EMSOFT 2001

Rate-Based Resource Allocation Models for Real-Time Computing

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Rate-Based Resource Allocation

The case against static priority scheduling

- Static priority scheduling in general, and Rate Monotonic scheduling in particular, dominates in the real-time systems literature
  - » VxWorks, VRTX, QNX, pSOSystems, LynxOS all support static priority scheduling
- Does one size fit all?
  - » "When you have a hammer, everything looks like a nail"
- Problems with static priority scheduling
  - » Feasibility is dependent on a predictable environment and well-behaved tasks.

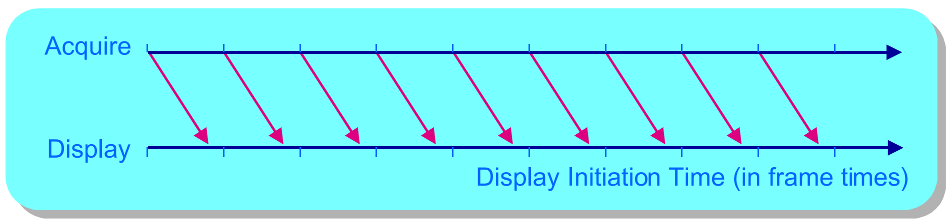
Rate-Based Resource Allocation

Overview

- The problem:
  - » How to allocate resources in an environment wherein…
    - Work arrives at well-defined but highly variable rates
    - Tasks may exceed their execution time estimates
  - » … and still guarantee adherence to deadlines
- The thesis:
  - » Static priority scheduling is the wrong tool for the job (existing task models are too simplistic)
  - » Rate-based scheduling abstractions can simplify the design and implementation of many real-time systems and improve performance and resource utilization

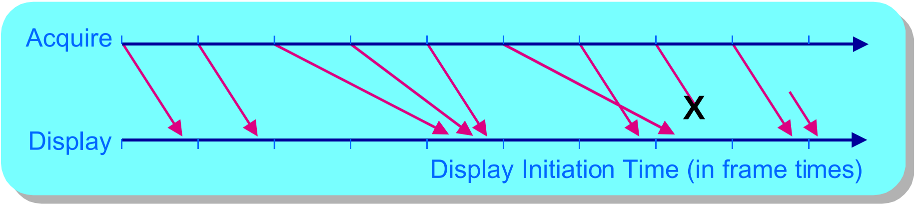
The Case Against Priority Scheduling

Example: Display-side multimedia processing



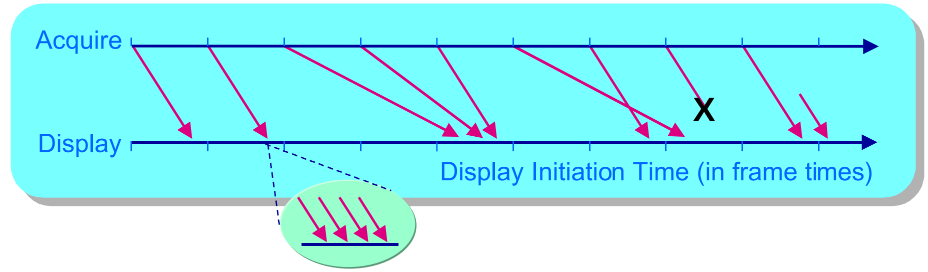
- The problem: Receive frames from the network and deliver to a display application so as to ensure...
  - » Continuous playout
  - » Minimal playout latency
- The theory: Multimedia is easy — it's periodic!
  - » Apply existing theory of periodic or sporadic tasks

Display-side Media Processing
The practice



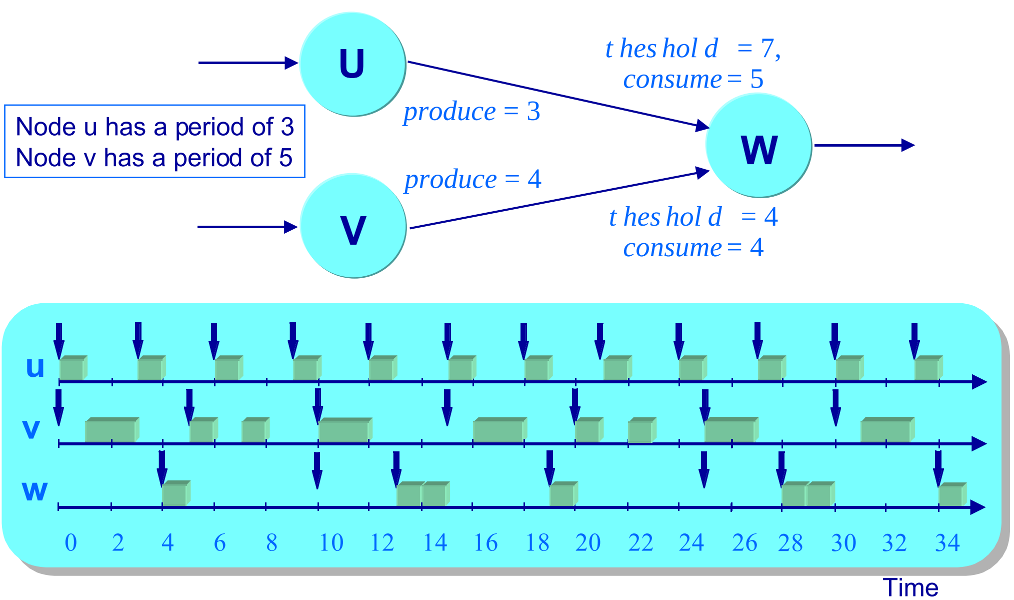
- Nothing is periodic in a distributed system!
- The effects of distributed systems pathology:
  - » Variable message transmission times
  - » Out-of-order message arrivals
  - » Lost & duplicate messages

Display-side Media Processing
Managing the Network Interface



- Packets fragmented in the network must be reassembled
  - » *Messages* have deadlines, *packets* do not
  - » Applications know about messages, operating systems do not

The Case Against Priority Scheduling
Example: Signal processing data flow graphs



Rate-Based Computing
Approaches

- Extend the Liu and Layland model of real-time tasks to allow the expression of real-time rates
  - » Hierarchical “server-based” scheduling — Create a “server” process that is scheduled as a periodic task and internally schedules the processing of aperiodic events
  - » Event-based scheduling — Process aperiodic events as if they were generated by a virtual “well behaved” periodic process
- Adapt “fluid-flow” models of resource allocation developed in the networking community for bandwidth allocation to CPU scheduling
  - » Provide a “virtual processor” abstraction wherein each task logically executes on a dedicated processor with $1/f(n)$ the capacity of the physical processor

An Event-Based Rate Model

The Rate-Based Execution (*RBE*) model

- Tasks make progress at the rate of processing x events every y time units and each event is processed within d time units (in the best case)
- For task i with rate specification (x_i, y_i, d_i), the j^{th} event for task i, arriving at time $t_{i,j}$, will be processed by time

$$D(i, j) = \begin{cases} t_{i,j} + d_i & \text{if } 1 \le j \le x_i \\ \text{MAX}(t_{i,j} + d_i,\ \ D(i, j-x_i)+y_i\,) & \text{if } j > x_i \end{cases}$$

  - » $D(i,j)$ gives the earliest possible deadline for the j^{th} instance of task i ($\ge t_{i,j} + d_i$)

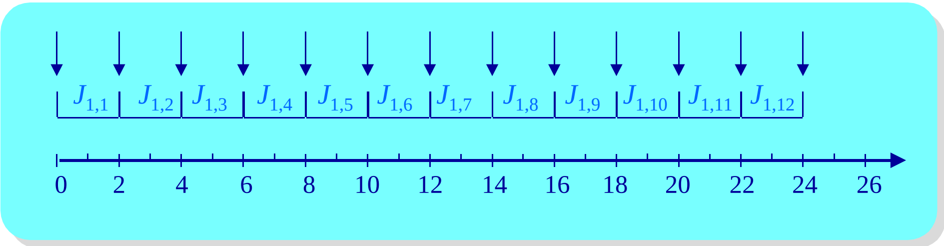
The RBE Task Model

Example: Periodic arrivals, periodic service

- Task with rate specification ($x = 1$, $y = 2$, $d = 2$)

$$D(i, j) = \begin{cases} t_{i,j} + d_i & \text{if } 1 \le j \le x_i \\ \text{MAX}(t_{i,j} + d_i,\ \ D(i, j-x_i)+y_i\,) & \text{if } j > x_i \end{cases}$$

  - » Deadlines separated by at least $y = d = 2$ time units
  - » Deadlines occur at least 2 time units after a job is released



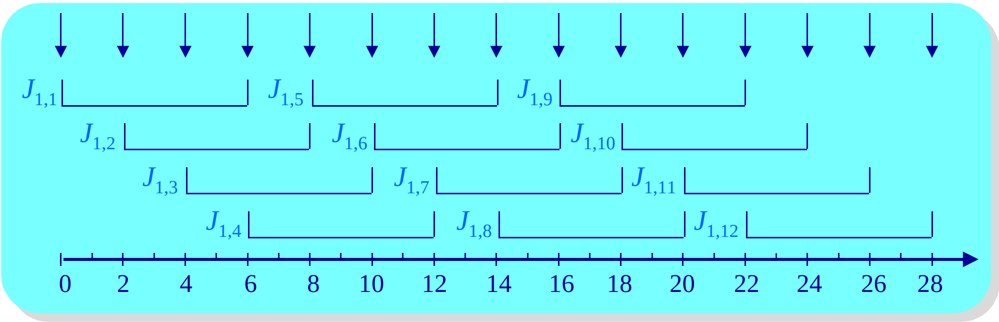
The RBE Task Model

Example: Periodic arrivals, *deadline ≠ period*

- Task with rate specification ($x = 1$, $y = 2$, $d = 6$)

$$D(i, j) = \begin{cases} t_{i,j} + d_i & \text{if } 1 \le j \le x_i \\ \text{MAX}(t_{i,j} + d_i,\ \ D(i, j-x_i)+y_i\,) & \text{if } j > x_i \end{cases}$$

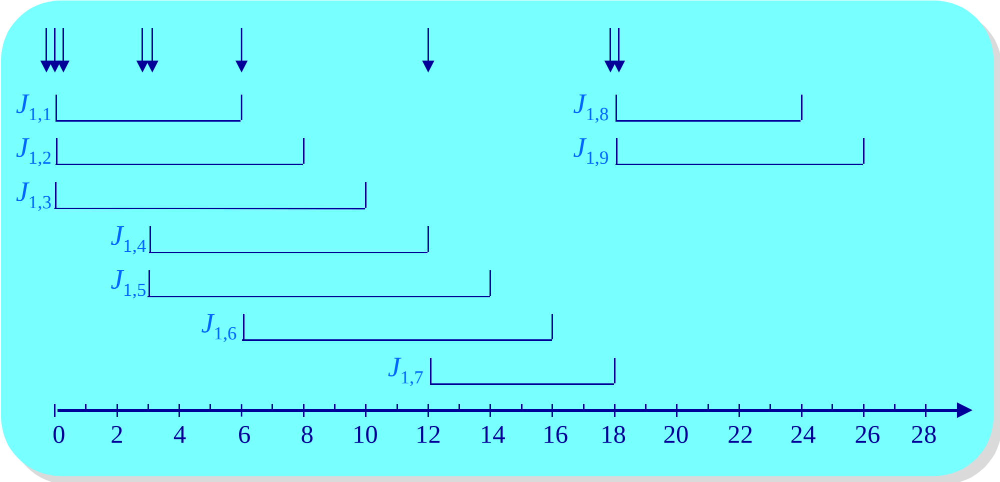
  - » Deadlines separated by at least $y = 2$ time units and occur at least $d = 6$ time units after a job is released



The RBE Task Model

Bursty arrivals

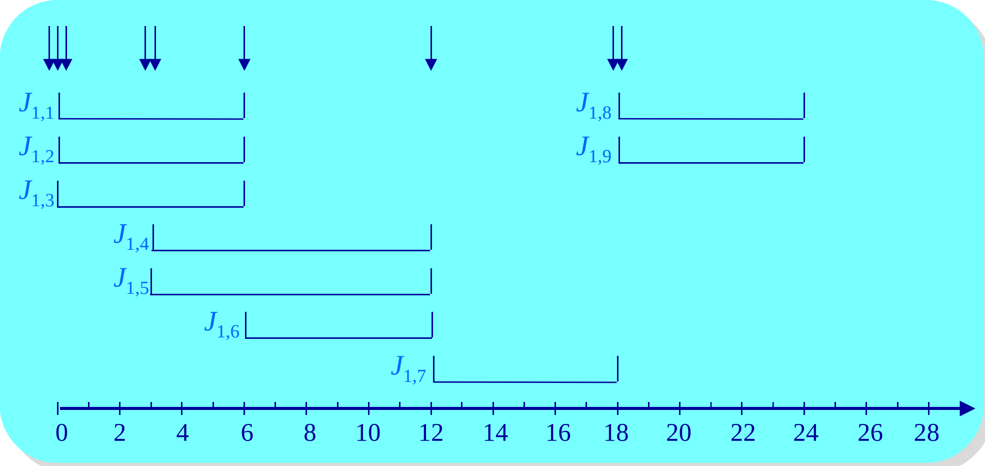
- Task with rate specification ($x = 1$, $y = 2$, $d = 6$)
  - » Deadlines separated by at least $y = 2$ time units and occur at least $d = 6$ time units after a job is released



The RBE Task Model

Bursty arrivals

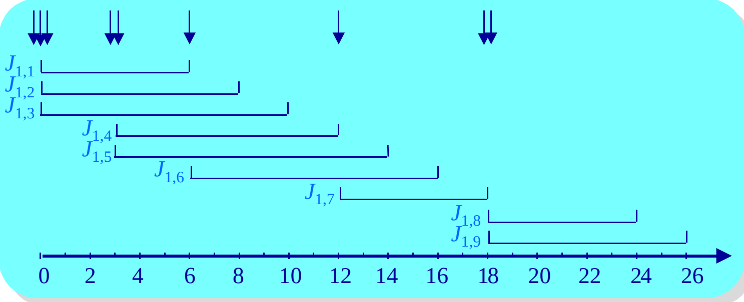
- Task with rate specification ($x = 3$, $y = 6$, $d = 6$)
  - » Deadlines separated by at least $y = 6$ time units and occur at least $d = 6$ time units after a job is released



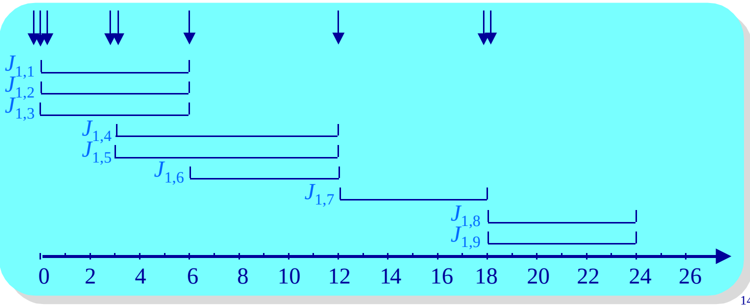
The RBE Task Model

Comparison of rate specifications

Rate specification ($x = 1$, $y = 2$, $d = 6$)



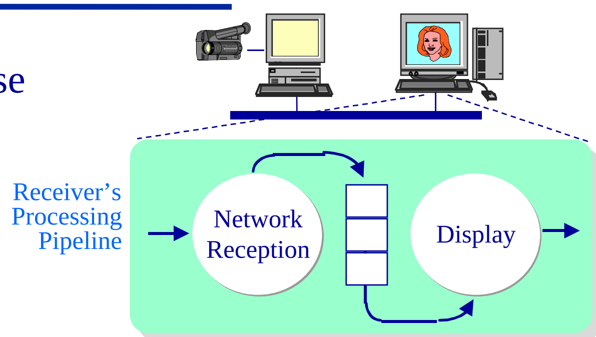
Rate specification ($x = 3$, $y = 6$, $d = 6$)



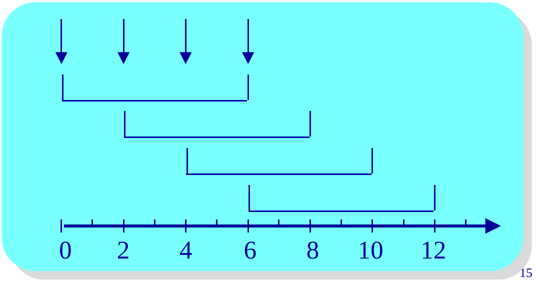
The RBE Task Model

RBE features/properties

- Provides better response time for non-real-time activities by integrating application-level buffering with the system run queue



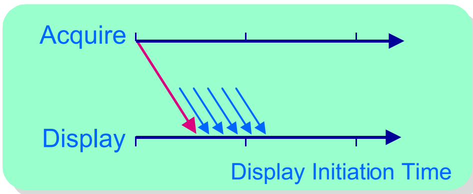
Rate specification ($x = 1$, $y = 2$, $d = 6$)



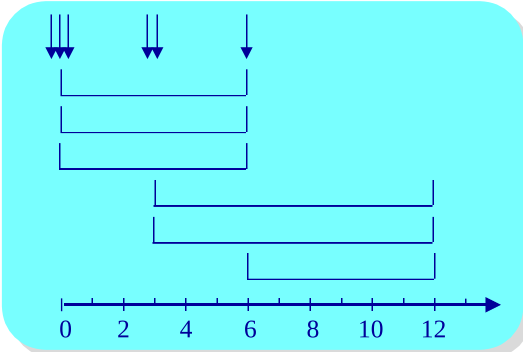
The RBE Task Model

RBE features/properties

- Provides a more natural way of modeling inbound packet processing of fragmented messages



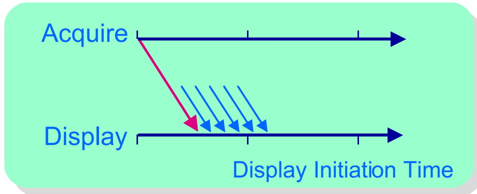
Rate specification ($x = 3$, $y = 6$, $d = 6$)



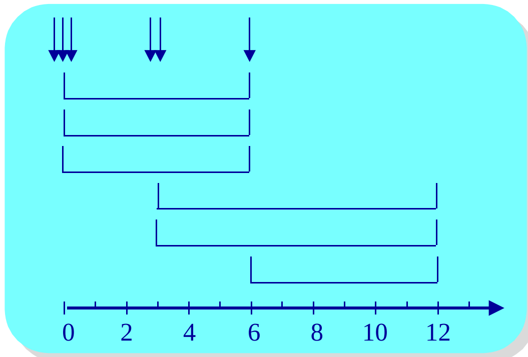
The RBE Task Model

RBE features/properties

- Provides isolation from arrival rates that exceed the rate specification
  - » (But does not provide isolation from tasks exceeding their stated execution time)



Rate specification
($x = 3$, $y = 6$, $d = 6$)



Fluid Flow Resource Allocation

Proportional share resource allocation

- Tasks are allocated a *share* of the processor's capacity
  - » Task i is assigned a *weight* w_i
  - » Task i's *share* of the CPU at time t is

$$f_i(t) = \frac{w_i}{\sum_{j \in A(t)} w_j}$$

- If tasks' weights remain constant in $[t_1, t_2]$ then task i receives

$$S_i(t_1,t_2) = \int_{t_1}^{t_2} f_i(t)\, dt = \frac{w_i}{\sum_j w_j}(t_2 - t_1)$$

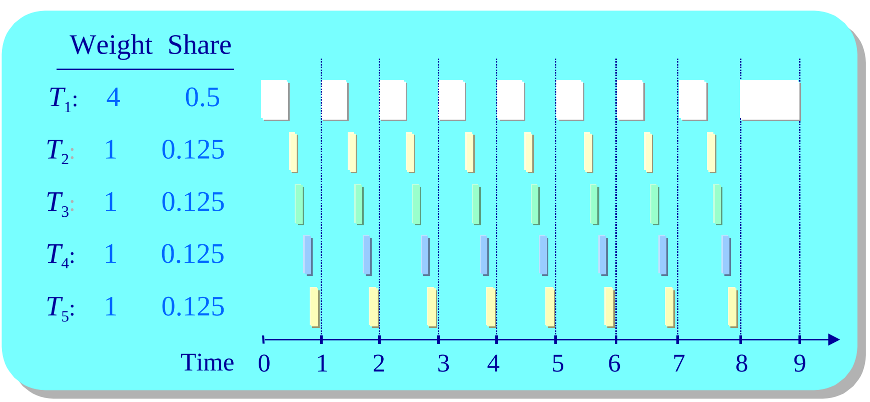
units of execution time in $[t_1, t_2]$

Proportional Share Resource Allocation

Fluid scheduling example

- Weighted round robin scheduling with an infinitesimally small quantum
- In $[t_1, t_2]$ (if total weight doesn't change) T_i receives

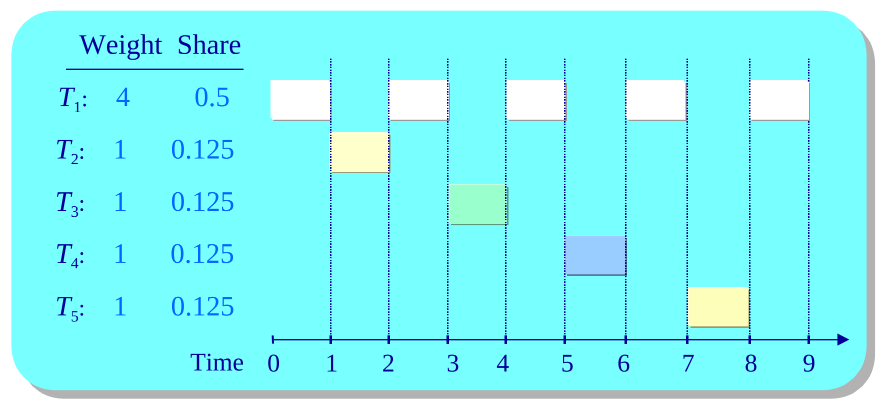
$$S_i(t_1,t_2) = \int_{t_1}^{t_2} f_i(t)\, dt = \frac{w_i}{\sum_{j \in A(t)} w_j}(t_2 - t_1)$$



Proportional Share Resource Allocation

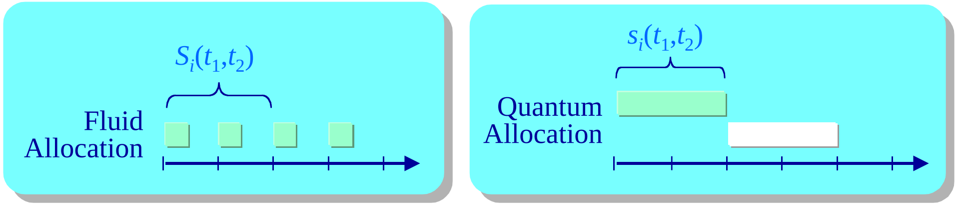
Quantum scheduling example

- Weighted round robin scheduling with integer quanta
  - » $q = 1$
- The quantum system doesn't proportionally allocate the resource over all time intervals



Proportional Share Resource Allocation

Task scheduling metrics & goals



- Schedule tasks so that their performance is as close as possible to that in the *fluid* system
- Why is fluid allocation important?
  - » What about real-time allocation?!

Approximating Fluid Allocation

Why is this so important?

- Fluid allocation implies real-time progress
- Weights are used to allocate a *relative* fraction of the CPU's capacity to a task

$$f_i(t) = \frac{w_i}{\Sigma_j w_j}$$

- Real-time progress requires a *constant* fraction of the CPU's capacity

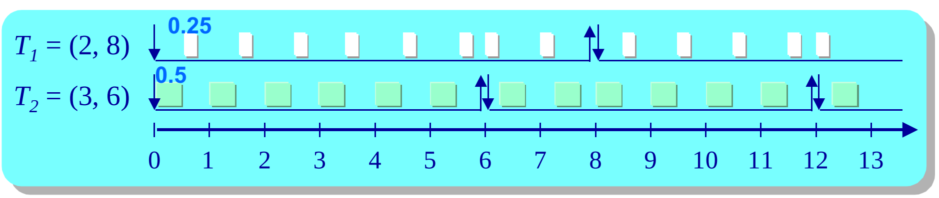
$$\forall t, \quad f_i(t) = \textit{execution cost}_i \times \textit{execution frequency}_i$$

  - » If a task must execute for 16 *ms* every 33 *ms* then allocating *f* = 0.5 ensures real-time execution
- Thus real-time performance can be achieved by adjusting weights dynamically so that the share remains constant

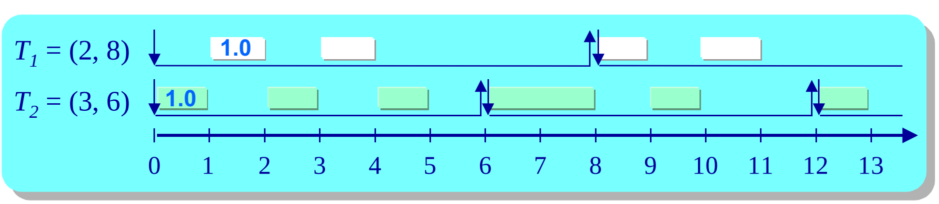
Proportional Share Resource Allocation

Real-time scheduling example

- Periodic tasks allocated a share equal to their processor utilization
  - » Round-robin scheduling with infinitesimally small quantum

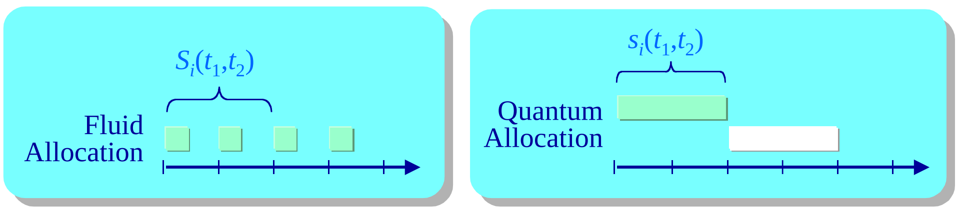


  - » With unit-sized quantum



Proportional Share Resource Allocation

Task scheduling metrics & goals



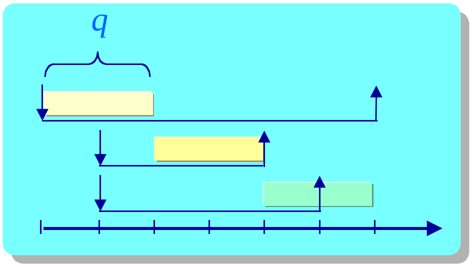
- Goal: Schedule tasks so that their performance is as close as possible to that in the *fluid* system
- Define the allocation error for task *i* at time *t* as

$$lag_i(t) = \left(\begin{matrix}\textit{allocation the task would have}\\ \textit{received in the fluid system}\end{matrix}\right) - \left(\begin{matrix}\textit{allocation the task has received}\\ \textit{in the quantum system}\end{matrix}\right)$$

$$= S_i(t_i,t) - s_i(t_i,t)$$

- Schedule tasks so that the lag is bounded for all tasks over all time intervals
  - » What is the least upper bound on lag?

Proportional Share Resource Allocation
Timing analysis



- Is a task guaranteed to complete before its deadline?
  - » How late can a task be?
- Theorem: *Let c be the size of the current request of task T. Task T's lag is bounded by*

$$-q < lag_T(t) < q$$

Rate-Based Resource Allocation
Summary

- There's life beyond rate monotonic scheduling
- Rate-based resource allocation simplifies systems wherein
  - » Work is generated at non-periodic but structured rates
  - » Tasks may "misbehave"
- Liu and Layland extensions
  - » Rate models demonstrate a fundamental distinction between static priority and deadline scheduling methods
- Fluid flow models
  - » Real-time ±*quantum*
  - » No fundamental distinction between real-time and non-real-time tasks
  - » Provide strict isolation between tasks