Verification of Real Time Systems - CS5270
4th lecture

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A warning...

Outline

1. Administration
   - Assignment 1
   - The road map...
2. Resource access
   - Priority Inversion
   - Priority Inheritance Protocol
   - Priority Ceiling Protocol

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Outline

Assignment 1

Assignment number 1: Correction

- Hand in Feb **15** - during lecture

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Where we are so far

Three topics so far

- **RT systems**
  - Motivation, modelling vs synthesis, hard vs soft, RT architectures
- **The real-time computing environment**
  - Temporal accuracy, clocks
  - TTP ? time triggered protocols
- **Scheduling**
  - Preemption, feasibility, schedulability

Where we are going

Formal basis for Uppaal:

- **Complete the scheduling part..**
  - PIP and PCP (today).
- **Formal basis for Uppaal**
  - Detailed study of a basis for efficient real-time analysis/model checking
  - Transition systems,
  - Automata,
  - Model checking
  - Timed transition systems,
  - Zones/regions (efficient timed systems)

This will all take some time... Perhaps 4/5 weeks

The immediate road map

After completing scheduling... four topics:

- **State transition systems**
  - some definitions
  - parallel composition
- **Timed transition systems**
  - formal definition
  - parallel composition
  - Reduction of a TTS (which has possibly infinite states and actions) to a finite TS by quotienting? (takes time)
- **Efficiency in TTS**
  - Regions
  - zones
- **Automata and safety properties**

The long distance road map

The local road map, and...

- **Verification of temporal properties**
  - LTL and CTL temporal/modal logic
  - The verification setting
- **CTL model checking**
  - Definition of CTL
  - Kripke structures
  - Definition of the modelling relation
  - Model checking algorithm **for CTL**
- **TCTL model checking**
  - Definition of TCTL
  - Model checking for TCTL

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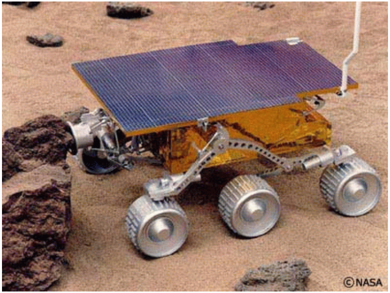
Mars pathfinder mission in 1997

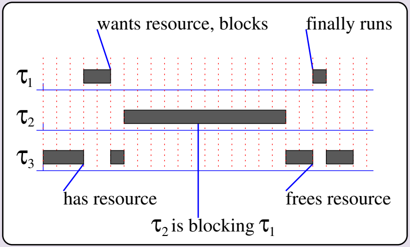
Ran into serious problems:



The spacecraft began experiencing total system **resets** with **loss of data** each time ... due to **priority inversion**...

Priority inversion scenario

Three prioritized tasks



Higher priority task τ_1 **blocked** by the much lower priority task that is holding a **shared resource**. The lower priority task τ_3 has acquired this resource and then been **preempted** by the medium priority task τ_2. In summary, τ_2 **is blocking** τ_1.

Priority inversion avoidance

On the pathfinder, the resource was a mutual exclusion semaphore

How can we avoid priority inversion?

- We could **disallow preemption** during the execution of a critical section, **but ...** this works only if critical sections are short, and might unneccesarily block higher priority processes that do not even use any shared resources.
- Or **use resource access protocols** such as
  - the priority **inheritance** protocol (PIP), or
  - the priority **ceiling** protocol (PCP).

Outline

PIP: Priority Inheritance Protocol

Tasks have nominal and active priorities...

- A **nominal priority** is assigned by the scheduling algorithm (RMS or EDF or some other algorithm).
- The **active priority** is assigned by the protocol dynamically, specifically to avoid priority inversion.
- In **PIP**, we use scheduling based on **active priorities**:
  - When τ_i blocks higher-priority tasks, then its active priority is set to the **highest** of the priorities of the tasks it blocks.
  - When a task is blocked on a semaphore, it **transmits** its active priority to the job that holds the semaphore

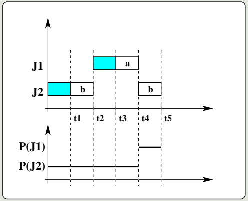
PIP: Priority Inheritance Protocol

Two viewpoints...

- When τ_i blocks higher-priority tasks, it temporarily **inherits** the highest priority of the blocked tasks. This prevents medium priority tasks from preempting τ_i and prolonging the blocking duration of the higher priority tasks.
- A task inherits the highest priority of the jobs blocked by it.
- When a task exits a critical section, it unlocks the semaphore; the job with the highest priority that is blocked on the semaphore, if any, is awakened.

PIP

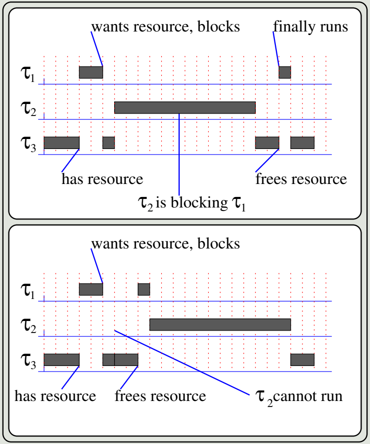
An example...



- At t_1, J2 does a **`wait(b)`**. Lock **succeeds**.
- At t_2, J1 is scheduled and begins, as $P(J1) > P(J2)$.
- At t_3, J1 does a **`wait(a)`**. Lock **succeeds**.
- At t_4, J1 does a **`wait(b)`**, and from PIP, transmits it's priority to J2. New priority is $P(J1)$.

PIP

Avoiding priority inversion example...



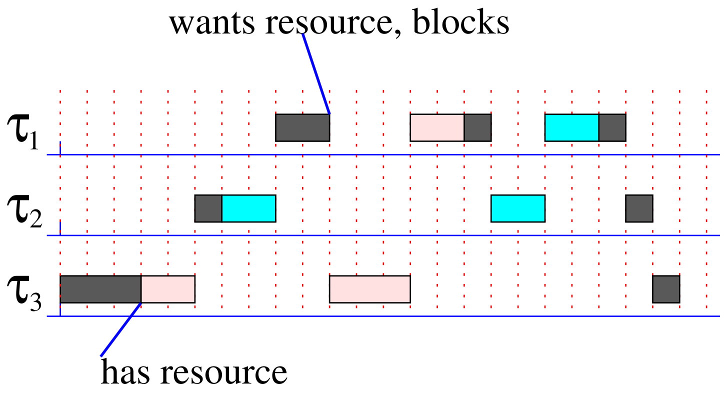
Properties of PIP

Good and bad news

- The **good news** is that if there are a set of distinct semaphores that can block a task τ then τ can be blocked for **at most** the duration of at most one critical section, one for each of the semaphores. It can never be as long as the WCET of a lower priority task.
- The **bad news**:
  - ***chained blocking***, where a task τ is blocked on critical sections held by lower priority jobs, and
  - ***deadlock***.

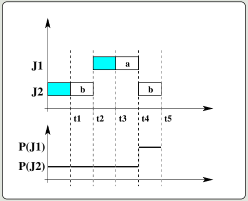
Chained blocking using PIP

In the worst case...



Deadlock using PIP

Deadlock example: J1 is ABBA, J2 is BAAB



- At t_1, J2 does a **wait(b)**. Lock **succeeds**.
- At t_2, J1 is scheduled and begins, as $P(J1) > P(J2)$.
- At t_3, J1 does a **wait(a)**. Lock **succeeds**.
- At t_4, J1 does a **wait(b)**.
- At t_5, J2 does a **wait(a)**. **Deadlock**

Longest blocking time

Example task set

	A	B	C	D
τ_1	**3**	**2**	**4**	**6**
τ_2	**4**	**0**	**6**	**8**
τ_3	**2**	**1**	**0**	**5**

- Consider three periodic tasks τ_1, τ_2 and τ_3 (having decreasing priority) which **share** four resources A, B, C and D accessed using the priority inheritance protocol.
- The longest duration D_{iR} for the task τ_i on resource R is given by the table. ($D_{iR} = 0$ means τ_i does not use at all the resource D).

Longest blocking time

Compute a (conservative) maximum blocking time for tasks:

$$
\begin{aligned}
B_i &= \min(B_i^\ell, B_i^s) \\
\text{and} \quad B_i^\ell &= \sum_{j=i+1}^{n} \max_k \, [D_{j,k} : C(S_k) \geq P_i] \\
\text{and} \quad B_i^s &= \sum_{k=1}^{m} \max_{j>i} \, [D_{j,k} : C(S_k) \geq P_i]
\end{aligned}
$$

where B_i^s is the sum of the durations of the longest critical sections guarded by semaphore S_k that can block τ_i, and B_i^ℓ is the sum of the durations of the longest critical sections in tasks with lower priority than τ_i, guarded by semaphore S_k, and that can block τ_i.

Longest blocking time

Computing the longest blocking time of example

- Use equation to derive the following ***blocking*** *times*

$$B_1^\ell = 8+5=13 \qquad B_1^s = 4+1+6+8=19$$
$$B_2^\ell = 5 \qquad B_2^s = 2+1+5=8$$
$$B_3^\ell = 0 \qquad B_3^s = 0$$

and so $B_1 = 13$, $B_2 = 5$ *and* $B_3 = 0$.

This calculation is **reasonably efficient**, but if you try to find a tighter bound, then the **complexity** of the algorithm would be much higher (it is **exponential**).

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Priority ceiling protocol

An extension of the priority inheritance protocol...

- **Avoids chained blocking** and **deadlocks**.
- The **underlying idea** is that a task is not allowed to enter a critical section if there are already locked semaphores which could block it eventually (due to a sub-critical section nested within the entering critical section).
- Hence, once a task enters a critical section, it can not be blocked by lower priority tasks till its completion.

Priority ceiling protocol

The protocol:

- Each semaphore S is assigned a priority ceiling $C(S)$, the priority of the highest priority task that can lock S.
- τ is allowed to lock S only if the priority of τ is strictly higher than the priority ceiling $C(S')$ of the semaphore S' where S' is the semaphore with the highest priority ceiling among all the semaphores which are currently locked by jobs other than τ.
- When τ gets blocked by S' then the priority of τ is transmitted to the job that currently holds S'.

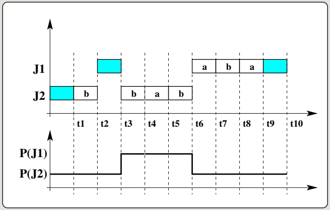
Priority ceiling protocol

The protocol:

- When τ' leaves a critical section guarded by S' then it unlocks S' and the highest priority job, if any, which is blocked by S' is awakened.
- The priority of τ' is set to the highest priority of the job that is blocked by some semaphore that τ' is still holding.
- If none, the priority of τ' is set to be its nominal one.

Priority ceiling protocol

ABBA and BAAB example OK with PCP:



- At t_1, J2 does a **`wait(b)`**. Lock **succeeds**.
- At t_2, J1 is scheduled and begins, as $P(J1) > P(J2)$.
- At t_3, J1 does a **`wait(a)`**. Due to PCP, J1 cannot lock *a*.
- At t_6, J2 releases *b* and we are back to normal running...

PCP blocking time

A computation using the previous task set

- The maximum blocking time B_i for each task if the resources are accessed using the Priority Ceiling Protocol is

$$B_i = \max_{j,k} \{D_{j,k} \mid P_j < P_i, C(S_k) \geq P_i\}$$

and we have that

$$\begin{aligned} B_1 &= \max(4,2,1,6,8,5) = 8 \\ B_2 &= \max(2,1,5) = 5 \\ B_3 &= 0 \end{aligned}$$