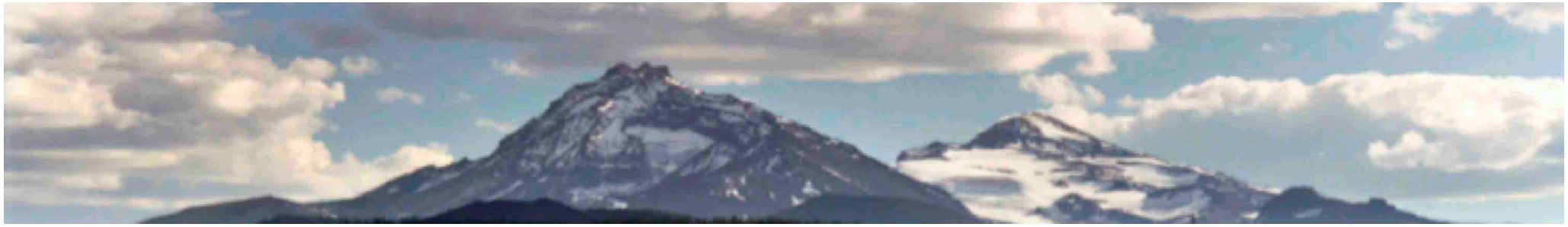

CS 415
Operating Systems
Threads

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Fall 2025

UNIVERSITY OF OREGON

Logistics

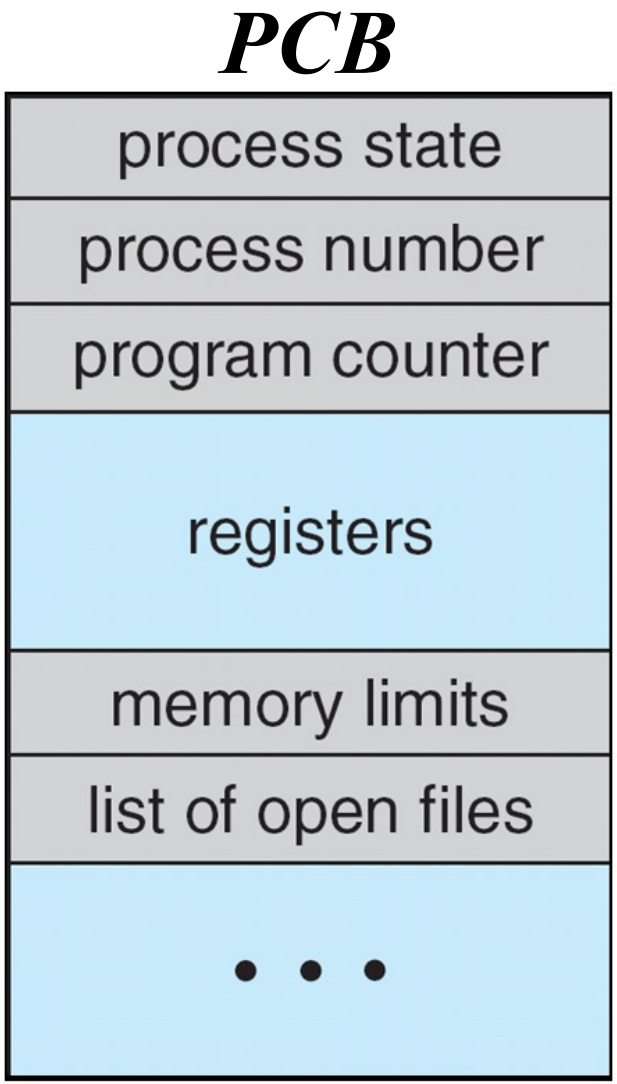
- Keep working hard on Project 1
  - Due 11:59pm on Friday
  - Please work individually
- Labs this week focus on answering questions
- Take advantage of TA office hours
  - Keep checking Canvas announcements
- Read Chapter 4 on threads
- Encourage you to come to office hours
  - Few people are coming now

Outline

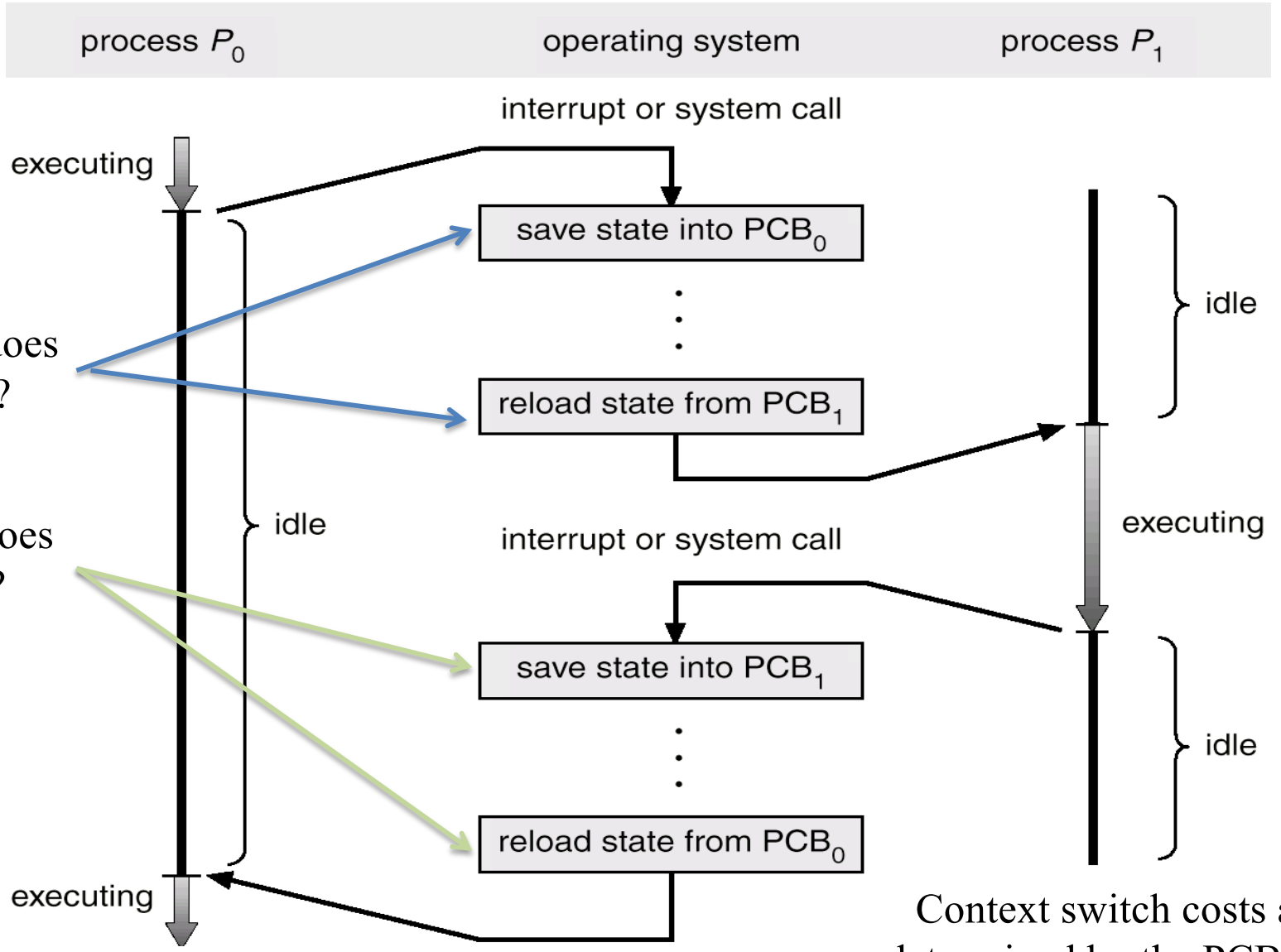
- Processes revisited
- Threads

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

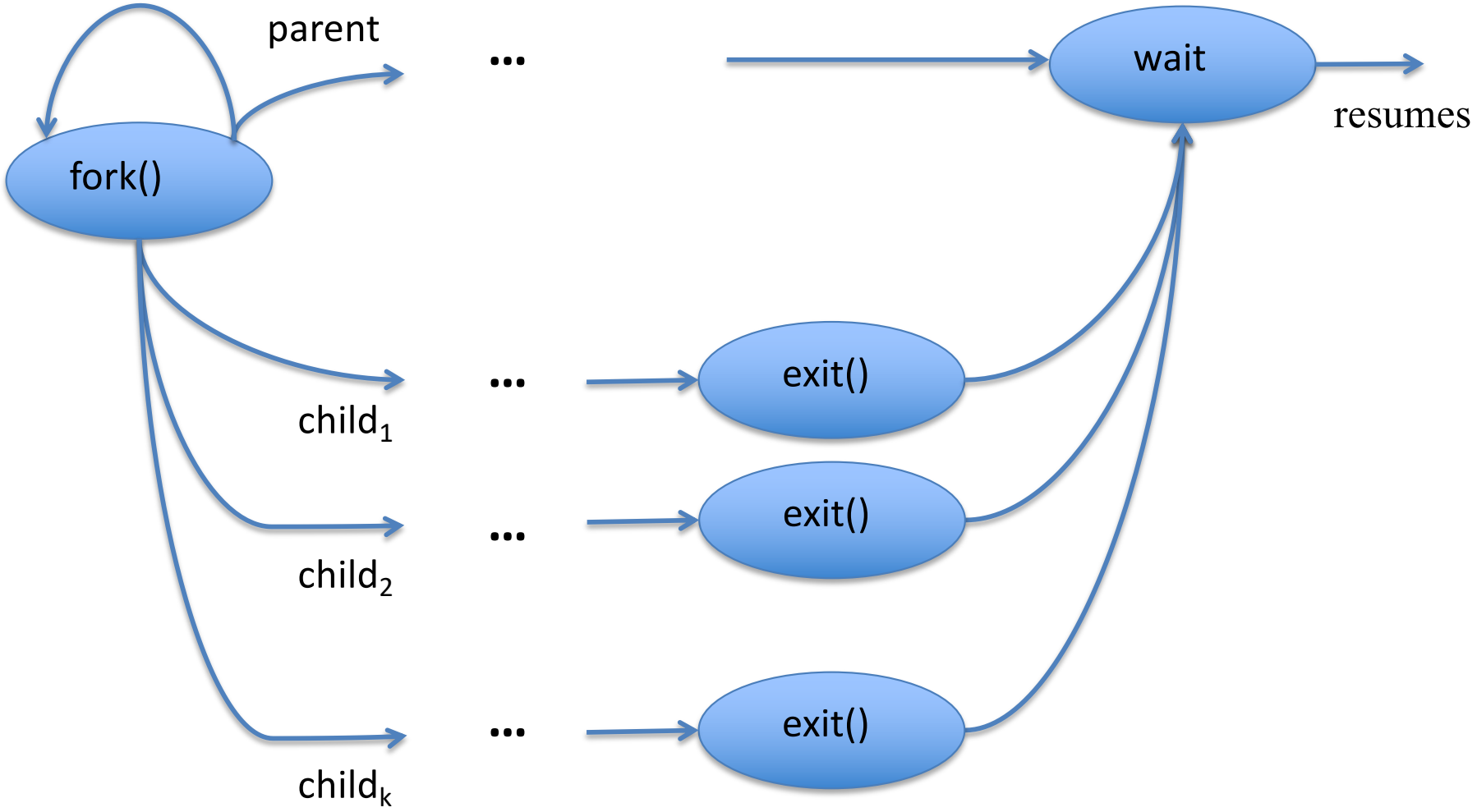


Context switch costs are determined by the PCB size

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?
  - 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?

Program with Multiple Processes



Program Creation System Calls

- *fork()*
  - Copy address space of parent and data (copy on write) to child process
- *vfork()*
  - Share the parent's address space
  - Shares address space AND physical memory between parent and child
  - Parent blocks and waits for child to exit or call exec()

Child process is independently executing

- *exec()*
  - Load new program and replace address space (for new child code)
  - 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
  - Calls a function pointed to by argument
  - Process address space and physical memory can be shared!

Child process is like in fork(), but it is much lighterweight!

Process Reimagined

- A process is "a program in execution"
  - Memory address space containing code and data
  - State information (PC, register, SP) => PCB details
  - Allocated physical memory
  - Other resources (e.g., open file descriptors)
- Consider a process in 2 respects (categories)
  1) A collection of resources required for execution
     - code, address space, memory, 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

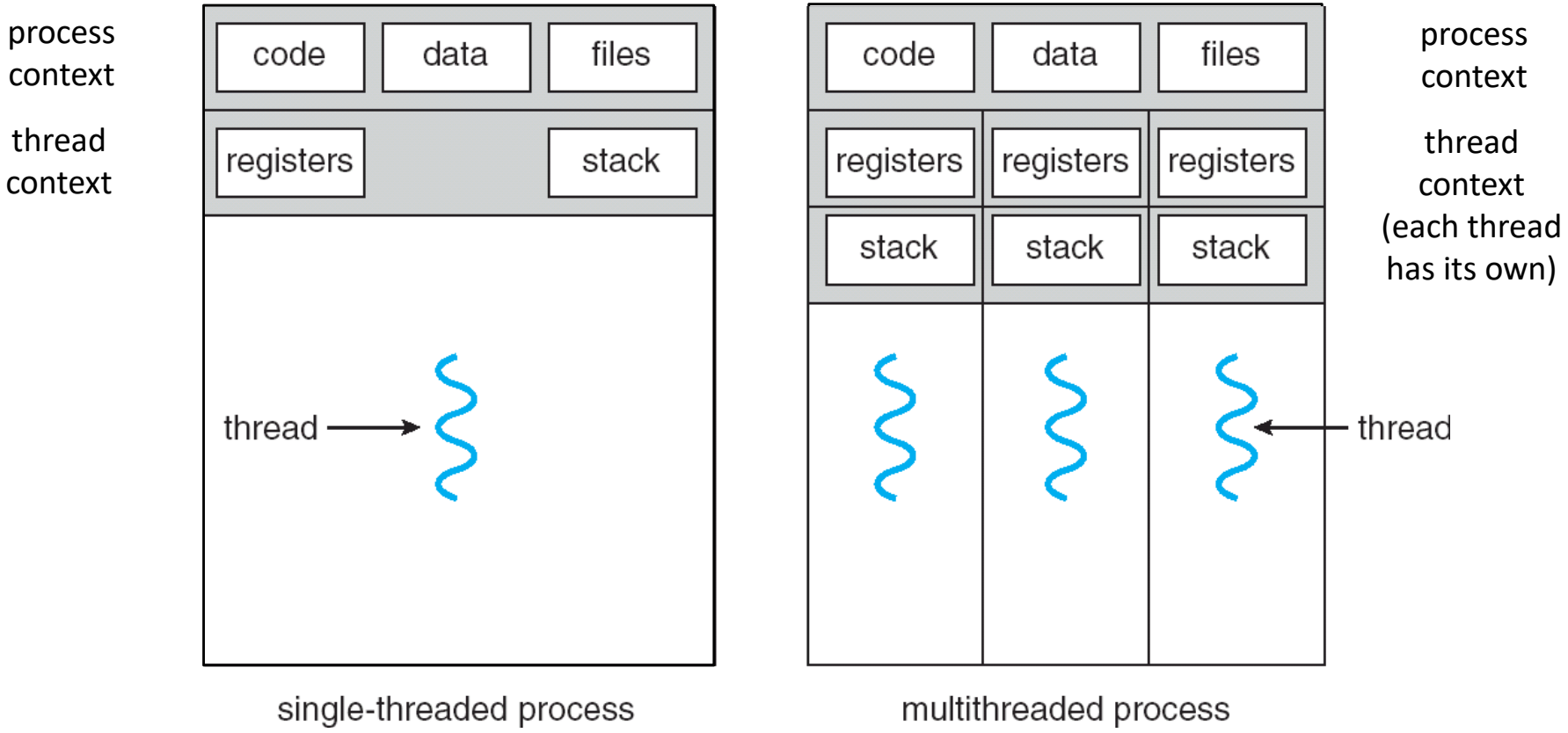
- ***Multiprogramming***
  - Running *multiple programs* on a computer at the same time
    - Concurrent (logically) execution
  - Each program is a process (or set of processes)
  - Processes of different programs are independent
- ***Multiprocessing***
  - Running *multiple processes* on a computer at the same time
  - Physical concurrently
  - OS schedules processes on processor(s)
- ***Multithreading***
  - Multiple *threads of execution* (*execution contexts*) in a single address space (of a process)
  - OS executes threads on processor(s)
  - Can be logical or physical concurrent

What Makes up a (Multithreaded) Process?

- Thread of execution (sequence of instructions) on a CPU
  - Program counter — *per thread*
  - Registers — *per thread*
- Memory
  - Address space (code and data) — *process*
    - address space and physical memory assigned is shared
  - Stack — *per thread*
    - each thread has its own stack pointer
    - separately located in the address space
  - Heap — *process*
    + private dynamic memory — *per thread*
    - separately located in the address space
- I/O — *process*
  - Share files, sockets, …
- PCB — *process*
  - A thread lives in a process and uses the PCB

Single-Threaded vs. Multithreaded

- A normal process is a special case of a multithreaded process
  - A process that contains just one thread!
- A multithreaded process has multiple threads
  - Where do they live? How do they get created?



Why Multithreaded Applications?

- Multiple threads share a common address space
  - More correctly, they share process resources, including memory!
- Why would you want to do that?
- Concurrency!
  - How do you get concurrency?
  - One way is to create multiple processes
  - Use IPC to support process-level concurrency
  - Issues?
- 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

- Suppose we do not care if the OS to enforces resource separation
  - This is a trust issue, in part (back off on isolation / protection)
  - Will introduces issues with respect to concurrency … What kind?
- Improve responsiveness
  - Possible to have a thread of execution that just responds to events
- 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

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 the same address space
    - think about what state will be needed for a thread
  - Want something similar to *fork()* but simpler
    - supply a function when starting the new thread
  - Remember this creates another thread of execution

Can a thread call exec() to run a new program?

- Yes, but the results are often NOT what you want
- exec() replaces the entire current process image with a new program.
  - All previous code, data, heap, stack, and threads are destroyed.
  - All other threads are terminated immediately.
  - Only the thread that called exec() survives long enough to run the new program's entry point (main()).
  - The process doesn't become "multi-threaded" anymore — it becomes the new program, running in a single thread.

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

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
  - CPU state and stack
  - signal mask
  - thread-specific data
  - alternate signal stack
  - error return value
  - scheduling policy/priority
  - Linux-specific (e.g., CPU affinity)

thread state is small
versus
process state
(stored in PCB)

Thread Programming and Execution

- Every process is created with 1 "thread of execution"
  - Starts executing program at main()
- Additional threads are created using a threading programming library
  - A new "thread of execution" is create
  - Thread runs in the context of the process
  - Multiple threads can be created
- A process is "executing" when 1 or more of its threads are executing
- Suppose there are N threads and only 1 CPU
  - 1 thread can be running
  - what's going on with the other N-1 threads?

Kernel Threads

- There is thread management support in the OS
  - Kernel operations for executing process threads
  - Thread "objects" in the kernel to hold thread context
  - Called *kernel threads*
- A process thread must have a kernel thread to run
  - Kernel thread acts like an "execution container"
- Nearly all OSes support a notion of threads
  - Linux -- thread and process abstractions are mixed
  - Mac OS X, Windows XP, …

Something Subtle Going on Here (1)

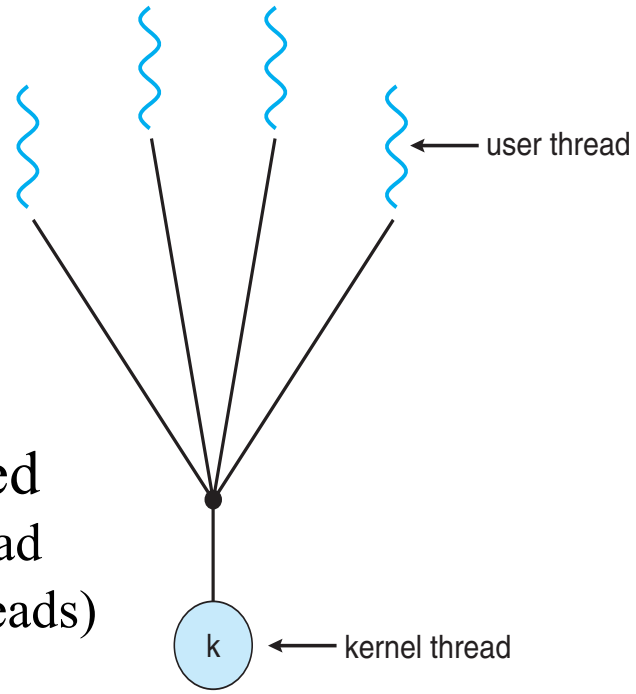
- A thread is just a (logical) unit of concurrency
  - It has a stack, a PC, a CPU state, and … that's it!
  - It is a "thread of execution" in the process code
- A thread can "execute" when it is assigned to a "resource" which is then scheduled on a CPU
  - That resource is a kernel thread
- Where is the thread when it is not executing?
  - Two parts
    - (user) thread control block (TCB) + kernel thread control block (KTCB)
  - Condition 1: no kernel thread assigned
    - Only TCB is saved in the memory of the process!
    - KTCB for that user thread does not exist.
  - Condition 2: kernel thread is currently assigned
    - TCB is saved in the memory of the process, AND
    - KTCB is saved in kernel memory space

Something Subtle Going on Here (2)

- In essence, ALL threads are process threads!
  - Called *user-level threads* to distinguish from kernel threads
- Kernel threads are just containers for user-level threads in order for them to execute
- There can be ***MANY*** more user-level threads than actual kernel threads … Why?
- They live "virtually" in the process until they are assigned a kernel thread and execute
  - User-level threads do not take up OS resources!
  - Only kernel threads do (in fact, they ARE the resources)
- Different models are used to assign user-level threads to kernel threads

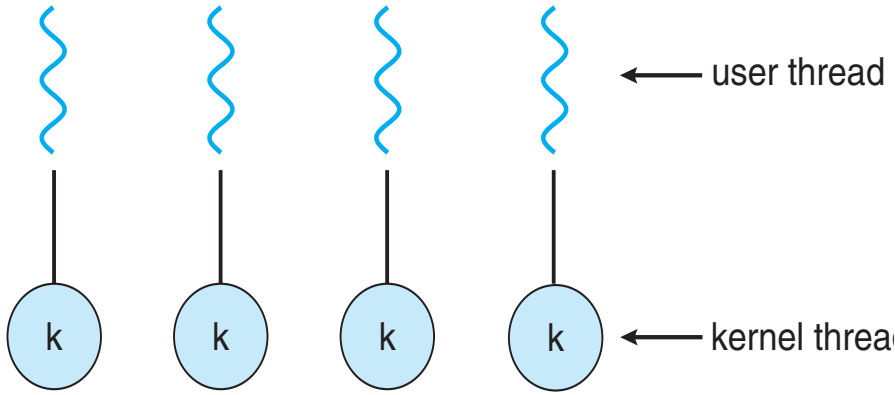
Many-to-One Thread Model

- Many user-level threads correspond to a *single* kernel thread
  - Kernel/OS is not aware of the mapping (OS only sees 1 thread)
  - Handled by a user-level thread library
- How does it work?
  - User-level thread library manages:
    - Create and execute a new thread
    - Maintain TCBs in process memory (user space)
    - Ready queue, waiting queues, etc.
    - Context switch between user-level threads
  - Upon yield, switch to another user thread in the same process
    - kernel is unaware
  - Upon wait (system calls), all threads are blocked
    - executing in kernel space by the single kernel thread
    - kernel is unaware there are other options (user threads)
    - cannot wait and run at the same time



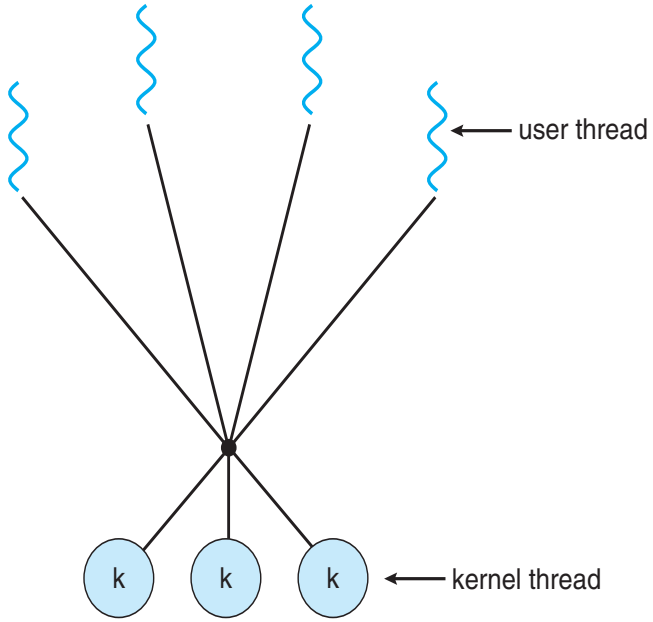
One-to-One Thread Model

- 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 user-level thread
- How does it work?
  - User-level thread library manages:
    - system call to kernel to create threads
    - provide user APIs
  - Upon yield, switch to another kernel thread in system
    - kernel is aware and handle context switch entirely
  - 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 set of user-level threads maps to a set of kernel threads
  - Sizes can be different (kernel set is no larger)
  - No need for the kernel to allocate resources for each new user-level thread
- How does it work?
  - User-level thread library manages:
    - map user threads to kernel thread dynamically
    - TCB, queues (same as N:1)
  - Upon yield, switch to another thread
    - User-level thread library does context switch
  - Upon wait, another thread in the process may run
    - if a kernel thread is available, user-level can assign a ready user thread to it



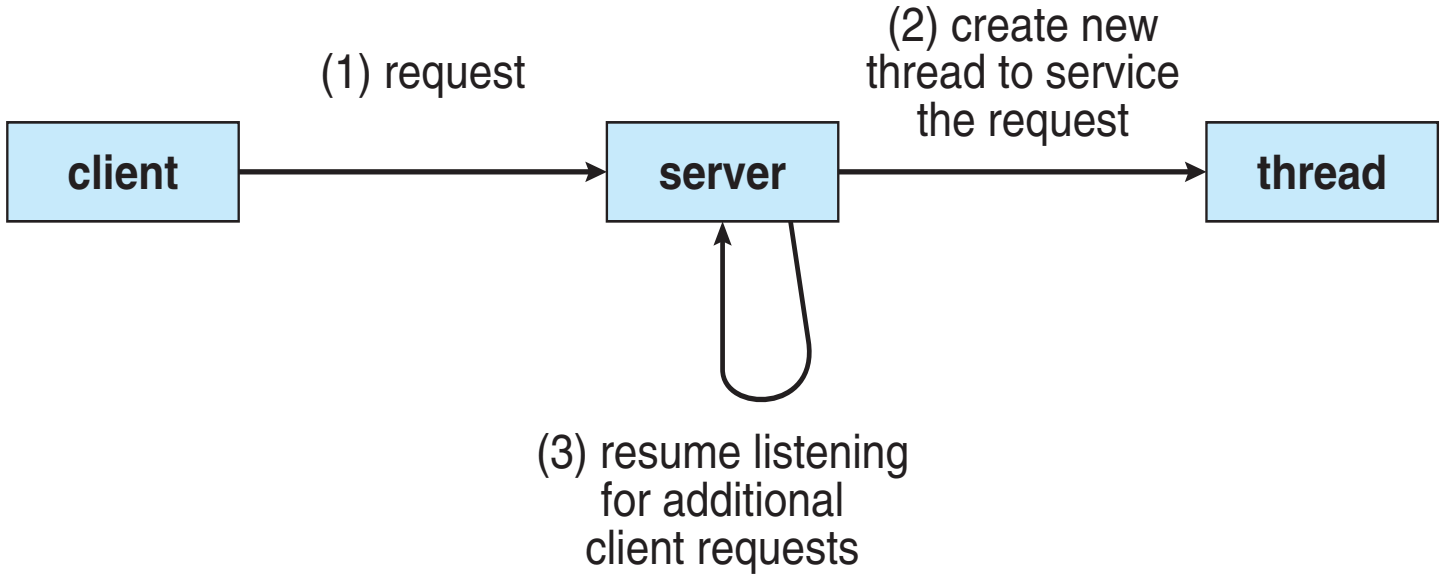
Thread Assignment

- How many kernel threads should a process have?
  - In an *M:N* model there can be significantly more user-level threads (*M*) than kernel-level threads (*N*)
  - Kernel threads are the "real" threads that can be allocated to a CPU (core) and run
  - Want to keep enough kernel threads to satisfy the desired level of concurrency in a program and activity in the system
- Suppose that all kernel threads except 1 are blocked
  - What happens if the last kernel thread blocks?
  - Does it matter if there are more user threads "ready" to run?
- In multiprocessing, *thread affinity* is the notion of assigning a thread to run on a particular CPU (core)
  - Help to improve the thread's performance by keeping its execution resources (CPU, cache, memory) local to CPU

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

Multithreaded Server Architecture



Linux Threads

- Linux uses a one-to-one thread model
  - Threads are called *tasks*
  - Limit (`cat /proc/sys/kernel/threads_max`)
- Linux views threads as "contexts of execution"
  - Threads are defined separately from processes
  - There is flexibility in what is private and shared
  - So, the line is blur in Linux implements
- Linux system call
  - *clone(int (*fn)(), void **stack, int flags, int argc, ...)*
  - Create a new thread (Linux task)
  - Start running at entry to *(*fn)()*
- 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
- *pthread_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: pthread_create()

- Interface
- *pthread_create(…)*
  - Thread ID {of the new thread}
    - set on return
  - Attributes {of the new thread}
    - stack size, scheduling information, etc.
  - Function {pointer}
    - start function for thread
  - Arguments {for function}
  - Return value, status {of the system call}

9

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);
}
```

Code for Creating/Joining 10 Threads

```
#define NUM_THREADS 10
/* declare "worker" threads*/
pthread_t workers[NUM_THREADS]

. . .

/* create "worker" threads */
for (int i=0; i<NUM_THREADS; i++)
  pthread_create(&(workers[i]), &attr, runner, argv[1]);

. . .

/* join "worker" threads, one by one *
for (int i=0; i<NUM_THREADS; i++)
  pthread_join(workers[i], NULL);
```

See code example pthread-simple.c

Who executes what?

- When your program starts
  - OS creates exactly one thread — called the main thread
  - Begins execution at the main() function
- All other threads created using pthread_create()
  - Execution at their own thread entry function
  - Not main()
- When main() function returns
  - Main thread exits
  - By default, the entire process terminates.
  - All other threads are also forcibly terminated, even if they are still running.
  - Exception: call pthread_exit instead of return in main() → other threads keep running

See code example
pthread-main-exit-all.c
Pthread-main-exit-keep-others.c

Meaning of "join" in Threading

- "join" in threading (as in pthread_join()), it means:
  - One thread waits for another thread to terminate before continuing.
  - Similar to wait() for processes
- Example: two workers
  - Worker A starts Worker B on a task.
  - Worker A then calls "join" on Worker B.
  - That means A waits until B finishes before A continues.
- By joining the target thread
  - Clean the target thread's resources (its stack and internal data)
  - Capture the return value of the target thread
- Any thread can call pthread_join() on another thread
  - Must be created in the same process
  - No other thread has already joined or detached it

See code example pthread-john.c

Meaning of "detach" in Threading

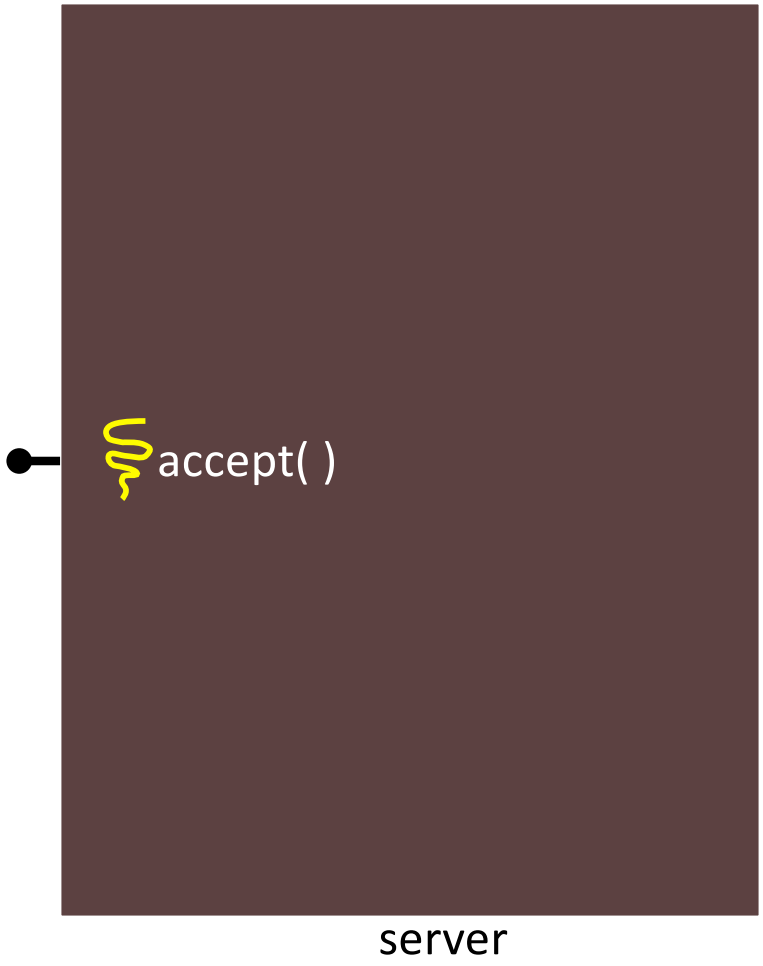
- When a thread is detached
  - The system will automatically reclaim its resources (stack, control block, etc.)
  - once the thread finishes — you don't need (and can't) call pthread_join() on it.
- **Joinable thread**: You must later pthread_join() it to clean it up.
- **Detached thread**: You cannot join it — it cleans itself up automatically.
- You detach a thread when:
  - You don't need to know when it finishes.
  - You don't need its return value.
  - You just want it to "run and go away" (fire-and-forget).
  - Typical for background tasks, logging, cleanup threads, etc.
- A thread can also detach itself!

See code example pthread-detach.c

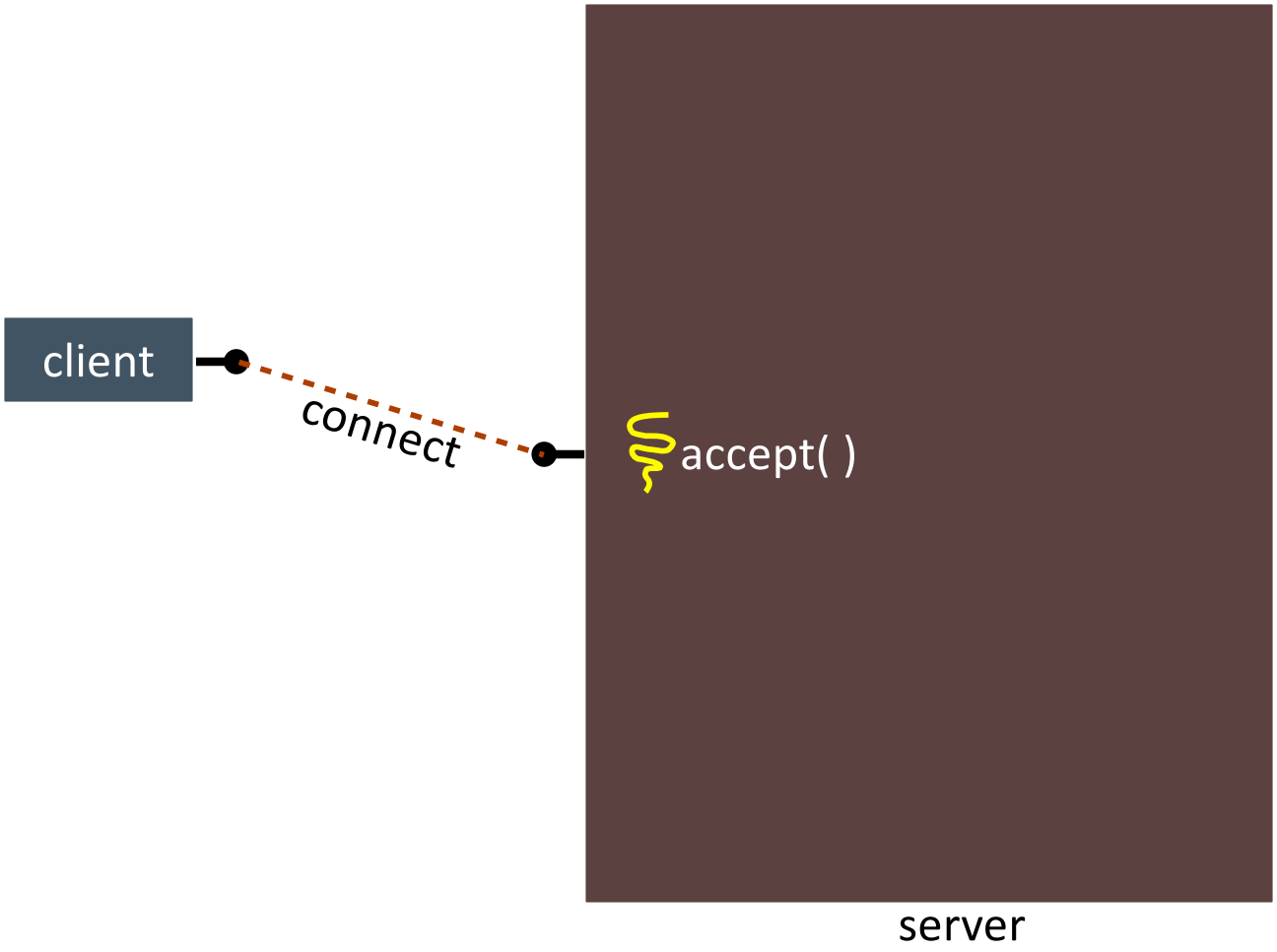
Concurrency with Threads

- 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

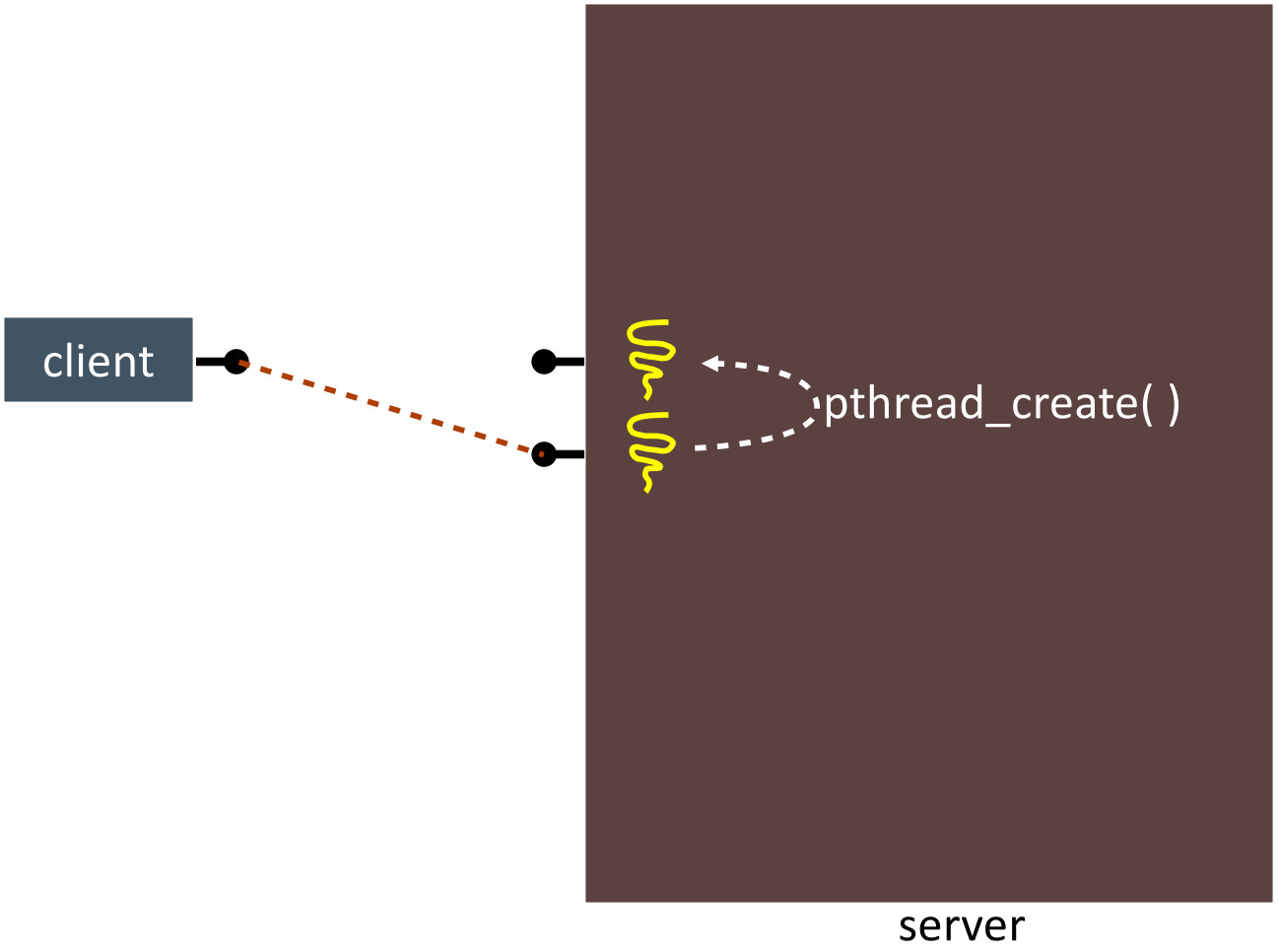
Client-Server with Pthreads (1)



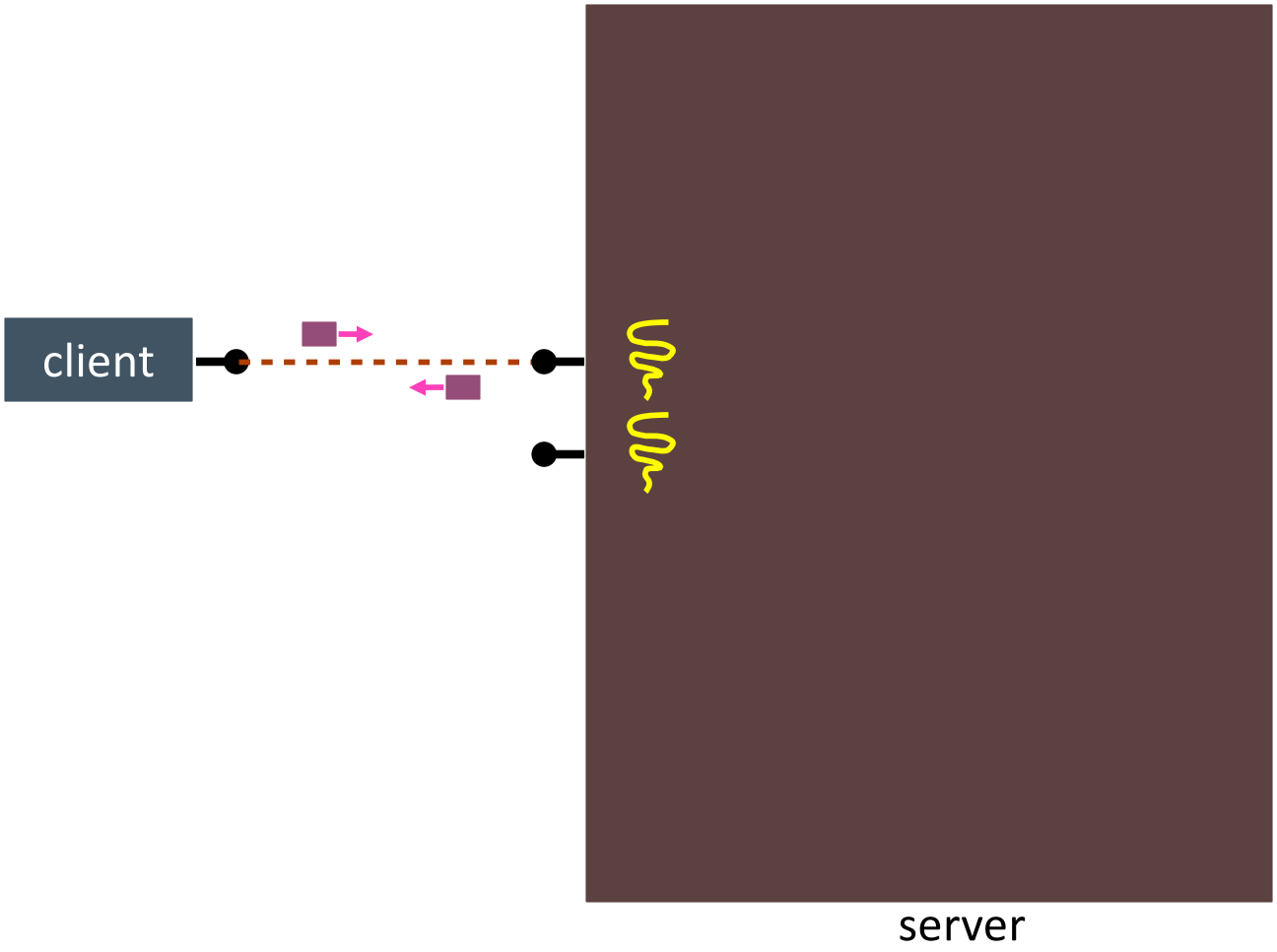
Client-Server with Pthreads (2)



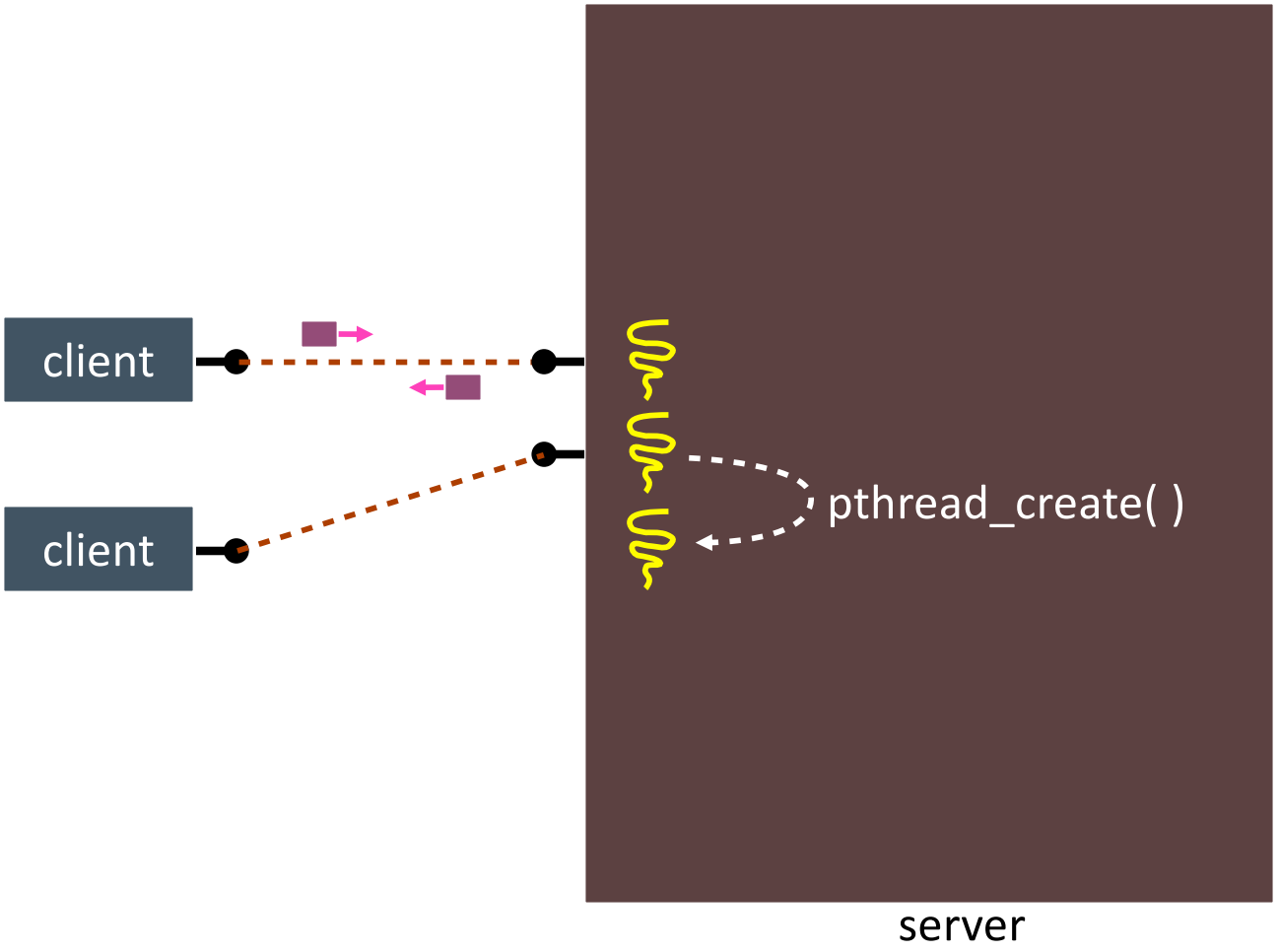
Client-Server with Pthreads (3)



Client-Server with Pthreads (4)

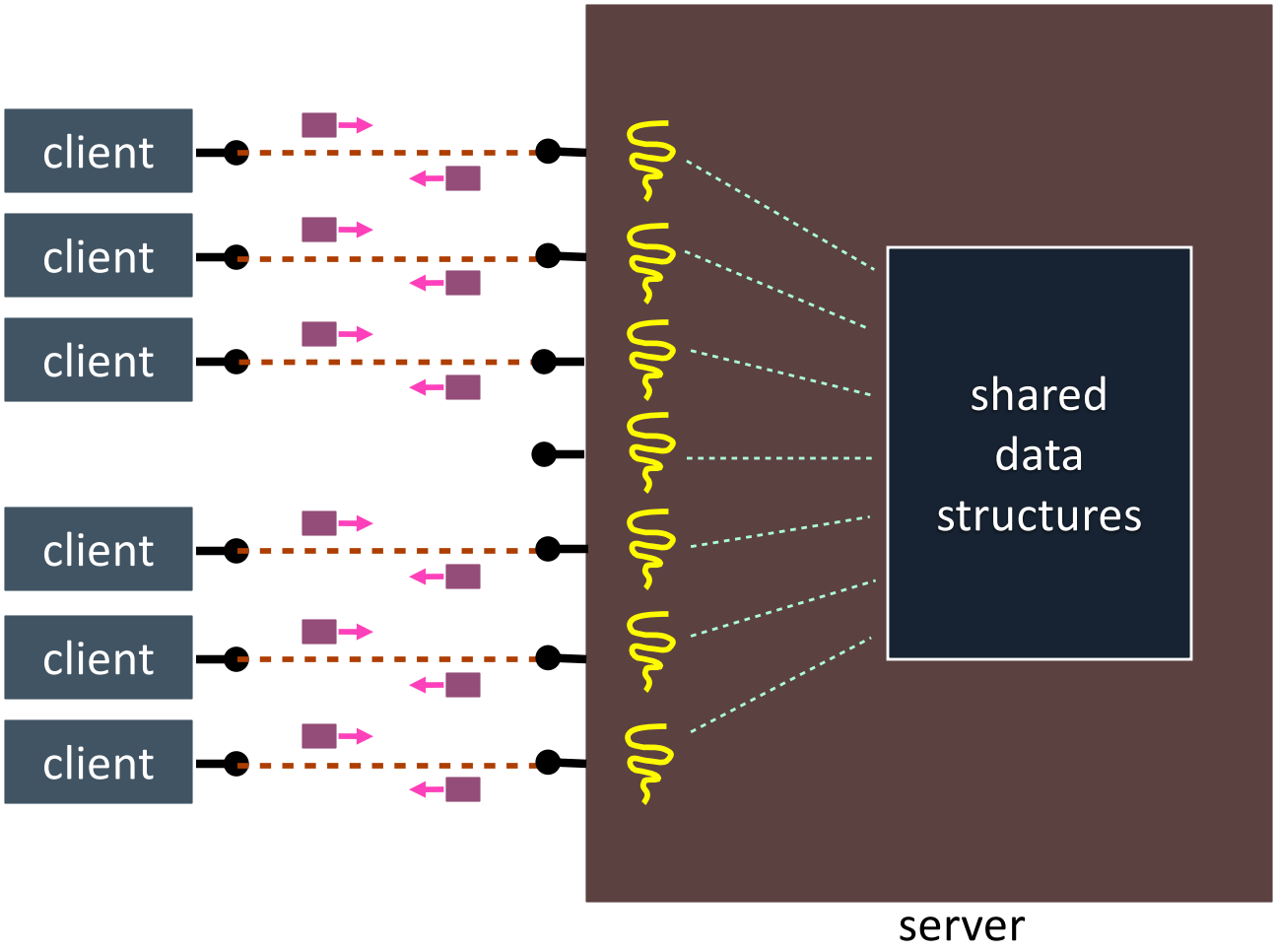


Client-Server with Pthreads (5)



Client-Server with Pthreads (5)

How is this different from processes?



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?

Contrasting Processes and Threads

- A process MUST have all necessary information for its execution stored in the OS (process context)
  - Stored in the PCB and takes space in the OS memory
- Each process has a default "thread of execution"
- All processes can execute independently
- A thread is part of (lives in) a process
- All threads in a process shared the process context
  - Each thread has a context: PC, stack, CPU state
- All threads are "user" threads in the sense that they have their own a PC and a stack
  - This requires very little storage
- For a thread to execute, it must be assigned to a "kernel" thread that will be managed by the OS
  - It can then be context switched (thread switch)

Compare Overhead of Processes and Threads

- Write a program to create N processes or threads

Processes

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/wait.h>

pid_t   pid;
int     status;

int main(int argc, char *argv[])
{
  int i, numprocesses;

  if(argc != 2) {
    fprintf(stderr, "USAGE: processes <INT>\n");
    exit(1);
  }

  numprocesses = atoi(argv[1]);          // # child processs to create

  for (i=0; i<numprocesses; i++) {
    pid = fork();
    if (pid == 0)                        // child process
      exit(0);                           // * immediate exits
    else                                 // parent process
      waitpid(pid, &status, 0);          // * waits for child process to exit
  };
  return 0;

}
```

Threads

```c
#include <stdlib.h>
#include <stdio.h>
#include <pthread.h>
#include <sys/time.h>
#include <unistd.h>

struct threadargs {
  int   id;
};
struct threadargs       threadARGS;

pthread_t       tid;                   // thread ID for publishers
pthread_attr_t  attr;                  // thread attributes
void            **retval;

void *routine(void *param);

void *routine(void *args) {
  int   tid;                           // thread id

  tid = ((struct threadargs *) args)->id;

} // routine


int main(int argc, char *argv[])
{
  int i, numthreads;

  if(argc != 2) {
    fprintf(stderr, "USAGE: threads <INT>\n");
    exit(1);
  }

  numthreads = atoi(argv[1]);          // # child threads to create

  for(i=0; i<numthreads; i++) {
    tid = i;
    pthread_create(&tid, &attr, routine, (void *) &threadARGS);
    pthread_join(tid,retval);
  }

} // main()
```

- Time for different N

★ **See program example**

Processes versus Threads Performance

```
ix 95% foreach i (1000 10000 100000 1000000)
foreach? echo Time the creation and shutdown of $i processes
foreach? time processes $i
foreach? echo Time the creation and shutdown of $i threads
foreach? time threads $i
foreach? end

Time the creation and shutdown of 1000 processes
0.209u 0.145s 0:00.33 103.0%    0+0k 46+0io 0pf+0w
Time the creation and shutdown of 1000 threads
0.000u 0.090s 0:00.08 112.5%    0+0k 48+0io 0pf+0w

Time the creation and shutdown of 10000 processes
2.233u 1.452s 0:03.49 105.4%    0+0k 6+0io 0pf+0w
Time the creation and shutdown of 10000 threads
0.086u 0.684s 0:00.67 113.4%    0+0k 8+0io 0pf+0w

Time the creation and shutdown of 100000 processes
22.277u 14.535s 0:35.22 104.4%  0+0k 6+0io 0pf+0w
Time the creation and shutdown of 100000 threads
0.633u 7.107s 0:06.85 112.8%    0+0k 8+0io 0pf+0w

Time the creation and shutdown of 1000000 processes
223.840u 144.968s 5:50.76 105.1%        0+0k 6+0io 0pf+0w
Time the creation and shutdown of 1000000 threads
6.392u 71.093s 1:08.34 113.3%   0+0k 8+0io 0pf+0w
```

N	Processes	Threads
1K	0.33 sec	0.08 sec
10K	3.49 sec	0.67 sec
100K	35.22 sec	6.85 sec
1M	5:50.75 sec	1:08.34 sec

Concurrent Threads

- All threads of a process are concurrent
- Benefits
  - All threads are running the same code (of the process)
  - Threads interact directly through shared memory
  - Lower overhead than processes
    - thread switching is faster
    - better utilization of the processor, especially with multiple cores
- Disadvantages
  - Maintaining shared memory consistency
    - synchronization is complicated (see later lecture)
  - One errant thread can affect the whole process
- More to come on this topic …

Thread Pools

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

- What about when a task is done?
  - Should we use terminate the thread executing it?
  - Suppose there is another task to run
  - Should we create another thread for this task?
- Concern for the time to create another thread
  - It is faster than setting up a process
  - But is it necessary?
- How could we improve performance?
  - Just have the current thread wait in a pool

Thread Interaction and 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 between threads?
  - Of course, there is nothing to prevent it
  - Would have to build messaging infrastructure to do it
    - likely would implement in shared memory
    - not really necessary to use OS mechanisms
- Hmm, can threads utilize IPC mechanisms
  - Certainly, if they were in different processes
  - Would need to make sure only 1 thread uses at a time to avoid consistency problems
  - Strange to use IPC for threads within the same process

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 (deferred) 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)*

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

Scheduler Activation

- It would be nice if the kernel told the application that a kernel thread was blocking
  - *Scheduler activation*
    - at thread block, the kernel tells the application via an *upcall*
    - an *upcall* is a general term for an invocation of application function from the kernel
  - User-level thread scheduler can then get a new user-level thread created
- Way of conveying information between the kernel and the user-level thread scheduler regarding the disposition of:
  - # user-level threads (increase or decrease)
  - User-level thread state
    - running to waiting, waiting to ready

Fork/Exec Issues

- Semantics are ambiguous for multithreaded processes
- *fork()*
  - How does it interact with threads?
  - Child process created with only 1 thread?

- *exec()*
  - What happens is process has more than 1 thread?
- *fork* then *exec*
  - Should all threads be copied?

Re-entrance and Thread-Safety

- *Re-entrant* code
  - Code that can be run by multiple threads concurrently
  - Can also be safely interrupted and called again ("re-entered") before the previous execution is finished
- *Thread-safe* libraries
  - Library code that permits multiple threads to invoke the safe function concurrently
  - Mainly concerned with variables that should be private to individual threads
  - Requires moving some global variables to local variables
- Requirements
  - Rely only on input data to the function or data that is already specific to a thread
    - can not (should not) use any shared data (e.g., global variables) that might be modified by a thread executing the function
  - Must be careful about locking (see later lectures)

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…
- UNIX signal model created decades before Pthreads standard
  - Conflicts arise as a result

Why not threads?

- Threads can interfere with one another
  - Need to be careful to maintain consistency
  - Impact of more threads on memory and caches
  - Bug in one thread can cause process problems
- Executing multiple threads may slow them down
  - Impact of single thread vs. switching among threads
- Harder to program a multi-threaded program
  - Multitasking hides context switching
  - Multi-threading 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
- Threads are useful, but not always the right solution
  - Could slow down system in some cases
  - Can be difficult to program
- Multiprogramming and multithreading are important concepts in modern operating systems

Next Class

- Scheduling