Overview of Real-Time Scheduling

Real-Time and Embedded Systems (M)

Lecture 3

UNIVERSITY
of
GLASGOW

Lecture Outline

- Overview of real-time scheduling algorithms
  - Clock-driven
  - Weighted round-robin
  - Priority-driven
    - Dynamic *vs*. static
    - Deadline scheduling: EDF and LST
    - Validation
- Outline relative strengths, weaknesses

Material corresponds to chapter 4 of Liu's book

Copyright © 2006 University of Glasgow
All rights reserved.

Approaches to Real-Time Scheduling

Different classes of scheduling algorithm used in real-time systems:

- Clock-driven
  - Primarily used for hard real-time systems where all properties of all jobs are known at design time, such that offline scheduling techniques can be used
- Weighted round-robin
  - Primarily used for scheduling real-time traffic in high-speed, switched networks
- Priority-driven
  - Primarily used for more dynamic real-time systems with a mix of time-based and event-based activities, where the system must adapt to changing conditions and events

Look at the properties of each in turn…

Copyright © 2006 University of Glasgow
All rights reserved.

Clock-Driven Scheduling

- Decisions about what jobs execute when are made at specific time instants
  - These instants are chosen before the system begins execution
  - Usually regularly spaced, implemented using a periodic timer interrupt
    - Scheduler awakes after each interrupt, schedules the job to execute for the next period, then blocks itself until the next interrupt
    - E.g. the helicopter example with an interrupt every $^{1}/_{180}{}^{th}$ of a second
    - E.g. the furnace control example, with an interrupt every 100ms

- Typically in clock-driven systems:
  - All parameters of the real-time jobs are fixed and known
  - A schedule of the jobs is computed off-line and is stored for use at run-time; as a result, scheduling overhead at run-time can be minimized
  - Simple and straight-forward, not flexible

[Will discuss in more detail in lecture 4]

Copyright © 2006 University of Glasgow
All rights reserved.

Weighted Round-Robin Scheduling

- Regular *round-robin* scheduling is commonly used for scheduling time-shared applications
  - Every job joins a FIFO queue when it is ready for execution
  - When the scheduler runs, it schedules the job at the head of the queue to execute for at most one time slice
    - Sometimes called a quantum – typically O(*tens of ms*)
  - If the job has not completed by the end of its quantum, it is preempted and placed at the end of the queue
  - When there are *n* ready jobs in the queue, each job gets one slice every *n* time slices (*n* time slices is called a round)

  - Only limited use in real-time systems

Copyright © 2006 University of Glasgow
All rights reserved.

Weighted Round-Robin Scheduling

- In *weighted round robin* each job J_i is assigned a weight w_i; the job will receive w_i consecutive time slices each round, and the duration of a round is $\sum_{i=1}^{n} w_i$
  - Equivalent to regular round robin if all weights equal 1
  - Simple to implement, since it doesn't require a sorted priority queue

- Partitions capacity between jobs according to some ratio
- Offers throughput guarantees
  - Each job makes a certain amount of progress each round

Copyright © 2006 University of Glasgow
All rights reserved.

Weighted Round-Robin Scheduling

- By giving each job a fixed fraction of the processor time, a round-robin scheduler may delay the completion of every job
  - A precedence constrained job may be assigned processor time, even while it waits for its predecessor to complete; a job can't take the time assigned to its successor to finish earlier
  - Not an issue for jobs that can incrementally consume output from their predecessor, since they execute concurrently in a pipelined fashion
    - E.g. Jobs communicating using Unix pipes
    - E.g. Wormhole switching networks, where message transmission is carried out in a pipeline fashion and a downstream switch can begin to transmit an earlier portion of a message, without having to wait for the arrival of the later portion

- Weighted round-robin is primarily used for real-time networking; will discuss more in lecture 17

Copyright © 2006 University of Glasgow
All rights reserved

Priority-Driven Scheduling

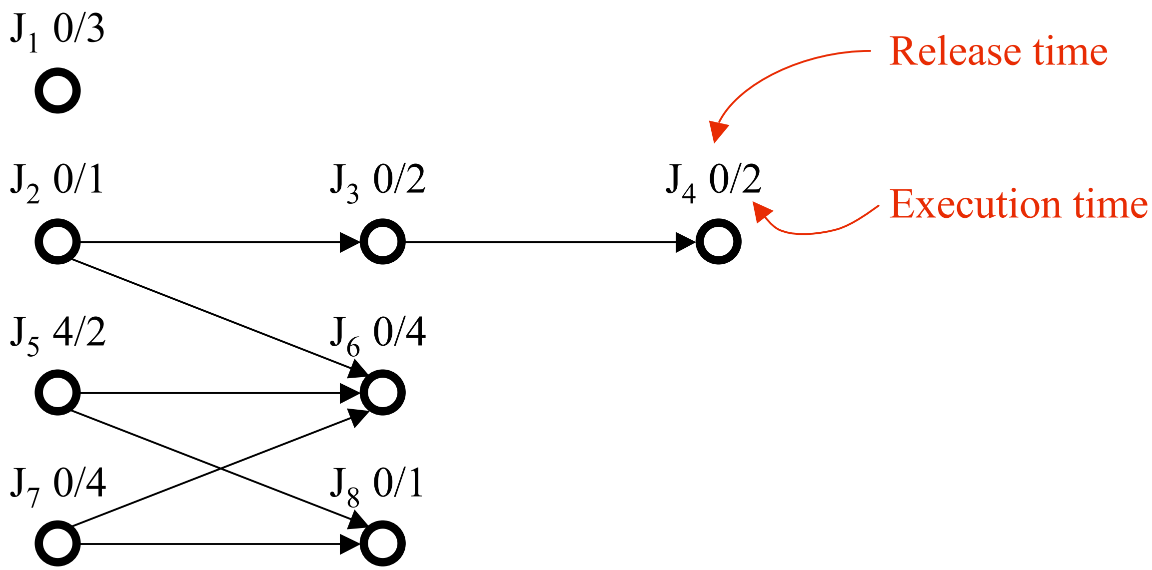
- Assign priorities to jobs, based on some algorithm
- Make scheduling decisions based on the priorities, when events such as releases and job completions occur
  - Priority scheduling algorithms are *event-driven*
  - Jobs are placed in one or more queues; at each event, the ready job with the highest priority is executed
  - The assignment of jobs to priority queues, along with rules such a whether preemption is allowed, completely defines a priority scheduling algorithm

- Priority-driven algorithms make *locally optimal* decisions about which job to run
  - Locally optimal scheduling decisions are often *not* globally optimal
  - Priority-driven algorithms *never* intentionally leave any resource idle
    - Leaving a resource idle is not locally optimal

Copyright © 2006 University of Glasgow
All rights reserved.

Example: Priority-Driven Scheduling

- Consider the following task:
  - Jobs J_1, J_2, …, J_8, where J_i had higher priority than J_k if $i < k$

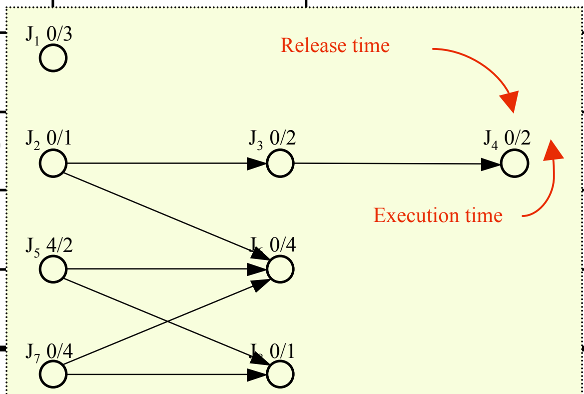


  - Jobs are scheduled on two processors P_1 and P_2
  - Jobs communicate via shared memory, so communication cost is negligible
  - The schedulers keep one common priority queue of ready jobs
  - All jobs are preemptable; scheduling decisions are made whenever some job becomes ready for execution or a job completes

Copyright © 2006 University of Glasgow
All rights reserved.

Example: Priority-Driven Scheduling

Time	Not yet released	Released but not yet ready to run	Ready to run	P_1	P_2	Completed
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						



Copyright © 2006 University of Glasgow
All rights reserved.

Example: Priority-Driven Scheduling

- Note: The ability to preempt lower priority jobs slowed down the overall completion of the task
  - This is not a general rule, but shows that priority scheduling results can be non-intuitive
  - Different priority scheduling algorithms can have very different properties

- Tracing execution of jobs using tables is an effective way to demonstrate correctness for systems with periodic tasks and fixed timing constraints, execution times, resource usage
  - Show that the system enters a repeating pattern of execution, and each hyper-period of that pattern meets all deadlines
  - Proof by exhaustive simulation
    - Provided the system has a manageably small number of jobs

Copyright © 2006 University of Glasgow
All rights reserved

Priority-Driven Scheduling

- Most scheduling algorithms used in *non* real-time systems are priority-driven
  - First-In-First-Out
  - Last-In-First-Out

    } Assign priority based on release time
  - Shortest-Execution-Time-First
  - Longest-Execution-Time-First

    } Assign priority based on execution time

- Real-time priority scheduling assigns priorities based on deadline or some other *timing constraint*:
  - Earliest deadline first
  - Least slack time first
  - Etc.

Copyright © 2006 University of Glasgow
All rights reserved.

Priority Scheduling Based on Deadlines

- Earliest deadline first (EDF)
  - Assign priority to jobs based on deadline
  - Earlier the deadline, higher the priority
  - Simple, just requires knowledge of deadlines

- Least Slack Time first (LST)
  - A job J_i has deadline d_i, execution time e_i, and was released at time r_i
  - At time $t < d_i$:
    - Remaining execution time $t_{\text{rem}} = e_i - (t - r_i)$
    - Slack time $t_{\text{slack}} = d_i - t - t_{\text{rem}}$
  - Assign priority to jobs based on slack time, t_{slack}
  - The smaller the slack time, the higher the priority
  - More complex, requires knowledge of execution times and deadlines
    - Knowing the actual execution time is often difficult a priori, since it depends on the data, need to use worst case estimates ($\Rightarrow$ poor performance)

Copyright © 2006 University of Glasgow
All rights reserved.

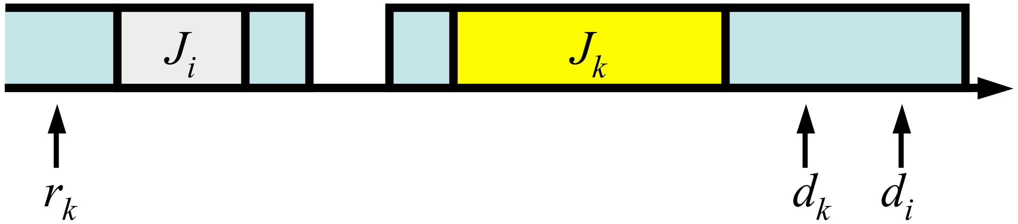
Optimality of EDF and LST

- These algorithms are optimal
  - i.e. they will always produce a feasible schedule if one exists
  - Constraints: on a single processor, as long as preemption is allowed and jobs do not contend for resources

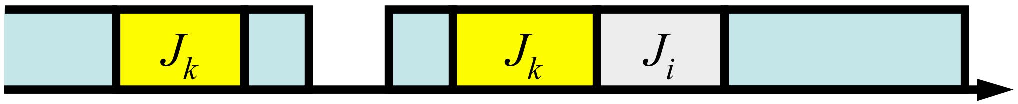
Copyright © 2006 University of Glasgow
All rights reserved.

Optimality of EDF and LST: Proof

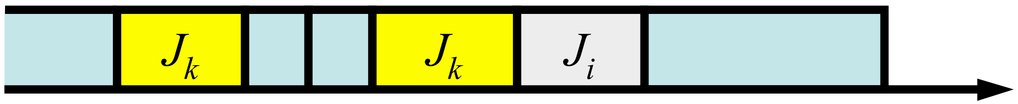
1. Any feasible schedule can be transformed into an EDF schedule
   - If J_i is scheduled to execute before J_k, but J_i's deadline is later than J_k's either:
     - The release time of J_k is after the J_i completes ⇒ they're already in EDF order
     - The release time of J_k is before the end of the interval in which J_i executes:



   - Swap J_i and J_k (this is always possible, since J_i's deadline is later than J_k's)



   - Move any jobs following idle periods forward into the idle period



⇒ the result is an EDF schedule

2. So, if EDF fails to produce a feasible schedule, no feasible schedule exists
   - If a feasible schedule existed it could be transformed into an EDF schedule, contradicting the statement that EDF failed to produce a feasible schedule

[Proof for LST is similar]

Copyright © 2006 University of Glasgow
All rights reserved

Non-Optimality of EDF and LST

- Neither algorithm is optimal if jobs are non-preemptable or if there is more than one processor
  - The book has examples which demonstrate EDF and LST producing infeasible schedules in these cases
    - This includes *non-strict* LST scheduling
  - Proof-by-counterexample

- EDF and LST are simple priority-driven scheduling algorithms; introduced to show how we can reason about such algorithms
  - Lectures 5-8 discuss other priority-driven scheduling algorithms

Copyright © 2006 University of Glasgow
All rights reserved.

Dynamic vs. Static Systems

- If jobs are scheduled on multiple processors, and a job can be dispatched from the priority run queue to any of the processors, the system is *dynamic*
- A job *migrates* if it starts execution on one processor and is resumed on a different processor
- If jobs are partitioned into subsystems, and each subsystem is bound statically to a processor, we have a *static* system
- Expect static systems to have inferior performance (in terms of overall response time of the jobs) relative to dynamic systems
  - But it is possible to validate static systems, whereas this is not always true for dynamic systems
  - For this reason, most *hard* real time systems are static

Copyright © 2006 University of Glasgow
All rights reserved.

Effective Release Times and Deadlines

- Sometimes the release time of a job may be later than that of its successors, or its deadline may be earlier than that specified for its predecessors
- This makes no sense: derive an *effective release time* or *effective deadline* consistent with all precedence constraints, and schedule using that
  - Effective release time
    - If a job has no predecessors, its effective release time is its release time
    - If it has predecessors, its effective release time is the maximum of its release time and the effective release times of its predecessors
  - Effective deadline
    - If a job has no successors, its effective deadline is its deadline
    - It if has successors, its effective deadline is the minimum of its deadline and the effective deadline of its successors

Copyright © 2006 University of Glasgow
All rights reserved.

Effective Release Times and Deadlines

- Note: definition of effective deadline does *not* take into account execution time of successor jobs
  - Would be more accurate, and needs to be done on multiprocessor systems
  - But: unnecessary on single processor with preemptable jobs

  - Feasible to schedule any set of jobs according to their actual release times and deadline, iff feasible to schedule according to effective release times and deadlines
    - Ignore precedence constraints, schedule using effective release times and deadlines as if all jobs independent
    - Resulting schedule might meet deadlines but not precedence constraints
      - If so, always possible to swap order of jobs within the schedule to meet deadlines and precedence constraints

Copyright © 2006 University of Glasgow
All rights reserved.

Validating Priority-Driven Scheduling

- Priority-driven scheduling has many advantages over clock-driven scheduling
  - Better suited to applications with varying time and resource requirements, since needs less a priori information
  - Run-time overheads are small
- But not widely used until recently, since difficult to validate
  - Scheduling anomalies can occur for multiprocessor or non-preemptable systems, or those which share resources
    - Reducing the execution time of a job in a task can increase the total response time of the task (see book for example)
    - Not sufficient to show correctness with worse-case execution times, need to simulate with all possible execution times for all jobs comprising a task
  - Can be proved that anomalies do not occur for independent, preemptable, jobs with fixed release times executed using any priority-driven scheduler on a single processor
    - Various stronger results exist for particular priority-driven algorithms

Copyright © 2006 University of Glasgow
All rights reserved.

Summary

- Have outlined different approaches to scheduling:
  - Clock-driven
  - Weighted round-robin
  - Priority-driven

  and some of their constraints

- Next session will be a tutorial to review the material covered to date, before we move onto detailed discussion of scheduling

- Problem set 1 now available: due at 2:00pm on 21st January

Copyright © 2006 University of Glasgow
All rights reserved.