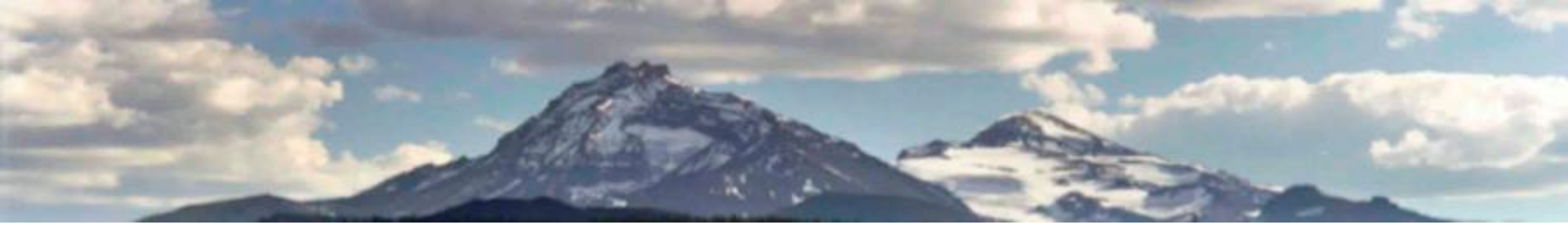

# CIS 415
# Operating Systems
# Threads

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Spring 2020

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# *Logistics*

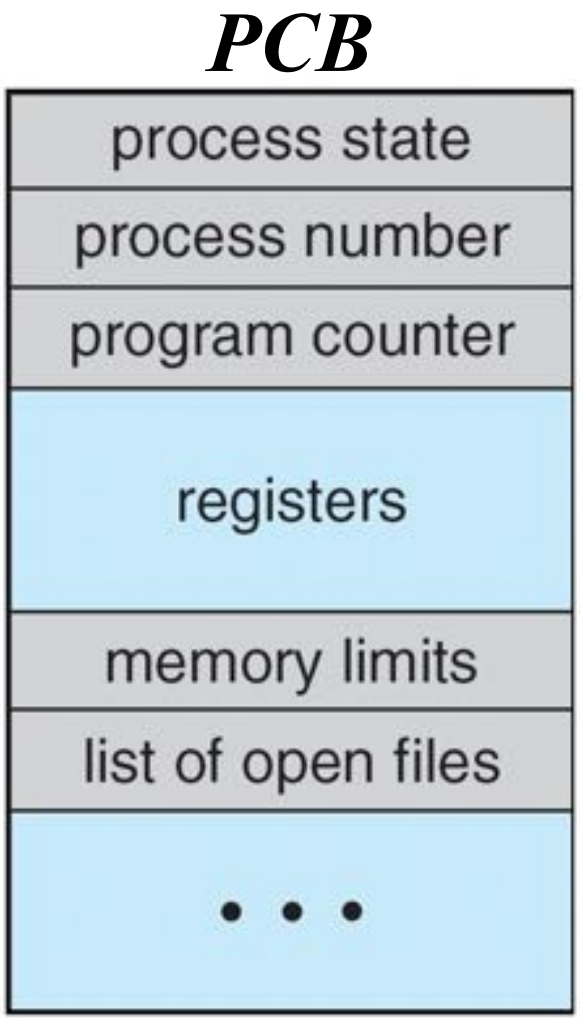
- Keep working hard on Project 1
  - Due Sunday, April 19, 11:59pm
- Lab this week covers systems call
- Read Chapter 4

# *Outline*

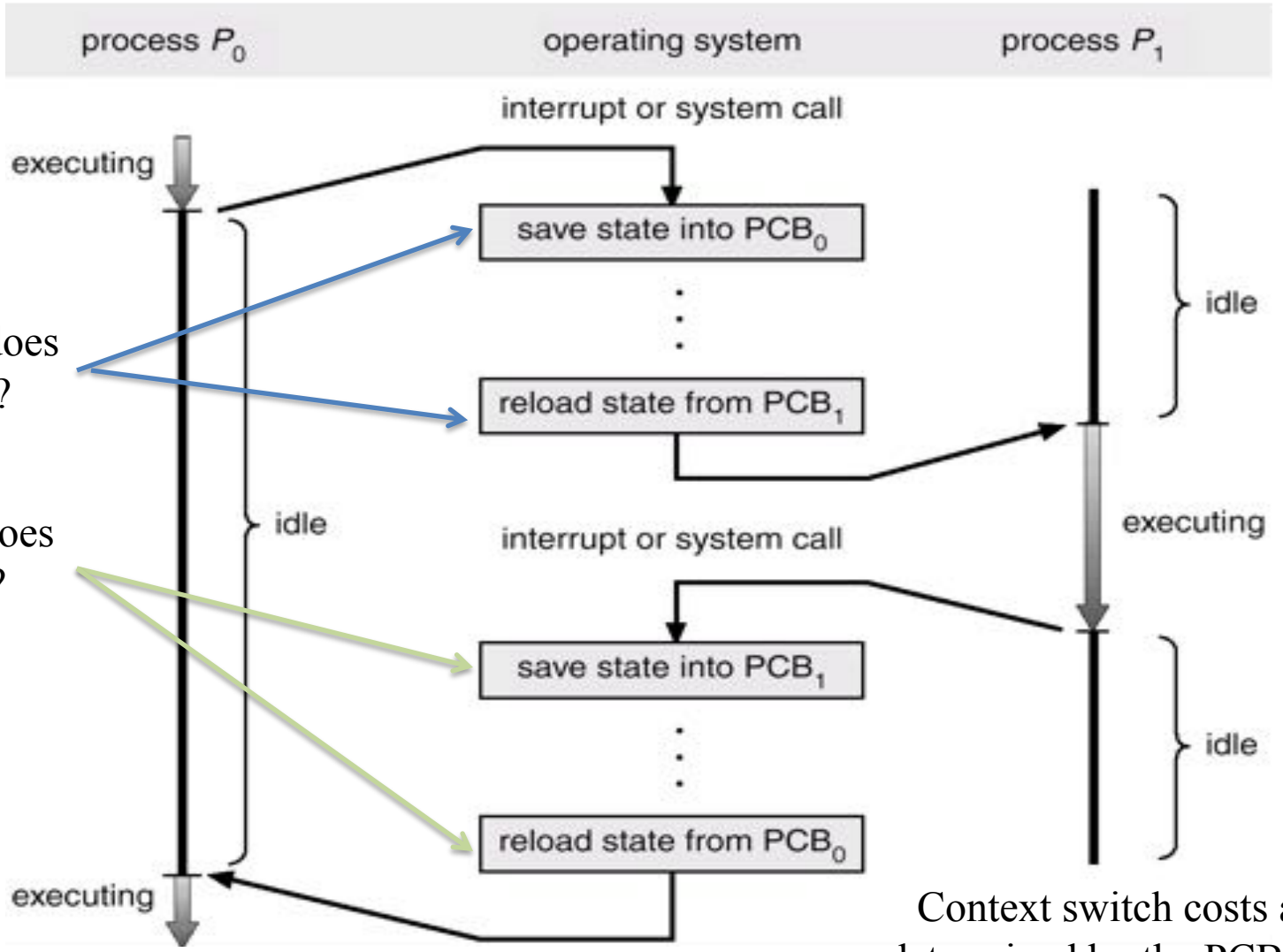
- Processes revisited
- Threads, threads, threads, ….

# *Process Control Block*

- Information associated with each process (aka *task control block)*
- Process state
  - Running, waiting, …
- Program counter
  - Location of instruction to next execute
- CPU registers
  - Contents of all process-centric registers
- CPU scheduling information
  - Priorities, scheduling queue pointers, …
- Memory-management information
  - Memory allocated to the process
  - Memory limits and other associated information
- Accounting information
  - CPU used, elapsed time, time limits, …
- I/O status information
  - I/O devices allocated to process, list of open files



# *Process Context Switch*

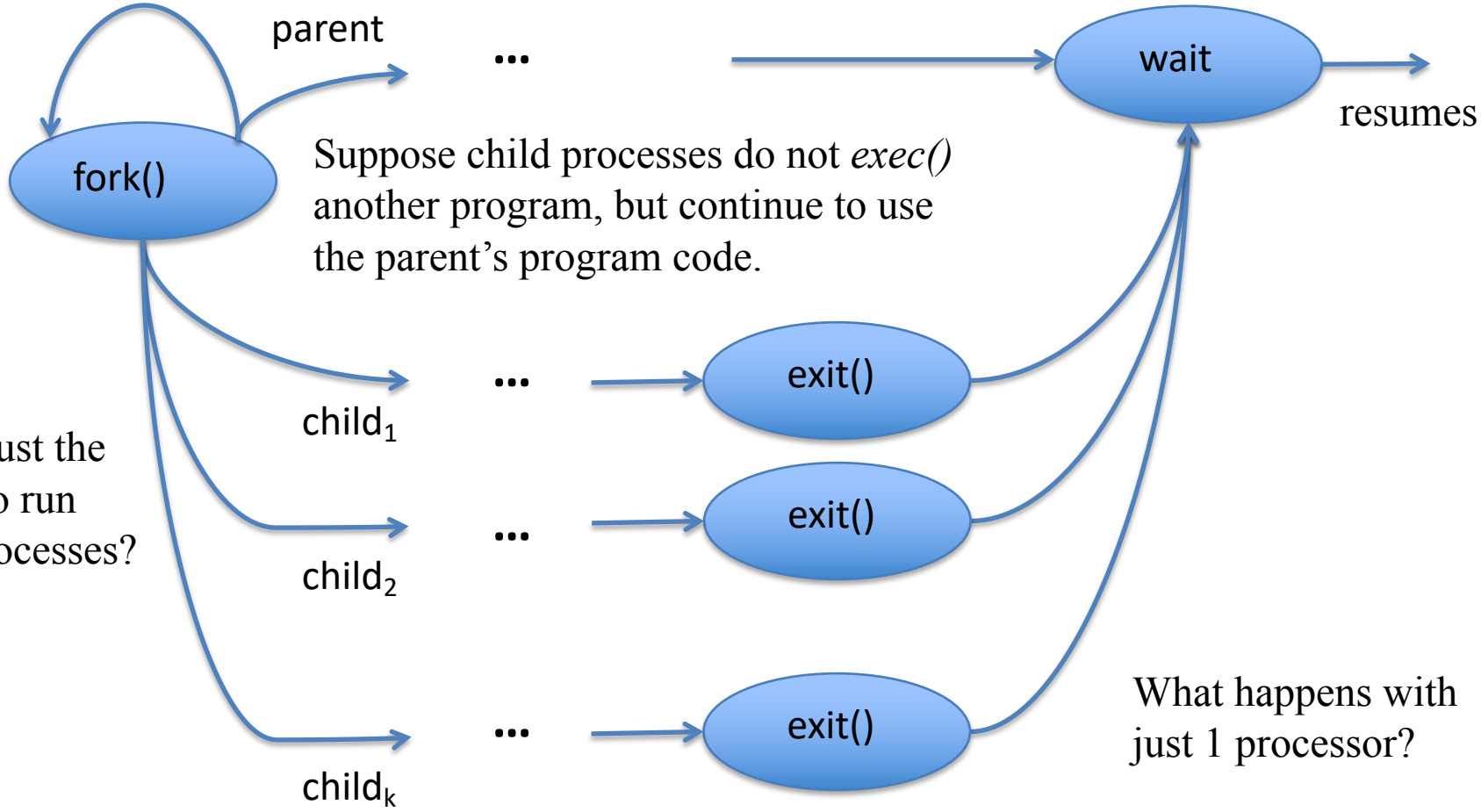



How long does this take?

How long does this take?

Context switch costs are determined by the PCB size

# Program with Multiple Processes




What must the OS do to run these processes?

What happens with just 1 processor?

What happens with >1 processors?

What does the child process state look like?

What is shared of the parent process?

# *Program Creation System Calls*

- *fork()*
  - Copy address space of parent and all threads
- *vfork()*
  - Do not copy the parent's address space
  - Share address space between parent and child
  - While parent blocks, child must exit or call exec
- *exec()*
  - Load new program and replace address space
  - Some resources may be transferred (open file descriptors)
  - Specified by arguments
- *clone()*
  - Like fork() but child shares some process context
  - More explicit control over what is shared
  - Process address space can be shared!
  - Calls a function pointed to by argument

The child is still considered a process, but lighterweight!

# *Process Model*

- Much of the OS's job is keeping processes from interfering with each other … Why?
- Each process has its OWN resources to use
  - Program code to execute, address space, files, …
- Processes are good for isolation (protection)
  - Prevent one process from affecting another process
- Processes are *heavyweight* … Why do you think?
  - Pay a price for isolation
  - A full "process swap" is required for multiprocessing
  - There is lots of process state to save and restore
  - OS must context switch between them
    - intervene to save/restore all process state
- Is there an alternative?

# *Why Threads?*

- A process is "a program in execution"
  - Memory address space containing code and data
  - Other resources (e.g., open file descriptors)
  - State information (PC, register, SP) => PCB details
- Consider a process in 2 respects (categories)
  1) Collection of resources required for execution
     - code, address space, open files, …
  2) A "thread of execution"
     - current state of execution (CPU state)
     - where the execution is now (PC)
- Suppose we think about these separately!
  - Resources
  - Execution state

# *Terminology*

- ***Multiprogramming***
  - Running multiple programs on a computer concurrently
  - Each program is a (set of) process(es)
  - Processes of different programs are independent
- ***Multiprocessing***
  - Running multiple processes on a computer concurrently
  - OS manages mapping of processes to processor(s)
- ***Multithreading***
  - Define multiple *execution contexts* (*threads of execution*) in a single address space (of a process)
  - OS manages mapping of threads to an address space
  - OS manages mapping of threads to processor(s)

# *What's a Thread?*

- Thread of execution through a program on a CPU
  - Program counter — *per thread*
  - Registers — *per thread*
- Memory
  - Address space — *process*
    - address space is shared!!!
  - Stack — *per thread*
    - each thread has its own stack pointer
  - Heap — *process*
    + private dynamic memory — *per thread*
- I/O
  - Share files, sockets, … — *process*

# *Why Multithreaded Applications?*

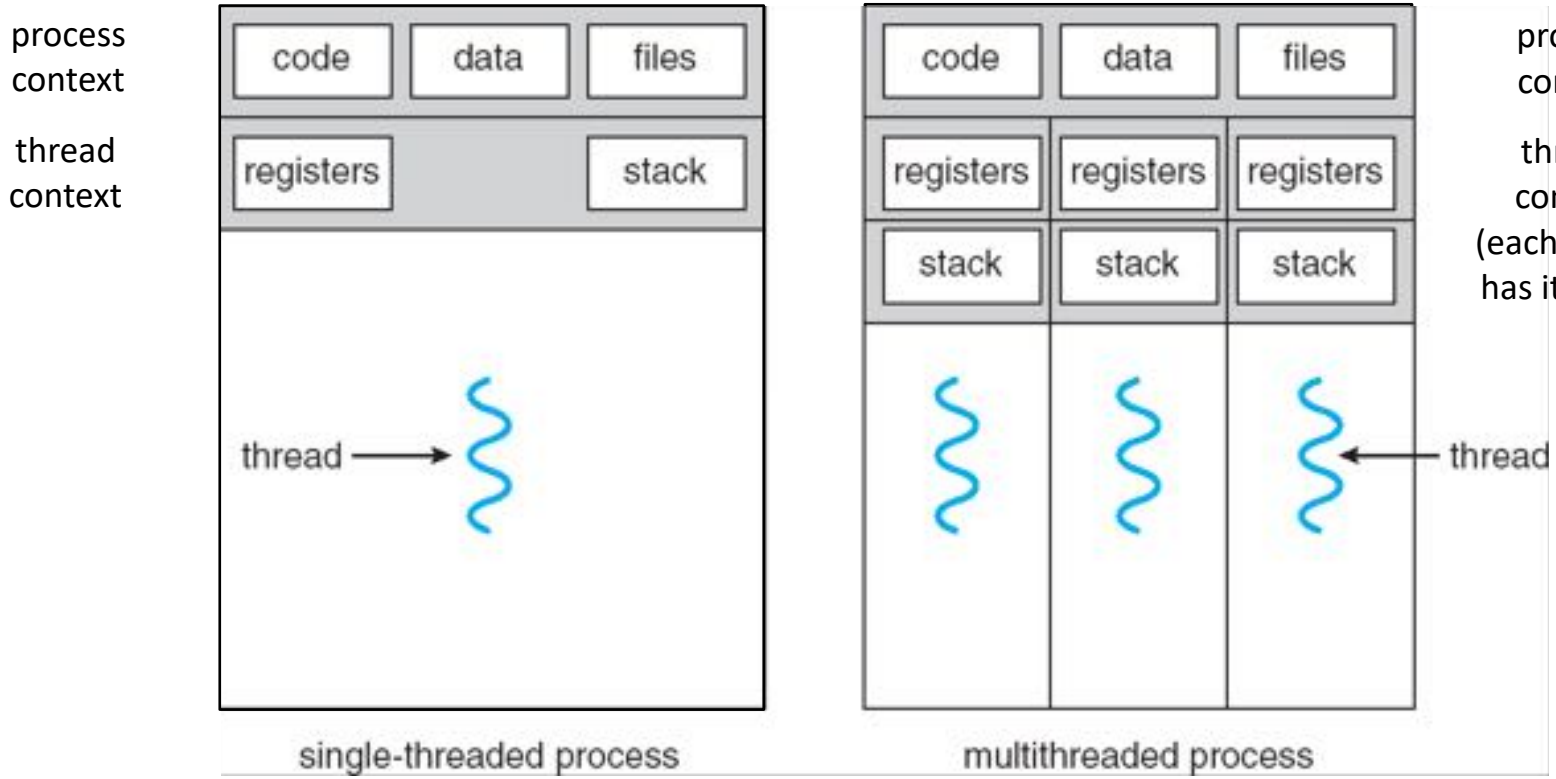
- Multiple threads sharing a common address space
  - More correctly, they share process resources, including memory!
- Why would you want to do that?
- Some applications could be written to support concurrency
  - How do you get concurrency?
  - One way is to create multiple processes
  - Use IPC to support process-level concurrency
- Some applications want to share data structures among concurrently executing parts of the computation
  - Is this possible with processes? => shared segments
  - Is it difficult with processes? => well, it is not that easy
  - Again, use IPC for process-level data sharing
- What is the problem? What is the solution?

# *Advantages of Threads*

- Threads could be used if there is no need for the OS to enforce resource separation
  - This is a trust issue, in part (back off on isolation / protection)
  - However, introduces more issues with respect to concurrency
- Improve responsiveness
  - Possible to have a thread of execution that never blocks
  - More to come about this …
- Resource sharing is facilitated
  - All threads in a process have equal access to resources
- Economy of resources
  - Thread-level resources are "cheaper" than process resources!
  - Threads are "lighter weight"
- Utilization of multiprocessors
  - Run multiple threads on multiple processes without the overhead of running multiple processes

# *Single-Threaded vs. Multithreaded*

- Regular UNIX process can be thought of as a special case of a multithreaded process
  - A process that contains just one thread!
- Multithreaded process has multiple threads



# *Working with Threads*

- In a C program
  - *main()* procedure defines the first thread
  - C programs always start at *main()*
- Now you want to create a second thread
  - Allocate resources to maintain a second execution context in same address space
    - think about what state will be needed for a thread
  - Want something similar to *fork()* but simpler
    - supply a procedure name when start the new thread
  - Remember this creates another thread of execution

# *Threads vs. Processes*

- Easier to create than a new process
- Less time to terminate a thread than a process
- Less time to switch between two threads
  - Within the same process
- Less communication overheads
  - Communicating between the threads of one process is simple because the threads share everything
  - Address space is shared …
  - … thus memory is shared (Hmm …  )

# *Which is Cheaper?*

- Create new process or create new thread (in existing process)?
- Context switch between processes or threads?
- Interprocess or interthread communication?
- Sharing memory between processes or threads?
- Terminating a process or terminating a thread (not the last one)?

| Process creation method | Time (sec), elapsed (real) |
|---|---|
| *fork()* | 22.27 (7.99) |
| *vfork()  (faster fork)* | 3.52 (2.49) |
| *clone()* | 2.97 (2.14) |

Time to create 100,000 processes (Linux 2.6 kernel, x86-32 system)

*clone()* creates a lightweight Linux process (thread)

# *Implications?*

- Consider a web server on a Linux platform
- Measure 0.22 ms per *fork()*
  - Maximum of (1000 / 0.22) = 4545.5 connections/sec
  - 0.45 billion connections per day per machine
    - fine for most servers
    - too slow for a few super-high-traffic front-line web services
- Facebook serves O(750 billion) page views per day
  - Guess ~1-20 HTTP connections per page
  - Would need 3,000 -- 60,000 machines just to handle *fork()*, without doing any work for each connection!
- What is the problem here?

# *Thread Attributes*

- Global to process:
  - memory
  - PID, PPID, GID, SID
  - controlling term
  - process credentials
  - record locks
  - FS information
  - timers
  - resource limits
  - and more...
- Local to specific thread:
  - thread ID
  - stack
  - signal mask
  - thread-specific data
  - alternate signal stack
  - error return value
  - scheduling policy/priority
  - Linux-specific (e.g., CPU affinity)

# *Threading Models*

- *Programming* – library or system call interface
  - Kernel threading (most common)
    - thread management support in the kernel
    - invoked via system call
    - NOTE: CPU only runs kernel threads!!!
  - User-space threading
    - thread management support in user-space library
    - threads are "thread switched" by a user-level library
    - linked into your program
- *Scheduling* – application or kernel scheduling
  - May create user-level or kernel-level threads

# *Kernel Threads*

- Thread management support in kernel
  - Sets of system calls for creating, invoking, and switching among threads
- Supported and managed directly by the OS
  - Thread objects in the kernel
- Nearly all OSes support a notion of threads
  - Linux -- thread and process abstractions are mixed
  - Solaris
  - Mac OS X
  - Windows XP
  - …

# *User-space Threads*

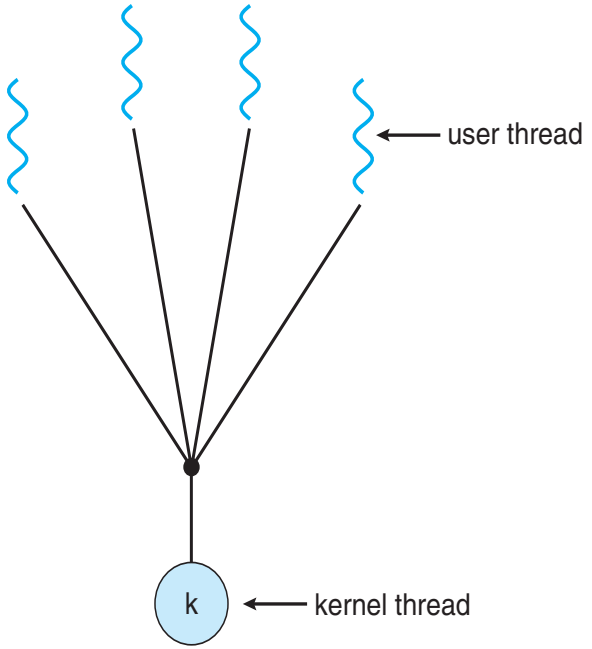
- Thread management support in user-space library
  - Sets of functions for creating, invoking, and switching among threads (all in user mode)
  - Need to switch threads stacks in user space …
- Linked into your program
  - Thread libraries
- Examples
  - Qthreads (http://www.cs.sandia.gov/qthreads/)
  - GNU Pth (http://www.gnu.org/software/pth/)
  - Cilk (https://en.wikipedia.org/wiki/Cilk)

# *Implementing User-space Threading*

- Threads can perform operations in user mode that are usually handled by the OS
  - Assumes cooperating threads so hardware enforcement of separation not required
- Idea:
  - Think of a "dispatcher" subroutine in the process that is called when a thread is ready to relinquish control to another thread
  - Manages stack pointer, program counter
  - Switches process's internal state among threads

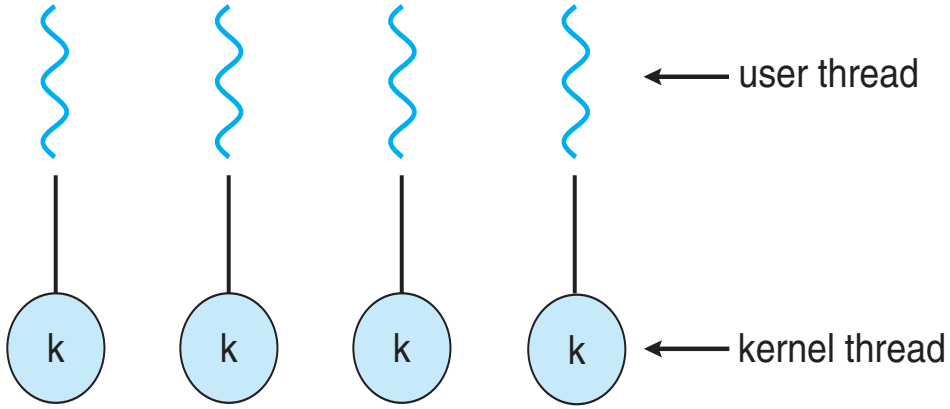
# *Many-to-One Thread Model*

- Many user-level threads correspond to a single kernel thread
  - Kernel is not aware of the mapping
  - Handled by a thread library
- How does it work?
  - Create and execute a new thread
  - Upon yield, switch to another user thread in the same process
    - kernel is unaware
  - Upon wait, all threads are blocked
    - kernel is unaware there are other options
    - can not wait and run at the same time



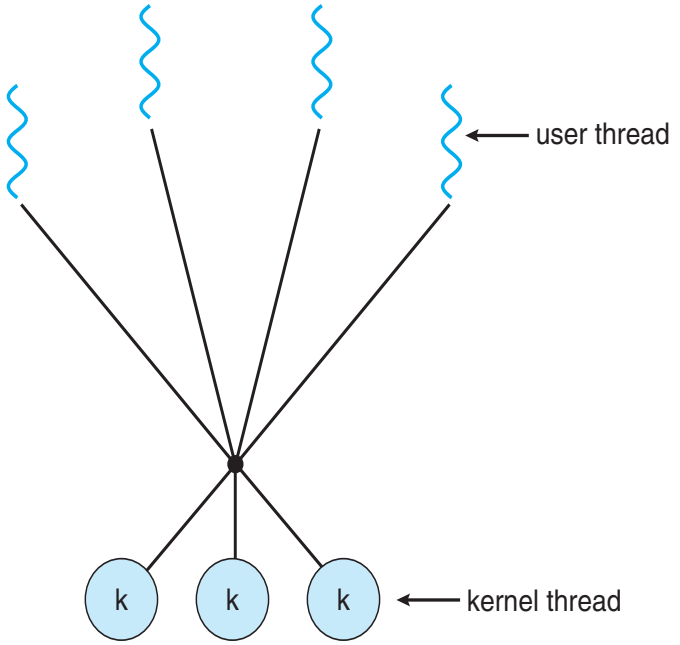
# One-to-One Thread Model

- One user-level thread per kernel thread
  - A kernel thread is allocated for every user-level thread
  - Must get the kernel to allocate resources for each new user-level thread
- How does it work?
  - Create new thread
    - system call to kernel
  - Upon yield, switch to another kernel thread in system
    - kernel is aware
  - Upon wait, another thread in the process may run
    - only the single kernel thread is blocked
    - kernel is aware there are other options in this process



# *Many-to-Many Thread Model*

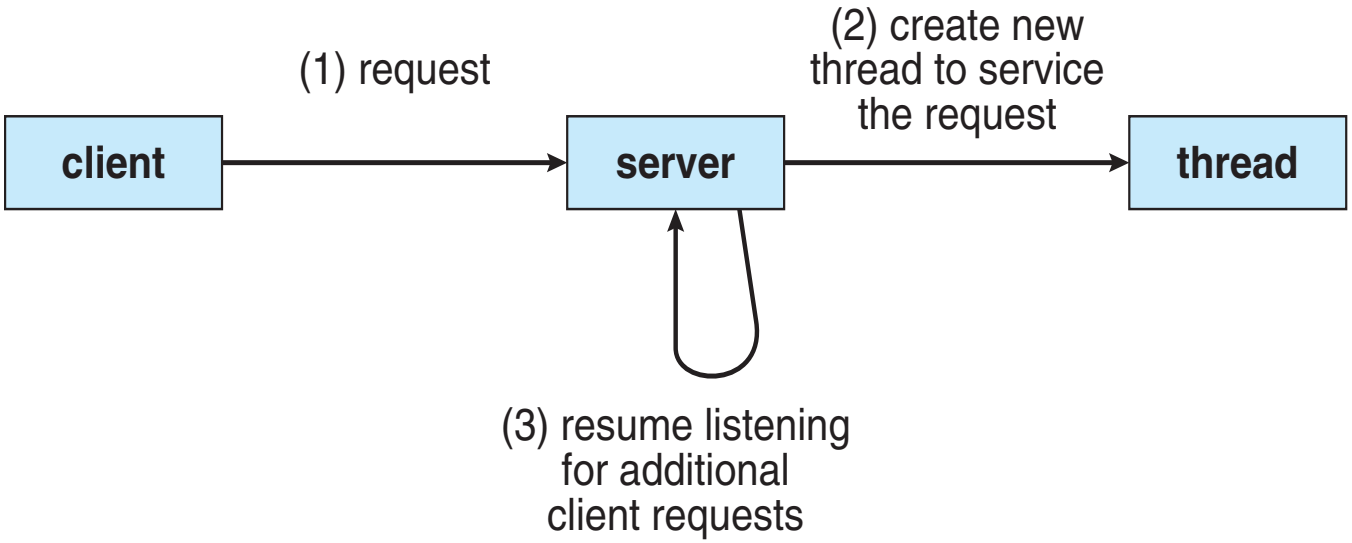
- A pool of user-level threads maps to a pool of kernel threads
  - Pool sizes can be different (kernel pool is no larger)
  - A kernel thread is pool is allocated for every user-level thread
  - No need for the kernel to allocate resources for each new user-level thread
- How does it work?
  - Create new thread
    - may map to kernel thread dynamically
  - Upon yield, switch to another thread
    - kernel is aware
  - Upon wait, another thread in the process may run
    - if a kernel thread is available to be scheduled to that process
    - kernel is aware of the mapping between user and kernel threads



# *Problems Solved with Threads*

- Imagine you are building a web server
  - You could allocate a pool of threads, one for each client
    - thread would wait for a request, get content file, return it
  - How would the different thread models impact this?
- Imagine you are building a web browser
  - You could allocate a pool of threads
    - some for user interface
    - some for retrieving content
    - some for rendering content
  - What happens if the user decided to stop the request?
    - mouse click on the stop button

# *Multithreaded Server Architecture*



# *Linux Threads*

- Linux uses a one-to-one thread model
  - Threads are called *tasks*
- Linux views threads as "contexts of execution"
  - Threads are defined separately from processes
  - There is flexibility in what is private and shared
- Linux system call
  - *clone(int (*fn)(), void **stack, int flags, int argc, ...)*
  - Create a new thread (Linux task)
- May be created in the same address space or not
  - Flags (on means "share"): clone VM, clone filesystem, clone files, clone signal handlers
  - If all these flags off, what system call is clone equal to?

# *POSIX Threads*

- POSIX Threads is a thread API specification
  - Does not define directly the implementation!
  - Could be implemented differently
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
  - Specification, not implementation
  - Provided either as user-level or kernel-level (very interesting)
  - API specifies behavior of the thread library
  - Implementation is up to development of the library

- Common in UNIX operating systems
  - Solaris, Linux, Mac OS X
- POSIX Threads is also known as *Pthreads*

# *POSIX Threads*

- *pthread_create()*
  - start the thread
- *pthread_self()*
  - return thread ID
- *pthread_equal()*
  - for comparisons of thread ID's
- *pthread_exit()*
  - or just return from the start function
- *thread_join()*
  - wait for another thread to terminate & retrieve value from pthread_exit()
- *pthread_cancel()*
  - terminate a thread, by TID
- *pthread_detach()*
  - thread is immune to join or cancel & runs independently until it terminates
- *pthread_attr_init()*
  - thread attribute modifiers

# *POSIX Threads FAQ*

- How to pass multiple arguments to start a thread?
  - Build a struct and pass a pointer to it
- Is the pthreads ID unique to the system?
  - No, just process – Linux task ids are system-wide
- After *pthread_create()*, which thread is running?
  - It acts like fork in that both threads are running
- How many threads terminate when …
  - *exit()* is called? – all in the process
  - *pthread_exit()* is called? – only the calling thread
- How are variables shared by threads?
  - Globals, local static, dynamic data (heap)

# *Pthreads Example*

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

int sum; /* this data is shared by the thread(s) */
void *runner(void *param); /* threads call this function */

int main(int argc, char *argv[])
{
   pthread_t tid; /* the thread identifier */
   pthread_attr_t attr; /* set of thread attributes */

   if (argc != 2) {
      fprintf(stderr,"usage: a.out <integer value>\n");
      return -1;
   }
   if (atoi(argv[1]) < 0) {
      fprintf(stderr,"%d must be >= 0\n",atoi(argv[1]));
      return -1;
   }
```

# *Pthreads Example (Cont.)*

```
   /* get the default attributes */
   pthread_attr_init(&attr);
   /* create the thread */
   pthread_create(&tid,&attr,runner,argv[1]);
   /* wait for the thread to exit */
   pthread_join(tid,NULL);

   printf("sum = %d\n",sum);
}

/* The thread will begin control in this function */
void *runner(void *param)
{
   int i, upper = atoi(param);
   sum = 0;

   for (i = 1; i <= upper; i++)
      sum += i;

   pthread_exit(0);
}
```

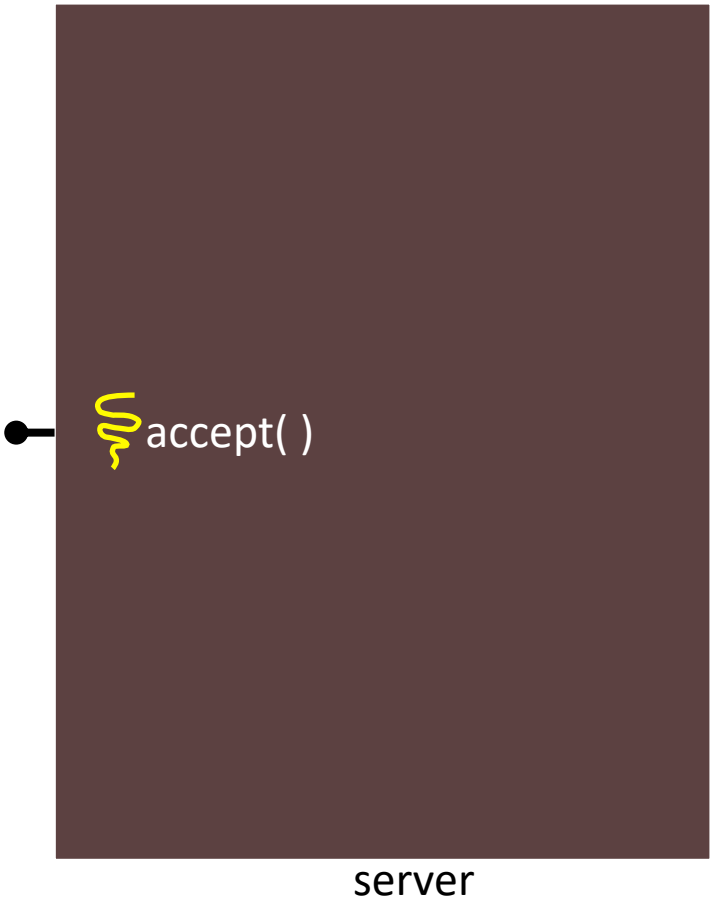
# *Pthreads Code for Joining 10 Threads*

```
#define NUM_THREADS 10

/* an array of threads to be joined upon */
pthread_t workers[NUM_THREADS];

for (int i = 0; i < NUM_THREADS; i++)
   pthread_join(workers[i], NULL);
```

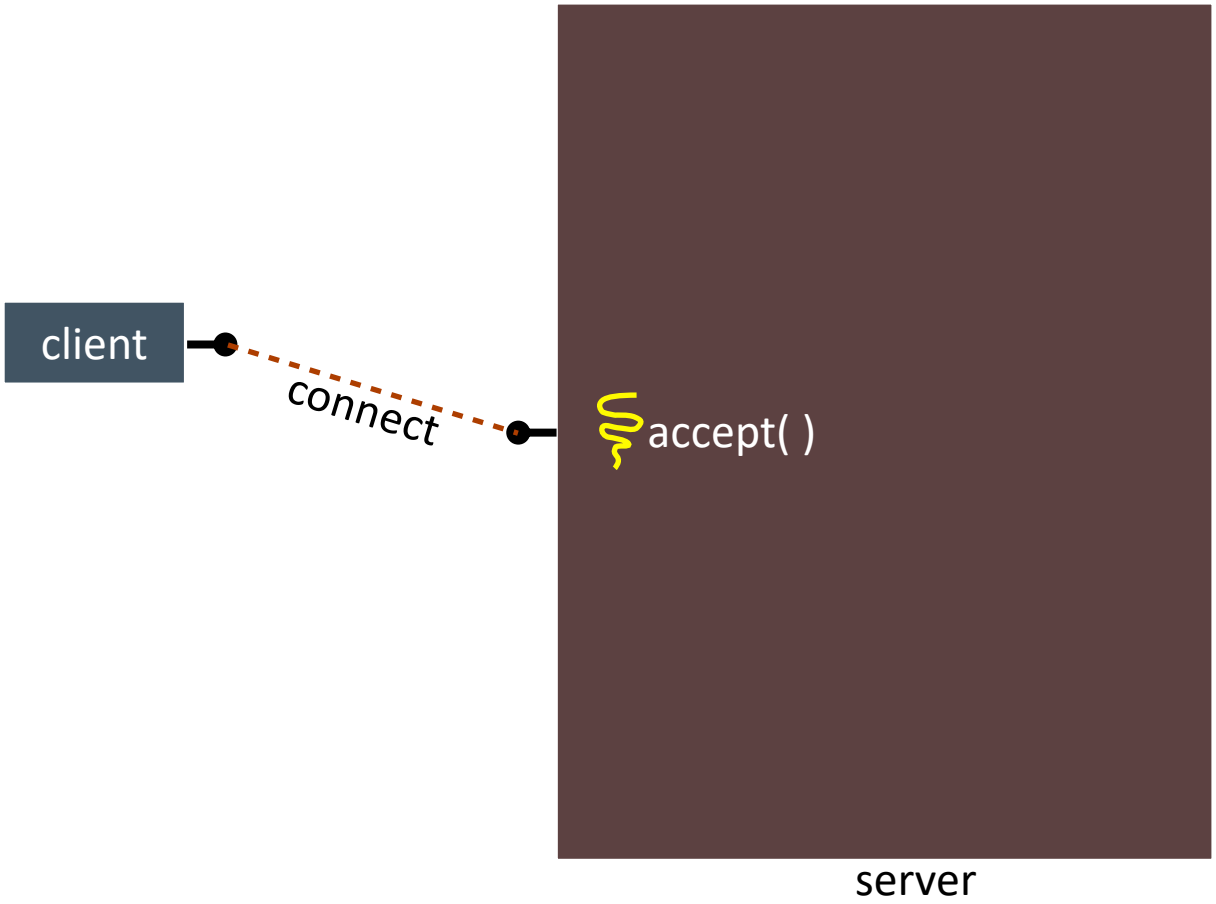
# *Concurrency with Threads*

- Consider the client-server example again
- Now want to run with just a single process
  - Need to use threads to get concurrency
- Process "main" (parent) thread waits for clients
  - Parent thread forks (or dispatches) a new thread to handle each new client connection
  - Responsibilities of the child thread:
    - handles the new connection
    - exits when the connection terminates

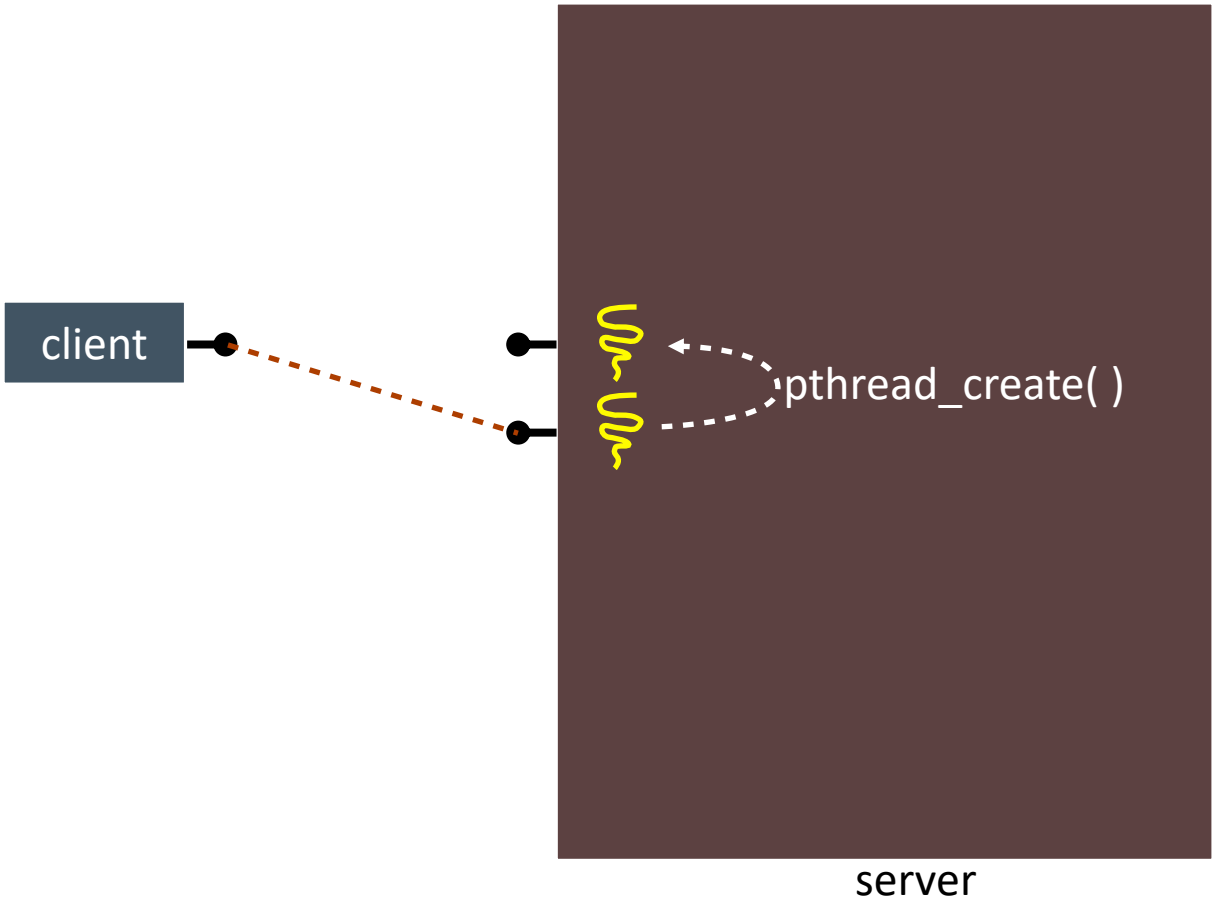
# *Client-Server with Pthreads (1)*



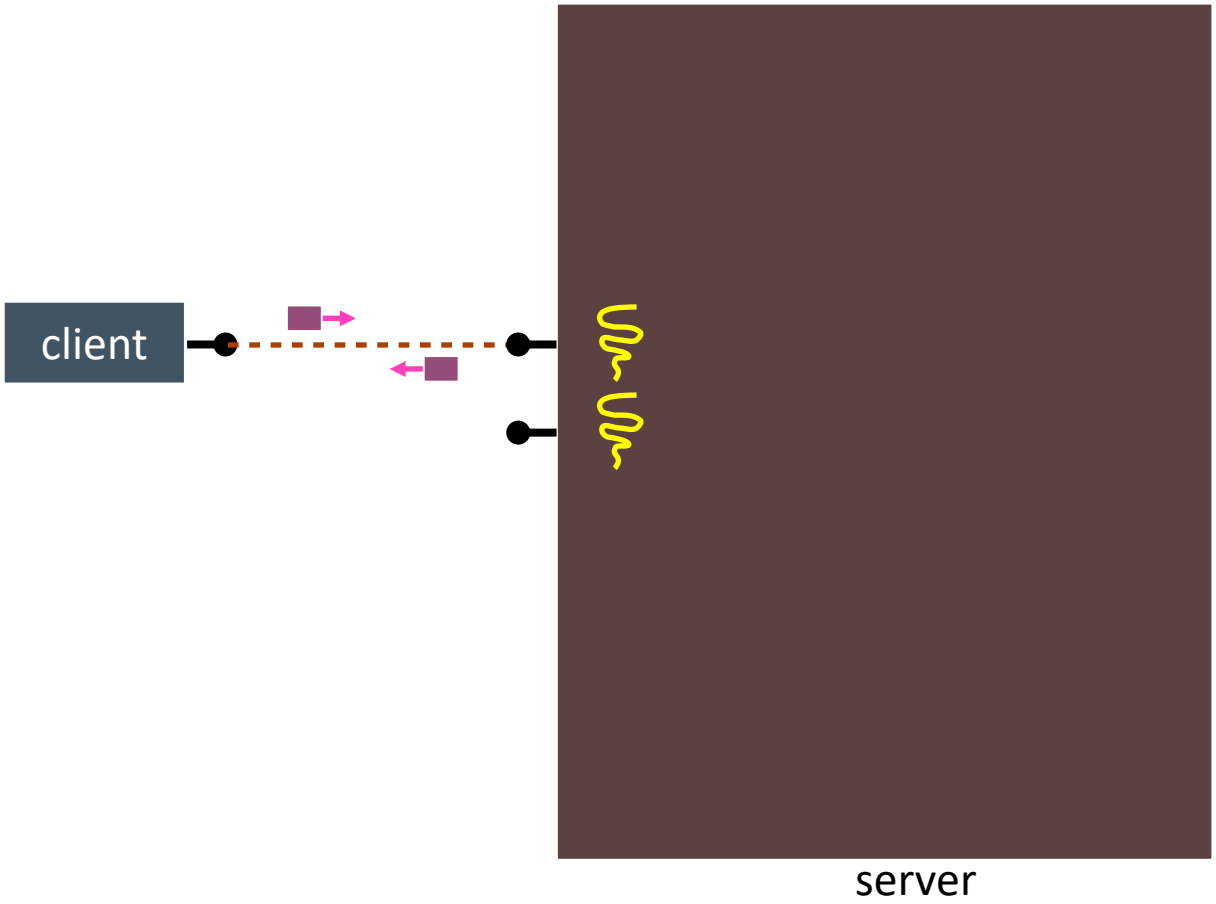
# Client-Server with Pthreads (2)



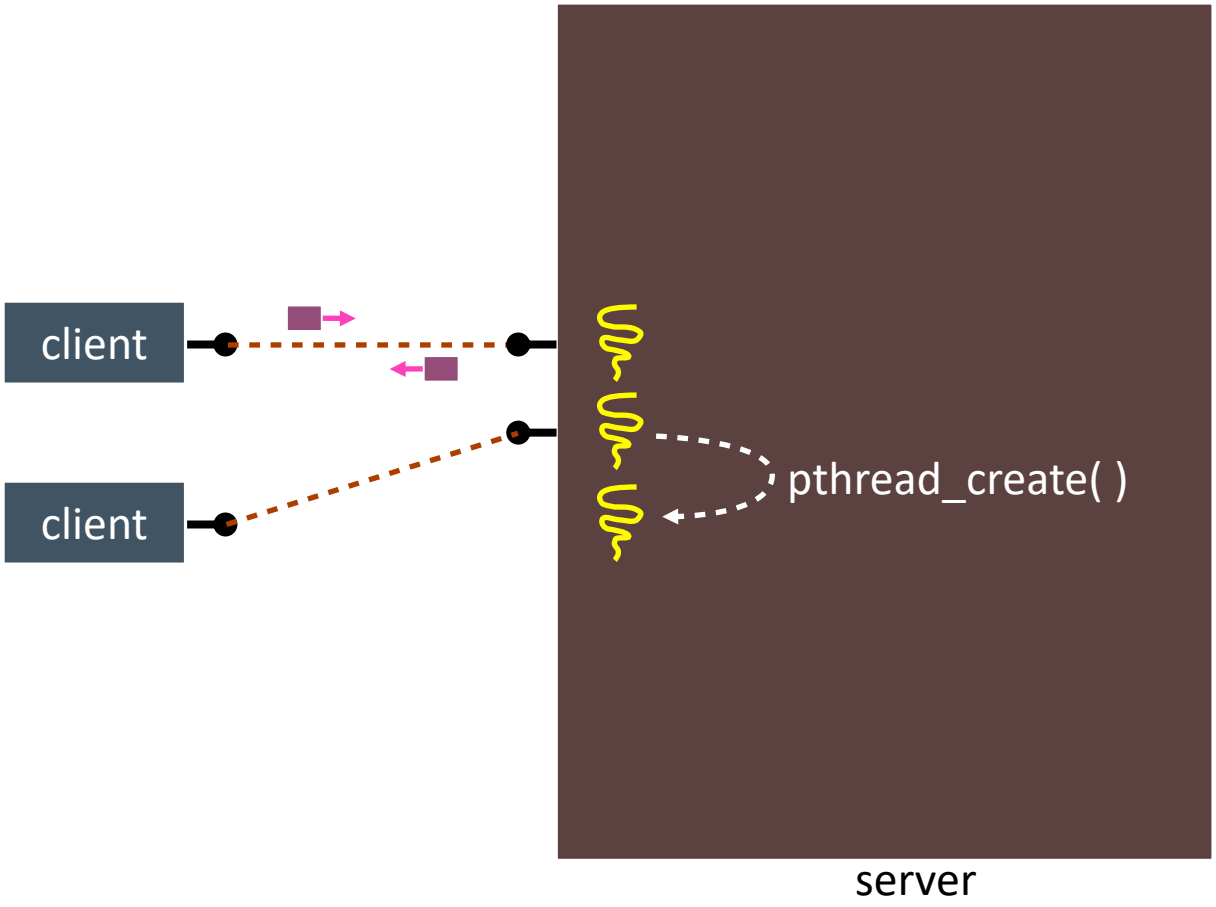
# Client-Server with Pthreads (3)



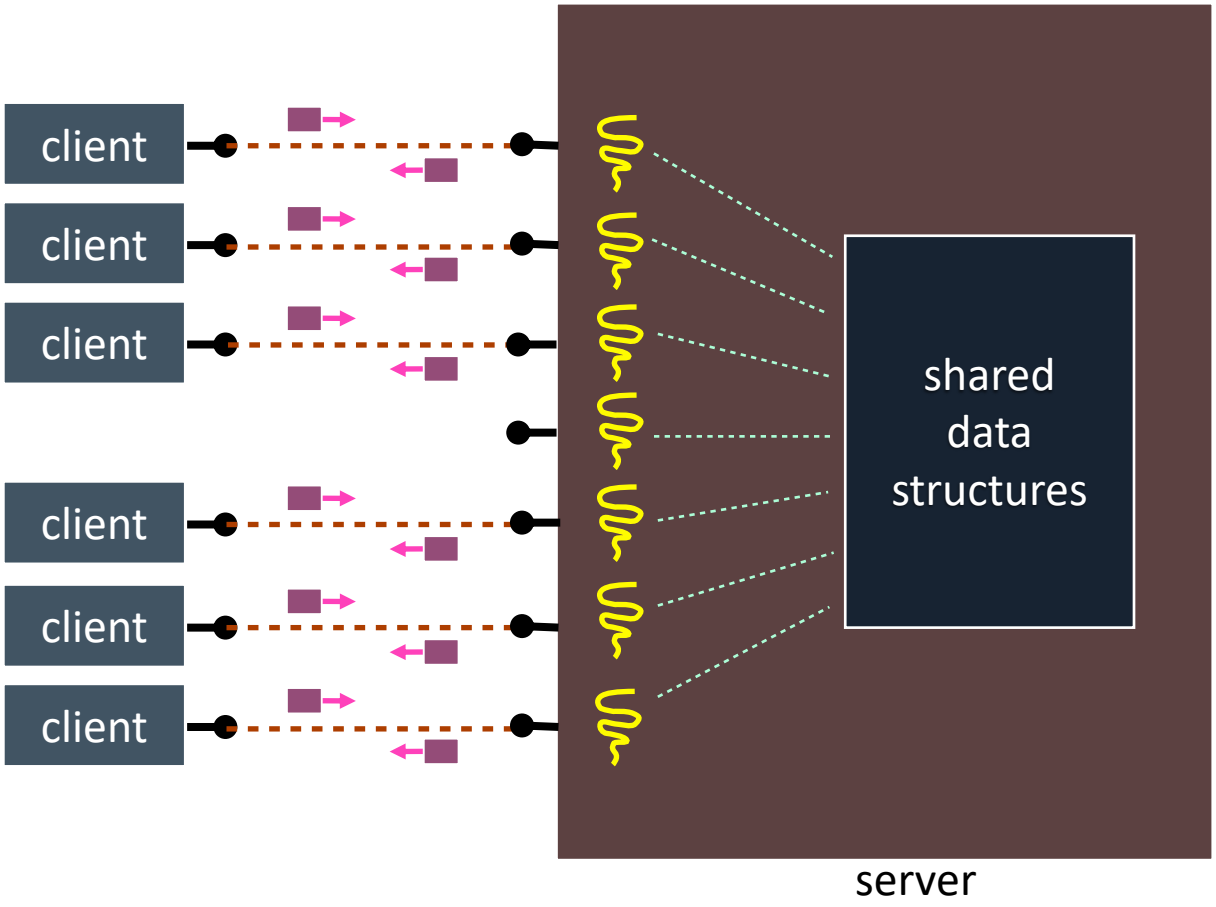
# *Client-Server with Pthreads (4)*



# Client-Server with Pthreads (5)



# *Client-Server with Pthreads (5)*



# *Implications?*

- Consider a web server on a Linux platform
- 0.0297 ms per thread create (time for *clone()*)
  - 10x faster than process forking
  - Maximum of (1000 / 0.0297) = ~33,670 connections/sec
  - 3 billion connections per day per machine
    - much, much better
- Facebook would need only 500 machines
- So, why do we need processes at all?
- Just write everything using threads
  - Writing safe multithreaded code can be complicated
  - Why? What are the issues?

# *Concurrent Threads*

- Benefits
  - All threads are running the same code
    - still the case that much of the code is identical!
  - Shared-memory communication is possible
  - Good CPU and network utilization
    - lower overhead than processes
- Disadvantages
  - Synchronization is complicated
  - Shared fate within a process
    - one rogue thread can hurt you badly
- More to come on this topic …

# *Inter-Thread Communication*

- Can you use shared memory?
  - Sure, it is there, might as well use it
  - Just need to allocate memory in the address space
    - No need for fancy IPC shared memory
- Can you use message passing?
  - Of course
  - Would have to build infrastructure though
- Hmm, can threads utilize IPC mechanisms
  - That is a good question actually
  - Would need to make sure only 1 thread uses at a time

# *Fork/Exec Issues*

- Semantics are ambiguous for multithreaded processes
- *fork()*
  - How does it interact with threads?
- *exec()*
  - What happens to the other threads?
- *fork*, then *exec*
  - Should all threads be copied?

# *Thread Cancellation*

- So, you want to stop a thread from executing
  - Do not need it anymore
  - It is just hanging around and you want to get rid of it
- Two choices
  - Synchronous cancellation
    - wait for the thread to reach a point where cancellation is permitted
    - no such operation in Pthreads, but can create your own
  - Asynchronous cancellation
    - terminate it now
    - *pthread_cancel(thread_id)*

# *Signal Handling*

- What's a signal?
  - A form of IPC
  - Send a particular signal to another process
- Receiver's signal handler processes signal on receipt
- Example
  - Tell the Internet daemon (*inetd*) to reread its config file
  - Send signal to inetd: *kill -SIGHUP <pid>*
  - inetd's signal handler for the SIGHUP signal re-reads the config file
- Note: some signals cannot be handled by the receiving process, so they cause default action (kill the process)

# *Signal Handling*

- Synchronous signals
  - Generated by the kernel for the process
  - Due to an exception -- divide by 0
    - events caused by the thread receiving the signal
- Asynchronous signals
  - Generated by another process
- Asynchronous signals are more difficult for multithreading

# *Signal Handling and Threads*

- So, you send a signal to a process
  - Which thread should it be delivered to?
- Choices
  - Thread to which the signal applies
  - Every thread in the process
  - Certain threads in the process
  - A specific signal receiving thread
- It depends…

# *Signal Handling and Threads*

- UNIX signal model created decades before Pthreads
  - Conflicts arise as a result
- Synchronous vs. asynchronous cases
- Synchronous
  - Signal is delivered to the same process that caused the signal
  - Which thread(s) would you deliver the signal to?
- Asynchronous
  - Signal generated by another process
  - Which thread(s) in this case?

# *Thread Pools*

- Pool of threads
  - Create (all) at initialization time
  - Assign task to a waiting thread
    - it is already made so it should be fast
  - Use all available threads

- What about when that task is done?
  - Suppose another request is in the queue …
  - … should we use running thread or another thread?
- Concern for the setup time cost
- Faster than setting up a process, but what is necessary?
  - How do we improve performance?

# *Scheduling*

- How many kernel threads to create for a process?
  - In M:N model
- If last kernel thread for an application is to be blocked
  - What happens?
  - Recall the relationship between kernel and user threads
- It be nice if the kernel told the application and the application had a way to get more kernel threads
  - Scheduler activation
    - at thread block, the kernel tells the application
  - Application can then get a new thread created
    - see lightweight threads

# *Re-entrance and Thread-Safety*

- Terms that you might hear:
- *Reentrant* code
  - Code that can be run by multiple threads concurrently
- *Thread-safe* libraries
  - Library code that permits multiple threads to invoke the safe function
- Requirements
  - Rely only on input data
    - Or thread-specific data
  - Must be careful about locking (later)

# *Why not threads?*

- Threads can interfere with one another
  - Impact of more threads on caches
  - Impact of more threads on TLB
  - Bug in one thread...
- Executing multiple threads may slow them down
  - Impact of single thread vs. switching among threads
- Harder to program a multithreaded program
  - Multitasking hides context switching
  - Multithreading introduces concurrency issues

# *Summary of Threads*

- Threads
  - A mechanism to improve performance and CPU utilization
- Kernel-space and user-space threads
  - Kernel threads are real, schedulable threads
  - User-space may define its own threads (but not real)
- Threading models and implications
  - Programming systems
  - Multi-threaded design issues
- Useful, but not a panacea
  - Slow down system in some cases
  - Can be difficult to program
- Multiprogramming and multithreading are important concepts in modern operating systems