Aperiodic Job Scheduling

Real-Time and Embedded Operating Systems

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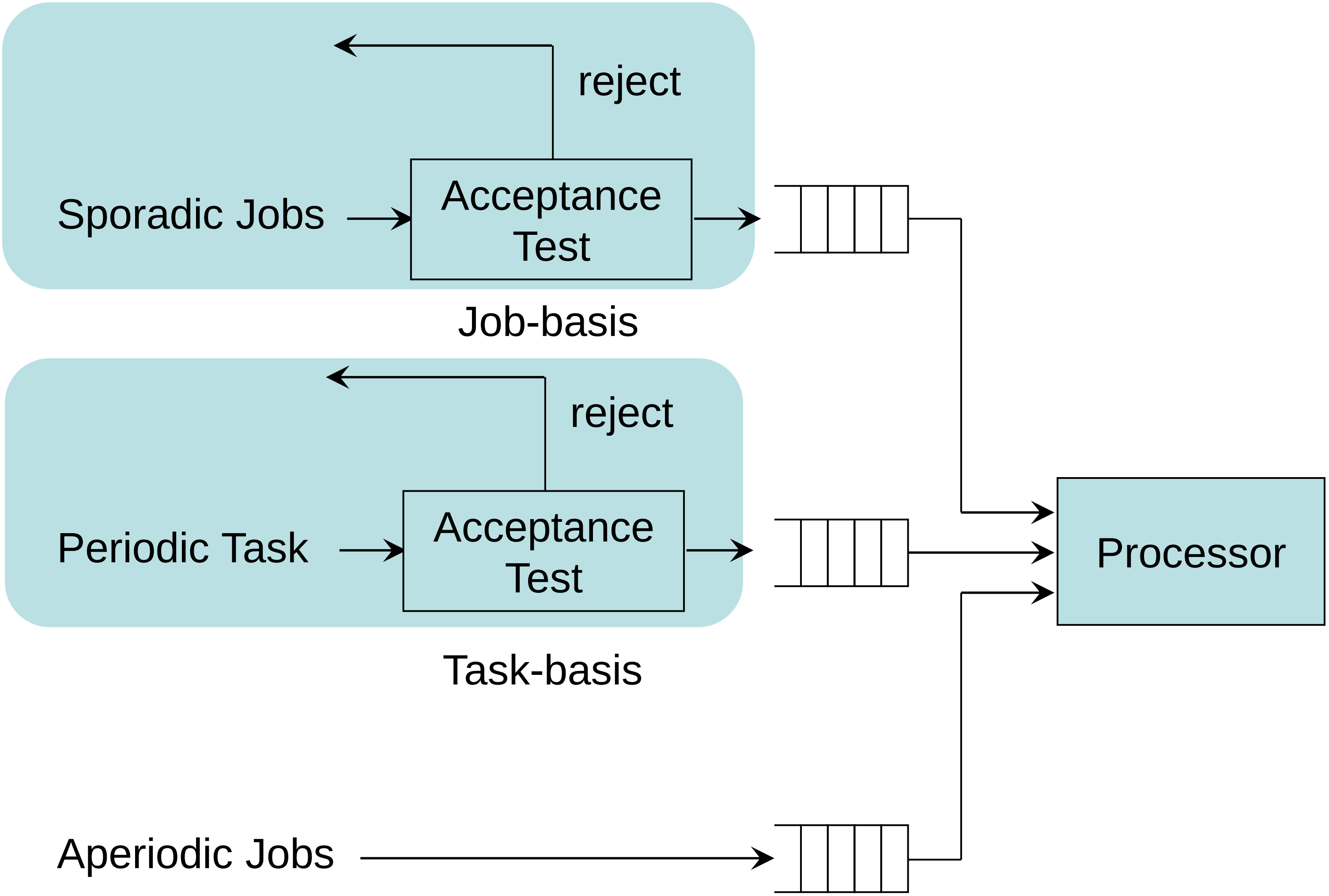

reject
Sporadic Jobs
Acceptance Test
Job-basis
reject
Periodic Task
Acceptance Test
Processor
Task-basis
Aperiodic Jobs

Aperiodic and Sporadic Jobs

- Definition
  - Jobs of apreiodic and sporadic tasks
    - Inter-arrival times are arbitrary
  - Aperiodic Jobs
    - Assigned to either no deadlines or soft deadlines
  - Sporadic Jobs
    - Assigned to hard deadlines

Aperiodic and Sporadic Jobs

- Handling of jobs
  - Apreiodic jobs
    - In a best-effort fashion
    - Accept anyway
  - Sporadic jobs
    - Accept them if their deadlines can be satisfied
    - Otherwise, reject them

Aperiodic and Sporadic Jobs

- Correctness
  - All accepted sporadic jobs and periodic jobs meet their respective deadlines

Aperiodic and Sporadic Jobs

- Optimality
  - Apreiodic jobs
    - Minimal job response times
  - Sporadic jobs
    - No accepted jobs miss their deadlines

Aperiodic and Sporadic Jobs

- What we are going to talk about are…
  - How to handle aperiodic jobs
    - Reserve a portion of CPU power for aperiodic jobs in fixed-priority and deadline-driven systems
    - Try to deliver good response
    - Schedulability of periodic tasks must not be affected
  - How to handle sporadic jobs
    - Employ the mechanisms proposed for aperiodic jobs
    - Test whether deadlines of sporadic jobs can be met

Part A: Handling Aperiodic Jobs

Brute-Force Methods & Server Design

Handling Aperiodic Jobs

- Approaches
  - Background execution
    - Improvement: slack stealing
  - Interrupt-driven execution
    - Improvement: slack stealing
  - Polled execution
    - Improvement: Bandwidth-preserving servers

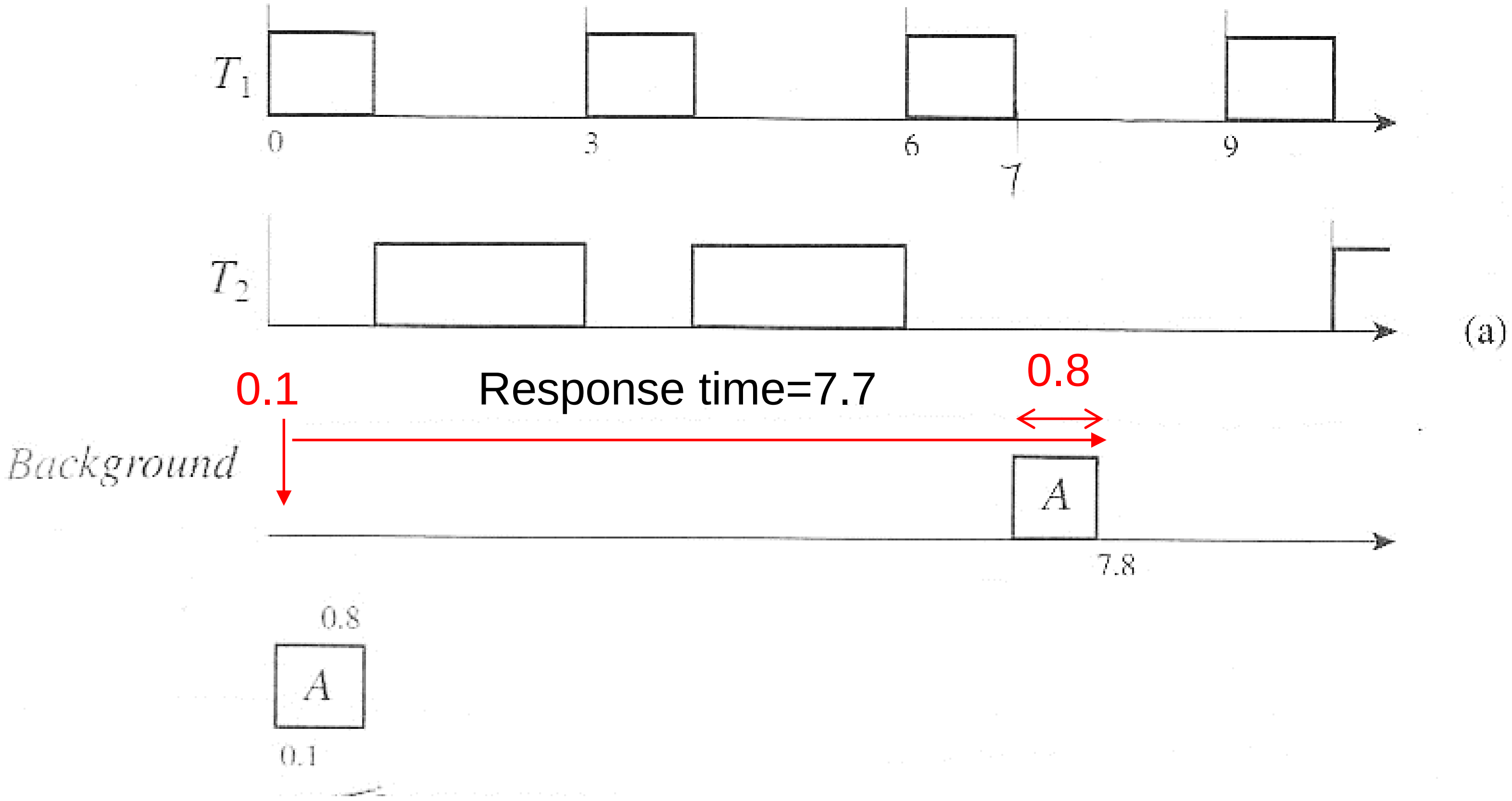
Brute-force methods

server

Brute-Force Method-1

- Background execution
  - Handle aperiodic jobs whenever there is no periodic jobs to execute
    - Simple
    - Always produce a correct schedule
    - Poor response time (of aperiodic jobs)

Background Execution

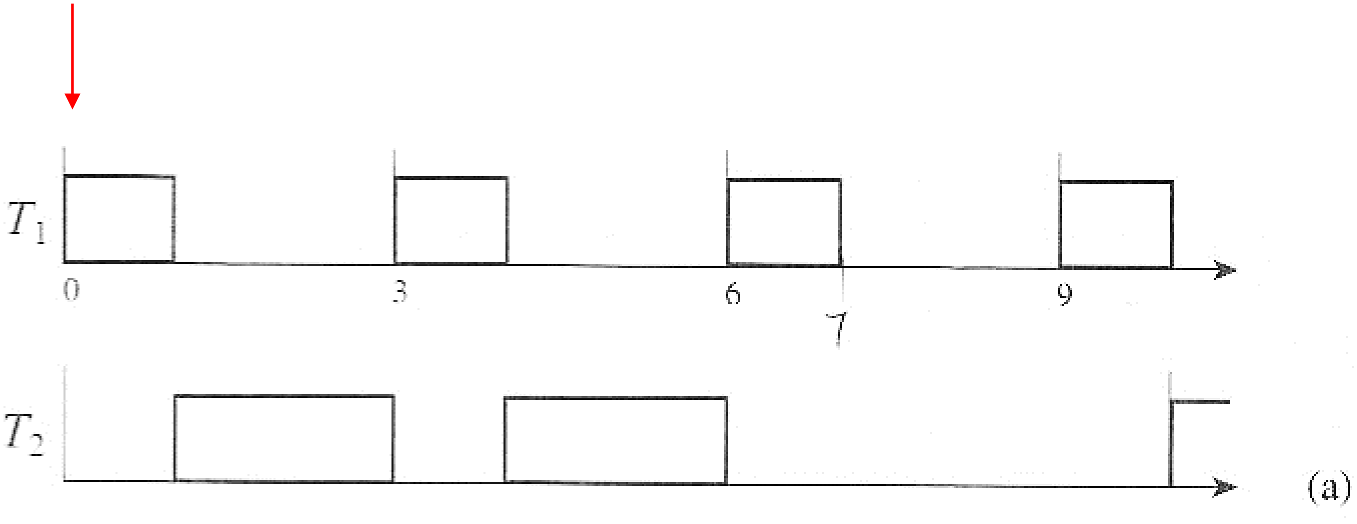


Brute-Force Method-2

- Interrupt execution
  - Opposite to background execution
  - On arrivals, aperiodic jobs immediately interrupts the currently running periodic job
  - Fastest response time
  - May damage the schedulability of periodic jobs

Interrupt Execution

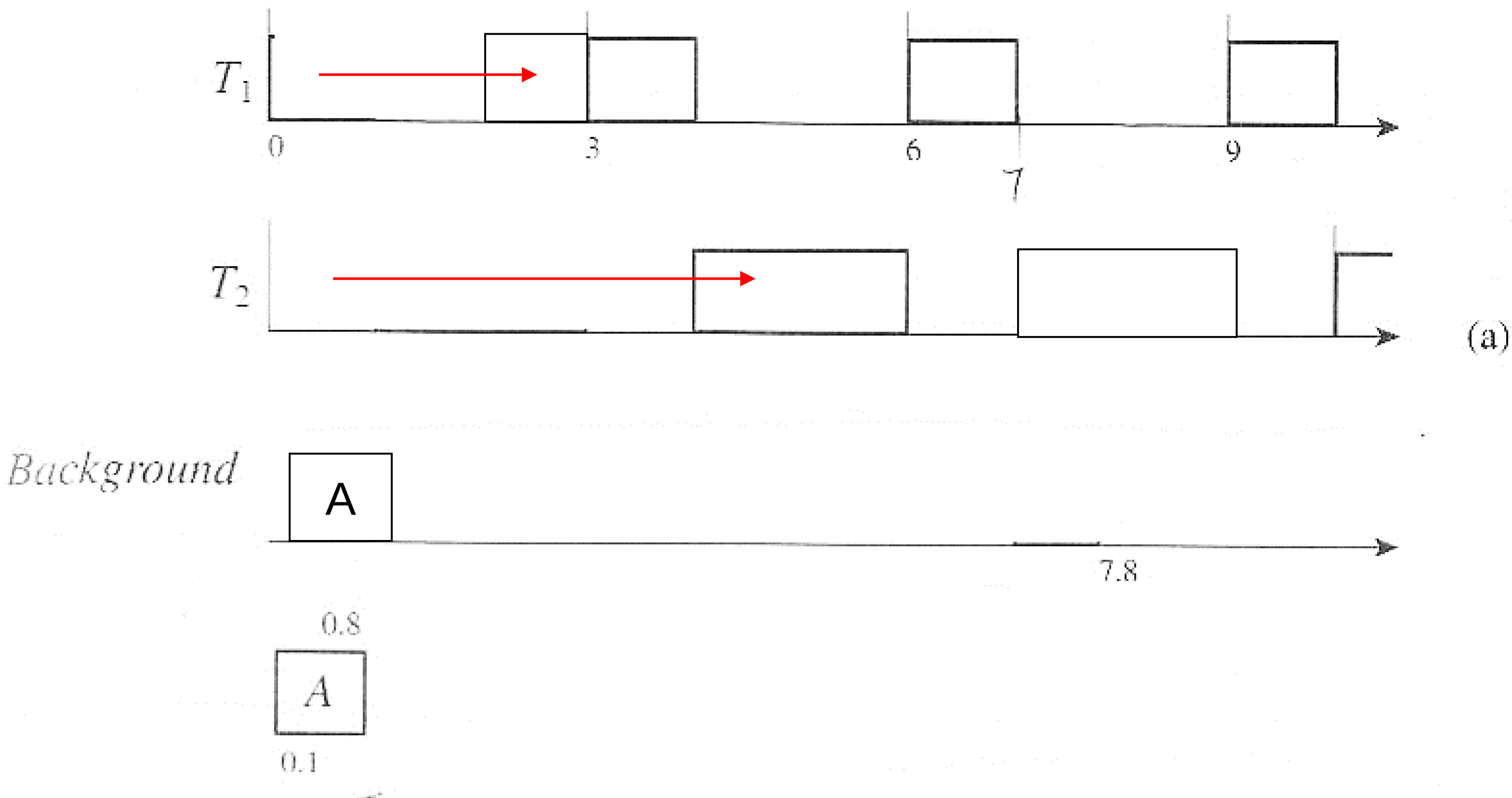
Arrival =0.1
If execution time > 2…



Improvement

- Slack stealing
  - To postpone periodic jobs when it is safe to do so
  - May be easily implemented in LSF algorithm, but hard to implement in EDF or RM

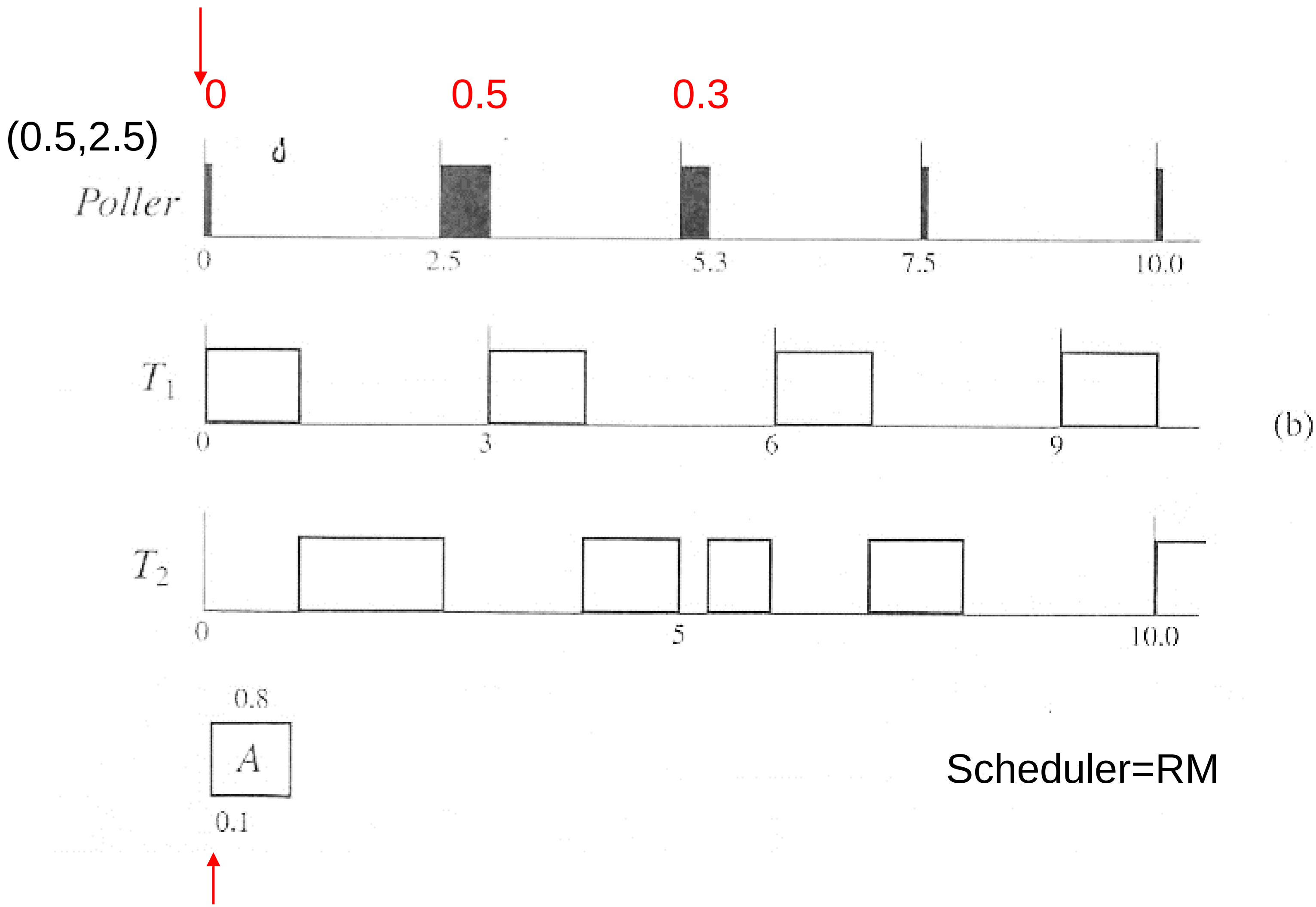
Slack Stealing



A Primitive Server Design

- Polled execution
  - A purely periodic task (polling server) that serves a queue of aperiodic jobs
  - When the polling server gains control of the CPU, it services aperiodic jobs in the queue
  - If the queue becomes empty, the polling server suspends immediately
    - The queue is not checked until the next polling period

The polling server loses all its budget at time 0, since there is no ready aperiodic jobs



Scheduler=RM

Aperiodic job A arrives at time 0.1

Polling Server

- Polling servers are easy to implement and analytically simple
- However, a polling server loses all its budget once its queue is empty
  - If we can *preserve* the residual budget, aperiodic jobs can be serviced and their response time can be shortened

Server Terminology

- Terminology (1/3)
  - Server
    - A task that serves aperiodic/sporadic jobs
    - Characterized by (c,p) in terms of schedulability
      - A server is *not* necessarily a periodic task
  - c: Server budget
    - A server is ready for execution if its budget is non-zero
  - c/p: Server size
    - A fraction of CPU time reserved for the server

Server Terminology

- Terminology (2/3)
  - Backlogged
    - A server is backlogged if there are some ready jobs in its queue
  - Eligible
    - A server is eligible if it has budget and is backlogged

Server Terminology

- Terminology (3/3)
  - Budget consumption rules
    - Define how budget is consumed when serving jobs
  - Budget replenishment rules
    - Define how budget is replenished
  - Server execution
    - When a server is eligible, it is scheduled with other periodic tasks as if it were a periodic task
    - When budget is exhausted, the server is suspended immediately

Advanced Server Designs

- Bandwidth-preserving servers
  - Deferrable servers
  - Sporadic servers
  - Constant utilization servers, total bandwidth servers, weighted fair-queuing servers
- These servers aim at improving responsiveness by
  - preserving budget as late as possible and
  - replenishing budget as early as possible

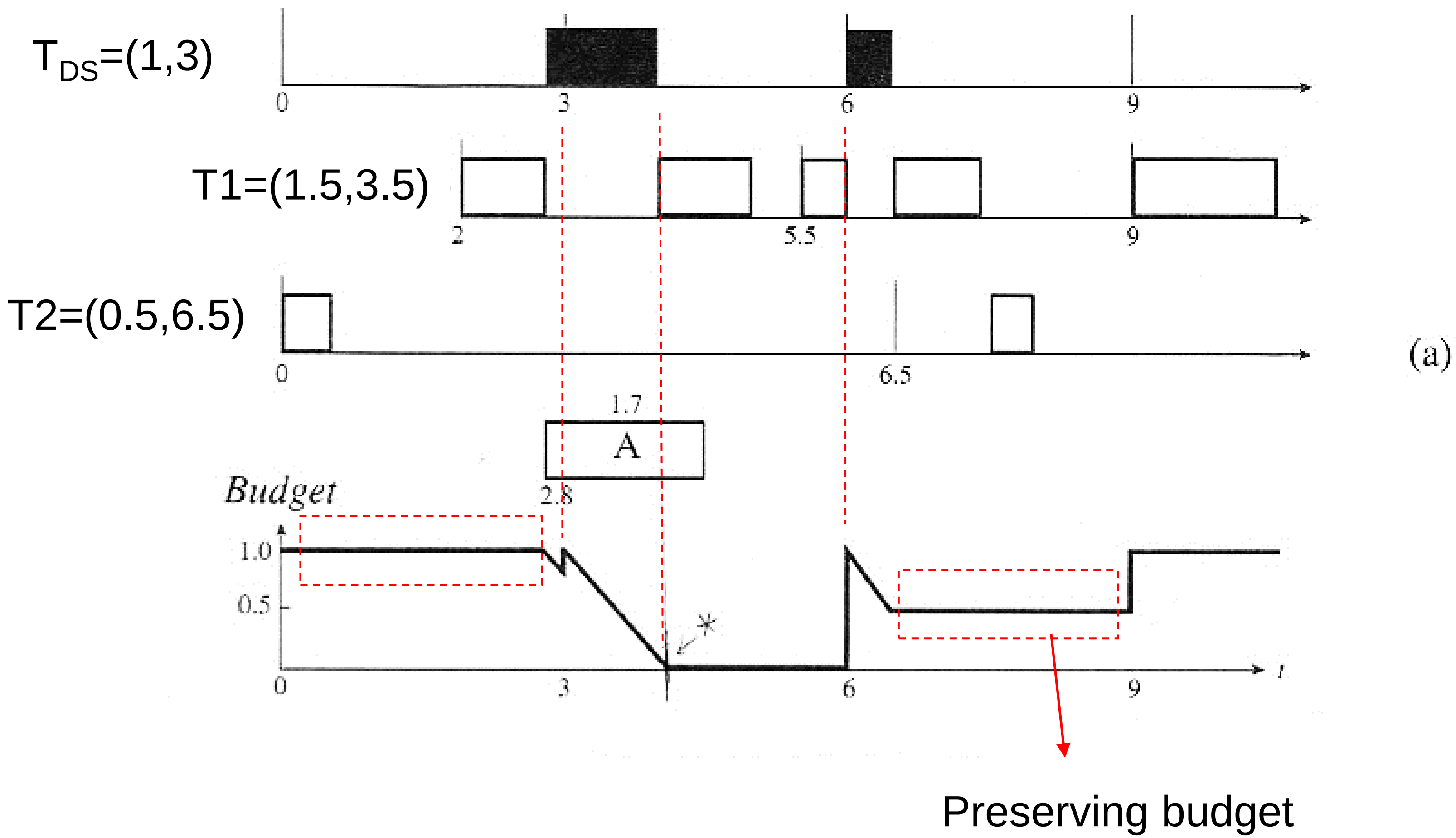
Bandwidth-Preserving Servers

- Deferrable servers ☜
- Sporadic servers (RM only)
- Priority-exchange servers
- Constant utilization servers and total bandwidth server (EDF only)

Deferrable Servers

- Let a deferrable server be (c_s, p_s)
- Consumption rules:
  - Budget is consumed at a rate of 1 when the server is serving aperiodic jobs
- Replenishment rules:
  - Budget is set to c_s at $k*p_s$, for $k=0,1,2,\ldots$

Deferrable Servers



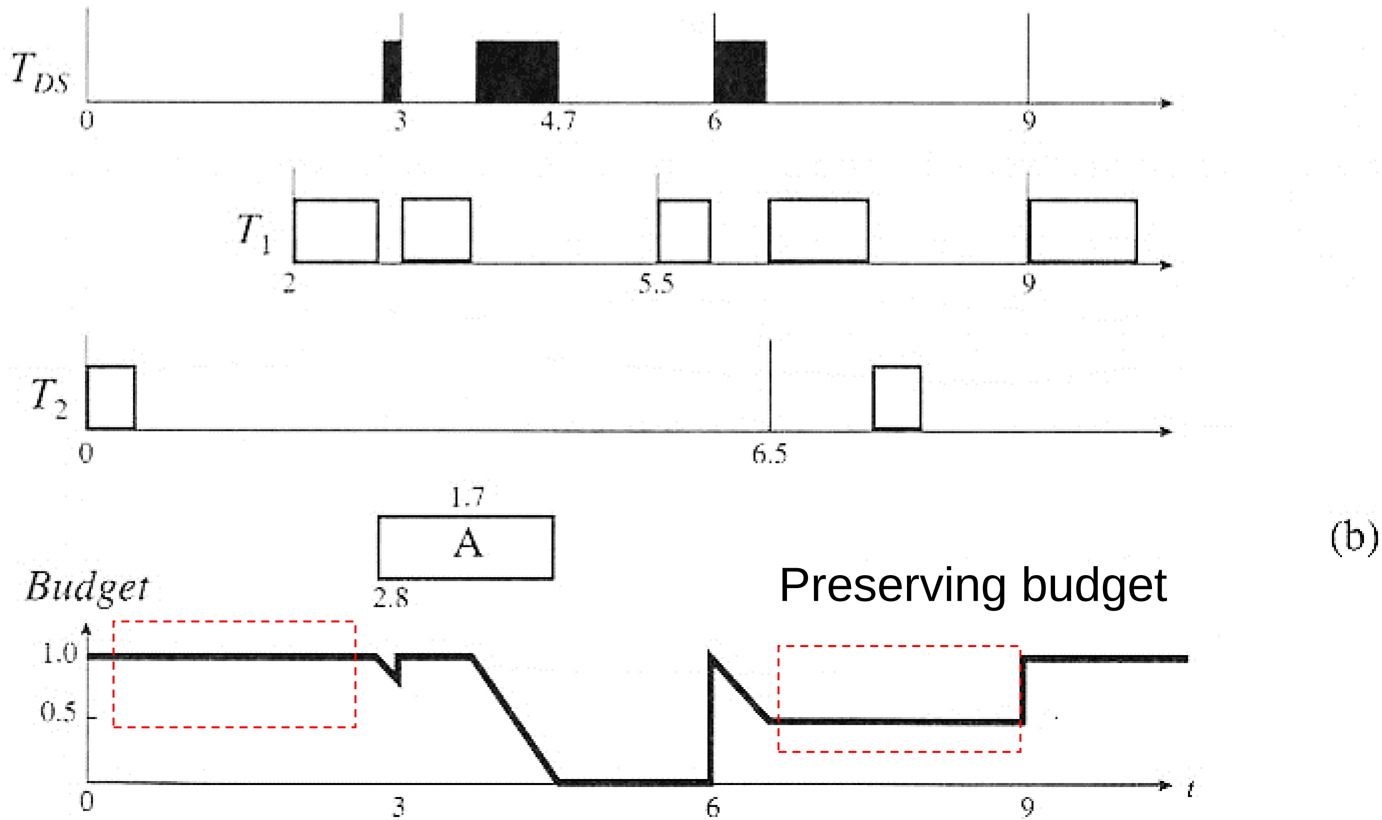
Fixed-priority (RM): priority $T_{DS} \rightarrow T_1 \rightarrow T_2$

Deferrable Servers

(1,3)

(1.5,3.5)

(0.5,6.5)



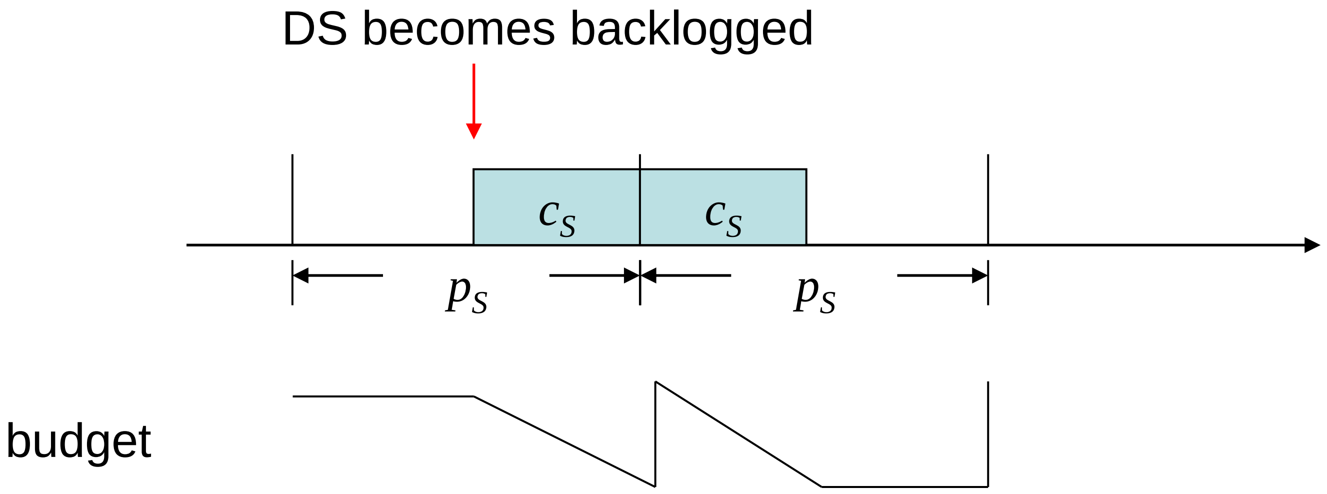
Deadline-driven (EDF): the deadline of a server job is the next replenishment time

Deferrable Servers

- Because budget is preserved, an aperiodic job may conflict with periodic jobs at any time
  - Differently, jobs of a purely periodic task is ready at the beginning of every period
- Does the task critical instant exist in the presence of a deferrable server?

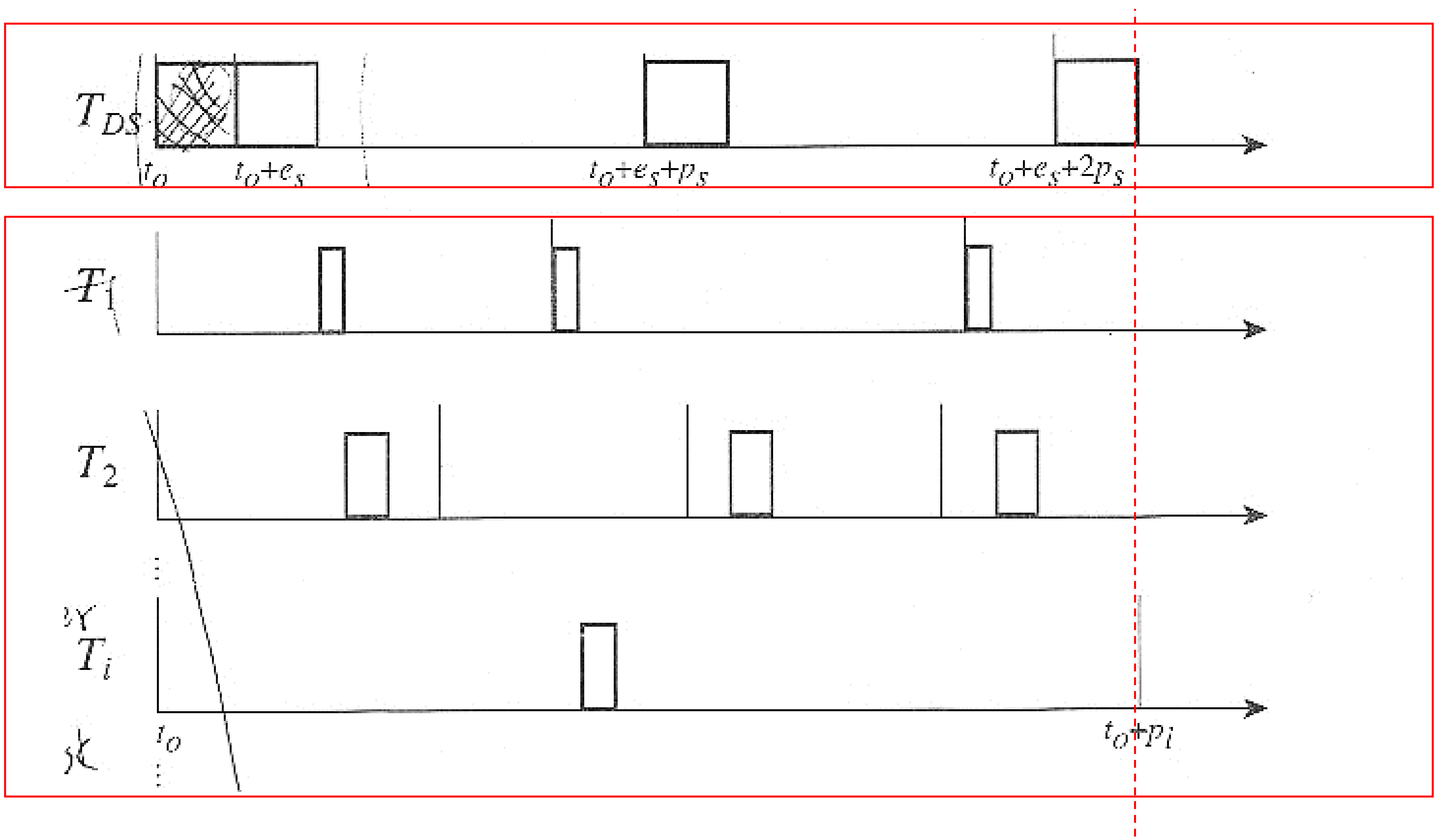
Deferrable Servers

- The below scenario shows when a deferrable server interferes low-priority tasks the most (aka double hit)



Deferrable Servers

- Critical instance of a periodic task T_i
  - Here, the deferrable server T_{DS} has the highest priority



Deferrable Servers

- Response time analysis
  - For each i, task T_i is schedulable if $R_{i,j}$ converges no later than P_i
  - DS=(c_s,p_s)

$$R_{i,0} = c_i$$

$$R_{i,j} = c_i + \boxed{c_s + \left\lceil \frac{R_{i,j-1} - c_s}{p_s} \right\rceil \times c_s} + \sum_{k=1}^{i-1} \left\lceil \frac{R_{i,j-1}}{p_k} \right\rceil \times c_k$$

Deferrable Servers

- Response time analysis is accurate, but can we use the utilization bound as a quick test?
- Bad news:
  - There is no know utilization bound if the priority of the deferrable server is arbitrary
- Good news (not really):
  - Consider a system of n independent, preemptible periodic tasks and $p_s<p_1<\ldots<p_n<2p_s$ and $p_n>p_s+c_s$ ←Too many restrictions…

$$U_{RM/DS}(n) = (n-1)[(\frac{u_{ds}+2}{u_{ds}+1})^{1/(n-1)} - 1]$$

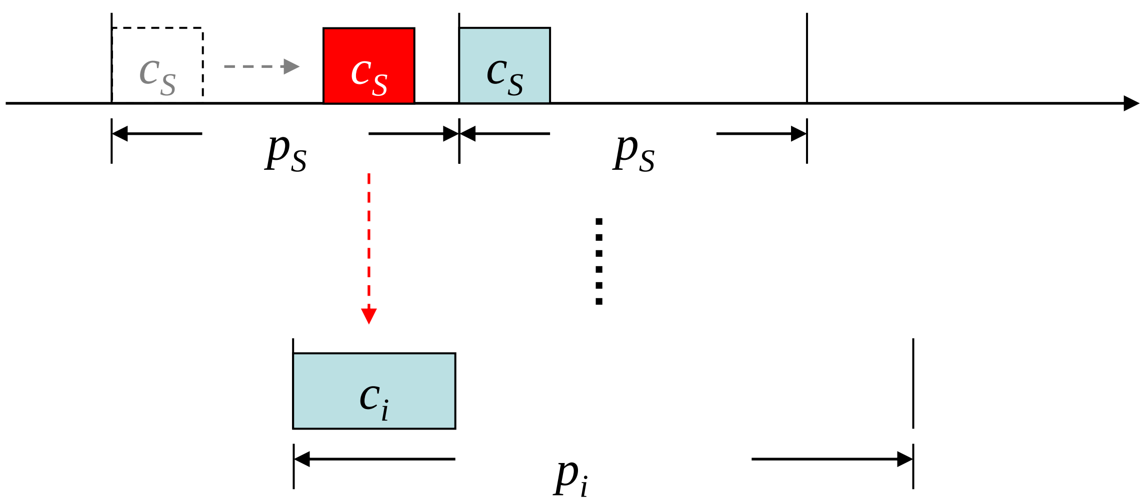
[Lehoczky87]

Deferrable Servers

- Yet another good news:
  – The Liu-and-Layland utilization bound is still useful here, if we take the interference from the server into consideration

Deferrable Server

- A high-priority deferrable server T_{DS} may interfere a low-priority task T_i by up to C_s units of time
  - The red c_s is not supposed to be there, if T_{ds} is a periodic task…



Deferrable Server

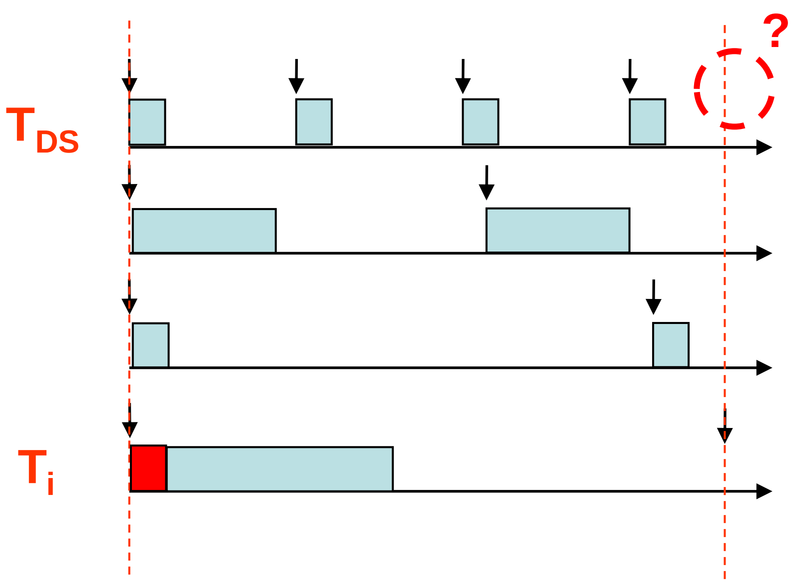
- Task set $\{T_1,\ldots,T_m,T_{DS},T_{m+2},\ldots T_n\}$
  - $\{T_1,\ldots,T_m,T_{DS}\}$ is schedulable if $\sum ci/pi \leqq U(m)$
  - For *i=(m+2)…n*, Task T_i is schedulable if

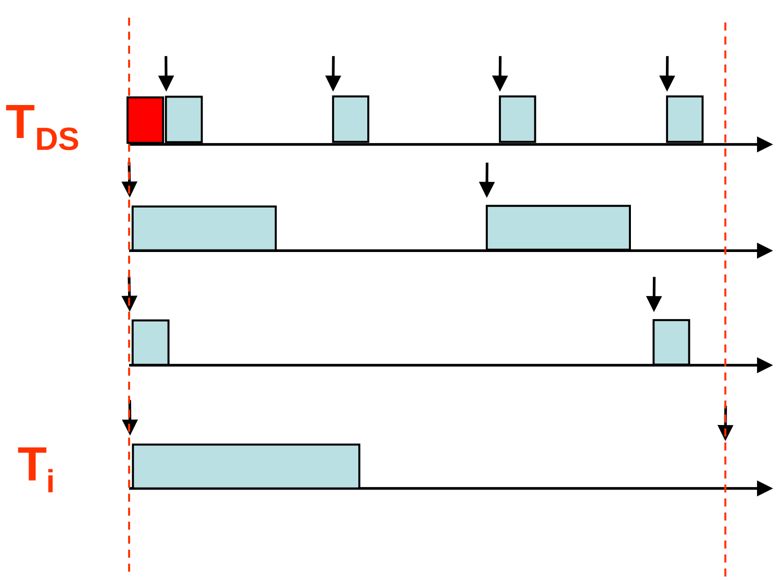
$$\sum_{j=1}^{i} \frac{c_j}{p_j} + \frac{c_s}{p_i} \leq U(i)$$

  - Let's try $T_1=(0.6,3)$, $T_{DS}=(0.8,4)$, $T_3=(0.5,5)$, $T_4=(1.4,7)$

Deferrable Servers

- Why treat the additional c_s as "extra computation time" of T_i?





Schedulable → schedulable

Deferrable Servers

- Schedulability of a deadline-driven system with a deferrable server
  - Consider task set $\{T_1,\ldots, T_n\} U \{(c_s,p_s)\}$
    - Let t be the deadline of a job of a periodic task
    - Let t^- (<t) be the latest time instant when the CPU is idle or is executing jobs with deadline later than t
      - In $(t^-,t]$, only jobs whose deadline <t are executed
    - We are interested in the maximum computation time in $(t^-,t]$ demanded by periodic tasks and the deferrable server

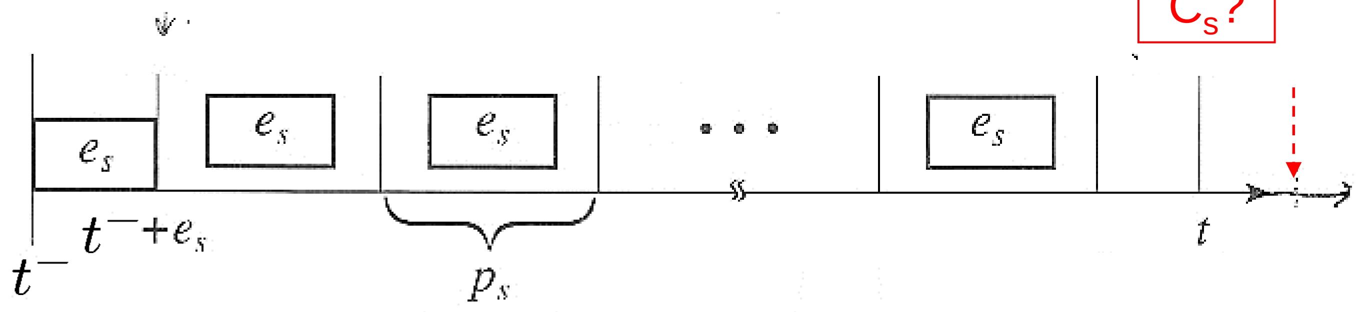
Deferrable Servers

- Deadline-driven systems
  - The maximum CPU time demanded by the deferrable server in time interval $(t^-,t]$ is

$$c_s + \left\lfloor \frac{t - t^- - c_s}{p_s} \right\rfloor c_s$$

The last job cannot affect jobs in $(t^-,t]$ because its deadline is later than t

C_s?



The maximum occurs when the term inside the floor function is an integer

Deferrable Servers

- Deadline-driven systems
  - The maximum CPU time demanded by periodic jobs is

$$\sum_{k=1}^{n} \left\lfloor \frac{t-t^{-}}{p_k} \right\rfloor c_k$$

Similarly, the maximum happens when the term inside the floor function is a integer

Deferrable Servers

- If the taskset is unschedulable, then the total CPU time demanded by periodic jobs and apreiodic jobs exceeds t-t$^-$

$$t - t^{-} < c_s + \left(\frac{t - t^{-} - c_s}{p_s}\right) c_s + \sum_{k=1}^{n} \frac{c_k}{p_k}(t - t^{-})$$

- Diving both sides of the inequality and then invert the above statement, we have the theorem:

Deferrable Servers

- A deadline-driven system with a deferrable server is schedulable if

$$\sum_{k=1}^{n} \frac{c_k}{p_k} + u_s \left(1 + \frac{p_s - c_s}{p_s}\right) \leq 1$$

[Ghazalie95]

Deferrable Servers

- RM
  - RTA
  - [Lehoczky87]
  - Revised U test
- EDF
  - [Ghazalie95]

- Deferrable servers has been adopted in Ada 2005 for real-time and concurrent programming

Bandwidth-Preserving Servers

- Deferrable servers
- Sporadic servers (RM only) ☜
- Priority-exchange servers
- Constant utilization servers and total bandwidth server (EDF only)

Sporadic Servers

- Deferrable servers have simple rules for budget consumption and replenishment, but they impose extra delays on periodic tasks
  - Double hits in priority-driven and deadline-driven scheduling
- Schedulability tests become quite complicated

Sporadic Servers

- Sporadic servers are designed to improve upon deferrable servers
  - Schedulability test for periodic systems with sporadic servers is very simple
  - However, sporadic servers have complicated consumption and replenishment rules

Sporadic Servers

- Design guideline: a sporadic server never demand processor time more than a periodic task (c,p) in any time interval
  - Sporadic servers can be characterized by the corresponding periodic tasks in terms of schedulability

Sporadic Servers

- A sporadic server can be characterized by (c,p)
  - Again, notice that a sporadic server is not a periodic task!
- Different designs of sporadic servers exist, and they aim at
  - preserving server budget as long as possible, and
  - replenishing server budget as early as possible

Sporadic Servers

- Simple sporadic servers in fixed-priority systems

- t_r denotes the latest (actual) replenishment time.
- t_f denotes the first instant after t_r at which the server begins to execute.
- t_e denotes the latest *effective replenishment time*.
- At any time t, *BEGIN* is the beginning instant of the earliest busy interval among the latest contiguous sequence of busy intervals of the higher-priority subsystem $\mathbf{T}_H$ that started before t. (Two busy intervals are contiguous if the later one begins immediately after the earlier one ends.)
- *END* is the end of the latest busy interval in the above defined sequence if this interval ends before t and equal to infinity if the interval ends after t.

Sporadic Servers

- Consumption rules

C1 The server is executing.

C2 The server has executed since t_r and $END < t$

- *Replenishment Rules of Simple Fixed-Priority Sporadic Server*:

R1 Initially when the system begins execution and each time when the budget is replenished, the execution budget $= e_s$, and t_r = the current time.

R2 At time t_f, if $END = t_f$, $t_e = \max(t_r, BEGIN)$. If $END < t_f$, $t_e = t_f$. The next replenishment time is set at $t_e + p_s$.

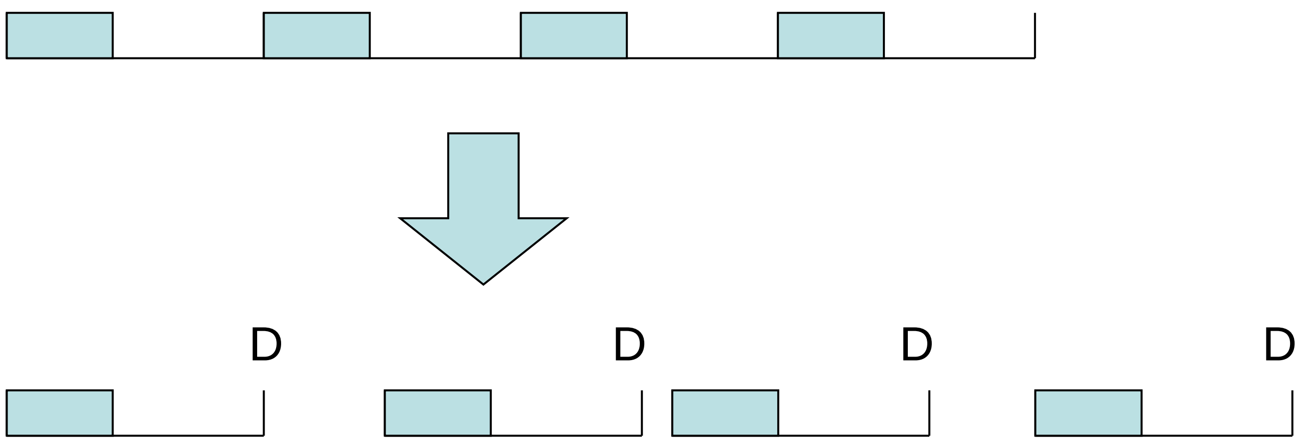
R3 The next replenishment occurs at the next replenishment time, except under the following conditions. Under these conditions, replenishment is done at times stated below.

(a) If the next replenishment time $t_e + p_s$ is earlier than t_f, the budget is replenished as soon as it is exhausted.

(b) If the system **T** becomes idle before the next replenishment time $t_e + p_s$ and becomes busy again at t_b, the budget is replenished at $\min(t_e + p_s, t_b)$.

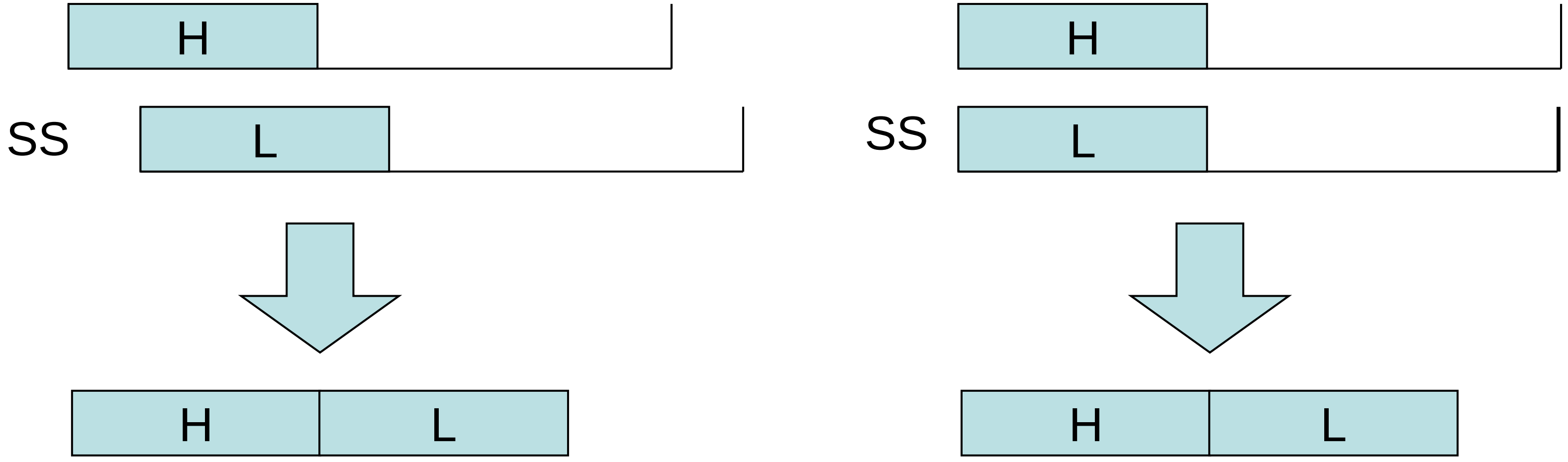
Simple Sporadic Servers

- Fact A: if a periodic task is schedulable in a fixed-priority system, then all its jobs are schedulable if their inter-arrival times are not shorter than its task period
  - Help preserve the budget as late as possible



Simple Sporadic Servers

- Fact B: when a low-priority job is delayed by a high-priority job, the produced schedule is the same as that produced by the two jobs arriving at the same time
  - Help replenish the budget as early as possible



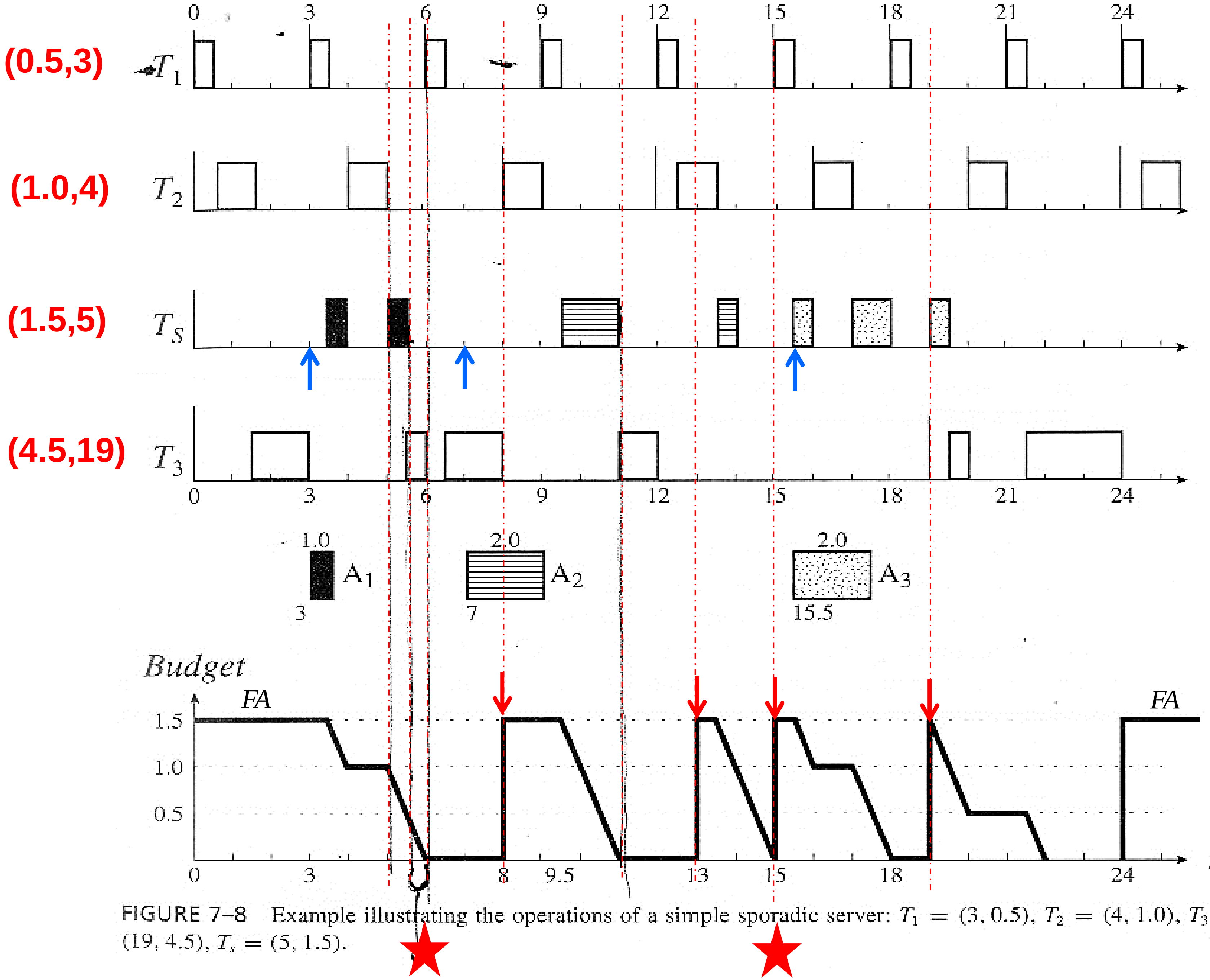


FIGURE 7–8 Example illustrating the operations of a simple sporadic server: $T_1 = (3, 0.5)$, $T_2 = (4, 1.0)$, $T_3 = (19, 4.5)$, $T_s = (5, 1.5)$.

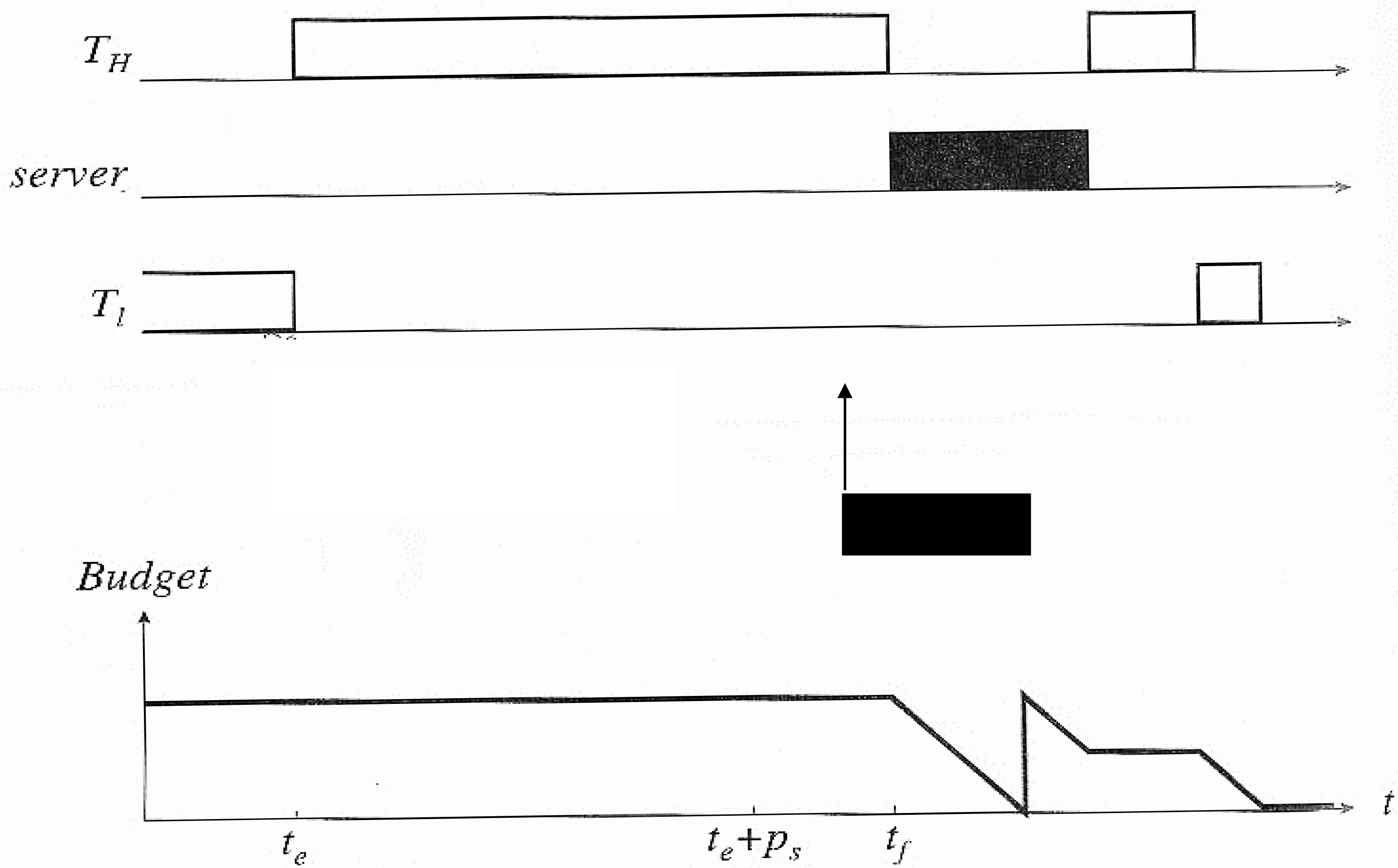
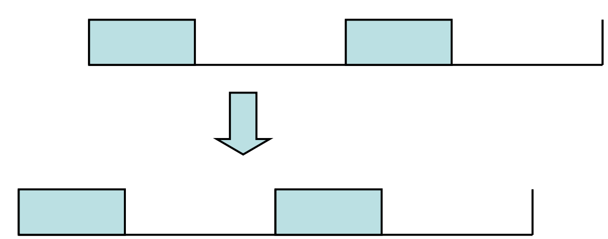


FIGURE 7–9 A situation where rule R3a applies.



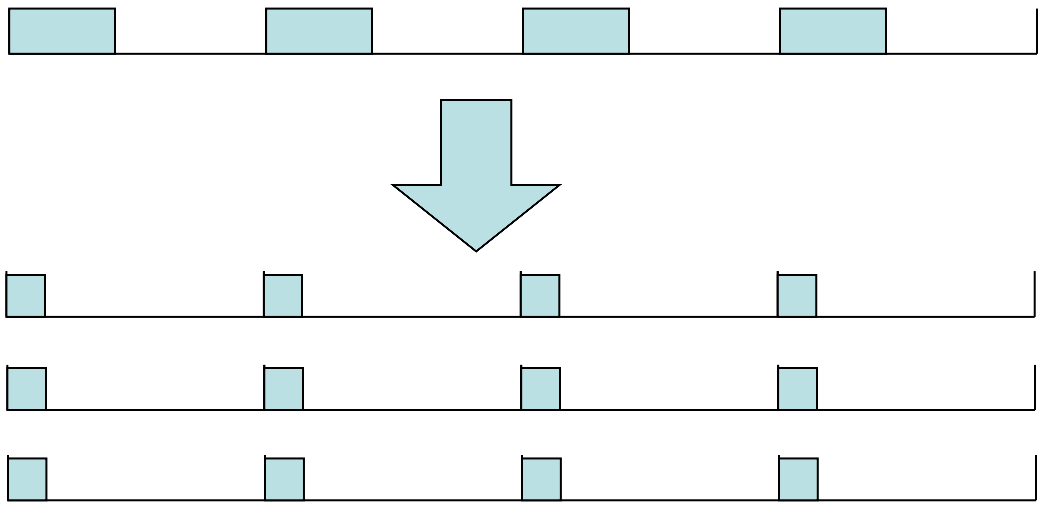
Sporadic Servers

- An idle simple sporadic server consumes its budget as all high-priority tasks are idle
  - Actually no aperiodic jobs are serviced, the consumed budget is wasted!
  - For further improvement, a sporadic server could be split into chunks [Sprunt 1989]
    - One “chunk” emulates a smaller sporadic server with the same “period”

Sporadic Servers

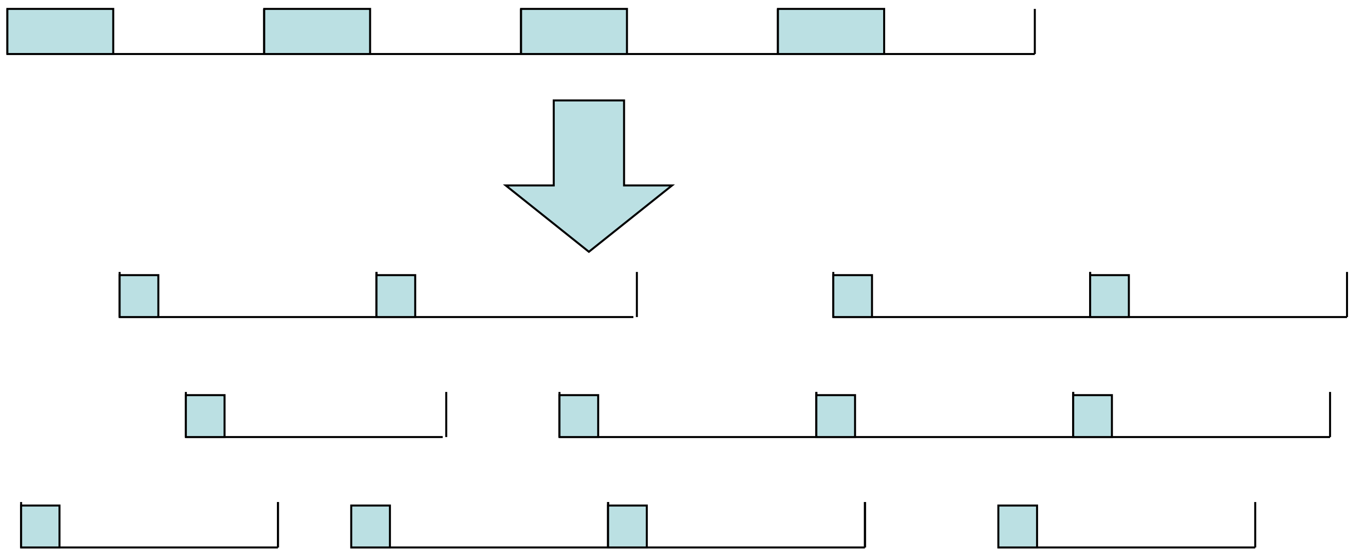
- Fact C: Let T be a periodic system. If $\{(c,p)\} \cup T$ is schedulable then $\{(c_1,p),(c_2,p),...,(c_n,p)\} \cup T$ is also schedulable, provided that

$$\sum_{i=1}^{n} c_i = c$$



Sporadic Servers

- Combining Fact A and Fact C



Chunks can be split and merged whenever needed

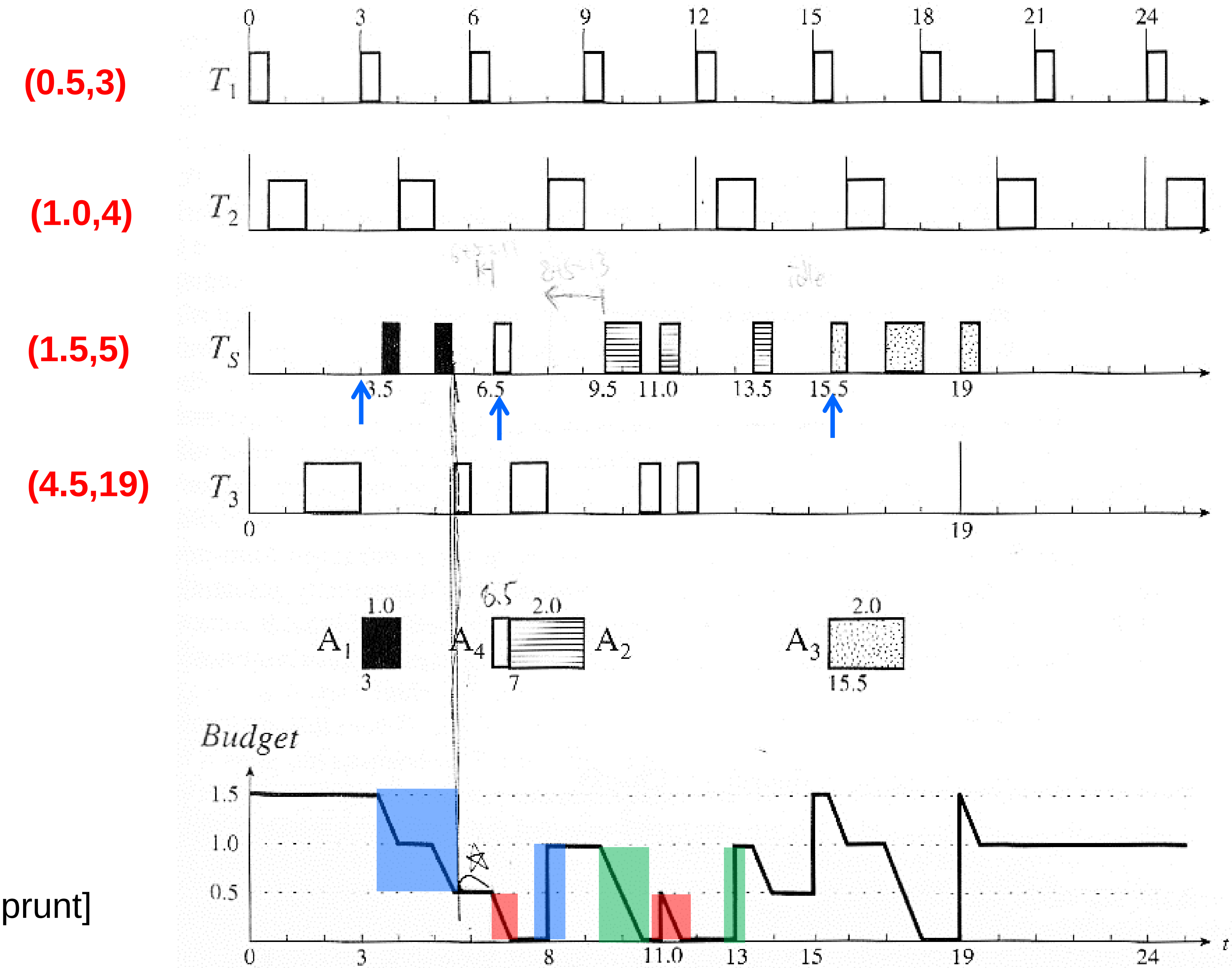


FIGURE 7–11 Example illustrating SpSL sporadic servers: $T_1 = (3, 0.5)$, $T_2 = (4, 1.0)$, $T_3 = (19, 4.5)$, $T_s = (5, 1.5)$

[Sprunt]

Sporadic Servers

- Response times in simple Sporadic Servers
  - A1:5.5, A2: 14, A3: 19.5
- Response times in Sprunt Sporadic Servers
  - A1: 5.5, A2: 14, A3: 19.5, A4: 7

Sporadic Servers

- Note that previous slides about sporadic servers are for fixed-priority systems
- In deadline-driven systems, both the concepts of simple sporadic servers [Liu] and “chunk” sporadic servers [Ghazalie] are still applicable
  - They are very complicated though
  - However, we have better, simpler solutions for deadline-driven scheduling!

Sporadic Servers

- Sporadic servers have been adopted by real-time POSIX standard
  - RTLinux
  - RTAI

POSIX specification on SS

- How to use
  - Call sched_setscheduler(pid, SCHED_SPORADIC, …)
  - Applicable to fixed-priority systems only
  - Also set an foreground priority sched_priority and a background priority
- Operation
  - The server runs at foreground priority if there is budget but switches to background priority otherwise.
  - Budget is replenished by the scheduler on periods

Sporadic Servers

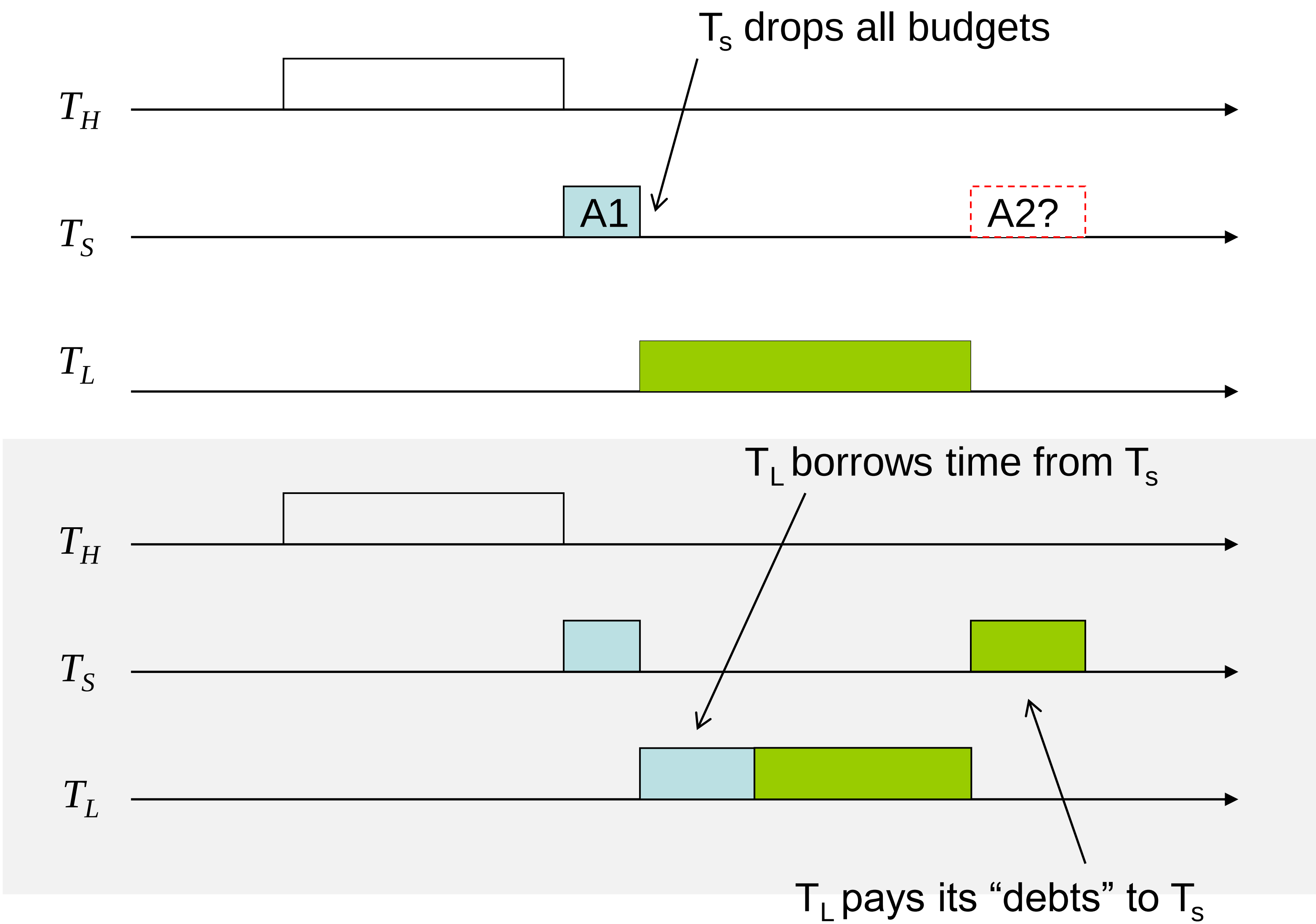
- Discussion
  - DS: simple cons/repl rules, complicated schedulability test
  - SS: simple schedulability test, complicated cons/repl rules

  - If you are a system engineer, which one will you take?

Bandwidth-Preserving Servers

- Deferrable servers
- Sporadic servers
- Priority-exchange servers ☜
- Constant utilization servers and total bandwidth server

Priority-Exchange Servers



Priority-Exchange Servers

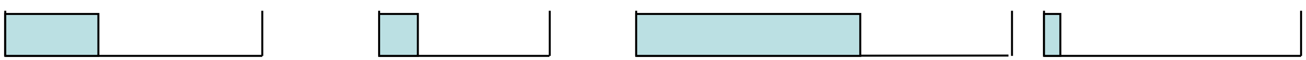
- Conceptually simple, but extremely hard to implement
  - May require hardware acceleration
- We shall then see the elegance and beauty of bandwidth-preserving servers for deadline-driven systems

Bandwidth-Preserving Servers

- Deferrable servers
- Sporadic servers (RM only)
- Priority-exchange servers
- Constant utilization servers and total bandwidth server (EDF only) ☜

Constant Utilization Servers

- Let a sporadic job is characterized by arrival time a, execution time c, deadline d
  - Define its density as $c/(d-a)$
- A sporadic task is of a stream of sporadic jobs



- Given any time point *t* that falls between the a_i and d_i of a sporadic job J_i,
  - $c_i/(d_i-a_i)$ is referred to as the instantaneous utilization (density) contributed by job J_i at time instant t

Constant Utilization Servers

- *Theorem*: A system of independent periodic jobs is schedulable by EDF if the total density of tasks is no larger than 1 at any time instant

- *Corollary*: A periodic system and a collection of sporadic tasks are schedulable by EDF if the sum of the total utilization of the former tasks and the total instantaneous utilization of the latter tasks is no greater than 1 at any time
  - Directly follows from the last theorem

Constant Utilization Servers

- Consumption rules is simple: A server consumes its budget when it is serving jobs
- Replenishment rules:

Replenishment Rules of a Constant Utilization Server of Size $\tilde{u}_s$

R1 Initially, $e_s = 0$, and $d = 0$.

R2 When an aperiodic job with execution time e arrives at time t to an empty aperiodic job queue,

(a) if $t < d$, do nothing;

(b) if $t \geq d$, $d = t + e/\tilde{u}_s$, and $e_s = e$.

R3 At the deadline d of the server,

(a) if the server is backlogged, set the server deadline to $d + e/\tilde{u}_s$ and $e_s = e$;

(b) if the server is idle, do nothing.

[Spuri 96]

Constant Utilization Servers

- As suggested by the name, the instantaneous utilization of every sporadic job equals to the server size
- CUS replenishes its budget at job deadlines

- Pitfall: A sporadic job may have two "deadlines":
  - The deadline comes with the job: d_a
  - The deadline assigned by CUS algorithm: d_b
  - Must satisfy $d_b <= d_a$

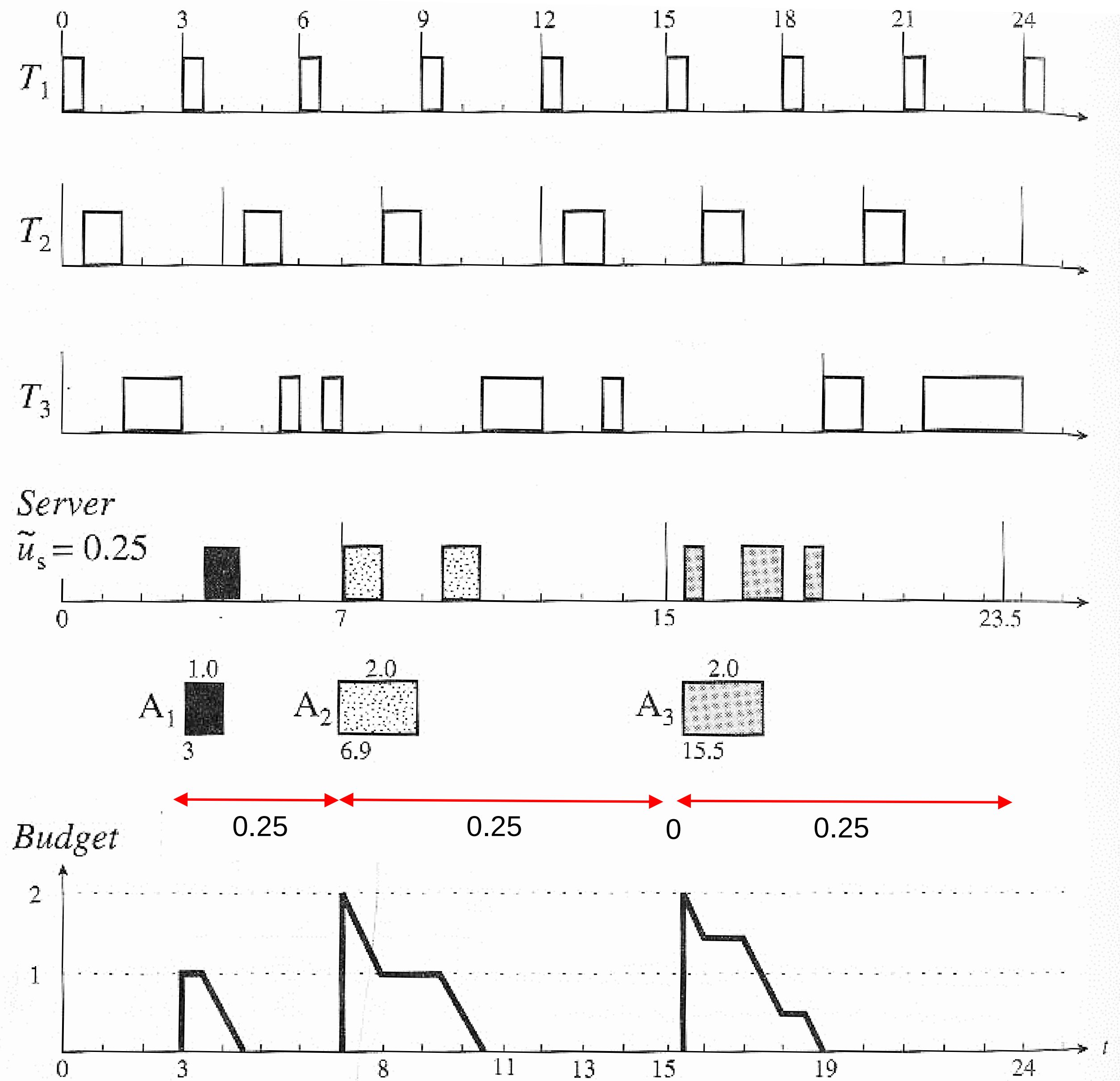


FIGURE 7–13 Example illustrating the operations of constant utilization server: $T_1 = (4, 0.5)$, $T_2 = (4, 1.0)$, $T_3 = (19, 4.5)$.

Total Bandwidth Servers

- A CUS replenishes its budget not earlier than job deadlines
  - A newly arriving job has to wait until the deadline of the latest aperiodic job, even if the server is currently idle
    - A2 in the last example
- Is early replenishment possible?
  - Yes: total bandwidth servers

Total Bandwidth Servers

- Consumption rules: the same as those of CUS
- Replenishment rules:

Replenishment Rules of a Total Bandwidth Server of size $\tilde{u}_s$

R1 Initially, $e_s = 0$ and $d = 0$.

R2 When an aperiodic job with execution time e arrives at time t to an empty aperiodic job queue, set d to $\max(d, t) + e/\tilde{u}_s$ and $e_s = e$.

R3 When the server completes the current aperiodic job, the job is removed from its queue.

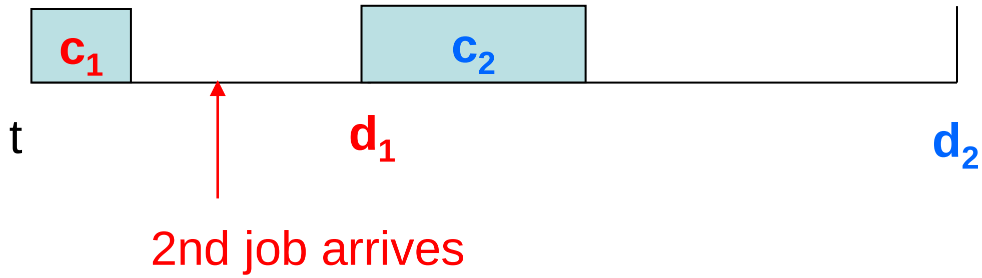
(a) If the server is backlogged, the server deadline is set to $d + e/\tilde{u}_s$, and $e_s = e$.

(b) If the server is idle, do nothing.

Instantly replenish server budget!

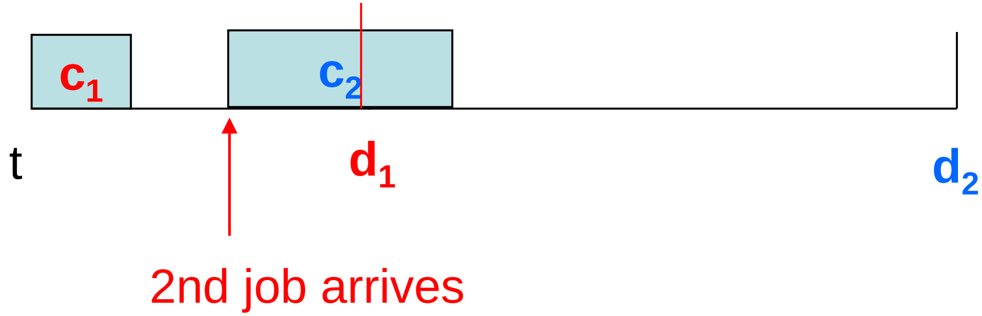
[Deng 97]

Total Bandwidth Servers



CUS:

$$\frac{c_1}{d_1 - t} = \frac{c_2}{d_2 - d_1} = u_s$$

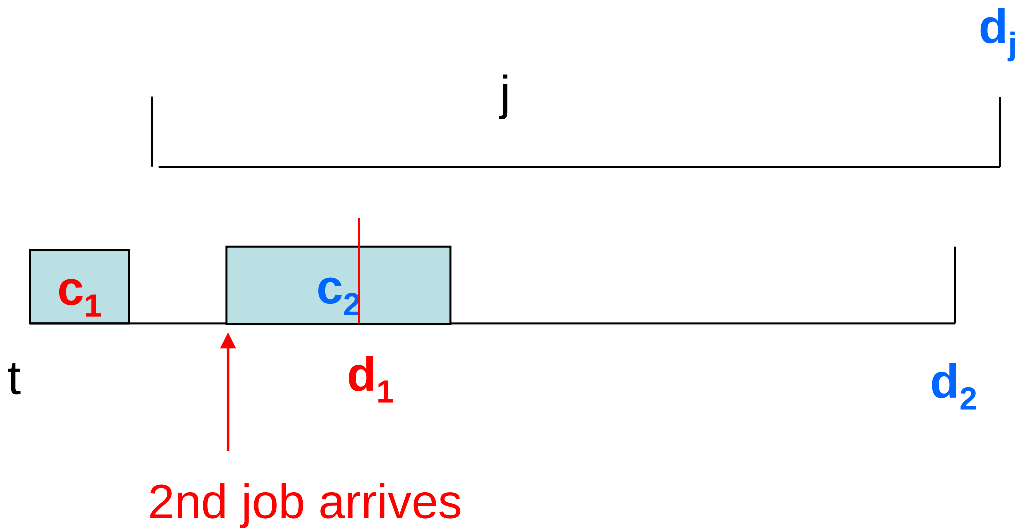


TBS:

Budget is replenished on the arrival of the 2nd job, and the job is assigned to a deadline $d_2 = d_1 + c_2/u_s$

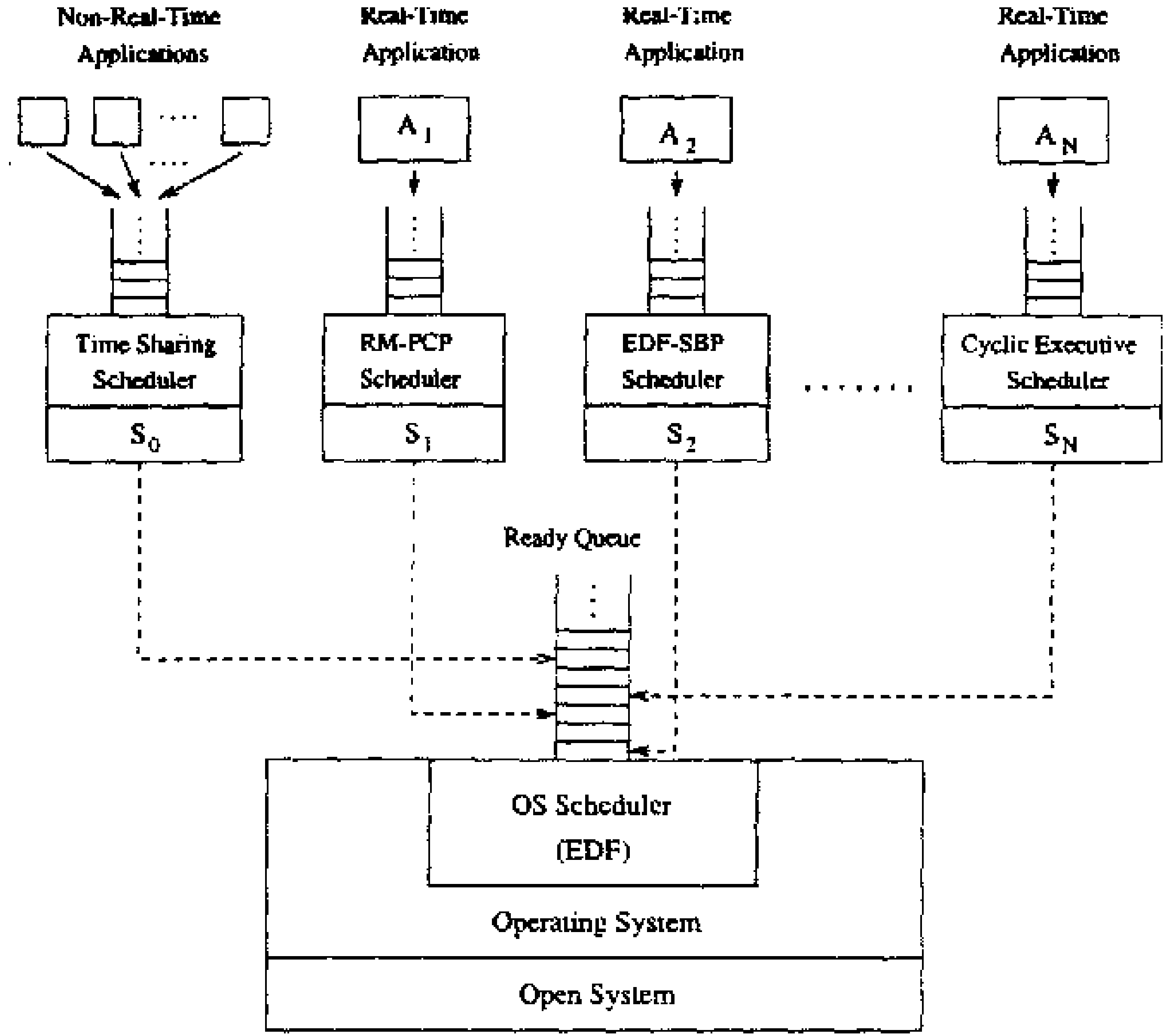
Total Bandwidth Servers

- Correctness of TBS:
  - Jobs affected by the early replenishment
    - Only those $d_j > d_2$
    - What about those $d_j<d_2$ or $d_j<d_1$?



Total Bandwidth Servers

- CUS/TBS are two good approaches for CPU bandwidth reservation
  - Service-level agreement, SLA
  - Quality of service, QoS
- Aperiodic jobs serviced by different servers would have an illusion that they are serviced by different CPUs with reduced power
  - This concept extends to open system, which can be applied to virtual machine scheduling



Deng, Z., J. Liu and J. Sun. "A scheme for scheduling hard real-time applications in open system environment." Proceedings Ninth Euromicro Workshop on Real Time Systems (1997): 191-199.

Part B: Checking Deadlines for Sporadic Jobs

Scheduling Sporadic Jobs

- So far we discussed many techniques to serve aperiodic jobs in periodic systems
- While serving aperiodic jobs, a servers has to check the deadlines of sporadic jobs
  - A server rejects an incoming sporadic job if it finds the sporadic deadline unsatisfiable

Scheduling Sporadic Jobs: Deadline-driven systems (EDF)

- CUS/TBS
  - Compare
    - (d1) the deadline of the sporadic job
    - (d2) the deadline assigned by server algorithm
  - If d2<=d1, then accept

Scheduling Sporadic Jobs: Priority-Driven Systems (RM)

- The concept of sporadic server:
  - "the server (c_s,p_s) receives at most c_s units of time every p_s units of time"

- The first sporadic job $S_1(r, c_{s,1}, d_{s,1})$ is accepted if

$$\rho_{s,1}(t) = \lfloor \frac{(d_{s,1} - r)}{p_s} \rfloor c_s - c_{s,1} \geq 0$$

Scheduling Sporadic Jobs: Priority-Driven Systems (RM)

- Acceptance test of job $S_i(r, c_{s,i}, d_{s,i})$

$$\rho_{s,i}(t) =$$

$$\lfloor \frac{(d_{s,i}-r)}{p_s} \rfloor c_s - c_{s,i} - \sum_{d_{s,k}<d_{s,i}} (c_{s,k} - \epsilon_{s,k}) \geq 0$$

  - $c_{s,k} - \epsilon_{s,k}$ stands for the remaining execution time of sporadic job S_k
  - If succeed, proceed to the next step

Scheduling Sporadic Jobs: Priority-Driven Systems (RM)

- Check if $\rho_{s,k} \geq 0$ for S_k, whose deadline is after $d_{s,i}$ and may be adversely affected by the acceptance of S_i

- If all tests succeed, S_i is accepted

Summary

- Serving aperiodic/sporadic jobs in periodic system
  - Priority-driven systems (DS, SS)
  - Deadline-driven systems (DS, TBS, CUS)
- Server designs are based on periodic task emulation
  - Can budget be retained as late as possible?
  - Can budget be replenished as early as possible?
- Aperiodic jobs are served in best-effort fashion
- Testing sporadic deadlines before admitting sporadic jobs