Real-Time Scheduling

Resource Access Control

[Some parts of this lecture are based on a real-time systems course of Colin Perkins

http://csperkins.org/teaching/rtes/index.html]

Current Assumptions

- Single processor
- Individual jobs

  (that possibly belong to periodic/aperiodic/sporadic tasks)
  - Jobs can be preempted at any time and never suspend themselves
- Jobs are scheduled using a priority-driven algorithm

  i.e., jobs are assigned priorities, scheduler executes jobs according to these priorities
- n resources $R_1, \ldots, R_n$ of distinct types
  - used in non-preemptable and mutually exclusive manner; *serially reusable*

Motivation & Notation

Resources may represent:

- Hardware devices such as sensors and actuators
- Disk or memory capacity, buffer space
- Software resources: locks, queues, mutexes etc.

Assume a lock-based concurrency control mechanism

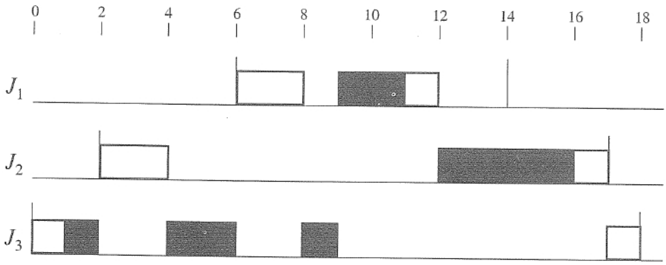
- A job wanting to use a resource R_k executes $L(R_k)$ to lock the resource R_k
- When the job is finished with the resource R_k, unlocks this resource by executing $U(R_k)$
- If lock request fails, the requesting job is **blocked** and has to wait, when the requested resource becomes available, it is unblocked

  In particular, a job holding a lock cannot be preempted by a higher priority job needing that lock

The segment of a job that begins at a lock and ends at a matching unlock is a *critical section* (CS)

- CS must be properly nested if a job needs multiple resources

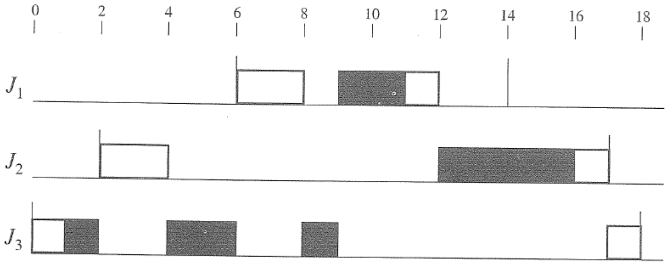
Example



J_1, J_2, J_3 scheduled according to EDF.

- At 0, J_3 is ready and executes
- At 1, J_3 executes $L(R)$ and is granted R
- J_2 is released at 2, preempts J_3 and begins to execute
- At 4, J_2 executes $L(R)$, becomes blocked, J_3 executes
- At 6, J_1 becomes ready, preempts J_3 and begins to execute
- At 8, J_1 executes $L(R)$, becomes blocked, and J_3 executes

Example



- At 9, J_3 executes $U(R)$ and both J_1 and J_2 are unblocked. J_1 has higher priority than J_2 and executes
- At 11, J_1 executes $U(R)$ and continues executing
- At 12, J_1 completes, J_2 has higher priority than J_3 and has the resource R, thus executes
- At 16, J_2 executes $U(R)$ and continues executing
- At 17, J_2 completes, J_3 executes until completion at 18

Priority Inversion

Definition 27

Priority inversion occurs when

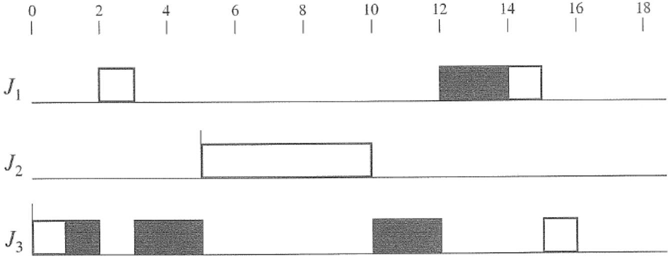
- a high priority job
- is blocked by a low priority job
- which is subsequently preempted by a medium priority job

Then effectively the medium priority job executes with higher priority than the high priority job even though they do not contend for resources

There may be arbitrarily many medium priority jobs that preempt the low priority job ⇒ uncontrolled priority inversion

Priority Inversion – Example

Uncontrolled priority inversion:



High priority job (J_1) can be blocked by low priority job (J_3) for unknown amount of time depending on middle priority jobs (J_2)

Deadlock

Definition 28 (suitable for resource access control)

A deadlock occurs when there is a set of jobs $\mathcal{D}$ such that each job of $\mathcal{D}$ is waiting for a resource previously allocated by another job of $\mathcal{D}$.

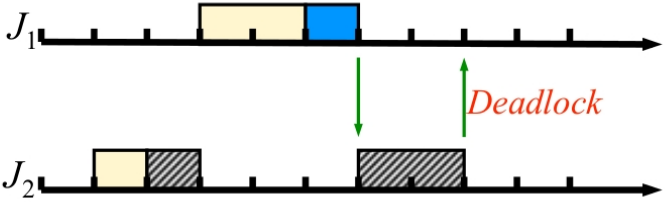
Deadlocks can be

- *detected:* regularly check for deadlock, e.g. search for cycles in a resource allocation graph regularly
- *avoided:* postpone unsafe requests for resources even though they are available (banker's algorithm, priority-ceiling protocol)
- *prevented:* many methods invalidating sufficient conditions for deadlock (e.g., impose locking order on resources)

See your operating systems course for more information ....

Deadlock – Example

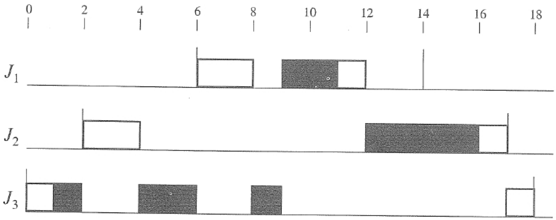
Deadlock can result from piecemeal acquisition of resources: classic example of two jobs J_1 and J_2 both needing both resources R and R'



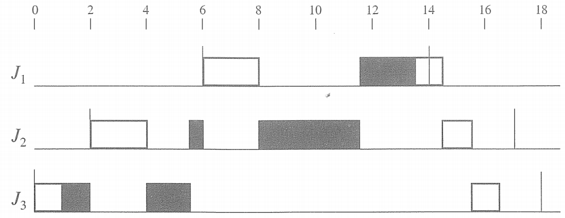
- J_2 locks R' and J_1 locks R
- J_1 tries to get R' and is blocked
- J_2 tries to get R and is blocked

Timing Anomalies due to Resources

Previous example, the critical section of J_3 has length 4



... the critical section of J_3 shortened to 2.5



... but response of J_1 becomes longer!

Controlling Timing Anomalies

Contention for resources causes timing anomalies, priority inversion and deadlock

Several protocols exist to control the anomalies

- Non-preemptive CS
- Priority inheritance protocol
- Priority ceiling protocol
- ....

Terminology:

- A job J_h is *blocked* by a job J_k when
  - the priority of J_k is lower than the priority of J_h and
  - J_k holds a resource R and
  - J_h executes $L(R)$.

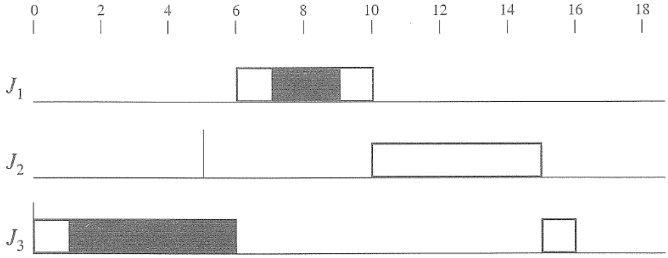
  In such situation we sometimes say that J_h is blocked by the corresponding critical section of J_k.

Non-preemptive Critical Sections

The protocol: when a job locks a resource, it is scheduled with priority higher than all other jobs (i.e., is non-preemptive)

Example 29

Jobs J_1, J_2, J_3 with release times $2, 5, 0$, resp., and with execution times $4, 5, 7$, resp.



Non-preemptive Critical Sections – Features

- no deadlock as no job holding a resource is ever preempted
- no priority inversion:
  - A job J_h can be blocked (by a lower priority job) *only at release time*.
    (Indeed, if J_h is not blocked at the release time r_h, it means that no lower priority job holds any resource at r_h. However, no lower priority job can be executed before completion of J_h, and thus no lower priority job may block J_h.)
  - If J_h is blocked at release time, then once the blocking critical section completes, no lower priority job can block J_h.
  - It follows that any job can be blocked only once, at release time, blocking time is bounded by duration of one critical section of a lower priority job.

Advantage: very simple; easy to implement both in fixed and dynamic priority; no prior knowledge of resource demands of jobs needed

Disadvantage: every job can be blocked by every lower-priority job with a critical section, even if there is no resource conflict

Priority-Inheritance Protocol

Idea: adjust the scheduling priorities of jobs during resource access, to reduce the duration of timing anomalies

(As opposed to non-preemptive CS protocol, this time the priority is not always increased to maximum)

Notation:

- *assigned priority* = priority assigned to a job according to a standard scheduling algorithm
- At any time t, each ready job J_k is scheduled and executes at its *current priority* $\pi_k(t)$ which may differ from its assigned priority and may vary with time
  - The current priority $\pi_k(t)$ of a job J_k may be raised to the higher priority $\pi_h(t)$ of another job J_h
  - In such a situation, the lower-priority job J_k is said to *inherit* the priority of the higher-priority job J_h, and J_k executes at its inherited priority $\pi_h(t)$

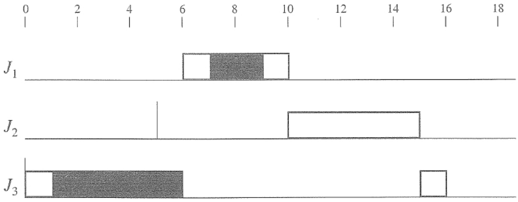
Priority-Inheritance Protocol

- **Scheduling rules**:
  - Jobs are scheduled in a preemptable priority-driven manner *according to their current priorities*
  - At release time, the current priority of a job is equal to its assigned priority
  - The current priority remains equal to the assigned priority, except when the priority-inheritance rule is invoked
- **Priority-inheritance rule**:
  - When a job J_h becomes blocked on a resource R, the job J_k which blocks J_h inherits the current priority $\pi_h(t)$ of J_h;
  - J_k executes at its inherited priority until it releases R; at that time, the priority of J_k is *set to the highest priority of all jobs still blocked by J_k after releasing R.*
    (the resulting priority may still be an inherited priority)
- **Resource allocation**: When a job J requests a resource R at t:
  - If R is free, R is allocated to J until J releases it
  - If R is not free, the request is denied and J is blocked

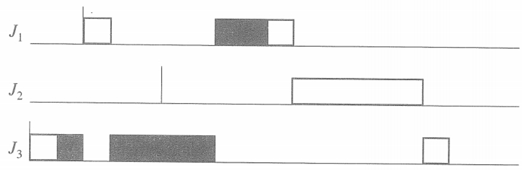
(Note that J is only denied R if the resource is held by another job.)

Priority-Inheritance Simple Example

non-preemptive CS:

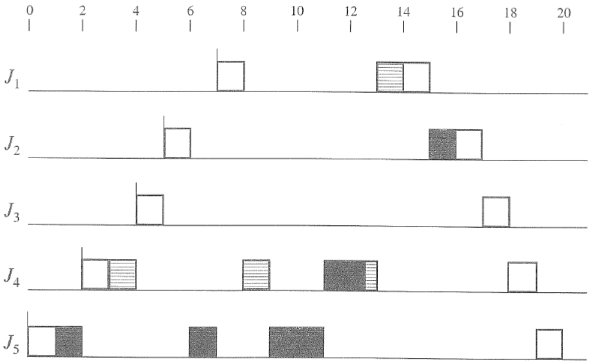


priority-inheritance:



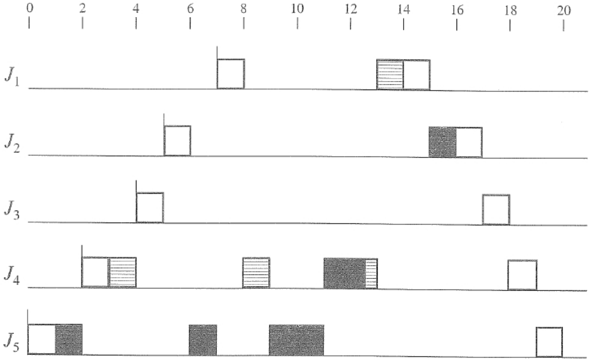
- At 3, J_1 is blocked by J_3, J_3 inherits priority of J_1
- At 5, J_2 is released but cannot preempt J_3 since the inherited priority of J_3 is higher than the (assigned) priority of J_2

Priority-Inheritance Example



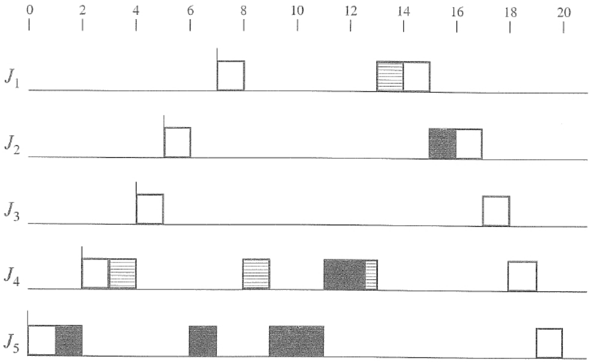
- At 0, J_5 starts executing at priority 5, at 1 it executes $L(Black)$
- At 2, J_4 preempts J_5 and executes
- At 3, J_4 executes $L(Shaded)$, J_4 continues to execute
- At 4, J_3 preempts J_4; at 5, J_2 preempts J_3
- At 6, J_2 executes $L(Black)$ and is blocked by J_5. Thus J_5 inherits the priority 2 of J_2 and executes

Priority-Inheritance Example



- At 8, J_1 executes $L(\textit{Shaded})$ and is blocked by J_4. Thus J_4 inherits the priority 1 of J_1 and executes
- At 9, J_4 executes $L(\textit{Black})$ and is blocked by J_5. Thus J_5 inherits the **current** priority 1 of J_4 and executes

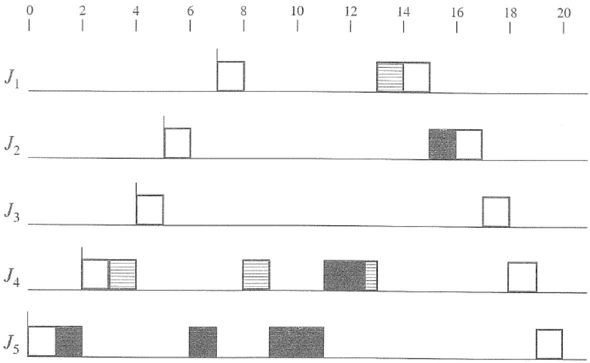
Priority-Inheritance Example



- At 11, J_5 executes $U(Black)$, its priority returns to 5 (the priority before locking *Black*). Now J_4 has the highest priority (1) and executes the Black critical section.

  Later, when J_4 executes $U(Black)$, the priority of J_4 remains 1 (since *Shaded* blocks J_1), and J_4 also finishes the *Shaded* critical section (at 13).

Priority-Inheritance Example



- At 13, J_4 executes $U(Shaded)$, its priority returns to 4. J_1 has now the highest priority and executes
- At 15, J_1 completes, J_2 is granted *Black* and has the highest priority and executes
- At 17, J_2 completes, afterwards J_3, J_4, J_5 complete.

Properties of Priority-Inheritance Protocol

- Simple to implement, does not require prior knowledge of resource requirements
- Jobs exhibit two types of "blocking"
  - (Direct) blocking due to resource locks

    i.e., a job J_ℓ locks a resource R, J_h executes $L(R)$ is directly blocked by J_ℓ on R
  - Priority-inheritance "blocking"

    i.e., a job J_h is preempted by a lower-priority job that inherited a higher priority
- Jobs may exhibit transitive blocking

  In the previous example, at 9, J_5 blocks J_4 and J_4 blocks J_1, hence J_5 inherits the priority of J_1
- Deadlock is *not* prevented

  In the previous example, let J_5 request *shaded* at 6.5, then J_4 and J_5 become deadlocked
- Can reduce blocking time (see next slide) compared to non-preemptable CS but does not guarantee to minimize blocking

Priority-Inheritance – Blocking Time (Optional)

$z_{\ell,k}$ = the k-th critical section of J_ℓ

A job J_h is blocked by $z_{\ell,k}$ if J_h has higher assigned priority than J_ℓ but has to wait for J_ℓ to exit $z_{\ell,k}$ in order to continue

$\beta^*_{h,\ell}$ = the set of all maximal critical sections $z_{\ell,k}$ that *may* block J_h, i.e., which correspond to resources that are (potentially) used by jobs with priorities equal or higher than J_h.

(recall that CS are properly nested, maximal CS which may block J_h is the one which is not contained within any other CS which may block J_h)

Theorem 30
Let J_h be a job and let $J_{h+1}, \ldots, J_{h+m}$ be jobs with lower priority than J_h. Then J_h can be blocked for at most the duration of one critical section in each *of $\beta^*_{h,\ell}$ where $\ell \in \{h+1, \ldots, h+m\}$.*

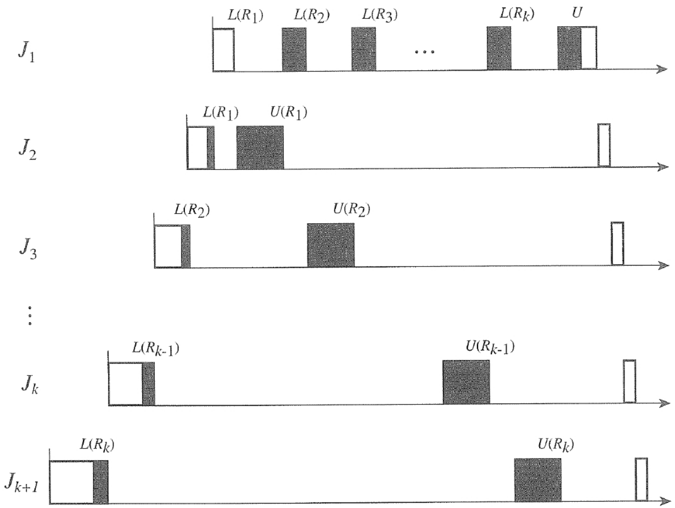
The theorem is a direct consequence of the next lemma.

Lemma 31

J_h can be blocked by J_ℓ only if J_ℓ is executing within a critical section $z_{\ell,k}$ of $\beta^*_{h,\ell}$ when J_h is released

- Assume that J_h is released at t and J_ℓ is in no CS of $\beta^*_{h,\ell}$ at t. We show that J_ℓ never executes between t and completion of J_h:
  - If J_ℓ is not in any CS at t, then its current priority at t is equal to its assigned priority and cannot increase. Thus, J_ℓ has to wait for completion of J_h as the current priority of J_h is always higher than the assigned priority of J_ℓ.
  - If J_ℓ is still in a CS at t, then this CS does not belong to $\beta^*_{h,\ell}$ and thus cannot block J_h before completion and cannot execute before completion of J_h.
- Assume that J_ℓ leaves $z_{\ell,k} \in \beta^*_{h,\ell}$ at time t. We show that J_ℓ never executes between t and completion of J_h:
  - If J_ℓ is not in any CS at t, then, as above, J_ℓ never executes before completion of J_h and cannot block J_h.
  - If J_ℓ is still in a CS at t, then this CS does not belong to $\beta^*_{h,\ell}$ because otherwise $z_{\ell,k}$ would not be maximal. Thus J_ℓ cannot block J_h, and thus J_ℓ is never executed before completion of J_h.

Priority-Inheritance – The Worst Case



J_1 is blocked for the total duration of all critical sections in all lower priority jobs.

Priority-Ceiling Protocol

The goal: to furhter reduce blocking times due to resource contention and to prevent deadlock

- in its basic form priority-ceiling protocol works under the assumption that the priorities of jobs and resources required by all jobs are known apriori

  can be extended to dynamic priority (job-level fixed priority), see later

Notation:

- The *priority ceiling* of any resource R_k is the highest priority of all the jobs that require R_k and is denoted by $\Pi(R_k)$
- At any time t, the current priority ceiling $\Pi(t)$ of the system is equal to the highest priority ceiling of the resources that are in use at the time
- If all resources are free, $\Pi(t)$ is equal to Ω, a newly introduced priority level that is lower than the lowest priority level of all jobs

Priority-Ceiling Protocol

The scheduling and priority-inheritance rules are the same as for priority-inheritance protocol

- **Scheduling rules**:
  - Jobs are scheduled in a preemptable priority-driven manner *according to their current priorities*
  - At release time, the current priority of a job is equal to its assigned priority
  - The current priority remains equal to the assigned priority, except when the priority-inheritance rule is invoked
- **Priority-inheritance rule**:
  - When job J_h becomes blocked on a resource R, the job J_k which blocks J_h inherits the current priority $\pi_h(t)$ of J_h;
  - J_k executes at its inherited priority until it releases R; at that time, the priority of J_k is *set to the highest priority of all jobs still blocked by J_k after releasing R.*
    (which may still be an inherited priority)

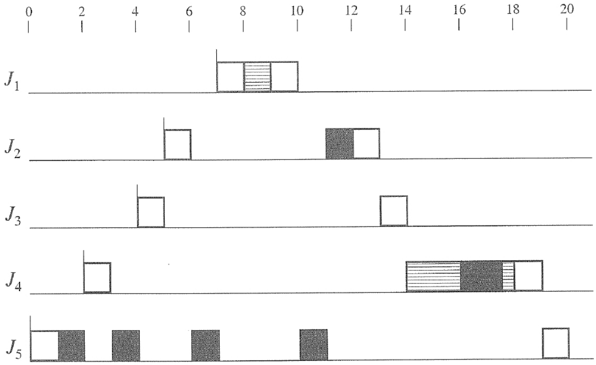
Priority-Ceiling Protocol

Resource allocation rules:

- When a job J requests a resource R held by another job, the request fails and the requesting job blocks
- When a job J requests a resource R at time t, and that resource is free:
  - If J's priority $\pi(t)$ is *strictly higher* than current priority ceiling $\Pi(t)$, R is allocated to J
  - If J's priority $\pi(t)$ is not higher than $\Pi(t)$, R is allocated to J only if J is the job holding the resource(s) whose priority ceiling is equal to $\Pi(t)$, otherwise J is blocked
    (Note that only one job may hold the resources whose priority ceiling is equal to $\Pi(t)$)

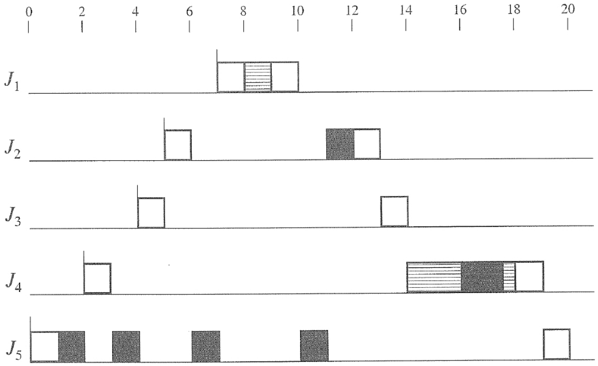
Note that unlike priority-inheritance protocol, the priority-ceiling protocol can deny access to an available resource.

Priority-Ceiling Protocol



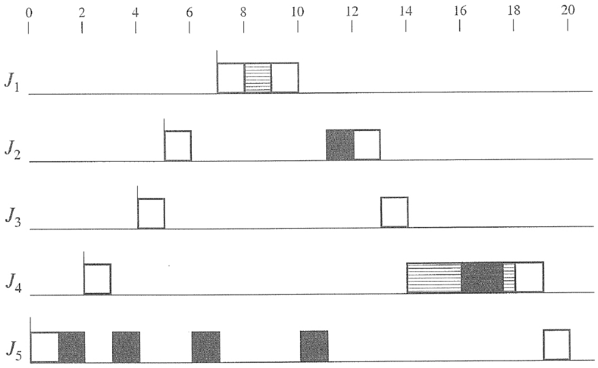
- At 1, $\Pi(t) = \Omega$, J_5 executes $L(\mathit{Black})$, continues executing
- At 3, $\Pi(t) = 2$, J_4 executes $L(\mathit{Shaded})$; because the ceiling of the system $\Pi(t)$ is higher than the current priority of J_4, job J_4 is blocked, J_5 inherits J_4's priority and executes at priority 4
- At 4, J_3 preempts J_5; at 5, J_2 preempts J_3. At 6, J_2 requests *Black* and is directly blocked by J_5. Consequently, J_5 inherits priority 2 and executes until preempted by J_1

Priority-Ceiling Protocol



- At 8, J_1 executes $L(Shaded)$, its priority is higher than $\Pi(t) = 2$, its request is granted and J_1 executes; at 9, J_1 executes $U(Shaded)$ and at 10 completes
- At 11, J_5 releases *Black* and its priority drops to 5; J_2 becomes unblocked, is allocated *Black* and executes

Priority-Ceiling Protocol



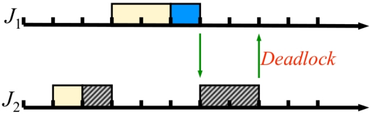
- At 14, J_2 and J_3 complete, J_4 is granted *Shaded* (because its priority is higher than $\Pi(t) = \Omega$) and executes
- At 16, J_4 executes $L(\mathit{Black})$ which is free, the priority of J_4 is not higher than $\Pi(16) = 1$ but J_4 is the job holding the resource whose priority ceiling is equal to $\Pi(16)$. Thus J_4 gets *Black*, continues to execute; the rest is clear

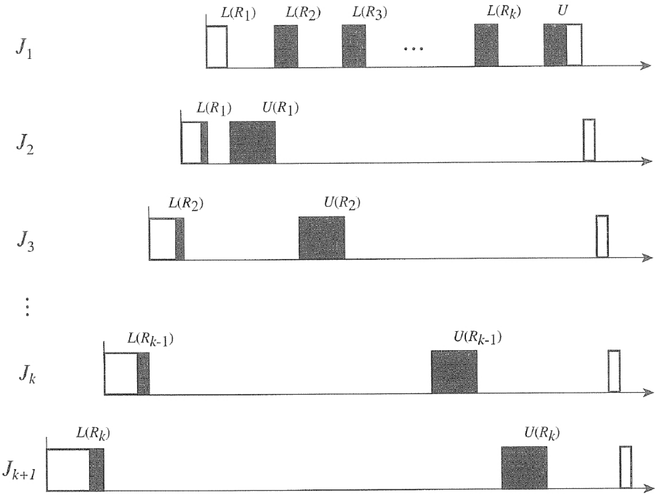
Priority-Ceiling Protocol

Theorem 32
Assume a system of preemptable jobs with fixed assigned priorities. Then

- *deadlock may never occur,*
- *a job can be blocked for at most the duration of one critical section.*

These situations cannot occur with priority ceiling protocol:





Differences between the priority-inheritance and priority-ceiling

- Priority-inheritance is greedy, while priority ceiling is not

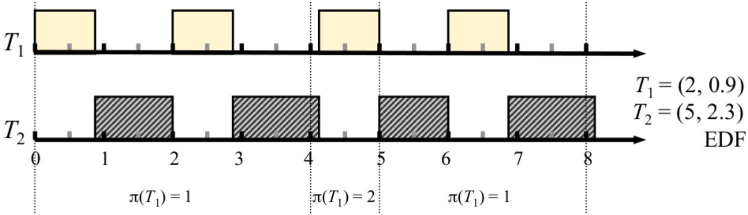
  The priority-ceiling protocol may withhold access to a free resource, i.e., a job can be prevented from execution by a lower-priority job which does not hold the requested resource – *avoidance "blocking"*
- The priority ceiling protocol forces a fixed order onto resource accesses thus eliminating deadlock

Resources in Dynamic Priority Systems

The priority ceiling protocol assumes fixed and known priorities

In a dynamic priority system, the priorities of the periodic tasks change over time, while the set of resources is required by each task remains constant

- As a consequence, the priority ceiling of each resource changes over time



What happens if T_1 uses resource X, but T_2 does not?

- Priority ceiling of X is 1 for $0 \leq t \leq 4$, becomes 2 for $4 \leq t \leq 5$, etc. even though the set of resources is required by the tasks remains unchanged

Resources in Dynamic Priority Systems

- If a system is job-level fixed priority, but task-level dynamic priority, a priority ceiling protocol can still be applied
  - Each job in a task has a fixed priority once it is scheduled, but may be scheduled at different priority to other jobs in the task (e.g. EDF)
  - Update the priority ceilings of all resources each time a new job is introduced; use until updated on next job release
- Has been proven to prevent deadlocks and no job is ever blocked for longer than the length of one critical section
  - But: very inefficient, since priority ceilings updated frequently
  - May be better to use priority inheritance, accept longer blocking

Schedulability Tests with Resources

How to adjust schedulability tests?

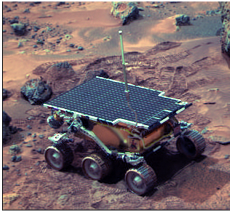
Add the blocking times to execution times of jobs; then run the test as normal

The blocking time b_i of a job J_i can be determined for all three protocols:

- non-preemptable CS $\Rightarrow$ b_i is bounded by the maximum length of a critical section in lower priority jobs
- priority-inheritance $\Rightarrow$ b_i is bounded by the total length of the m longest critical sections where m is the number of jobs that may block J_i

  (For a more precise formulation see Theorem 2.)
- priority-ceiling $\Rightarrow$ b_i is bounded by the maximum length of a critical section

Mars Pathfinder vs Priority Inversion



- Mars Pathfinder = a US spacecraft that landed on Mars in July 4th, 1997.
- Consisted of a lander and a lightweight wheeled robotic Mars rover called Sojourner
  - What Happened:
    - Few days in to the mission, not long after Pathfinder started gathering meteorological data, it began experiencing total system resets, each resulting in losses of data.
    - Apparently a software problem caused these resets.
  - The system:
    - Pathfinder used the well-known real-time embedded systems kernel VxWorks by Wind River.
    - VxWorks uses preemptive priority-based scheduling, in this case a deadline monotonic algorithm.
    - Pathfinder contained an "information bus" (a shared memory) used for communication, synchronized by locks.

Mars Pathfinder – The Problem

- Problematic tasks:
  - A bus management task ran frequently with high priority to move data in/out of the bus. If the bus has been locked, then this thread itself had to wait.
  - A meteorological data gathering task ran as an infrequent, low priority thread, and used the bus to publish its data.
  - The bus was also used by a communication task that ran with medium priority.
- Occasionally the communication task (medium priority) was invoked at the precise time when the bus management task (high priority) was blocked by the meteorological data gathering task (low priority) – priority inversion!
- The bus management task was blocked for considerable amount of time by the communication task, which caused a watchdog timer to go off, notice that the bus management task has not been executed for some time, which typically means that something had gone drastically wrong, and initiate a total system reset.

Mars Pathfinder – Solution

- JPL (Jet Propulsion Laboratory) engineers spent hours and hours running the system on a spacecraft replica.
- Early in the morning, after all but one engineer had gone home, the engineer finally reproduced a system reset on the replica.

Solution: Turn the priority inheritance on!

This was done online using a C language interpreter which allowed to execute C functions on-the-fly.

A short code changed a mutex initialization parameter from FALSE to TRUE.