

CSE 120
**Principles of Operating
Systems**

Spring 2017

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.

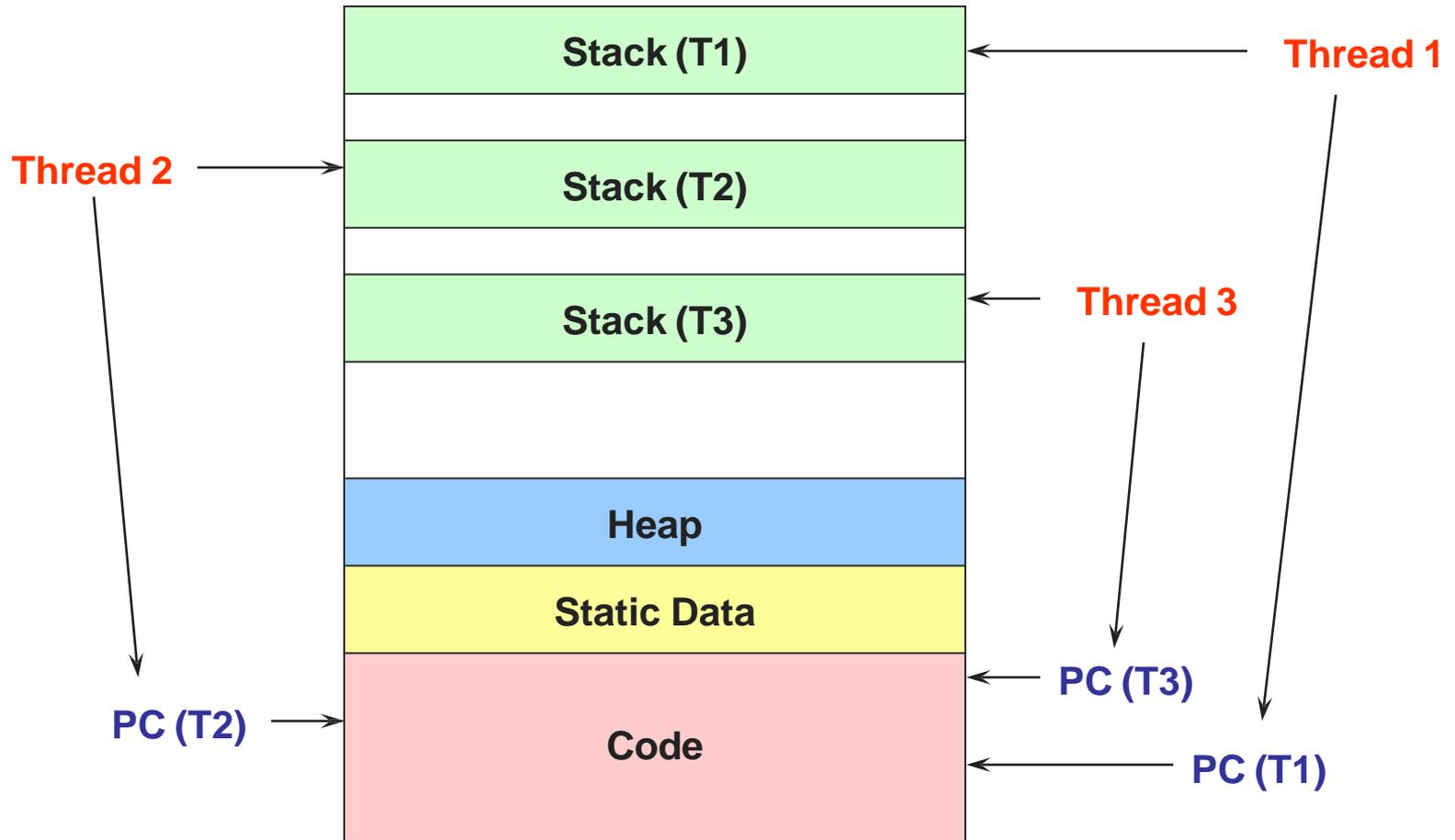
Rethinking Processes

- 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**

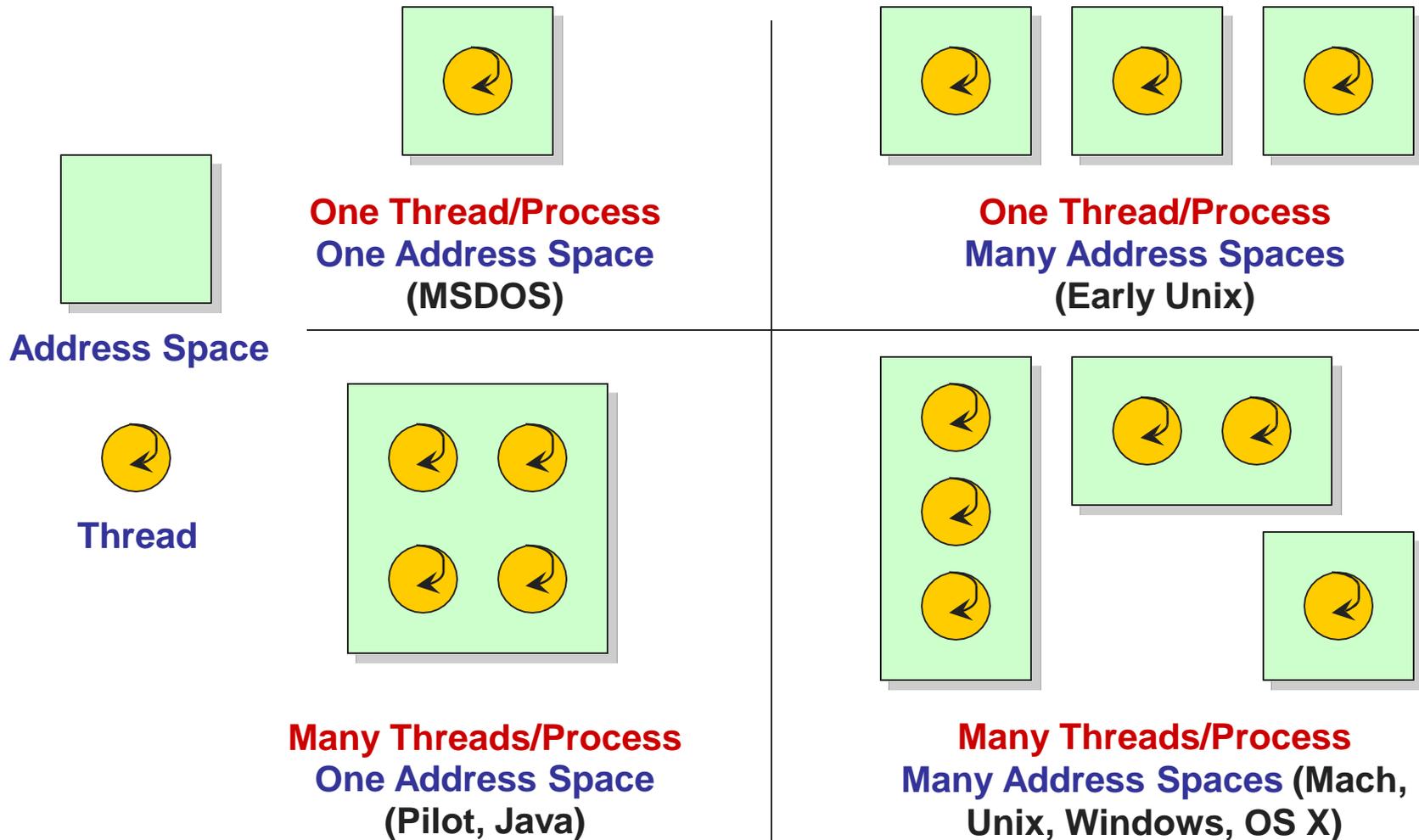
Threads

- 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

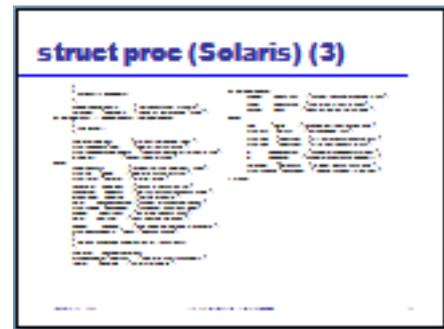
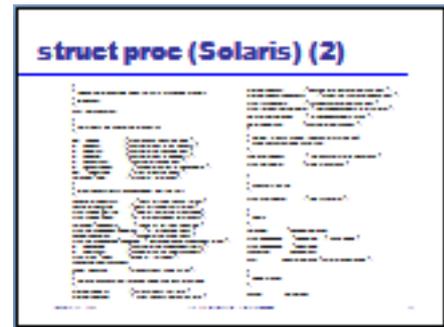
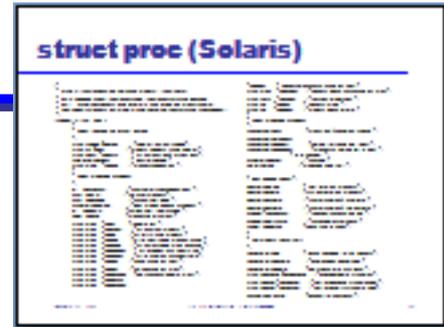
User-Level Threads

- 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

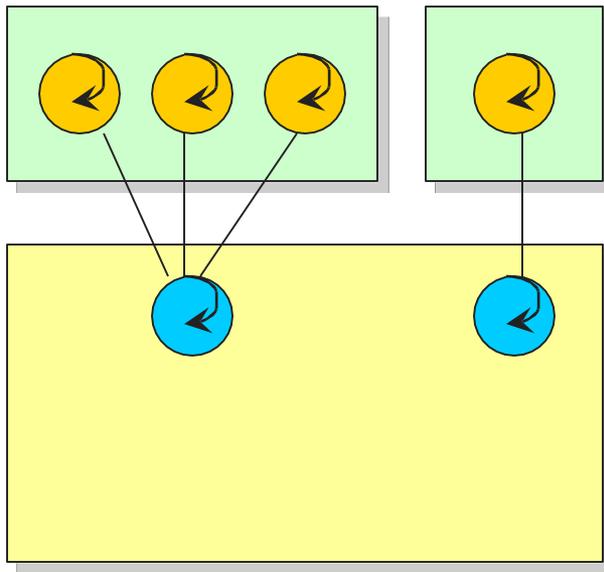
Kernel vs. User Threads

- 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

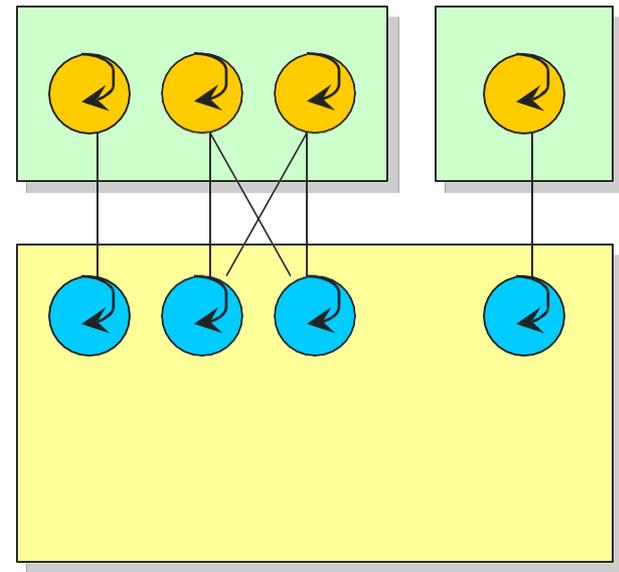
Kernel and User Threads

- 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...

















