Resource Sharing and Priority Ceiling Protocols

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A classic paper on real-time systems

- L. Sha, R. Rajkumar, and J. P. Lehoczky, Priority Inheritance Protocols: An Approach to Real-Time Synchronization. In *IEEE Transactions on Computers*, vol. 39, pp. 1175-1185, Sep. 1990.

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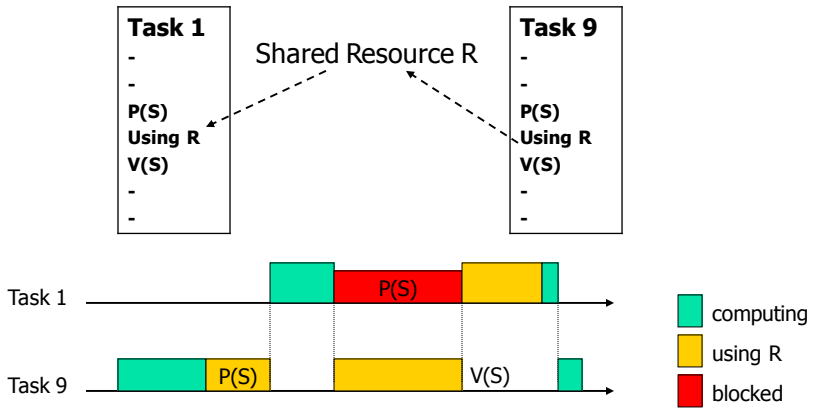
The simpliest form of priority inversion



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Priority inversion problem

- Assume 3 tasks: A, B, C with priorities Ap<Bp<Cp
- Assume semaphore: S shared by A and C
- The following may happen:
  - A gets S by P(S)
  - C wants S by P(S) and blocked
  - B is released and preempts A
  - Now B can run for a long long period .....
  - A is blocked by B, and C is blocked by A
  - So C is blocked by B
- The above senario is called 'priority inversion'
- It can be much worse if there are more tasks with priorities in between Bp and Cp, that may block C as B does!

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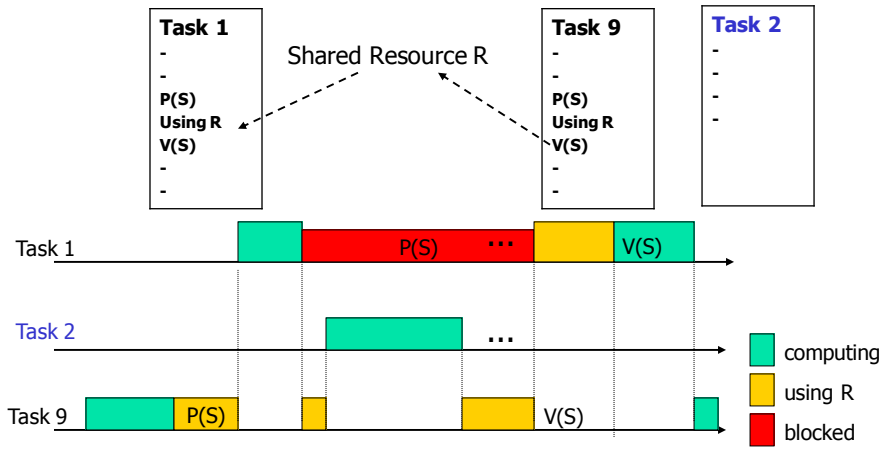
Un-bounded priority inversion



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Solutions

- Tasks are 'forced' to follow pre-defined rules when requesting and releasing resources (locking and unlocking semaphores)
- The rules are called 'Resource access protocols'

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Semaphore, Dijkstra 60s

- A semaphore is a simple data structure with
  - a counter
    - the number of ”copies of a resource”
    - binary semaphore
  - a queue
    - Tasks waiting

  and two operations:

  - P(S): get or wait for semaphore
  - V(S): release semaphore

Shared resources may be protected using semaphores

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Implementation of Semaphores: SCB

- SCB: Semaphores Control Block

Counter
Queue of TCBs (tasks waiting)
Pointer to next SCB

The queue should be sorted by priorities (Why not FIFO?)

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Implementation of semaphores: P-operation

- P(scb):

```
Disable-interrupt;
If scb.counter>0 then
   scb.counter - -1;
end then
else
     save-context();
     current-tcb.state := blocked;
     insert(current-tcb, scb.queue);
     dispatch();
     load-context();
end else
Enable-interrupt
```

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Implementation of Semaphores: V-operation

- V(scb):

```
Disable-interrupt;
If not-empty(scb.queue)  then
       tcb := get-first(scb.queue);
       tcb.state := ready;
       insert(tcb, ready-queue);
       save-context();
       schedule(); /* dispatch invoked*/
       load-context();
 end then
 else scb.counter ++1;
 end else
Enable-interrupt
```

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Resource Access Protocols

- Highest Priority Inheritance
  - Non preemption protocol (NPP)
- Basic Priority Inheritance Protocol (BIP)
  - POSIX (RT OS standard) mutexes
- Priority Ceiling Protocols (PCP)
- Immedate Priority Inheritance
  - Highest Locker's priority Protocol (HLP)
    - Ada95 (protected object) and POSIX mutexes

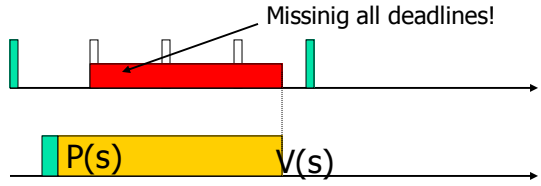
Non Preemption Protocol (NPP)

- Modify P(S) so that the "caller" is assigned the highest priority if it succeeds in locking S
  - Highest priority=non preemtion!
- Modify V(S) so that the "caller" is assigned its own priority back when it releases S

This is the simplest method to avoid Priority Inversion!

NPP: + and –

- Simple and easy to implement (+), how?
- Deadlock free (++)
- Number of blockings = 1 (+)
- Allow low-priority tasks to block high-priority tasks including those that have no sharing resources (-)



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Basic Priority Inheritance Protocol (BIP)

- supported in RT POSIX
- Idea:
  - A gets semaphore S
  - B with higher priority tries to lock S, and blocked by S
  - B transfers its priority to A (so A is resumed and run with B's priority)
- Run time behaviour: whenever a lower-priotity task blocks a higher priority task, it inherits the priority of the blocked task

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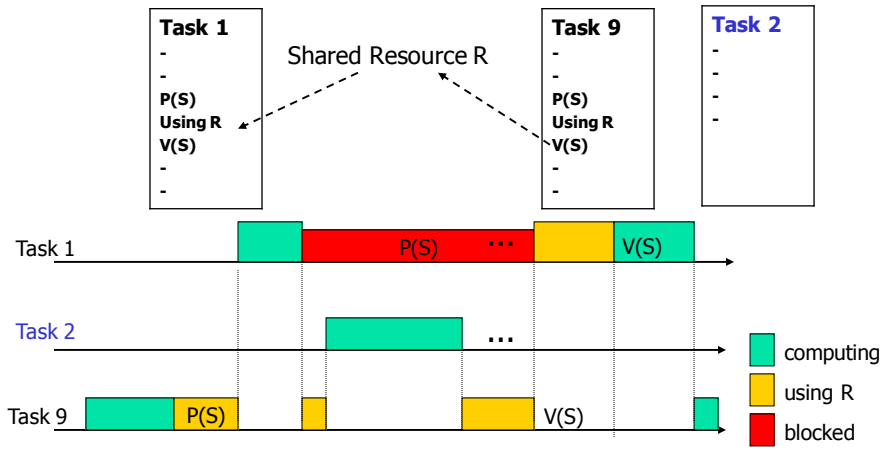
Un-bounded priority inversion



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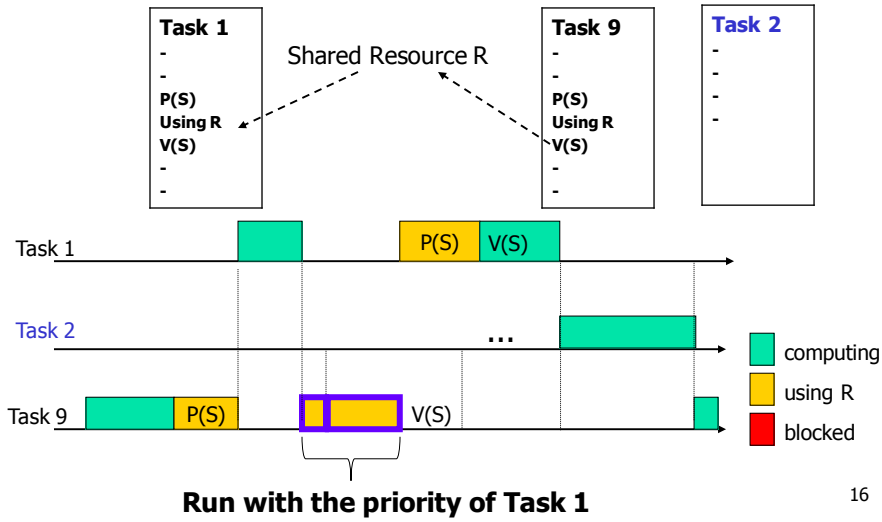
BIP protocol: Example



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Implementation of Ceiling Protocols

- Main ideas:
  - Priority-based scheduling
  - Implement P/V operations on Semaphores to assign task priorities dynamically

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Semaphore Control Block for BIP

counter
queue
Pointer to next SCB
Holder

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Standard P-operation (without BIP)

- P(scb):

```
Disable-interrupt;
If scb.counter>0 then  {scb.counter - -1;
else
  {save-context( );
   current-task.state := blocked;
   insert(current-task, scb.queue);
   dispatch();
   load-context() }
 Enable-interrupt
```

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P-operation with BIP

- P(scb):

```
Disable-interrupt;
If scb.counter>0 then  {scb.counter - -1;
                        scb.holder:= current-task
                        add(current-task.sem-list,scb)}
else
  {save-context( );
   current-task.state := blocked;
   insert(current-task, scb.queue);
   save(scb.holder.priotiry);
   scb.holder.priority := current-task.priority;
   dispatch();
   load-context() }
Enable-interrupt
```

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Standard V-operation (without BIP)

- V(scb):

```
Disable-interrupt;
If not-empty(scb.queue)  then
        { next-to-run := get-first(scb.queue);
          next-to-run.state := ready;
          insert(next-to-run, ready-queue);
          save-context();
          schedule(); /* dispatch invoked*/
          load-context() }
    else scb.counter ++1;
Enable-interrupt
```

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V-operation with BIP

- V(scb):

```
Disable-interrupt;
current-task.priority := ”original/previous priority”
      /* restore the previous priority of the ”caller” */
      If not-empty(scb.queue)   then
        { next-to-run := get-first(scb.queue);
          next-to-run.state := ready;
          scb.holder := next-to-run;
          add(next-to-run.sem-list, scb);
          insert(next-to-run, ready-queue);
          save-context();
          schedule(); /* dispatch invoked*/
          load-context() }
    else scb.counter ++1;
Enable-interrupt
```

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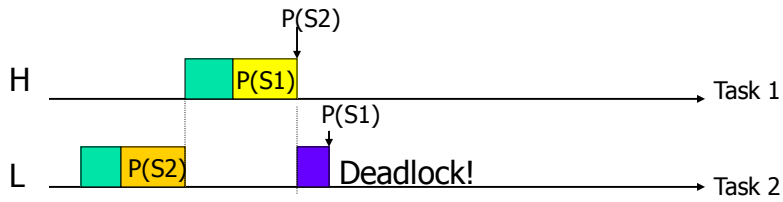
Problem 1: potential deadlock



Task 2: ... P(S2) ... P(S1)...
Task 1: ... P(S1) ... P(S2)...

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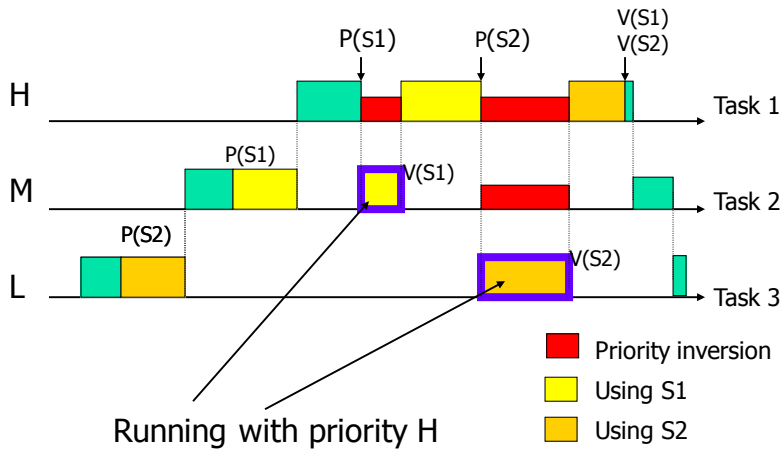
Problem 2: chained blocking – many preemptions



Task H needs M resources may be blocked M times:
→ many preemptions/run-time overheads
→ maximal blocking= at least, the sum of all CS sections for lower-priority tasks

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Properties of BIP: + and -

- Bounded Priority inversion (+)
- Reasonable Run-time performance (+)
- Potential deadlocks (-)
- Chain-blocking – many preemptions (-)

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Immediate Priority Inheritance:

=Highest Locker's Priority Protocol (HLP)

- Adopted in Ada95 (protected object), POSIX mutexes
- Idea: define the ceiling C(S) of a semaphore S to be the highest priority of all tasks that use S during execution. Note that C(S) can be calculated statically (off-line).

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Run-time behaviour of HLP

- Whenever a task succeeds in holding a semaphor S, its priority is changed dynamically to the maximum of its current priority and C(S).
- When it finishes with S, it sets its priority back to what it was before

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Priority Ceiling of Semaphore: Examples

	Priority	Share Semaphors
Task 1	H	S3
Task 2	M	S1, S
Task 3	L	S1, S2
Task 4	Lower	S2, S

Ceiling of semaphors

C(S1)=M
C(S2)=L
C(S3)=H
C(S)=M

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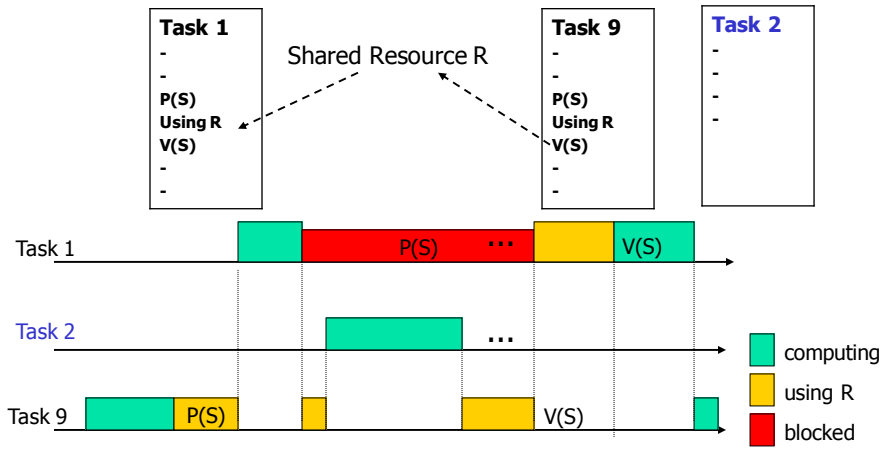
Un-bounded priority inversion



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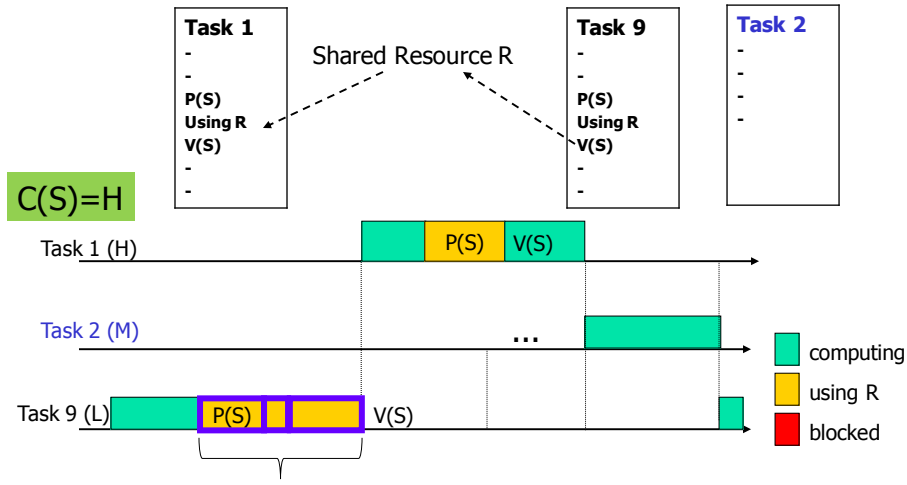
HLP protocol: Example



Run with the priority of C(S): H

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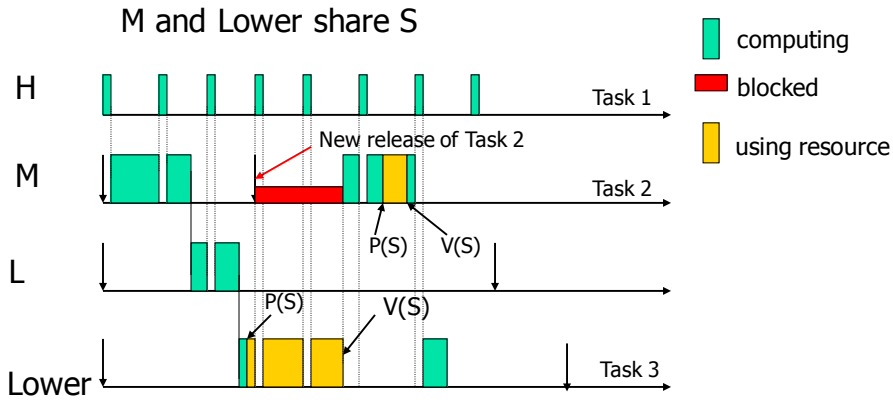
HLP Protocol: Example



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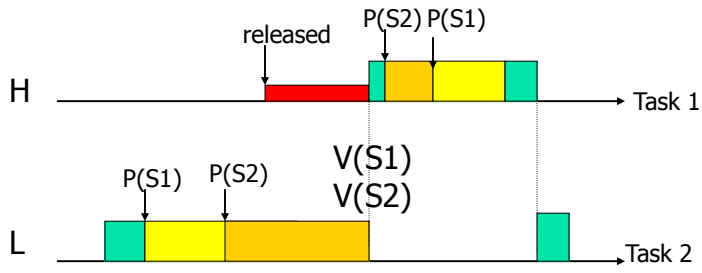
Property 1: Deadlock free (HLP)



Once task 2 gets S1, it runs with pri H, task 1 will be blocked (no chance to get S2 before task 2)

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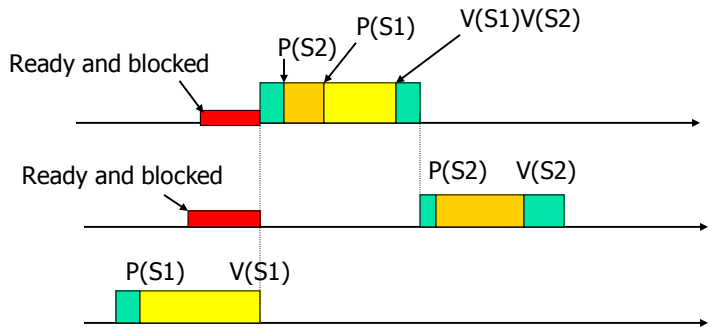
Property 2:

Tasks will be blocked (by priority inversion) at most once



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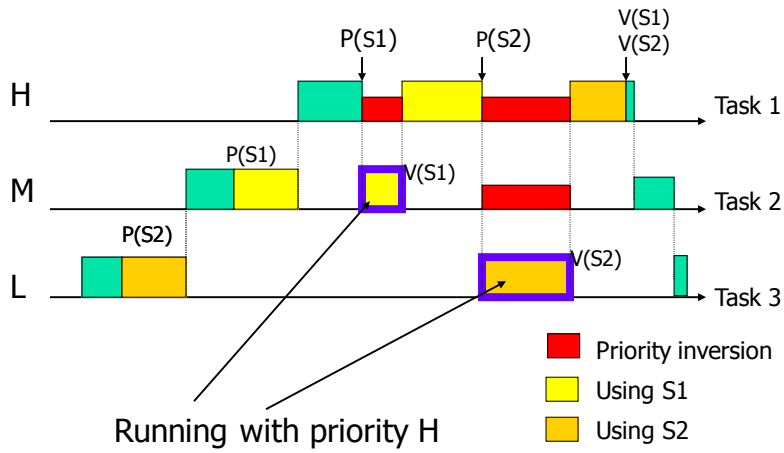
BIP: Chained blocking – many preemptions



Task H needs M resources may be blocked M times:
→ many preemptions/run-time overheads
→ maximal blocking= at least, the sum of all CS sections for lower-priority tasks

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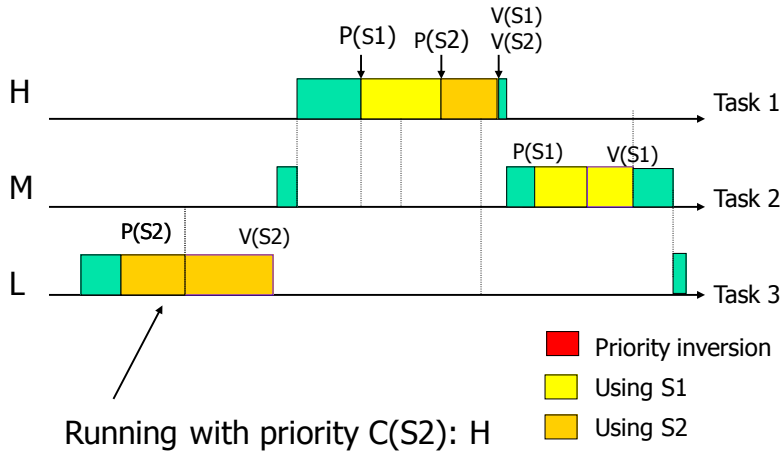
C(S1)=H
C(S2)=H

HLP: at most one blocking



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HLP: Blocking time calculation

- Let
  - CS(k,S) denote the computing time for the critical section that task k uses semaphore S.
- Then the maximal blocking time B for task i is as follows:
  - B=max{CS(k,S)| task i,k share S, pri(k)<pri(i)<=C(S)}

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Implementation of HLP

- Calculate the ceiling for all semaphores
- Modify SCB
- Modify P and V-operations

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Semaphore Control Block for HLP

counter
queue
Pointer to next SCB
Ceiling

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P-operation with HLP

- P(scb):

```
Disable-interrupt;
If scb.counter>0 then
      { scb.counter - -1;
       save(current-task.priority);
       current-task.priority := Ceiling(scb) }
else
   {save-context();
    current-task.state := blocked
    insert(current-task, scb.queue);
    dispatch();
    load-context() }
Enable-interrupt
```


V-operation with HLP

- V(scb):

```
Disable-interrupt;
"restore previous priority"
If not-empty(scb.queue)  then
      next-to-run := get-first(scb.queue);
      next-to-run.state := ready;
      next-to-run.priority := Ceiling(scb);
      insert(next-to-run, ready-queue);
      save-context();
      schedule(); /* dispatch invoked*/
      load-context();
 end then
 else scb.counter ++1;
 end else
Enable-interrupt
```

Properties of HLP: + and -

- Bounded priority inversion
- Deadlock free (+), Why?
- Number of blocking = 1 (+), Why?
- The extreme case of HLP=Non-preemtion (-)
  - E.g when the highest priority task uses all semaphors, the lower priority tasks will inherit the highest priority

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Summary

	NPP	BIP	HLP
Bounded Priority Inversion	yes	yes	yes
Avoid deadlock	yes	no	yes
Avoid Un-necessary blocking	no	yes	yes/no
Blocking time calculalation	Easy	hard	easy

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Priority Ceiling Protocol (combining HLP and BIP)

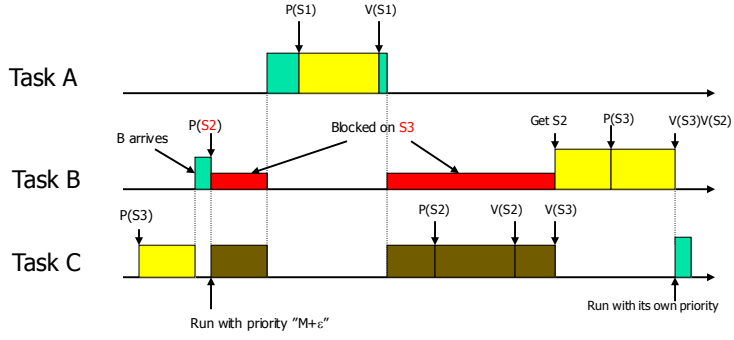
- Each semaphore S has a Ceiling C(S)
- Run-time behaviour:
  - Assume that S is the semaphore with highest ceiling of all semaphores locked by *other* tasks currently:
    - C(S) is "the current system ceiling"
  - If A wants to lock any semaphore, it must have a strictly higher priority than C(S) i.e. Pri(A) > C(S). Otherwise A is blocked, and it transmitts its priority(+ε) to the task currently holding S

Example: PCP

A: ...P(S1)...V(S1)...
B: ...P(S2)...P(S3)...V(S3)...V(S2)...
C: ...P(S3)...P(S2)...V(S2)...V(S3)

Prio(A)=H
Prio(B)=M
Prio(C)=L

C(S1)=H
C(S2)=C(S3)=M

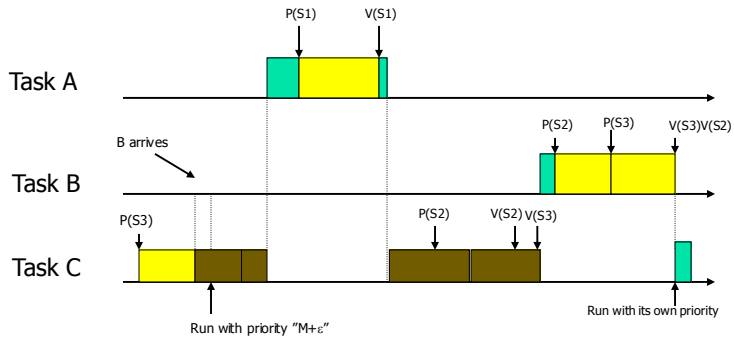


Example: HLP

A: ...P(S1)...V(S1)...
B: ...P(S2)...P(S3)...V(S3)...V(S2)...
C: ...P(S3)...P(S2)...V(S2)...V(S3)

Prio(A)=H
Prio(B)=M
Prio(C)=L

C(S1)=H
C(S2)=C(S3)=M



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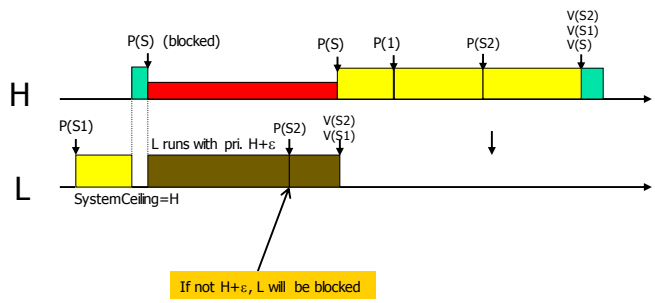
Why adding ε?

Example: assume

- tasks H and L (H has higher priority than L)
- both share semaphores S1, S2
- H uses S (not shared)
- Thus, ceiling(Si)= H and
- SystemCeiling = H if any semaphore is locked



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PCP: Blocking time calculation

- Let
  - CS(k,S) denote the computing time for the critical section that task k uses semaphore S.
- The maximal blocking time for task i:
  - B = max{CS(k,S)| task i,k share S, pri(k)<pri(i)<=C(S)}

(which is the same as HLP)

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Exercise: implementation of PCP

- Implement P,V-operations that follow PCP
- (this is not so easy)

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Properties of PCP: + and -

- Bounded priority inversion (+)
- Deadlock free (+)
- Number of blocking = 1 (+)
- Better response times for high priority tasks (+)
  - Avoid un-necessary blocking
- Not easy to implement (-)

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Summary

	NPP	BIP	HLP	PCP
Bounded Priority Inversion	yes	yes	yes	yes
Deadlock free	yes	no	yes	yes
Un-necessary blocking	yes	no	yes/no	no
Blocking time calculalation	easy	hard	easy	easy
Number of blocking	1	>1	1	1
Implementation	easy	easy	easy	hard

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