CS 153
Design of Operating Systems

Fall 19

Lecture 6: Threads

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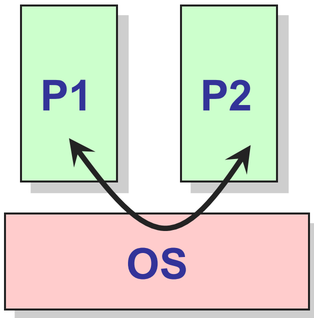
Processes



- Recall that …
  - A process includes:
    - » An address space (defining all the code and data pages)
    - » OS resources (e.g., open files) and accounting info
    - » Execution state (PC, SP, regs, etc.)
    - » PCB to keep track of everything
  - Processes are completely isolated from each other

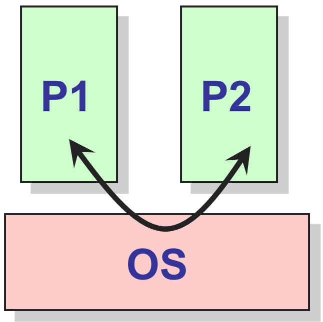
Process: check your understanding

- What are the units of execution?
  - Processes
- How are those units of execution represented?
  - Process Control Blocks (PCBs)
- How is work scheduled in the CPU?
  - Process states, process queues, context switches
- What are the possible execution states of a process?
  - Running, ready, waiting, …
- How does a process move from one state to another?
  - Scheduling, I/O, creation, termination
- How are processes created?
  - CreateProcess (NT), fork/exec (Unix)

Some issues with processes

- Creating a new process is costly because of new address space and data structures that must be allocated and initialized
  - Recall struct proc in xv6 or Solaris

- Communicating between processes is costly because most communication goes through the OS
  - Inter Process Communication (IPC) – we will discuss later
  - Overhead of system calls and copying data



Parallel Programs

- Also recall our web server example that forks off copies of itself to handle multiple simultaneous requests
- 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
- This situation is very inefficient (CoW helps)
  - 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: Separate resources from execution state
- Exec state also called thread of control, or thread

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

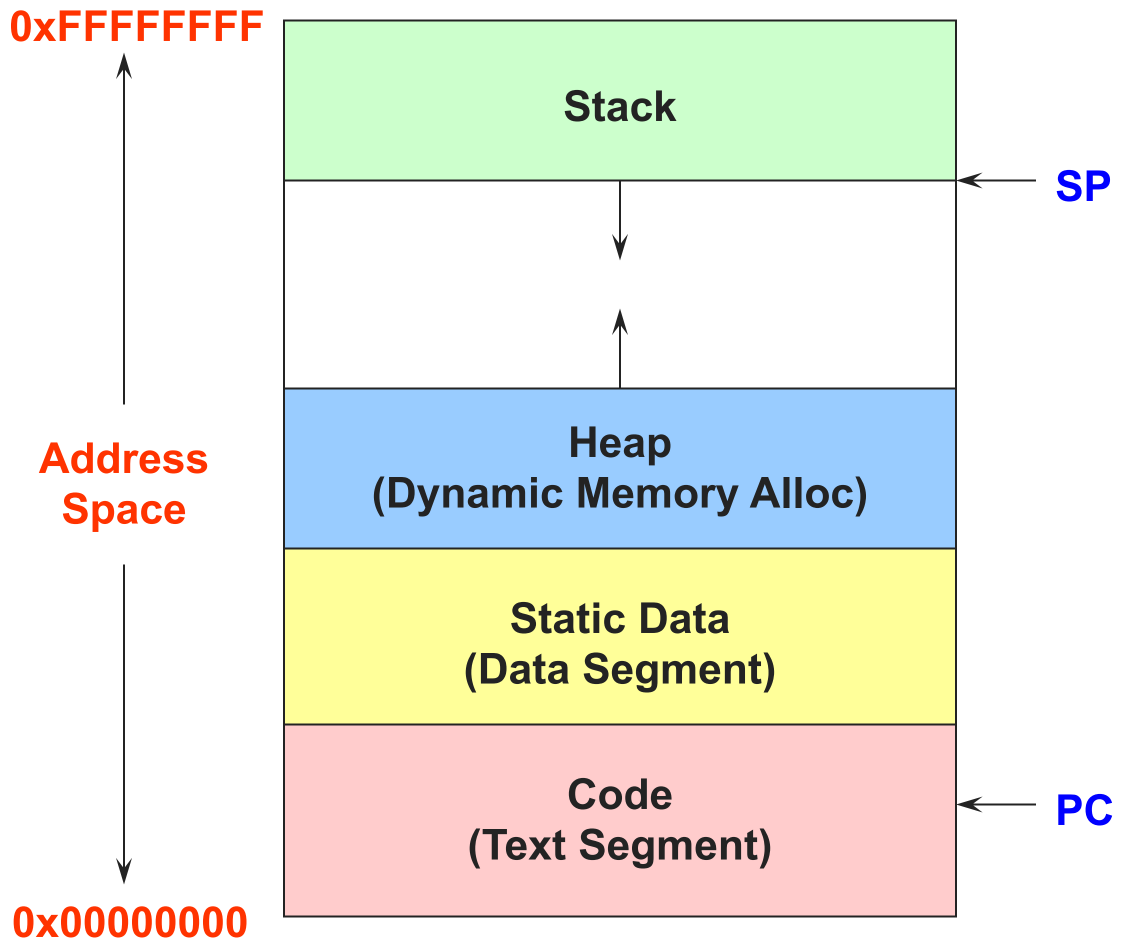
- An execution stack encapsulating the state of procedure calls
- The program counter (PC) indicating the next instruction
- A set of general-purpose registers with current values
- Current execution state (Ready/Running/Waiting)

Threads

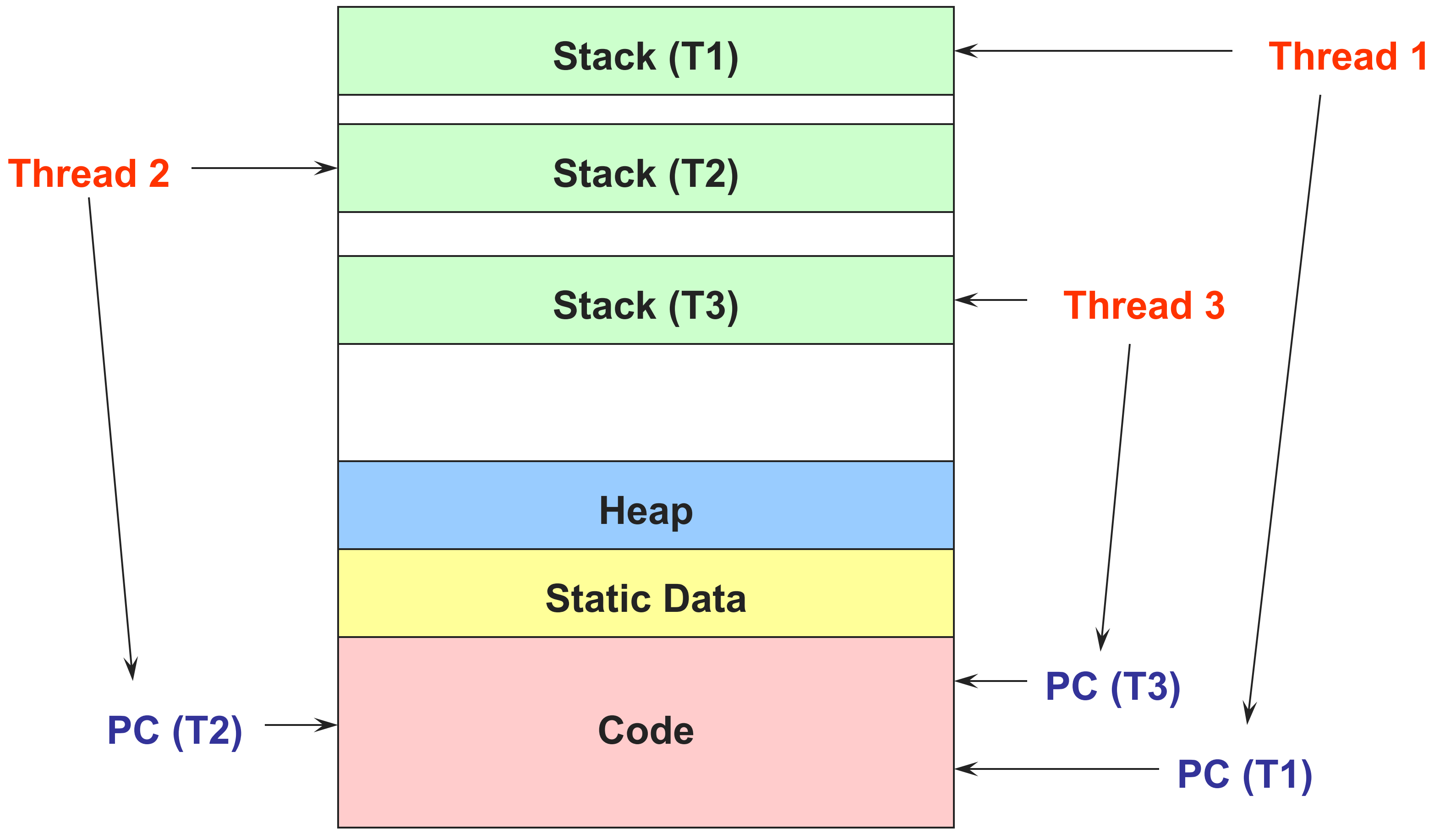
- Separate execution and resource container roles
  - The thread defines a sequential execution stream within a process (PC, SP, registers)
  - The process defines the address space, resources, and general process attributes (everything but threads)

- Threads become the unit of scheduling
  - Processes are now the containers in which threads execute
  - Processes become static, threads are the dynamic entities

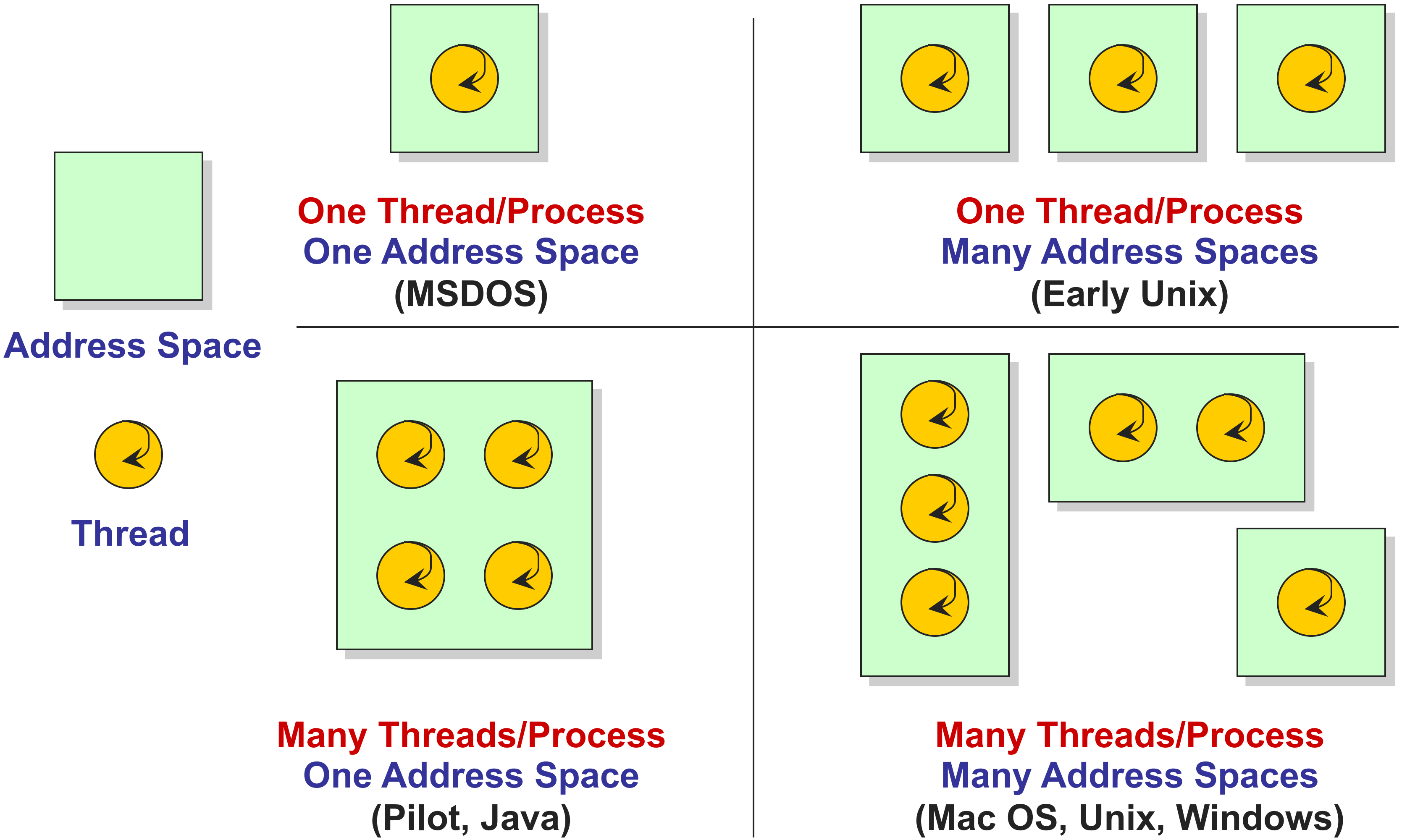
Recap: Process Address Space



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

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);
}
```

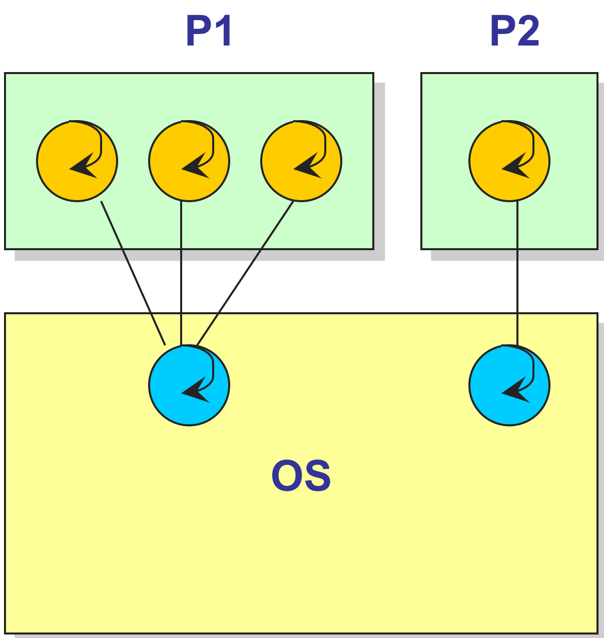
Implementing threads

- Kernel Level Threads
  - All thread operations are implemented in the kernel
  - The OS schedules all of the threads in the system
  - Don’t have to separate from processes
- OS-managed threads are called kernel-level threads or lightweight processes
  - Windows: threads
  - Solaris: lightweight processes (LWP)
  - POSIX Threads (pthreads): PTHREAD_SCOPE_SYSTEM

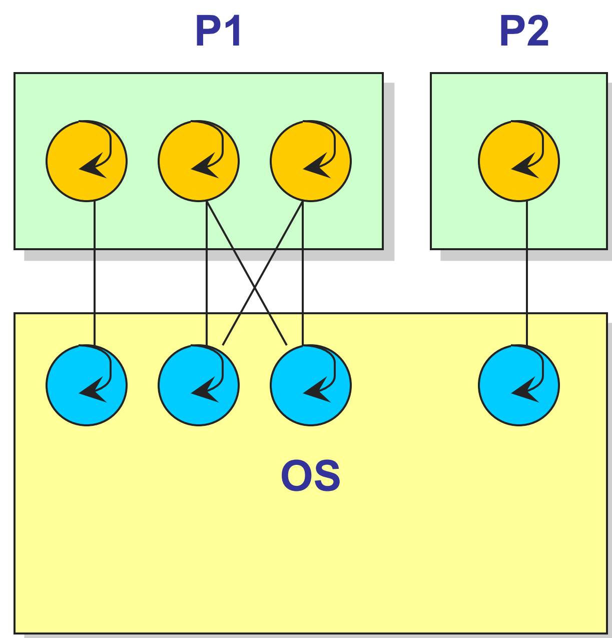
Alternative: User-Level Threads

- Implement threads using user-level library
- ULTs 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

KLT vs. ULT

- 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 ☺

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

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()

- 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()

```
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 (*not* its TCB)
  - 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 (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
- What about security?

Test: Preemptive Scheduling

```
int count = 0; //shared variable since its global
void twiddledee() {
  int i=0; //for part b this will be global and shared
  for (i=0; i<2; i++) {
    count = count * count; //assume count read from memory once
} }
void twiddledum() {
  int i=0; // for part b, this will be global and shared
  for(i=0; i<2; i++) { count = count - 1;} }
void main() {
  thread_fork(twiddledee);
  thread_fork(twiddledum);
  print count; }
```

What are all the values that could be printed in main?

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