Operating System Principles: Deadlocks – Problems and Solutions

CS 111

Operating Systems

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Outline

- The deadlock problem
  - Approaches to handling the problem
- Handling general synchronization bugs
- Simplifying synchronization

Deadlock

- What is a deadlock?
- A situation where two entities have each locked some resource
- Each needs the other's locked resource to continue
- Neither will unlock till they lock both resources
- Hence, neither can ever make progress

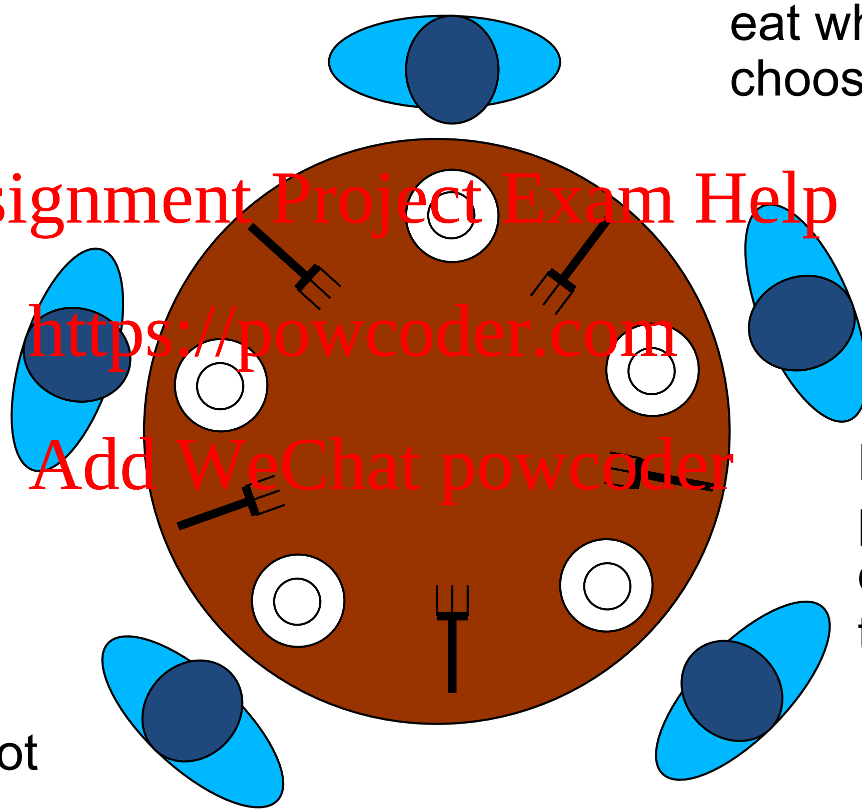
The Dining Philosophers Problem

Five philosophers at a table

Five plates of pasta

Five forks

Philosophers try to eat whenever they choose to



A philosopher needs two forks to eat pasta, but must pick them up one at a time

Ensure that philosophers will not deadlock while trying to eat

Philosophers will not negotiate with one another

The problem demands an <u>absolute</u> solution

Dining Philosophers and Deadlock

- This problem is the classic illustration of deadlocking
- It was created to illustrate deadlock problems
- It is a very artificial problem
  - It was carefully designed to cause deadlocks
  - Changing the rules eliminates deadlocks
  - But then it couldn't be used to illustrate deadlocks
  - Actually, one point of it is to see how changing the rules solves the problem

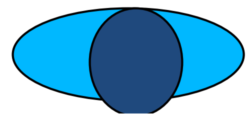
One Possible Dining Philosophers Deadlock

All five philosophers try to eat at the same time

Each grabs one fork

Result?

- No philosopher has two forks
- So no philosopher can eat



Deadlock!

- But no philosopher will release a fork before he eats
- So no philosopher will ever eat again

Why Are Deadlocks Important?

- A major peril in cooperating parallel processes
  - They are relatively common in complex applications
  - They result in catastrophic system failures
- Finding them through debugging is very difficult
  - They happen intermittently and are hard to diagnose
  - They are much easier to prevent at design time
- Once you understand them, you can avoid them
  - Most deadlocks result from careless/ignorant design
  - An ounce of prevention is worth a pound of cure

Deadlocks May Not Be Obvious

- Process resource needs are ever-changing
  - Depending on what data they are operating on
  - Depending on where in computation they are
  - Depending on what errors have happened
- Modern software depends on many services
  - Most of which are ignorant of one another
  - Each of which requires numerous resources
- Services encapsulate much complexity
  - We do not know what resources they require
  - We do not know when/how they are serialized

Deadlocks are not the only synchronization problem . . .

Deadlocks and Different Resource Types

- Commodity Resources
  - Clients need an amount of it (e.g., memory)
  - Deadlocks result from over-commitment
  - Avoidance can be done in resource manager
- General Resources
  - Clients need a specific instance of something
    - A particular file or semaphore
    - A particular message or request completion
  - Deadlocks result from specific dependency relationships
  - Prevention is usually done at design time

Four Basic Conditions For Deadlocks

- For a deadlock to occur, these conditions must hold:

1. Mutual exclusion

2. Incremental allocation

3. No pre-emption
4. Circular waiting

Deadlock Conditions: 1. Mutual Exclusion

- The resources in question can each only be used by one entity at a time
- If multiple entities can use a resource, then just give it to all of them
- If only one can use it, once you've given it to one, no one else gets it
  - Until the resource holder releases it

Deadlock Condition 2: Incremental Allocation

- Processes/threads are allowed to ask for resources whenever they want
  - As opposed to getting everything they need before they start
- If they must pre-allocate all resources, either:
  - They get all they need and run to completion
  - They don't get all they need and abort
- In either case, no deadlock

Deadlock Condition 3: No Pre-emption

- When an entity has reserved a resource, you can't take it away from him
  - Not even temporarily
- If you can, deadlocks are simply resolved by taking someone's resource away
  - To give to someone else
- But if you can't take anything away from anyone, you're stuck

Deadlock Condition 4: Circular Waiting

- A waits on B which waits on A
- In graph terms, there's a cycle in a graph of resource requests

- Could involve a lot more than two entities

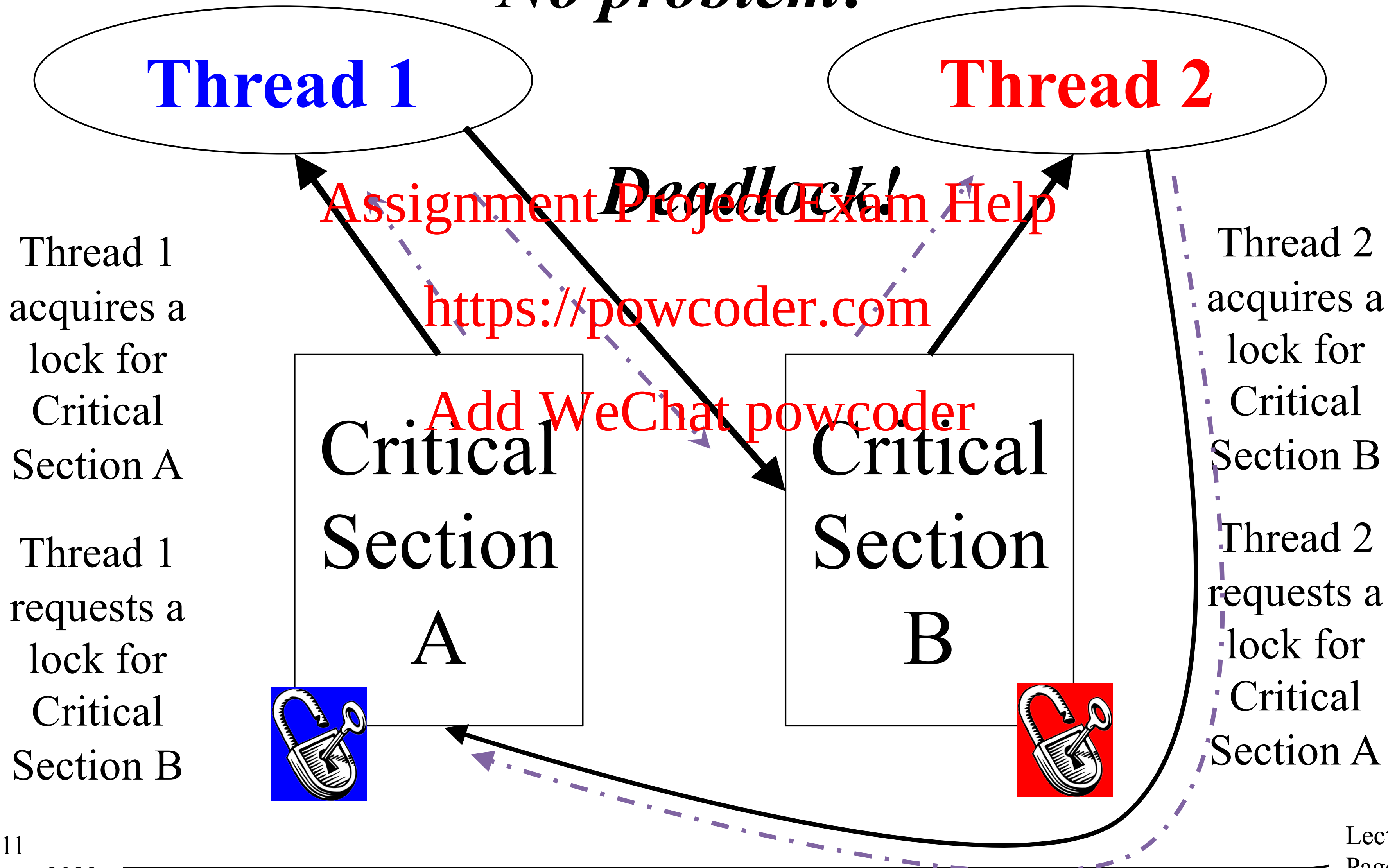
- But if there is no such cycle, someone can complete without anyone releasing a resource
  - Allowing even a long chain of dependencies to eventually unwind
  - Maybe not very fast, though . . .

We can’t give him the lock right now, but . . .

A Wait-For Graph

Hmmmm . . .

No problem!



Deadlock Avoidance

- Use methods that guarantee that no deadlock can occur, by their nature
- Advance reservations
  - The problems of under/over-booking
  - Dealing with rejection

Avoiding Deadlock Using Reservations

- Advance reservations for commodity resources
  - Resource manager tracks outstanding reservations
  - Only grants reservations if resources are available
- Over-subscriptions are detected early
  - Before processes ever get the resources
- Client must be prepared to deal with failures
  - But these do not result in deadlocks
- Dilemma: over-booking vs. under-utilization

Overbooking Vs. Under Utilization

- Processes generally cannot perfectly predict their resource needs
- To ensure they have enough, they tend to ask for more than they will ever need
- Either the OS:
  - Grants requests until everything's reserved
    - In which case most of it won't be used
  - Or grants requests beyond the available amount
    - In which case sometimes someone won't get a resource he reserved

How does the OS handle overbooking memory?

Handling Reservation Problems

- Clients seldom need all resources all the time
- All clients won't need max allocation at the same time
- Question: can one safely over-book resources?
  - For example, seats on an airplane
- What is a "safe" resource allocation?
  - One where everyone will be able to complete
  - Some people may have to wait for others to complete
  - We must be sure there are no deadlocks

Commodity Resource Management in Real Systems

- Advanced reservation mechanisms are common
  - Memory reservations
  - Disk quotas, Quality of Service contracts
- Once granted, system must guarantee reservations
  - Allocation failures only happen at reservation time
  - One hopes before the new computation has begun
  - Failures will not happen at request time
  - System behavior is more predictable, easier to handle
- But clients must deal with reservation failures

Dealing With Reservation Failures

- Resource reservation eliminates deadlock
- Apps must still deal with reservation failures
  - Application design should handle failures gracefully
    - E.g., refuse to perform new request, but continue running
  - App must have a way of reporting failure to requester
    - E.g., error messages or return codes
  - App must be able to continue running
    - All critical resources must be reserved at start-up time

Isn't Rejecting App Requests Bad?

- It's not great, but it's better than failing later
- With advance notice, app may be able to adjust service to not need the unavailable resource
- If app is in the middle of servicing a request, we may have other resources allocated
  – And the request half-performed
  – If we fail then, all of this will have to be unwound
  – Could be complex, or even impossible

Deadlock Prevention

- Deadlock avoidance tries to ensure no lock ever causes deadlock
- Deadlock prevention tries to assure that a particular lock doesn't cause deadlock
- By attacking one of the four necessary conditions for deadlock
- If any one of these conditions doesn't hold, no deadlock

Four Basic Conditions For Deadlocks

- For a deadlock to occur, these conditions must hold:

1. Mutual exclusion

2. Incremental allocation

3. No pre-emption
4. Circular waiting

1. Mutual Exclusion

- Deadlock requires mutual exclusion
  - P1 having the resource precludes P2 from getting it

- You can't deadlock over a shareable resource

  - Perhaps maintained with atomic instructions
  - Even reader/writer locking can help

    - Readers can share, writers may be handled other ways
- You can't deadlock on your private resources
  - Can we give each process its own private resource?

2. Incremental Allocation

- Deadlock requires you to block holding resources while you ask for others

1. Allocate all of your resources in a single operation
   - If you can’t get everything, system returns failure and locks nothing
   - When you return, you have all or nothing
2. Non-blocking requests
   - A request that can't be satisfied immediately will fail
3. Disallow blocking while holding resources
   - You must release all held locks prior to blocking
   - Reacquire them again after you return

Releasing Locks Before Blocking

- Could be blocking for a reason not related to resource locking
- How can releasing locks before you block help?
- Won't the deadlock just o attempt to reacquire them?
  - When you reacquire them, you will be required to do so in a single all-or-none transaction
  - Such a transaction does not involve hold-and-block, and so cannot result in a deadlock

Note: deadlock solutions solve deadlocks – they don't necessarily solve all your other problems!

They may even create new ones

3. No Pre-emption

- Deadlock can be broken by resource confiscation
  - Resource “leases” with time-outs and “lock breaking”
  - Resource can be seized & reallocated to new client
- Revocation must be enforced
  - Invalidate previous owner's resource handle
  - If revocation is not possible, kill previous owner
- Some resources may be damaged by lock breaking
  - Previous owner was in the middle of critical section
  - May need mechanisms to audit/repair resource
- Resources must be designed with revocation in mind

You solved your deadlock, but you broke your resource.

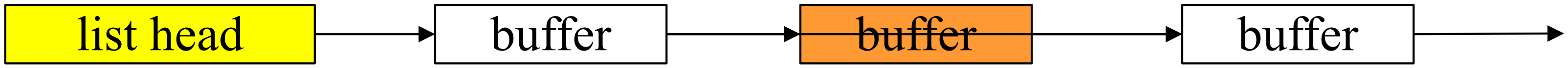
When Can The OS "Seize" a Resource?

- When it can revoke access by invalidating a process' resource handle
  - If process has to use a system service to access the resource, that service can stop honoring requests
- When can't the OS revoke a process' access to a resource?
  - If the process has direct access to the object
    - E.g., the object is part of the process' address space
    - Revoking access requires destroying the address space
    - Usually killing the process

4. Circular Dependencies

- Use *total resource ordering*
  - All requesters allocate resources in same order
  - First allocate R1 and then R2 afterwards
  - Someone else may have R2 but he doesn't need R1
- Assumes we know how to order the resources
  - Order by resource type (e.g., groups before members)
  - Order by relationship (e.g., parents before children)
- May require a *lock dance*
  - Release R2, allocate R1, reacquire R2

Lock Dances



<u>list head</u> must be locked for searching, adding & deleting

<u>individual buffers</u> must be locked to perform I/O & other operations

To avoid deadlock, we must always lock the <u>list head</u> before we lock an <u>individual buffer</u>.

Because we can't lock the list head while we hold the buffer lock

To find a desired buffer:

read lock list head
search for desired buffer
lock desired buffer
unlock list head
return (locked) buffer

To delete a (locked) bu

unlock buffer
write lock list head
search for desired buffer
lock desired buffer
remove from list
unlock list head

Which Approach Should You Use?

- There is no one universal solution to all deadlocks
  - Fortunately, we don't need one solution for all resources
  - We only need a solution for each resource
- Solve each individual problem any way you can
  - Make resources sharable wherever possible
  - Use reservations for commodity resources
  - Ordered locking or no hold-and-block where possible
  - As a last resort, leases and lock breaking
- OS must prevent deadlocks in all system services
  - Applications are responsible for their own behavior

One More Deadlock "Solution"

- Ignore the problem
- In many cases, deadlocks are very improbable
- Doing anything to avoid or prevent them might be very expensive
- So just forget about them and hope for the best
- But what if the best doesn't happen?

Deadlock Detection and Recovery

- Allow deadlocks to occur
- Detect them once they have happened
  - Preferably as soon as possible after they occur
- Do something to break the deadlock and allow someone to make progress
- Is this a good approach?
  - Either in general or when you don't want to avoid or prevent deadlocks?

Implementing Deadlock Detection

- To detect all deadlocks, need to identify all resources that can be locked
  - Not always clear in an OS
  - Especially if some locks are application level
- Must maintain wait-for graph or equivalent structure
- When lock requested, structure is updated and checked for deadlock
  - Better to just to reject the lock request?
  - And not let the requester block?

Deadlocks Outside the OS

- Some applications use locking internally
  - Not as an OS feature
  - But built into their own code
- Database systems are a main example
  - They often allow locking of records
  - And often enforce that locking
- The OS knows nothing of those locks
  - And thus offers no help in handling those deadlocks
- Deadlock detection may make sense here
  - Since the database knows of all relevant locks

Deadlocks here typically handled by rolling back one of the deadlocked transactions.

Not All Synchronization Bugs Are Deadlocks

- There are lots of reasons systems hang and make no progress
- Sometimes it really is a deadlock
- Sometimes it's something else
  - Livelock
  - Flaws in lock implementation
  - Simple bugs in how code operates
- If there are no locks, it's not a deadlock
- Even if there are locks, it might not be

Of course, just finding out your problem isn't a deadlock doesn't necessarily help solve it

An approach that handles the whole range of synchronization problems would be helpful

Dealing With General Synchronization Bugs

- Deadlock detection seldom makes sense
  - It is extremely complex to implement
  - Only detects true deadlocks for a known resource
  - Not always clear cut what you should do if you detect one
- Service/application *health monitoring* is better
  - Monitor application progress/submit test transactions
  - If response takes too long, declare service "hung"
- Health monitoring is easy to implement
- It can detect a wide range of problems
  - Deadlocks, live-locks, infinite loops & waits, crashes

Related Problems That Health Monitoring Can Handle

- Live-lock
  - Process is running, but won't free R1 until it gets message
  - Process that will send the message is blocked for R1

- Sleeping Beauty, waiting for "Prince Charming"

  - A process is blocked, awaiting some completion that will never happen
  - E.g., the sleep/wakeup race we talked about earlier

- Priority inversion hangs
  - Like the Mars Pathfinder case
- None of these is a true deadlock
  - Wouldn't be found by a deadlock detection algorithm
  - But all leave the system just as hung as a deadlock
- Health monitoring handles them

How To Monitor Process Health

- Look for obvious failures
  - Process exits or core dumps
- Passive observation to detect hangs
  - Is process consuming CPU time, or is it blocked?
  - Is process doing network and/or disk I/O?
- External health monitoring
  - “Pings”, null requests, standard test requests
- Internal instrumentation
  - White box audits, exercisers, and monitoring

What To Do With "Unhealthy" Processes?

- Kill and restart "all of the affected software"
- How many and which processes to kill?
  - As many as necessary, but as few as possible
  - The hung processes may not be the ones that are broken
- How will kills and restarts affect current clients?
  - That depends on the service APIs and/or protocols
  - Apps must be designed for cold/warm/partial restarts
- Highly available systems define restart groups
  - Groups of processes to be started/killed as a group
  - Define inter-group dependencies (restart B after A)

Failure Recovery Methodology

- Retry if possible ... but not forever
  - Client should not be kept waiting indefinitely
  - Resources are being held while waiting to retry
- Roll-back failed operations and return an error
- Continue with reduced capacity or functionality
  - Accept requests you can handle, reject those you can't
- Automatic restarts (cold, warm, partial)
- Escalation mechanisms for failed recoveries
  - Restart more groups, reboot more machines

Making Synchronization Easier

- Locks, semaphores, mutexes are hard to use correctly

  - Might not be used when needed

  - Might be used incorrectly

  - Might lead to deadlock, livelock, etc.
- We need to make synchronization easier for programmers
  - But how?

One Approach

- We identify shared resources
  - Objects whose methods may require serialization
- We write code to operate on those objects
  - Just write the code
  - Assume all critical sections will be serialized
- Complier generates the serialization
  - Automatically generated locks and releases
  - Using appropriate mechanisms
  - Correct code in all required places

Monitors – Protected Classes

- Each monitor object has a semaphore
  - Automatically acquired on <u>any</u> method invocation
  - Automatically released on method return
- Good encapsulation
  - Developers need not identify critical sections
  - Clients need not be concerned with locking
  - Protection is completely automatic
- High confidence of adequate protection

Monitors: Use

```
monitor CheckBook {
    // object is locked when any method is invoked
    private int balance;
    public int balance() {
        return(balance);
    }
    public int debit(int amount) {
        balance -= amount;
        return( balance)
    }
}
```

Monitors: Simplicity vs. Performance

- Monitor locking is very conservative
  - Lock the entire object on any method
  - Lock for entire duration of any method invocations
- This can create performance problems
  - They eliminate conflicts by eliminating parallelism
  - If a thread blocks in a monitor a convoy can form
- TANSTAAFL
  - Fine-grained locking is difficult and error prone
  - Coarse-grained locking creates bottle-necks

Java Synchronized Methods

- Each object has an associated mutex
  - Only acquired for specified methods
    - Not all object methods need be synchronized
  - Nested calls (by same thread) do not reacquire
  - Automatically released upon final return
- Static synchronized methods lock class mutex
- Advantages
  - Finer lock granularity, reduced deadlock risk
- Costs
  - Developer must identify serialized methods

Using Java Synchronized Methods

```
class CheckBook {
    private int balance;
    // object is not locked when this method is invoked
    public int balance() {
        return(balance)
    }
    // object is locked when this method is invoked
    public synchronized int debit(int amount) {
        balance -= amount;
        return( balance)
    }
}
```

Conclusion

- Parallelism is necessary in modern computers to achieve high speeds
- Parallelism brings with it many chances for serious errors
  - Generally non-deterministic errors
  - Deadlock is just one of them
- Those working with parallel code need to understand synchronization
  - Its problems and the solutions to those problems
  - And the costs associated with the solutions