Operating System Principles: Semaphores and Other Synchronization Primitives

CS 111

Operating Systems

Peter Reiher

Outline

- Semaphores
- Mutexes and object locking
- Getting good performance with locking

Semaphores

- A theoretically sound way to implement locks
  - With important extra functionality critical to use in computer synchronization problems
- Thoroughly studied and precisely specified
  - Not necessarily so usable, however
- Like any theoretically sound mechanism, could be gaps between theory and implementation

Computational Semaphores

- Concept introduced in 1968 by Edsger Dijkstra
  - Cooperating sequential processes
- THE classic synchronization mechanism
  - Behavior is well specified and universally accepted
  - A foundation for most synchronization studies
  - A standard reference for all other mechanisms
- More powerful than simple locks
  - They incorporate a FIFO waiting queue
  - They have a counter rather than a binary flag

Semaphores - Operations

- Semaphore has two parts:
  - An integer counter (initial value unspecified)
  - A FIFO waiting queue
- P (proberen/test) ... "wait"
  - Decrement counter, if count >= 0, return
  - If counter < 0, add process to waiting queue
- V (verhogen/raise) ... "post" or "signal"
  - Increment counter
  - If queue non-empty, wake one of the waiting process

Using Semaphores for Exclusion

- Initialize semaphore count to one
  - Count reflects # threads allowed to hold lock

- Use P/wait operation to take the lock

  - The first wait will succeed

  - Subsequent waits will block
- Use V/post operation to release the lock
  - Increment semaphore count to indicate one less waiting request
  - If any threads are waiting, unblock the first in line

Using Semaphores for Notifications

- Initialize semaphore count to zero
  - Count reflects # of completed events

- Use P/wait operation to await completion

  - If already posted, it will return immediately

  - Else all callers will block until V/post is called
- Use V/post operation to signal completion
  - Increment the count
  - If any threads are waiting, unblock the first in line
- One signal per wait: no broadcasts

Counting Semaphores

- Initialize semaphore count to ...
  – The number of available resources
- Use P/wait operation to consume a resource
  – If available, it will return immediately
  – Else all callers will block until V/post is called
- Use V/post operation to produce a resource
  – Increment the count
  – If any threads are waiting, unblock the first in line
- One signal per wait: no broadcasts

Semaphores For Mutual Exclusion

```
struct account {
        struct semaphore s;         /* initialize count to 1, queue empty, lock 0       */
        int balance;
        …
};

int write_check( struct account *a, int amount ) {
        int ret;
        wait( &a->semaphore );          /* get exclusive access to the account              */

                if ( a->balance >= amount ) { /* check for adequate funds               */
                        amount -= balance;
                        ret = amount;
                } else {
                        ret = -1;
                }

        post( &a->semaphore );          /* release access to the account                    */
        return( ret );
}
```

Limitations of Semaphores

- Semaphores are a very basic mechanism
  - They are simple, and have few features
  - More designed for proofs than synchronization
- They lack many practical synchronization features
  - It is easy to deadlock with semaphores
  - One cannot check the lock without blocking
  - They do not support reader/writer shared access
  - No way to recover from a wedged V operation
  - No way to deal with priority inheritance
- Nonetheless, most OSs support them

Locking to Solve High Level Synchronization Problems

- Mutexes and object level locking
- Problems with locking
- Solving the problems

Mutexes

- A Linux/Unix locking mechanism
- Intended to lock sections of code
  - Locks expected to be held briefly
- Typically for multiple threads of the same process
- Low overhead and very general

Object Level Locking

- Mutexes protect code critical sections
  - Brief durations (e.g., nanoseconds, milliseconds)
  - Other threads operating on the same data
  - All operating in a single address space
- Persistent objects (e.g., files) are more difficult
  - Critical sections are likely to last much longer
  - Many different programs can operate on them
  - May not even be running on a single computer
- Solution: lock objects (rather than code)
  - Typically somewhat specific to object type

Linux File Descriptor Locking

int flock(*fd*, *operation*)

- Supported *operations*:
  - LOCK_SH … shared lock (multiple allowed)
  - LOCK_EX … exclusive lock (one at a time)
  - LOCK_UN … release a lock
- Lock applies to open instances of same *fd*
  - Lock passes with the relevant fd
  - Distinct opens are not affected
- Locking with flock() is purely advisory
  - Does not prevent reads, writes, unlinks

Advisory vs Enforced Locking

- Enforced locking
  - Done within the implementation of object methods
  - Guaranteed to happen, whether or not user wants it
  - May sometimes be too conservative
- Advisory locking
  - A convention that "good guys" are expected to follow
  - Users expected to lock object before calling methods
  - Gives users flexibility in what to lock, when
  - Gives users more freedom to do it wrong (or not at all)
  - Mutexes and flocks() are advisory locks

Linux Ranged File Locking

int lockf(*fd*, *cmd*, *offset*, *len*)

- Supported *cmds*:
  - F_LOCK … get/wait for an exclusive lock
  - F_ULOCK … release a lock
  - F_TEST/F_TLOCK … test, or non-blocking request
  - *offset/len* specifies portion of file to be locked
- Lock applies to file (not the open instance)
  - Process specific
  - Closing any fd for the file releases for all of a process' fds for that file
- Locking may be enforced
  - Depending on the underlying file system

Locking Problems

- Performance and overhead
- Contention
  - Convoy formation
  - Priority inversion

Performance of Locking

- Locking often performed as an OS system call
  - Particularly for enforced locking

- Typical system call overheads for lock operations

- If they are called frequently, high overheads
- Even if not in OS, extra instructions run to lock and unlock

Locking Costs

- Locking called when you need to protect critical sections to ensure correctness
- Many critical sections are very brief
  - In and out in a matter of nano-seconds
- Overhead of the locking operation may be much higher than time spent in critical section

What If You Don't Get Your Lock?

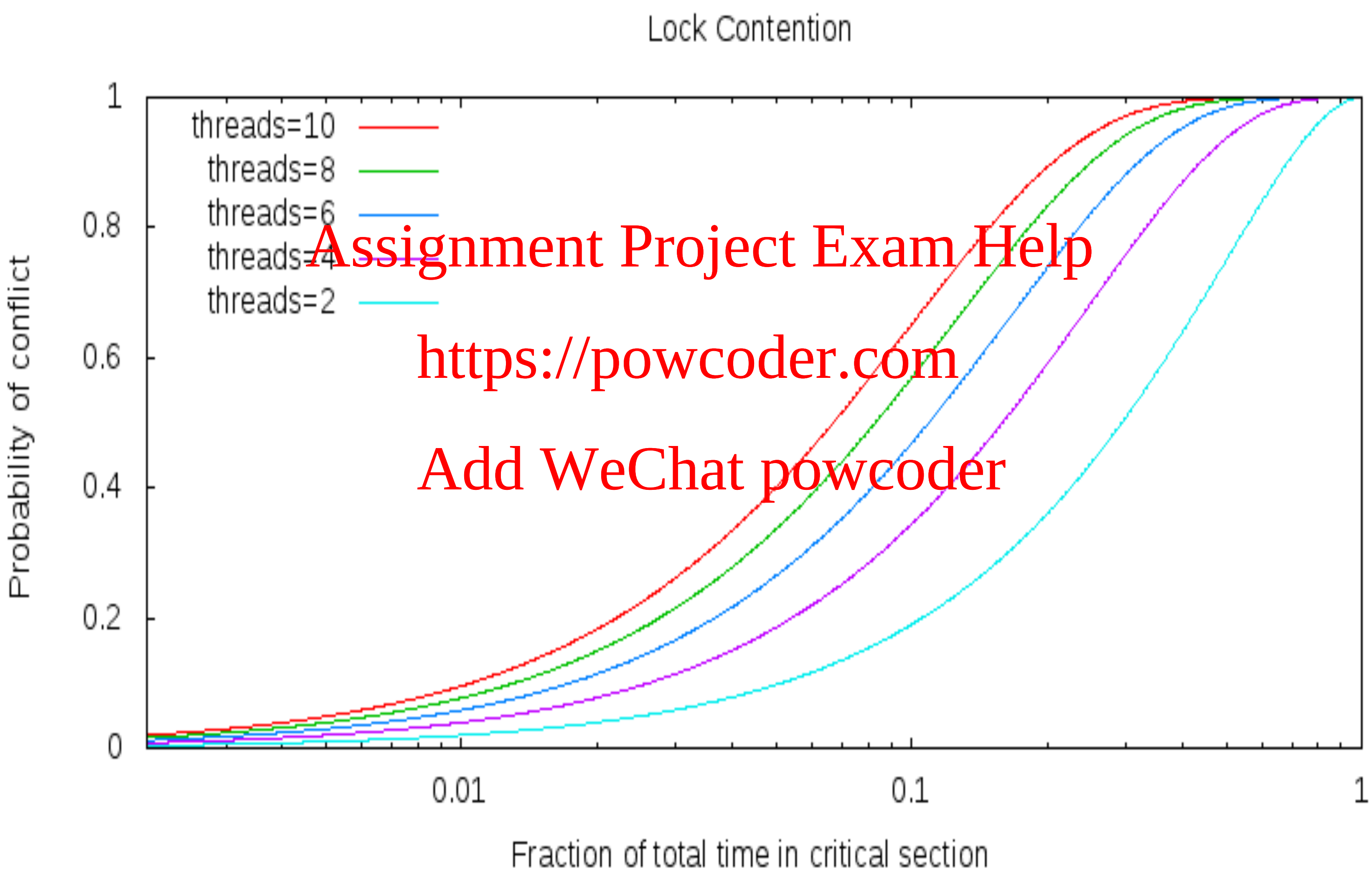
- Then you block
- Blocking is much more expensive than getting a lock
  - E.g., 1000x
  - Micro-seconds to yield and context switch
  - Milliseconds if swapped-out or a queue forms
- Performance depends on conflict probability

$$C_{expected} = (C_{block} * P_{conflict}) + (C_{get} * (1 - P_{conflict}))$$

What If Everyone Needs One Resource?

- One process gets the resource
- Other processes get in line behind him
  - Forming a *convoy*
  - Processes in a convoy are all blocked waiting for the resource
- Parallelism is eliminated
  - B runs after A finishes
  - C after B
  - And so on, with only one running at a time
- That resource becomes a *bottleneck*

Probability of Conflict



Convoy Formation

- In general

$$P_{conflict} = 1 - \underbrace{(1 - (T_{critical} / T_{total}))^{threads}}_{\textit{Nobody else in critical section at the same time}}$$

- Unless a FIFO queue forms

$$P_{conflict} = 1 - (1 - ((T_{wait} + T_{critical}) / T_{total}))^{threads}$$

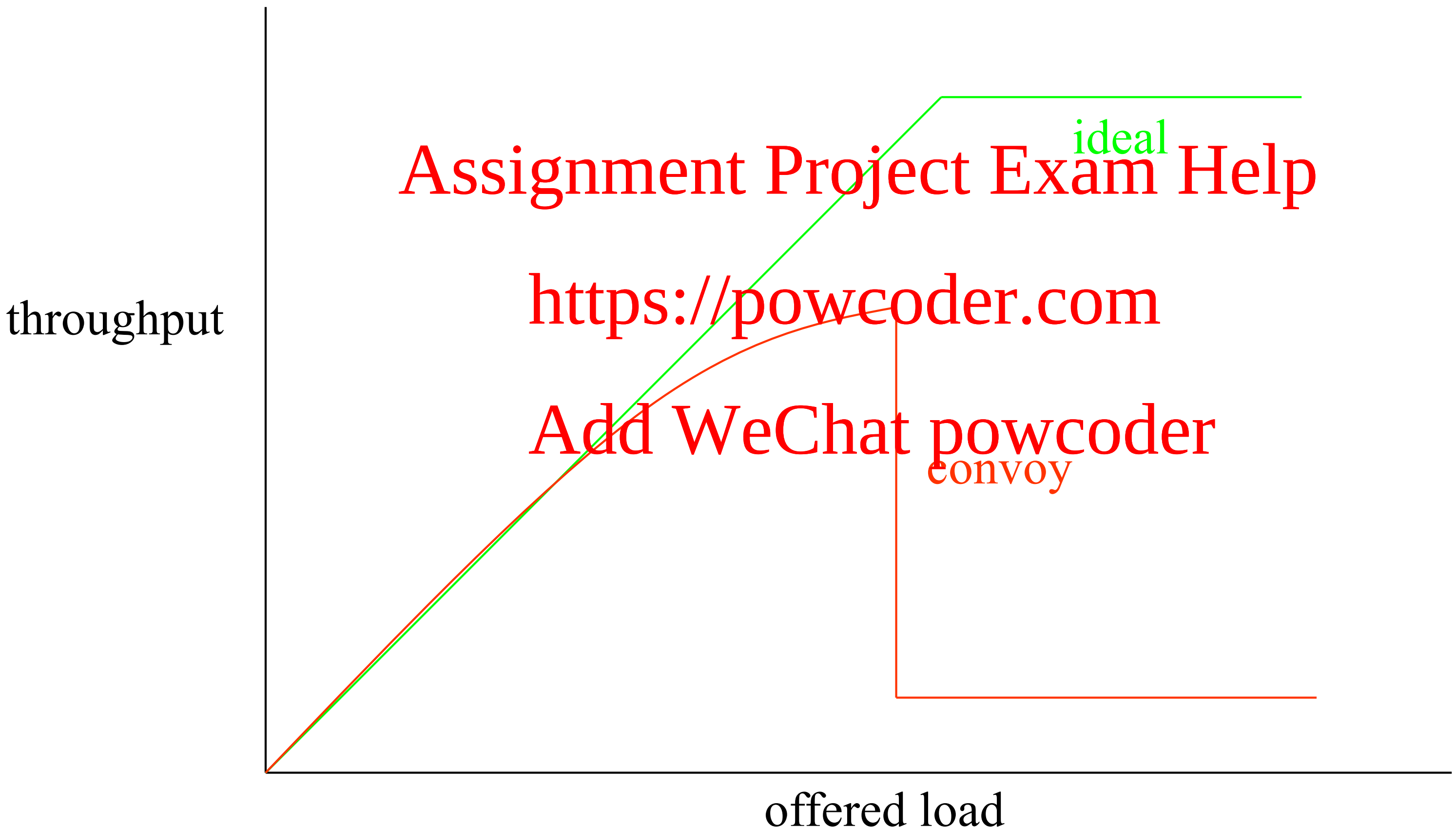
  Newcomers have to get into line

  And an (already huge) T_{wait} gets even longer

- If T_{wait} reaches the mean inter-arrival time

  The line becomes permanent, parallelism ceases

Performance: Resource Convoys



Priority Inversion

- Priority inversion can happen in priority scheduling systems that use locks
  - A low priority process P1 has mutex M1 and is preempted
  - A high priority process P2 blocks for mutex M1
  - Process P2 is effectively reduced to priority of P1
- Depending on specifics, results could be anywhere from inconvenient to fatal

Priority Inversion on Mars

- A real priority inversion problem occurred on the Mars Pathfinder rover
- Caused serious problems with system resets
- Difficult to find

The Pathfinder Priority Inversion

- Special purpose hardware running VxWorks real time OS
- Used preemptive priority scheduling
  – So a high priority task should get the processor
- Multiple components shared an "information bus"
  – Used to communicate between components
  – Essentially a shared memory region
  – Protected by a mutex

A Tale of Three Tasks

- A high priority bus management task (at P1) needed to run frequently
  - For brief periods, during which it locked the bus
- A low priority meteorological task (at P3) ran occasionally
  - Also for brief periods, during which it locked the bus
- A medium priority communications task (at P2) ran rarely
  - But for a long time when it ran
  - But it didn't use the bus, so it didn't need the lock
- P1>P2>P3

What Went Wrong?

- Rarely, the following happened:
  - The meteorological task ran and acquired the lock
  - And then the bus management task would run
  - It would block waiting for the lock
    - Don't pre-empt low priority if you're blocked anyway
- Since meteorological task was short, usually not a problem
- But if the long communications task woke up in that short interval, what would happen?

The Priority Inversion at Work

Priority

B

B's priority of P1 is higher than C's, but B can't run because it's waiting on a lock held by M

A HIGH PRIORITY TASK DOESN'T RUN AND A LOW PRIORITY TASK DOES

Lock Bus

But M won't run again until C completes

M can't interrupt C, since it only has priority P3

M won't release the lock until it runs again

M

Time

The Ultimate Effect

- A watchdog timer would go off every so often
  - At a high priority
  - It didn't need the bus
  - A health monitoring mechanism
- If the bus management task hadn't run for a long time, something was wrong
- So the watchdog code reset the system
- Every so often, the system would reboot

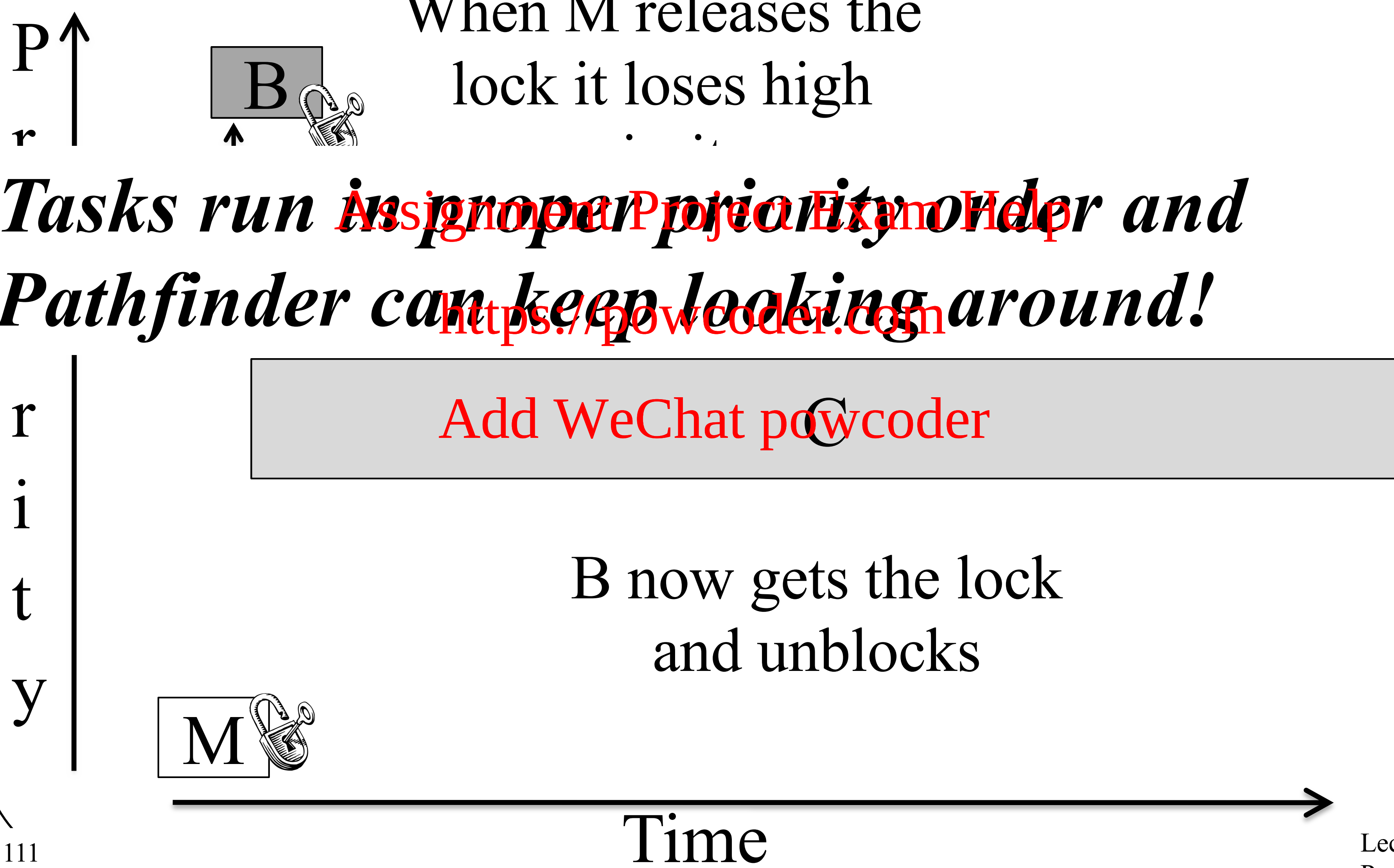
Handling Priority Inversion Problems

- In a priority inversion, lower priority task runs because of a lock held elsewhere
  - Preventing the higher priority task from running
- In the Mars Rover case, the meteorological task held a lock
  - A higher priority bus management task couldn't get the lock
  - A medium priority, but long, communications task preempted the meteorological task
  - So the medium priority communications task ran instead of the high priority bus management task

Solving Priority Inversion

- Temporarily increase the priority of the meteorological task
  - While the high priority bus management task was blocked by it
  - So the communications task wouldn't preempt it
  - When lock is released, drop meteorological task's priority back to normal
- *Priority inheritance*: a general solution to this kind of problem

The Fix in Action



Tasks run in proper priority order and Pathfinder can keep looking around!

Solving Locking Problems

- Reducing overhead
- Reducing contention

Reducing Overhead of Locking

- Not much more to be done here
- Locking code in operating systems is usually highly optimized
- Certainly typical users can't do better

Reducing Contention

- Eliminate the critical section entirely
  - Eliminate shared resource, use atomic instructions
- Eliminate preemption during critical section
- Reduce time spent in critical section
- Reduce frequency of entering critical section
- Reduce <u>exclusive</u> use of the serialized resource
- Spread requests out over more resources

Eliminating Critical Sections

- Eliminate shared resource
  - Give everyone their own copy
  - Find a way to do your work without it
- Use atomic instructions
  - Only possible for simple operations
- Great when you can do it
- But often you can't

Eliminate Preemption in Critical Section

- If your critical section cannot be preempted, no synchronization problems
- May require disabling interrupts
  - As previously discussed, not always an option

Reducing Time in Critical Section

- Eliminate potentially blocking operations
  - Allocate required memory before taking lock
  - Do I/O before taking or after releasing lock
- Minimize code inside the critical section
  - Only code that is subject to destructive races
  - Move all other code out of the critical section
  - Especially calls to other routines
- Cost: this may complicate the code
  - Unnaturally separating parts of a single operation

Reduced Frequency of Entering Critical Section

- Can we use critical section less often?
  - Less use of high-contention resource/operations
  - Batch operations
- Consider "sloppy counters"
  - Move most updates to a private resource
  - Costs:
    - Global counter is not always up-to-date
    - Thread failure could lose many updates
  - Alternative:
    - Sum single-writer private counters when needed

Remove Requirement for Full Exclusivity

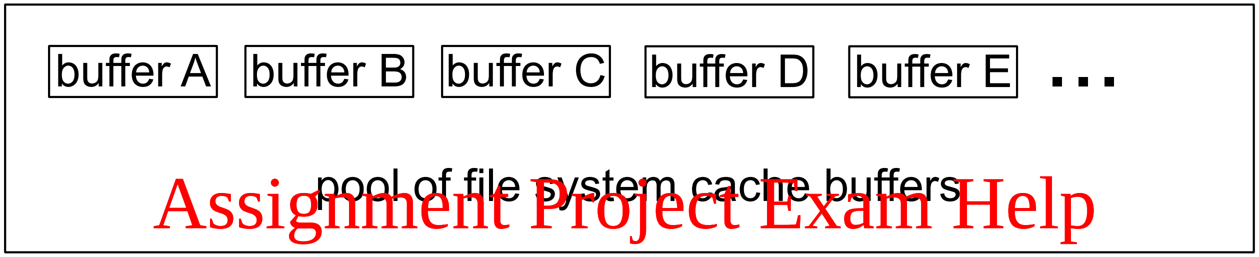
- Read/write locks
- Reads and writes are not equally common
  – File reads and writes: reads/writes > 50
  – Directory search/create: reads/writes > 1000
- Only writers require exclusive access
- Read/write locks
  – Allow many readers to share a resource
  – Only enforce exclusivity when a writer is active
  – Policy: when are writers allowed in?
    - Potential starvation if writers must wait for readers

Spread Requests Over More Resources

- Change lock granularity
- Coarse grained - one lock for many objects
  - Simpler, and more idiot-proof
  - Greater resource contention (threads/resource)
- Fine grained - one lock per object (or sub-pool)
  - Spreading activity over many locks reduces contention
  - Dividing resources into pools shortens searches
  - A few operations may lock multiple objects/pools
- TANSTAAFL
  - Time/space overhead, more locks, more gets/releases
  - Error-prone: harder to decide what to lock when

Lock Granularity – Pools vs. Elements

- Consider a pool of objects, each with its own lock



- Most operations lock only one buffer within the pool
- But some operations require locking the entire pool
  - Two threads both try to add buffer AA to the cache
  - Thread 1 looks for buffer B while thread 2 is deleting it
- The pool lock could become a bottle-neck, so
  - Minimize its use
  - Reader/writer locking
  - Sub-pools ...

The Snake in the Garden

- Locking is great for preventing improper concurrer
- With care be made to perform v
- But that c
- If we arer cking can lead to ou r
- Deadlock