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 **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 basic unit of scheduling
  - Processes are now the **containers** in which threads execute
  - Processes become static, threads are the dynamic entities
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
  ♦ 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);
    }
}
```

```c
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
User and Kernel Stacks
System Calls / Events

Use kernel stack during system call, event handling
Kernel Threads

- Multiple kernel threads (OS manages, schedules)
- Physical parallelism (run on multiple cores)
- Multiple, separate system calls / events
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 \textit{100x faster} than kernel threads
  ♦ pthreads: PTHREAD_SCOPE_PROCESS
  ♦ Java: Thread
Small and Fast...

• Nachos thread class

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

- Multiple user threads (app manages, schedules)
- Multiplexed on one “kernel” thread (no OS support needed)
- Only one system call / event at a time, no physical parallelism
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”)
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 voluntarily give up the CPU with yield

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

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

- What is the output of running these two threads?
yield

- 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