Deadlock Prevention and Avoidance

7L. Higher level synchronization
7M. Lock-Free operations
8A. Overview of Deadlocks
8B. Deadlock Avoidance
8C. Deadlock Prevention
8D. Monitoring and Recovery
8E. Priority Inversion

Synchronization is Difficult

- recognizing potential critical sections
  – potential combinations of events
  – interactions with other pieces of code
- choosing the mutual exclusion method
  – there are many different mechanisms
  – with different costs, benefits, weaknesses
- correctly implementing the strategy
  – correct code, in all of the required places
  – maintainers may not understand the rules

We need a "Magic Bullet"

- 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)
        }
}
```


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

Java Synchronized: use

```
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

Encapsulated Locking

- opaquely encapsulate implementation details
  - make class easier to use for clients
  - preserve the freedom to change it later
- locking is entirely internal to class
  - search/update within the methods
  - critical sections involve only class resources
  - critical sections do not span multiple operations
  - no possible interactions with external resources

Client Locking

- Class cannot correctly synchronize all uses
- critical section spans multiple class operations
  - updates in a higher level transaction
- client-dependent synchronization needs
  - locking needs depend on how object is used
  - client may control access to protected objects
  - client may select best serialization method
- potential interactions with other resources
  - deadlock prevention must be at higher level

Non-Blocking Single Reader/Writer

```
int SPSC_put(SPSC *fifo, unsigned char c) {
    if (SPSC_bytesIn(fifo) == fifo->full)
        return(-1);
    *(fifo->write) = c;
    if (fifo->write == fifo->wrap)
        fifo->write = fifo->start;
    else
        fifo->write++;
    return( c );
}
```

```
int SPSC_get(SPSC *fifo) {
    if (SPSC_bytesIn(fifo) == 0)
        return(-1);
    int ret = *(fifo->read);
    if (fifo->read == fifo->wrap)
        fifo->read = fifo->start;
    else
        fifo->read++;
    return(ret);
}
```

```
int SPSC_bytesIn(SPSC *fifo) {
    return(fifo->write >= fifo->read ?
        fifo->write – fifo->read :
        fifo->full – (fifo->read – fifo->write));
}
```

Atomic Instructions – Compare & Swap

```
/*
 * Concept: Atomic Compare and Swap
 *       this is implemented in hardware, not code
 */
int CompareAndSwap( int *ptr, int expected, int new) {
    int actual = *ptr;
    if (actual == expected)
          *ptr = new;
    return( actual );
}
```


Solving the checkbook problem

```
int current_balance;
Writecheck( int amount ) {
   int oldbal, newbal;
   do {
      oldbal = current_balance;
      newbal = oldbal - amount;
      if (newbal <0) return (ERROR);
   } while (!compare_and_swap( &current_balance, oldbal, newbal))
...
}
```


Lock-Free Multi-Writer

```
// push an element on to a singly linked LIFO list
void SLL_push(SLL *head, SLL *element) {
    do {
         SLL *prev = head->next;
         element->next = prev;
    } while ( CompareAndSwap(&head->next, prev, element) != prev);
}
```


Spin Locks vs Atomic Updates

```
void SLL_push(SLL *head, SLL *element) {
    do {
         SLL *prev = head->next;
         element->next = prev;
    } while ( CompareAndSwap(&head->next, prev,  element) != prev);
}
```

```
DLL_insert(DLL *head, DLL*element) {
    while(TestAndSet(lock,1) == 1);
         DLL *last = head->prev;
         element->prev = last;
         element->next = head;
         last->next = element;
         head->prev = element;
    lock = 0;
}
```


(Spin Locks vs Atomic Update Loops)

- both involve spinning on an atomic update
- a spin-lock
  - spins until the lock is released
  - which could take a very long time
- an atomic update loop
  - spins until there is no conflict during the update
  - conflicting updates are actually very rare
  - if you fail, someone else must have succeeded
- comparable for <u>very</u> brief critical sections
  - e.g. a one-digit number of instructions

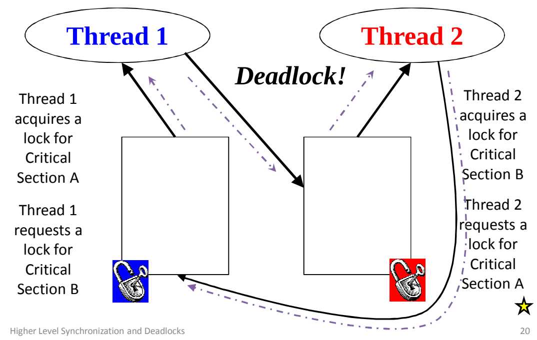
Evaluating Lock-Free Operations

- Effectiveness/Correctness
  - effective against all conflicting updates
  - cannot be used for complex critical sections
- Progress
  - no waiting for un-conflicted operations
  - no possibility of deadlock or convoy
- Fairness
  - small possibility of brief spins
- Performance
  - expensive instructions, but cheaper than syscalls

What is a Deadlock?

- Two (or more) processes or threads
  - cannot complete without all required resources
  - each holds a resource the other needs
- No progress is possible
  - each is blocked, waiting for another to complete
- Related problem: live-lock
  - processes not blocked, but cannot complete
- Related problem: priority inversion
  - high priority actor blocked by low priority actor

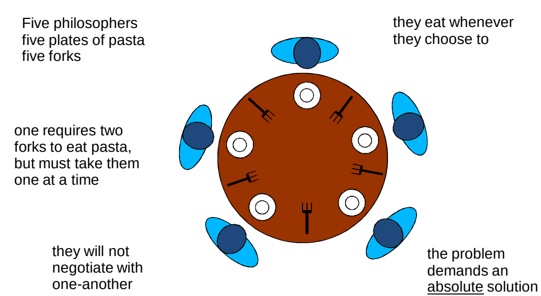
Resource Dependency Graph



Why Study Deadlocks?

- 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

The Dining Philosophers Problem



(The Dining Philosophers Problem)

- 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

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

Many Types of Deadlocks

- Different deadlocks require different solutions
- Commodity resource deadlocks
  - e.g. memory, queue space
- General resource deadlocks
  - e.g. files, critical sections
- Heterogeneous multi-resource deadlocks
  - e.g. P1 needs a file, P2 needs memory
- Producer-consumer deadlocks
  - e.g. P1 needs a file, P2 needs a message from P1

Commodity vs. General Resources

- 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 network
  - prevention is usually done at design time

Commodity Resource Problems

- memory deadlock
  - we are out of memory
  - we need to swap some processes out
  - we need memory to build the I/O request
- critical resource exhaustion
  - a process has just faulted for a new page
  - there are no free pages in memory
  - there are no free pages on the swap device

Avoidance – Advance Reservations

- advance reservations for commodities
  - 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

Real Commodity Resource Management

- advanced reservation mechanisms are common
  - Unix setbreak system call to allocate more memory
  - disk quotas, Quality of Service contracts
- once granted, reservations are guaranteed
  - 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 Rejection

- reservations eliminate difficult failures
  - recovering from a failure in mid-computation
  - may involve awkward and complex unwinding
- graceful handling of reservation failures
  - fail new request, but continue running
  - try to reserve essential resources at start-up time
- keep trying until it works ... not so good
  - may impose un-bounded delay on requestor
  - freeing resources or shedding load could help

Pre-reserving critical resources

- 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
- 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

Over-Booking vs. Under Utilization

- Problem: reservations overestimate requirements
  - 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

Deadlock Prevention

- Deadlock has <u>four necessary conditions</u>:
  1. **mutual exclusion**
     P1 cannot use a resource until P2 releases it
  2. **hold and wait**
     process already has R1 blocks to wait for R2
  3. **no preemption**
     R1 cannot be taken away from P1
  4. **circular dependency**
     P1 has R1, and needs R2
     P2 has R2, and needs R1

Attack #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 attacked in other ways
- you can't deadlock if you have private resources
  - can we give each process its own private resource?

Attack #2: hold and block

deadlock requires you to block holding resources

1. allocate all resources in a single operation
   - you hold nothing while blocked
   - when you return, you have <u>all or nothing</u>
2. disallow blocking while holding resources
   - you must release all held locks prior to blocking
   - reacquire them again after you return
3. non-blocking requests
   - a request that can't be satisfied immediately will fail

Attack #3: non-preemption

- deadlock prevents forwards progress
  - can we *back-out* of the deadlock?
  - reclaim resource(s) from current holders
- use *leases* rather than locks
  - process only has resource for a limited time
  - after which ownership is automatically lost
- forceful resource confiscation
- termination ... with extreme prejudice

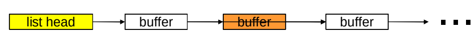
When is Preemption Feasible?

- Is access mediated by the operating system?
  – e.g. all object access is via system calls
  – we can revoke access, and return errors
- Can we force a graceful release of resource?
  – make a *claw-back* call to the current owner
- Does confiscation leave resource corrupted?
  – we can un-map a segment or kill a process
  – can we return resource to a default initial state?
  – is it protected by all-or-none updates?

Attack #4: circular dependencies

- 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" to preserve ordering



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:

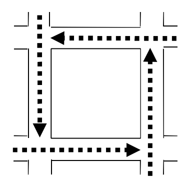
read lock list head
search for desired buffer
lock desired buffer
unlock list head
return (locked) buffer

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

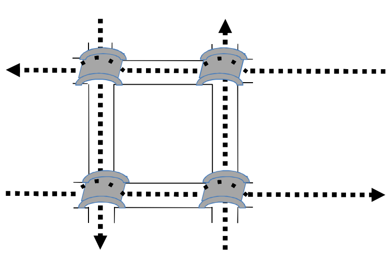
Deadlock – Practical Examples

- the problem – urban gridlock
  – resource: being in the intersection
  – deadlock: nobody can get through



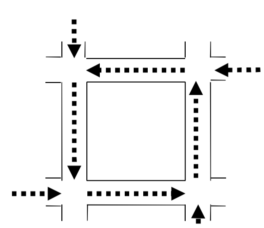
Prevention: Mutual Exclusion

- Build overpass bridges for east/west traffic



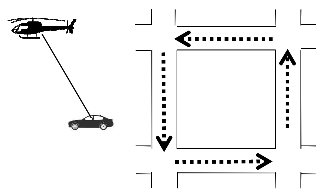
Prevention: Hold and Block

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



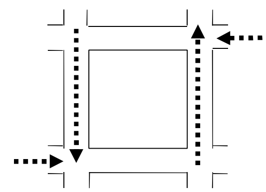
Prevention: Preemption

- Helicopters forcibly remove blocking vehicles



Prevention: Circular Dependencies

- decree a total ordering for right of way
  - e.g., North beats West beats South beats East



Deadlocks: divide and conquer!

- There is no one universal solution to all deadlocks
  - fortunately, we don't need a universal solution
  - 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

Closely related forms of "hangs"

- live-lock
  - process is running, but won't free R1 until it gets msg
  - process that will send the message is blocked for R1
- Sleeping Beauty, waiting for "Prince Charming"
  - a process is blocked, awaiting some completion
  - but, for some reason, it will never happen
- neither of these is a true deadlock
  - wouldn't be found by deadlock detection algorithm
  - both leave the system just as hung as a deadlock

Deadlock vs. "hang" detection

- deadlock detection seldom makes sense
  - it is extremely complex to implement
  - only detects true deadlocks for known resources
- service/application "health monitoring" does
  - 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

Hang/Failure Detection Methodology

- 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

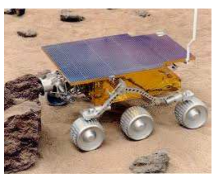
Automated Recovery

- kill and restart "all of the affected software"
- how will this affect service/clients
  - design services to automatically fail-over
  - components can warm-start, fall back to last check-point, or cold start
- which, and how many processes to kill?
  - define service failure/recovery zones
  - processes to be started/killed as a group
  - progressive levels of increasingly scope/severity

When formal detection makes sense

- Problem: Priority Inversion (a demi-deadlock)
  - preempted low priority process P1 has mutex M1
  - high priority process P2 blocks for mutex M1
  - process P2 is effectively reduced to priority of P1
- Consequences:
  - depends on what high priority process does
    - might go unnoticed
    - might be a minor performance issue
    - might result in disaster

Priority Inversion on Mars



- occurred on the Mars Pathfinder rover
- caused serious problems with system resets
- very difficult to find

The Pathfinder Priority Inversion

- Special purpose h/w, VxWorks real-time OS
- preemptive priority scheduling
  - to ensure execution of most critical tasks
- shared an "information bus"
  - shared memory region
  - used to communicate between components
  - shared data protected by a mutex lock

A Tale of Three Tasks

- P1: critical, high priority bus management task
  - ran frequently for brief periods, holding bus lock
  - watchdog timer made sure that P1 was still running
- P3: low priority meteorological task
  - ran occasionally, for brief periods, holding bus lock
  - Also for brief periods, during which it locked the bus
- P2: medium priority communications task
  - ran rarely, for longtime, did not need or hold bus loc
- A very rare race condition:
  - P3 had the lock, and was preempted by P2
  - P1 can preempt P2, but blocks until P3 completes
  - P1 is now waiting for (much lower priority) P3
  - watchdog timer concludes P1 has failed, resets system

Solution: Priority Inheritance

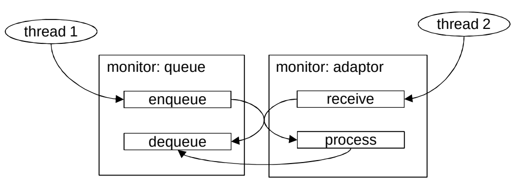
- Identify resource that is blocking P1
- Identify current owner of that resource (P3)
- Temporarily raise P3 priority to that of P1
  - until P3 releases the mutex
- P3 now preempts P2, runs to completion
- P3 releases lock, and loses inherited priority
- P1 preempts P2 and runs
- P2 resumes execution

Assignments

- Projects
  - get started on 2B … contention and granularity
- Reading (light)
  - Metrics and Measurement
  - Load and Stress Testing

Supplementary Slides

nested monitors – example



(nested monitors – simpler isn't safer)

- consider two monitors:
  - QUEUE with methods: enqueue, dequeue
  - ADAPTOR with methods: process, receive
    - where ADAPTORs are implemented with QUEUEs
- possible static deadlocks:
  - QUEUE.enqueue adds entry, calls ADAPTOR.process
  - ADAPTOR.process calls QUEUE.dequeue
- possible dynamic deadlocks:
  - thread 1 calls QUEUE.enque, calls ADAPTOR.process
  - thread 2 calls ADAPTOR.receive, calls QUEUE.enqueue

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
- There Ain't No Such Thing As A Free Lunch
  - fine-grained locking is difficult and error prone
  - coarse-grained locking creates bottle-necks

Monitors: implementation

```
monitor generic {
    semaphore mutex = 1;
    … other private data …
// public external entrypoints … all protected by mutex
    public:         method_1(parms) {
                        p(&mutex);
                        _method_1(parms);
                        v(&mutex); }
// real implementations
        _method_1(parms) { … }
}
```

Limitations of atomic instructions

- only update a small number of contiguous bytes
  - cannot be used to atomically change multiple locations (e.g. insertions in a doubly-linked list)
- they operate on a single memory bus
  - cannot be used to update records on disk
  - cannot be used across a network
  - lock-out and synchronized write are very expensive
- they are not higher level locking operations
  - they cannot "wait" until a resource becomes available