Posix & Buffering

Computer Systems Programming, Spring 2024

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Poll Everywhere

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- Any questions on HW0?

Administrivia

- HW0 is due on Friday
  - Can already setup your docker environment, please do that.
  - I have office hours later today and on Friday
- Pre-semester survey out today on canvas
  - For credit, but answers are anonymous
  - Due **TONIGHT** Wednesday January 31st at 11:59 pm
- HW1 to be released on Friday or Monday
  - should have everything you need either after Wednesday's or Monday's lecture

Lecture Outline

Lecture Outline

- **The OS**
- C arrays and C++ Arrays
- POSIX I/O
- Locality

Remember This?

Math / Logic

Algorithms

Software / Applications

Libraries, APIs, System Calls

Operating System / Kernel } **Today, we are here!**

Firmware / Drivers

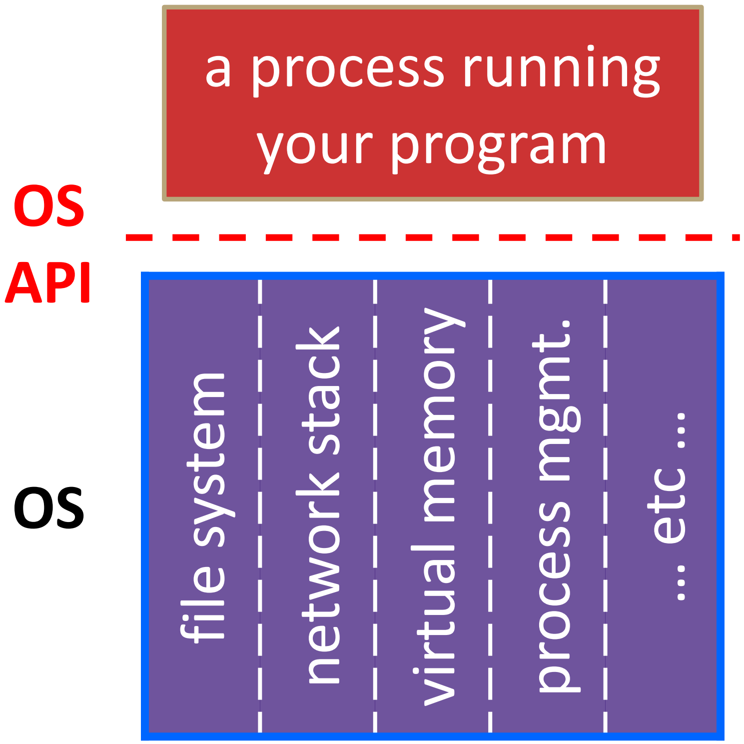
Hardware

What's an OS?

- Software that:
  - Directly interacts with the hardware
    - OS is trusted to do so; user-level programs are not
    - OS must be ported to new hardware; user-level programs are portable
  - Abstracts away messy hardware devices
    - Provides high-level, convenient, portable abstractions (*e.g.* files, disk blocks)
  - Manages (allocates, schedules, protects) hardware resources
    - Decides which programs have permission to access which files, memory locations, pixels on the screen, etc. and when

OS: Abstraction Provider

- The OS is the "layer below"
  - A module that your program can call (with system calls)
  - Provides a powerful OS API – POSIX, Windows, etc.



File System
- open(), read(), write(), close(), …

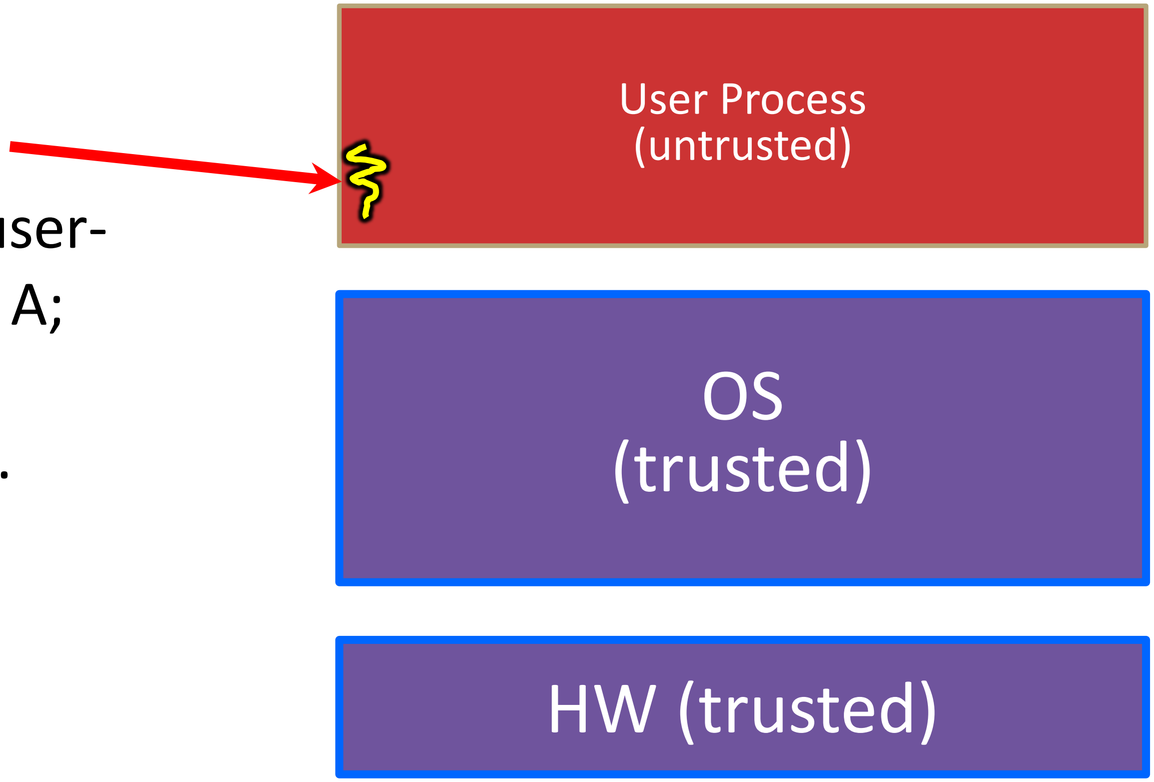
Network Stack
- connect(), listen(), read(), write(), ...

Virtual Memory
- brk(), shm_open(), …

Process Management
- fork(), wait(), nice(), …

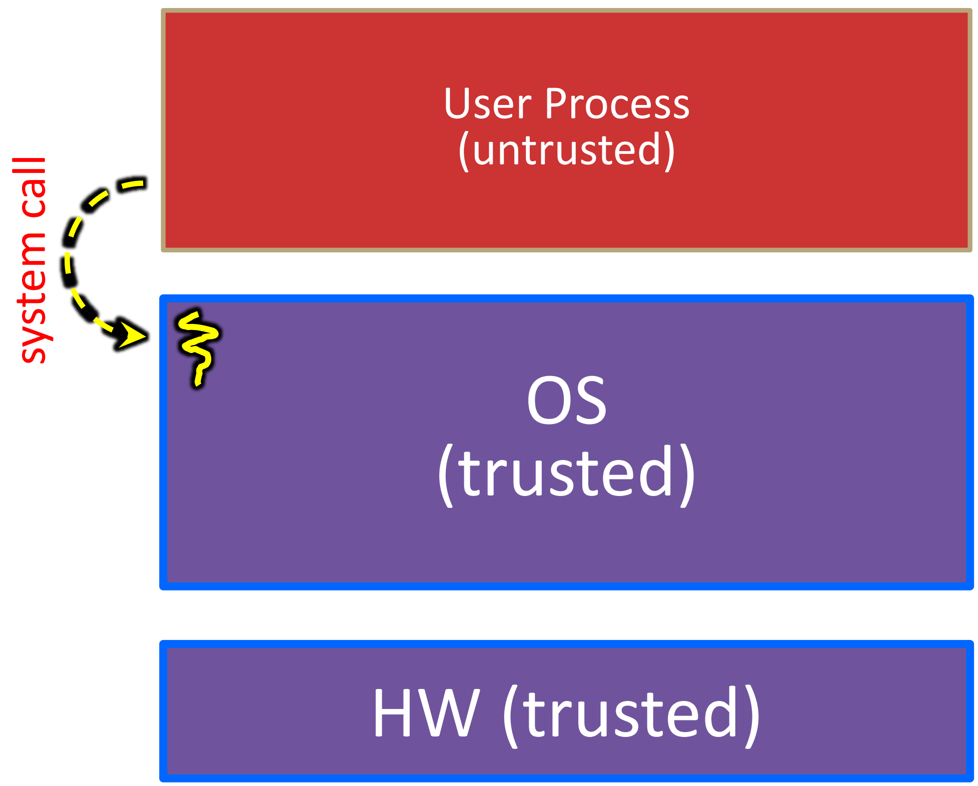
System Call Trace (high-level view)

A CPU (thread of execution) is running user-level code in Process A; the CPU is set to *unprivileged mode*.



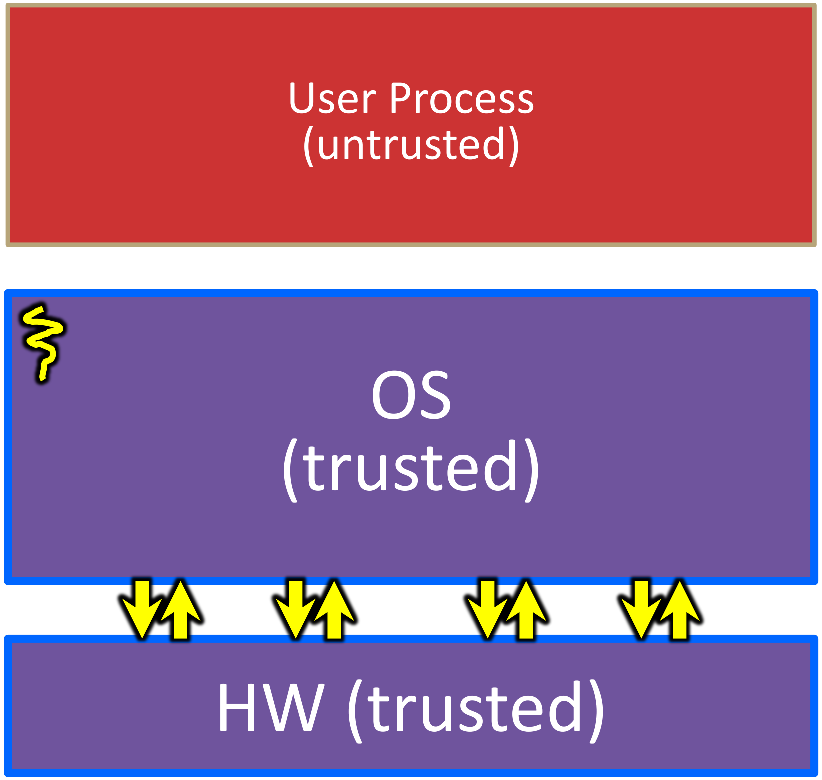
System Call Trace (high-level view)

Code in Process invokes a system call; the hardware then sets the CPU to *privileged mode* and traps into the OS, which invokes the appropriate system call handler.



System Call Trace (high-level view)

Because the CPU executing the thread that's in the OS is in privileged mode, it is able to use *privileged instructions* that interact directly with hardware devices like disks.

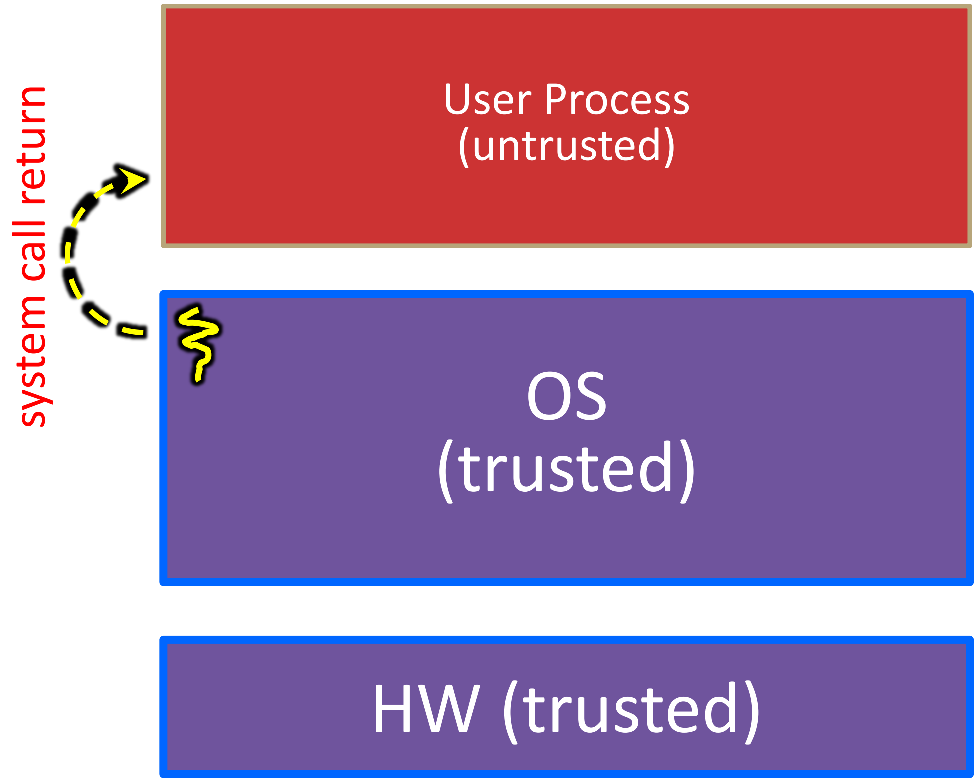


System Call Trace (high-level view)

Once the OS has finished servicing the system call, which might involve long waits as it interacts with HW, it:

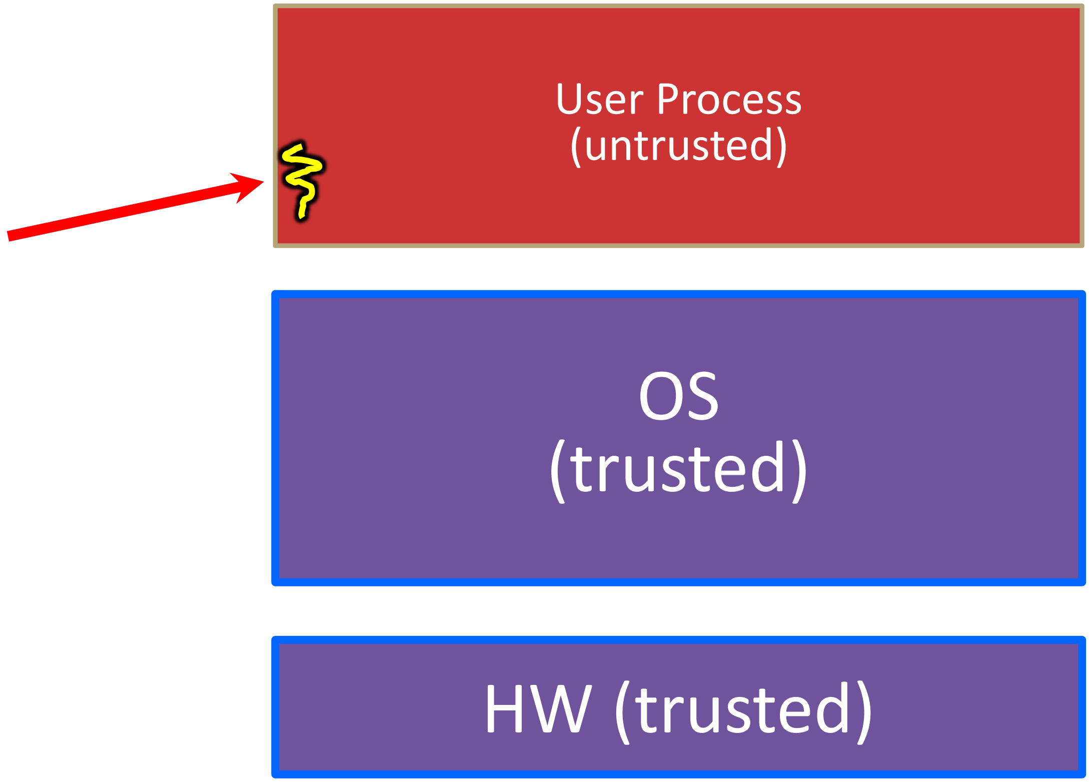
(1) Sets the CPU back to unprivileged mode and

(2) Returns out of the system call back to the user-level code in Process A.



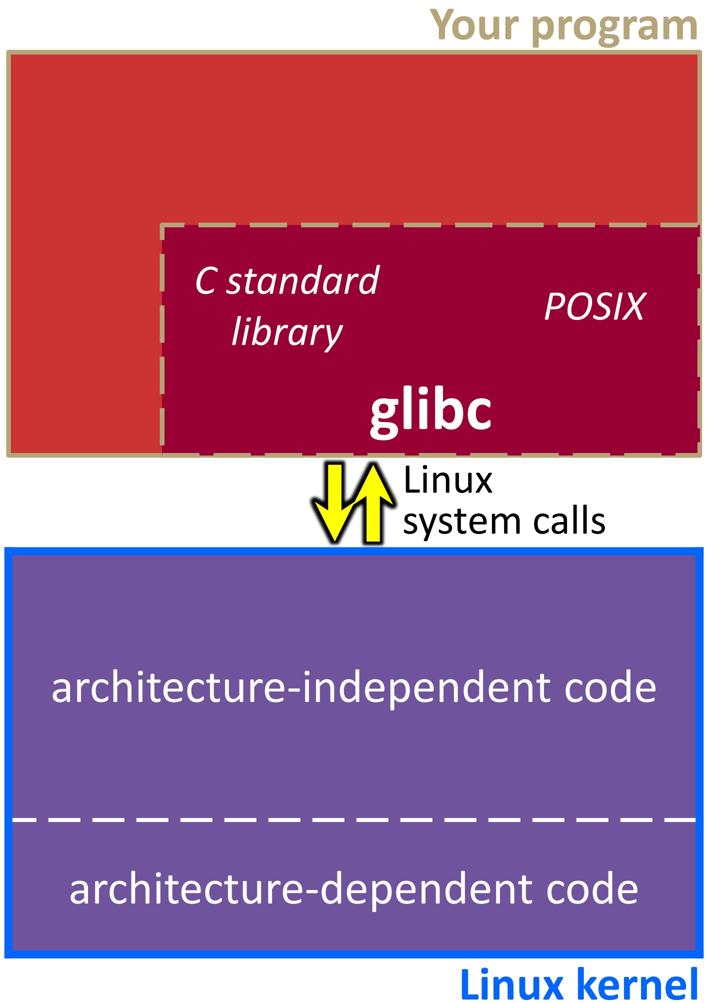
System Call Trace (high-level view)

The process continues executing whatever code is next after the system call invocation.



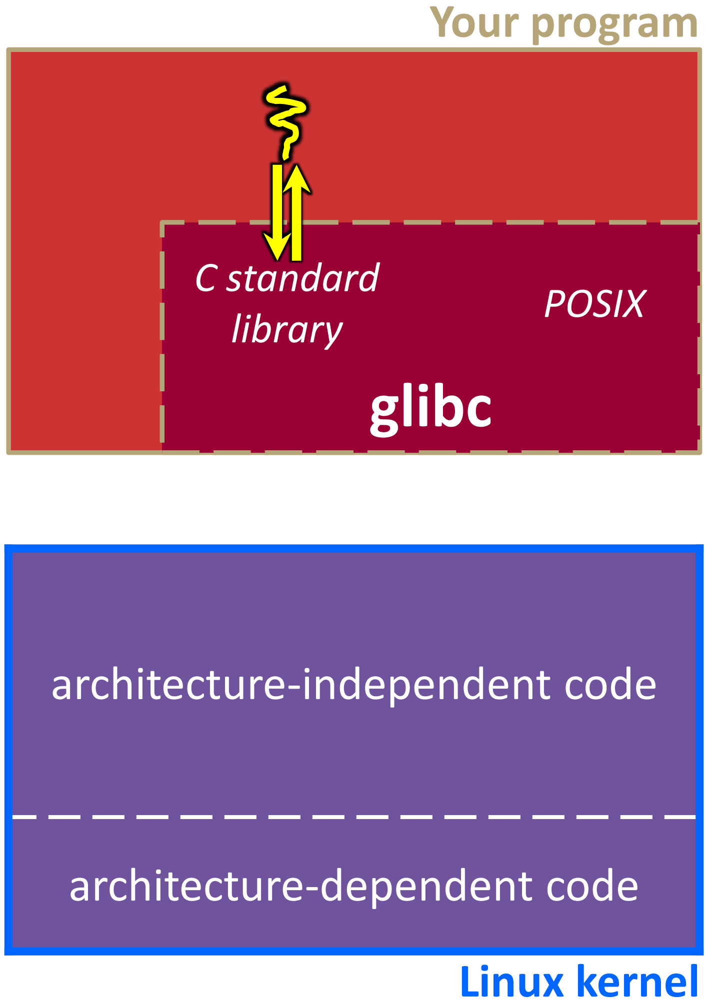
"Library calls" on x86/Linux

- A more accurate picture:
  - Consider a typical Linux process
  - Its thread of execution can be in one of several places:
    - In your program's code
    - In `glibc`, a shared library containing the C standard library, POSIX, support, and more
    - In the Linux architecture-independent code
    - In Linux x86-64 code



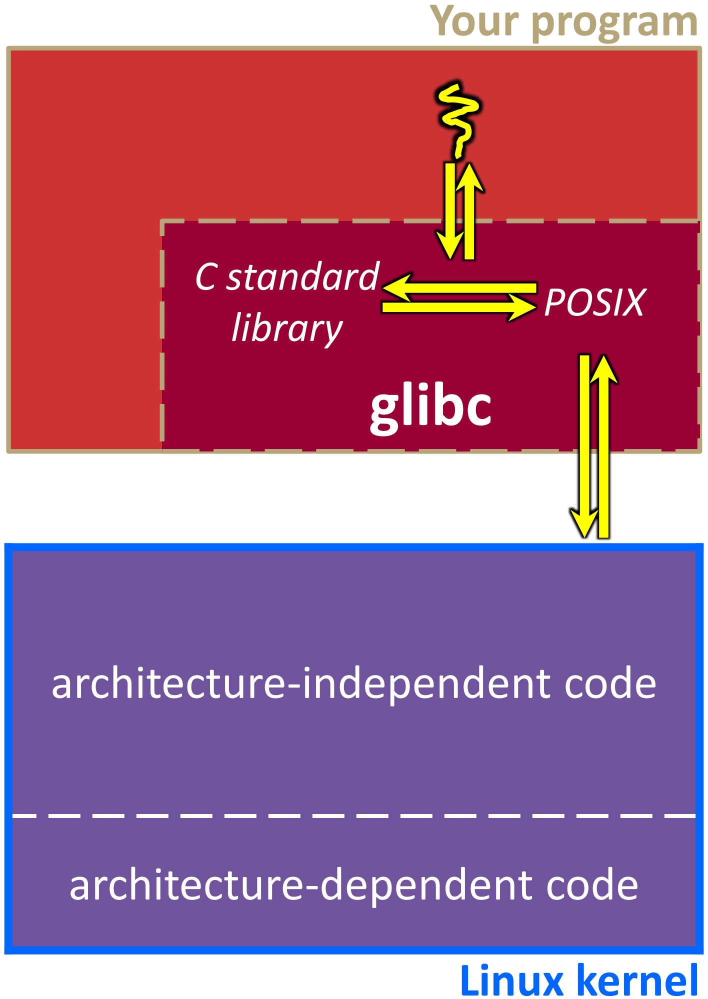
"Library calls" on x86/Linux: Option 1

- Some routines your program invokes may be entirely handled by `glibc` without involving the kernel
  - *e.g.* **`strcmp`**`()` from `stdio.h`
  - There is some initial overhead when invoking functions in dynamically linked libraries (during loading)
    - But after symbols are resolved, invoking `glibc` routines is basically as fast as a function call within your program itself!



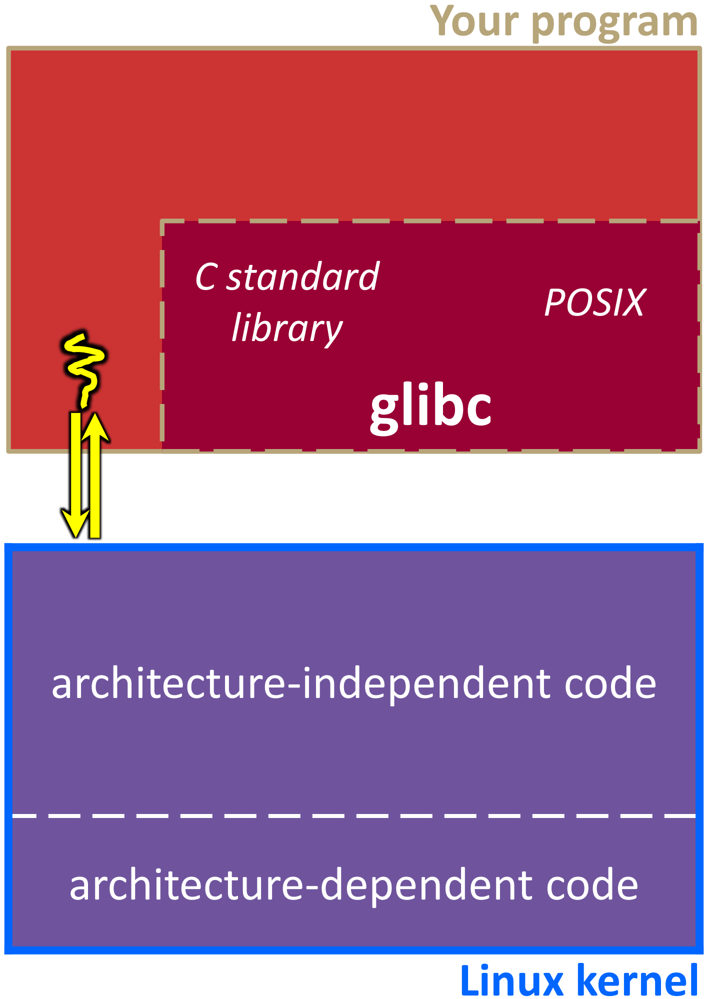
"Library calls" on x86/Linux: Option 2

- Some routines may be handled by `glibc`, but they in turn invoke Linux system calls
  - *e.g.* POSIX wrappers around Linux `syscalls`
    - POSIX **`readdir()`** invokes the underlying Linux **`readdir()`**
  - *e.g.* C `stdio` functions that read and write from files
    - **`fopen()`**, **`fclose()`**, **`fprintf()`** invoke underlying Linux **`open()`**, **`close()`**, **`write()`**, etc.



"Library calls" on x86/Linux: Option 3

- Your program can choose to directly invoke Linux system calls as well
  - Nothing is forcing you to link with `glibc` and use it
  - But relying on directly-invoked Linux system calls may make your program less portable across UNIX varieties



A System Call Analogy

- The OS is a very wise and knowledgeable wizard
  - It has many dangerous and powerful artifacts, but it doesn't trust others to use them. Will perform tasks on request.
- If a civilian wants to access a "magical" feature, they must fill out a request to the wizard.
  - It takes some time for the wizard to start processing the request, they must ensure they do everything safely
  - The wizard will handle the powerful artifacts themselves. The user WILL NOT TOUCH ANYTHING.
  - Wizard will take a second to analyze results and put away artifacts before giving results back to the user.

If You're Curious

- Download the Linux kernel source code
  - Available from http://www.kernel.org/
- `man`, section 2: Linux system calls
  - `man 2 intro`
  - `man 2 syscalls`
- `man`, section 3: `glibc`/`libc` library functions
  - `man 3 intro`
- *The* book: *The Linux Programming Interface* by Michael Kerrisk (keeper of the Linux man pages)

Lecture Outline

- The OS
- **C arrays and C++ Arrays**
- POSIX I/O
- Locality

std::array

- Similar to vector, we have array
  - Both contain a sequence of data that we can index into
- Main differences: the size
  - Vector is resizable (grows to whatever length we need)
  - Array is a static size (size is determined at compile time)
- Main differences: the allocation
  - To support being resizable, vector uses a lot of dynamic allocation
  - **Array does not use any dynamic allocation**

array example

```
int main(int argc, char* argv[]) {
  array<int, 3> arr {6, 5, 4};
  // arr.push_back(3); push_back does not exist!

  cout << arr.size() << endl; // prints 3
  cout << arr.at(2) << endl;  // prints 4

  // iterates through all elements and prints them
  for (const auto& element : arr) {
     cout << element << endl;
  }

  return EXIT_SUCCESS;
}
```

Arrays in C

- Definition: `type name[size]`
  - Allocates `size*sizeof(type)` bytes of *contiguous* memory
  - Normal usage is a compile-time constant for `size` (*e.g.* `int scores[175];`)
  - Initially, array values are “garbage”

- Size of an array
  - **Not stored anywhere** – array does not know its own size!
  - The programmer will have to store the length in another variable or hard-code it in

Using C Arrays

Optional when initializing

- Initialization: `type name[size] = {val0,…,valN};`
  - `{}` initialization can *only* be used at time of definition
  - If no size supplied, infers from length of array initializer

- Array name used as identifier for "collection of data"
  - `name[index]` specifies an element of the array and can be used as an assignment target or as a value in an expression
  - Array name (by itself) produces the address of the start of the array
    - Cannot be assigned to / changed

```c
int primes[6] = {2, 3, 5, 6, 11, 13};
primes[3] = 7;
primes[100] = 0;   // memory smash!
```

No IndexOutOfBounds
Hope for segfault

C Arrays as Parameters

- It's tricky to use arrays as parameters
  - What happens when you use an array name as an argument?
  - Arrays do not know their own size

Passes in address of start of array

```
int sumAll(int a[]) {
  int i, sum = 0;
  for (i = 0; i < ...???
}
```

```
int sumAll(int* a) {
  int i, sum = 0;
  for (i = 0; i < ...???
}
```

Equivalent

- Note: Array syntax works on pointers
  - E.g. `ptr[3] = ...;`

Solution: Pass Size as Parameter

```
int sumAll(int* a, int size) {
  int i, sum = 0;
  for (i = 0; i < size; i++) {
    sum += a[i];
  }
  return sum;
}
```

- Standard idiom in C programs

C Pointer Arithmetic

- We can do arithmetic on addresses to iterate through arrays.

```
int a[] = {0, 3, 5, 9};
int size = 4;

int sum = 0;
int* ptr = a; // &(a[0])
for (int i = 0; i < size; i++) {
  sum += ptr[i];
}
```

```
int a[] = {0, 3, 5, 9};
int size = 4;

int sum = 0;
int* ptr = a; // &(a[0])
int* end = ptr + size;
for (; ptr != end; ptr++) {
  sum += *ptr;
}
```

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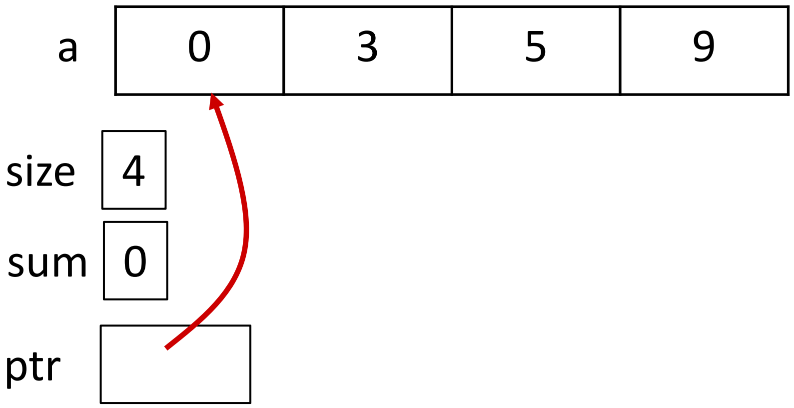

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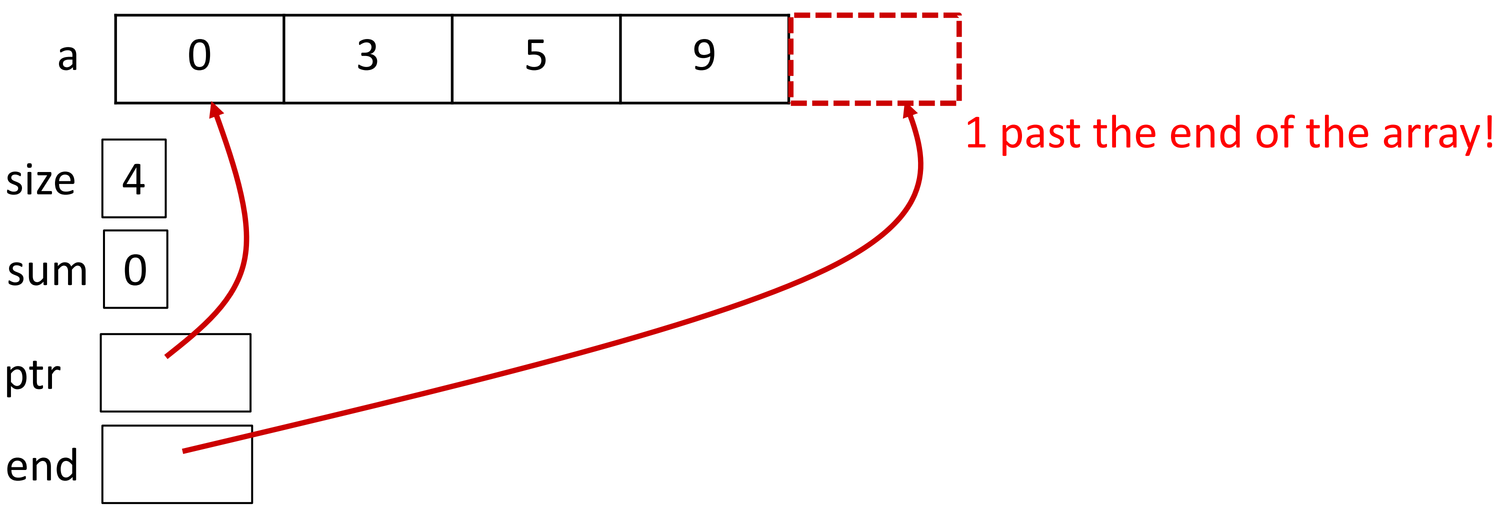

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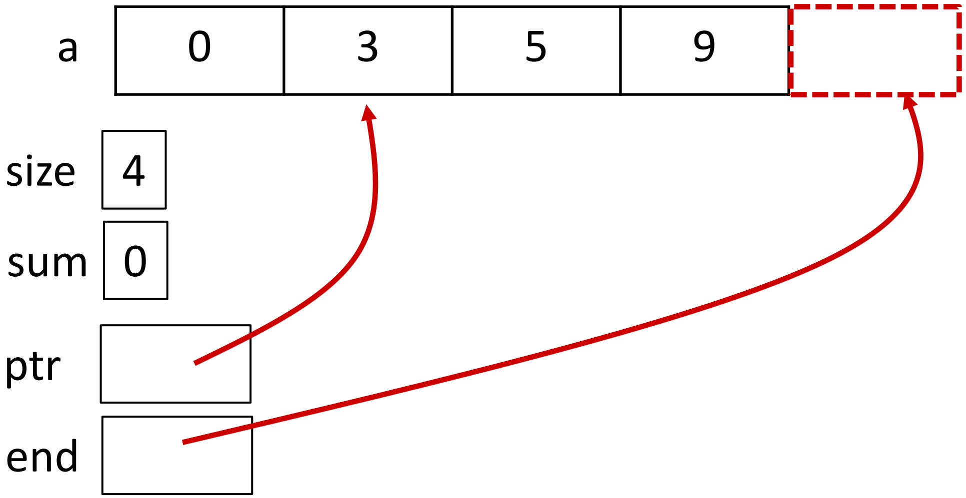

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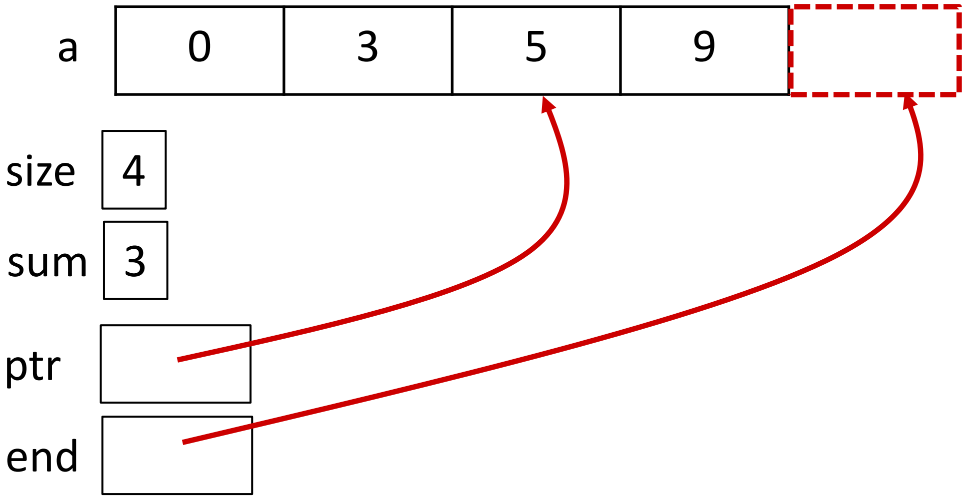

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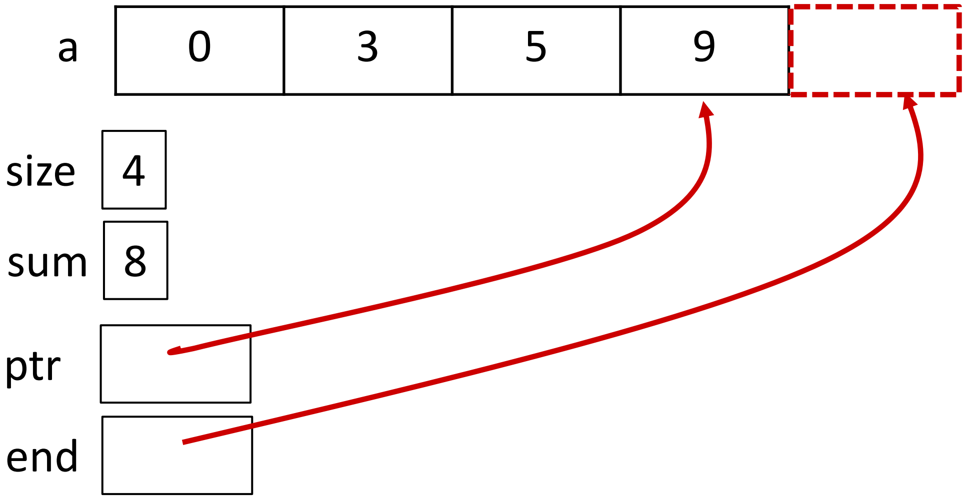

C Pointer Arithmetic

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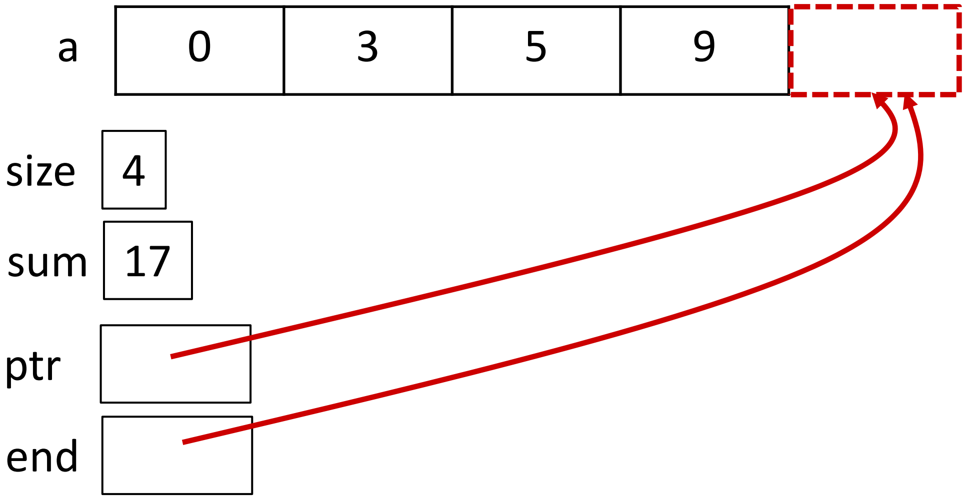


C++ Arrays

- C arrays are considered dangerous, and not safe to use
  - Length is not attached to the array
  - There is no bounds checking
  - Arrays are not readable code
    Consider this CIS 5480 Example:
    What do you think "commands" represents?

```
// example from CIS 5480
struct parsed_command {
  int num_commands;
  char*** commands;
};
```

- In our code, we will use C++ Arrays instead, but we need to call C code that expects C arrays…

C++ Arrays -> C array

- Can use .data() and .size() to convert to a C array

```
int sumAll(int* a, int size) {
  int i, sum = 0;
  for (i = 0; i < size; i++) {
    sum += a[i];
  }
  return sum;
}

int main(){
  array<int, 1024> arr{};
  sumAll(arr.data(), arr.size());
}
```

Lecture Outline

- The OS
- C arrays and C++ Arrays
- **POSIX I/O**
- Locality

Aside: File I/O & Disk

- File System:
  - Provides long term storage of data:
    - Persist after a program terminates
    - Persists after computer turns off

  - Data is organized into files & directories
    - A directory is pretty much a “folder”

  - Interaction with the file system is handled by the operating system and hardware. (To make sure a program doesn’t put the entire file system into an invalid state)

C Standard Library I/O

- In 5930, you've seen the C standard library to access files
  - Use a provided `FILE*` *stream* abstraction
  - `fopen()`, `fread()`, `fwrite()`, `fclose()`, `fseek()`

- These are convenient and portable
  - They are buffered*
  - They are implemented using lower-level OS calls

From C to POSIX

- Most UNIX-en support a common set of lower-level file access APIs: POSIX – Portable Operating System Interface
  - `open()`, `read()`, `write()`, `close()`, `lseek()`
    - Similar in spirit to their `f*()` counterparts from the C std lib
    - Lower-level and unbuffered compared to their counterparts
    - Also less convenient
  - C stdlib doesn't provide everything POSIX does
    - You will have to use these to read file system directories and for network I/O, so we might as well learn them now

open()/close()

- To open a file:
  - Pass in the filename and access mode
    - Similar to `fopen()`
  - Get back a "file descriptor"
    - Similar to `FILE*` from `fopen()`, but is just an `int`
    - Defaults: 0 is `stdin`, 1 is `stdout`, 2 is `stderr`
      - `-1 indicates error`

Used to identify a file w/ the OS

```
#include <fcntl.h>     // for open()
#include <unistd.h>    // for close()
  ...
  int fd = open("foo.txt", O_RDONLY);
  if (fd == -1) {
    perror("open failed");
    exit(EXIT_FAILURE);
  }
  ...
  close(fd);
```

Reading from a File

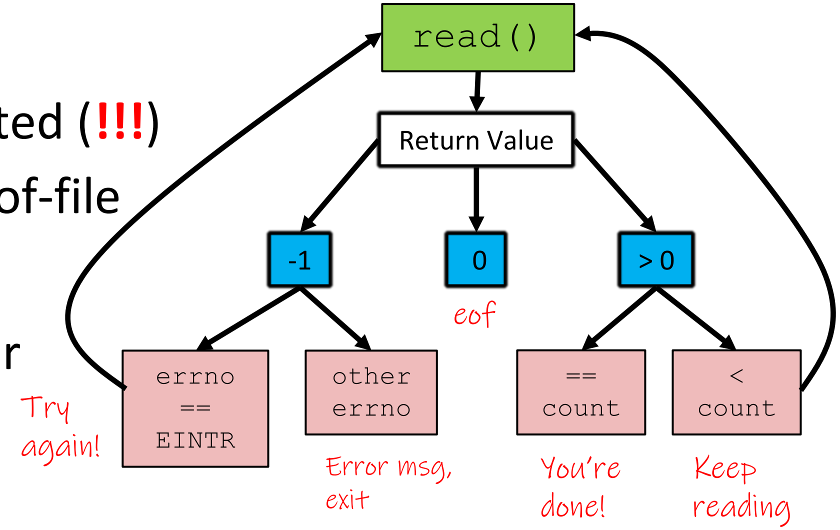
Stores read result in buf

Number of bytes

```
ssize_t read(int fd, void* buf, size_t count);
```

signed

- Returns the number of bytes read
  - Might be fewer bytes than you requested (**!!!**)
  - Returns **0** if you're already at the end-of-file
  - Returns **-1** on error (and sets `errno`)
  - Advances forward in the file by number of bytes read



- There are some surprising error modes (check `errno`)
  - `EBADF`: bad file descriptor
  - `EFAULT`: output buffer is not a valid address
  - `EINTR`: read was interrupted, please try again (ARGH!!!! 😤😠)
  - And many others…

Defined in errno.h

Poll Everywhere

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- Let's say we want to read 'n' bytes. Which is the correct completion of the blank below?

```
array<char, n> buf {}; // buffer
int bytes_left = n;
int result;          // result of read()

while (bytes_left > 0) {
  result = read(fd, ______, bytes_left);
  if (result == -1) {
    if (errno != EINTR) {
      // a real error happened,
      // so return an error result
    }
    // EINTR happened,
    // so do nothing and try again
    continue;  Keyword that jumps
               to beginning of loop
  }
  bytes_left -= result;
}
```

A. buf.data()

B. buf.data() + bytes_left

C. buf.data() + bytes_left - n

D. buf.data() + n - bytes_left

E. We're lost…

Poll Everywhere

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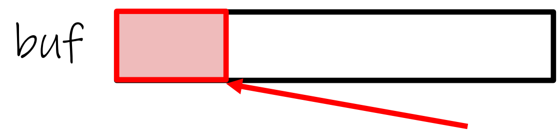
- Let's say we want to read 'n' bytes. Which is the correct completion of the blank below?

if first read only reads n/4 bytes



Want to start reading here
buf + n/4

bytes_left = n * 3/4

= buf + n - bytes_left

```
array<char, n> buf {}; // buffer
int bytes_left = n;
int result;        // result of read()

while (bytes_left > 0) {
  result = read(fd, ______, bytes_left);
  if (result == -1) {
    if (errno != EINTR) {
      // a real error happened,
      // so return an error result
    }
    // EINTR happened,
    // so do nothing and try again
    continue;
  }
  bytes_left -= result;
}
```

Keyword that jumps to beginning of loop

A. buf.data()

B. buf.data() + bytes_left

C. buf.data() + bytes_left - n

D. buf.data() + n - bytes_left

E. We're lost…

One method to **`read()`** n bytes

```
int fd = open(filename, O_RDONLY);
array<char, 1024> buf {};  // buffer of appropriate size
int bytes_left = 1024;
int result;

while (bytes_left > 0) {
  result = read(fd, buf.data() + (1024 - bytes_left), bytes_left);
  if (result == -1) {
    if (errno != EINTR) {
      // a real error happened, so exit the program
      // print out some error message to cerr
      exit(EXIT_FAILURE);
    }
    // EINTR happened, so do nothing and try again
    continue;  Keyword that jumps to beginning of loop
  } else if (result == 0) {
    // EOF reached, so stop reading
    break;  To prevent an infinite loop
  }
  bytes_left -= result;
}
close(fd);
```

Other Low-Level Functions

- Read man pages to learn about:
  - **`write`**`()` – write data
    - `#include <unistd.h>`
  - **`lseek`**`()` – reposition and/or get file offset
    - `#include <unistd.h>`
  - **`opendir`**`()`, **`readdir`**`()`, **`closedir`**`()` – deal with directory listings
    - Make sure you read the section 3 version (*e.g.* `man 3 opendir`)
    - `#include <dirent.h>`

- A useful shortcut sheet (from CMU): http://www.cs.cmu.edu/~guna/15-123S11/Lectures/Lecture24.pdf

HW1 Overview

- In HW1, you will be implementing two file readers
- SimpleFileReader
  - A relatively simple C++ class that acts as a wrapper around POSIX
- BufferedFileReader
  - Similar to SimpleFileReader but maintains an internal buffer for improver performance <u>due to locality</u>
  - Also implements token parsing

Lecture Outline

- The OS
- C arrays and C++ Arrays
- POSIX I/O
- **Locality**

Locality

- A major factor in performance is the locality of data
  - data that is "closer" is quicker to fetch

Numbers are out of date, but order of magnitude is same

- Have you seen this?
  - More on this when talking about memory (Jeff Dean from LADIS '09)

Numbers Everyone Should Know

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

- https://colin-scott.github.io/personal_website/research/interactive_latency.html

Buffering

- 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

Buffering Example

Arrow signifies what will be executed next

NOTE: using fopen/fread/fclose just for example.
They will NOT be used in HW1 or in the rest of the class

```
int main(int argc, char** argv) {
  array<char,2> buf {};
→ FILE* fin = fopen("hi.txt", "rb");

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

  fread(buf.data()+1, sizeof(char), 1, fin);

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

Buffering Example

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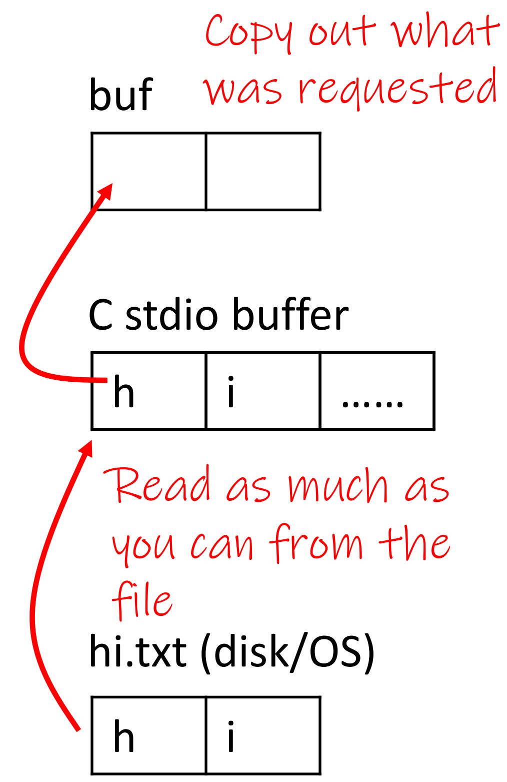

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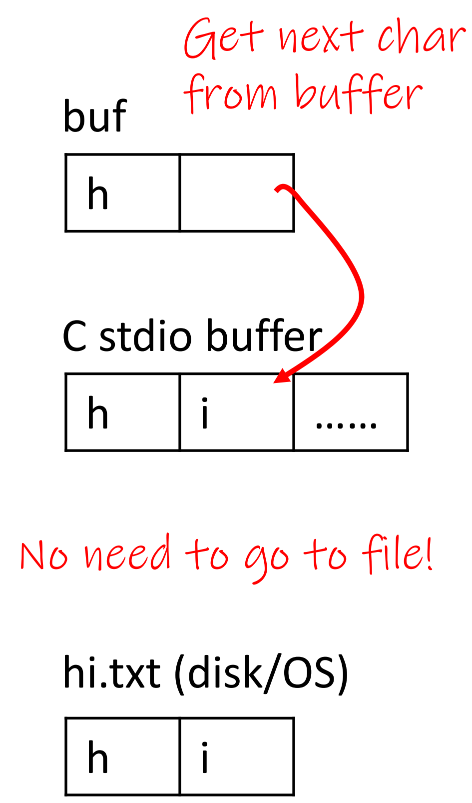
  // read "hi" one char at a time
  fread(buf.data(), sizeof(char), 1, fin);

→ fread(buf.data()+1, sizeof(char), 1, fin);

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



Buffering Example

Arrow signifies what will be executed next

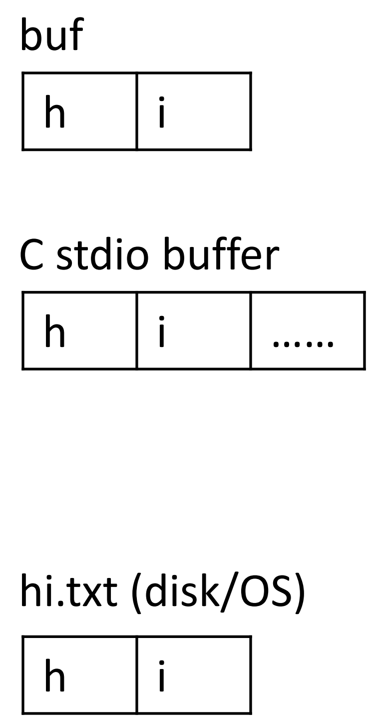
NOTE: using fopen/fread/fclose just for example.
They will NOT be used in HW1 or in the rest of the class

```
int main(int argc, char** argv) {
  array<char,2> buf {};
  FILE* fin = fopen("hi.txt", "rb");

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

  fread(buf.data()+1, sizeof(char), 1, fin);

→ fclose(fin);
  return EXIT_SUCCESS;
}
```



Buffering Example

Arrow signifies what will be executed next

NOTE: using fopen/fread/fclose just for example.
They will NOT be used in HW1 or in the rest of the class

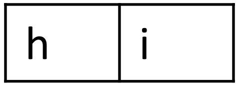
```
int main(int argc, char** argv) {
  array<char,2> buf {};
  FILE* fin = fopen("hi.txt", "rb");

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

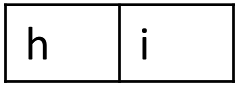
  fread(buf.data()+1, sizeof(char), 1, fin);

  fclose(fin);
→ return EXIT_SUCCESS;
}
```

buf



hi.txt (disk/OS)



GAP SLIDE

- Helps clearly indicate we are going on to a new example

No Buffering Example

Arrow signifies what will be executed next

```
int main(int argc, char** argv) {
  array<char,2> buf {};
  int file = open("hi.txt", O_RDONLY);

  // read "hi" one char at a time
  read(file, buf.data(), 1);       // <- arrow

  read(file, buf.data()+1, 1);

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

No Buffering Example

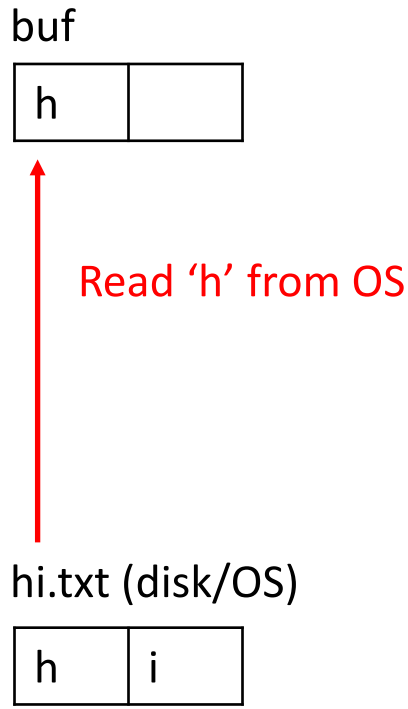
Arrow signifies what will be executed next

```
int main(int argc, char** argv) {
  array<char,2> buf {};
  int file = open("hi.txt", O_RDONLY);

  // read "hi" one char at a time
  read(file, buf.data(), 1);

→ read(file, buf.data()+1, 1);

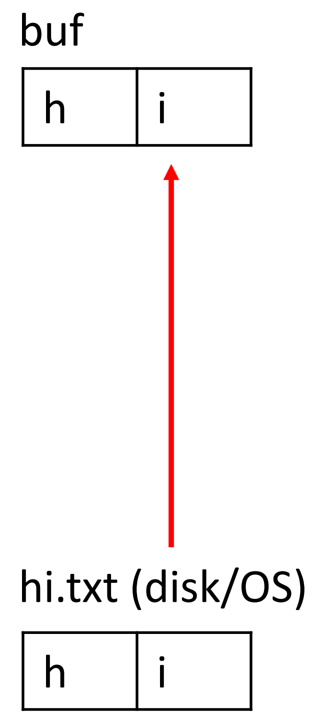
  close(file);
  return EXIT_SUCCESS;
}
```



No Buffering Example

Arrow signifies what will be executed next

Read ‘i’ from OS




```
int main(int argc, char** argv) {
  array<char,2> buf {};
  int file = open("hi.txt", O_RDONLY);

  // read "hi" one char at a time
  read(file, buf.data(), 1);

  read(file, buf.data()+1, 1);

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

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