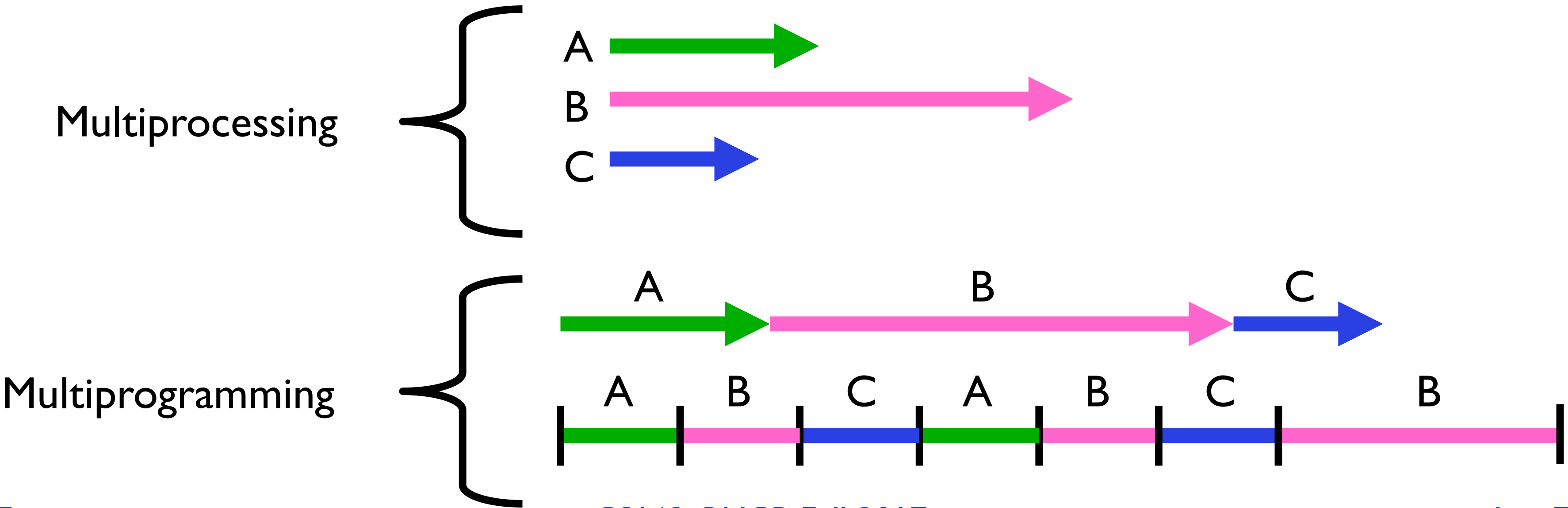
Synchronization(Too much milk)

Edited slids from http://cs162.eecs.Berkeley.edu

Multiprocessing vs Multiprogramming

- Remember Definitions:
  - Multiprocessing ≡ Multiple CPUs or cores or hyperthreads (HW per-instruction interleaving)
  - 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, …



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"

Why allow cooperating threads?

- 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

Can Threads Make This Easier?

- Threads yield overlapped I/O and computation without having to "deconstruct" code into non-blocking fragments
  - 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?
- Or, what are the possible values of x below?

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

  – X could be 1 or 2 (non-deterministic!)
  – Could even be 3 for serial processors:
    » Thread A writes 0001, B writes 0010 → scheduling order ABABABBA yields 3!

Atomic Operations

- To understand a concurrent program, we need to know what the underlying indivisible 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
  - Consequently – weird example that produces "3" on previous slide can't happen
- 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

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:

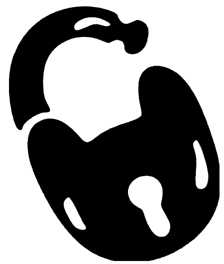
Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

Definitions

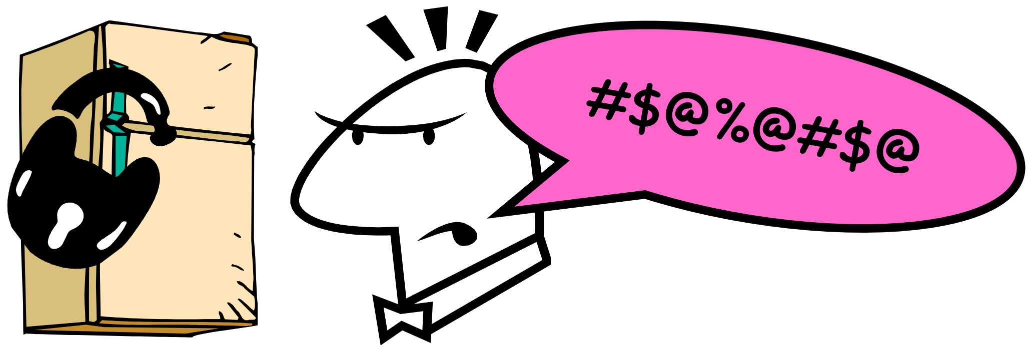
- Synchronization: using atomic operations to ensure cooperation between threads
  - For now, only loads and stores are atomic
  - We are going to show that its hard to build anything useful with only reads and writes
- Mutual Exclusion: ensuring that only one thread does a particular thing at a time
  - One thread *excludes* the other while doing its task
- Critical Section: piece of code that only one thread can execute at once. Only one thread at a time will get into this section of code
  - Critical section is the result of mutual exclusion
  - 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



- For example: fix the milk problem by putting a key on the refrigerator
  - Lock it and take key if you are going to go buy milk
  - Fixes too much: roommate angry if only wants OJ



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

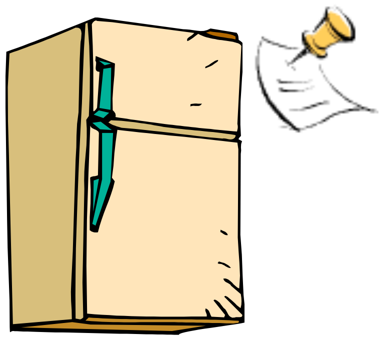
Too Much Milk: Correctness Properties

- Need to be careful about correctness of concurrent programs, since non-deterministic
  - Impulse is to start coding first, then when it doesn't work, pull hair out
  - Instead, think first, then code
  - Always write down behavior first
- 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;
   }
}
```



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):

Thread A

```
if (noMilk) {


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

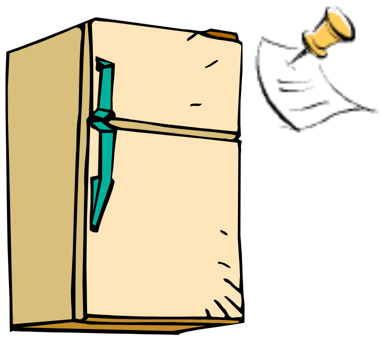
Thread B

```
if (noMilk) {
   if (noNote) {







     leave Note;
     buy Milk;
     remove Note;
   }
}
```

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?
  - Still too much milk but only occasionally!
  - Thread can get context switched after checking milk and note but before buying milk!
- Solution makes problem worse since fails intermittently
  - Makes it really hard to debug…
  - Must work despite what the 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) {
      leave Note;
      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

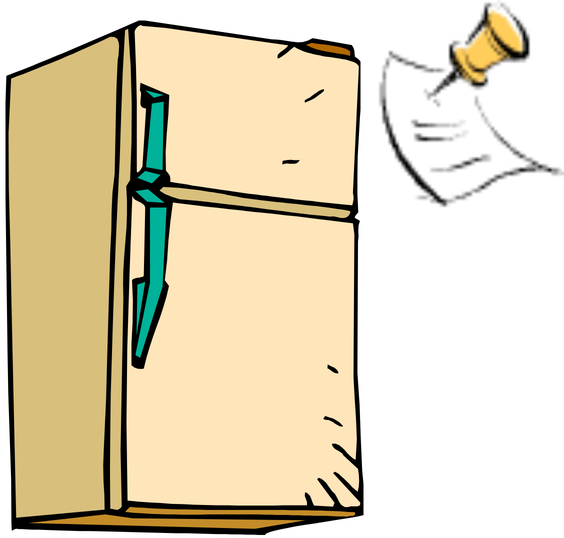
```
leave note A;
if (noNote B) {
   if (noMilk) {
      buy Milk;
   }
}
remove note A;
```

Thread B

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

- Does this work?
- Possible for neither thread to buy milk
  – Context switches at exactly the wrong times can lead each to think that the other is going to buy
- Really insidious:
  – Extremely unlikely that this would happen, but will at worse possible time
  – Probably something like this in UNIX

Too Much Milk Solution #2: problem!



- I thought *you* had the milk! But I thought *you* had the milk!
- This kind of lockup is called "starvation!"

Review: 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

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};

if (noMilk) {
    buy milk;}
}
remove note A;
```

happened before

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

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};

if (noMilk) {
    buy milk;}
}
remove note A;
```

happened before

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

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

happened before

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

Wait for note B to be remove

```
if (noMilk) {
    buy milk;}
}
remove note A;
```

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

happened before

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

```
leave note A;
while (note B) {\\X
    do nothing;
};

if (noMilk) {
    buy milk;}
}
remove note A;
```

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

happened before

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

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

```
if (noMilk) {
    buy milk;}
}
remove note A;
```

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

Wait for note B to be remove

```
if (noMilk) {
    buy milk;}
}
remove note A;
```

happened before

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

Review: 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 higher-level primitives than atomic load & store
  - Build even higher-level programming abstractions on this hardware support

Too Much Milk: Solution #4

- Suppose we have some sort of implementation of a lock
  - `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 and both see it's free, 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"
- Of course, you can make this even simpler: suppose you are out of ice cream instead of milk
  - Skip the test since you always need more ice cream ;-)

Where are we going with synchronization?

Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- We are going to implement various higher-level synchronization primitives using atomic operations
  – Everything is pretty painful if only atomic primitives are load and store
  – Need to provide primitives useful at user-level

Summary

- Concurrent threads are a very useful abstraction
  – Allow transparent overlapping of computation and I/O
  – Allow use of parallel processing when available

- Concurrent threads introduce problems when accessing shared data
  – Programs must be insensitive to arbitrary interleavings
  – Without careful design, shared variables can become completely inconsistent

- 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