Concurrency: Locks and synchronization

Slides by Prof. Cox

Constraining concurrency

- **Synchronization**
  - Controlling thread interleavings
- **Some events are independent**
  - No shared state
  - Relative order of these events don’t matter
- **Other events are dependent**
  - Output of one can be input to another
  - Their order can affect program results

Goals of synchronization

1. **All interleavings must give correct result**
   - Correct concurrent program
   - Works no matter how fast threads run
   - Important for your projects!
2. **Constrain program as little as possible**
   - Why?
   - Constraints slow program down
   - Constraints create complexity

“Too much milk” principals

“Too much milk” rules

- **The fridge must be stocked with milk**
  - Milk expires quickly, so never > 1 milk
- **Landon and Melissa**
  - Can come home at any time
  - If either sees an empty fridge, must buy milk
  - Code (no synchronization)

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

Unsynchronized code will break

Time		
3:00	Look in fridge (no milk)	
3:05	Go to grocery store	
3:10		Look in fridge (no milk)
3:15	Buy milk	
3:20		Go to grocery store
3:25	Arrive home, stock fridge	
3:30		Buy milk
3:35		Arrive home, stock fridge Too much milk!

What broke?

- **Code worked sometimes, but not always**
  - Code contained a **race condition**
  - Processor speed caused incorrect result
- **First type of synchronization**
  - **Mutual exclusion** inside **critical sections**

Synchronization concepts

- **Mutual exclusion**
  - Ensure 1 thread doing something at a time
  - E.g., 1 person shops at a time
  - Code blocks are **atomic** w/re to each other
  - Threads can’t run code blocks at same time

Synchronization concepts

- **Critical section**
  - Code block that must run atomically
  - “with respect to some other pieces of code”
- **If A and B are critical w/re to each other**
  - Threads mustn’t interleave code from A and B
  - A and B mutually exclude each other
- **Conflicting code is often same block**
  - But executed by different threads
  - Reads/writes shared data (e.g., screen, fridge)

Back to “Too much milk”

- **What is the critical section?**

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

- **Landon and Melissa’s critical sections**
  - Must be atomic w/re to each other

“Too much milk” solution 1

- **Assume only atomic load/store**
  - Build larger atomic section from load/store
- **Idea:**
  1. Leave notes to say you’re taking care of it
  2. Don’t check milk if there is a note

Solution 1 code

- **Atomic operations**
  - Atomic load: check note
  - Atomic store: leave note

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

Does it work?

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

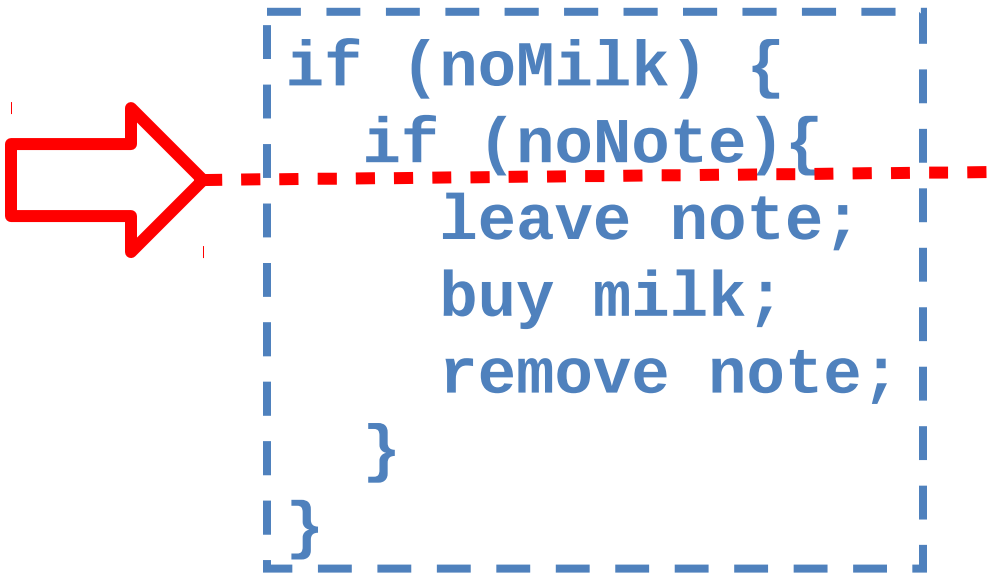
```
if (noMilk) {
  if (noNote){
    leave note;
    buy milk;
    remove note;
  }
}
```

Is this better than no synchronization at all?

What if “if” sections are switched?

What broke?

- **Melissa's events can happen**
  - After Landon checks for a note
  - Before Landon leaves a note



Next solution

- **Idea:**
  - Change the order of “leave note”, “check note”
  - Kind of like a reservation
  - Requires labeled notes (else you’ll see your note)

Does it work?

```
leave noteLandon
if (no noteMelissa){
  if (noMilk){
    buy milk;
  }
}
remove noteLandon
```

```
leave noteMelissa
if (no noteLandon){
  if (noMilk){
    buy milk;
  }
}
remove noteMelissa
```

Nope. (Illustration of “starvation.”)

What about now?

```
while (noMilk){
  leave noteLandon
  if(no noteMelissa){
    if(noMilk){
      buy milk;
    }
  }
  remove noteLandon
}
```

```
while (noMilk){
  leave noteMelissa
  if(no noteLandon){
    if(noMilk){
      buy milk;
    }
  }
  remove noteMelissa
}
```

Nope.
(Same starvation problem as before)

Next solution

- **We’re getting closer**
- **Problem**
  - Who buys milk if both leave notes?
- **Solution**
  - Let Landon hang around to make sure job is done

Does it work?

```
leave noteLandon
while (noteMelissa){
  do nothing
}
if (noMilk){
  buy milk;
}
remove noteLandon
```

```
leave noteMelissa
if (no noteLandon){
  if (noMilk){
    buy milk;
  }
}
remove noteMelissa
```

Yes! It does work! Can you show it?

Downside of solution

- **Complexity**
  - Hard to convince yourself it works
- **Asymmetric**
  - Landon and Melissa run different code
  - Approach doesn’t apply to > 2 people
- **Landon consumes CPU while waiting**
  - **Busy-waiting**
  - However, only needed atomic load/store

Raising the level of abstraction

- **Mutual exclusion with atomic load/store**
  - Painful to program
  - Wastes resources
  - Need more HW support
  - Will be covered later
- **OS can provide higher level abstractions**

Too much milk solution

```
leave noteLandon
while (noteMelissa){
  do nothing
}
if (noMilk){
  buy milk;
}
remove noteLandon
```

```
leave noteMelissa
if (no noteLandon){
  if (noMilk){
    buy milk;
  }
}
remove noteMelissa
```

Downside of solution

- **Complexity**
  - Hard to convince yourself it works
- **Asymmetric**
  - Landon and Melissa run different code
  - Approach doesn’t apply to > 2 people
- **Landon consumes CPU while waiting**
  - **Busy-waiting**
  - However, only needed atomic load/store

Raising the level of abstraction

- **Locks**
  - Also called **mutexes**
  - Provide mutual exclusion
  - Prevent threads from entering a critical section
- **Lock operations**
  - Lock (aka **`Lock::acquire`**)
  - Unlock (aka **`Lock::release`**)

Lock operations

- **Lock: wait until lock is free, then acquire it**

```
do {
  if (lock is free) {
    acquire lock
    break
  }
} while (1)
```

Must be atomic with respect to other threads calling this code

  - This is a busy-waiting implementation
  - We'll fix this in a few lectures
- **Unlock: atomic `release lock`**

Too much milk, solution 2

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

Block is not atomic.
Must atomically

- **check if lock is free**
- **grab it**

Why doesn't the note work as a lock?

Elements of locking

1. **The lock is initially free**
2. **Threads acquire lock before an action**
3. **Threads release lock when action completes**
4. **Lock() must wait if someone else has lock**

- **Key idea**
  - All synchronization involves waiting
- **Threads are either running or blocked**

Too much milk with locks?

```
lock ()
if (noMilk) {
   buy milk
}
unlock ()
```

```
lock ()
if (noMilk) {
   buy milk
}
unlock ()
```

- **Problem?**
  - Waiting for lock while other buys milk

Too much milk “w/o waiting”?

```
lock ()
if (noNote && noMilk){
  leave note “at store”
  unlock ()
  buy milk
  lock ()
  remove note
  unlock ()
} else {
  unlock ()
}
```

Not holding lock

```
lock ()
if (noNote && noMilk){
  leave note “at store”
  unlock ()
  buy milk
  lock ()
  remove note
  unlock ()
} else {
  unlock ()
}
```

Only hold lock while handling shared resource.

What about this?

```
lock ()
if (noMilk && noNote){
  leave note “at store”
  unlock ()
  buy milk
  stock fridge
  remove note
} else {
  unlock ()
}
```

```
lock ()
if (noMilk && noNote){
  leave note “at store”
  unlock ()
  buy milk
  stock fridge
  remove note
} else {
  unlock ()
}
```

Example: thread-safe queue

```
enqueue () {
  lock (qLock)
  // ptr is private
  // head is shared
  new_element = new node();
  if (head == NULL) {
    head = new_element;
  } else {
    node *ptr;
    // find queue tail
    for (ptr=head;
         ptr->next!=NULL;
         ptr=ptr->next){}

    ptr->next=new_element;
  }
  new_element->next=0;
  unlock(qLock);
}
```

```
dequeue () {
  lock (qLock);
  element=NULL;
  if (head != NULL) {
    // if queue non-empty
    if (head->next!=0) {
      // remove head
      element=head->next;
      head->next=
        head->next->next;
    } else {
      element = head;
      head = NULL;
    }
  }
  unlock (qLock);
  return element;
}
```

What can go wrong?

Thread-safe queue

- **Can enqueue unlock anywhere?**
  - No
- **Must leave shared data**
  - In a consistent/sane state
- **Data invariant**
  - “consistent/sane state”
  - “always” true

```
lock (qLock)
// ptr is private
// head is shared
new_element = new node();
if (head == NULL) {
head = new_element;
} else {
  node *ptr;
  // find queue tail
  for (ptr=head;
       ptr->next!=NULL;
       ptr=ptr->next){}

  ptr->next=new_element;
}
unlock(qLock); // safe?
new_element->next=0;
}
```

Invariants

- **What are the queue invariants?**
  - Each node appears once (from head to null)
  - Enqueue results in prior list + new element
  - Dequeue removes exactly one element
- **Can invariants ever be false?**
  - Must be
  - Otherwise you could never change states

More on invariants

- **So when is the invariant broken?**
  - Can only be broken while lock is held
  - And only by thread holding the lock

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More on invariants

- **So when is the invariant broken?**
  - Can only be broken while lock is held
  - And only by thread holding the lock
- **Really a “public” invariant**
  - The data’s state in when the lock is free
  - Like having your house tidy before guests arrive
- **Hold a lock whenever manipulating shared data**

More on invariants

- **What about reading shared data?**
  - Still must hold lock
  - Else another thread could break invariant
  - (Thread A prints Q as Thread B enqueues)

How about this?

I'm always holding a lock while accessing shared state.

ptr may not point to tail after lock/unlock.

```
enqueue () {
  lock (qLock)
  // ptr is private
  // head is shared
  new_element = new node();
  if (head == NULL) {
    head = new_element;
  } else {
    node *ptr;
    // find queue tail
    for (ptr=head;
         ptr->next!=NULL;
         ptr=ptr->next){}
    unlock(qLock);
    lock(qLock);
    ptr->next=new_element;
  }
  new_element->next=0;
  unlock(qLock);
```

Lesson:

- **Thinking about individual accesses is not enough**
- **Must reason about dependencies between accesses**

What about Java? Too much milk

```
synchronized (obj){
  if (noMilk) {
    buy milk
  }
}
```

```
synchronized (obj){
  if (noMilk) {
    buy milk
  }
}
```

- **Every object is a lock**
- **Use synchronized key word (lock =“{“, unlock=“}”)**

Synchronizing methods

```
public class CubbyHole {
  private int contents;

  public int get() {
    return contents;
  }

  public synchronized void put(int value) {
    contents = value;
  }
}
```

- **What does this mean? What is the lock?**
  - “this” is the lock

Synchronizing methods

```
public class CubbyHole {
  private int contents;

  public int get() {
    return contents;
  }

  public void put(int value)
    synchronized (this) {
      contents = value;
    }
  }
```

- **Equivalent to “synchronized (this)” block**

Intro to ordering constraints

- **Say you want dequeue to wait while the queue is empty**
- **Can we just busy-wait?**
  - No!
  - Still holding lock

```
dequeue () {
  lock (qLock);
  element=NULL;
  while (head==NULL) {}
  // remove head
  element=head->next;
  head->next=NULL;
  unlock (qLock);
  return element;
}
```

Release lock before spinning?

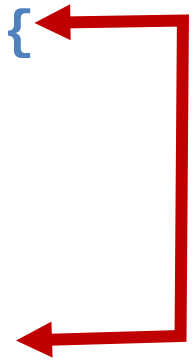
What can go wrong?
Head might be NULL when we try to remove entry

```
dequeue () {
  lock (qLock);
  element=NULL;
  unlock (qLock);
  while (head==NULL) {}
  lock (qLock);
  // remove head
  element=head->next;
  head->next=NULL;
  unlock (qLock);
  return element;
}
```

One more try

- **Does it work?**
  - Seems ok
- **Why?**
  - ShS protected
- **What's wrong?**
  - Busy-waiting
  - Wasteful

```
dequeue () {
  lock (qLock);
  element=NULL;
  while (head==NULL) {
    unlock (qLock);
    lock (qLock);
  }
  // remove head
  element=head->next;
  head->next=NULL;
  unlock (qLock);
  return element;
}
```



Ideal solution

- **Would like dequeueing thread to “sleep”**
  - Add self to “waiting list”
  - Enqueuer can wake up when Q is non-empty
- **Problem: what to do with the lock?**
  - Why can’t dequeueing thread sleep with lock?
  - Enqueuer would never be able to add

Release the lock before sleep?

```
enqueue () {
  acquire lock
  find tail of queue
  add new element
  if (dequeuer waiting){
    remove from wait list
    wake up dequeuer
  }
  release lock
}
```

```
dequeue () {
  acquire lock
  …
  if (queue empty) {
    release lock
    add self to wait list
    sleep
    acquire lock
  }
  …
  release lock
}
```

Does this work?

Release the lock before sleep?

```
enqueue () {
  acquire lock
  find tail of queue
  add new element
  if (dequeuer waiting){
    remove from wait list
    wake up dequeuer
  }
  release lock
}
```

```
dequeue () {
  acquire lock
  …
  if (queue empty) {
    release lock
    add self to wait list
    sleep
    acquire lock
  }
  …
  release lock
}
```

Thread can sleep forever

Release the lock before sleep?

```
enqueue () {
  acquire lock
  find tail of queue
  add new element
  if (dequeuer waiting){
    remove from wait list
    wake up dequeuer
  }
  release lock
}
```

```
dequeue () {
  acquire lock
  …
  if (queue empty) {
    add self to wait
    release lock
    sleep
    acquire lock
  }
  …
  release lock
}
```

Release the lock before sleep?

```
enqueue () {
  acquire lock
  find tail of queue
  add new element
  if (dequeuer waiting){
    remove from wait list
    wake up dequeuer
  }
  release lock
}
```

```
dequeue () {
  acquire lock
  …
  if (queue empty) {
    add self to wait list
    release lock
    sleep
    acquire lock
  }
  …
  release lock
}
```

In Monday's Class

- **Mutual exclusion is necessary, but insufficient**
- **Still need ordering constraints**
  - Often must wait for something to happen
  - Use something called “monitors”