Real Time Operating Systems and Middleware

Introduction to Real-Time Systems

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Some Information

- Slides available from
  `http://www.disi.unitn.it/~abeni/RTOS`
- Interested students can have a look at:
  - *Giorgio Buttazzo,* **"HARD REAL-TIME COMPUTING SYSTEMS: Predictable Scheduling Algorithms and Applications"**, Second Edition, Springer, 2005
- Exam: Written exam + Optional project
  - You will be asked questions about *all* the course
- Prerequisites:
  - Programming skills: C, C++
  - Some knowledge about Operating Systems

Prerequisites

- You must know how to code in C / C++
  - This is not about knowing the C syntax...
  - It is about writing good C code
  - If you do not feel confident enough with C, have a look at **"The C Programming Language"** by *Kerrigan* and *Ritchie*
  - Some notes about C programming are available on the course web site
- About Operating Systems:
  - "Sistemi Operativi I", or similar exams
  - References: a good OS book (Stallings, Tanenbaum, ...)
  - How to use a shell, the `make` command, and how to compile and execute programs

Overview of the Course - 1

- Real-Time Systems: what are they?
  - Real-Time Computing, Temporal Constraints
  - Definitions and task model
  - Real-Time scheduling
- Notes about real-time programming, RT-POSIX, pthreads, ...
- Real-Time Scheduling
  - Fixed Priority scheduling, RM, DM
  - EDF and dynamic priorities
  - Resource Sharing (Priority Inversion, etc...)

Overview of the Course - 2

- Operating System structure
  - Notes about traditional kernel structures
  - Sources of kernel latencies
  - Some approaches to real-time kernels:
    - dual kernel approach
    - interrupt pipes
    - microkernels
    - monolithic kernels and RT

Real-Time Operating Systems

- Real-Time operating system (RTOS): OS providing support to Real-Time applications
- Real-Time application: the correctness depends not only on the output values, but also on the time when such values are produced
- Operating System:
  - Set of computer programs
  - Interface between applications and hardware
  - Control the execution of application programs
  - Manage the hardware and software resources
- OS as...
  - A Service Provider for user programs (interface...)
  - A Resource Manager

Operating System as a Resource Manager

- Process Management
- Memory Management
- File Management
  - VFS
  - File System
- Networking
- Device Drivers
- Graphical Interface

Resources must be managed so that
real-time applications are served properly

Operating System Services

- Services (Kernel Space):
  - Process Synchronisation, Inter-Process Communication (IPC)
  - Process / Thread Scheduling
  - I / O
  - Virtual Memory

Specialised API?

- Resource Manager (device drivers...)
  - Interrupt Handling
  - Device Management
  - ...

OS Structure?

Typical Applications

- Air traffic control
- Flight control systems
- Robotics
- Telecommunication systems
- Nuclear / chemical power plants
- Multimedia systems
- Automotive systems

Real-Time Systems: What???

- Real-Time application: the time when a result is produced matters
  - a correct result produced too late is equivalent to a wrong result, or to no result
  - characterised by temporal constraints that have to be respected
- Example: mobile vehicle with a software module that
  1. Detects obstacles
  2. Computes a new trajectory to avoid them
  3. Computes the commands for engine, brakes, . . .
  4. Sends the commands

Real-Time Systems: What???

- If the commands are correctly computed, but are not sent in time...
- ...The vehicle crashes into the obstacle before receiving the commands!
- Examples of temporal constraints:
  - must react to external events in a predictable time
  - must repeat a given activity at a precise rate
  - must end an activity before a specified time

More About Temporal Constraints

- Explicit: included in the specification of the system activities
  - “open the valve in 10 seconds”
  - “read the altimeter every 200ms”
  - “send the position within 40ms”
- Implicit: do not appear in the system specification, but must be respected to meet the requirements
  - “avoid obstacles while running at speed v”
  - “slide a surface with speed v and force F”
- They can always be modelled using the concept of *deadline*

Real-Time & Determinism

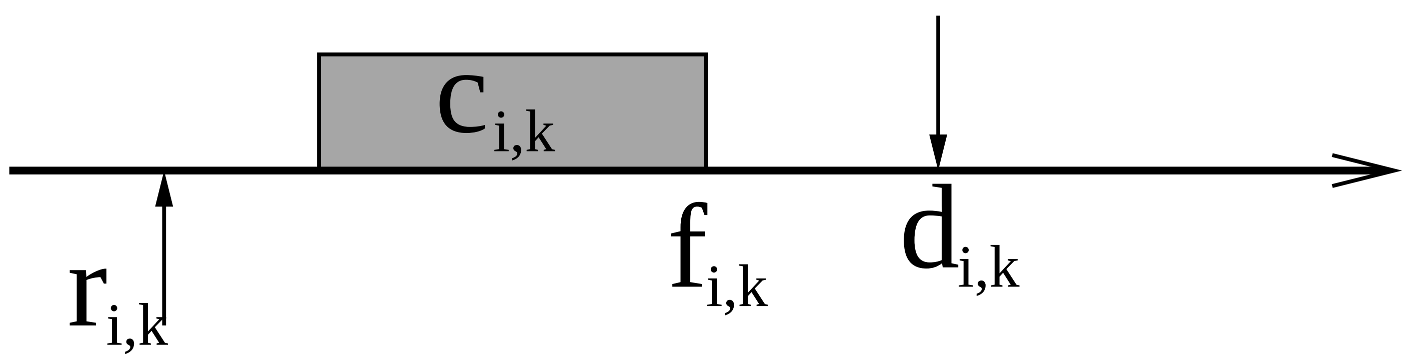
- A Real-Time system is not just a “fast system” . . .
- . . . Because speed is always relative to a specific environment.
- Running faster is good, but does not guarantee a correct behaviour
  - It must be possible to *prove* that temporal constraints are always respected
  - . . . $\Rightarrow$ worst-case analysis
- In general, fast systems tend to minimise the average response time of a task set . . .
- . . . While a real-time system *must* guarantee the timing behaviour of RT tasks!

Processes, Threads, and Tasks

- Algorithm $\rightarrow$ logical procedure used to solve a problem
- Program $\rightarrow$ formal description of an algorithm, using a *programming language*
- Process $\rightarrow$ instance of a program (program in execution)
  - Thread $\rightarrow$ flow of execution
  - Task $\rightarrow$ process or thread
- A task can be seen as a sequence of actions . . .
- . . . and a deadline must be associated to each activity!
  - Some kind of formal model is needed to identify activities and associate deadlines to them

Mathematical model of a task - 1

- Real-Time task τ_i: stream of jobs (or instances) $J_{i,k}$
- Each job $J_{i,k} = (r_{i,k}, c_{i,k}, d_{i,k})$:
  - Arrives at time $r_{i,k}$ (activation time)
  - Executes for a time $c_{i,k}$
  - Finishes at time $f_{i,k}$
  - Should finish within an absolute deadline $d_{i,k}$



Mathematical model of a task - 2

- Summing up, a job is an abstraction used to associate deadlines (temporal constraints) to activities
  - $r_{i,k}$ is the time when job $J_{i,k}$ is *activated* (by an external event, a timer, an explicit activation, etc...)
  - $c_{i,k}$ is the time needed by job $J_{i,k}$ to complete
  - $d_{i,k}$ is the absolute time instant by which job $J_{i,k}$ must complete
    - job $J_{i,k}$ respects its deadline if $f_{i,k} \leq d_{i,k}$
- the response time of job $J_{i,k}$ is $\rho_{i,k} = f_{i,k} - r_{i,k}$

Periodic Tasks

A periodic task $\tau_i = (C_i, D_i, T_i)$ is a stream of jobs $J_{i,k}$, with

$$\begin{aligned} r_{i,k+1} &= r_{i,k} + T_i \\ d_{i,k} &= r_{i,k} + D_i \\ C_i &= \max_k \{c_{i,k}\} \end{aligned}$$

- T_i is the task *period*;
- D_i is the task *relative deadline*;
- C_i is the task worst-case execution time (WCET);
- R_i is the worst-case response time:
  $R_i = max_k\{\rho_{i,k}\} = max_k\{f_{i,k} - r_{i,k}\}$;
  - for the task to be correctly scheduled, it must be $R_i \leq D_i$.

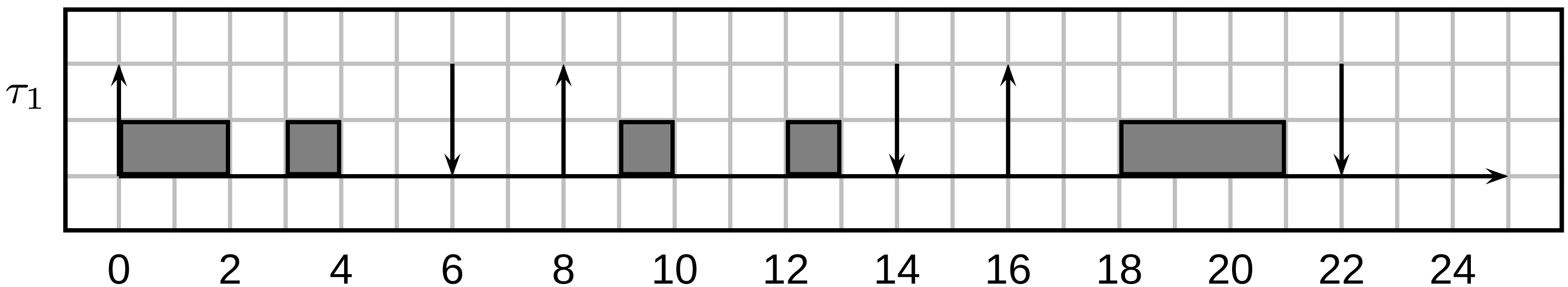
Periodic Task Model

- A periodic task has a regular structure (cycle):
  - activate periodically (period T_i)
  - execute a computation
  - suspend waiting for the next period

```
void *PeriodicTask(void *arg)
{
  <initialization>;
  <start periodic timer, period = T>;
  while (cond) {
    <read sensors>;
    <update outputs>;
    <update state variables>;
    <wait next activation>;
  }
}
```

Graphical representation

Tasks are graphically represented by using a GANNT chart. For example, the following picture shows a schedule of a periodic task $\tau_1 = (3, 6, 8)$ (with $WCET_1 = 3$, $D_1 = 6$, $P_1 = 8$)



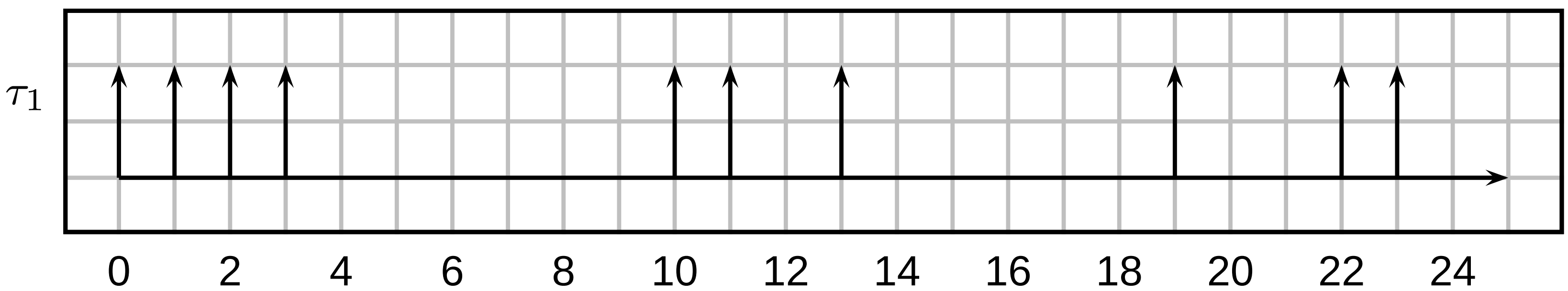
Notice that, while job $J_{1,1}$ and $J_{1,3}$ execute for 3 units of time (WCET), job $J_{1,2}$ executes for only 2 units of time.

Aperiodic Tasks

- *Aperiodic* tasks are not characterised by periodic arrivals:
  - A minimum interarrival time between activations does not exist
  - Sometimes, aperiodic tasks do not have a particular structure
- Aperiodic tasks can model:
  - Tasks that respond to events that occur rarely. Example: a mode change.
  - Tasks that respond to events that happen with an irregular structure. Example: bursts of packets arriving from the network.

Aperiodic Tasks - Example

The following example shows a possible arrival pattern for an aperiodic task τ_1



Notice that arrivals might be bursty, and there is not a minimum time between them.

Sporadic tasks

- *Sporadic* tasks are aperiodic tasks characterised by a *minimum interarrival time* between jobs.
- In this sense, they are similar to periodic tasks, but...
  - Periodic task $\Rightarrow$ activated by a periodic timer
  - Sporadic task $\Rightarrow$ activated by an external event (for example, the arrival of a packet from the network)

```
void *SporadicTask(void *)
{
  <initialization>;
  while (cond) {
    <computation>;
    <wait event>;
  }
}
```

Mathematical model of a sporadic task

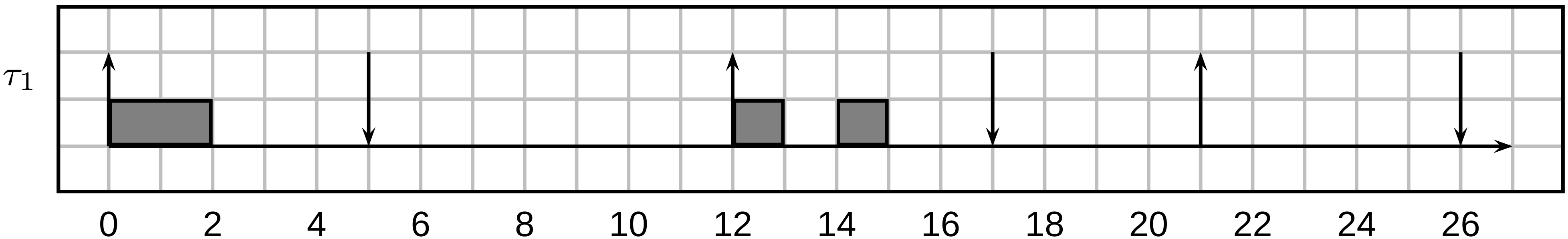
Similar to a periodic task: a sporadic task $\tau_i = (C_i, D_i, T_i)$ is a stream of jobs $J_{i,k}$, with

$$\begin{aligned} r_{i,k+1} &\geq r_{i,k} + T_i \\ d_{i,k} &= r_{i,k} + D_i \\ C_i &= \max_k \{c_{i,k}\} \end{aligned}$$

- T_i is the task *minimum interarrival time* (MIT);
- D_i is the task *relative deadline*;
- C_i is the task worst-case execution time (WCET).
- Again, for the task to be correctly scheduled it must be $R_i \leq D_i$.

Graphical representation

The following example, shows a possible schedule of a sporadic task $\tau_1 = (2, 5, 9)$.



Notice that

$$\begin{aligned} r_{1,2} &= 12 > r_{1,1} + T_1 = 9 \\ r_{1,3} &= 21 = r_{1,2} + T_1 = 21 \end{aligned}$$

Task Criticality - 1

- A deadline is said to be *hard* if a deadline miss causes a critical failure in the system
- A task is said to be a *hard real-time task* if all its deadlines are hard
  - All the task's deadlines have to be guaranteed ($\forall j, \rho_{i,j} \leq D_i \Rightarrow R_i \leq D_i$) a priori, before starting the task
- Examples:
  - The controller of a mobile robot, must detect obstacles and react within a time dependent on the robot speed, otherwise the robot will crash into the obstacles.

Task Criticality - 2

- A deadline is said to be *soft* if a deadline miss causes a degradation in the *Quality of Service*, but is not a catastrophic event
- A task is said to be a *soft real-time task* if it has soft deadlines
  - Some deadlines can be missed without compromising the correctness of the system...
  - ... But the number of missed deadlines must be kept under control, because the “quality” of the results depend on the number of missed deadlines

Soft Real-Time Requirements - 1

- Characterising the a soft real-time task can be difficult...
  - What's the tradeoff between "non compromising the system correctness" and not considering missed deadlines?
  - Some way to express the QoS experienced by a (soft) real-time task is needed
- The QoS of a soft task can be expressed in different ways. Examples are:
  - no more than X consecutive deadlines can be missed
  - no more than X deadlines in an interval of time T can be missed

Soft Real-Time Requirements - 2

- Other examples of soft real-time constraints:
  - the *deadline miss probability* must be less than a specified value
    - $P\{f_{i,j} > d_{i,j}\} \leq R_{max}$
    - the *deadline miss ratio* can be used instead

$$\frac{\text{number of missed deadlines}}{\text{total number of deadlines}} \leq R_{max}$$

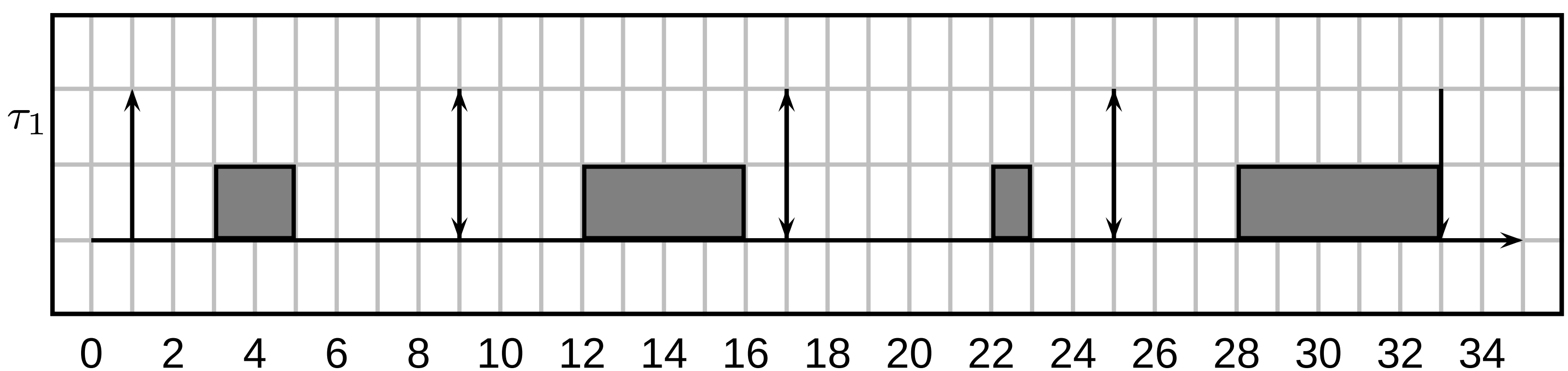
  - the maximum *tardiness* must be less than a specified value
    - $\frac{R_i}{D_i} < L$
  - ...

Example of Soft Real-Time

- Audio / Video player:
  - fps: 25 $\Rightarrow$ frame period: $40ms$
  - if a frame is played *a little bit* too late, the user might even be unable to notice any degradation in the QoS...
  - ...but *skipped frames* can be disturbing
    - missing a lot of frames by $5ms$ can be better than missing only few frames by $40ms$!
- In some robotic systems, some actuations can be delayed with little consequences on the control quality
- In any case, soft real-time does not mean no guarantee on deadlines...

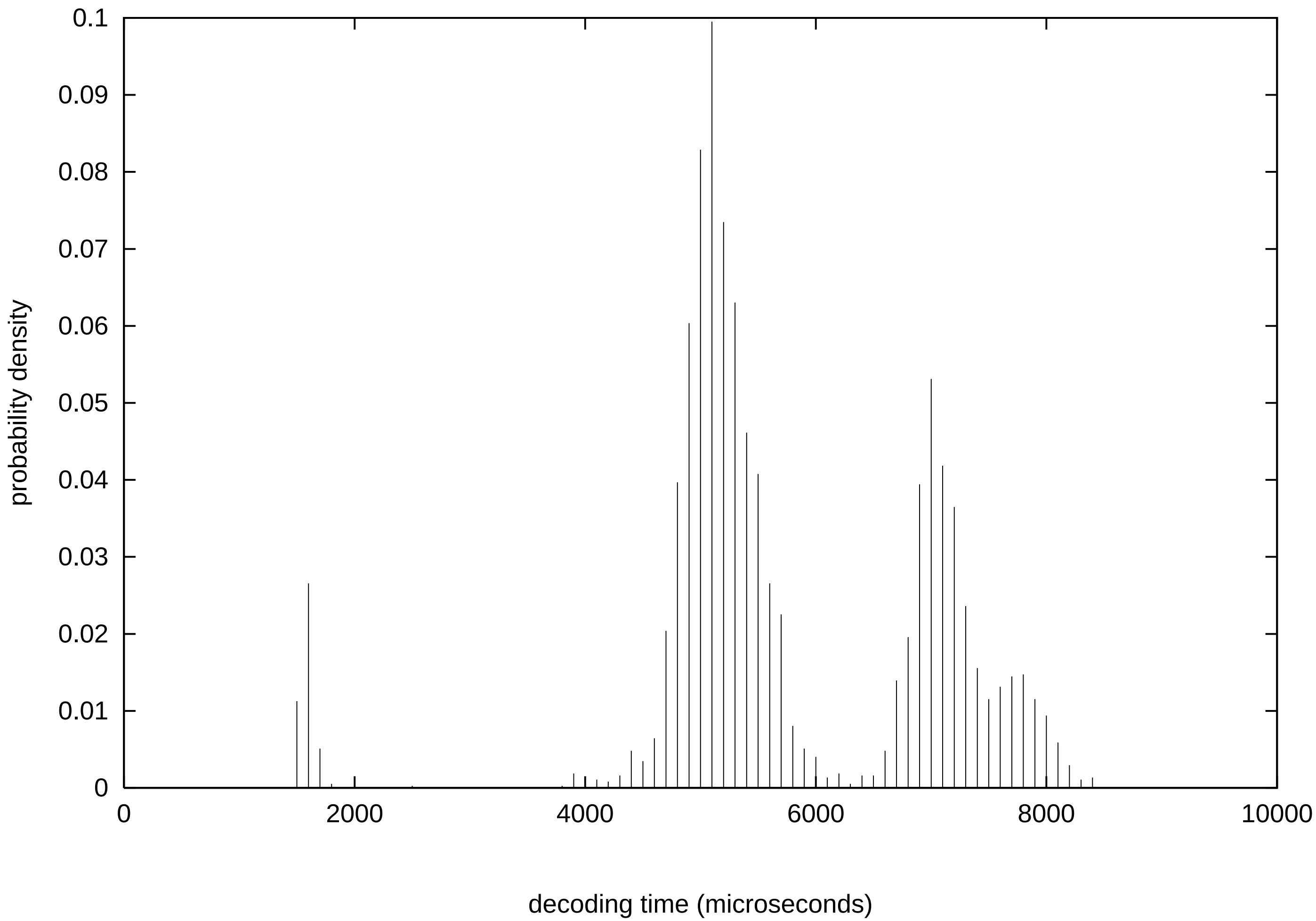
Job Execution Times

- Tasks can have variable execution times between different jobs
- Execution times might depend on different factors:
  - Input data
  - Hardware issues (cache effects, pipeline stalls, etc...)
  - The internal state of the task
  - ...



Variable Execution Times: Video Player

Distribution of the job execution times for a video player (frame decoding times for an MPEG video)



Maximum vs Average Load - 1

- In a hard real-time system, *all* the deadlines must be respected
  - This must be guaranteed in advance
  - The worst case has to be considered
  - $\Rightarrow$ a *necessary* condition for respecting all the deadlines is based on maximum execution times
- Maximum execution times might be too pessimistic for soft real-time systems (causing bad system utilization)
  - But the system must not be “overloaded” (see stable queues in queueing theory) $\Rightarrow$ the *average* system load must be less than 1
  - The system must be designed based on average execution times

Maximum vs Average Load - 2

- Worst possible situation: maximum execution time $C_i = \max_i\{c_{i,j}\}$ (WCET)
  - Very difficult (almost impossible?) to compute in advance
  - Often *estimated* by running a sufficient number of jobs
- Average situation: average execution time $\overline{c_i} = \frac{\sum_{j=1}^{N} c_{i,j}}{N}$
  - Used to compute the average load...
  - ...In a soft real-time system, the average load must be less than 1

System Utilization

- The maximum utilization (load) for a periodic or sporadic task $\tau_i = (C_i, T_i, T_i)$ (with $D_i = T_i$) is

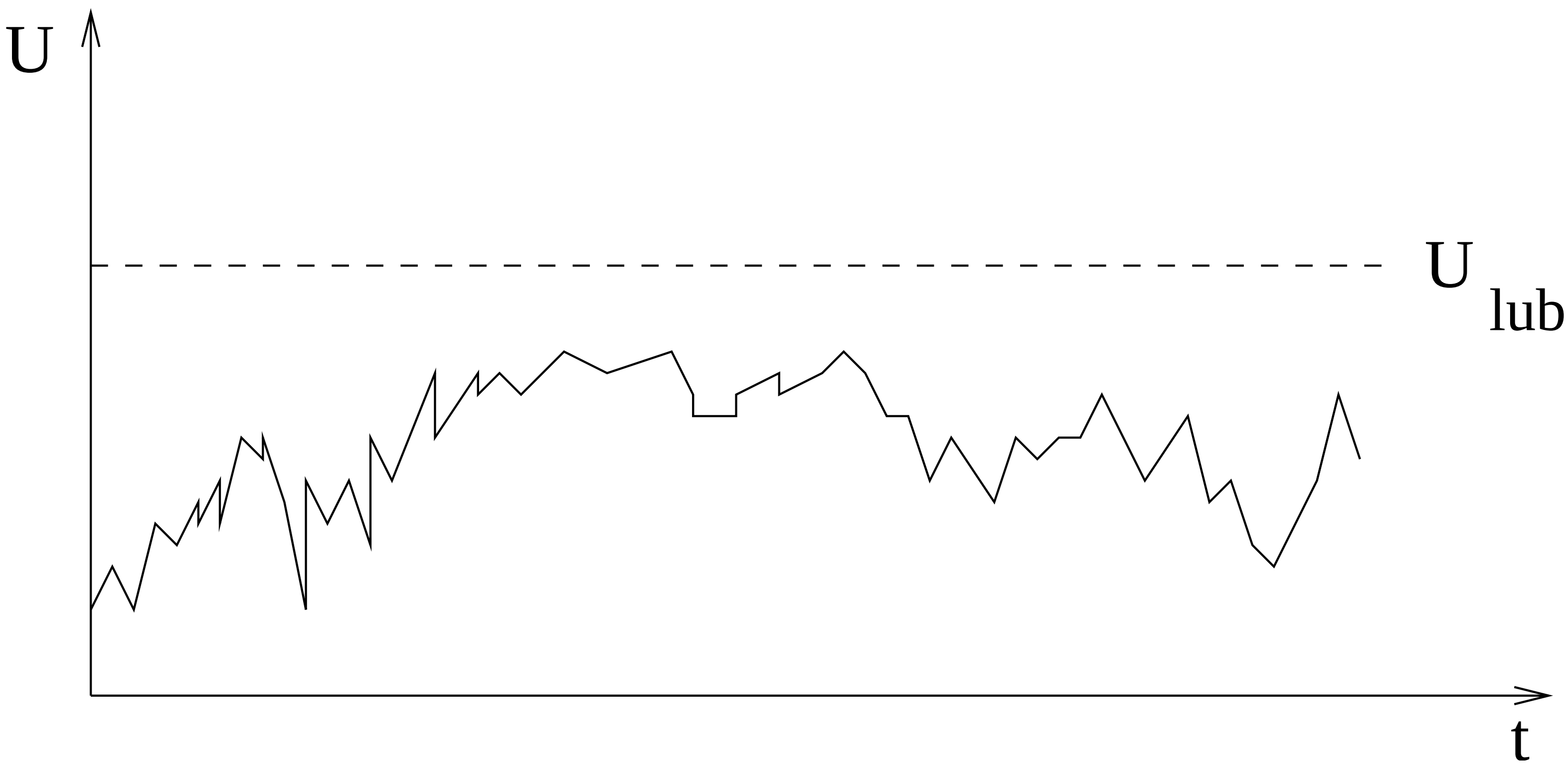
$$U_i = \frac{C_i}{T_i}$$

- The system utilization (load) is defined as

$$U = \sum_i U_i$$

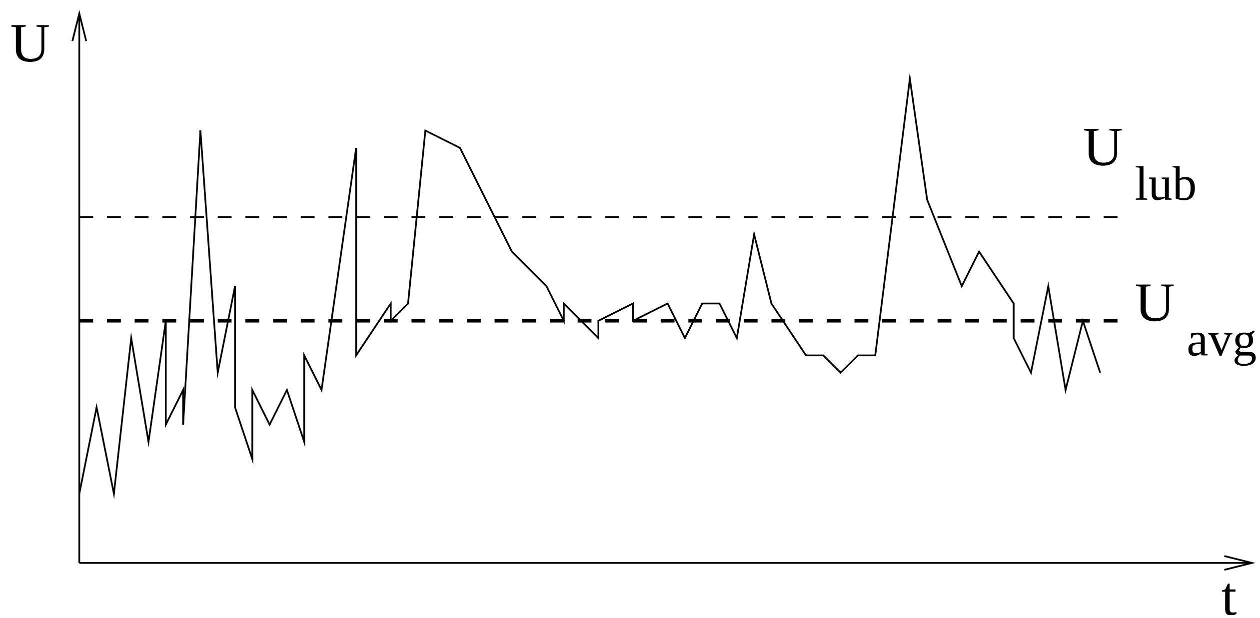
  - For periodic or sporadic tasks with $T_i = D_i$, $U = \sum_i \frac{C_i}{T_i}$
- Example: $\tau_1 = (2, 6, 6)$, $\tau_2 = (2, 8, 8)$, $\tau_3 = (4, 12, 12)$
  - $U_1 = 1/3 = 0.\overline{3}; U_2 = 2/8 = 0.25; U_3 = 0.\overline{3} \Rightarrow U = 0.91\overline{6}$

Maximum Utilization & RT Guarantees



Average utilization & RT Guarantees

- If the average utilization is less than U_{lub}, the task set may or may not be schedulable:



Average utilization & RT Guarantees

- If the average utilization is greater than U_{lub}, the task set is “probably” not schedulable: