CS162
Operating Systems and Systems Programming
Lecture 5

Introduction to Networking, Concurrency (Processes and Threads)

February 1st, 2017

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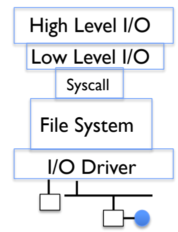
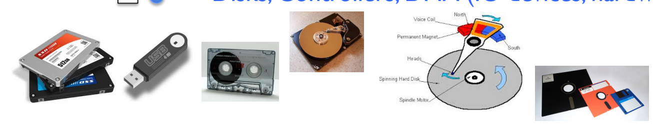
Recall: Storage Stack

Application / Service



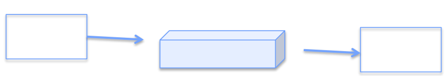
- Streams (file pointer, buffering,)
- Handles (file descriptor, general, …)
- Registers (sys calls & file descriptor)
- Descriptors (file info associated to file desc.)
- Commands & Data Transfers (abstracts away IO devices)
- Disks, Controllers, DMA (IO devices, hardware)



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

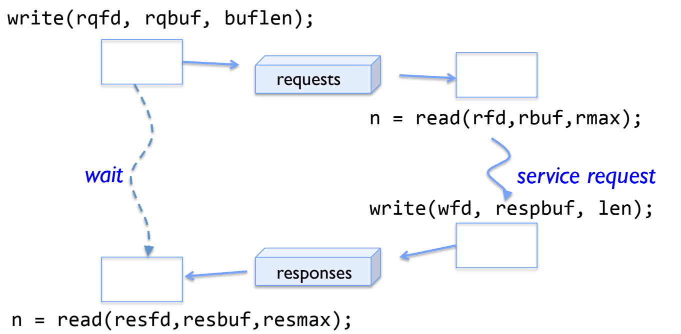
```
write(wfd, wbuf, wlen);
```

```
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)



Request Response Protocol

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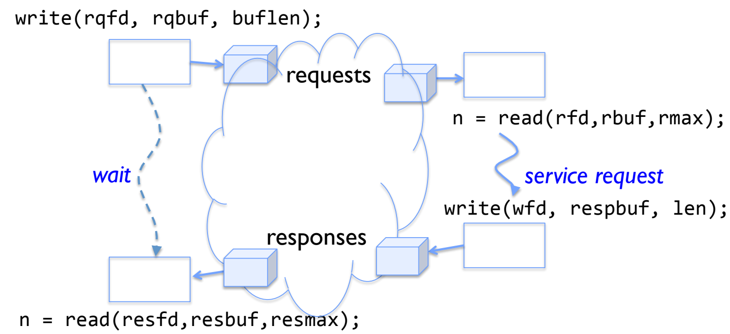
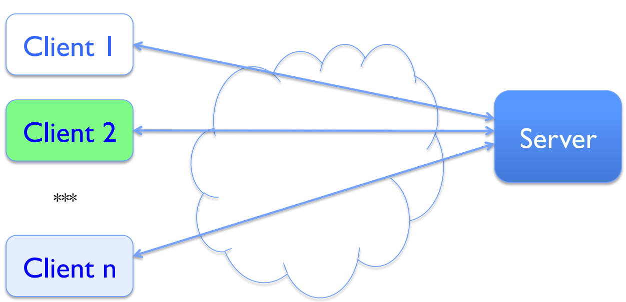


Client-Server Models

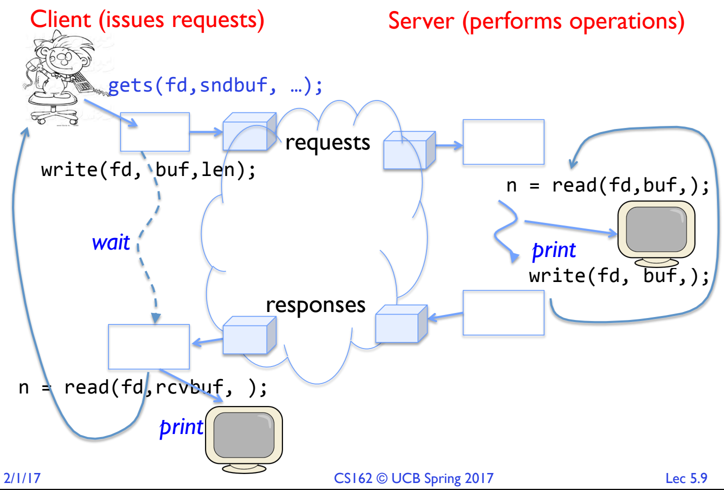


- File servers, web, FTP, Databases, …
- Many clients accessing a common server

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
- Data transfer like files
  - Read / Write against a descriptor (though other API available, e.g., send(), recv())
- 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 */
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  }
}
```

wait

```
void server(int consockfd) {
  char reqbuf[MAXREQ];
  int n;
  while (1) {
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    n = read(consockfd,reqbuf,MAXREQ-1); /* Recv */
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```

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 */
}
```


Files vs. Sockets

- 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 two-way pipes between processes
    - » Possibly worlds away

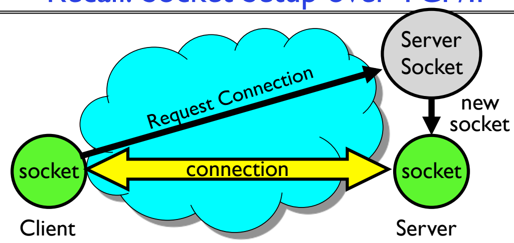
Namespaces for communication over IP

- 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"

Use of Sockets in TCP

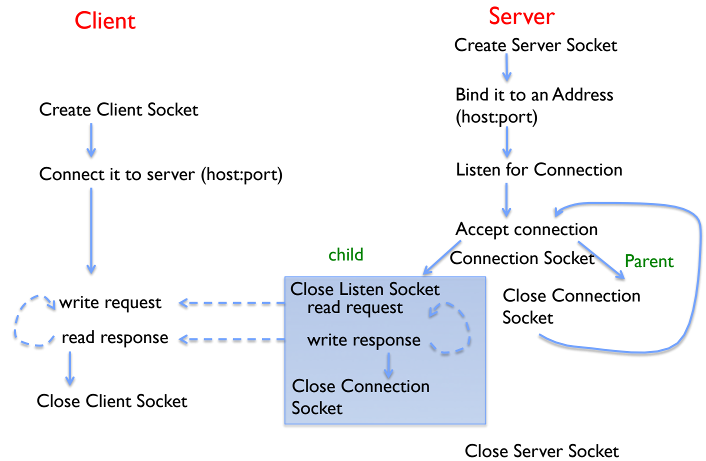
- On server: set up "server-socket"
  - Create socket, Bind to protocol (TCP), local address, port
  - Call listen(): tells server socket to accept incoming requests
  - Perform multiple accept() calls on socket to accept incoming connection request
  - Each successful accept() returns a new socket for 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

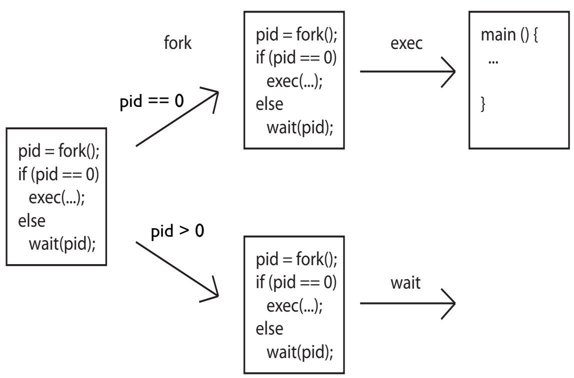


- Server Socket: Listens for new connections
  - Produces new sockets for each unique connection
- Things to remember:
  - Connection involves 5 values:
    `[Client Addr, Client Port, Server Addr, Server Port, Protocol]`
  - Often, Client Port "randomly" assigned by OS during client socket setup
  -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

Example: Server Protection and Parallelism



Recall: UNIX Process Management



Recall: 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 */
    }
  }
close(lstnsockfd);
```

Callouts: server conn socket; server listen socket; close conn sovket; go to accept(); close listen socket; handle client transfers; done; close conn socket

Server Address - Itself

```
struct sockaddr_in {
  short sin_family;
  unsigned short sin_port;
  struct in_addr sin_addr;
  char sin_zero[8];
} serv_addr;

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" (which is *big endian*)

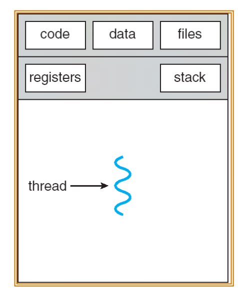
Administrivia

- We ended up processing the waitlist!
- Group formation deadline has passed!
  - If you have not found a group, post a private Piazza message
- Midterm #1 confirmed:
  - February 27th 6:30-8 PM

BREAK

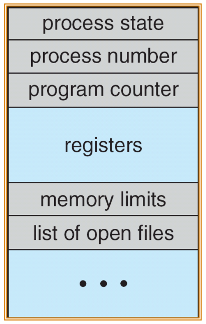
Recall: Traditional UNIX Process

- 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)



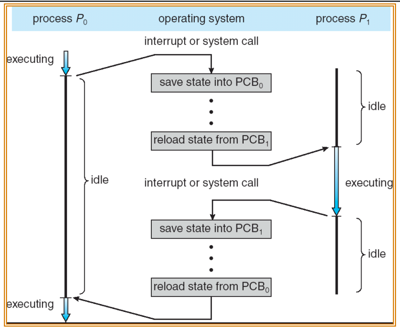
How do we Multiplex Processes?

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



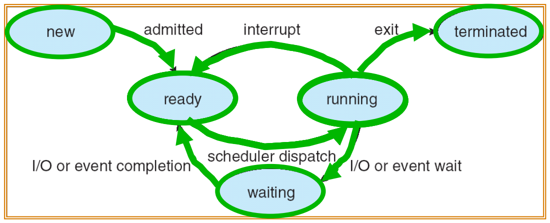
Process Control Block

CPU Switch From Process A to Process B



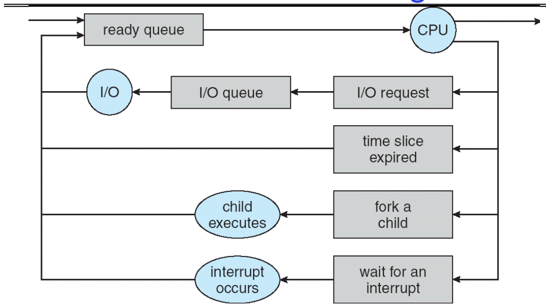
- This is also called a "context switch"
- Code executed in kernel above is ***overhead***
  - Overhead sets minimum practical switching time
  - Less overhead with hyperthreading, but… contention for resources instead

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

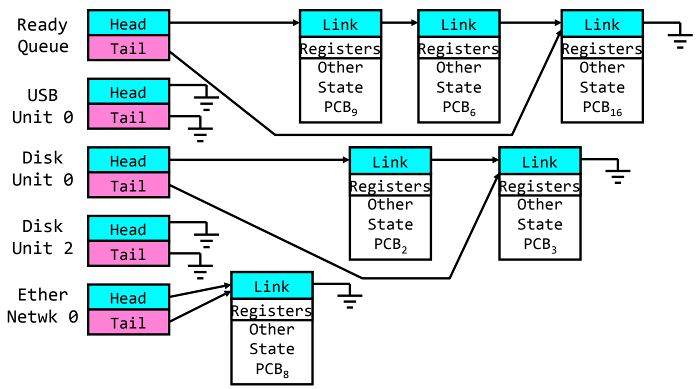
Process Scheduling



- 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

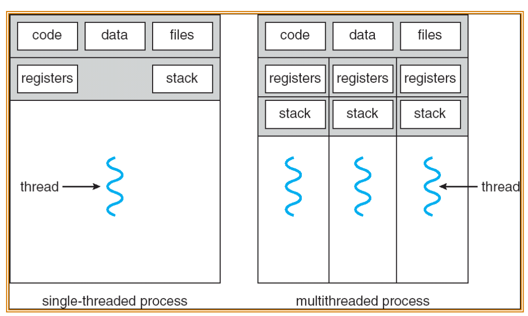
- Process not running ⇒ PCB is in some scheduler queue
  - Separate queue for each device/signal/condition
  - Each queue can have a different scheduler policy



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
- 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
- Execution Stack
  - Parameters, temporary variables
  - Return PCs are kept while called procedures are executing

Shared vs. Per-Thread State

Shared State	Per–Thread State	Per–Thread State
Heap	Thread Control Block (TCB): Stack Information, Saved Registers, Thread Metadata	Thread Control Block (TCB): Stack Information, Saved Registers, Thread Metadata
Global Variables		
Code	Stack	Stack

Execution Stack Example

```
addrX: A(int tmp) {
         if (tmp<2)
           B();
addrY:   printf(tmp);
       }
       B() {
         C();
addrU: }
       C() {
         A(2);
addrV: }
       A(1);
addrZ: exit;
```

- Stack holds function arguments, return address
- Permits recursive execution
- Crucial to modern languages

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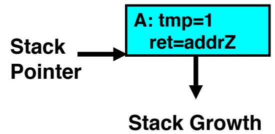

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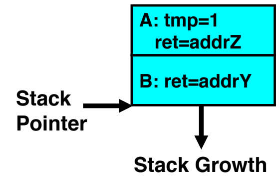

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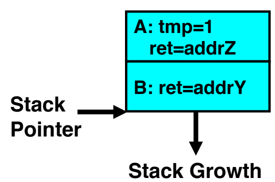

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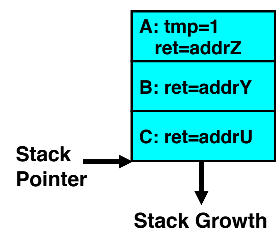
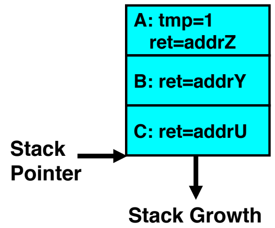


- Stack holds function arguments, return address
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example

```
addrX:  A(int tmp) {
  .       if (tmp<2)
  .         B();
  .
addrY:    printf(tmp);
  .     }
  .     B() {
  .       C();
addrU:  }
  .     C() {
  .       A(2);
  .
addrV:  }
  .     A(1);
addrZ:  exit;
```



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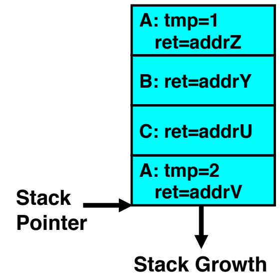

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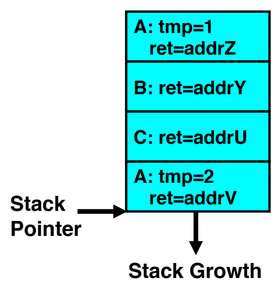

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  .
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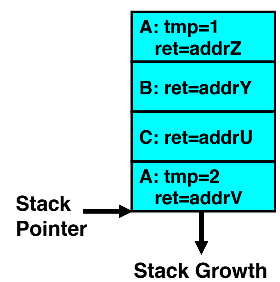
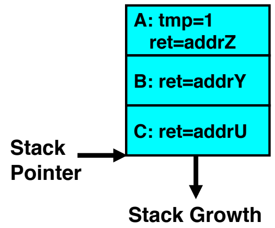


Output:
2

Execution Stack Example

```
addrX: A(int tmp) {
  .      if (tmp<2)
  .        B();
  .
addrY:   printf(tmp);
  .    }
  .    B() {
  .      C();
addrU: }
  .    C() {
  .      A(2);
  .
addrV: }
  .    A(1);
  .
addrZ: exit;
```



Output:
2

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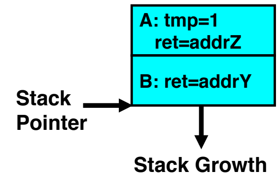
Execution Stack Example

```
addrX: A(int tmp) {
  .      if (tmp<2)
  .        B();
  .
addrY:   printf(tmp);
  .    }
  .    B() {
  .      C();
addrU: }
  .    C() {
  .      A(2);
  .
addrV: }
  .    A(1);
  .
addrZ: exit;
```



Output:
2

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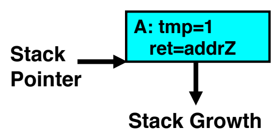
Execution Stack Example

```
addrX: A(int tmp) {
  .      if (tmp<2)
  .        B();
  .
addrY:   printf(tmp);
  .    }
  .    B() {
  .      C();
addrU: }
  .    C() {
  .      A(2);
  .
addrV: }
  .    A(1);
  .
addrZ: exit;
```



Output:
2
1

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Execution Stack Example

```
addrX: A(int tmp) {
  .      if (tmp<2)
  .        B();
  .
addrY:   printf(tmp);
  .    }
  .    B() {
  .      C();
addrU: }
  .    C() {
  .      A(2);
  .
addrV: }
  .    A(1);
  .
addrZ: exit;
```

Output:
2
1

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Motivational Example for Threads

- Imagine the following C program:

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

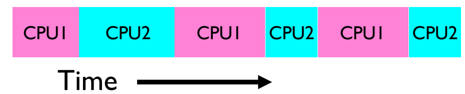
- What is the behavior here?
  - Program would never print out class list
  - Why? `ComputePI` would never finish

Use of Threads

- Version of program with Threads (loose syntax):

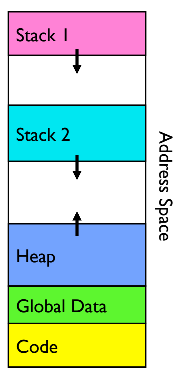
```
main() {
    ThreadFork(ComputePI, "pi.txt"));
    ThreadFork(PrintClassList, "classlist.txt"));
}
```

- 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

Recall: Signals – infloop.c

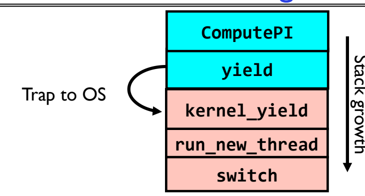
```
#include <stdlib.h>
#include <stdio.h>
#include <sys/types.h>

#include <unistd.h>
#include <signal.h>

void signal_callback_handler(int signum)
{
  printf("Caught signal %d - phew!\n",signum);
  exit(1);
}

int main() {
  signal(SIGINT, signal_callback_handler);
  while (1) {}
}
```

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(); /* cleanup */
}
```

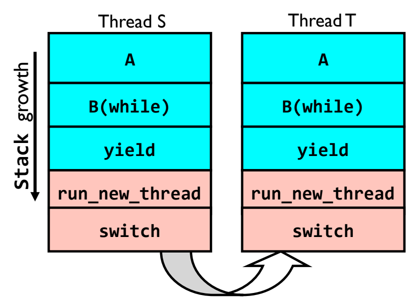
- How does dispatcher switch to a new thread?
  - Save anything next thread may trash: PC, regs, stack pointer
  - Maintain isolation for each thread

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 */
}
```

Some Numbers

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

  *The working set is subset of memory used by process in a time window

- Moral: Context switching depends mostly on cache limits and the process or thread's hunger for memory

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)