CSE 120
Principles of Operating Systems

Spring 2016

Lecture 4: Threads

Processes

- Recall that a process includes many things
  - An address space (defining all the code and data pages)
  - OS resources (e.g., open files) and accounting information
  - Execution state (PC, SP, regs, etc.)
- Creating a new process is costly because of all of the data structures that must be allocated and initialized
  - Recall struct proc in Solaris
  - …which does not even include page tables, perhaps TLB flushing, etc.
- Communicating between processes is costly because most communication goes through the OS
  - Overhead of system calls and copying data

Concurrent Programs

- Recall our Web server example that forks off copies of itself to handle multiple simultaneous requests
  - Or any parallel program that executes on a multiprocessor
- To execute these programs we need to
  - Create several processes that execute in parallel
  - Cause each to map to the same address space to share data
    - » They are all part of the same computation
  - Have the OS schedule these processes in parallel (logically or physically)
- This situation is very inefficient
  - Space: PCB, page tables, etc.
  - Time: create data structures, fork and copy addr space, etc.

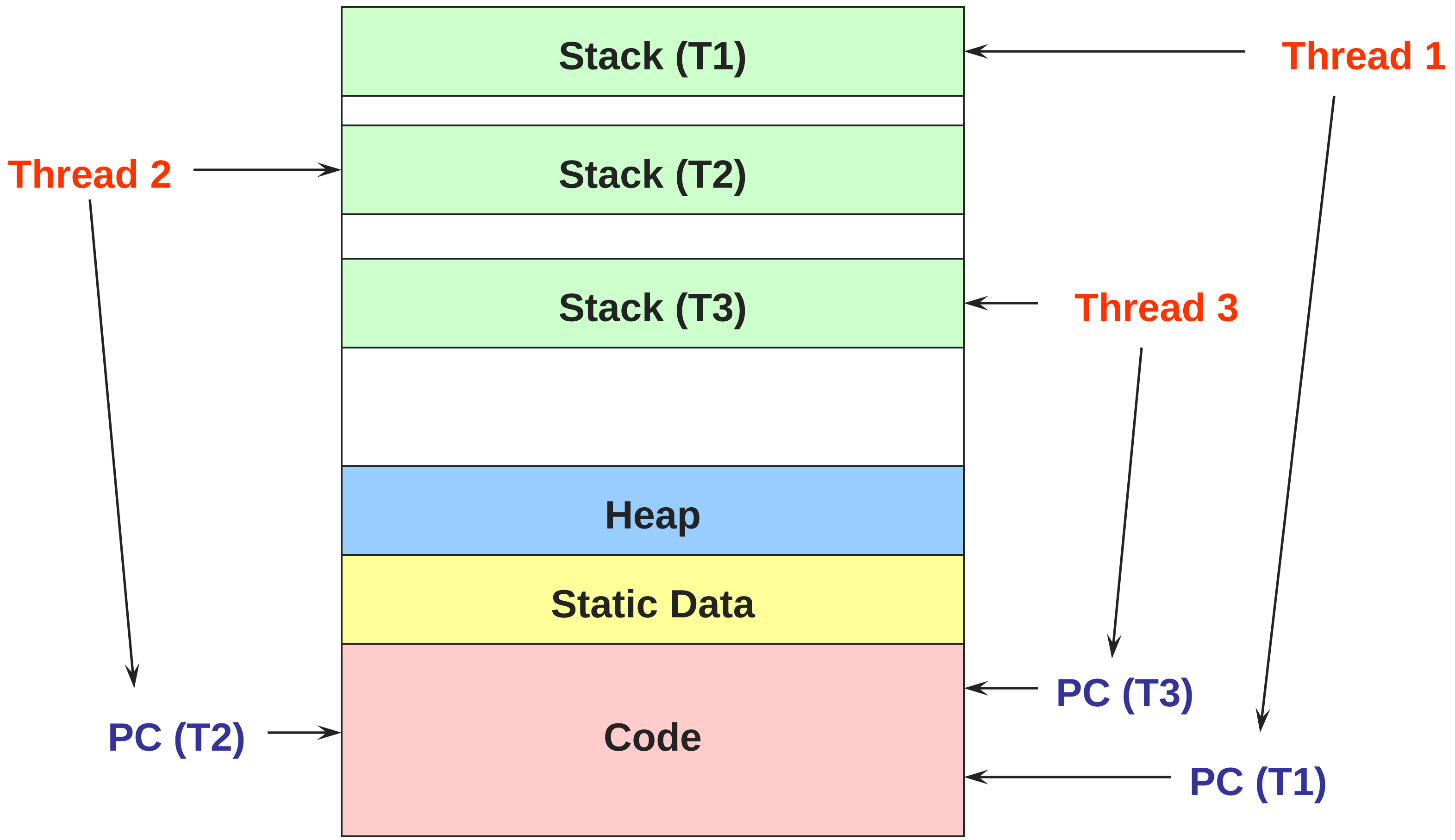
Rethinking Processes

- What is similar in these cooperating processes?
  - They all share the same code and data (address space)
  - They all share the same privileges
  - They all share the same resources (files, sockets, etc.)
- What don't they share?
  - Each has its own execution state: PC, SP, and registers
- Key idea: Why don't we separate the concept of a process from its execution state?
  - Process: address space, privileges, resources, etc.
  - Execution state: PC, SP, registers
- Exec state also called thread of control, or thread

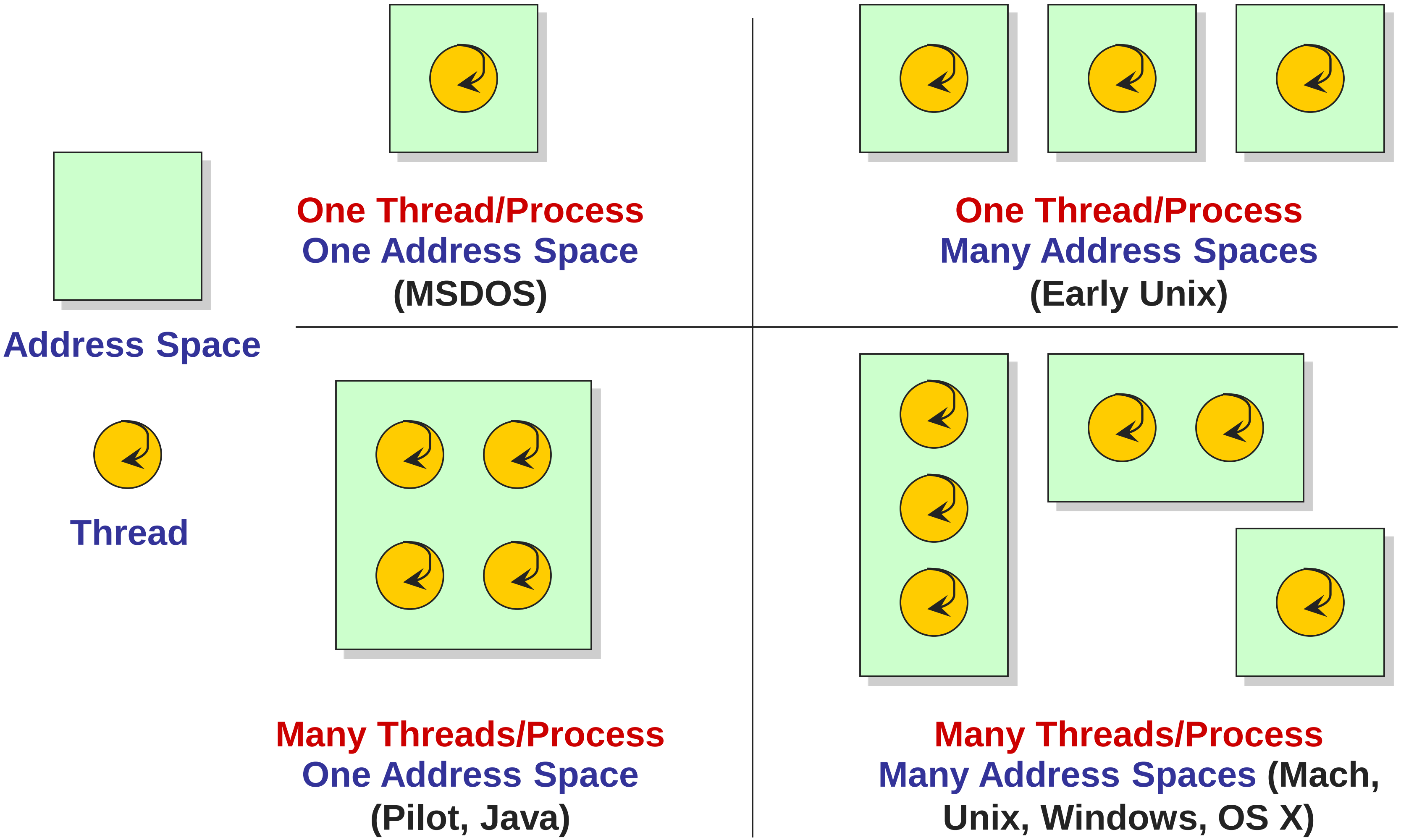
Threads

- Modern OSes (Windows, Unix, OS X) separate the concepts of processes and threads
  - The thread defines a sequential execution stream within a process (PC, SP, registers)
  - The process defines the address space and general process attributes (everything but threads of execution)
- A thread is bound to a single process
  - Processes, however, can have multiple threads
- Threads become the unit of scheduling
  - Processes are now the containers in which threads execute
  - Processes become static, threads are the dynamic entities

Threads in a Process



Thread Design Space



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
  - Although today even cell phones are multicore

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);
}
```

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 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

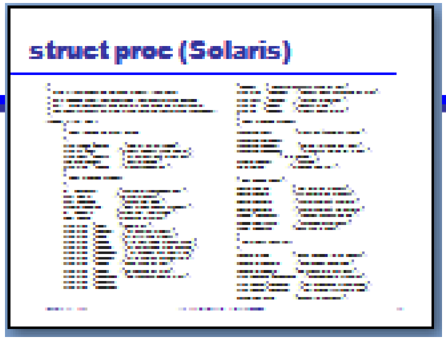
User-Level Threads

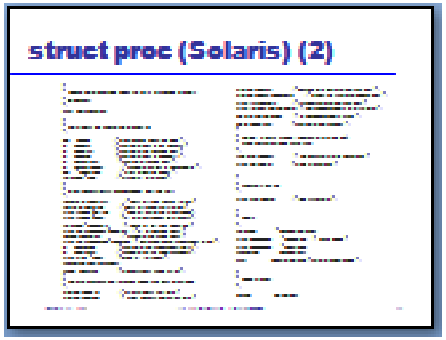
- To make threads cheap and fast, they need to be implemented at user level
  - Kernel-level threads are managed by the OS
  - User-level threads are managed entirely by the run-time system (user-level library)
- User-level threads are small and fast
  - A thread is simply represented by a PC, registers, 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

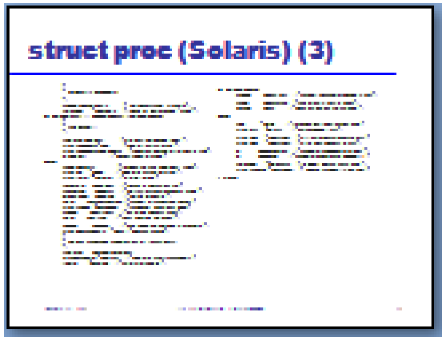
Small and Fast...

- Nachos thread class

```
public class KThread {
    int status;
    String name;
    Runnable target;
    TCB tcb;
    int id;
    <Methods>
};
```







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

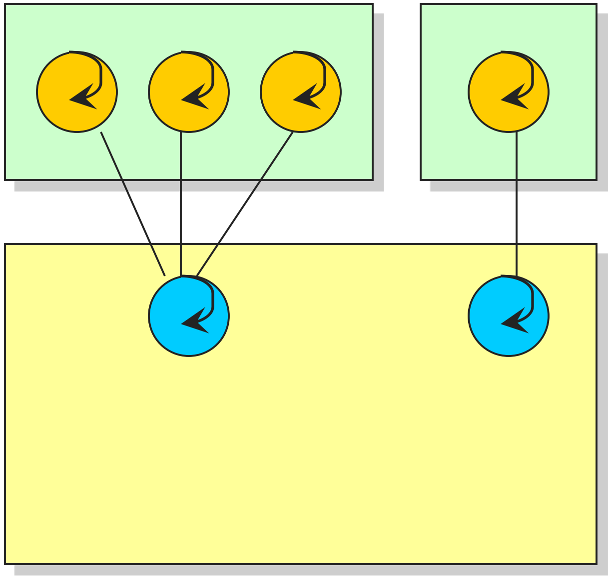
Kernel vs. User Threads

- Kernel-level threads
  - Integrated with OS (informed scheduling)
  - Slower to create, manipulate, synchronize
- User-level threads
  - Faster 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

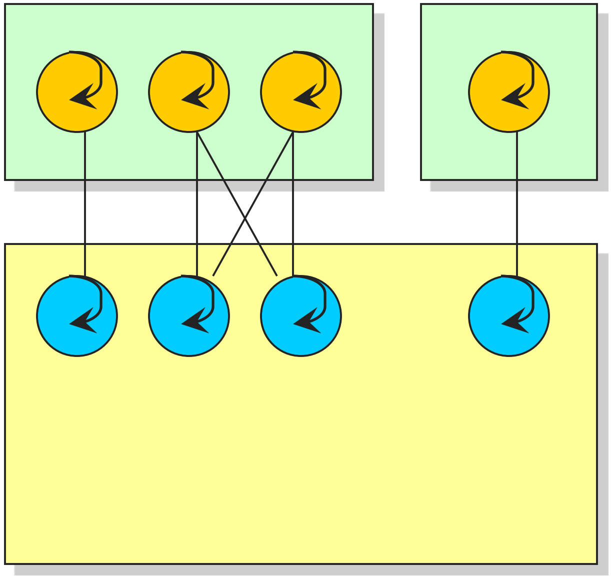
Kernel and User Threads

- Or use both kernel and user-level threads
  - Can associate a user-level thread with a kernel-level thread
  - Or, multiplex user-level threads on top of kernel-level threads
- Java Virtual Machine (JVM) (also C#)
  - Java threads are user-level threads
  - On older Unix, only one "kernel thread" per process
    - » Multiplex all Java threads on this one kernel thread
  - On modern OSes
    - » Can multiplex Java threads on multiple kernel threads
    - » Can have more Java threads than kernel threads
    - » Why?

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

Implementing Threads

- Implementing threads has a number of issues
  - Interface
  - Context switch
  - Preemptive vs. non-preemptive
  - Scheduling
  - Synchronization (next lecture)
- Focus on user-level threads
  - Kernel-level threads are similar to original process management and implementation in the OS
  - What you will be dealing with in Nachos
  - Not only will you be *using* threads in Nachos, you will be *implementing* more thread functionality

Sample Thread Interface

- thread_fork(procedure_t) [KThread::fork]
  - Create a new thread of control
  - Also thread_create(), thread_setstate()
- thread_stop() [KThread::sleep]
  - Stop the calling thread; also thread_block
- thread_start(thread_t) [KThread::ready]
  - Start the given thread
- thread_yield() [KThread::yield]
  - Voluntarily give up the processor
- thread_exit() [KThread::finish]
  - Terminate the calling thread; also thread_destroy

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
  - But it is implemented at user-level in a library
- 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()

- Wait a second. How does thread_yield() work?
- 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?
  - It means that *another thread* called thread_yield!
- Execution trace of ping/pong
  - printf("ping\n");
  - thread_yield();
  - printf("pong\n");
  - thread_yield();
  - …

Implementing thread_yield()

```
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)
    - » Push all machine state onto its stack
  - Restores context of the next thread
    - » Pop all machine state from the next thread's stack
  - The next thread becomes the current thread
  - Return to caller as new thread
- 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
  - Timer interrupt handler forces current thread to “call” thread_yield
    - » How do you do this?

Threads Summary

- The operating system as a large multithreaded program
  - Each process executes as a thread within the OS
- Multithreading is also very useful for applications
  - Efficient multithreading requires fast primitives
  - Processes are too heavyweight
- 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
- Now, how do we get our threads to correctly cooperate with each other?
  - Synchronization…

Next time...

- Read Chapters 28, 29