Buffering, POSIX I/O, System Calls

CSE 333 Spring 2021

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About how long did Exercise 3 take you?

A. [0, 2) hours
B. [2, 4) hours
C. [4, 6) hours
D. [6, 8) hours
E. 8+ Hours
F. I didn’t submit / I prefer not to say

Administrivia

- Exercise 4 posted today, due Monday (4/19)
  - Given a full week since it is totally new, and HW1 is due
- Homework 1 due Thursday night (4/15)
  - Clean up "to do" comments, but leave "STEP #" markers
  - Graded not just on correctness, also code quality.
  - OH Thursday may go late. Check the Ed discussion board for more
  - Late days: don't tag `hw1-final` until you are really ready
    - Please use them if you need to!
- Homework 2
  - Starting with HW 2, projects will be done in partners ☺
    - More info to be posted on Ed later today

Lecture Outline

- **C Stream Buffering**
- POSIX Lower-Level I/O
- System Calls

Buffering

- By default, `stdio` uses buffering for streams:
  - Data written by **`fwrite`**`()` is copied into a buffer allocated by `stdio` inside your process' address space
  - As some point, the buffer will be "drained" into the destination:
    - When you explicitly call **`fflush`**`()` on the stream
    - When the buffer size is exceeded (often 1024 or 4096 bytes)
    - For `stdout` to console, when a newline is written (*"line buffered"*) or when some other function tries to read from the console
    - When you call **`fclose`**`()` on the stream
    - When your process exits gracefully (**`exit`**`()` or `return` from **`main`**`()`)

Buffering Example

buffered_hi.c

```c
int main(int argc, char** argv) {
  FILE* fout = fopen("test.txt", "wb");

  // write "hi" one char at a time
  if (fwrite("h", sizeof(char), 1, fout) < 1) {
    perror("fwrite failed");
    fclose(fout);
    return EXIT_FAILURE;
  }

  if (fwrite("i", sizeof(char), 1, fout) < 1) {
    perror("fwrite failed");
    fclose(fout);
    return EXIT_FAILURE;
  }

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

C stdio buffer

h	i	……

test.txt (disk)

h	i

No Buffering Example

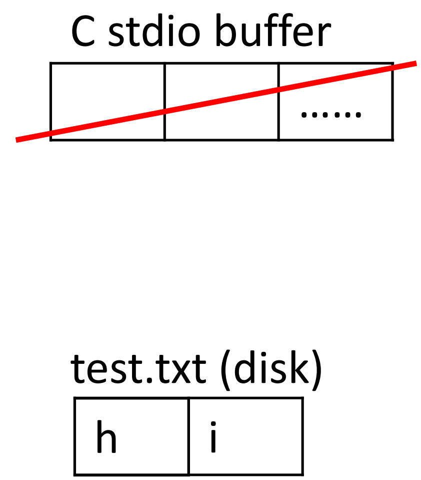
unbuffered_hi.c

```c
int main(int argc, char** argv) {
  FILE* fout = fopen("test.txt", "wb");
  setbuf(fout, NULL); // turn off buffering

  // write "hi" one char at a time
  if (fwrite("h", sizeof(char), 1, fout) < 1) {
    perror("fwrite failed");
    fclose(fout);
    return EXIT_FAILURE;
  }

  if (fwrite("i", sizeof(char), 1, fout) < 1) {
    perror("fwrite failed");
    fclose(fout);
    return EXIT_FAILURE;
  }

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



Why Buffer?

- Performance – avoid disk accesses
  - Group many small writes into a single larger write
  - Disk Latency = 😱😱😱 (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

- Convenience – nicer API
  - We'll compare C's `fread()` with POSIX's `read()`

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
    - What if you signal another process to read the file you just wrote to?

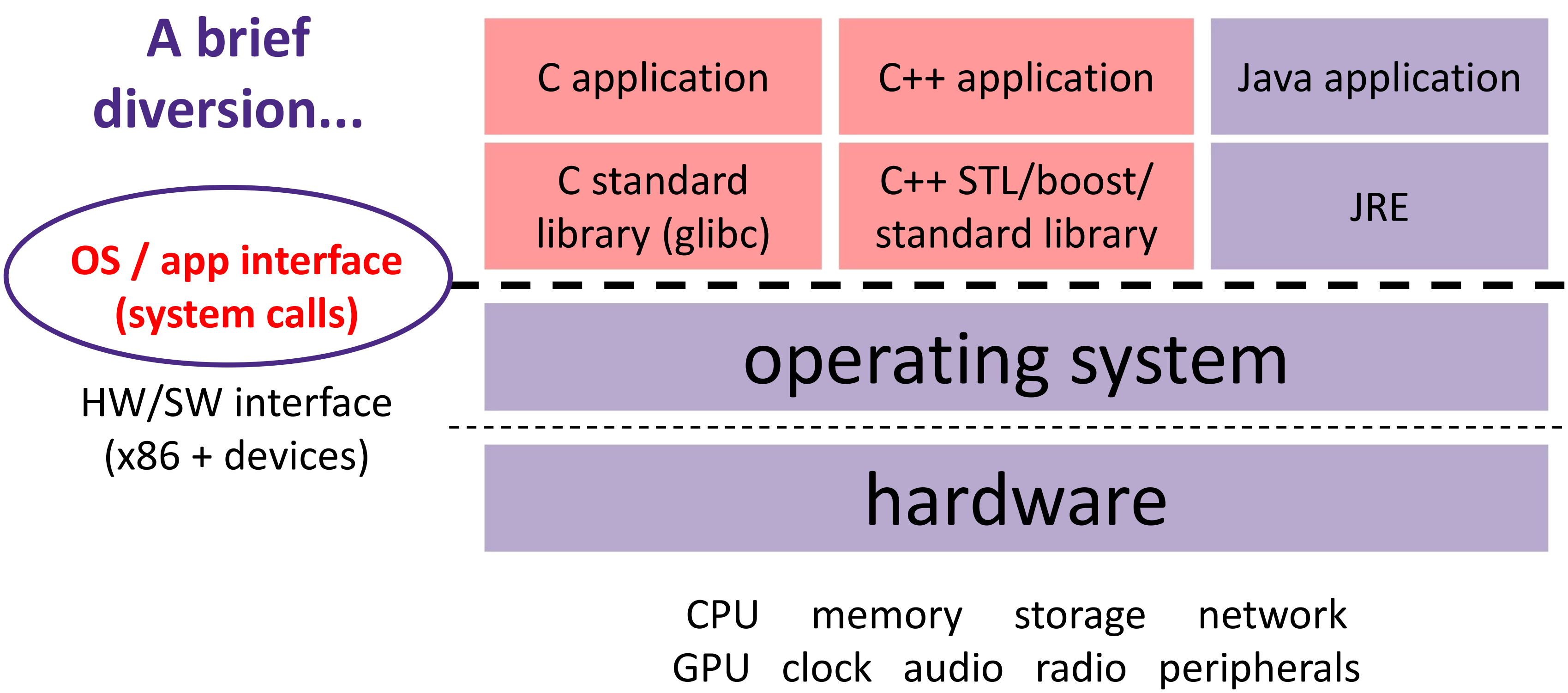
- Performance – buffering takes time
  - Copying data into the `stdio` buffer consumes CPU cycles and memory bandwidth
  - Can potentially slow down high-performance applications, like a web server or database (*"zero-copy"*)

- When is buffering faster? Slower?

Lecture Outline

- C Stream Buffering
- **POSIX Lower-Level I/O**
- System Calls

Remember This Picture?



We Need To Go Deeper…

- So far we'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()

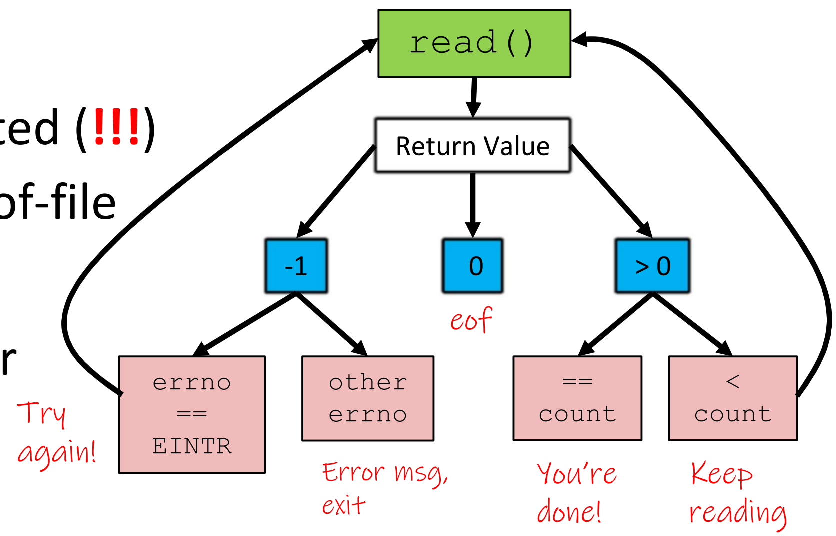
- To open a file:
  - Pass in the filename and access mode
    - Similar to **fopen()**
  - Get back a "file descriptor"
    - Similar to `FILE*` from **fopen()**, but is just an `int`
    - Defaults: **0** is `stdin`, **1** is `stdout`, **2** is `stderr`
      - `-1 indicates error`

```
#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

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

- 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…

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

```
char* buf = ...;  // buffer of size n
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;
}
```

A. buf

B. buf + bytes_left

C. buf + bytes_left - n

D. buf + n - bytes_left

E. We're lost...

One method to `read()` n bytes

```
int fd = open(filename, O_RDONLY);
char* buf = ...;  // buffer of appropriate size
int bytes_left = n;
int result;

while (bytes_left > 0) {
  result = read(fd, buf + (n - bytes_left), 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;
  } else if (result == 0) {
    // EOF reached, so stop reading
    break;
  }
  bytes_left -= result;
}

close(fd);
```

readN.c

Other Low-Level Functions

- Read man pages to learn about:
  - `write()` – write data
    - `#include <unistd.h>`
  - `fsync()` – flush data to the underlying device
    - `#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

C Standard Library vs. POSIX

- C std lib implements a subset of POSIX
  - *e.g.* POSIX provides directory manipulation that C std lib doesn't
- C std lib implements automatic buffering
- C std lib has a nicer API

- The two are similar but C std lib builds on top of POSIX
  - Choice between high-level and low-level
  - Will depend on the requirements of your application

Lecture Outline

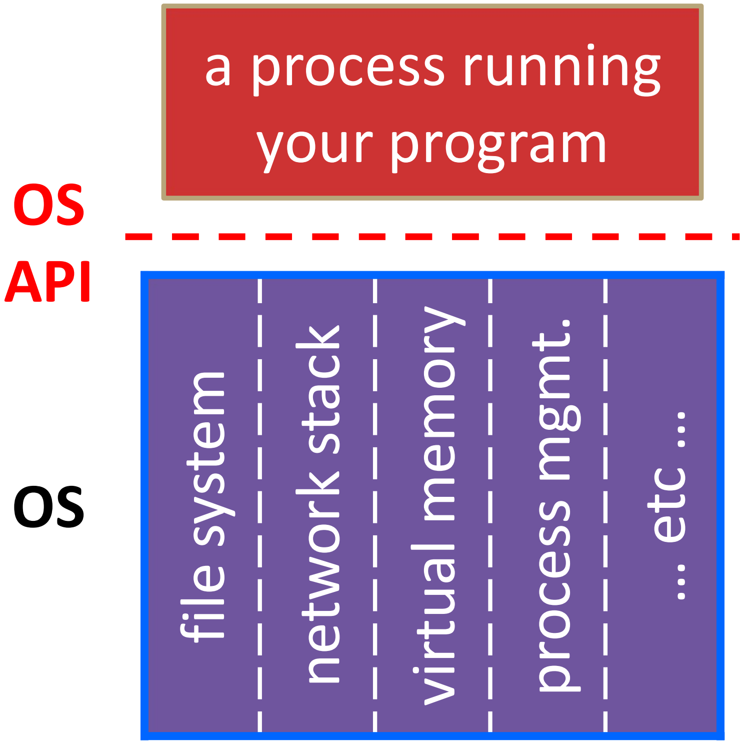
- C Stream Buffering
- POSIX Lower-Level I/O
- **System Calls**

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

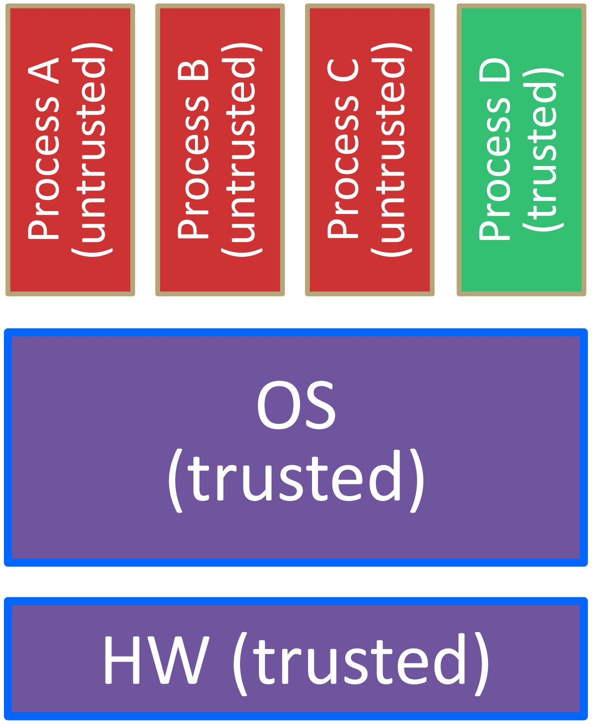
- brk(), shm_open(), ...

Process Management

- fork(), wait(), nice(), ...

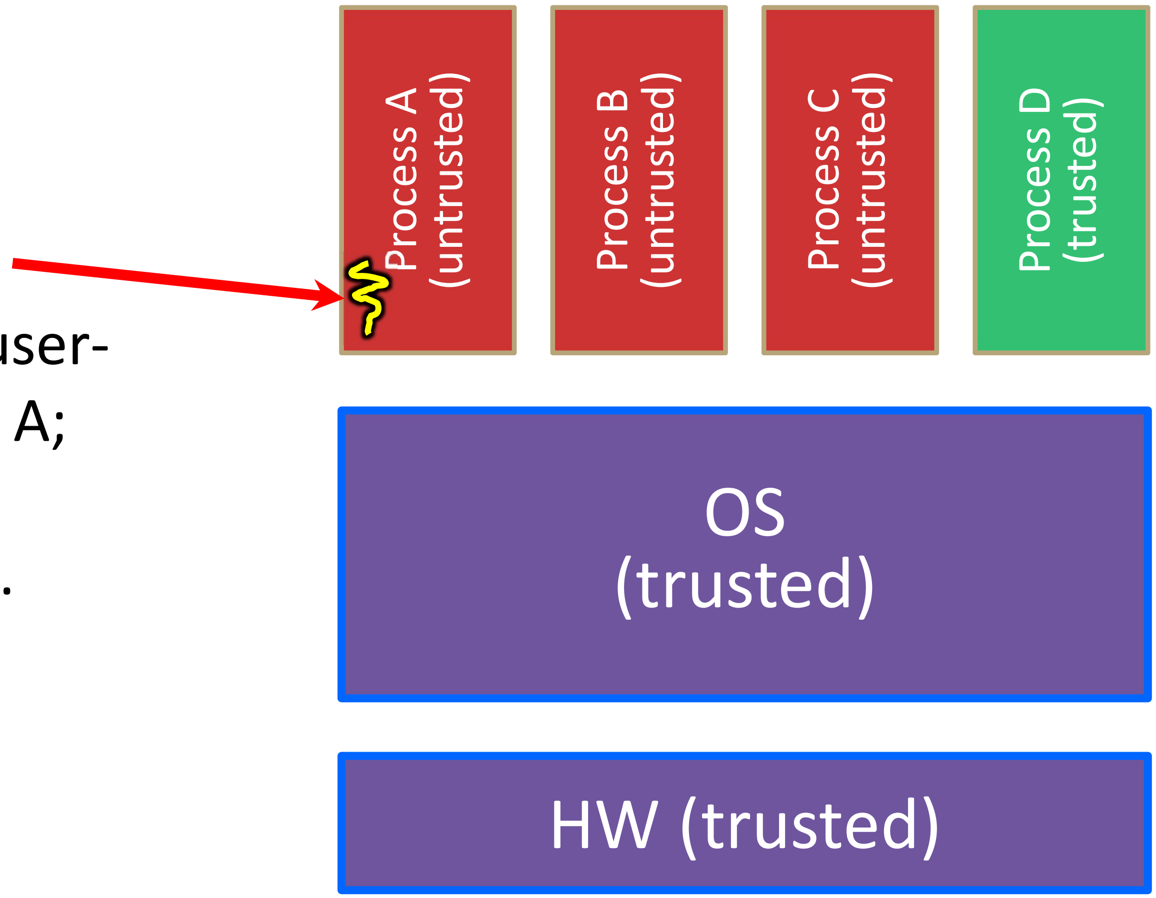
OS: Protection System

- OS isolates process from each other
  - But permits controlled sharing between them
    - Through shared name spaces (*e.g.* file names)
- OS isolates itself from processes
  - Must prevent processes from accessing the hardware directly
- OS is allowed to access the hardware
  - User-level processes run with the CPU (processor) in unprivileged mode
  - The OS runs with the CPU in privileged mode
  - User-level processes invoke system calls to safely enter the OS



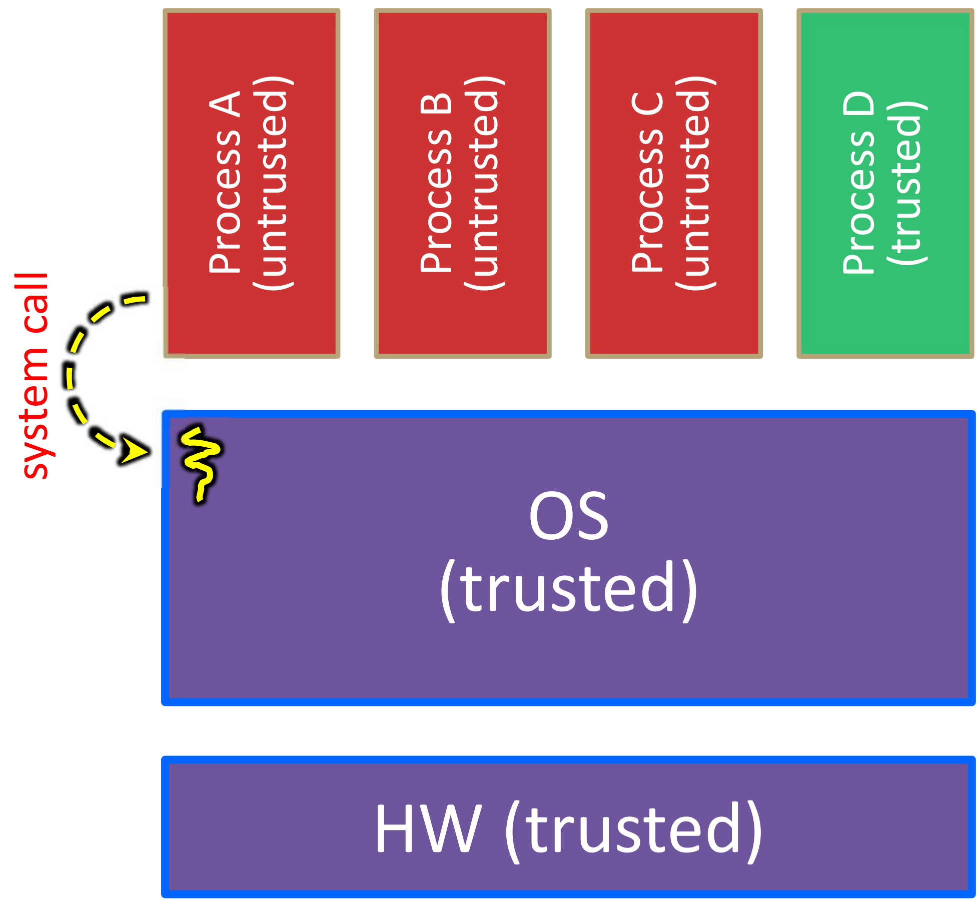
System Call Trace (high-level view)

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



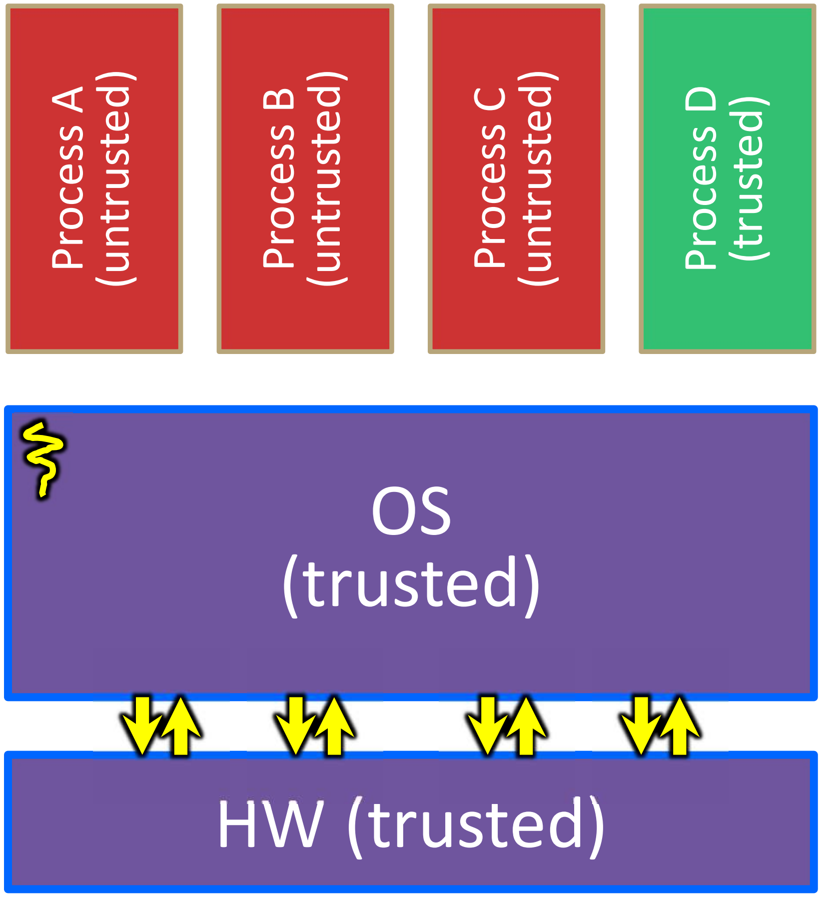
System Call Trace (high-level view)

Code in Process A 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.

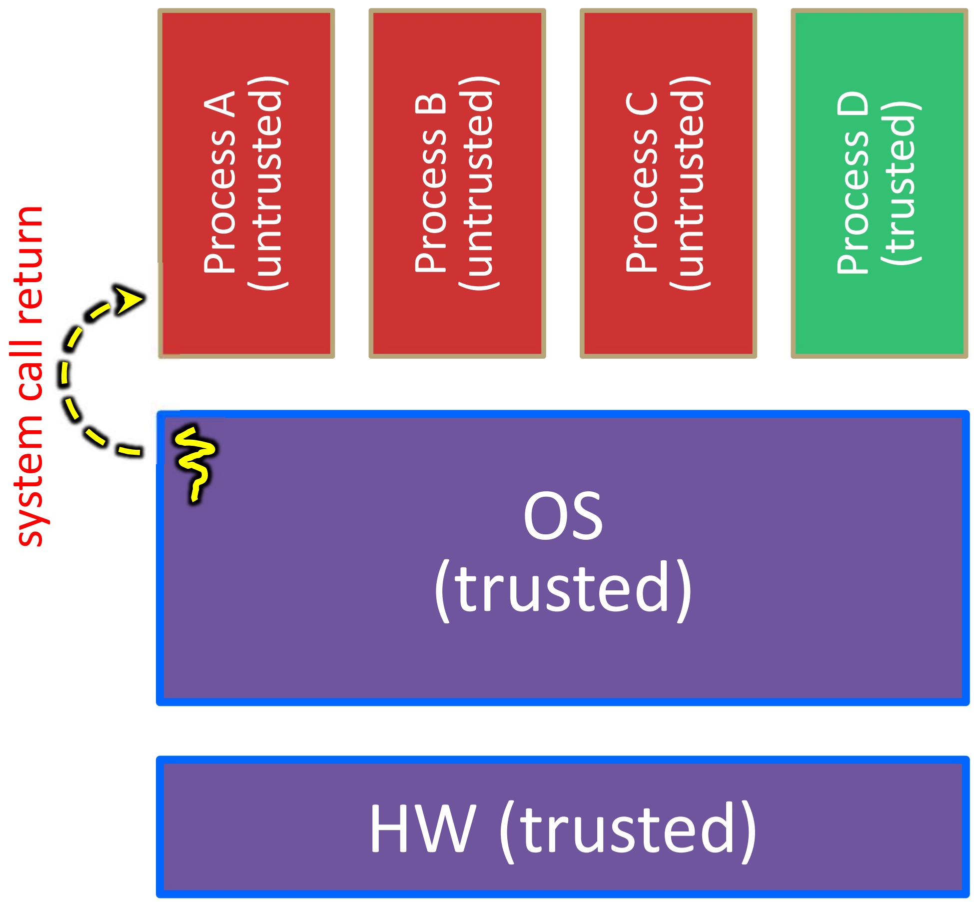


System Call Trace (high-level view)

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

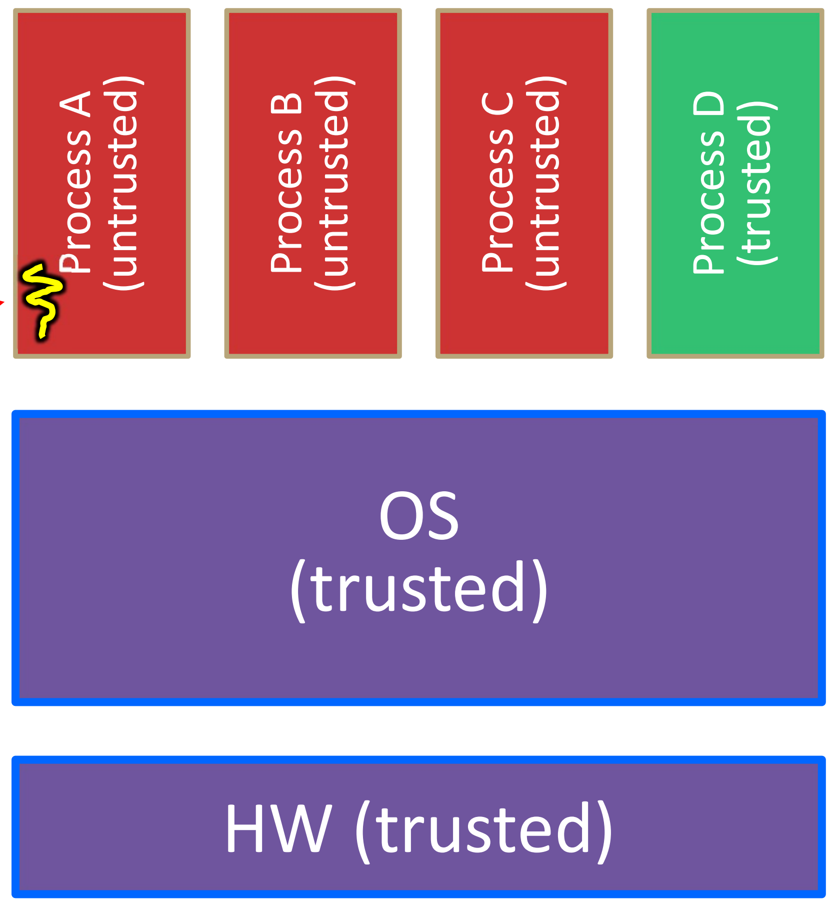
(1) Sets the CPU back to unprivileged mode and

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



System Call Trace (high-level view)

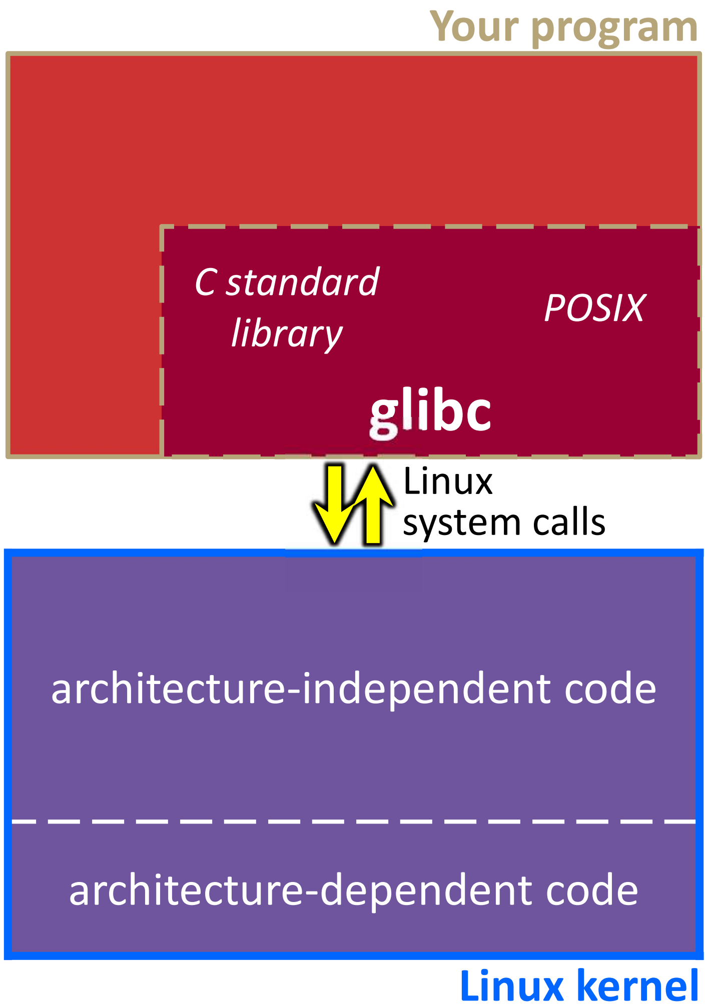
The process continues executing whatever code is next after the system call invocation.



Useful reference:
CSPP § 8.1–8.3
(the 351 book)

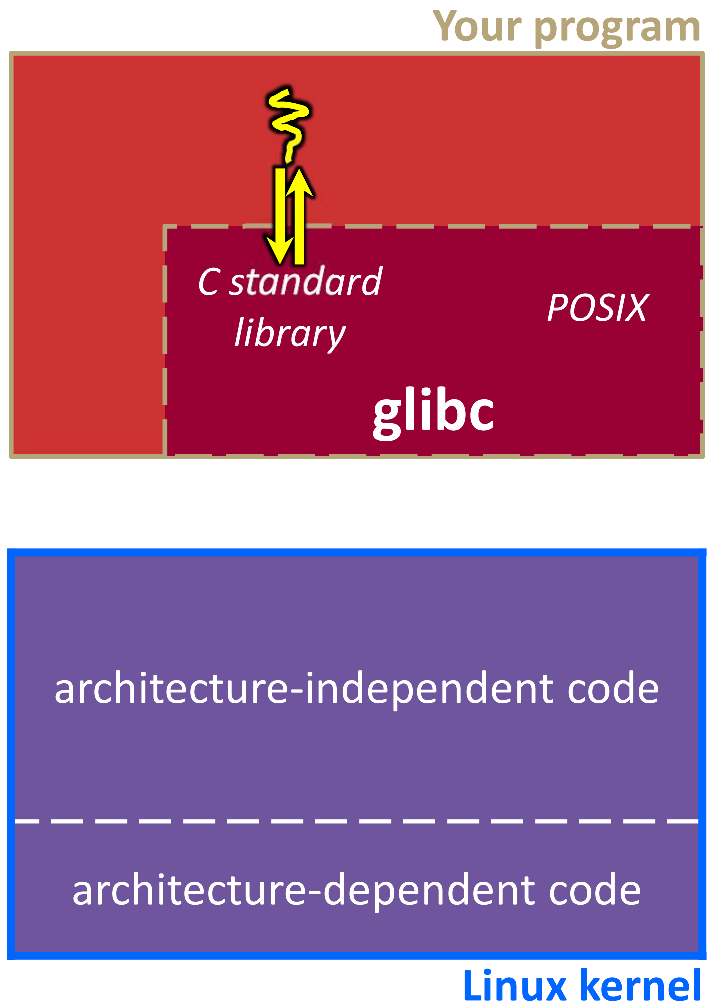
"Library calls" on x86/Linux

- 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



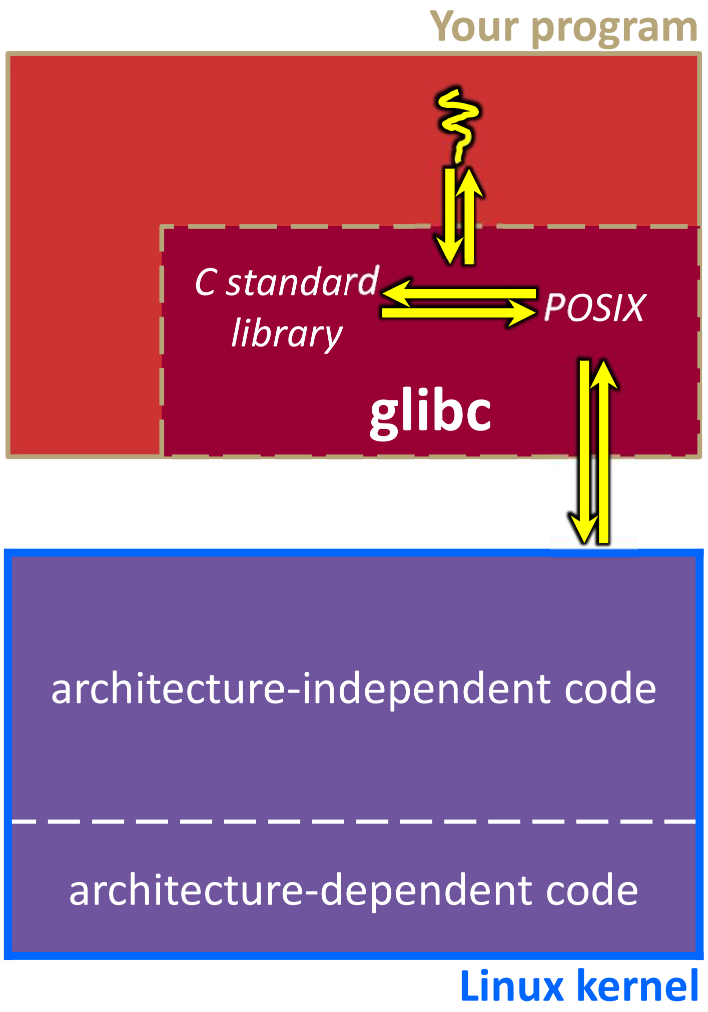
"Library calls" on x86/Linux: Option 1

- 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!



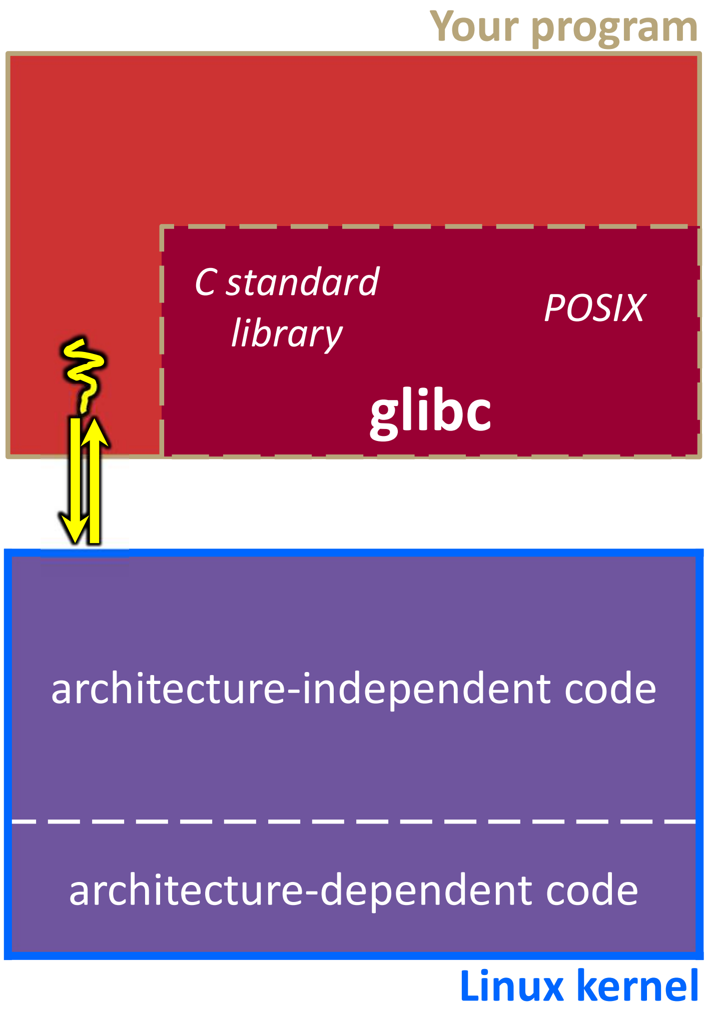
"Library calls" on x86/Linux: Option 2

- 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.



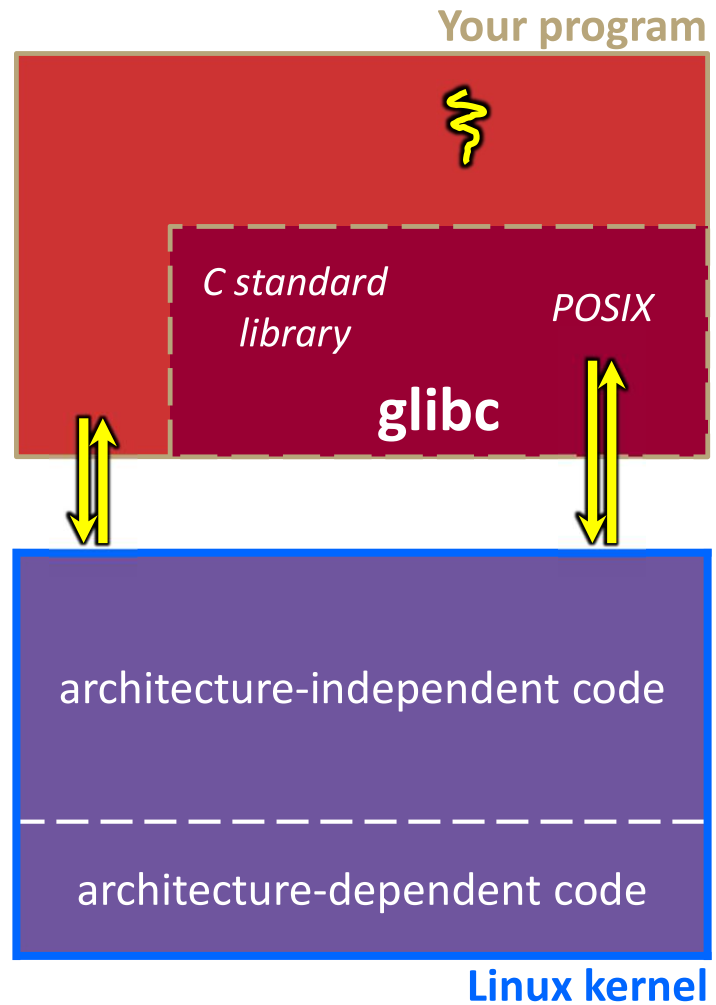
"Library calls" on x86/Linux: Option 3

- 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



Details on x86/Linux

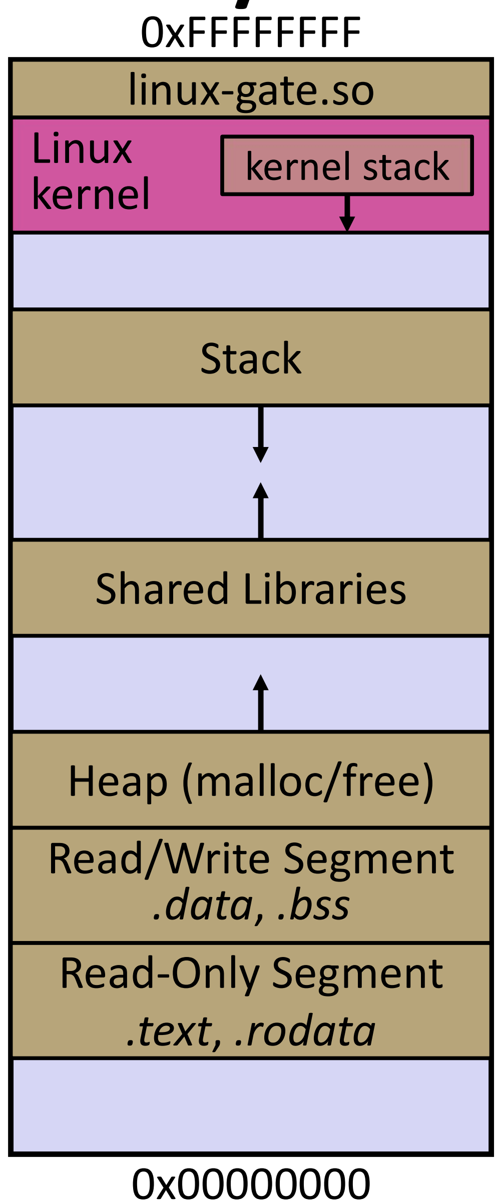
- Let's walk through how a Linux system call actually works
  - We'll assume *32-bit x86* using the modern `SYSENTER` / `SYSEXIT` x86 instructions
    - x86-64 code is similar, though details always change over time, so take this as an example – not a debugging guide

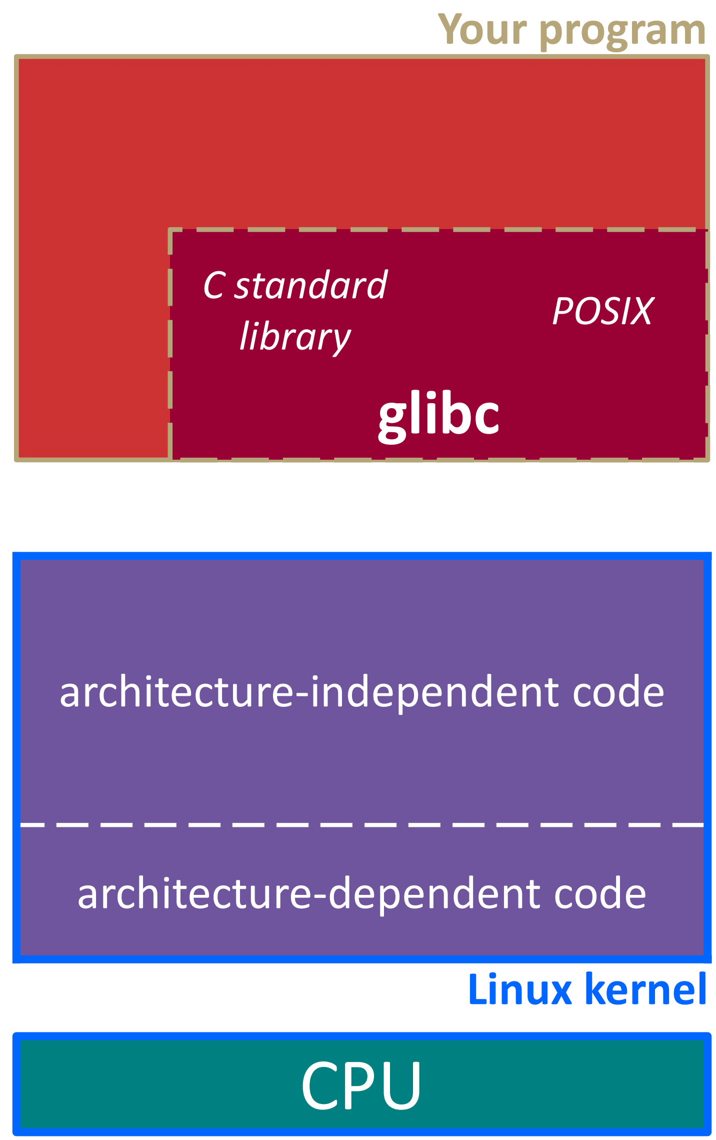


System Calls on x86/Linux

Remember our process address space picture?

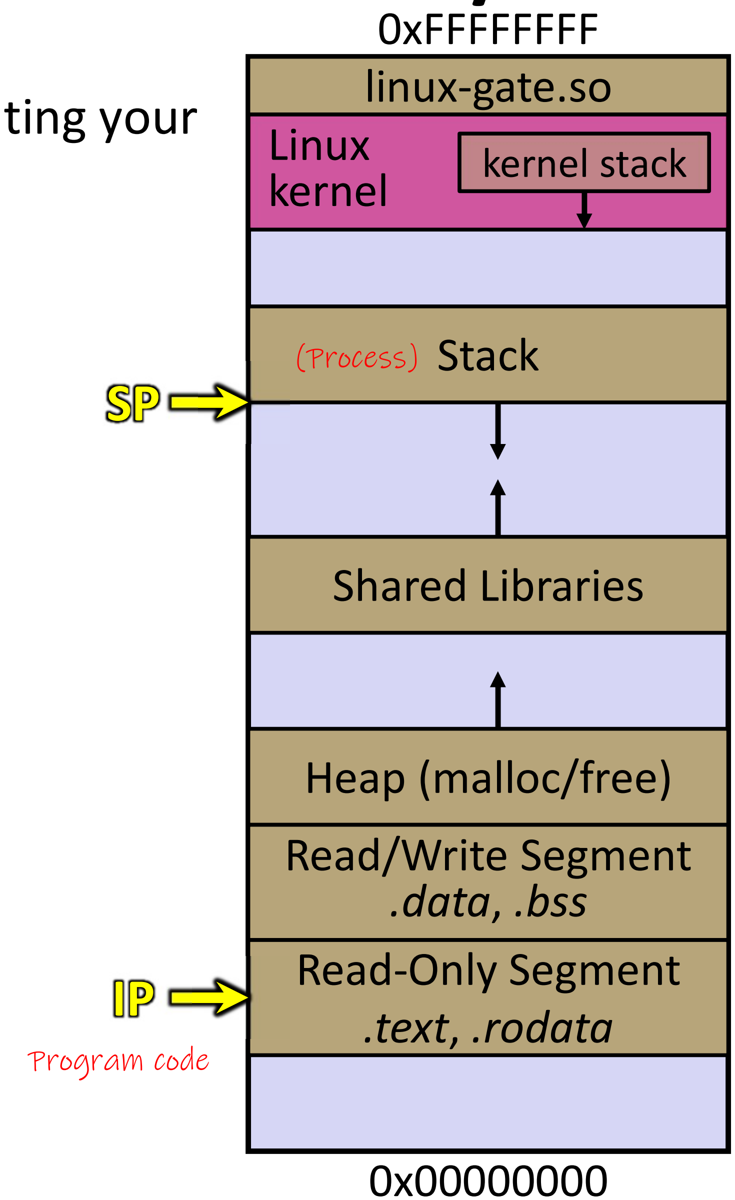
- Let's add some details:

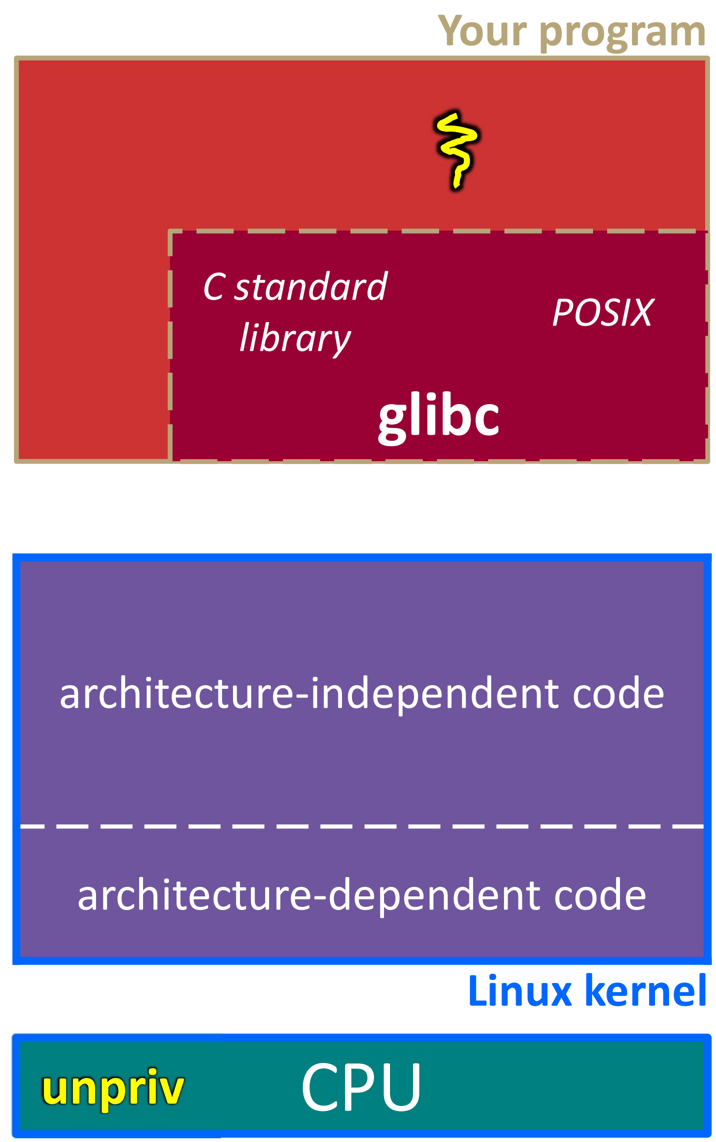




System Calls on x86/Linux

Process is executing your program code

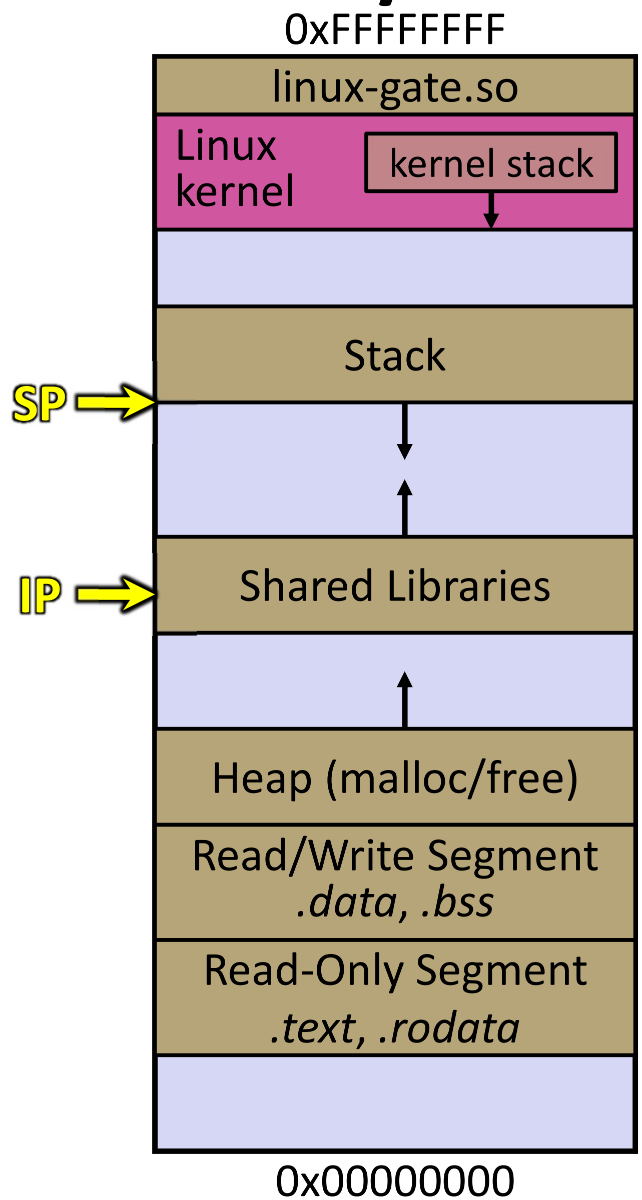


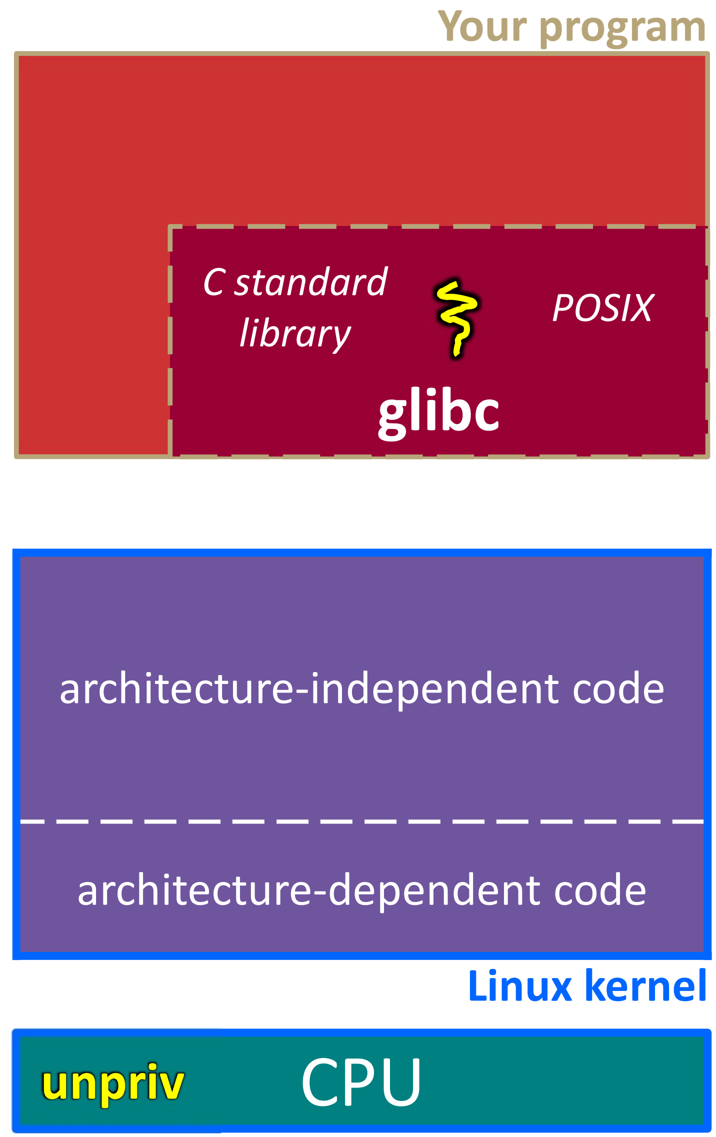


System Calls on x86/Linux

Process calls into a `glibc` function

- *e.g.* **`fopen`**`()`
- We'll ignore the messy details of loading/linking shared libraries

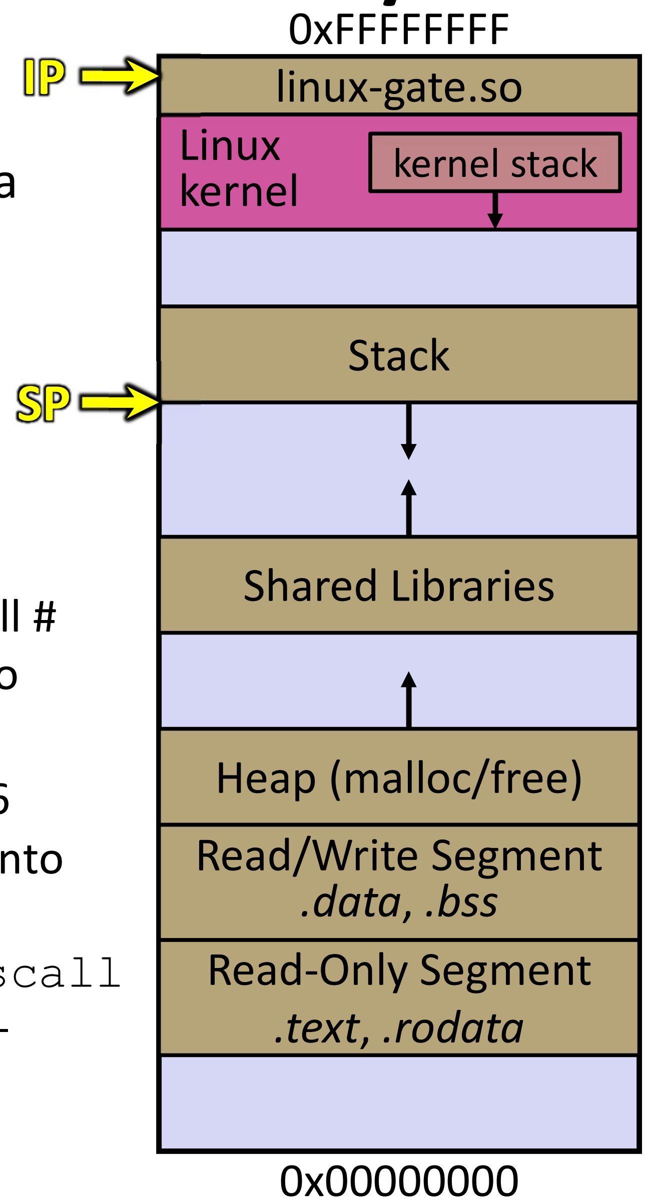


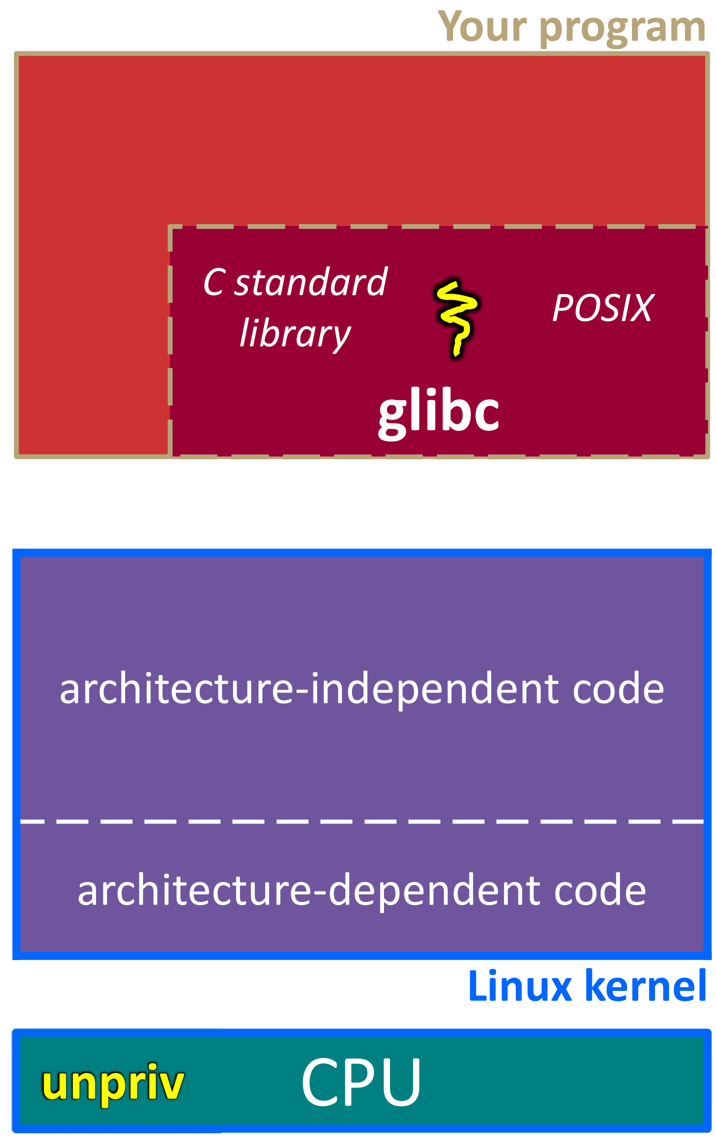


System Calls on x86/Linux

`glibc` begins the process of invoking a Linux system call

- `glibc`'s **`fopen()`** likely invokes Linux's **`open()`** system call
- Puts the system call # and arguments into registers
- Uses the **`call`** x86 instruction to call into the routine `__kernel_vsyscall` located in `linux-gate.so`

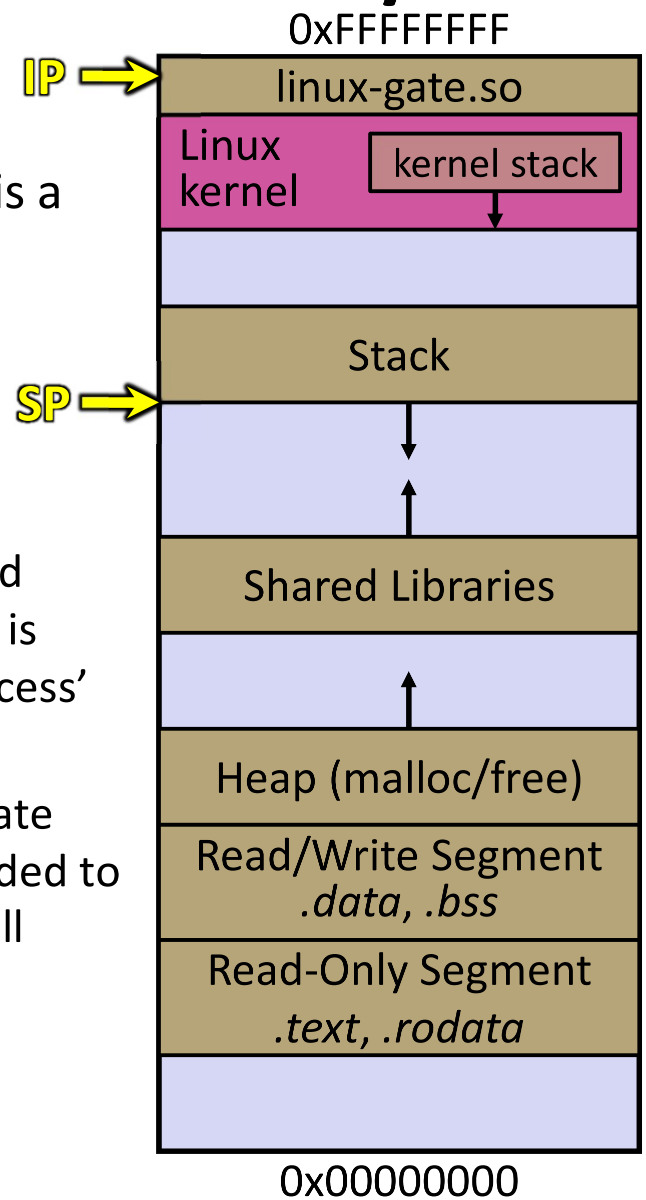


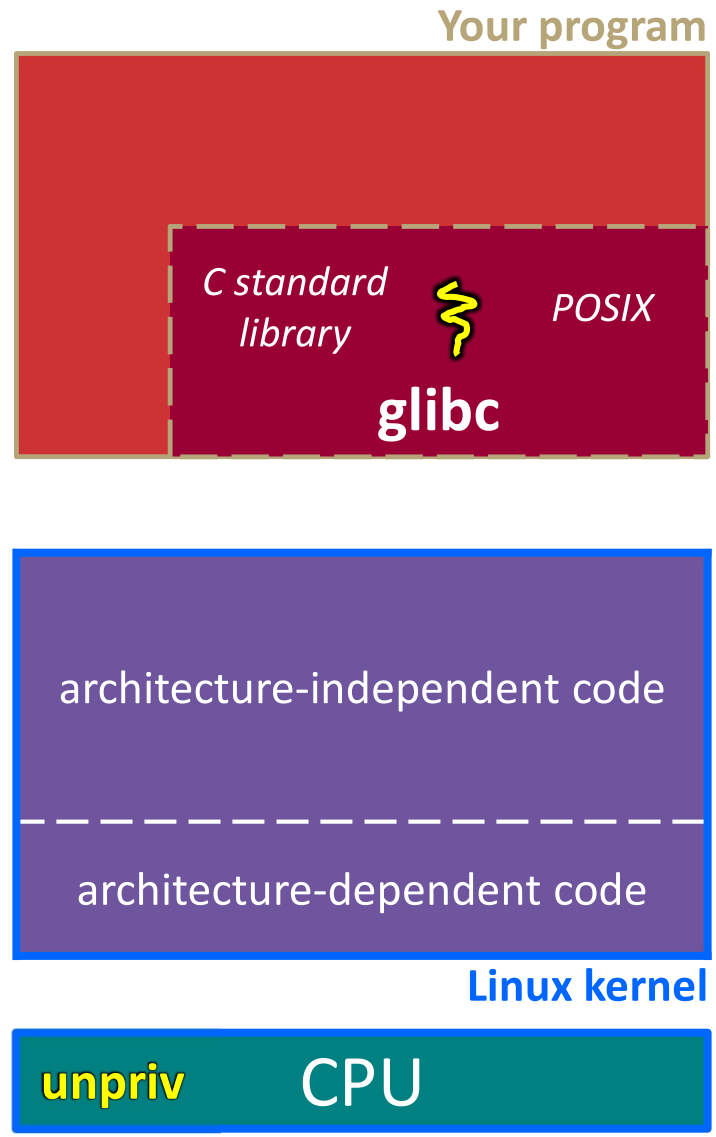


System Calls on x86/Linux

`linux-gate.so` is a **vdso**

- A virtual dynamically-linked shared object
- Is a kernel-provided shared library that is plunked into a process' address space
- Provides the intricate machine code needed to trigger a system call

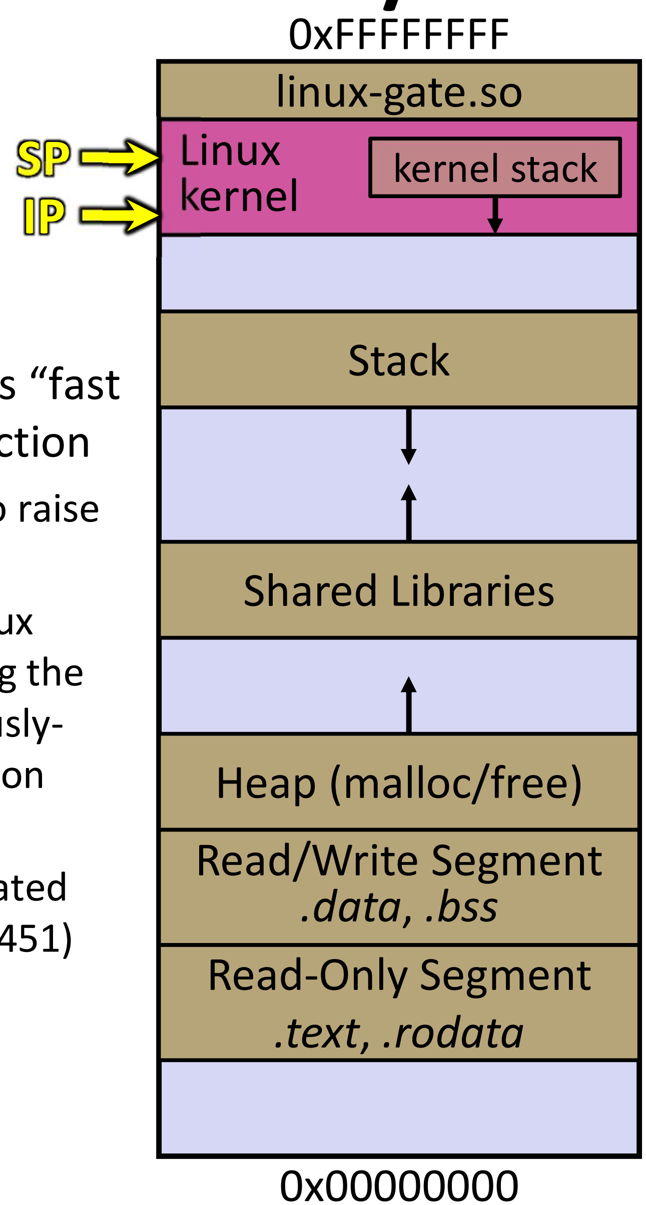


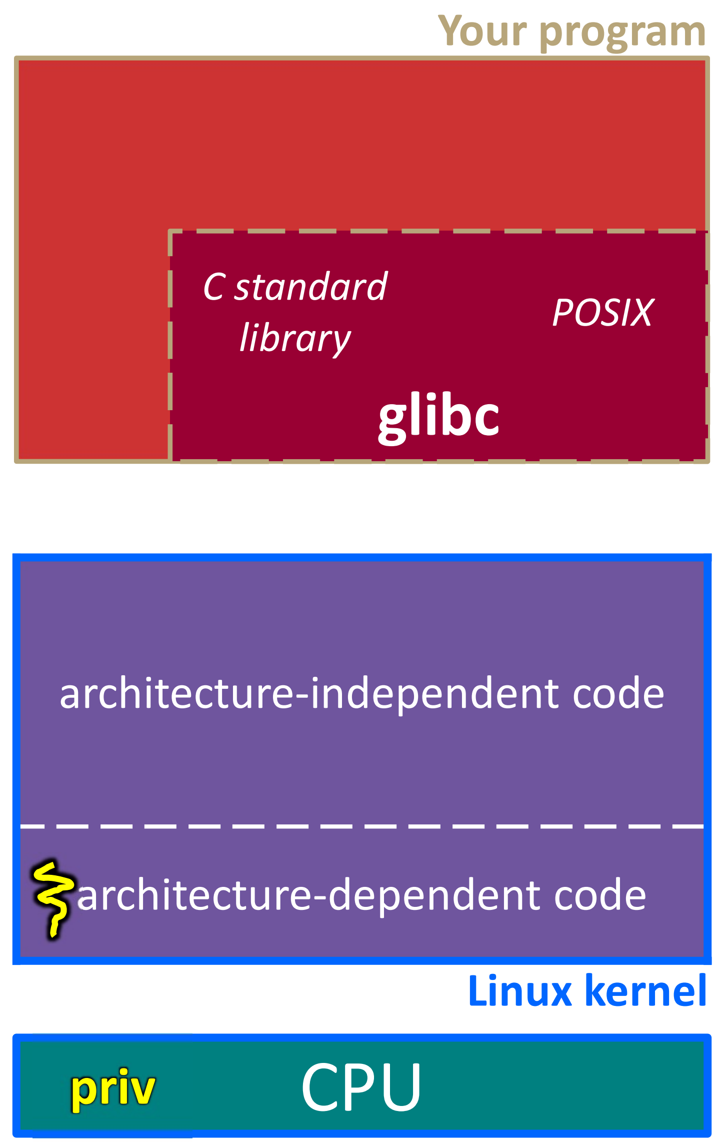


System Calls on x86/Linux

`linux-gate.so` eventually invokes the `SYSENTER` x86 instruction

- `SYSENTER` is x86's "fast system call" instruction
  - Causes the CPU to raise its privilege level
  - Traps into the Linux kernel by changing the SP, IP to a previously-determined location
  - Changes some segmentation-related registers (see CSE451)

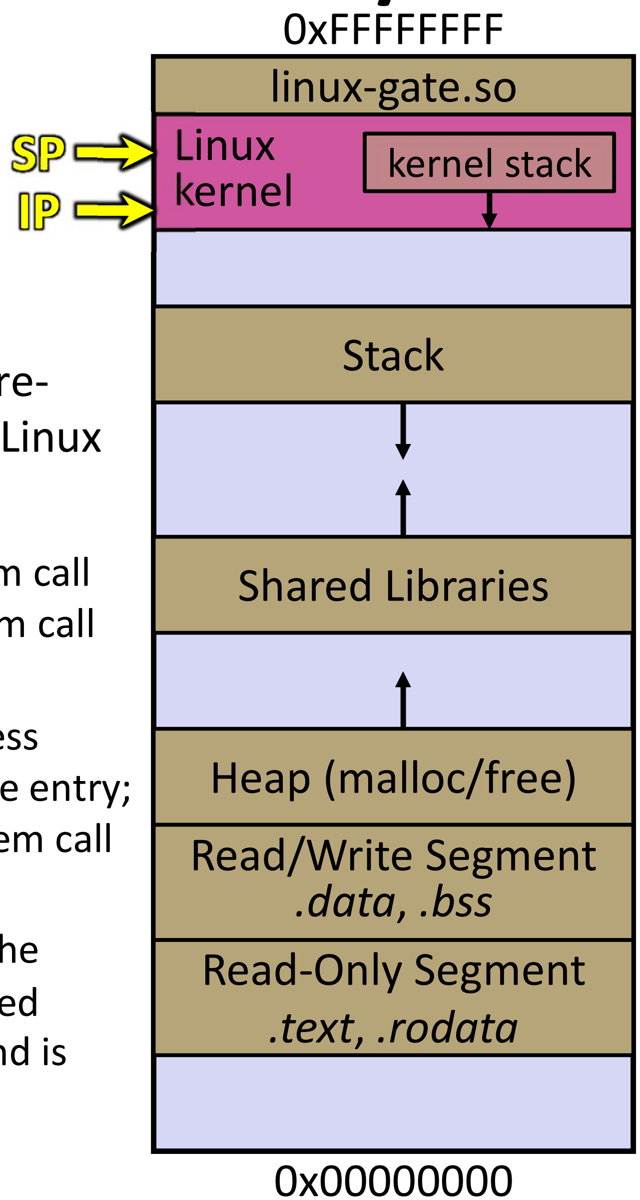


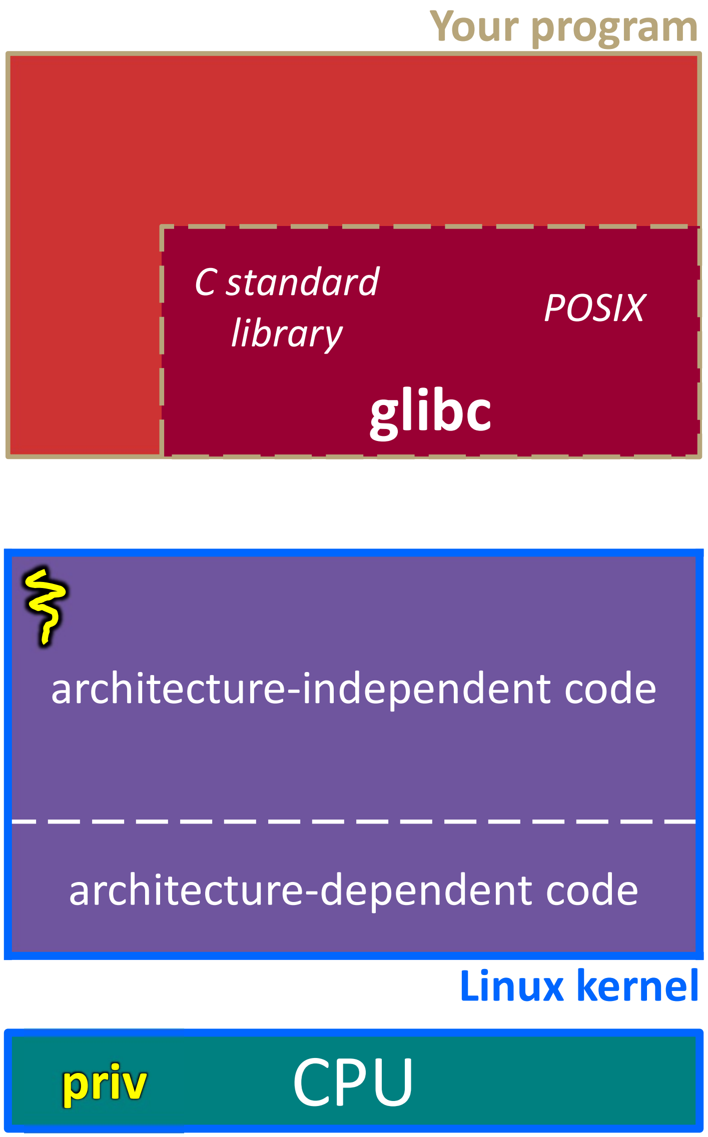


System Calls on x86/Linux

The kernel begins executing code at the `SYSENTER` entry point

- Is in the architecture-dependent part of Linux
- It's job is to:
  - Look up the system call number in a system call dispatch table
  - Call into the address stored in that table entry; this is Linux's system call handler
    - For `open()`, the handler is named `sys_open`, and is system call #5

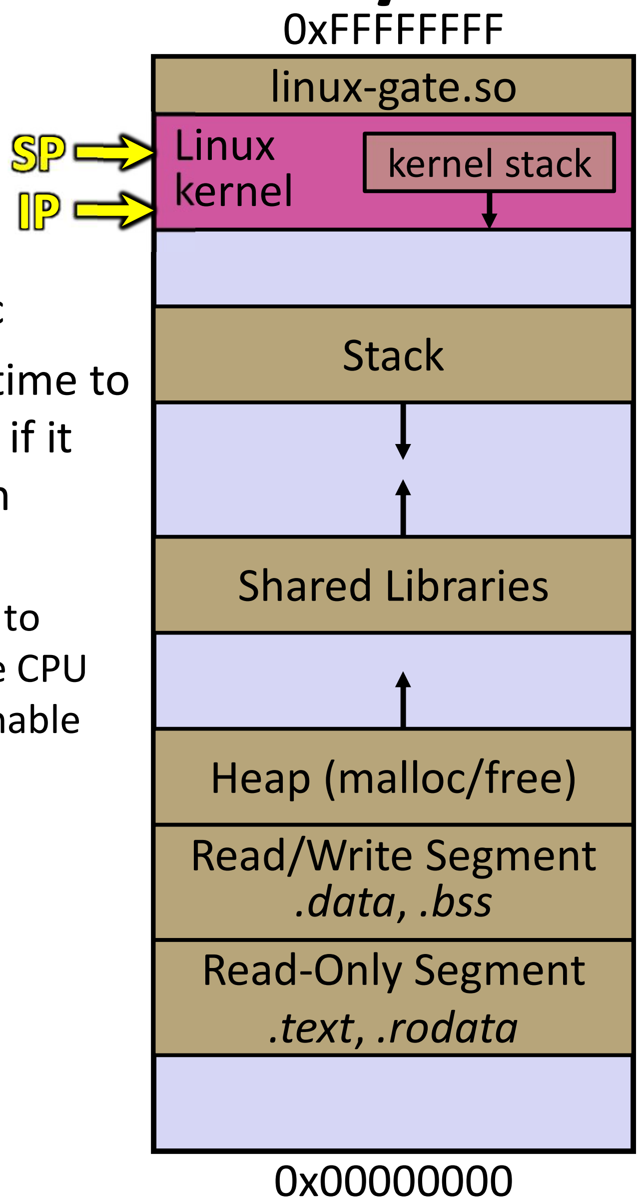


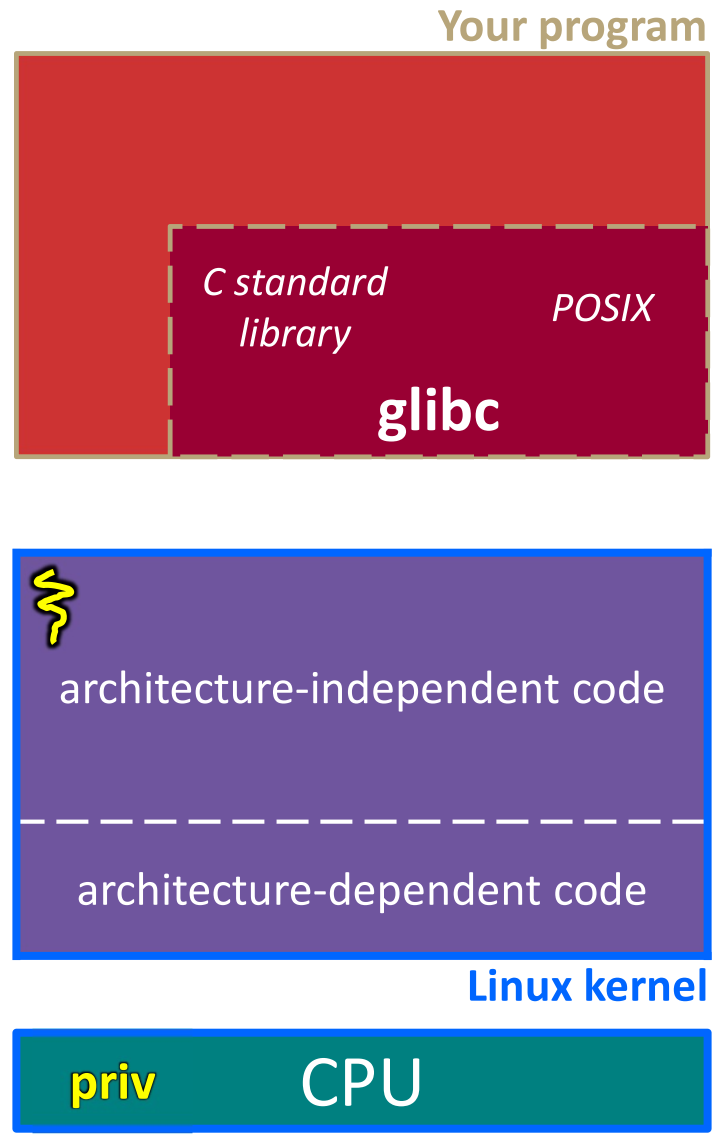


System Calls on x86/Linux

The system call handler executes

- What it does is system-call specific
- It may take a long time to execute, especially if it has to interact with hardware
  - Linux may choose to context switch the CPU to a different runnable process

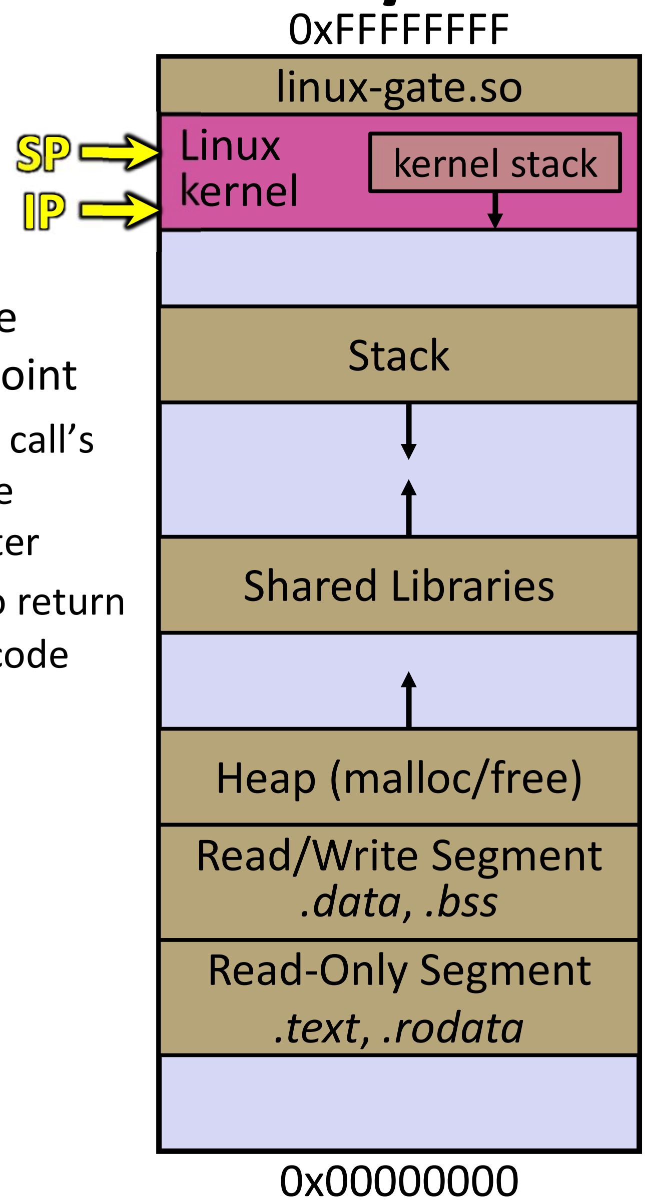


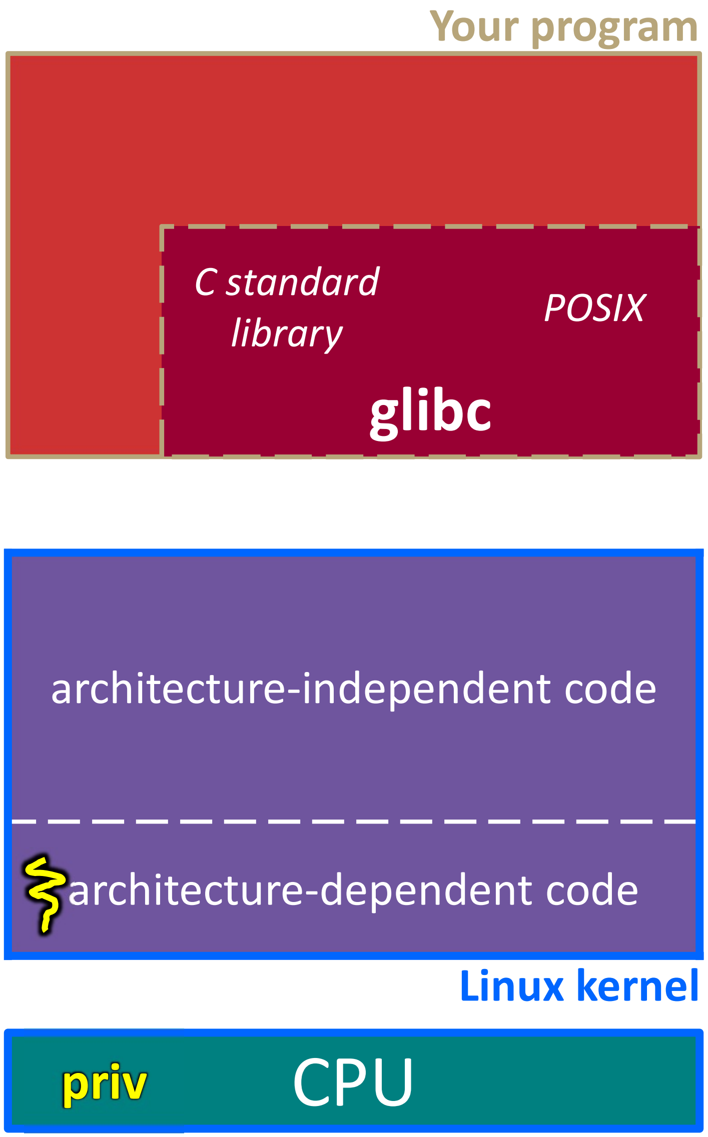


System Calls on x86/Linux

Eventually, the system call handler finishes

- Returns back to the system call entry point
  - Places the system call's return value in the appropriate register
  - Calls `SYSEXIT` to return to the user-level code

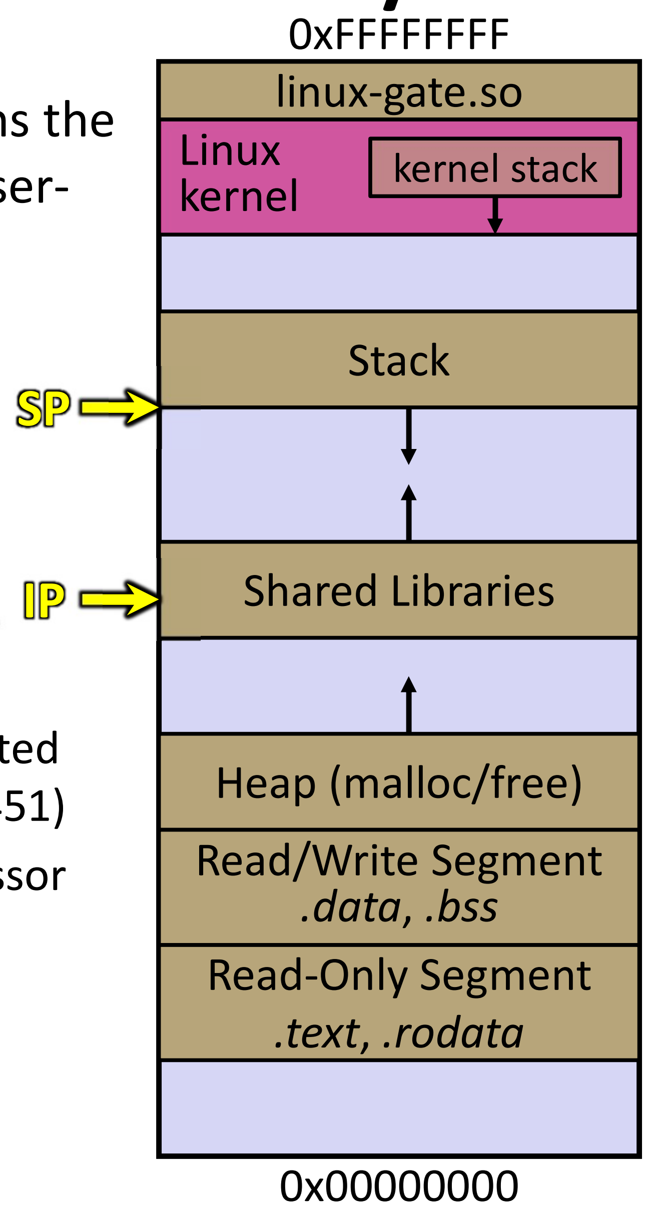


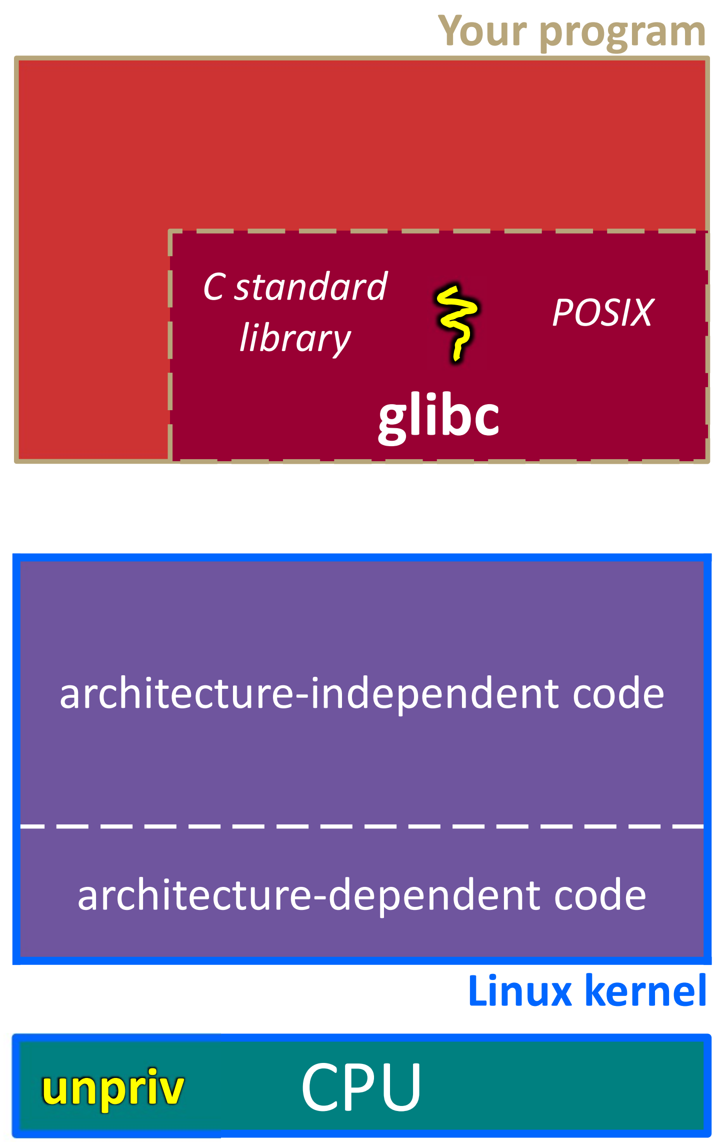


System Calls on x86/Linux

`SYSEXIT` transitions the processor back to user-mode code

- Restores the IP, SP to user-land values
- Sets the CPU back to unprivileged mode
- Changes some segmentation-related registers (see CSE451)
- Returns the processor back to `glibc`

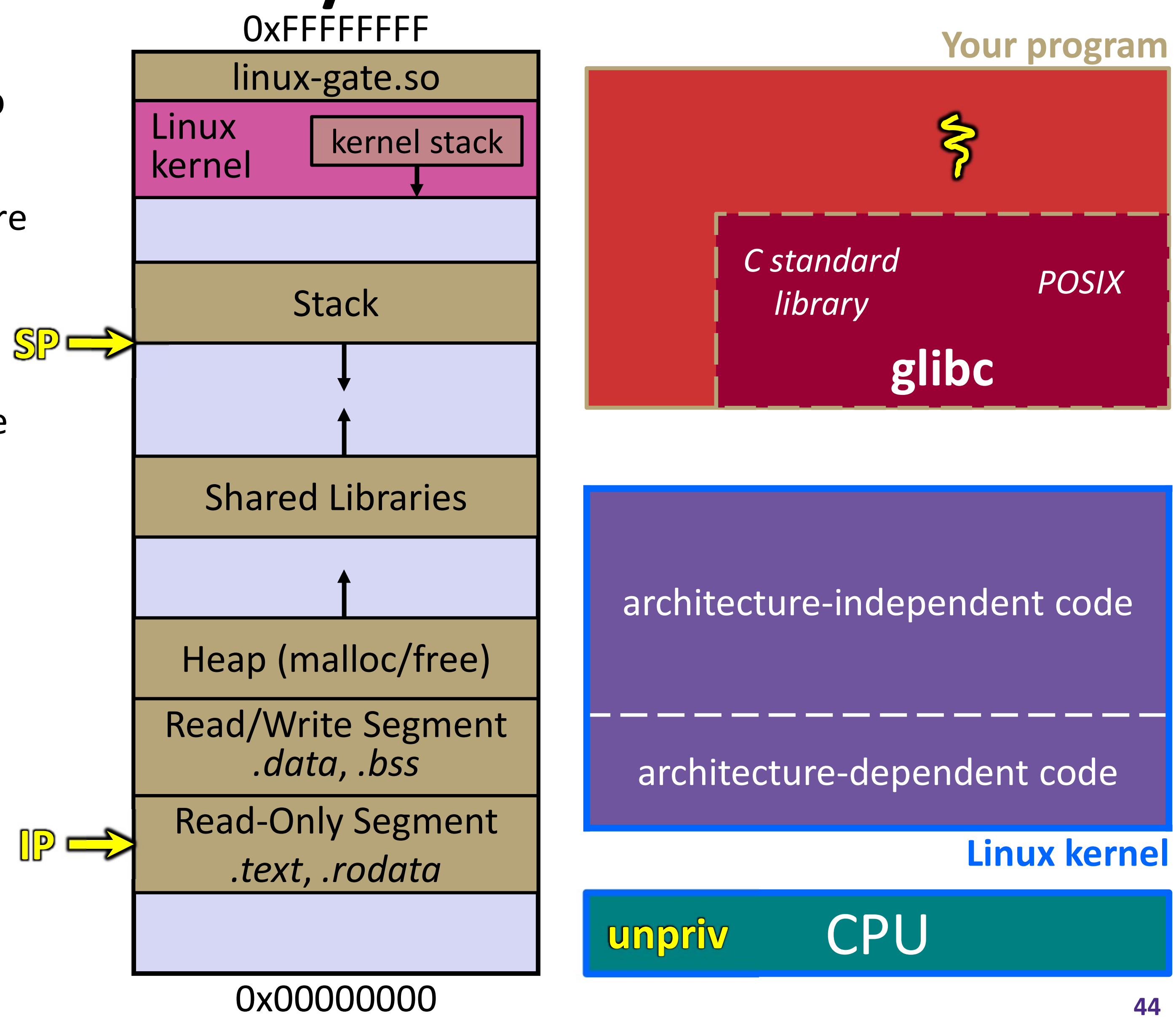




System Calls on x86/Linux

`glibc` continues to execute

- Might execute more system calls
- Eventually returns back to your program code



System Calls - Simplified Version

- The OS is a super complicated program "Overseer" program for the computer.
  - It is the only software that is directly trusted with Hardware access
- If a user process wants to access an OS feature, they must invoke a system call
  - A system call involves context-switching into the OS, which has some overhead
  - The OS will handle hardware/special functionality directly, user processes will not touch anything themselves. User process will wait for OS to finish
  - OS will eventually finish, return result to user, and context switch back

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.

strace

- A useful Linux utility that shows the sequence of system calls that a process makes:

```
bash$ strace ls 2>&1 | less
execve("/usr/bin/ls", ["ls"], [/* 41 vars */]) = 0
brk(NULL)                               = 0x15aa000
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
  0x7f03bb741000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=126570, ...}) = 0
mmap(NULL, 126570, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f03bb722000
close(3)                                = 0
open("/lib64/libselinux.so.1", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\300j\0\0\0\0\0\0"...,
  832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=155744, ...}) = 0
mmap(NULL, 2255216, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) =
  0x7f03bb2fa000
mprotect(0x7f03bb31e000, 2093056, PROT_NONE) = 0
mmap(0x7f03bb51d000, 8192, PROT_READ|PROT_WRITE,
  MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x23000) = 0x7f03bb51d000
... etc ...
```

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)