University of Glasgow | School of Computing Science

Priority-driven Scheduling of Aperiodic and Sporadic Tasks (1)

Advanced Operating Systems (M)
Lecture 6

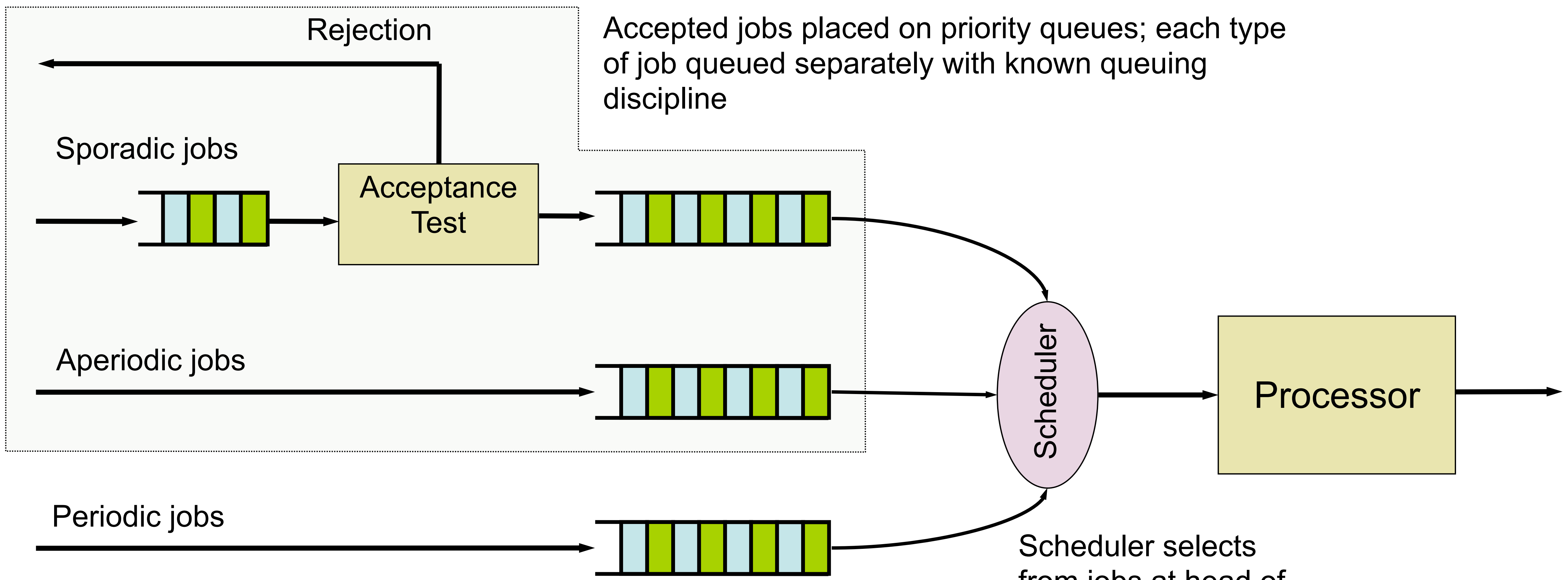
Lecture Outline

- Assumptions, definitions and system model
- Simple approaches
  - Background, interrupt-driven and polled execution
  - Periodic servers
- Bandwidth-preserving servers
  - Deferrable server
  - Sporadic server
  - …

Assumptions

- One processor system; independent preemptable periodic tasks scheduled using a priority-driven algorithm
  - Parameters of all periodic tasks are known
  - In the absence of aperiodic and sporadic jobs, periodic tasks meet deadlines
- Aperiodic and/or sporadic jobs exist
  - They are independent of each other, and of the periodic tasks
  - They can be preempted at any time

System Model



Accepted jobs placed on priority queues; each type of job queued separately with known queuing discipline

Scheduler selects from jobs at head of priority queues

The Scheduling Problem

- Based on the execution time and deadline of each newly arrived sporadic job, decide whether to accept or reject the job
  - Accepting the job implies that the job will complete within its deadline, without causing any periodic task or previously accepted sporadic job to miss its deadline
  - Do *not* accept a sporadic job if cannot guarantee it will meet its deadline

- Aim to complete each aperiodic job as soon as possible, without causing periodic tasks or accepted sporadic jobs to miss deadlines
  - Aperiodic jobs are always accepted

Definitions: Correctness

- A *correct schedule* is one where all periodic tasks, and any sporadic tasks *that have been accepted*, meet their deadlines
- A scheduling algorithm supporting aperiodic and/or sporadic jobs is a correct algorithm if it only produces correct schedules for the system

Definitions: Optimality

- An aperiodic job scheduling algorithm is *optimal* if it minimises either:
  - The response time of the job at the head of the aperiodic job queue
  - The average response time of all aperiodic jobs for a given queuing discipline

- A sporadic job scheduling algorithm is optimal if it accepts a new sporadic job, and schedules that job to complete by its deadline, if and only if the new job can be correctly scheduled to complete in time
  - An optimal algorithm always produces a feasible schedule if the job is accepted

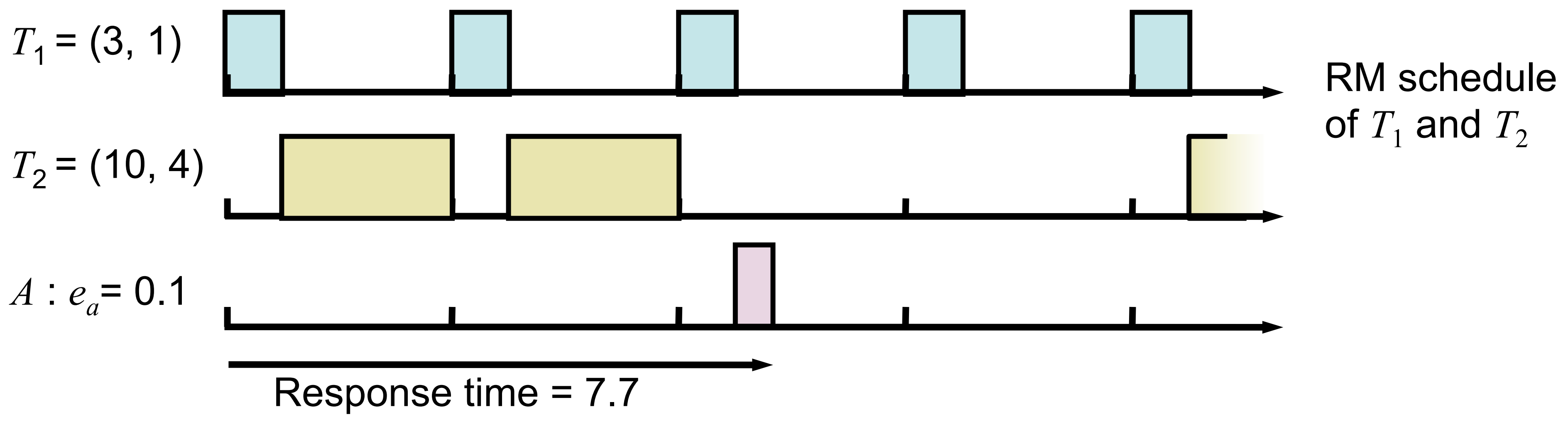
Scheduling Aperiodic Jobs

- Consider the simple case: scheduling aperiodic jobs along with a system of periodic jobs
  - Ignore sporadic jobs for now

- Two simple approaches:
  - Execute the aperiodic jobs in the background
  - Execute the aperiodic jobs by interrupting the periodic jobs

Background Scheduling of Aperiodic Jobs

- Aperiodic jobs are scheduled and executed only at times when there are no periodic or sporadic jobs ready for execution
  - Clearly produces *correct* schedules; extremely simple to implement
  - Not *optimal* since it is almost guaranteed to delay execution of aperiodic jobs in favour of periodic and sporadic jobs, giving unduly long response times for the aperiodic jobs



Interrupt Scheduling of Aperiodic Jobs

- How can we improve the response time for aperiodic jobs?
- Whenever an aperiodic job arrives, the execution of periodic tasks is interrupted, and the aperiodic job is executed.
    - Reduces response times of aperiodic jobs
    - But likely *not correct*, and will often cause periodic/sporadic tasks in the system to miss some deadlines

Slack Stealing for Aperiodic Jobs

- Background or interrupt driven execution not ideal
- A better alternative is *slack stealing*
    - Periodic jobs are be scheduled to complete before their deadline; there may be slack time between completion of the periodic job and its deadline
    - Since we know the execution time of periodic jobs, can move the slack time earlier in the schedule, running periodic jobs ‘just in time’ to meet their deadlines
    - Execute aperiodic jobs in the slack time, ahead of periodic jobs
- Reduces response time for aperiodic jobs and is correct, but complex and difficult to reason about
    - Computing available slack is difficult in practice for priority-driven systems

Polled Execution for Aperiodic Jobs

- Another common way to schedule aperiodic jobs is using a *polling server*
  - A periodic job (p_s, e_s) scheduled according to the periodic algorithm, generally as the highest priority job
  - When executed, it examines the aperiodic job queue
    - If an aperiodic job is in the queue, it is executed for up to e_s time units
    - If the aperiodic queue is empty, the polling server self-suspends, giving up its execution slot
    - The server does not wake-up once it has self-suspended, aperiodic jobs which become active during a period are not considered for execution until the next period begins
- Simple to prove correctness, performance less than ideal – since execute aperiodic jobs in particular time-slots – can we improve?
  - Yes, this is the simplest periodic-server for aperiodic jobs

Periodic Servers

- A task that behaves much like a periodic task, but is created for the purpose of executing aperiodic jobs, is a *periodic server*
  - A periodic server, $T_{PS} = (p_{PS}, e_{PS})$ never executes for more than e_{PS} units of time within each period p_{PS}
    - The parameter e_{PS} is execution budget of the periodic server
    - When a server is scheduled and executes aperiodic jobs, it consumes its budget at the rate of 1 per unit time; the budget has been exhausted when it reaches 0
    - A time instant when the budget is replenished is called a replenishment time
  - A periodic server is backlogged whenever the aperiodic job queue is nonempty; it is idle if the queue is empty
  - The periodic server is scheduled as any other periodic task based upon the priority scheme used by the scheduling algorithm
    - Except: the server is eligible for execution only when scheduled *and when it is backlogged and has non-zero budget*

Periodic Servers

- Different kinds of periodic server differ in how the budget is consumed when idle, and when the budget is replenished

- A polling server is a simple kind of periodic server
    - The budget is replenished to e_s at the beginning of each period
    - The budget is immediately consumed if there is no work when the server is scheduled

Bandwidth-Preserving Servers

- A deficiency of polling server: if server is scheduled when not backlogged, it loses its budget
  - An aperiodic job arriving just after the polling server has been scheduled and found the aperiodic job queue empty will have to wait until the next replenishment time
  - Want to preserve execution budget of the server when it finds an empty queue, to execute an aperiodic job that arrives later in the period, if doing so will not affect the correctness of the schedule
- Algorithms that improve the polling approach in this way are *bandwidth-preserving server* algorithms

Bandwidth-Preserving Servers

- Bandwidth-preserving servers are periodic servers with extra budget *consumption* and *replenishment* rules
- How do such servers work?
  - A backlogged bandwidth-preserving server is ready for execution when it has budget
  - The scheduler keeps track of the consumption of the budget and suspends the server when its is exhausted, or the server becomes idle
  - The scheduler moves the server back to the ready queue once it replenishes its budget, if the server is backlogged at that time
  - If arrival of an aperiodic job causes the server to become backlogged, and it has budget, the server is put back on the ready queue: this overcomes limitation of polling server

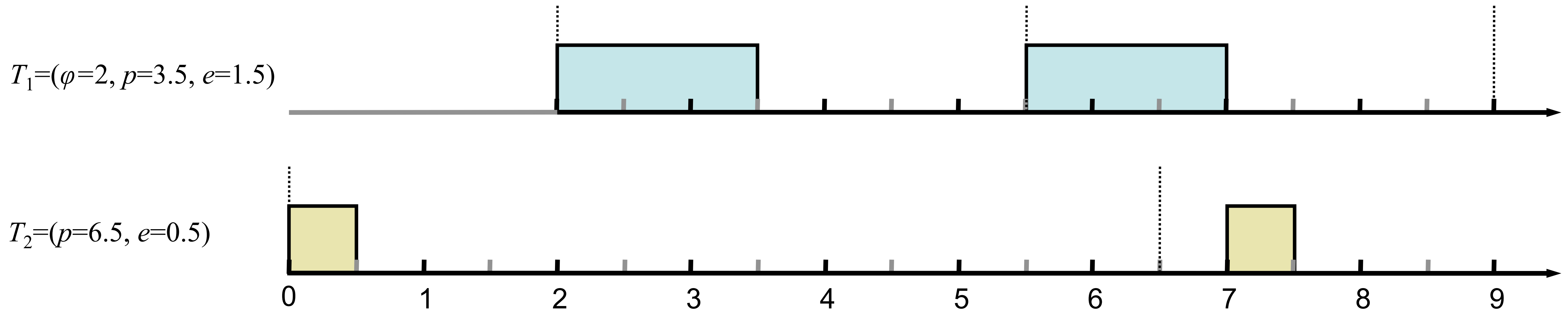
Bandwidth-Preserving Servers

- Many types of bandwidth-preserving server:
  - Deferrable servers
  - Sporadic servers
  - Constant utilisation servers
  - Total bandwidth servers
  - Weighted fair queuing servers
  - …

Deferrable Server

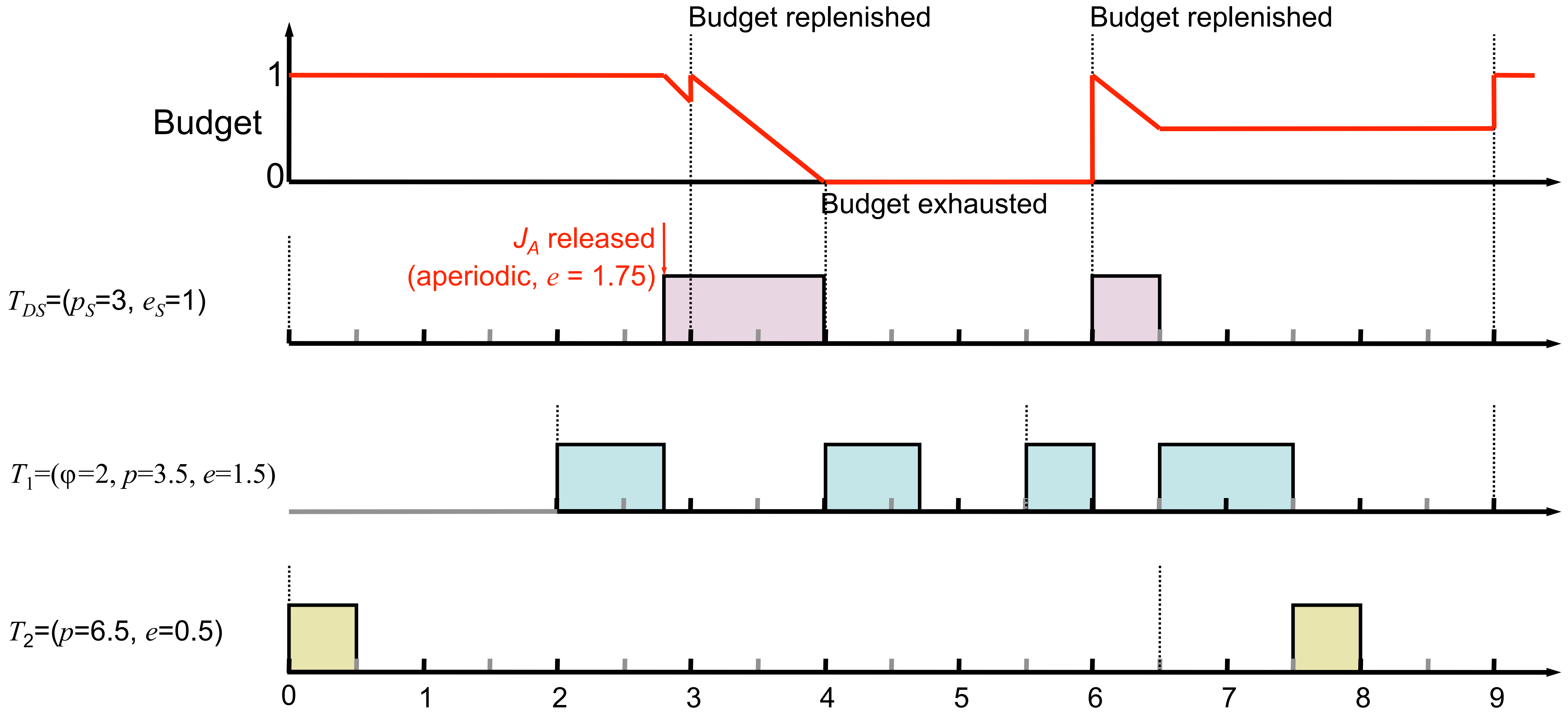
- The simplest bandwidth-preserving server
  - Improves response time of aperiodic jobs, compared to polling server
- Consumption rule:
  - The budget is consumed at the rate of one per unit time whenever the server executes
  - Unused budget is retained throughout the period, to be used whenever there are aperiodic jobs to execute
    - Instead of discarding the budget if no aperiodic job to execute at start of period, keep in the hope a job arrives
- Replenishment rule:
  - The budget is set to e_S at multiples of the period
    - i.e. time instants $k \cdot p_S$, for $k = 0, 1, 2, \ldots$
  - Note: the server is not allowed to carry over budget from period to period

Deferrable Server: Example



Periodic tasks T_1 and T_2 are scheduled according to the rate monotonic algorithm

Deferrable Server: Example



Add the deferrable server, scheduled according to the rate monotonic priority, but with the budget consumption and replenishment rules affecting its execution time

The deferrable server is usually run at highest priority, but this is not strictly required

Deferrable Server: Schedulability (1)

- Maximum schedulable utilisation test fails
  - Utilisation varies depending on arrival times of jobs executed by server
  - Use time demand analysis based on critical instants to determine if the system can be scheduled
- Finding the critical instants:
  - Assume a fixed-priority system T in which $D_i \leq p_i \; \forall \; i$ scheduled with a deferrable server (p_S, e_S) that has the highest priority among all tasks
  - A critical instant of every periodic tasks T_i occurs at a time t_0 when all of the following are true:
    - One of its jobs $J_{i,c}$ is released at t_0
    - A job in every higher-priority periodic task is released at t_0
    - The budget of the server is e_S at t_0, one or more aperiodic jobs are released at t_0, and they keep the server backlogged hereafter
    - The next replenishment time of the server is $t_0 + e_S$

Deferrable Server: Schedulability (1)

- The definition of critical instant is identical to that for the periodic tasks without the deferrable server + the worst-case requirements for the server

   - The time-demand function is:
   $$w_i(t) = \underbrace{e_i}_{\text{Execution time of job } J_i} + \underbrace{\sum_{k=1}^{i-1}\left\lceil \frac{t}{p_k}\right\rceil e_k}_{\text{Execution time of higher priority jobs started during this interval}} + \underbrace{e_s + \left\lceil \frac{t-e_s}{p_s}\right\rceil e_s}_{\text{Execution time of deferrable server}}$$

   - To determine whether the task T_i is schedulable, we simply have to check whether $w_i(t) \leq t$ for some $t \leq D_i$

   - Remember, this is a sufficient condition, not necessary – i.e., if this condition is not true, the system may not be schedulable

Deferrable Server: Schedulability (1)

- In general, no maximum schedulable utilization can determine schedulability for a fixed-priority system with a deferrable server
  - One special case: a system of n independent, preemptable periodic tasks, whose periods satisfy $p_s < p_1 < p_2 < \ldots < p_n < 2p_s$ and $p_n > p_s + e_s$, where the relative deadlines equal their respective periods, can be scheduled rate-monotonically with a deferrable server provided $U < U_{RM/DS}(n)$ where:

$$U_{RM/DS}(n) = (n-1)\left\lfloor \left(\frac{u_s+2}{u_s+1}\right)^{\frac{1}{(n-1)}} - 1 \right\rfloor$$

Deferrable Server: Schedulability (2)

- It is easier to reason about the schedulability of a deadline-driven system with a deferrable server
  - The deadline of a deferrable server is its next replenishment time
  - A periodic task T_i in a system of N independent, preemptable, periodic tasks is schedulable with a deferrable server with period p_S, execution budget e_S and utilization u_S, according to the EDF algorithm if:

$$\sum_{k=1}^{N} \frac{e_k}{\min(D_k, p_k)} + u_s \left(1 + \frac{p_s - e_s}{D_i}\right) \leq 1$$

  - Must be calculated for each task in the system, since D_i included

  - Example: tasks T_1=(3, 0.6), T_2=(5.0, 0.5), T_3=(7, 1.4) scheduled with a deferrable server p_s=4, e_s=0.8
  - The left-hand side of the above inequality is 0.913, 0.828 and 0.792 respectively; hence the three tasks are schedulable

Summary

- Assumptions, definitions and system model
- Simple approaches
    - Background, interrupt-driven and polled execution
    - Periodic servers
- Bandwidth-preserving servers
    - Deferrable server
    - …

- Should have an initial understanding of how to schedule aperiodic jobs in a more optimal manner