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
- Communicating between processes is also 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
  ♦ 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 \textit{thread} defines a sequential execution stream within a process (PC, SP, registers)
  - The \textit{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 basic unit of scheduling
  - Processes are now the \textit{containers} in which threads execute
  - Processes become static, threads are the dynamic entities
Threads in a Process

- Stack (T1)
- Stack (T2)
- Stack (T3)
- Heap
- Static Data
- Code

Thread 1
- PC (T1)

Thread 2
- PC (T2)

Thread 3
- PC (T3)
Thread Design Space

One Thread/Process
One Address Space
(MSDOS)

Many Threads/Process
One Address Space
(Pilot, Java)

One Thread/Process
Many Address Spaces
(Early Unix)

Many Threads/Process
Many Address Spaces
(Mach, Unix, Windows, OS X)
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
• Recall our forking Web server:

```c
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

```c
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
    - User-level thread operations 100x faster than kernel threads
  - pthreads: PTHREAD_SCOPE_PROCESS
  - Java: Thread
Small and Fast...

- Nachos thread class

```java
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
  ♦ Correctness, performance
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#, others)
  ♦ 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
Nachos Thread API

- **KThread.fork**
  - Run a new thread (also “create”)
- **KThread.sleep**
  - Stop the calling thread (also “stop”, “block”, “suspend”)
- **KThread.ready**
  - Start the given thread (also “start”, “resume”)
- **KThread.yield**
  - Voluntarily give up the processor
- **KThread.join**
  - Block until another thread finishes (Project 1)
- **KThread.finish**
  - Terminate the calling thread (also “exit”, “destroy”)

April 12, 2018
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 might you implement sleep(time)?
Non-Preemptive Scheduling

- Threads can voluntarily give up the CPU with yield

Ping Thread

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

Pong Thread

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

- What is the output of running these two threads?
• Wait a second. How does yield() work?
• The semantics of 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 yield to return?
  ♦ It means that another thread called yield!
• Execution trace of ping/pong
  ♦ printf(“ping\n”);
  ♦ yield();
  ♦ printf(“pong\n”);
  ♦ yield();
  ♦ …
Implementing yield

```c
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;
}
```

- 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 yield, sleep, or finish cause a context switch
- Preemptive scheduling uses involuntary context switches
  - Need to regain control of processor asynchronously
  - Use timer interrupt
  - Timer interrupt handler forces current thread to “call” yield
    » See Alarm.timerInterrupt
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
- Homework #1 due