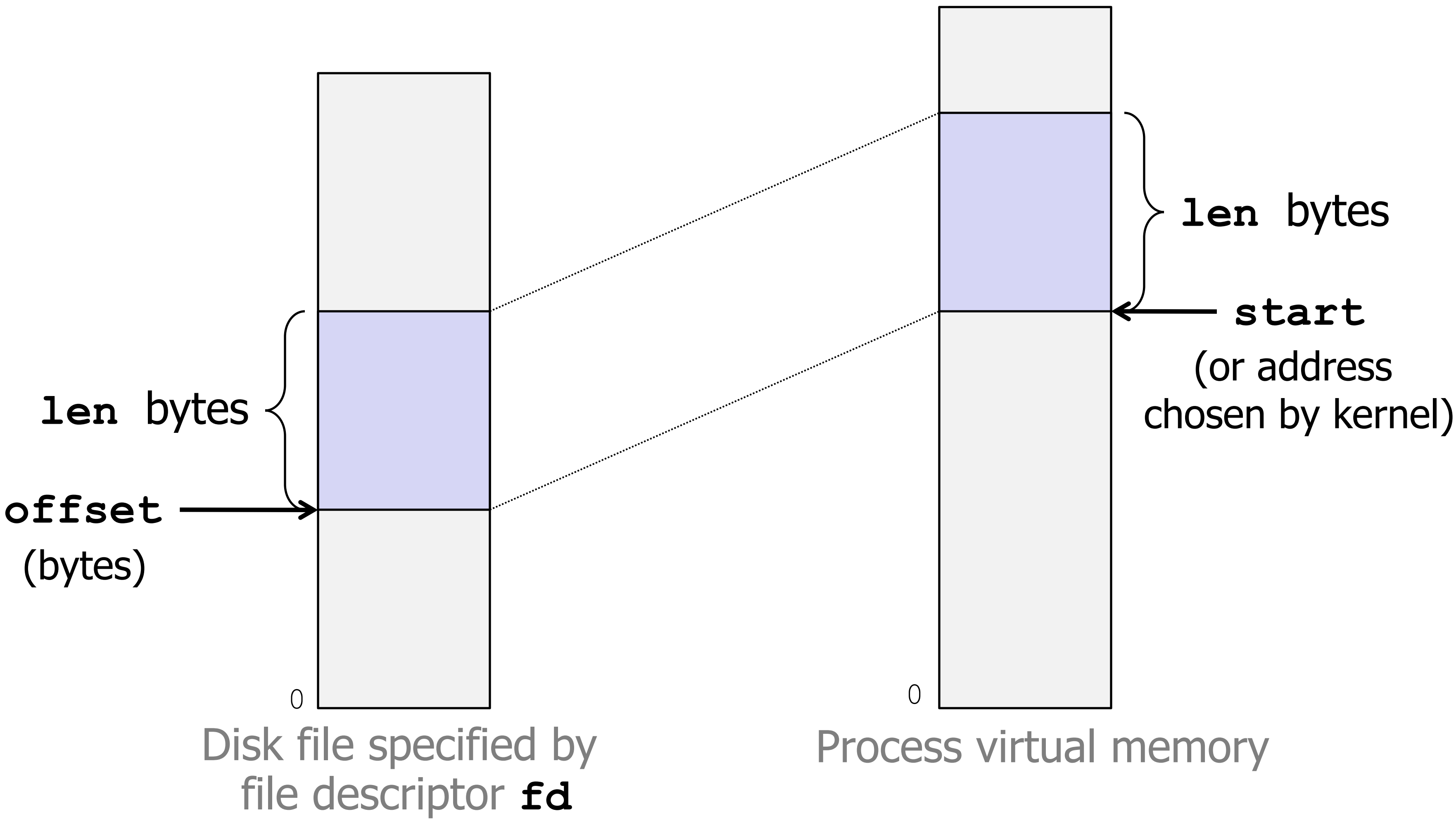
sync: blocks

async: returns error, indicates "would block"

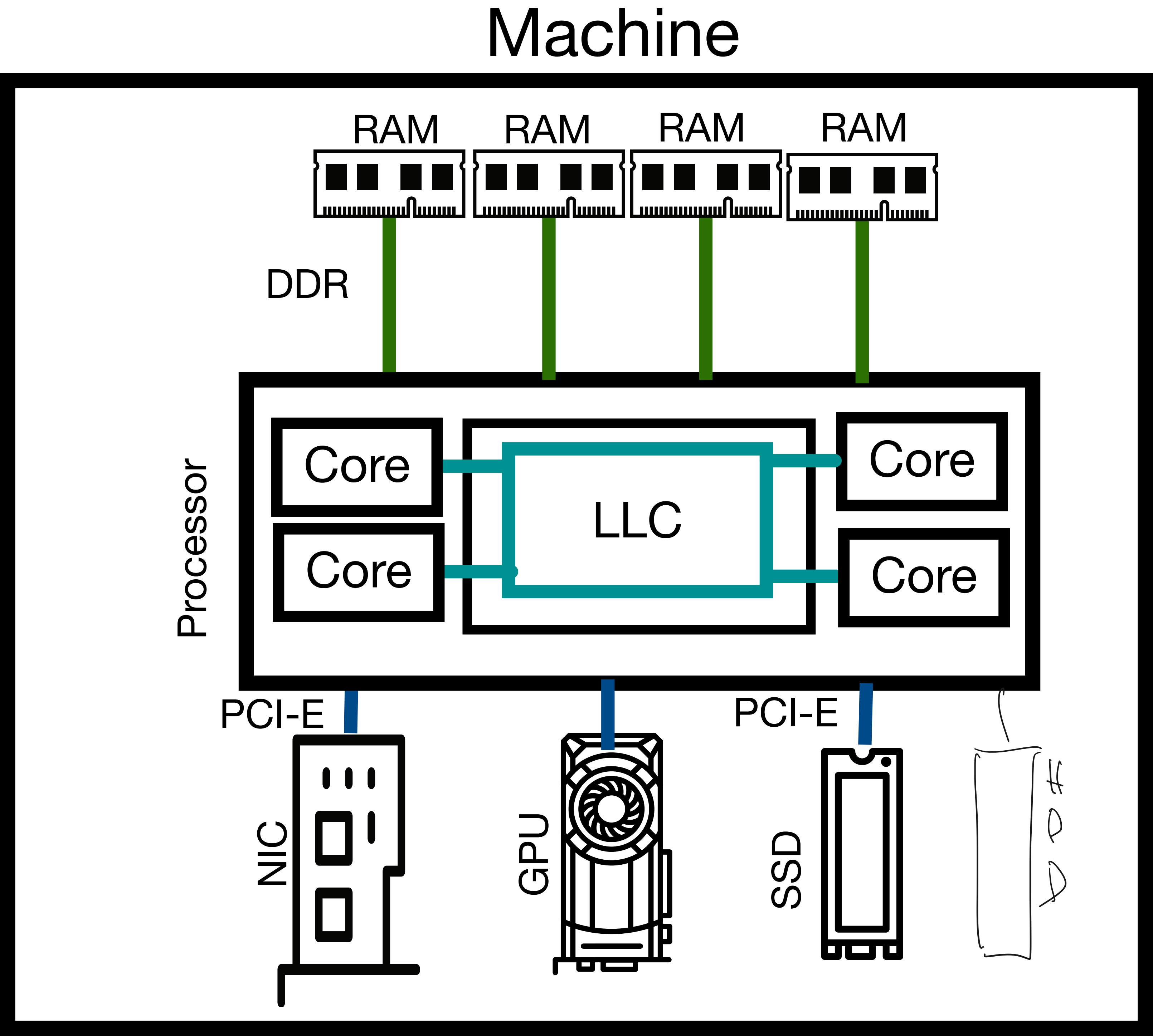
```
read (fd, buf, sz);

write (fd, buf, sz);
```

User-Level Memory Mapping

```
void *mmap(void *start, int len,
           int prot, int flags, int fd, int offset)
```



```c
#include <fcntl.h>
#include <stdio.h>
#include <stdlib.h>
#include <sys/mman.h>
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>

void mmapcopy(int fd, int size);

int main(int argc, char **argv) {
  struct stat stat;
  int fd;

  /* Check for required cmd line arg */
  if (argc != 2) {
    printf("usage: %s <filename>\n", argv[0]);
    exit(0);
  }

  /* Copy input file to stdout */
  if ((fd = open(argv[1], O_RDONLY, 0)) < 0)
    perror("open");

  fstat(fd, &stat);
  mmapcopy(fd, stat.st_size);

  close(fd);

  return 0;
}

void mmapcopy(int fd, int size) {

    /* Ptr to memory mapped area */
    char *bufp;

    bufp = mmap(NULL, size, PROT_READ, MAP_PRIVATE, fd, 0);

    write(STDOUT_FILENO, bufp, size);

    return;
}
```


Machine
RAM
RAM
RAM
RAM
DDR
Processor
Core
Core
LLC
Core
Core
PCI-E
PCI-E
NIC
GPU
SSD
HDD

```
CS 202, Fall 2021
Handout 9 (Class 15)

1. Example use of I/O instructions: boot loader

    Below is the WeensyOS boot loader

    It may be helpful to understand the overall picture

    This code demonstrates I/O, specifically with the disk: the
    bootloader reads in the kernel from the disk.

    See the functions boot_waitdisk() and boot_readsect(). Compare to Figures 36.5
    and 36.6 in OSTEP.

/* boot.c */
#include "x86-64.h"
#include "elf.h"

// boot.c
//
//   WeensyOS boot loader. Loads the kernel at address 0x40000 from
//   the first IDE hard disk.
//
//   A BOOT LOADER is a tiny program that loads an operating system into
//   memory. It has to be tiny because it can contain no more than 510 bytes
//   of instructions: it is stored in the disk's first 512-byte sector.
//
//   When the CPU boots it loads the BIOS into memory and executes it. The
//   BIOS intializes devices and CPU state, reads the first 512-byte sector of
//   the boot device (hard drive) into memory at address 0x7C00, and jumps to
//   that address.
//
//   The boot loader is contained in bootstart.S and boot.c. Control starts
//   in bootstart.S, which initializes the CPU and sets up a stack, then
//   transfers here. This code reads in the kernel image and calls the
//   kernel.
//
//   The main kernel is stored as an ELF executable image starting in the
//   disk's sector 1.

#define SECTORSIZE      512
#define ELFHDR          ((elf_header*) 0x10000) // scratch space

void boot(void) __attribute__((noreturn));
static void boot_readsect(uintptr_t dst, uint32_t src_sect);
static void boot_readseg(uintptr_t dst, uint32_t src_sect,
                         size_t filesz, size_t memsz);

// boot
//    Load the kernel and jump to it.
void boot(void) {
    // read 1st page off disk (should include programs as well as header)
    // and check validity
    boot_readseg((uintptr_t) ELFHDR, 1, PAGESIZE, PAGESIZE);
    while (ELFHDR->e_magic != ELF_MAGIC) {
        /* do nothing */
    }

    // load each program segment
    elf_program* ph = (elf_program*) ((uint8_t*) ELFHDR + ELFHDR->e_phoff);
    elf_program* eph = ph + ELFHDR->e_phnum;
    for (; ph < eph; ++ph) {
        boot_readseg(ph->p_va, ph->p_offset / SECTORSIZE + 1,
                     ph->p_filesz, ph->p_memsz);
    }

    // jump to the kernel
    typedef void (*kernel_entry_t)(void) __attribute__((noreturn));
    kernel_entry_t kernel_entry = (kernel_entry_t) ELFHDR->e_entry;
    kernel_entry();
}
```



```


// boot_readseg(dst, src_sect, filesz, memsz)
//    Load an ELF segment at virtual address `dst` from the IDE disk's sector
//    `src_sect`. Copies `filesz` bytes into memory at `dst` from sectors
//    `src_sect` and up, then clears memory in the range
//    `[dst+filesz, dst+memsz)`.
static void boot_readseg(uintptr_t ptr, uint32_t src_sect,
                         size_t filesz, size_t memsz) {
    uintptr_t end_ptr = ptr + filesz;
    memsz += ptr;

    // round down to sector boundary
    ptr &= ~(SECTORSIZE - 1);

    // read sectors
    for (; ptr < end_ptr; ptr += SECTORSIZE, ++src_sect) {
        boot_readsect(ptr, src_sect);
    }

    // clear bss segment
    for (; end_ptr < memsz; ++end_ptr) {
        *(uint8_t*) end_ptr = 0;
    }
}


// boot_waitdisk
//    Wait for the disk to be ready.
static void boot_waitdisk(void) {
    // Wait until the ATA status register says ready (0x40 is on)
    // & not busy (0x80 is off)
    while ((inb(0x1F7) & 0xC0) != 0x40) {
        /* do nothing */
    }
}


// boot_readsect(dst, src_sect)
//    Read disk sector number `src_sect` into address `dst`.
static void boot_readsect(uintptr_t dst, uint32_t src_sect) {
    // programmed I/O for "read sector"
    boot_waitdisk();
    outb(0x1F2, 1);             // send `count = 1` as an ATA argument
    outb(0x1F3, src_sect);      // send `src_sect`, the sector number
    outb(0x1F4, src_sect >> 8);
    outb(0x1F5, src_sect >> 16);
    outb(0x1F6, (src_sect >> 24) | 0xE0);
    outb(0x1F7, 0x20);          // send the command: 0x20 = read sectors

    // then move the data into memory
    boot_waitdisk();
    insl(0x1F0, (void*) dst, SECTORSIZE/4); // read 128 words from the disk
}
```

```
2. Two more examples of I/O instructions

    (a) Reading keyboard input

    The code below is an excerpt from WeensyOS's k-hardware.c

    This reads a character typed at the keyboard (which shows up on the
    "keyboard data port" (kEYBOARD_DATAREG)).

    /* Excerpt from WeensyOS x86-64.h */
    // Keyboard programmed I/O
    #define KEYBOARD_STATUSREG      0x64
    #define KEYBOARD_STATUS_READY   0x01
    #define KEYBOARD_DATAREG        0x60

    int keyboard_readc(void) {
        static uint8_t modifiers;
        static uint8_t last_escape;

        if ((inb(KEYBOARD_STATUSREG) & KEYBOARD_STATUS_READY) == 0) {
            return -1;
        }

        uint8_t data = inb(KEYBOARD_DATAREG);
        uint8_t escape = last_escape;
        last_escape = 0;

        if (data == 0xE0) {         // mode shift
            last_escape = 0x80;
            return 0;
        } else if (data & 0x80) {   // key release: matters only for modifier ke
ys
            int ch = keymap[(data & 0x7F) | escape];
            if (ch >= KEY_SHIFT && ch < KEY_CAPSLOCK) {
                modifiers &= ~(1 << (ch - KEY_SHIFT));
            }
            return 0;
        }

        int ch = (unsigned char) keymap[data | escape];

        if (ch >= 'a' && ch <= 'z') {
            if (modifiers & MOD_CONTROL) {
                ch -= 0x60;
            } else if (!(modifiers & MOD_SHIFT) != !(modifiers & MOD_CAPSLOCK))
{
                ch -= 0x20;
            }
        } else if (ch >= KEY_CAPSLOCK) {
            modifiers ^= 1 << (ch - KEY_SHIFT);
            ch = 0;
        } else if (ch >= KEY_SHIFT) {
            modifiers |= 1 << (ch - KEY_SHIFT);
            ch = 0;
        } else if (ch >= CKEY(0) && ch <= CKEY(21)) {
            ch = complex_keymap[ch - CKEY(0)].map[modifiers & 3];
        } else if (ch < 0x80 && (modifiers & MOD_CONTROL)) {
            ch = 0;
        }

        return ch;
    }
```



```

    (b) Setting the cursor position

    The code below is also excerpted from WeensyOS's k-hardware.c.  It
    uses I/O instructions to set a blinking cursor in the upper left of
    the screen.

    // console_show_cursor(cpos)
    //    Move the console cursor to position `cpos`, which should be between 0
    //    and 80 * 25.

    void console_show_cursor(int cpos) {
        if (cpos < 0 || cpos > CONSOLE_ROWS * CONSOLE_COLUMNS) {
            cpos = 0;

        outb(0x3D4, 14);        // Command 14 = upper byte of position
        outb(0x3D5, 0 / 256);   // row 0
        outb(0x3D4, 15);        // Command 15 = lower byte of position
        outb(0x3D5, 0 % 256);   // column 0

    }
```

3. Memory-mapped I/O

a. Here is a 32-bit PC's physical memory map:

```
    +------------------+  <- 0xFFFFFFFF (4GB)
    |      32-bit      |
    |  memory mapped   |
    |     devices      |
    |                  |
    /\/\/\/\/\/\/\/\/\/\

    /\/\/\/\/\/\/\/\/\/\
    |                  |
    |      Unused      |
    |                  |
    +------------------+  <- depends on amount of RAM
    |                  |
    |                  |
    | Extended Memory  |
    |                  |
    |                  |
    +------------------+  <- 0x00100000 (1MB)
    |     BIOS ROM     |
    +------------------+  <- 0x000F0000 (960KB)
    |  16-bit devices, |
    |  expansion ROMs  |
    +------------------+  <- 0x000C0000 (768KB)
    |   VGA Display    |
    +------------------+  <- 0x000A0000 (640KB)
    |                  |
    |    Low Memory    |
    |                  |
    +------------------+  <- 0x00000000
```

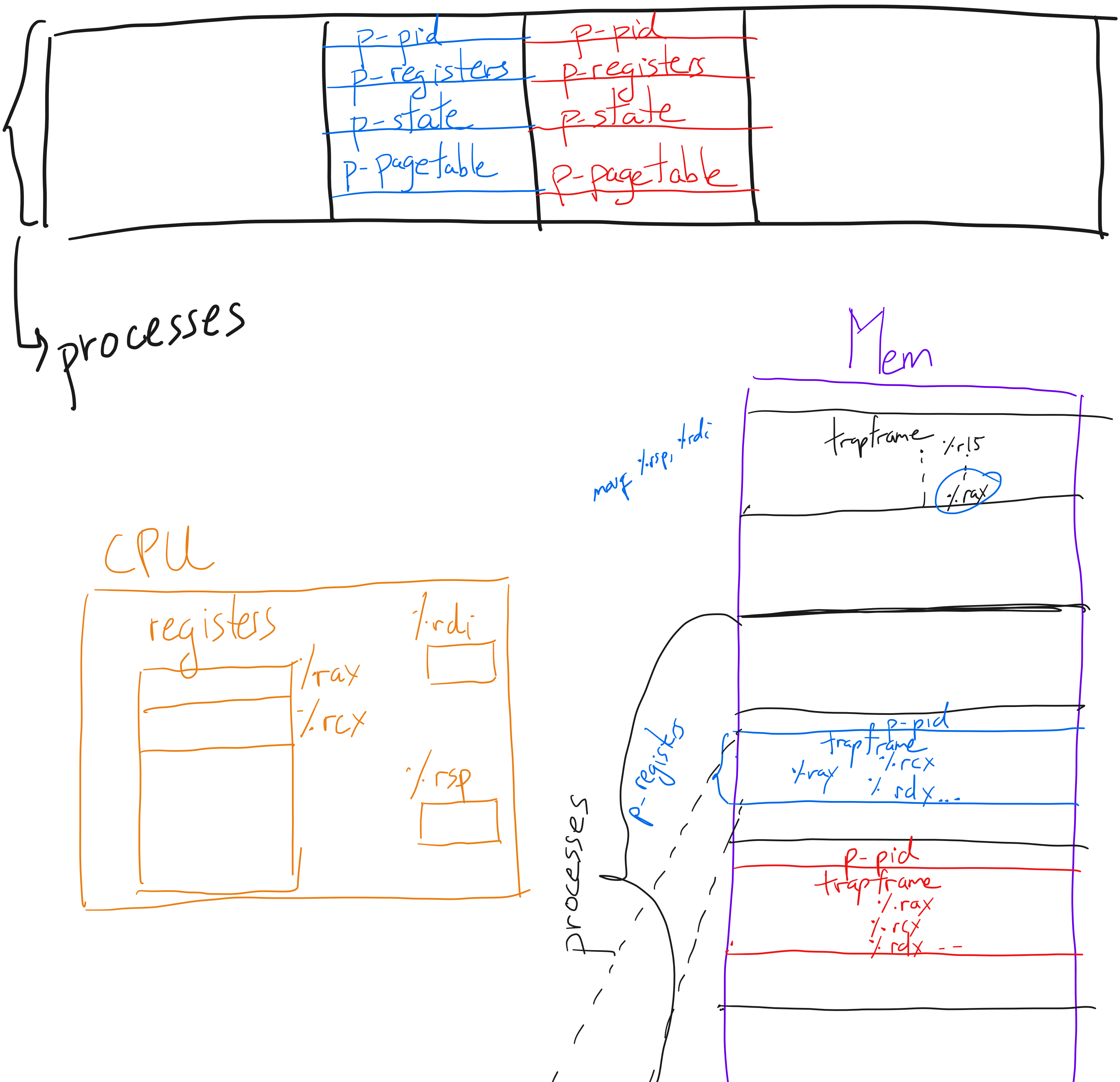
[Credit to Frans Kaashoek, Robert Morris, and Nickolai Zeldovich for this picture]

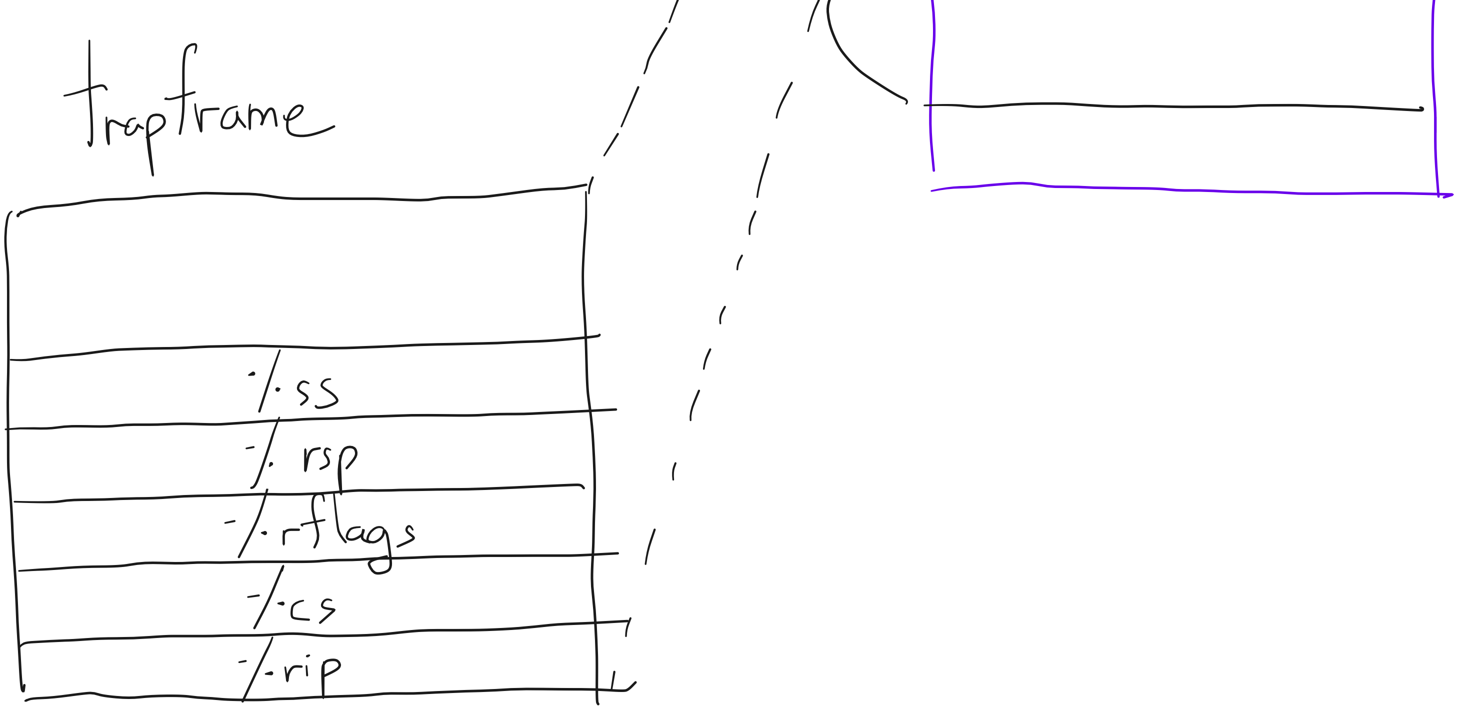
b. Loads and stores to the device memory "go to hardware".

An example is in the console printing code from WeensyOS. Here is an excerpt from link/shared.ld:

```
/* Compare the address below to the map above. */
PROVIDE(console = 0xB8000);

/*
 * prints a character to the console at the specified
 * cursor position in the specified color.
 * Question: what is going on in the check
 *       if (c == '\n')
 * ?
 * Hint: '\n' is "C" for "newline" (the user pressed enter).
 */
static void console_putc(printer* p, unsigned char c, int color) {
    console_printer* cp = (console_printer*) p;
    if (cp->cursor >= console + CONSOLE_ROWS * CONSOLE_COLUMNS) {
        cp->cursor = console;
    }
    if (c == '\n') {
        int pos = (cp->cursor - console) % 80;
        for (; pos != 80; pos++) {
            *cp->cursor++ = ' ' | color;
        }
    } else {
        *cp->cursor++ = c | color;
    }
}
```

Context switches in WeensyOS





trapframe
%ss
%rsp
%rflags
%cs
%rip