Resource Management in Real-Time Systems

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Based on the book and accompanying materials to
Alan Burns and Andy Wellings, Real-Time Systems and Programming Languages, Addison Wesley Longmain, 2001
http://www.cs.york.ac.uk/rts/books/RTSBookThirdEdition.html#Teaching%20Aids

and slides from Giorgio Buttazzo

Outline

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Shared resources, critical sections

Definition (Shared resource)

A resource accessed from multiple threads of execution that must be used in a *mutually exclusive manner*.
Examples: data structure in memory, device, ...

- Access to shared resources must be “protected” by mutexes, spinlocks, disabling of interrupts/preemption, RCU, etc. $\Rightarrow$ locks.
- Locks can be **nested**.

Definition (Critical section)

Critical section is a segment of a job (piece of code) that begins with lock operation and ends with matching unlock operation.

Problem

Priority Inversion

A high priority task is blocked by a lower priority task for an **unbounded** interval of time.

Deadline Inversion

A task with short deadline is blocked by a task with longer deadline for an **unbounded** interval of time.

Real-Time computing is about determinism and unbounded blocking is not deterministic!

Terminology

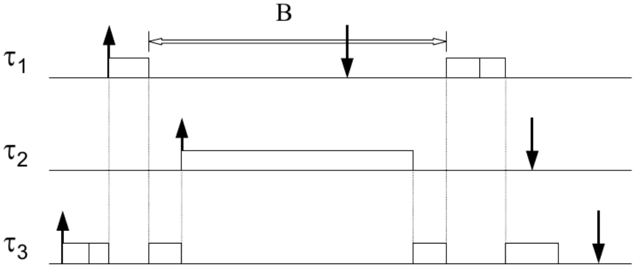
Blocking, preemption

- If a task is waiting for a lower-priority task, it is said to be blocked. Note: VxWorks calls this state “pending”.
- If a task is waiting for a higher priority task, it is said to be preempted.

Priority inversion

- If a task is blocked waiting for an **unrelated** lower-priority task to complete some required computation then the priority model is, in some sense, being undermined.
- The blocked task is said to suffer priority inversion.

Conflict in concurrent access to a critical section



Solution

Introduce a **concurrency control protocol** (resource access protocol) to control the access to shared resources.

A resource access protocol, is a set of rules that govern

1. when and under what conditions each request for resource is granted and
2. how jobs requiring resources are scheduled.

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Fixed Priority Protocols

- Non Preemptive Protocol (NPP)
  - Cyclic scheduling, `taskLock()`

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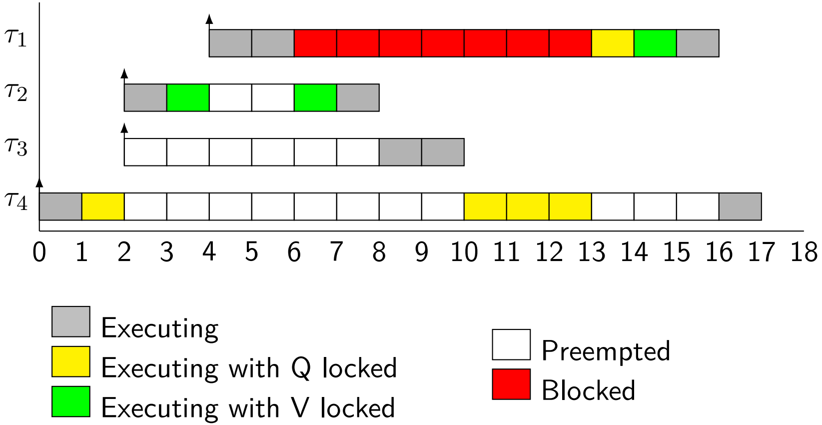
- Priority Ceiling Protocol (PCP)
- Immediate Priority Ceiling Protocol (IPCP)
- Stack Resource Policy (SRP) – also for dynamic priority

Priority Inversion

- To illustrate an extreme example of priority inversion, consider the executions of four periodic tasks $\tau_{1,\ldots,4}$ and two resources: Q and V

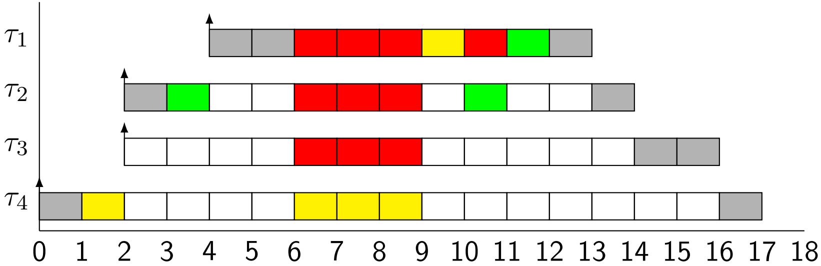
Task	Priority	Execution Sequence	Release Time
τ_1	4	E E Q V E	4
τ_2	3	E V V E	2
τ_3	2	E E	2
τ_4	1	E Q Q Q Q E	0

Example of Priority Inversion



Priority Inheritance

- If task p is blocking task q, then p runs with q's priority



Calculating Blocking

- If a task has m critical sections that can lead to it being blocked then the maximum number of times it can be blocked is m
- The task i has an upper bound on its blocking B_i given by:

$$B_i = \sum_{k=1}^{K} \text{canblock}(k, i)\, C(k),$$

where

- K is the number of critical sections in the system,
- $\text{canblock}(k, i)$ is 1 if task i can suffer blocking from critical section k, i.e. if k is executed by a task with lower priority than i, and 0 otherwise,
- $C(k)$ is the worst-case execution time of critical section k.

Blocking Term (cont.)

$$B_i = \sum_{k=1}^{K} \text{canblock}(k, i) C(k),$$

- In fact, the above formula for B_i is too pessimistic. The total number of terms in the sum is at most $v \times l$, where v is the number of resources accessed by task i and l is the number of lower priority tasks that can conflict with task i.
- Don't forget that nested blocking can create a blocking chain.

Schedulability Analysis and Blocking

Response-Time Analysis

$$\underset{i=1,\dots,n}{\forall i} \qquad R_i = C_i + B_i + \sum_{j=1}^{i-1} \left\lceil \frac{R_i}{T_j} \right\rceil C_j \leq D_i$$

Utilization-based Analysis

$$\underset{i=1,\dots,n}{\forall i} \qquad \left(\sum_{j=1}^{i} \frac{C_j}{T_j} \right) + \frac{B_i}{T_i} = U_i + \frac{B_i}{T_i} \leq U_{RM}(i)$$

Priority Ceiling Protocols

Two forms

- Original priority ceiling protocol (OPCP)
- Immediate priority ceiling protocol (IPCP)

On a single processor

- A high-priority task can be blocked at most once during its execution by lower-priority tasks
- Deadlocks are prevented
- Transitive blocking is prevented
- Mutual exclusive access to resources is ensured (by the protocol itself)

Original priority ceiling protocol (OPCP)

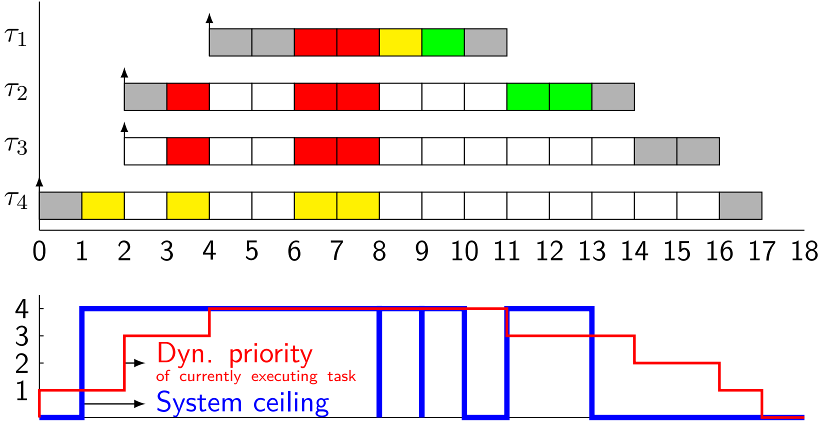
1. Each task has a static default priority assigned (perhaps by the deadline monotonic scheme)
2. A task has a dynamic priority that is the maximum of its own static priority and any it inherits due to it blocking higher-priority tasks.
3. Each resource k has a static ceiling value $\lceil k \rceil$ defined as the maximum priority of the tasks that use it
4. A task can only lock a resource if its dynamic priority is higher than the system ceiling i.e. the ceiling of any currently locked resource (excluding any that it has already locked itself)

Blocking term calculation

$$B_i = \max_{k=1}^{K} \mathsf{usage}(k, i)\, C(k)$$

OPCP example

$\left\lceil \boxed{Q} \right\rceil = 4, \left\lceil \boxed{V} \right\rceil = 4$

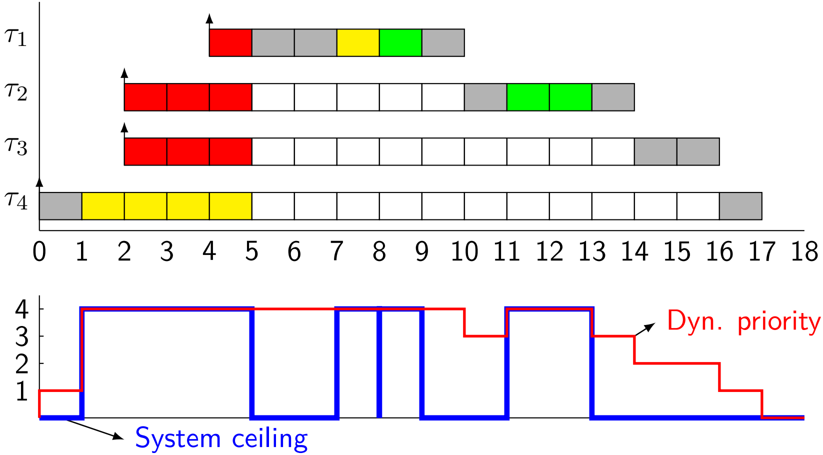


Immediate priority ceiling protocol (IPCP)

- Each task has a static default priority assigned (perhaps by the deadline monotonic scheme).
- Each resource k has a static ceiling value $\lceil k \rceil$ defined as the maximum priority of the tasks that use it.
- A task has a dynamic priority that is the maximum of its own static priority and the ceiling values of any resources it has locked
- As a consequence, a task will only suffer a block at the very beginning of its execution
- Once the task starts actually executing, all the resources it needs must be free; if they were not, then some task would have an equal or higher priority and the task's execution would be postponed

IPCP example

$\lceil \boxed{Q} \rceil = 4, \lceil \boxed{V} \rceil = 4$



OPCP versus IPCP

Although the worst-case behavior of the two ceiling schemes is identical (from the scheduling view point), there are some points of difference:

- IPCP is easier to implement than the OPCP as blocking relationships need not to be monitored
- IPCP leads to less context switches as blocking is prior to first execution
- IPCP requires more priority movements as this happens with all resource usage
- OPCP changes priority only if an actual block has occurred

Note that IPCP is called Priority Protect Protocol in POSIX and Priority Ceiling Emulation in Real-Time Java

Outline

Dynamic Priority Protocols

- Dynamic Priority Inheritance (DPI)
- Dynamic Priority Ceiling (DPC)
- Dynamic Deadline Modification (DDM)
- Stack Resource Policy (SRP)

Stack Resource Policy

[Baker 1990]

- Generalization of PCP
- Works both with fixed and dynamic priorities
- Limits blocking to the beginning of the job
- Prevents deadlock
- Supports multi-unit resources
- Allows stack sharing (stack is considered as a “special resource”)
- Is easy to implement

Stack Resource Policy

For each resource R_k

- Maximum units: N_k
- Available units: n_k

For each task τ_i the system keeps:

- its resource requirements: $\mu_i(R_k) \in \mathbb{Z}$
- a priority p_i: RM: $p_i \propto 1/T_i$ EDF: $p_i \propto 1/d_i$
- a static preemption level: $\pi_i \propto 1/D_i$

Stack Resource Policy

- Resource ceiling:

$$\mathcal{C}_k(n_k) = \max_j \{\pi_j : n_k < \mu_j(R_k)\}$$

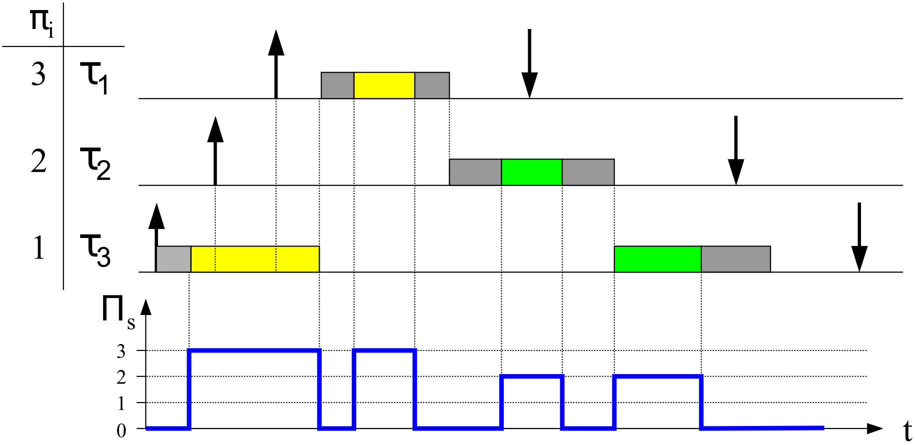
- System ceiling:

$$\Pi_s = \max_k \{\mathcal{C}_k(n_k)\}$$

- SRP Rule:

A job cannot preempt until p_i is the highest and $\pi_i > \Pi_s$.

Example

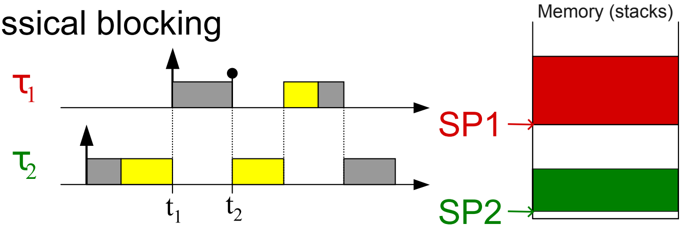


SRP: Properties

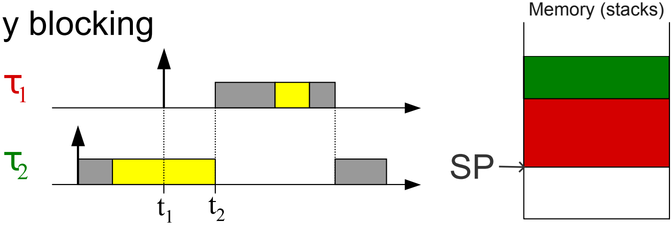
- Blocking always occurs at preemption time
- A task never blocks on a wait/lock primitive
  (semaphore queues are not needed)
- Semaphores are still needed to update the system ceiling
- Early blocking allows stack sharing

SRP: Stack sharing

Classical blocking



Early blocking



Stack sharing

- If tasks can be grouped in M subsets with the same preemption level, then tasks within a group cannot preempt each other.
- Then the stack size is the sum of the stack memory needed by M tasks.

Example

If we have 100 tasks with 10 preemption levels and each task requires 10 kB of stack, then

$$\text{Stack size} = \begin{cases} \text{1 MB without SRP} \\ \text{100 KB under SRP} \end{cases}$$

Schedulability of EDF with SRP

- n tasks
- Tasks τ_i ordered by increasing relative deadlines D_i
- B_i is the execution time of the longest critical section of any task τ_k such that $D_i \leq D_k$ or zero it there is no such τ_k

$$\underset{k=1,\ldots,n}{\forall k} \left(\sum_{i=1}^{k} \frac{C_i}{D_i} \right) + \frac{B_k}{D_k} \leq 1$$