Processes
(Chapters 3-6)

CS 4410
Operating Systems

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Fred B. Schneider, E. Sirer, R. Van Renesse]

Process vs Program

- A program consists of code and data
  - specified in some programming language
- Typically stored in a file on disk
- "*Running a program*" = creating a process
  - you can run a program multiple times!
    - one after another or even concurrently

What is an “*Executable*”?

An executable is a file containing:

- executable code
  - CPU instructions
- data
  - information manipulated by these instructions

- Obtained by *compiling* a program
  - and linking with libraries

What is a “*Process*”?

- An executable running on an abstraction of a computer:

  - Address Space (memory) +
    Execution Context (registers incl. PC and SP)
    - manipulated through machine instructions
  - Environment (clock, files, network, …)
    - manipulated through system calls

A good abstraction:

- is portable and hides implementation details
- has an intuitive and easy-to-use interface
- can be instantiated many times
- is efficient to implement

Process ≠ Program

A program is passive:

code + data

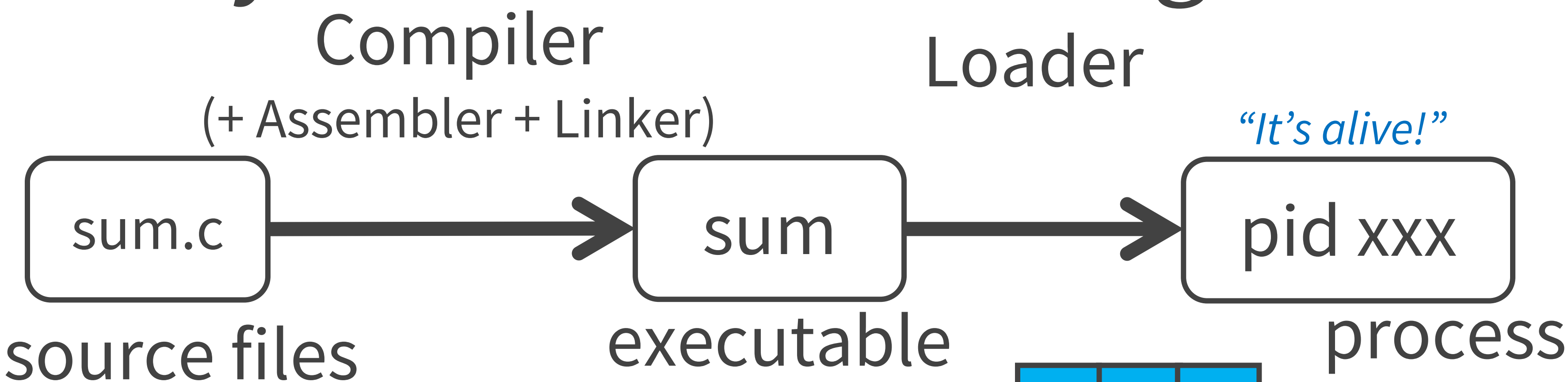
A process is ***alive:***

mutable data + registers + files + …

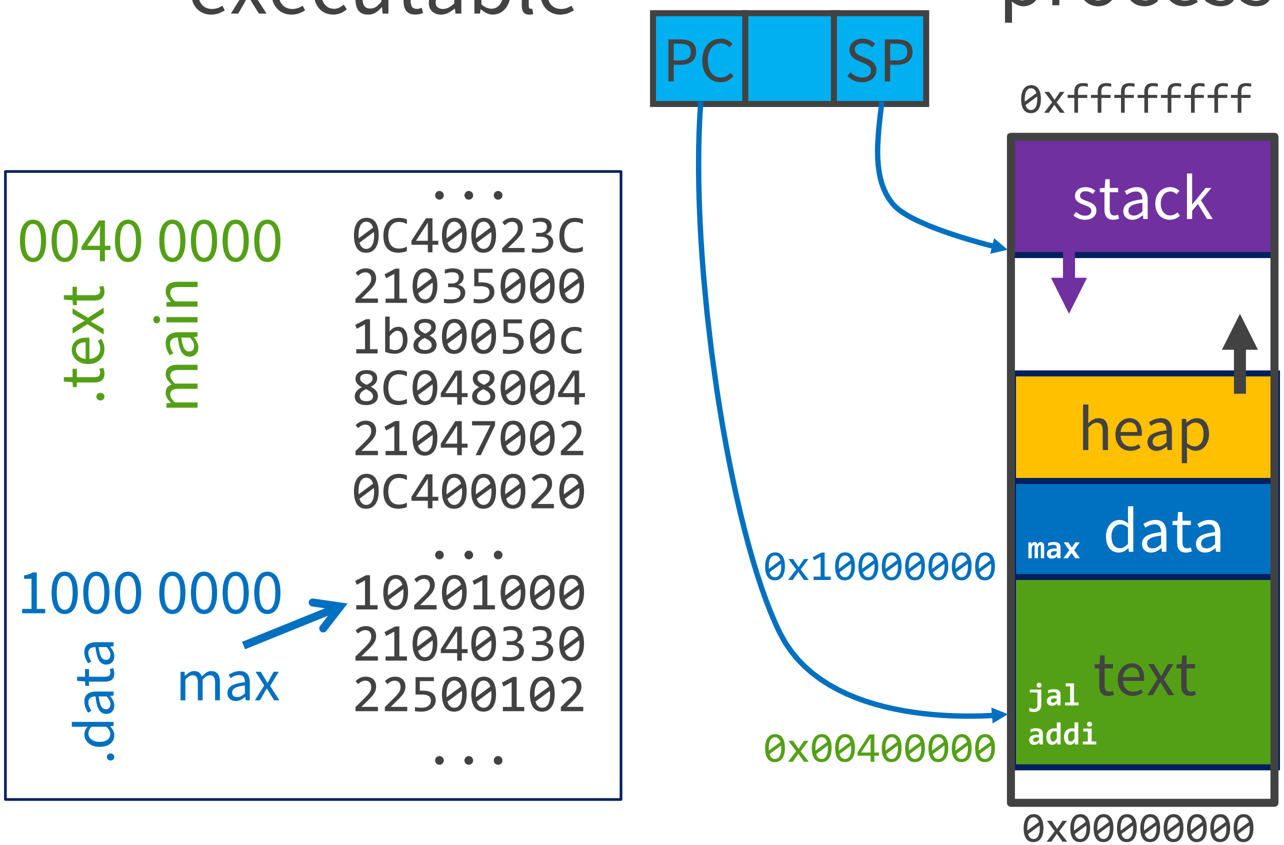
Same program can be run multiple time simultaneously (1 program, 2 processes)

```
> ./program &
> ./program &
```

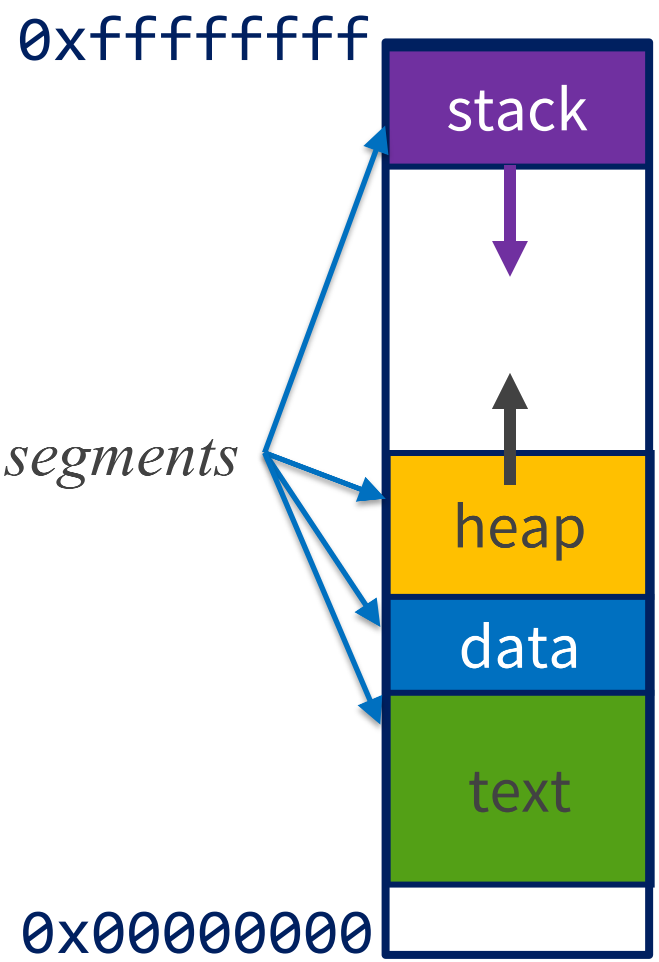
A Day in the Life of a Program




```c
#include <stdio.h>

int max = 10;

int main () {
   int sum = 0;
   add(max, &sum);
   printf("%d", sum);
   ...

}
```



Logical view of process memory



call stack

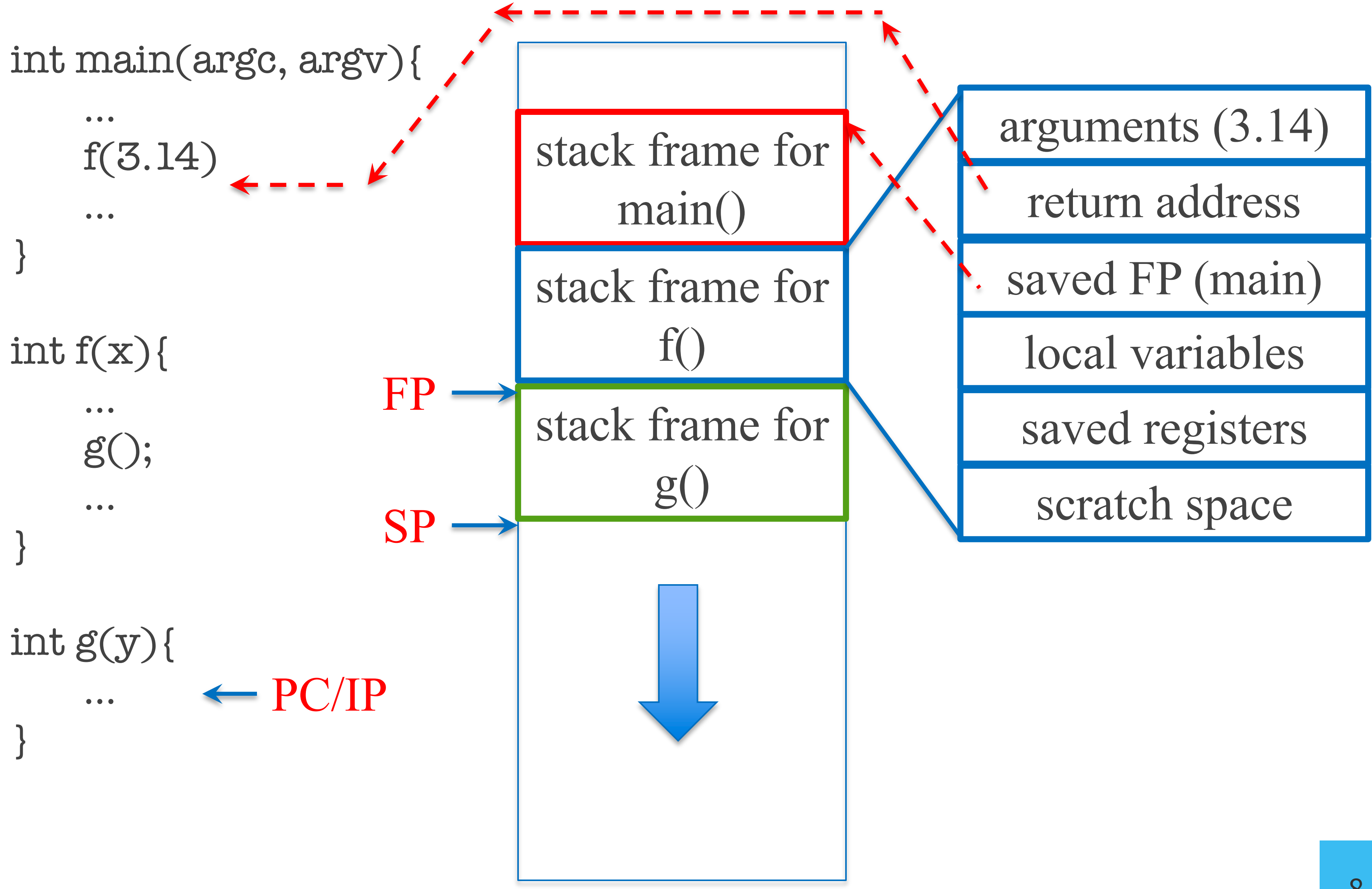
heap used for memory allocation (malloc)

data segment contains global variables

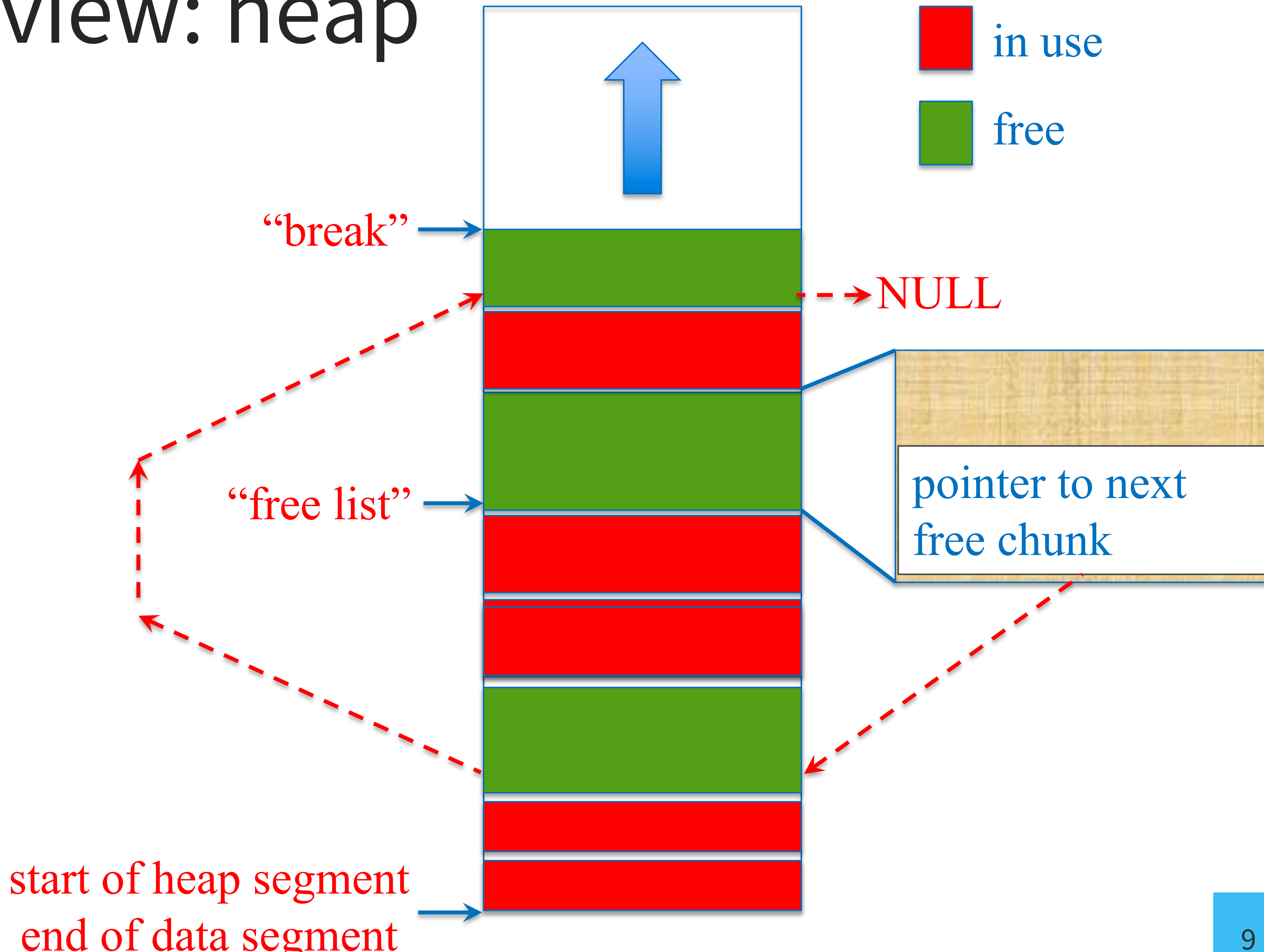
read-only text segment contains code and constants

How many bits in an address for this CPU?
Why is address 0 not mapped?

Review: stack (aka call stack)



Review: heap



in use
free
"break"
NULL
pointer to next free chunk
"free list"
start of heap segment
end of data segment

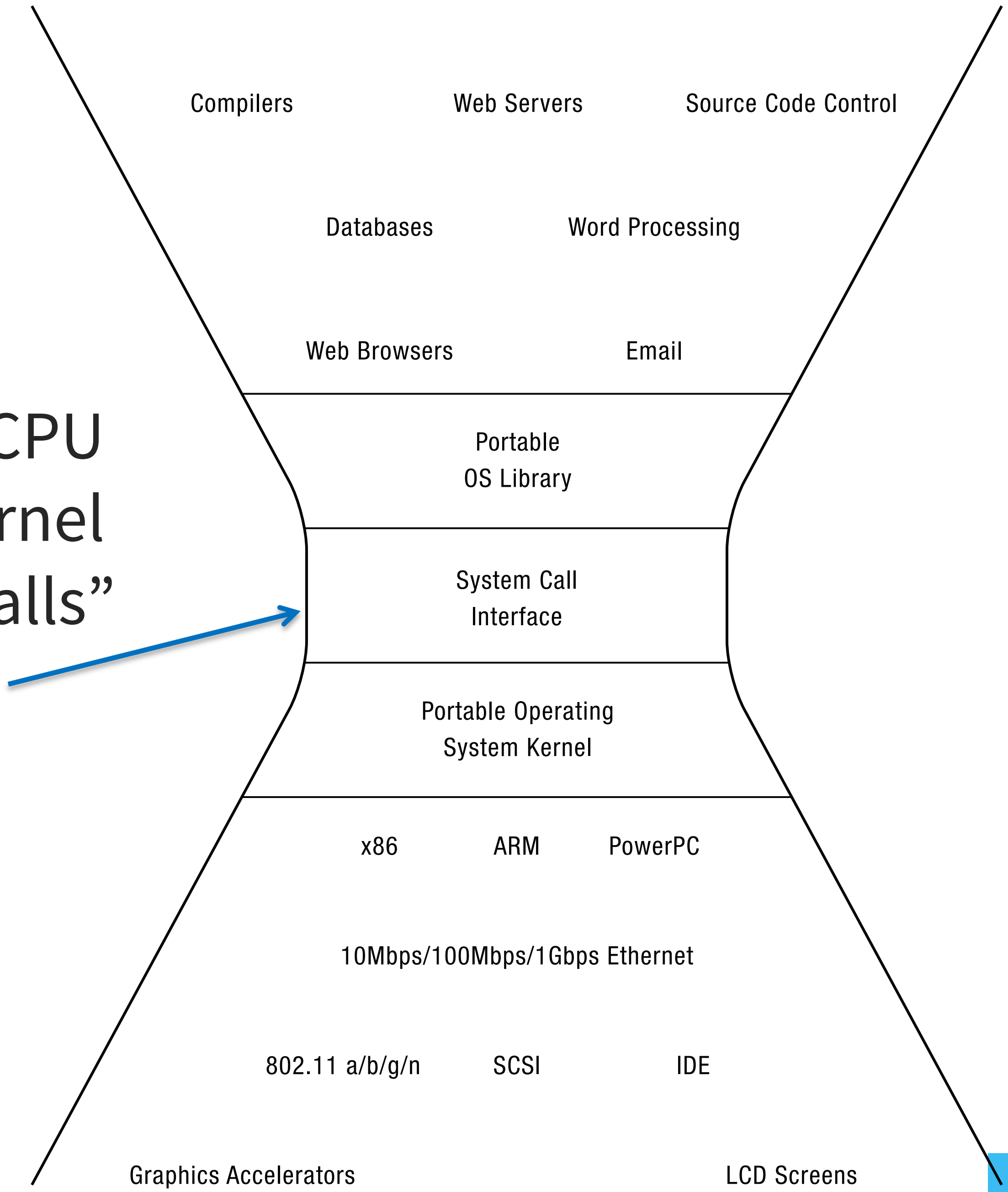
Environment

- CPU, registers, memory allow you to implement algorithms
- But how do you
  - ❑ read input / write to screen
  - ❑ create/read/write/delete files
  - ❑ create new processes
  - ❑ send/receive network packets
  - ❑ get the time / set alarms
  - ❑ terminate the current process

?

System Calls

- A process runs on CPU
- Can access O.S. kernel through “system calls”
- *Skinny interface*
  - Why?



Why a "skinny" interface?

- Portability
  - easier to implement and maintain
  - e.g., many implementations of "Posix" interface
- Security
  - "small attack surface": easier to protect against vulnerabilities

not just the O.S. interface. Internet "IP" layer is another good example of a skinny interface

Executing a system call

Process:

1. Calls system call function in library
2. Places arguments in registers and/or pushes them onto user stack
3. Places syscall type in a dedicated register
4. Executes `syscall` machine instruction

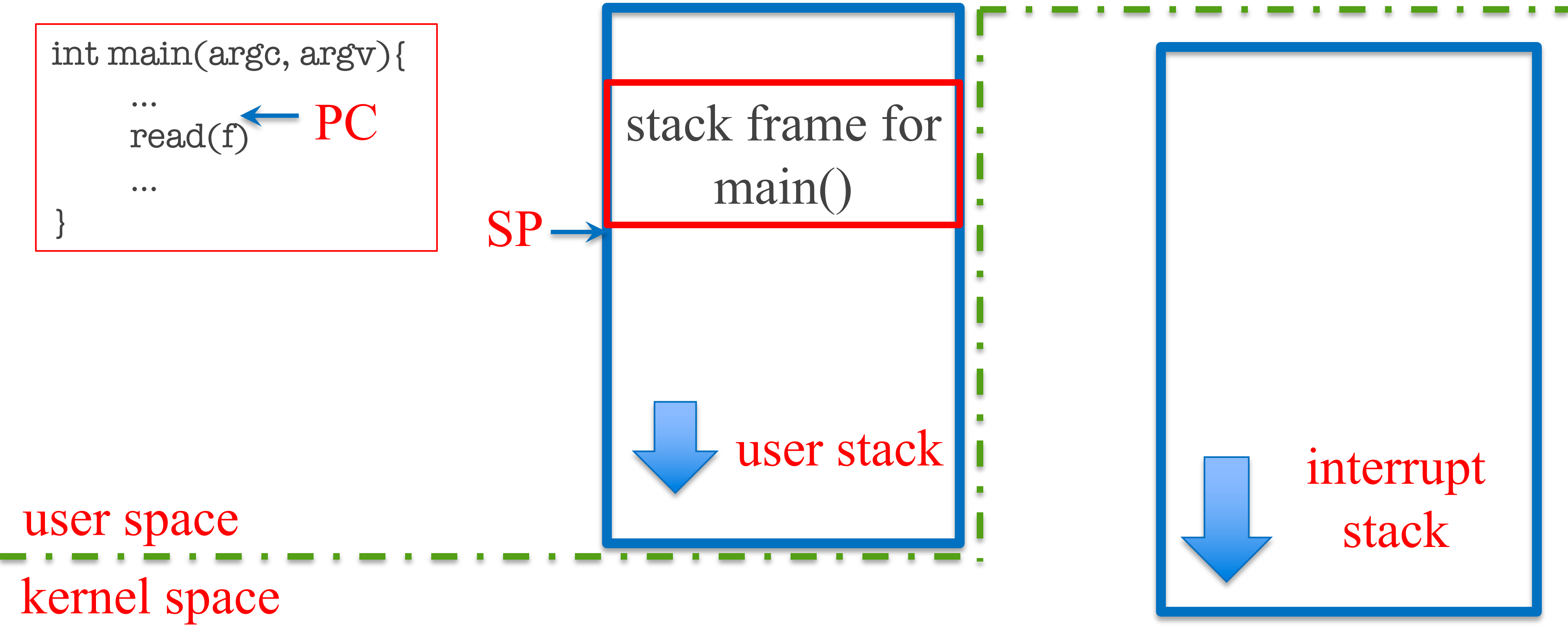
Kernel:

5. Executes `syscall` interrupt handler
6. Places result in dedicated register
7. Executes `return_from_interrupt`

Process:

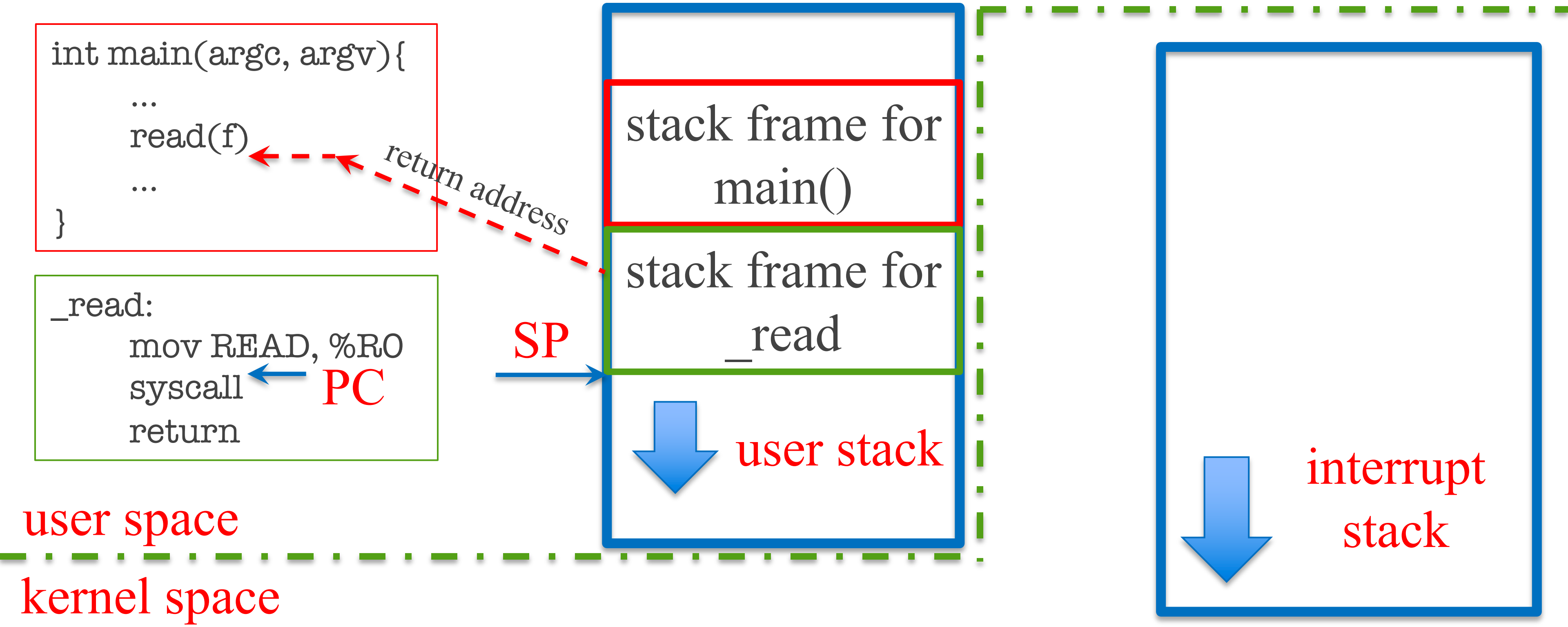
8. Executes `return_from_function`

Executing read System Call



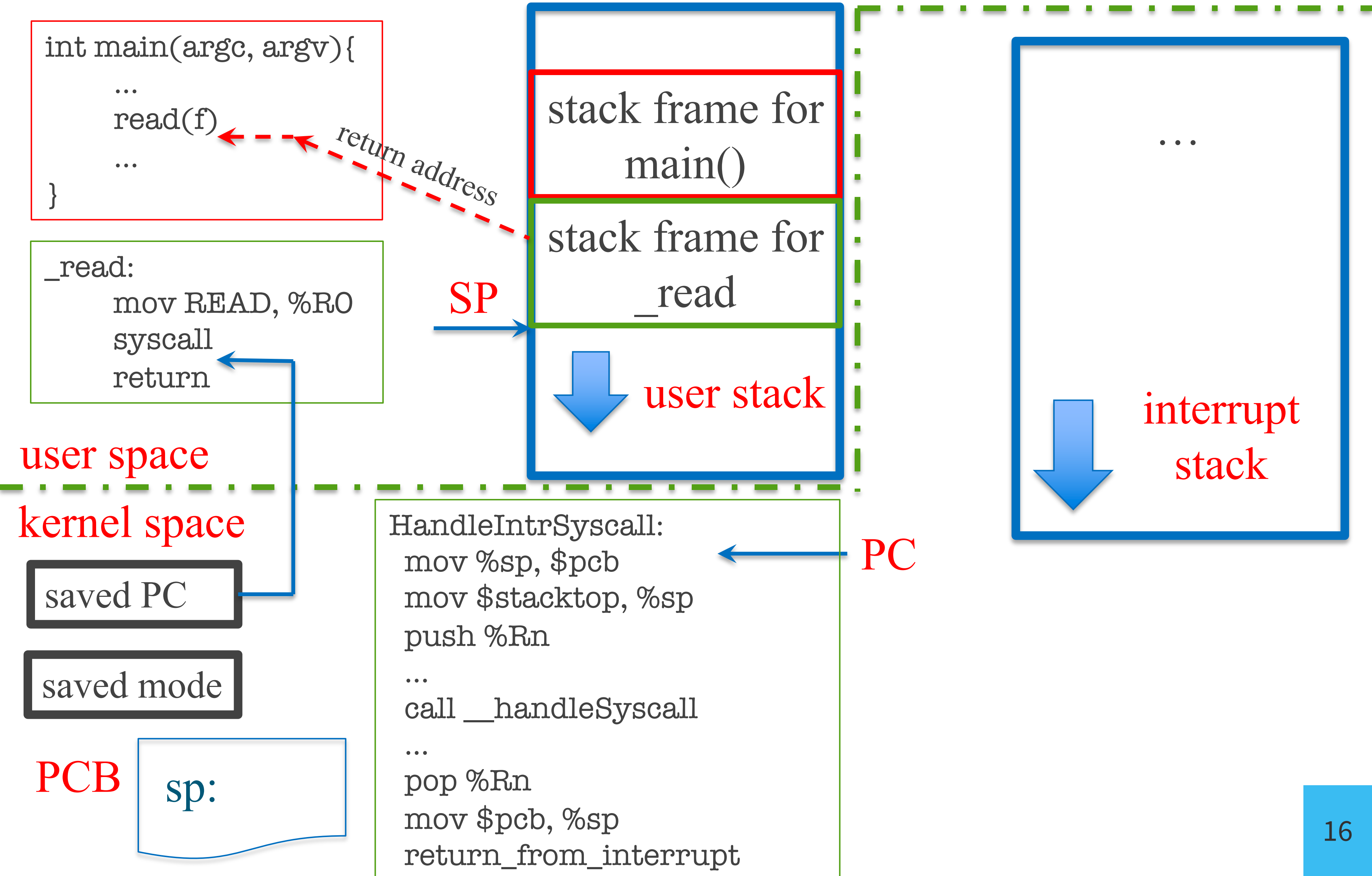
note interrupt stack empty while process running

Executing read System Call

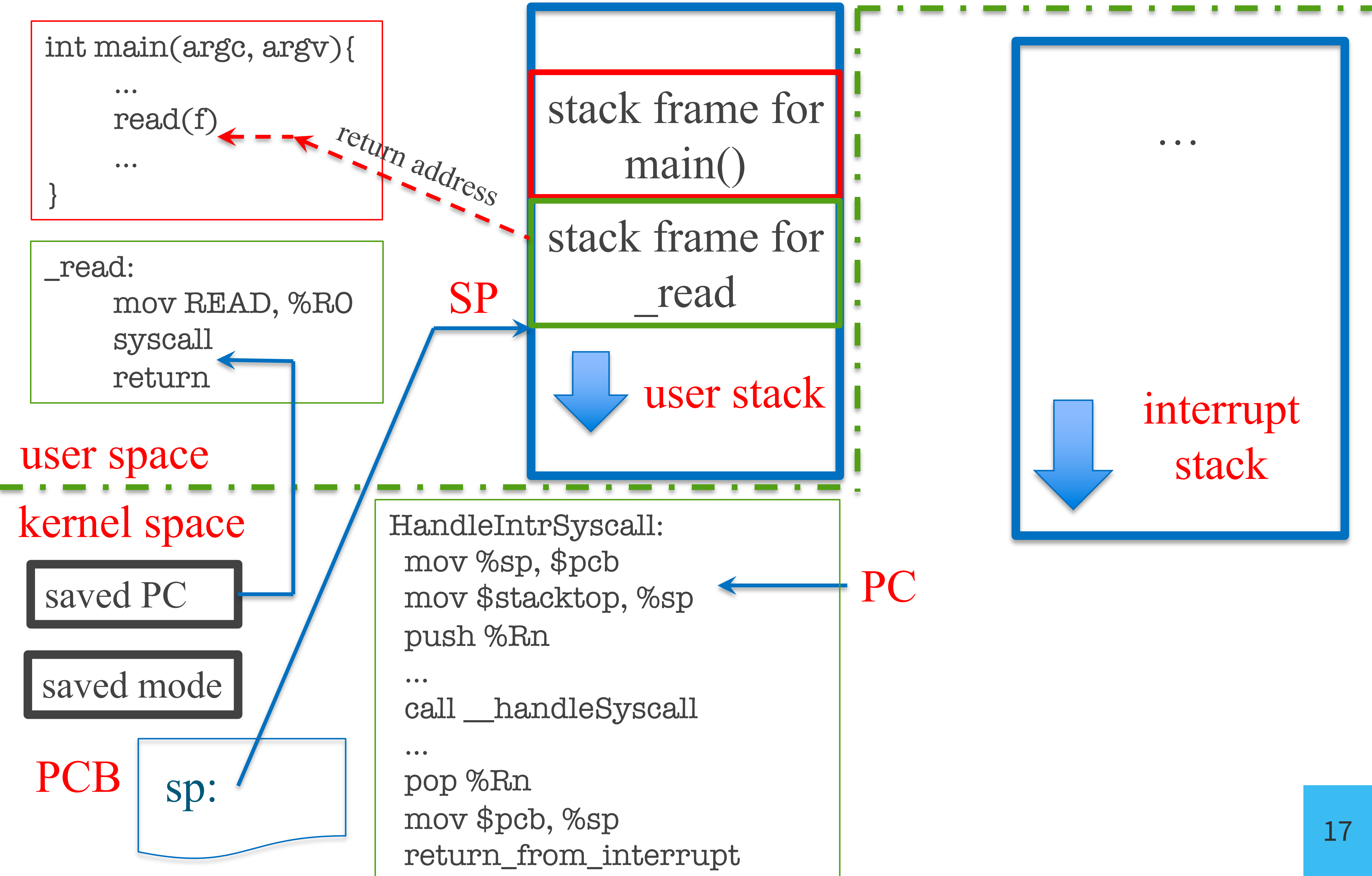


note interrupt stack empty while process running

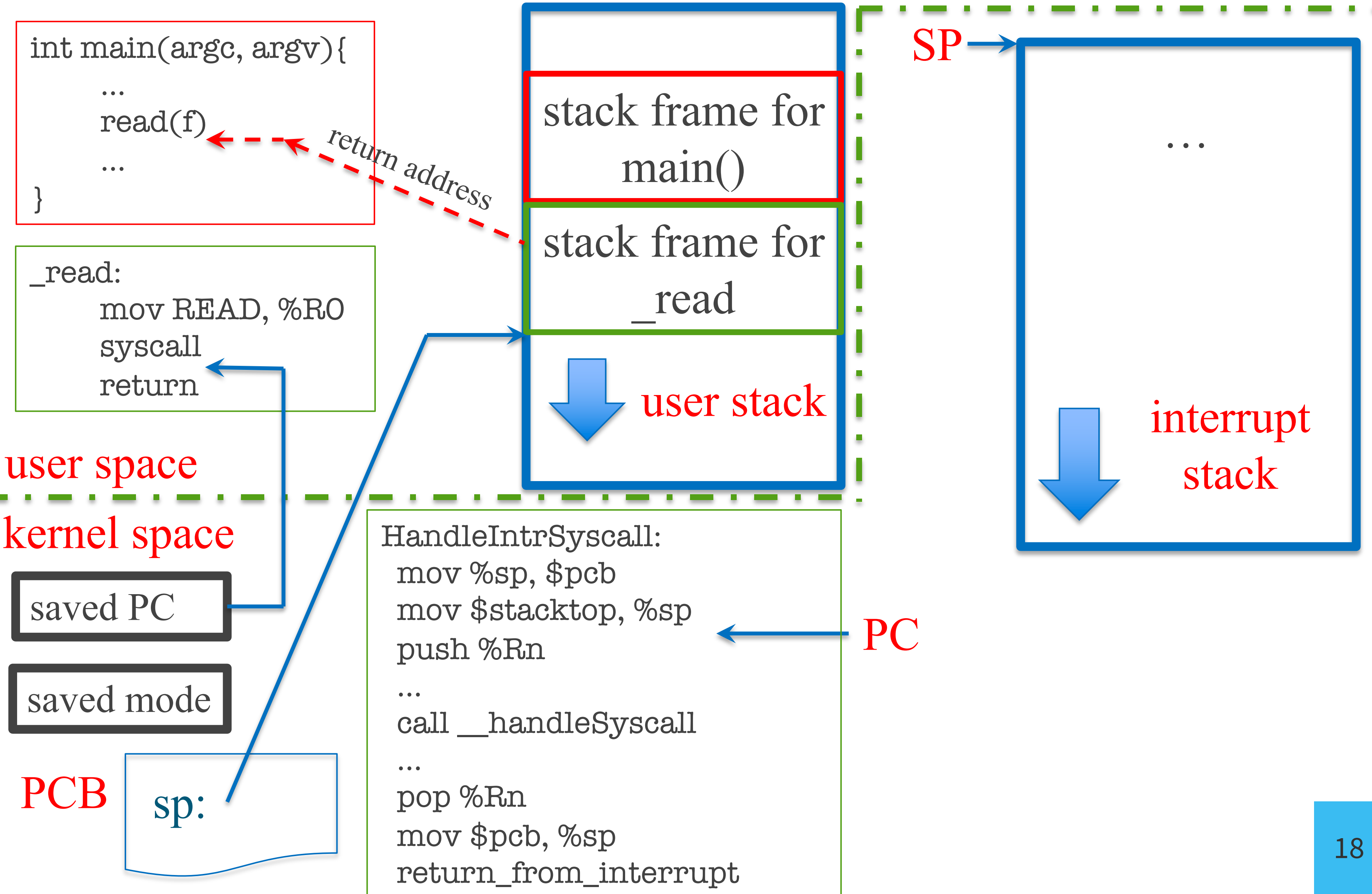
Executing read System Call



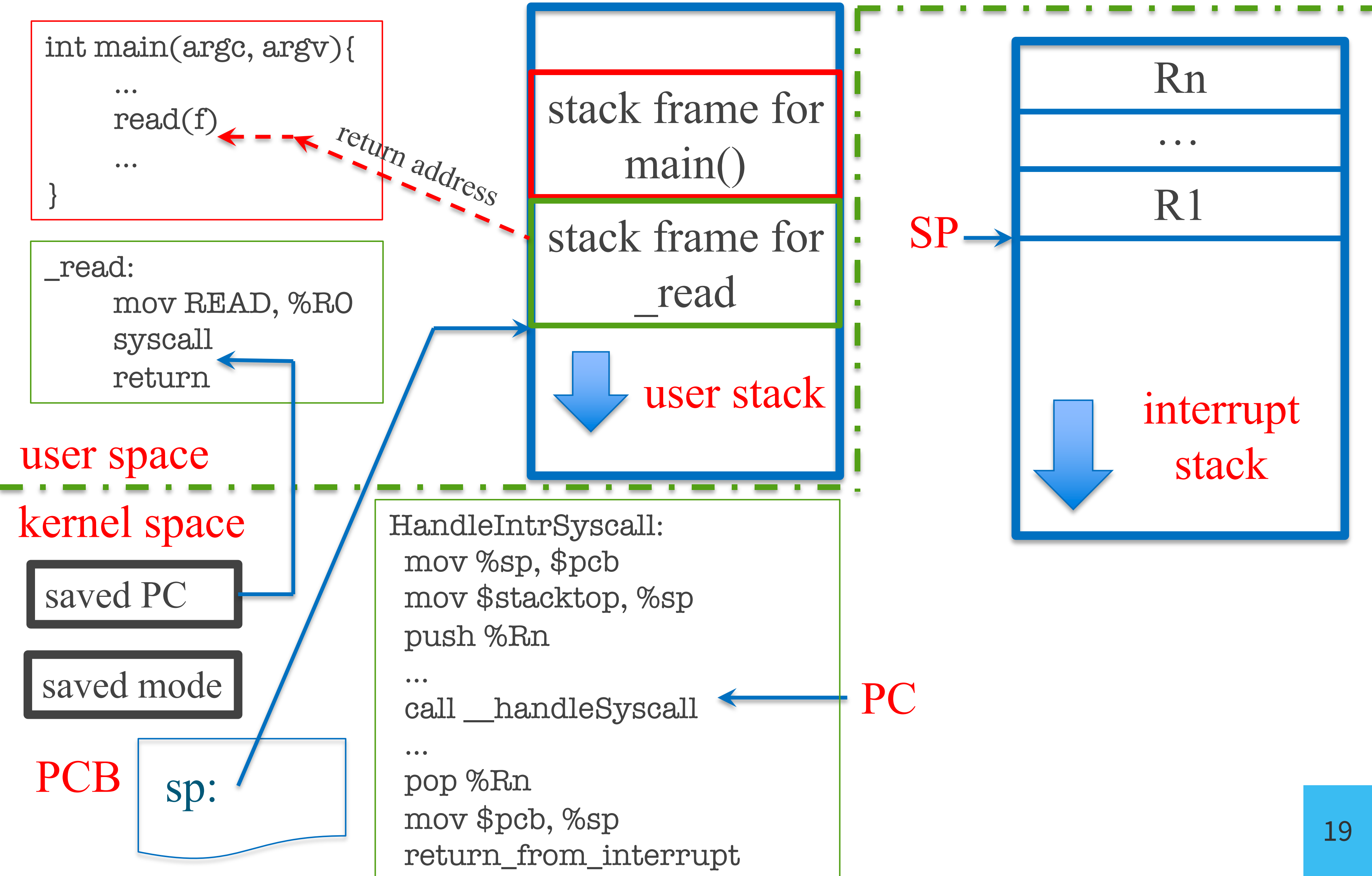
Executing read System Call



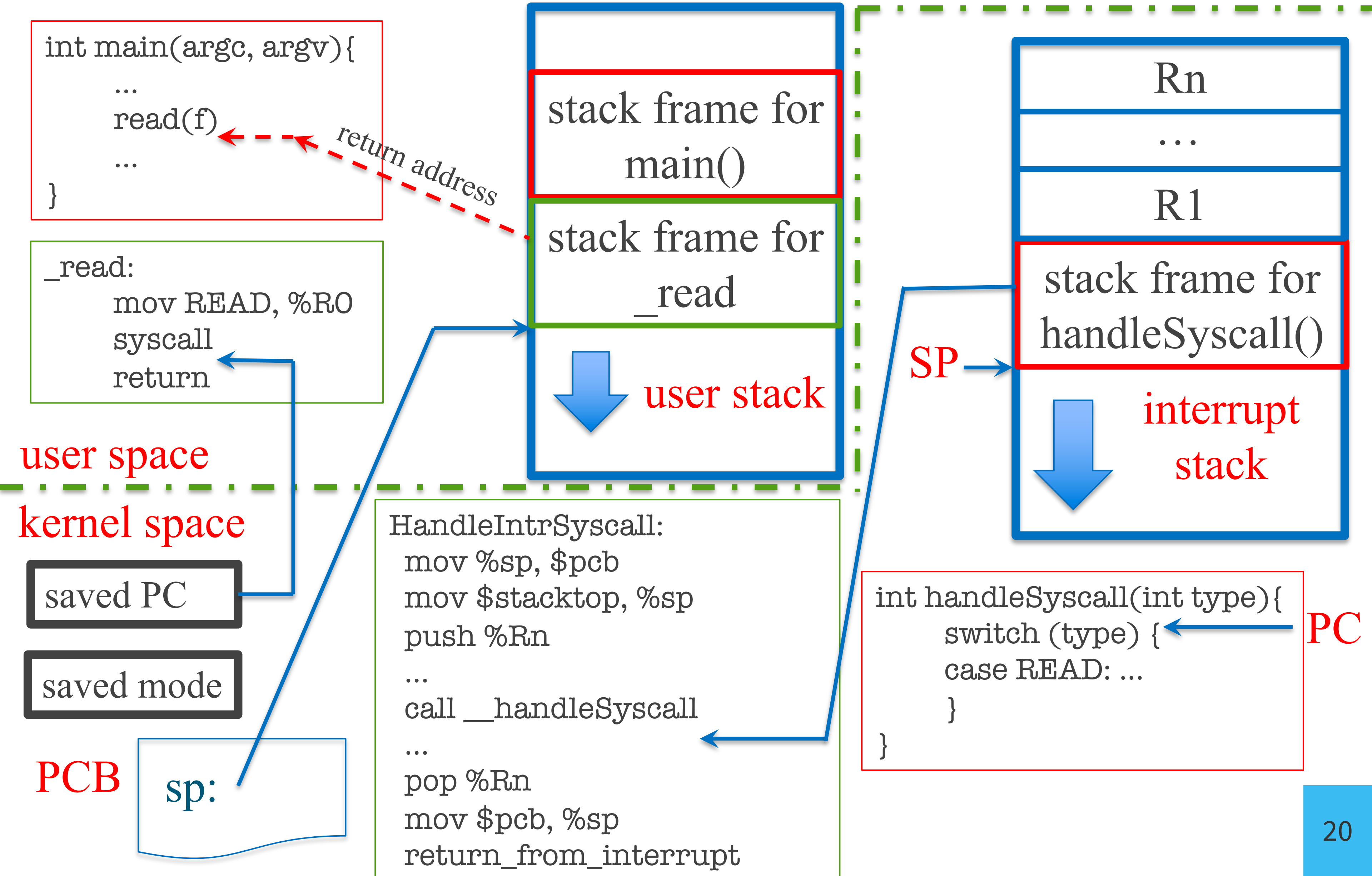
Executing read System Call



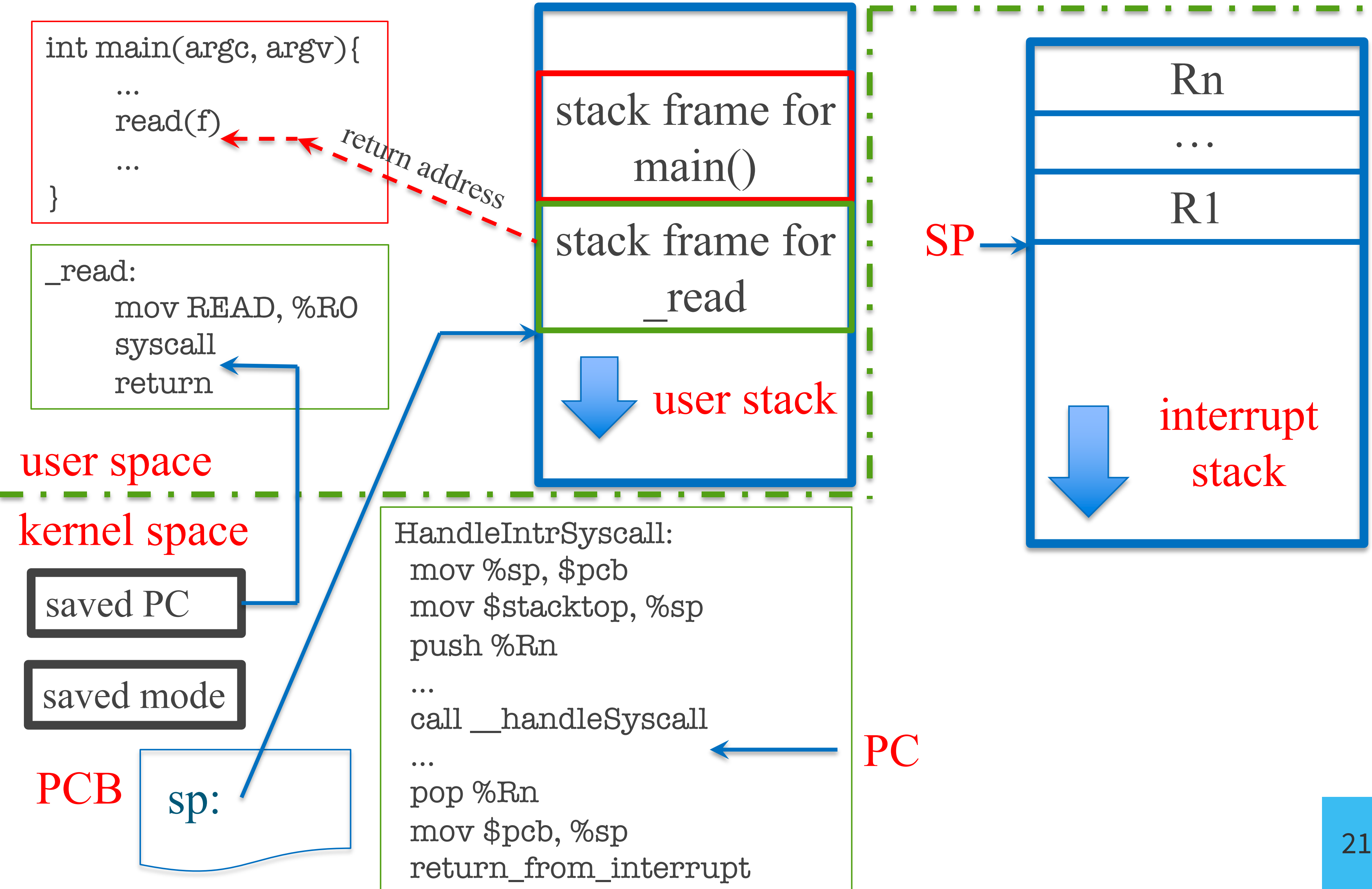
Executing read System Call



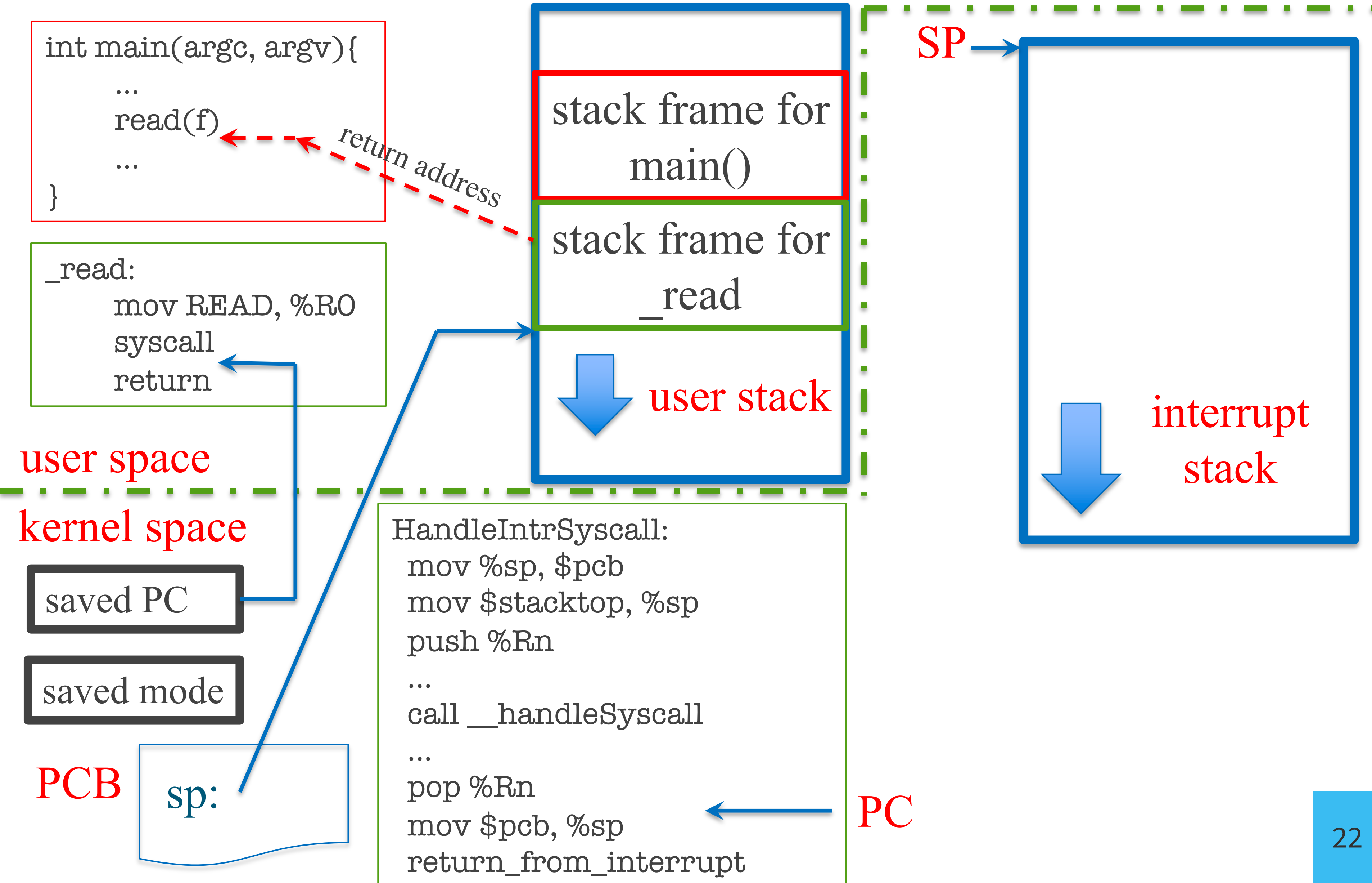
Executing read System Call



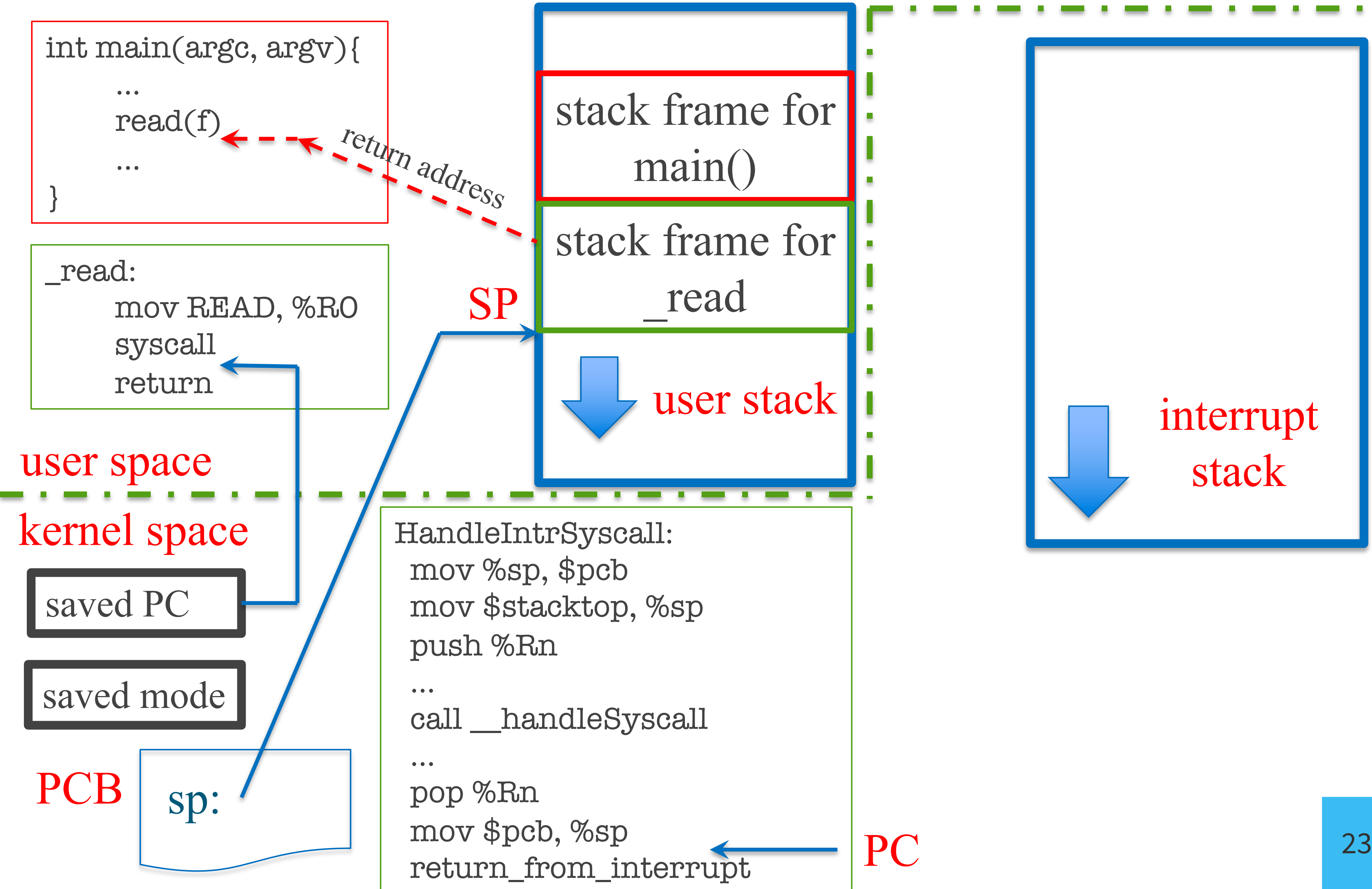
Executing read System Call



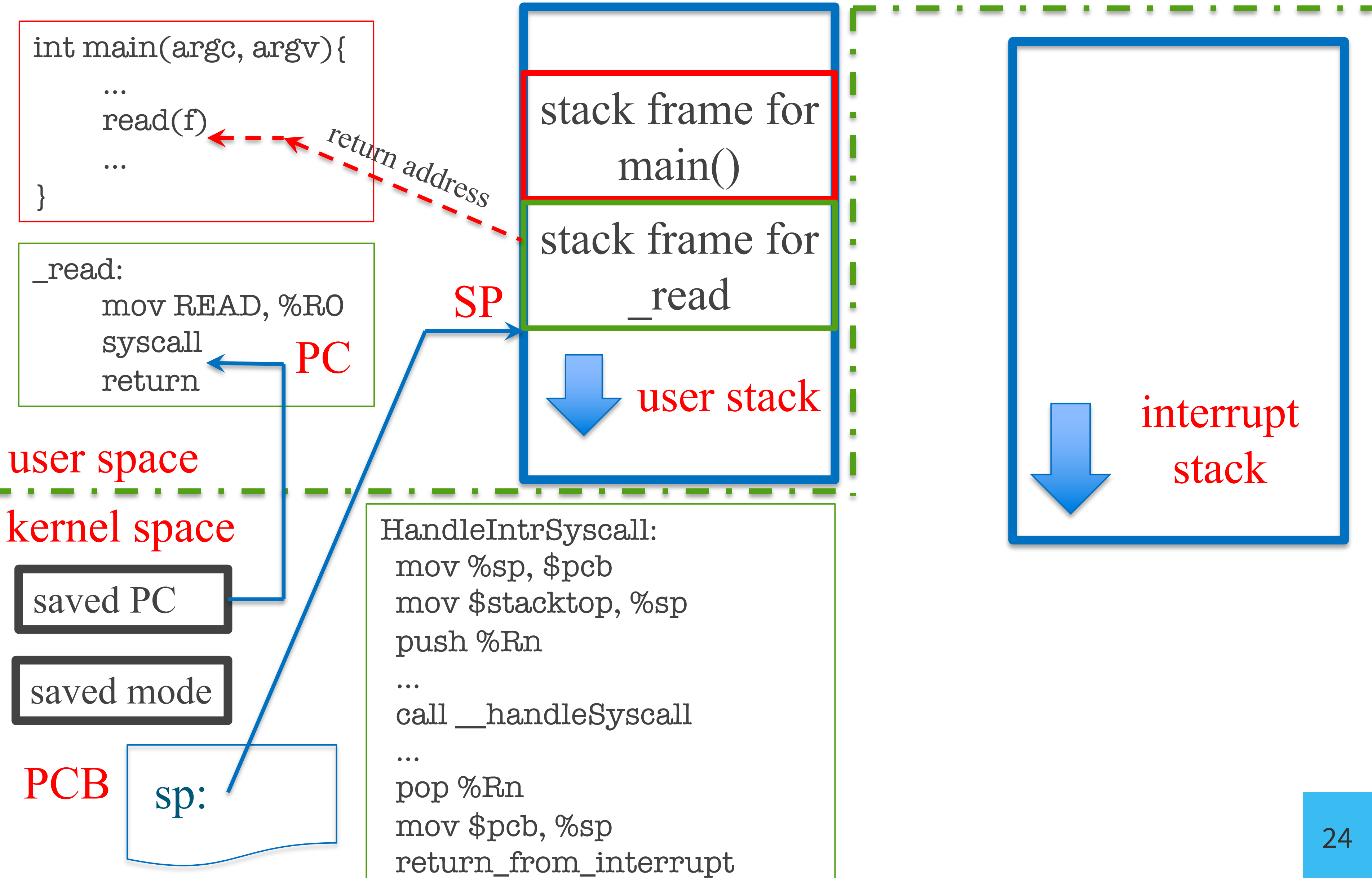
Executing read System Call



Executing read System Call



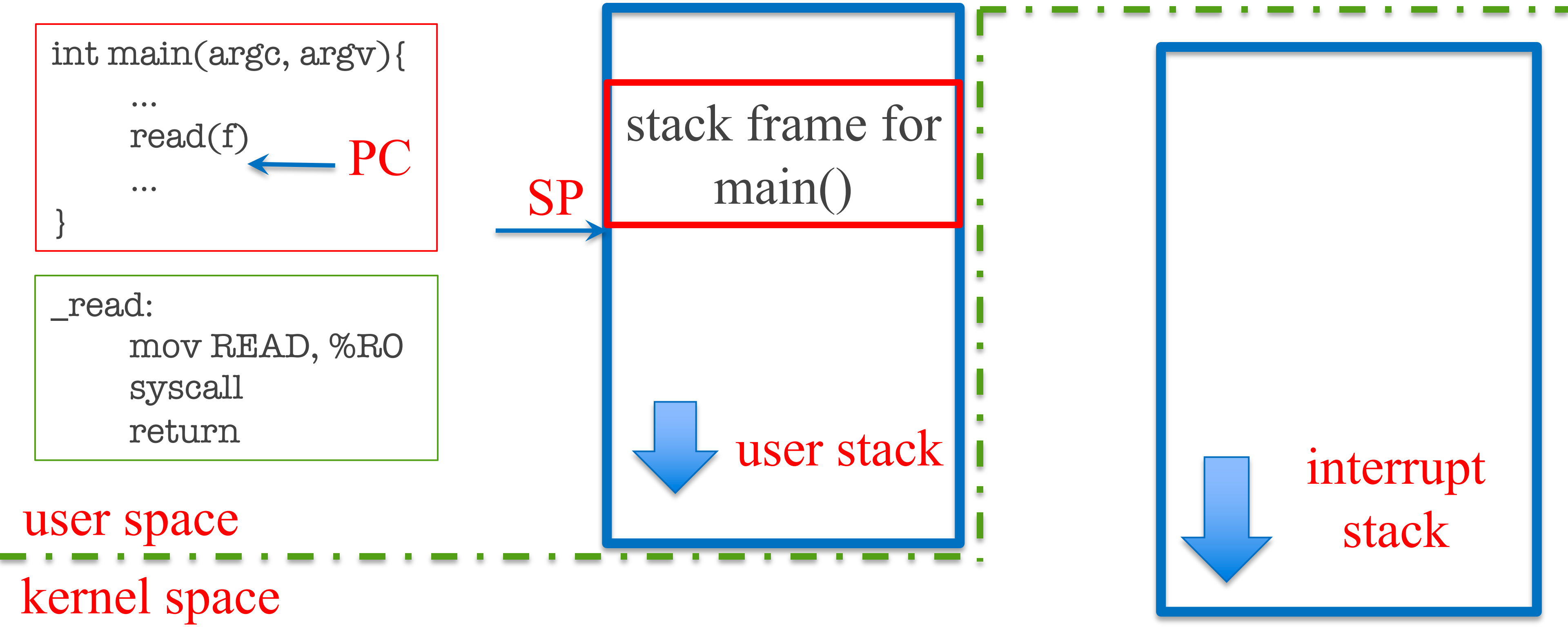
Executing read System Call



Executing read System Call

```
int main(argc, argv){
        ...
        read(f)
        ...
}
```

```
_read:
        mov READ, %RO
        syscall
        return
```



What if `read` needs to "block"?

- `read` may need to block if
  - ➢ reading from terminal
  - ➢ reading from disk and block not in cache
  - ➢ reading from remote file server

should run another process!

How to run multiple processes?

(*on a single core*)

A process physically runs on the CPU

But *somehow* each process has its own:

- Registers
- Memory
- I/O resources
- “thread of control”

- *even though there are usually more processes than the CPU has cores*

➔ *need to multiplex, schedule, … to create virtual CPUs for each process*

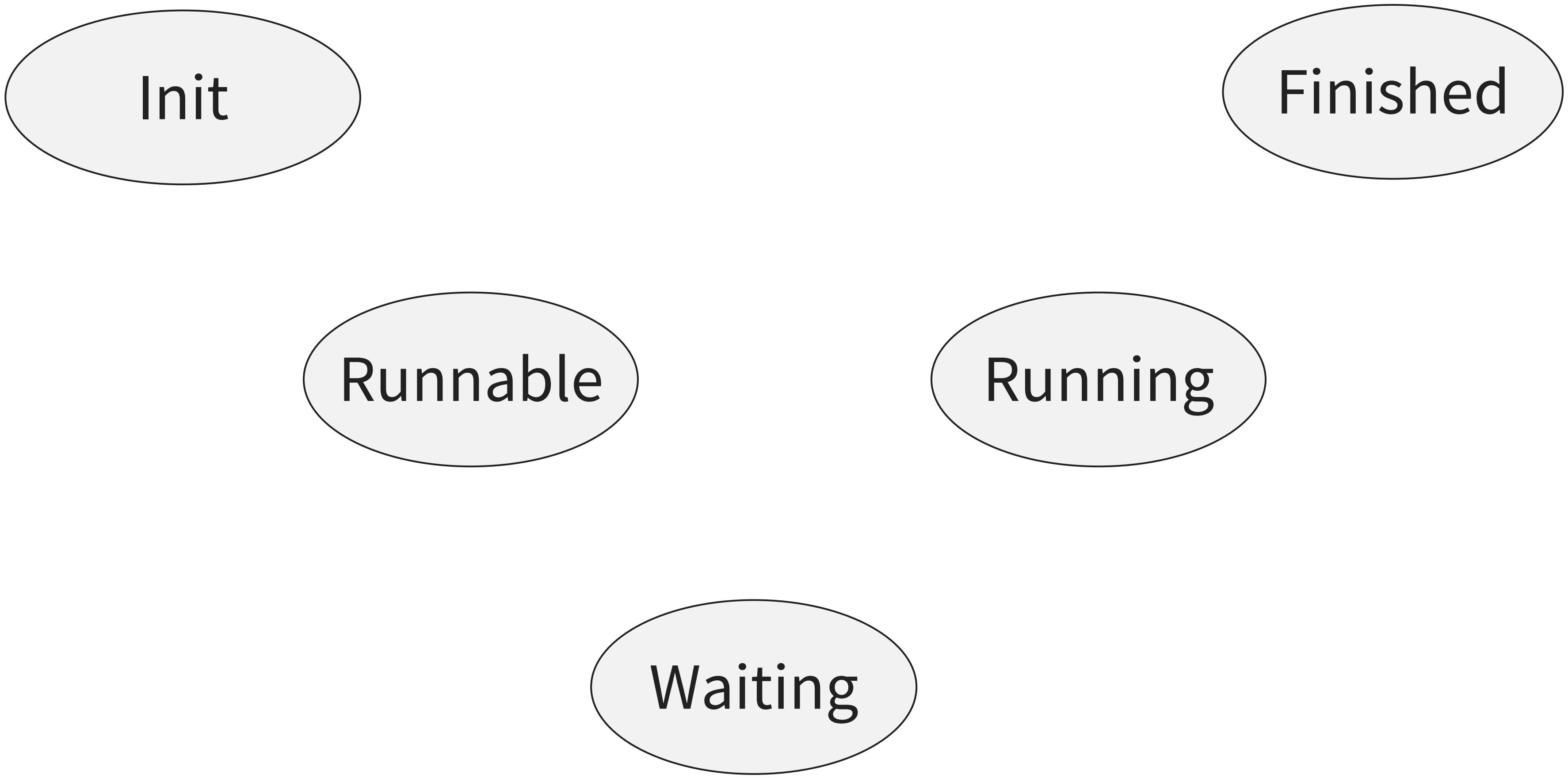
For now, assume we have a single core CPU

Process Control Block (PCB)

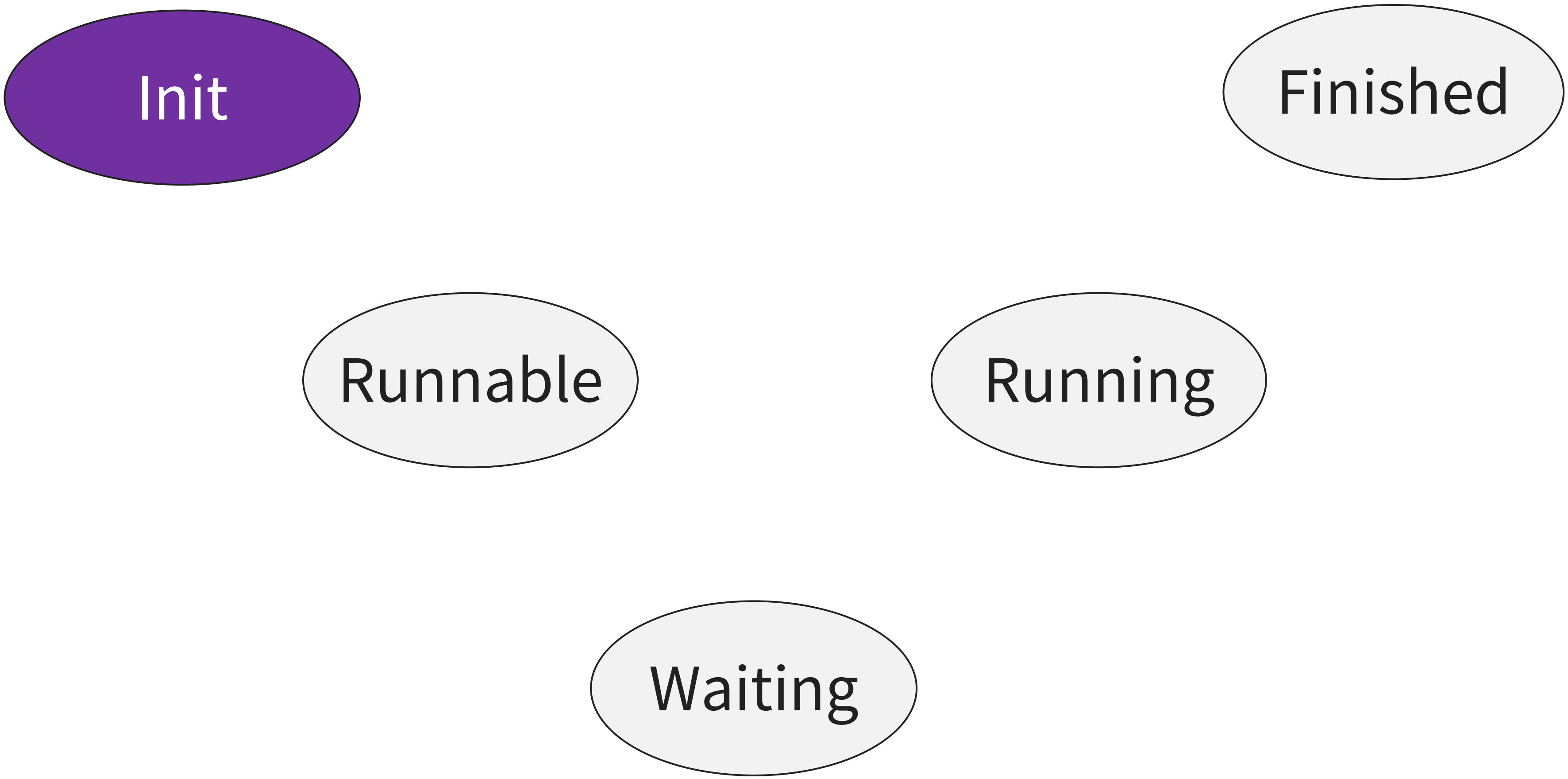
For each process, the OS has a PCB containing:

- location in memory (page table)
- location of executable on disk
- which user is executing this process (`uid`)
- process identifier (`pid`)
- process status (running, waiting, finished, *etc.*)
- scheduling information
- interrupt stack
- saved user SP
  - points into user stack
- saved kernel SP
  - points into interrupt stack
  - interrupt stack contains saved registers and kernel call stack for this process
- *… and more!*

Process Life Cycle

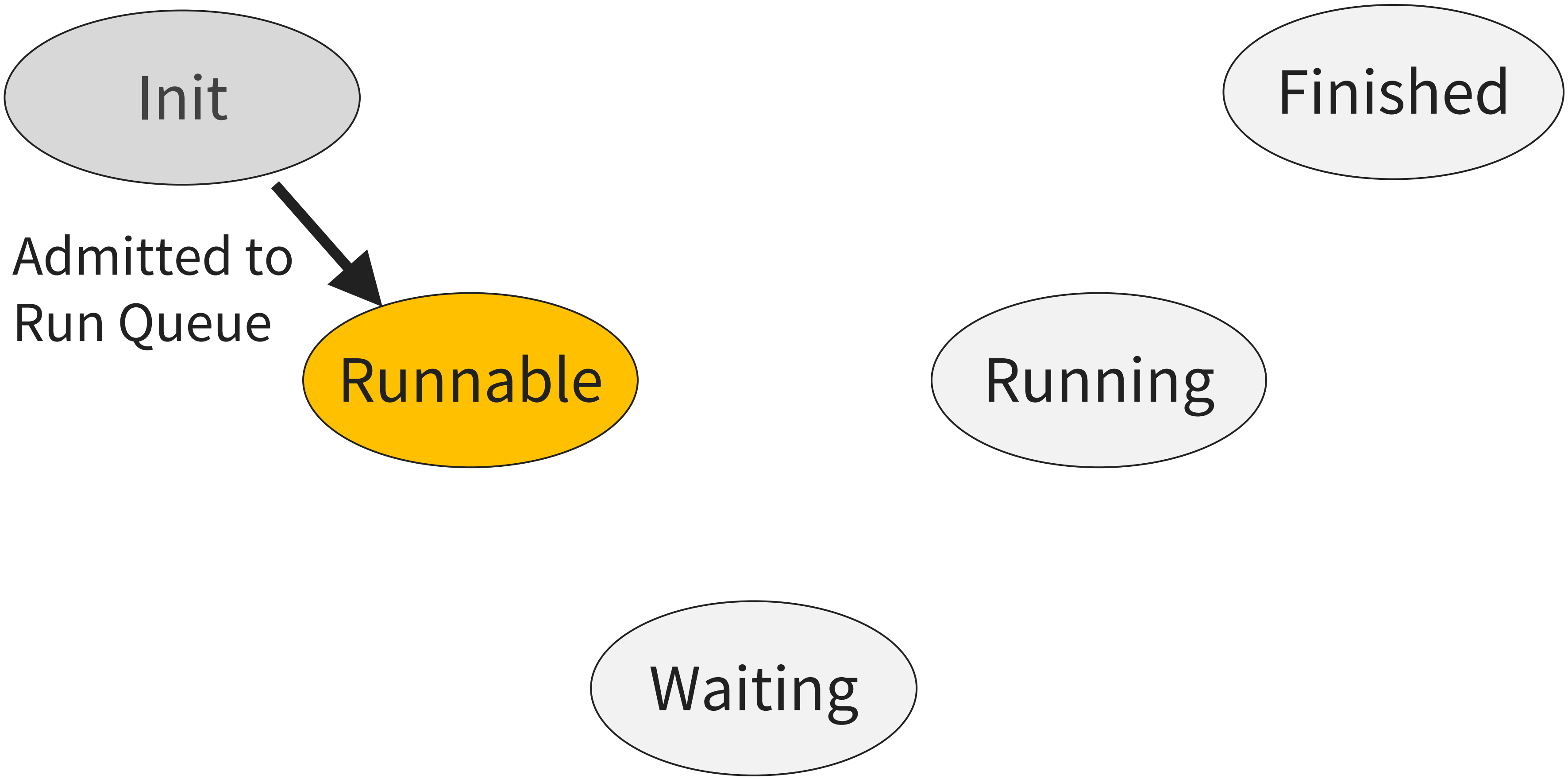


Process creation



PCB status: being created
Registers: uninitialized

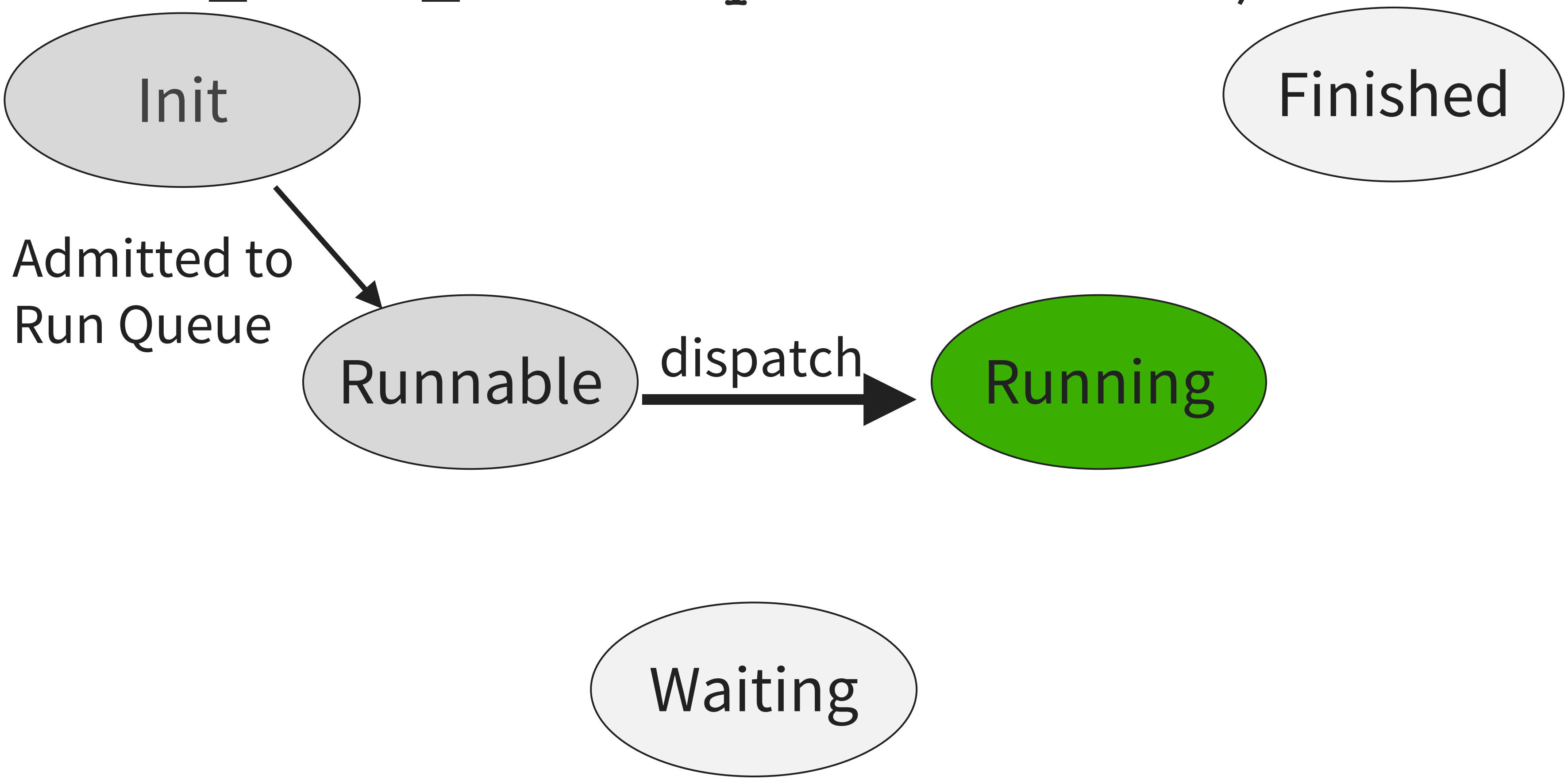
Process is Ready to Run



PCB: on Run Queue (aka Ready Queue)

Registers: pushed by kernel code onto interrupt stack

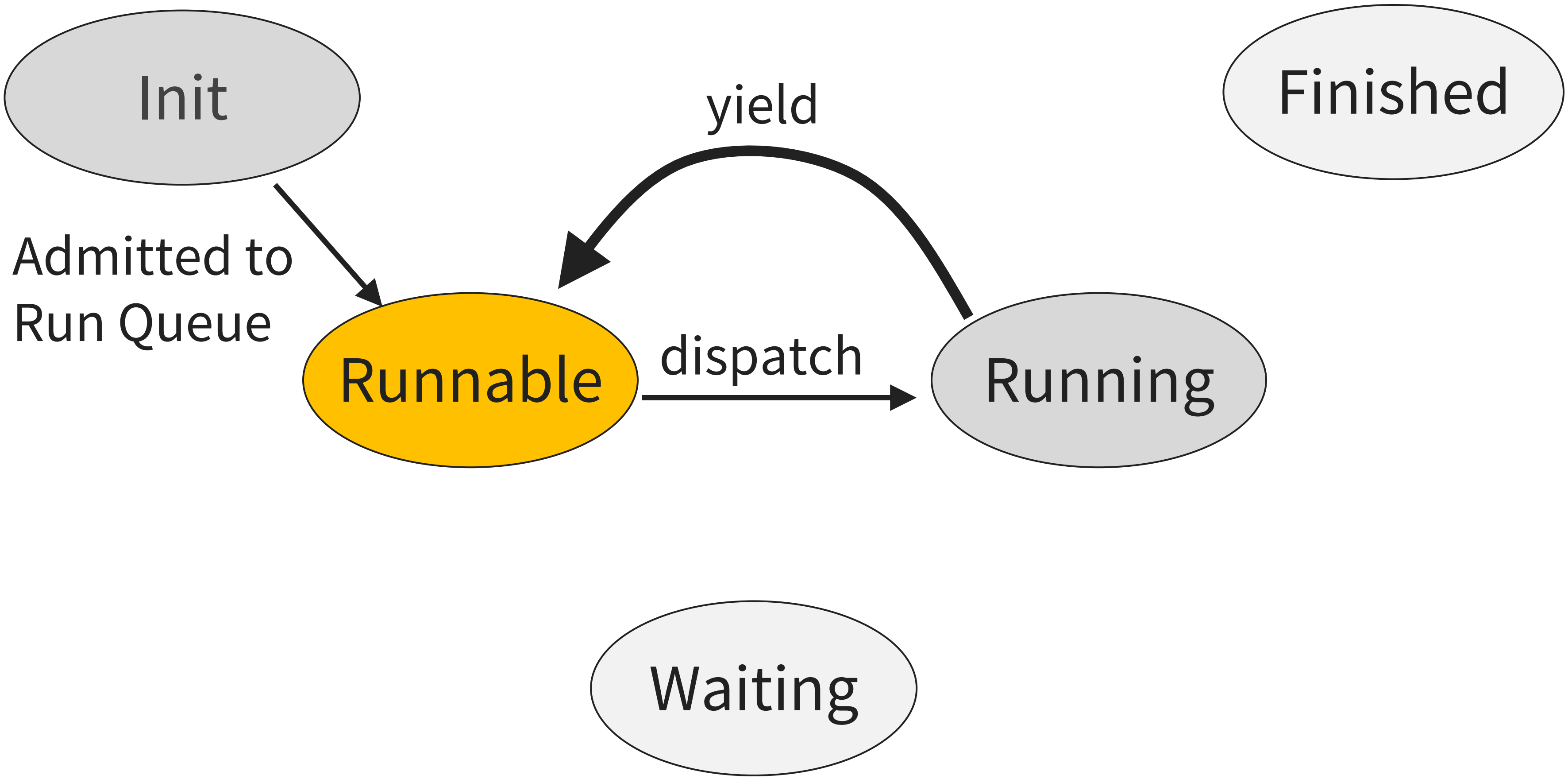
Process is Running
(in supervisor mode, but may `return_from_interrupt` to user mode)



PCB: currently executing

Registers: popped from interrupt stack into CPU

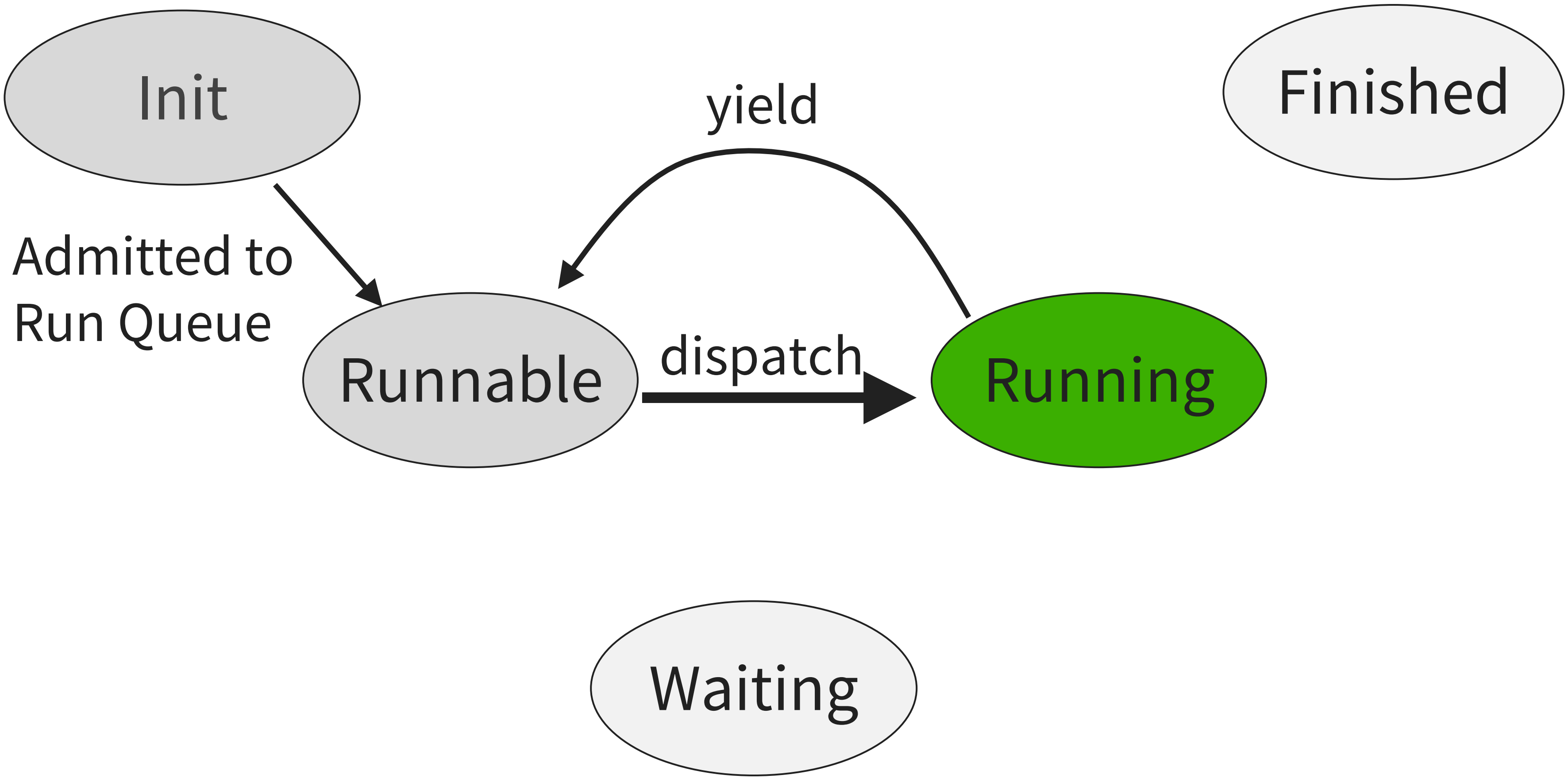
Process Yields (on clock interrupt)



PCB: on Run queue

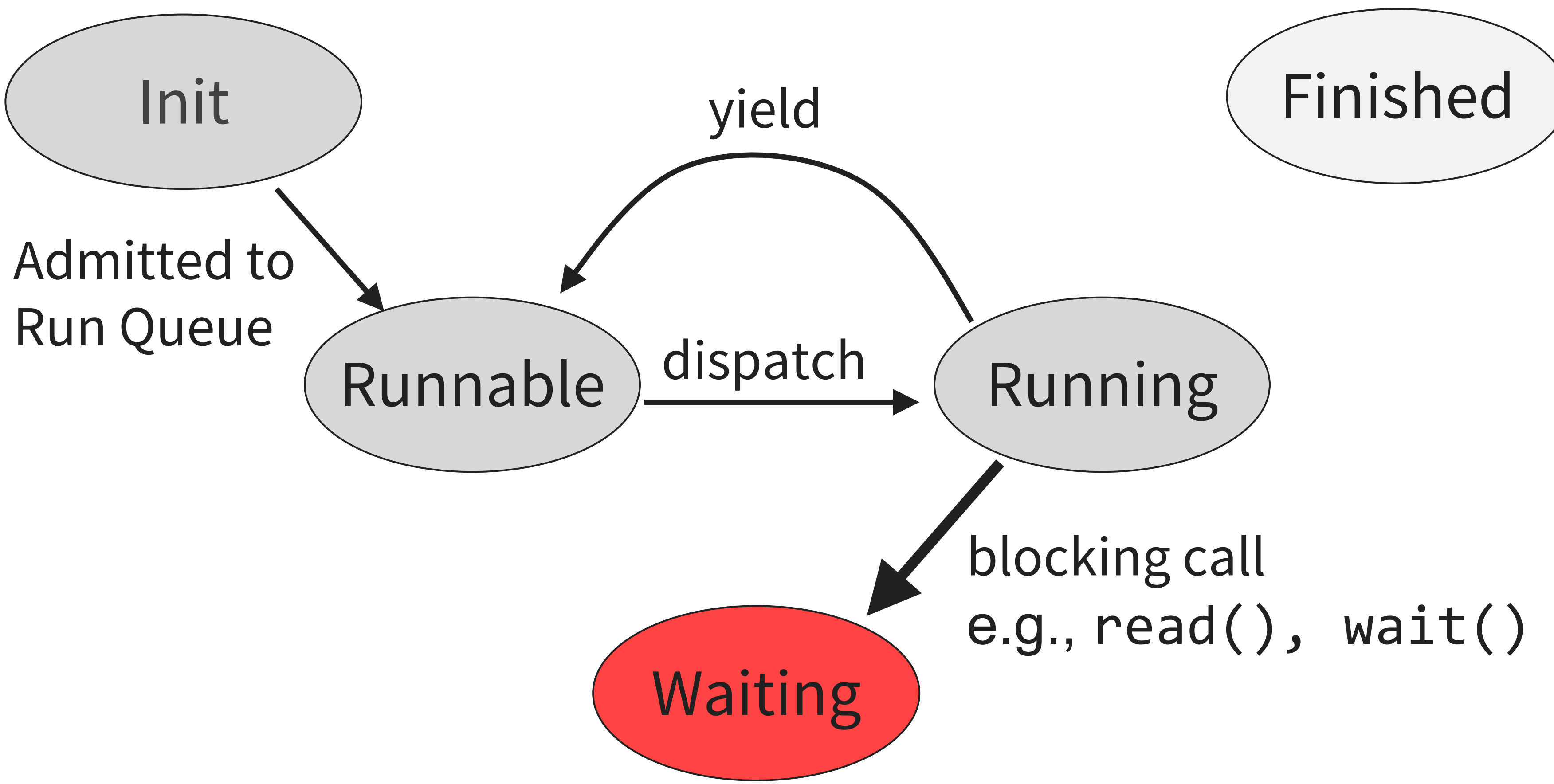
Registers: pushed onto interrupt stack (sp saved in PCB)

Process is Running Again!



PCB: currently executing
Registers: sp restored from PCB; others restored from stack

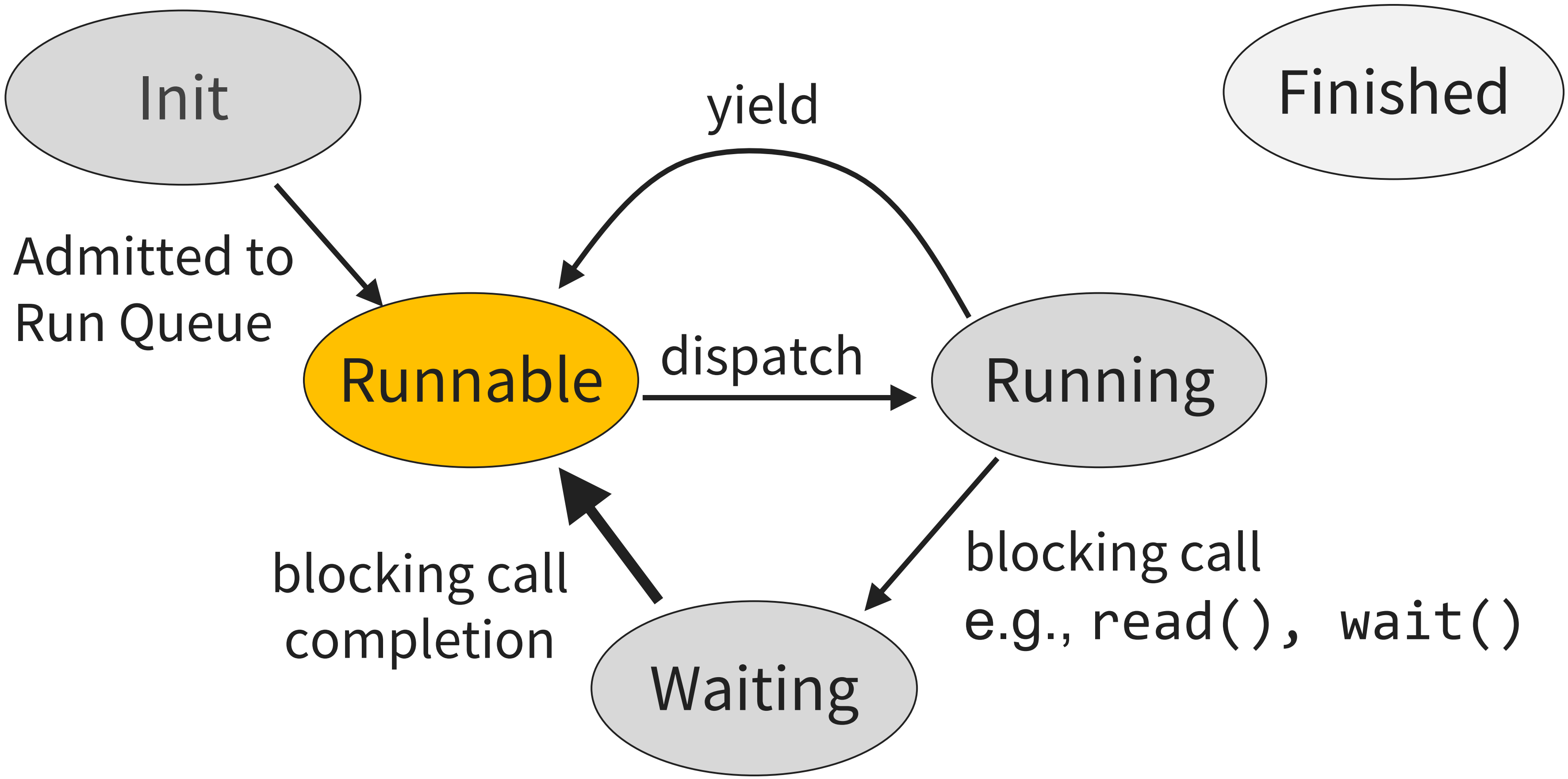
Process is Waiting



PCB: on specific waiting queue (file input, …)

Registers: on interrupt stack

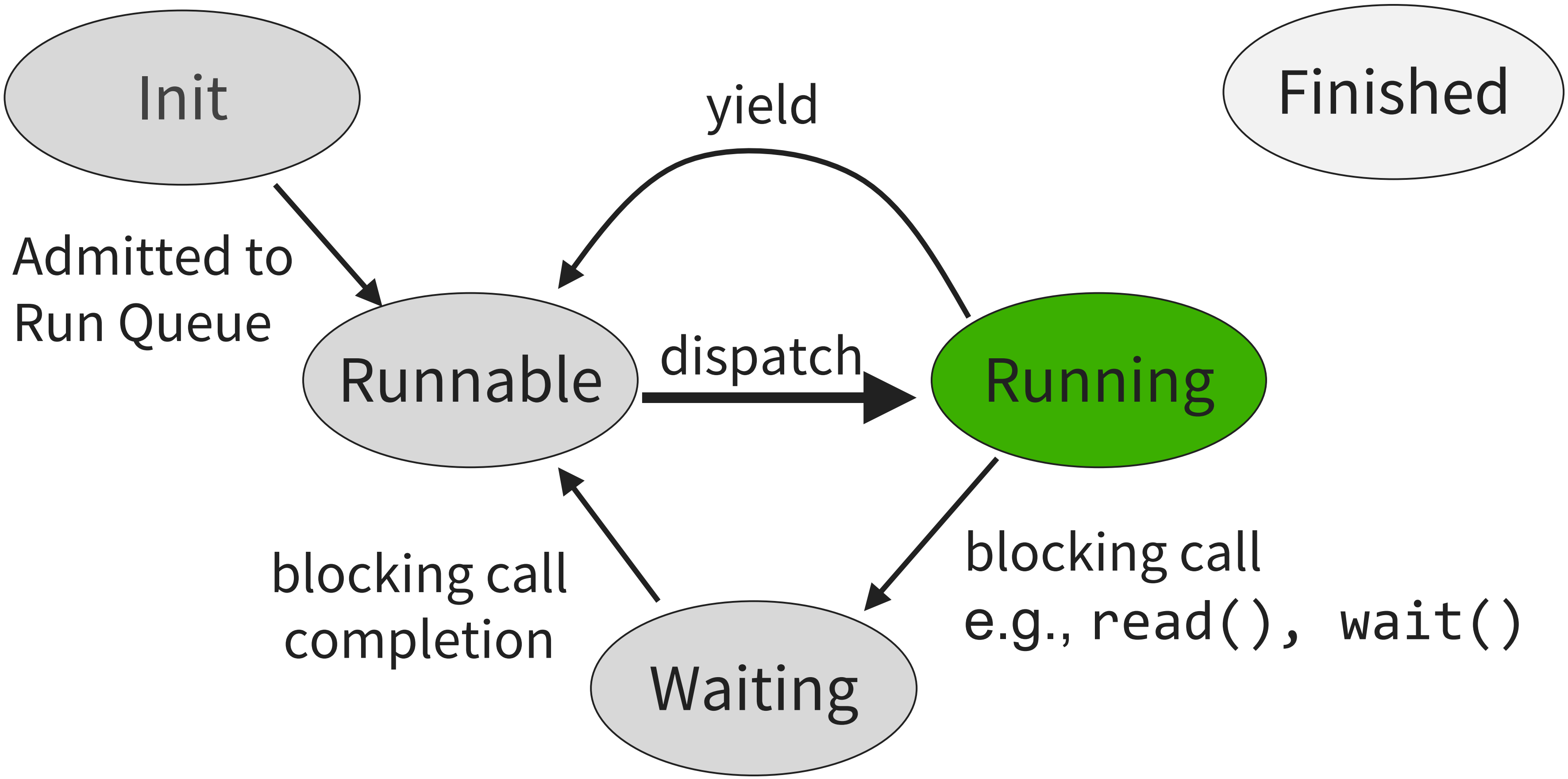
Process is Ready Again!



PCB: on run queue

Registers: on interrupt stack

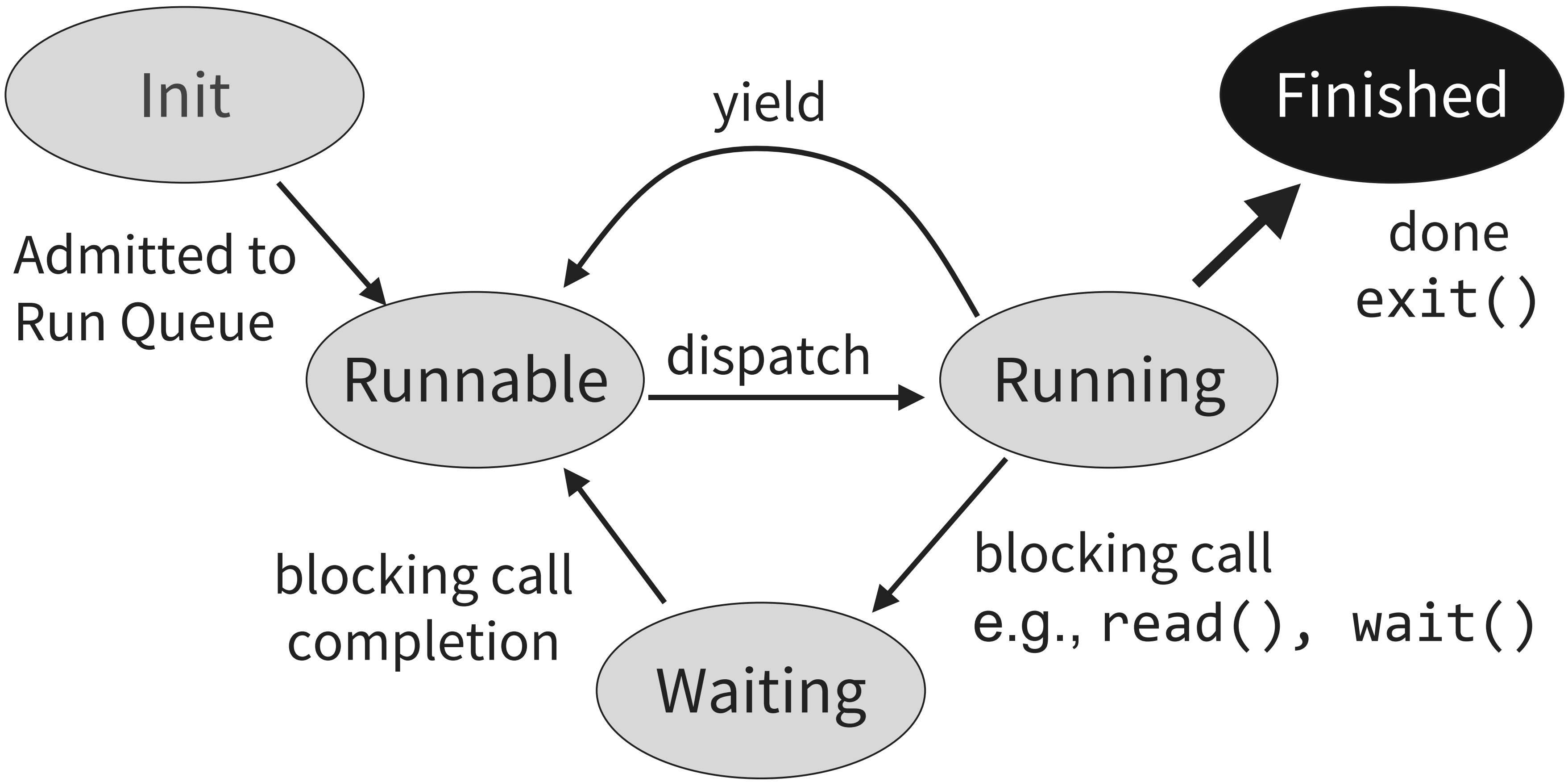
Process is Running Again!



PCB: currently executing

Registers: restored from interrupt stack into CPU

Process is Finished (Process = Zombie)



PCB: on Finished queue, ultimately deleted
Registers: no longer needed

Invariants to keep in mind

- At most 1 process is RUNNING at any time *(per core)*
- When CPU is in user mode, current process is RUNNING and its interrupt stack is empty
- If process is RUNNING
  - its PCB is not on any queue
  - *however, not necessarily in user mode*
- If process is RUNNABLE or WAITING
  - its interrupt stack is non-empty and can be switched to
    - i.e., has its registers saved on top of the stack
  - its PCB is either
    - on the run queue (if RUNNABLE)
    - on some wait queue (if WAITING)
- If process is FINISHED
    - its PCB is on finished queue

Cleaning up zombies

- Process cannot clean up itself

WHY NOT?

- Process can be cleaned up
  - either by any other process
    - check for zombies just before returning to RUNNING state
  - or by parent when it waits for it
    - but what if the parent dies first?
  - or by dedicated "reaper" process

- Linux uses combination:
  - usually parent cleans up child process when waiting
  - if parent dies before child, child process is inherited by the initial process, which is continually waiting

How To Yield/Wait?

Switching from executing the current process to another runnable process

- Process 1 goes from RUNNING → RUNNABLE/WAITING
- Process 2 goes from RUNNABLE → RUNNING

1. save kernel registers of process 1 on its interrupt stack
2. save kernel sp of process 1 in its PCB
3. restore kernel sp of process 2 from its PCB
4. restore kernel registers from its interrupt stack

ctx_switch(&old_sp, new_sp)

```
ctx_switch:
    addi sp,sp,-64 // reserve frame
    sw s0,4(sp)
    sw s1,8(sp)
    sw s2,12(sp)
    sw s3,16(sp)
    sw s4,20(sp)
    sw s5,24(sp)
    sw s6,28(sp)
    sw s7,32(sp)
    sw s8,36(sp)
    sw s9,40(sp)
    sw s10,44(sp)
    sw s11,48(sp)
    sw ra,52(sp) // save return addr
    sw sp,0(a0)  // save old sp
    mv sp,a1     // set new sp
    lw s0,4(sp)
    lw s1,8(sp)
    lw s2,12(sp)
    lw s3,16(sp)
    lw s4,20(sp)
    lw s5,24(sp)
    lw s6,28(sp)
    lw s7,32(sp)
    lw s8,36(sp)
    lw s9,40(sp)
    lw s10,44(sp)
    lw s11,48(sp)
    lw ra,52(sp)  // return addr
    addi sp,sp,64 // free frame
    ret           // return
```

(author: Yunhao Zhang)

USAGE:

```
struct pcb *current, *next;

void yield(){
    assert(current->state == RUNNING);
    current->state = RUNNABLE;
    runQueue.add(current);
    next = scheduler();
    next->state = RUNNING;
    ctx_switch(&current->sp, next->sp)
    current = next;
}
```

What if there are no more RUNNABLE processes?

- `scheduler()` would return `NULL` and things blow up
- solution: always run a low priority process that sits in an infinite loop executing the RISC-V WFI (Wait For Interrupt) or x86 `HLT` instruction or … (fill in your favorite CPU)
  - which waits for the next interrupt, saving energy when there's nothing to do

Three “kinds” of context switches

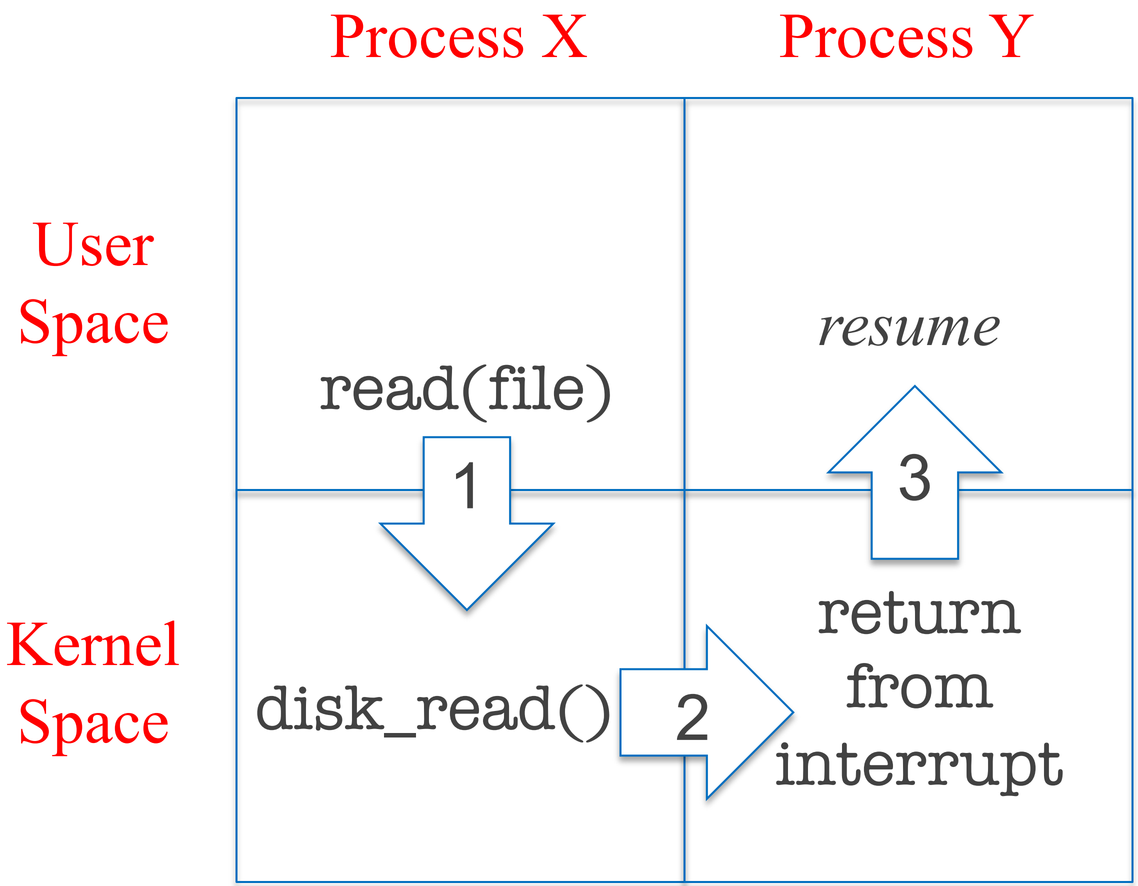
1. Interrupt: From user to kernel space
   - system call, exception, or interrupt
2. Yield: In kernel space, between two processes
   - happens inside the kernel, switching from one PCB/interrupt stack to another
3. Return-From-Interrupt: From kernel space to user space
   - Through a `return_from_interrupt` instruction

Note that each involves a stack switch:

1. Px user stack → Px interrupt stack
2. Px interrupt stack → Py interrupt stack
3. Py interrupt stack → Py user stack

A *context* is ”the CPU state,” which is captured in its registers. By context switching, the CPU can play different roles at different times

Example switch between processes



1. save process X user registers
2. save process X kernel registers and restore process Y kernel registers
3. restore process Y user registers

before step 2: scheduler picks a runnable process

A word on “abstraction”

- We manage complexity through abstraction
- When I say “tea water,” I mean the water that is used for tea
  - but it’s just water
  - that same water will serve different purposes in its existence
- When I say “kernel memory,” I mean the memory that is used for the kernel
  - but it’s just memory
  - it’s the same kind of memory that is used for processes
- Actors in a play: same actors can play multiple roles in their lives, sometimes even in the same play
  - actors are time multiplexed, same as registers of a CPU
  - the kernel SP is just the SP that is used by the kernel
  - when you’re watching “Woman King,” you’re supposed to imagine seeing *Nanisca*, not *Viola Davis*

A “process” is an abstraction

- Abstract computer with abstract memory, registers, and peripherals
- Some “hardware” computer can be multiplexed to run multiple processes
  - *time multiplexed*: registers
  - *space multiplexed*: disk

Review

- A *process* is an abstraction of a computer
- A *context* captures the state of the processor:
  - registers (including PC and SP)
- The implementation uses *two* contexts:
  - user context
  - kernel (supervisor) context
- A *Process Control Block (PCB)* is a kernel data structure that saves contexts and has other information about the process

System calls to create a new process

Windows:

CreateProcess(…);

UNIX (Linux):

fork() + exec(…)

CreateProcess (Simplified)

System Call:

```
if (!CreateProcess(
    NULL,  // No module name (use command line)
    argv[1],// Command line
    NULL,  // Process handle not inheritable
    NULL,  // Thread handle not inheritable
    FALSE, // Set handle inheritance to FALSE
    0,     // No creation flags
    NULL,  // Use parent's environment block
    NULL,  // Use parent's starting directory
    &si,   // Pointer to STARTUPINFO structure
    &pi )  // Ptr to PROCESS_INFORMATION structure
)
```

[Windows]

~~CreateProcess~~ ~~(Simplified)~~ fork (actual form)

System Call:

```
int pid = fork(  void ☺
    NULL,   // No module name (use command line)
    argv[1],// Command line
    NULL,   // Process handle not inheritable
    NULL,   // Thread handle not inheritable
    FALSE,  // Set handle inheritance to FALSE
    0,      // No creation flags
    NULL,   // Use parent's environment block
    NULL,   // Use parent's starting directory
    &si,    // Pointer to STARTUPINFO structure
    &pi )
)
```

pid = process identifier

[UNIX]

Kernel actions to create a process

fork():

- Allocate ProcessID
- Create & initialize PCB
- Create and initialize a new address space
- Inform scheduler that new process is ready to run

exec(program, arguments):

- Load the program into the address space
- Copy arguments into memory in address space
- Initialize h/w context to start execution at “start”

Windows **createProcess(…)** does both

Creating and Managing Processes

`fork()`	Create a child process as a clone of the current process. Returns to both parent and child. Returns child pid to parent process, 0 to child process.
`exec` `(prog, args)`	Run the application **prog** in the current process with the specified arguments (*replacing any code and data that was in the process already*)
`wait` `(&status)`	Pause until a child process has exited
`exit` `(status)`	Tell the kernel the current process is complete and should be garbage collected.
`kill` `(pid, type)`	Send an interrupt of a specified type to a process. (a bit of a misnomer, no?)

[UNIX]

Fork + Exec

```
Process 1
Program A
```

PC

```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

```
child_pid  ?
```

Fork + Exec

fork returns twice!

Process 1
Program A

```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

PC → `if (child_pid==0)`

child_pid: 42

Process 42
Program A

```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

PC → `if (child_pid==0)`

child_pid: 0

[UNIX]

Fork + Exec

Process 1
Program A

PC →
```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

child_pid 42

Waits until child exits.

Process 42
Program A

PC →
```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

child_pid 0

[UNIX]

Fork + Exec

```
Process 1
Program A
```

```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

PC

```
child_pid 42
```

```
Process 42
Program A
```

```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

PC

```
child_pid 0
```

if *and* ***else***
both executed!

[UNIX]

Fork + Exec

Process 1
Program A

PC

```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

child_pid 42

Process 42
Program B

PC

```
main() {
   ...

   exit(3);
}
```

Fork + Exec

Process 1
Program A

```
child_pid = fork();
if (child_pid==0)
  exec(B);
else
  wait(&status);
```

PC

child_pid 42

status 3

Code example (fork.c)

```
#include <stdio.h>
#include <unistd.h>

int main() {
   int child_pid = fork();

   if (child_pid == 0) {      // child process
        printf("I am process %d\n", getpid());
   }
   else {                     // parent process.
        printf("I am the parent of process %d\n", child_pid);
   }
   return 0;
}
```

Possible outputs?

Shell

What is a Shell?

- is an interpreter (i.e., just another program)
- language allows user to create/manage programs
- Example shells:
  - sh Original Unix shell (Stephen Bourne, AT&T Bell Labs, 1977)
  - bash “Bourne-Again” Shell (free, Linux, MacOSX)
  - cmd Windows shell (Therese Stowell, Microsoft, 1987)
  - PowerShell (2006)
  - …

Runs at user-level. Uses syscalls: fork, exec, etc.

What is a Shell?

- Reads lines of input
  - command [arg1 …]
- And executes them
- Full programming language in its own right
- e.g. (sh, bash):

```
$ for x in a b c
> do echo $x                # echo is a print command
> done
```

Shell has state

- Just like other programming languages
- State includes:
  - environment variables
  - home directory (directory == folder)
  - working directory
  - list of processes
- Commands often modify the state

Environment Variables

- Each process has access to a collection of *environment variables*
  - implicit arguments to the process
- Each env variable has a name and a value
  - both are strings
- One env variable is the search "path"
  - list of folders/directories to find executables
- For example:
  - **PATH**=/bin:/usr/bin:/usr/local/bin

Some important sh commands

- echo [args] # print arguments
- ls # list the working directory
- pwd # print working directory
- cd [dir] # change working directory
  - default is “home” directory
- ps # list running processes

$\$x$ returns the value of (environment) variable x

“flags” (aka options)

- arguments to command that start with ‘-’
- examples:
  - ls –l # long listing
  - ps –a # print all processes

“foreground” vs. “background”

The shell either

- is reading from standard input
- is waiting for a process to finish
  - this is the *foreground* process
  - other processes are *background processes*
- To start a background process, add ‘&’
  - e.g.:
    - (sleep 5; echo hello)&
    - x & y # runs x in background and y in foreground

Background processes should not read from standard input!

Why not?

Pipelines

- x | y
  - runs both x and y in foreground
  - output of x is input to y
  - finishes when both x and y finish
- e.g.:
  - echo robbert | tr b B

Threads! (Chapters 25-27)

Other terms for threads:

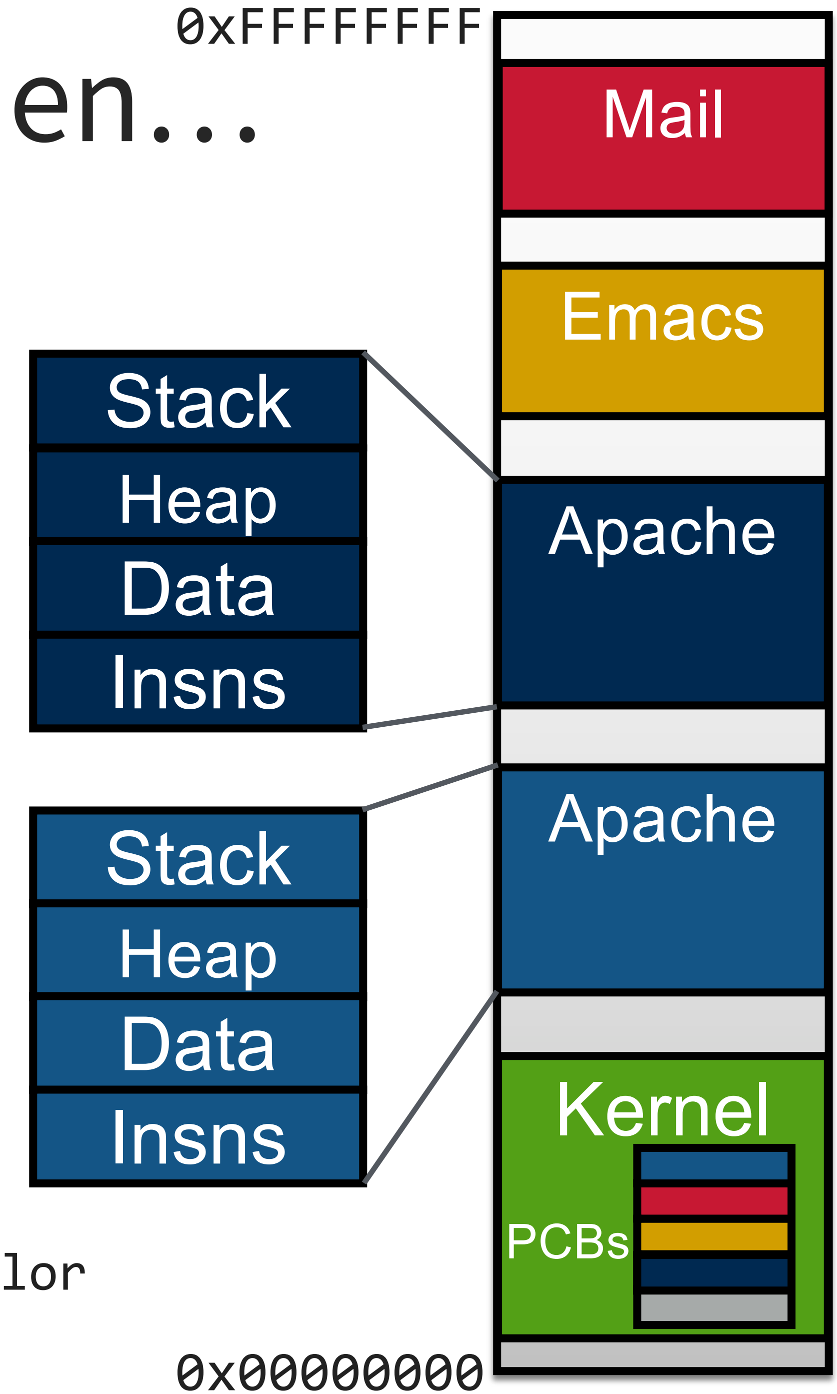
- Lightweight Process
- Thread of Control
- Task

What happens when…

Apache wants to run multiple concurrent computations?

Two heavyweight address spaces for two concurrent computations

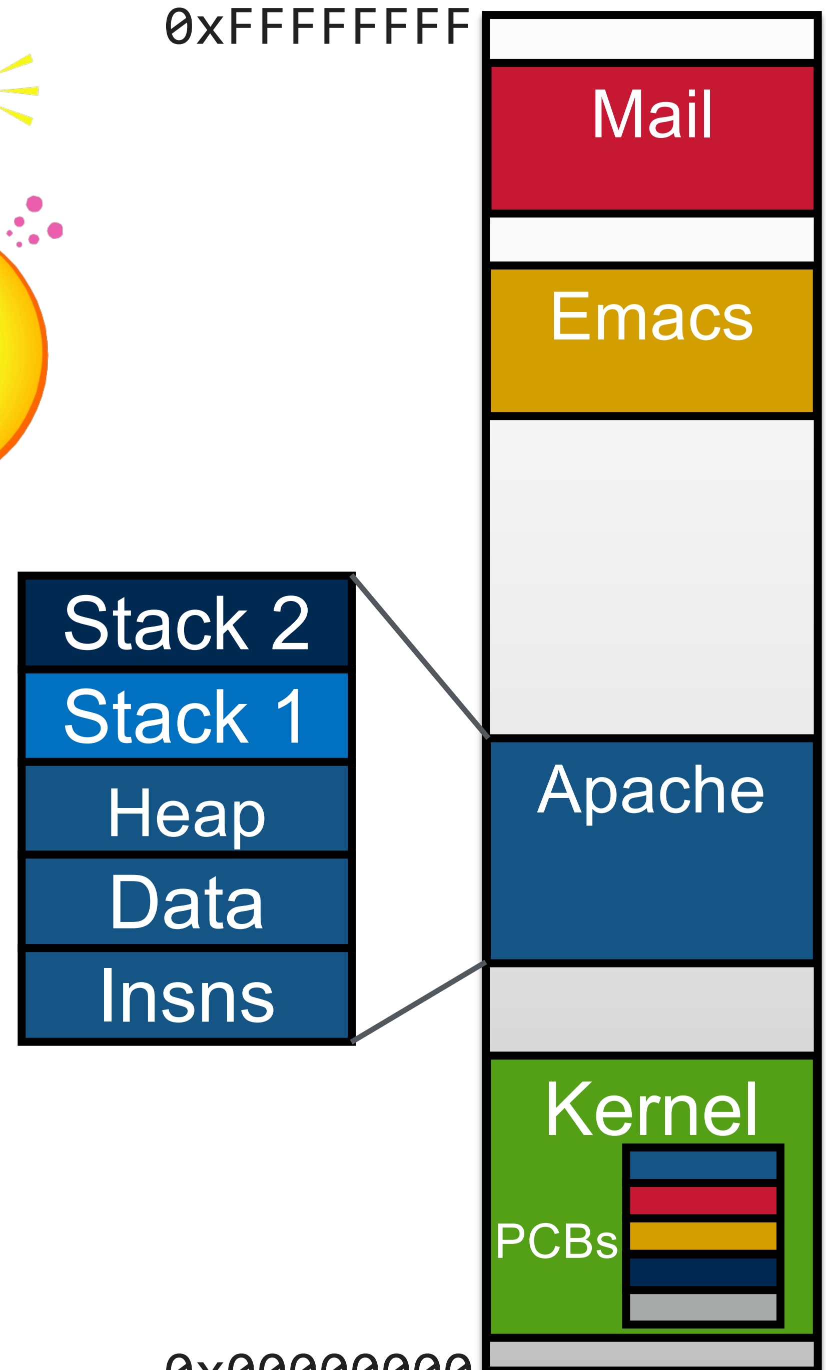
Hard to share cache, etc.



Physical address space
Each process' address space by color
(shown contiguous to look nicer)

Idea

Place concurrent computations in the same address space!



Process vs. Thread Abstraction

- A process is an abstraction of a computer
  - ➢CPU, memory, devices
- A thread is an abstraction of a core
  - ➢registers (incl. PC and SP)

Unbounded #computers, each with unbounded #cores

- Different processes typically have their own (virtual) memory, but different threads share virtual memory.

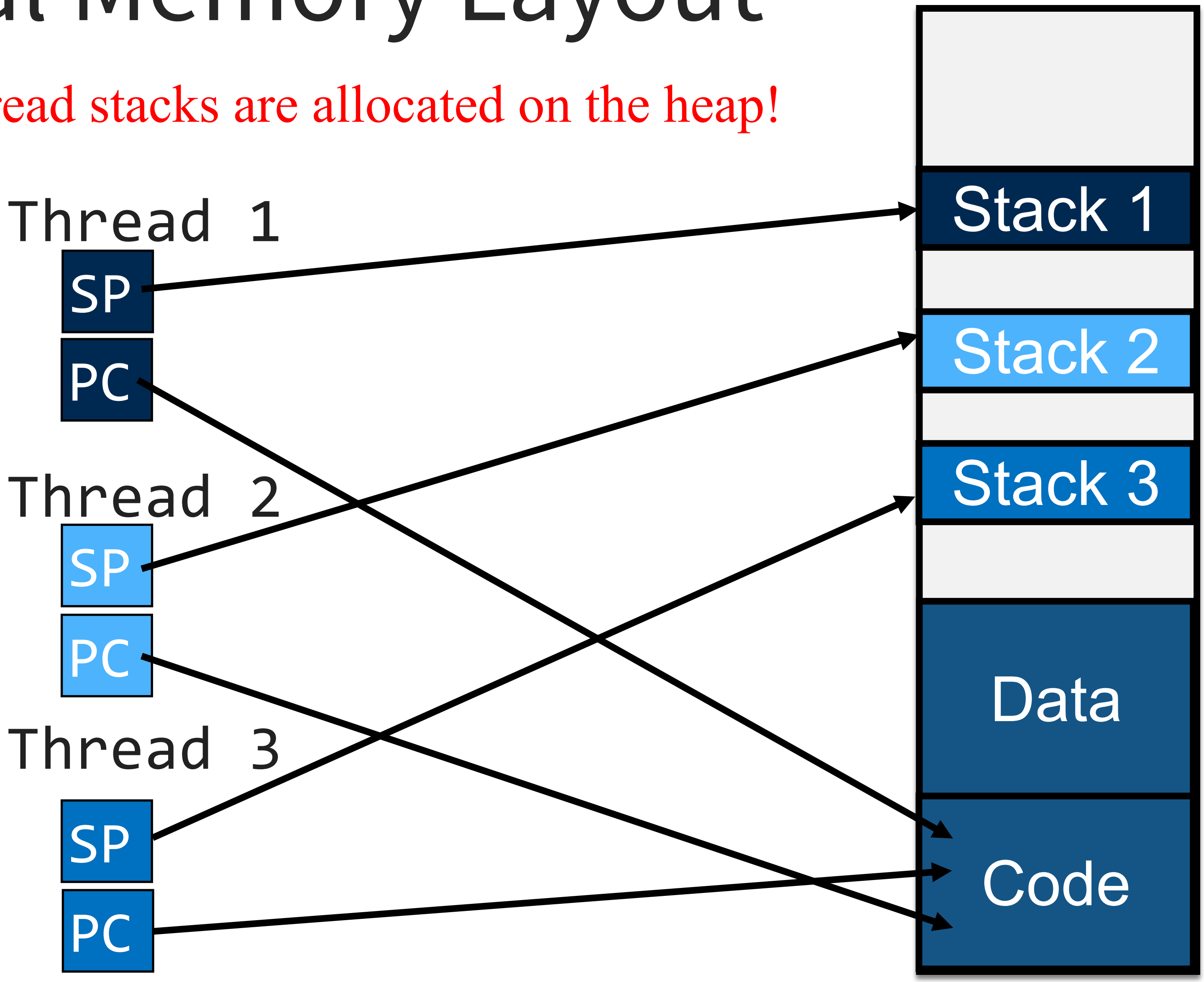
- Different processes tend to be mutually distrusting, but threads must be mutually trusting. Why?

Nomenclature Warning

- In “concurrency literature”, threads are often called “processes” or “processors”

Virtual Memory Layout

Thread stacks are allocated on the heap!



Why Threads?

Concurrency

- exploiting multiple CPUs/cores

Mask long latency of I/O

- doing useful work while waiting

Responsiveness

- high priority GUI threads / low priority work threads

Encourages natural program structure

- Expressing logically concurrent tasks
- update screen, fetching data, receive user input

Some Thread Examples

```
for (k = 0; k < n; k++) {
    a[k] = b[k] × c[k] + d[k] × e[k]
}
```

Web server:

1. get network message (URL) from client
2. get URL data from disk
3. compose response
4. send response

Simple Thread API

`void thread_create(func,arg)`	Creates a new thread that will execute function **func** with the arguments **arg**
`void thread_yield()`	Calling thread gives up processor. Scheduler can resume running this thread at any point.
`void thread_exit()`	Finish caller

Preemption

- Two kinds of threads:
  - Non-preemptive: explicitly yield to other threads
  - Preemptive: yield automatically upon clock interrupts

- Most modern threading systems are preemptive
  - but not 4411 P1 project

Implementation of Threads

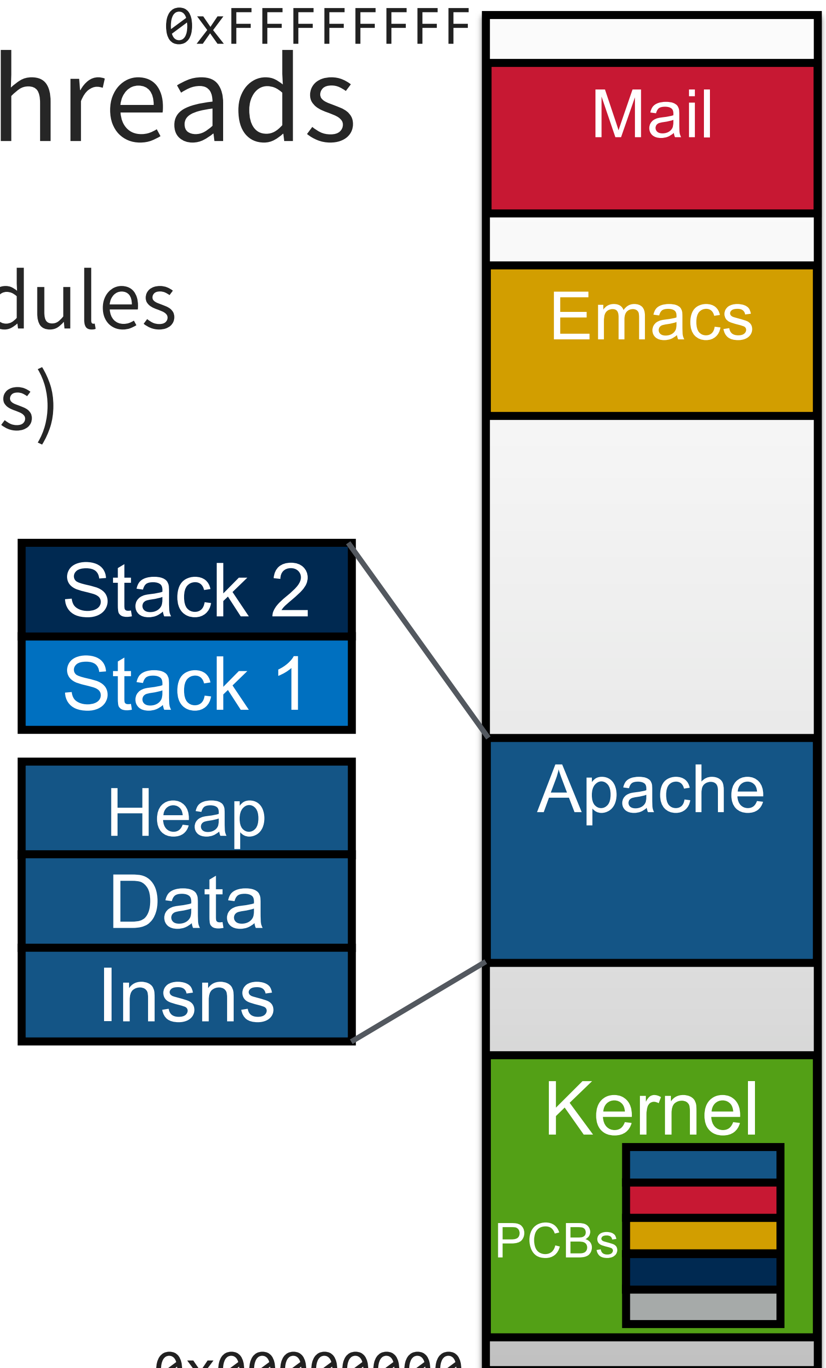
One abstraction, two implementations:

1. “kernel threads”: each thread has its own PCB in the kernel, but the PCBs point to the same physical memory
2. “user threads”: one PCB for the process; threads implemented entirely in user space. Each thread has its own Thread Control Block (TCB) and context

#1: Kernel-Level Threads

Kernel knows about, schedules threads (just like processes)

- Separate PCB for each thread
- PCBs have:
  - **same:** page table base register
  - **different:** PC, SP, registers, interrupt stack

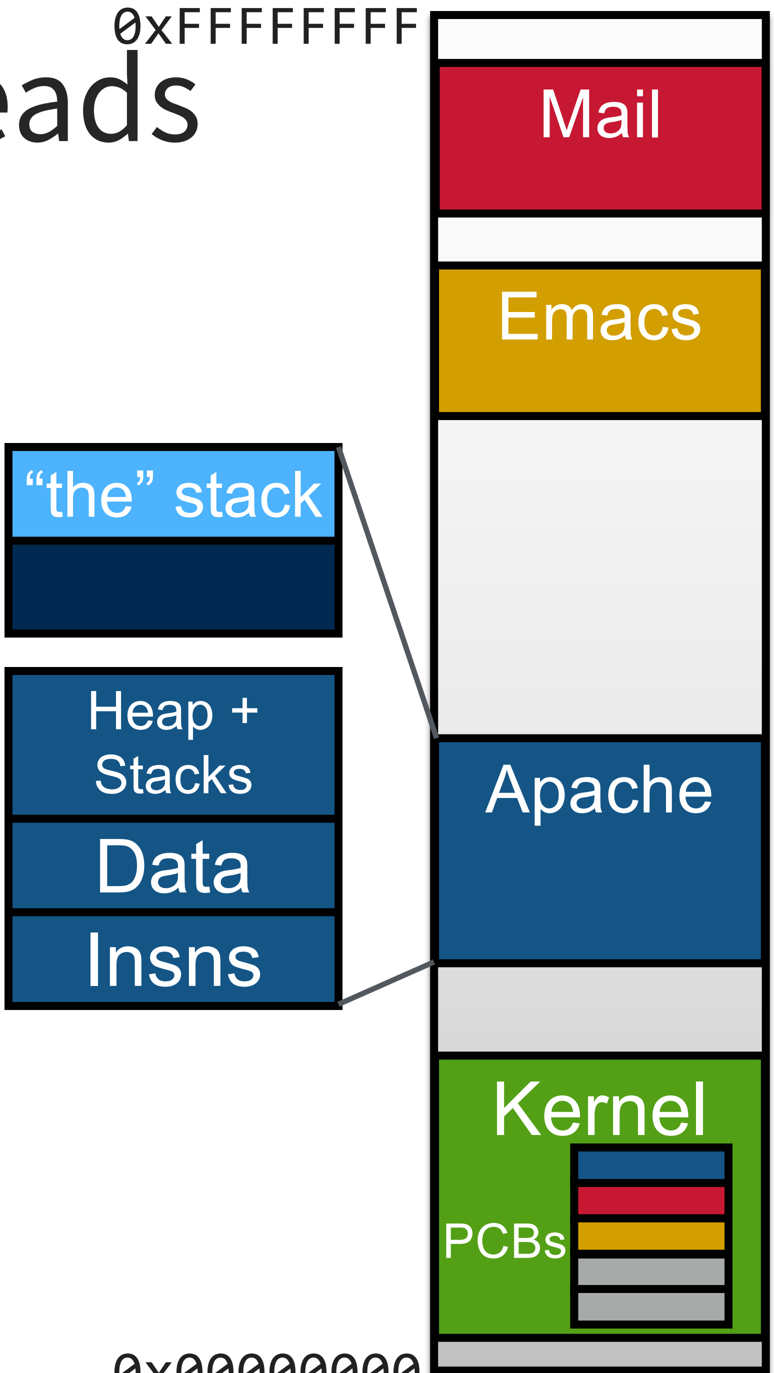


#2: User-Level Threads

Run mini-OS in user space
- Real OS unaware of threads
- Single PCB
- Thread Control Block (TCB) for each thread

Generally more efficient than kernel-level threads (Why?)

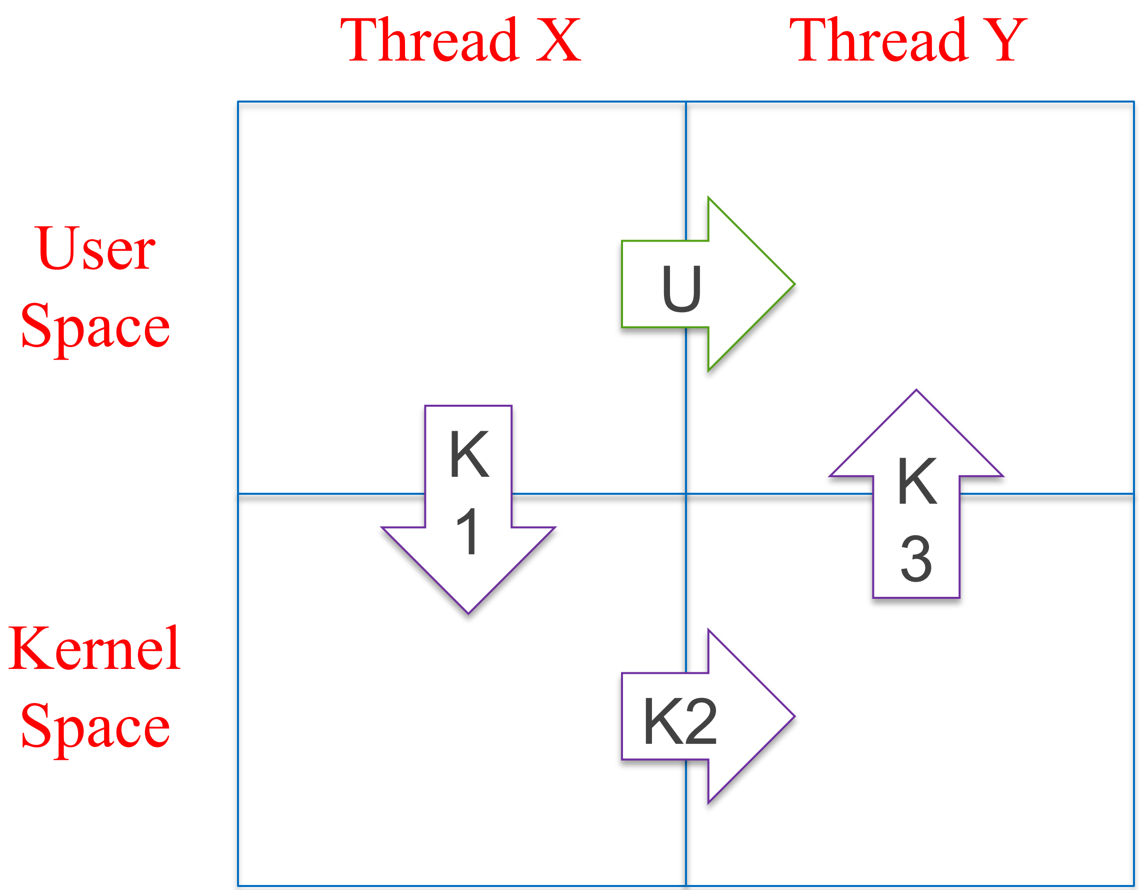
But kernel-level threads simplify system call handling and scheduling (Why?)



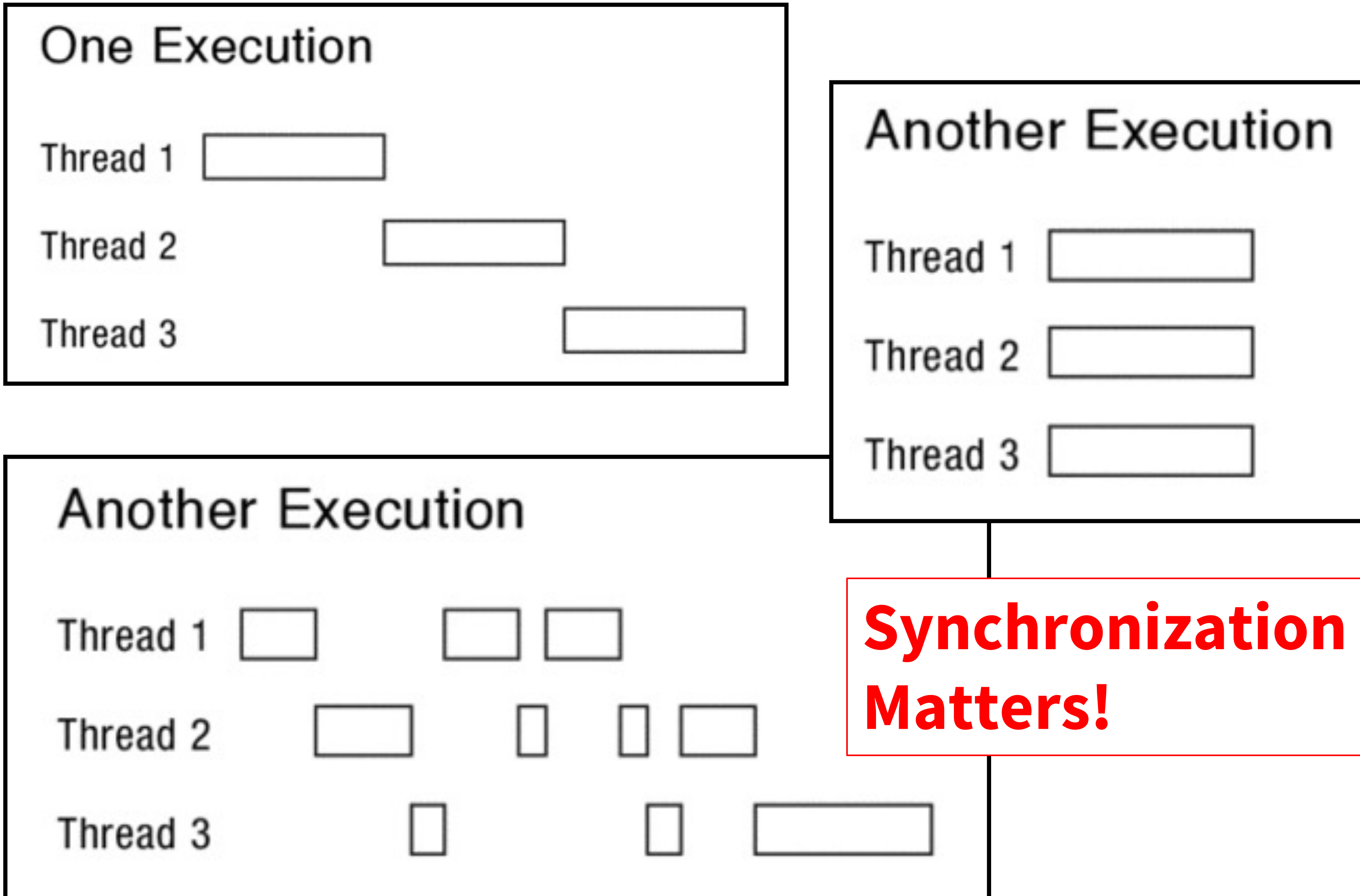
Kernel- vs User-level Threads

Kernel-Level Threads	User-level Threads
• Easy to implement: just processes with shared page table	• Requires user-level context switches, scheduler
• Threads can run blocking system calls concurrently	• Blocking system call blocks all threads: needs O.S. support for non-blocking system calls
• Thread switch requires three context switches	• Thread switch efficiently implemented in user space

Kernel vs User Thread Switch



Do **not** presume to know the schedule



Synchronization Matters!