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

1 Introduction

2 Fixed Priority Protocols
   - Priority Inheritance Protocol
   - Priority Ceiling Protocols

3 Dynamic Priority Protocols
   - Stack Resource Policy
1. Introduction

2. Fixed Priority Protocols
   - Priority Inheritance Protocol
   - Priority Ceiling Protocols

3. Dynamic Priority Protocols
   - Stack Resource Policy
Introduction

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. ⇒ 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.
Introduction

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!
Introduction

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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   ■ Priority Inheritance Protocol
   ■ Priority Ceiling Protocols

3 Dynamic Priority Protocols
   ■ Stack Resource Policy
Fixed Priority Protocols

- Non Preemptive Protocol (NPP)
  - Cyclic scheduling, taskLock()
Fixed Priority Protocols

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  - Cyclic scheduling, `taskLock()`
- Priority Inheritance Protocol (PIP)
  - Mutexes in VxWorks and Linux
Fixed Priority Protocols

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- Priority Ceiling Protocol (PCP)
- Immediate Priority Ceiling Protocol (IPCP)
Non Preemptive Protocol (NPP)
  - Cyclic scheduling, `taskLock()`
Priority Inheritance Protocol (PIP)
  - Mutexes in VxWorks and Linux
Priority Ceiling Protocol (PCP)
Immediate Priority Ceiling Protocol (IPCP)
Stack Resource Policy (SRP) – also for dynamic priority
To illustrate an extreme example of priority inversion, consider the executions of four periodic tasks $\tau_1, \ldots, \tau_4$ and two resources: $Q$ and $V$.

<table>
<thead>
<tr>
<th>Task</th>
<th>Priority</th>
<th>Execution Sequence</th>
<th>Release Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_1$</td>
<td>4</td>
<td>$\text{E E Q V E}$</td>
<td>4</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>3</td>
<td>$\text{E V V V E}$</td>
<td>2</td>
</tr>
<tr>
<td>$\tau_3$</td>
<td>2</td>
<td>$\text{E E}$</td>
<td>2</td>
</tr>
<tr>
<td>$\tau_4$</td>
<td>1</td>
<td>$\text{E Q Q Q Q Q E}$</td>
<td>0</td>
</tr>
</tbody>
</table>
Example of Priority Inversion

- \( \tau_1 \): Executing
- \( \tau_2 \): Executing with Q locked
- \( \tau_3 \): Executing with V locked
- \( \tau_4 \): Preempted

Time slots: 0 to 18

Legend:
- Gray: Executing
- Yellow: Executing with Q locked
- Green: Executing with V locked
- White: Preempted
- Red: Blocked
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 $k$. 
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

\[ \forall i \, R_i = C_i + B_i + \sum_{j=1}^{i-1} \left\lfloor \frac{R_j}{T_j} \right\rfloor C_j \leq D_i \]

Utilization-based Analysis

\[ \forall i \, \left( \sum_{j=1}^{i} \frac{C_j}{T_j} \right) + \frac{B_i}{T_i} = U_i + \frac{B_i}{T_i} \leq U_{RM}(i) \]
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

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

\[
\begin{align*}
Q &= 4, \\
V &= 4
\end{align*}
\]

System ceiling

Dyn. priority of currently executing task

System ceiling
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

\[
\begin{align*}
\lceil Q \rceil &= 4, \\
\lceil V \rceil &= 4
\end{align*}
\]
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.
Dynamic Priority Protocols

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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 $k$
- Maximum units: $N_k$
- Available units: $n_k$

For each task $\tau_i$ 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:**
  \[
  C_k(n_k) = \max_j \{ \pi_j : n_k < \mu_j(R_k) \}
  \]

- **System ceiling:**
  \[
  \Pi_s = \max_k \{ C_k(n_k) \}
  \]

- **SRP Rule:**
  A job cannot preempt until \( p_i \) is the highest and \( \pi_i > \Pi_s \).
Stack Resource Policy [Baker 1990]

- It works both with fixed and dynamic priority
- It limits blocking to 1 critical section
- It prevents deadlock
- It supports multi-unit resources
- It allows stack sharing
- It is easy to implement

For each resource $R_k$:
- Maximum units: $N_k$
- Available units: $n_k$

For each task $\tau_i$ the system keeps:
- Its resource requirements:
- A priority $p_i$
- A static preemption level $T_p$
- A maximum dynamic priority $d_p$

Example

```
\begin{array}{c|c}
\pi_i & \\
\hline
3 & \tau_1 \\
2 & \tau_2 \\
1 & \tau_3 \\
\end{array}
```

```
\begin{array}{c|c|c}
\tau_i & \Pi_s & t \\
\hline
\tau_1 & 3 & \downarrow \\
\tau_2 & 2 & \downarrow \\
\tau_3 & 1 & \downarrow \\
\end{array}
```

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

SRP: Stack sharing

Classical blocking stack

Early blocking stack
SRP: Notes

- Blocking always occurs at preemption time
- A task never blocks on a wait/lock primitive (semaphore queues are not needed)
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For each resource \( R_k \):
- Maximum units: \( N_k \)
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For each task \( \tau_i \) the system keeps:
- Its resource requirements
- A priority \( \pi_i \)
- A static preemption level

Resource ceiling
System ceiling
\[
\text{max}_{k \in \text{system}} \left( n_k \right) = \prod_{k \in \text{system}} N_k
\]

SRP Rule
A job cannot preempt until \( \pi_i \) is the highest and \( \pi_i > \prod_{k \in \text{system}} \pi_k \)

SRP: Stack sharing

Classical blocking
\[
\tau_1 \quad \tau_2
\]

Early blocking
\[
\tau_1 \quad \tau_2
\]
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

\[
\text{Stack size} = \begin{cases} 
1 \text{ MB without SRP} \\
100 \text{ KB under SRP}
\end{cases}
\]
Schedulability of EDF with SRP

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

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