Announcement

- Project 0 Due
- Project 1 out

- Homework 1 due on Thursday
  - Submit it to Gradescope
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 costly because most communication goes through the OS
  - Overhead of system calls and copying data
Parallel Programs

● To execute these programs we need to
  – Create several processes that execute in parallel
  – 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.

● Solution: possible to have cooperating “processes”? 
Rethinking Processes

- What is similar in these cooperating “tasks”?  
  - 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

- **Thread vs Process**
  - A *thread* defines a sequential execution stream within a process (PC, SP, registers)
  - A *process* defines the address space and general process attributes (everything but threads of execution)
- A thread is bound to a single process
  - A process, however, can have multiple threads
- **Threads become the unit of scheduling**
  - Processes are now the *containers* in which threads execute
Threads: Lightweight Processes

A sequential execution stream within a process

(a) Three processes each with one thread
(b) One process with three threads
The Thread Model

- **Shared information**
  - Processor info: parent process, time, etc
  - Memory: segments, page table, and stats, etc
  - I/O and file: communication ports, directories and file descriptors, etc

- **Private state**
  - State (ready, running and blocked)
  - Registers
  - Program counter
  - Execution stack
  - **Why?**

- **Each thread execute separately**
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)
A 2-min Explainer Video

- https://www.youtube.com/watch?v=Dhf-DYO1K78
Analogy

- Process: 3 projects for different classes (CSE120, CSE140, CSE110)
  - Each one has different text book, different web pages, different TAs/Instructors

- Threads: 3 activities in CSE120 (Homework, Lectures, Projects)
  - Share the same concepts (textbook)
  - Share TA/Tutors
  - All of them are going on in parallel (within one quarter)
  - Each has their own things, too
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:

```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);
}
```

Difference from fork()?
Thread Usage: Web Server

- Web server process
  - Dispatcher thread
  - Worker thread
  - Web page cache

- User space
- Kernel space

- Network connection
A thread can wait for I/O, while the other threads can still running.

What if it is single-threaded?
Windows Thread Lists from Performance Monitor
### Mac OS – Activity Monitor

<table>
<thead>
<tr>
<th>PID</th>
<th>Process Name</th>
<th>User</th>
<th>% CPU</th>
<th>Threads</th>
<th>Real Mem</th>
<th>Kind</th>
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</table>

- **CPU Usage**
  - % User: 8.00%
  - % System: 7.88%
  - % Idle: 84.12%
  - Threads: 926
  - Processes: 132

- **System Memory**

- **Disk Activity**

- **Disk Usage**

- **Network**
Thread Information on Linux

- Process information:
  - Read /proc/[your PID]/stat file

- Thread information (2.6 kernel):
  - Read /proc/[your PID]/task/[thread ID]/stat
Kernel-supported 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*
  - NT: threads
  - Solaris: lightweight processes (LWP)
  - POSIX Threads (pthreads): PTHREAD_SCOPE_SYSTEM
Kernel-Supported 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 too much 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 more fine-grained concurrency, need even “cheaper” threads
User-Level-Supported Threads

- To make threads cheap and fast, they need to be implemented at user level
  - Kernel-level supported threads are managed by the OS
  - User-level supported threads are managed entirely by the runtime system (user-level library)

- User-level-supported 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
User level threads

Kernel level Supported threads

User level supported threads

Kernel
Small and Fast...

- Nachos thread control block

```c
class Thread {
    int *stack;
    int *stackTop;
    int machineState[MachineStateSize];
    ThreadStatus status;
    char *name;
    <Methods>
};
```
User Level Supported 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
Tradeoffs between the two

- **Kernel-level supported threads**
  - Integrated with OS (informed scheduling)
  - Slow to create, manipulate, synchronize

- **User-level supported threads**
  - Fast to create, manipulate, synchronize
  - Not integrated with OS (uninformed scheduling)

- Understanding the differences between kernel and user-level supported threads is important
  - For programming (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 pthreads)
  - 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 NT, modern Unix
    - Can multiplex Java threads on multiple kernel threads
    - Can have more Java threads than kernel threads
Implementing Threads

- Implementing threads has a number of issues
  - Interface
  - Context switch
  - Preemptive vs. non-preemptive
  - Scheduling
  - Synchronization (next lecture)

- Focus on user-level supported threads
  - Kernel-level supported 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)`
  - 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_join(t)` or `t.join()`
  - causes the current thread to pause execution until t's thread terminates
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**

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

**Pong Thread**

```c
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();
  - ...

- In other words, it context switches to another thread

- It means that another thread called thread_yield!
Implementing thread_yield()

```c
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;
}
```

- 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 the 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
  - See code/threads/switch.s in Nachos
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
  - How?
    - Use timer/alarm interrupt
    - Timer/Alarm interrupt handler forces current thread to “call” thread_yield
      - How do you do this?
Blocking Vs. non-blocking System Calls

- **Blocking system call**
  - Usually I/O related: `read()`, `fread()`, `getc()`, `write()`
  - Doesn’t return until the call completes
  - The process/thread is switched to blocked state
  - When the I/O completes, the process/thread becomes ready
  - Simple
  - **Real life example: attending a lecture**

- **Using non-blocking system call for I/O**
  - Asynchronous I/O
  - Complicated
  - The call returns once the I/O is initiated, and the caller continue
  - Once the I/O completes, an interrupt is delivered to the caller
  - **Real life example: apply for job**
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…