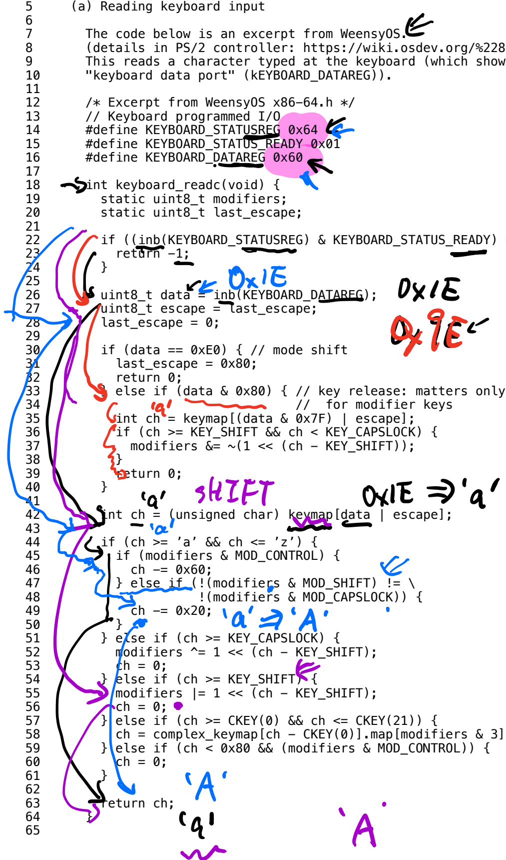
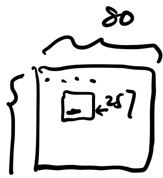
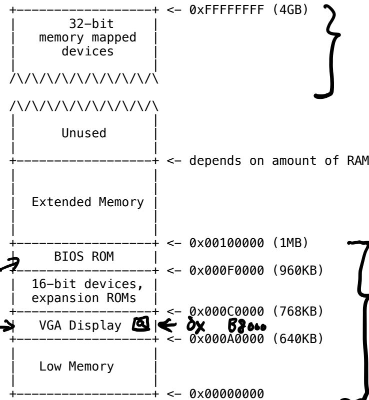
```
1   CS5600 Week11.b
2
3   1. Two examples of I/O instructions
4
5     (a) Reading keyboard input
6
7       The code below is an excerpt from WeensyOS.
8       (details in PS/2 controller: https://wiki.osdev.org/%228042%22_PS/2_Controller)
9       This reads a character typed at the keyboard (which shows up on the
10      "keyboard data port" (KEYBOARD_DATAREG)).
11
12      /* Excerpt from WeensyOS x86-64.h */
13      // Keyboard programmed I/O
14      #define KEYBOARD_STATUSREG 0x64
15      #define KEYBOARD_STATUS_READY 0x01
16      #define KEYBOARD_DATAREG 0x60
17
18      int keyboard_readc(void) {
19        static uint8_t modifiers;
20        static uint8_t last_escape;
21
22        if ((inb(KEYBOARD_STATUSREG) & KEYBOARD_STATUS_READY) == 0) {
23          return -1;
24        }
25
26        uint8_t data = inb(KEYBOARD_DATAREG);
27        uint8_t escape = last_escape;
28        last_escape = 0;
29
30        if (data == 0xE0) { // mode shift
31          last_escape = 0x80;
32          return 0;
33        } else if (data & 0x80) { // key release: matters only
34                                  //   for modifier keys
35          int ch = keymap[(data & 0x7F) | escape];
36          if (ch >= KEY_SHIFT && ch < KEY_CAPSLOCK) {
37            modifiers &= ~(1 << (ch - KEY_SHIFT));
38          }
39          return 0;
40        }
41
42        int ch = (unsigned char) keymap[data | escape];
43
44        if (ch >= 'a' && ch <= 'z') {
45          if (modifiers & MOD_CONTROL) {
46            ch -= 0x60;
47          } else if (!(modifiers & MOD_SHIFT) != \
48                     !(modifiers & MOD_CAPSLOCK)) {
49            ch -= 0x20;
50          }
51        } else if (ch >= KEY_CAPSLOCK) {
52          modifiers ^= 1 << (ch - KEY_SHIFT);
53          ch = 0;
54        } else if (ch >= KEY_SHIFT) {
55          modifiers |= 1 << (ch - KEY_SHIFT);
56          ch = 0;
57        } else if (ch >= CKEY(0) && ch <= CKEY(21)) {
58          ch = complex_keymap[ch - CKEY(0)].map[modifiers & 3];
59        } else if (ch < 0x80 && (modifiers & MOD_CONTROL)) {
60          ch = 0;
61        }
62
63        return ch;
64      }
65
```




```
66
67  (b) Setting the cursor position
68
69    The code below is also excerpted from WeensyOS. It uses I/O
70    instructions to set a blinking cursor. To set the cursor to
71    the upper left of the screen, run:  console_show_cursor(0)
72
73    // console_show_cursor(cpos)
74    //   Move the console cursor to position 'cpos',
75    //   which should be between 0 and 80 * 25.
76
77    void console_show_cursor(int cpos) {
78      if (cpos < 0 || cpos > CONSOLE_ROWS * CONSOLE_COLUMNS)
79        cpos = 0;
80
81      outb(0x3D4, 14); // Command 14 = upper byte of position
82      outb(0x3D5, cpos / 256); // upper byte (256 = 2^8)
83      outb(0x3D4, 15); // Command 15 = lower byte of position
84      outb(0x3D5, cpos % 256); // lower byte
85
86    }
87
88    // if interested, see details: https://wiki.osdev.org/Text_Mode_Cursor
```



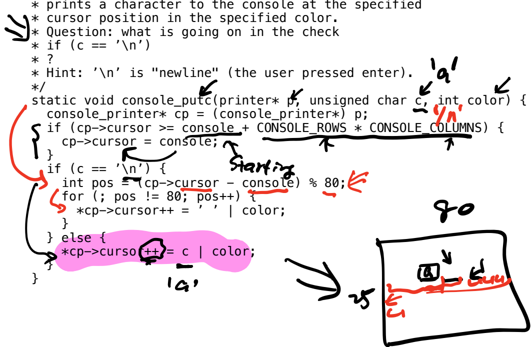
```
 89
 90  2. Memory-mapped I/O
 91
 92     (a) Here is a 32-bit PC's physical memory map:
 93
```



```
 94        +------------------+ <- 0xFFFFFFFF (4GB)
 95        |      32-bit      |
 96        |  memory mapped   |
 97        |     devices      |
 98        |                  |
 99        /\/\/\/\/\/\/\/\/\/\
100
101        /\/\/\/\/\/\/\/\/\/\
102        |                  |
103        |      Unused      |
104        |                  |
105        +------------------+ <- depends on amount of RAM
106        |                  |
107        |                  |
108        | Extended Memory  |
109        |                  |
110        |                  |
111        +------------------+ <- 0x00100000 (1MB)
112        |     BIOS ROM     |
113        +------------------+ <- 0x000F0000 (960KB)
114        |  16-bit devices, |
115        |  expansion ROMs  |
116        +------------------+ <- 0x000C0000 (768KB)
117        |   VGA Display    |
118        +------------------+ <- 0x000A0000 (640KB)
119        |                  |
120        |    Low Memory    |
121        |                  |
122        +------------------+ <- 0x00000000
123
124     [Credit to Frans Kaashoek, Robert Morris, and
125     Nickolai Zeldovich for this picture]
126
```



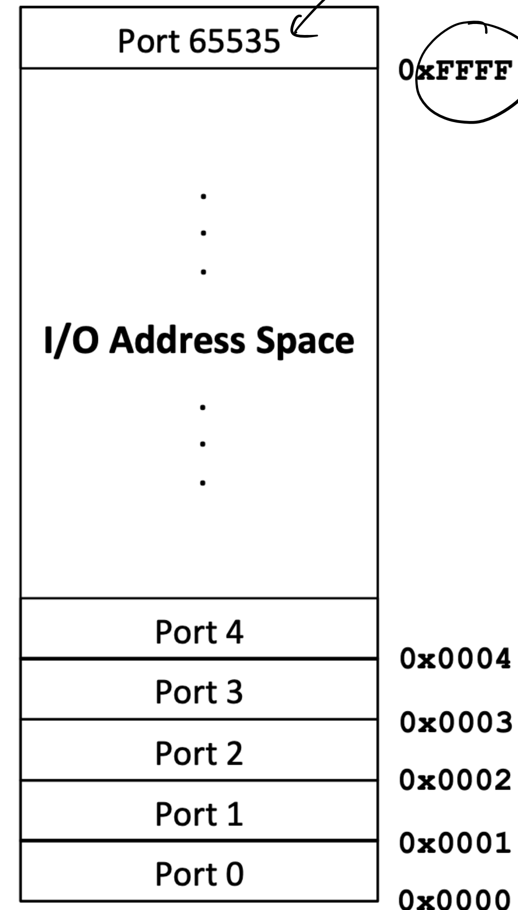
```
127
128    (b) Loads and stores to the device memory "go to hardware".
129
130      Here is an excerpt of the console printing code from WeensyOS.
131
132
133      /* Compare the address below to the map in panel 2(a). */
134      PROVIDE(console = 0xB8000);
135
136      This is an excerpt about printing; notice how it uses the address
137      "console":
138
139      /*
140      * prints a character to the console at the specified
141      * cursor position in the specified color.
142      * Question: what is going on in the check
143      * if (c == '\n')
144      * ?
145      * Hint: '\n' is "newline" (the user pressed enter).
146      */
```



```
147      static void console_putc(printer* p, unsigned char c, int color) {
148        console_printer* cp = (console_printer*) p;
149        if (cp->cursor >= console + CONSOLE_ROWS * CONSOLE_COLUMNS) {
150          cp->cursor = console;
151        }
152        if (c == '\n') {
153          int pos = (cp->cursor - console) % 80;
154          for (; pos != 80; pos++) {
155            *cp->cursor++ = ' ' | color;
156          }
157        } else {
158          *cp->cursor++ = c | color;
159        }
160      }
```

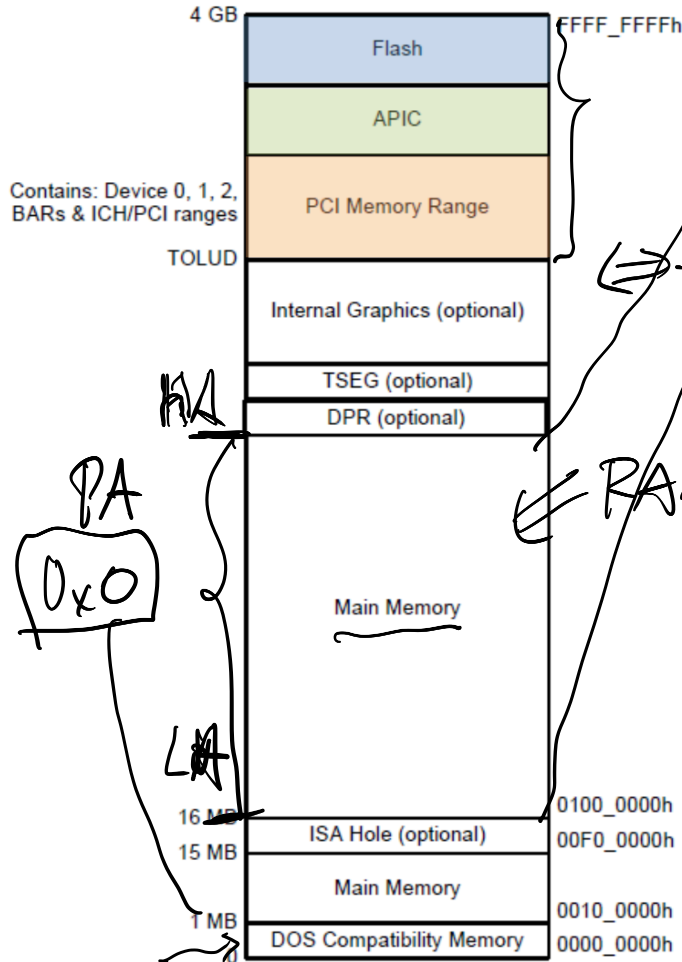
Port I/O Address Space

- Software and hardware architectures of x86 architecture support a separate address space called "I/O Address Space"
  - Separate from memory space
- Access to this separate I/O space is handled through a set of I/O instructions
  - IN,OUT, INS, OUTS
- Access requires Ring0 privileges
  - Access requirement does not apply to all operating modes (like Real-Mode)
- The processor allows 64 KB+3 bytes to be addressed within the I/O space
- Harkens back to a time when memory was not so plentiful
- You may never see port I/O when analyzing high-level applications, but in systems programming (and especially BIOS) you will see lots of port I/O
- One of the biggest impediments to understanding what's going on in a BIOS



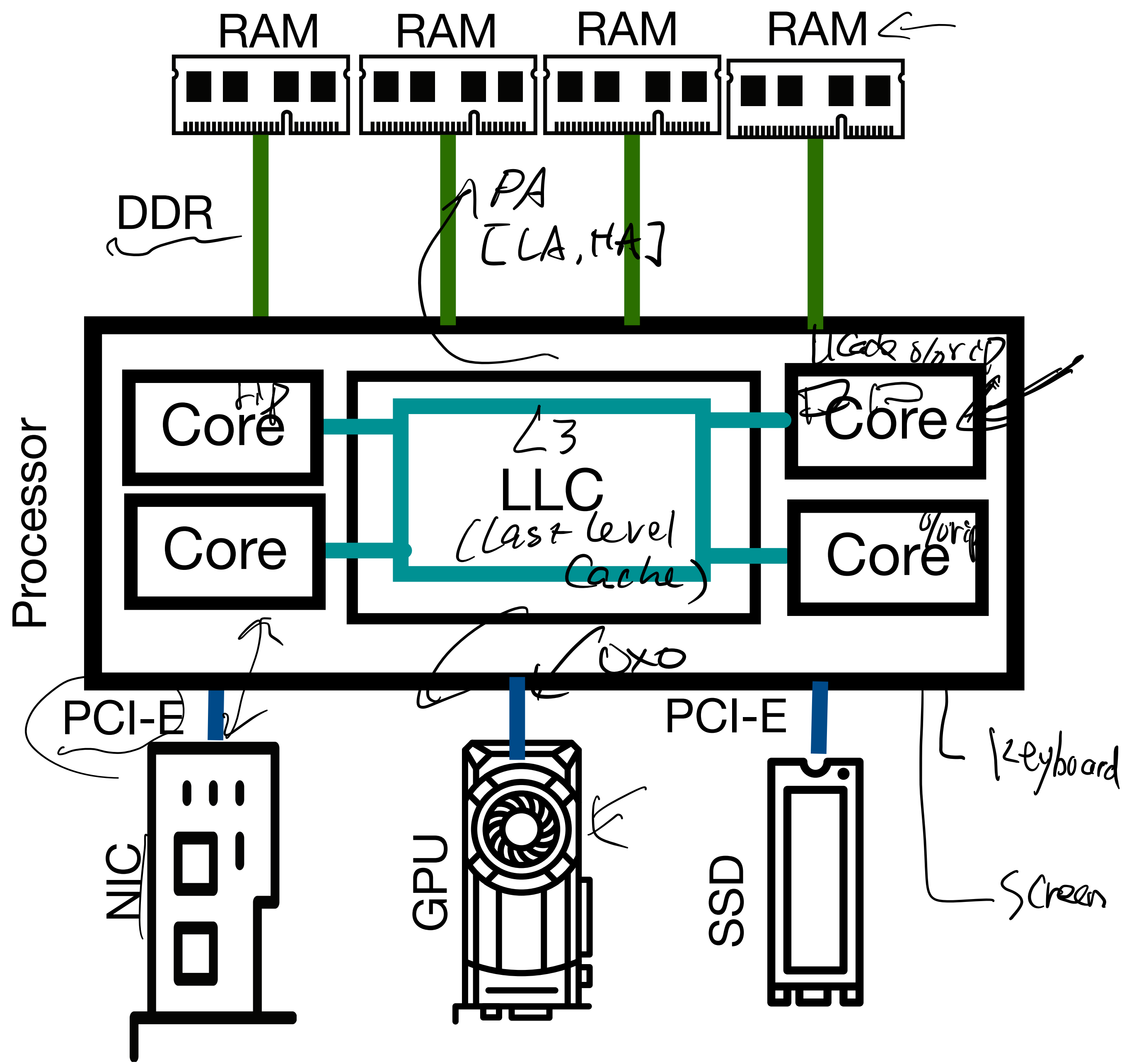
Intel Programmer's guide, Vol 1, 16.1

Memory Mapped IO

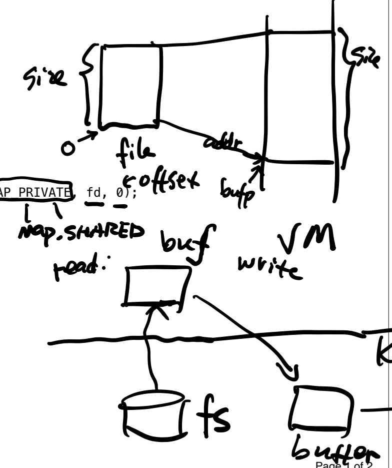


- The colored regions are memory mapped devices
- Accesses to these memory ranges are decoded to a device itself
- Flash refers to the BIOS flash
- APIC is the Advanced Programmable Interrupt Controller
- PCI Memory range is programmed by BIOS in the PCIEXBAR

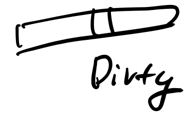
Machine

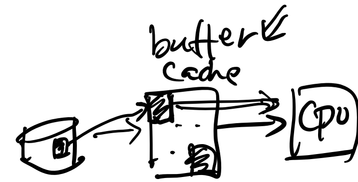


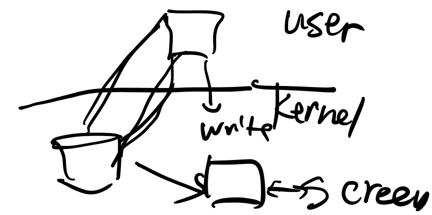
```
1   CS5600, Handout week11.a
2
3   /* file: mmap.c */
4
5   #include <fcntl.h>
6   #include <stdio.h>
7   #include <stdlib.h>
8   #include <sys/mman.h>
9   #include <sys/stat.h>
10  #include <sys/types.h>
11  #include <unistd.h>
12
13  void mmapwrite(int fd, int size);
14  void normalwrite(int fd, int size);
15
16  int main(int argc, char **argv) {
17      struct stat stat;
18      int fd;
19
20      if (argc != 2) {  // Check for required cmd line arg
21          printf("usage: %s <filename>\n", argv[0]);
22          exit(0);
23      }
24
25      /* Copy input file to stdout */
26      if ((fd = open(argv[1], O_RDONLY, 0)) < 0)
27          perror("open");
28
29      fstat(fd, &stat);
30
31      // option 1
32      mmapwrite(fd, stat.st_size);
33
34      /* // option 2
35       * normalwrite(fd, stat.st_size);
36       */
37
38      close(fd);
39
40      return 0;
41  }
42
43  void mmapwrite(int fd, int size) {
44
45      /* Ptr to memory mapped area */
46      char *bufp;
47
48      bufp = mmap(NULL, size, PROT_READ, MAP_PRIVATE, fd, 0);
49
50      write(STDOUT_FILENO, bufp, size);
51
52      return;
53  }
54
55
56  void normalwrite(int fd, int size) {
57
58      char *buf = malloc(size);
59
60      read(fd, buf, size);
61
62      write(STDOUT_FILENO, buf, size);
63
64      return;
65  }
```




```
Question:
Which runs faster, option 1 or option 2? by how much?

Exercise:
Try to run both options by yourself:

  $ cat /dev/urandom | head -c 1000000000 > 1G.file
  $ make mmap
  $ time ./mmap 1G.file > /dev/null

  $ vim mmap.c
  // switch to option 2
  $ make mmap
  $ time ./mmap 1G.file > /dev/null
```







32 bit ⇒ 36 bit ⇒ 48 bit ⇒ 57 bit

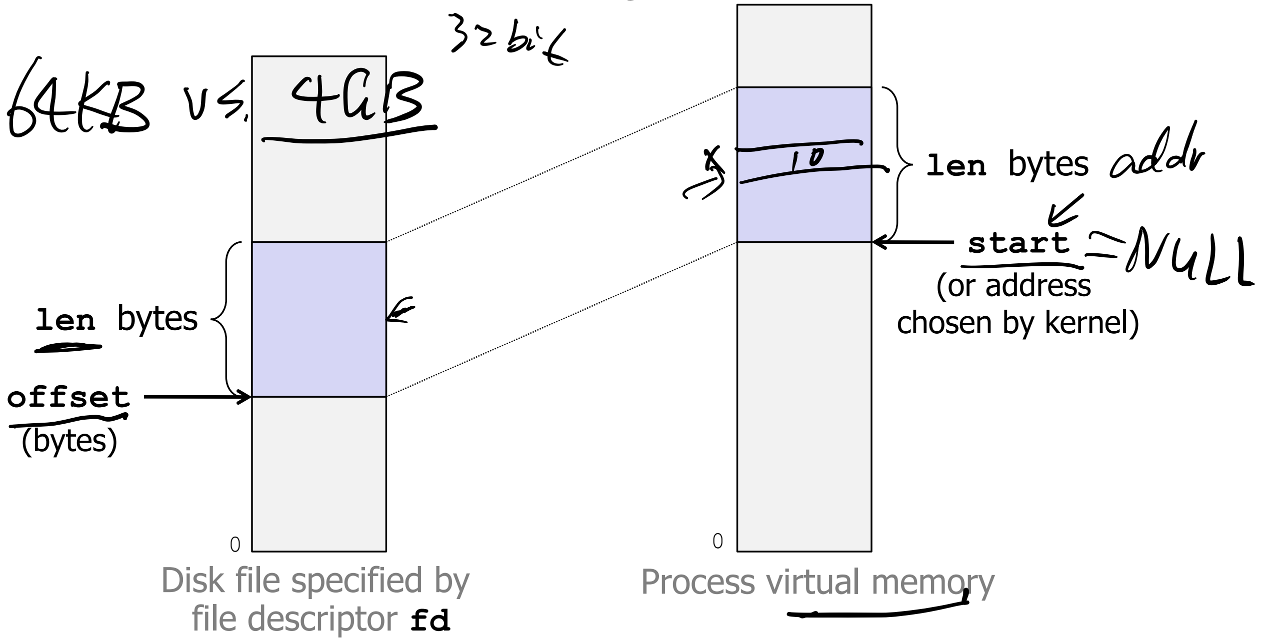
$2^4 = 16$

48 bit

$2^{48} = 256$ TB

User-Level Memory Mapping

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



read(fd, buf, size)

write(fd, buf, size)

int a = addr[x]

addr[x] = 10;

1. Last time
2. mmap
3. I/O architecture
4. device drivers

VM

I/O

- Lab3.
  - review session.
- Lab2.

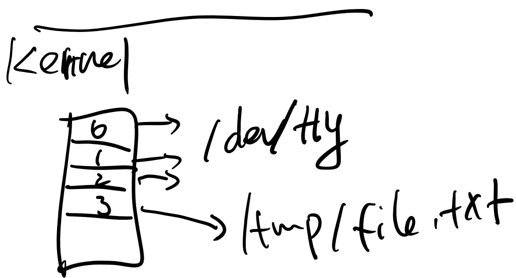
- page faults.
  1. PTE's P=0
  2. permission check

- mmap → syscall

recall:

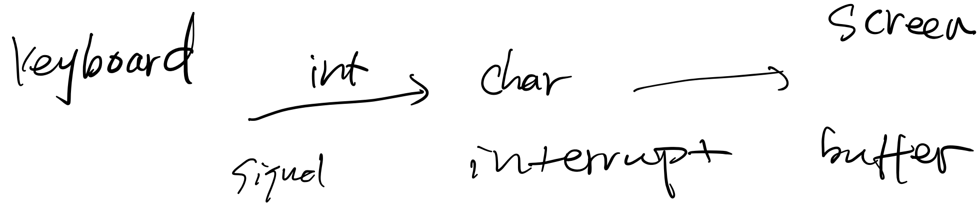
(3) fd = open("/tmp/file.txt", mode)

↳ ? 0/1 int { 0 1 2



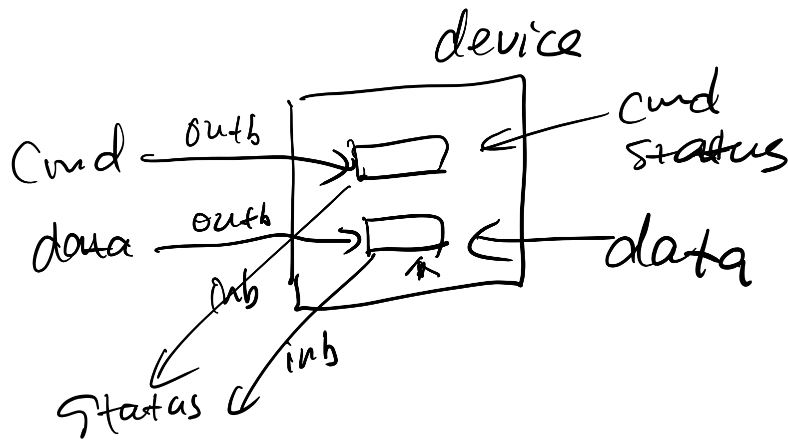
{ read (fd, ...)
write (fd, ...)

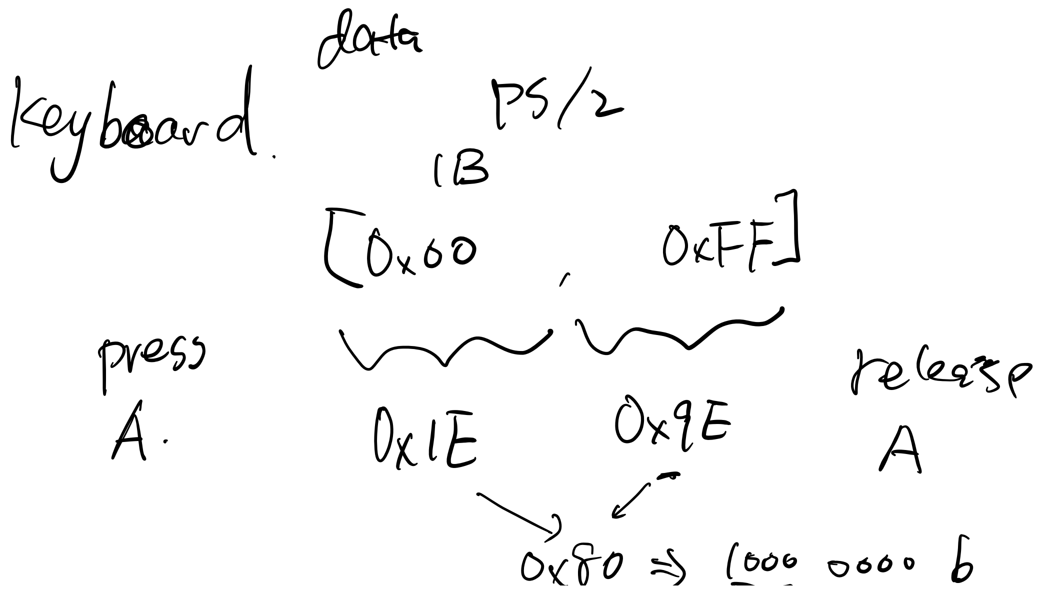
• file-based data structure



① Port I/O ✓

• inb/outb/inw/intw





② memory-mapped I/O

③ interrupt

④ via memory (DMA)