CS162
Operating Systems and Systems Programming
Lecture 4

Synchronization, Atomic operations, Locks

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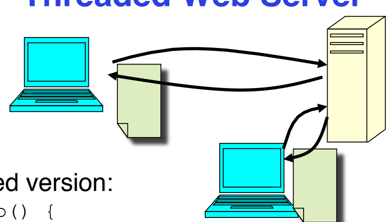
Why allow cooperating threads?

- 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
  – Multiprocessors – chop up program into parallel pieces
- Advantage 3: Modularity
  – Chop large problem up into simpler pieces
    » To compile, for instance, gcc calls cpp | cc1 | cc2 | as | ld
    » Makes system easier to extend

Threaded Web Server



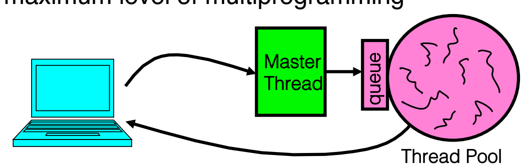
- Multithreaded version:

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

- Advantages of threaded version:
  – 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
- What if too many requests come in at once?

Thread Pools

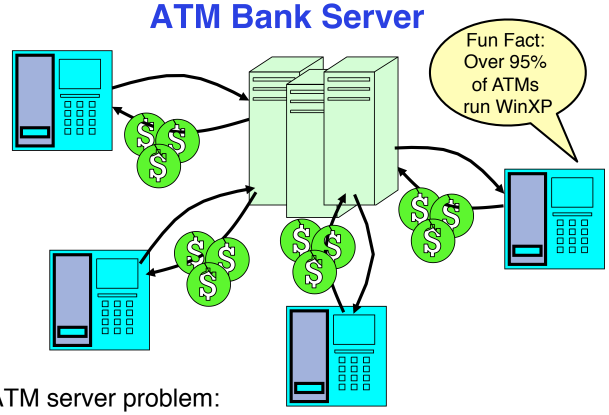
- Problem with previous version: Unbounded Threads
  – When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded "pool" of threads, representing the maximum level of multiprogramming




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

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

ATM Bank Server



- ATM server problem:
  - Service a set of requests
  - Do so without corrupting database
  - Don't hand out too much money

ATM bank server example

- Suppose we wanted to implement a server process to handle requests from an ATM network:

```
BankServer() {
   while (TRUE) {
      ReceiveRequest(&op, &acctId, &amount);
      ProcessRequest(op, acctId, amount);
   }
}
ProcessRequest(op, acctId, amount) {
   if (op == deposit) Deposit(acctId, amount);
   else if …
}
Deposit(acctId, amount) {
   acct = GetAccount(acctId); /* may use disk I/O */
   acct->balance += amount;
   StoreAccount(acct); /* Involves disk I/O */
}
```

- How could we speed this up?
  - More than one request being processed at once
  - Multiple threads (multi-proc, or overlap comp and I/O)

Can Threads Help?

- One thread per request!

- Requests proceeds to completion, blocking as required:

```
Deposit(acctId, amount) {
  acct = GetAccount(actId); /* May use disk I/O */
  acct->balance += amount;
  StoreAccount(acct);       /* Involves disk I/O */
}
```

- Unfortunately, shared state can get corrupted:

Thread 1	Thread 2
`load r1, acct->balance`	
	`load r1, acct->balance`
	`add r1, amount2`
	`store r1, acct->balance`
`add r1, amount1`	
`store r1, acct->balance`	

Problem is at the lowest level

- Most of the time, threads are working on separate data, so scheduling doesn't matter:

Thread A	Thread B
x = 1;	y = 2;

- However, What about (Initially, y = 12):

Thread A	Thread B
x = 1;	y = 2;
x = y+1;	y = y*2;

  - What are the possible values of x?

Thread A	Thread B
x = 1;	
x = y+1;	
	y = 2;
	y = y*2

x=13

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	y = 2;
	y = y*2;
x = 1;	
x = y+1;	

x=5

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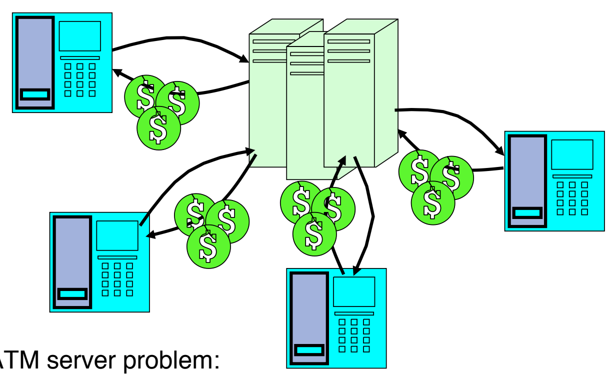
x = 1;	
x = y+1;	
	y= y*2;

x=3

Recap: ATM Bank Server



- ATM server problem:
  – Service a set of requests
  – Do so without corrupting database
  – Don't hand out too much money

Recap: Challenge of Threads

- Speed up server by using multiple threads (one per request)
  – Can use multi-processor, or overlap comp and I/O
- Requests proceeds to completion, blocking as required:

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Preemption can occur at any time!

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x=3

Preemption can occur at any time!

Goals for Today

- Concurrency examples and sharing
- Synchronization
- Hardware Support for Synchronization

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Slides courtesy of Anthony D. Joseph, John Kubiatowicz, AJ Shankar, George Necula, Alex Aiken, Eric Brewer, Ras Bodik, Ion Stoica, Doug Tygar, and David Wagner.

Correctness Requirements

- Threaded programs must work for all interleavings of thread instruction sequences
  - Cooperating threads inherently non-deterministic and non-reproducible
  - Really hard to debug unless carefully designed!
- Example: Therac-25
  - Machine for radiation therapy
    - » Software control of electron accelerator and electron beam/ Xray production
    - » Software control of dosage
  - Software errors caused overdoses and the death of several patients
    - » A series of race conditions on shared variables and poor software design
    - » "They determined that data entry speed during editing was the key factor in producing the error condition: If the prescription data was edited at a fast pace, the overdose occurred."

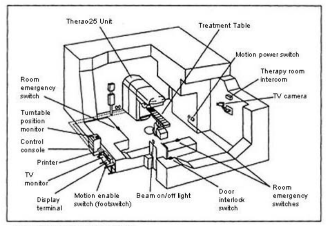
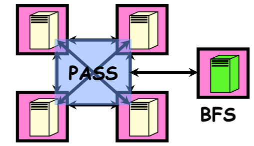


Figure 1. Typical Therac-25 facility

Space Shuttle Example

- Original Space Shuttle launch aborted 20 minutes before scheduled launch
- Shuttle has five computers:
  - Four run the "Primary Avionics Software System" (PASS)
    - » Asynchronous and real-time
    - » Runs all of the control systems
    - » Results synchronized and compared 440 times per second
  - The Fifth computer is the "Backup Flight System" (BFS)
    - » Stays synchronized in case it is needed
    - » Written by completely different team than PASS



- Countdown aborted because BFS disagreed with PASS
  - A 1/67 chance that PASS was out of sync one cycle
  - Bug due to modifications in initialization code of PASS
    - » A delayed init request placed into timer queue
    - » As a result, timer queue not empty at expected time to force use of hardware clock
  - Bug not found during extensive simulation

Atomic Operations

- To understand a concurrent program, we need to know what the underlying atomic operations are!
- Atomic Operation: an operation that always runs to completion or not at all
  - It is *indivisible:* it cannot be stopped in the middle and state cannot be modified by someone else in the middle
  - Fundamental building block – if no atomic operations, then have no way for threads to work together
- On most machines, memory references and assignments (i.e. loads and stores) of words are atomic
- Many instructions are not atomic
  - Double-precision floating point store often not atomic
  - VAX and IBM 360 had an instruction to copy a whole array

Concurrency Challenges

- Multiple computations (threads) executing in parallel to
  - share resources, and/or
  - share data
- Fine grain sharing:
  - ⇑ increase concurrency → better performance
  - ⇓ more complex
- Coarse grain sharing:
  - ⇑ Simpler to implement
  - ⇓ Lower performance
- Examples:
  - Sharing CPU for 10ms vs. 1min
  - Sharing a database at the row vs. table granularity

Motivation: "Too much milk"

- Great thing about OS's – analogy between problems in OS and problems in real life
  - Help you understand real life problems better
  - But, computers are much stupider than people
- Example: People need to coordinate:

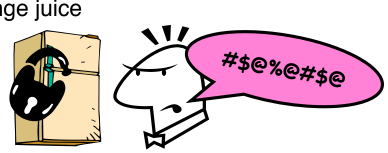
Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

Definitions

- Synchronization: using atomic operations to ensure cooperation between threads
  - For now, only loads and stores are atomic
  - We'll show that is hard to build anything useful with only reads and writes
- Critical Section: piece of code that only one thread can execute at once
- Mutual Exclusion: ensuring that only one thread executes critical section
  - One thread *excludes* the other while doing its task
  - Critical section and mutual exclusion are two ways of describing the same thing

More Definitions

- Lock: prevents someone from doing something
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting
- Example: fix the milk problem by putting a lock on refrigerator
  - Lock it and take key if you are going to go buy milk
  - Fixes too much (coarse granularity): roommate angry if only wants orange juice



  - Of Course – We don't know how to make a lock yet

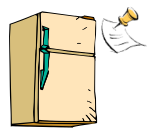
Too Much Milk: Correctness Properties

- Need to be careful about correctness of concurrent programs, since non-deterministic
  - Always write down **desired** behavior first
  - Impulse is to start coding first, then when it doesn't work, pull hair out
  - Instead, think first, then code
- What are the correctness properties for the "Too much milk" problem?
  - Never more than one person buys
  - Someone buys if needed
- Restrict ourselves to use only atomic load and store operations as building blocks

Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
  - Leave a note before buying (kind of "lock")
  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

```
if (noMilk) {
   if (noNote) {
      leave Note;
      buy milk;
      remove note;
   }
}
```



- Result?

Too Much Milk: Solution #1

- Still too much milk but only occasionally!

```
  Thread A                  Thread B
if (noMilk)
  if (noNote) {
                         if (noMilk)
                           if (noNote) {
    leave Note;
    buy milk;
    remove note;
  }
}
                               leave Note;
                               buy milk;
                               …
```

- Thread can get context switched after checking milk and note but before leaving note!
- Solution makes problem worse since fails intermittently
  - Makes it really hard to debug…
  - Must work despite what the thread dispatcher does!

Too Much Milk: Solution #1½

- Clearly the Note is not quite blocking enough
  - Let's try to fix this by placing note first
- Another try at previous solution:

```
leave Note;
if (noMilk) {
   if (noNote) {
      buy milk;
   }
}
remove Note;
```

- What happens here?
  - Well, with human, probably nothing bad
  - With computer: no one ever buys milk

Too Much Milk Solution #2

- How about labeled notes?
  - Now we can leave note before checking
- Algorithm looks like this:

Thread A	Thread B

`leave note A;`
`if (noNote B) {`
`   if (noMilk) {`
`      buy Milk;`
`   }`
`}`
`remove note A;`
	`leave note B;`
	`if (noNote A) {`
	`   if (noMilk) {`
	`      buy Milk;`
	`   }`
	`}`
	`remove note B;`

- Does this work?

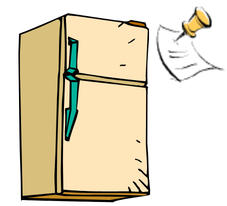
Too Much Milk Solution #2

- Possible for neither thread to buy milk!

```
Thread A                         Thread B
leave note A;
                                 leave note B;
                                 if (noNote A) {
                                    if (noMilk) {
                                       buy Milk;
                                    }
                                 }
if (noNote B) {
   if (noMilk) {
      buy Milk;
      …
                                 remove note B;
```

- Really insidious:
  - Unlikely that this would happen, but will at worse possible time

Too Much Milk Solution #2: problem!



- *I'm* not getting milk, *You're* getting milk
- This kind of lockup is called "starvation!"

Administrivia

- Section assignments posted on Piazza
  - Most groups were assigned 1st or 2nd preference
  - Attend assigned sections THIS week
- Nachos Project I begins tomorrow (Threads)
  - Start reading walkthrough and code NOW
  - Download Nachos tar file
  - Set up Java environment, Eclipse, version control
  - More details in sections
- Sections will have weekly quizzes
  - New grade breakdown: 50% projects, 40% exams, 5% participation (lectures/sections/Piazza), 5% quizzes
  - May have quizzes in lectures

5min Break

Too Much Milk Solution #3

- Here is a possible two-note solution:

Thread A
```
leave note A;
while (note B) {\\X
   do nothing;
}
if (noMilk) {
   buy milk;
}
remove note A;
```

Thread B
```
leave note B;
if (noNote A) {\\Y
   if (noMilk) {
      buy milk;
   }
}
remove note B;
```

- Does this work? Yes. Both can guarantee that:
  - It is safe to buy, or
  - Other will buy, ok to quit
- At X:
  - if no note B, safe for A to buy,
  - otherwise wait to find out what will happen
- At Y:
  - if no note A, safe for B to buy
  - Otherwise, A is either buying or waiting for B to quit

Solution #3 discussion

- Our solution protects a single "Critical-Section" piece of code for each thread:

```
if (noMilk) {
   buy milk;
}
```

- Solution #3 works, but it's really unsatisfactory
  - Really complex – even for this simple an example
    - » Hard to convince yourself that this really works
  - A's code is different from B's – what if lots of threads?
    - » Code would have to be slightly different for each thread
  - While A is waiting, it is consuming CPU time
    - » This is called "busy-waiting"
- There's a better way
  - Have hardware provide better (higher-level) primitives than atomic load and store
  - Build even higher-level programming abstractions on this new hardware support

High-Level Picture

- The abstraction of threads is good:
  - Maintains sequential execution model
  - Allows simple parallelism to overlap I/O and computation
- Unfortunately, still too complicated to access state shared between threads
  - Consider "too much milk" example
  - Implementing a concurrent program with only loads and stores would be tricky and error-prone
- We'll implement higher-level operations on top of atomic operations provided by hardware
  - Develop a "synchronization toolbox"
  - Explore some common programming paradigms

Too Much Milk: Solution #4

- Suppose we have some sort of implementation of a lock (more in a moment)
  - `Lock.Acquire()` – wait until lock is free, then grab
  - `Lock.Release()` – unlock, waking up anyone waiting
  - These must be atomic operations – if two threads are waiting for the lock, only one succeeds to grab the lock
- Then, our milk problem is easy:

```
milklock.Acquire();
if (nomilk)
   buy milk;
milklock.Release();
```

- Once again, section of code between `Acquire()` and `Release()` called a "Critical Section"

How to Implement Lock?

- Lock: prevents someone from accessing something
  - Lock before entering critical section (e.g., before accessing shared data)
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting
    - » Should sleep if waiting for long time

- Hardware lock instructions
  - Is this a good idea?
  - What about putting a task to sleep?
    - » How do handle interface between hardware and scheduler?
  - Complexity?
    - » Each feature makes hardware more complex and slower

Naïve use of Interrupt Enable/Disable

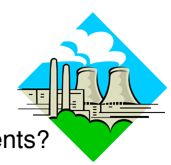
- How can we build multi-instruction atomic operations?
  - Recall: dispatcher gets control in two ways.
    - » Internal: Thread does something to relinquish the CPU
    - » External: Interrupts cause dispatcher to take CPU
  - On a uniprocessor, can avoid context-switching by:
    - » Avoiding internal events (although virtual memory tricky)
    - » Preventing external events by disabling interrupts
- Consequently, naïve Implementation of locks:

```
LockAcquire { disable Ints; }
LockRelease { enable Ints; }
```


Naïve use of Interrupt Enable/Disable: Problems

- Can't let user do this! Consider following:

```
LockAcquire();
While(TRUE) {;}
```



- Real-Time system—no guarantees on timing!
  - Critical Sections might be arbitrarily long
- What happens with I/O or other important events?
  - "Reactor about to meltdown. Help?"

Better Implementation of Locks by Disabling Interrupts

- Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```
int value = FREE;
```

```
Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    Go to sleep();
    // Enable interrupts?
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

```
Release() {
  disable interrupts;
  if (anyone on wait queue) {
    take thread off wait queue
    Put at front of ready queue
  } else {
    value = FREE;
  }
  enable interrupts;
}
```

New Lock Implementation: Discussion

- Disable interrupts: avoid interrupting between checking and setting lock value
  - Otherwise two threads could think that they both have lock

```
Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    Go to sleep();
    // Enable interrupts?
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

Critical Section

- Note: unlike previous solution, critical section very short
  - User of lock can take as long as they like in their own critical section
  - Critical interrupts taken in time

Interrupt re-enable in going to sleep

- What about re-enabling ints when going to sleep?

Enable Position
Enable Position
Enable Position

```
Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    go to sleep();
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

- Before putting thread on the wait queue?
  - Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  - Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  - Misses wakeup and still holds lock (deadlock!)
- Want to put it after sleep(). But, how?

How to Re-enable After Sleep()?

- Since ints are disabled when you call sleep:
  - Responsibility of the next thread to re-enable ints
  - When the sleeping thread wakes up, returns to acquire and re-enables interrupts

Thread A		Thread B
.		
.		
disable ints		
sleep	context switch →	
		yield return
		enable ints
		.
		.
		.
		disable int
	← context switch	yield
sleep return		
enable ints		
.		
.		

Summary

- Introduced important concept: Atomic Operations
  - An operation that runs to completion or not at all
  - These are the primitives on which to construct various synchronization primitives
- Showed construction of Locks using interrupts
  - Using careful disabling of interrupts
  - Must be very careful not to waste/tie up machine resources
    - » Shouldn't disable interrupts for long
  - Key ideas: Use a separate lock variable, and use hardware mechanisms to protect modifications of that variable