Rate-Based Execution Models For Real-Time Multimedia Computing

Extensions to Liu & Layland Scheduling Models For Rate-Based Execution

Kevin Jeffay
Department of Computer Science
University of North Carolina at Chapel Hill
jeffay@cs.unc.edu

September 23, 1997

http://www.cs.unc.edu/~jeffay/courses/pisa

Outline

- Rate Based Execution: The case against Liu & Layland style models of real-time computing
- A Liu & Layland extension for rate-based execution?
- Fluid-flow models of resource allocation for real-time services
- Proportional share CPU scheduling
- On the duality of proportional share and traditional Liu & Layland style resource allocation

Extensions of the Liu & Layland Model

Objectives

- Support notions of execution rate that are more general than periodic execution
- Support integrated real-time device and application processing
- Support responsive non-real-time computing

Rate-Based Computing

Concept

- Schedule tasks at the *average rate* at which they are expected to be invoked
  - » Make buffering a first-class concept in the model
  - » Understand the fundamental relationships between feasibility, latency, and processing rate
- Develop a model of tasks wherein:
  - » Tasks complete execution before a well-defined deadline
  - » Tasks make progress at application-specified rates
  - » No constraints are placed on the external environment

Rate-Based Computing
Beyond periodic & sporadic models

- An event-based model — *rate-based execution*
  - » Process make progress at the rate of processing x events every y time units, each event is processed within d time units
- A time-sharing model — *proportional share resource allocation*
  - » Processes make progress at a precise, uniform rate — as if executing on a dedicated processor with $1/n^{th}$ original capacity

Rate-Based Computing
Overview of results

- We will demonstrate that
  - » the theory of dynamic priority task systems extends nicely to handle rate-based execution
  - » unless constraints are placed on the external environment, *no* static priority scheduling algorithm can guarantee that a set of rate-based tasks execute in real-time

Rate-Based Execution
Formal model

- Process make progress at the rate of processing x events every y time units, each event is processed within d time units
- 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

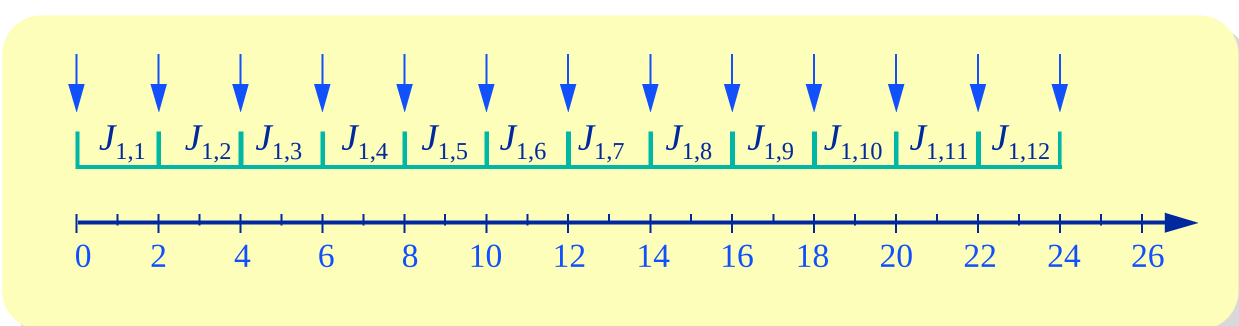
$$D(i,j) = \begin{cases} t_{i,j} + d_i & \text{if } 1 \le j \le x_i \\ \text{MAX}(t_{i,j} + d_i,\ D(i, j-x_i) + y_i) & \text{if } j > x_i \end{cases}$$

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

Rate-Based Execution
Example: Periodic arrivals, periodic service

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

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

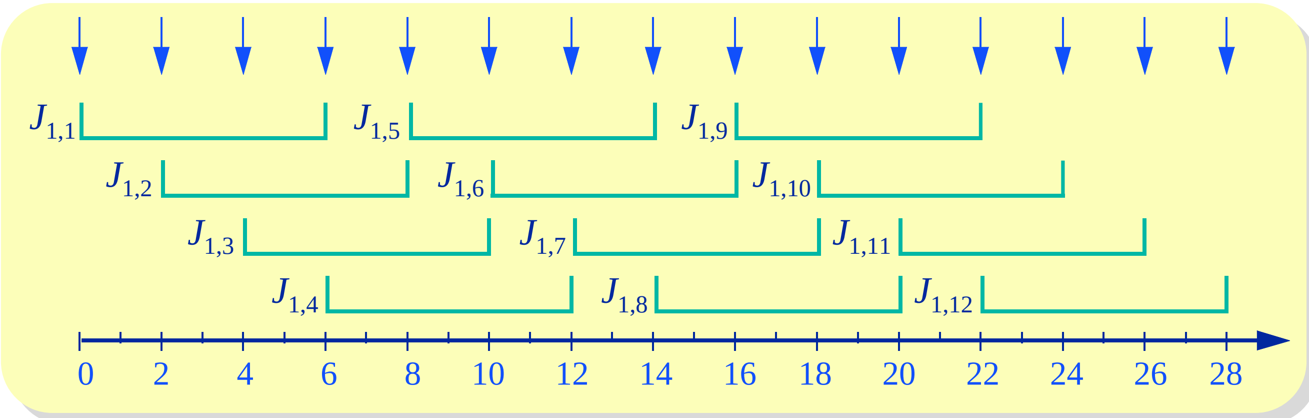


Rate-Based Execution

Example: Periodic arrivals, *deadline ≠ period*

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

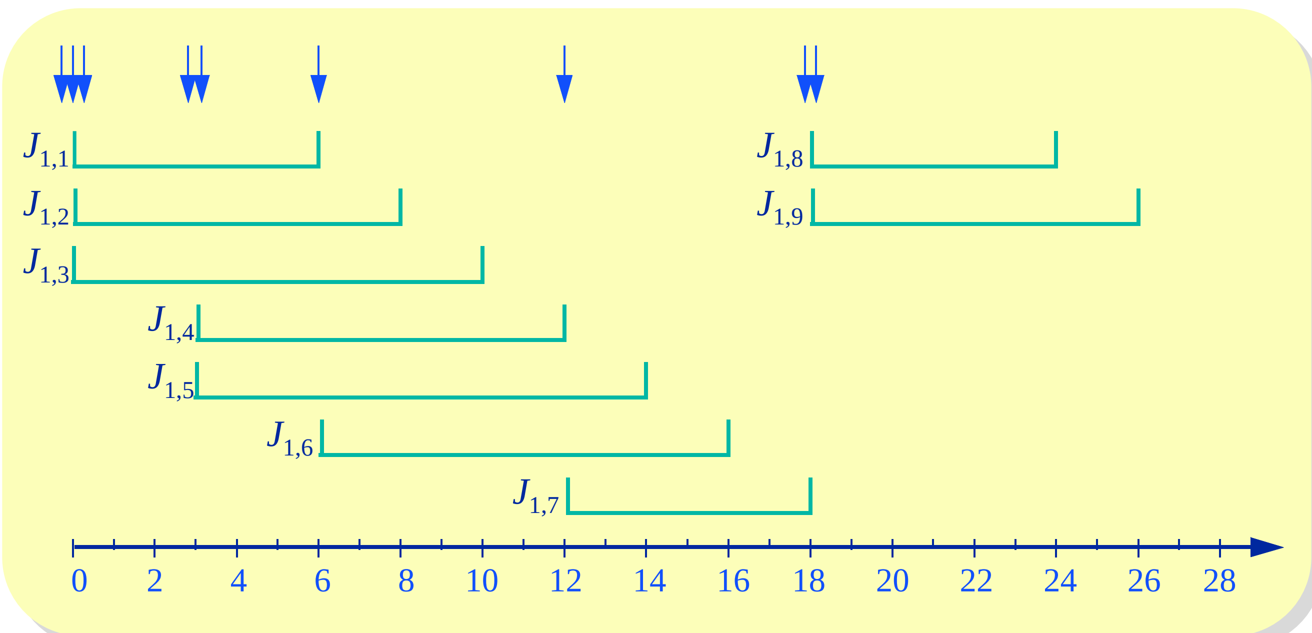
$$D(i, j) = \begin{cases} t_{i,j} + d_i & \text{if } 1 \le j \le x_i \\ \text{MAX}(t_{i,j} + d_i,\ D(i, j-x_i)+y_i) & \text{if } j > x_i \end{cases}$$



Rate-Based Execution

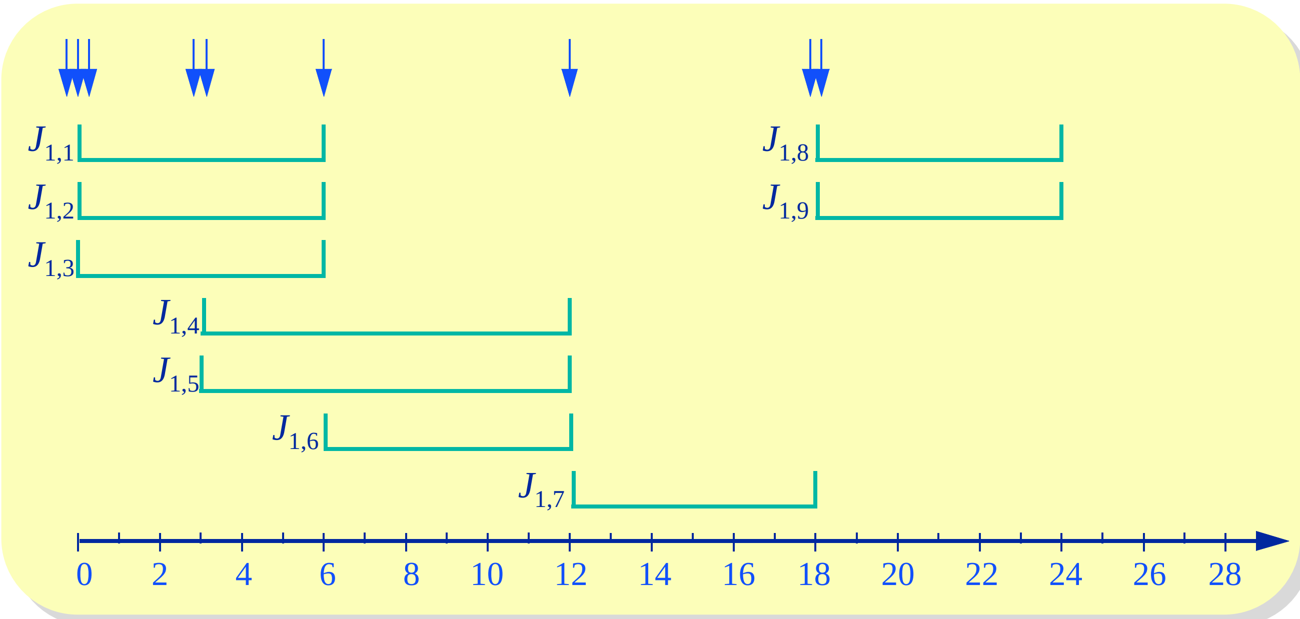
Bursty arrivals

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



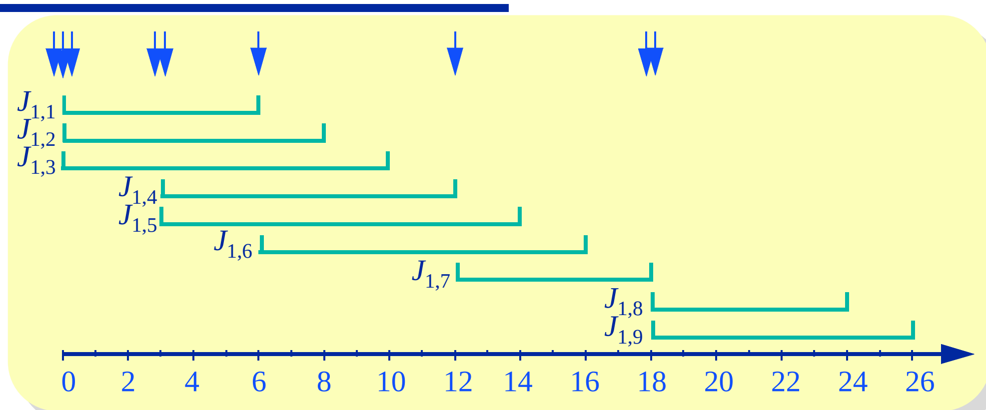
Rate-Based Execution
Bursty arrivals

- Task with rate specification ($x = 3$, $y = 6$, $d = 6$)

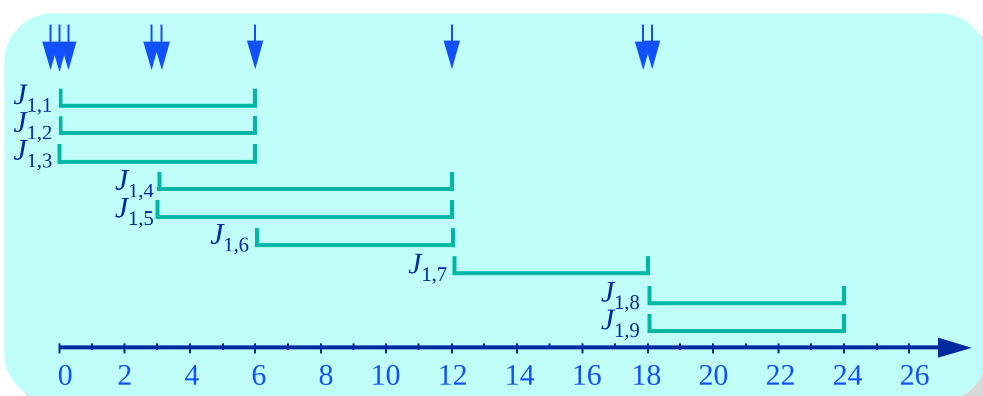


Rate-Based Execution
Comparison

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



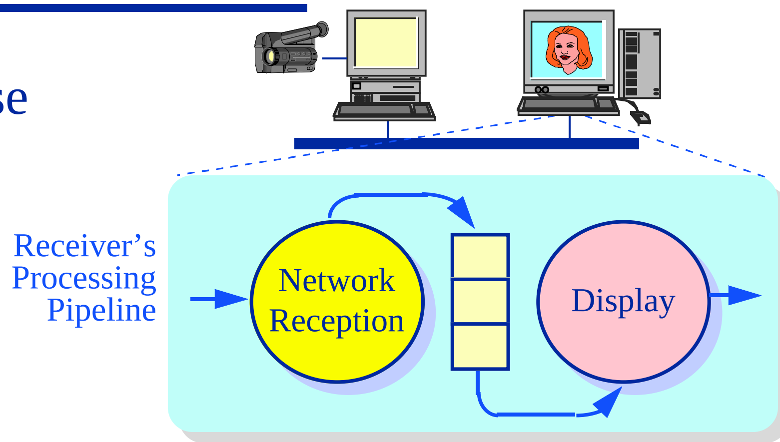
Rate specification
($x = 3$, $y = 6$, $d = 6$)



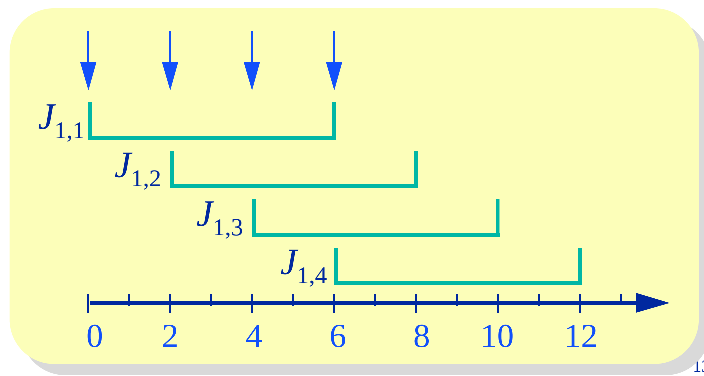
Using RBE Tasks

What problems do they solve?

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



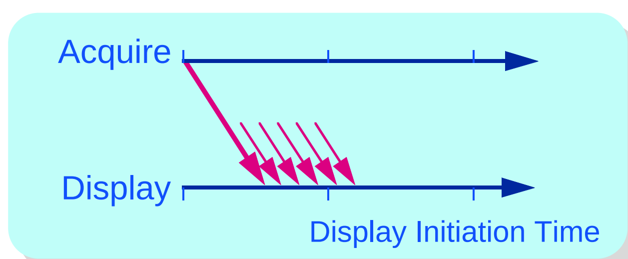
Rate specification
($x = 1$, $y = 2$, $d = 6$)



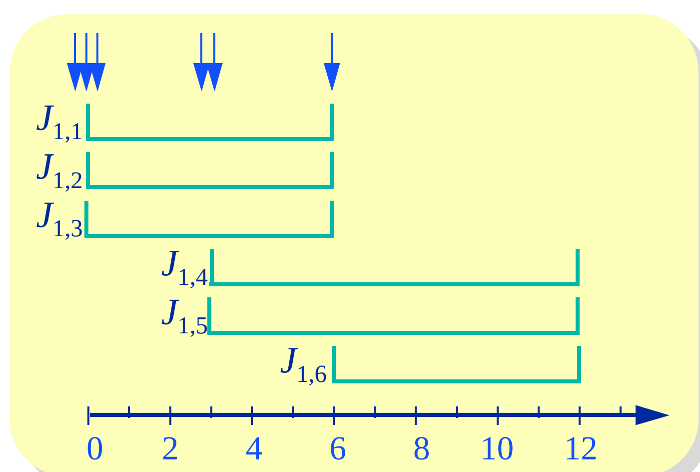
Using RBE Tasks

What problems do they solve?

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



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



Rate-Based Execution
Conjectures

- Captures the essence of real-time computing on the desktop
- Provides a framework for tuning application performance to network performance
- Minimizes response time for non-real-time activities
- One can precisely characterize the conditions under which a rate-specification is realizable

Rate-Based Execution
Is it new?

- RBE is an amalgam of three technologies
  - » the Synthesis operating system (Columbia)
    - ❖ software phased-lockedloops
  - » the Dash operating system (Berkeley)
    - ❖ a “leaky bucket” model applied to operating system processes
    - ❖ processes characterized by an average rate and a “burst” size
  - » the YARTOS real-time operating system (UNC)
    - ❖ the producer/consumer data-flow model of computation
- Novel aspects
  - » separation of throughput and response time specifications
  - » provably real-time

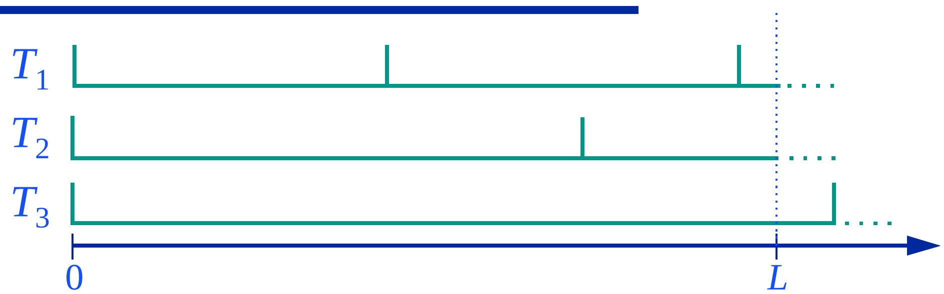
A Theory of Rate-Based Execution

Goal and basic concepts

- The goal is to develop conditions on model parameters which, if satisfied by a set of tasks, imply that every job of every task will complete execution before its deadline
- Feasibility and schedulability analysis
  - » feasibility — conditions under which a set of tasks are guaranteed to execute correctly
    - ❖ an absolute measure of correctness
  - » schedulability — conditions under which a set of tasks are guaranteed to execute correctly when scheduled by a given algorithm
    - ❖ a relative measure of correctness

A Theory of Rate-Based Execution

Review



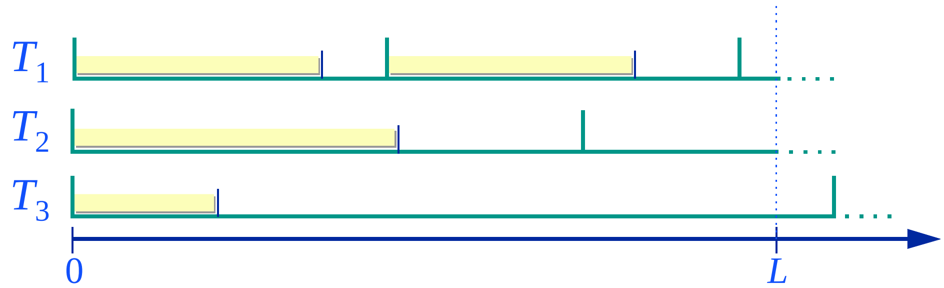
- Schedulability analysis of periodic tasks $T_i = (c_i, p_i)$
  - » Static priority assignment: "Level *i* busy period analysis"

$$\forall i,\ 1 \le i \le n,\ \exists L,\ 1 \le L \le p_i:\ L \ge \sum_{j=1}^{i} \left\lceil \frac{L}{p_j} \right\rceil c_j$$

  - » Dynamic priority assignment: "Processor demand analysis"

$$\forall L,\ L > 0:\ L \ge \sum_{i=1}^{n} \left\lfloor \frac{L}{p_i} \right\rfloor c_i$$

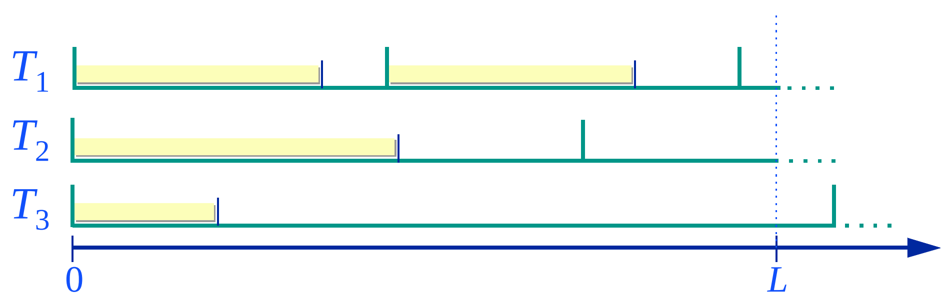
A Theory of Rate-Based Execution
Review



- Feasibility analysis of periodic tasks with *deadline ≠ period*
  - » Under earliest deadline first scheduling

$$\forall L, L > 0: \; L \geq \sum_{i=1}^{n} \left\lfloor \frac{L - d_i + p_i}{p_i} \right\rfloor c_i$$

A Theory of Rate-Based Execution
Feasibility analysis



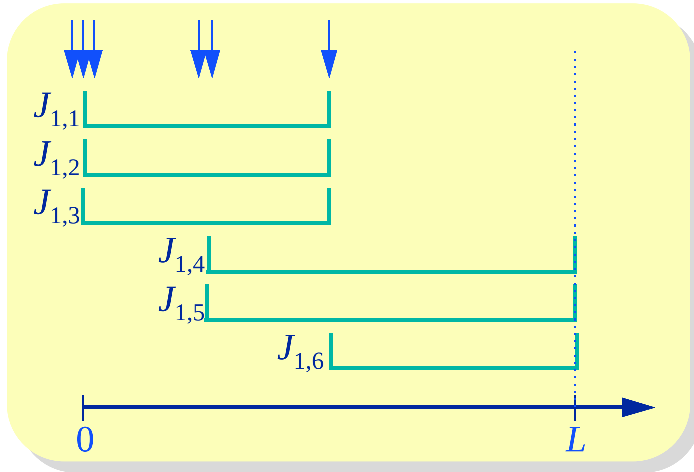
- Consider a set of *RBE* tasks with rate specification (x, y, c, d)
- Feasibility conditions are precisely the same as for periodic tasks

$$\forall L, L > 0: \; L \geq \sum_{i=1}^{n} \left\lfloor \frac{L - d_i + y_i}{y_i} \right\rfloor x_i c_i$$

A Theory of Rate-Based Execution

Feasibility proof sketch

$T = (x, y, d)$
$= (3, 6, 6)$

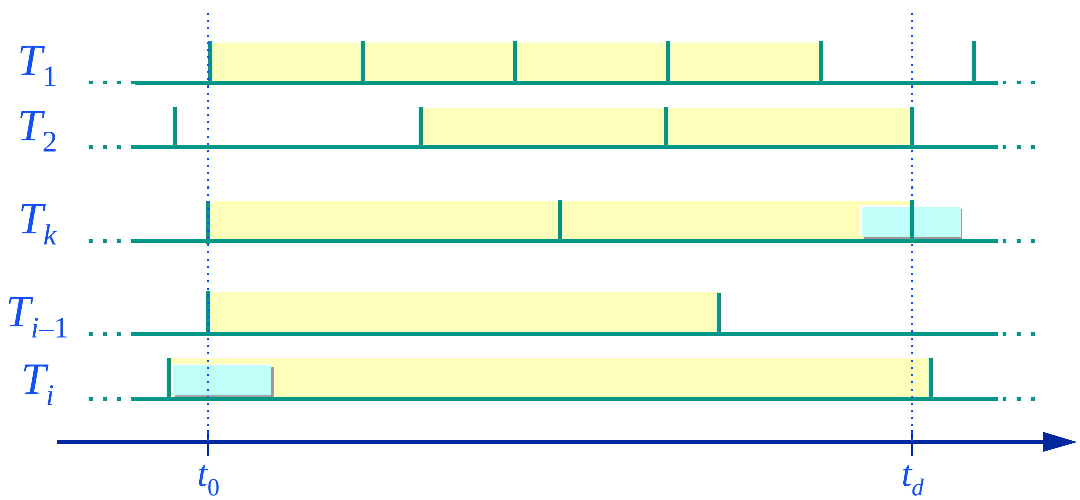


- What is the maximum number of jobs of an *RBE* task with deadlines in an interval $[0, L]$, $L \geq d$?

$$x + \left\lfloor \frac{L-d}{y} \right\rfloor x \;=\; \left\lfloor \frac{L-d}{y} + 1 \right\rfloor x \;=\; \left\lfloor \frac{L-d+y}{y} \right\rfloor x$$

A Theory of Rate-Based Execution

Feasibility proof sketch



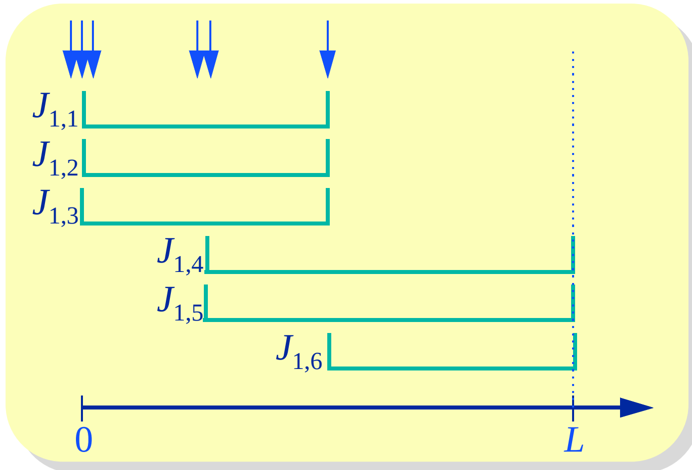
- When scheduled by an *EDF* scheduler

$$\sum_{i=1}^{n} \left\lfloor \frac{t_d - t_0 - d_i + y_i}{y_i} \right\rfloor x_i c_i \;>\; t_d - t_0$$

A Theory of Rate-Based Execution

On the relationship to periodic tasks

$T = (x, y, d)$
$= (3, 6, 6)$

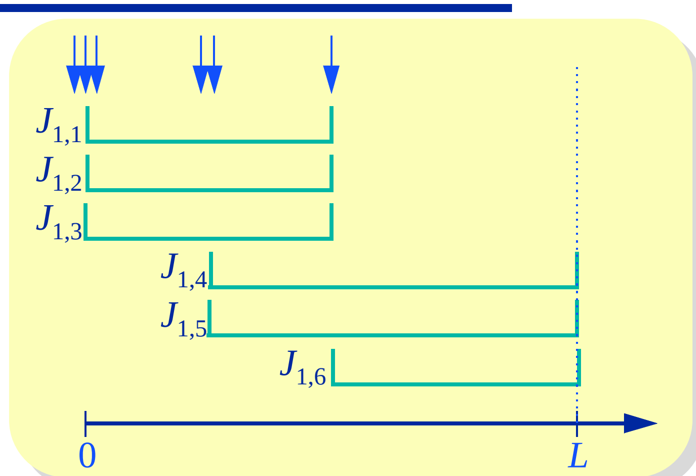


- What is the maximum number of jobs of an *RBE* task with deadlines in an interval $[0, L]$, $L \geq d$?
  - » It can never be greater than the corresponding periodic task
  - » In the RBE model, "early" task invocations receive the same deadlines they would have had they been invoked "on time"

A Theory of Rate-Based Execution

On the relationship to periodic tasks

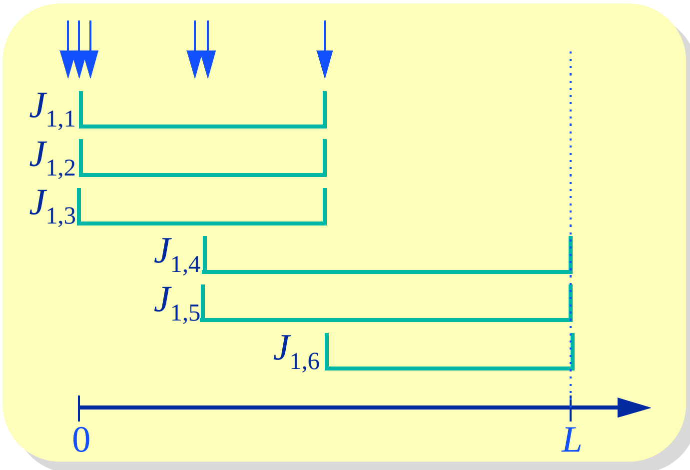
$T = (x, y, d)$
$= (3, 6, 6)$



- But can't an RBE task be modeled as x instances of a periodic task (with some appropriate precedence relationship between instances)?

A Theory of Rate-Based Execution

A corollary on static priority scheduling



$$L \geq \sum_{j=1}^{i} \left\lceil \frac{L}{p_j} \right\rceil c_j$$

- Under a static priority scheduling scheme, the processor demand in any interval can be unbounded
  - » thus event driven, rate-based execution is not possible under static priority scheduling schemes

A Theory of Rate-Based Execution

Feasibility analysis under preemption constraints

- When preemption is allowed at arbitrary points, feasibility conditions are precisely the same as for periodic tasks

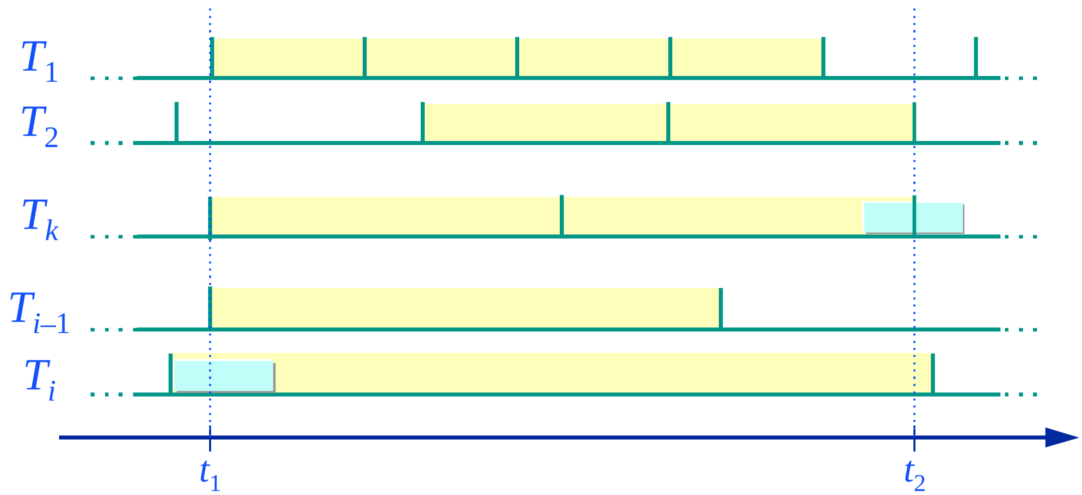
$$\forall L, L > 0: \; L \geq \sum_{i=1}^{n} \left\lfloor \frac{L - d_i + y_i}{y_i} \right\rfloor x_i c_i$$

- The same holds for non-preemptive systems

$$\begin{array}{l} \forall i, \quad 1 < i \leq n \\ \forall L, d_1 < L < d_i \end{array} \qquad L \geq c_i + \sum_{j=1}^{i-1} \left\lfloor \frac{L - 1 - d_j + y_j}{y_j} \right\rfloor x_j c_j$$

A Theory of Rate-Based Execution

Feasibility analysis under preemption constraints

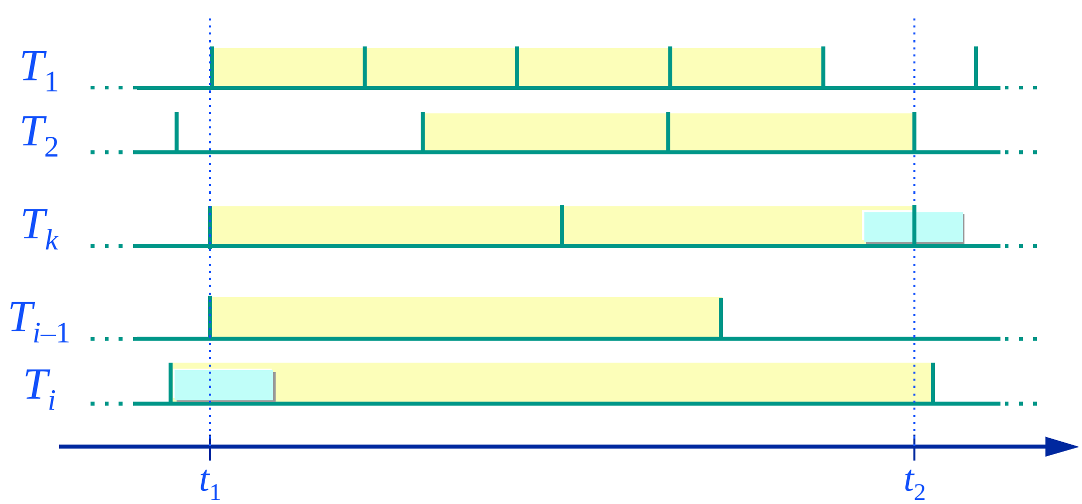


- Non-preemptive scheduling conditions

$$\forall i, \quad 1 < i \le n \qquad L \ge c_i + \sum_{j=1}^{i-1} \left\lfloor \frac{L-1}{p_j} \right\rfloor c_j$$
$$\forall L, \; p_1 < L < p_i$$

A Theory of Rate-Based Execution

Feasibility analysis under preemption constraints



- Non-preemptive scheduling conditions

$$\forall i, \quad 1 < i \le n \qquad L \ge c_i + \sum_{j=1}^{i-1} \left\lfloor \frac{L-1-d_j+y_j}{y_j} \right\rfloor x_j c_j$$
$$\forall L, \; d_1 < L < d_i$$

A Theory of Rate-Based Execution

Summary

- There exists an efficient (pseudo-polynomial time) decision procedure for determining both feasibility and schedulability
  - » If processor utilization less than 1.0
- The *earliest-deadline-first* scheduling algorithm is optimal
- The feasibility and schedulability of a set of “periodic tasks” was never inherently tied to the fact that tasks are invoked strictly periodically
  - » The only requirement is that deadlines be separated by at least a constant amount of time

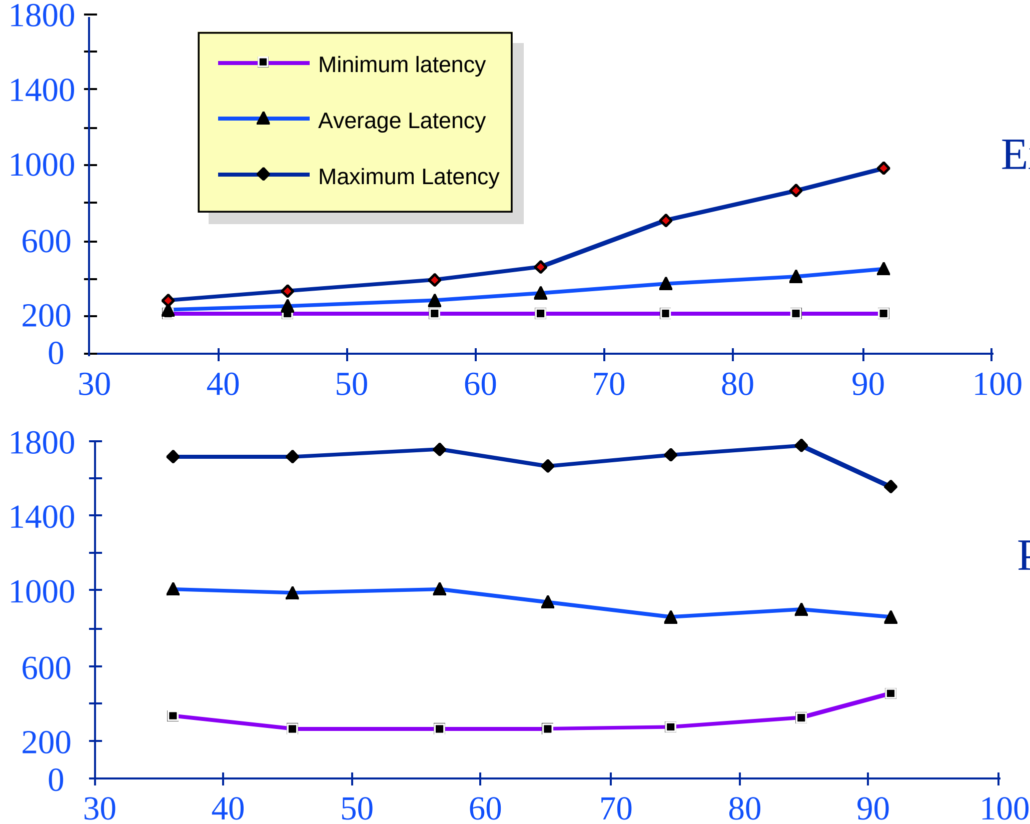
Rate-Based Execution

Applying the theory

- Kernel issues
  - » RBE task implementation
  - » admission control
  - » rate enforcement
  - » rate negotiation
- Application issues
  - » rate specifications
  - » mechanisms for rate feedback and adaptation

Applying the Theory

Latency comparison (latency *v.* CPU utilization)

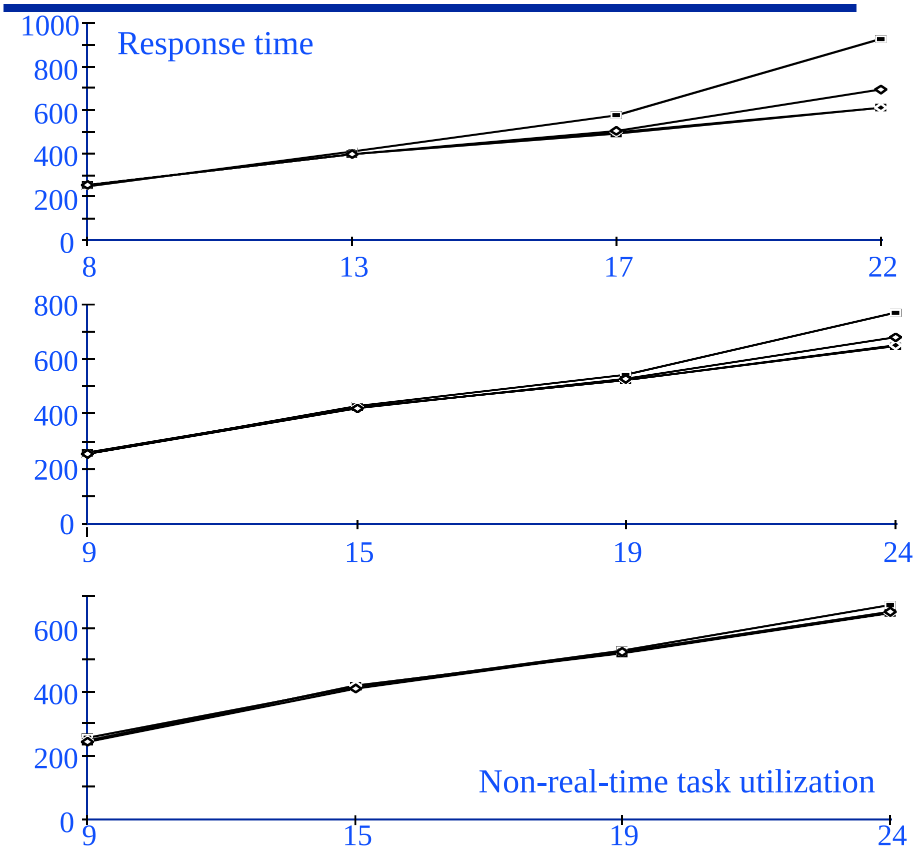


RBE Execution

Periodic Server

Applying the Theory

Non-real-time task response time comparison



75% Real-time task utilization

50% Real-time task utilization

25% Real-time task utilization

Rate-Based Execution

Warts

- Requires extensive kernel modifications to support
  - » Defining a new, event-based programming model

- Intel: *This is really great stuff. Will it work in Windows?*