3. Scheduling issues

Common approaches – 1

- **Clock-driven (time-driven) scheduling**
  - Scheduling decisions are made beforehand (off line) and then carried out at predetermined time instants
    - The time instants normally occur at regular intervals signaled by a clock interrupt
    - The scheduler first dispatches jobs to execution as due in the current time period and then suspends itself until then next schedule time
    - The scheduler uses an off-line schedule to dispatch
  - All parameters that matter must be known in advance
  - The schedule is static and cannot be changed at run time
  - The run-time overhead incurred in executing the schedule is minimal

Common approaches – 2

- **Weighted round-robin scheduling**
  - Basic round-robin scheme
    - All ready jobs are placed in a FIFO queue
    - The job at head of queue is allowed to execute for one *time slice*
      - If not complete by end of time slice it is placed at the tail of the queue
    - All jobs in the queue are given one time slice in one *round*
  - Weighted correction (as applied to scheduling of network traffic)
    - Jobs are assigned differing amounts of CPU time according a predetermined 'weight' (fraction) attribute
      - A job gets w time slices per round – one round is $\sum w$ of ready jobs
    - Not good for jobs with precedence relations
      - Response time would be much worse since RR increases that for every job already
    - Fine for producer-consumer jobs that can operate concurrently in a pipeline

Common approaches – 3

- **Priority-driven (event-driven) scheduling**
  - This class of algorithms is *greedy*
    - They never leave available processing resources unutilized
    - An available resource may stay unused iff there is no job ready to use it
      - They seek local optimization
    - A *clairvoyant* alternative may instead defer access to the CPU to incur less contention and thus reduce job response time
    - Anomalies may occur when job parameters change dynamically
  - Scheduling decisions are made at run time when changes occur to the "ready queue" and thus on local knowledge
    - The event causing a scheduling decision is called "*dispatching point*"
  - It includes algorithms also used in non real-time systems
    - FIFO, LIFO, SETF (shortest execution time first), LETF (longest e.t. first)
    - Normally applied at every round of RR scheduling

Preemption vs. non preemption

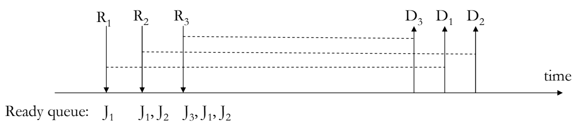
- Can we compare the performance of preemptive scheduling with that of non-preemptive scheduling?
  - There is no response that is valid in general
    - When all jobs have the same release time and the time overhead of preemption is negligible then preemptive scheduling is certainly better
  - It would be interesting to know whether the improvement of the last finishing time (a.k.a. *minimum makespan*) under preemptive scheduling pays off the time overhead of preemption
  - For 2 CPU we do know that the minimum makespan for non-preemptive scheduling is never worse than 4/3 of that for preemptive

Further definitions

- Precedence constraints effect release time and deadline
  - One job's release time cannot follow that of a successor job
  - One job's deadline cannot precede that of a predecessor job
- ***Effective release time***
  - For a job with predecessors this is the maximum (latest) value between its own release time and the effective release time of its predecessors
  - More specifically the maximum (latest) effective release time of its predecessors plus the WCET of the corresponding job
- ***Effective deadline***
  - For a job with successors this is the minimum (earliest) value between its deadline and the effective deadline of its successors
  - More specifically the minimum (earliest) effective deadline of its successors less the WCET of the corresponding job
  - In the single-processor case and with preemptive scheduling we may consider ERT and ED and then disregard the precedence constraints

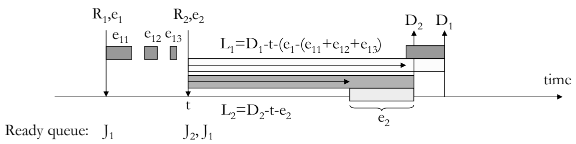
Optimality – 1

- Priorities can be assigned in accord to (effective) deadlines
  - **Earliest Deadline First** scheduling is *optimal* for single processor systems with preemption enabled and independent jobs
    - For any given job set, EDF produces a feasible schedule if one exists
    - The optimality of EDF falls short under other hypotheses (e.g., no preemption, multi-core)



Optimality – 2

- Priorities can also be assigned in accord to slack (*laxity*)
  - The slack at time **t** of a job J with deadline **d** and remaining time of execution **r** is: [(**d** – **t**) – **r**]
  - *Least Slack Time First* (**Least Laxity First**) scheduling is optimal under the same hypotheses as for EDF optimality
    - LLF however is far more onerous than EDF to implement as it requires to keep tab of execution time

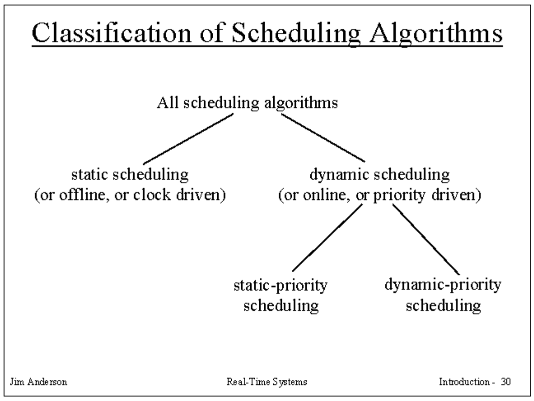


Optimality – 3

- If the goal is that jobs just make their deadlines then having jobs complete any earlier has not much point
  - The **Latest Release Time** algorithm follows this logic and schedules jobs backwards from the latest deadline
    - LRT first sets the job with the latest deadline and then the job with the latest release time and so forth
      - A later release time earns a greater deadline
    - LRT does not belong in the priority-driven class as it may defer the execution of a ready job
- Greedy algorithms may cause jobs to incur greater interference

Predictability of execution

- Initial intuition
  - The execution of job set J under a given scheduling algorithm is **predictable** if the actual start time and the actual response time of every job in J vary within the bounds of the *maximal* and *minimal schedule*
    - *Maximal schedule*: the schedule created by the scheduling algorithm with the WCET of every job
    - *Minimal schedule*: analogously for the BCET
- **Theorem**: the execution of independent jobs with given release time under preemptive priority-driven scheduling on a single processor is predictable



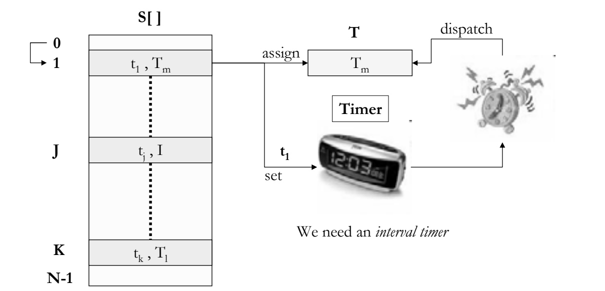
Clock-driven scheduling – 1

- **Workload model**
  - N periodic tasks with N constant and statically defined
    - In Jim Anderson's definition of periodic (not Jane Liu's)
  - The (Φ_i, p_i, e_i, D_i) parameters of every task T_i are constant and statically known
- The schedule is static and committed off line before system start to a table **S** of decision times t_k
  - $S[t_k] = T_i$ if a job of task T_i must be dispatched at time t_k
  - $S[t_k]$ = I (*idle*) otherwise
  - Schedule computation can be as sophisticated as we like since we pay for it only once and before execution
  - Jobs cannot overrun otherwise the system is in error

Clock-driven scheduling – 2

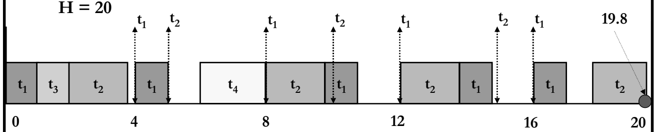
```
Input: stored schedule S(t_k) for k = 0,..,N-1; H (hyper-period)
SCHEDULER:
  i := 0; k = 0; set timer to expire at t_k ;
  do forever :
    sleep until timer interrupt;
    if an aperiodic job is executing
      preempt;
    end if;
    current task T := S(t_k);
    i := i+1; k := i mod N;
    set timer to expire at floor (i / N) × H + t_k ;
    if current task T = Idle
      execute job at head of aperiodic queue;
    else execute job of task T;
    end if;
  end do;
end SCHEDULER
```


Clock-driven scheduling – 3



Example

J = {t_1 = (0, 4, 1, 4), t_2 = (0, 5, 1.8, 5), t_3 = (0, 20, 1, 20), t_4 = (0, 20, 2, 20)}
U = 0.76
H = 20



- Static schedule table S for J would need 17 entries
  - That's too many and too fragmented!
- Can you tell why 17?

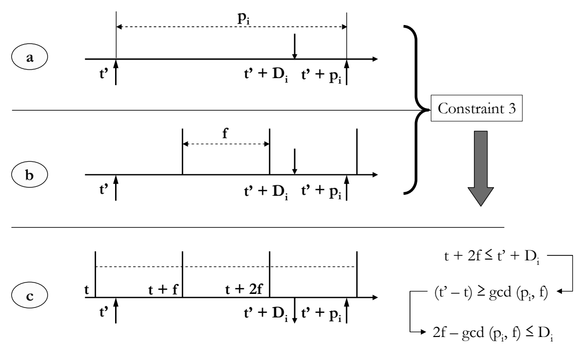
Clock-driven scheduling – 4

- Obvious reasons suggest we should minimize the size and complexity of the cyclic schedule (table S)
  - The scheduling point t_k should occur at <u>regular intervals</u>
    - Each such interval is termed ***minor cycle*** (*frame*) and has duration *f*
    - We need a *periodic timer*
    - Within minor cycles there is no preemption but a single minor cycle may contain the execution of <u>multiple</u> jobs
  - Φ_i for every task T_i is a non-negative integer multiple of *f*
    - The first job of every task has release time (forcedly) set at the beginning of a minor cycle
- We must therefore enforce some artificial constraints

Clock-driven scheduling – 5

- **Constraint 1**: Every job must complete within *f*
  - **$f \geq \max_i (e_i)$** so that *overrun* situations can be detected
- **Constraint 2**: *f* must be an integer divisor of hyper-period H
  - Hyper-period H contains an integer number F of minor cycles
  - Hyper-period H beginning at minor cycle kF for k=0,…,N-1 is termed ***major cycle***
- **Constraint 3**: the time span between the job's release time and deadline should be $\geq f$
  - To aid the scheduler in policing that each job completes by its deadline
  - Using some math this can be expressed as:
    $2f - gcd(p_i, f) \leq D_i$ for every task t_i

Understanding constraint 3



Clock-driven scheduling – 5

- It is very likely that the original parameters of some task set T may prove unable to satisfy all three constraints for the given *f* simultaneously
- In that case we must decompose T's jobs by *slicing* their larger e_i into fragments small enough to artificially yield a "good" *f*

Example

- T = {(0, 4, 1, 4), (0, 5, 2, 7), (0, 20, 5, 20)}
- H = 20
- [**c1**] : f ≥ 5
- [**c2**] : f = {2, 4, 5, 20}
- [**c3**] : f ≤ 4

Clock-driven scheduling – 6

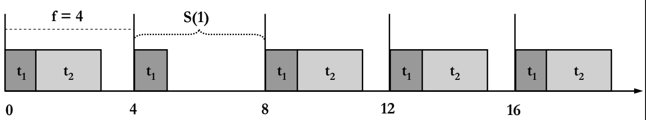
- To construct a cyclic schedule we must therefore make three design decisions
  - Fix an *f*
  - Slice (the large) jobs
  - Assign (jobs and) slices to minor cycles
- There is a very unfortunate inter-play among these decisions
  - Cyclic scheduling thus is very fragile to any change in system parameters

Clock-driven scheduling – 7

```
Input: stored schedule S(k) for k = 0,..,F-1;
CYCLIC_EXECUTIVE:
  t := 0; k = 0;
  do forever:
    sleep until clock interrupt @ time t × f;
    currentBlock = S(k);
    t := t+1; k := t mod F;
    if last job not completed take action;
    end if;
    execute slices in currentBlock;
    while the aperiodic job queue is not empty do
      execute aperiodic job at top of queue;
    end do;
  end do;
end SCHEDULER
```


Example (slicing) – 1/2

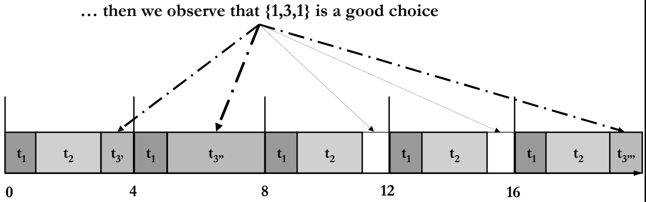
J = {t_1 = (0, 4, 1, 4), t_2 = (0, 5, 2, 7), t_3 = (0, 20, 5, 20)}, H = 20
t_3 causes disruption since we need $e_3 \le f \le 4$ to satisfy c3
We must therefore slice e_3 : how many slices do we need?



We first look at the schedule with f=4 and without t_3 to see what least-disruptive opportunities we have …

Example (slicing) – 2/2

… then we observe that {1,3,1} is a good choice



t_3 = {$t_{3'}$ = (0, 20, 1, X), $t_{3''}$ = (0, 20, 3, Y), $t_{3'''}$ = (0, 20, 1, 20)}
F = (H / f) = 5
where X < Y ≤ 20 to represent the applicable precedence constraints between the slices

Design issues – 1

- Completing a job much ahead of its deadline is of no use
- If we have spare time we might give aperiodic (event-driven) jobs more opportunity to execute and thus make the system more responsive
- The principle of ***slack stealing*** allows aperiodic jobs to execute in preference to periodic jobs when possible
  - Every minor cycle include some amount of slack time not used for scheduling periodic jobs
    - The slack is a static attribute of each minor cycle
- A scheduler does slack stealing if it assigns the available slack time at the beginning of every minor cycle (instead of at the end)
  - This provision requires a fine-grained interval timer to signal the end of the slack time

Design issues – 2

- What can we do to handle ***overruns*** ?
  - Halt the job found running at the start of the new minor cycle
    - But that job may not be the one that overrun!
    - Even if it was, stopping it would only serve a useful purpose if producing a late result had no residual *utility*
  - Defer halting until after the job has completed all its "critical actions"
    - To avoid the risk that a premature halt may leave the system in an inconsistent state
  - Allow the job some extra time by delaying the start of the next minor cycle
    - Plausible if producing a late result still had *utility*

Design issues – 3

- What can we do to handle ***mode changes***?
- A mode change is when the system incurs some reconfiguration of its function and workload parameters
- Two main axes of design decisions
  - With or without deadline during the transition
  - With or without overlap between outgoing and incoming operation modes

Overall evaluation

- **Pro**
  - Comparatively simple design
  - Simple and robust implementation
  - Complete and cost-effective verification
- **Con**
  - Very fragile design
    - Construction of the schedule table is a NP-hard problem
    - High extent of undesirable architectural coupling
  - All parameters must be fixed a priori at the start of design
    - Choices may be made arbitrarily to satisfy the constraints on f
    - Totally inapt for sporadic jobs

Priority-driven scheduling

- Base principle
  - Every job is assigned a priority
  - The job with the highest priority is selected for execution
- ***Dynamic-priority scheduling***
  - Distinct jobs of the same task may have distinct priorities
- ***Static-priority scheduling***
  - All jobs of the same task have one and same priority

Dynamic-priority scheduling

- Two main algorithms
  - ***Earliest Deadline First*** (EDF)
  - ***Least Laxity First*** (LLF)
- **<u>Theorem</u>** (Liu & Layland, 1973): EDF is optimal for independent jobs with preemption
  - Also true with sporadic tasks
  - The relative deadline for periodic tasks may be arbitrary with the respect to period (<, =, >)
- Result trivially applicable to LLF
- EDF is not optimal for jobs that do not allow preemption

Static (fixed)-priority scheduling (FPS)

- Two main variants with respect to the strategy for priority assignment
  - ***Rate monotonic***
    - A task with lower period (faster rate) gets higher priority
  - ***Deadline monotonic***
    - A task with higher urgency (shorter deadline) gets higher priority
  - What about "*execution*-monotonic"?
- Before looking at those strategies in more detail we need to fix some basic notions

Dynamic scheduling: comparison criteria – 1

- Priority-driven scheduling algorithms that disregard job urgency perform poorly
  - Hence we were right in not considering the WCET as a factor of relevance
- How to compare the performance of scheduling algorithms?
- ***Schedulable utilization*** is a useful criterion
  - An algorithm can produce a feasible schedule for a task set J on a single processor if U(J) does not exceed its schedulable utilization
  - For single processors the highest theoretical value of schedulable utilization is 1
  - **Theorem** (Liu & Layland, 1973): the schedulable utilization of EDF is 1
- For arbitrary deadlines, ***density*** $\Delta_k = e_k / \min(D_k, p_k)$ is an important factor
  - $\Delta > U$ if $D_i < p_i$ for some task
  - $\Sigma (e_i / \min(D_k, p_k)) = \Delta \leq 1$ is a sufficient ***schedulability condition*** for EDF

Dynamic scheduling: comparison criteria – 2

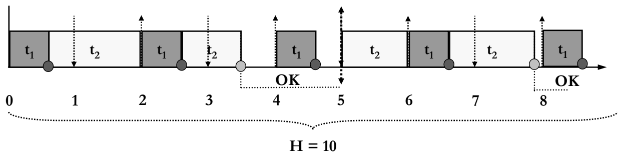
- The schedulable utilization criterion alone is not sufficient: we must consider predictability too
  - In case of transient overload the behavior of static-priority scheduling can be determined in advance and it is reasonable
    - The overrun of any job of a given task *t* does not hinder the tasks with higher priority than *t*
  - The behavior of EDF under transient overload is much more difficult to determine
    - EDF becomes a source of instability
  - Under EDF a job that missed its deadline is more urgent than a job with a deadline in the future
    - EDF becomes a source of (rising) instability

Dynamic scheduling: comparison criteria – 3

- Other figures of merit for comparison
  - **Normalized Mean Response Time** (NMRT)
    - Ratio between the job response time and the CPU time actually consumed for its execution
    - The larger the NMRT value, the larger the task idle time
  - **Guaranteed Ratio** (GR)
    - Number of tasks (jobs) whose execution can be guaranteed versus the total number of tasks that request execution

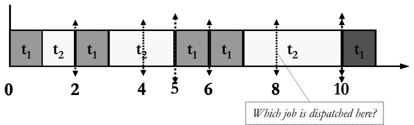
Example (EDF) – 1

T = {t_1= (0, 2, 0.6, 1), t_2= (0, 5, 2.3, 5)}
Density **Δ(T) = $e_1/D_1 + e_2/D_2$ = 1.06 > 1**
U(T) = e1/p1 + e2/p2 = 0.76 < 1
What happens to T under EDF?



Example (EDF) – 2

T = {t_1= (0, 2, 1, 2), t_2= (0, 5, 3, 5)}
U(T) = $e_1/p_1 + e_2/p_2$ = 1.1
T has no feasible schedule: what job suffers most under EDF?



T = {t_1= (0, 2, 0.8, 2), t_2= (0, 5, 3.5, 5)}
U(T) = $e_1/p_1 + e_2/p_2$ = 1.1
T has no feasible schedule: what job suffers most under EDF?

What about
T = {t1 = (0, 2, 0.8, 2), t2 = (0, 5, 4, 5)} with U(T) = 1.2 ?

Critical instant – 1

- Feasibility and schedulability tests must consider the ***worst case*** for all tasks
  - The worst case for task T_i occurs when the worst possible relation holds between its release time and that of all higher-priority tasks
  - The actual case may differ depending on the admissible relation between D_i and p_i
- The notion of ***critical instant***, if one exists, captures the worst case
  - The ***response time*** R_i for a job of task T_i with release time on the critical instant is the longest possible value for task T_i

Critical instant – 2

- **Theorem**: under FPS with $D_i \le p_i$, the critical instant for task T_i occurs when the release time of *any* of its jobs is in phase with a job of every higher-priority task in the task set
- Given task T_i we must find **max (W_{ij})** among all its jobs
  - $W_{i,j} = e_i + \Sigma_{(k=1,\ldots,i-1)} \lceil (W_{i,j} + \Phi_i - \Phi_k)/p_k \rceil e_k - \Phi_i$
    - Task indices assigned in decreasing order of priority
  - The equation captures the interference that any job j of task T_i incurs from jobs of all higher-priority tasks $\{T_k\}$ in the interval from the release time of the first job of task T_k (at phase Φ_k) to the response time of job j of T_i , which occurs at $\Phi_i + W_{i,j}$

Time-demand analysis – 1

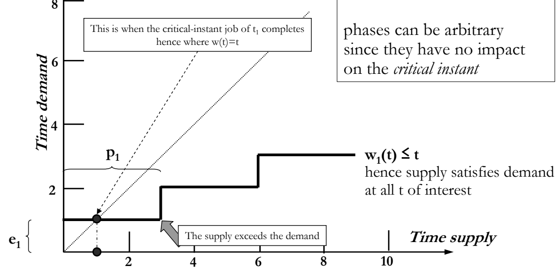
- When Φ is 0 for all jobs considered then this equation captures the absolute worst case for task T_i
- This equation stands at the basis of ***Time Demand Analysis*** which investigates how **W** varies as a function of time
  - So long as $W(t) \le t$ *for some t* within the time interval of interest the supply satisfies the demand, hence the job can complete in time
- **Theorem** [Lehoczky & Sha & Ding, 1989]: $w(t) \le t$ is necessary and sufficient
  - The obvious question is for which 't' to check
  - The method proposes to check at all periods of all higher-priority tasks (obviously until the deadline of the task under study)

Time demand analysis – 2

T = {t_1= (-, 3, 1, 3), t_2=(-, 5, 1.5, 5), t_3= (-, 7, 1.25, 7)}

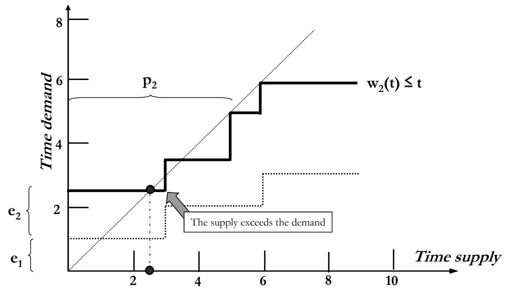
U(T) = $\Sigma\ e_i/p_i$ = 0.82

phases can be arbitrary since they have no impact on the *critical instant*



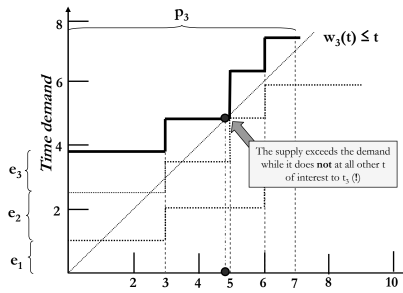
Time demand analysis – 3

T = {t_1= (-, 3, 1, 3), t_2=(-, 5, 1.5, 5), t_3= (-, 7, 1.25, 7)}



Time demand analysis – 4

T = {t_1= (-, 3, 1, 3), t_2=(-, 5, 1.5, 5), t_3= (-, 7, 1.25, 7)}



For D < p it suffices to verify ($w(t) \le t$) at time instants that are multiple of the period of the highest-priority tasks and ≤ D

Time demand analysis – 4

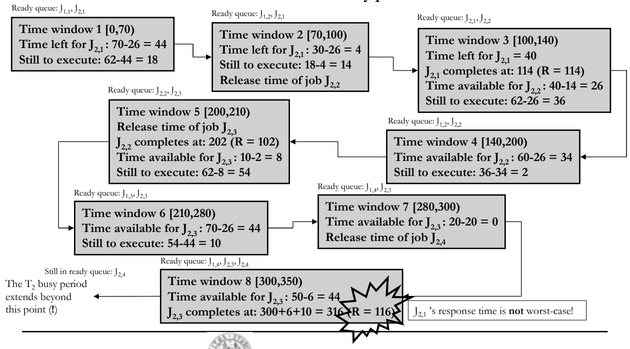
- It is straightforward to extend TDA to determine the response time of tasks
- The smallest value t that satisfies the fixed-point equation $t = e_i + \Sigma_{(k=1,\ldots,i-1)} \lceil t/p_k \rceil e_k$ is the *worst-case response time* of task T_i
- Solutions methods to calculate this value were independently proposed by
  - [Joseph & Pandia, 1986]
  - [Audsley & Burns & Richardson & Tindell & Wellings, 1993]

Time demand analysis – 5

- Does anything change in the definition of critical instant when D > p ?
- **Theorem** [Lehoczky & Sha & Strosnider & Tokuda, 1991]:
  The first job of task T_i may *not* be the one that incurs the worst-case response time
- We must therefore consider all jobs of task T_i within the so-called ***level-i busy period***
  - The (t_0, t) time interval within which the processor is busy executing jobs with priority ≥ i, release time in (t_0, t) and response time falling within t
    - The release time in (t_0, t) captures the whole backlog of interfering jobs
    - The response time of all those jobs falling within t ensures that the busy period includes their completion

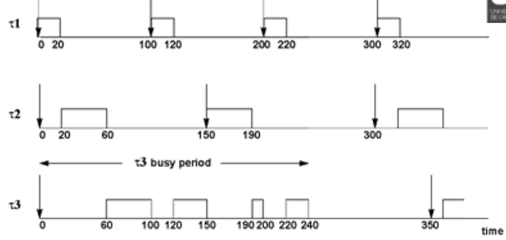
Example

T_1 = {-, 70, 26, 70}, T_2 = {-, 100, 62, 120}
Let's look at the level-2 busy period



Level-i busy period

T_1 = {-, 100, 20, 100}, T_2 = {-, 150, 40, 150}, T_3 = {-, 350, 100, 350} ⇒ U = 0.75
The same definition of level-i busy period holds also for D ≤ p
but its width is obviously shorter!



Summary

- Initial survey of scheduling approaches
- Important definitions and criteria
- Detail discussion and evaluation of main scheduling algorithms
- Initial considerations on analysis techniques