System Calls, POSIX I/O

CSE 333 Spring 2019

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Administrivia

- Exercise 7 posted *tomorrow*, due Monday (4/22)

- Homework 1 due tomorrow night (4/18)
  - Watch that `hashtable.c` doesn't violate the modularity of `ll.h`
  - Watch for pointer to local (stack) variables
  - Use a debugger (*e.g.* `gdb`) if you're getting segfaults
  - Advice: clean up "to do" comments, but leave "step #" markers for graders
  - Late days: don't tag `hw1-final` until you are really ready
  - Bonus: if you add unit tests, put them in a new file and adjust the Makefile
- Homework 2 will be released on Friday (4/19)

Lecture Outline

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

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 Issues

- What happens if…
  - Your computer loses power before the buffer is flushed?
  - Your program assumes data is written to a file and signals another program to read it?

- Performance implications:
  - Data is *copied* 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"*)

Buffering Issue Solutions

- Turn off buffering with **`setbuf`**`(stream, NULL)`
  - Unfortunately, this may also cause performance problems
    - *e.g.* if your program does many small **`fwrite`**`()`s, each one will now trigger a system call into the Linux kernel
- Use a different set of system calls
  - POSIX (OS layer) provides **`open`**`()`, **`read`**`()`, **`write`**`()`, **`close`**`()`, etc.
    - No buffering is done at the user level
- But… what about the layers below?
  - The OS caches disk reads and writes in the FS *buffer* cache
  - Disk controllers have caches too!

Lecture Outline

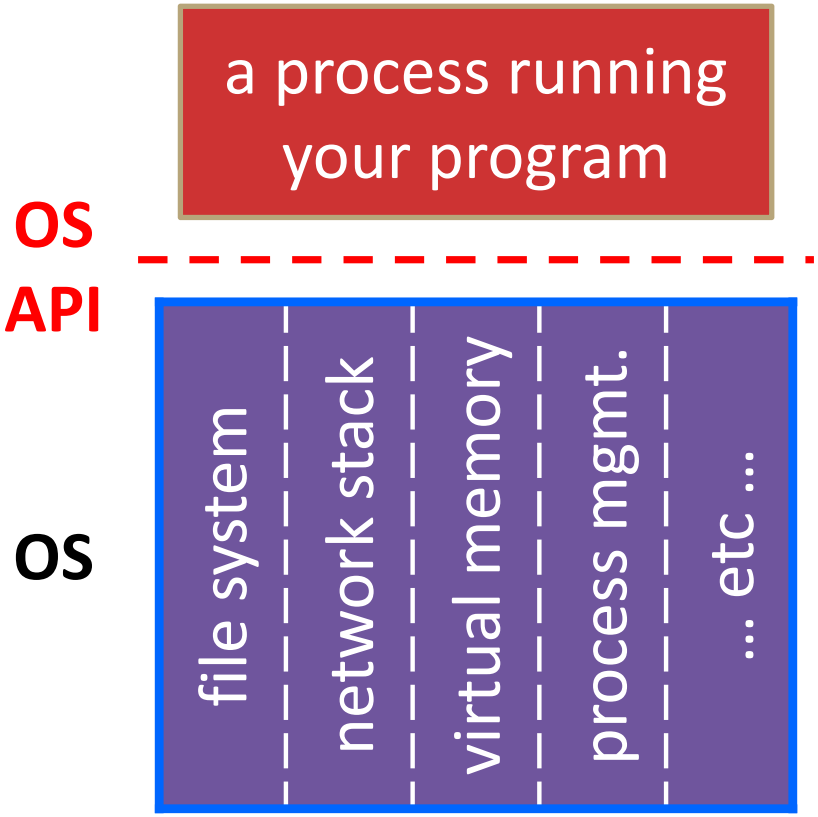
- C Stream Buffering
- **System Calls**
- POSIX Lower-Level I/O
- C++ Preview

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(), …

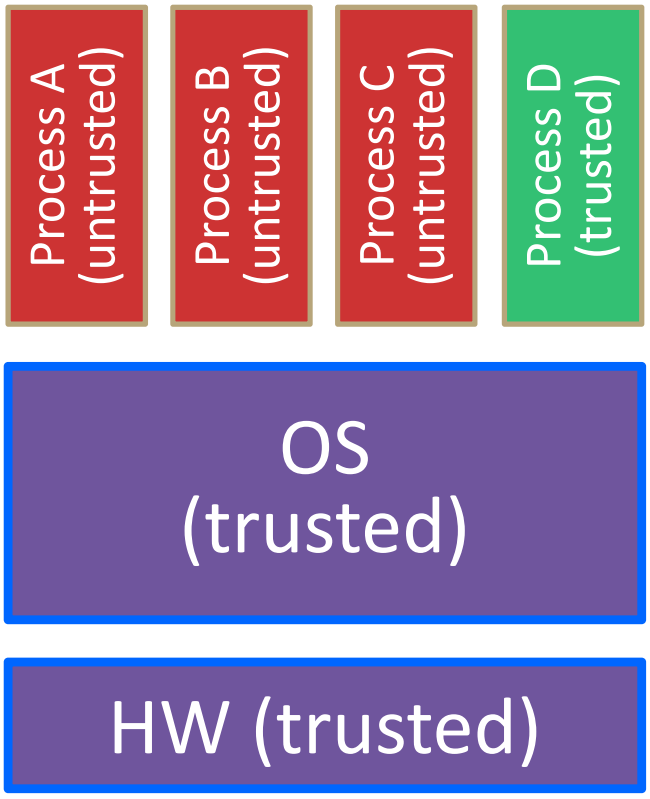
Network Stack
- connect(), listen(), read(), write(), ...

Virtual Memory
- brk(), shm_open(), …

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

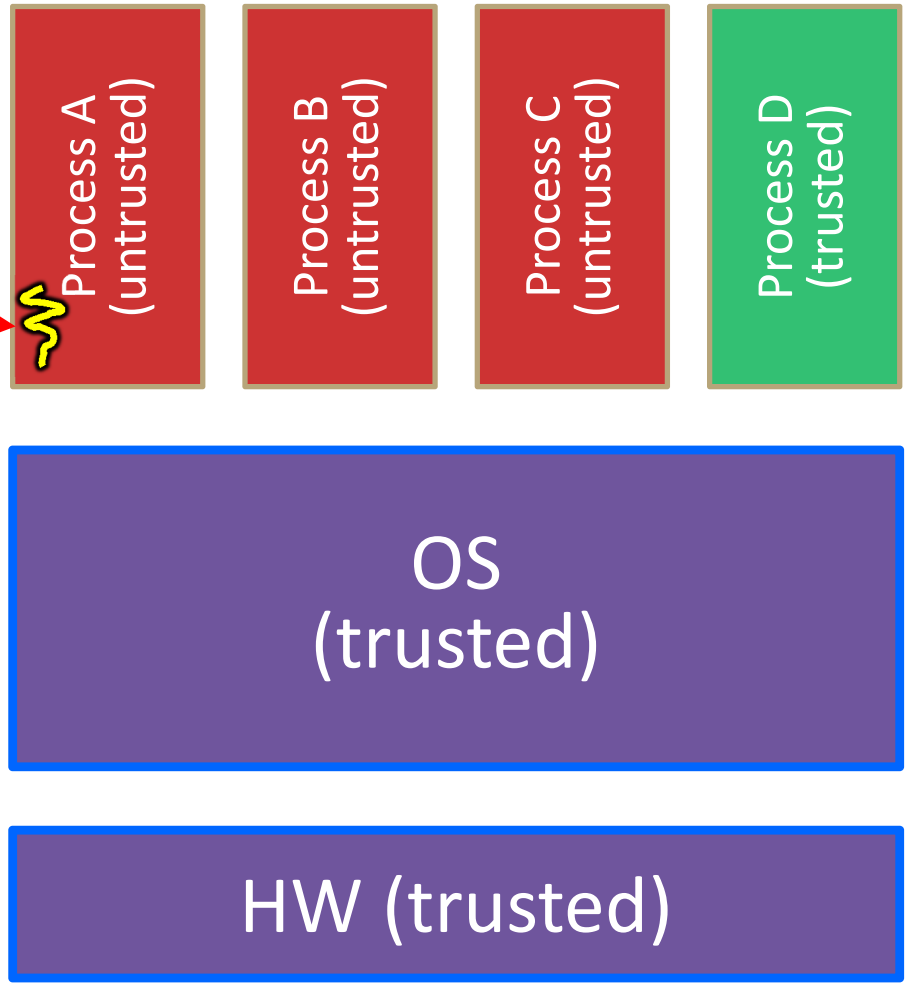
OS: Protection System

- 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



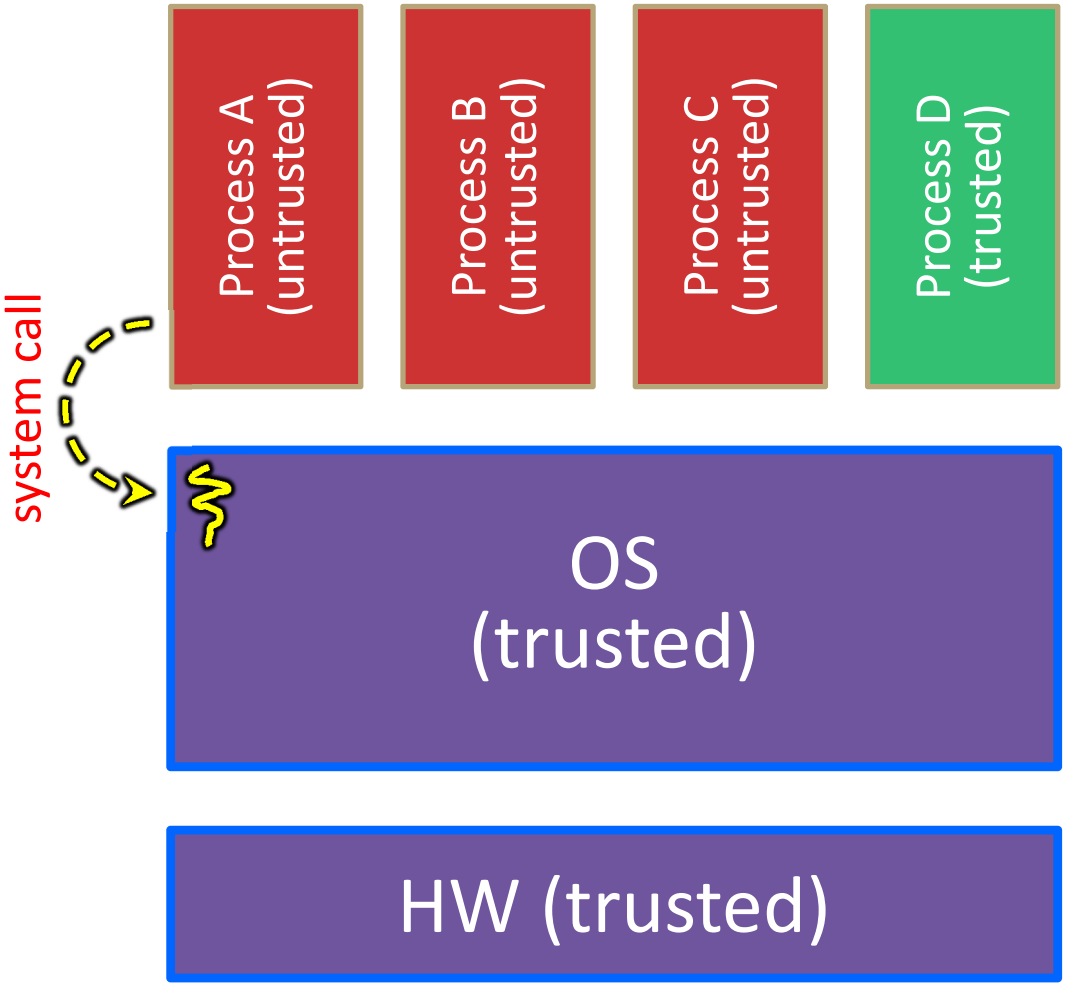
System Call Trace

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



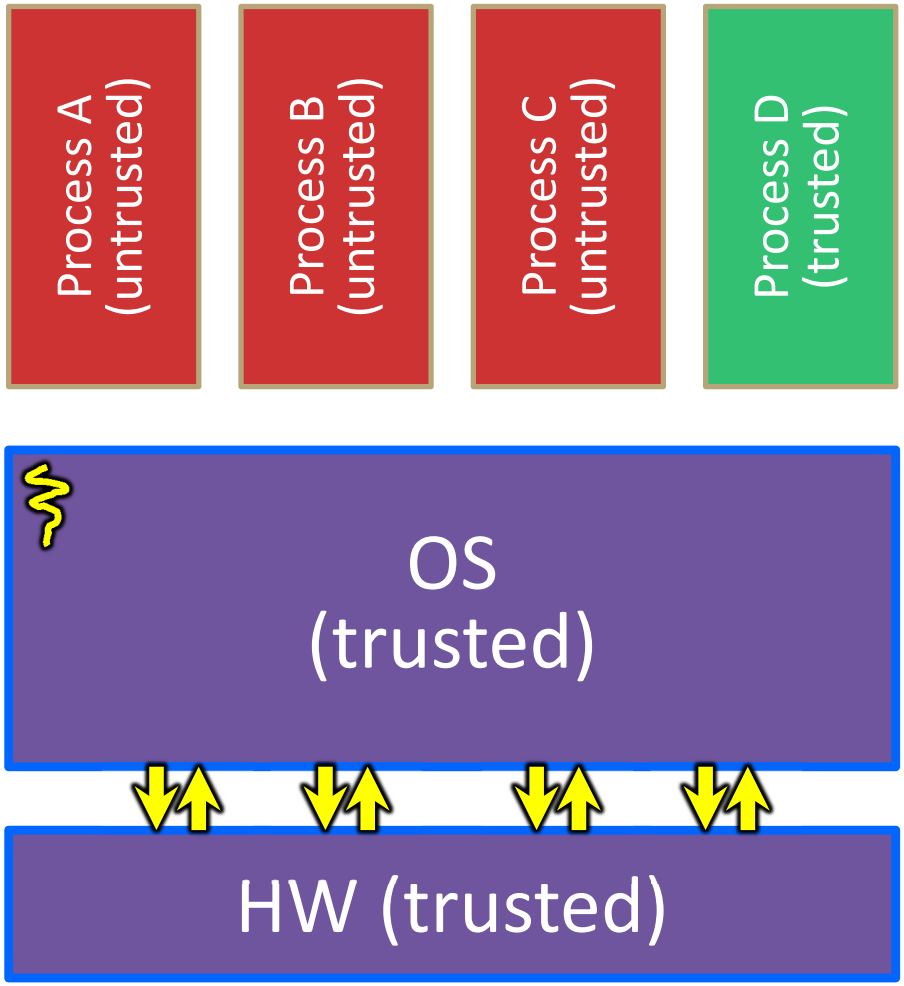
System Call Trace

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

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.

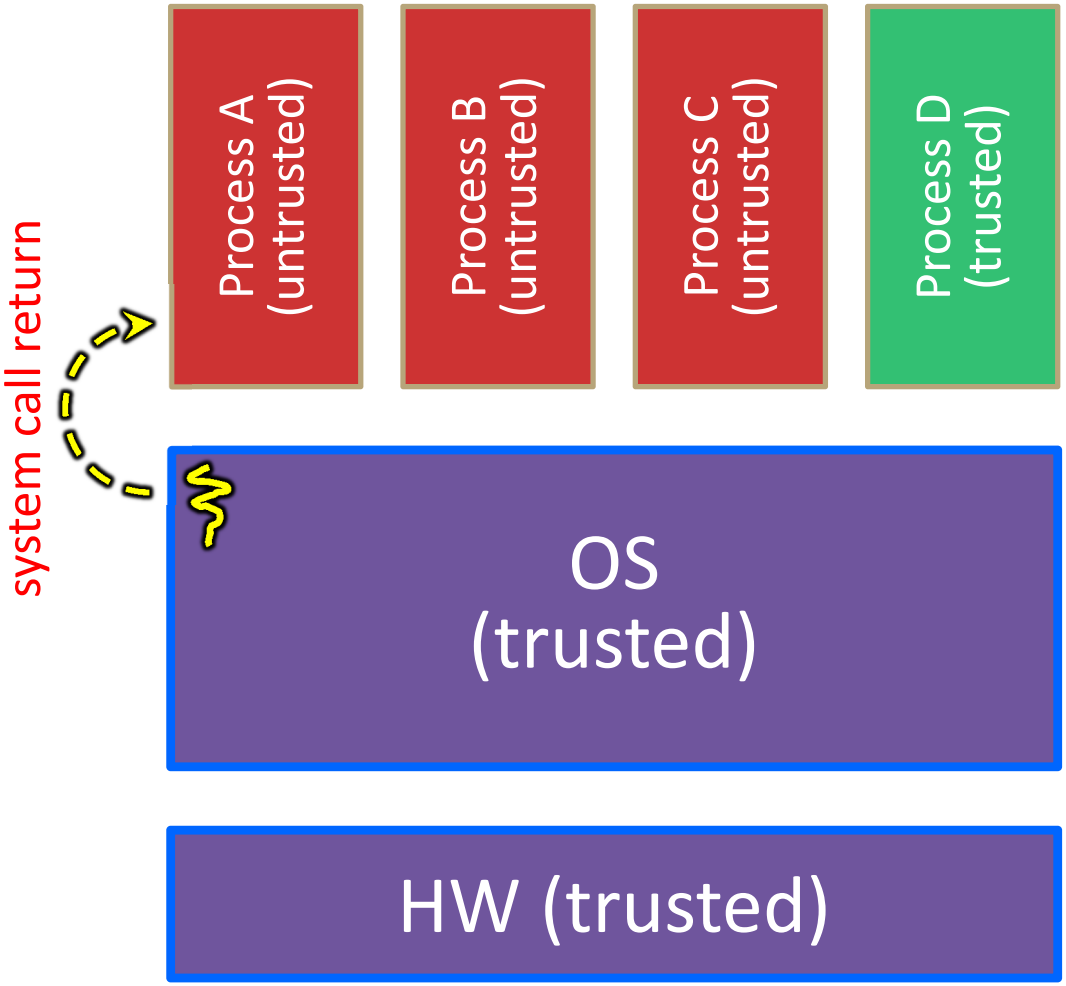


System Call Trace

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

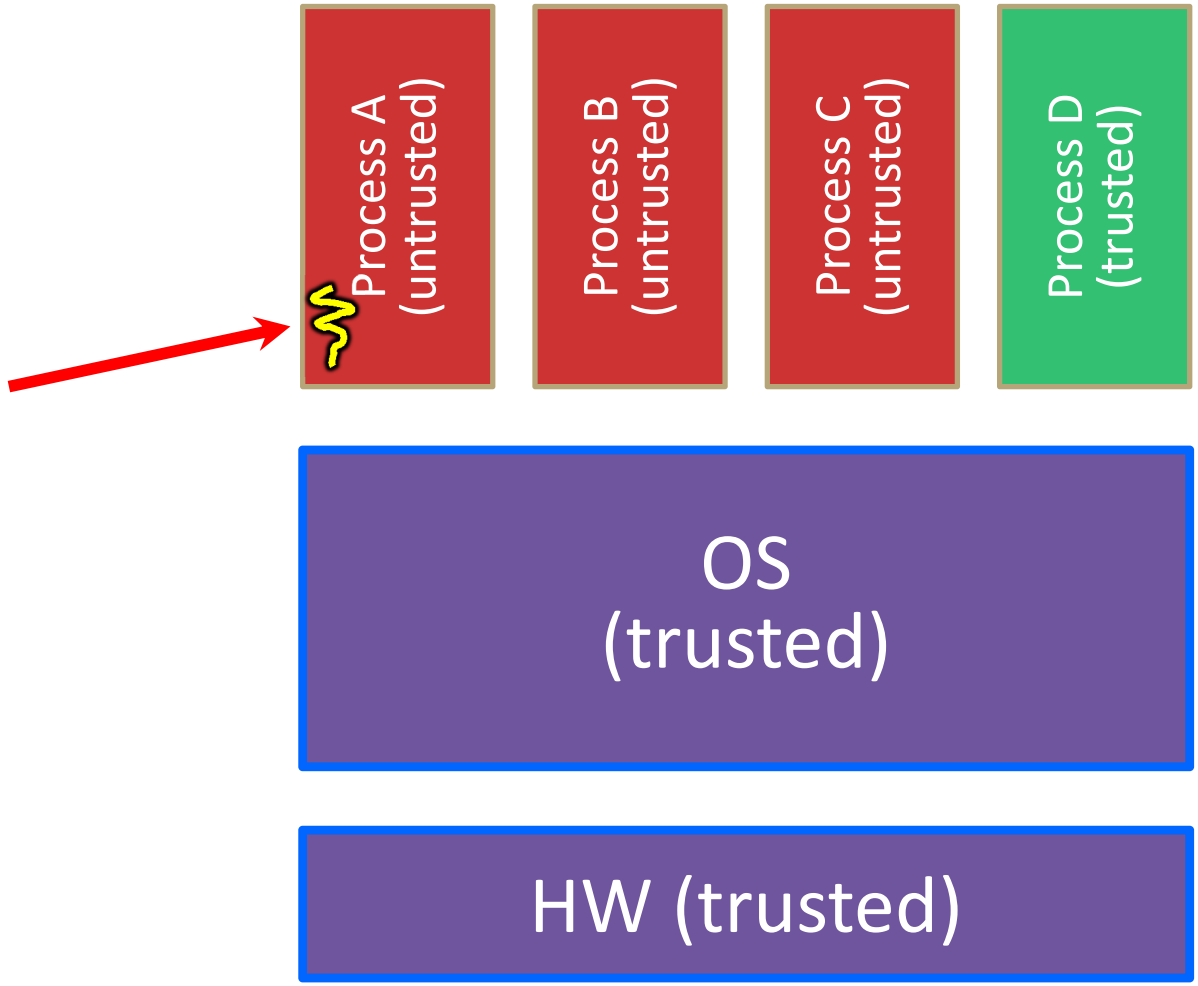
(1) Sets the CPU back to unprivileged mode and

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



System Call Trace

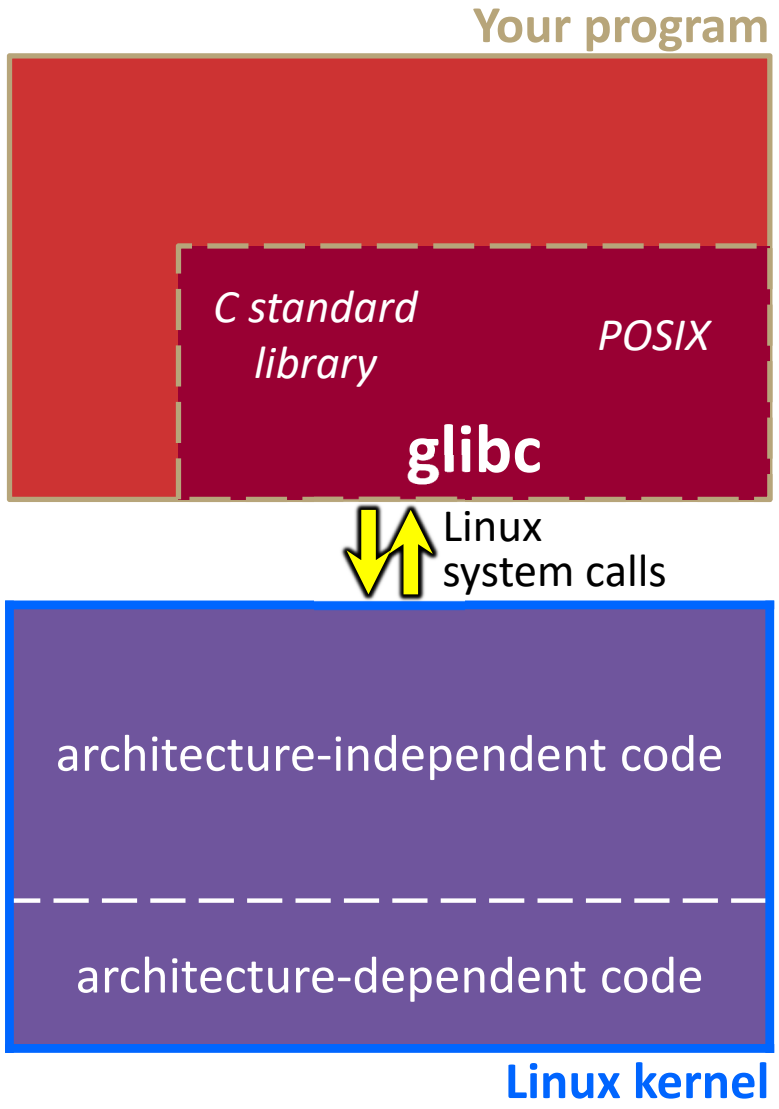
The process continues executing whatever code is next after the system call invocation.



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

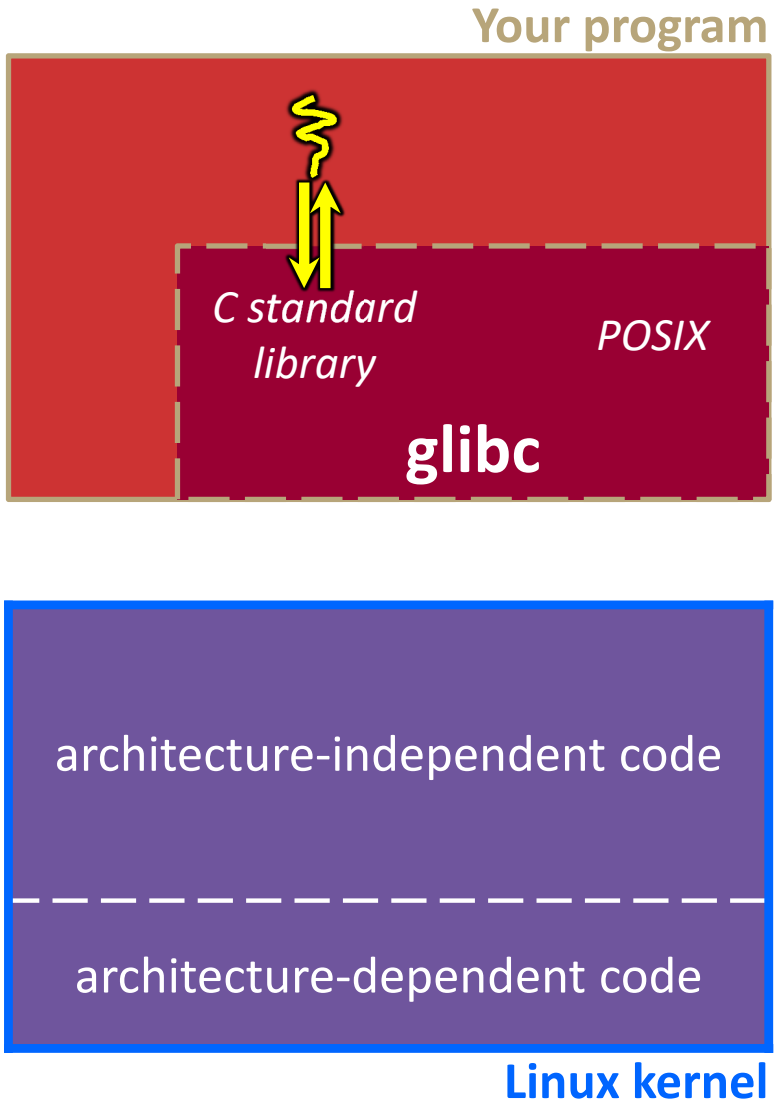
Details on x86/Linux

- 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



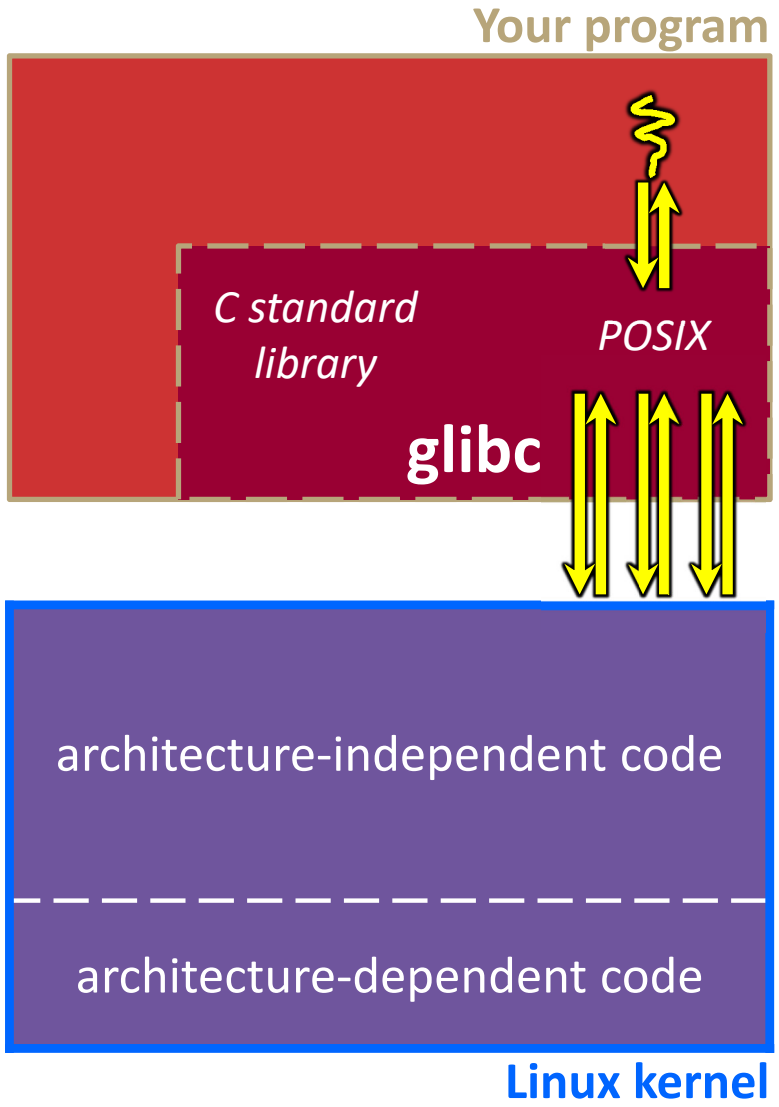
Details on x86/Linux

- 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!



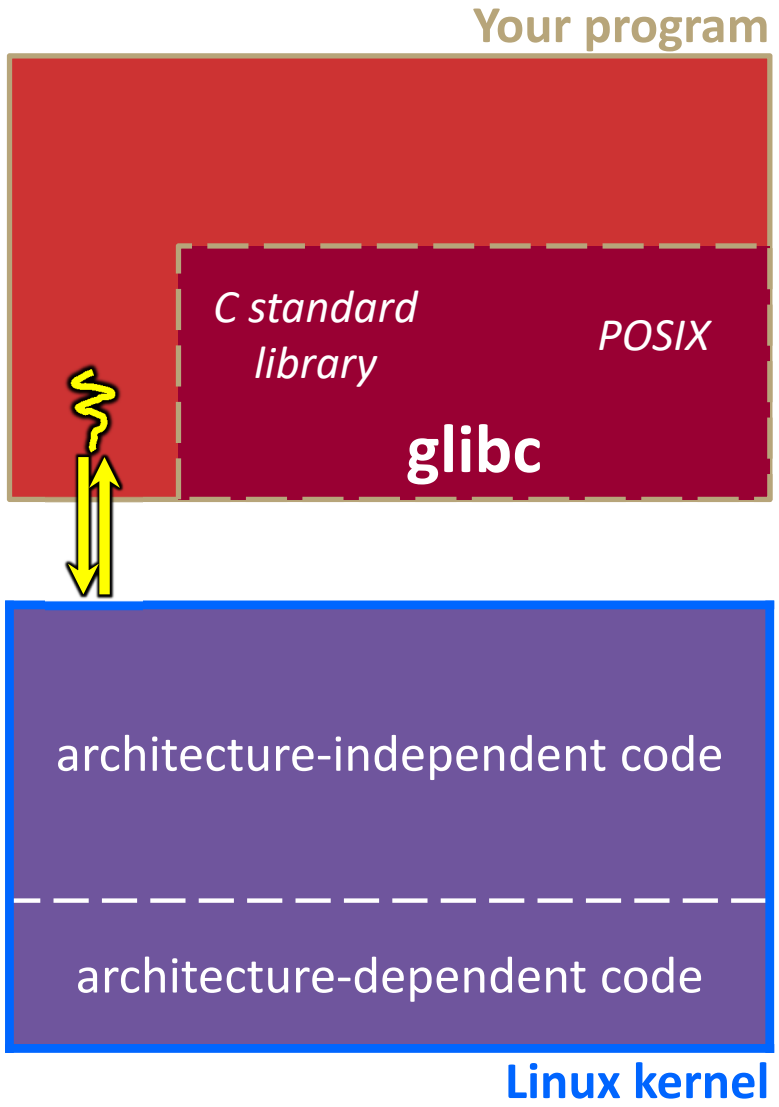
Details on x86/Linux

- 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.



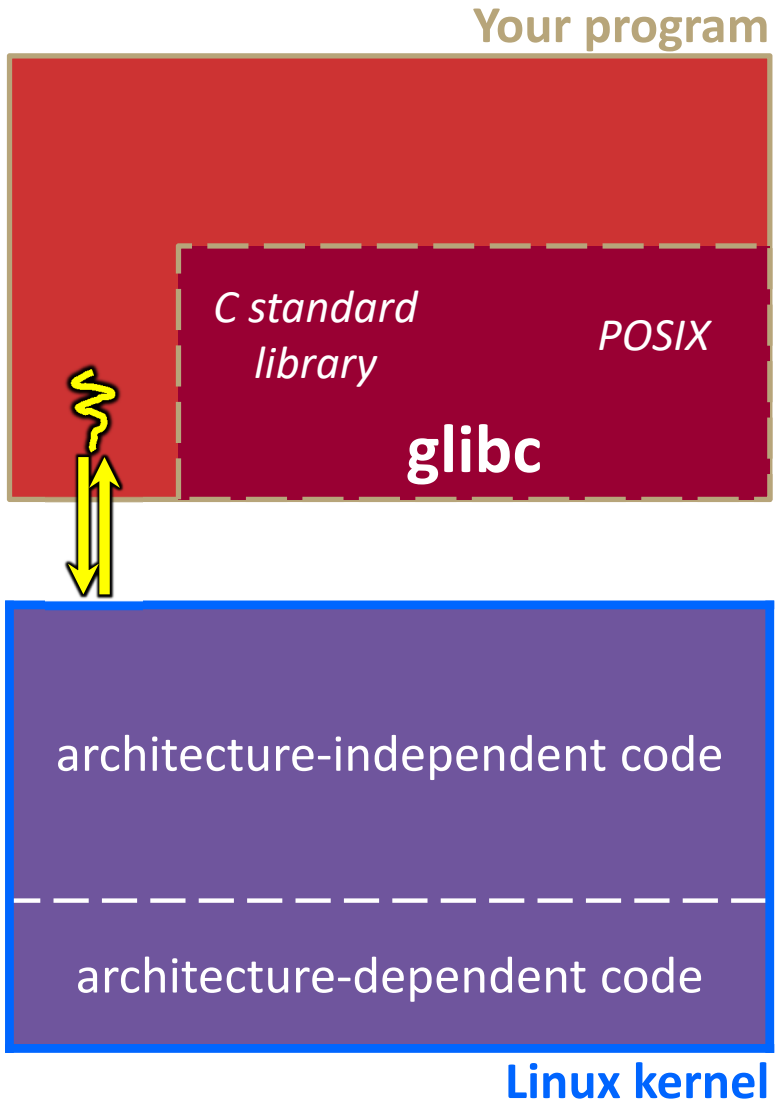
Details on x86/Linux

- 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

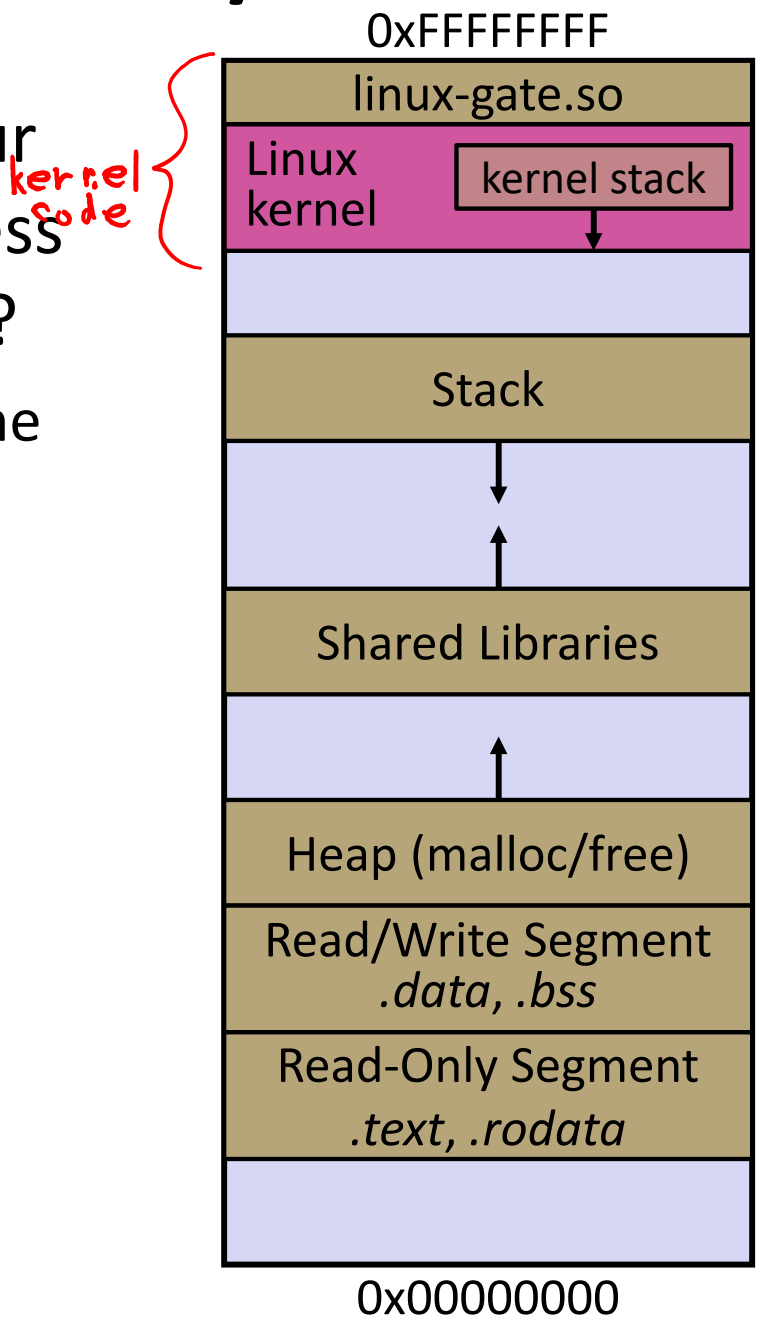
- Let's walk through how a Linux system call actually works
  - We'll assume *32-bit x86* using the modern `SYSENTER` / `SYSEXIT` x86 instructions
    - x86-64 code is similar, though details always change over time, so take this as an example – not a debugging guide

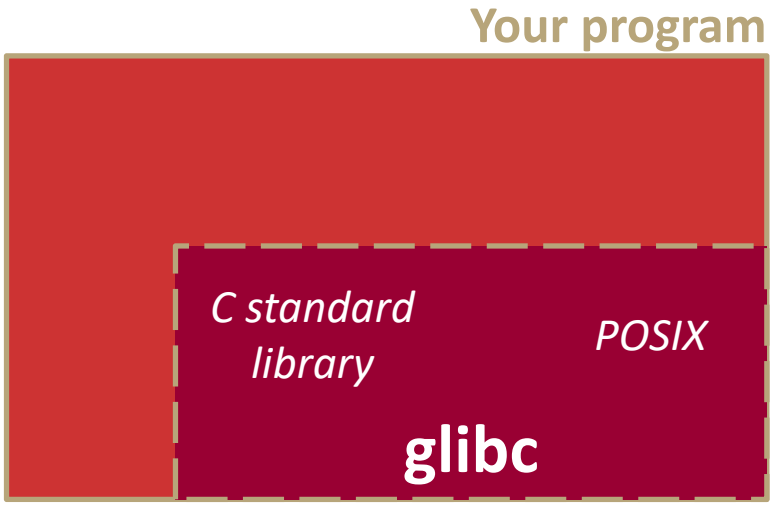


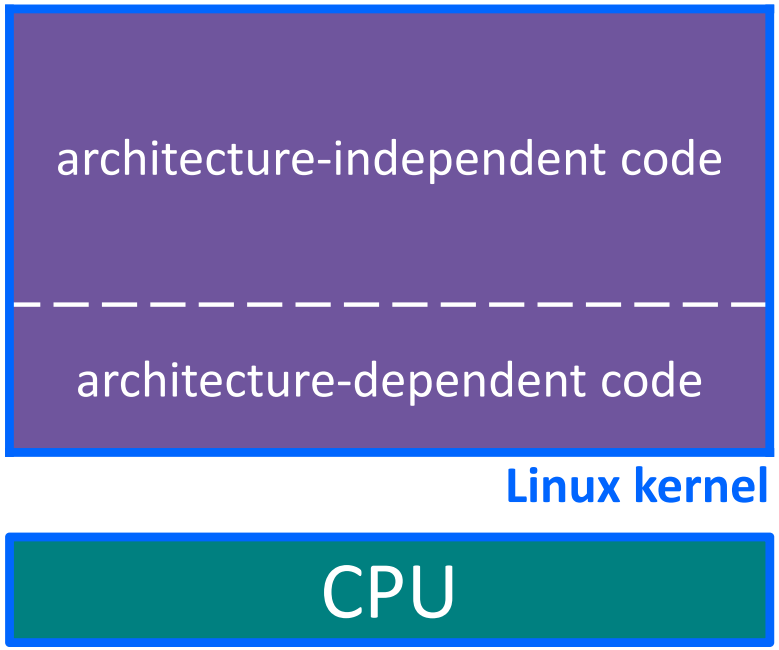
Details on x86/Linux

Remember our process address space picture?

- Let's add some details:

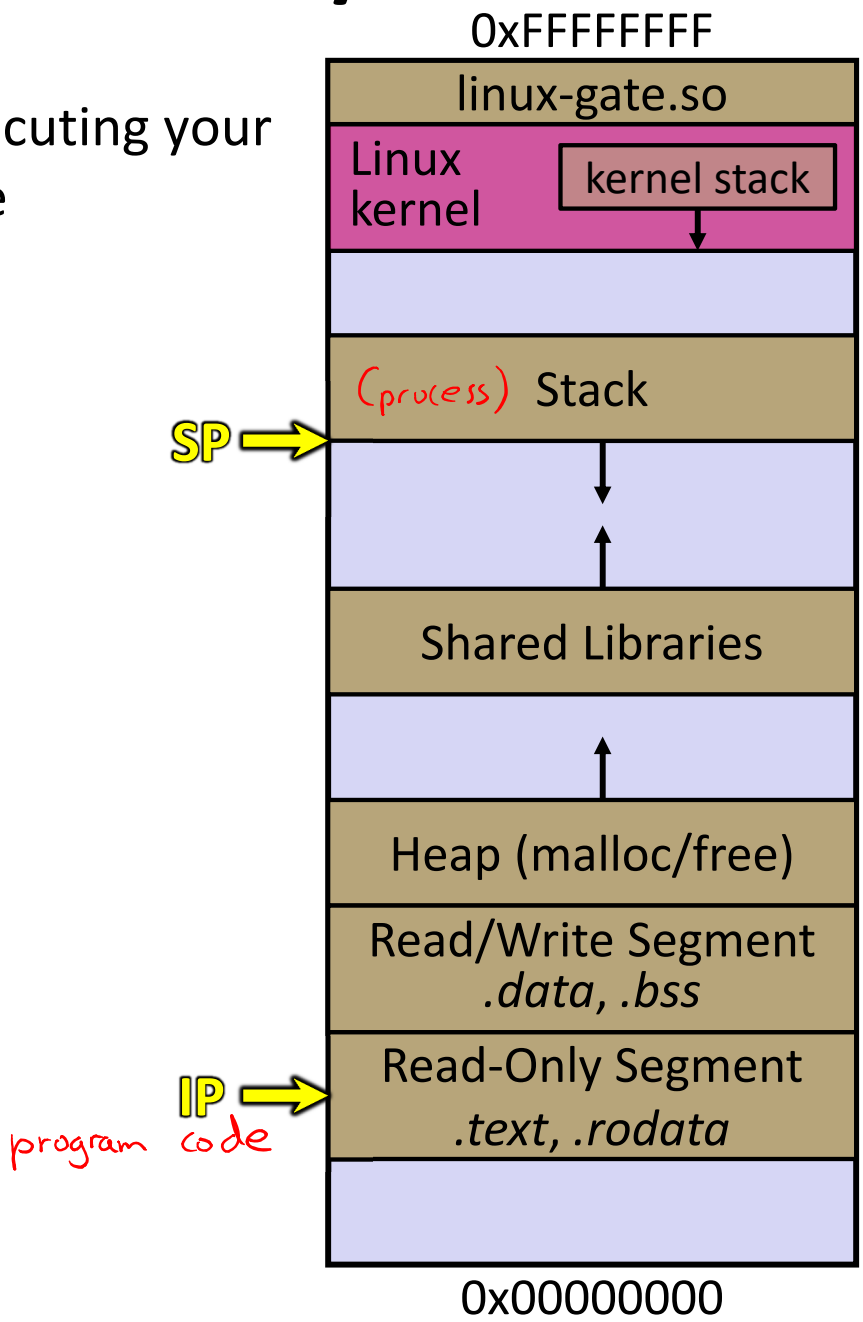


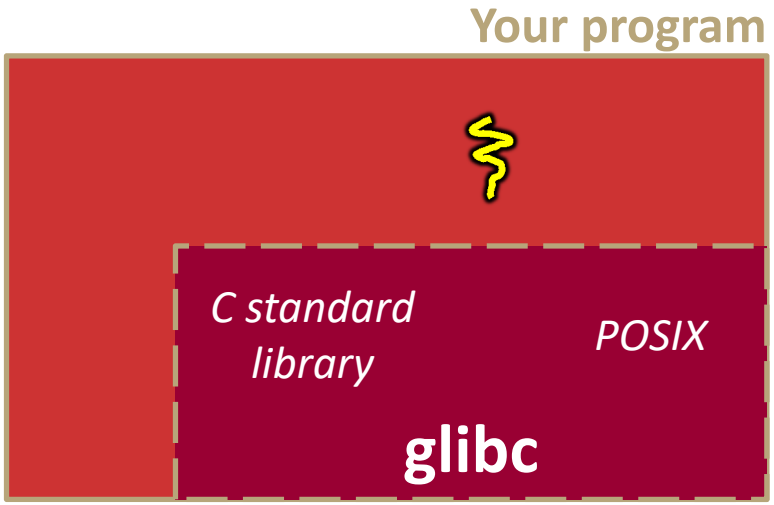


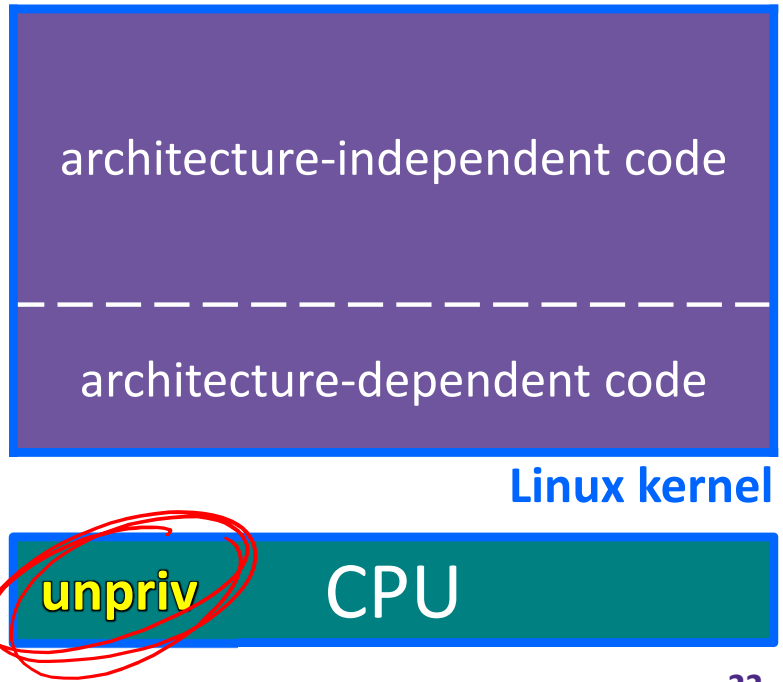


Details on x86/Linux

Process is executing your program code



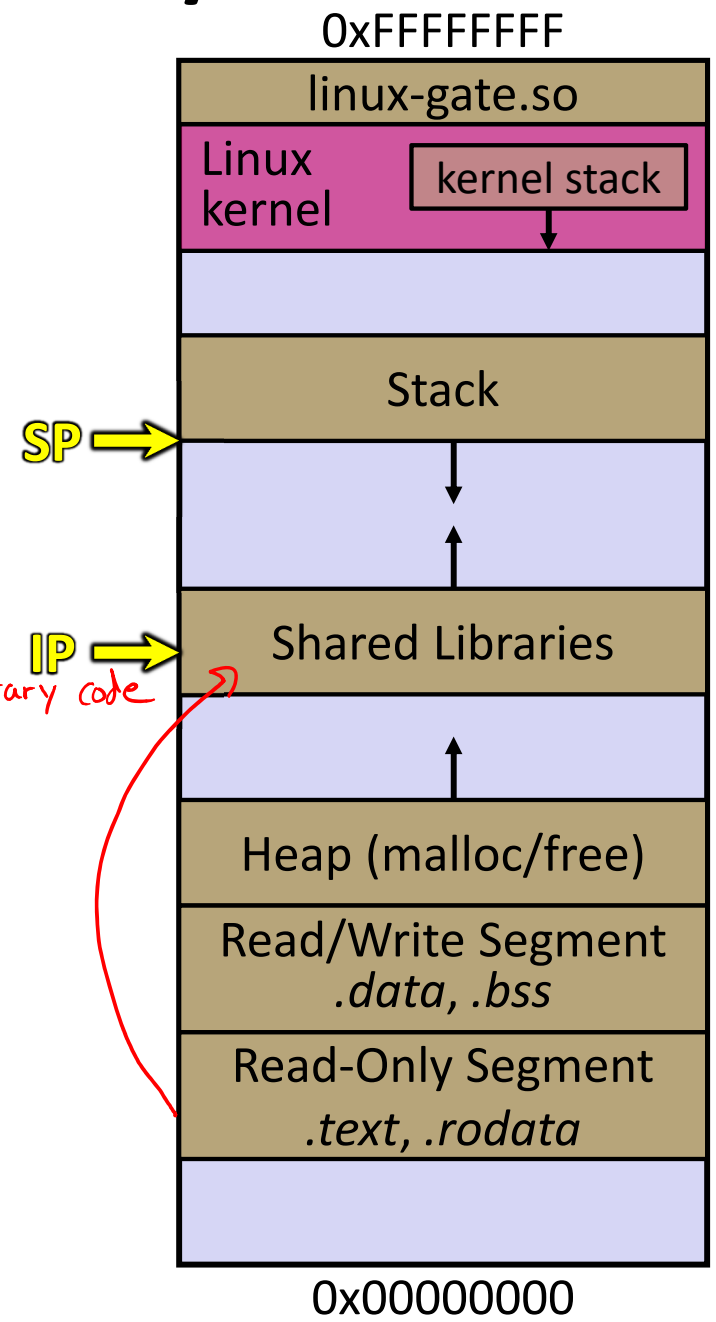


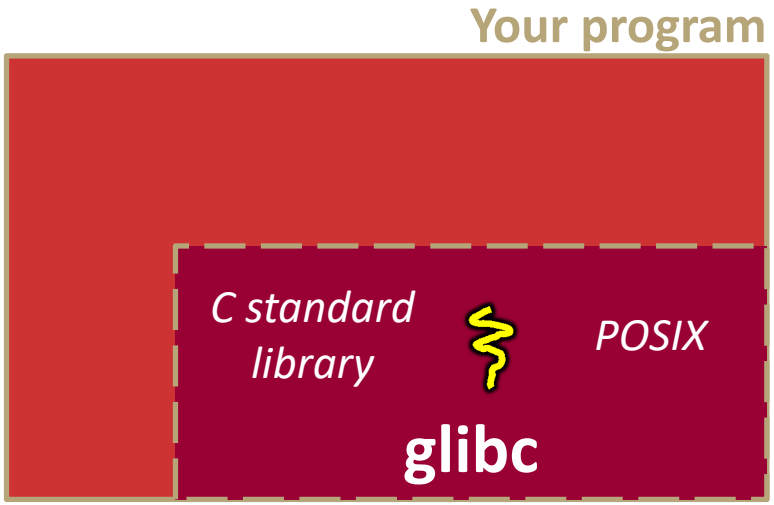


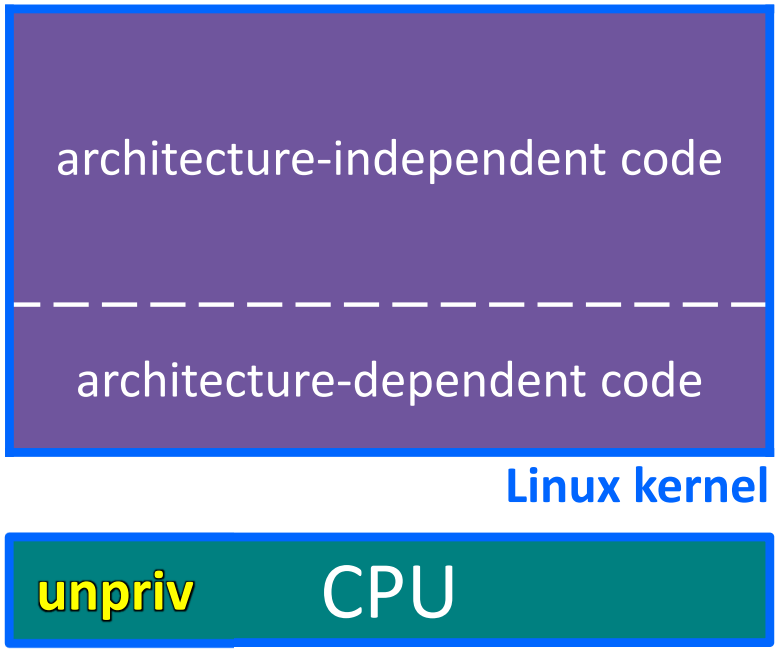
Details on x86/Linux

Process calls into a `glibc` function

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



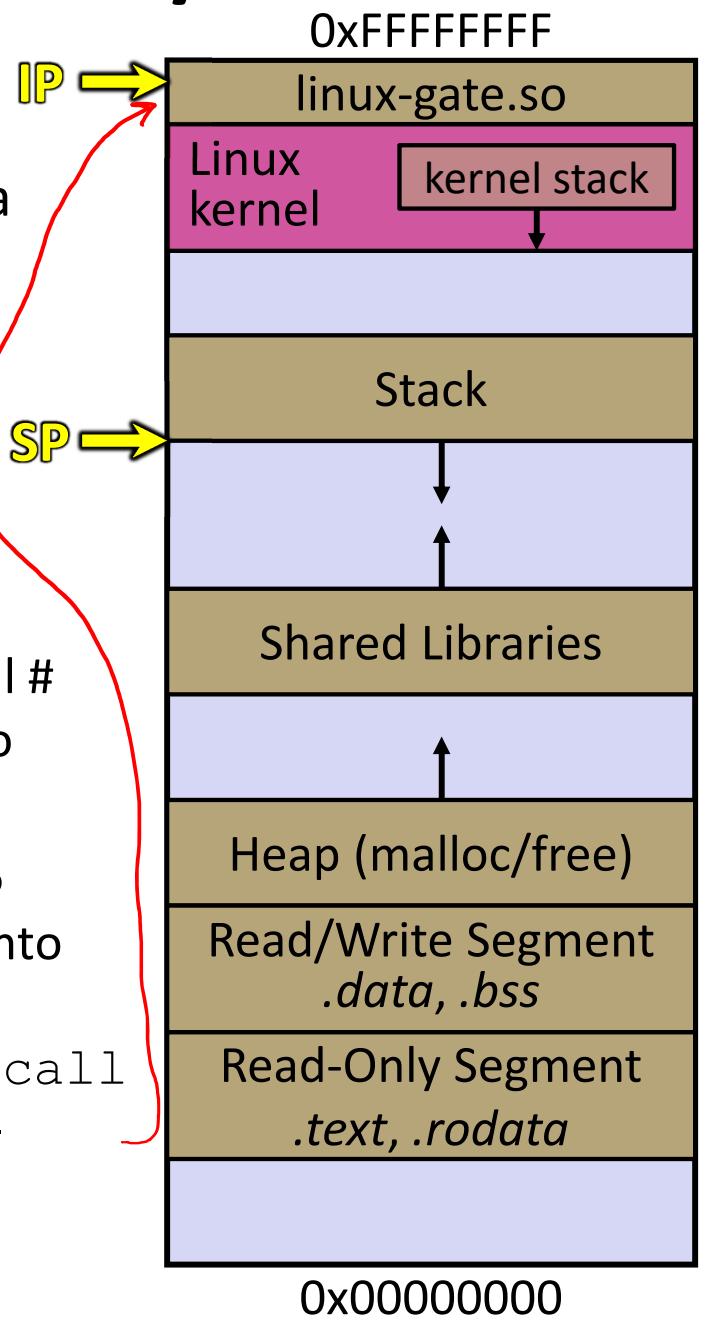


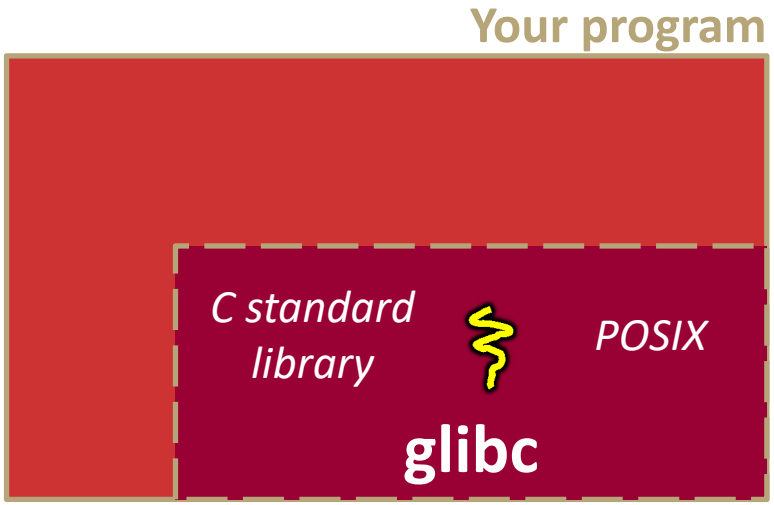


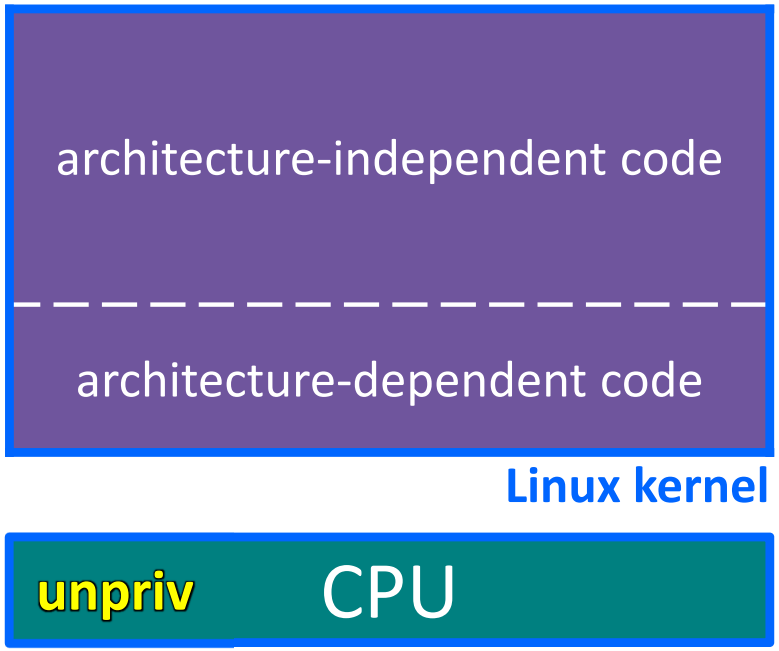
Details on x86/Linux

`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`





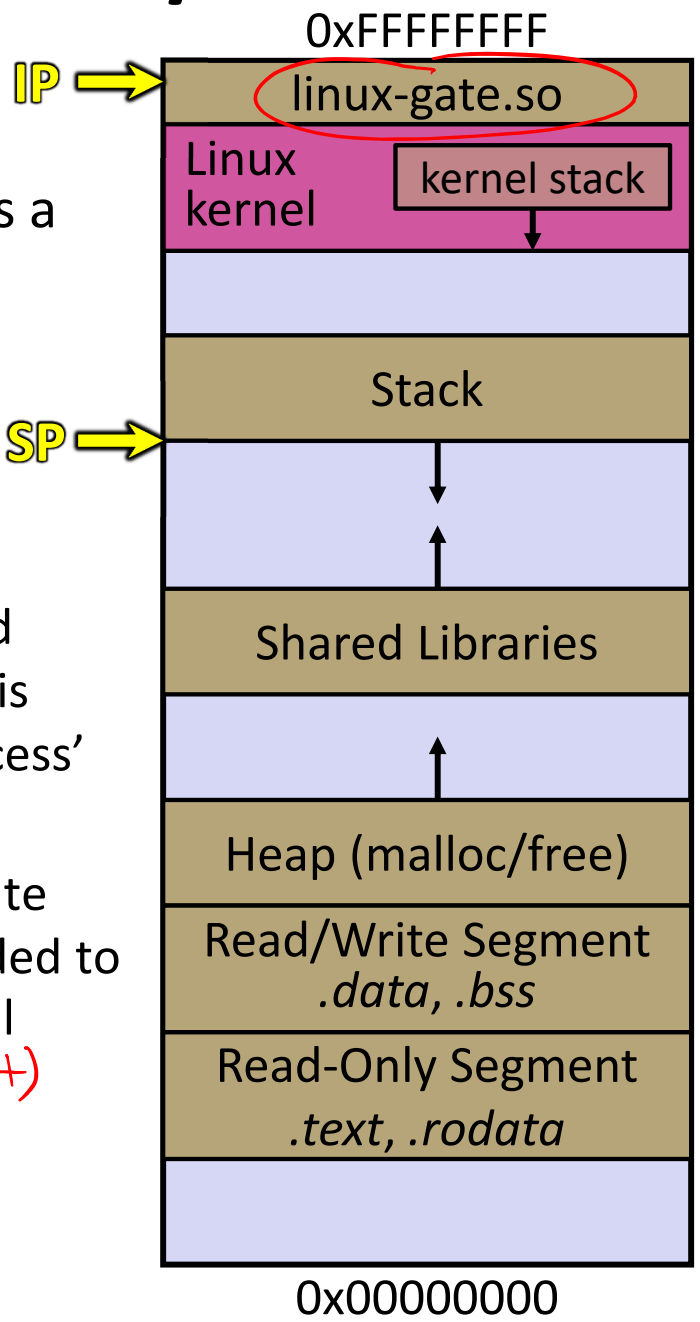


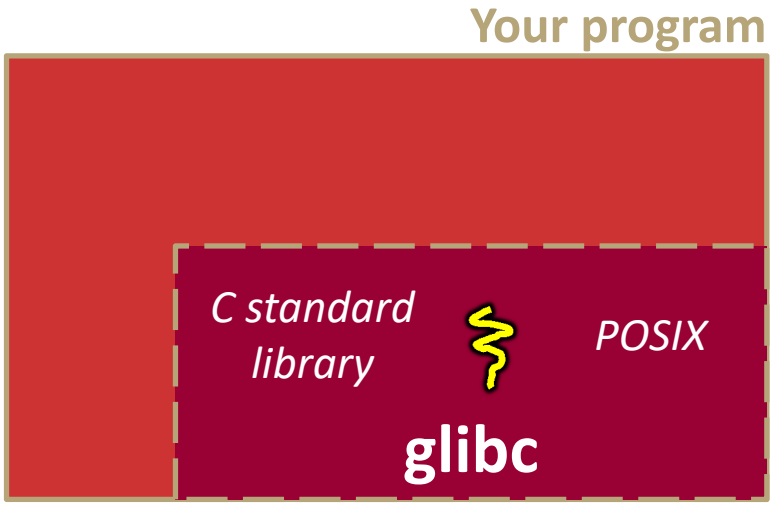
Details on x86/Linux

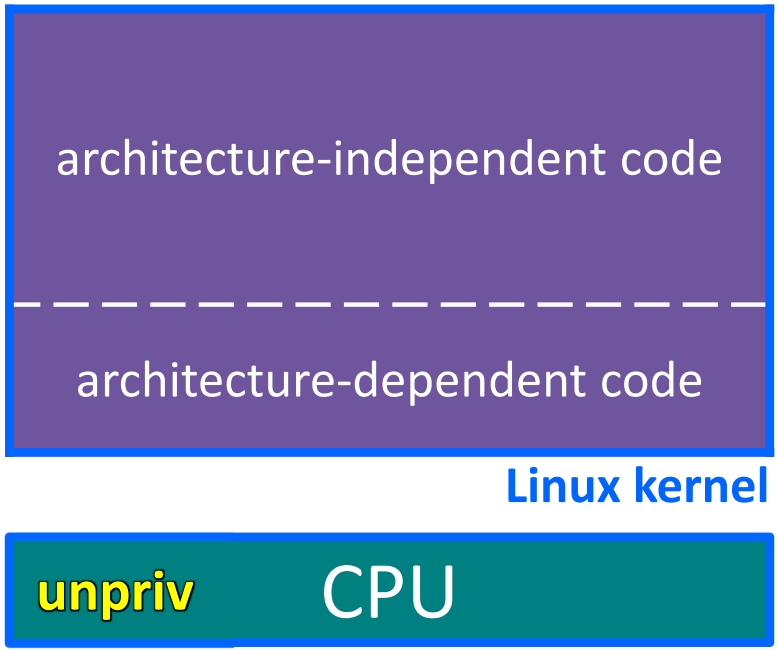
`linux-gate.so` is a **vdso**

- 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

(details not important)



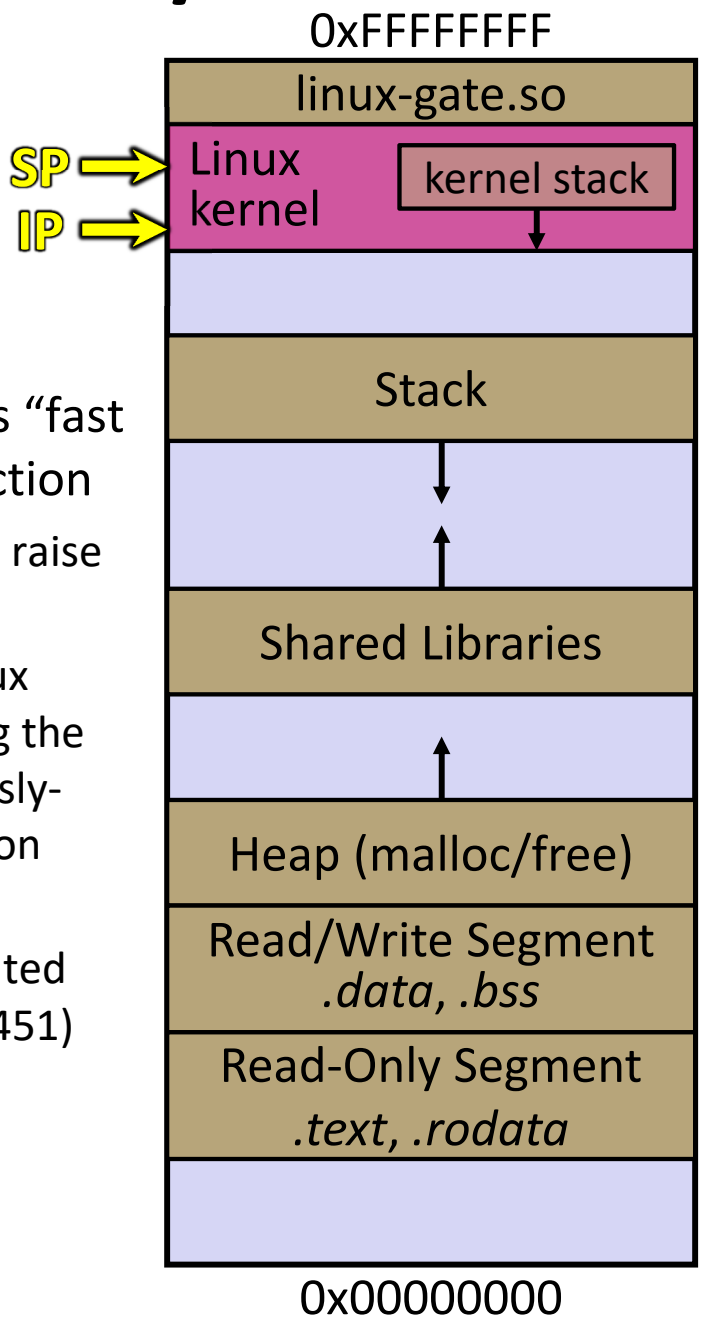


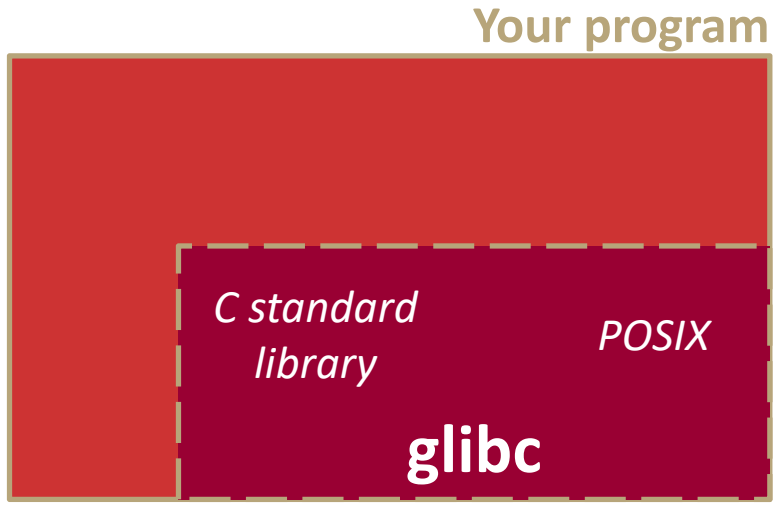


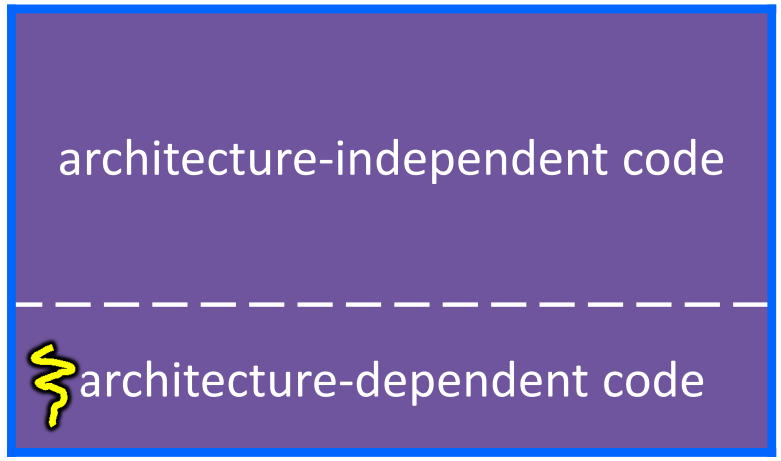
Details on x86/Linux

`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)



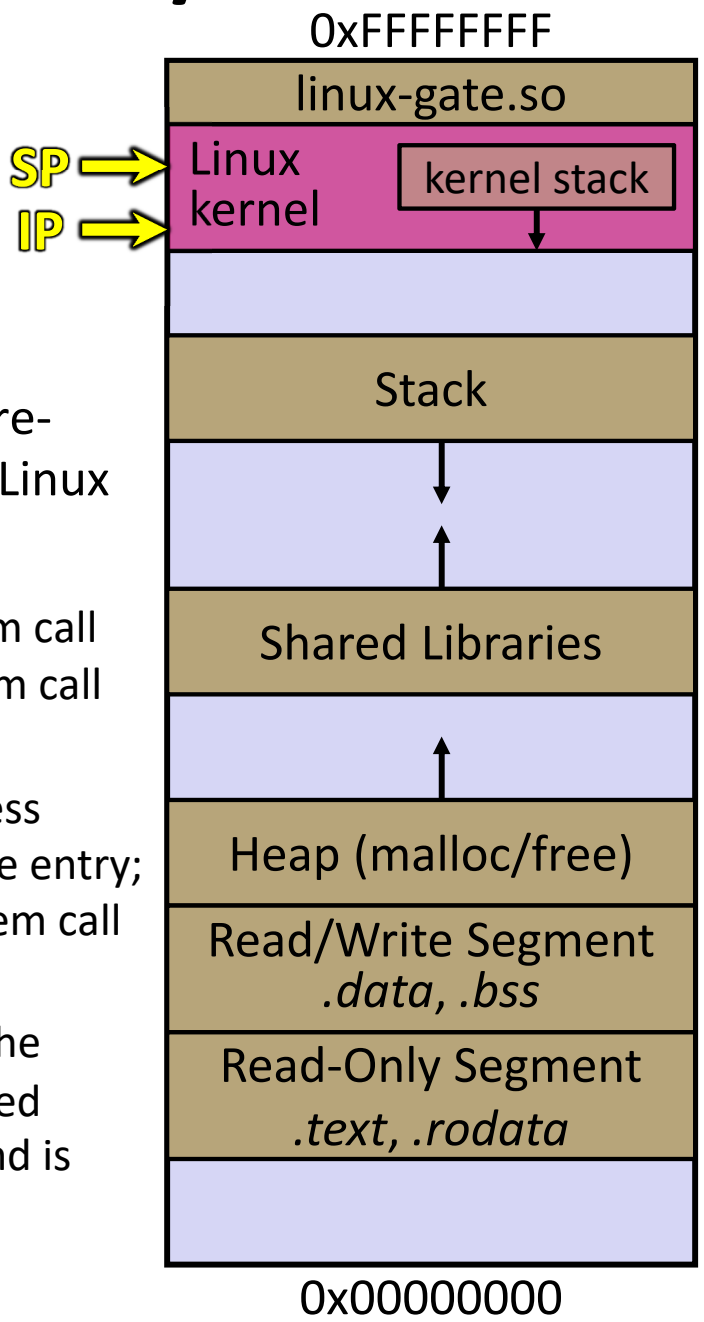


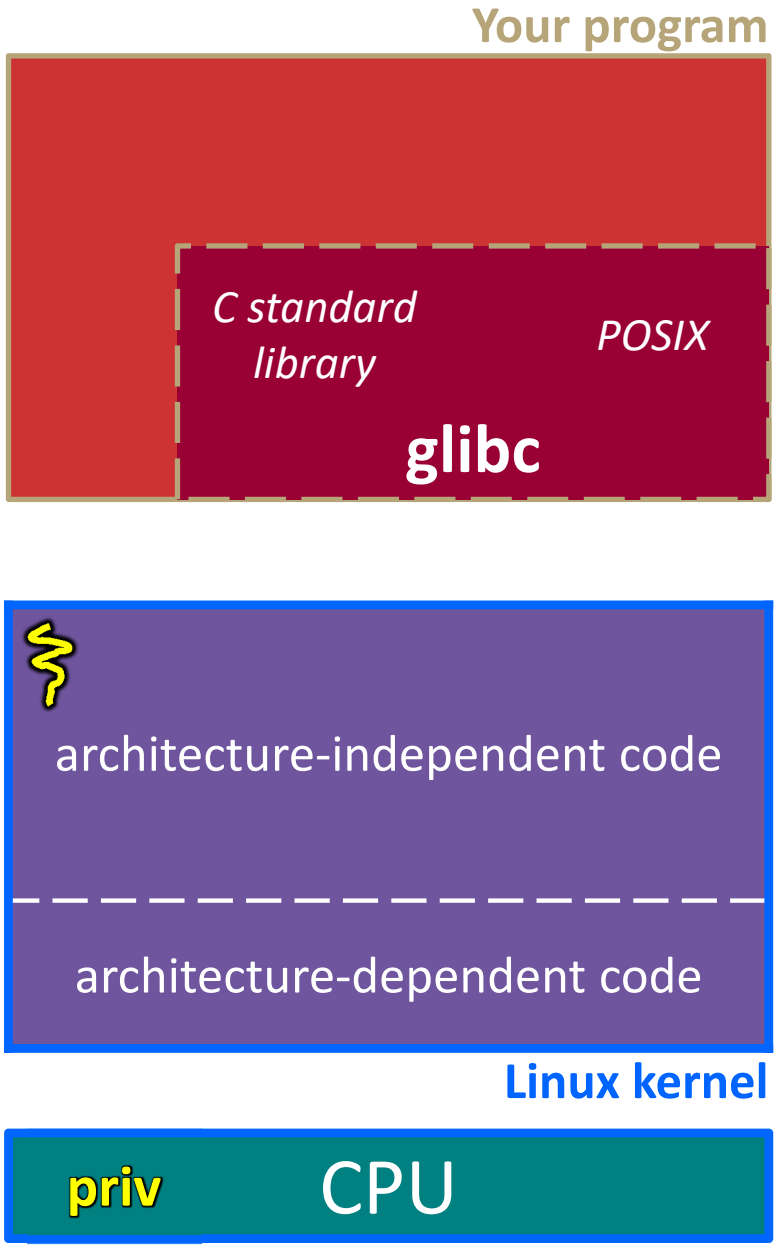


Details on x86/Linux

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

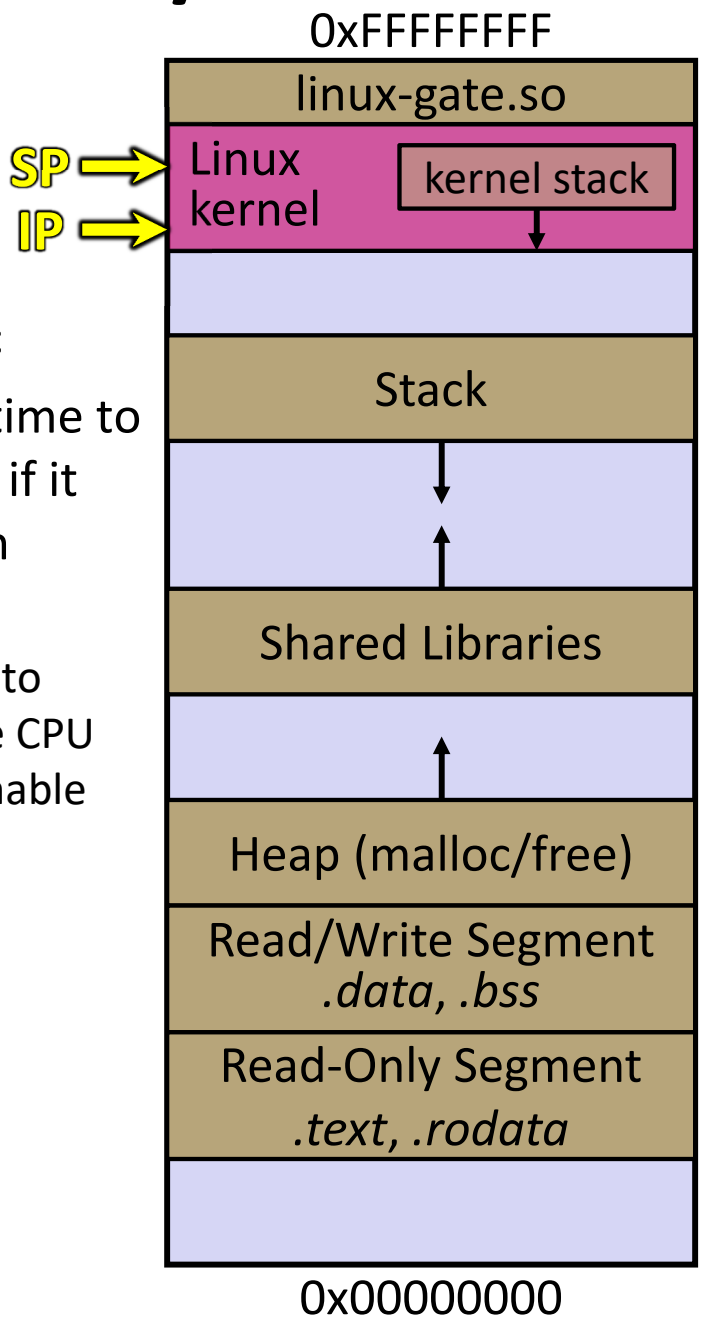


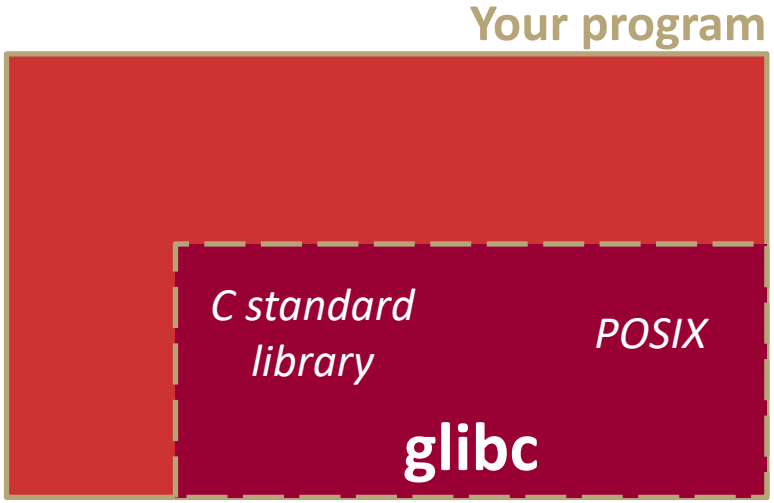


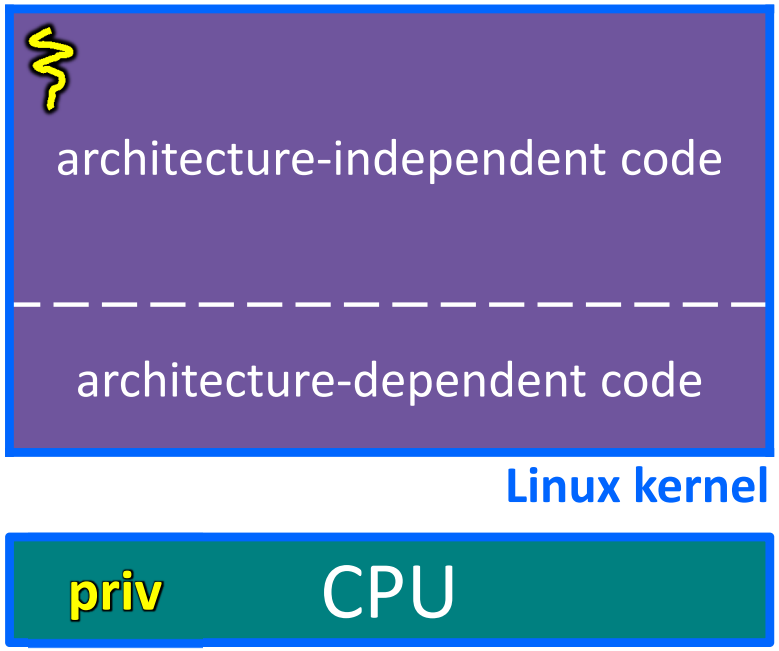
Details on x86/Linux

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



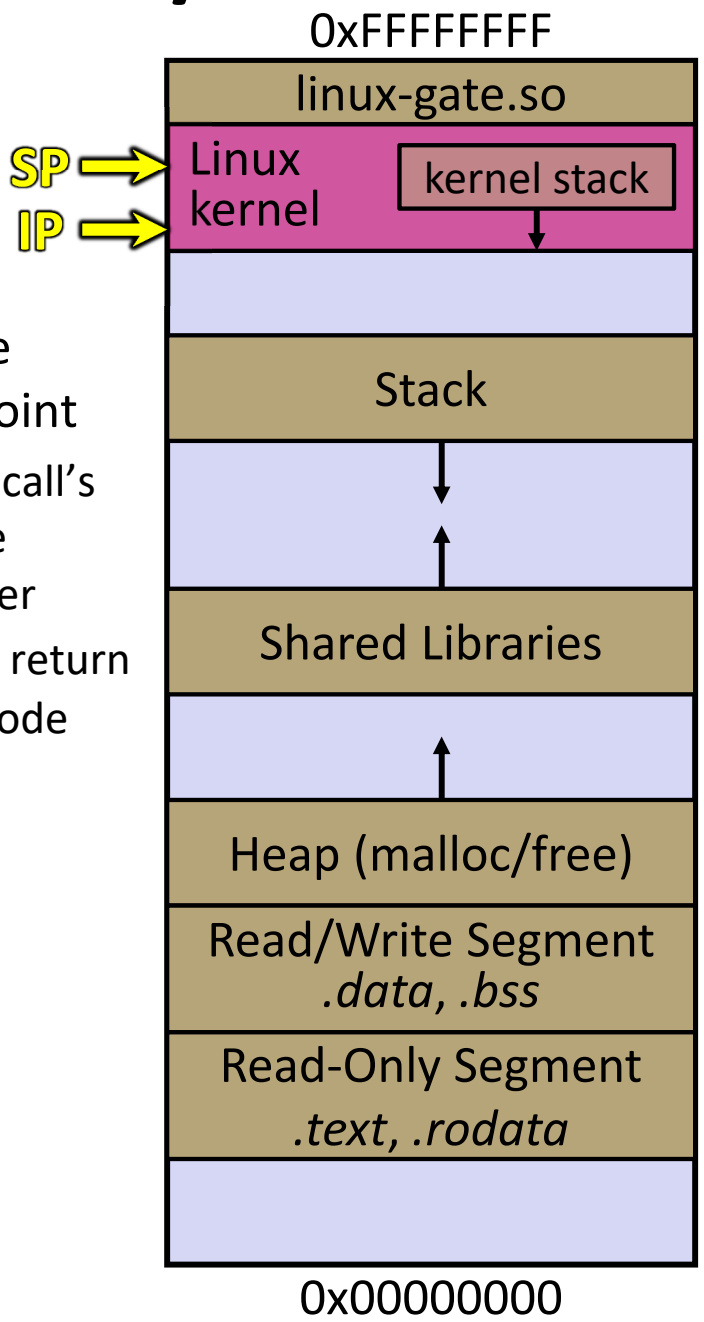


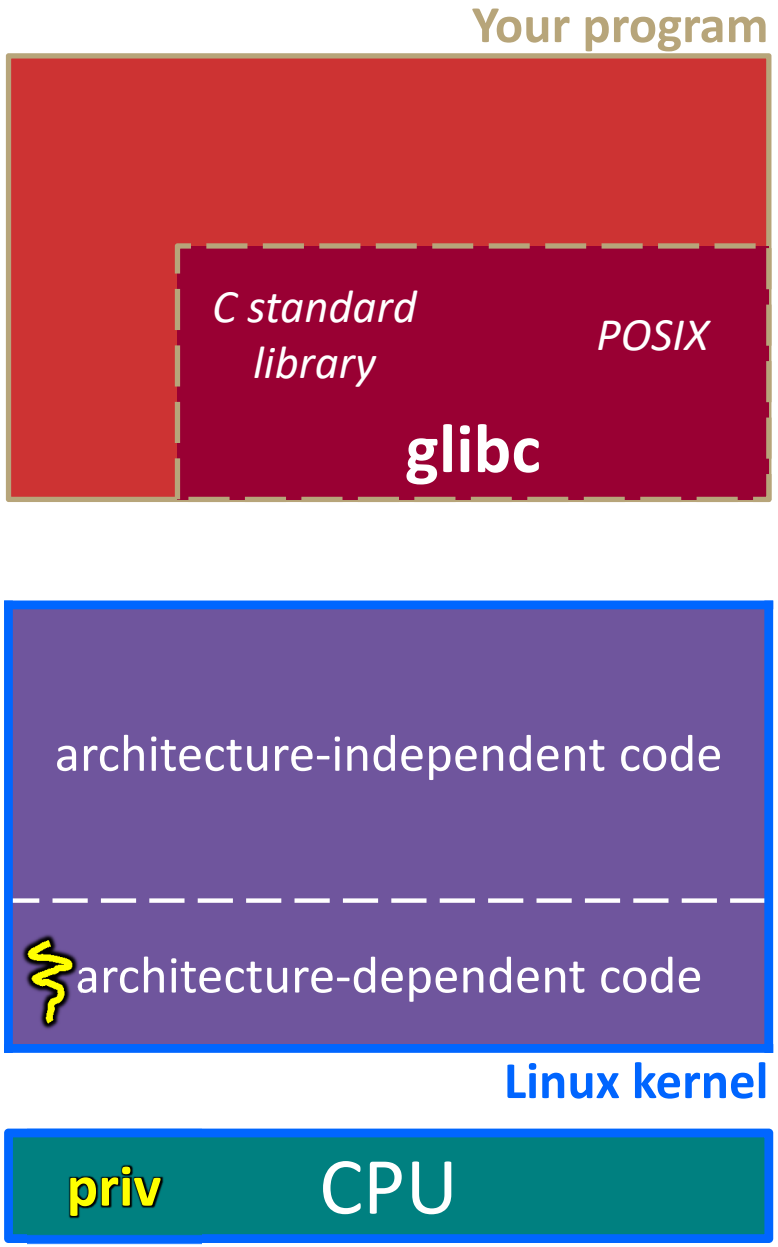


Details on x86/Linux

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

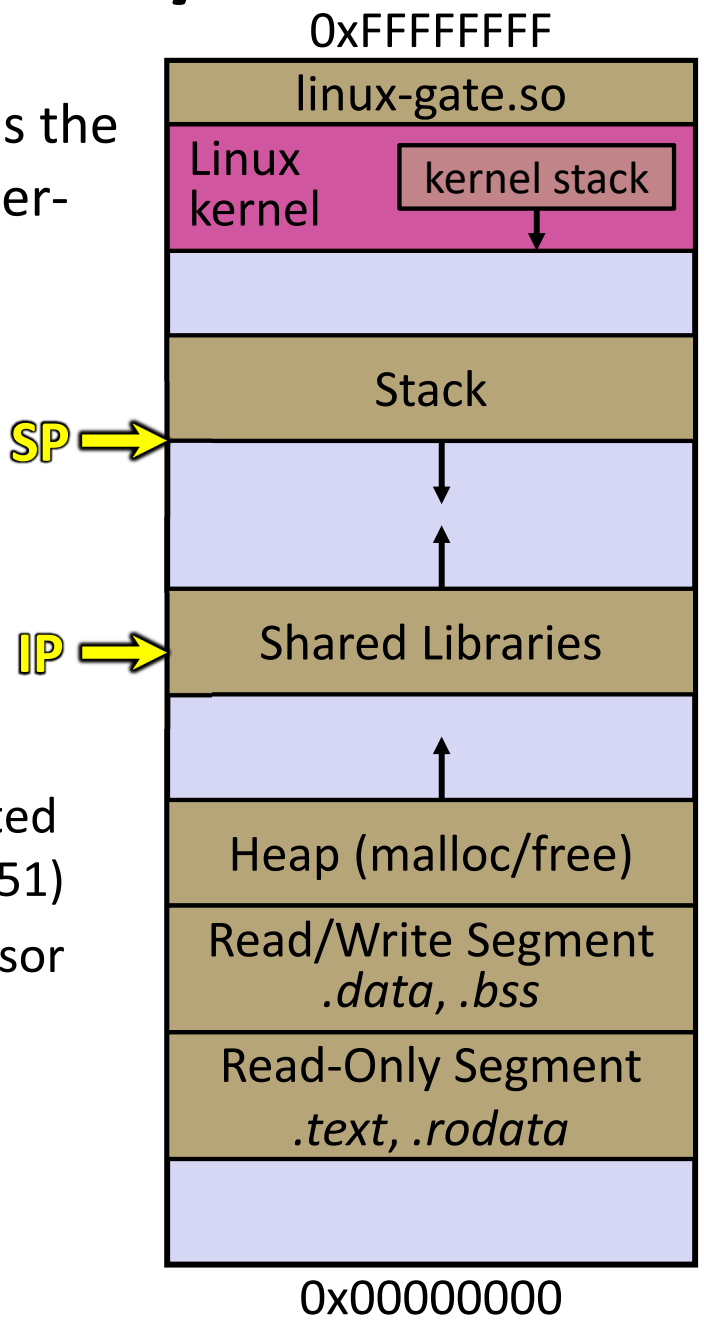


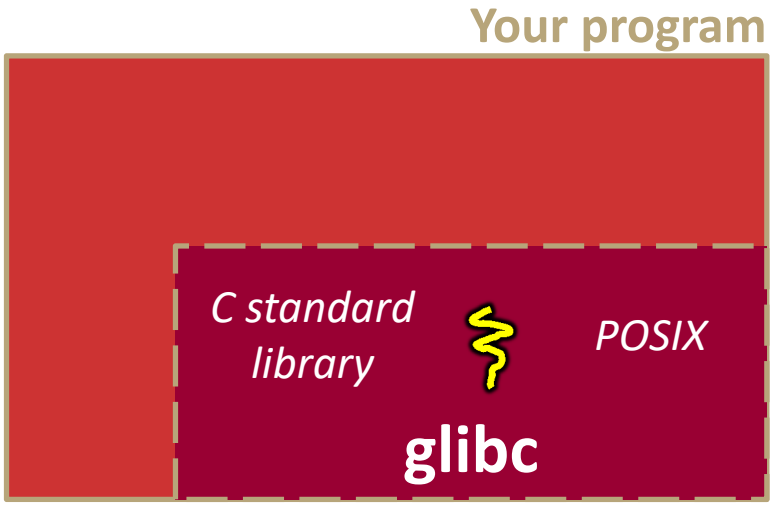


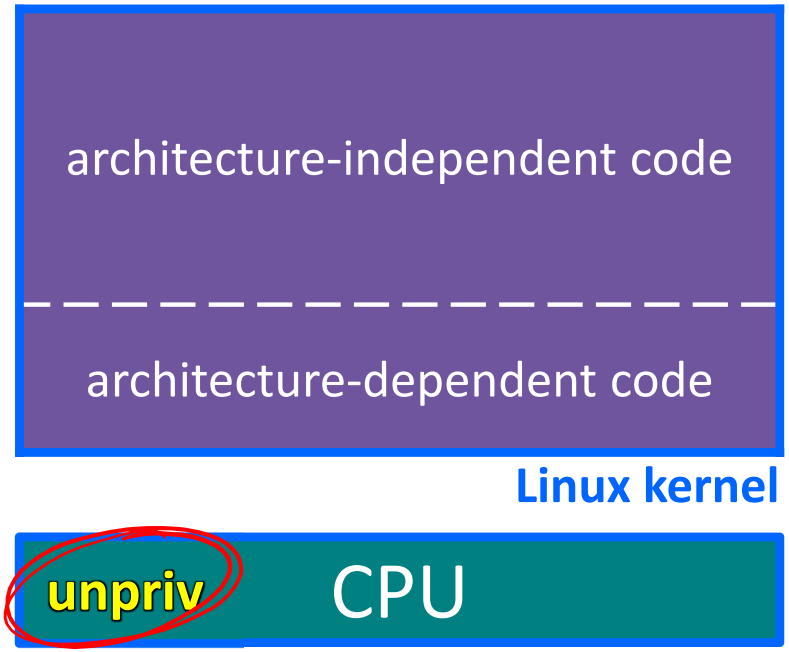
Details on x86/Linux

`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`



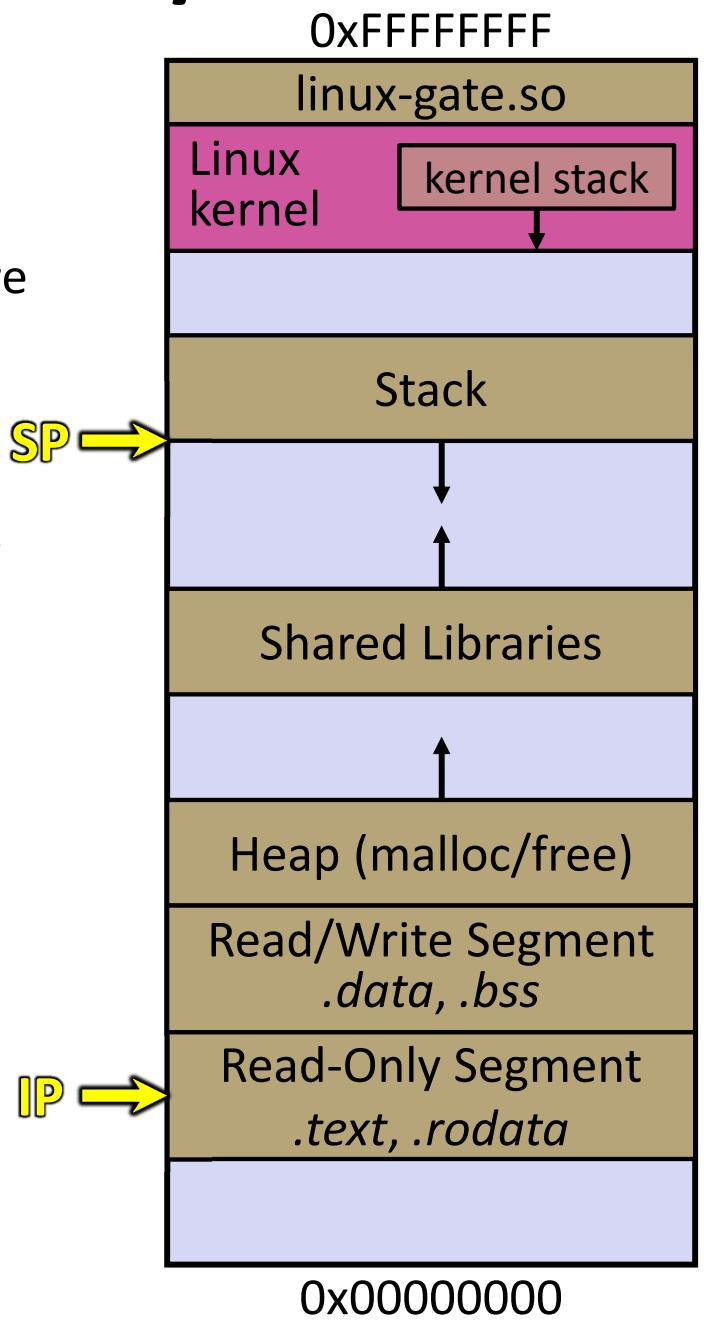


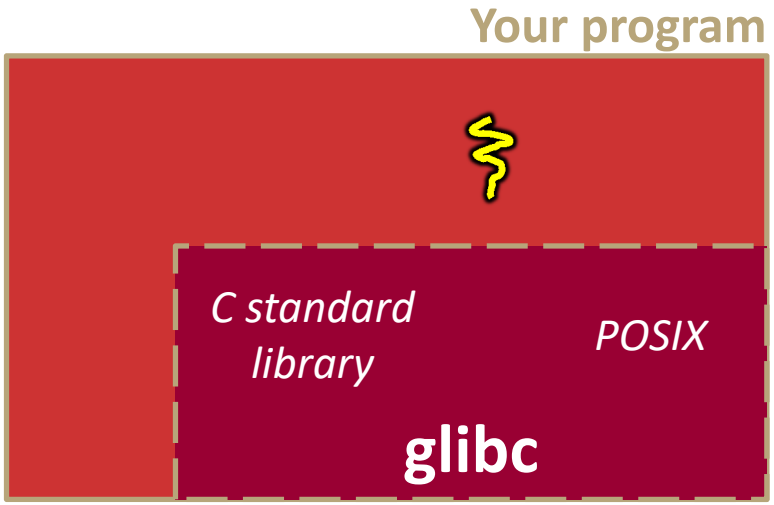


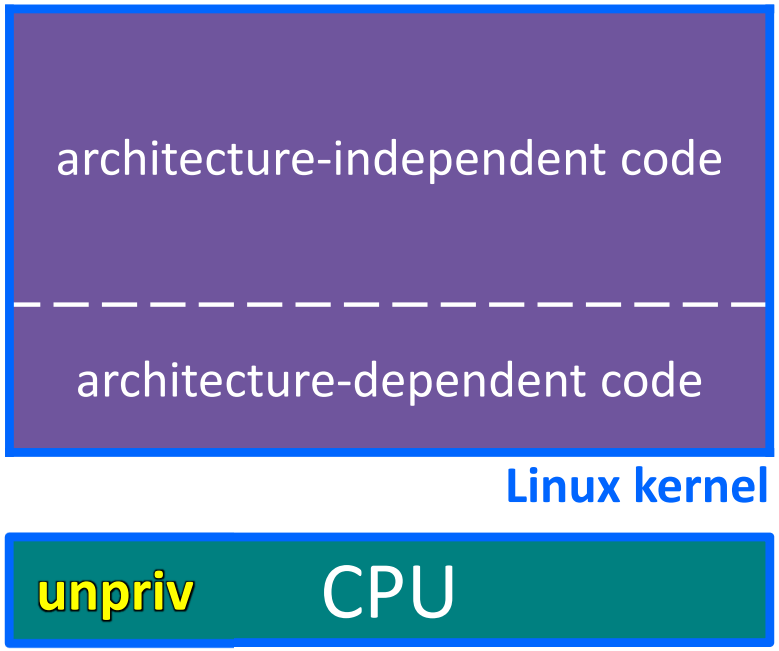
Details on x86/Linux

`glibc` continues to execute

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







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\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 1: user commands

- `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

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

C Standard Library File I/O

- So far you've used 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

Lower-Level File Access

- 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 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

open()/close()

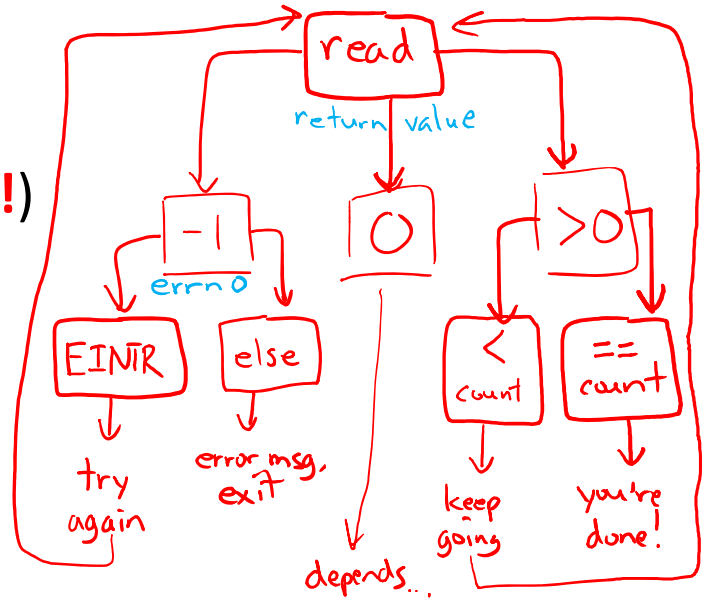
- To open a file:
  - Pass in the filename and access mode
    - Similar to **fopen**()
  - Get back a "file descriptor"
    - Similar to `FILE*` from **fopen**(), but is just an `int`
    - Defaults: **0** is `stdin`, **1** is `stdout`, **2** is `stderr`

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

Reading from a File

try to read count bytes

- `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`)

- There are some surprising error modes (check `errno`)

these are defined in errno.h

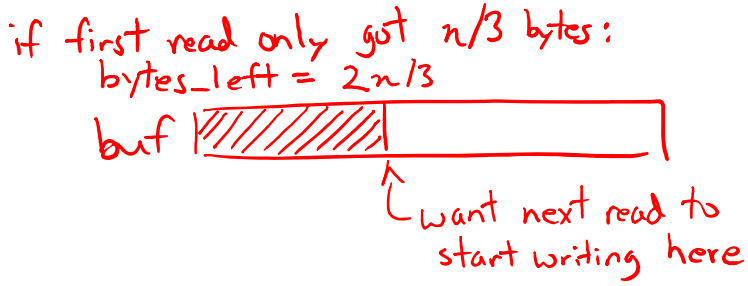
  - `EBADF`: bad file descriptor
  - `EFAULT`: output buffer is not a valid address
  - `EINTR`: read was interrupted, please try again (ARGH!!!! 😤😤)
  - And many others…

One way to `read()` n bytes

- Which is the correct completion of the blank below?
  - Vote at http://PollEv.com/justinh

```
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);
```

prevent infinite loop if EOF reached

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