AADL : about scheduling analysis

Summary

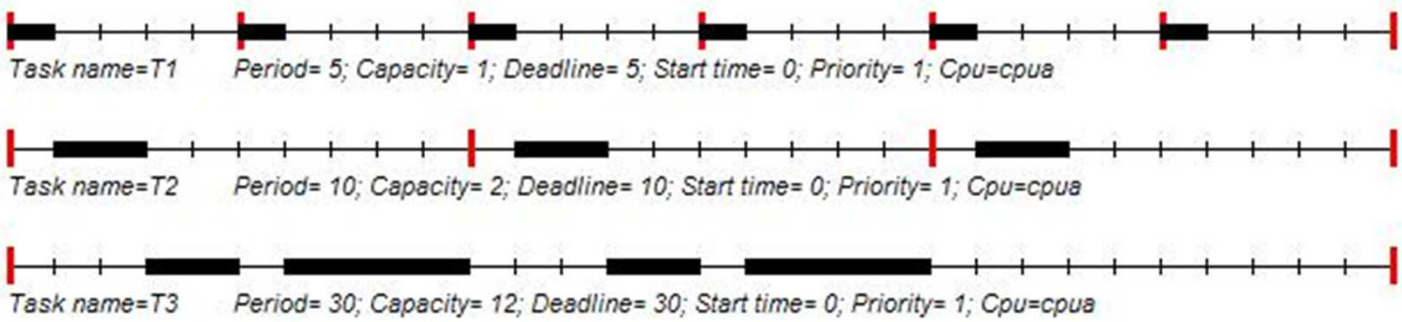
1. Issues about real-time scheduling : AADL to the rescue
2. Focus on fixed-priority scheduling:
   - Basics on uniprocessor
3. AADL components/properties to scheduling analysis
4. An example with Cheddar

Real-Time scheduling theory

1. **A set of tasks models** (to model functions of the system)
2. **A set of analytical methods** (feasibility tests)
   - **E.g. Worst Case Response Time**

$$R_i \leq Deadline \qquad R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{P_j} \right\rceil \cdot C_j$$

3. **A set of scheduling algorithms**: build the full scheduling/GANTT diagram



Real-Time scheduling theory is hard to apply

- Real-Time scheduling theory
  - Theoretical results defined from 1974 to 1994: feasibility tests exist for uniprocessor, periodic tasks, shared resources
  - Extension through simulation for other cases
- Now supported at a decent level by POSIX 1003 RTOS, ARINC653, …
- Industry demanding
  - Yet, hard to use

Real-Time scheduling theory is hard to apply

- Feasibility tests not always exist for modern architectures
  - Multi-cores, distributed, asynchronous, hierarchical
- Requires strong theoretical knowledge
  - Numerous theoretical results: how to choose the right one ?
  - Numerous assumptions for each result.
  - How to abstract/model a system to access schedulability ? (e.g. task dependency)
- How to integrate scheduling analysis in the process ?
  - When to apply it ? What about tools ?

It is the role of an ADL to hide those details

AADL to the rescue ?

- AADL helps modeling a full system, including hardware, task sets, connections, RTOS features, …
- All of these elements are mandatory to apply real-time scheduling theory
  - Example: an AADL model can include periodic tasks and usual scheduling policies
    - Worst case execution time (or WCET), period, deadline
    - Fixed priority scheduling
- However, in many cases, the models stay too complex
  - Dependent tasks, shared buffers or buses, …

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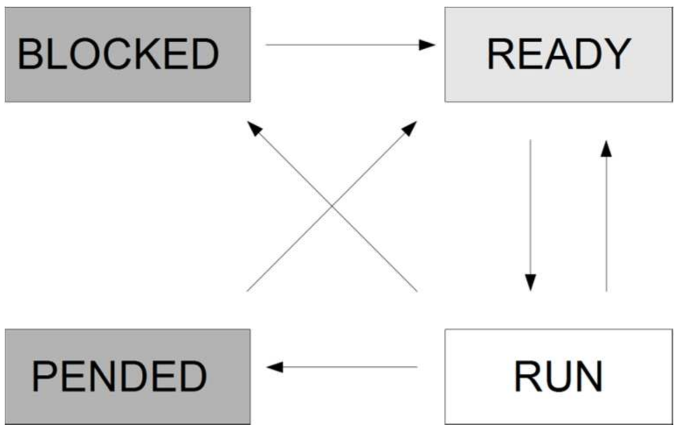
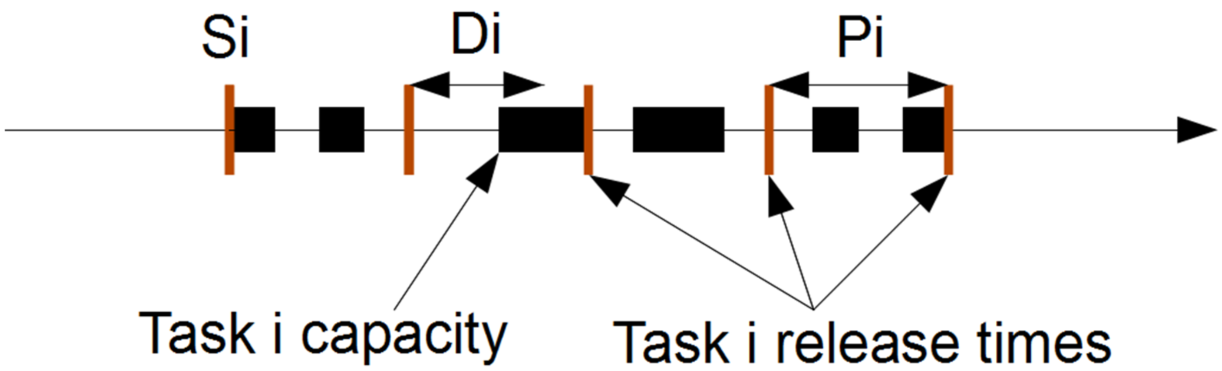
Real-time scheduling theory : models of task

- **Task:** sequence of statements + data + state.



- **Usual task types:**
  - Independent tasks or dependent tasks.
  - Periodic and sporadic tasks (critical functions).
    Aperiodic tasks (non critical functions).

Real-time scheduling theory : models of task



- **Usual parameters of a periodic task i:**
  - **Period:** Pi (duration between two periodic release times). A task starts a job for each release time.
  - **Deadline to meet:** Di, timing constraint to meet, relative to the period/job.
  - **First task release time (first job):** Si.
  - **Worst case execution time of each job:** Ci (or capacity or WCET).
  - **Priority:** allows the scheduler to choose the task to run.

Real-time scheduling theory : models of task

- **Assumptions for the next slides (synchronous periodic task with deadlines on requests):**
  - All tasks are periodic.
  - All tasks are independent.
  - $\forall i$: Pi=Di : a task must end its current job before its next release time.
  - $\forall i$: Si=0 => called critical instant (worst case on processor demand).

Uniprocessor usual real-time scheduling policies

- **On-line/off-line scheduling:** the scheduling is computed before or at execution time?
- **Fixed/dynamic priority scheduler:** priorities may change at execution time?
- **Preemptive or non preemptive scheduling:** can we stop a task during its execution ?

- **Online, preemptive, fixed priority scheduler** with Rate Monotonic priority assignment (RM, RMS, RMA).

Uniprocessor fixed priority scheduling

- **Fixed priority scheduling :**
  - Scheduling based on fixed priority => critical applications.
  - Priorities are assigned at design time (off-line).
  - Efficient and simple feasibility tests.
  - Scheduler easy to implement into real-time operating systems.
- **Rate Monotonic priority assignment :**
  - Optimal assignment in the case of fixed priority scheduling and uniprocessor.
  - Periodic tasks only.

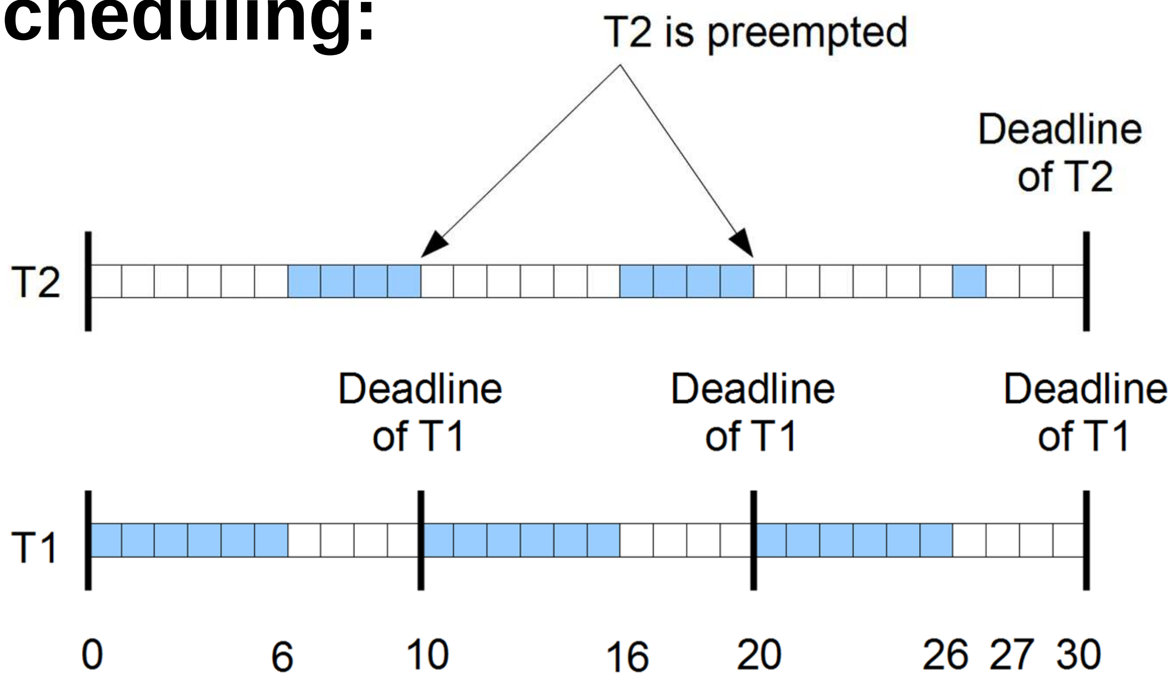
Uniprocessor fixed priority scheduling

- **Two steps:**
  1. **Rate monotonic priority assignment:**
     - the highest priority tasks have the smallest periods. Priorities are assigned off-line (e.g. at design time, before execution).

  2. **Fixed priority scheduling**:
     - at any time, run the ready task which has the highest priority level.

Uniprocessor fixed priority scheduling

- **Rate Monotonic assignment and preemptive fixed priority scheduling:**



  - Assuming VxWorks priority levels (high=0 ; low=255)
  - T1 : C1=6, P1=10, Prio1=0
  - T2 : C2=9, P2=30, Prio2=1

Uniprocessor fixed priority scheduling

- **Feasibility/Schedulability tests:**
  1. **Run simulations on hyperperiod** = [0,LCM(Pi)]. Sufficient and necessary (exact result). Any priority assignment and preemptive/non preemptive scheduling.
  2. **Processor utilization factor test:**
     $U = \sum_{i=1}^{n} Ci/Pi \leq n.(2^{\frac{1}{n}}-1)$
     Rate Monotonic assignment and preemptive scheduling. Sufficient but not necessary. Does not compute an exact result.
  3. **Task worst case response time, noted ri** : delay between task release time and task end time. Sometime an exact result. Any priority assignment but preemptive scheduling.

Uniprocessor fixed priority scheduling

- **Compute ri, task i worst case response time:**
  - Assumptions: preemptive scheduling, synchronous periodic tasks.
  - Task i response time = task i capacity + delay the task i has to wait for higher priority task j. Or:

$$R_i = C_i + \sum_{j \in hp(i)} waiting\ time\ due\ to\ j \qquad or\ R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{P_j} \right\rceil \cdot C_j$$

  - hp(i) is the set of tasks which have a higher priority than task i. $\lceil x \rceil$ returns the smallest integer not smaller than x.

Uniprocessor fixed priority scheduling

- To compute task response time: compute wi^k with:

$$wi^n = Ci + \sum_{j \in hp(i)} \lceil wi^{n-1}/Pj \rceil . Cj$$

- Start with wi^0=Ci.
- Compute $wi^1, wi^2, wi^3, \ldots wi^k$ upto:
  - If wi^k >Pi. No task response time can be computed for task i. Deadlines will be missed !
  - If wi^k = wi^{k-1}. wi^k is the task i response time. Deadlines will be met.

Uniprocessor fixed priority scheduling

- **Example:** T1(P1=7, C1=3), T2 (P2=12, C2=2), T3 (P3=20, C3=5)

$$w1^0 = C1 = 3 \Rightarrow r1 = 3$$
$$w2^0 = C2 = 2$$
$$w2^1 = \text{C2} + \left\lceil \frac{w2^0}{P1} \right\rceil . C1 = 2 + \left\lceil \frac{2}{7} \right\rceil . 3 = 5$$
$$w2^2 = \text{C2} + \left\lceil \frac{w2^1}{P1} \right\rceil . C1 = 2 + \left\lceil \frac{5}{7} \right\rceil . 3 = 5 \Rightarrow r2 = 5$$
$$w3^0 = C3 = 5$$
$$w3^1 = \text{C3} + \left\lceil \frac{w3^0}{P1} \right\rceil . C1 + \left\lceil \frac{w3^0}{P2} \right\rceil . C2 = 10$$
$$w3^2 = \text{C3} + \left\lceil \frac{w3^1}{P1} \right\rceil . C1 + \left\lceil \frac{w3^1}{P2} \right\rceil . C2 = 13$$
$$w3^3 = \text{C3} + \left\lceil \frac{w3^2}{P1} \right\rceil . C1 + \left\lceil \frac{w3^2}{P2} \right\rceil . C2 = 15$$
$$w3^4 = \text{C3} + \left\lceil \frac{w3^3}{P1} \right\rceil . C1 + \left\lceil \frac{w3^3}{P2} \right\rceil . C2 = 18$$
$$w3^5 = \text{C3} + \left\lceil \frac{w3^4}{P1} \right\rceil . C1 + \left\lceil \frac{w3^4}{P2} \right\rceil . C2 = 18 \Rightarrow r3 = 18$$

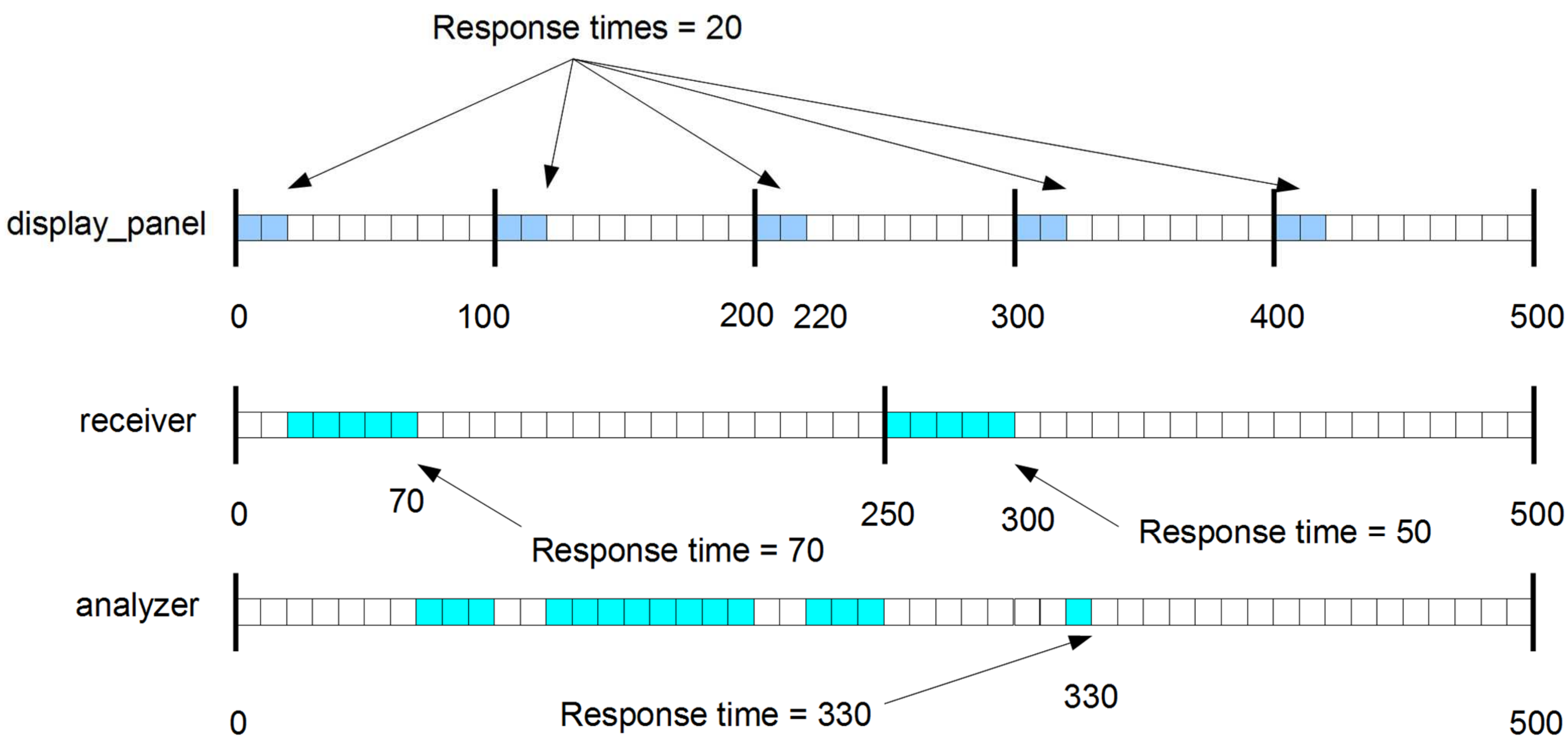
Uniprocessor fixed priority scheduling

- **Example with the AADL case study:**
  - “display_panel” thread which displays data. P=100, C=20.
  - “receiver” thread which sends data. P=250, C=50.
  - “analyser” thread which analyzes data. P=500, C=150.

- **Processor utilization factor test:**
  - U=20/100+150/500+50/250=0.7
  - Bound=$3.(2^{\frac{1}{3}} - 1)$=0.779
  - U≤Bound => deadlines will be met.

- **Task response time:** R_analyser=330, R_display_panel=20, R_receiver=70.
- **Run simulations on hyperperiod:** [0,LCM(Pi)] = [0,500].

Uniprocessor fixed priority scheduling



Fixed priority and shared resources

- Previous tasks were independent … does not really exist in true life.

- **Task dependencies :**
  - Shared resources.
    - E.g. with AADL: threads may wait for AADL protected data component access.
  - Precedencies between tasks.
    - E.g with AADL: threads exchange data by data port connections.

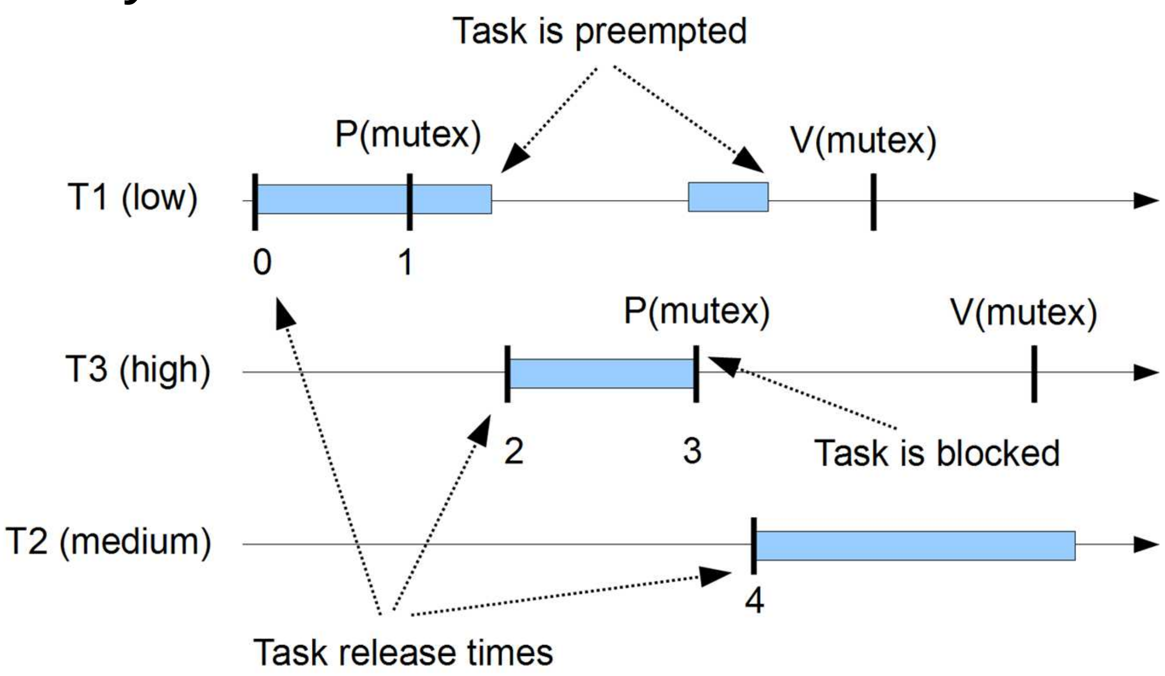
Fixed priority and shared resources

- Shared resources are usually modeled by semaphores.
- **We use specific semaphores implementing inheritance protocols:**
  - To take care of priority inversion.
  - To compute worst case task blocking time for the access to a shared resource. Blocking time Bi.

- **Inheritance protocols:**
  - PIP (Priority inheritance protocol**)**, can not be used with more than one shared resource due to deadlock.
  - PCP (Priority Ceiling Protocol) , implemented in most of real-time operating systems (e.g. VxWorks).
  - Several implementations of PCP exists: OPCP, ICPP, …

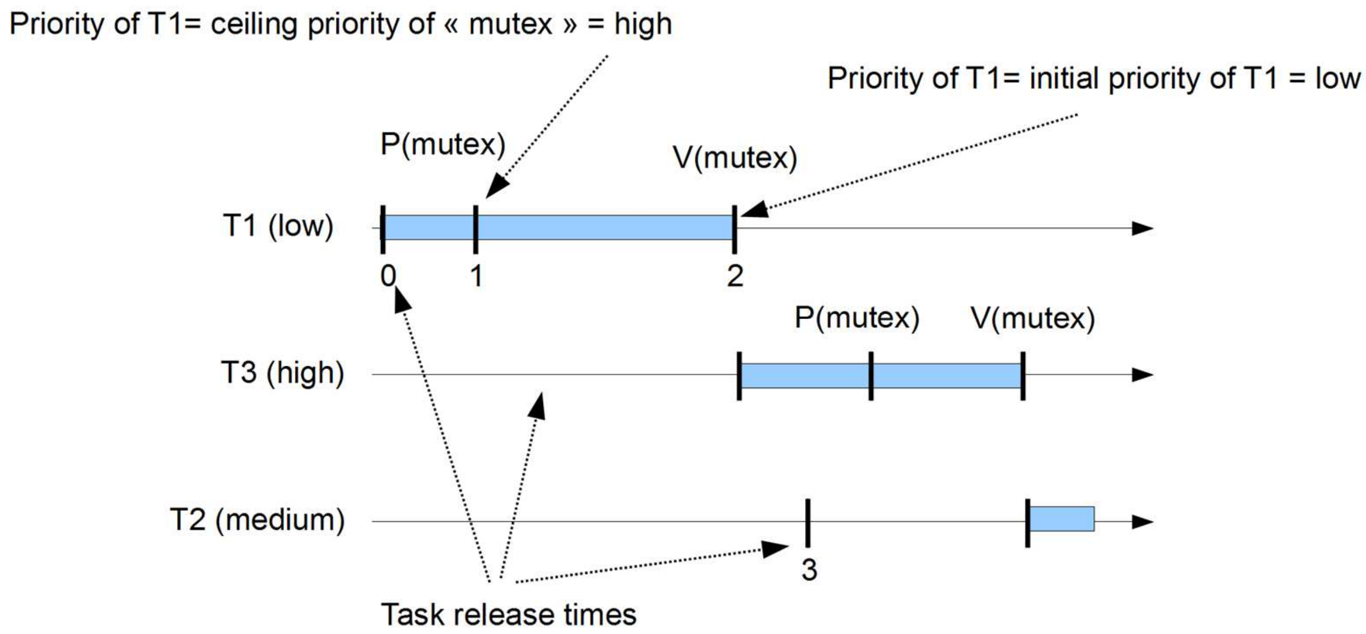
Fixed priority and shared resources

- **What is Priority inversion:** a low priority task blocks a high priority task



- Bi = worst case on the shared resource waiting time.

Fixed priority and shared resources



- **ICPP (Immediate Ceiling Priority Protocol):**
  - Ceiling priority of a resource = maximum static priority of the tasks which use it.
  - Dynamic task priority = maximum of its own static priority and the ceiling priorities of any resources it has locked.
  - Bi=longest critical section ; prevent deadlocks

Fixed priority and shared resources

- **How to take into account the waiting time Bi:**

  - Processor utilization factor test :

$$\forall\, i, 1 \leq i \leq n : \sum_{k=1}^{i-1} \frac{Ck}{Pk} + \frac{Ci+Bi}{Pi} \leq i.(2^{\frac{1}{i}} - 1)$$

  - Worst case response time :

$$R_i = B_i + C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{P_j} \right\rceil \cdot C_j$$

To conclude on scheduling analysis

- **Many feasibility tests:** depending on task, processor, scheduler, shared resource parameters or dependencies. What about uniprocessor or multiprocessor or hierarchical or distributed?

$$R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{P_j} \right\rceil \cdot C_j$$

- **Many assumptions :** require preemptive and fixed priority scheduling, synchronous periodic independent tasks with deadlines on requests …

Many feasibility tests …. Many assumptions …

How to choose them?

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4. An example with Cheddar

AADL to the rescue ?

- **Issues:**
  - Ensure all required model elements are given for the analysis
  - Ensure model elements are compliant with analysis requirements
- **AADL helps because:**
  - AADL as a pivot language between tools. International standard.
  - Close to the real-time scheduling theory: real-time scheduling concepts can be found. Ex:
    - Component categories: thread, data, processor
    - Property sets: `Thread_Properties`, `Timing_Properties`, `Communication_Properties`, `AADL_Project`

Property sets for scheduling analysis

- **Properties related to processor:**

```
Preemptive_Scheduler : aadlboolean applies to (processor);

 Scheduling_Protocol:
  inherit list of Supported_Scheduling_Protocols
  applies to (virtual processor, processor);
 -- RATE_MONOTONIC_PROTOCOL,
 -- POSIX_1003_HIGHEST_PRIORITY_FIRST_PROTOCOL, ..
```

Property sets for scheduling analysis

- **Properties related to the threads/data:**

```
Compute_Execution_Time: Time_Range
 applies to (thread, subprogram, …);

Deadline: inherit Time => Period applies to (thread, …)

Period: inherit Time applies to (thread, …);

Dispatch_Protocol: Supported_Dispatch_Protocols
 applies to (thread);
--  Periodic, Sporadic, Timed, Hybrid, Aperiodic, Backgr
...

Priority: inherit aadlinteger applies to (thread, …, dat

Concurrency_Control_Protocol:
 Supported_Concurrency_Control_Protocols applies to (dat
--  None, PCP, ICPP, …
```

Property sets for scheduling analysis

- **Example:**

```
thread implementation receiver.impl
  properties
    Dispatch_Protocol => Periodic;
    Compute_Execution_Time => 31 ms .. 50 ms;
    Deadline => 250 ms;
    Period => 250 ms;
end receiver.impl;

data implementation target_position.impl
  properties
    Concurrency_Control_Protocol
        => PRIORITY_CEILING_PROTOCOL;
end target_position.impl;
```

```
process implementation processing.others
  subcomponents
    receiver : thread receiver.impl;
    analyzer : thread analyzer.impl;
    target : data target_position.impl;
    . . .
processor implementation leon2
  properties
    Scheduling_Protocol =>
          RATE_MONOTONIC_PROTOCOL;
      Preemptive_Scheduler => true;
end leon2;

system implementation radar.simple
subcomponents
  main : process processing.others;
  cpu : processor leon2;
   . . .
```

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Cheddar : a framework to access schedulability

- **Cheddar tool =**

  analysis framework (queueing system theory & real-time scheduling theory)

  + internal ADL (architecture description language)

  + various standard ADL parsers (AADL, MARTE UML)

  + simple model editor.

- **Two versions :**
  - Open source (Cheddar) : educational and research.
  - Industrial (AADLInspector) : Ellidiss Tech product.
- **Supports :** Ellidiss Tech., Conseil régional de Bretagne, BMO, EGIDE/Campus France, Thales Communication

- **AADL is a rich language : Cheddar proposes design patterns to help engineers to select relevant feasibility tests**

A “design pattern” approach to increase real-time scheduling usability

- **Define a set of AADL design patterns of real-time systems.**

  = models a typical thread communication or synchronization.

  = set of constraints on entities of the AADL model.

- **For each design pattern, define feasibility tests that can be applied according to their applicability assumptions.**

- **Schedulability analysis of a AADL model:**
  1. Checks compliancy of the AADL model with one of the design-patterns … which then gives which feasibility tests can be applied.
  2. Compute these feasibility tests.

A “design pattern” approach to increase real-time scheduling usability

- **Specification of various design patterns:**
  - **Time-triggered :** time triggered architecture (data port connection)
  - **Ravenscar** : shared data and PCP (data component).
  - **Black board :** readers/writers synchronization
  - **Queued buffer :** producer/consumer synchronization
  - **…**
  - **Compositions of design patterns.**
- **Example of the Ravenscar design-pattern**.

The «Ravenscar» design pattern

- **Ravenscar:**
  - Part of the Ada 1995 standard
  - A set of guidelines/constraints to enable efficient and deterministic task scheduling of Ada programs
  - Later extended to Java RTSJ, C/POSIX, and AADL

- **Objective: remove all that prevent Ada programs analysis**
  1. All Ada tasks are either periodic or sporadic
  2. Communication through shared data, no Ada rendez-vous
  3. Shared data protected by PCP
  4. Static, no dynamic creation of Ada tasks
  5. Fixed priority preemptive scheduling similar to POSIX 1003

- **Feasibility test to compute:** worst case thread response time + thread blocking time due to data component access.

The «Ravenscar» design pattern

Radar Example:

```
thread implementation receiver.impl
  properties
    Dispatch_Protocol => Periodic;
    Compute_Execution_Time =>  31 ms ..  50 ms;
    Deadline  =>  250 ms;
    Period =>  250 ms;
end receiver.impl;

data implementation target_position.impl
  properties
    Concurrency_Control_Protocol
        => PRIORITY_CEILING_PROTOCOL;
end target_position.impl;
```

```
process implementation processing.others
  subcomponents
    receiver : thread receiver.impl;
    analyzer : thread analyzer.impl;
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    . . .
processor implementation leon2
  properties
    Scheduling_Protocol =>
          RATE_MONOTONIC_PROTOCOL;
      Preemptive_Scheduler => true;
end leon2;

system implementation radar.simple
subcomponents
  main : process processing.others;
  cpu : processor leon2;
   . . .
```

The «Ravenscar» design pattern

- **Demos:**
  - Scheduling analysis of the radar example with Cheddar
  - .. And with AADLInspector also