CS162
Operating Systems and Systems Programming
Lecture 4

Thread Dispatching

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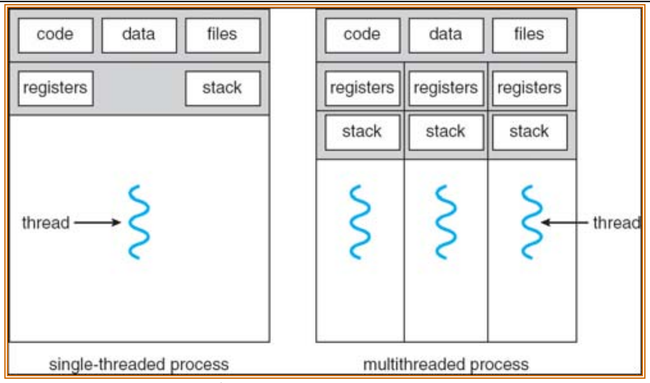
Recall: Modern Process with Multiple Threads

- Process: *Operating system abstraction to represent what is needed to run a single, multithreaded program*
- Two parts:
  - Multiple Threads
    - » Each thread is a *single, sequential stream of execution*
  - Protected Resources:
    - » Main Memory State (contents of Address Space)
    - » I/O state (i.e. file descriptors)
- Why separate the concept of a thread from that of a process?
  - Discuss the "thread" part of a process (concurrency)
  - Separate from the "address space" (Protection)
  - Heavyweight Process ≡ Process with one thread

Recall: Single and Multithreaded Processes



- Threads encapsulate concurrency
  - "Active" component of a process
- Address spaces encapsulate protection
  - Keeps buggy program from trashing the system
  - "Passive" component of a process

Goals for Today

- Further Understanding Threads
- Thread Dispatching
- Beginnings of Thread Scheduling

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.

Classification

# threads Per AS: / # of addr spaces:	One	Many
One	MS/DOS, early Macintosh	Traditional UNIX
Many	Embedded systems (Geoworks, VxWorks, JavaOS,etc) JavaOS, Pilot(PC)	Mach, OS/2, Linux, Win 95?, Mac OS X, Win NT to XP, Solaris, HP-UX

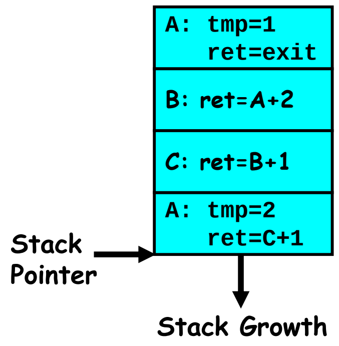
- Real operating systems have either
  - One or many address spaces
  - One or many threads per address space
- Did Windows 95/98/ME have real memory protection?
  - No: Users could overwrite process tables/System DLLs

Thread State

- State shared by all threads in process/addr space
  - Contents of memory (global variables, heap)
  - I/O state (file system, network connections, etc)
- State "private" to each thread
  - Kept in TCB ≡ Thread Control Block
  - CPU registers (including, program counter)
  - Execution stack – what is this?
- Execution Stack
  - Parameters, Temporary variables
  - return PCs are kept while called procedures are executing

Execution Stack Example

```
A(int tmp) {
  if (tmp<2)
    B();
  printf(tmp);
}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

MIPS: Software conventions for Registers

0	zero	constant 0	16	s0	callee saves
1	at	reserved for assembler	. . .		(callee must save)
2	v0	expression evaluation &	23	s7	
3	v1	function results	24	t8	temporary (cont'd)
4	a0	arguments	25	t9	
5	a1		26	k0	reserved for OS kernel
6	a2		27	k1	
7	a3		28	gp	Pointer to global area
8	t0	temporary: caller saves	29	sp	Stack pointer
. . .		(callee can clobber)	30	fp	frame pointer
15	t7		31	ra	Return Address (HW)

- Before calling procedure:
  - Save caller-saves regs
  - Save v0, v1
  - Save ra
- After return, assume
  - Callee-saves reg OK
  - gp,sp,fp OK (restored!)
  - Other things trashed

Single-Threaded Example

- Imagine the following C program:

```
main() {
    ComputePI("pi.txt");
    PrintClassList("clist.text");
}
```

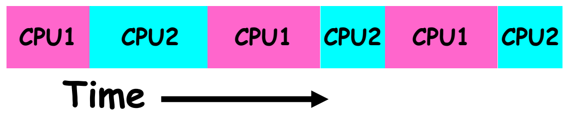
- What is the behavior here?
  - Program would never print out class list
  - Why? ComputePI would never finish

Use of Threads

- Version of program with Threads:

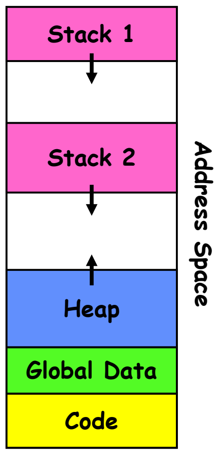
```
main() {
    CreateThread(ComputePI("pi.txt"));
    CreateThread(PrintClassList("clist.text"));
}
```

- What does "CreateThread" do?
  - Start independent thread running given procedure
- What is the behavior here?
  - Now, you would actually see the class list
  - This *should* behave as if there are two separate CPUs



Memory Footprint of Two-Thread Example

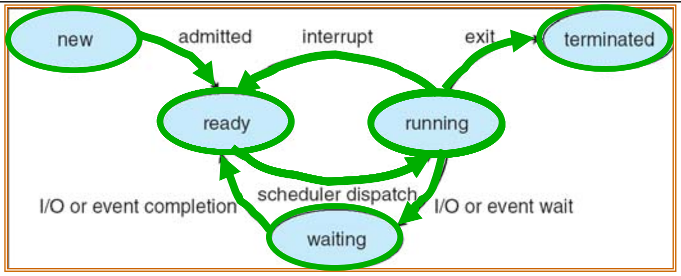
- If we stopped this program and examined it with a debugger, we would see
  - Two sets of CPU registers
  - Two sets of Stacks
- Questions:
  - How do we position stacks relative to each other?
  - What maximum size should we choose for the stacks?
  - What happens if threads violate this?
  - How might you catch violations?



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)
- In Nachos: "Thread" is a class that includes the TCB
- OS Keeps track of TCBs in protected memory
  - In Array, or Linked List, or …

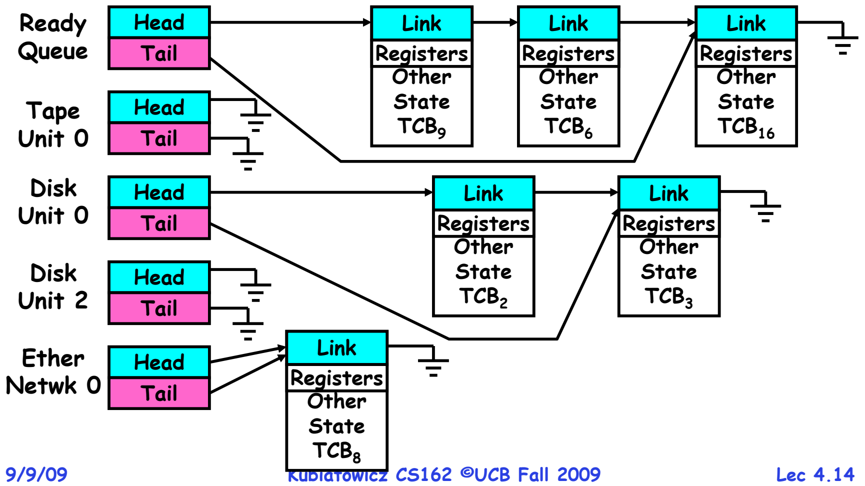
Lifecycle of a Thread (or Process)



- 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

Ready Queue And Various I/O Device Queues

- Thread not running ⇒ TCB is in some scheduler queue
  - Separate queue for each device/signal/condition
  - Each queue can have a different scheduler policy



Administrivia

- Tentative Group assignments now posted on website
  - Check out the "Group/Section Assignment" link
  - Please attend your newly assigned section!
- As you can see, we are a bit unbalanced in sections.
  - Many of you didn't listen: you only listed one section without sending me email to explain!
  - *Those of you who only selected one section must send me a NEW email explaining why you can only make one section*
    - » *I expect 15 of these messages. Make sure to include your group number and list of members*
- Anyone without a group?
  - Please come up to talk with me afterwards
- Sections in this class are mandatory
  - Go to the section that you have been assigned!
  - Important information will be given in section
  - 5% of grade is participation

Administrivia (2)

- Information about Subversion on Handouts page
  - Make sure to take a look
- We understand that there have been problems with the Subversion server
  - Hopefully will be already fixed
- Other things on Handouts page
  - Interesting papers
  - Synchronization examples
  - Previous finals/solutions
- Reader now available at Copy Central on Hearst
- RSS feeds available (see top of lectures page)
- 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

Dispatch Loop

- Conceptually, the dispatching loop of the operating system looks as follows:

```
Loop {
   RunThread();
   ChooseNextThread();
   SaveStateOfCPU(curTCB);
   LoadStateOfCPU(newTCB);
}
```

- This is an *infinite* loop
  - One could argue that this is all that the OS does
- Should we ever exit this loop???
  - When would that be?

Running a thread

Consider first portion: `RunThread()`

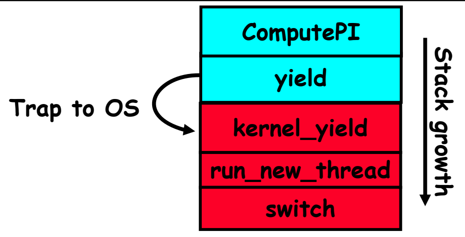
- How do I run a thread?
  - Load its state (registers, PC, stack pointer) into CPU
  - Load environment (virtual memory space, etc)
  - Jump to the PC
- How does the dispatcher get control back?
  - Internal events: thread returns control voluntarily
  - External events: thread gets *preempted*

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();
   }
}
```

Stack for Yielding Thread



- How do we run a new thread?

```
run_new_thread() {
   newThread = PickNewThread();
   switch(curThread, newThread);
   ThreadHouseKeeping(); /* next Lecture */
}
```

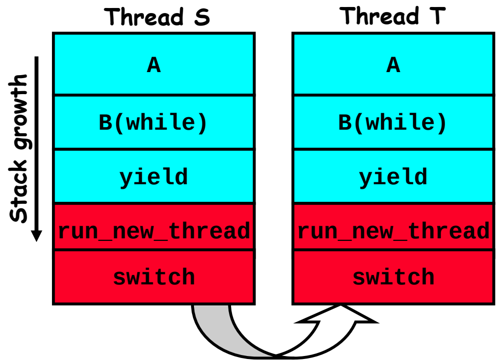
- How does dispatcher switch to a new thread?
  - Save anything next thread may trash: PC, regs, stack
  - Maintain isolation for each thread

What do the stacks look like?

- Consider the following code blocks:

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

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

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



Saving/Restoring state (often called "Context Switch)

```
Switch(tCur,tNew) {
   /* Unload old thread */
   TCB[tCur].regs.r7 = CPU.r7;
           …
   TCB[tCur].regs.r0 = CPU.r0;
   TCB[tCur].regs.sp = CPU.sp;
   TCB[tCur].regs.retpc = CPU.retpc; /*return addr*/

   /* Load and execute new thread */
   CPU.r7 = TCB[tNew].regs.r7;
           …
   CPU.r0 = TCB[tNew].regs.r0;
   CPU.sp = TCB[tNew].regs.sp;
   CPU.retpc = TCB[tNew].regs.retpc;
   return; /* Return to CPU.retpc */
}
```

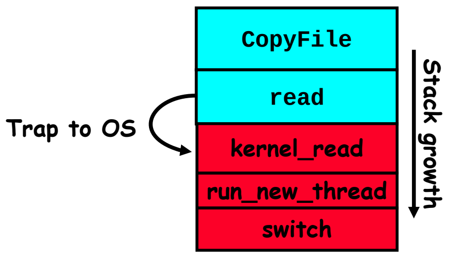
Switch Details

- How many registers need to be saved/restored?
  - MIPS 4k: 32 Int(32b), 32 Float(32b)
  - Pentium: 14 Int(32b), 8 Float(80b), 8 SSE(128b),…
  - Sparc(v7): 8 Regs(32b), 16 Int regs (32b) * 8 windows = 136 (32b)+32 Float (32b)
  - Itanium: 128 Int (64b), 128 Float (82b), 19 Other(64b)
- retpc is where the return should jump to.
  - In reality, this is implemented as a jump
- There is a real implementation of switch in Nachos.
  - See switch.s
    - » Normally, switch is implemented as assembly!
  - Of course, it's magical!
  - But you should be able to follow it!

Switch Details (continued)

- What if you make a mistake in implementing switch?
  - Suppose you forget to save/restore register 4
  - Get intermittent failures depending on when context switch occurred and whether new thread uses register 4
  - System will give wrong result without warning
- Can you devise an exhaustive test to test switch code?
  - No! Too many combinations and inter-leavings
- Cautionary tail:
  - For speed, Topaz kernel saved one instruction in switch()
  - Carefully documented!
    - » Only works As long as kernel size < 1MB
  - What happened?
    - » Time passed, People forgot
    - » Later, they added features to kernel (no one removes features!)
    - » Very weird behavior started happening
  - Moral of story: Design for simplicity

What happens when thread blocks on I/O?

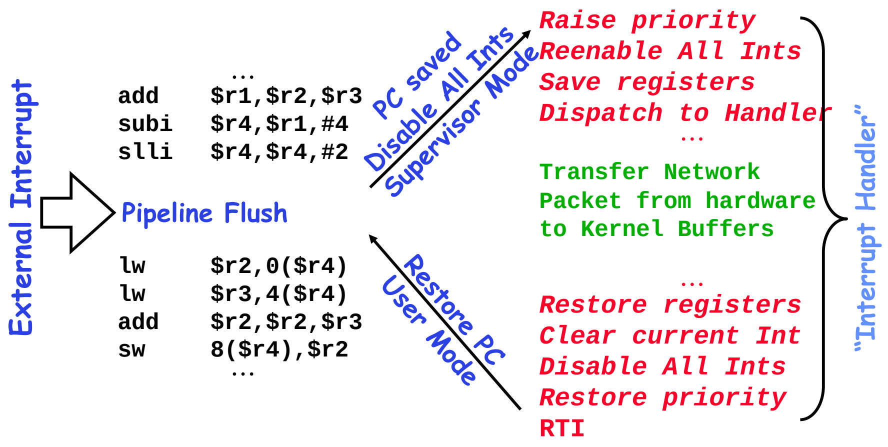


- What happens when a thread requests a block of data from the file system?
  - User code invokes a system call
  - Read operation is initiated
  - Run new thread/switch
- Thread communication similar
  - Wait for Signal/Join
  - Networking

External Events

- What happens if thread never does any I/O, never waits, and never yields control?
  - Could the ComputePI program grab all resources and never release the processor?
    - » What if it didn't print to console?
  - Must find way that dispatcher can regain control!
- Answer: Utilize External Events
  - Interrupts: signals from hardware or software that stop the running code and jump to kernel
  - Timer: like an alarm clock that goes off every some many milliseconds
- If we make sure that external events occur frequently enough, can ensure dispatcher runs

Example: Network Interrupt



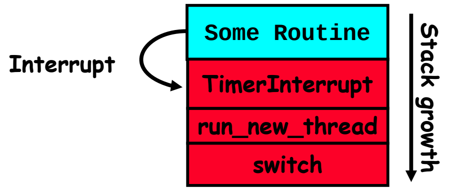
```
        …
add     $r1,$r2,$r3
subi    $r4,$r1,#4
slli    $r4,$r4,#2

lw      $r2,0($r4)
lw      $r3,4($r4)
add     $r2,$r2,$r3
sw      8($r4),$r2
        …
```

```
Raise priority
Reenable All Ints
Save registers
Dispatch to Handler
        …
Transfer Network
Packet from hardware
to Kernel Buffers
        …
Restore registers
Clear current Int
Disable All Ints
Restore priority
RTI
```

- An interrupt is a hardware-invoked context switch
  - No separate step to choose what to run next
  - Always run the interrupt handler immediately

Use of Timer Interrupt to Return Control

- Solution to our dispatcher problem
  - Use the timer interrupt to force scheduling decisions



- Timer Interrupt routine:

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

- I/O interrupt: same as timer interrupt except that `DoHousekeeping()` replaced by `ServiceIO()`.

Choosing a Thread to Run

- How does Dispatcher decide what to run?
  - Zero ready threads – dispatcher loops
    - » Alternative is to create an "idle thread"
    - » Can put machine into low-power mode
  - Exactly one ready thread – easy
  - More than one ready thread: use scheduling priorities
- Possible priorities:
  - LIFO (last in, first out):
    - » put ready threads on front of list, remove from front
  - Pick one at random
  - FIFO (first in, first out):
    - » Put ready threads on back of list, pull them from front
    - » This is fair and is what Nachos does
  - Priority queue:
    - » keep ready list sorted by TCB priority field

Summary

- The state of a thread is contained in the TCB
  - Registers, PC, stack pointer
  - States: New, Ready, Running, Waiting, or Terminated
- Multithreading provides simple illusion of multiple CPUs
  - Switch registers and stack to dispatch new thread
  - Provide mechanism to ensure dispatcher regains control
- Switch routine
  - Can be very expensive if many registers
  - Must be very carefully constructed!
- Many scheduling options
  - Decision of which thread to run complex enough for complete lecture