Priority-driven Scheduling of Periodic Tasks (1)

Real-Time and Embedded Systems (M)

Lecture 5

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Lecture Outline

- Assumptions
- Fixed-priority algorithms
  - Rate monotonic
  - Deadline monotonic
- Dynamic-priority algorithms
  - Earliest deadline first
  - Least slack time
- Relative merits of fixed- and dynamic-priority scheduling
- Schedulable utilization and proof of schedulability

Material in lectures 5 & 6 corresponds to chapter 6 of Liu's book

Assumptions

- Priority-driven scheduling of periodic tasks on a single processor
- Assume a restricted periodic task model:
  - A fixed number of independent periodic tasks exist
    - Jobs comprising those tasks:
      - Are ready for execution as soon as they are released
      - Can be pre-empted at any time
      - Never suspend themselves
    - New tasks only admitted after an acceptance test; may be rejected
    - The period of a task defined as minimum inter-release time of jobs in task
  - There are no aperiodic or sporadic tasks
  - Scheduling decisions made immediately upon job release and completion
    - Algorithms are event driven, not clock driven
    - Never intentionally leave a resource idle
  - Context switch overhead negligibly small; unlimited priority levels

Dynamic versus Static Systems

- Recall from lecture 3:
  - If jobs are scheduled on multiple processors, and a job can be dispatched to any of the processors, the system is *dynamic*
  - If jobs are partitioned into subsystems, each subsystem bound statically to a processor, we have a *static* system
  - Difficult to determine the best- and worst-case performance of dynamic systems, so most hard real-time systems built are static
- In static systems, the scheduler for each processor schedules the jobs in its subsystem independent of the schedulers for the other processors

⇒ Results demonstrated for priority-driven uniprocessor systems are applicable to each subsystem of a static multiprocessor system

  - They are *not* applicable to dynamic multiprocessor systems

Fixed- and Dynamic-Priority Algorithms

- A priority-driven scheduler is an on-line scheduler
  - It does *not* pre-compute a schedule of tasks/jobs: instead assigns priorities to jobs when released, places them on a run queue in priority order
  - When pre-emption is allowed, a scheduling decision is made whenever a job is released or completed
  - At each scheduling decision time, the scheduler updates the run queues and executes the job at the head of the queue

- Jobs in a task may be assigned the same priority (*task level fixed-priority*) or different priorities (*task level dynamic-priority*)
- The priority of each job is usually fixed (*job level fixed-priority*); but some systems can vary the priority of a job after it has started (*job level dynamic-priority*)
  - Job level dynamic-priority usually very inefficient

Rate Monotonic Scheduling

- Best known fixed-priority algorithm is *rate monotonic* scheduling
- Assigns priorities to tasks based on their periods
  - The shorter the period, the higher the priority
  - The *rate* (of job releases) is the inverse of the period, so jobs with higher rate have higher priority
- Very widely studied and used

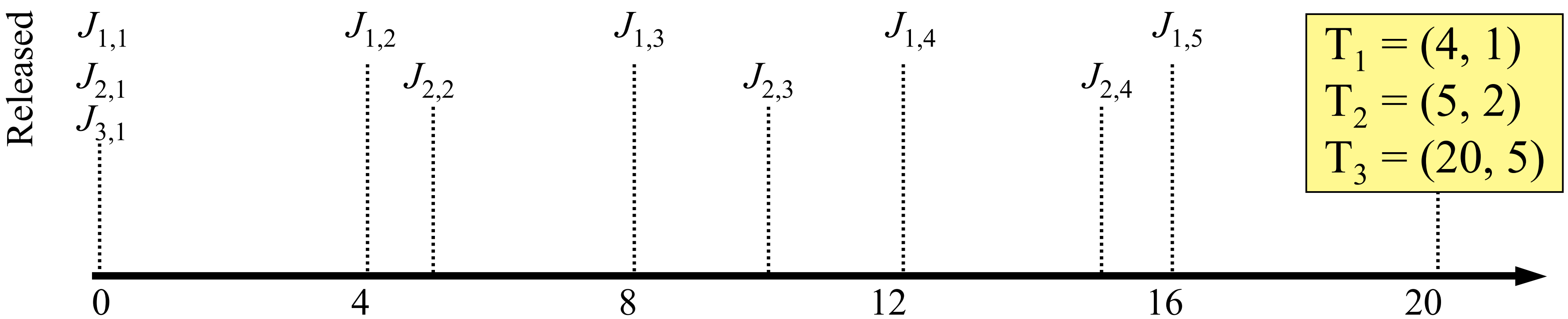
- For example, consider a system of 3 tasks:
  - $T_1 = (4, 1)$ $\Rightarrow$ rate $= {}^1/_4$
  - $T_2 = (5, 2)$ $\Rightarrow$ rate $= {}^1/_5$
  - $T_3 = (20, 5)$ $\Rightarrow$ rate $= {}^1/_{20}$

  - Relative priorities: $T_1 > T_2 > T_3$

Example: Rate Monotonic Scheduling

Time	Ready to run	Running
0		
1		
2		
3		
4		
5		
6		
7		
8		
9		

Time	Ready to run	Running
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		



Deadline Monotonic Scheduling

- The *deadline monotonic* algorithm assigns task priority according to relative deadlines – the shorter the relative deadline, the higher the priority
- When relative deadline of every task matches its period, then rate monotonic and deadline monotonic give identical results
- When the relative deadlines are arbitrary:
  - Deadline monotonic can sometimes produce a feasible schedule in cases where rate monotonic cannot
  - But, rate monotonic always fails when deadline monotonic fails

- Deadline monotonic preferred to rate monotonic
  - If deadline ≠ period

Dynamic-Priority Algorithms

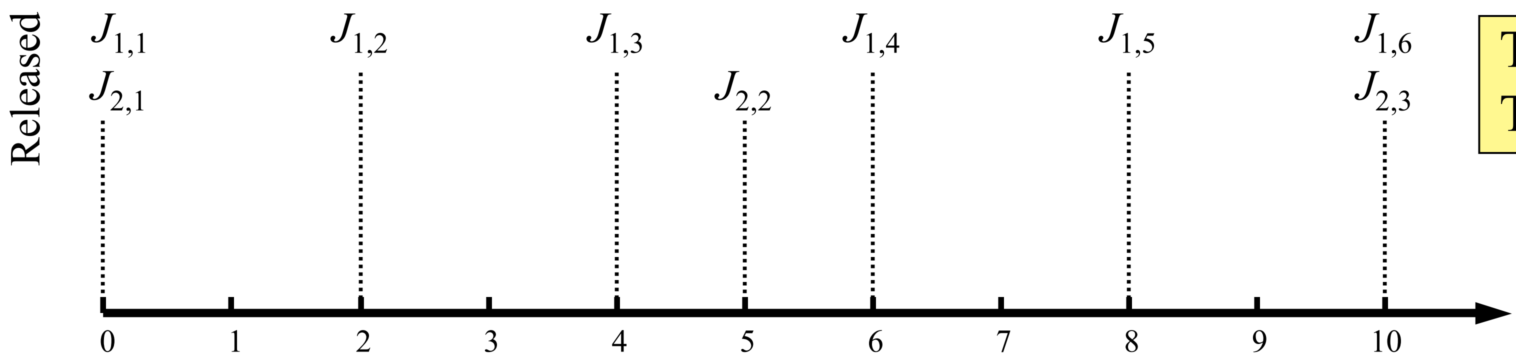
- Discussed several dynamic-priority algorithms in lecture 3:
  - Earliest deadline first (EDF)
    - The job queue is ordered by earliest deadline
  - Least slack time first (LST)
    - The job queue is ordered by least slack time
    - Two variations:
      - Strict LST – scheduling decisions are made also whenever a queued job's slack time becomes smaller than the executing job's slack time – *huge* overheads, not used
      - Non-strict LST – scheduling decisions made only when jobs release or complete
  - First in, first out (FIFO)
    - Job queue is first-in-first-out by release time
  - Last in, first out (LIFO)
    - Job queue is last-in-first-out by release time

- Focus on EDF as commonly used example

Example: Earliest Deadline First

Time	Ready to run	Running

Time	Ready to run	Running



$T_1 = (2, 1)$
$T_2 = (5, 2.5)$

Relative Merits

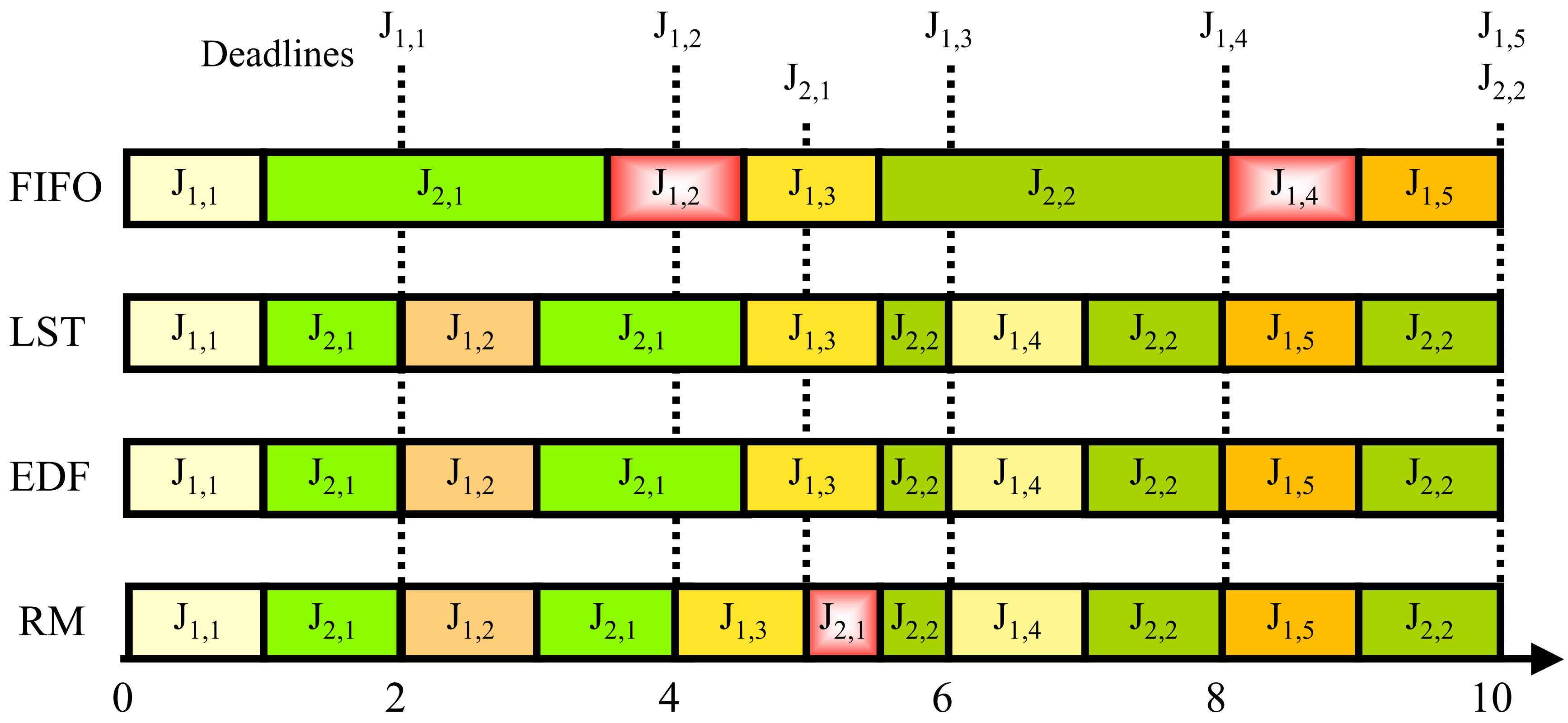
- Fixed- and dynamic-priority scheduling algorithms have different properties; neither appropriate for all scenarios

- Algorithms that do not take into account the urgencies of jobs in priority assignment usually perform poorly
  - E.g FIFO, LIFO
- The EDF algorithm gives higher priority to jobs that have missed their deadlines than to jobs whose deadline is still in the future
  - Not necessarily suited to systems where occasional overload unavoidable
- Dynamic algorithms like EDF can produce feasible schedules in cases where RM and DM cannot
  - But fixed priority algorithms often more predictable, lower overhead

Example: Comparing Different Algorithms

- Compare performance of RM, EDF, LST and FIFO scheduling
- Assume a single processor system with 2 tasks:
  - $T_1 = (2, 1)$
  - $T_2 = (5, 2.5)$ $H = 10$
- The total utilization is 1.0 $\Rightarrow$ no slack time
  - Expect some of these algorithms to lead to missed deadlines!
  - This is one of the cases where EDF works better than RM/DM

Example: RM, EDF, LST and FIFO



- Demonstrate by exhaustive simulation that LST and EDF meet deadlines, but FIFO and RM don't

Schedulability Tests

- Simulating schedules is both tedious and error-prone… can we demonstrate correctness without working through the schedule?

- Yes, in some cases. This is a *schedulability test*
  - A test to demonstrate that all deadlines are met, when scheduled using a particular algorithm
  - An efficient schedulability test can be used as an on-line acceptance test; clearly exhaustive simulation is too expensive

Schedulable Utilization

- Recall: a periodic task T_i is defined by the 4-tuple (ϕ_i, p_i, e_i, D_i) with utilization $u_i = e_i / p_i$
- Total utilization of the system $U = \sum_{i=1}^{n} u_i$ where $0 \leq U \leq 1$

- A scheduling algorithm can feasibly schedule any system of periodic tasks on a processor if U is equal to or less than the maximum schedulable utilization of the algorithm, U_{ALG}
  - If $U_{ALG} = 1$, the algorithm is optimal

- Why is knowing of U_{ALG} important? It gives a schedulability test, where a system can be validated by showing that $U \leq U_{ALG}$

Schedulable Utilization: EDF

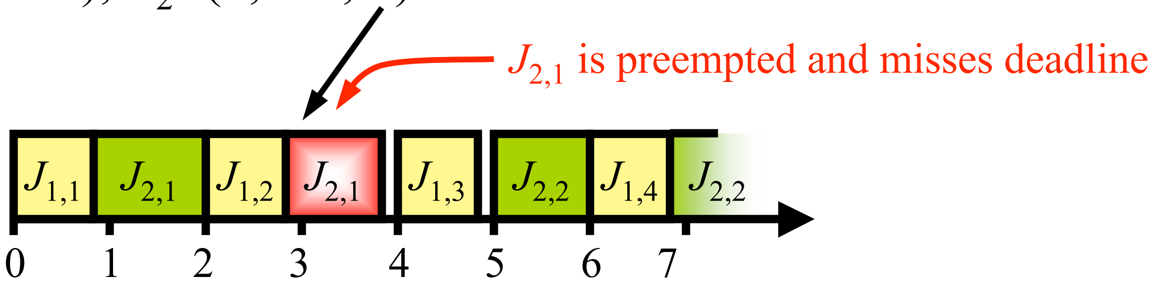
- Theorem: a system of independent preemptable periodic tasks with $D_i = p_i$ can be feasibly scheduled on one processor using EDF if and only if $U \leq 1$
  - $U_{EDF} = 1$ for independent, preemptable periodic tasks with $D_i = p_i$

    [Expected since EDF proved optimal in lecture 3 – see the book for proof]
  - Corollary: result also holds if deadline longer than period: $U_{EDF} = 1$ for independent preemptable periodic tasks with $D_i \geq p_i$

- Notes:
  - Result is independent of ϕ_i
  - Result can also be shown to apply to strict LST

Schedulable Utilization: EDF

- What happens if $D_i < p_i$ for some i? The test doesn't work…
  - E.g. $T_1 = (2, 0.8)$, $T_2=(5, 2.3, 3)$



- However, there is an alternative test:
  - The density of the task, T_i, is $\delta_i = e_i / \min(D_i, p_i)$
  - The density of the system is $\Delta = \delta_1 + \delta_2 + \ldots + \delta_n$
  - Theorem: A system T of independent, preemptable periodic tasks can be feasibly scheduled on one processor using EDT if $\Delta \leq 1$.
- Note:
  - This is a sufficient condition, but not a necessary condition – i.e. a system is guaranteed to be feasible if $\Delta \leq 1$, but might still be feasible if $\Delta > 1$ (would have to run the exhaustive simulation to prove)

Schedulable Utilization: EDF

- How can you use this in practice?
  - Assume using EDF to schedule multiple periodic tasks, known execution time for all jobs

  ⇒ Choose the periods for the tasks such that the schedulability test is met

- Example: a simple digital controller:
  - Control-law computation task, T_1, takes $e_1 = 8$ ms, sampling rate is 100 Hz (i.e. $p_1 = 10$ ms)

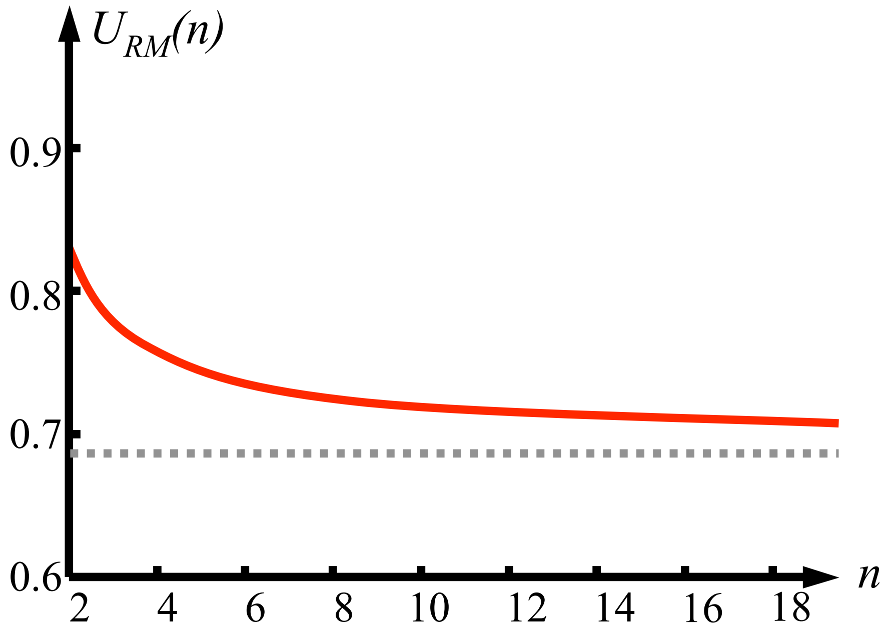
    ⇒ u_1 is 0.8

    ⇒ the system is guaranteed to be schedulable
  - Want to add a built-in self test task, T_2, taking 50ms - will the system still work?

Schedulable Utilization of RM

- Theorem: a system of n independent preemptable periodic tasks with $D_i = p_i$ can be feasibly scheduled on one processor using RM if and only if $U \leq n \cdot (2^{1/n} - 1)$

  - $U_{RM}(n) = n \cdot (2^{1/n} - 1)$
  - For large $n \rightarrow \ln 2$ (i.e. $n \rightarrow 0.69314718056\ldots$)
  - [Proof in book - complicated!]



  - $U \leq U_{RM}(n)$ is a sufficient, but not necessary, condition – i.e. a feasible rate monotonic schedule is *guaranteed* to exist if $U \leq U_{RM}(n)$, but *might* still be possible if $U > U_{RM}(n)$

Schedulable Utilization of RM

- What happens if the relative deadlines for tasks are not equal to their respective periods?
- Assume the deadline is some multiple υ of the period: $D_k = \upsilon \cdot p_k$
- It can be shown that:

$$U_{RM}(n,\upsilon) = \begin{cases} \upsilon & 0 \le \upsilon \le 0.5 \\ n((2\upsilon)^{1/n} - 1) + 1 - \upsilon & \text{for } 0.5 \le \upsilon \le 1 \\ \upsilon(n-1)\left[\left(\dfrac{\upsilon+1}{\upsilon}\right)^{1/n - 1} - 1\right] & \upsilon = 2, 3, \ldots \end{cases}$$

Schedulable Utilization of RM

n	$\upsilon = 4.0$	$\upsilon = 3.0$	$\upsilon = 2.0$	$\upsilon = 1.0$	$\upsilon = 0.9$	$\upsilon = 0.8$	$\upsilon = 0.7$	$\upsilon = 0.6$	$\upsilon = 0.5$
2	0.944	0.928	0.898	0.828	0.783	0.729	0.666	0.590	0.500
3	0.926	0.906	0.868	0.779	0.749	0.708	0.656	0.588	0.500
4	0.917	0.894	0.853	0.756	0.733	0.698	0.651	0.586	0.500
5	0.912	0.888	0.844	0.743	0.723	0.692	0.648	0.585	0.500
6	0.909	0.884	0.838	0.734	0.717	0.688	0.646	0.585	0.500
7	0.906	0.881	0.834	0.728	0.713	0.686	0.644	0.584	0.500
8	0.905	0.878	0.831	0.724	0.709	0.684	0.643	0.584	0.500
9	0.903	0.876	0.829	0.720	0.707	0.682	0.642	0.584	0.500
∞	0.892	0.863	0.810	0.693	0.687	0.670	0.636	0.582	0.500

$D_i > p_i \Rightarrow$ Schedulable utilization increases

$D_i < p_i \Rightarrow$ Schedulable utilization decreases

$D_i = p_i$

Summary

Key points:

- Different priority scheduling algorithms
  - Earliest deadline first, least slack time, rate monotonic, deadline monotonic
  - Each has different properties, suited for different scenarios
- Scheduling tests, concept of maximum schedulable utilization
  - Examples for different algorithms

Next lecture: practical factors, more schedulability tests…