4.a Fixed-Priority Scheduling

Credits to A. Burns and A. Wellings

Simple workload model

- The application is assumed to consist of a fixed set of tasks
- All tasks are *periodic* with known periods
  - This defines the *periodic workload model*
- The tasks are completely *independent* of each other
- All system overheads (context-switch times, interrupt handling and so on) are ignored
  - Assumed to have zero cost or otherwise negligible
- All tasks have a deadline equal to their period $(D = T)$
  - Each task must complete before it is next released
- All tasks have a fixed WCET (*a safe and tight upper-bound*)
  - Operation modes are not considered

Standard notation

B:	Worst-case blocking time for the task (if applicable)
C:	Worst-case computation time (WCET) of the task
D:	Deadline of the task
I:	The interference time of the task
J:	Release jitter of the task
N:	Number of tasks in the system
P:	Priority assigned to the task (if applicable)
R:	Worst-case response time of the task
T:	Minimum time between task releases (or task period)
U:	The utilization of each task (equal to C/T)
a-Z:	The name of a task

Fixed-priority scheduling (FPS)

- At present the most widely used approach
  - The distinct focus of this segment
- Each task has a fixed (static) priority computed off-line
- The ready tasks are dispatched to execution in the order determined by their priority
- In real-time systems the "priority" of a task is derived from its temporal requirements, not its importance to the correct functioning of the system or its integrity

Preemption and non-preemption /1

- With priority-based scheduling, a high-priority task may be released during the execution of a lower priority one
- In a *preemptive* scheme, there will be an immediate switch to the higher-priority task
- With *non-preemption*, the lower-priority task will be allowed to complete before the other may execute
- Preemptive schemes enable higher-priority tasks to be more reactive, hence they are preferred

Preemption and non-preemption /2

- Alternative strategies allow a lower priority task to continue to execute for a bounded time
- These schemes are known as *deferred preemption* or *cooperative dispatching*
- Schemes such as EDF can also take on a preemptive or non-preemptive form
- **Value-based scheduling** (VBS) can too
  - VBS is useful when the system becomes overloaded and some *adaptive* scheme of scheduling is needed
  - VBS consists in assigning a *value* to each task and then employing an on-line *value-based scheduling algorithm* to decide which task to run next

Rate-monotonic priority assignment

- Each task is assigned a (unique) priority based on its period
  - The shorter the period, the higher the priority
  - Tasks are assigned distinct priorities (!)
- For any two tasks τ_i, τ_j we have $T_i < T_j \rightarrow P_i > P_j$
  - ***Rate monotonic*** assignment is **optimal** under preemptive priority-based scheduling
- **Nomenclature**
  - Priority 1 as numerical value is the lowest (least) priority but the indices are still sorted highest to lowest (**!**)

Utilization-based analysis

- A simple *schedulability test* (thus sufficient but not necessary) exists for rate monotonic scheduling
  - But only for task sets with $D = T$

$$U \equiv \sum_{i=1}^{N} \frac{C_i}{T_i} \leq N\,(2^{1/N} - 1)$$

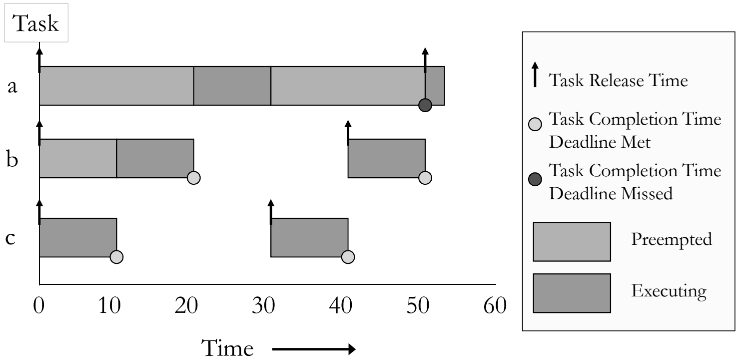
$$U \leq 0.69 \text{ as } N \rightarrow \infty$$

Example: task set A

Task	Period	Computation Time	Priority	Utilization
	T	**C**	**P**	**U**
a	50	12	1 (low)	0.24
b	40	10	2	0.25
c	30	10	3 (high)	0.33

- The combined utilization is 0.82 (or 82%)
- This is above the threshold for three tasks (0.78), hence this task set fails the utilization test
- Then we have no a-priori answer

Timeline for task set A



Example: task set B

Task	Period	Computation Time	Priority	Utilization
	T	**C**	**P**	**U**
a	80	32	1 (low)	0.40
b	40	5	2	0.125
c	16	4	3 (high)	0.25

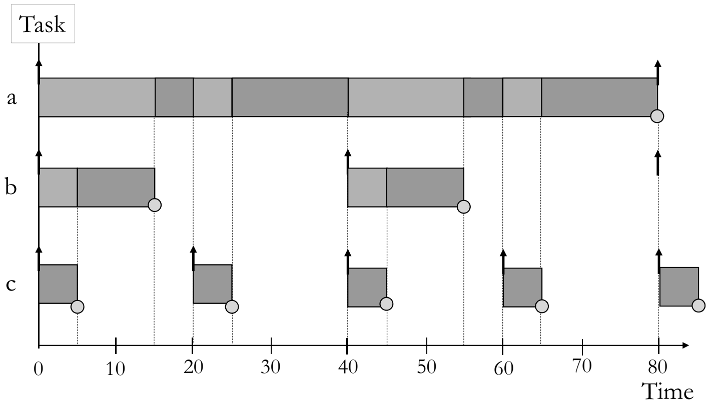
- The combined utilization is 0.775
- This is below the threshold for three tasks (0.78), hence this task set will meet all its deadlines

Example: task set C

Task	Period	Computation Time	Priority	Utilization
	T	**C**	**P**	**U**
a	80	40	1 (low)	0.50
b	40	10	2	0.25
c	20	5	3 (high)	0.25

- The combined utilization is 1.0
- This is above the threshold for three tasks (0.78) but the task set will meet all its deadlines (**!**)

Timeline for task set C



Critique of utilization-based tests

- They are not exact
- They are not general
- But they are Ω(N)
  - Which makes them interesting for a large class of users
- The test is said to be sufficient but not necessary and as such falls in the class of *schedulability tests*

Response time analysis /1

- The worst-case response time R_i of task τ_i is first calculated and then checked (trivially) with its deadline

$$R_i \le D_i$$

$$R_i = C_i + I_i$$

  - Where I is the interference from higher-priority tasks

Calculating R

- Within R_i, each higher priority task τ_j will execute a $\left\lceil \frac{R_i}{T_j} \right\rceil$ times
  - The ceiling function $\lceil f \rceil$ gives the smallest integer greater than the fractional number f on which it acts
    - E.g., the ceiling of 1/3 is 1, of 6/5 is 2, and of 6/3 is 2
- The total interference suffered by τ_i from τ_j in R_i is given by $\left\lceil \frac{R_i}{T_j} \right\rceil C_j$

Response time equation

$$R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

- Where $hp(i)$ is the set of tasks with priority higher than task τ_i
- Solved by forming a recurrence relationship

$$w_i^{n+1} = C_i + \sum_{j \in hp(i)} \left\lceil \frac{w_i^n}{T_j} \right\rceil C_j$$

- The set of values $w_i^0, w_i^1, w_i^2, ..., w_i^n, ..$ is monotonically non-decreasing
- When $w_i^n = w_i^{n+1}$ the solution to the equation has been found
- w_i^0 must not be greater than C_i (e.g. 0 or C_i)

Response time algorithm

```
for i in 1..N loop -- for each task in turn
  n := 0
  w_i^n := C_i
loop
    calculate new w_i^{n+1}
    if  w_i^{n+1} = w_i^n then
      R_i = w_i^n
      exit value found
    end if
    if  w_i^{n+1} > T_i  then
      exit value not found
    end if
    n := n + 1
  end loop
end loop
```

If the recurrence does not converge before T_i we can still set a termination condition that attempts to determine how long past T_i job *i* completes

Example: task set D

Task	Period	Computation Time	Priority	Utilization
	T	C	P	U
a	7	3	3 (high)	0.4285…
b	12	3	2	0.25
c	20	5	1 (low)	0.25

$$R_a = 3$$

$$w_b^0 = 3$$

$$w_b^1 = 3 + \left\lceil \frac{3}{7} \right\rceil 3 = 6$$

$$w_b^2 = 3 + \left\lceil \frac{6}{7} \right\rceil 3 = 6$$

$$R_b = 6$$

Example (cont'd)

$$w_c^0 = 5$$

$$w_c^1 = 5 + \left\lceil \frac{5}{7} \right\rceil 3 + \left\lceil \frac{5}{12} \right\rceil 3 = 11$$

$$w_c^2 = 5 + \left\lceil \frac{11}{7} \right\rceil 3 + \left\lceil \frac{11}{12} \right\rceil 3 = 14$$

$$w_c^3 = 5 + \left\lceil \frac{14}{7} \right\rceil 3 + \left\lceil \frac{14}{12} \right\rceil 3 = 17$$

$$w_c^4 = 5 + \left\lceil \frac{17}{7} \right\rceil 3 + \left\lceil \frac{17}{12} \right\rceil 3 = 20$$

$$w_c^5 = 5 + \left\lceil \frac{20}{7} \right\rceil 3 + \left\lceil \frac{20}{12} \right\rceil 3 = 20$$

$$R_c = 20$$

Revisiting task set C

Task	Period	Computation Time	Priority	Response Time
	T	C	P	R
a	80	40	1 (low)	80
b	40	10	2	15
c	20	5	3 (high)	5

- The combined utilization is 1.0
- This is above the utilization threshold for three tasks (0.78) hence the utilization-based schedulability test failed
- But RTA shows that the task set will meet all its deadlines (cf. the impasse we had at page 169)

Response time analysis /2

- RTA is a *feasibility test*
  - Thus exact, hence necessary and sufficient
- If the task set passes the test then all its tasks will meet all their deadlines
- If it fails the test then, at run time, some tasks will miss their deadline and FPS tells us exactly which
  - Unless the computation time estimations (the WCET) themselves turn out to be pessimistic

Sporadic tasks

- Sporadic tasks have a ***minimum inter-arrival time***
  - Which should be preserved at run time if schedulability is to be ensured, but how can it ?
- They also require $D \leq T$
- The RTA for FPS works perfectly for D<T as long as the stopping criterion becomes

$$W_i^{n+1} > D_i$$

- Interestingly this also works perfectly well with *any* priority ordering

Hard and soft tasks

- In many situations the WCET given for sporadic tasks are considerably higher than the average case
- Interrupts often arrive in bursts and an abnormal sensor reading may lead to significant additional computation
- Measuring schedulability with WCET may lead to very low processor utilizations being observed in the actual running system
  - We need some common sense to contain pessimism

General common-sense guidelines

- **Rule 1** : All tasks (hard *and* soft) should be schedulable using average execution times and average arrival rates for both periodic and sporadic tasks
  - There may therefore be situations in which it is not possible to meet all current deadlines
  - This condition is known as a *transient overload*
- **Rule 2** : All hard real-time tasks should be schedulable using WCET and worst-case arrival rates of all tasks (including soft)
  - No hard real-time task will therefore miss its deadline
  - If Rule 2 incurs unacceptably low utilizations for non-worst-case jobs then WCET values or arrival rates must be reduced

Handing aperiodic tasks /1

- These do not have minimum inter-arrival times
  - And consequently also no deadline
  - However we may be interested in the system being responsive to them
- We can run aperiodic tasks at a priority below the priorities assigned to hard tasks
  - In a preemptive system they therefore cannot steal resources from the hard tasks
- But this does not provide adequate support to soft tasks which will often miss their deadlines
- To improve the situation for soft tasks, a server can be employed
- Servers protect the processing resources needed by hard tasks but otherwise allow soft tasks to run as soon as possible

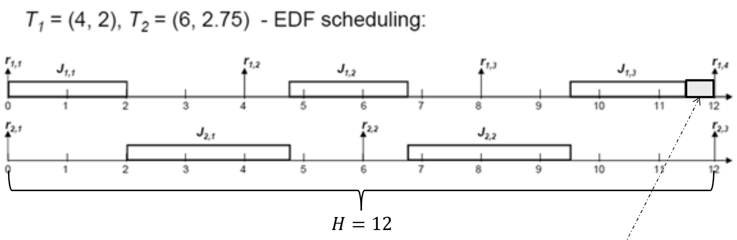
Handing aperiodic tasks /2

- Besides preserving hard tasks and giving fair opportunities to soft tasks we still would like to schedule aperiodic jobs in a manner that minimizes
  - The response time of the job at the head of the aperiodic job queue
  - Or else the average response time of *all* aperiodic jobs for a given queuing discipline
- Possible solutions
  - Execute the aperiodic jobs in the background
  - Execute the aperiodic jobs by interrupting the periodic jobs
  - Slack stealing
  - Use dedicated servers

Handing aperiodic tasks /3

- ***Slack stealing***
  - Difficult for preemptive systems because, for them, the slack $\sigma(t)$ is a function of the time t at which it is computed
  - The slack stealer is ready when the aperiodic queue is not empty and it is suspended otherwise
  - When ready and $\sigma(t) > 0$ the slack stealer is assigned the highest priority and when $\sigma(t) = 0$ the lowest
  - Static computation of $\sigma(t)$ for some t is useful but only when the release jitter in the system is very low
    - Under EDF $\sigma(t = 0) = min_i\{\sigma_i(0)\}$ where $\sigma_i(0) = D_i - \sum_{k=1,..,i} e_k$ for all jobs released in the hyperperiod starting at $t = 0$

Computing the slack under EDF



$\sigma_{1,1}(0) = 4 - 2 = 2$
$\sigma_{2,1}(0) = 6 - 2 - 2.75 = 1.25$
$\sigma_{1,2}(0) = 8 - 2 - 2.75 - 2 = 1.25$
$\sigma_{2,2}(0) = 12 - 2 - 2.75 - 2 - 2.75 = 2.5$
$\sigma_{1,3}(0) = 12 - 2 - 2.75 - 2 - 2.75 - 2 = \mathbf{0.5}$

Computing the slack under FPS /1

- The amount of slack an FPS system has in a time interval may depend on *when* the slack is used
- To minimise the response time of an aperiodic job J_a the decision on when to schedule J_a must obviously consider the execution time of J_a
  - No slack stealing algorithm under FPS can minimise the response time of *every* aperiodic job even with prior knowledge of their arrival and execution times
  - Better not be greedy in using the available slack

Computing the slack under FPS /2

- The slack of periodic jobs of τ_i should be computed based on their *effective deadline* D_i^e
  - For a job of τ_i this occurs at the beginning of the level-$i-1$ busy period that precedes D_i so that $D_i^e \le D_i$
- Hence the initial slack $\sigma_{i,j}(0)$ of every periodic job $J_{i,j}$ in the hyperperiod is determined as

$$max\left(0, D_{i,j}^e - \sum_{k=1}^{i} \left\lceil \frac{D_{i,j}^e}{T_k} \right\rceil C_k\right)$$

Handing aperiodic tasks /4

- ***Periodic server*** (TPS) – general model
  - A (T_{ps}, C_{ps}) periodic task scheduled at the highest priority to only execute aperiodic jobs
    - The TPS has a ***budget*** of C_{ps} time units and a ***replenishment period*** of length T_{ps}
    - When the TPS is scheduled and executes aperiodic jobs, it consumes its budget at the rate of 1 unit per unit of time
    - Budget exhausted when $C_{ps} = 0$ and replenished at due time
  - The TPS is *backlogged* when the aperiodic job queue is nonempty and it is idle otherwise
    - Eligible for execution only when ready, backlogged and $C_{ps} > 0$

Handing aperiodic tasks /5

- ***Polling server*** (PS), a simple kind of TPS
  - It is given a fixed budget that it uses to serve aperiodic task requests that is replenished at every period
  - The budget is immediately consumed if the PS is scheduled while idle
    - Ready periodic tasks – if any – execute instead
  - It is <u>not</u> ***bandwidth preserving***
    - An aperiodic job that arrives just after the PS has been scheduled while idle must wait until the next replenishment time
  - Bandwidth-preserving servers need additional rules for consumption and replenishment of their budget

Handing aperiodic tasks /6

- ***Deferrable Server*** (DS), a bandwidth-preserving TPS
  - DS retains its budget if no aperiodic tasks require execution
    - If an aperiodic task requires execution during the server period, it can be served immediately: the DS does not sleep when idle but stays ready to serve
  - The budget is replenished at the start of the new period (!)
    - If an aperiodic request arrives ε time units before the end of T_{ds} the request begins to be served and blocks periodic tasks; when the budget is replenished new aperiodic requests may be served for the full budget
  - DS worst-case contribution to $\omega(t)$ is $C_{ds} + \left\lceil \frac{t-C_{ds}}{T_{ds}} \right\rceil C_{ds}$ delaying hard tasks <u>longer</u> than one server budget per period

Handing aperiodic tasks /7

- ***Priority Exchange*** (PE), similar in principle to DS
  - If PE server is idle when scheduled, it exchanges its own priority with that of the pending periodic task with priority lower than itself and highest amongst all other pending periodic tasks
  - The selected periodic task <u>inherits</u> PE's higher priority until an aperiodic task arrives or PE's ready period ends

Handing aperiodic tasks /8

- ***Sporadic Server*** (SS), fixes the bug in DS
  - The budget is replenished <u>only when exhausted</u> and at a minimum guaranteed distance from its earlier execution
    - Hence not periodically!
  - This places a tighter bound on its interference and makes schedulability analysis simpler and less pessimistic
- This is the default server policy in POSIX

SS rules under FPS

- ***Consumption rules***
  - At time $t > t_r$ where t_r is the latest replenishment time a backlogged SS consumes budget only if it is executing or no higher-priority task is ready
- ***Replenishment rules***
  - t_r is recorded at the time that SS' budget is set to C_{ss}
    - $t_r = 0$ when the system begins execution
  - The effective replenishment time t_e, the time at which SS should become running, is determined at time t_f when SS first begins to execute since t_r
    - t_e is set to the latest time instant at which a lower-priority task executes in (t_r, t_f) or to t_r if higher-priority tasks had been busy in that interval
    - The next replenishment time is set to $t_e + T_{ss}$
- ***Exception***
  - If $t_e + T_{ss} < t_f$ SS is late and budget is replenished as soon as exhausted

Handing aperiodic tasks /9

- SS is more complex than PS or DS
  - Its rules require keeping tab of a lot of data, several cases to consider when making scheduling decisions
  - This complexity is acceptable because the schedulability of a SS is easy to demonstrate
    - SS under FPS can be seen just like a periodic task τ_s with (p_s, e_s)
- Under EDF or LLF scheduling we can use a dynamic variant of SS as well as other bandwidth-preserving server algorithms
  - *Constant utilization server*
  - *Total bandwidth server*
  - *Weighted fair queuing server*

Task sets with D < T

- For $D = T$, Rate Monotonic priority assignment (a.k.a. ordering) is optimal
- For $D < T$, ***Deadline Monotonic*** priority ordering is optimal

$$D_i < D_j \Rightarrow P_i > P_j$$

DMPO is optimal /1

- Deadline monotonic priority ordering (DMPO) is optimal

  any task set Q that is schedulable by priority-driven scheme W it is also schedulable by DMPO

- The proof of optimality of DMPO involves transforming the priorities of Q as assigned by W until the ordering becomes as assigned by DMPO
- Each step of the transformation will preserve schedulability

DMPO is optimal /2

- Let τ_i, τ_j be two tasks with adjacent priorities in Q such that under W we have $P_i > P_j \wedge D_i > D_j$
- Define scheme W' to be identical to W except that tasks τ_i, τ_j are swapped
- Now consider the schedulability of Q under W'
- All tasks $\{\tau_k\}$ with priority $P_k > P_j$ will be unaffected
- All tasks $\{\tau_s\}$ with priority $P_s < P_i$ will be unaffected as they will experience the same interference from τ_j and τ_i
- Task τ_j which was schedulable under W, now has a higher priority, suffers less interference, and hence must be schedulable under W'

DMPO is optimal /3

- All that is left to show is that task τ_i, which has had its priority lowered, is still schedulable
- Under W we have $R_j \leq D_j, D_j < D_i$ and $R_i \leq T_i$
- Task τ_j only interferes once during the execution of task τ_i hence $R_i' = R_j \leq D_j < D_i$
  - Under W' task τ_i completes at the time task τ_j did under W
  - Hence task τ_i is still schedulable after the switch
- Priority scheme W' can now be transformed to W'' by choosing two more tasks that are in the wrong order for DMPO and switching them

Summary

- A simple (periodic) workload model
- Delving into fixed-priority scheduling
- A (rapid) survey of schedulability tests
- Some extensions to the workload model
- Priority assignment techniques