CS 153
Design of Operating Systems

Winter 2016

Lecture 6: Threads

Recap: Process Components

- A process is named using its process ID (PID)
- A process contains all of the state for a program in execution

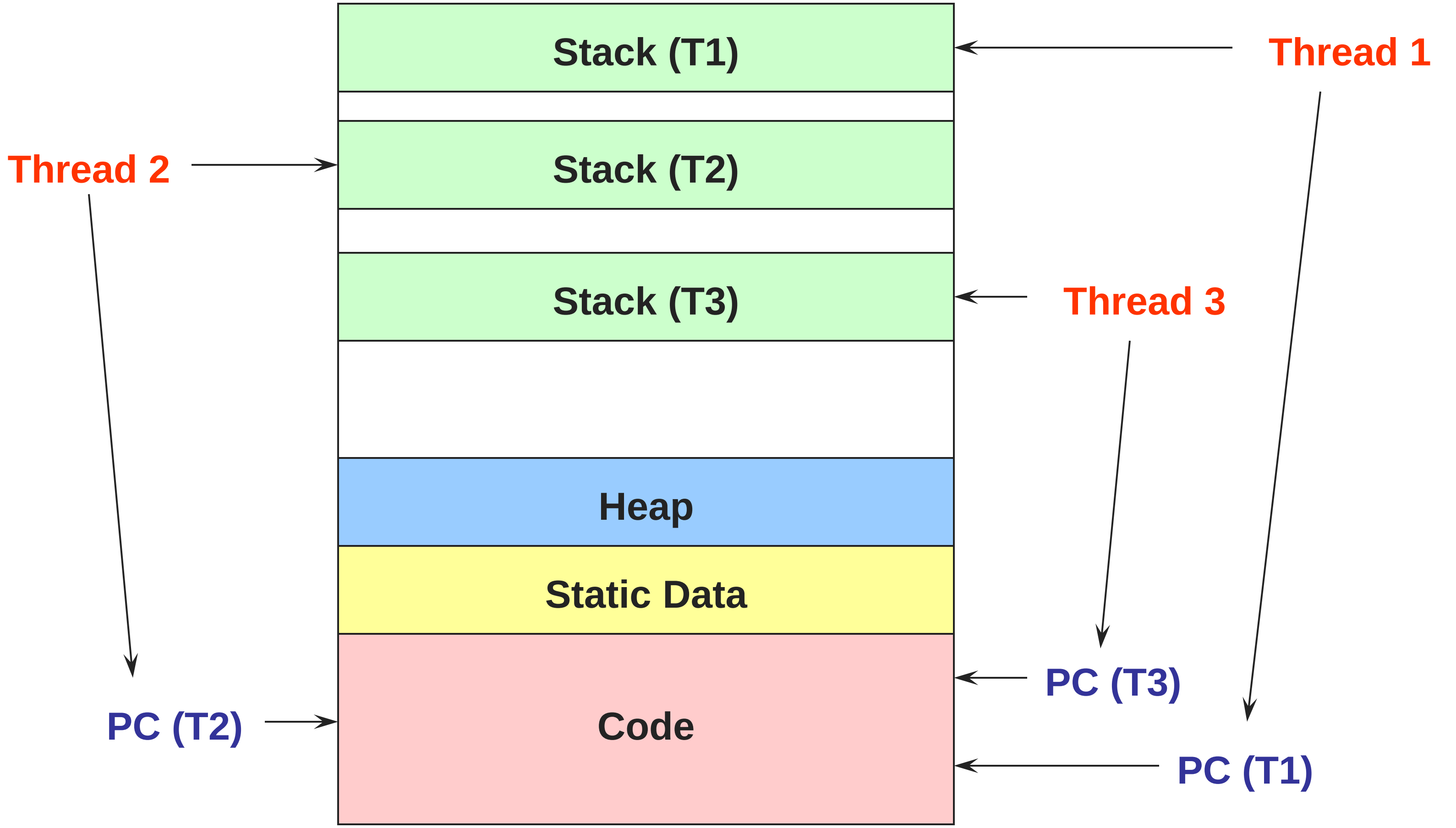
Per-Process State

- An address space
- The code for the executing program
- The data for the executing program
- A set of operating system resources
  - » Open files, network connections, etc.

Per-Thread State

- An execution stack encapsulating the state of procedure calls
- The program counter (PC) indicating the next instruction
- A set of general-purpose registers with current values
- Current execution state (Ready/Running/Waiting)

Threads in a Process



Process/Thread Separation

- Separating threads and processes makes it easier to support multithreaded applications
  - Concurrency does not require creating new processes
- Concurrency (multithreading) can be very useful
  - Improving program structure
  - Handling concurrent events (e.g., Web requests)
  - Writing parallel programs
- So multithreading is even useful on a uniprocessor

Threads: Concurrent Servers

- Using fork() to create new processes to handle requests in parallel is overkill for such a simple task
- Recall our forking Web server:

```
while (1) {
  int sock = accept();
  if ((child_pid = fork()) == 0) {
    Handle client request
    Close socket and exit
  } else {
    Close socket
  }
}
```

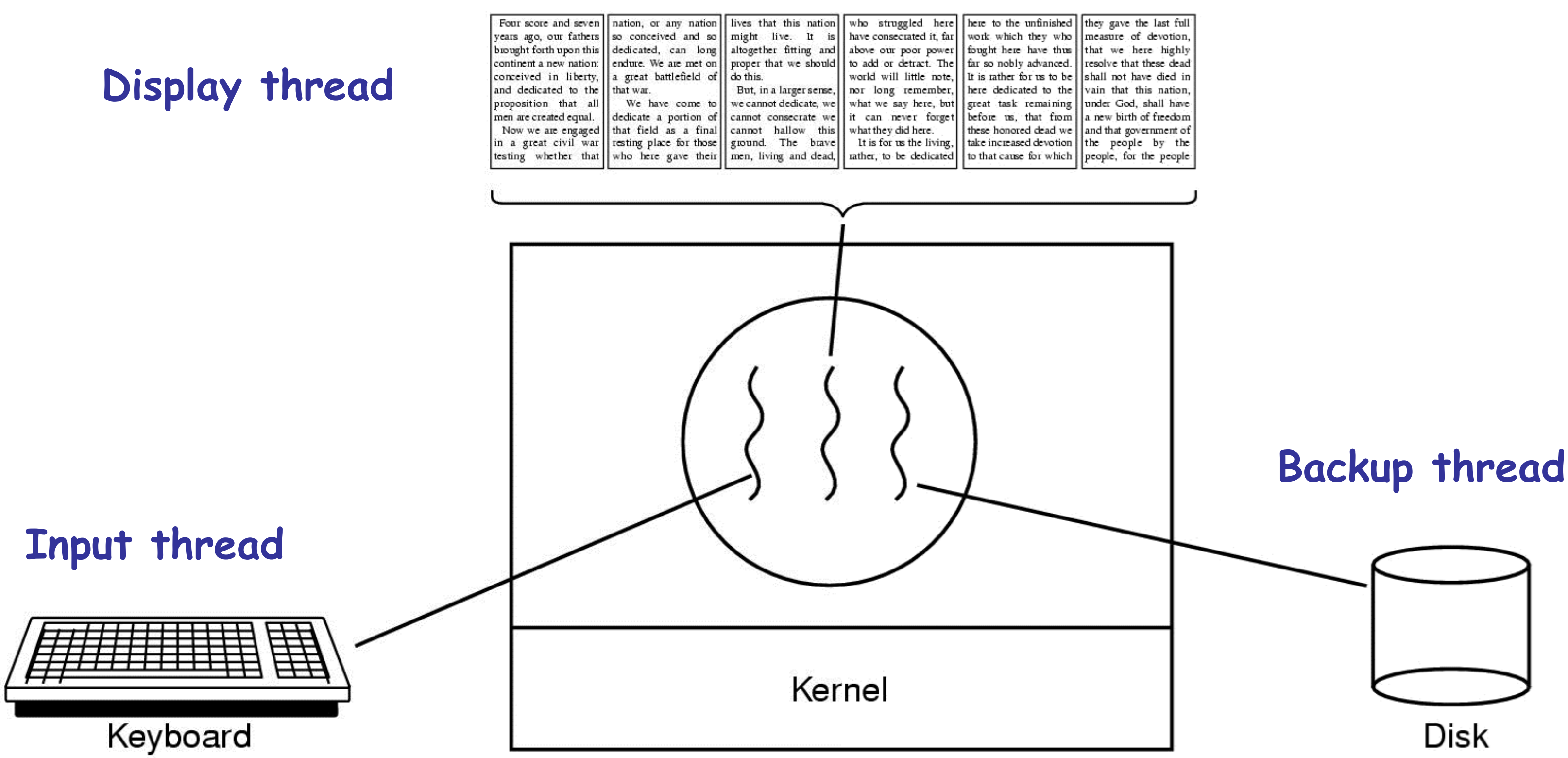
Threads: Concurrent Servers

- Instead, we can create a new thread for each request

```
web_server() {
   while (1) {
     int sock = accept();
     thread_fork(handle_request, sock);
   }
}

handle_request(int sock) {
     Process request
     close(sock);
}
```

A Word Process w/3 Threads



Kernel-Level Threads

- We have taken the execution aspect of a process and separated it out into threads
  - To make concurrency cheaper
- As such, the OS now manages threads *and* processes
  - All thread operations are implemented in the kernel
  - The OS schedules all of the threads in the system
- OS-managed threads are called kernel-level threads or lightweight processes
  - Windows: threads
  - Solaris: lightweight processes (LWP)
  - POSIX Threads (pthreads): PTHREAD_SCOPE_SYSTEM

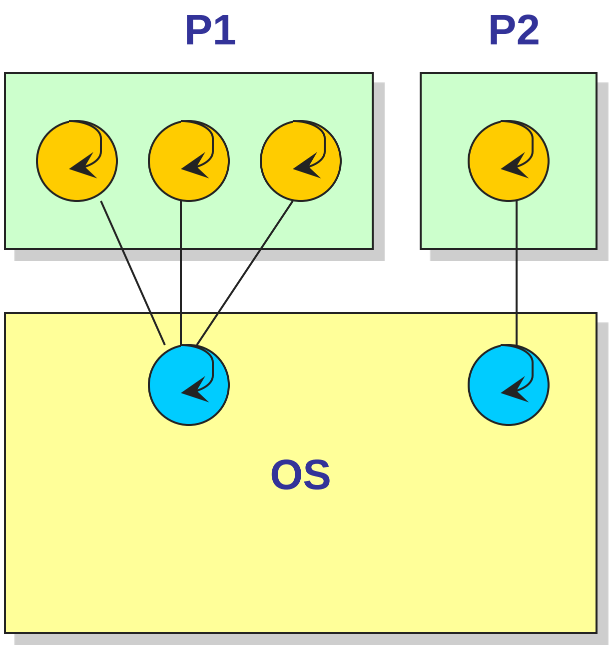
Kernel Thread Limitations

- Kernel-level threads make concurrency much cheaper than processes
  - Much less state to allocate and initialize
- However, for fine-grained concurrency, kernel-level threads still suffer from too much overhead
  - Thread operations still require system calls
    - » Ideally, want thread operations to be as fast as a procedure call
  - Kernel-level threads have to be general to support the needs of all programmers, languages, runtimes, etc.
- For such fine-grained concurrency, need even "cheaper" threads

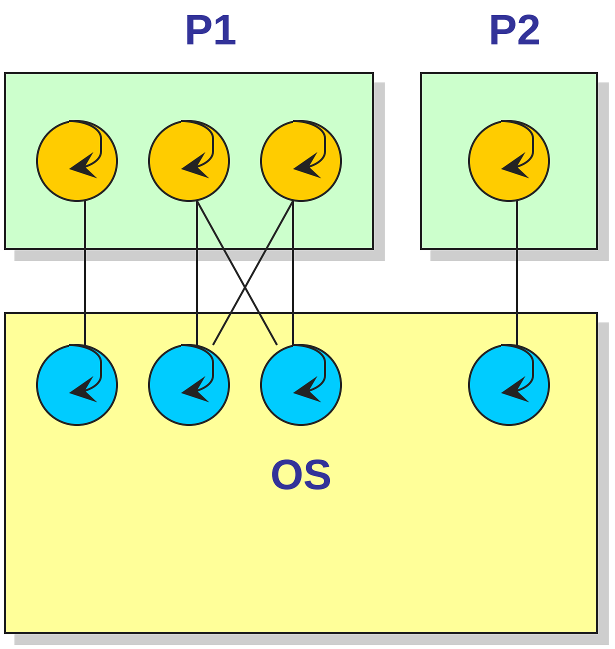
User-Level Threads

- To make threads cheap and fast, they need to be implemented at user level
  - Kernel-level threads are managed by the OS
  - User-level threads are managed entirely by the run-time system (user-level library)
- User-level threads are small and fast
  - A thread is simply represented by a PC, registers, stack, and small thread control block (TCB)
  - Creating a new thread, switching between threads, and synchronizing threads are done via procedure call
    - » No kernel involvement
  - User-level thread operations 100x faster than kernel threads
  - pthreads: PTHREAD_SCOPE_PROCESS

User and Kernel Threads



Multiplexing user-level threads on a single kernel thread for each process



Multiplexing user-level threads on multiple kernel threads for each process

U/L Thread Limitations

- But, user-level threads are not a perfect solution
  - As with everything else, they are a tradeoff
- User-level threads are invisible to the OS
  - They are not well integrated with the OS
- As a result, the OS can make poor decisions
  - Scheduling a process with idle threads
  - Blocking a process whose thread initiated an I/O, even though the process has other threads that can execute
  - Unscheduling a process with a thread holding a lock
- Solving this requires communication between the kernel and the user-level thread manager

Kernel vs. User Threads

- Kernel-level threads
  - Integrated with OS (informed scheduling)
  - Slow to create, manipulate, synchronize
- User-level threads
  - Fast to create, manipulate, synchronize
  - Not integrated with OS (uninformed scheduling)
- Understanding the differences between kernel and user-level threads is important
  - For programming (correctness, performance)
  - For test-taking

Implementing Threads

- Implementing threads has a number of issues
  - Interface
  - Context switch
  - Preemptive vs. non-preemptive
  - Scheduling
  - Synchronization (next lecture)
- Focus on kernel-level threads
  - What you will be dealing with in Pintos
  - Not only will you be *using* threads in Pintos, you will be *implementing* more thread functionality (e.g., sleep)

Sample Thread Interface

- thread_fork(procedure_t)
  - Create a new thread of control
  - Also thread_create(), thread_setstate()
- thread_stop()
  - Stop the calling thread; also thread_block
- thread_start(thread_t)
  - Start the given thread
- thread_yield()
  - Voluntarily give up the processor
- thread_exit()
  - Terminate the calling thread; also thread_destroy
- Where are they called? User-space or kernel-space?

Thread Scheduling

- The thread scheduler determines when a thread runs
- It uses queues to keep track of what threads are doing
  - Just like the OS and processes
  - Implemented at user-level in a library for user-level threads
- Run queue: Threads currently running (usually one)
- Ready queue: Threads ready to run
- Are there wait queues?
  - How would you implement thread_sleep(time)?

Non-Preemptive Scheduling

- Threads voluntarily give up the CPU with thread_yield

Ping Thread

```
while (1) {
    printf("ping\n");
    thread_yield();
}
```

Pong Thread

```
while (1) {
    printf("pong\n");
    thread_yield();
}
```

- What is the output of running these two threads?

thread_yield()

- The semantics of thread_yield are that it gives up the CPU to another thread
  - In other words, it context switches to another thread
- So what does it mean for thread_yield to return?
- Execution trace of ping/pong
  - printf("ping\n");
  - thread_yield();
  - printf("pong\n");
  - thread_yield();
  - …

Implementing thread_yield() (PintOS hint)

```
thread_yield() {
   thread_t old_thread = current_thread;
   current_thread = get_next_thread();
   append_to_queue(ready_queue, old_thread);
   context_switch(old_thread, current_thread);
   return;
}
```

As old thread

As new thread

- The magic step is invoking context_switch()
- Why do we need to call append_to_queue()?

Thread Context Switch

- The context switch routine does all of the magic
  - Saves context of the currently running thread (old_thread)
  - Restores context of the next thread
  - The next thread becomes the current thread
  - Return to caller as new thread
  - In Pintos, it is the *switch_threads()* in switch.S
- This is all done in assembly language
  - It works at the level of the procedure calling convention, so it cannot be implemented using procedure calls

Preemptive Scheduling

- Non-preemptive threads have to voluntarily give up CPU
  - A long-running thread will take over the machine
  - Only voluntary calls to thread_yield(), thread_stop(), or thread_exit() causes a context switch

- Preemptive scheduling causes an involuntary context switch
  - Need to regain control of processor asynchronously
  - Use timer interrupt (How do you do this?)
  - Timer interrupt handler forces current thread to "call" thread_yield

Threads Summary

- Processes are too heavyweight for multiprocessing
  - Time and space overhead
- Solution is to separate threads from processes
  - Kernel-level threads much better, but still significant overhead
  - User-level threads even better, but not well integrated with OS
- Scheduling of threads can be either preemptive or non-preemptive

- Now, how do we get our threads to correctly cooperate with each other?
  - Synchronization…

Next time…

- Read
  - Chapter 5.1—5.3 in book