15-410

The Thread
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Bruce Maggs

"Real concurrency – in which one program actually continues to function while you call up and use another – is more amazing but of small use to the average person. How many programs do you have that take more than a few seconds to perform any task?" – NYT, 4/25/1989

Synchronization

Project 1

- By end of today...
  - Console (output) should really be working
  - Should have some progress (at least design) for kbd, timer

Write good code

- Console driver will be used *(and extended)* in P3

Book Report Goals

Some of you are going to grad. school

Some of you are wondering about grad. school

Some of you are *in* grad. school

- **You should be able to read a Ph.D. dissertation**

More generally

- **Looking at something *in depth* is different**
- **Not like a textbook**

Book Report Goals

There's more than one way to do it

- But you don't have time to try all the ways in 410
- Reading about other ways is good, maybe fun

Habituation

- Long-term career development requires study

Writing skills (a little!)

- “Summarizing” a book in a page is tough

Book Report

Read the "handout"

Browse the already-approved list

Pick something (soon)

- Don't make me stop the car...

Read a bit before you sleep at night

- or: before you sleep in the morning
- and/or: Thanksgiving break

Recommended by previous OS students!

- They recommend starting early, too

Road Map

Thread lecture

Synchronization lectures

- Probably *three*

Yield lecture

This is important

- When you leave here, you will use threads
- Understanding threads will help you understand the kernel

Please make sure you *understand* threads

- We'll try to help by assigning you P2

Outline

Textbook chapters

- Already: Chapters 1 through 3
- Today: Chapter 4 (roughly)
- Soon: Chapters 6 & 7
- Transactions (6.9) will be deferred

Outline

Thread = schedulable registers

- (that's *all* there is)

Why threads?

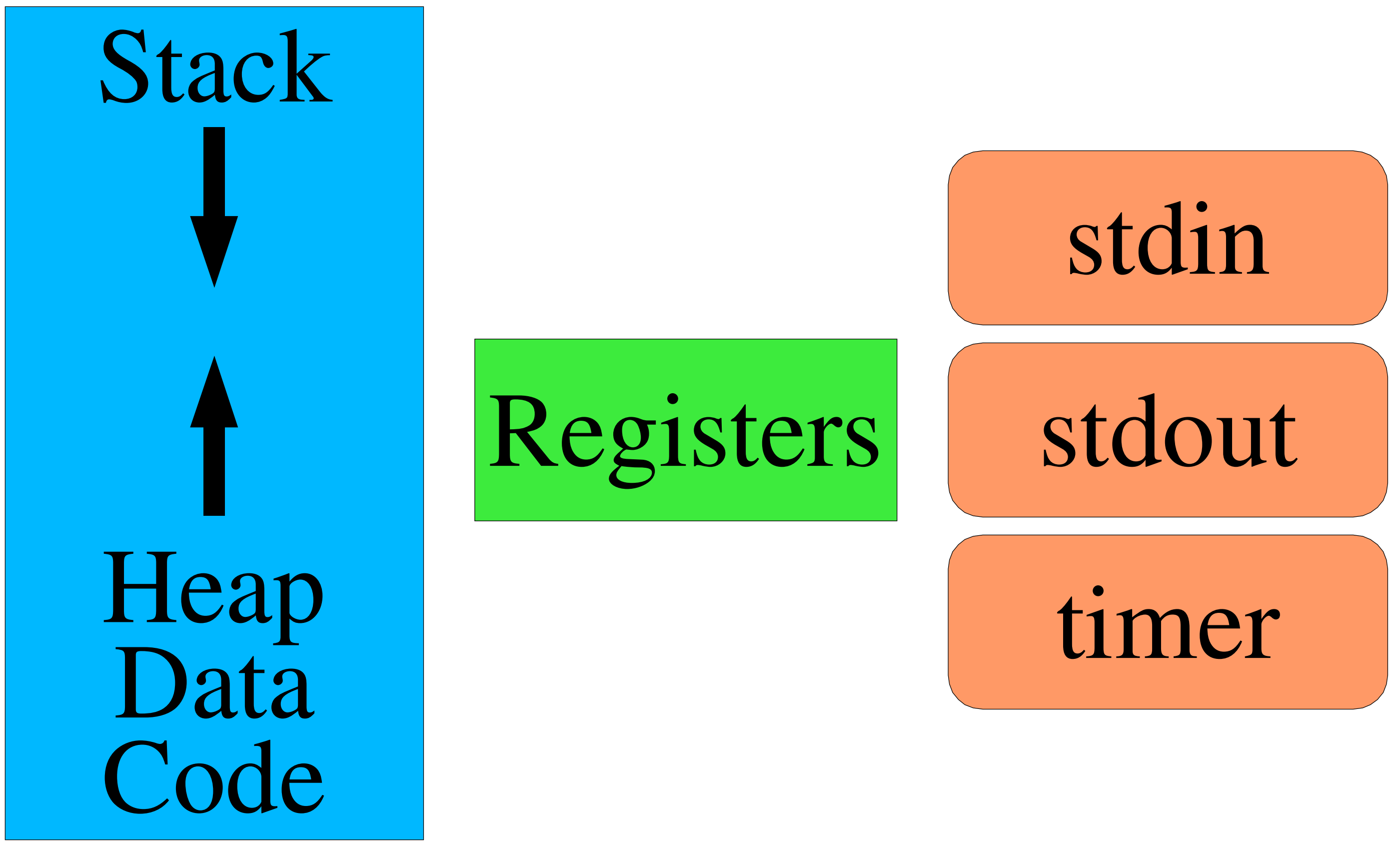
Thread flavors (ratios)

(Against) cancellation

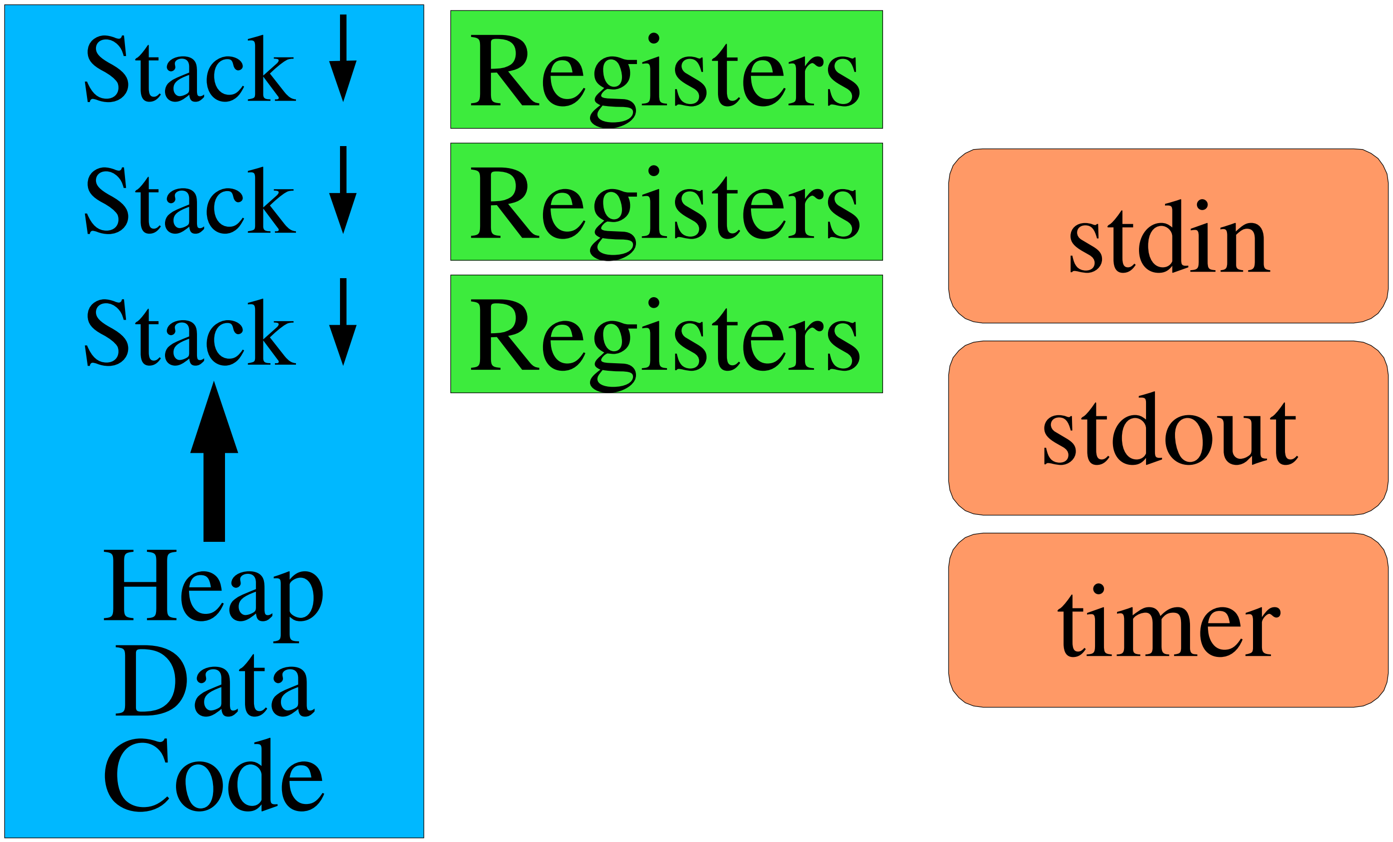
Race conditions

- 1 simple, 1 ouch
- *Make sure you really understand this*

Single-threaded Process



Multi-threaded Process



What does that *mean*?

Three stacks

- Three sets of “local variables”

Three register sets

- Three stack pointers
- Three %eax's (etc.)

Three *schedulable RAM mutators*

- (heartfelt but partial apologies to the ML crowd)

Three potential bad interactions

Why threads?

Shared access to data structures

Responsiveness

Speedup on multiprocessors

Shared access to data structures

Database server for multiple bank branches

- Verify multiple rules are followed
  - Account balance
  - Daily withdrawal limit
- Multi-account operations (transfer)
- Many accesses, each modifies tiny fraction of database

Server for a multi-player game

- Many players
- Access (& update) shared world state
  - Scan multiple objects
  - Update one or two objects

Shared access to data structures

Process per player?

- *Processes* share objects only via system calls
- Hard to make game objects = operating system objects

Process per game object?

- "Scan multiple objects, update one"
- Lots of message passing between processes
- Lots of memory wasted for lots of processes
- *Slow*

Shared access to data structures

Thread **per player**

- Game objects inside single memory address space
- Each thread can access & update game objects
- Shared access to OS objects (files)

Thread-switch is cheap

- Store N registers
- Load N registers

Responsiveness

“Cancel” button vs. decompressing large JPEG

- **Handle mouse click *during* 10-second process**
  - **Map (x,y) to “cancel button” area**
  - **Verify that button-release happens in button area of screen**
- **...without JPEG decompressor understanding clicks**

Multiprocessor speedup

More CPUs can't help a single-threaded process!

PhotoShop color dither operation

- Divide image into regions
- One dither thread per CPU
- Can (sometimes) get linear speedup

Kinds of threads

User-space (N:1)

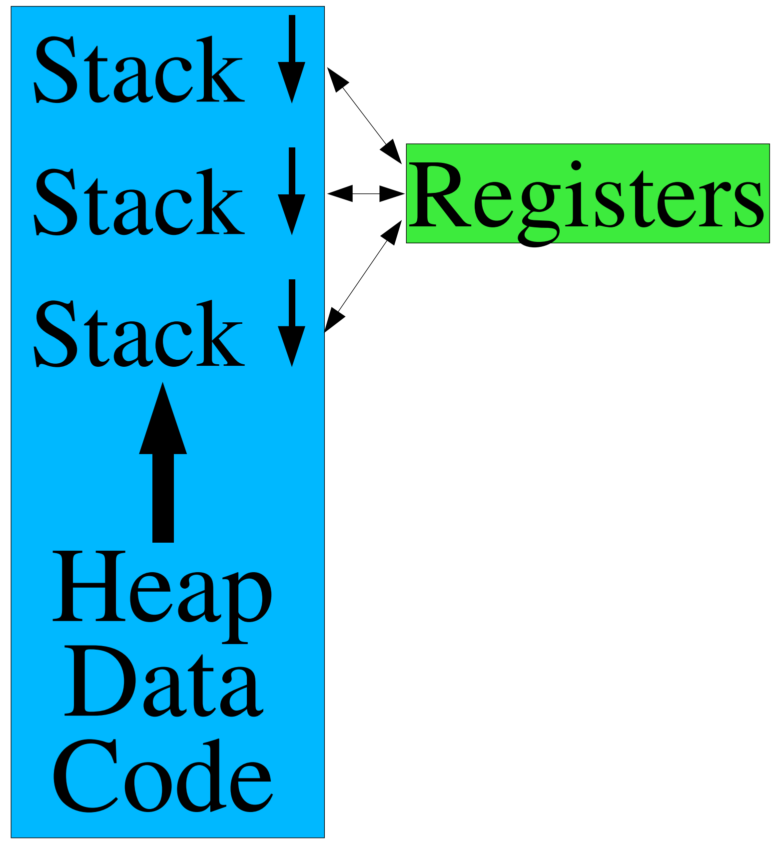
Kernel threads (1:1)

Many-to-many (M:N)

User-space threads (N:1)

Internal threading

- Thread library adds threads to a process
- Thread switch just swaps registers
  - Small piece of asm code
  - Maybe called yield()



User-space threads (N:1)

+ No change to operating system

- Any system call probably blocks all "threads"
  - "The process" makes a system call
  - Kernel blocks "the process"
  - (special non-blocking system calls can help)

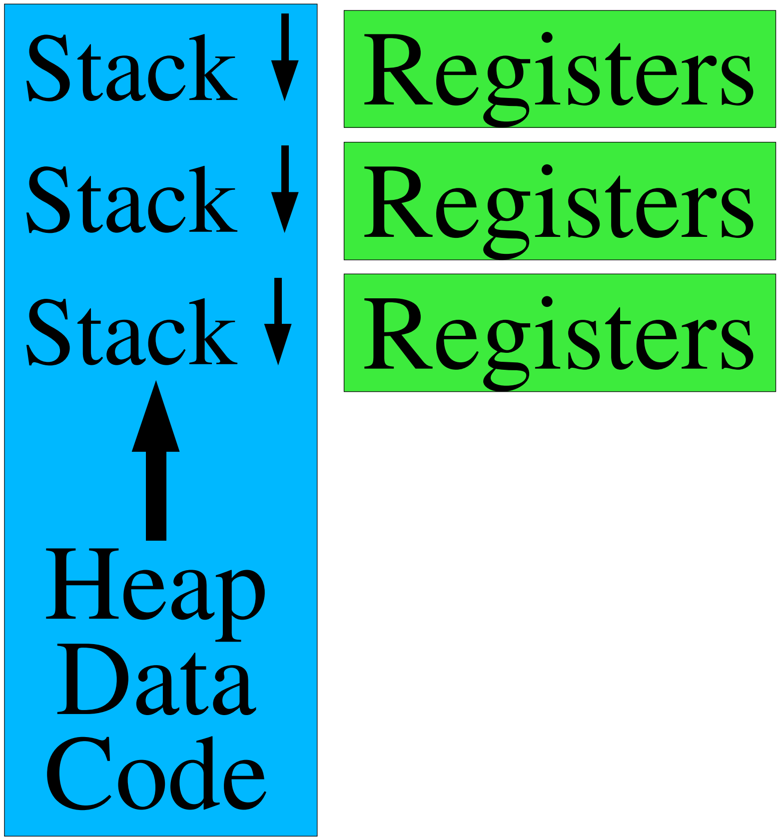
- "Cooperative scheduling" awkward/insufficient
  - Must manually insert many calls to yield()

- Cannot go faster on multiprocessor machines

Pure kernel threads (1:1)

OS-supported threading

- OS knows thread/process ownership
- Memory regions shared & reference-counted



Pure kernel threads (1:1)

Every thread is sacred

- Kernel-managed register set
- Kernel stack when the thread is running kernel code
- “Real” (timer-triggered) scheduling

Features

+ Program runs faster on multiprocessor

+ CPU-hog threads don't get all the CPU time

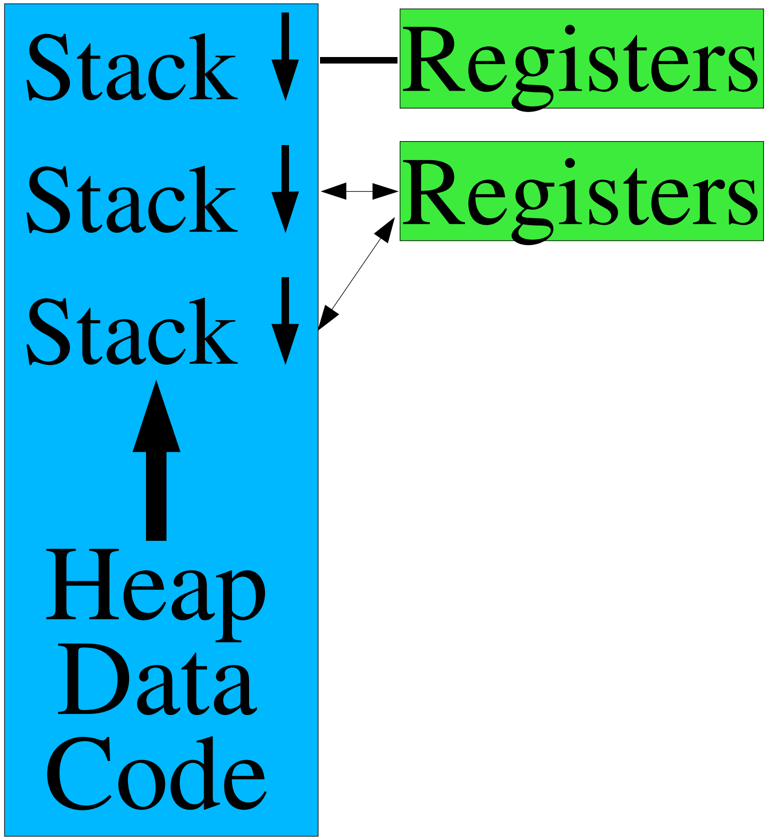
- User-space libraries must be rewritten to be “thread safe”

- Requires more kernel memory
  - 1 PCB $\Rightarrow$ N TCB's,
  - 1 k-stack $\Rightarrow$ N k-stacks

Many-to-many (M:N)

Middle ground

- OS provides kernel threads
- M user threads *share* N kernel threads



Many-to-many (M:N)

Sharing patterns

- Dedicated
  - User thread 12 owns kernel thread 1
- Shared
  - 1 kernel thread per hardware CPU
  - Each kernel thread executes next runnable user thread
- Many variations, see text

Features

- Great when all the schedulers work together as you expected!

(Against) Thread Cancellation

Thread cancellation

- We don't want the result of that computation
  - ("Cancel button")

Asynchronous (immediate) cancellation

- Stop execution *now*
  - Free stack, registers
  - Poof!
- Hard to garbage-collect resources (open files, ...)
- Invalidates data structure consistency!

(Against) Thread Cancellation

Deferred ("pretty please") cancellation

- Write down “thread #314, please go away”
- Threads must check for cancellation
- Or define safe cancellation points
  - “Any time I call close() it's ok to zap me”

The only safe way (IMHO)

Race conditions

What you think

```
ticket = next_ticket++; /* 0 ⇒ 1 */
```

What really happens (in general)

```
ticket = temp = next_ticket; /* 0 */
++temp; /* 1, but not visible */
next_ticket = temp; /* 1 is visible */
```

Murphy' s Law (of threading)

The world may *arbitrarily interleave* execution

- Multiprocessor
  - N threads executing instructions *at the same time*
  - Of course effects are interleaved!
- Uniprocessor
  - Only one thread running at a time...
  - But N threads runnable, timer counting down toward zero...

The world will choose the *most painful* interleaving

- "Once chance in a million" happens every minute

Race Condition – Your Hope

T0		*T1*	
`tkt = tmp = n_tkt;`	0		
`++tmp;`	1		
`n_tkt = tmp;`	1		
		`tkt = tmp = n_tkt;`	1
		`++tmp;`	2
		`n_tkt = tmp;`	2
`Final value`	1		2

Race Condition – Your Bad Luck

T0		*T1*	
`tkt = tmp = n_tkt;`	0		
		`tkt = tmp = n_tkt;`	0
`++tmp;`	1		
		`++tmp;`	1
`n_tkt = tmp;`	1		
		`n_tkt = tmp;`	1
Final value	1		1

Two threads have same "ticket"!

What happened?

Each thread did "something reasonable"

- ...assuming no other thread were touching those objects
- ...that is, assuming *"mutual exclusion"*

The world is cruel

- Any possible scheduling mix *will* happen sometime
- The one you fear will happen...
- The one you didn't think of will happen...

The #! shell-script hack

What's a "shell script"?

- A file with a bunch of (shell-specific) shell commands

```
#!/bin/sh
echo "My hovercraft is full of eels"
sleep 10
exit 0
```

- Or: a security race-condition just waiting to happen...

The #! shell-script hack

What's "#!"?

- A venerable hack

You say

- execl("/foo/script", "script", "arg1", 0);

/foo/script begins...

- #!/bin/sh

The kernel rewrites your system call...

- execl("/bin/sh" "/foo/script" "arg1" , 0);

The shell does

- open("/foo/script", O_RDONLY, 0);

The setuid invention

U.S. Patent #4,135,240

- Dennis M. Ritchie
- January 16, 1979

The concept

- A program with *stored privileges*
- When executed, runs with *two* identities
  - invoker's identity
  - program owner's identity
- Can switch identities at will
  - Open some files as invoker
  - Open other files as program-owner

Setuid example - printing a file

Goals

- Every user can queue files
- Users cannot delete other users' files

Solution

- Queue directory owned by user `printer`
- Setuid `queue-file` program
  - Create queue file as user `printer`
  - Copy joe's data as user `joe`
- User `printer` controls user `joe`'s queue access

Race condition example

Process 0	*Process 1*
`ln -s /bin/lpr /tmp/lpr`	
	`run /tmp/lpr`
	`[setuid to user "printer"]`
	`start "/bin/sh /tmp/lpr..."`
`rm /tmp/lpr`	
`ln -s /my/exploit /tmp/lpr`	
	`script = open("/tmp/lpr");`
	`execute /my/exploit`

What happened?

Intention

- Assign privileges to program contents

What happened?

- Privileges were assigned to program *name*
- Program name was re-bound to different *contents*

How would you fix this?

How to solve race conditions?

Carefully analyze operation sequences

Find subsequences which must be *uninterrupted*

- “Critical section”

Use a *synchronization mechanism*

- Next time!

Summary

Thread: What, why

Thread flavors (ratios)

Race conditions

- ***Make sure you really understand this***