Real-Time Computing

Definition of Real-Time Computing

- Real-time computing is computing in which the time of the computation plays an essential role in the result.
- This includes:
  - Computations that measure time
  - Computations that must meet deadlines
  - Computations that synchronize other computations based on time

Example of Real-Time

(from Briand and Roy, *Meeting deadlines in hard real-time systems*, IEEE Press, 1999)

- July 20, 1969, landing module 10k feet above the Moon:
  - Houston: “Eagle, you’re go for a landing.”
  - Houston: “One minute [of fuel left].
    ...
  - Lander: 100 feet, 3 1/2 down, 9 forward.”
  - Houston: “30 Seconds.”
  - Lander: “OK, engine stop.”

Example of Real-Time

(from Briand and Roy, *Meeting deadlines in hard real-time systems*, IEEE Press, 1999)

- “During the descent of the Eagle [landing module], an incorrect switch position caused the analog-to-digital conversion circuit of the rendezvous to send some bursts of high-priority requests to the computer. After 15 percent of the computer resources were tied up in responding to the spurious requests, jobs began to miss their deadlines. A hardware recovery mechanism detected the timing fault and restarted the computer.”

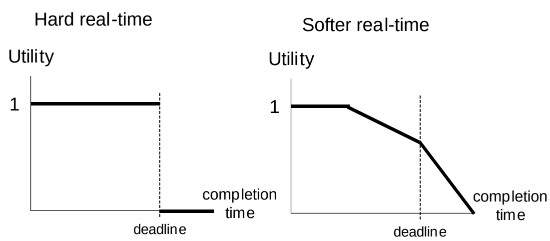
Distinctions

- Hard real-time: Deadlines must be met in order for the system to be correct.
- Soft real-time: It is desirable for deadlines to be met, but if not, the system can still be correct.
- “Real-time” does not necessarily mean “fast”.

Hard Real-Time Examples

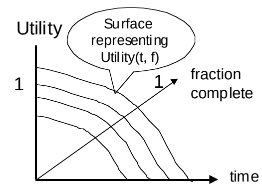
- Vehicular fuel or rendezvous problems
  - Lunar lander
  - Train scheduling
  - Baggage handlers
  - Assembly lines
- Production deadlines
  - Newspaper
  - Live TV show
  - Graduation

Hardness Expressed as a Utility Function



Progressive Utility

- A generalization of the preceding concept regards Utility as a function of both time *and* fraction of the task completed.



Real-Time includes Communication

- Obviously communication, as well as computation, must be taken into account if the system consists of multiple components

Common Aspects of Real-Time Systems

- Deadlines
- Scheduled task start times
- Timeouts
- Periodic & Aperiodic tasks
- Priorities among tasks

Real-Time Operating Systems

- Solaris, when generated with real-time features
- VxWorks (Wind River Systems, Inc.)

Scheduling Algorithms

- Choices of performance metric to meet requirement:
  - Total completion time among all tasks
  - Average response time over all tasks
  - Weighted sum of completion times
  - Maximum lateness
  - Number of late tasks

Scheduling to Meet Deadlines

- Assume a set of tasks $\{T_i\}$
- Associate with each task T_i:
  - computation time C_i
  - deadline D_i
- Suppose we want to minimize maximum lateness

Scheduling to Meet Deadlines

- Minimize maximum lateness
- 1-processor case
- Jackson's Rule: EDF (Earliest Deadline First):

  Execute tasks in order of decreasing deadlines.

Proof that Jackson's Rule works

- Let S' be a schedule that executes the tasks in some order other than by Jackson's Rule.
- Let S be a schedule that executes an pair of tasks out-of-order in S' in order of decreasing deadline.
- We want to show that the maximum lateness of S is no more than that of S'

Proof that Jackson's Rule works

- In S' there are two tasks T_a and T_b such that $D_a \le D_b$ but T_b precedes T_a.
- Let L_i be the *lateness* of task T_i, defined as

  $L_i = F_i - D_i$
  = Finish time - Deadline
- In schedule S, the combined lateness of T_a and T_b is:

  $\max(L_a, L_b)$

Proof that Jackson's Rule works

- We want to show that:

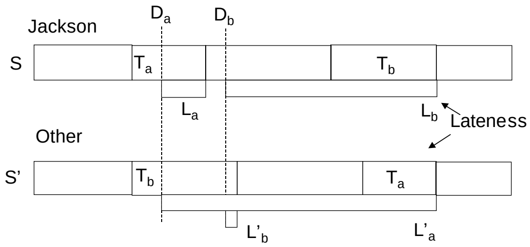
  $\max(L_a, L_b) \le \max(L'_a, L'_b)$
  where the ' designates S' vs. S.
- Consider two cases:
  - $L_a < L_b$
  - $L_a \ge L_b$
- We will show that the inequality holds in either case.

Proof of Jackson's Rule

- Case $L_a < L_b$:

$\max(L_a, L_b) = L_b$	def'n of max
$= F_b - D_b$	def'n of L
$= F'_a - D_b$	a and b are flipped in S' vs S
$\le F'_a - D_a$	assumption $D_a \le D_b$
$= L'_a$	
$\le \max(L'_a, L'_b)$	

Jackson's Rule with $L_a < L_b$

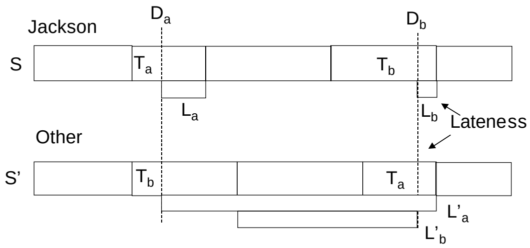


Proof of Jackson's Rule

- Case $L_a \geq L_b$:

$\max(L_a, L_b) = L_a$	def'n of max
$= F_a - D_a$	def'n of L
$< F'_a - D_a$	assumption that T_b precedes T_a in S'
$= L'_a$	def'n of L
$\leq \max(L'_a, L'_b)$	def'n of max

Jackson's Rule with $L_a \geq L_b$



Corollary to Jackson's Rule

- Assume that tasks are numbered in order of increasing deadlines D_i.
- Let C_i be the corresponding computation time.
- Then all tasks can be executed so as to meet their deadline provided that
  forall i
  $\mathrm{sum}(C_i, k = 1 \text{ to } i) \leq D_i$

Limitation of Jackson's Rule

- The set of all tasks is not always presented in advance.
- New tasks may arrive at arbitrary times.
- To minimize maximum lateness in this setting, it may be necessary to *preempt* a task already being executed.
- This issue is addressed by Horn's rule.

Horn's Rule (1974)

- Arrange execution, using preemption if necessary, so that:
  - At every instant the task with the current earliest deadline is being executed.
- Horn's rule can be proved similar to Jackson's.

Horn's Rule (1974)

- If preemption is not allowed, then Horn's rule does not minimize maximum lateness.
- Example:

Task	Time	Deadline	Arrival
T_1	4	7	0
T_2	2	5	1

Horn's Rule (1974)

- Example:

Task	Time	Deadline	Arrival
T_1	4	7	0
T_2	2	5	1

- Horn's rule says: start T_1 at time 0, which would make T_2 wait to time 4. The max lateness would be 1.
- The optimum way would be do nothing at time 0, start T_2 at time 1, then start T_1 at time 3. The maximum lateness would be 0.

Exercise

- What happens in the previous example if preemption is allowed?

Hard Problem

- Finding an optimal non-preemptive schedule when arrival times are arbitrary is NP-hard.
- An enumerative, branching, algorithm can be used.

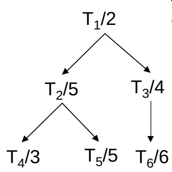
Lawler's Algorithm (1973)

- Schedules a set of simultaneously arriving tasks on one process subject to precedence constraints.
- Minimizes maximum lateness for 1 processor, non-preemptive.

Lawler's Algorithm (1973)

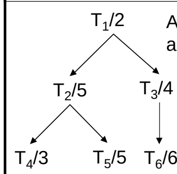
- Build a stack, selecting tasks with latest deadline first (LDF), subject to precedence constraints.
- Execute the tasks in order of popping from the stack.

Example: Lawler's Algorithm



Assume all computation times are 1 and deadlines are as shown.

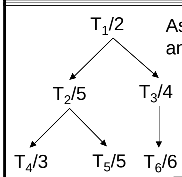
Example: Lawler's Algorithm



Assume all computation times are 1 and deadlines are as shown.

Stacking order (LDF, obeying precedence):
$T_6/6$, $T_5/5$, $T_3/4$, $T_4/3$, $T_2/5$, $T_1/2$

Example: Lawler's Algorithm



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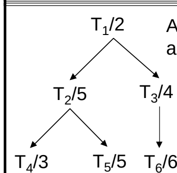
Stacking order (LDF, obeying precedence):
$T_6/6$, $T_5/5$, $T_3/4$, $T_4/3$, $T_2/5$, $T_1/2$

Execution order:	$T_1/2$,	$T_2/5$,	$T_4/3$,	$T_3/4$,	$T_5/5$,	$T_6/6$
Completion:	1	2	3	4	5	6

Example: Lawler's Algorithm



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Execution order:	$T_1/2$,	$T_2/5$,	$T_4/3$,	$T_3/4$,	$T_5/5$,	$T_6/6$
Completion:	1	2	3	4	5	6

Using EDF, the order would be:	$T_1/2$,	$T_3/4$,	$T_2/5$,	$T_4/3$,	$T_5/5$,	$T_6/6$
Completion:	1	2	3	4	5	6

One task would be late, so max. lateness = 1.

Other Algorithms

- An optimal method for the preemptive arbitrary-arrival case is also known (run time $O(n^2)$).
- This and the previous methods may be found in reference:
  - G.C. Buttazo
    Hard Real-Time Computing Systems
    Kluwer Academic Publishers, 1977.

Periodic Tasks

- Many realtime systems are based on periodic tasks, where each task T_i has:
  - Computation time C_i
  - Period P_i
  - Phase ϕ_i
- The meaning of "period" is that, for each i, T_i must execute once every time P_i units.
- The meaning of "phase" is that, for each i, the earliest time at which T_i is available within the current P_i period is at relative time ϕ_i.

Priority, Periodicity, and RMA

- Assume that tasks are **preemptable**.
- A task that is preempted by another is said to have ***lower priority***.
- Obviously tasks with shorter periods should generally have higher priority, since lower priority tasks can be preempted, then resumed, to allow higher priority tasks to meet their periodic deadlines.
- Since shorter period $\Rightarrow$ higher rate, this is called **rate-monotonic analysis** (RMA).

Preemption Costs

- In general, there will be a cost (delay) associated with preempting a task.
- For now, we assume that this cost is negligible.

Note on RMA Assumption

- RMA is a mathematical notion.
- It should not be inferred that every set of user priorities will agree with RMA.

Example of RMA

- Three periodic tasks:

Task	Time	Period	Phase
T_1	0.5	2	0
T_2	2	6	1
T_3	1.75	10	3

- For example, since T_1 has period 10 and phase 3, it is available at 3, 13, 23, 33, … .

Exercise

- Given the previous table, construct a schedule that schedules the tasks periodically.
- Remember that tasks can be preempted.