CS162
Operating Systems and Systems Programming
Lecture 5

Cooperating Threads

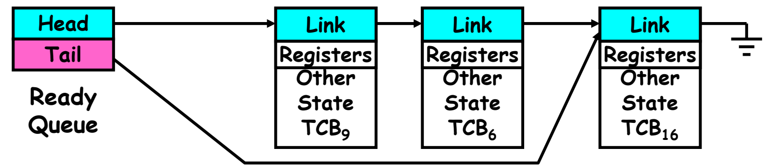
September 13, 2006

Prof. John Kubiatowicz

http://inst.eecs.berkeley.edu/~cs162

Review: Per Thread State

- Each Thread has a *Thread Control Block* (TCB)
  - Execution State: CPU registers, program counter, pointer to stack
  - Scheduling info: State (more later), priority, CPU time
  - Accounting Info
  - Various Pointers (for implementing scheduling queues)
  - Pointer to enclosing process? (PCB)?
  - Etc (add stuff as you find a need)
- OS Keeps track of TCBs in protected memory
  - In Arrays, or Linked Lists, or …



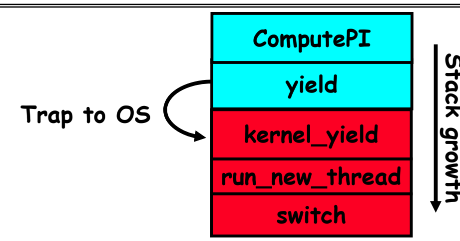
Review: Yielding through Internal Events

- Blocking on I/O
  - The act of requesting I/O implicitly yields the CPU
- Waiting on a "signal" from other thread
  - Thread asks to wait and thus yields the CPU
- Thread executes a `yield()`
  - Thread volunteers to give up CPU

```
computePI() {
    while(TRUE) {
        ComputeNextDigit();
        yield();
    }
}
```

  - Note that `yield()` must be called by programmer frequently enough!

Review: Stack for Yielding Thread



- How do we run a new thread?

```
run_new_thread() {
    newThread = PickNewThread();
    switch(curThread, newThread);
    ThreadHouseKeeping(); /* Later in lecture */
}
```

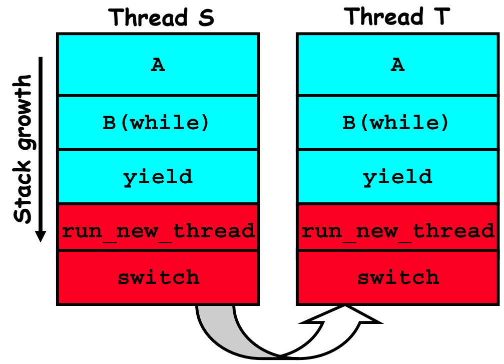
- How does dispatcher switch to a new thread?
  - Save anything next thread may trash: PC, regs, stack
  - Maintain isolation for each thread

Review: Two Thread Yield Example

- Consider the following code blocks:

```
proc A() {
   B();

}
proc B() {
   while(TRUE) {
      yield();
   }
}
```



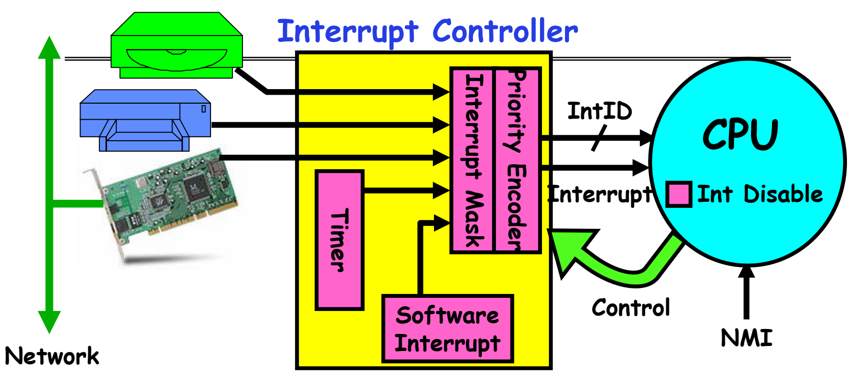
- Suppose we have 2 threads:
  - Threads S and T

Goals for Today

- More on Interrupts
- Thread Creation/Destruction
- Cooperating Threads

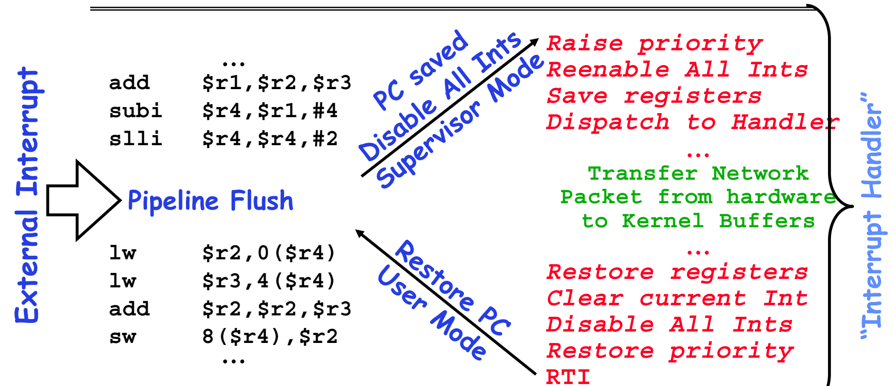
Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from my lecture notes by Kubiatowicz.

Interrupt Controller



- Interrupts invoked with interrupt lines from devices
- Interrupt controller chooses interrupt request to honor
  - Mask enables/disables interrupts
  - Priority encoder picks highest enabled interrupt
  - Software Interrupt Set/Cleared by Software
  - Interrupt identity specified with ID line
- CPU can disable all interrupts with internal flag
- Non-maskable interrupt line (NMI) can't be disabled

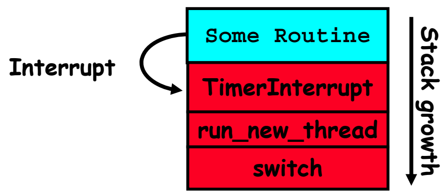
Example: Network Interrupt



- Disable/Enable All Ints ⇒ Internal CPU disable bit
  - RTI reenables interrupts, returns to user mode
- Raise/lower priority: change interrupt mask
- Software interrupts can be provided entirely in software at priority switching boundaries

Review: Preemptive Multithreading

- Use the timer interrupt to force scheduling decisions

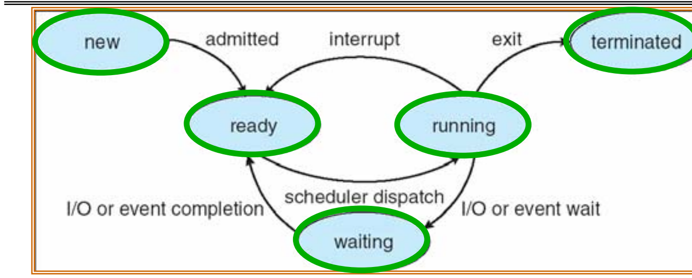


- Timer Interrupt routine:

```
TimerInterrupt() {
    DoPeriodicHouseKeeping();
    run_new_thread();
}
```

- This is often called preemptive multithreading, since threads are prempted for better scheduling
  - Solves problem of user who doesn't insert yield();

Review: Lifecycle of a Thread (or Process)



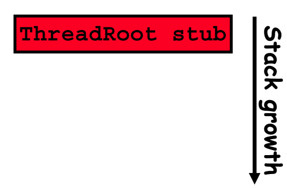
- As a thread executes, it changes state:
  - new: The thread is being created
  - ready: The thread is waiting to run
  - running: Instructions are being executed
  - waiting: Thread waiting for some event to occur
  - terminated: The thread has finished execution
- "Active" threads are represented by their TCBs
  - TCBs organized into queues based on their state

`ThreadFork()`: Create a New Thread

- `ThreadFork()` is a user-level procedure that creates a new thread and places it on ready queue
  - We called this `CreateThread()` earlier
- Arguments to `ThreadFork()`
  - Pointer to application routine (fcnPtr)
  - Pointer to array of arguments (fcnArgPtr)
  - Size of stack to allocate
- Implementation
  - Sanity Check arguments
  - Enter Kernel-mode and Sanity Check arguments again
  - Allocate new Stack and TCB
  - Initialize TCB and place on ready list (Runnable).

How do we initialize TCB and Stack?

- Initialize Register fields of TCB
  - Stack pointer made to point at stack
  - PC return address ⇒ OS (asm) routine `ThreadRoot()`
  - Two arg registers initialized to `fcnPtr` and `fcnArgPtr`
- Initialize stack data?
  - No. Important part of stack frame is in registers (ra)
  - Think of stack frame as just before body of `ThreadRoot()` really gets started

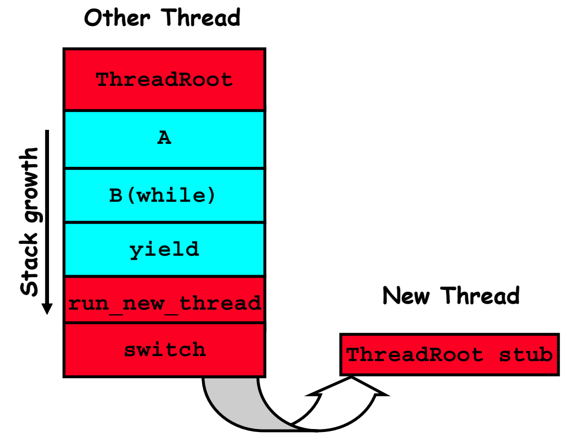


Initial Stack

Administrivia

- If you haven't generated a new key yet (and given a passcode), you *must* do this NOW!
  - We need the ssh keys to make the group accounts
  - You should have `.ssh2/cs162-xx`, `.ssh2/cs162-xx.pub`, and `.ssh2/identification` files
  - Notify us if you change your keys
- Sections in this class are mandatory
  - Make sure that you go to the section that you have been assigned!
  - Sections are up off the home page
- Reader is available at Copy Central on Hearst
- Should be reading Nachos code by now!
  - Start working on the first project
  - Set up regular meeting times with your group
  - Try figure out group interaction problems early on

How does Thread get started?

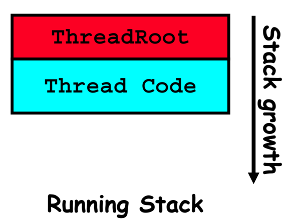


- Eventually, `run_new_thread()` will select this TCB and return into beginning of `ThreadRoot()`
  - This really starts the new thread

What does `ThreadRoot()` look like?

- ThreadRoot() is the root for the thread routine:

```
ThreadRoot() {
   DoStartupHousekeeping();
   UserModeSwitch(); /* enter user mode */
   Call fcnPtr(fcnArgPtr);
   ThreadFinish();
}
```



- Startup Housekeeping
  - Includes things like recording start time of thread
  - Other Statistics
- Stack will grow and shrink with execution of thread
- Final return from thread returns into ThreadRoot() which calls ThreadFinish()
  - ThreadFinish() will start at user-level

What does `ThreadFinish()` do?

- Needs to re-enter kernel mode (system call)
- "Wake up" (place on ready queue) threads waiting for this thread
  - Threads (like the parent) may be on a wait queue waiting for this thread to finish
- Can't deallocate thread yet
  - We are still running on its stack!
  - Instead, record thread as "waitingToBeDestroyed"
- Call `run_new_thread()` to run another thread:

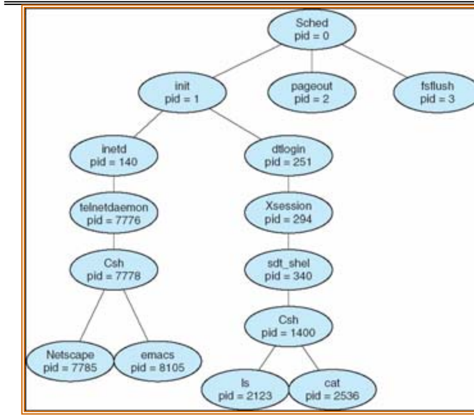
```
run_new_thread() {
   newThread = PickNewThread();
   switch(curThread, newThread);
   ThreadHouseKeeping();
}
```

  - `ThreadHouseKeeping()` notices waitingToBeDestroyed and deallocates the finished thread's TCB and stack

Additional Detail

- Thread Fork is not the same thing as UNIX fork
  - UNIX fork creates a new *process* so it has to create a new address space
  - For now, don't worry about how to create and switch between address spaces
- Thread fork is very much like an asynchronous procedure call
  - Runs procedure in separate thread
  - Calling thread doesn't wait for finish
- What if thread wants to exit early?
  - `ThreadFinish()` and `exit()` are essentially the same procedure entered at user level

Parent-Child relationship

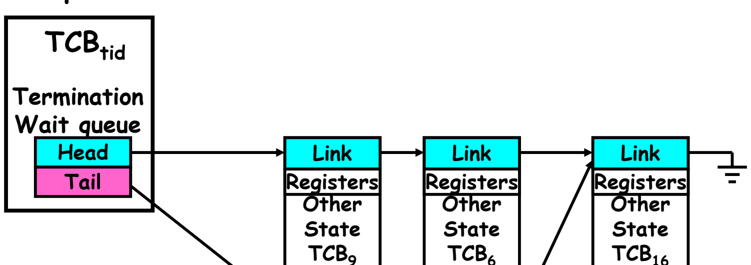


Typical process tree for Solaris system

- Every thread (and/or Process) has a parentage
  - A "parent" is a thread that creates another thread
  - A child of a parent was created by that parent

ThreadJoin() system call

- One thread can wait for another to finish with the `ThreadJoin(tid)` call
  - Calling thread will be taken off run queue and placed on waiting queue for thread `tid`
- Where is a logical place to store this wait queue?
  - On queue inside the TCB



- Similar to `wait()` system call in UNIX
  - Lets parents wait for child processes

Use of Join for Traditional Procedure Call

- A traditional procedure call is logically equivalent to doing a ThreadFork followed by ThreadJoin
- Consider the following normal procedure call of B() by A():

```
A() { B(); }
B() { Do interesting, complex stuff }
```

- The procedure A() is equivalent to A'():

```
A'() {
   tid = ThreadFork(B,null);
   ThreadJoin(tid);
}
```

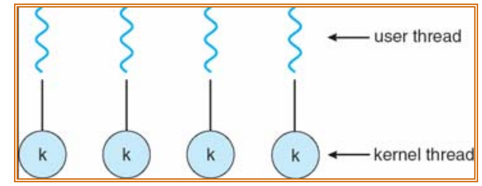
- Why not do this for every procedure?
  - Context Switch Overhead
  - Memory Overhead for Stacks

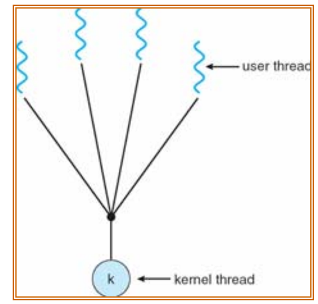
Kernel versus User-Mode threads

- We have been talking about Kernel threads
  - Native threads supported directly by the kernel
  - Every thread can run or block independently
  - One process may have several threads waiting on different things
- Downside of kernel threads: a bit expensive
  - Need to make a crossing into kernel mode to schedule
- Even lighter weight option: User Threads
  - User program provides scheduler and thread package
  - May have several user threads per kernel thread
  - User threads may be scheduled non-premptively relative to each other (only switch on yield())
  - Cheap
- Downside of user threads:
  - When one thread blocks on I/O, all threads block
  - Kernel cannot adjust scheduling among all threads

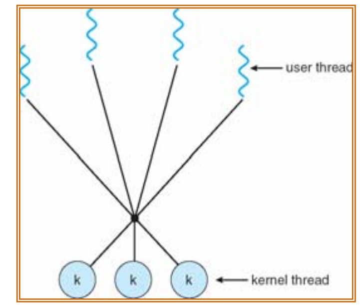
Threading models mentioned by book

Simple One-to-One Threading Model





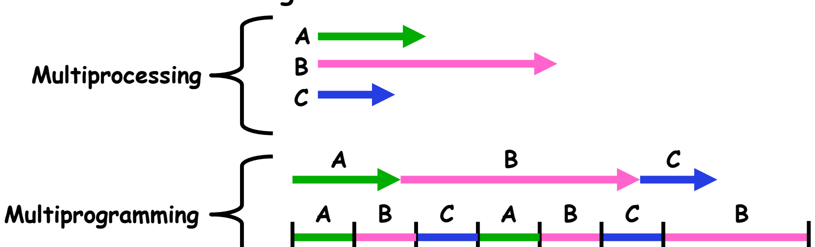
Many-to-One



Many-to-Many

Multiprocessing vs Multiprogramming

- Remember Definitions:
  - Multiprocessing ≡ Multiple CPUs
  - Multiprogramming ≡ Multiple Jobs or Processes
  - Multithreading ≡ Multiple threads per Process
- What does it mean to run two threads "concurrently"?
  - Scheduler is free to run threads in any order and interleaving: FIFO, Random, …
  - Dispatcher can choose to run each thread to completion or time-slice in big chunks or small chunks



Correctness for systems with concurrent threads

- If dispatcher can schedule threads in any way, programs must work under all circumstances
  - Can you test for this?
  - How can you know if your program works?
- Independent Threads:
  - No state shared with other threads
  - Deterministic ⇒ Input state determines results
  - Reproducible ⇒ Can recreate Starting Conditions, I/O
  - Scheduling order doesn't matter (if `switch()` works!!!)
- Cooperating Threads:
  - Shared State between multiple threads
  - Non-deterministic
  - Non-reproducible
- Non-deterministic and Non-reproducible means that bugs can be intermittent
  - Sometimes called "Heisenbugs"

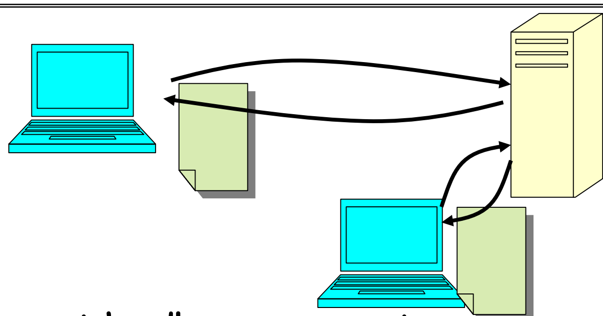
Interactions Complicate Debugging

- Is any program truly independent?
  - Every process shares the file system, OS resources, network, etc
  - Extreme example: buggy device driver causes thread A to crash "independent thread" B
- You probably don't realize how much you depend on reproducibility:
  - Example: Evil C compiler
    - » Modifies files behind your back by inserting errors into C program unless you insert debugging code
  - Example: Debugging statements can overrun stack
- Non-deterministic errors are really difficult to find
  - Example: Memory layout of kernel+user programs
    - » depends on scheduling, which depends on timer/other things
    - » Original UNIX had a bunch of non-deterministic errors
  - Example: Something which does interesting I/O
    - » User typing of letters used to help generate secure keys

Why allow cooperating threads?

- People cooperate; computers help/enhance people's lives, so computers must cooperate
  - By analogy, the non-reproducibility/non-determinism of people is a notable problem for "carefully laid plans"
- Advantage 1: Share resources
  - One computer, many users
  - One bank balance, many ATMs
    - » What if ATMs were only updated at night?
  - Embedded systems (robot control: coordinate arm & hand)
- Advantage 2: Speedup
  - Overlap I/O and computation
    - » Many different file systems do read-ahead
  - Multiprocessors – chop up program into parallel pieces
- Advantage 3: Modularity
  - More important than you might think
  - Chop large problem up into simpler pieces
    - » To compile, for instance, gcc calls cpp | cc1 | cc2 | as | ld
    - » Makes system easier to extend

High-level Example: Web Server



- Server must handle many requests
- Non-cooperating version:

```
serverLoop() {
    con = AcceptCon();
    ProcessFork(ServiceWebPage(),con);
}
```

- What are some disadvantages of this technique?

Threaded Web Server

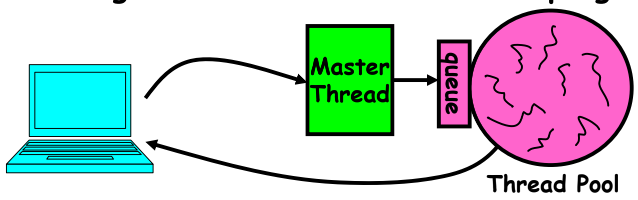
- Now, use a single process
- Multithreaded (cooperating) version:

```
serverLoop() {
     connection = AcceptCon();
     ThreadFork(ServiceWebPage(),connection);
}
```

- Looks almost the same, but has many advantages:
  - Can share file caches kept in memory, results of CGI scripts, other things
  - Threads are *much* cheaper to create than processes, so this has a lower per-request overhead
- Question: would a user-level (say one-to-many) thread package make sense here?
  - When one request blocks on disk, all block…
- What about Denial of Service attacks or digg / Slash-dot effects?

Thread Pools

- Problem with previous version: Unbounded Threads
  - When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded "pool" of worker threads, representing the maximum level of multiprogramming




```
master() {
   allocThreads(worker,queue);
   while(TRUE) {
      con=AcceptCon();
      Enqueue(queue,con);
      wakeUp(queue);
   }
}
```

```
worker(queue) {
   while(TRUE) {
      con=Dequeue(queue);
      if (con==null)
         sleepOn(queue);
      else
         ServiceWebPage(con);
   }
}
```


Summary

- Interrupts: hardware mechanism for returning control to operating system
  - Used for important/high-priority events
  - Can force dispatcher to schedule a different thread (premptive multithreading)
- New Threads Created with `ThreadFork()`
  - Create initial TCB and stack to point at `ThreadRoot()`
  - `ThreadRoot()` calls thread code, then `ThreadFinish()`
  - `ThreadFinish()` wakes up waiting threads then prepares TCB/stack for distruction
- Threads can wait for other threads using `ThreadJoin()`
- Threads may be at user-level or kernel level
- Cooperating threads have many potential advantages
  - But: introduces non-reproducibility and non-determinism
  - Need to have Atomic operations