# CS162
# Operating Systems and Systems Programming
# Lecture 5

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

September 10th, 2018

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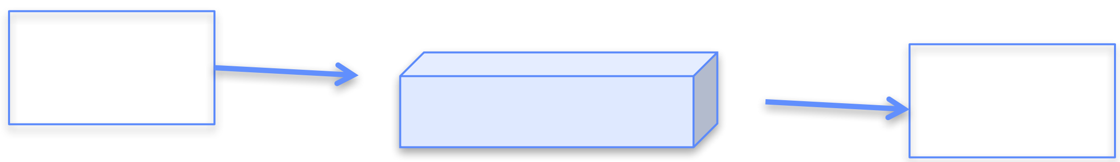
http://cs162.eecs.Berkeley.edu

# Communication between processes

- Can we view files as communication channels?

```
write(wfd, wbuf, wlen);
```

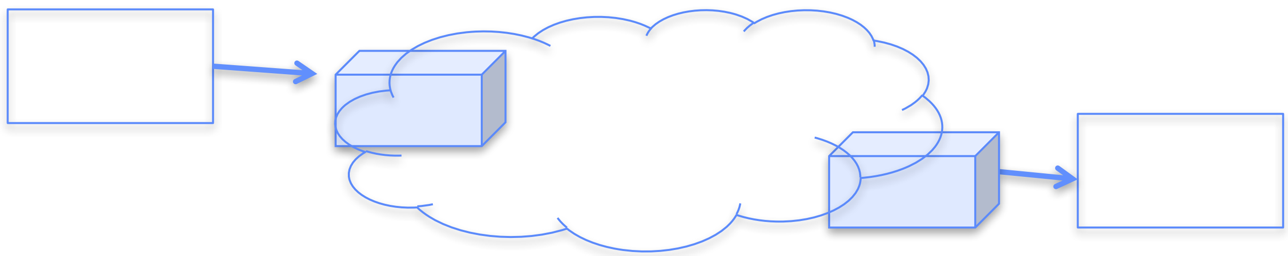


```
n = read(rfd,rbuf,rmax);
```

- Producer and Consumer of a file may be distinct processes
  – May be separated in time (or not)
- However, what if data written once and consumed once?
  – Don't we want something more like a queue?
  – Can still look like File I/O!

# Communication Across the world looks like file IO

```
write(wfd, wbuf, wlen);
```



```
n = read(rfd,rbuf,rmax);
```

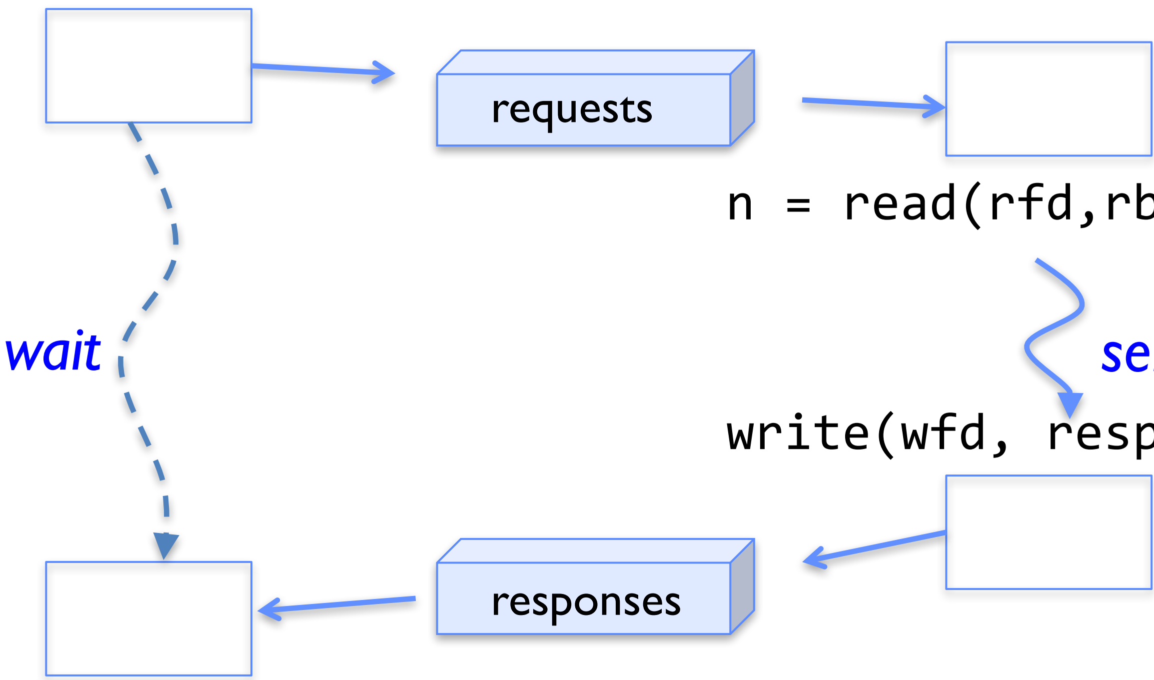
- Connected queues over the Internet
  - But what's the analog of open?
  - What is the namespace?
  - How are they connected in time?

# Request Response Protocol

**Client (issues requests)**

**Server (performs operations)**

```
write(rqfd, rqbuf, buflen);
```




```
n = read(rfd,rbuf,rmax);
```

```
write(wfd, respbuf, len);
```

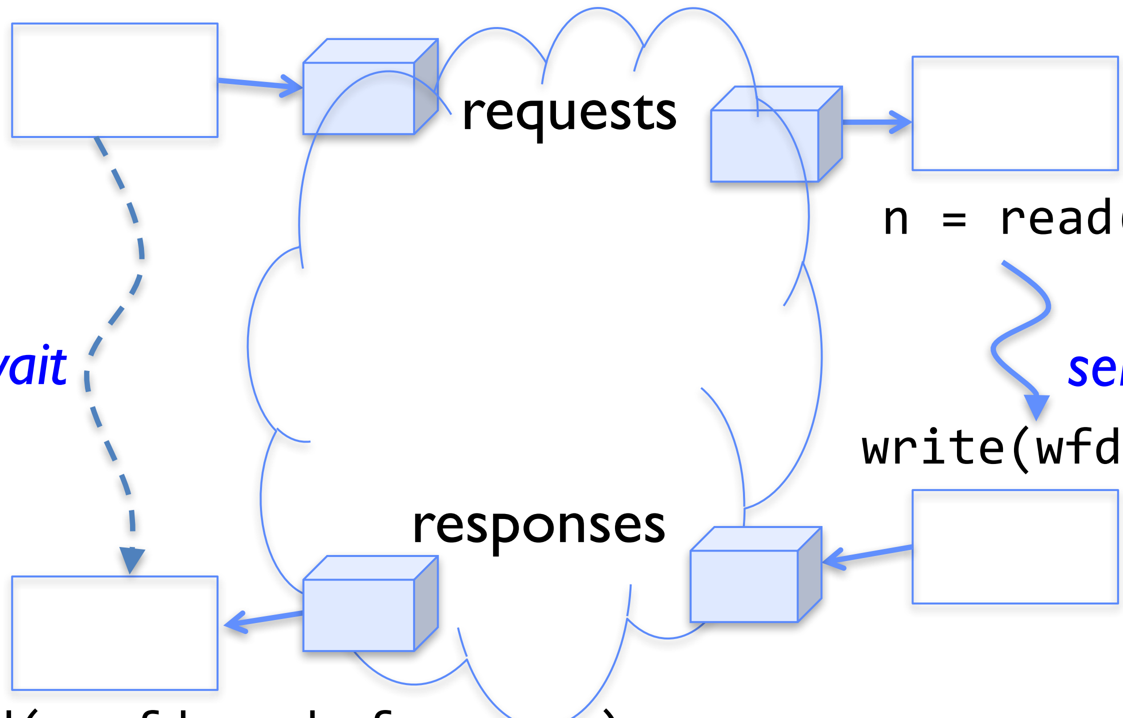
```
n = read(resfd,resbuf,resmax);
```

# Request Response Protocol

**Client (issues requests)**

**Server (performs operations)**

```
write(rqfd, rqbuf, buflen);
```




```
n = read(rfd,rbuf,rmax);
```

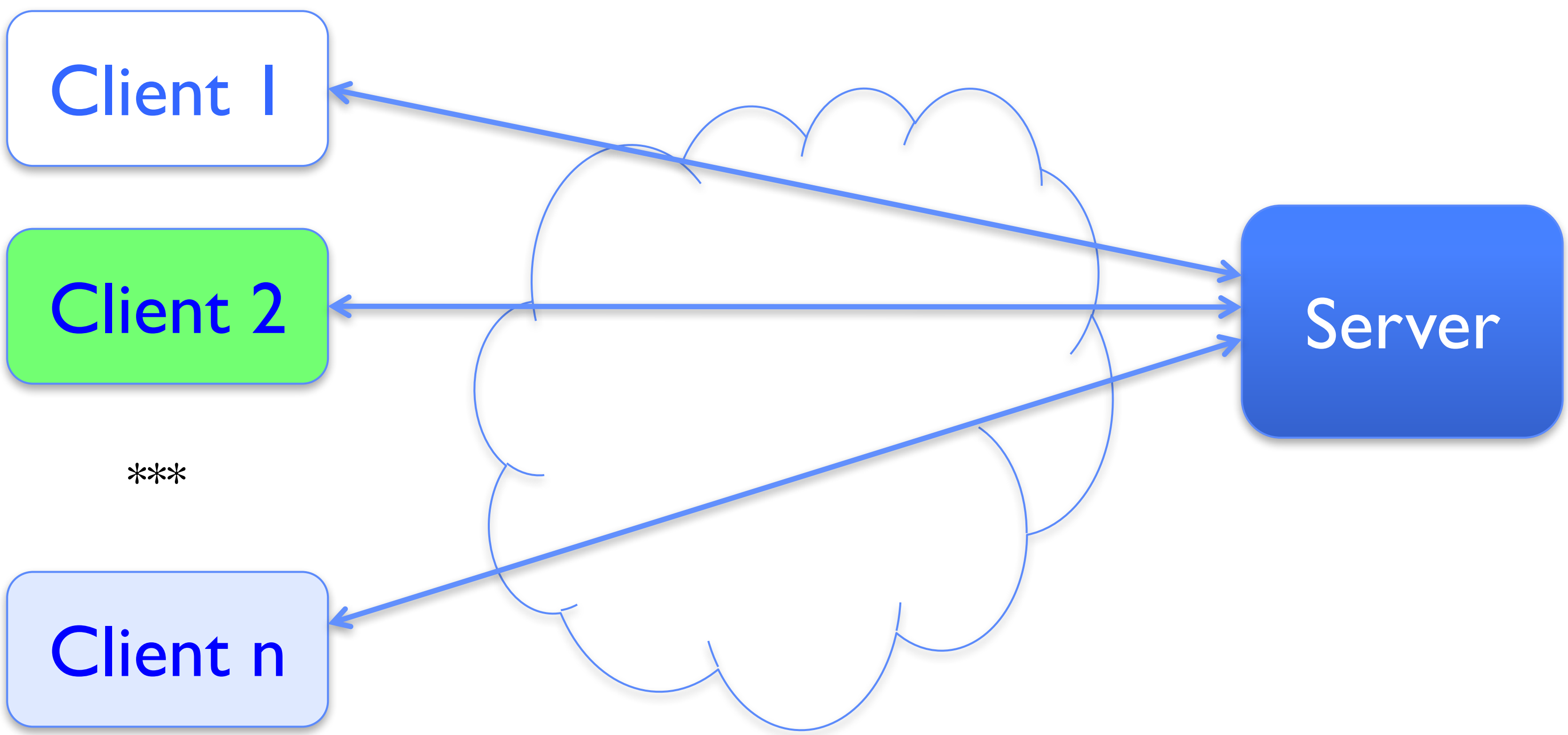
*wait*

*service request*

```
write(wfd, respbuf, len);
```

```
n = read(resfd,resbuf,resmax);
```

# Client-Server Models

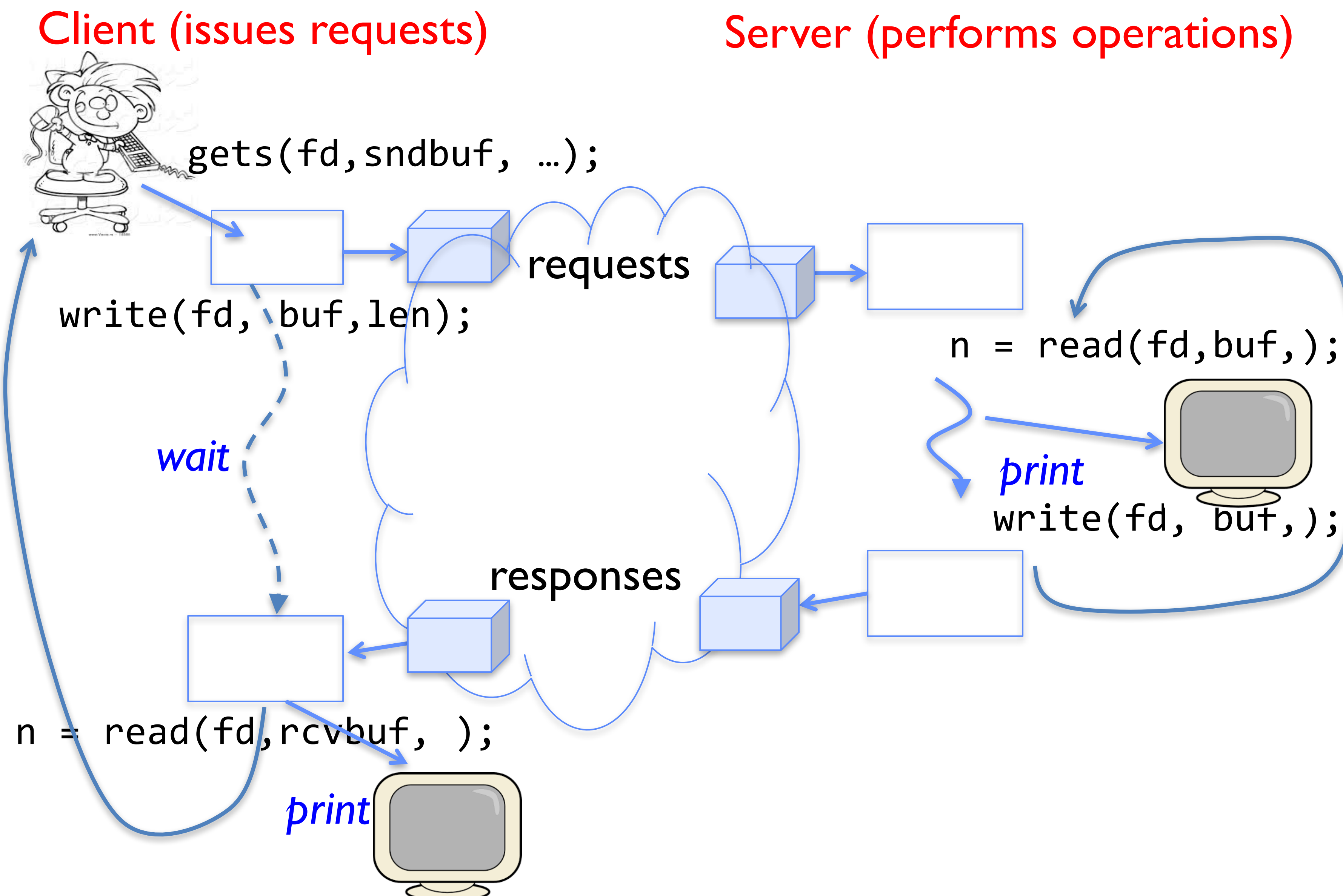



- File servers, web, FTP, Databases, …
- Many clients accessing a common server

# Sockets

- Socket: an abstraction of a network I/O queue
  – Mechanism for inter-process communication
  – Embodies one side of a communication channel
    » Same interface regardless of location of other end
    » Local machine ("UNIX socket") or remote machine ("network socket")
  – First introduced in 4.2 BSD UNIX: big innovation at time
    » Now most operating systems provide some notion of socket
- Data transfer like files
  – Read / Write against a descriptor
- Over ANY kind of network
  – Local to a machine
  – Over the internet (TCP/IP, UDP/IP)
  – OSI, Appletalk, SNA, IPX, SIP, NS, …

# Silly Echo Server – running example



# Echo client-server example

```
void client(int sockfd) {
  int n;
  char sndbuf[MAXIN]; char rcvbuf[MAXOUT];
  getreq(sndbuf, MAXIN);        /* prompt */
  while (strlen(sndbuf) > 0) {
    write(sockfd, sndbuf, strlen(sndbuf)); /* send */
    memset(rcvbuf,0,MAXOUT);               /* clear */
    n=read(sockfd, rcvbuf, MAXOUT-1);      /* receive */
    write(STDOUT_FILENO, rcvbuf, n);           /* echo */
    getreq(sndbuf, MAXIN);                 /* prompt */
  }
}
```

```
void server(int consockfd) {
  char reqbuf[MAXREQ];
  int n;
  while (1) {
    memset(reqbuf,0, MAXREQ);
    n = read(consockfd,reqbuf,MAXREQ-1); /* Recv */
    if (n <= 0) return;
    n = write(STDOUT_FILENO, reqbuf, strlen(reqbuf));
    n = write(consockfd, reqbuf, strlen(reqbuf)); /* echo*/
  }
}
```

# Prompt for input

```
char *getreq(char *inbuf, int len) {
  /* Get request char stream */
  printf("REQ: ");              /* prompt */
  memset(inbuf,0,len);          /* clear for good measure */
  return fgets(inbuf,len,stdin); /* read up to a EOL */
}
```

# Socket creation and connection

- File systems provide a collection of permanent objects in structured name space
  - Processes open, read/write/close them
  - Files exist independent of the processes

- Sockets provide a means for processes to communicate (transfer data) to other processes.

- Creation and connection is more complex

- Form 2-way pipes between processes
  - Possibly worlds away

# Namespaces for communication over IP

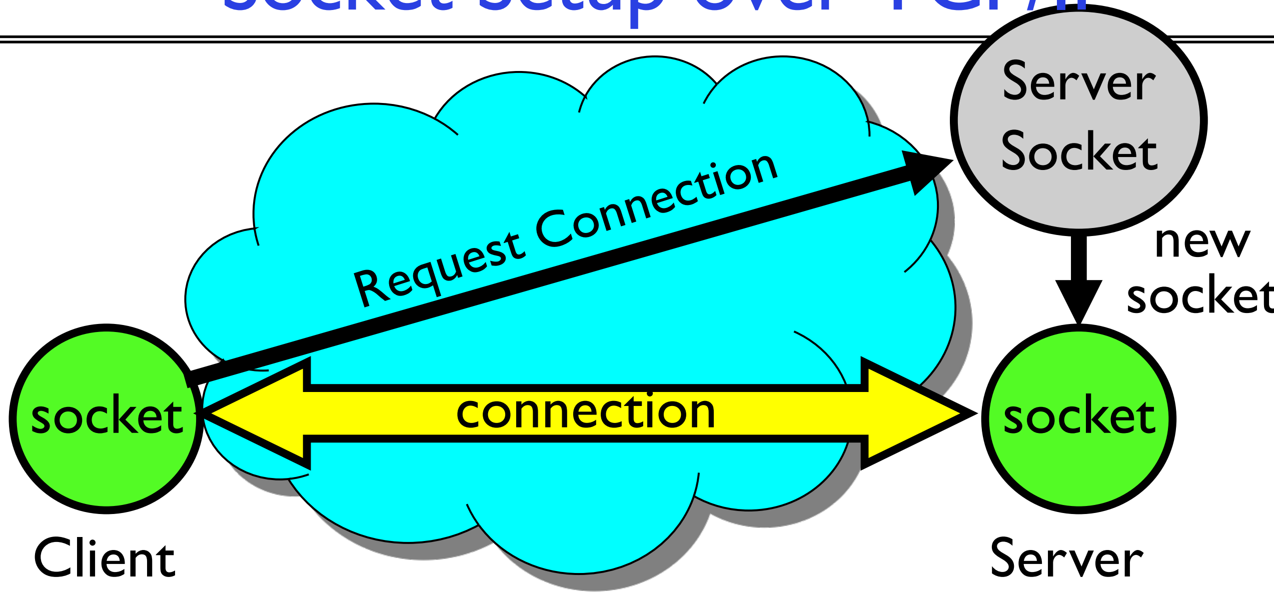
- Hostname
  - www.eecs.berkeley.edu
- IP address
  - 128.32.244.172 (IPv4 32-bit)
  - fe80::4ad7:5ff:fecf:2607 (IPv6 128-bit)
- Port Number
  - 0-1023 are "well known" or "system" ports
    - » Superuser privileges to bind to one
  - 1024 – 49151 are "registered" ports (registry)
    - » Assigned by IANA for specific services
  - 49152–65535 ($2^{15}+2^{14}$ to $2^{16}-1$) are "dynamic" or "private"
    - » Automatically allocated as "ephemeral Ports"

# Using Sockets for Client-Server (C/C++)

- 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

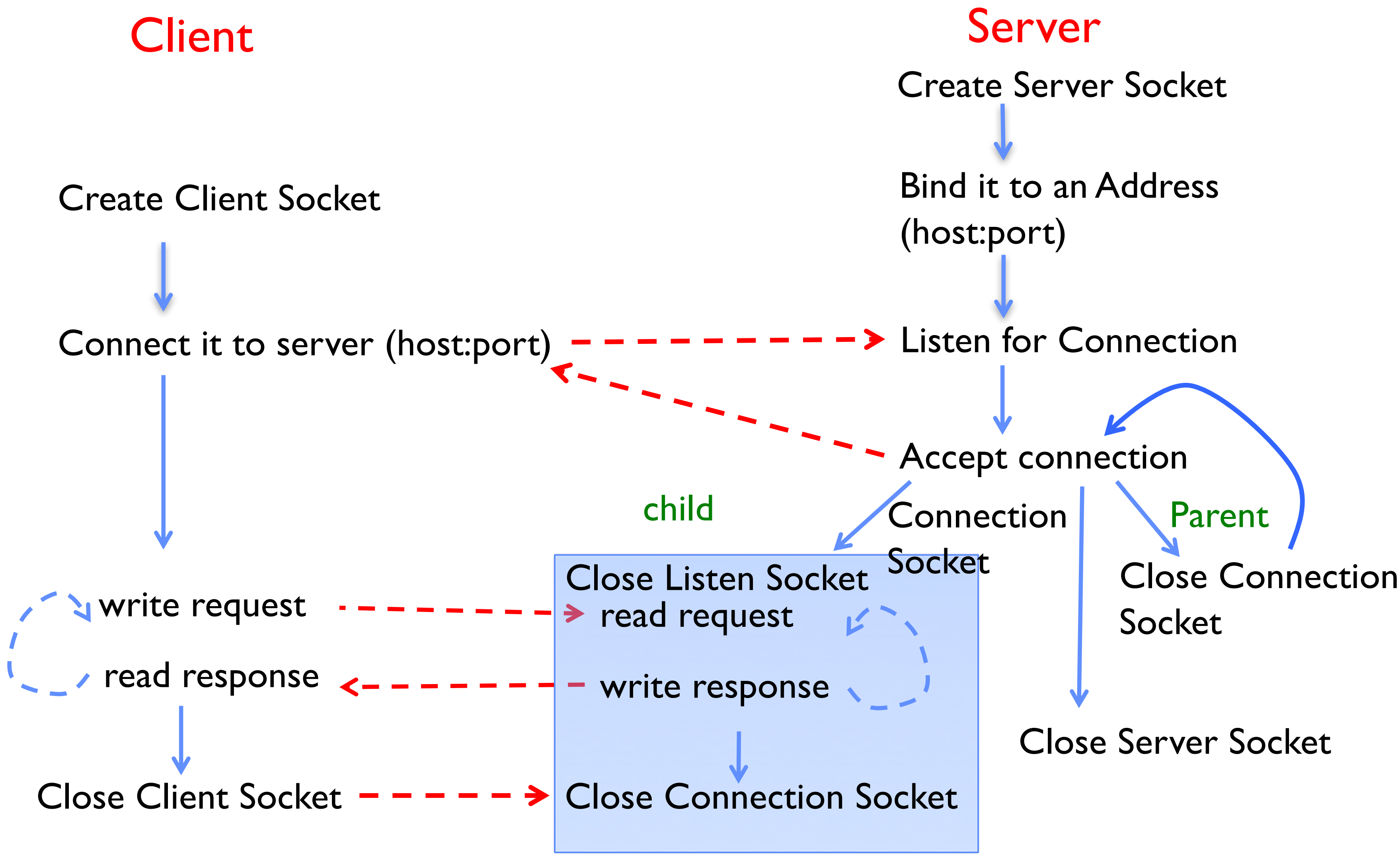
- On client:
  - Create socket; bind to protocol (TCP), remote address, port
  - Perform **`connect()`** on socket to make connection
  - If **`connect()`** successful, have socket connected to server

# 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 by OS during client socket setup
  - Server Port often "well known" (0-1023)
    - » 80 (web), 443 (secure web), 25 (sendmail), etc

# Example: Server Protection and Parallelism



# Server Protocol (v3)

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

      server(consockfd);

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

# Server Address - Itself

```
struct sockaddr_in {
  short sin_family;  // address family, e.g., AF_INET
  unsigned short sin_port; // port # (in network byte ordering)
  struct in_addr sin_addr; // host address
  char sin_zero[8]; // for padding to cast it to sockaddr
} serv_addr;

memset((char *) &serv_addr,0, sizeof(serv_addr));
serv_addr.sin_family      = AF_INET;  // Internet address family
serv_addr.sin_addr.s_addr = INADDR_ANY; // get host address
serv_addr.sin_port        = htons(portno);
```

- Simple form
- Internet Protocol
- Accepting any connections on the specified port
- In "network byte ordering" (which is *big endian*)

# 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;
}
```

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  return server;
}
```

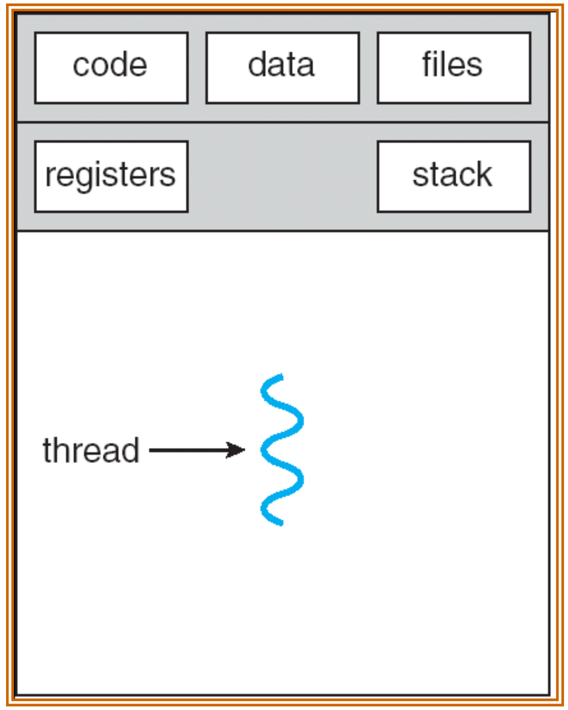
# Administrivia

- TA preferences due tonight at 11:59PM
  - We will try to accommodate your needs, but have to balance both over-popular and under-popular sections
- Attend section and get to know your TAs!

# BREAK

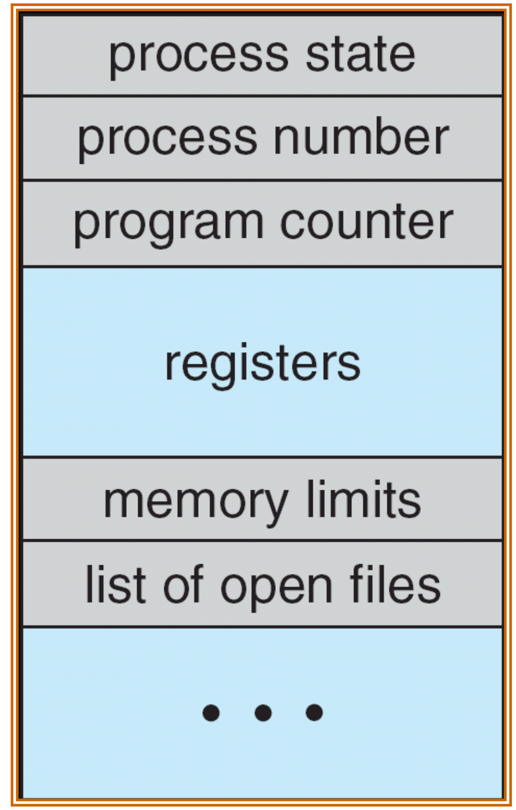
# Recall: Traditional UNIX Process

- Process: OS abstraction of 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 [ACTIVE PART]
    - » Code executed as a sequential stream of execution (i.e., thread)
    - » Includes State of CPU registers
  - Protected resources [PASSIVE PART]:
    - » Main memory state (contents of Address Space)
    - » I/O state (i.e. file descriptors)



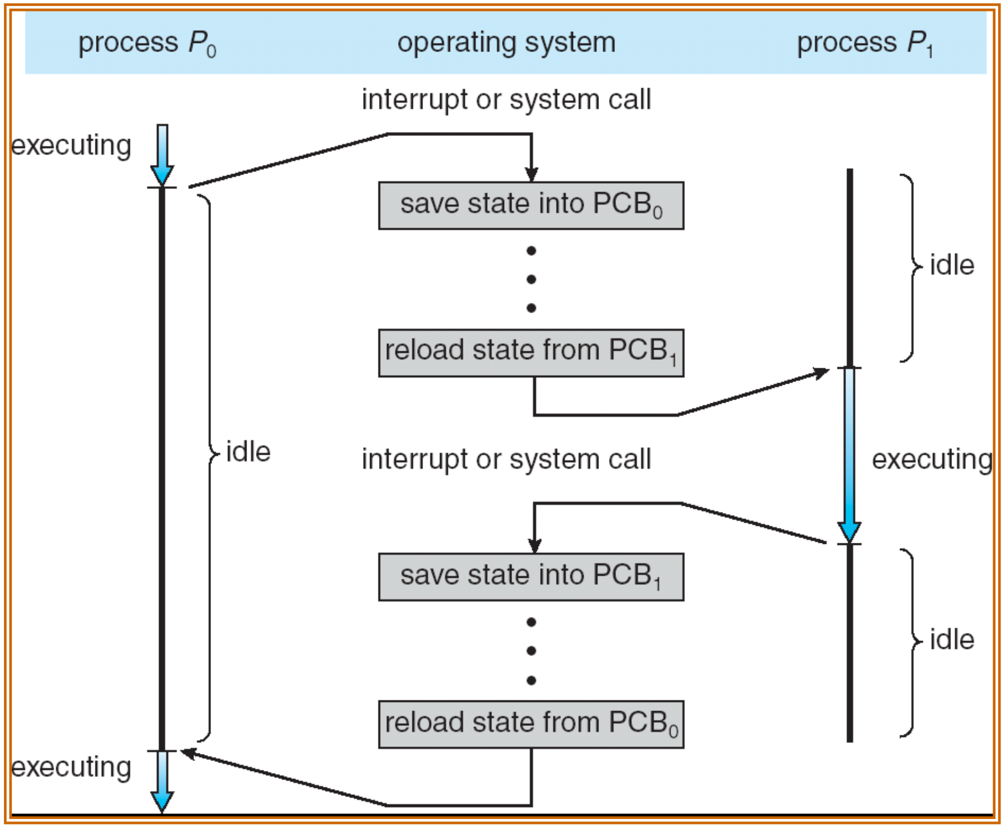
# How do we Multiplex Processes?

- 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 Trnslation: Give each process their own address space
    - » Kernel/User duality: Arbitrary multiplexing of I/O through system calls



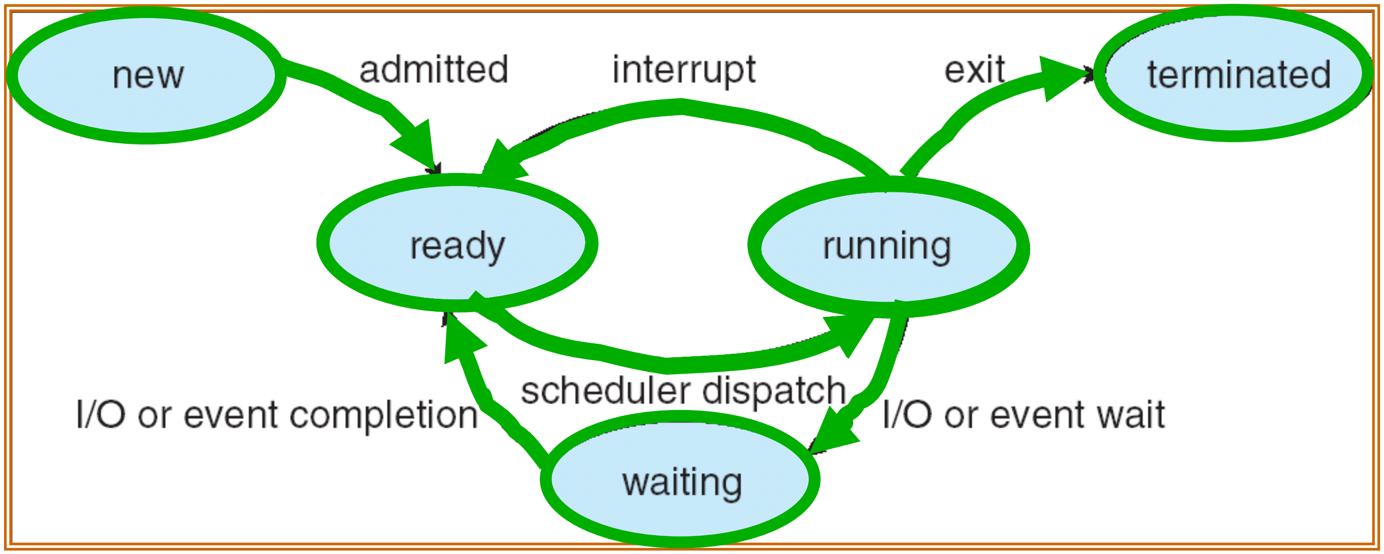

**Process Control Block**

# CPU Switch From Process A to Process B



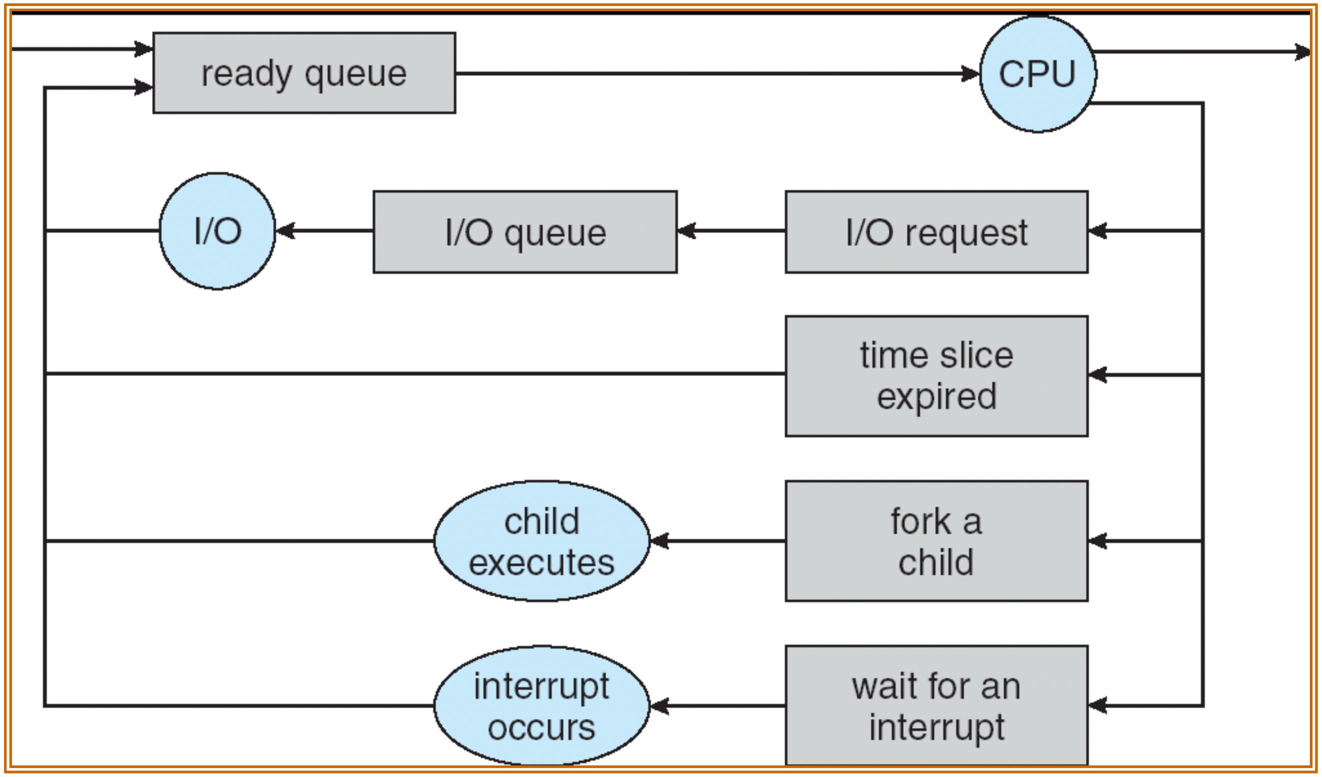

- This is also called a "context switch"
- Code executed in kernel above is ***overhead***
  – Overhead sets minimum practical switching time
  – Less overhead with SMT/hyperthreading, but… contention for resources instead

# 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

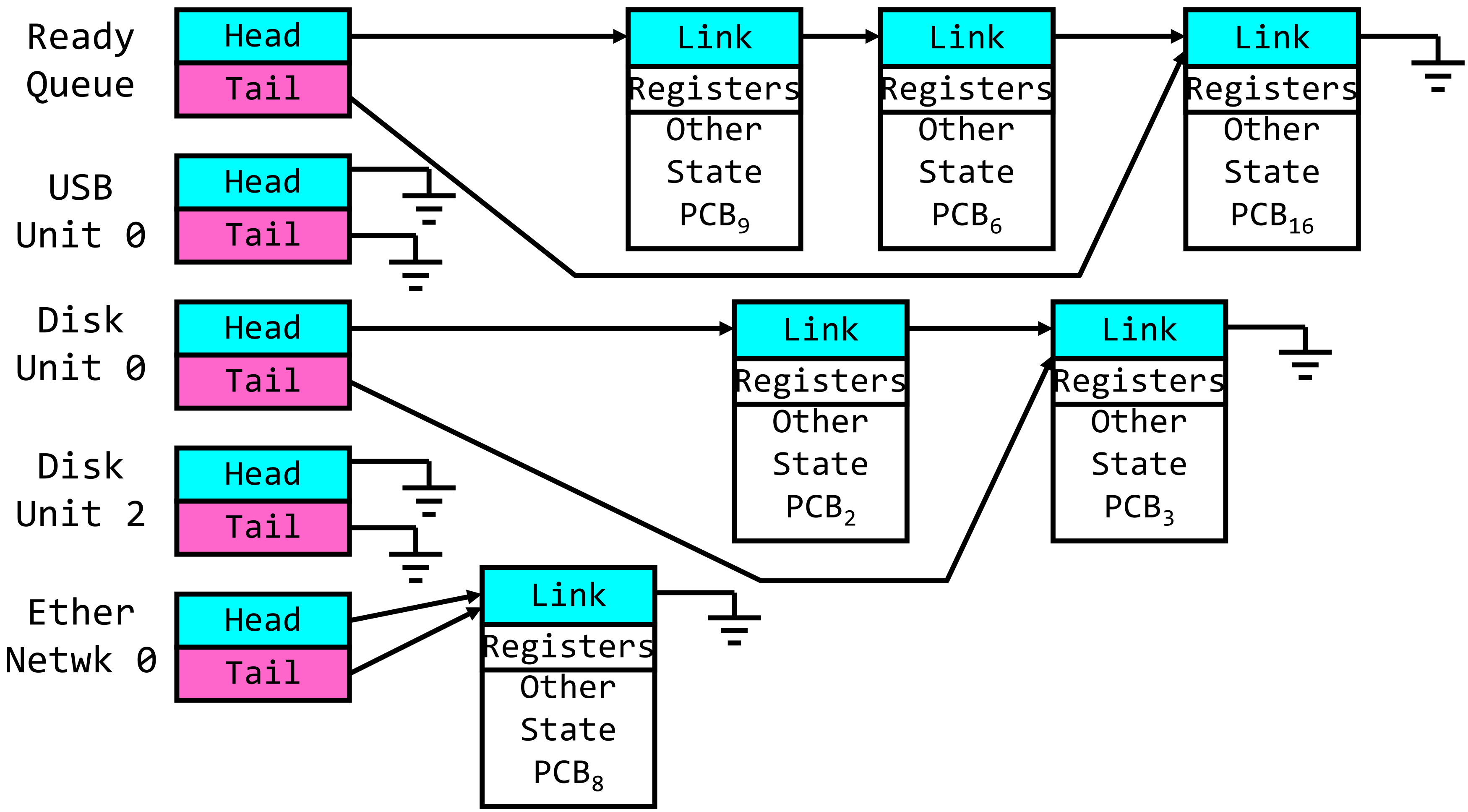
# Process Scheduling




- 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

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



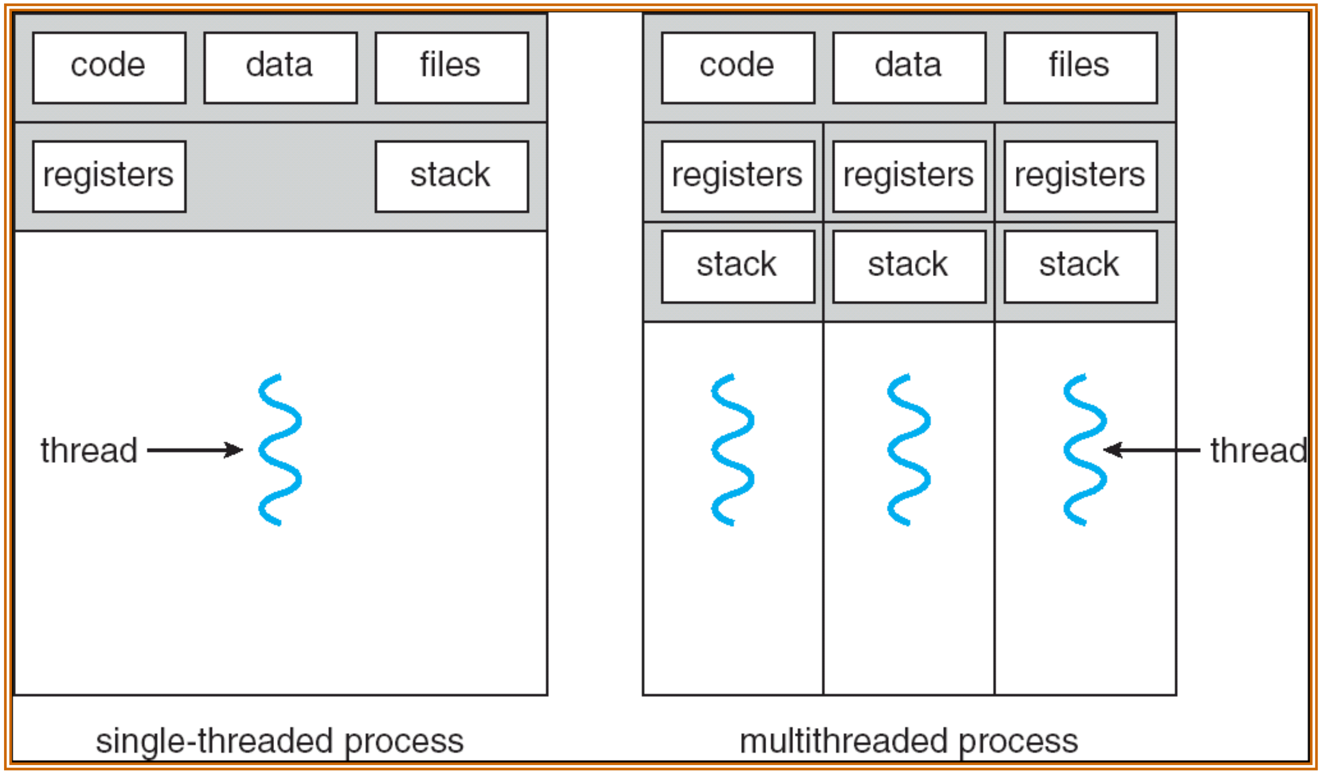
# Modern Process with Threads

- 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*
  - Sometimes called multitasking, as in Ada …

- 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 ≡ Process with one thread

# Single and Multithreaded Processes

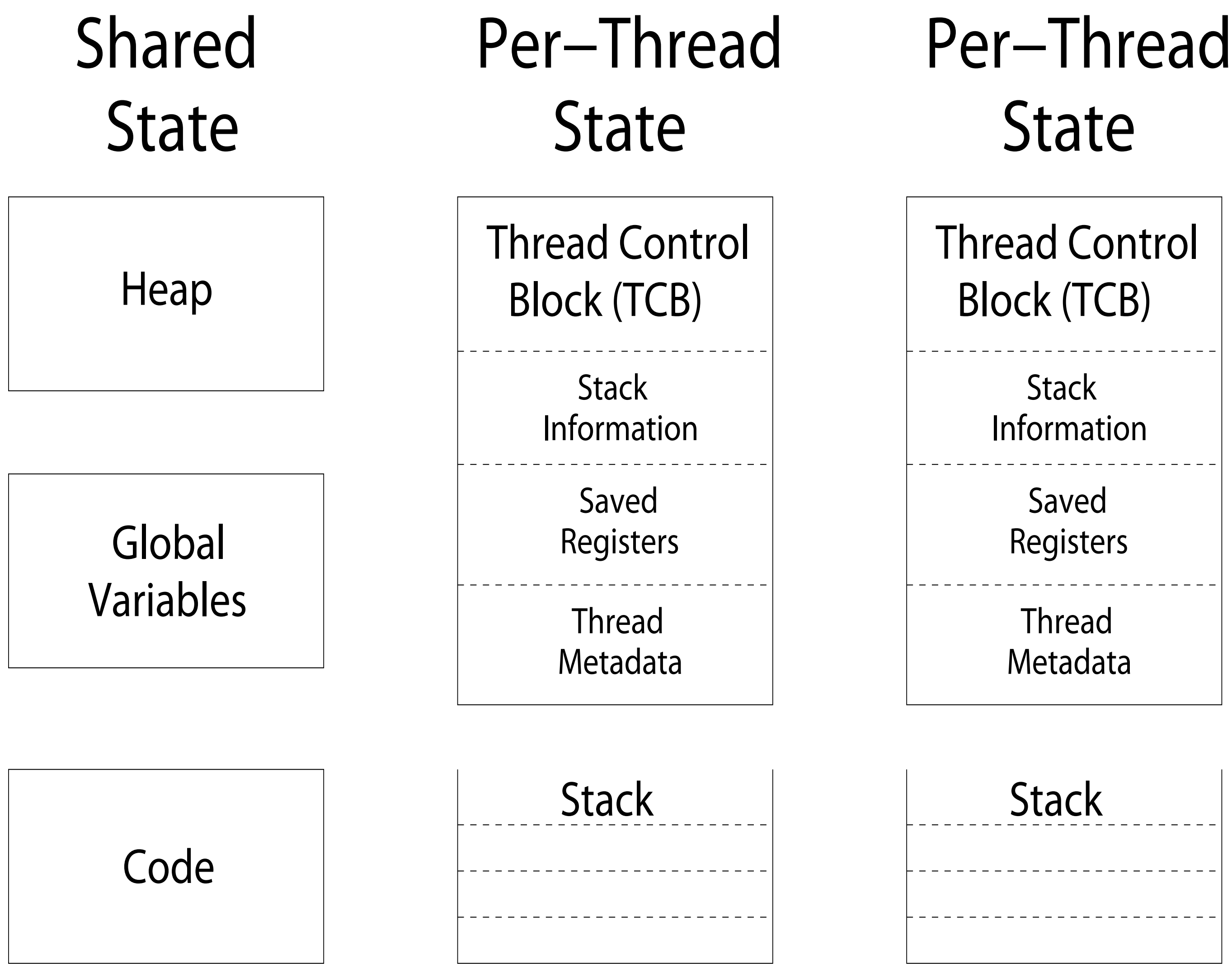



- Threads encapsulate concurrency: "Active" component
- Address spaces encapsulate protection: "Passive" part
  - Keeps buggy program from trashing the system
- Why have multiple threads per address space?

# Thread State

- State shared by all threads in process/address 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

# Shared vs. Per-Thread State



# Execution Stack Example

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

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

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Stack Pointer → 

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A: tmp=1
   ret=exit
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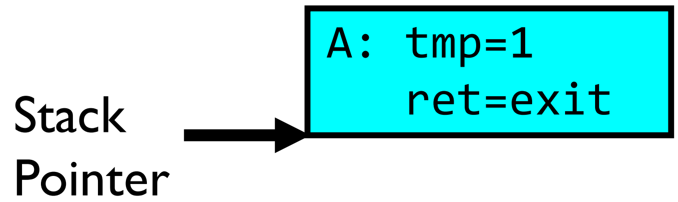


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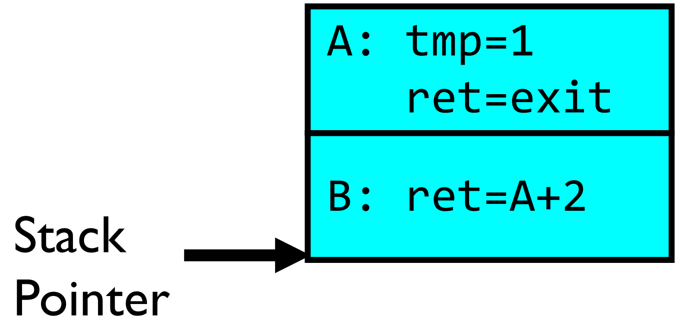


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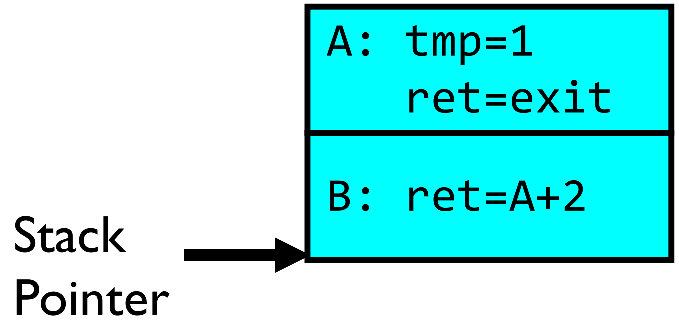


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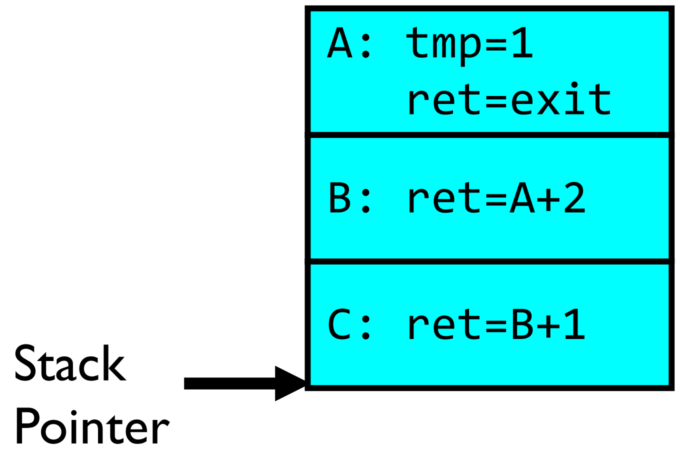


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A+1:       B();
A+2:     printf(tmp);
       }
       B() {
B:       C();
B+1:   }
       C() {
C:       A(2);
C+1:   }
       A(1);
exit:
```
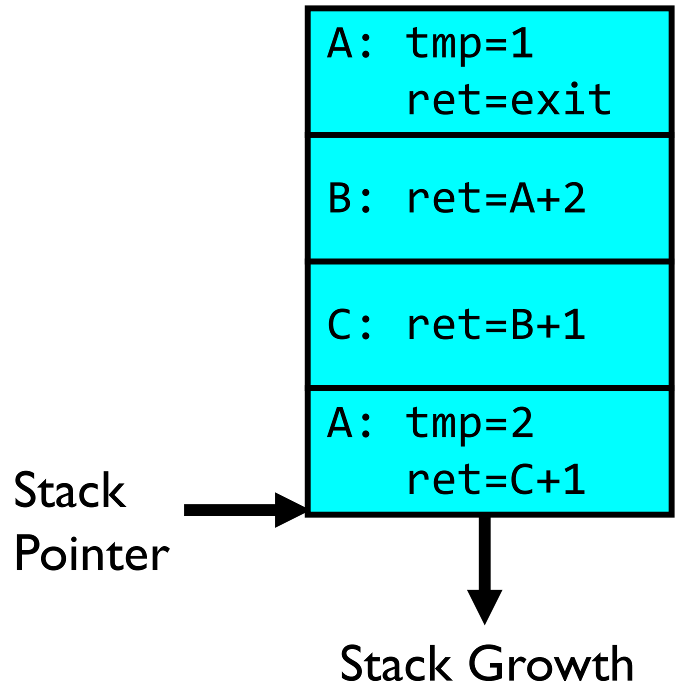
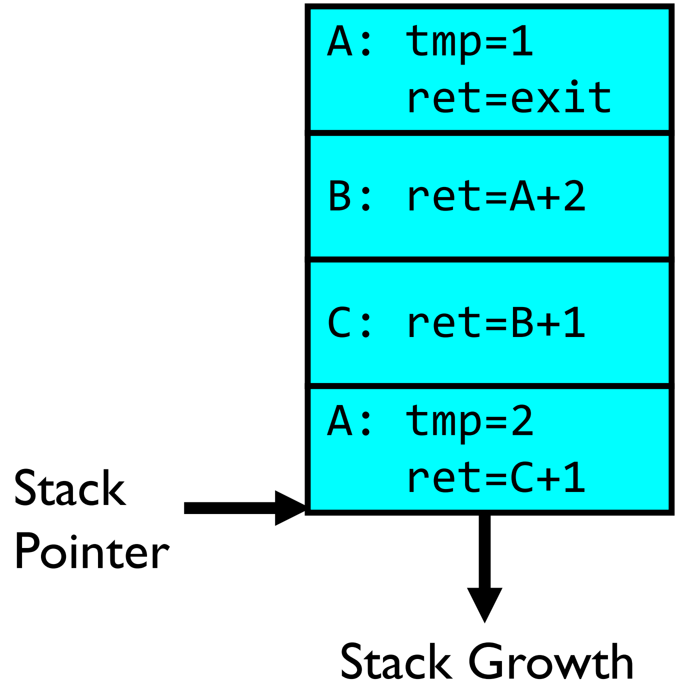




- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

# Execution Stack Example

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




**Output:** >2

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# Execution Stack Example

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

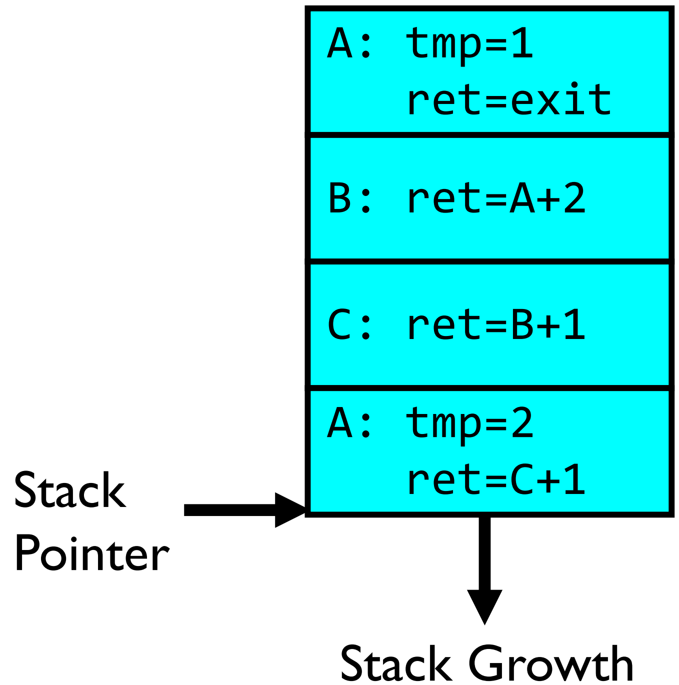


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A:         if (tmp<2)
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         }
         B() {
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         C() {
C:         A(2);
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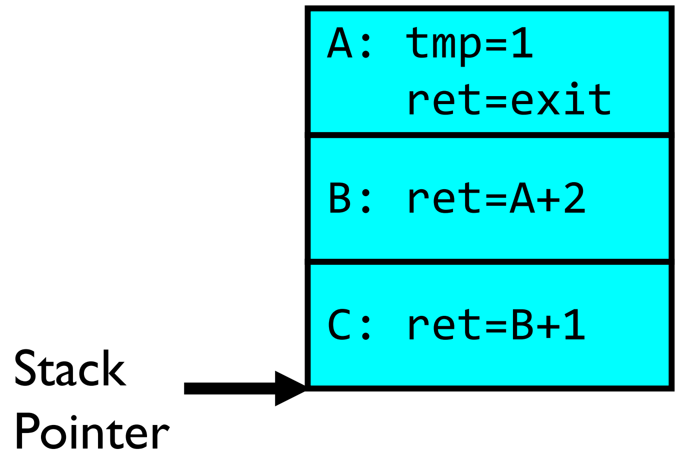
         A(1);
exit:
```




**Output:** >2

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        A(int tmp) {
A:        if (tmp<2)
A+1:        B();
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        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```

| |
|---|
| A: tmp=1<br>ret=exit |
| B: ret=A+2 |

Stack Pointer

**Output:** >2

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

# Execution Stack Example

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

Stack Pointer

```
A: tmp=1
   ret=exit
```

**Output:** `>2 1`

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

# Execution Stack Example

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

Stack Pointer → 

```
A: tmp=1
   ret=exit
```

**Output:** `>2 1`

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

# Execution Stack Example

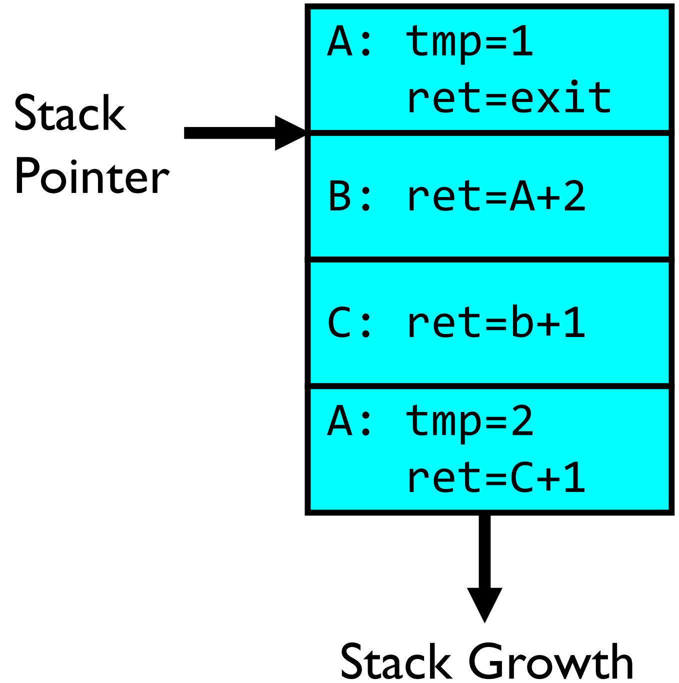
```
A(int tmp) {
  if (tmp<2)
    B();
  printf(tmp);
}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```

**Output:** `>2 1`

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

# 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("classlist.txt");
}
```

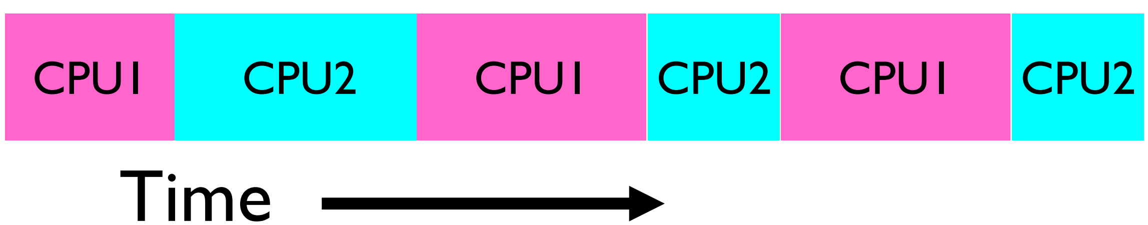
- What is the behavior here?
  - Program would never print out class list
  - Why? **`ComputePI`** would never finish

# Use of Threads

- Version of program with Threads (loose syntax):

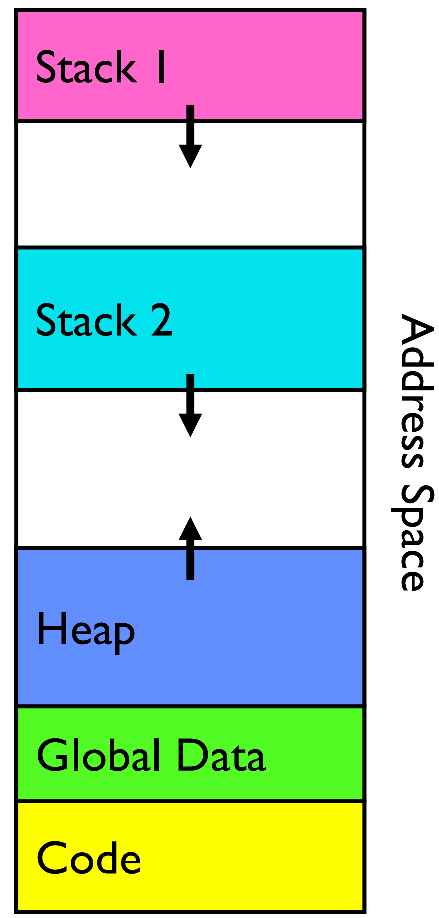
```
main() {
    ThreadFork(ComputePI, "pi.txt"));
    ThreadFork(PrintClassList, "classlist.txt"));
}
```

- 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
  - Pintos: `thread_join`
- `thread_exit`
  - Quit thread and clean up, wake up joiner if any
  - Pintos: `thread_exit`

- `pThreads`: POSIX standard for thread programming [POSIX.1c, Threads extensions (IEEE Std 1003.1c-1995)]

# 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

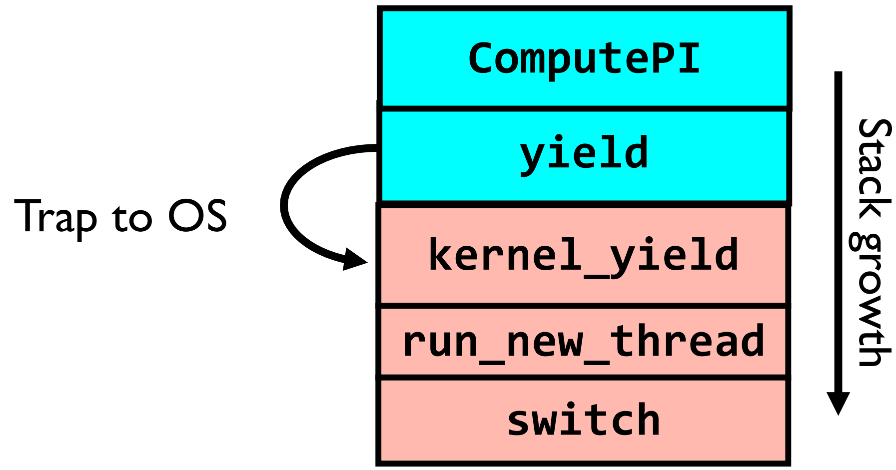
- How does the dispatcher get control back?
  - Internal events: thread returns control voluntarily
  - External events: thread gets *preempted*

# 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 pointer
  – Maintain isolation for each thread

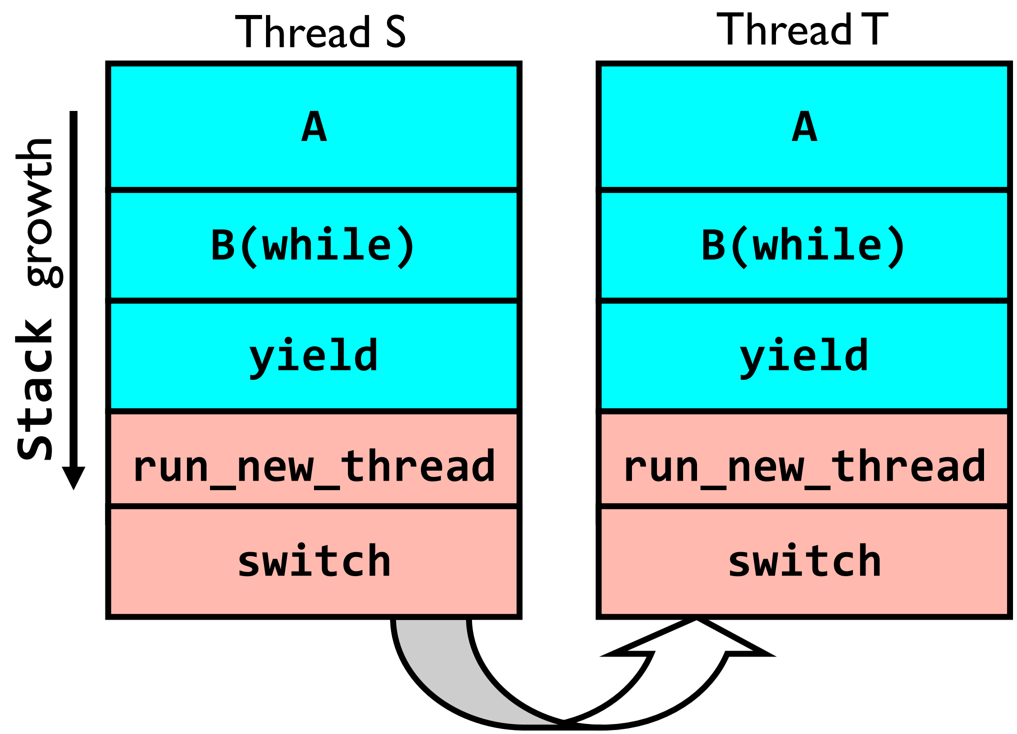
# What Do the Stacks Look Like?

- 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 32
  - Get intermittent failures depending on when context switch occurred and whether new thread uses register 32
  - 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 tale:
  - 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

# Summary

- Socket: an abstraction of a network I/O queue (IPC mechanism)

- Processes have two parts
  – One or more 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)