Low-Level I/O, C++ Preview

CSE 333 Spring 2018

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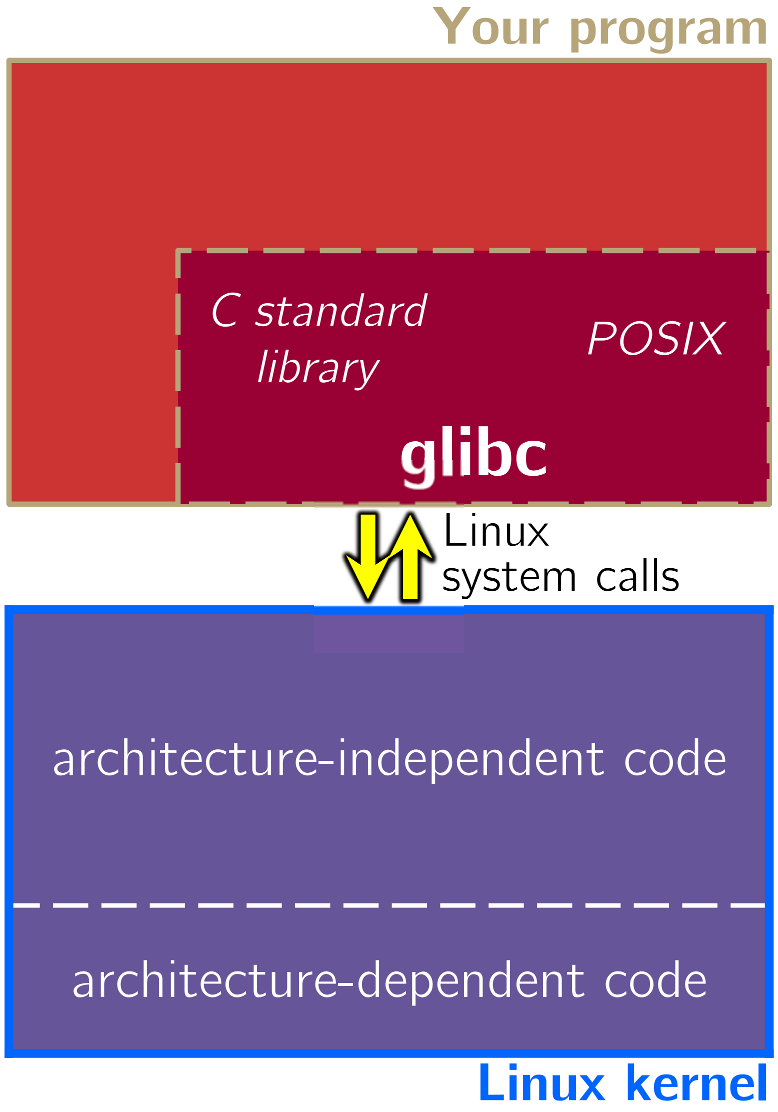
Administrivia

- Exercise 7 posted *tomorrow*, due Monday

- Homework 1 due tomorrow night (4/12)
  - 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

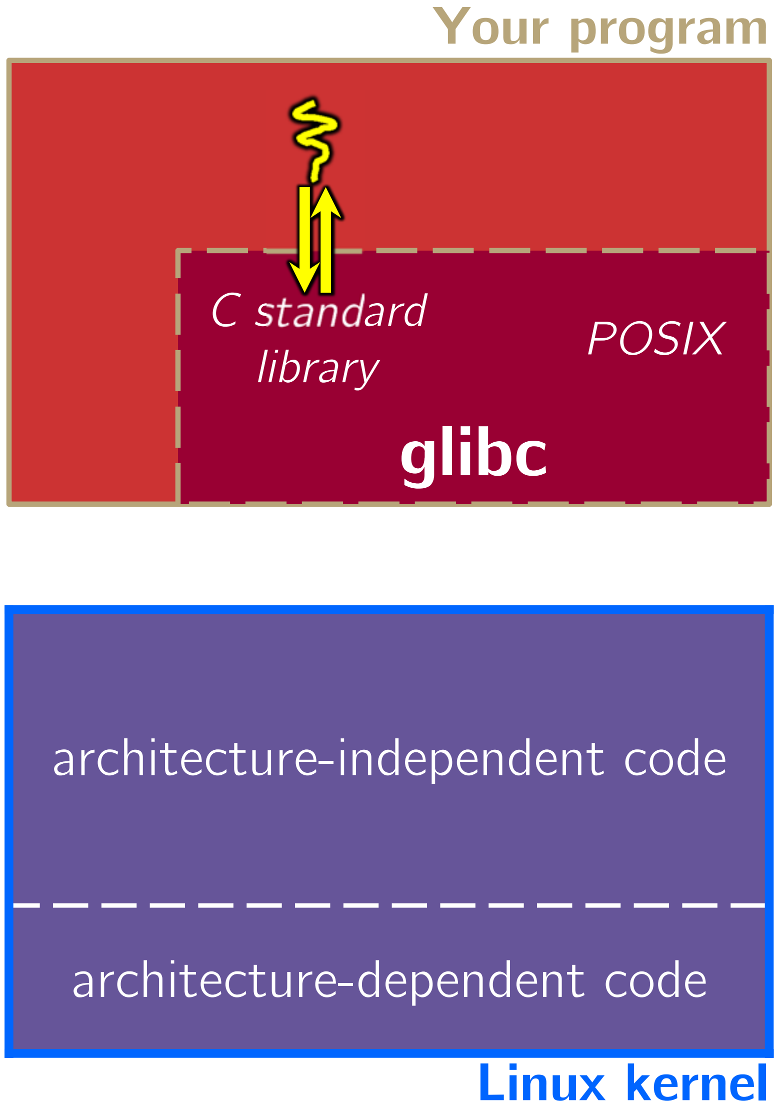
Details on x86/Linux

- 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



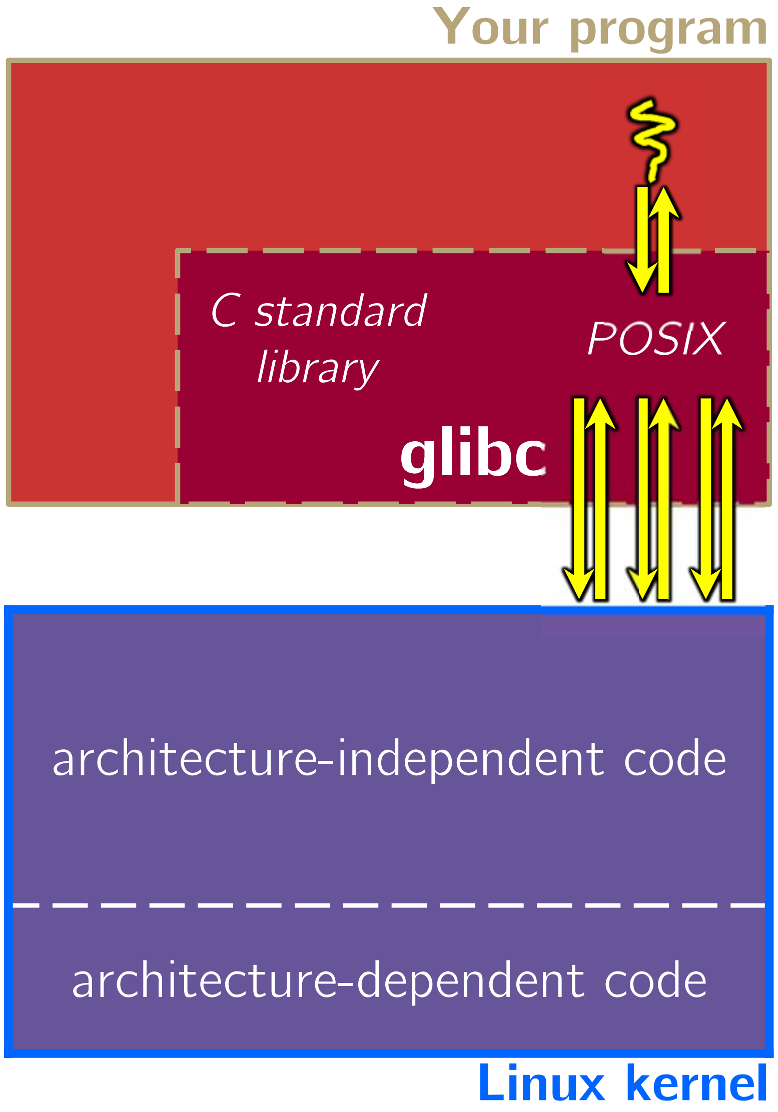
Details on x86/Linux

- 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 nearly as fast as a function call within your program itself!



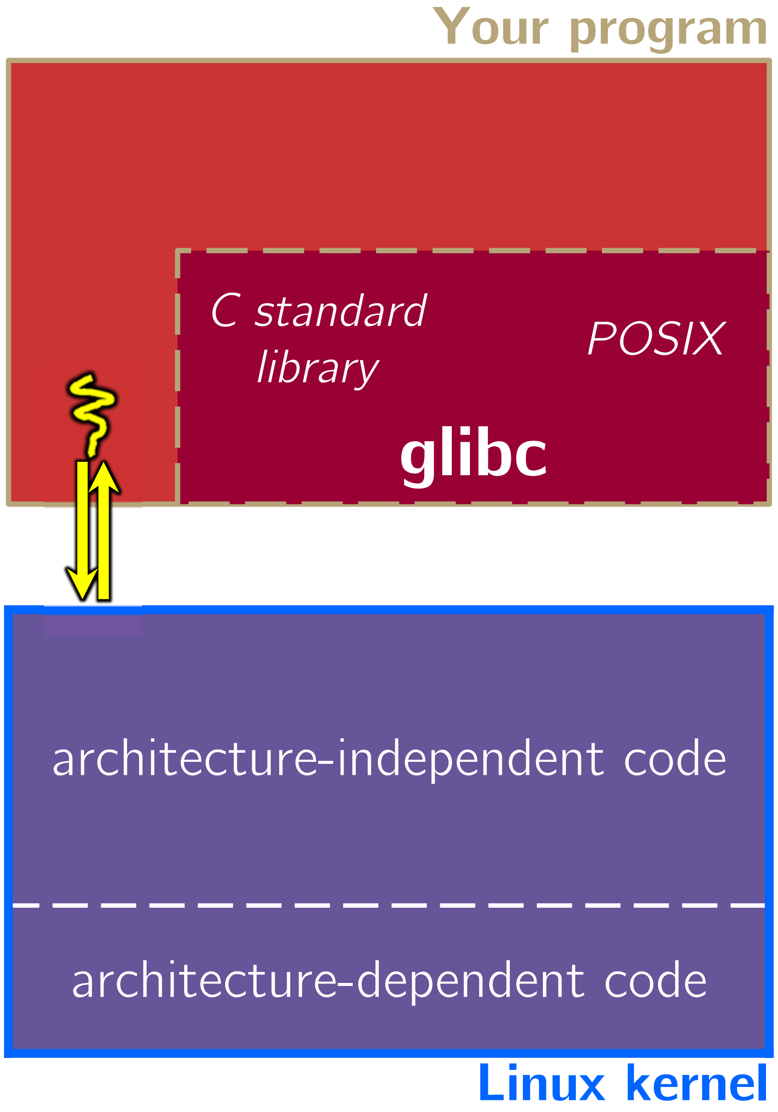
Details on x86/Linux

- 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.



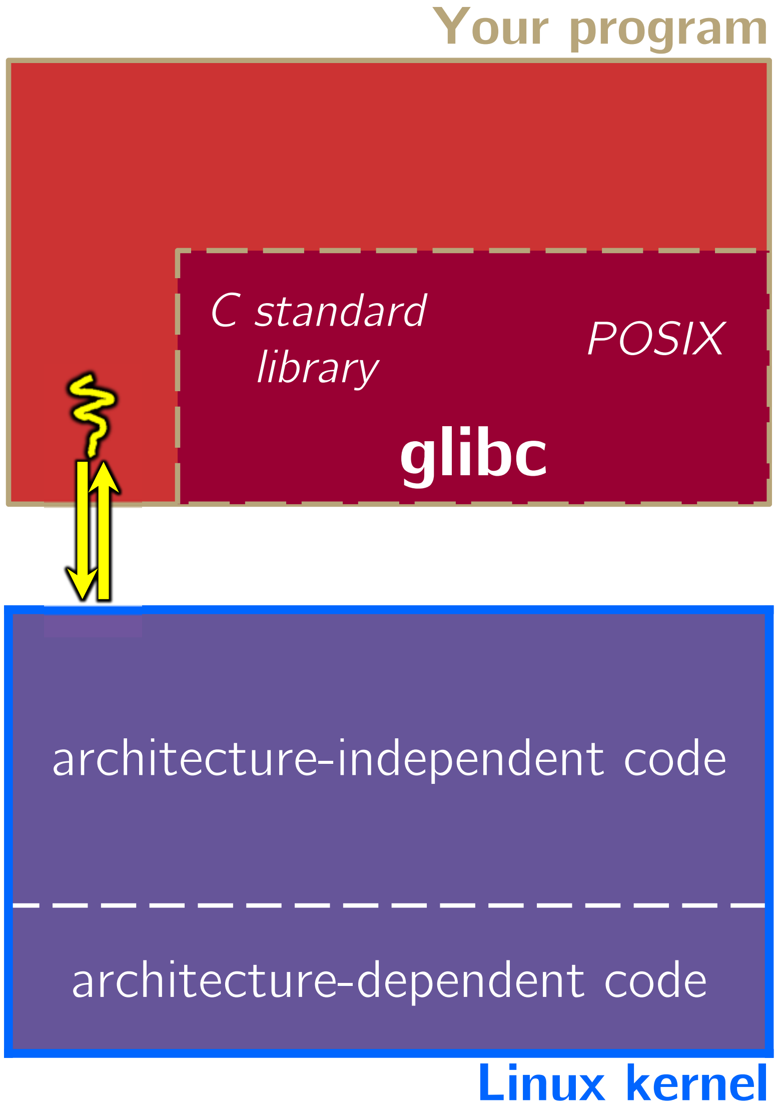
Details on x86/Linux

- 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

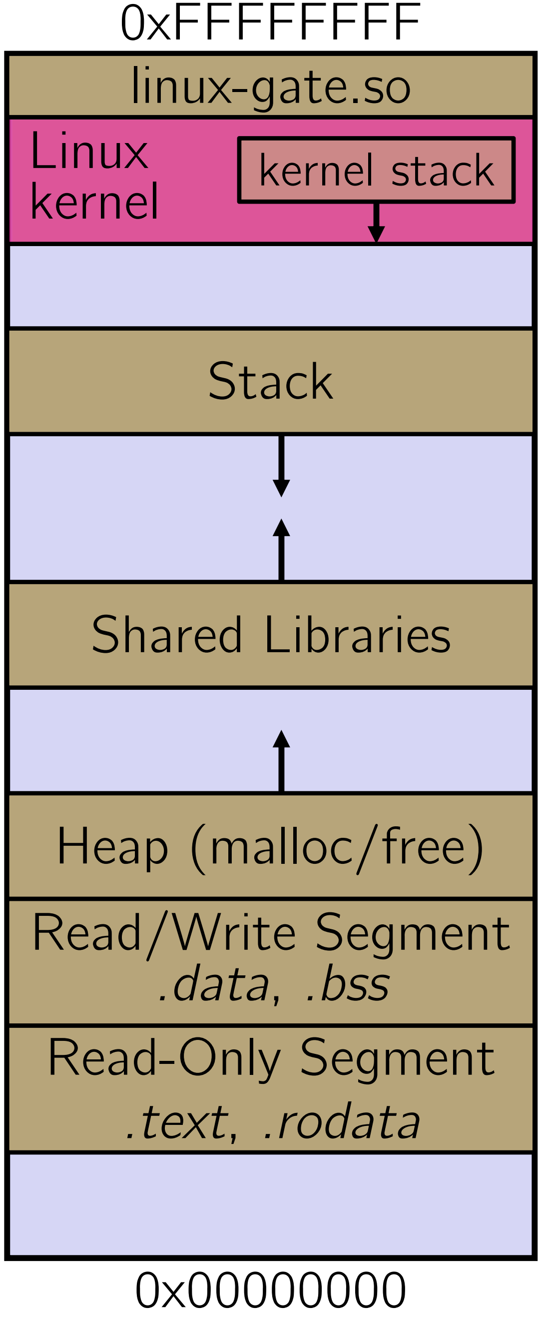
- Let's walk through how a Linux system call actually works
  - We'll assume *32-bit x86* using the modern **`SYSENTER`** / **`SYSEXIT`** x86 instructions
    - x86-64 code is similar, though details always change over time, so take this as an example – not a debugging guide



Details on x86/Linux

Remember our process address space picture?

- Let’s add some details:



0xFFFFFFFF

linux-gate.so

Linux kernel

kernel stack

Stack

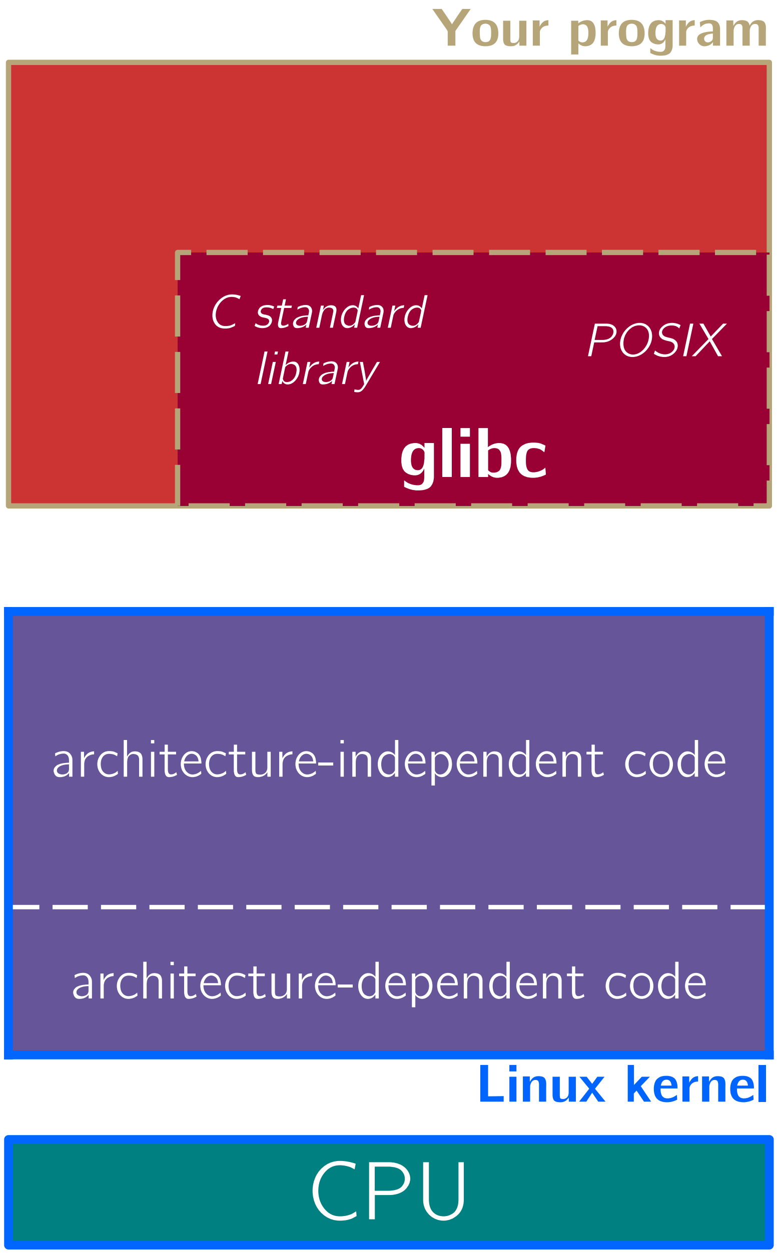
Shared Libraries

Heap (malloc/free)

Read/Write Segment
.data, .bss

Read-Only Segment
.text, .rodata

0x00000000



Your program

C standard library

POSIX

glibc

architecture-independent code

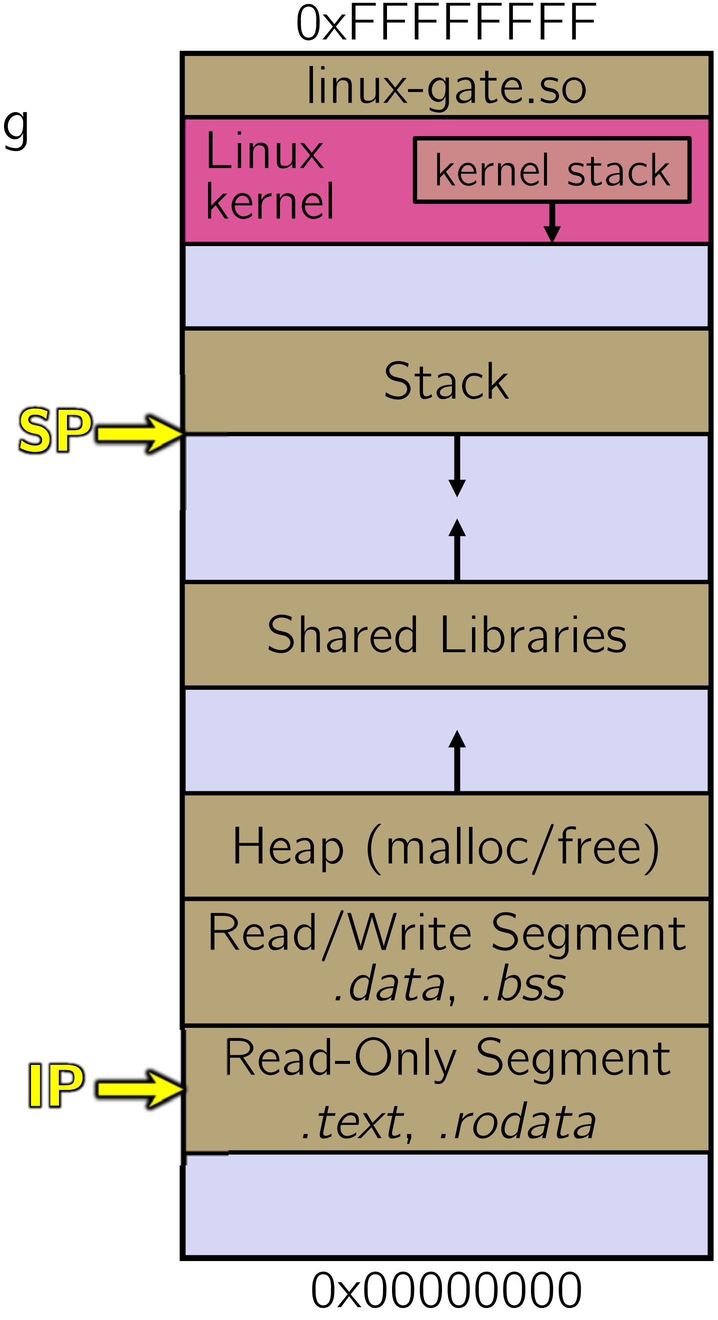
architecture-dependent code

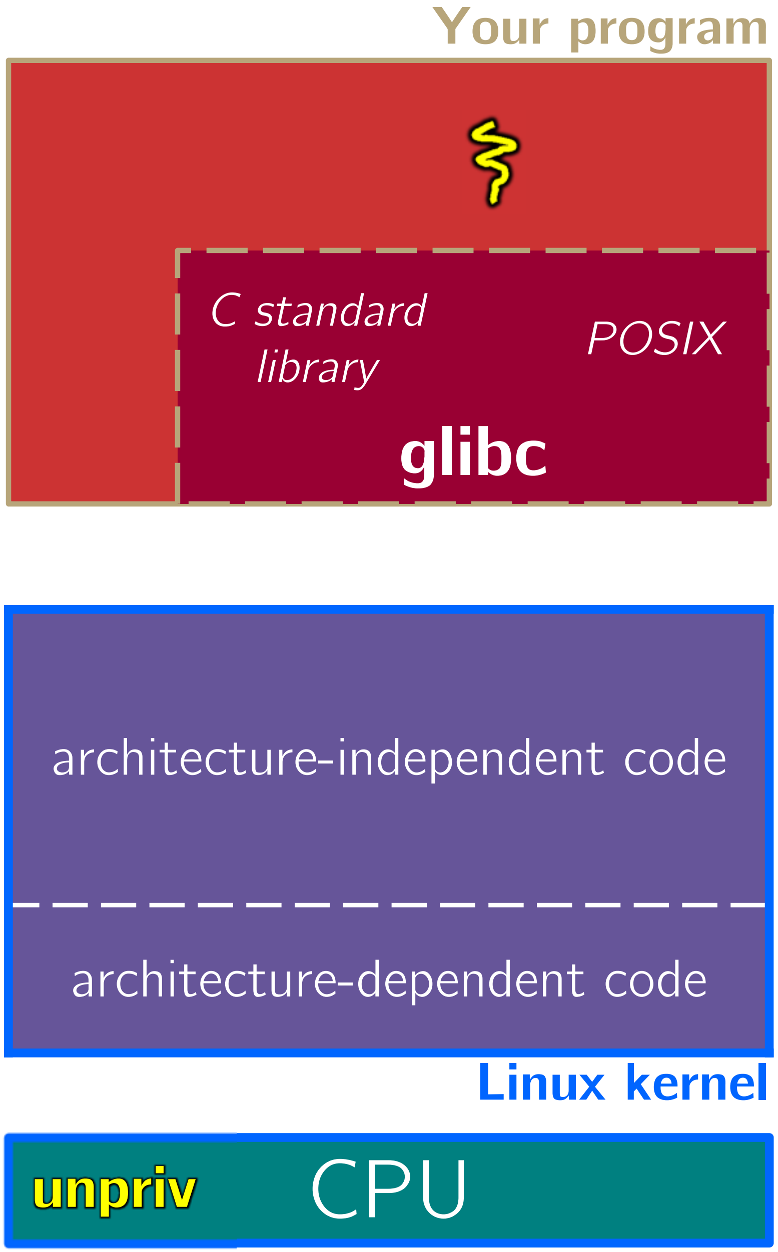
Linux kernel

CPU

Details on x86/Linux

Process is executing your program code

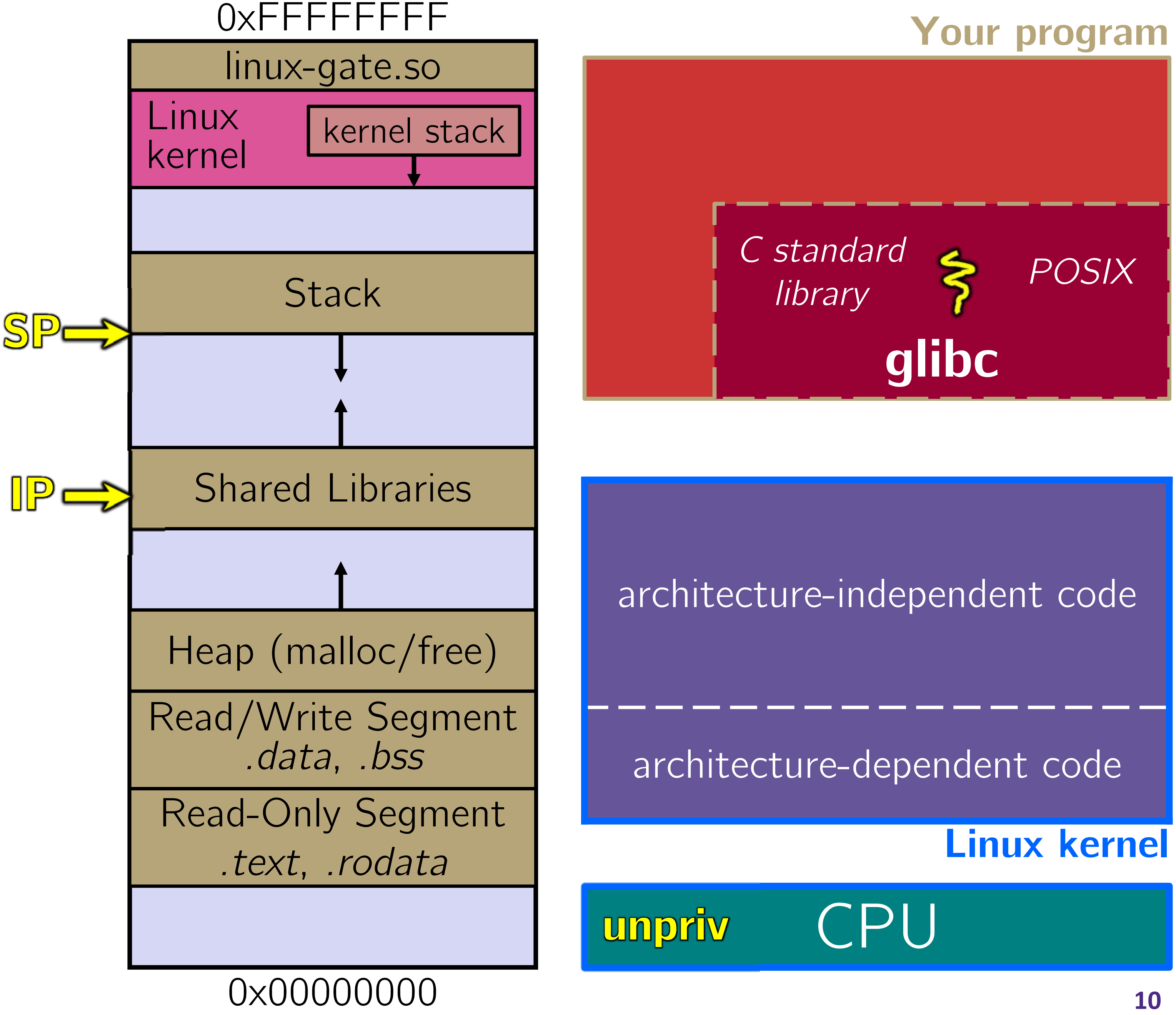




Details on x86/Linux

Process calls into a `glibc` function

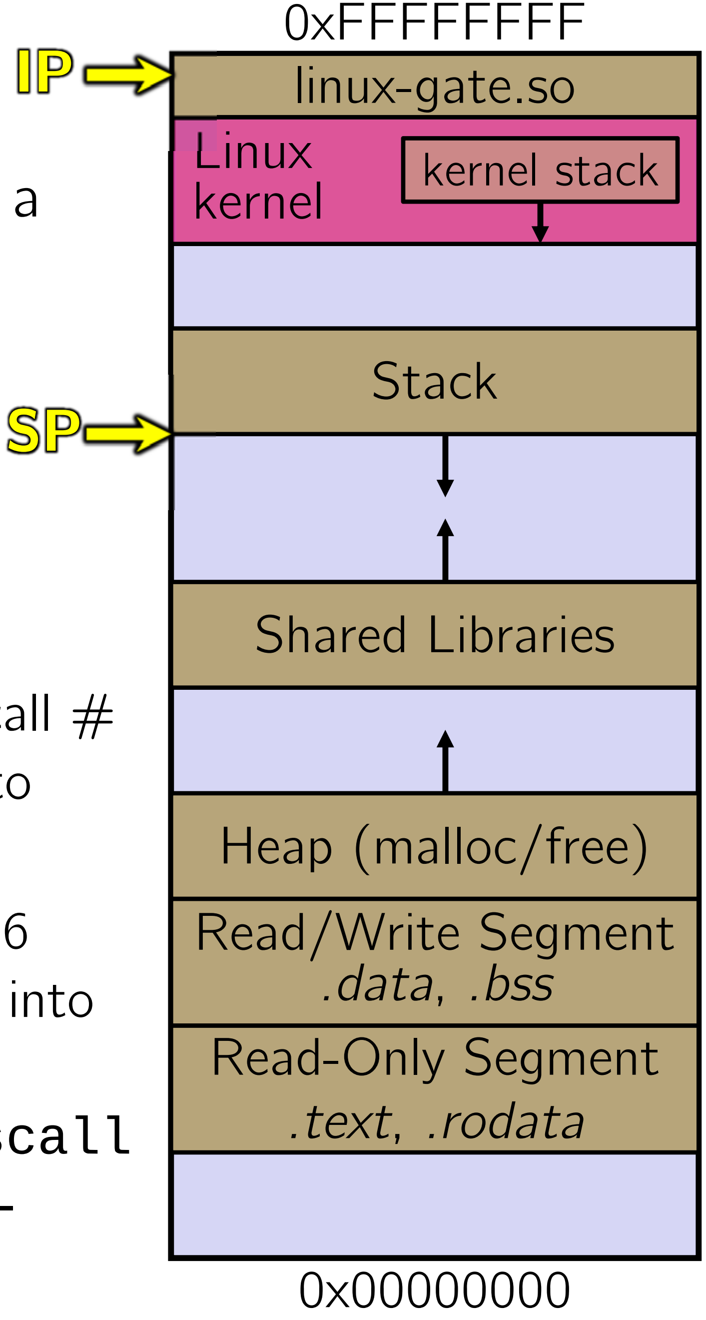
- *e.g.* `fopen()`
- We'll ignore the messy details of loading/linking shared libraries



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`



0xFFFFFFFF

IP

linux-gate.so

Linux kernel

kernel stack

Stack

SP

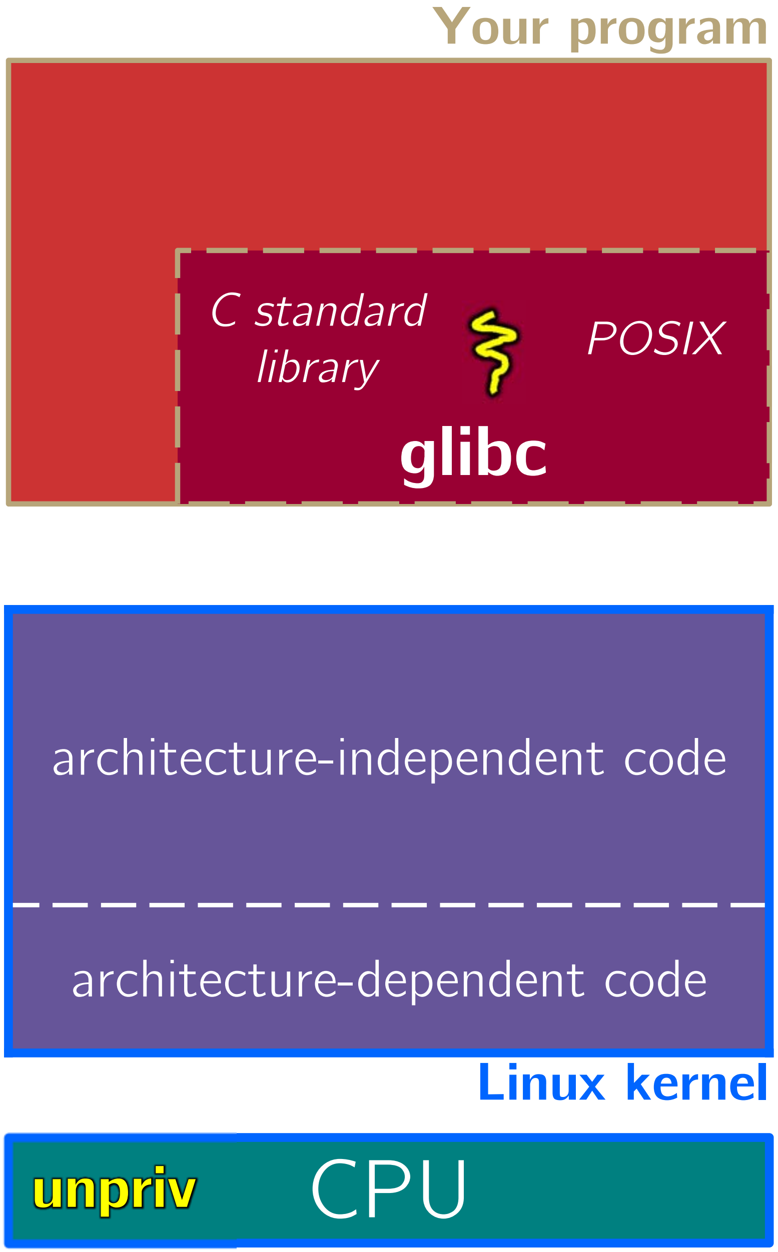
Shared Libraries

Heap (malloc/free)

Read/Write Segment
.data, .bss

Read-Only Segment
.text, .rodata

0x00000000



Your program

C standard library

POSIX

glibc

architecture-independent code

architecture-dependent code

Linux kernel

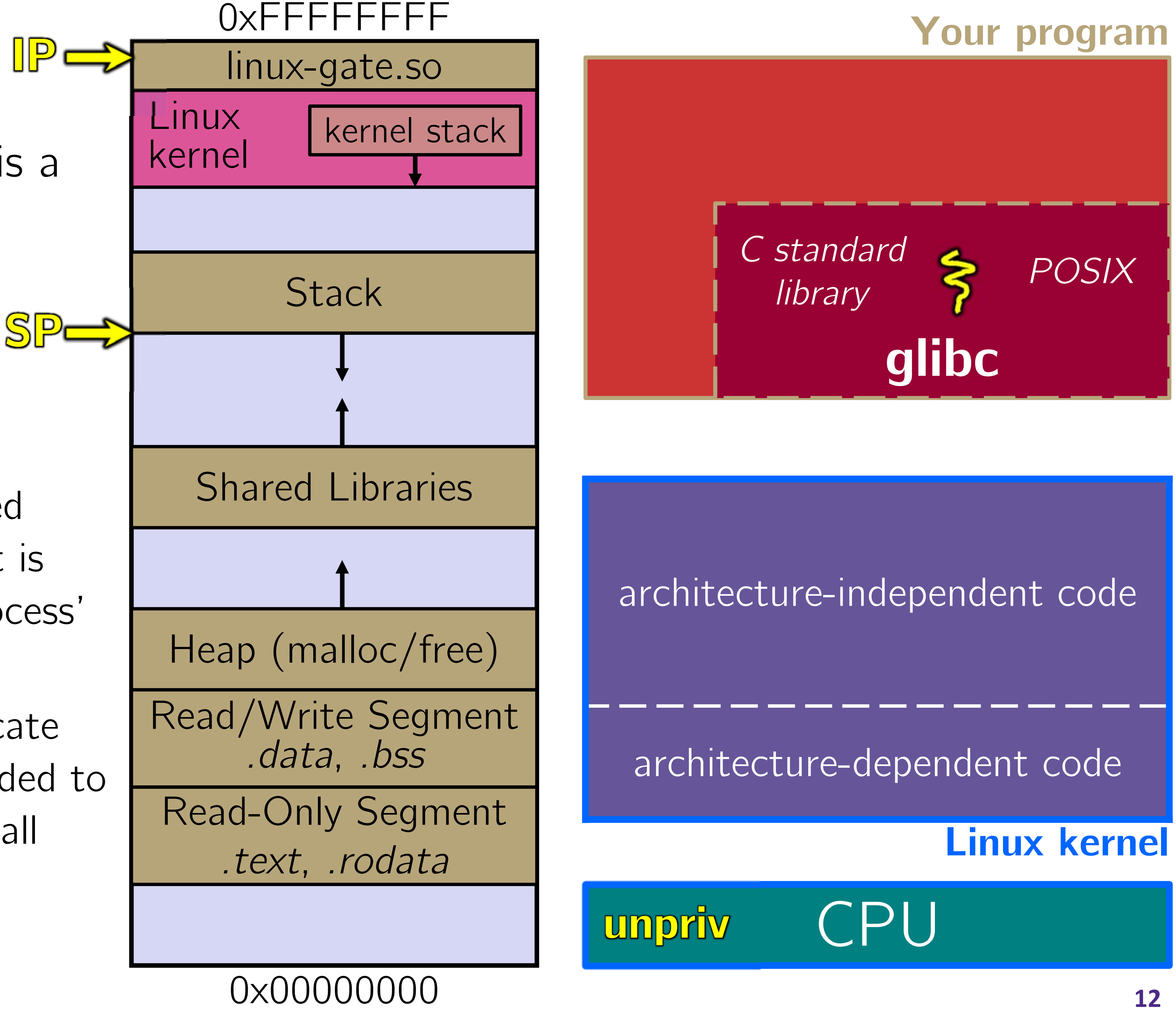
unpriv

CPU

Details on x86/Linux

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

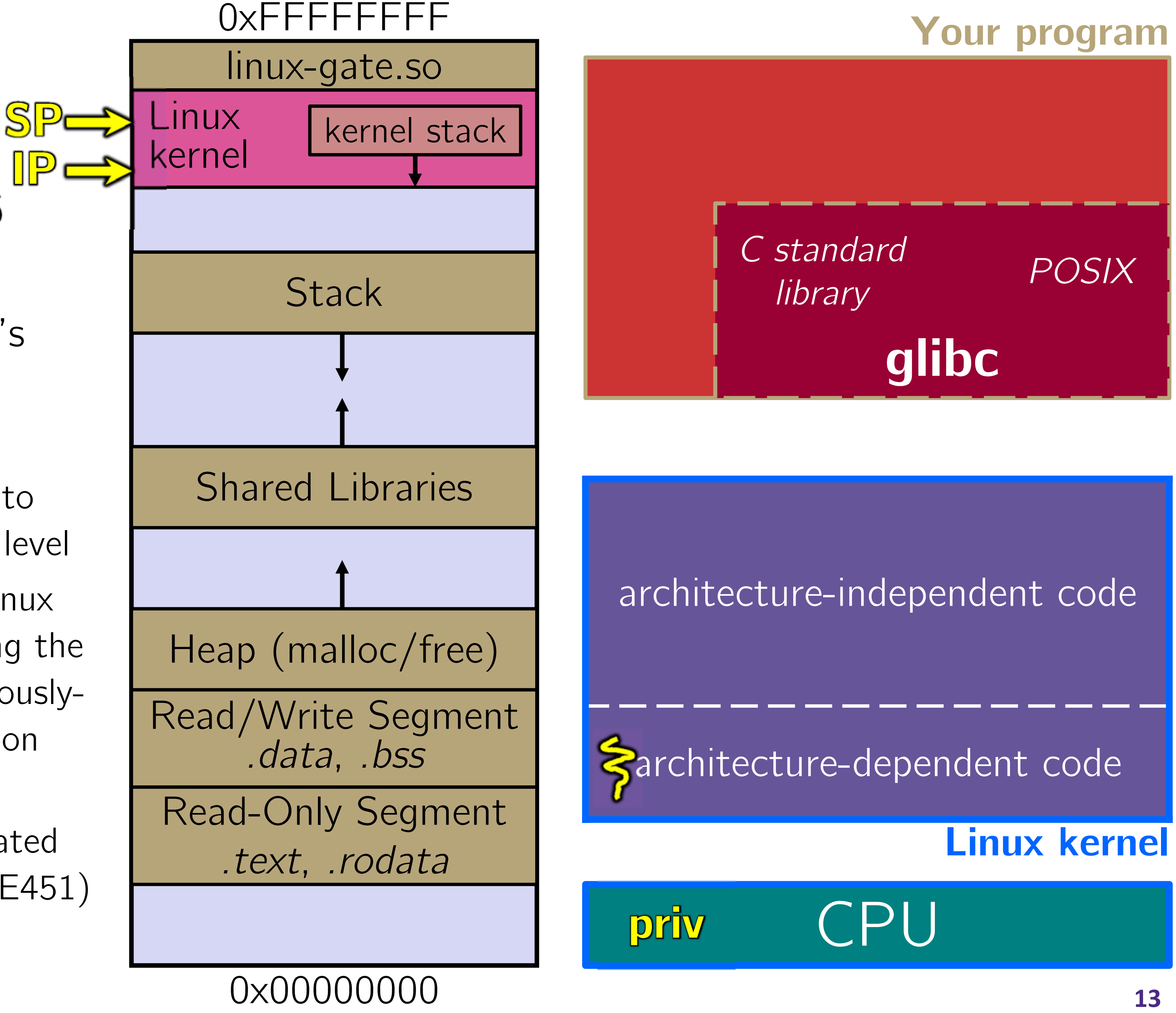
- A virtual dynamically linked shared object
- Is a kernel-provided shared library that is plunked into a process' address space
- Provides the intricate machine code needed to trigger a system call



Details on x86/Linux

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

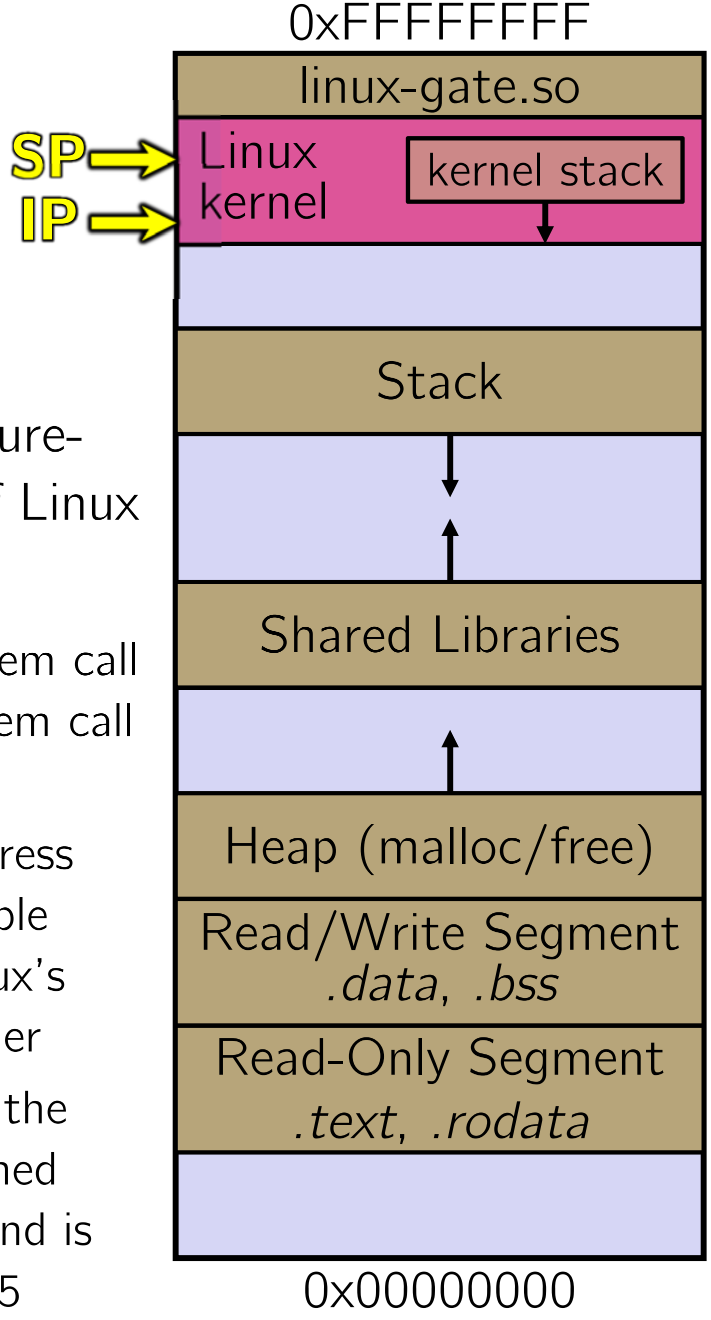
- **SYSENTER** is x86's "fast system call" instruction
  - Causes the CPU to raise its privilege level
  - Traps into the Linux kernel by changing the SP, IP to a previously-determined location
  - Changes some segmentation-related registers (see CSE451)

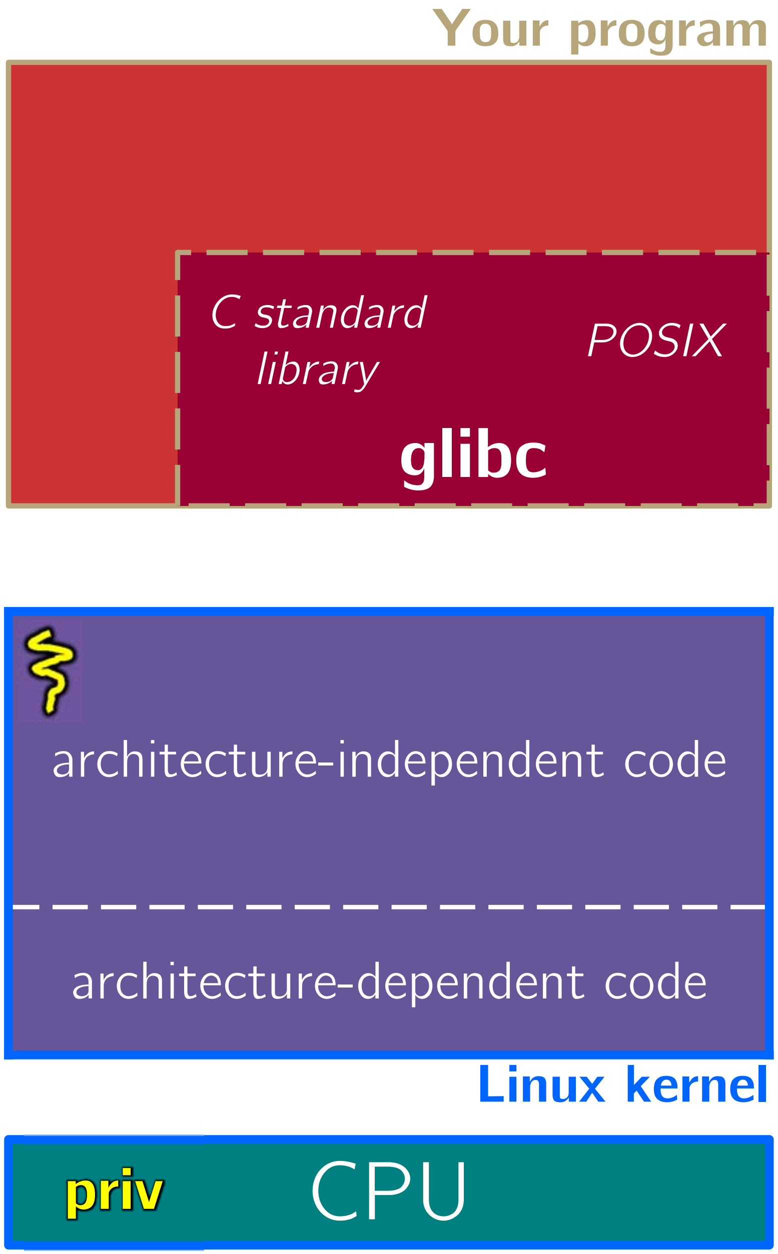


Details on x86/Linux

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

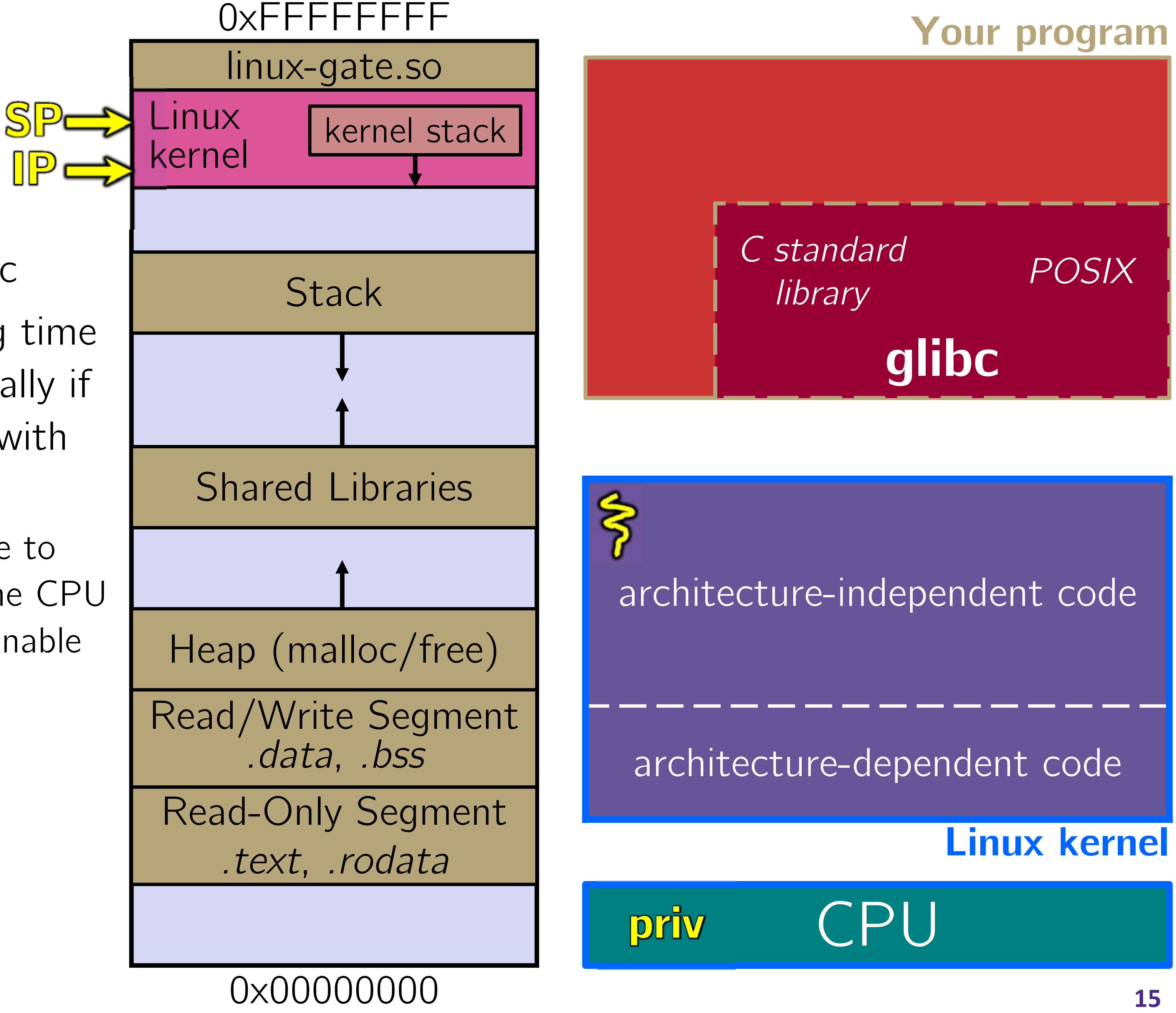




Details on x86/Linux

The system call handler executes

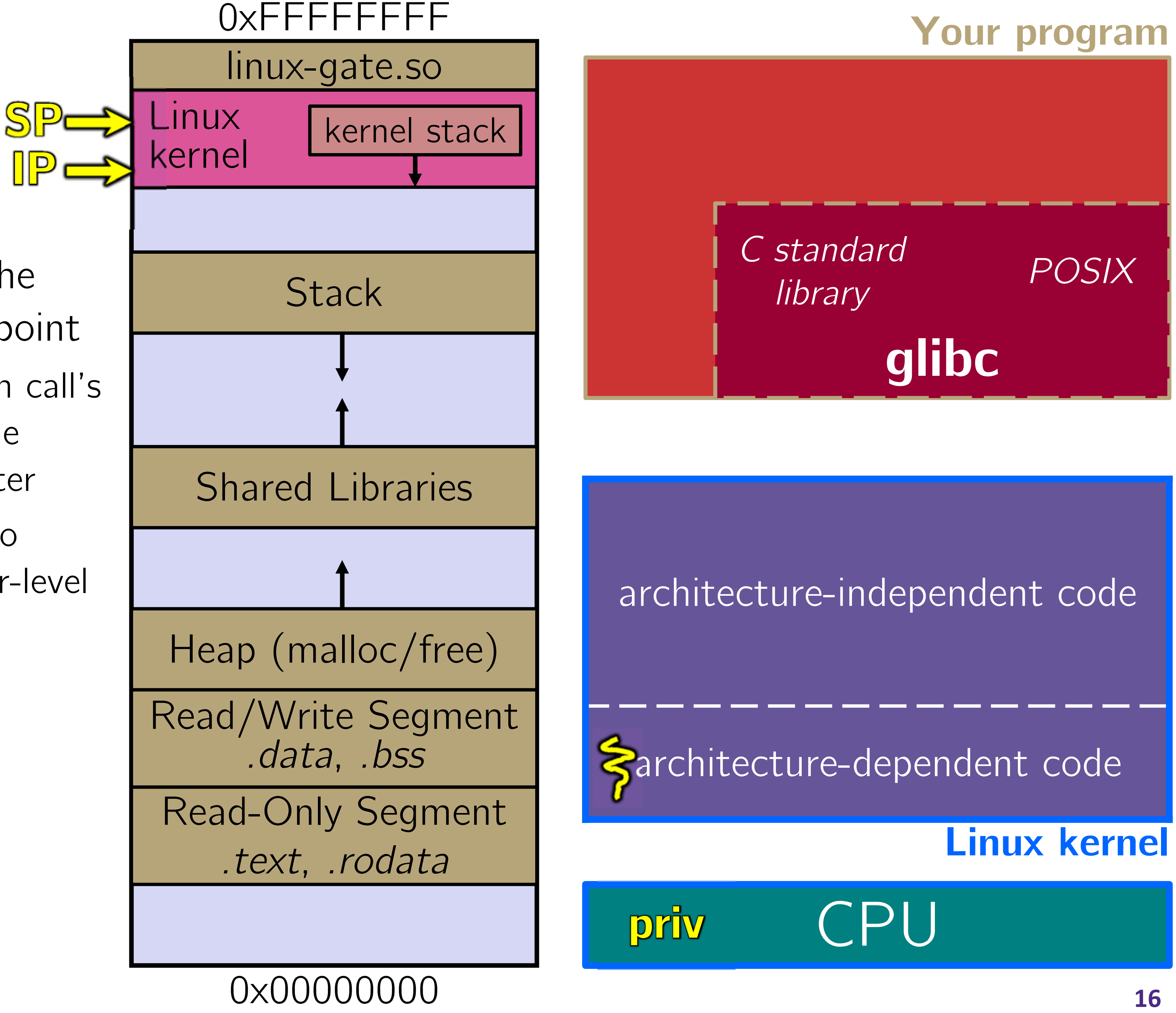
- What it does is system-call specific
- It may take a long time to execute, especially if it has to interact with hardware
  - Linux may choose to context switch the CPU to a different runnable process



Details on x86/Linux

Eventually, the system call handler finishes

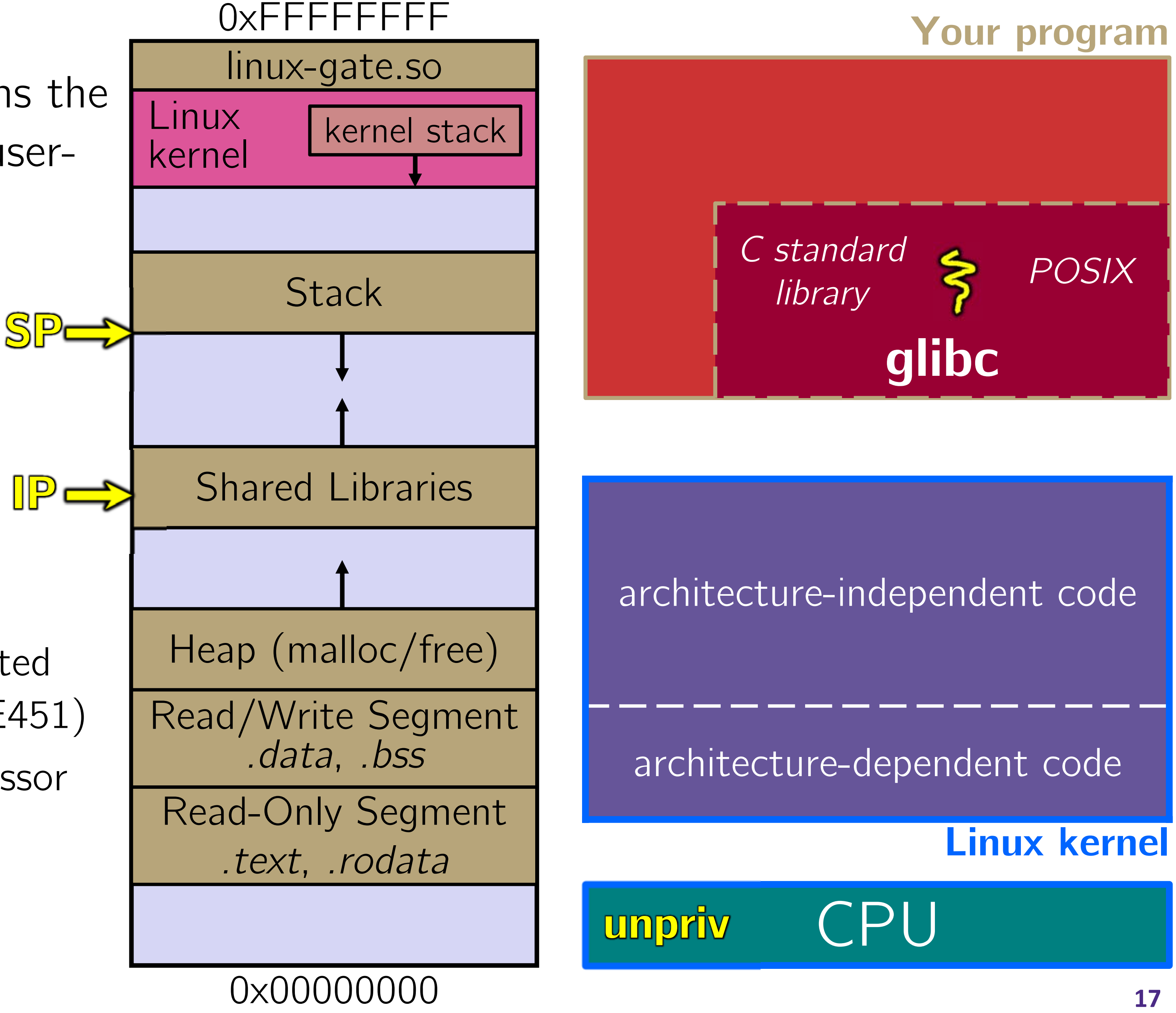
- Returns back to the system call entry point
  - Places the system call's return value in the appropriate register
  - Calls **`SYSEXIT`** to return to the user-level code



Details on x86/Linux

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

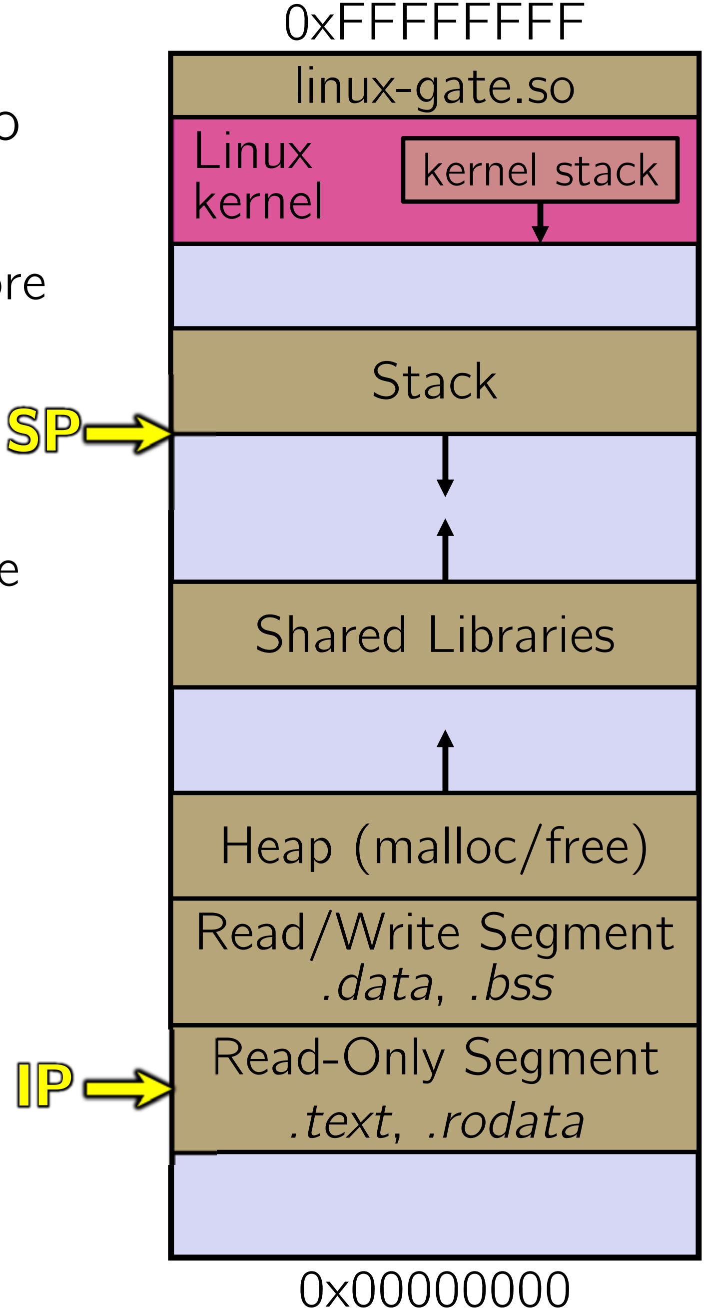
- Restores the IP, SP to user-land values
- Sets the CPU back to unprivileged mode
- Changes some segmentation-related registers (see CSE451)
- Returns the processor back to `glibc`

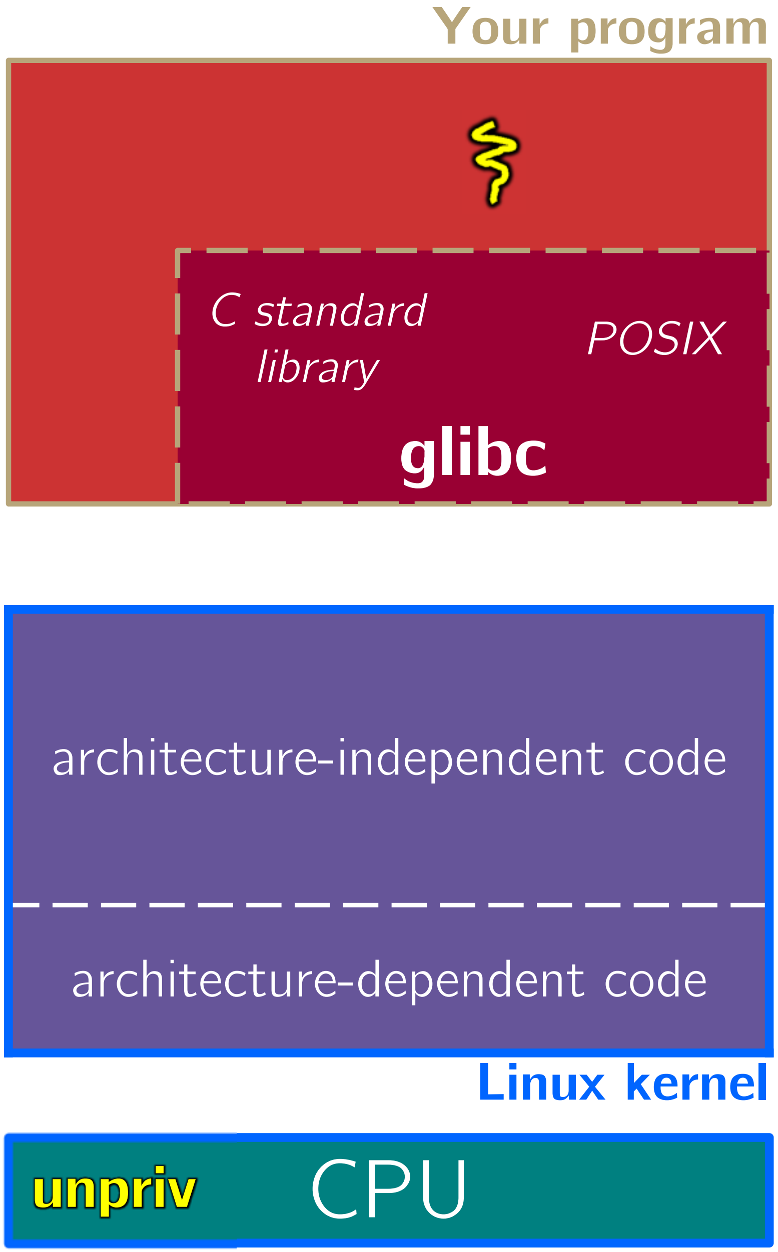


Details on x86/Linux

`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\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`

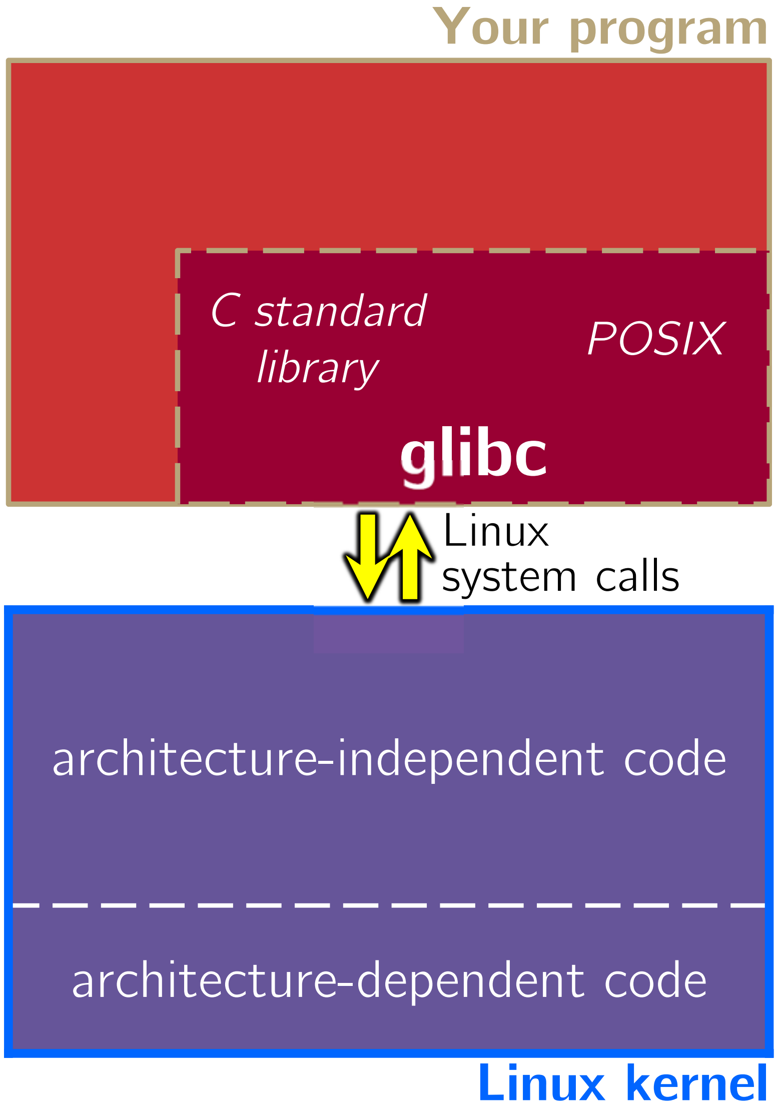
- *The* book: *The Linux Programming Interface* by Michael Kerrisk (keeper of the Linux man pages)

Lecture Outline

- **Lower-Level I/O**
- C++ Preview

Remember This Picture?

- Your program can access many layers of APIs:
  - C standard library
  - POSIX compatibility API
  - Underlying OS system calls



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 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()
  ...
  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
  - On error, the `errno` global variable is set
    - You need to check it to see what kind of error happened
      - `EBADF:` bad file descriptor
      - `EFAULT:` output buffer is not a valid address
      - `EINTR:` read was interrupted, please try again (ARGH!!!! 😤😫)
      - And many others…

One method 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);
```

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

Lecture Outline

- Lower-Level I/O
- **C++ Preview**
  - **Comparison to C**

C

- We had to work hard to mimic encapsulation, abstraction
    - **Encapsulation:** hiding implementation details
        - Used header file conventions and the "static" specifier to separate private functions from public functions
        - Cast structures to void* to hide implementation-specific details (generalize)
    - **Abstraction:** associating behavior with encapsulated state
        - Function that operate on a LinkedList were not really tied to the linked list structure
        - We passed a linked list to a function, rather than invoking a method on a linked list instance

C++

- A major addition is support for classes and objects!
  - Classes
    - Public, private, and protected **methods** and **instance variables**
    - (multiple!) inheritance
  - Polymorphism
    - Static polymorphism: multiple functions or methods with the same name, but different argument types (overloading)
      - Works for all functions, not just class members
    - Dynamic (subtype) polymorphism: derived classes can override methods of parents, and methods will be dispatched correctly

C

- We had to emulate generic data structures
  - Generic linked list using `void*` payload
  - Pass function pointers to generalize different “methods” for data structures
    - Comparisons, deallocation, pickling up state, etc.

C++

- Supports templates to facilitate generic data types
  - Parametric polymorphism – same idea as Java generics, but different in details, particularly implementation
  - To declare that x is a vector of ints: `vector<int> x;`
  - To declare that x is a vector of floats: `vector<float> x;`
  - To declare that x is a vector of (vectors of floats): `vector<vector<float>> x;`

C

- We had to be careful about namespace collisions
  - C distinguishes between external and internal linkage
    - Use `static` to prevent a name from being visible outside a source file (as close as C gets to "private")
    - Otherwise, name is global and visible everywhere
  - We used naming conventions to help avoid collisions in the global namespace
    - *e.g.* `LLIteratorNext` vs. `HTIteratorNext`, etc.

C++

- Permits a module to define its own namespace!
  - The linked list module could define an “**`LL`**” namespace while the hash table module could define an “**`HT`**” namespace
  - Both modules could define an Iterator class
    - One would be globally named `LL::Iterator` and the other would be globally named `HT::Iterator`
- Classes also allow duplicate names without collisions
  - Namespaces group and isolate names in collections of classes and other “global” things (somewhat like Java packages)

C

- C does not provide any standard data structures
  - We had to implement our own linked list and hash table
  - As a C programmer, you often reinvent the wheel… poorly
    - Maybe if you're clever you'll use somebody else's libraries
    - But C's lack of abstraction, encapsulation, and generics means you'll probably end up tweak them or tweak your code to use them

C++

- The C++ standard library is huge!
  - **Generic containers:** bitset, queue, list, associative array (including hash table), deque, set, stack, and vector
    - And iterators for most of these
  - **A `string` class:** hides the implementation of strings
  - **Streams:** allows you to stream data to and from objects, consoles, files, strings, and so on
  - And more…

C

- Error handling is a pain
  - Have to define error codes and return them
  - Customers have to understand error code conventions and need to constantly test return values
  - *e.g.* if `a()` calls `b()`, which calls `c()`
    - `a` depends on `b` to propagate an error in `c` back to it

C++

- Supports exceptions!
  - `try` / `throw` / `catch`
  - If used with discipline, can simplify error processing
    - But, if used carelessly, can complicate memory management
    - Consider: `a()` calls `b()`, which calls `c()`
      - If `c()` throws an exception that `b()` doesn't catch, you might not get a chance to clean up resources allocated inside `b()`
- But much C++ code still needs to work with C & old C++ libraries, so still uses return codes, exit(), etc.

Some Tasks Still Hurt in C++

- Memory management
  - C++ has no garbage collector
    - You have to manage memory allocation and deallocation and track ownership of memory
    - It's still possible to have leaks, double frees, and so on
  - But there are some things that help
    - "Smart pointers"
      - Classes that encapsulate pointers and track reference counts
      - Deallocate memory when the reference count goes to zero

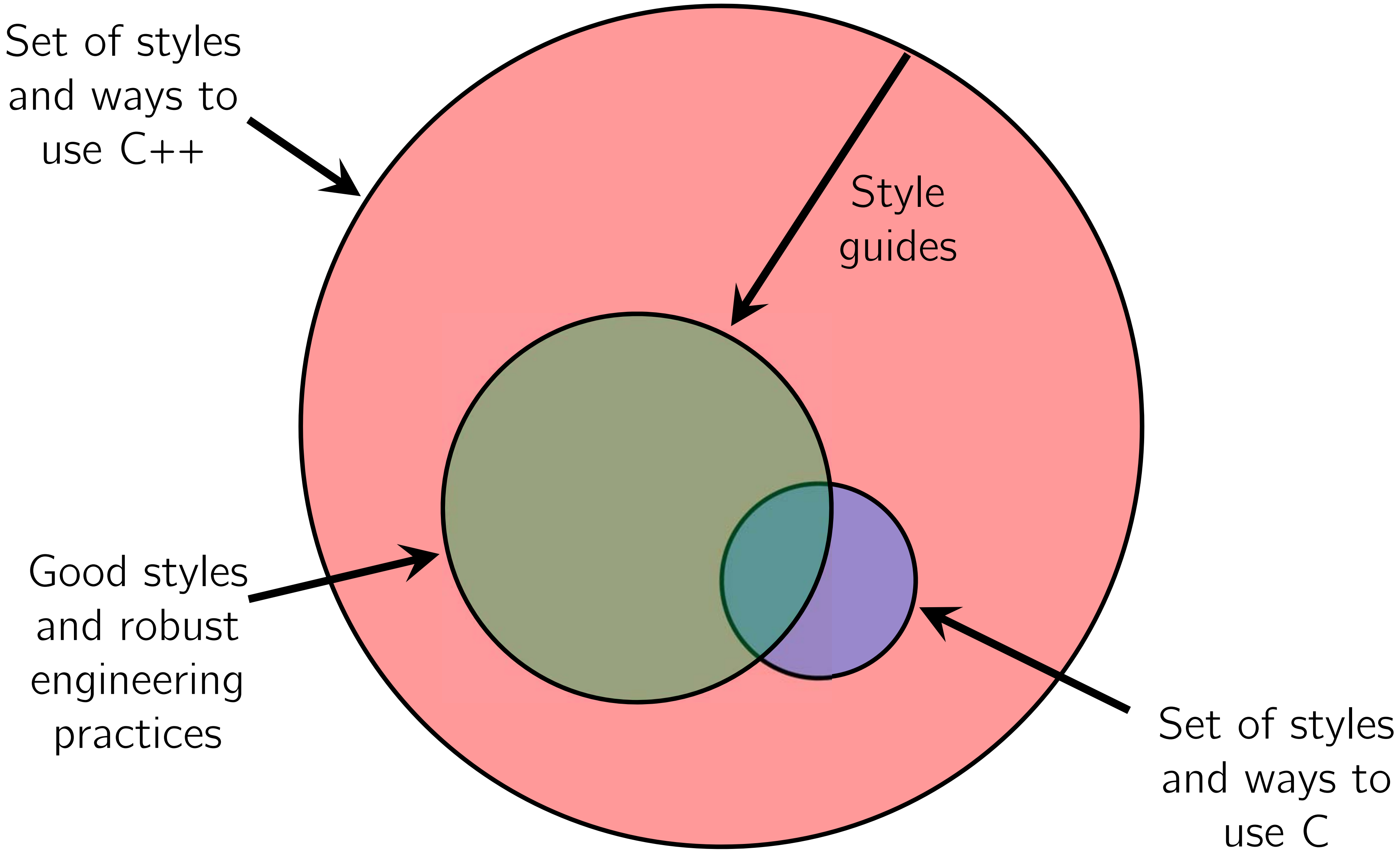
Some Tasks Still Hurt in C++

- C++ doesn’t guarantee type or memory safety
  - You can still:
    - Forcibly cast pointers between incompatible types
    - Walk off the end of an array and smash memory
    - Have dangling pointers
    - Conjure up a pointer to an arbitrary address of your choosing

C++ Has Many, Many Features

- Operator overloading
  - Your class can define methods for handling "**+**", "**->**", etc.
- Object constructors, destructors
  - Particularly handy for stack-allocated objects
- Reference types
  - Truly pass-by-reference instead of always pass-by-value
- Advanced Object Orientedness
  - Multiple inheritance, virtual base classes, dynamic dispatch

How to Think About C++



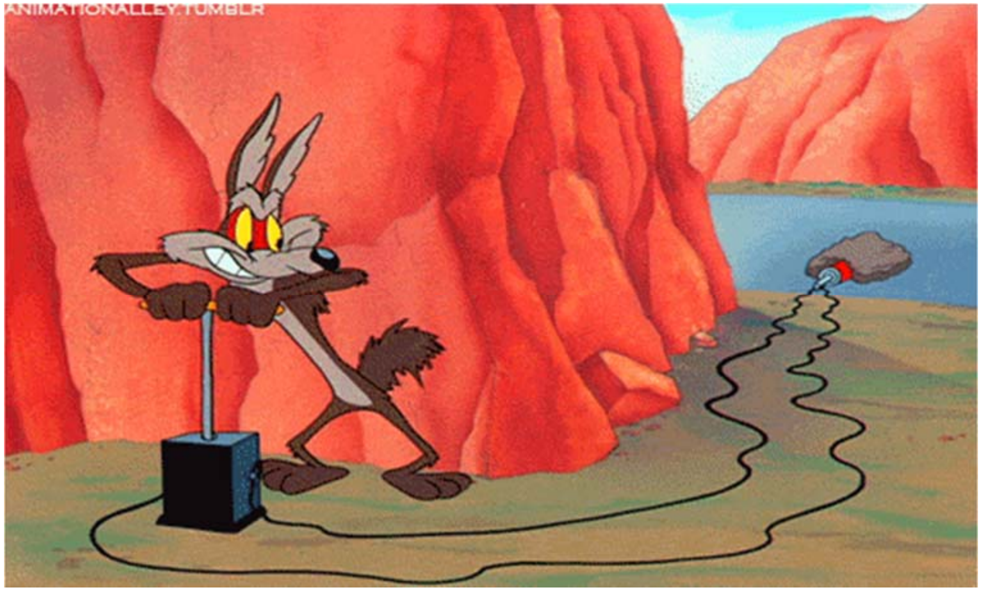
Set of styles and ways to use C++

Style guides

Good styles and robust engineering practices

Set of styles and ways to use C

Or…



In the hands of a disciplined programmer, C++ is a powerful tool

But if you're not so disciplined about how you use C++…