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

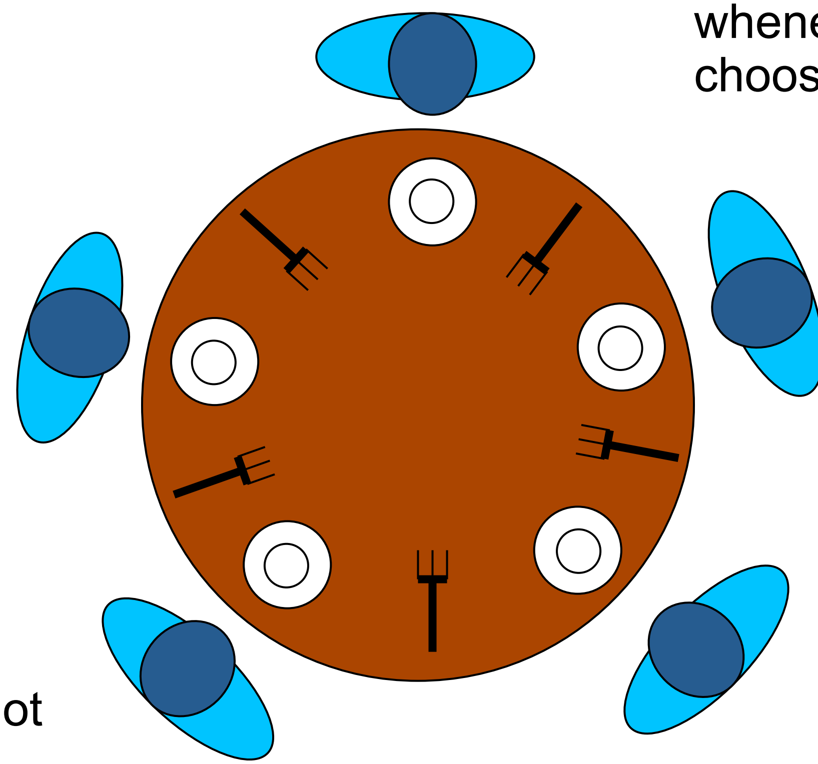
Deadlock

- 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
five plates of pasta
five forks

Philosophers eat
whenever they
choose to



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

Philosophers will not
negotiate with
one-another

The problem
demands an
absolute solution

Dining Philosophers and Deadlock

- This problem is the classical 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 eliminate 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

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 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 <u>design time</u>

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 it away from anyone, you're stuck

Deadlock Condition 4: Circular Waiting

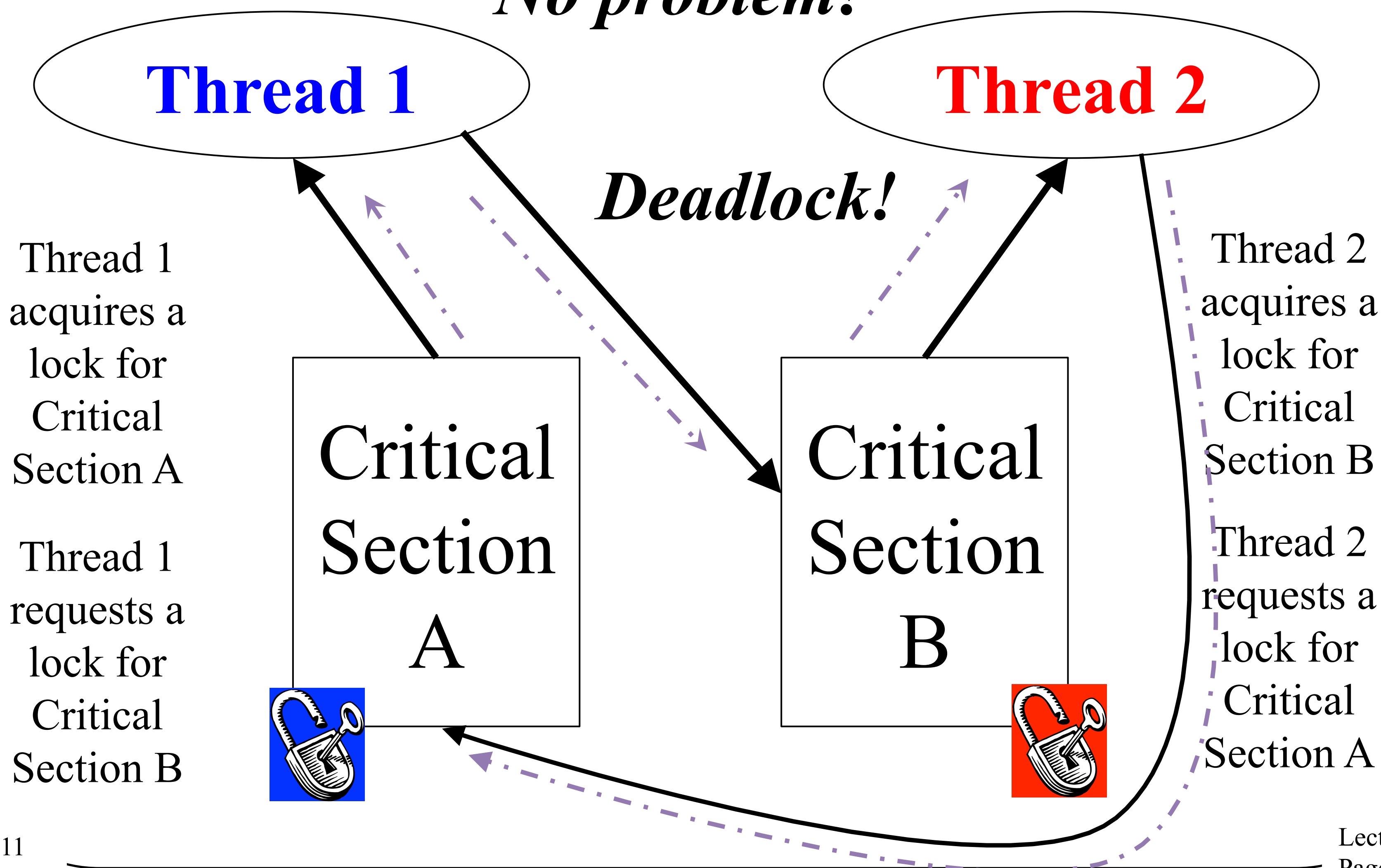
- A waits on B which waits on A
- In graph terms, there's a cycle in a graph of resource requests
- Could involve a lot more than two entities
- But if there is no such cycle, someone can complete without anyone releasing a resource
  - Allowing even a long chain of dependencies to eventually unwind
  - Maybe not very fast, though . . .

A Wait-For Graph

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

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
  - The Bankers' Algorithm
- Practical commodity resource management
- Dealing with rejection
- Reserving critical resources

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 till 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

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
  - Hopefully before the new computation has begun
  - Failures will not happen at request time
  - System behavior 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 not to 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

System Services and Reservations

- System services must never deadlock for memory
- Potential deadlock: swap manager
  - Invoked to swap out processes to free up memory
  - May need to allocate memory to build I/O request
  - If no memory available, unable to swap out processes
  - So it can't free up memory, and system wedges
- Solution:
  - Pre-allocate and hoard a few request buffers
  - Keep reusing the same ones over and over again
  - Little bit of hoarded memory is a small price to pay to avoid deadlock
- That's just one example system service, of course

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 <u>all or nothing</u>
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 occur when you 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

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

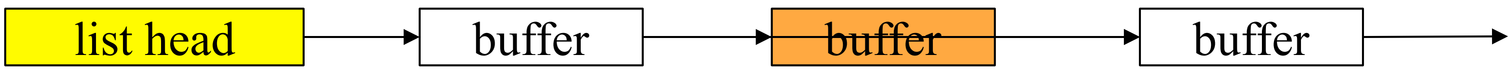
When Can The OS "Seize" a Resource?

- 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 no longer honor requests
- When is it not possible to 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



list head must be locked for searching, adding & deleting

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

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

To find a desired buffer:

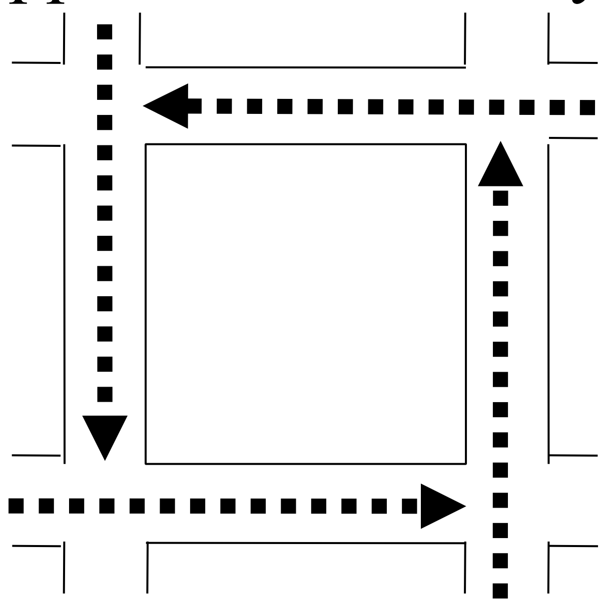
read lock list head
search for desired buffer
lock desired buffer
unlock list head
return (locked) buffer

To delete a (locked) buffer from list

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

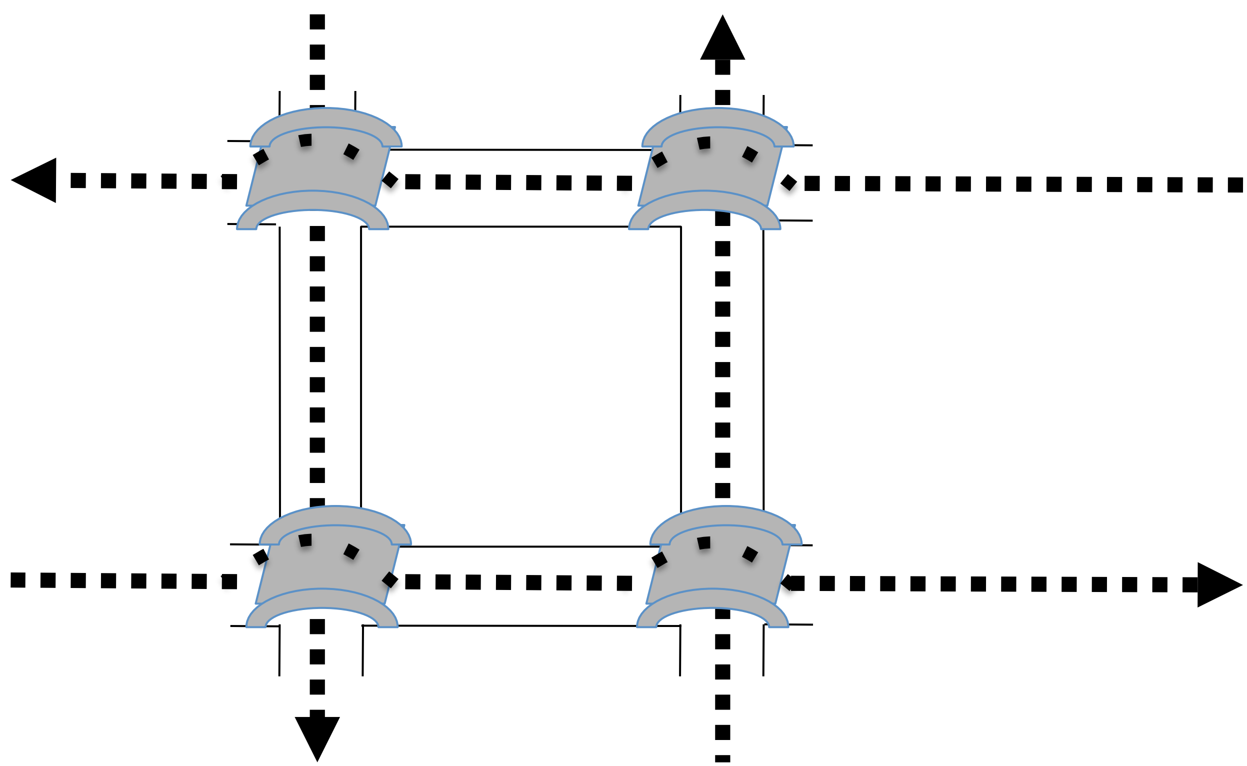
An Example of Breaking Deadlocks

- The problem – urban traffic gridlock
  - "Resource" is the ability to pass through intersection
  - Deadlock happens when nobody can get through



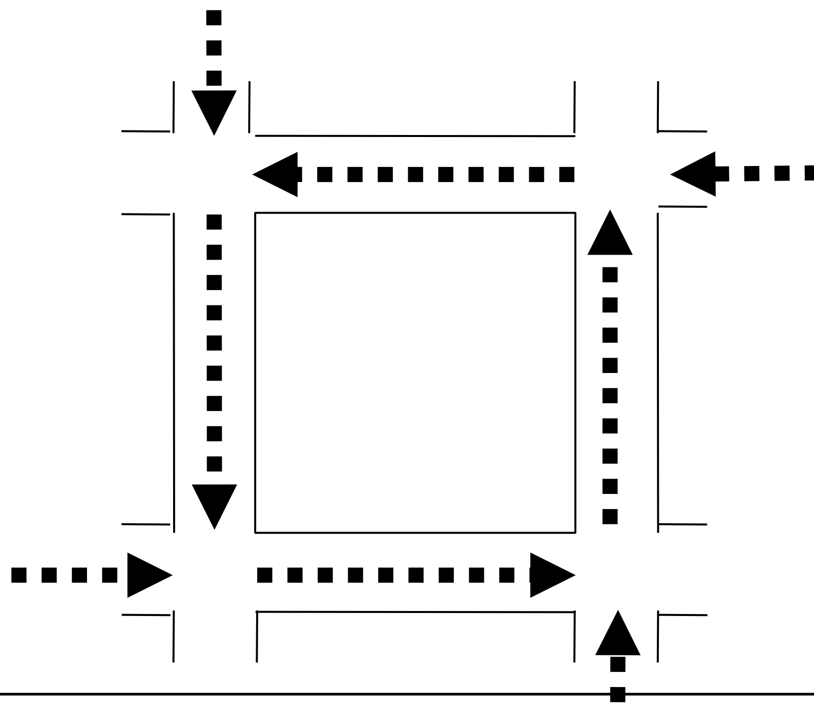
Using Attack Approach 1 To Prevent Deadlock

- Avoid mutual exclusion
- Build overpass bridges for east/west traffic



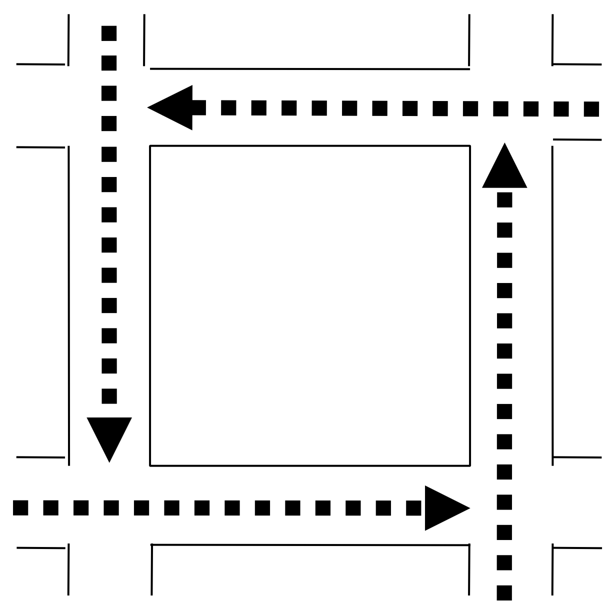
Using Attack Approach 2 To Prevent Deadlock

- Make it illegal to enter the intersection if you can't exit it
  – Thus, preventing "holding" of the intersection



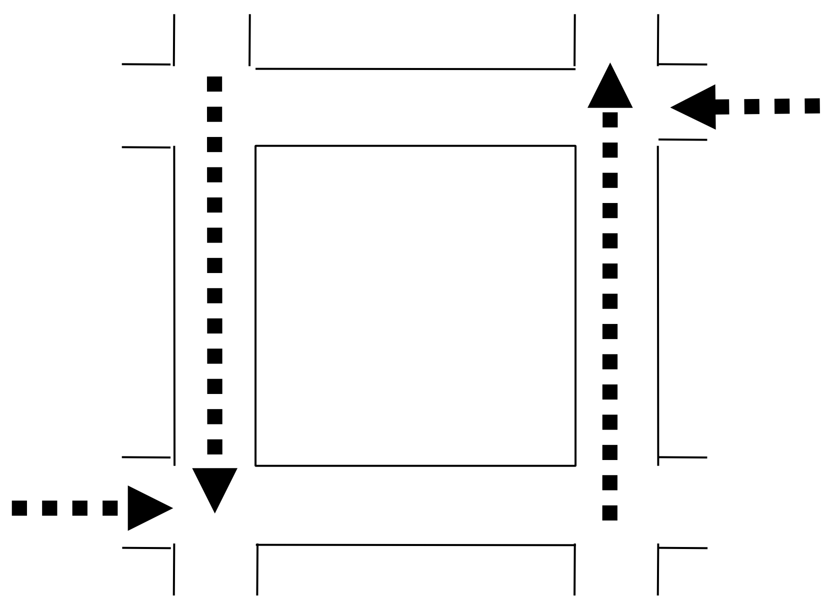
Using Attack Approach 3 To Prevent Deadlock

- Allow preemption
  - Force some car to pull over to the side



Using Attack Approach 4 To Prevent Deadlock

- Avoid circular dependencies by decreeing a totally ordered right of way
  - E.g., North beats West beats South beats East



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

- Need to identify all resources that can be locked
- Need to maintain wait-for graph or equivalent structure
- When lock requested, structure is updated and checked for deadlock
  - In which case, might it not be better just to reject the lock request?
  - And not let the requester block?

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 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
- Priority inversion hangs
  - Which we talked about before
- None of these is a true deadlock
  - Wouldn't be found by deadlock detection algorithm
  - 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 <u>class</u> has a semaphore
  - Automatically acquired on method invocation
  - Automatically released on method return
  - Automatically released/acquired around CV waits
- 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 {
	// class 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 class (not merely a specific object)
  - 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

Evaluating Monitors

- Correctness
  - Complete mutual exclusion is assured
- Fairness
  - Semaphore queue prevents starvation
- Progress
  - Inter-class dependencies can cause deadlocks
- Performance
  - Coarse grained locking is not scalable

Java Synchronized Methods

- Each object has an associated mutex
  - Acquired before calling a synchronized method
  - 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;
    public int balance() {
        return(balance);
    }
    // object is locked when this method is invoked
    public synchronized int debit(int amount) {
        balance -= amount;
        return( balance)
    }
}
```

Evaluating Java Synchronized Methods

- Correctness
  - Correct if developer chose the right methods
- Fairness
  - Priority thread scheduling (potential starvation)
- Progress
  - Safe from single thread deadlocks
- Performance
  - Fine grained (per object) locking
  - Selecting which methods to synchronize