CS162
Operating Systems and Systems Programming
Lecture 5

Introduction to Networking (Finished), Concurrency (Processes and Threads)

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Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes. *When slides are obtained from other sources, a a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

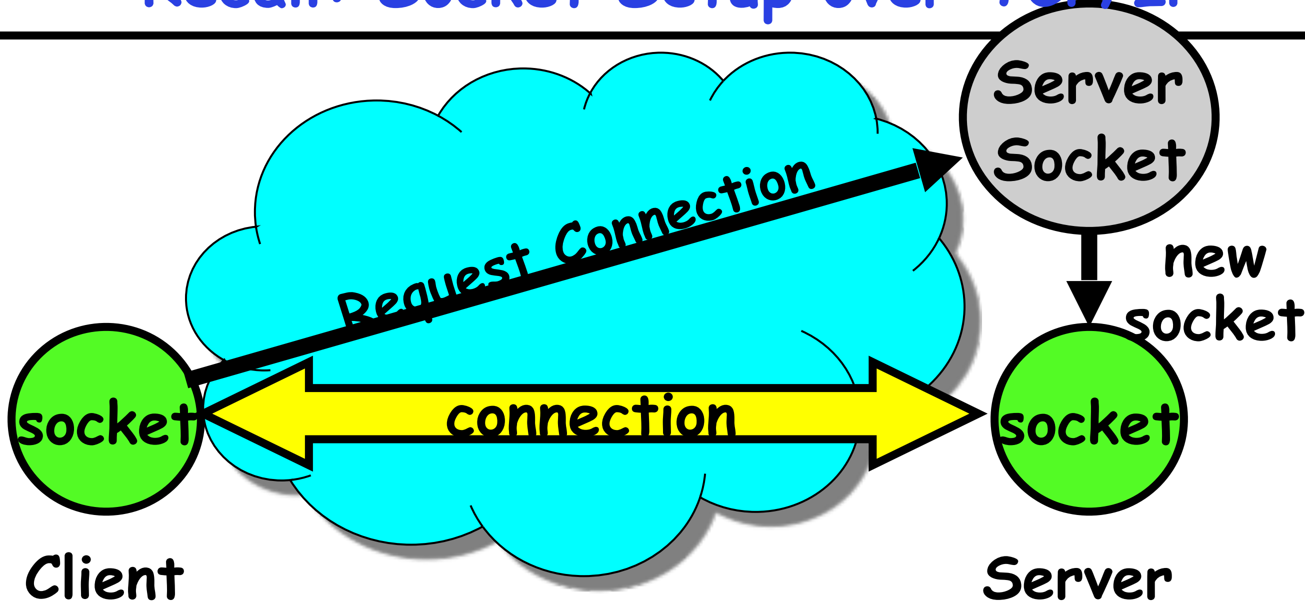
Recall: Namespaces for communication over IP

- Hostname
  - www.eecs.berkeley.edu
- IP address
  - 128.32.244.172 (ipv4 format)
- Port Number
  - 0-1023 are "well known" or "system" ports
    - » Superuser privileges to bind to one
  - 1024 – 49151 are "registered" ports (registry)
    - » Assigned by IANA for specific services
  - 49152–65535 ($2^{15}+2^{14}$ to $2^{16}-1$) are "dynamic" or "private"
    - » Automatically allocated as "ephemeral Ports"

Recall: Use of Sockets in TCP

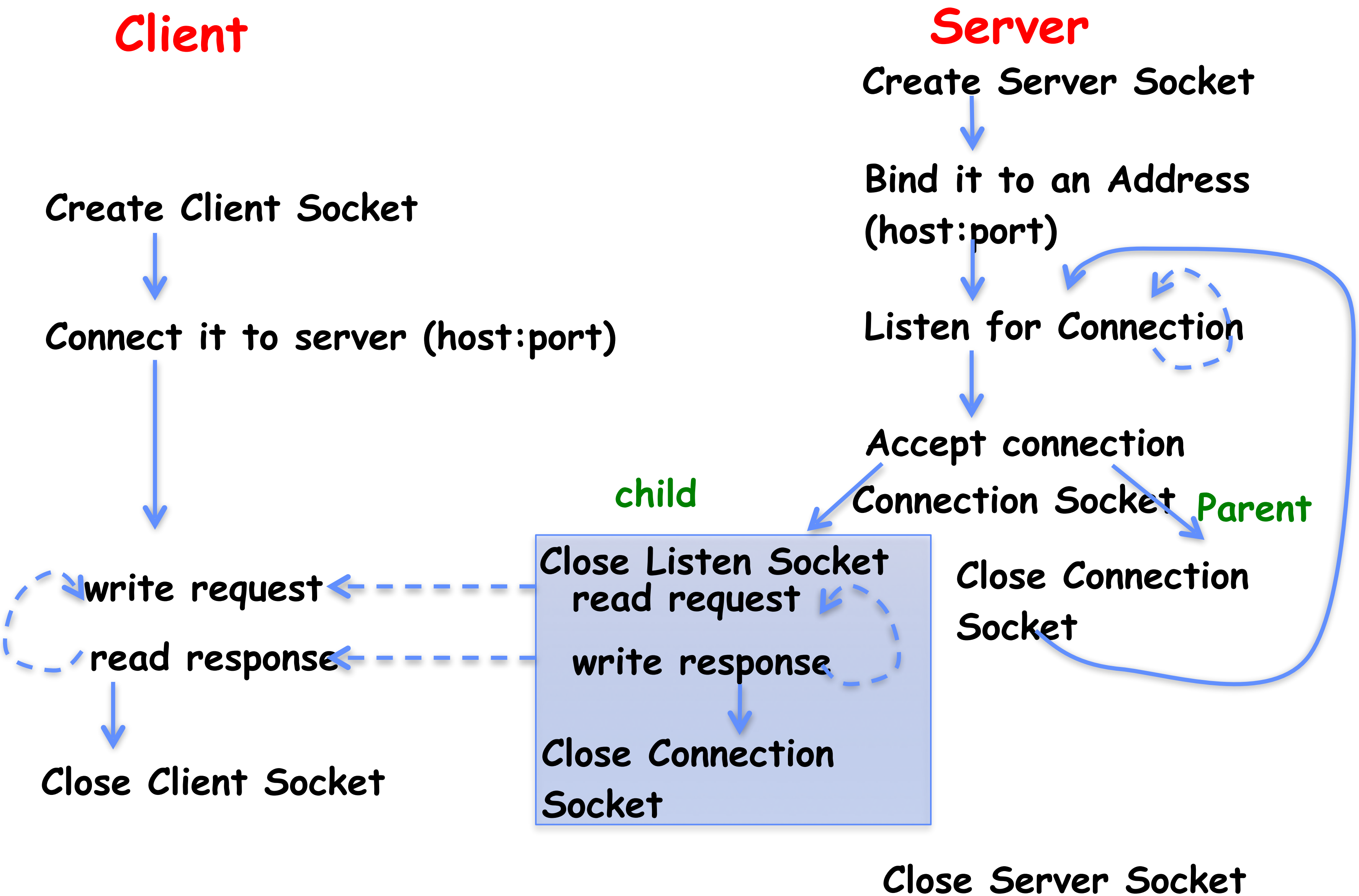
- **Socket:** an abstraction of a network I/O queue
  - Embodies one side of a communication channel
    - » Same interface regardless of location of other end
    - » Could be local machine (called "UNIX socket") or remote machine (called "network socket")
  - First introduced in 4.2 BSD UNIX: big innovation at time
    - » Now most operating systems provide some notion of socket
- Using Sockets for Client-Server (C/C++ interface):
  - On server: set up "server-socket"
    - » Create socket, Bind to protocol (TCP), local address, port
    - » Call listen(): tells server socket to accept incoming requests
    - » Perform multiple accept() calls on socket to accept incoming connection request
    - » Each successful accept() returns a new socket for a new connection; can pass this off to handler thread
  - On client:
    - » Create socket, Bind to protocol (TCP), remote address, port
    - » Perform connect() on socket to make connection
    - » If connect() successful, have socket connected to server

Recall: Socket Setup over TCP/IP



- Server Socket: Listens for new connections
  - Produces new sockets for each unique connection
- Things to remember:
  - Connection involves 5 values:
    [Client Addr, Client Port, Server Addr, Server Port, Protocol]
  - Often, Client Port "randomly" assigned
    » Done by OS during client socket setup
  - Server Port often "well known"
    » 80 (web), 443 (secure web), 25 (sendmail), etc
    » Well-known ports from 0—1023

Example: Server Protection and Parallelism



Recall: Server Protocol (v3)

```
while (1) {
    listen(lstnsockfd, MAXQUEUE);
    consockfd = accept(lstnsockfd, (struct sockaddr *) &cli_addr,
                                                       &clilen);
    cpid = fork();                  /* new process for connection */
    if (cpid > 0) {                 /* parent process */
      close(consockfd);
    } else if (cpid == 0) {          /* child process */
      close(lstnsockfd);            /* let go of listen socket */

      server(consockfd);

      close(consockfd);
      exit(EXIT_SUCCESS);            /* exit child normally */
    }
  }
close(lstnsockfd);
```

Server Address - itself

```
memset((char *) &serv_addr,0, sizeof(serv_addr));
serv_addr.sin_family      = AF_INET;
serv_addr.sin_addr.s_addr = INADDR_ANY;
serv_addr.sin_port        = htons(portno);
```

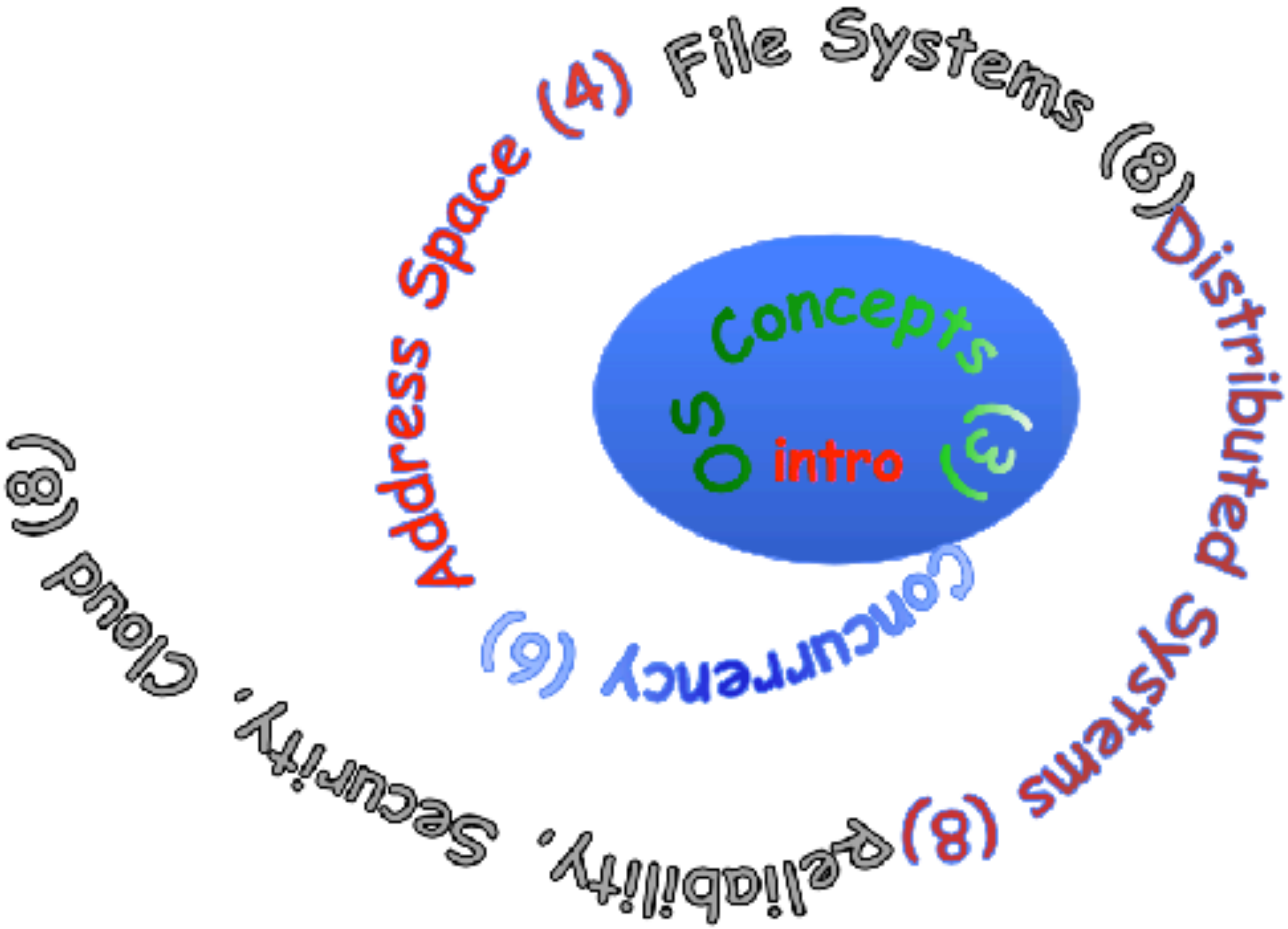
- Simple form
- Internet Protocol
- accepting any connections on the specified port
- In "network byte ordering"

Client: getting the server address

```
struct hostent *buildServerAddr(struct sockaddr_in *serv_addr,
                                char *hostname, int portno) {
  struct hostent *server;

  /* Get host entry associated with a hostname or IP address */
  server = gethostbyname(hostname);
  if (server == NULL) {
    fprintf(stderr,"ERROR, no such host\n");
    exit(1);
  }

  /* Construct an address for remote server */
  memset((char *) serv_addr, 0, sizeof(struct sockaddr_in));
  serv_addr->sin_family = AF_INET;
  bcopy((char *)server->h_addr,
        (char *)&(serv_addr->sin_addr.s_addr), server->h_length);
  serv_addr->sin_port = htons(portno);

return server;
}
```

BIG OS Concepts so far

- Processes
- Address Space
- Protection
- Dual Mode
- Interrupt handlers (including syscall and trap)
- File System
  - Integrates processes, users, cwd, protection
- Key Layers: OS Lib, Syscall, Subsystem, Driver
  - User handler on OS descriptors
- Process control
  - fork, wait, signal, exec
- Communication through sockets
- Client-Server Protocol

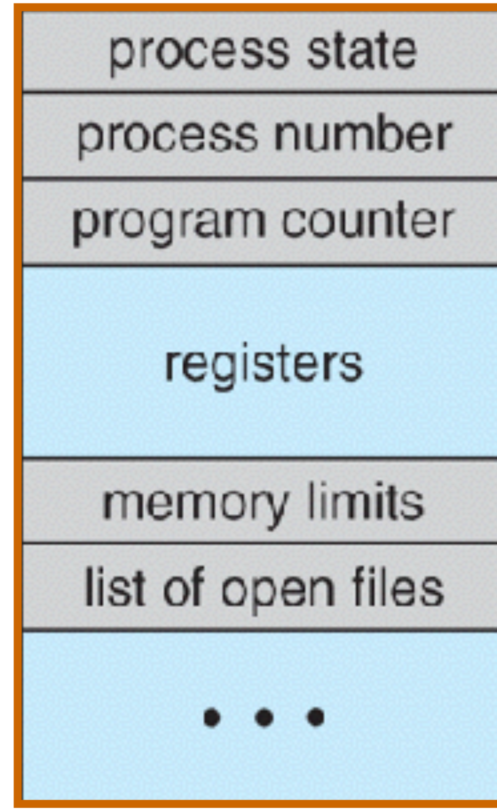

OS intro
Concepts (3)
Concurrency (6)
Address Space (4)
File Systems (8)
Distributed Systems (8)
Reliability, Security, Cloud (8)

Recall: Traditional UNIX Process

- Process: Operating system abstraction to represent what is needed to run a single program
  - Often called a "HeavyWeight Process"
  - No concurrency in a "HeavyWeight Process"
- Two parts:
  - Sequential program execution stream
    - » Code executed as a sequential stream of execution (i.e., thread)
    - » Includes State of CPU registers
  - Protected resources:
    - » Main memory state (contents of Address Space)
    - » I/O state (i.e. file descriptors)

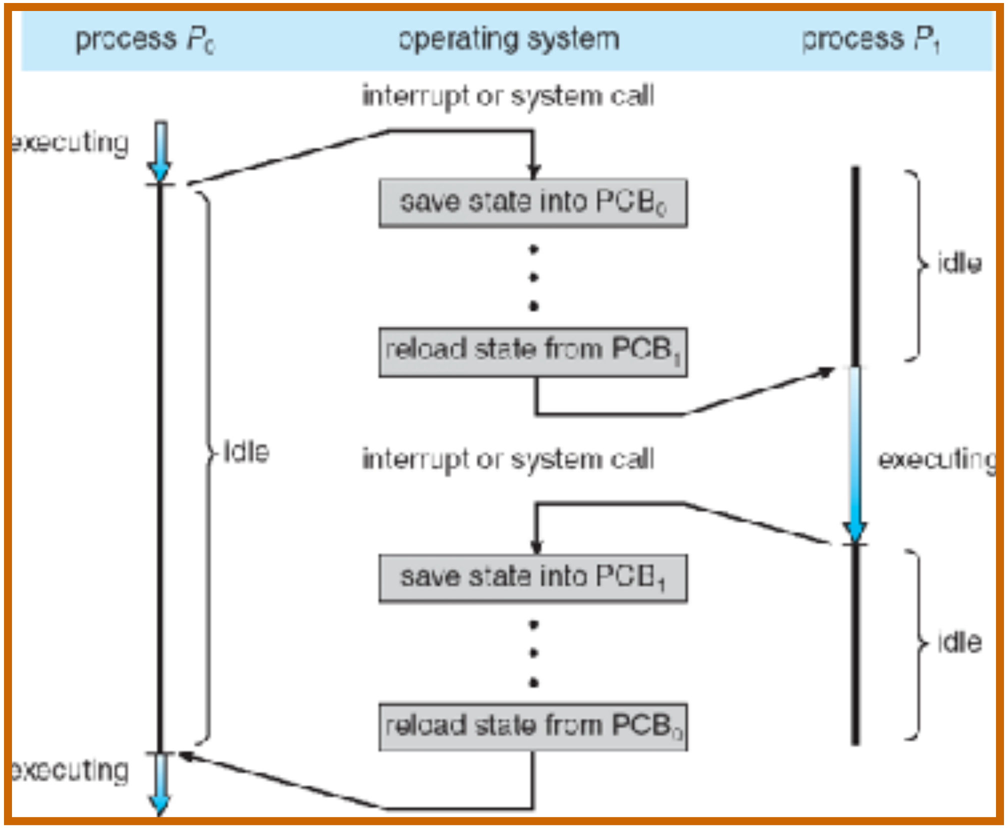
How do we Multiplex Processes?

- The current state of process held in a process control block (PCB):
  - This is a "snapshot" of the execution and protection environment
  - Only one PCB active at a time
- Give out CPU time to different processes (Scheduling):
  - Only one process "running" at a time
  - Give more time to important processes
- Give pieces of resources to different processes (Protection):
  - Controlled access to non-CPU resources
  - Example mechanisms:
    - » Memory Mapping: Give each process their own address space



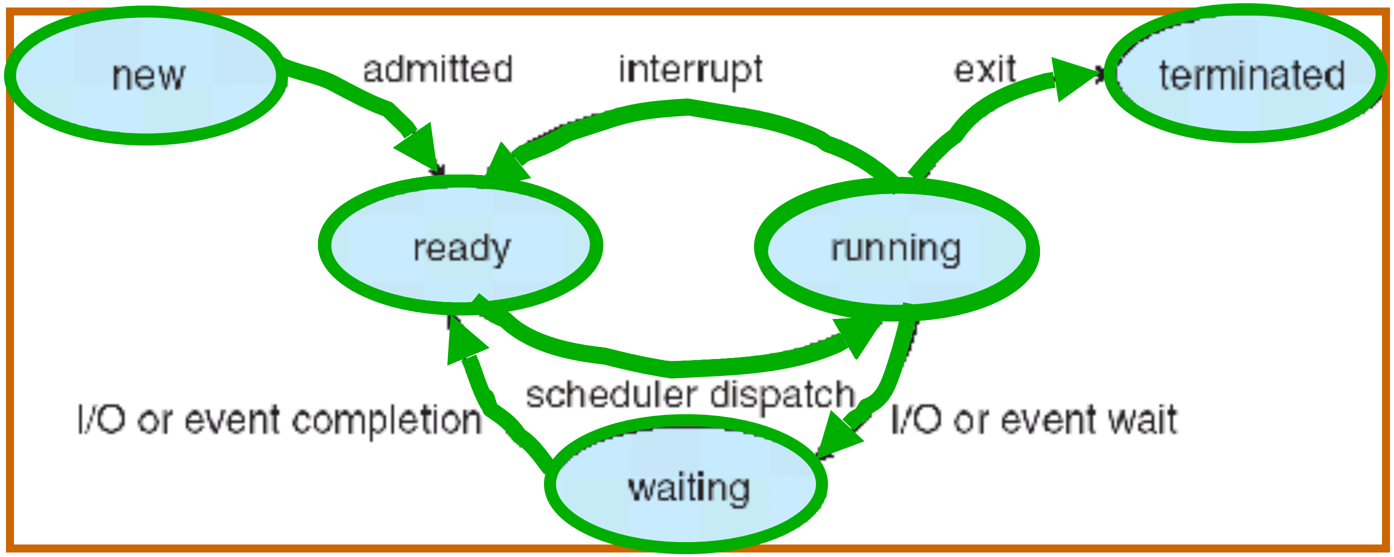
Process Control Block

CPU Switch From Process to Process



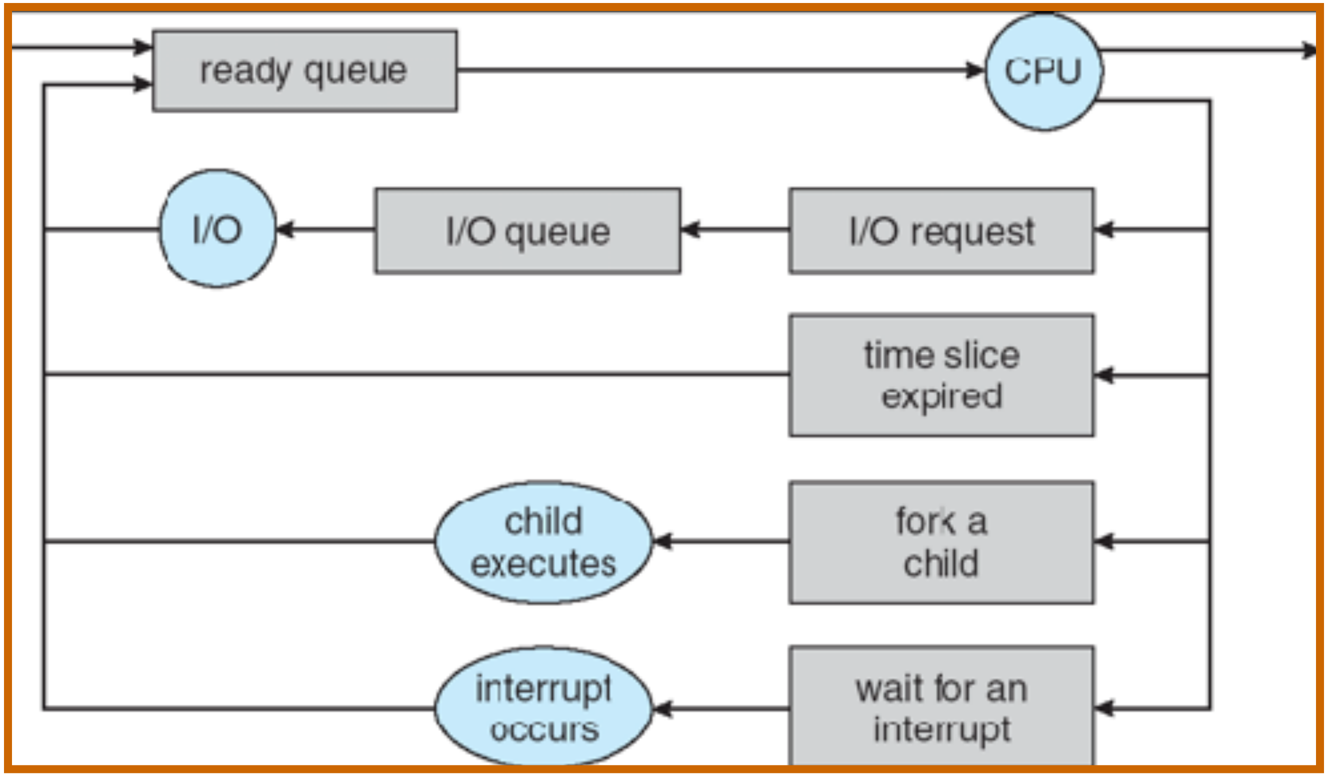
- This is also called a "context switch"
- Code executed in kernel above is overhead
  - Overhead sets minimum practical switching time

Lifecycle of a Process



- As a process executes, it changes state:
  - new: The process is being created
  - ready: The process is waiting to run
  - running: Instructions are being executed
  - waiting: Process waiting for some event to occur
  - terminated: The process has finished execution

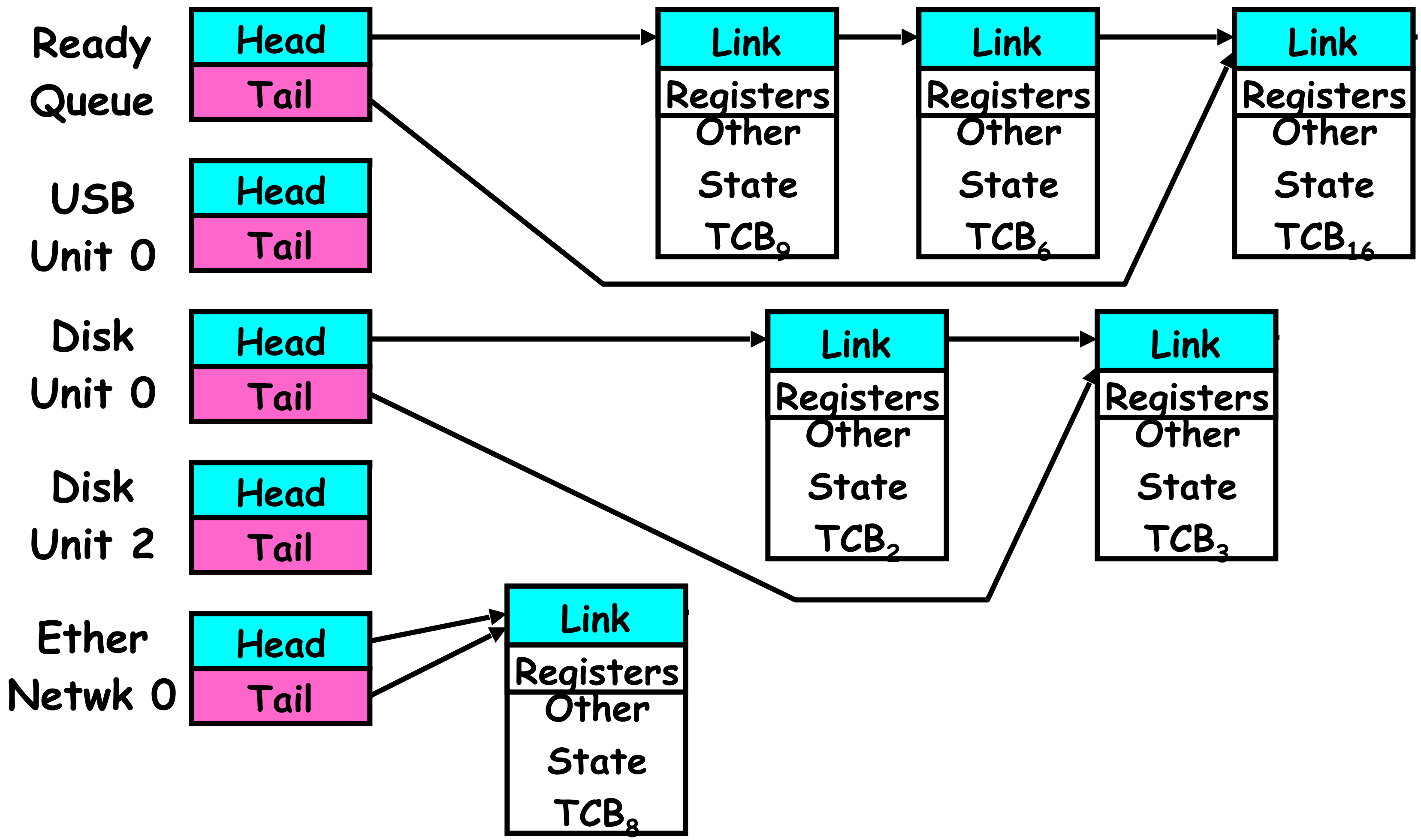
Process Scheduling



- PCBs move from queue to queue as they change state
  - Decisions about which order to remove from queues are Scheduling decisions
  - Many algorithms possible (few weeks from now)

Ready Queue And Various I/O Device Queues

- Thread not running ⇒ TCB is in some scheduler queue
  - Separate queue for each device/signal/condition
  - Each queue can have a different scheduler policy



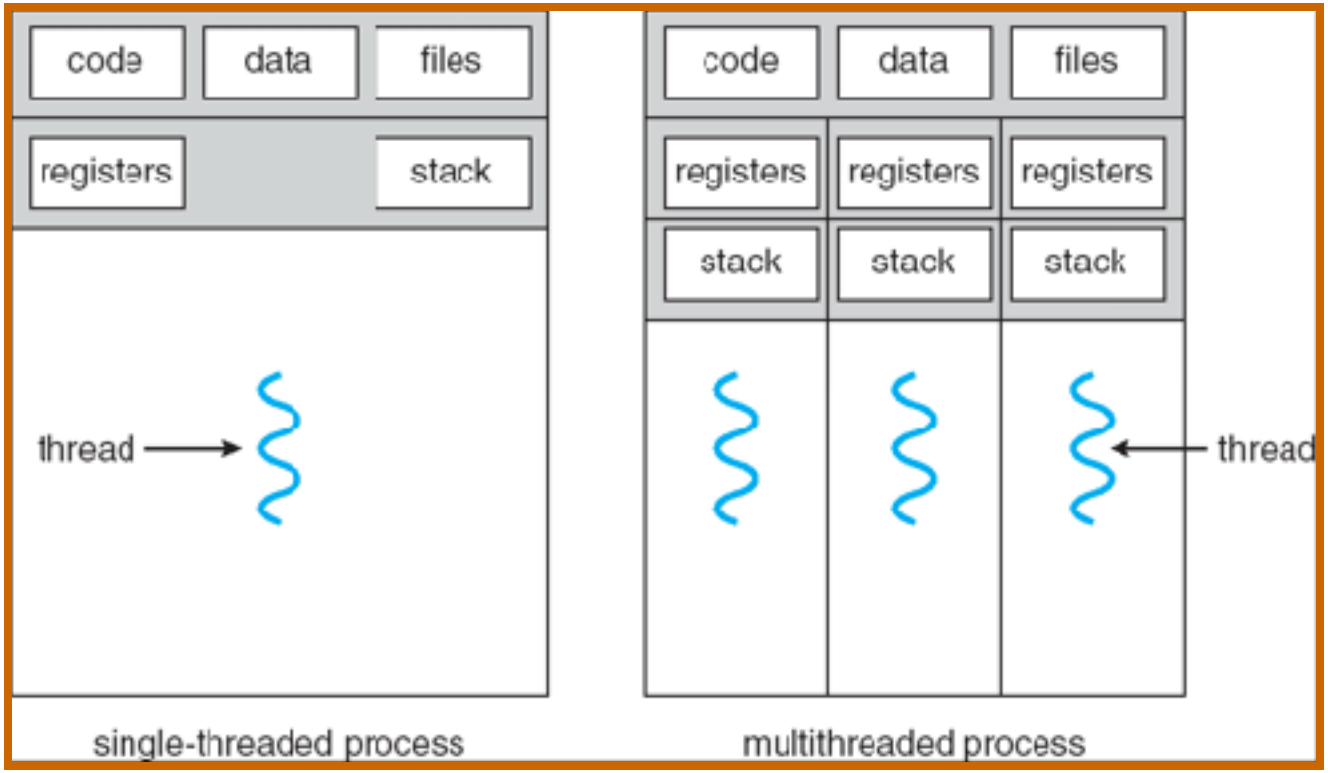
Administrivia

- Group signups: 4 members/group
  - Groups need to be finished by next Wednesday!
- Finding info on your own is a good idea!
  - Learn your tools, like "man"
  - Can even type "man xxx" into google!
    - » Example: "man ls"

Modern Process with Threads

- Thread: a sequential execution stream within process (Sometimes called a "Lightweight process")
  - Process still contains a single Address Space
  - No protection between threads
- Multithreading: a single program made up of a number of different concurrent activities
- Why separate the concept of a thread from that of a process?
  - Discuss the "thread" part of a process (concurrency)
  - Separate from the "address space" (protection)
  - Heavyweight Process $\equiv$ Process with one thread

Single and Multithreaded Processes



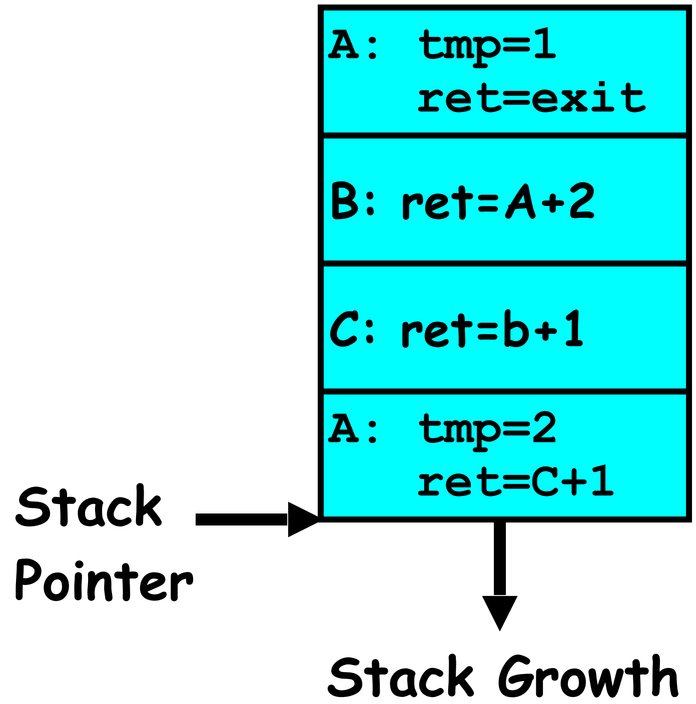
- Threads encapsulate concurrency: "Active" component
- Address spaces encapsulate protection: "Passive" part
  - Keeps buggy program from trashing the system
- Why have multiple threads per address space?

Thread State

- State shared by all threads in process/addr space
  - Content of memory (global variables, heap)
  - I/O state (file descriptors, network connections, etc)
- State "private" to each thread
  - Kept in TCB ≡ Thread Control Block
  - CPU registers (including, program counter)
  - Execution stack – what is this?
- Execution Stack
  - Parameters, temporary variables
  - Return PCs are kept while called procedures are executing

Execution Stack Example

```
A(int tmp) {
  if (tmp<2)
    B();
  printf(tmp);
}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Motivational Example for Threads

- Imagine the following C program:

```
main() {
    ComputePI("pi.txt");
    PrintClassList("clist.text");
}
```

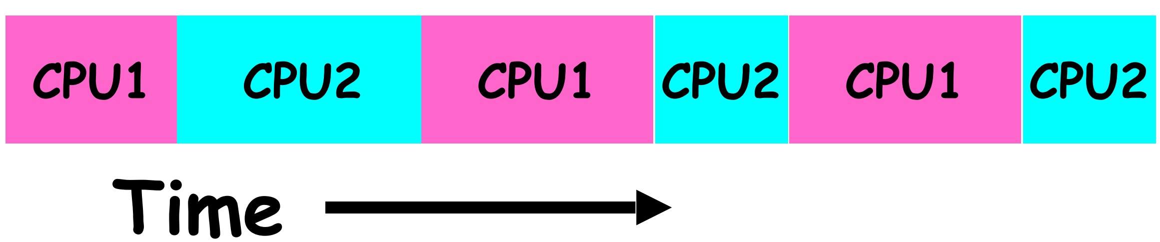
- What is the behavior here?
  - Program would never print out class list
  - Why? ComputePI would never finish

Use of Threads

- Version of program with Threads (loose syntax):

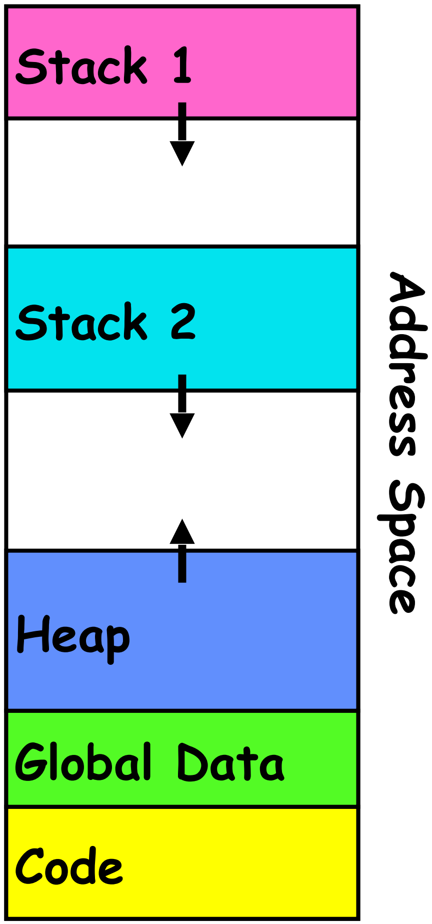
```
main() {
    ThreadFork(ComputePI("pi.txt"));
    ThreadFork(PrintClassList("clist.text"));
}
```

- What does "ThreadFork()" do?
  - Start independent thread running given procedure
- What is the behavior here?
  - Now, you would actually see the class list
  - This should behave as if there are two separate CPUs



Memory Footprint: Two-Threads

- If we stopped this program and examined it with a debugger, we would see
  - Two sets of CPU registers
  - Two sets of Stacks
- Questions:
  - How do we position stacks relative to each other?
  - What maximum size should we choose for the stacks?
  - What happens if threads violate this?
  - How might you catch violations?



Actual Thread Operations

- thread_fork(func, args)
  - Create a new thread to run func(args)
  - Pintos: thread_create
- thread_yield()
  - Relinquish processor voluntarily
  - Pintos: thread_yield
- thread_join(thread)
  - In parent, wait for forked thread to exit, then return
- thread_exit
  - Quit thread and clean up, wake up joiner if any
  - Pintos: thread_exit

- pThreads: POSIX standard for thread programming

Dispatch Loop

- Conceptually, the dispatching loop of the operating system looks as follows:

```
Loop {
    RunThread();
    ChooseNextThread();
    SaveStateOfCPU(curTCB);
    LoadStateOfCPU(newTCB);
}
```

- This is an infinite loop
  – One could argue that this is all that the OS does
- Should we ever exit this loop???
  – When would that be?

Running a thread

Consider first portion: `RunThread()`

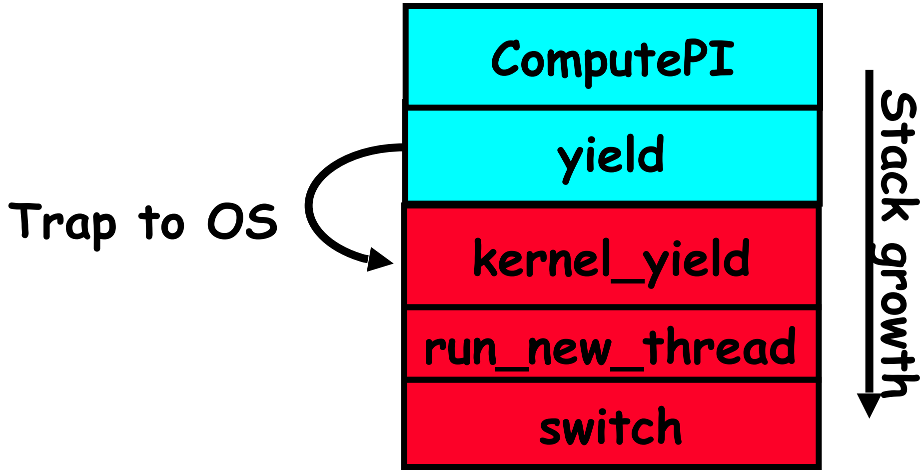
- How do I run a thread?
  - Load its state (registers, PC, stack pointer) into CPU
  - Load environment (virtual memory space, etc)
  - Jump to the PC
- How does the dispatcher get control back?
  - Internal events: thread returns control voluntarily
  - External events: thread gets preempted

Internal Events

- Blocking on I/O
  - The act of requesting I/O implicitly yields the CPU
- Waiting on a "signal" from other thread
  - Thread asks to wait and thus yields the CPU
- Thread executes a `yield()`
  - Thread volunteers to give up CPU

```
computePI() {
    while(TRUE) {
        ComputeNextDigit();
        yield();
    }
}
```

Stack for Yielding Thread



- How do we run a new thread?

```
run_new_thread() {
    newThread = PickNewThread();
    switch(curThread, newThread);
    ThreadHouseKeeping(); /* Do any cleanup */
}
```

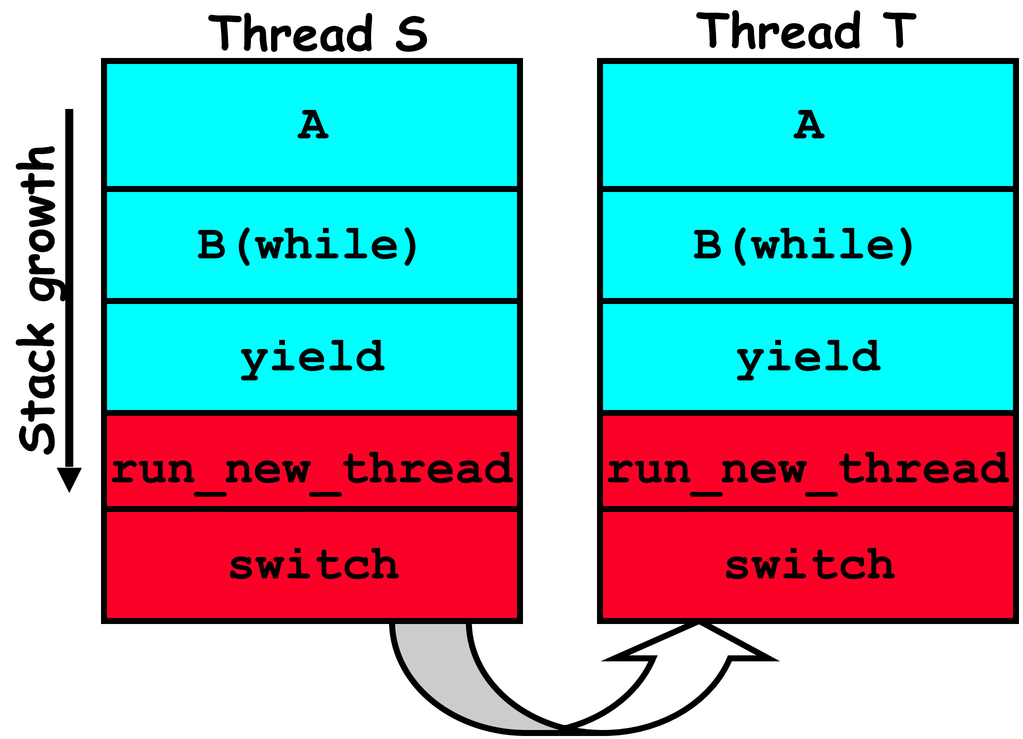
- How does dispatcher switch to a new thread?
  - Save anything next thread may trash: PC, regs, stack
  - Maintain isolation for each thread

What do the stacks look like?

- Consider the following code blocks:

```
proc A() {
    B();
}
proc B() {
    while(TRUE) {
        yield();
    }
}
```

- Suppose we have 2 threads:
  - Threads S and T



Saving/Restoring state (often called "Context Switch)

```
Switch(tCur,tNew) {
   /* Unload old thread */
   TCB[tCur].regs.r7 = CPU.r7;
         …
   TCB[tCur].regs.r0 = CPU.r0;
   TCB[tCur].regs.sp = CPU.sp;
   TCB[tCur].regs.retpc = CPU.retpc; /*return addr*/

   /* Load and execute new thread */
   CPU.r7 = TCB[tNew].regs.r7;
         …
   CPU.r0 = TCB[tNew].regs.r0;
   CPU.sp = TCB[tNew].regs.sp;
   CPU.retpc = TCB[tNew].regs.retpc;
   return; /* Return to CPU.retpc */
}
```

Switch Details (continued)

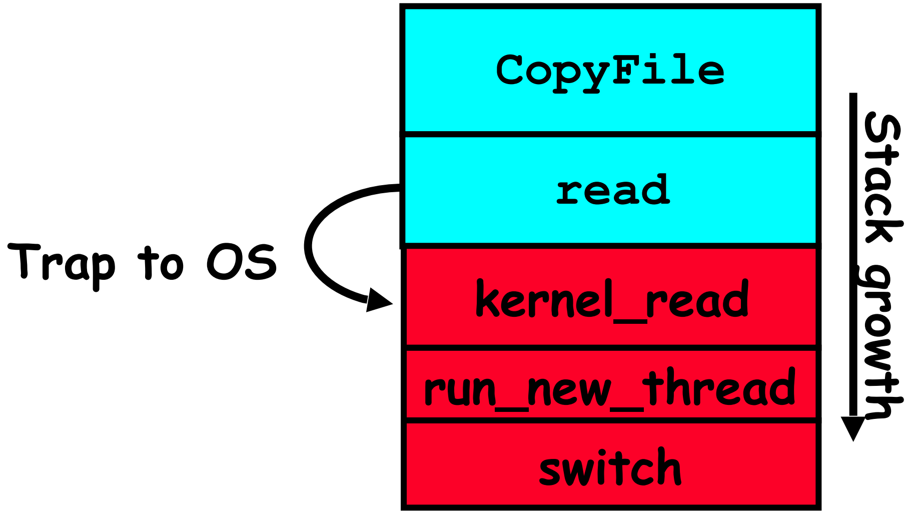
- What if you make a mistake in implementing switch?
  - Suppose you forget to save/restore register 4
  - Get intermittent failures depending on when context switch occurred and whether new thread uses register 4
  - System will give wrong result without warning
- Can you devise an exhaustive test to test switch code?
  - No! Too many combinations and inter-leavings
- Cautionary tail:
  - For speed, Topaz kernel saved one instruction in switch()
  - Carefully documented!
    - » Only works As long as kernel size < 1MB
  - What happened?
    - » Time passed, People forgot
    - » Later, they added features to kernel (no one removes features!)
    - » Very weird behavior started happening
  - Moral of story: Design for simplicity

Some Numbers

- Frequency of performing context switches: 10-100ms
- Context switch time in Linux: 3-4 μsecs (Current Intel i7 & E5).
  - Thread switching faster than process switching (100 ns).
  - But switching across cores about 2x more expensive than within-core switching.
- Context switch time increases sharply with the size of the working set*, and can increase 100x or more.

  * The working set is the subset of memory used by the process in a time window.
- Moral: Context switching depends mostly on cache limits and the process or thread's hunger for memory.

What happens when thread blocks on I/O?

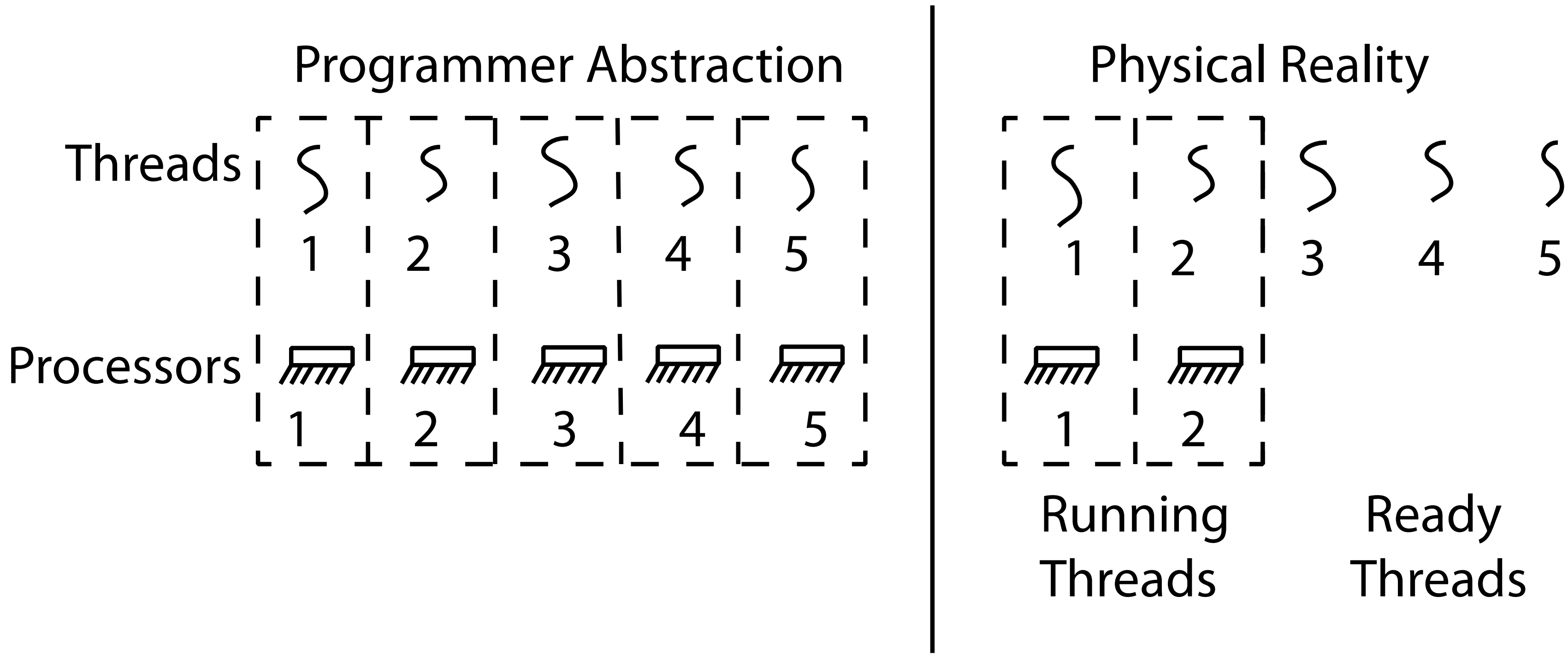


- What happens when a thread requests a block of data from the file system?
  - User code invokes a system call
  - Read operation is initiated
  - Run new thread/switch
- Thread communication similar
  - Wait for Signal/Join
  - Networking

External Events

- What happens if thread never does any I/O, never waits, and never yields control?
  - Could the ComputePI program grab all resources and never release the processor?
  - Must find way that dispatcher can regain control!
- Answer: Utilize External Events
  - Interrupts: signals from hardware or software that stop the running code and jump to kernel
  - Timer: like an alarm clock that goes off every some many milliseconds
- If we make sure that external events occur frequently enough, can ensure dispatcher runs

Thread Abstraction

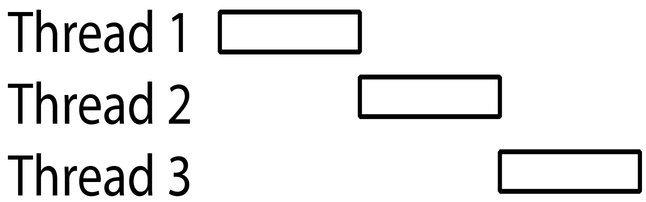


- **Infinite number of processors**
- **Threads execute with variable speed**
  - **Programs must be designed to work with any schedule**

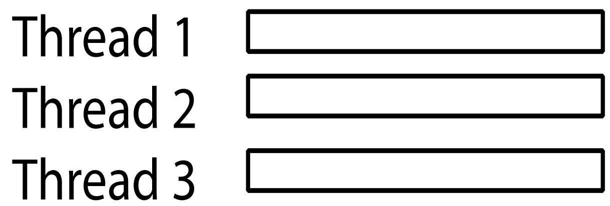
Programmer vs. Processor View

Programmer's View	Possible Execution #1	Possible Execution #2	Possible Execution #3
.	.	.	.
.	.	.	.
.	.	.	.
x = x + 1;	x = x + 1;	x = x + 1	x = x + 1
y = y + x;	y = y + x;	....	y = y + x
z = x +5y;	z = x + 5y;	thread is suspended	....
.	.	other thread(s) run	thread is suspended
.	.	thread is resumed	other thread(s) run
.	.	....	thread is resumed
		y = y + x	....
		z = x + 5y	z = x + 5y

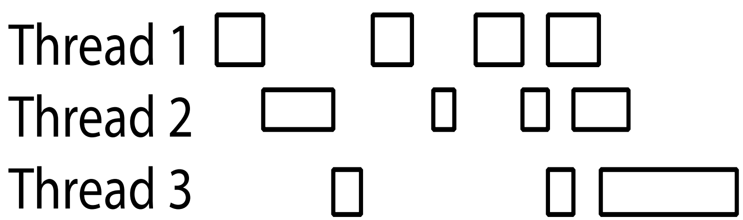
Possible Executions



a) One execution

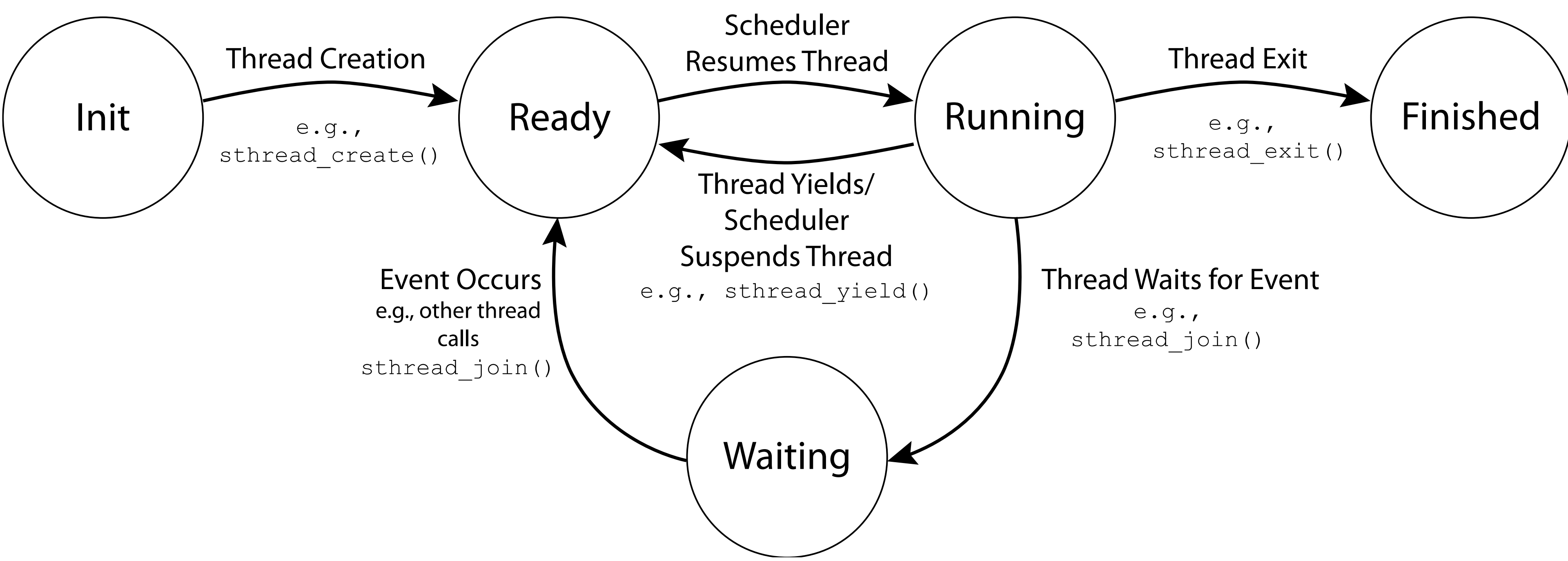


b) Another execution

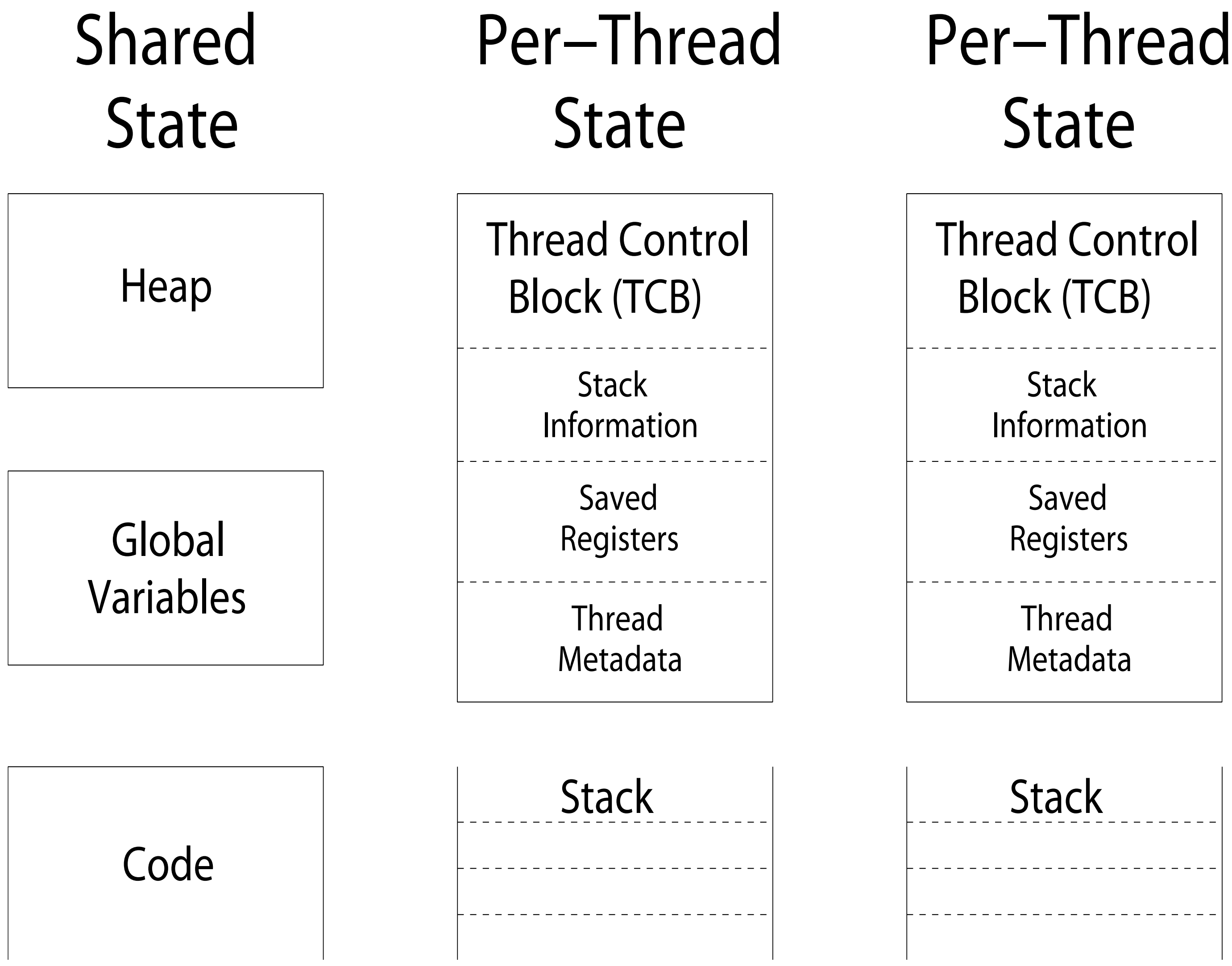


c) Another execution

Thread Lifecycle



Shared vs. Per-Thread State

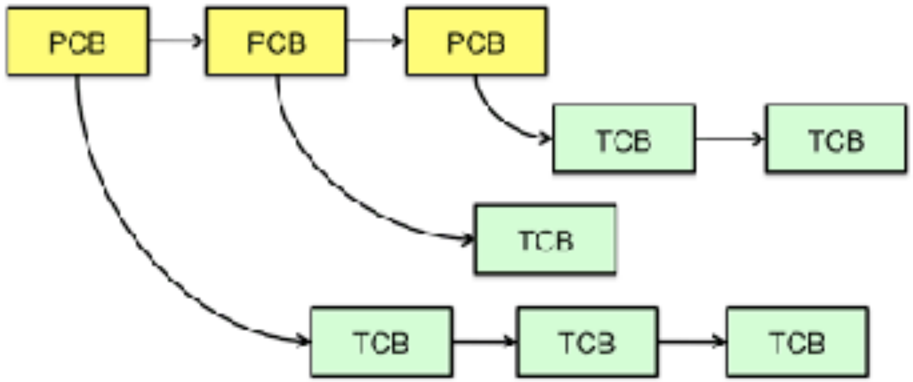


Per Thread Descriptor (Kernel Supported Threads)

- Each Thread has a Thread Control Block (TCB)
  - Execution State: CPU registers, program counter (PC), pointer to stack (SP)
  - Scheduling info: state, priority, CPU time
  - Various Pointers (for implementing scheduling queues)
  - Pointer to enclosing process (PCB) – user threads
  - Etc (add stuff as you find a need)
- OS Keeps track of TCBs in "kernel memory"
  - In Array, or Linked List, or …
  - I/O state (file descriptors, network connections, etc)

Multithreaded Processes

- PCB points to multiple TCBs:



- Switching threads within a block is a simple thread switch
- Switching threads across blocks requires changes to memory and I/O address tables.

Summary

- Processes have two parts
  - Threads (Concurrency)
  - Address Spaces (Protection)
- Concurrency accomplished by multiplexing CPU Time:
  - Unloading current thread (PC, registers)
  - Loading new thread (PC, registers)
  - Such context switching may be voluntary (`yield()`, I/O operations) or involuntary (timer, other interrupts)
- Protection accomplished restricting access:
  - Memory mapping isolates processes from each other
  - Dual-mode for isolating I/O, other resources
- Various Textbooks talk about processes
  - When this concerns concurrency, really talking about thread portion of a process
  - When this concerns protection, talking about address space portion of a process