Devices, Drivers, DMA, Buffering

Computer Operating Systems, Fall 2023

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Administrivia

- MILESTONE 1 IS DUE between Friday 11/10 – Tuesday 11/14
  - Expecting around 60% progress on this
  - Should have stand-alone PennFAT
  - Must meet with your TA in the specified window to demonstrate what you have implemented

- Recitation after lecture today will be about PennFAT

Administrivia

- I synched a bunch of grades to canvas. **PLEASE CHECK THAT THEY ARE ACCURATE**
  - All check-ins
  - Project 0 & peer-eval
- Midterm Grades Posted
  - Regrade requests open, due Saturday night @ midnight

Poll Everywhere

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- Any questions, comments or concerns from last lecture?

Lecture Outline

- Device Drivers
  - LC4_GETC
- Stdio Buffering
  - fflush()
  - fsync()

I/O

- Reading/writing anything “beyond” memory is called I/O
  - We call the locations we read/write to I/O devices

- I/O devices include:
  - Keyboard
  - Mouse
  - Files
  - Graphics Displays
  - Networks
  - Etc.

Devices

- There are other "devices" than just the file storage
  - Auxiliary hardware that extends the functionality of the computer. The computer sends and/or receives data to communicate with the device
  - Sometimes called "Peripheral Devices"

- Examples:
  - Mouse
  - Keyboard
  - Game Controller
  - Printer
  - Network adapter
  - Projector
  - etc

Kinds of Devices

- These devices have many different functionalities and characteristics
- Block based vs character based
  - File system is block based
  - Keyboards are character based
- Shared by many processes
  - Network card, disk
- User related vs OS related
  - Keyboard vs system clock

Device Drivers

- How does a computer support these various device types?

- Each device has a *driver*: a piece of software that acts as the interface to the device. Abstracts away some of the hardware details of the device
  - Contains device specific routines for communicating with the computer and routines for controlling/configuring the device

- Your computer comes with some device drivers installed
- When you plug in a new device, your computer will start installing device drivers for that device.

IOCTL

- Input/Output Control
- The provided Linux system calls (e.g. read, write) are not enough to express the different functions a device may have.
- `int ioctl(int fd, int request, ...)`
  - Specify the file descriptor of the device you want to interact with
  - Request contains information on what you would like to do (and some other information)
  - Variadic arguments (usually a char* or void*)

Device Naming & Separation

- It can be difficult to keep track of which device is using what resources. If we use memory mapped I/O, what addresses belong to which files?

- If we have everything resident in OS memory, then it could also be difficult to manage concurrent processes accessing the same device

Everything is File

- Idea: Give each device a named file and have most requests go through the filesystem.

- The filesystem allows us to name our devices.
  - /dev/ directory contains various devices as “files”
  - For example, /dev/printer1

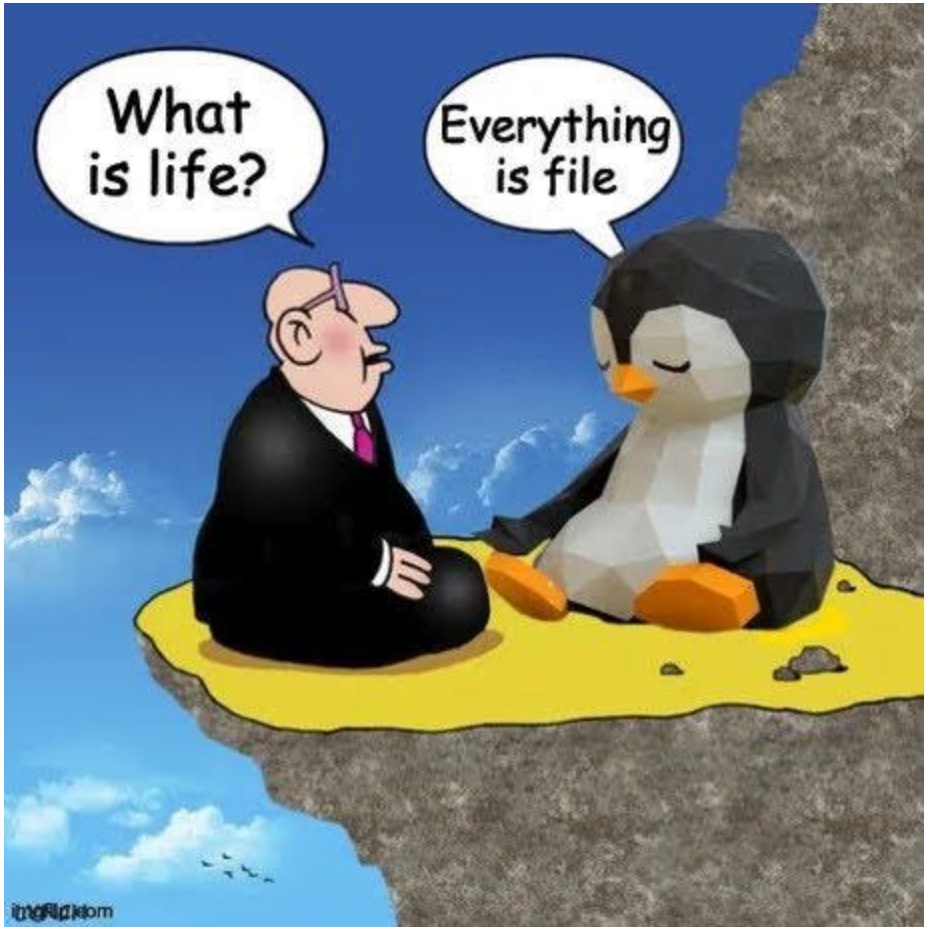
- I/O requests through the file system are already scheduled, have an order enforced, and are checked to be concurrent safe*
  - (from the filesystem level, user can still mess it up)

Everything is File

- Note: these devices are not like normal "files" as discussed previously

- These things just appear as files and can be read/written to perform some functionality.

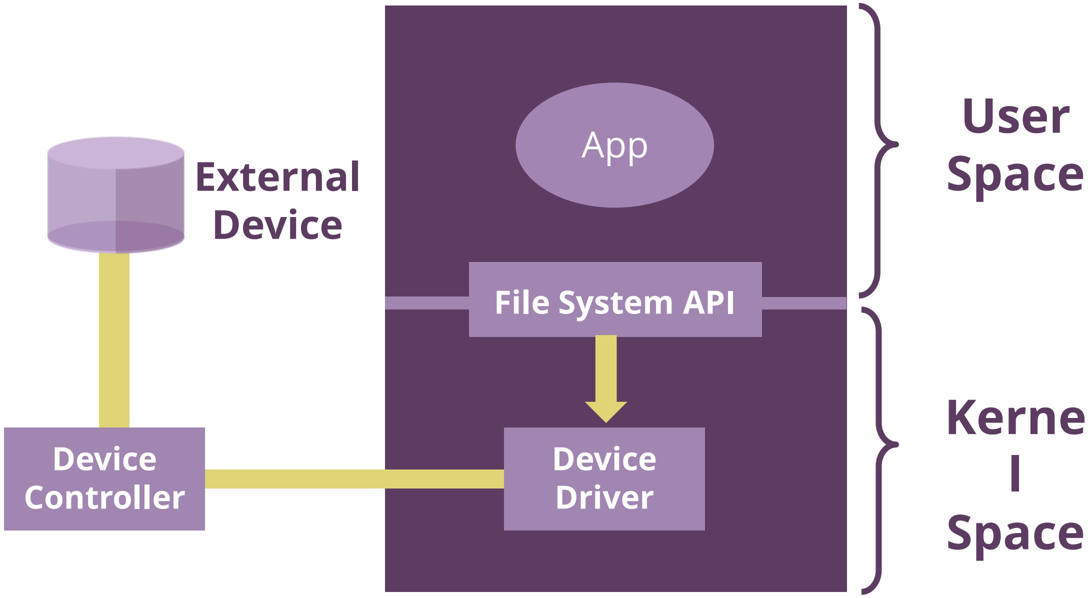
- Many things are files in linux, it provides a nice consistent interface to interact with devices.



Special Devices

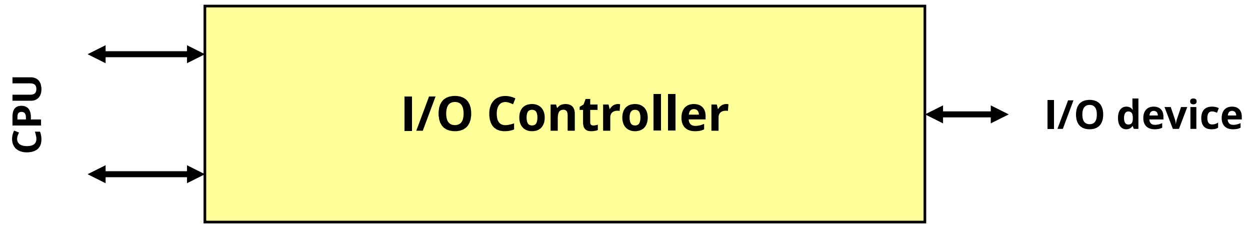
- Some special devices that exist in /dev/
- /dev/urandom and /dev/random
  - Provides bytes by the computers cryptographically secure pseudorandom number generator
- /dev/null
  - Discards anything that is written to it and reports the write as a success.
- /dev/fd/
  - Directory containing the open file descriptors for the running process
- /dev/stdin, /dev/stdout, /dev/stderr
  - Access to the process' standard streams

I/O Architecture



I/O Devices & Controllers

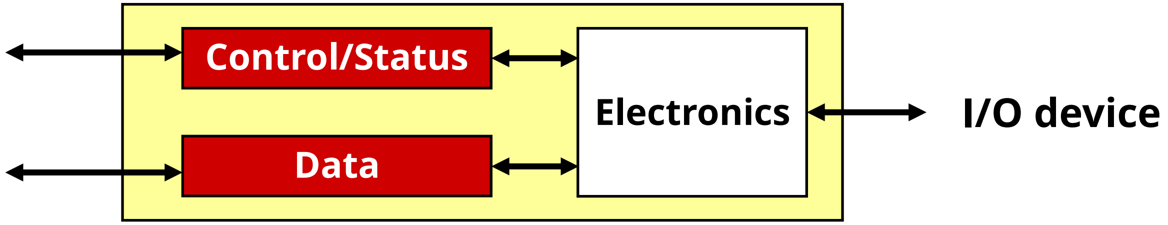
- Most I/O devices are not purely digital, they have their own hardware
  - Electro-mechanical: e.g. keyboard, mouse, disk, motor
  - Analog/digital: e.g. touchscreen, network interface, monitor, speaker, mic
- … all have digital interfaces presented by an I/O Controller
  - I/O Device (analog/digital mix) talks to controller
  - CPU (digital) talks to controller (typically through a device driver)
  - Controller acts as a translator: digital (CPU) <-> analog (device)



I/O Controller to CPU Interface

- I/O controller interface abstracts I/O device as "device registers"
  - Control/Status: may be one register or two
    - Control: lets us toggle options on the device (we won't focus on this)
    - Status: lets us know if we are data is ready to be read/written
  - Data: may be more than one register
    - The data we are reading/writing
- Example: CPU reading data from input device
  - CPU checks status register if input is available
  - Reads input the data register

Similar steps for writing.
More details later!



How can we handle I/O with code/asm?

- **Two common options**
- We could create new "I/O instructions" for the ISA
  - Designate opcode(s) for I/O
  - Register and operation encoded in instruction
- Memory-mapped I/O (Using LDR/STR for LC4)
  - Assign a memory address to each device register
  - Use conventional loads and stores
  - Hardware intercepts loads/stores to these address
  - No actual memory access performed
    (MMU and caches get more complicated as a result)
  - LC4 (and most other platforms) do this
  - This allows for the I/O code to be written in C and is more portable to other systems.

Poll Everywhere

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- Do you see any problem with this way of getting data from a device (e.g. file/keyboard/etc.)
  - This is what we did in LC4

```
char getc() {
  while(*device_status == NOT_READY) {
    // do nothing
  }
  char user_input = *device_data;
  return user_input;
}
```

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Busy waiting ☹

Poll Everywhere

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- Do you see any problem with this way of getting data from a device (e.g. file/keyboard/etc.)
  - This is trying to make this "No hang", do not block if character is not available

```
char getc() {
  if (*device_status == NOT_READY) {
    return NOT_READY;
  }
  char user_input = *device_data;
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}
```

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char getc() {
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  }
  char user_input = *device_data;
  return user_input;
}
```

Busy waiting still possible… What happens if the process is blocked on waiting for input?

Interrupts

- Can instead have the hardware device interrupt the CPU to let the OS know that some I/O request is done

- Allows OS to not run blocked processes, and scheduler other processes that will utilize the CPU

Question: what?

- How do interrupts work to solve the problem we just discussed?

- If the CPU is not doing the work, then what is?

CPU vs Co-processors

- The CPU is the **C**entral **P**rocessing **U**nit
  - The set of instructions that are possible is fixed, but the exact instructions & program changes.
  - This allows the CPU to be more “general purpose”
- Our computer also has Coprocessors
  - These are hardware devices that also perform some computation to supplement the CPU.
  - Usually more specialized
  - Examples: Graphics Processing Unit (GPU), Floating Point Unit (FPU), I/O processors, network cards, sound cards, etc.
  - What these do and how they are controlled can vary a lot.

DMA

- To support co-processors, they are usually Direct Memory Access (DMA)
  - If DMA is supported, then allowed coprocessors can directly access memory independently of CPU

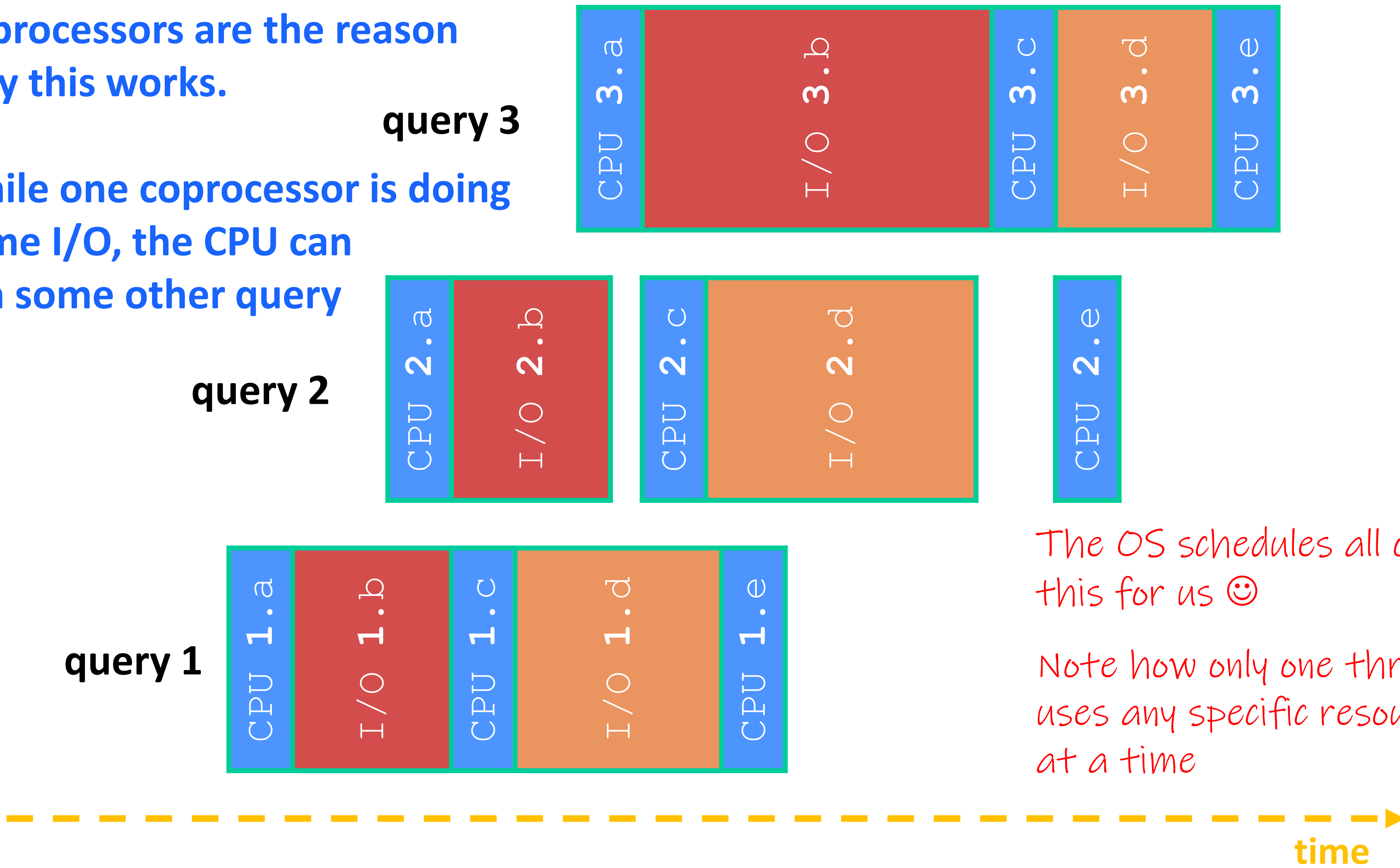
- In our I/O example, this means that an I/O request looks something like:
  - First the CPU sends a request to the I/O coprocessor for a storage medium to perform some read/write.
  - The coprocessor can fulfill this request and access memory directly to store what is read or get what needs to be written
  - The CPU does other things while the I/O request is running and eventually is interrupted by the coprocessor when the request is done.

Multi-threaded Search Engine (Execution)

*Running with 1 CPU

Remember this?
Coprocessors are the reason why this works.

While one coprocessor is doing some I/O, the CPU can run some other query



The OS schedules all of this for us ☺

Note how only one thread uses any specific resource at a time

Lecture Outline

- d

Poll Everywhere

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- If we compile this and run it, how many times is hello printed?

```
int main() {
  if (fork() == 0) {
    write(STDOUT_FILENO, "hello", 5);
  }
  if (fork() == 0) {
    write(STDOUT_FILENO, "hello", 5);
  }
  return EXIT_SUCCESS;
}
```

Raise Your Hands

- If we compile this and run it, how many times is hello printed?

```
int main() {
  if (fork() == 0) {
    printf("hello");
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  if (fork() == 0) {
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  }
  return EXIT_SUCCESS;
}
```

Raise Your Hands

- If we compile this and run it, how many times is hello printed?

```
int main() {
  if (fork() == 0) {
    printf("hello\n");
  }
  if (fork() == 0) {
    printf("hello\n");
  }
  return EXIT_SUCCESS;
}
```

C stdio vs POSIX

- Why are we getting these different outputs?

- Let's start with the first two. Both use different ways of writing to standard out.

  - C stdio : user level portable library for **st**andar**d** **i**nput/**o**utput. Should work on any environment that has the C standard library
    - E.g. printf, fprintf, fputs, getline, etc.

  - POSIX C API: **P**ortable **O**perating **S**ystem **I**nterface. Functions that are supported by many operating systems to support many OS-level concepts (Input/Output, networking, processes, threads…)

Buffered writing

- By default, C `stdio` uses buffering on top of POSIX:
  - When one writes with **`fwrite`**`()`, the data being written is copied into a buffer allocated by `stdio` inside your process' address space
  - As some point, once enough data has been written, the buffer will be "flushed" to the operating system.
    - When the buffer fills (often 1024 or 4096 bytes)
  - This prevents invoking the write system call and going to the filesystem too often

Buffered Writing Example

Arrow signifies what will be executed next

```
int main(int argc, char** argv) {
  char buf[2] = {'h', 'i'};
→ FILE* fout = fopen("hi.txt", "wb");

  // read "hi" one char at a time
  fwrite(&buf, sizeof(char), 1, fout);

  fwrite(&buf+1, sizeof(char), 1, fout);

  fclose(fout);
  return EXIT_SUCCESS;
}
```

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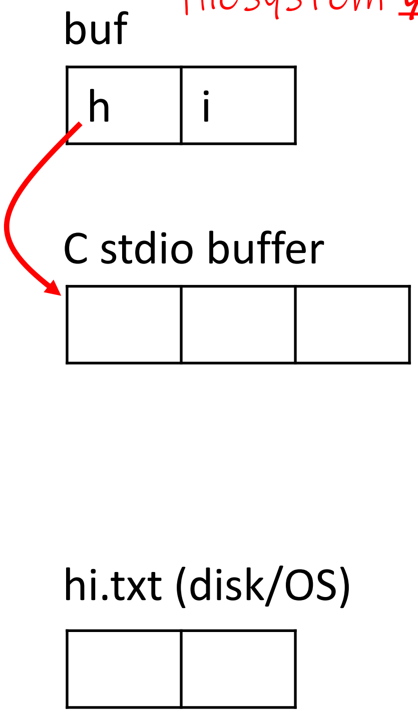
}
```

Store 'h' into buffer, so that we do not go to filesystem *yet*



Buffered Writing Example

Arrow signifies what will be executed next

Store 'i' into buffer, so that we do not go to filesystem *yet*

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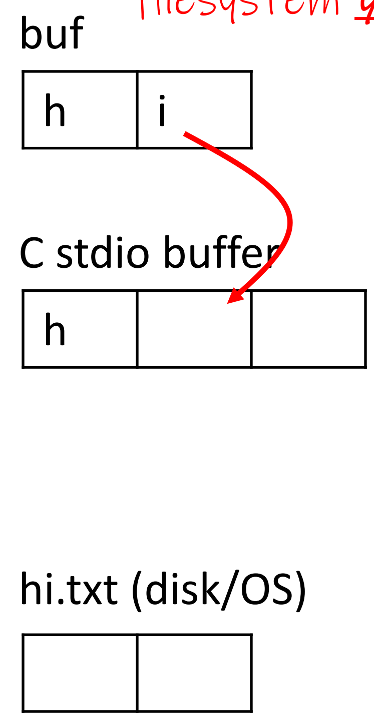

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```

buf

h	i

C stdio buffer

h	i	

When we call fclose, we deallocate and flush the buffer to disk

hi.txt (disk/OS)

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buf

h	i

hi.txt (disk/OS)

h	i

Unbuffered Writing Example

Arrow signifies what will be executed next

```
int main(int argc, char** argv) {
  char buf[2] = {'h', 'i'};
→ int fd = open("hi.txt", O_WRONLY | O_CREAT);

  // read "hi" one char at a time
  write(fd, &buf, sizeof(char));

  write(fd, &buf+1, sizeof(char));

  close(fd);
  return EXIT_SUCCESS;
}
```

buf

h	i

hi.txt (disk/OS)

Unbuffered Writing Example

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buf

h	i

hi.txt (disk/OS)

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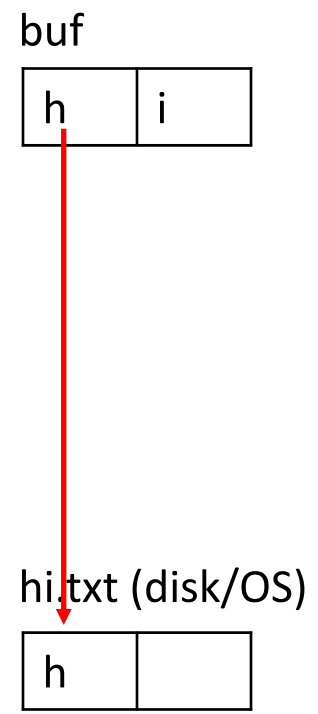

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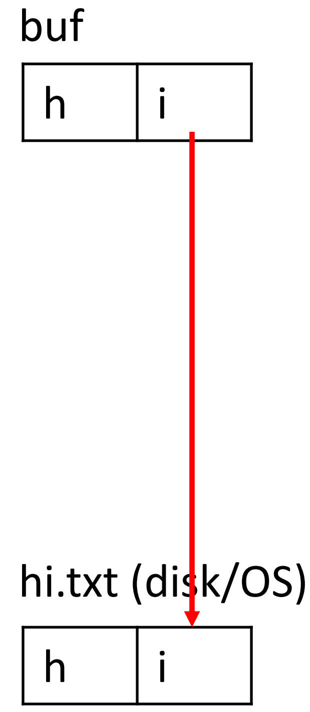

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buf

h	i

Two OS/File system accesses instead of one ☹

hi.txt (disk/OS)

h	i

Buffered Reading

- By default, C `stdio` uses buffering on top of POSIX:
  - When one reads with **`fread()`**, a lot of data is copied into a buffer allocated by `stdio` inside your process' address space
  - Next time you read data, it is retrieved from the buffer
    - This avoids having to invoke a system call again
  - As some point, the buffer will be "refreshed":
    - When you process everything in the buffer (often 1024 or 4096 bytes)
  - Similar thing happens when you write to a file

Buffered Reading Example

Arrow signifies what will be executed next

```c
int main(int argc, char** argv) {
  char buf[2];
  FILE* fin = fopen("hi.txt", "rb");   // ← arrow

  // read "hi" one char at a time
  fread(&buf, sizeof(char), 1, fin);

  fread(&buf+1, sizeof(char), 1, fin);

  fclose(fin);
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buf

hi.txt (disk/OS)

h	i

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  char buf[2];
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  // read "hi" one char at a time
  fread(&buf, sizeof(char), 1, fin);    <-- (arrow)

  fread(&buf+1, sizeof(char), 1, fin);

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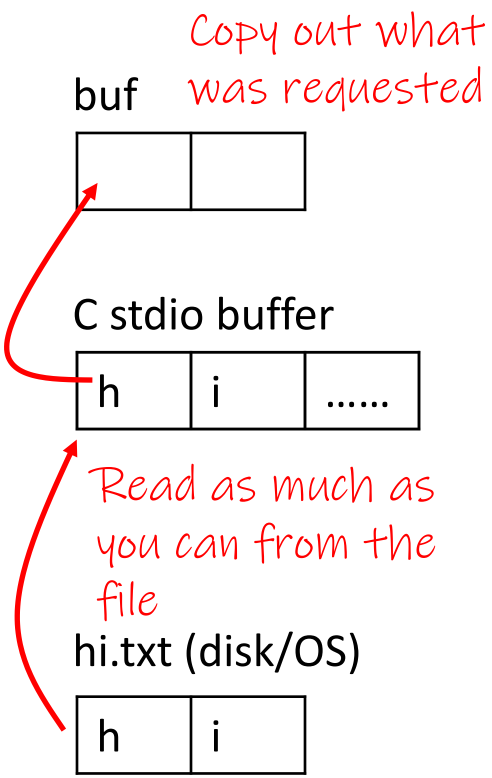
```



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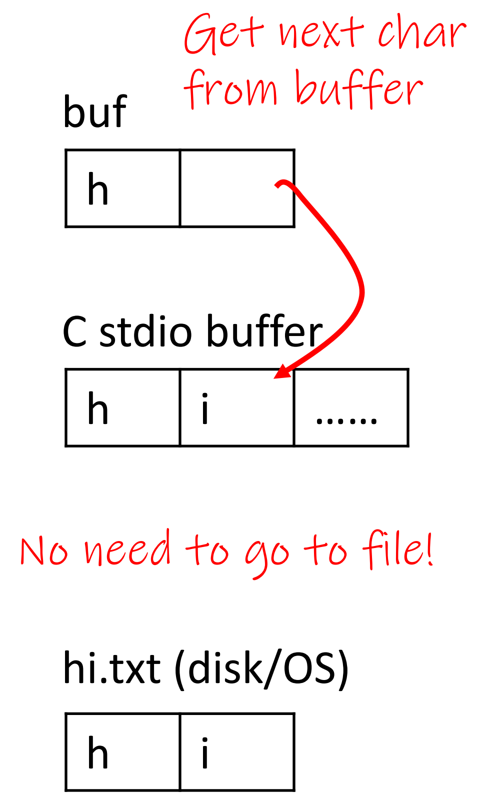

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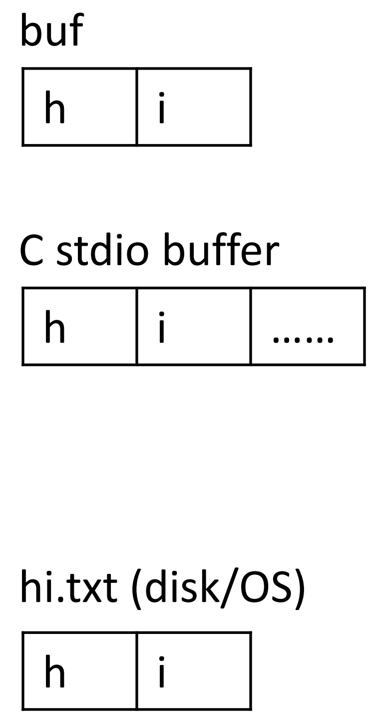

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buf

h	i

hi.txt (disk/OS)

h	i

Why NOT Buffer?

- Reliability – the buffer needs to be flushed
  - Loss of computer power = loss of data
  - "Completion" of a write (*i.e.* return from **`fwrite()`**) does not mean the data has actually been written

- Performance – buffering takes time
  - Copying data into the `stdio` buffer consumes CPU cycles and memory bandwidth
  - Can potentially slow down high-performance applications, like a web server or database (*"zero-copy"*)

- When is buffering faster? | Slower?

Many small writes
Or only writing a little

Large writes

Fork Problem Explained

Arrow signifies what will be executed next. I execute processes in parallel and "in sync" for demonstration purposes

- Remember: printf (and stdio) buffers input in the programs address space

```
int main() {
  if (fork() == 0) {
    printf("hello");
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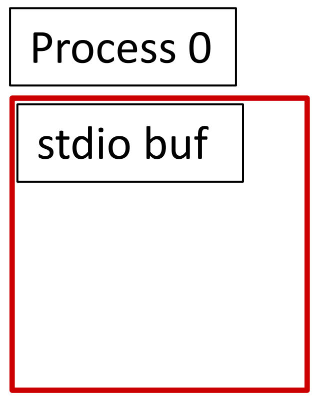

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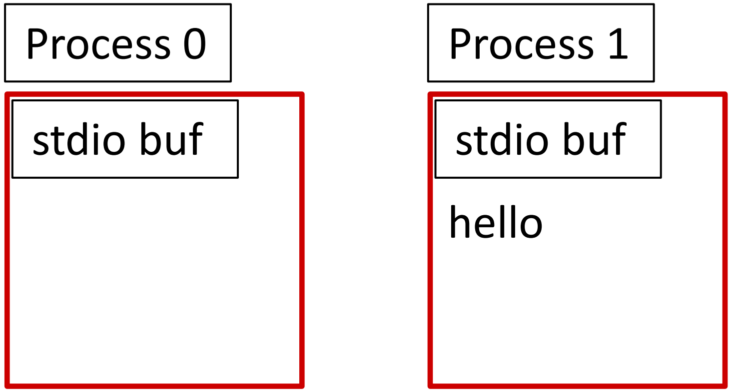

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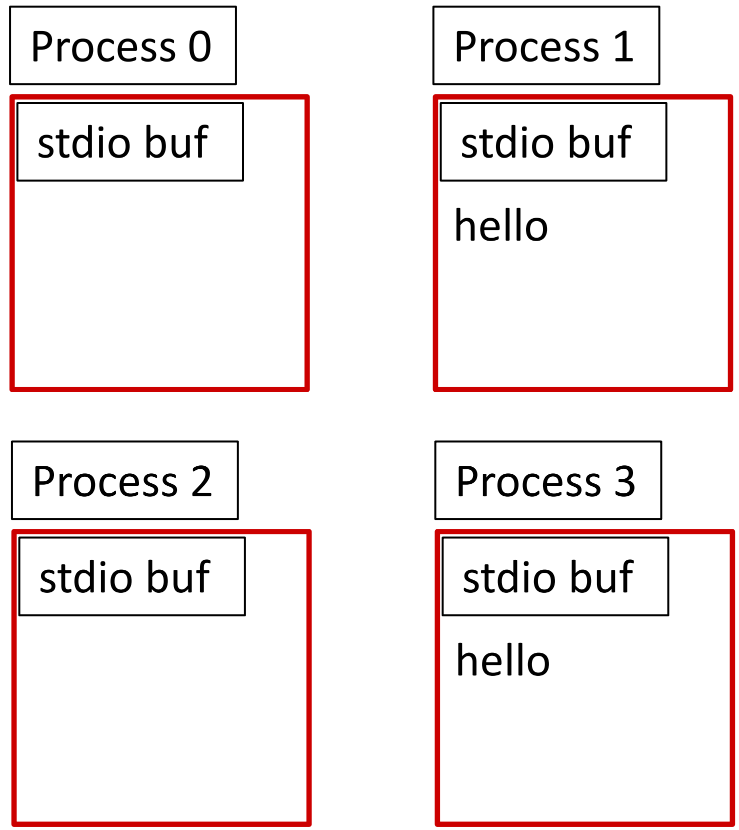

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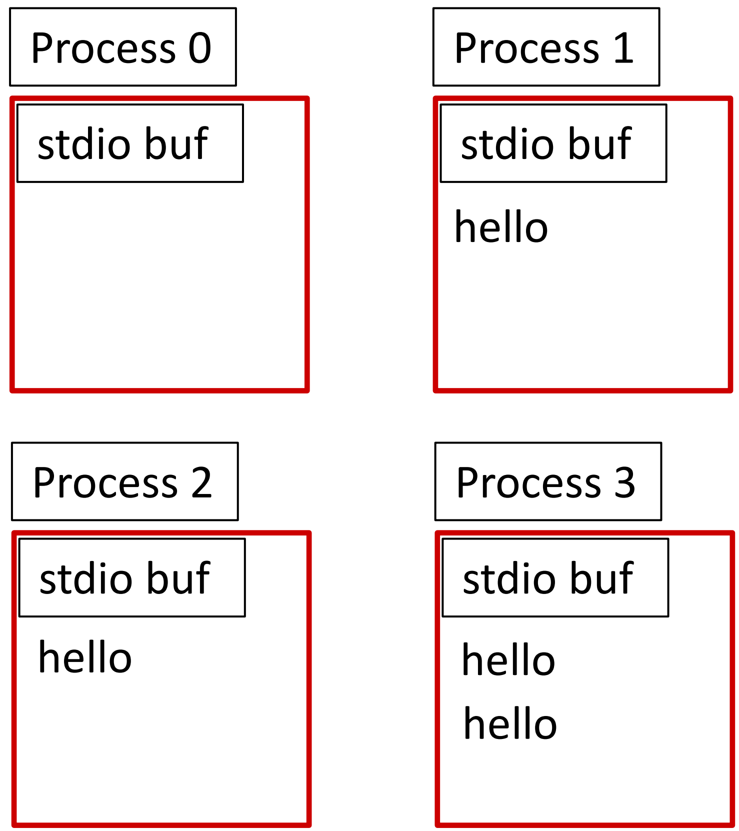

Hello is printed 4 times!

Fork Problem Explained (pt.2)

- Why did we get different outputs when printf printed a newline character after hello?
  - Only difference was:

```
printf("hello");
```

vs

```
printf("hello\n");
```

- All we needed to do to get the expected output was add a \n. why?

- `printf` prints to stdout and by default stdout is line buffered. Meaning it flushes the buffer on a newline character
  - If we ran ./prog > out.txt (redirect the output), we would get different output since buffering policy changes.

How to flush/modify the cstdio buffer

- For C stdio:
  - ```
    int fflush(FILE* stream);
    ```
  - Flushes the stream to the OS/filesystem
  - ```
    int setvbuf(FILE* stream, char* buf,
                int mode, size_t size);
    ```
  - Has a family of related functions like setbuf(), setbuffer(), setlinebuf();
  - Can set the stream to be unbuffered or a specified buffer

How to flush POSIX?

- When we write to a file with POSIX it is sent to the filesystem, is it immediately sent to disc? No
  - Well, we do have the block cache… so it may not be written to disc
  - Since all File I/O requests go to the file system, if another process accesses the same file, then it should see the data even if it is the block cache and not in disc.
  - If we lose power though…

How to flush POSIX to disk

- Two functions
  - ```
    int fsync(int fd);
    ```
  - Flushes all in-core data and metadata to the storage medium
  - ```
    int fdatasync(int fd);
    ```
  - Sends the file data to disk
  - Does not flush modified metadata unless necessary for data.

- C stdio is usually implemented using POSIX on posix compliant systems
  - **`fflush`** may not necessarily call **`fsync`**