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About how long did Exercises 4 and 6 take you? (two polls)

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

Systems Programming
Buffering, POSIX I/O, System Calls

Instructors:

Amber Hu Justin Hsia

Teaching Assistants:

Ally Tribble Blake Diaz Connor Olson
Grace Zhou Jackson Kent Janani Raghavan
Jen Xu Jessie Sun Jonathan Nister
Mendel Carroll Rose Maresh Violet Monserate

Relevant Course Information

- Exercise 7 posted today, due Monday (1/26)
  - Given extra time because HW1 is due
- Grades through Exercise 4 are released
  - Style grading will get stricter, minor issues upgraded to major
- Homework 1 due Thursday night (1/22)
  - Clean up "to do" comments, but leave "STEP #" markers
  - Graded not just on correctness, also code quality (**50/50**)
  - OHs Thursday may go late; check Ed discussion board
  - Late days counted based on tag commit time; weekend is one day
- Homework 2 released on Friday
  - Partner declaration form and matching form are released

Lecture Outline (1/3)

- **C Stream Buffering**
- POSIX Lower-Level I/O
- System Calls (High-Level View)

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

```
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;
}
```

buffered_hi.c

C stdio buffer

'h'	'i'	…

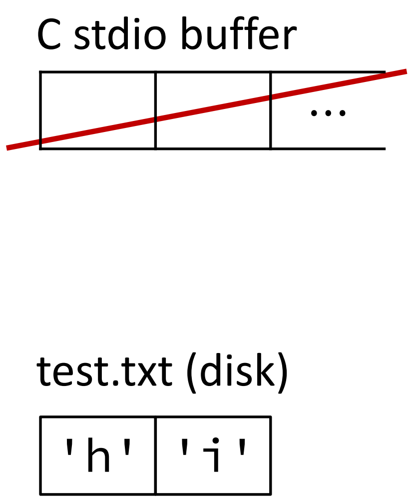
test.txt (disk)

'h'	'i'

No Buffering Example

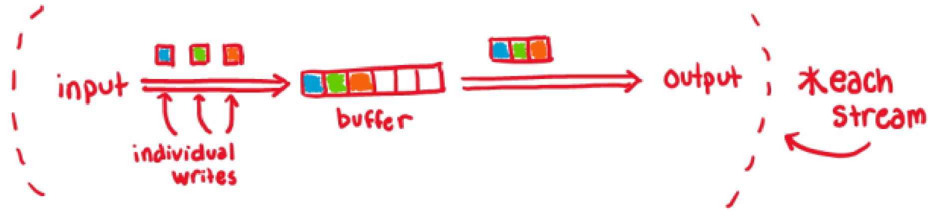
```
int main(int argc, char** argv) {
  FILE* fout = fopen("test.txt", "wb");
  setbuf(fout, NULL); // turn off buffering

  // 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;
}
```

unbuffered_hi.c



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
  - Writing to a buffer (*i.e.*, return from `fwrite()`) does not mean the data has actually been written to the file/console
    - Segfaults leave buffered data unflushed

- 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"*)

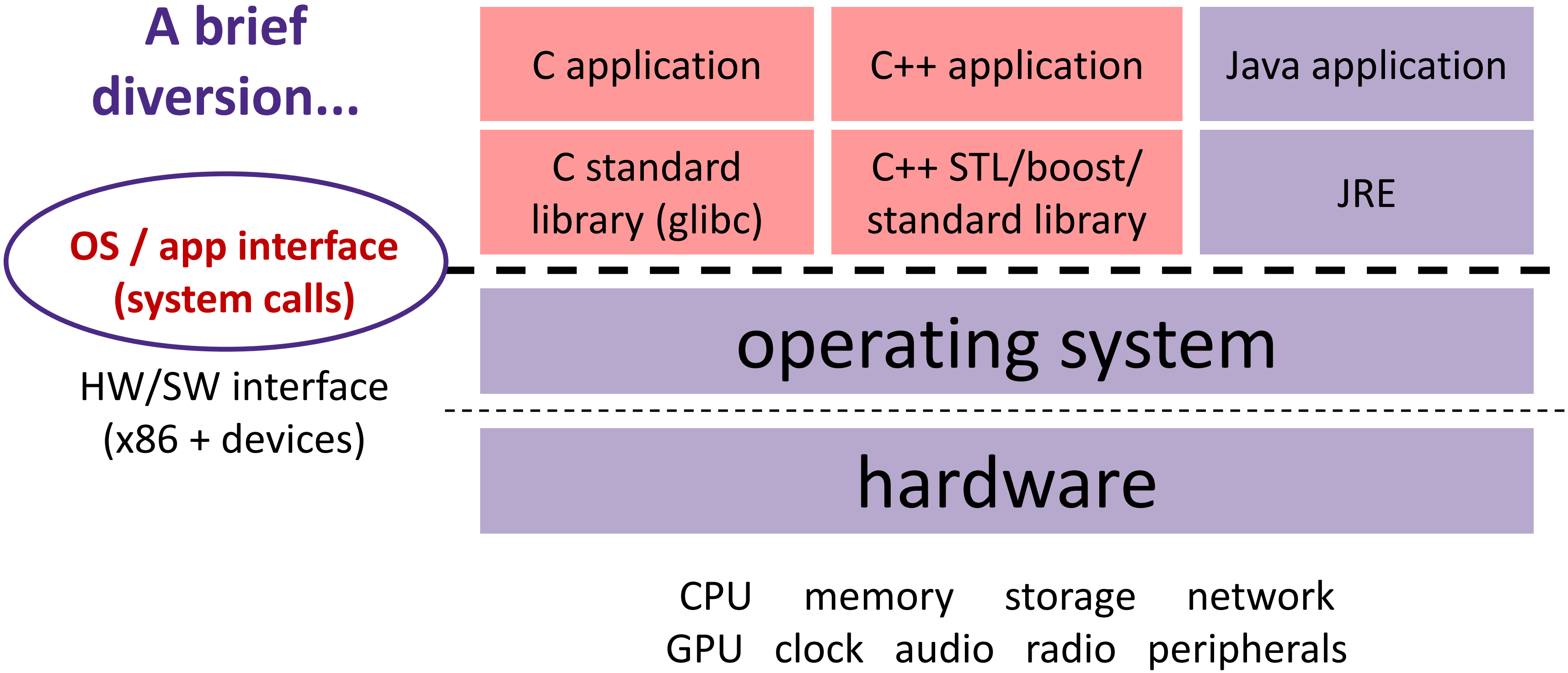
- When is buffering faster? Slower?

Lecture Outline (2/3)

- C Stream Buffering
- **POSIX Lower-Level I/O**
- System Calls (High-Level View)

Remember This Picture?

A brief diversion...



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 (by default, can be disabled)
  - They are implemented using lower-level OS calls

From C to POSIX

- Most UNIX-like OS support a common set of lower-level 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
  - You will have to use these to read file system directories and for network I/O, so we might as well learn them now
    - These are functionalities that C stdio *doesn't* provide!

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`
    - **-1** indicates an 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);
```

- Open descriptors: **0** (`stdin`), **1** (`stdout`), **2** (`stderr`)

Reading from a File

- `ssize_t read(int fd, void* buf, size_t count);`
  - Advances forward in the file by number of bytes read
- 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`)
- There are some surprising error modes (check `errno`)
- `EBADF`: bad file descriptor
- `EFAULT`: output buffer is not a valid address
- `EINTR/EAGAIN`: read was interrupted, please try again (ARG! 😠)
- And many others…

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We want to read ‘n’ bytes. Which is the correct completion of the blank below?

```c
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…

Other Low-Level Functions

- Read man pages to learn about:
  - `write()` – write data
    - `#include <unistd.h>`
  - `fsync()` – flush disk cache
    - `#include <unistd.h>`
  - `opendir()`, `readdir()`, `closedir()` – deal with directory listings
    - Make sure you read the section 3 version (*e.g.*, `man 3 opendir`)
    - Go to section tomorrow to learn more!
    - `#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 standard library implements a <u>subset of POSIX</u>
  - *e.g.*, POSIX provides directory manipulation that C std lib doesn't
- C standard library implements <u>automatic buffering</u>
- C standard library has a <u>nicer API</u>

- The two are similar but C standard library builds on top of POSIX
  - Choice between high-level and low-level
  - Will depend on the requirements of your application
  - You can use both in Exercise 7!

Lecture Outline (3/3)

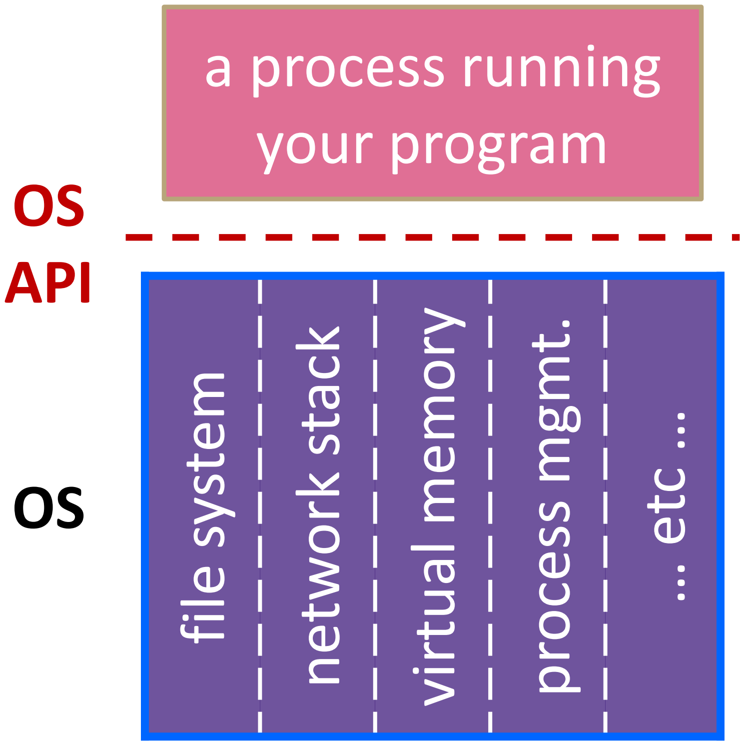
- C Stream Buffering
- POSIX Lower-Level I/O
- **System Calls (High-Level View)**

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
  - Manages (allocates, schedules, protects) hardware resources
    - Decides which programs can access which files, memory locations, pixels on the screen, etc. and when
  - Abstracts away messy hardware devices
    - Provides high-level, convenient, portable abstractions (*e.g.*, files, disk blocks)

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

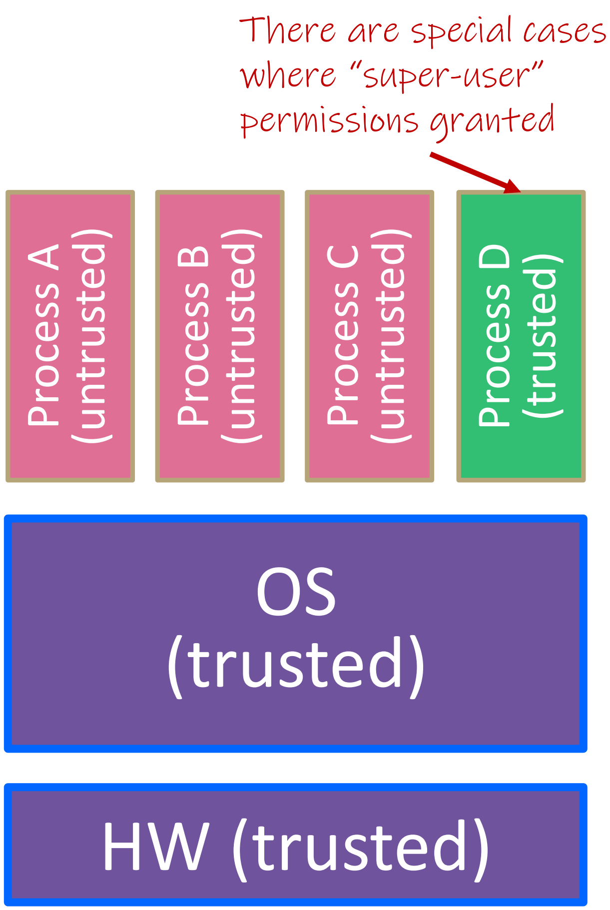
- brk(), shm_open(), …

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 Analogy

- The OS is a bank manager overseeing safety deposit boxes in the vault
  - Is the only one allowed in the vault and has the keys to the safety deposit boxes

- If a client wants to access a deposit box (*i.e.*, add or remove items), they must request that the bank manager do it for them
  - Takes time to locate and travel to box and find the right key
  - Client must wait in the lobby while the bank manager accesses the box – prevents messing with requested box or other boxes
  - Takes time to put box away, return from vault, and let client know that request was fulfilled

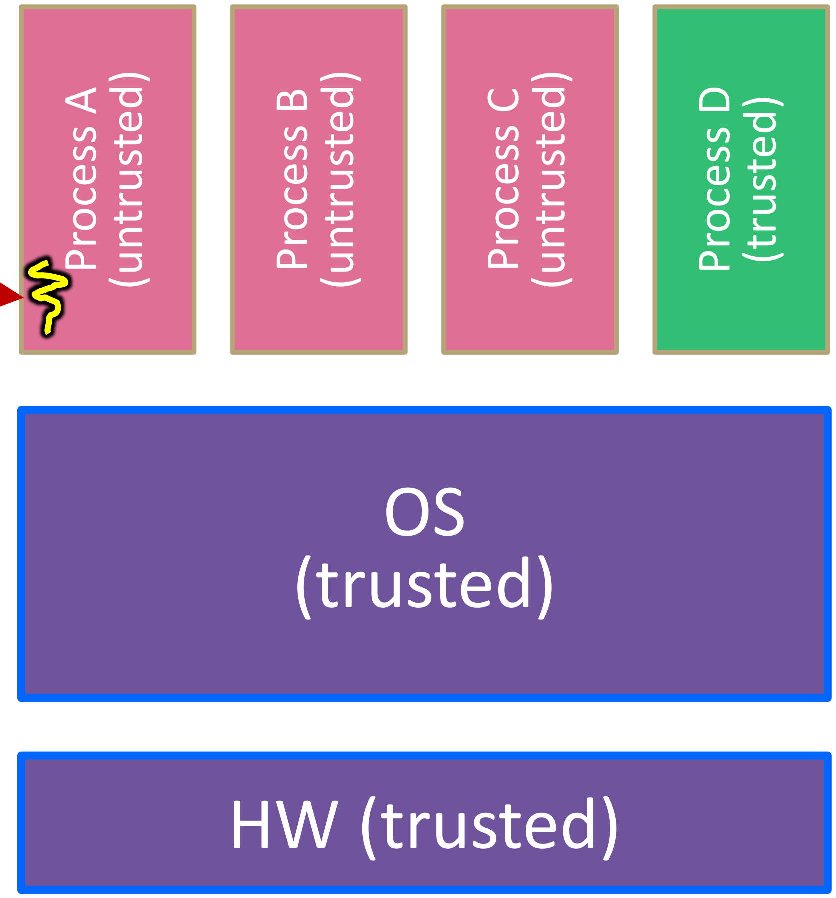
System Calls Simplified Overview

- The operating system (OS) is a super complicated "program overseer" program for the computer
  - 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/kernel, which has some overhead
  - The OS will handle hardware/special functionality directly (in privileged mode) while user processes wait and don't touch anything themselves
  - OS will eventually finish, return result to user process, and context switch back

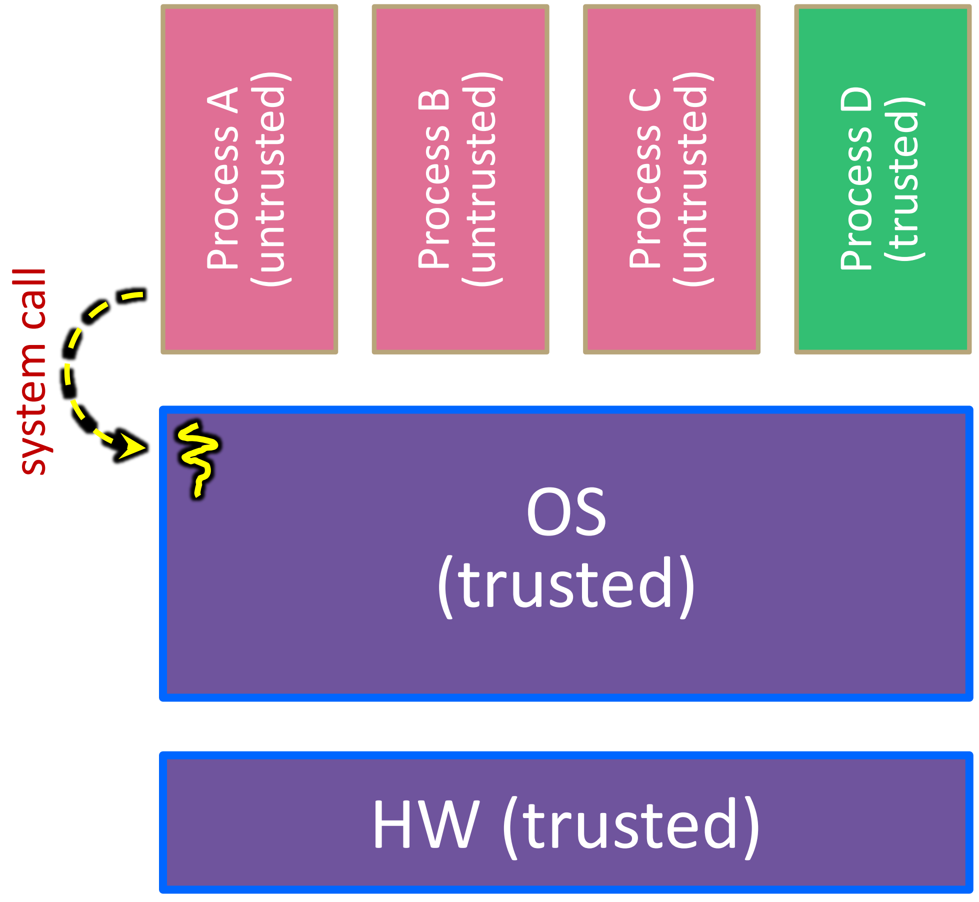
System Call Trace (high-level view, 1/5)

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



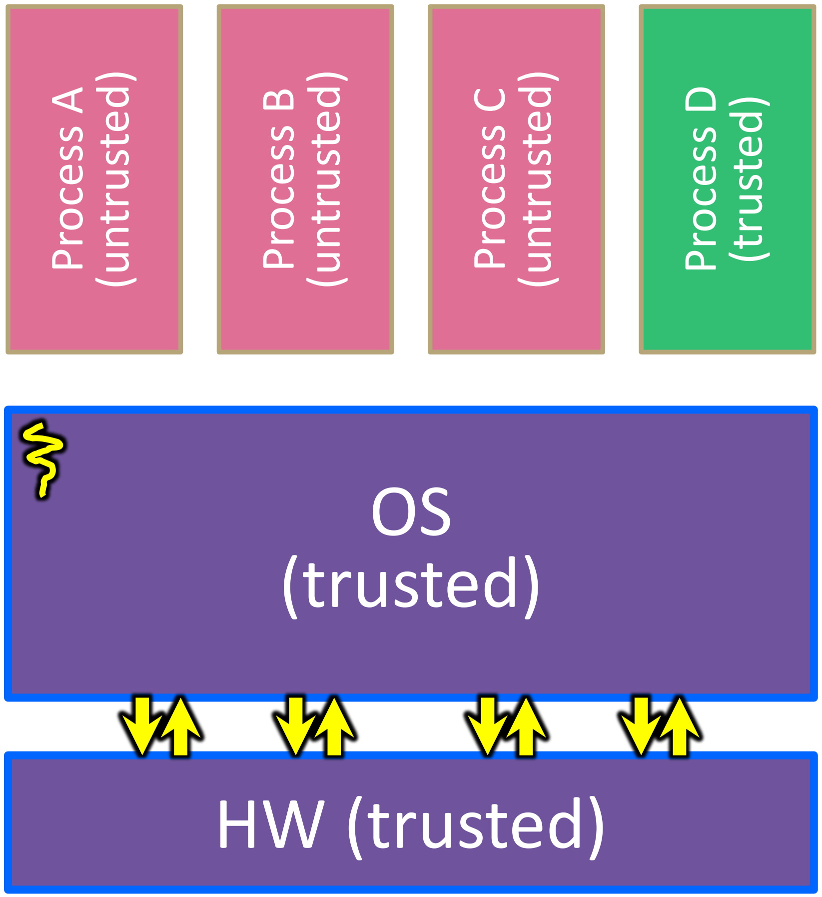
System Call Trace (high-level view, 2/5)

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, 3/5)

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.

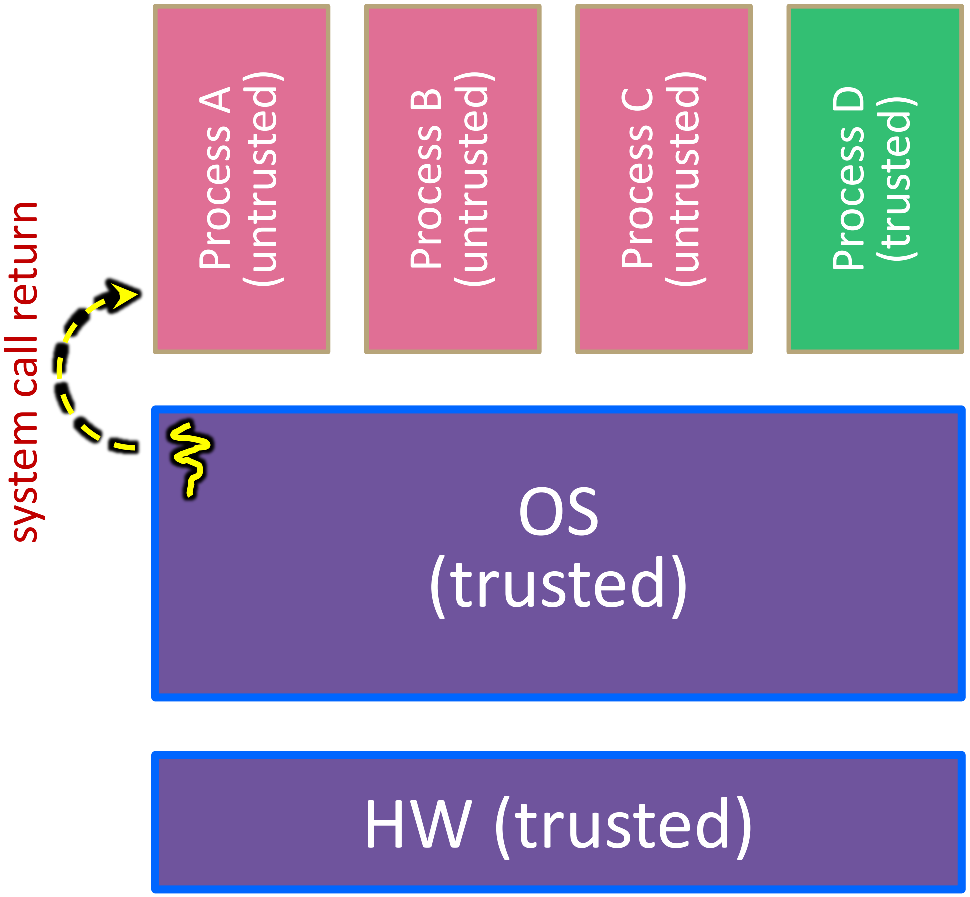


System Call Trace (high-level view, 4/5)

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

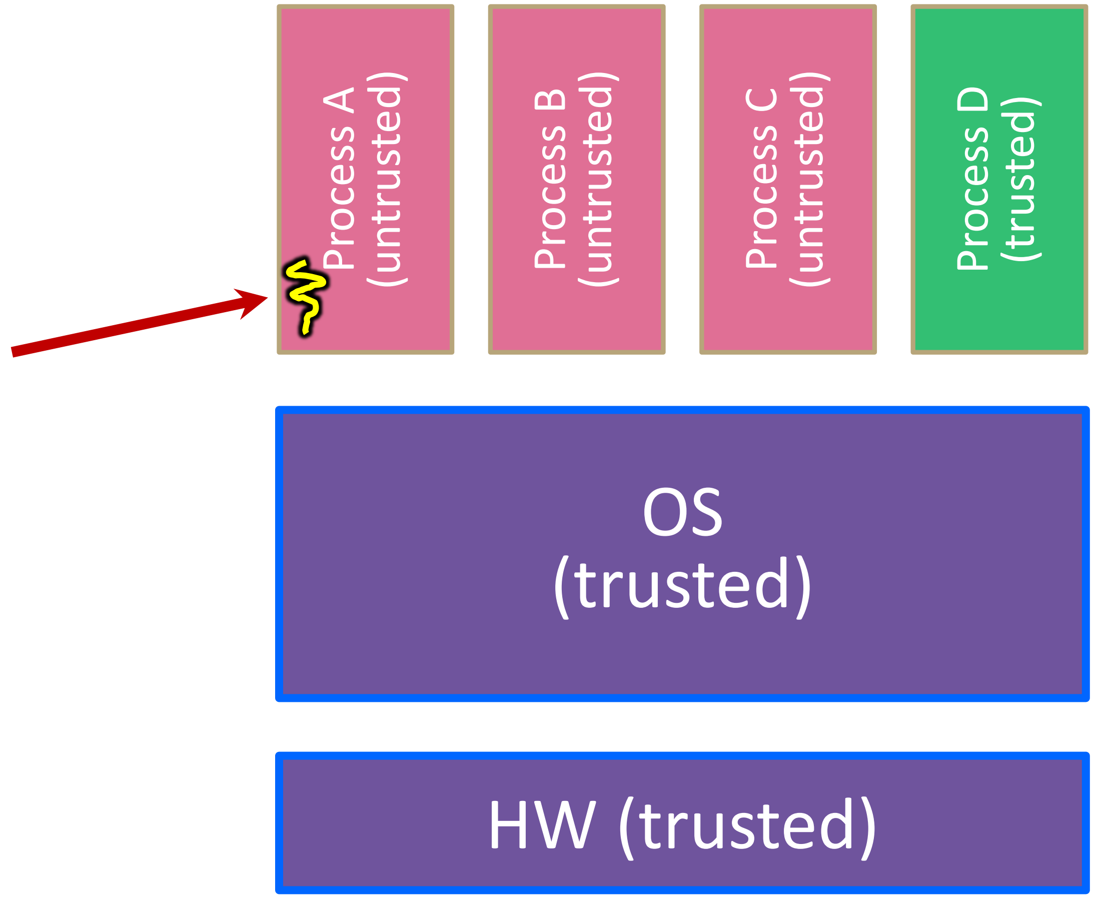
(1) Sets the CPU back to unprivileged mode and

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



System Call Trace (high-level view, 5/5)

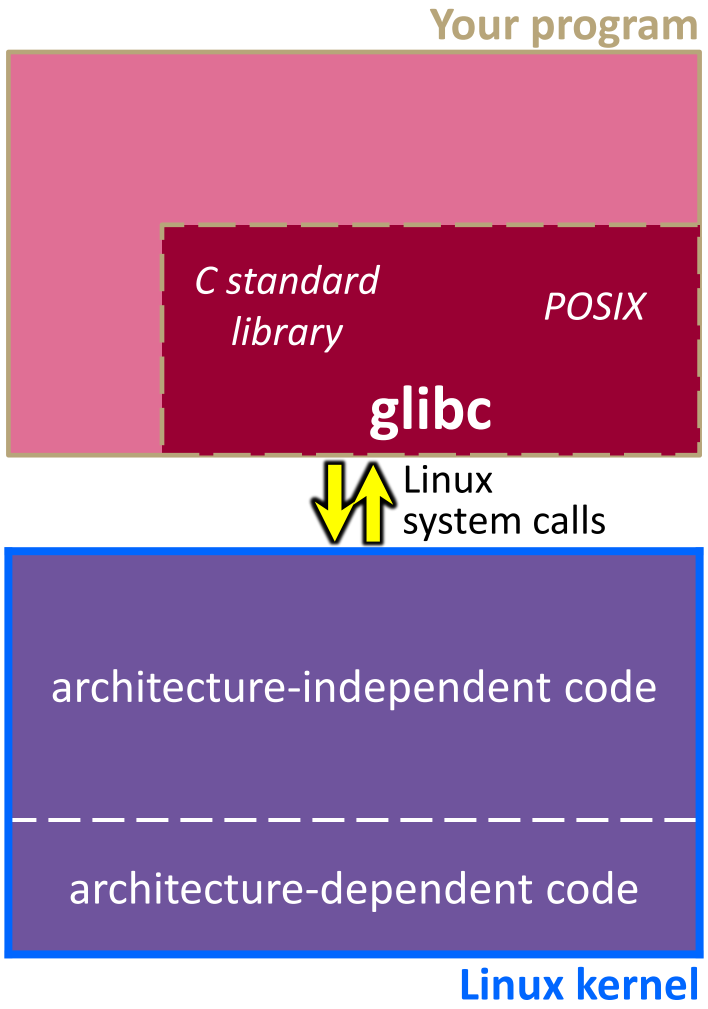
The process continues executing whatever code is next after the system call invocation.



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

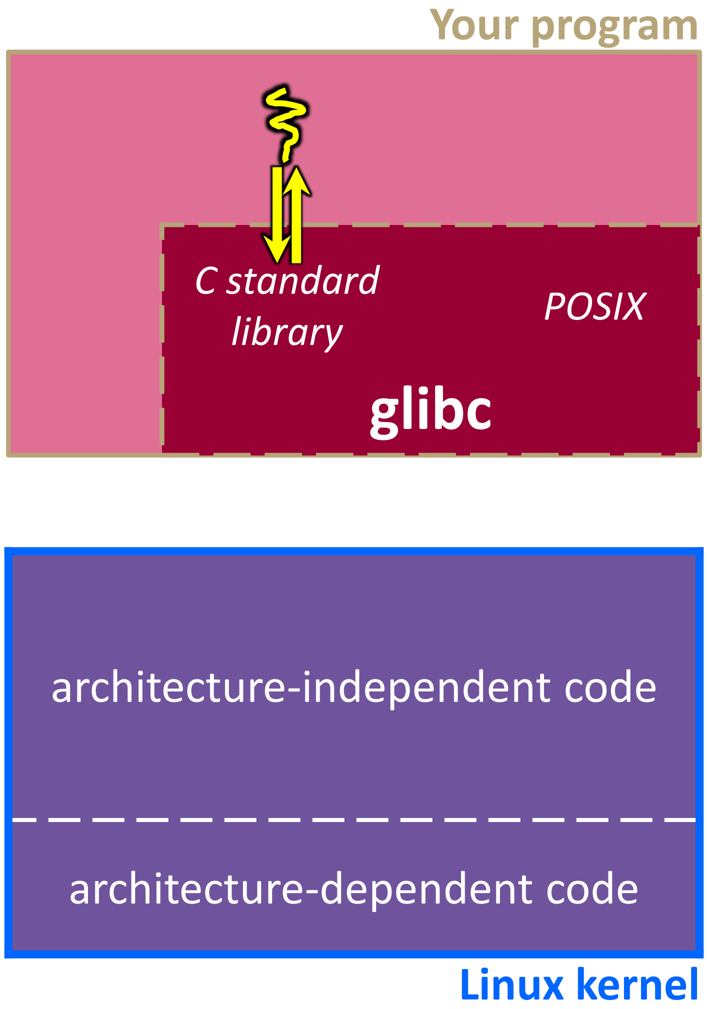
"Library calls" on x86/Linux

- 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



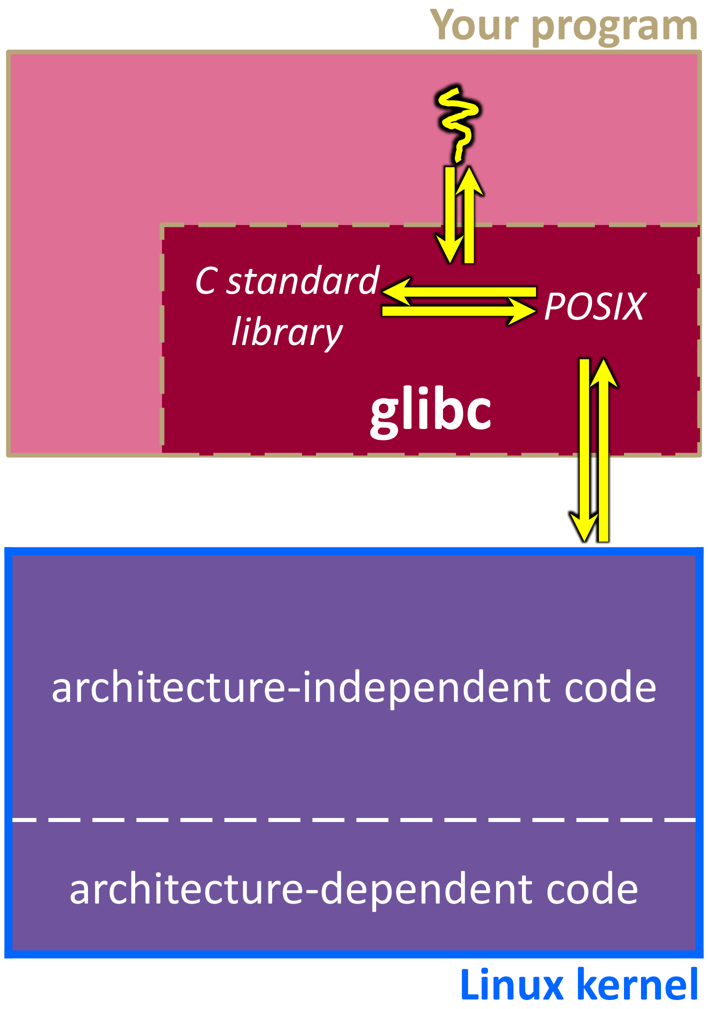
"Library calls" on x86/Linux: Option 1

- 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!



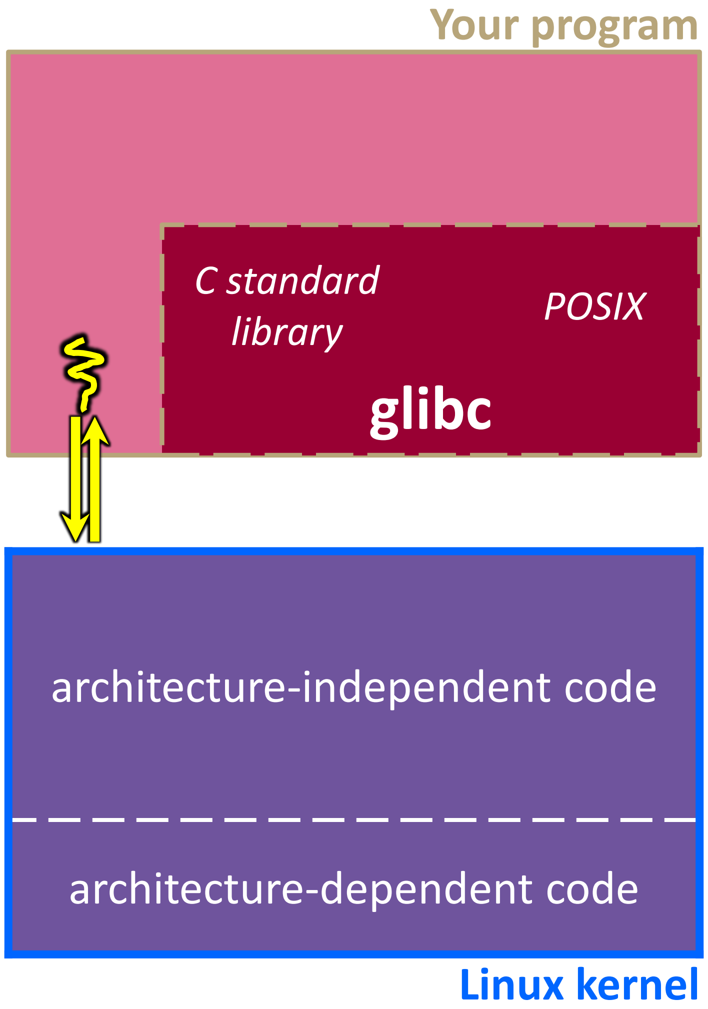
"Library calls" on x86/Linux: Option 2

- 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



strace

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

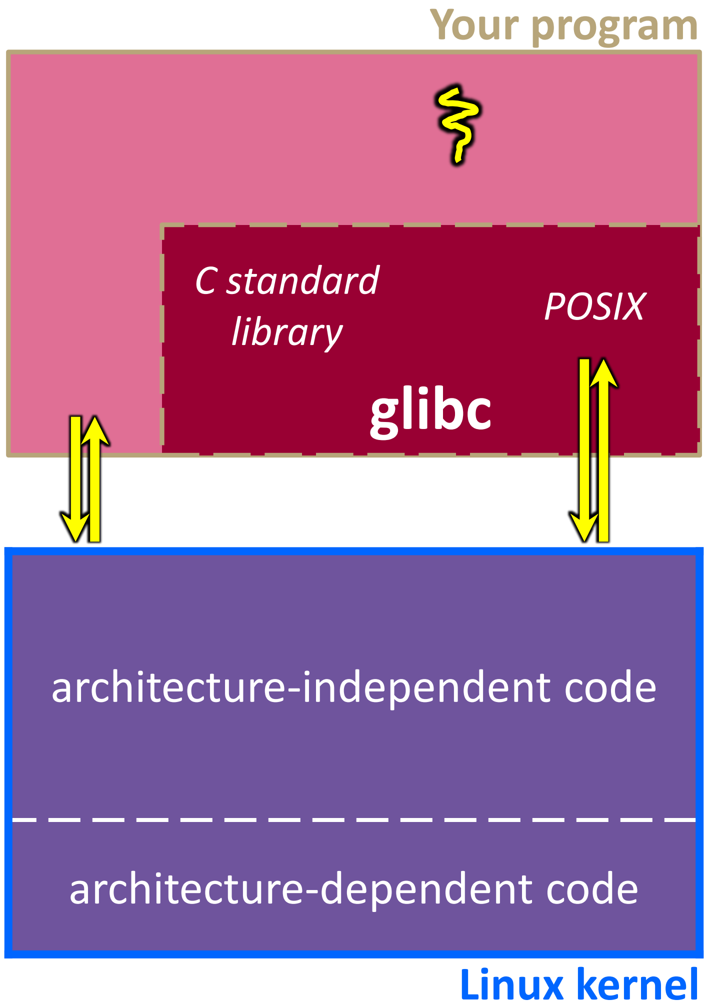
```
$ strace ls 2>&1 | less
execve("/usr/bin/ls", ["ls"], [/* 41 vars */]) = 0
brk(NULL)                                        = 0x15aa000
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
   0x7f03bb741000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or 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 ...
```

BONUS SLIDES

"Story time" about system calls on x86/Linux

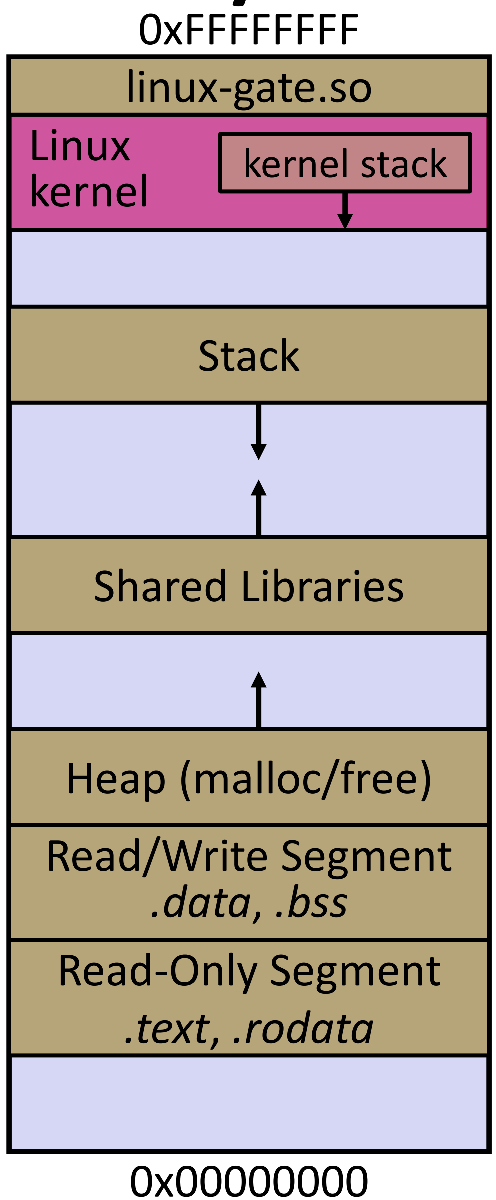
Details on x86/Linux

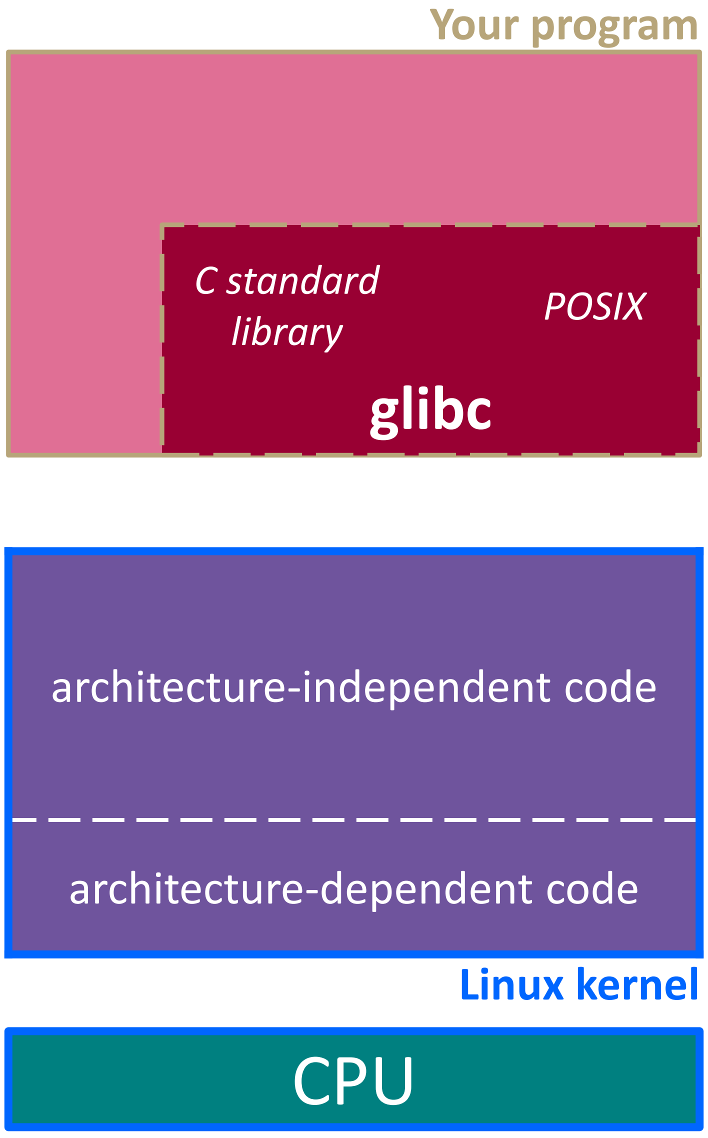
- Let's walk through how a Linux system call actually works
  - We'll assume *32-bit x86* using the modern SYSENTER / SYSEXIT x86 instructions
    - x86-64 code is similar, though details always change over time, so take this as an example – not a debugging guide



System Calls on x86/Linux (1/11)

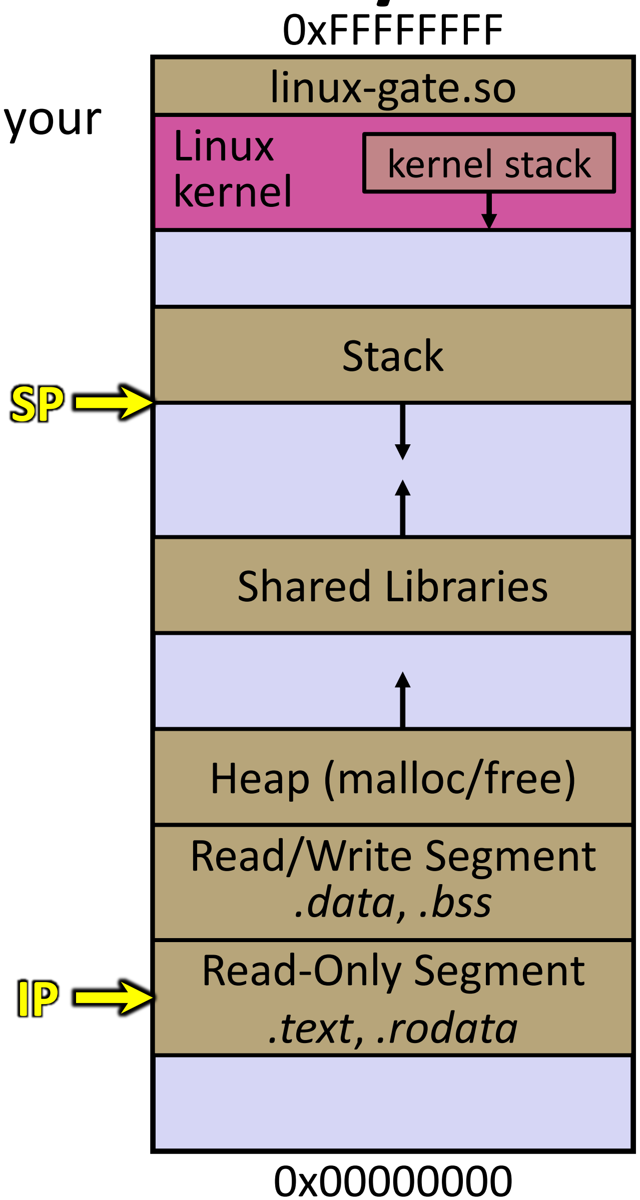
- Remember our process address space picture?
  - Let's add some details:

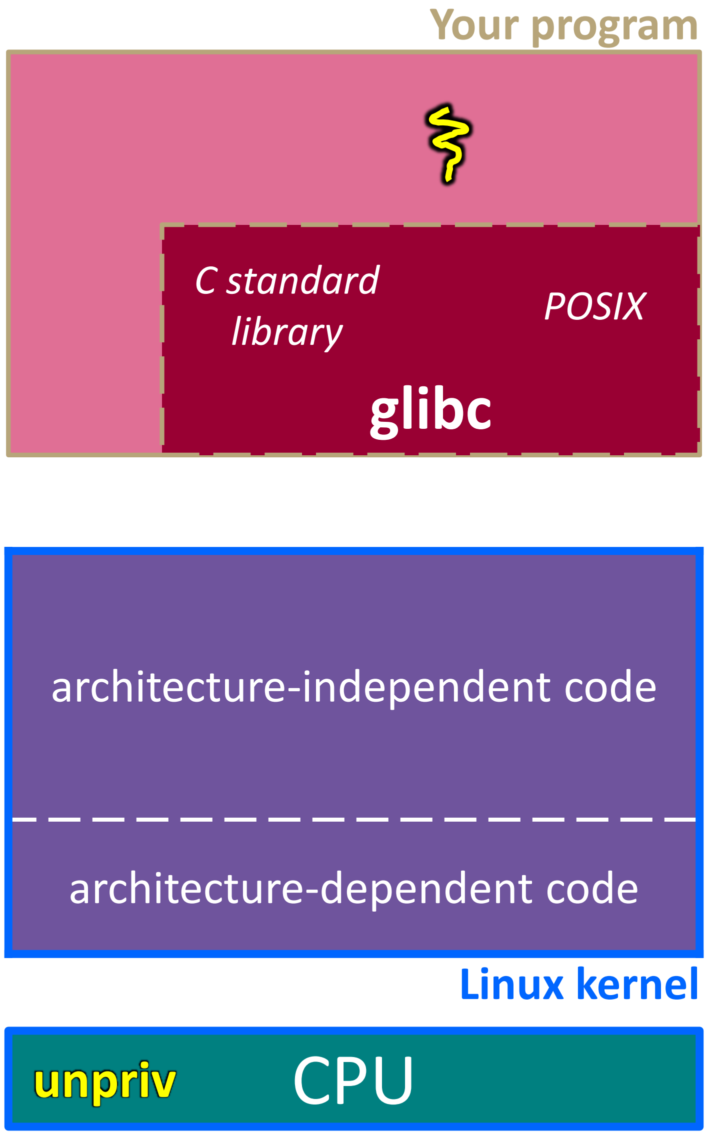




System Calls on x86/Linux (2/11)

Process is executing your program code

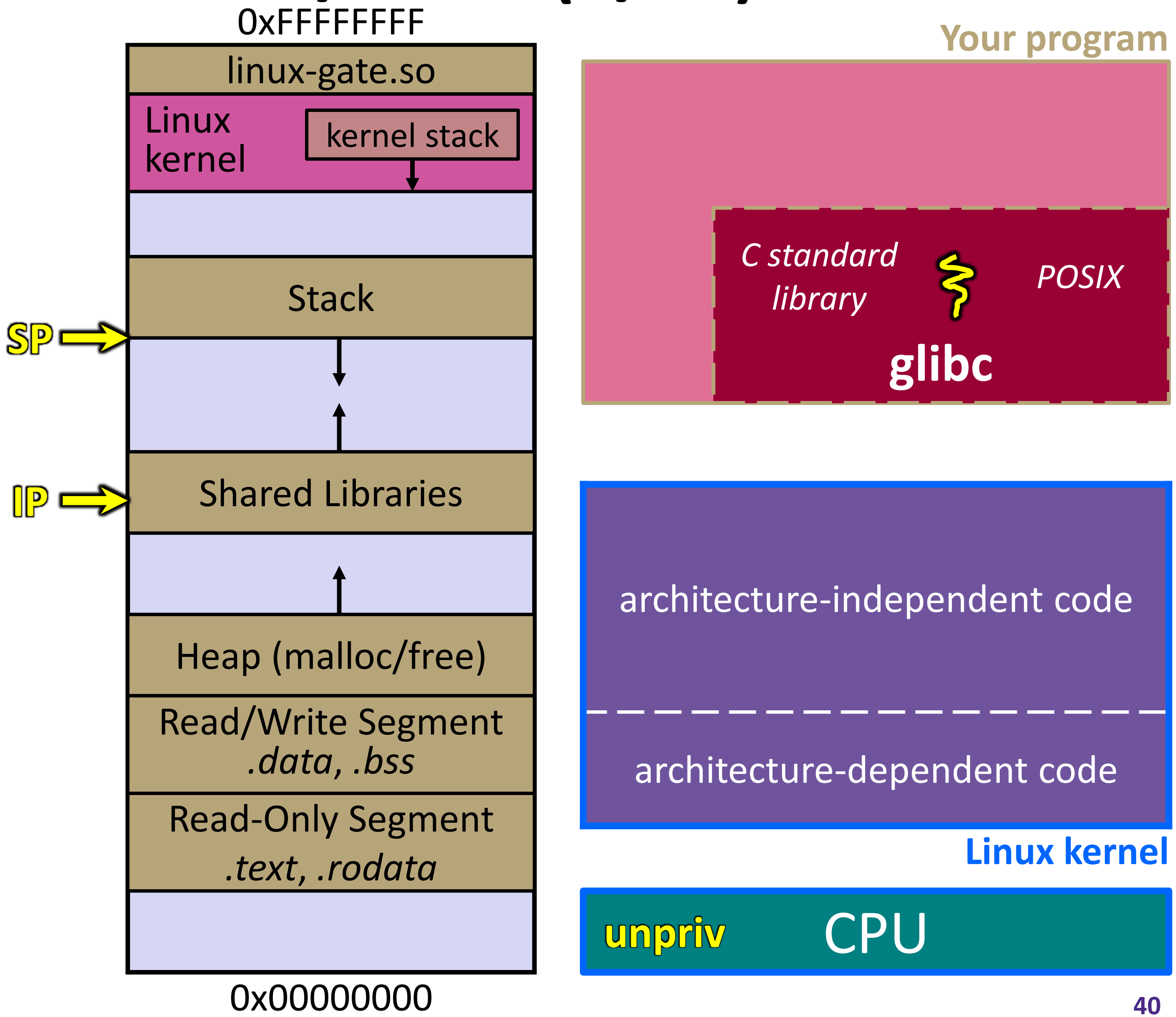




System Calls on x86/Linux (3/11)

Process calls into a `glibc` function

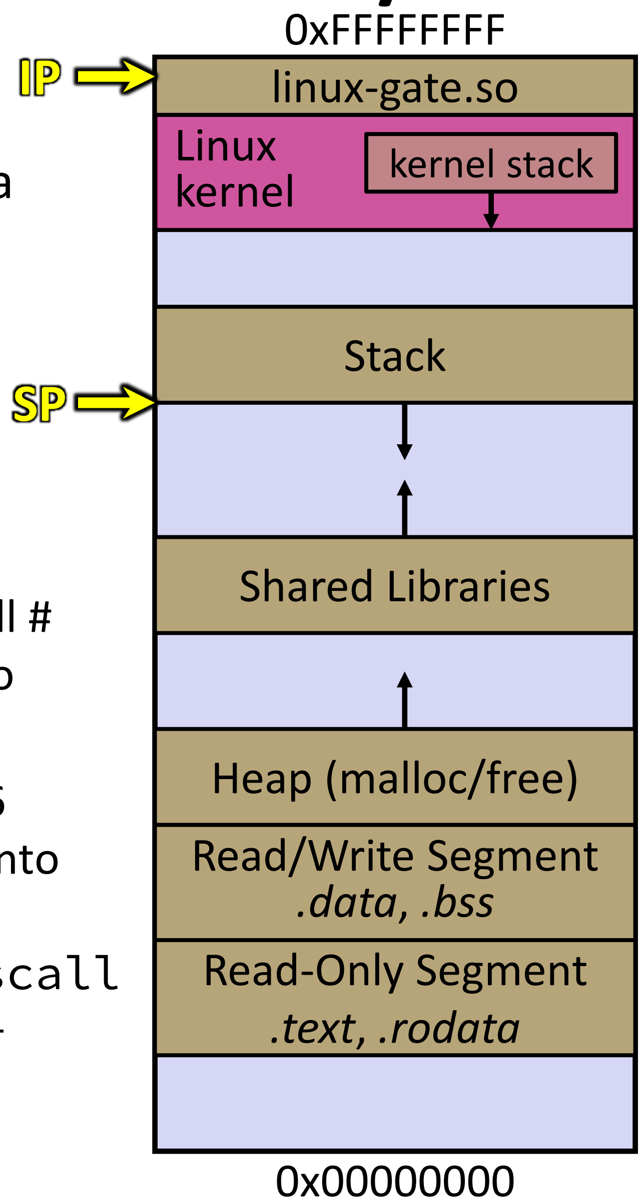
- *e.g.*, **`fopen`**`()`
- We'll ignore the messy details of loading/linking shared libraries

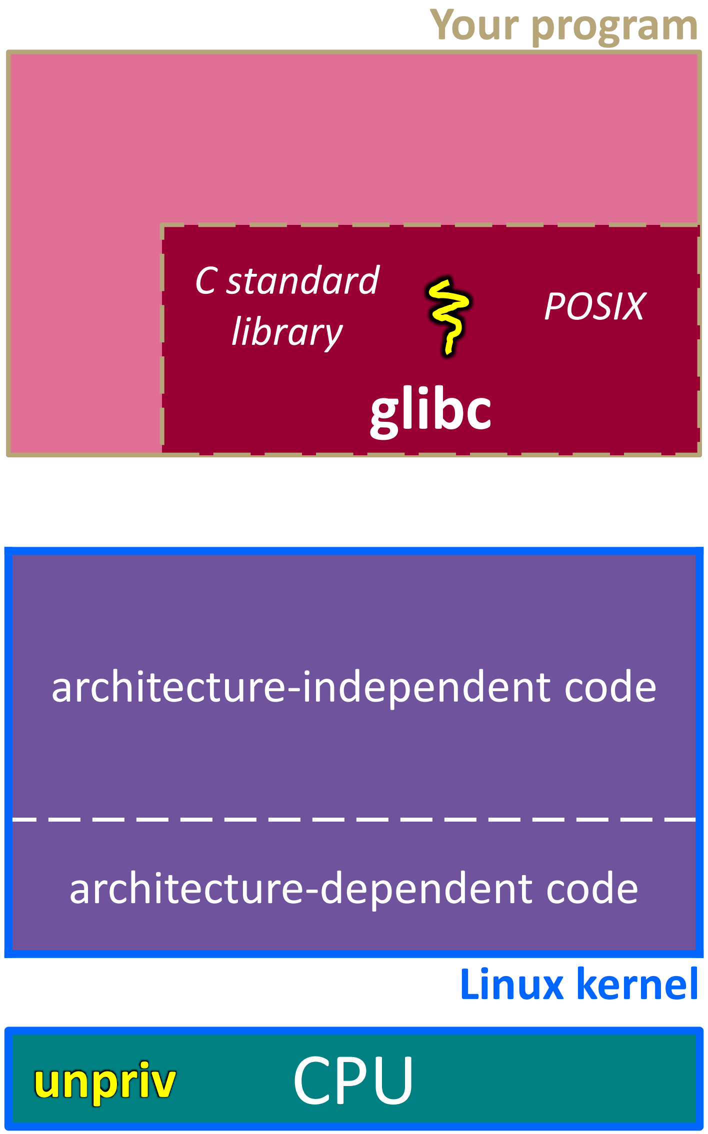


System Calls on x86/Linux (4/11)

`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`

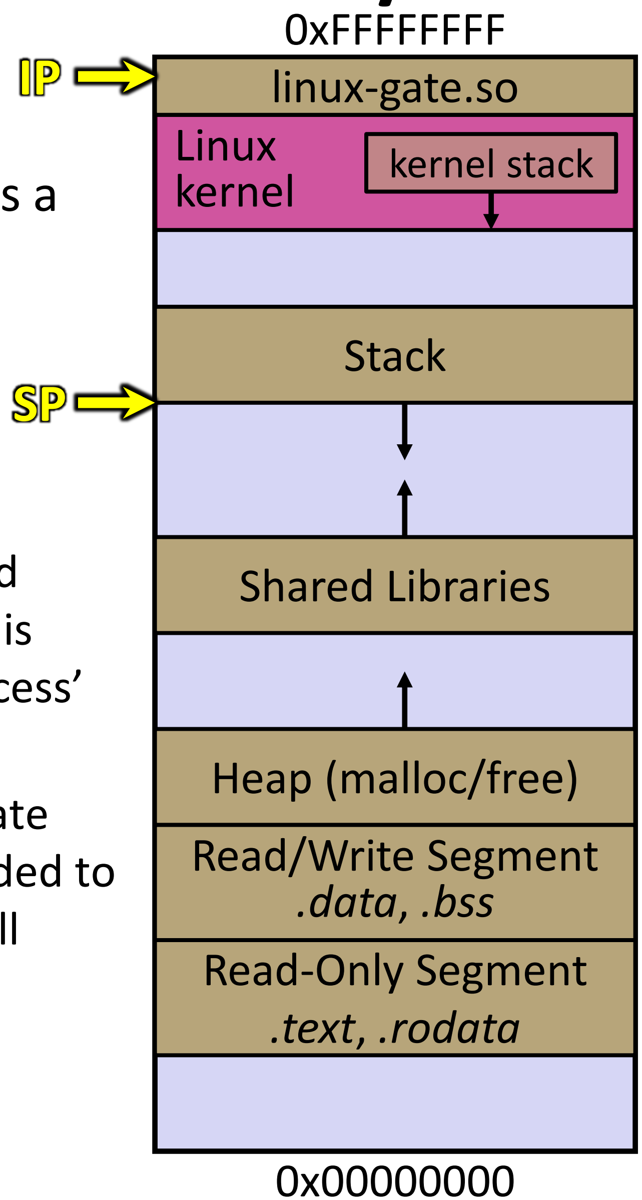


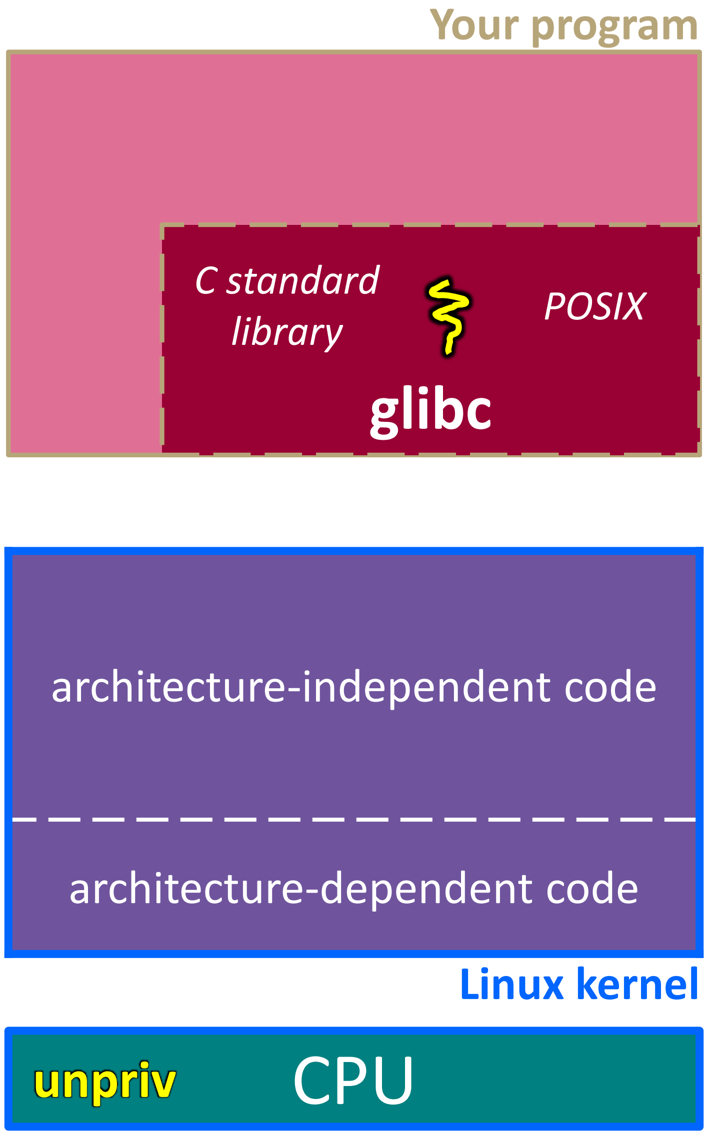


System Calls on x86/Linux (5/11)

`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

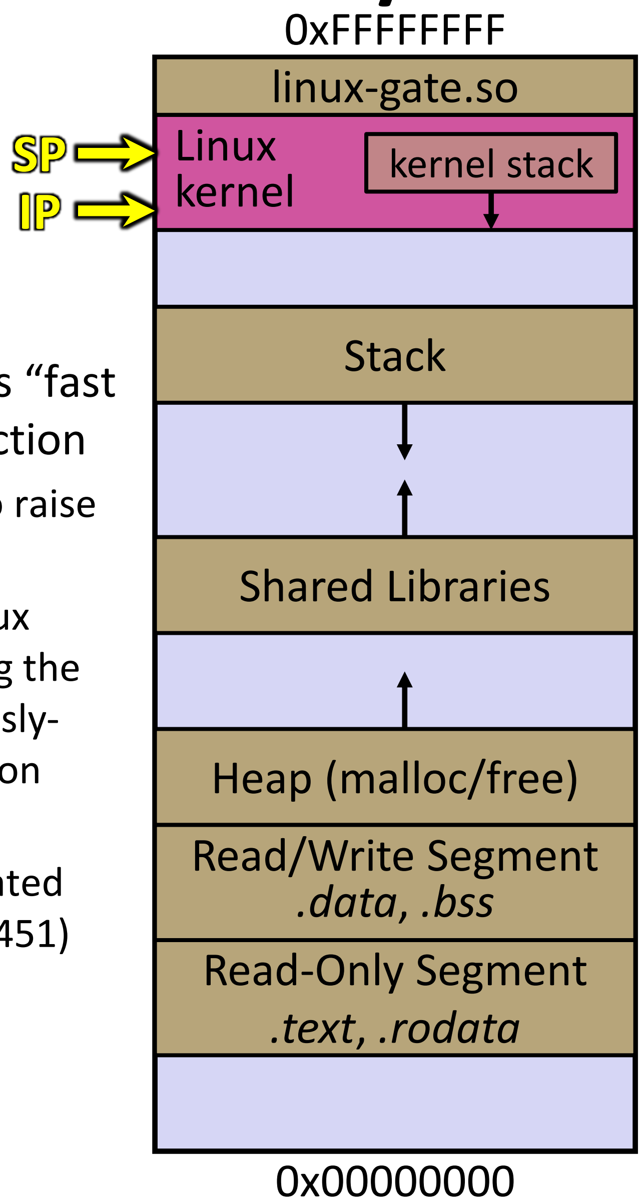


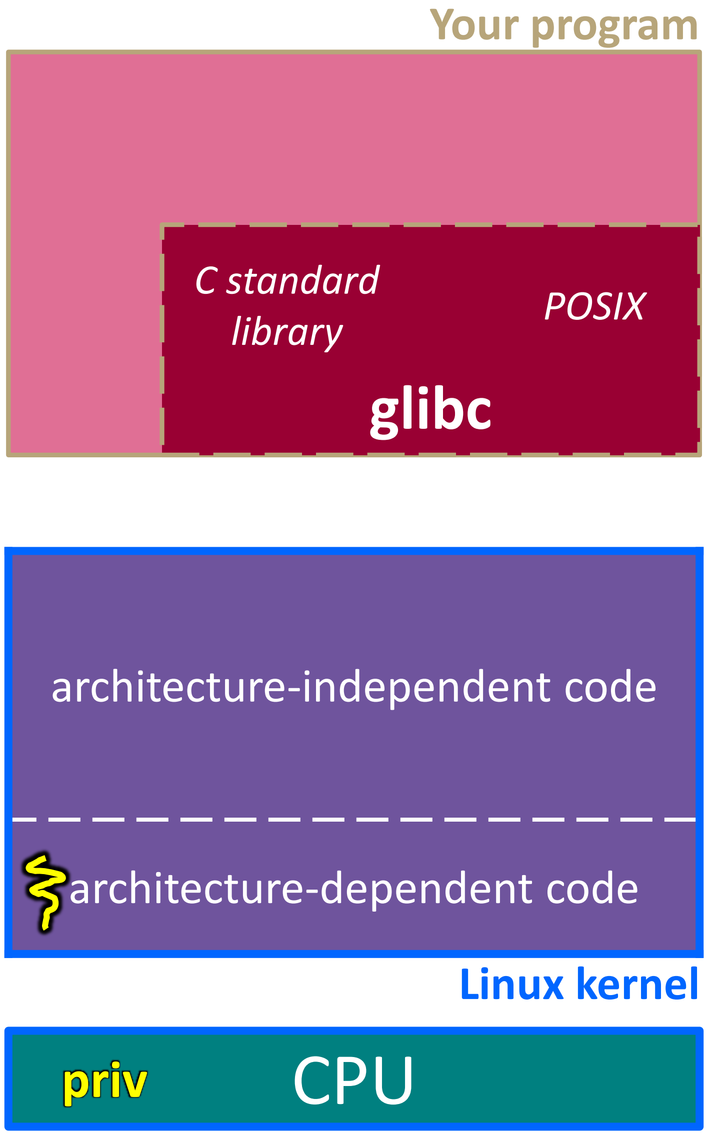


System Calls on x86/Linux (6/11)

`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)

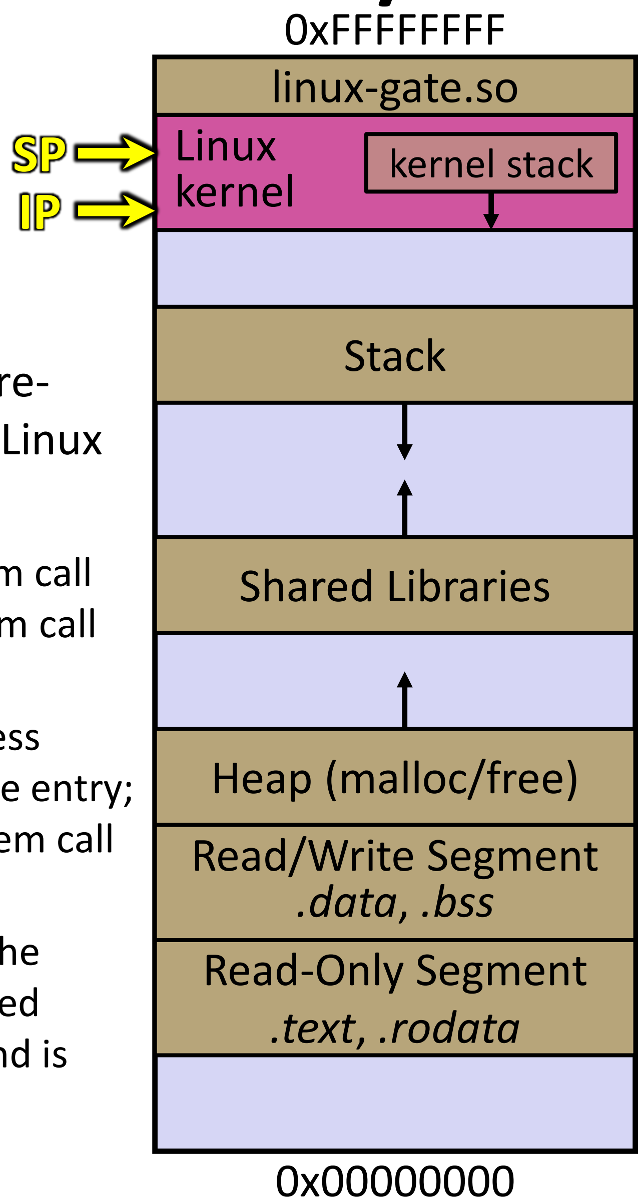


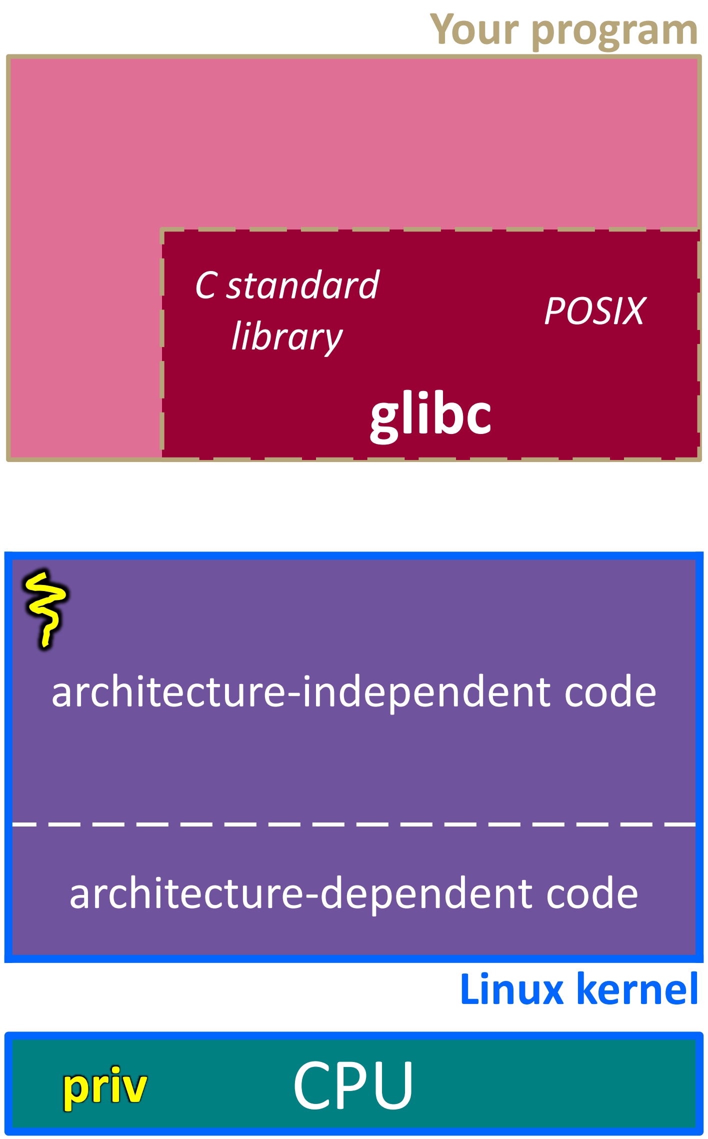


System Calls on x86/Linux (7/11)

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

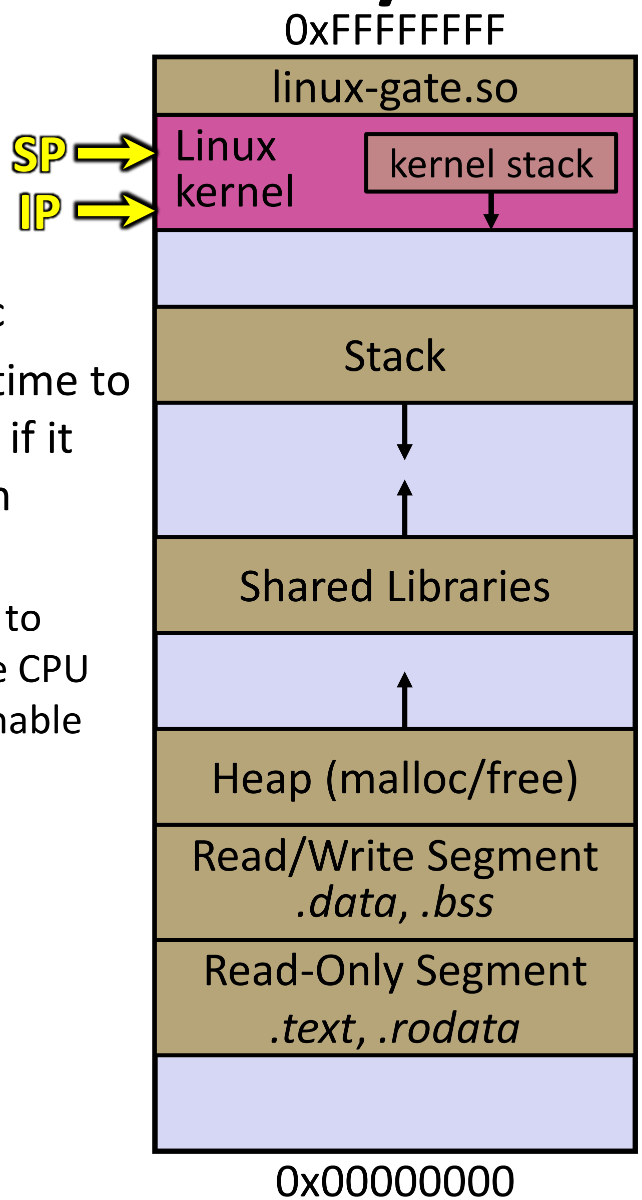


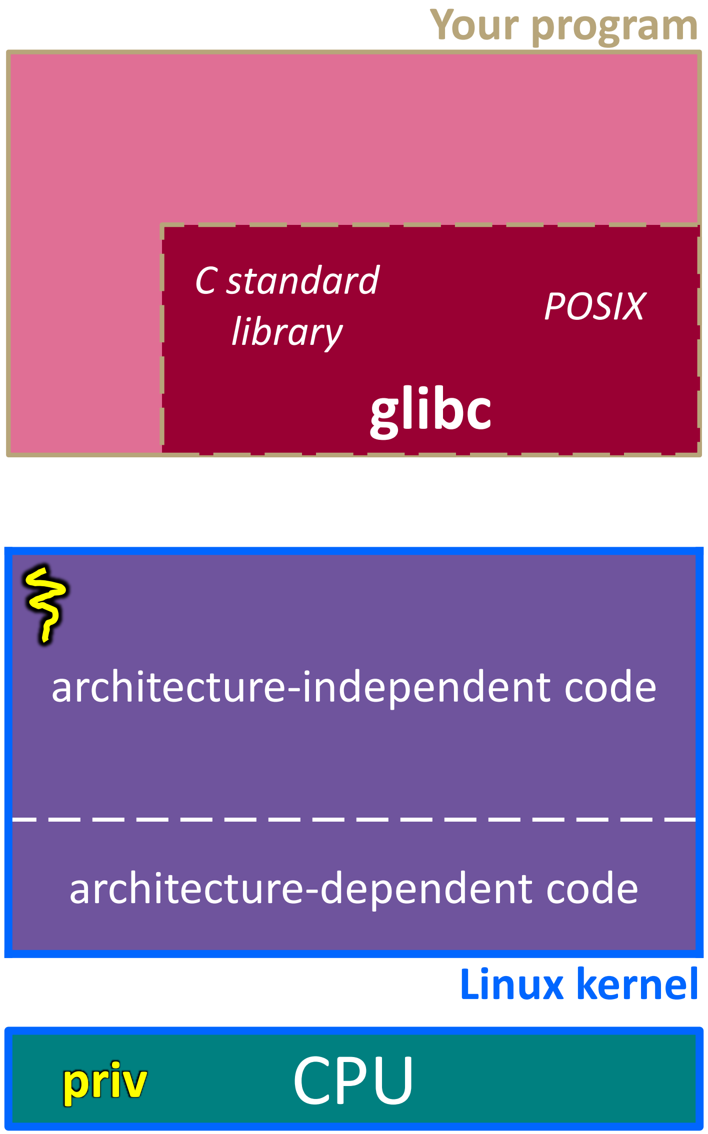


System Calls on x86/Linux (8/11)

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

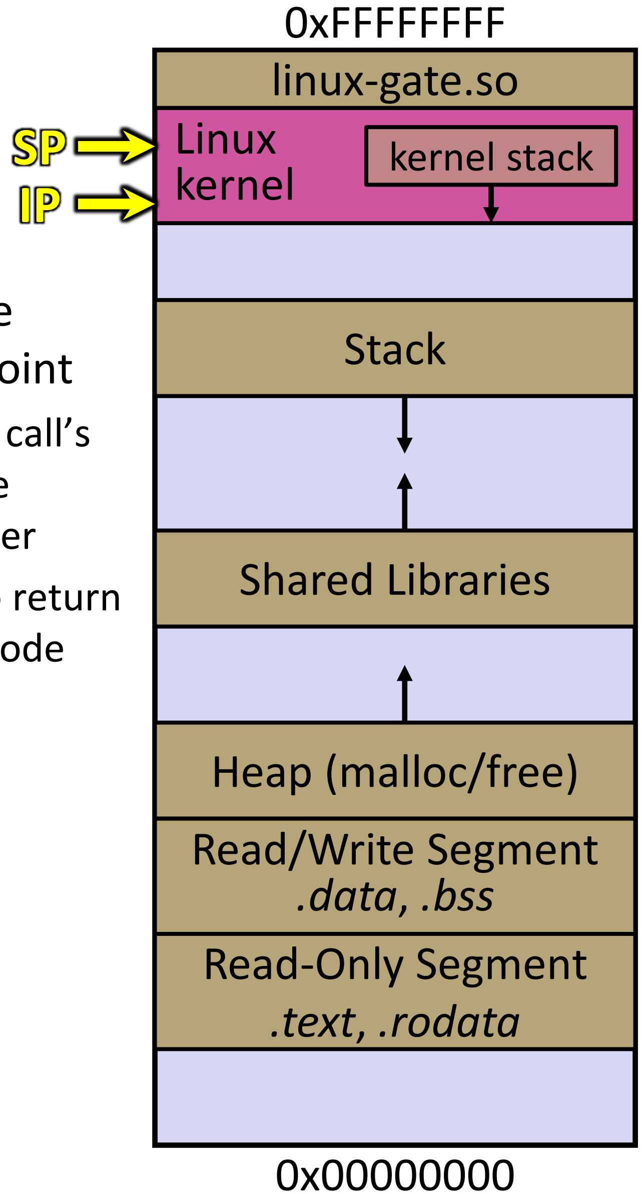


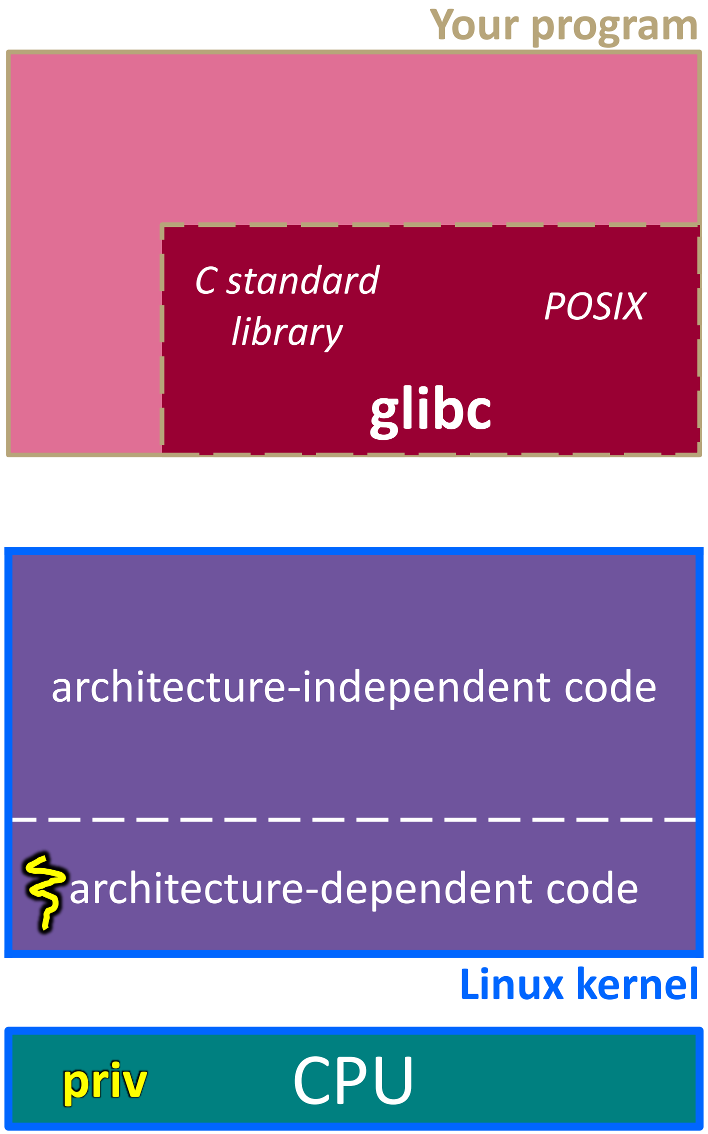


System Calls on x86/Linux (9/11)

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

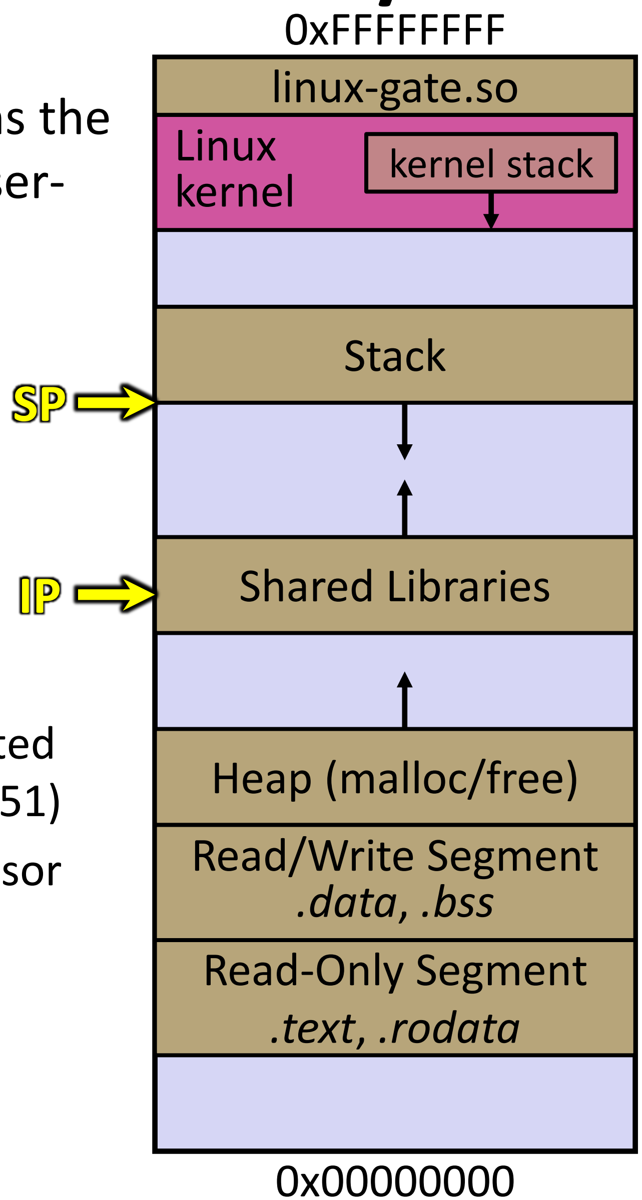


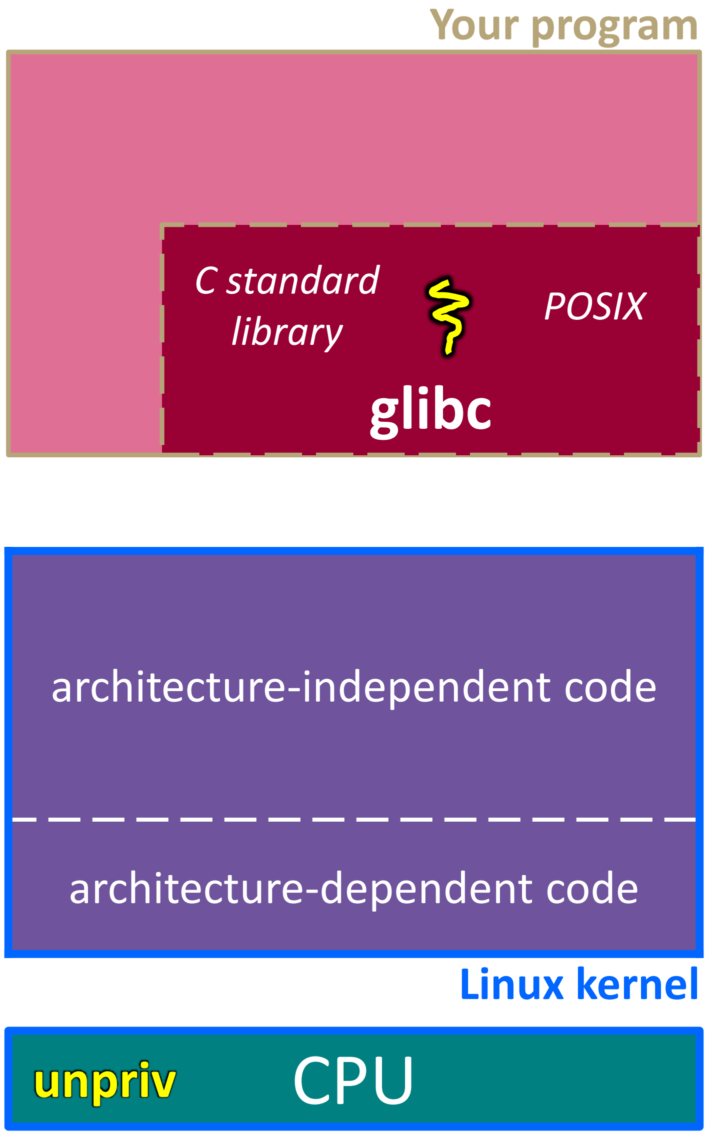


System Calls on x86/Linux (10/11)

`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 (11/11)

`glibc` continues to execute

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