Operating Systems, Concurrency and Time

mutual exclusion

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Questions

- Mutual exclusion is apparently an important concern or problem
  - where does it occur, in which contexts?
  - what are solutions and approaches?
  - what are performance concerns?
  - what is the effect of blocking on timing?

Mutual exclusion

- One way of looking at the bridge problem is to regard the bridge as a *shared resource*
  - acquired by cars from both directions

- We say
  - 'the bridge is accessed under *mutual exclusion*'
  - or: 'the entry/exit actions form a *critical section*'

- Programming mutual exclusion means, in fact, turning *sequences of atomic actions* into a single transaction that can be regarded as atomic
  - using locking/unlocking as, for example, through spinlocks
    - 'low-level synchronization'
  - or using the concept of a (binary) *semaphore* or *mutex*

Mutual exclusion

- What to protect?
  - resources, to achieve non-interrupted interaction
    - memory locations, computing resources, network
- How to protect?
  - protect the instruction sequences that access the resource
    - admitting just one at any time
    - protecting a (set of) instruction sequence(s) means that everything accessed from that sequence is lumped together as a shared resource
  - choose a reasonable granularity, e.g. in sharing data
    - associate a locking mechanism with data items
    - decide which data to protect together
- Which method of exclusion?
  - ‘high-level’ primitives delivered by the OS
  - ‘low-level’ primitives like spin-locks

Where is low-level synchronization relevant?

- *When the overhead for queueing the blocking process and switching to another one is too much*
- *When such queueing is being implemented*

- Both cases happen frequently inside the implementation of the kernel
  - typically, multiprocessor implementations of shared data structures (scheduler, process management, kernel activities)
  - device drivers
  - interrupt service routines
    - particularly, nested interrupts

Requirement: locking periods must be very brief and bounded!

- Spinlocks are also available to multithreaded programs
  - particularly, with modern hyper threaded processors or multiple cores

pthread spinlock API

- Declare and initialize a spinlock
- Shared by threads in same process, or via shared memory across processes (pshared)
- Responsibility of programmer to avoid deadlock
  - though *pthread_spin_lock()* returns EDEADLK

```
#include <pthread.h>
int pthread_spin_init(pthread_spinlock_t *lock, int pshared);
/* pshared: possibly allocate in shared process space */
int pthread_spin_destroy(pthread_spinlock_t *lock);
int pthread_spin_lock(pthread_spinlock_t *lock);
int pthread_spin_trylock(pthread_spinlock_t *lock);
/* return EBUSY if busy */
int pthread_spin_unlock(pthread_spinlock_t *lock);
```

Synchronization with spinlocks

- What is needed is to perform two actions together as a single atomic step, as provided with *spinlocks*

- Example: *Test&Set* (hardware instructions by the processor):
  - **func** *Test&Set (lock): <old := lock; lock := true; return old>*
  - *<lock := false>*
- Use shared variable *lock* (init *false*)

```
P_X = while true do
        StateX := 1;
        StateX := 2;
        while Test&Set (lock)
        do skip od;
        StateX := 3; StateX := 4;
        lock := false;
        StateX := 5
      od
```

||

```
P_Y = while true do
        StateY := 1;
        StateY := 2;
        while Test&Set (lock)
        do skip od;
        StateY := 3; StateY := 4;
        lock := false;
        StateY := 5
      od
```

Implementation of spinlocks

```
; Intel syntax

locked:                     ; The lock variable. 1 = locked, 0 = unlocked.
     dd      0

spin_lock:
     mov     eax, 1         ; Set the EAX register to 1.

     xchg    eax, [locked]  ; Atomically swap the EAX register with
                            ;  the lock variable.
                            ; This will always store 1 to the lock, leaving
                            ;  the previous value in the EAX register.

     test    eax, eax       ; Test EAX with itself. Among other things, this will
                            ;  set the processor's Zero Flag if EAX is 0.
                            ; If EAX is 0, then the lock was unlocked and
                            ;  we just locked it.
                            ; Otherwise, EAX is 1 and we didn't acquire the lock.

     jnz     spin_lock      ; Jump back to the MOV instruction if the Zero Flag is
                            ;  not set; the lock was previously locked, and so
                            ; we need to spin until it becomes unlocked.

     ret                    ; The lock has been acquired, return to the calling
                            ;  function.

spin_unlock:
     mov     eax, 0         ; Set the EAX register to 0.

     xchg    eax, [locked]  ; Atomically swap the EAX register with
                            ;  the lock variable.

     ret                    ; The lock has been released.
```

(from wikipedia)

- Is this complete?
- Does it work for
  - 1 processor?
  - multiple processors
- Are there problem scenarios?

Single processor case

- On a single processor, the two processes are executed interleaved; the ‘busy waiting’ makes no sense then (why?).

- The technique for a single processor is to inhibit interrupts for the duration of the critical section.
  - must all interrupts be disabled?

```
P_X = while true do
        StateX := 1;
        StateX := 2;
        disable_interrupts();
        StateX := 3; StateX := 4;
        enable_interrupts();
        StateX := 5
      od
```

||

```
P_Y = while true do
        StateY := 1;
        StateY := 2;
        disable_interrupts();
        StateY := 3; StateY := 4;
        enable_interrupts();
        StateY := 5
      od
```

Exclusion with multiple processors

- A processor *P* requiring exclusion needs to block interference from *P* itself and from other processors
  - respectively, using interrupt disabling and spinlocks
    - why does interrupt disabling work?
    - in which order does this have to occur?
- The idea with spinlocks is that the common case is that of no contention. Resources are wasted in case of contention. If there is contention,
  - an implementation that continuously assigns a new value to a variable also triggers the cache coherency infrastructure continuously.
  - *P* is blocked and wasting cycles.
    - be selective in what is being blocked: only those actions that interfere with what the spinlock is protecting
    - could yield the processor temporarily while waiting
- We need predictability in implementations
  - make the implementation *fair* and/or *prioritized*
- We need to support *nesting*

First approximation: multi-processor

- spinlock (lock):

  disable_interrupts(); / of 'this' processor only */*

  while *Test&Set(lock)* **do** *skip* **od**

- unlock (lock)

  lock := false; enable_interrupts()

Second approximation: cache friendly

- spinlock (lock)

  disable_interrupts();
  while *Test&Set(lock)* **do**
  while *lock* **do** *skip* **od**
  od

- unlock (lock)

  lock := false; enable_interrupts()

Third approximation: nesting

- Just enabling interrupts is wrong in case of nesting
  - why?
- Local (recursive) context management is a better structuring
  - requires strict nesting of spinlock() / unlock() for different locks

- spinlock (lock):

  OldContext := disable_interrupts();
  while *Test&Set(lock)* **do**
  while *lock* **do** *skip* **od**
  od

- unlock (lock):

  lock := false; restore_context (OldContext)

- (*OldContext* is a fresh local variable of the **caller**)

Fourth approximation: reducing local blocking

- In case of contention, the local processor is blocked. This can be reduced.

- spinlock (lock):

```
OldContext := disable_interrupts();
while Test&Set(lock) do
    while lock  do
        restore_context (OldContext);
        "possibly: pause sometime or suspend";
        OldContext := disable_interrupts();
    od
od
```

- unlock (lock):

```
lock := false; restore_context (OldContext)
```

Semaphores (Dijkstra)

- Semaphore s is an integer *s* with initial value $s_0 \geq 0$ and *atomic* operations *P(s)* and *V(s).* The effect of these operations is defined as follows:

  P(s): < await(s>0); s := s-1 >

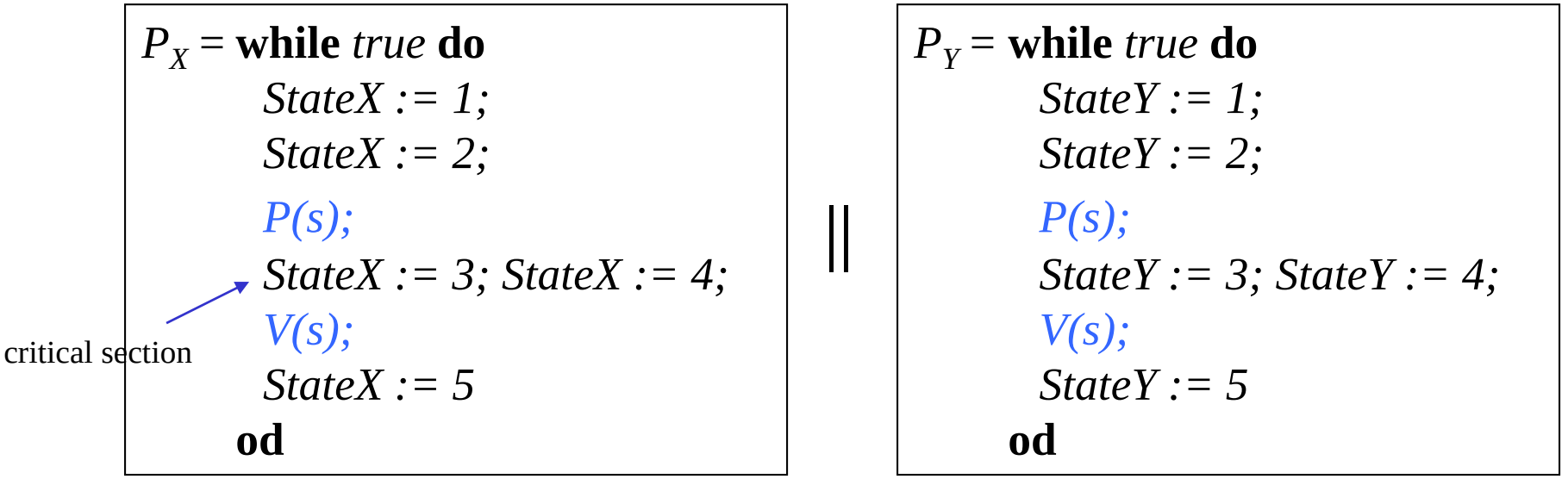
  V(s): < s := s+1 >

- "< >" denotes again atomicity: the implementation of *P* and *V* must guarantee this
- '*await(s>0)*' represents blocking until '*s>0*' holds. This is indivisibly combined with a decrement of *s*
- a semaphore is therefore always non-negative
- Other names for *P* and *V*: *wait/signal, wait/post, lock/unlock*

- Semaphores can be used to implement mutual exclusion

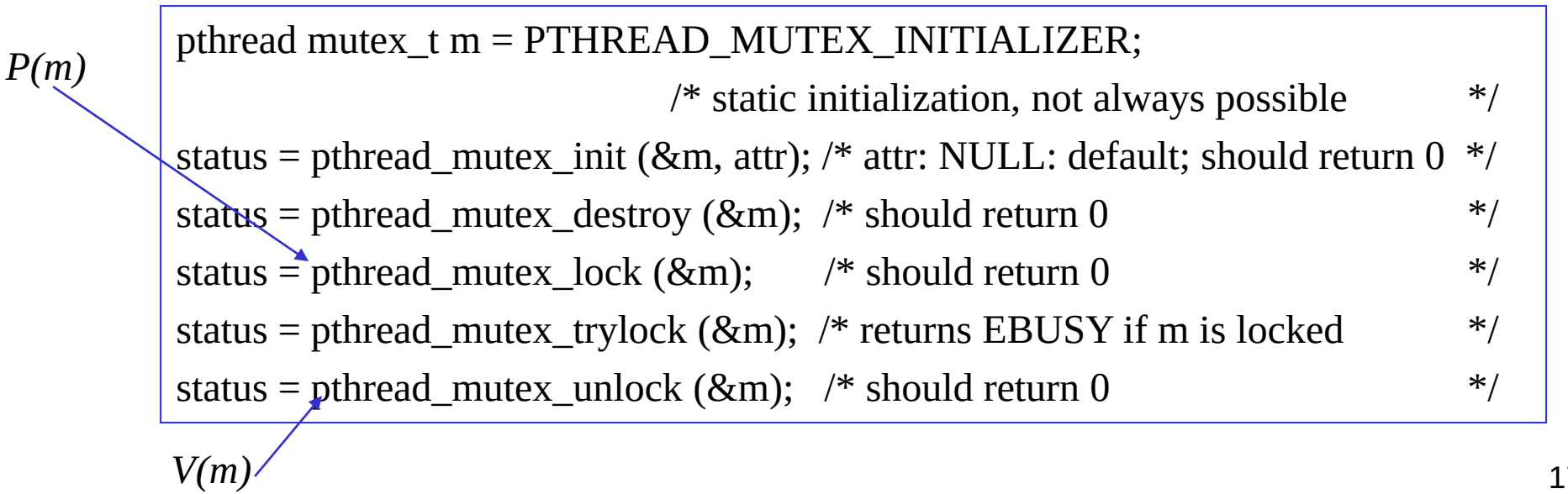
Example

- Let $s_0 = 1$
- At most one process can ‘pass’ the semaphore
  - two processes passed would mean the semaphore was decreased twice
  - hence, the value would be negative
- This semaphore *s* can only be 1 or 0 because of the behavior of the program
  - therefore, other terminology is sometimes used, e.g. *lock() / unlock()*



POSIX: mutex (1003.1c)

- Special, two-state (i.e., 1 / 0) semaphore: *mutex*
  - between threads
  - specifically for mutual *ex*clusion
- Restrictions
  - don't use copies of a mutex in the calls below
  - *lock()* and *unlock()* always by same thread ("ownership")



Exercises

M.1 The implementation given for *Spinlock()* was not fair. Can you find under which circumstances this unfairness may lead to starvation? Can you make it more fair by adding some more state information?

M.2 Instead of *Test&Set()*, other atomic operations are sometimes provided. Examples are:

- *Fetch&Add (x): <prev := x; x := x+1; return(prev)>*
- *Swap(x,y): <t := x; x := y; y := t>*

Make implementations of *Spinlock()* and *Unlock()* using these primitives.

M.3 The order in the implementation of *Spinlock()* was to first disable interrupts and then acquire the lock. Could it be the other way round? Explain why, or why not. Is the order in *Unlock()* relevant? And what if a process/thread can be assigned to another processor?

Exercises

M.4 Semaphore or Mutex implementations need a data structure to record the semaphore state, including a list of waiters. Give a pseudo code for such an implementation and explain where exclusion is required. Which exclusion method should be used there?

M.5 Suppose we do not disable interrupts in the *Spinlock()* implementation. Explain potential problems.

M.6 Suppose a process (or thread, interrupt routine) acquires two spinlocks, and other processes do the same. Show how this can lead to a deadlock. Propose a solution to this problem.

Reducing blocking and deadlock

- A complete disabling of interrupts is quite heavy and often not necessary.
  - Instead, an *interrupt level* is used which is part of the current processor state. Only tasks/interrupts higher than this level may interrupt the current execution.
  - For this to work, these higher interrupts must not access the spinlock or the protected resources.

- In order to avoid deadlock, locks must be required in fixed order. This can be achieved, for example, by a serial ID.

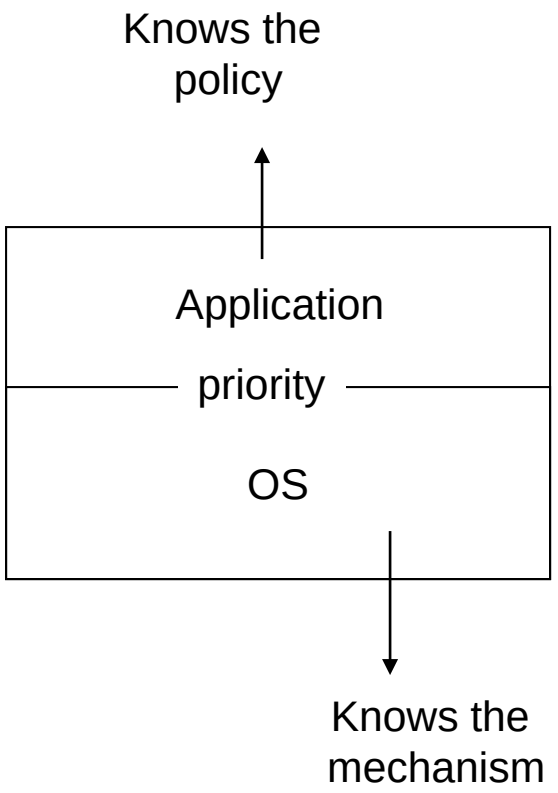
- Fairness can be achieved using Lamports' *ticket algorithm*. This is straightforward using *Fetch&Add* as a primitive but can be implemented using *Test&Set* as well. Fair spinlocks are also called *queued spinlocks.*

Priority

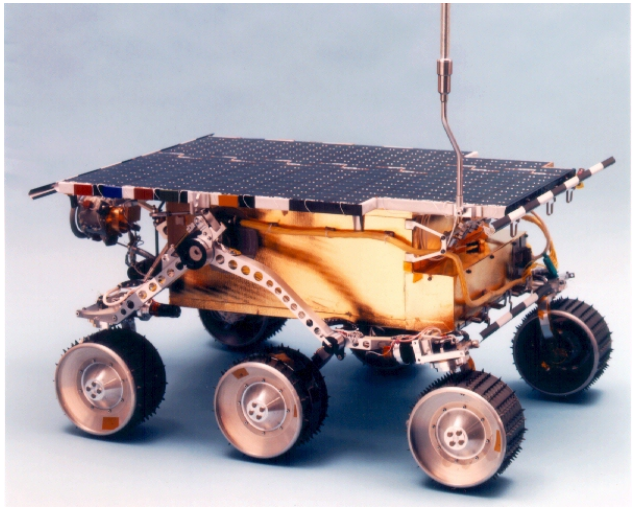
- Scheduling of threads is preemptive, and priority-based

- *Priority:* an intermediate between application and OS
  - the selected thread is the one with the highest priority
  - does not always reflect importance, but is used to control *schedulability*

- Separation of concerns: policy and mechanism
  - the programmer, or the OS, assigns priority
    - they do this according to a certain *policy,* they know what is best
  - the OS knows how to implement priority based scheduling
    - the *mechanism*



Mars Rover Pathfinder

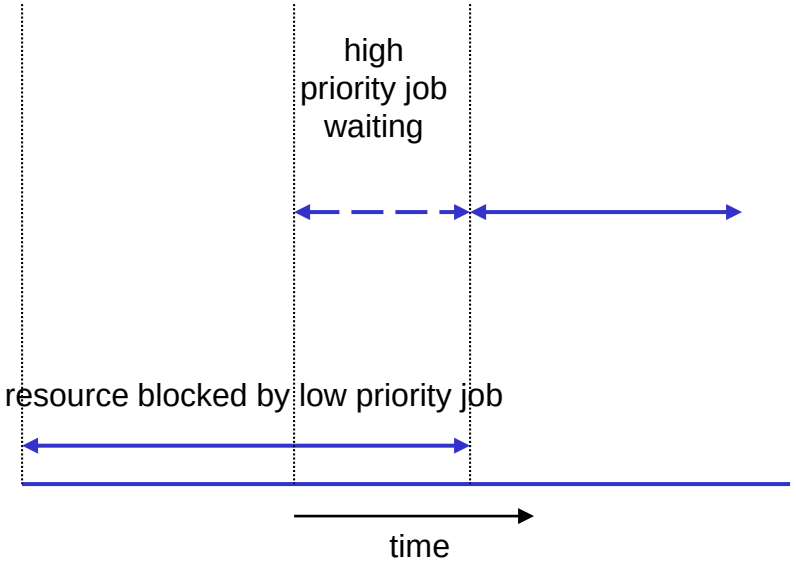


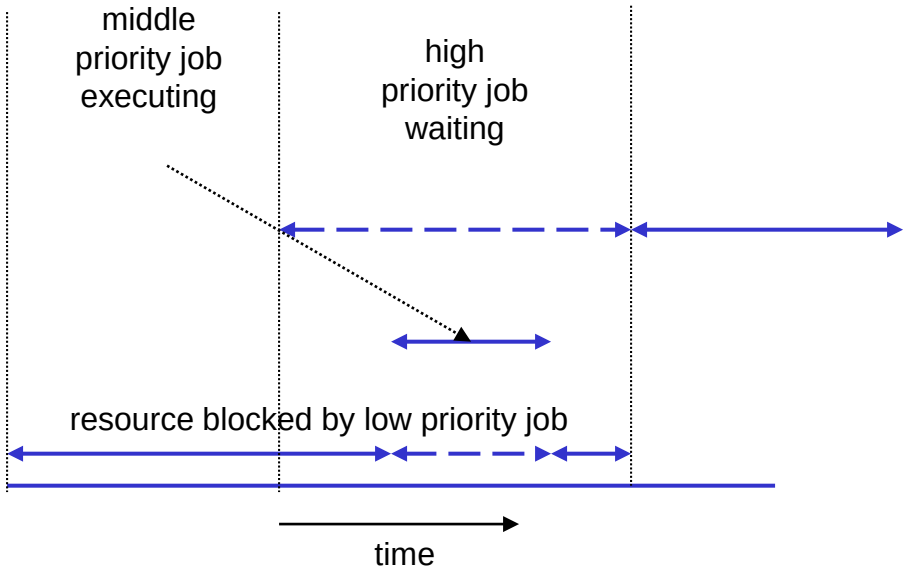
- July 4, 1997, landing on Mars
- After a few days into the mission random resets occurred
  - after start of gathering meteorological data
- Attributed to ‘software glitches’ or ‘system overload’
- OS: VxWorks

- Cause: shared resource: information bus
  - high priority task: moves important information
  - low priority meteorological data gathering task: gets interrupted by a middle priority, unrelated task
  - a watchdog reset is triggered upon a long delay of the high priority task
  - .... priority inversion
  - .... forgot to declare the correspondent semaphore as ‘priority ceiling’ (or inheritance)

Priority inversion

- A low priority job obtains a resource; a high priority job waits on it
- A middle priority job pre-empts the low priority job
  - the high priority job now waits on the middle priority job
  - ... and executes effectively at the low priority
- Unbounded inversion



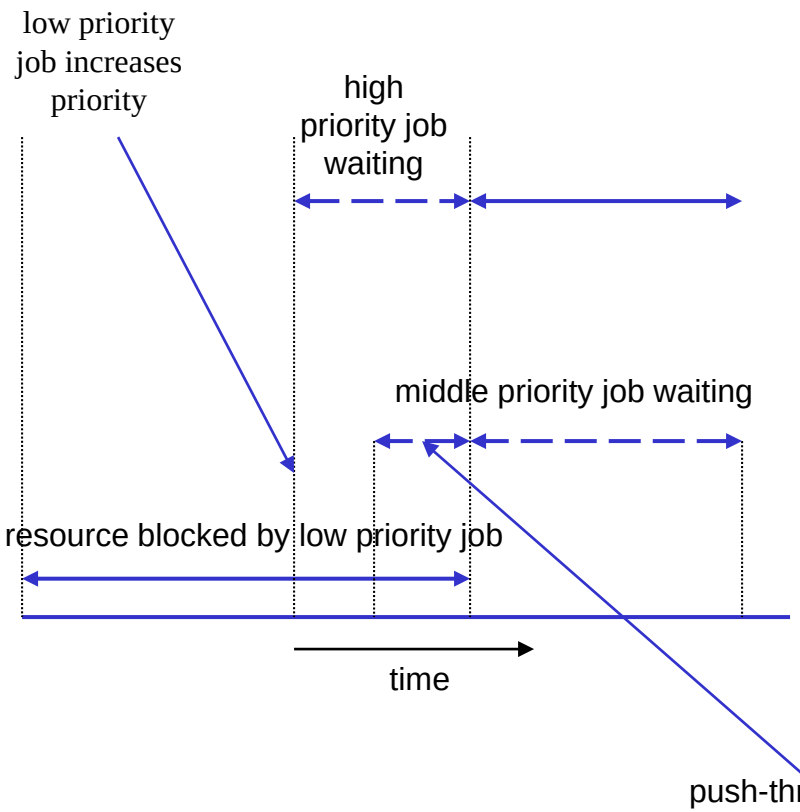


Concurrency control protocols

- Concurrency control protocols manage concurrent and competitive access to resources
  - they manipulate priority for this purpose
  - but may also put restrictions

- A (concurrency control) policy should
  - at least bound the inversion time
  - adhere to the job priorities as good as possible

Priority inheritance protocol



- The priority of a job *P* is *dynamically adjusted* to be the maximum of
  - the priority of any job that is blocked on the allocated resources of *P*
  - (... and its own priority)
  - this adjustment is done *transitively*, i.e., if the priority of a waiter becomes adjusted then this adjustment is forwarded
- ...middle priority jobs will wait now.

Sources and types of blocking

- Direct blocking
  - another job holds the resource
- Push-through blocking
  - job *A* suffers push-through blocking if a lower priority job changes priority temporarily to a higher one than *A*
    - due to a specific concurrency control protocol
- Chained blocking (transitive blocking)
  - sequence of blockings
    - job *A* blocks on (resource *R0* held by) job *B*
    - job *B* blocks on (resource *R1* held by) job *C*

Chained blocking

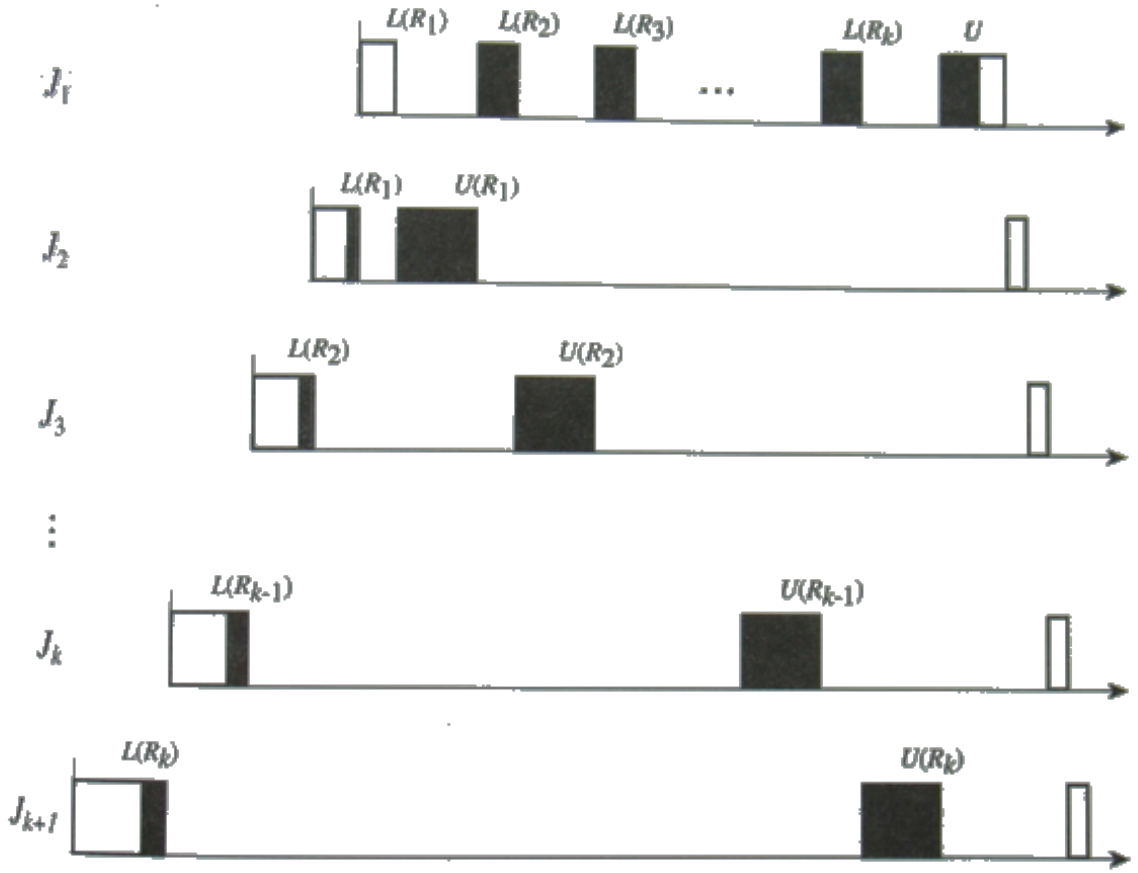


FIGURE 8–9 A worst-case blocking scenario for priority-inheritance protocol.

Sources and types of blocking

- Direct blocking
  - another job holds the resource
- Push-through blocking
  - job *A* suffers push-through blocking if a lower priority job changes priority temporarily to a higher one than *A*
    - due to a specific concurrency control protocol
- Chained blocking (transitive blocking)
  - sequence of blockings
    - job *A* blocks on (resource *R0* held by) job *B*
    - job *B* blocks on (resource *R1* held by) job *C*
- Deadlock:
  - circular waiting (no chain but circle), greedy consumers
  - blocking critical sections
- Avoidance blocking
  - blocking according to a strategy to avoid some of the above

(immediate) Priority Ceiling

- Each resource (mutex) has a *ceiling* which is the maximum priority of any job ever using it

- Rule:
  - the dynamic priority of a job is the maximum ceiling of any resource it has acquired
    - hence, adjusted upon *Lock()* and *Unlock()*

- Properties, on a single processor (!):
  - this simply means that a job using a resource *cannot be pre-empted by any other job that uses the same resource*
    - no need to represent a queue of waiters
    - while executing, the resources of a job are free (mimics an ‘interrupt level’)
  - avoids cyclic deadlock
  - avoids chained blocking
  - wait on at most one lower priority job

POSIX: mutex (1003.1c-2008)

Defining the attribute

- the type (deadlocking, deadlock-detecting, recursive, etc).
- the robustness (what happens when the owner dies)
- the process-shared attribute (for sharing a mutex across process boundaries).
- the protocol (concurrency control).
- the priority ceiling (max priority of a user of *m* – new dynamic priority of caller).

```
pthread mutex_t m = PTHREAD_MUTEX_INITIALIZER;
                                    /* static initialization, not always possible      */
status = pthread_mutex_init (&m, attr); /* attr: NULL: default; should return 0  */
status = pthread_mutex_destroy (&m);  /* should return 0                          */
status = pthread_mutex_lock (&m);       /* should return 0                        */
status = pthread_mutex_trylock (&m);  /* returns EBUSY if m is locked            */
status = pthread_mutex_unlock (&m);   /* should return 0                         */
```

Exercises

M.7 Consider 4 repetitive tasks, *A, B, C* and *D* sharing two resources, *r1* and *r2* protected by mutexes *m1* and *m2.* Jobs of the 4 tasks are as follows.

- *A: d; Lock(m1); d; Lock(m2); d; Unlock(m1); d; Unlock(m2)*
- *B*: *d; Lock(m2); d; Lock(m1); d; Unlock(m1); d; Unlock(m2)*
- *C*: *d; Lock(m1); d; Unlock(m1)*
- *D*: *d; Lock(m2); d; Unlock(m2)*

Here, *d* refers to a variable delay representing some idleness or computing (not really relevant). Priority of *A=4, B=3, C=2, D=1* (4 is highest).

Draw Gantt charts in case of no concurrency control, priority inheritance and priority ceiling. Show occurrence of inversion, chained blocking and deadlock and show the dynamic priority.