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NICTA

COMP9242 Advanced Operating Systems

S2/2013 Week 9: Real-Time Systems

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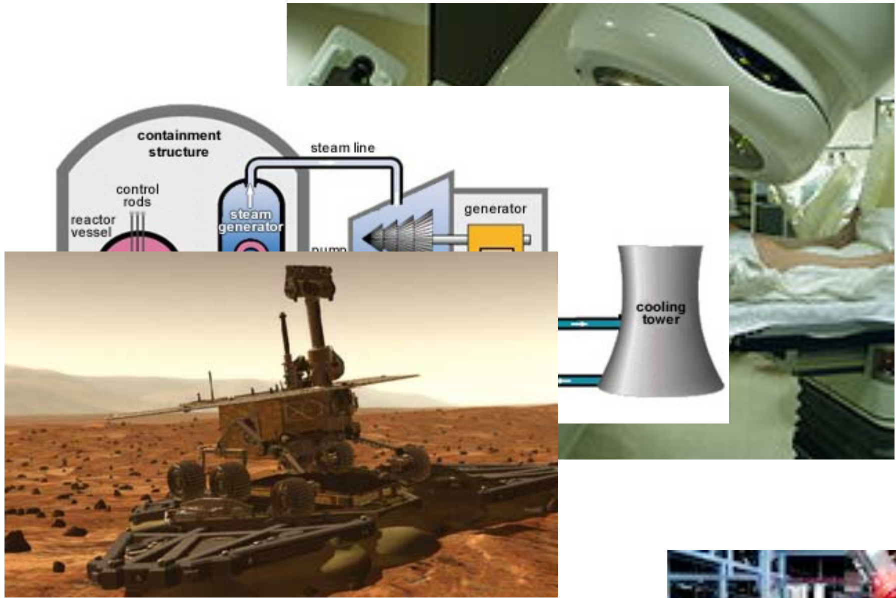
Note: Substantial re-use of material from Stefan M Petters (ex-NICTA)

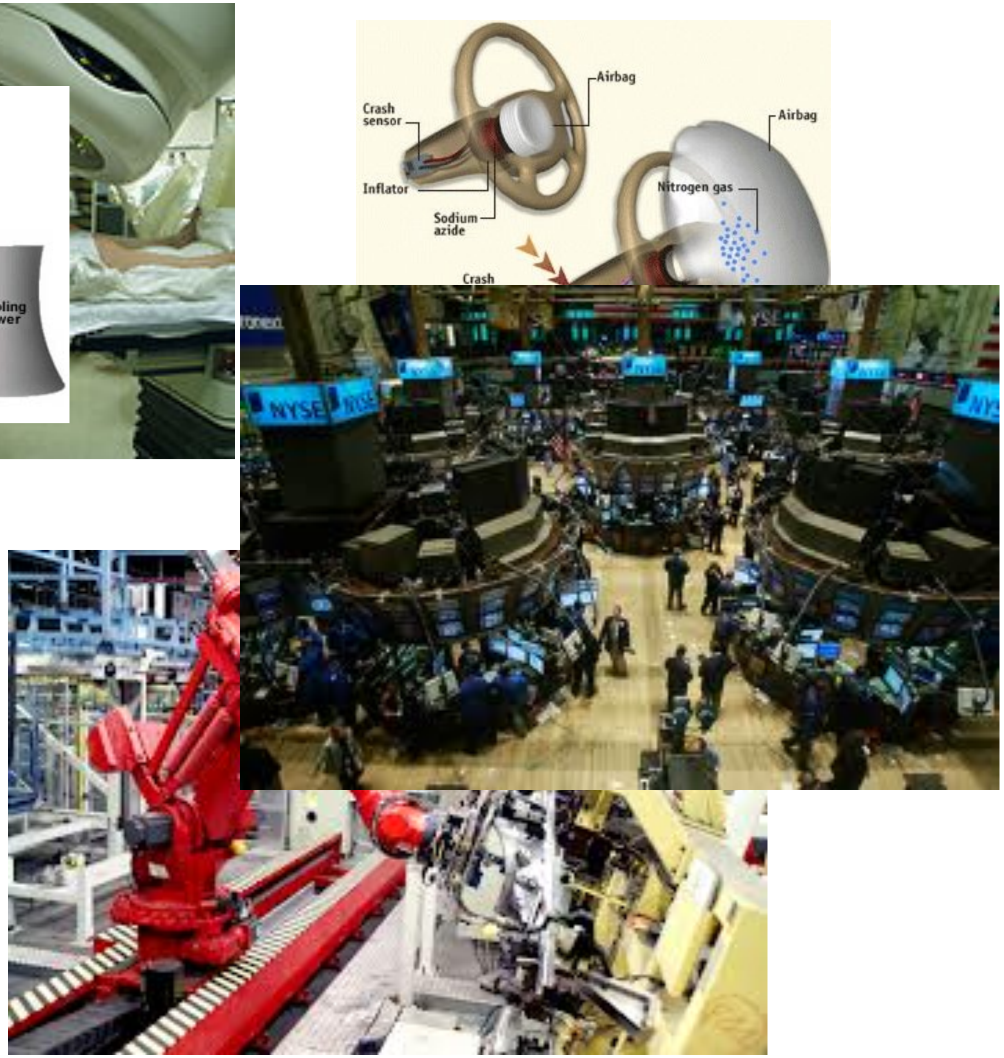
Real-Time System: Definition

A real-time system is any information processing system which has to respond to externally generated input stimuli within a finite and specified period

- Correctness depends not only on the logical result (function) but also the time it was delivered
- Failure to respond is as bad as delivering the wrong result!

Real-Time Systems





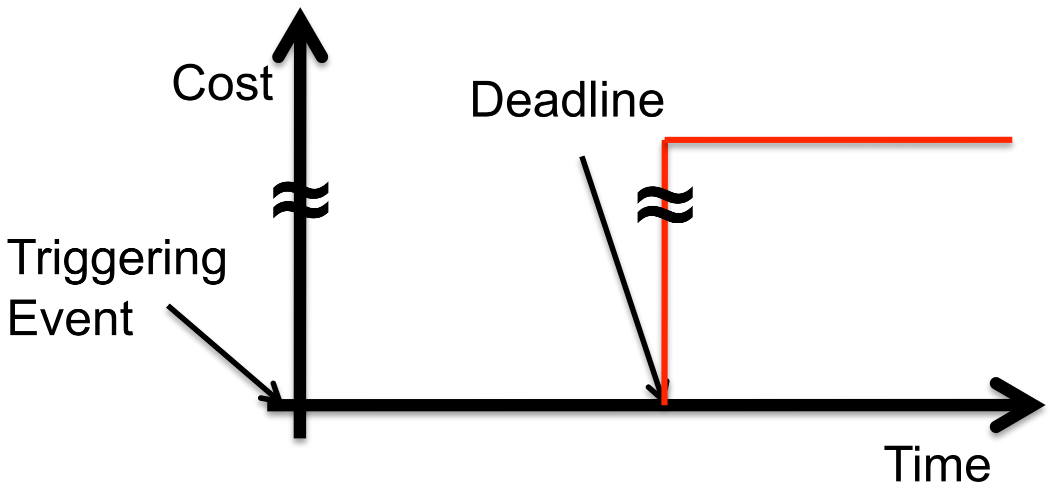
Types of Real-Time Systems

- Hard real-time systems
- Weakly-hard real-time systems
- Firm real-time systems
- Soft real-time systems
- Best-effort systems

- Real-time systems typically deal with *deadlines*:
  - A deadline is a time instant by which a response has to be completed
  - A deadline is usually specified as *relative* to an event
    - The *relative deadline* is the *maximum allowable response time*
    - Absolute deadline: event time + relative deadline

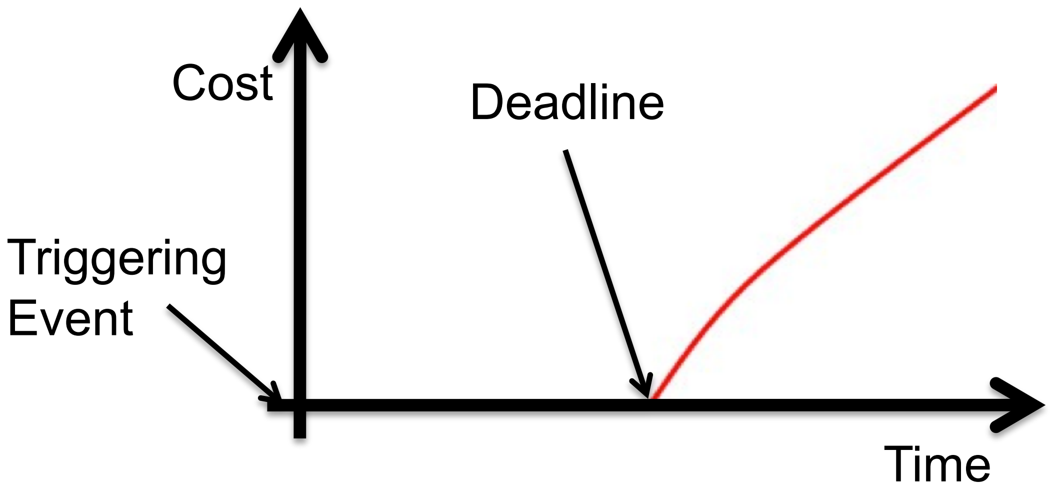
Hard Real-Time Systems

- Deadline miss is “catastrophic”
  - safety-critical system: failure results in death, severe injury
  - mission-critical system: failure results in massive financial damage
- Steep and real “cost” function



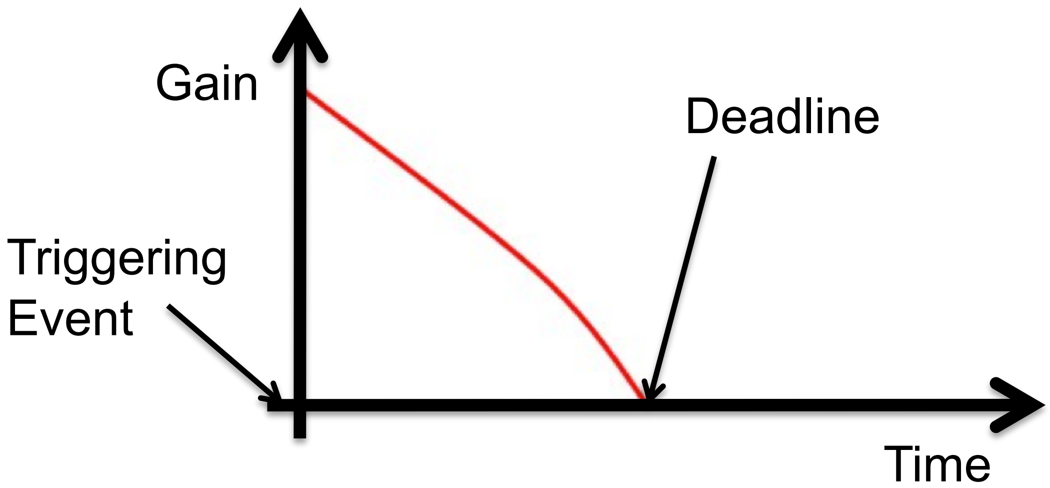
Soft Real-Time Systems

- Deadline miss is undesired but tolerable
  - Frequently results on quality-of-service (QoS) degradation
    - eg audio, video renderingSteep “cost” function
- Cost of deadline miss may be abstract



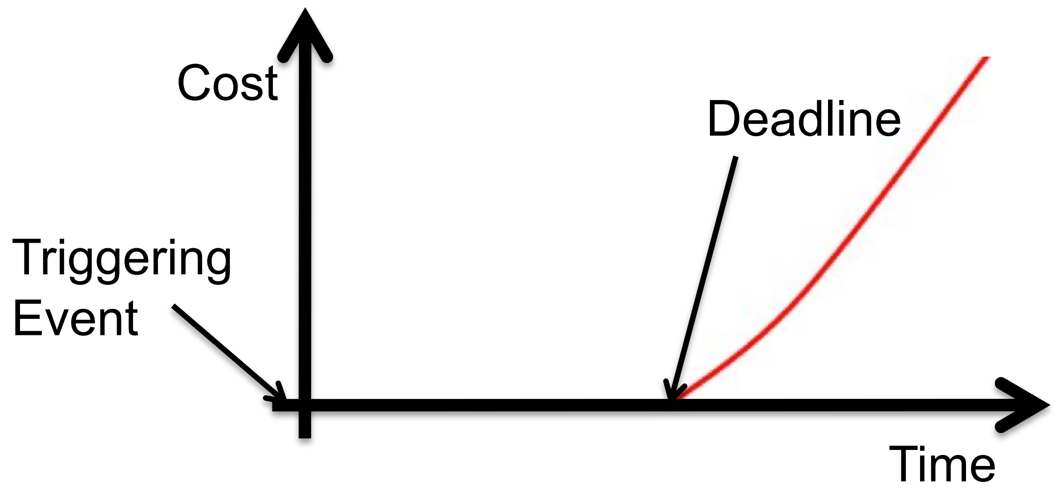
Firm Real-Time Systems

- Deadline miss makes computation obsolete
  - Typical examples are forecast systems
    - weather forecast
    - trading systems
- Cost may be loss of revenue (gain)



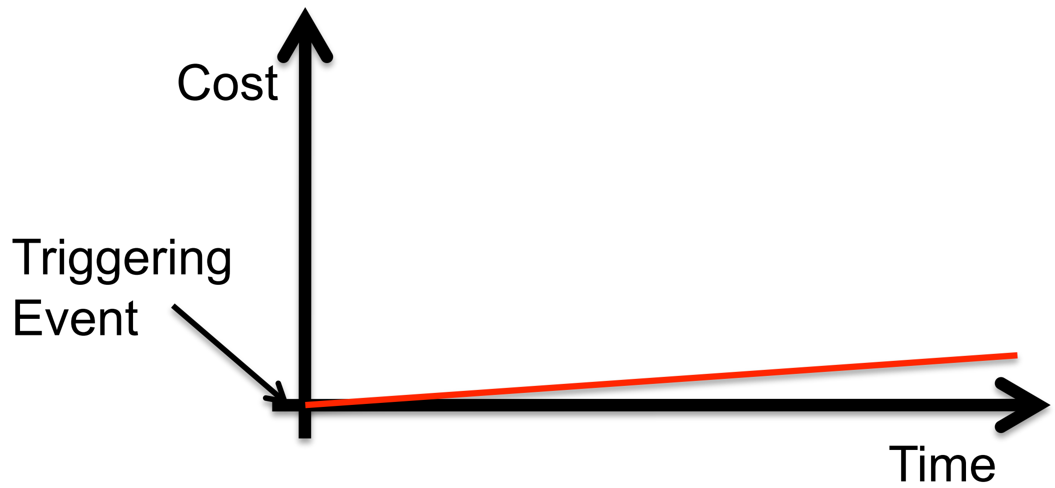
Weakly-Hard Real-Time Systems

- Tolerate a (small) fraction of deadline misses
  - Most feedback control systems (including life-supporting ones!)
    - occasionally missed deadline can be compensated at next event
    - system becomes unstable if too many deadlines are missed
  - Typically integrated with other fault tolerance
    - electro-magnetic interference, other hardware issues



Best-Effort Systems

- No deadlines, timeliness is not part of required operation
- In reality, there is at least a nuissance factor to excessive duration
  - response time to user input
- Again, “cost” may be reduced gain



Real-Time Operating System (RTOS)

- Designed to support real-time operation
  - Fast context switches, fast interrupt handling?
  - Yes, but *predictable* response time is more important
    - "Real time is not real fast"
  - Analysis of *worst-case execution time* (WCET)
- Support for *scheduling policies* appropriate for real time
- Classical RTOSes very primitive
  - single-mode execution
  - no memory protection
  - essentially a scheduler with a threads package
  - "real-time executive"
- Many modern uses require actual OS technology for isolation
  - generally microkernels

Approaches to Real Time

- Clock-driven (cyclic)
  - Typical for control loops
  - Fixed order of actions, round-robin execution
  - *Statically* determined (static schedule)
    - need to know all execution parameters at system configuration time

- Event-driven
  - Typical for reactive systems (sensors & actuators)
  - Static or dynamic schedules

Real-Time System Operation

- Event-triggered
  - timer interrupt
  - asynchronous events
- Time-triggered
  - Pre-defined temporal relation of events
  - event is not serviced until its defined *release time* has arrived
- Rate-based
  - activities get assigned CPU shares ("*rates*")

Real-Time Task Model

- **Job**: unit of work to be executed
  - … resulting from an event or time trigger
- **Task**: set of related jobs which provide some system function
  - A *task* is a sequence of *jobs* (typically executing same function)
  - Job *i+1* of of a task cannot start until job *i* is completed/aborted

- Periodic tasks
  - Time-driven and all relevant characteristics known a priori
    - Task t characterized by period T_i, deadline, D_i and execution time C_i
    - Applies to all jobs of task
- Aperiodic tasks
  - Event driven, characteristics are not known a priori
    - Task t characterized by period $T_{i,}$ deadline D_i and arrival distribution
- Sporadic tasks
  - Aperiodic but with known minimum inter-arrival time T_i
  - treated similarly to periodic task with period T_i

Standard Task Model

C: Worst-case computation time (WCET)

T: Period (periodic) or minimum inter-arrival time (sporadic)

D: Deadline (relative, frequently D=T)

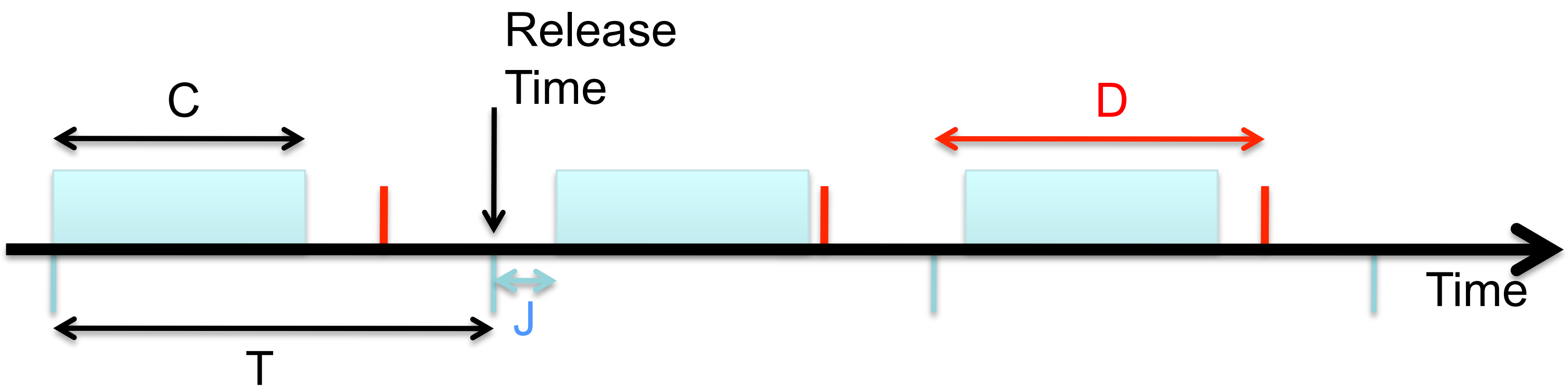
J: Release jitter

P: Priority: higher number is higher priority

B: Worst-case blocking time

R: Worst-case response time

U: Utilisation; U=C/T



Task Constraints

- Deadline constraint: must complete before deadline
- Resource constraints:
  - Shared (R/O), exclusive (W-X) access
  - Energy
  - Precedence constraints:

    $t_1 \Rightarrow t_2$: t_2 execution cannot start until t_1 is finished
  - Fault-tolerance requirements
    - eg redundancy

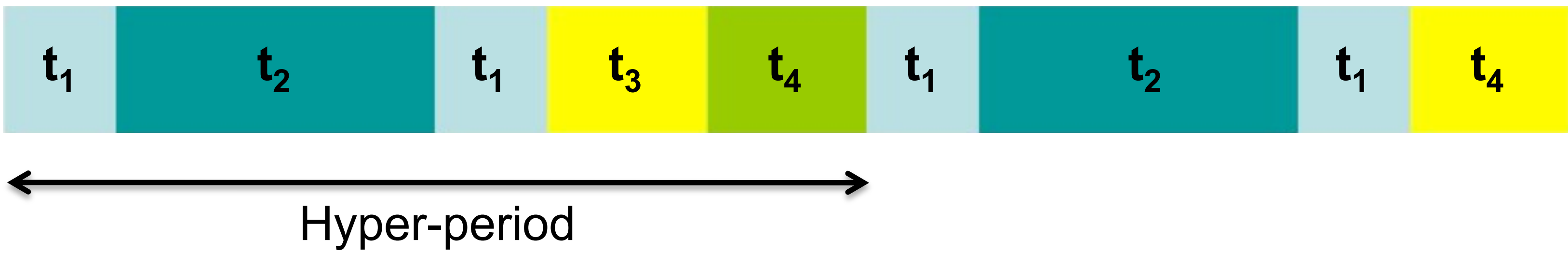
- Scheduler's job to ensure that constraints are met!

Scheduling

- Preemptive vs non-preemptive
- Static (fixed, off-line) vs dynamic (on-line)
- Clock-driven vs priority-based
  - clock-driven is static, only works for very simple systems
  - priorities can be static (pre-computed and fixed) or dynamic
  - dynamic priority adjustment can be at task-level (each job has fixed prio) or job-level (jobs change prios)

Clock-Driven (Time-Triggered) Scheduling

- Typically implemented as time "frames" adding up to "base rate"
- Advantages
  - fully deterministic
  - "cyclic executive" is trivial
    - loop waiting for timer tick, followed by function calls to jobs
    - minimal overhead
- Disadvantage:
  - Big latencies if event rate doesn't match base rate (hyper-period)
  - Inflexible



Non-Preemptive Scheduling

- Minimises context-switching overhead
  - Significant cost on modern processors (pipelinies, caches)
- Easy to analyse timeliness
- Drawbacks:
  - Larger response times for “important” tasks
  - Reduced utilisation, schedulability
    - In many cases cannot produce schedule despite plenty idle time
- Only used in very simple systems

Fixed-Priority Scheduling (FPS)

- Real-time priorities are absolute:
  - Scheduler always picks highest-priority job
- Fixed priorities obviously easy to implement, low overhead
- Drawbacks: inflexible, sub-optimal
  - Cannot schedule some systems which are schedulable preemptively

Rate-Monotonic (RM) Scheduling

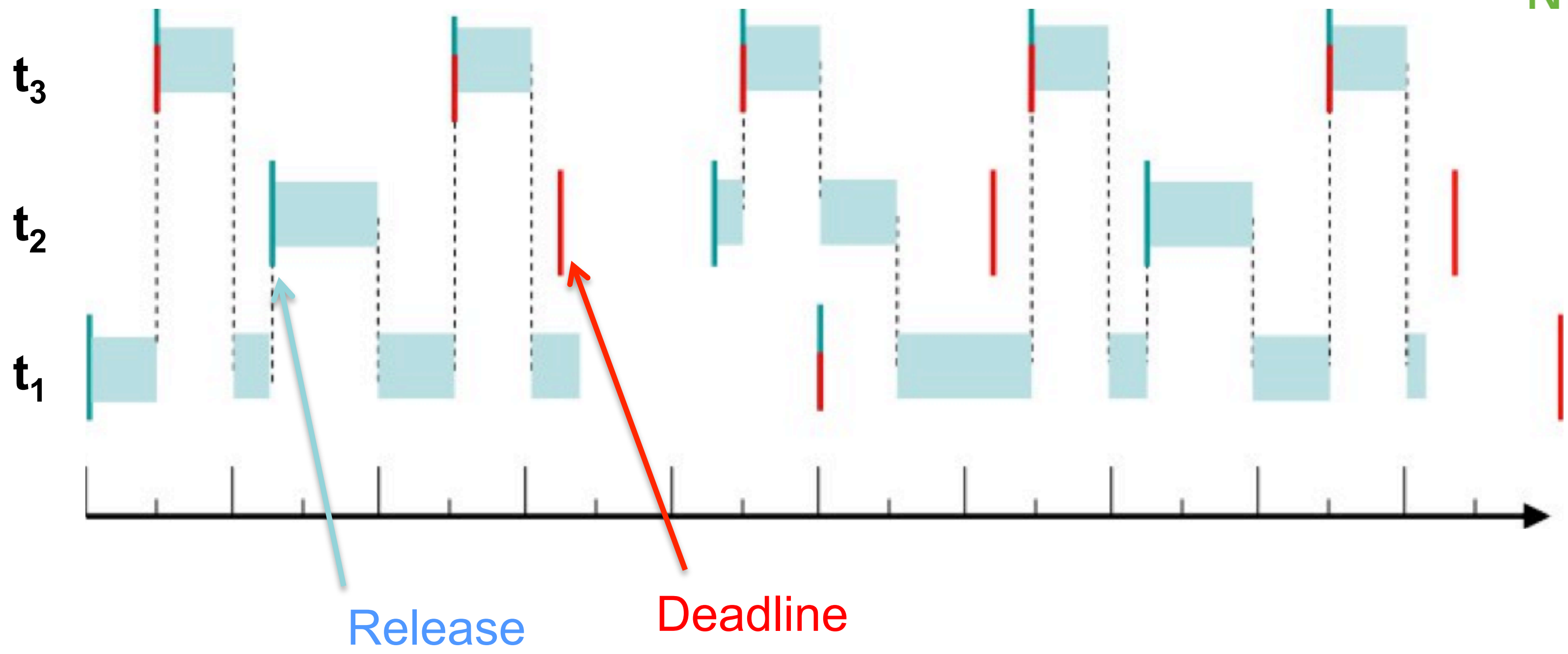
- RM: Standard approach to fixed priority assignment
  - $T_i < T_j \Rightarrow P_i > P_j$
  - 1/T is the "rate" of a task
- RM is *optimal* (as far as fixed priorities go)
- Schedulability test: RM can schedule n tasks with D=T if

  $U \equiv \sum C_i/T_i \leq n(2^{1/n}-1)$
  - sufficient but not necessary condition

n	1	2	3	4	5	10	∞
U[%]	100	82.8	78.0	75.7	74.3	71.8	69.3

- If D<T replace by *deadline-monotonic* (DM):
  - $D_i < D_j \Rightarrow P_i > P_j$
- DM is also optimal (but schedulability bound is more complex)

FPS Example



	P	C	T	D	U [%]	release
t_3	3	5	20	20	25	5
t_2	2	8	30	20	27	12
t_1	1	15	50	50	30	0
					82	

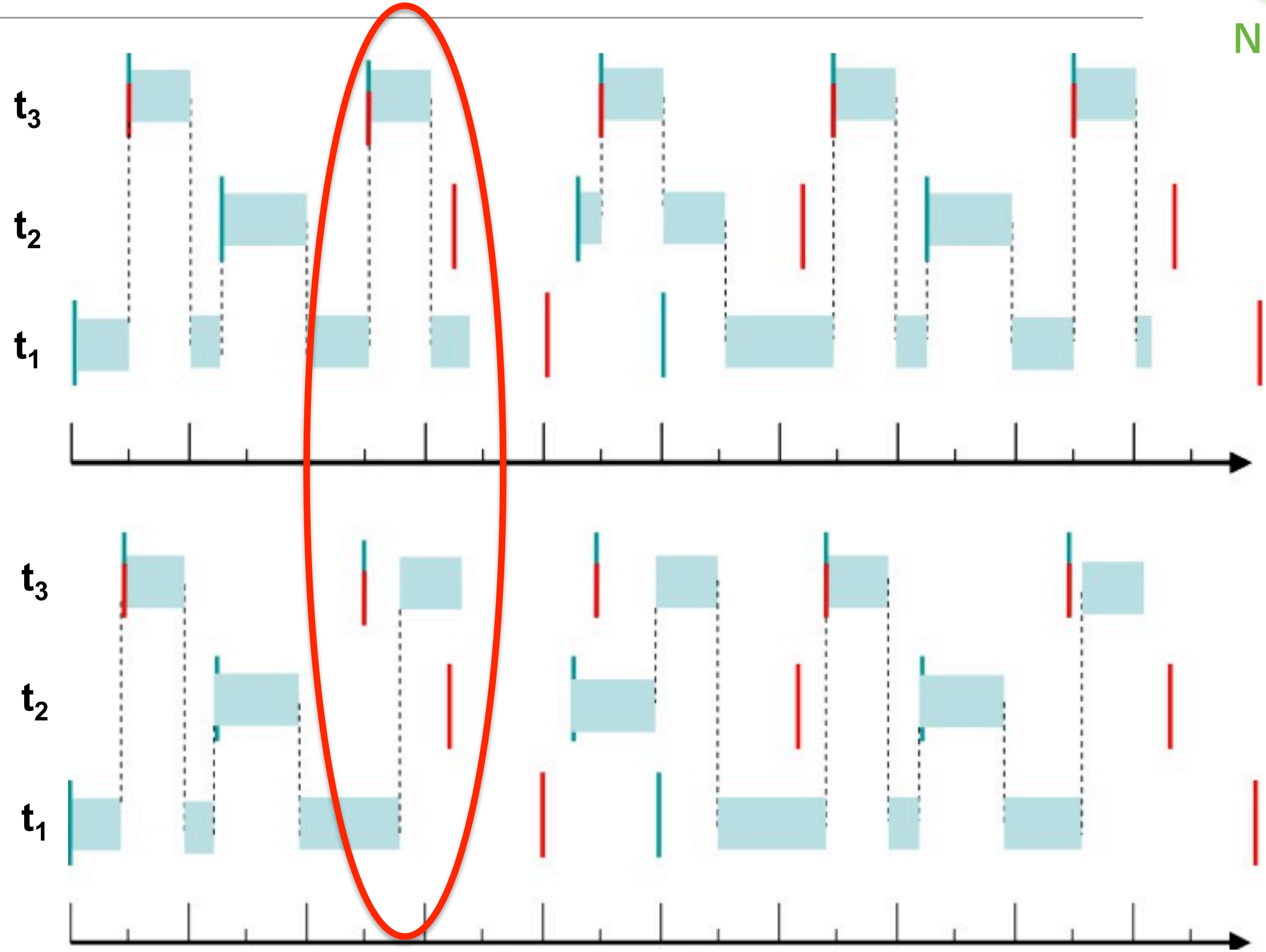
Earliest Deadline First (EDF)

- Dynamic scheduling policy
- Job with closest deadline executes
- Preemptive EDS with D=T is *optimal*: n jobs can be scheduled iff

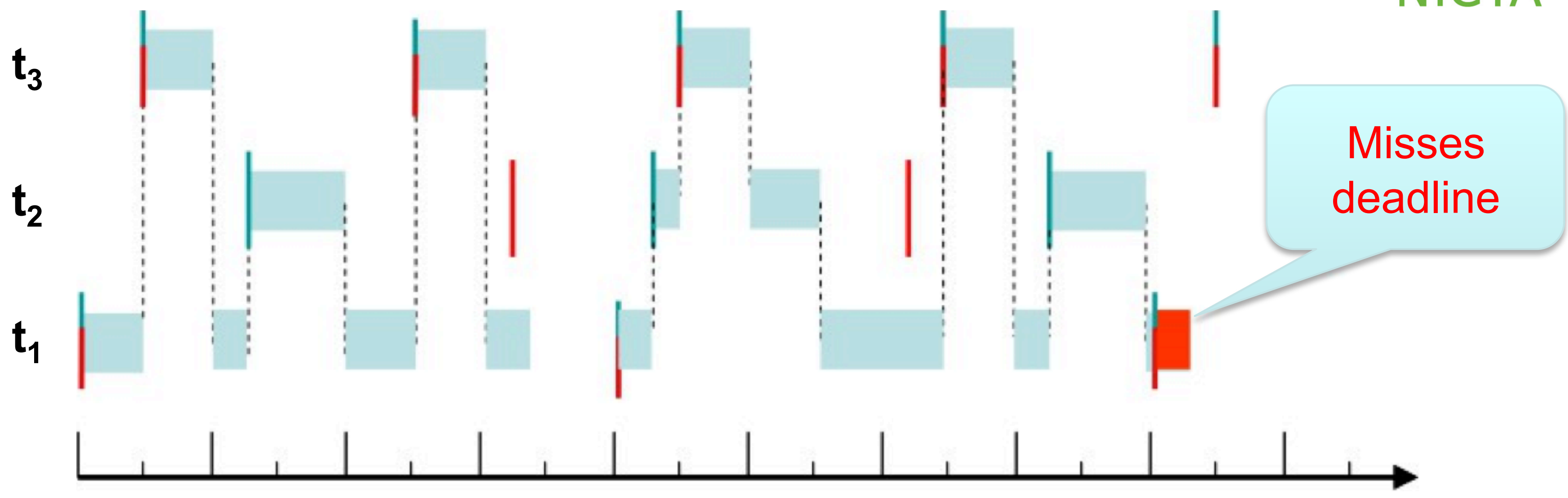
  $U \equiv \sum C_i/T_i \leq 1$

  - necessary and sufficient condition
  - no easy test if $D \neq T$

FPS vs EDF

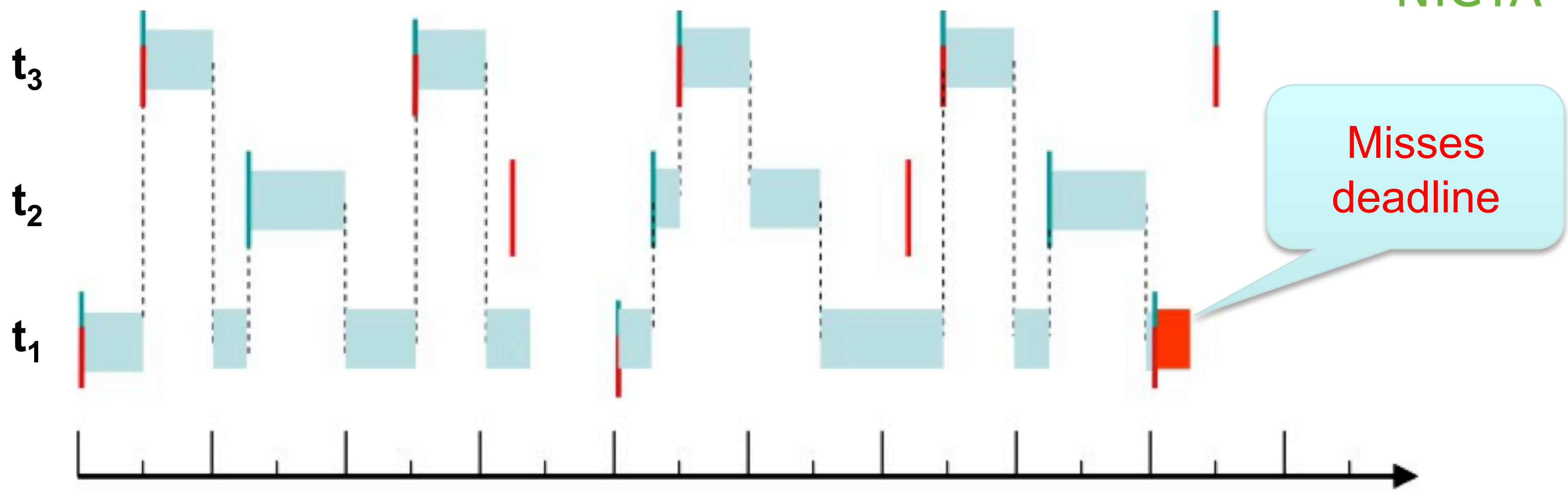


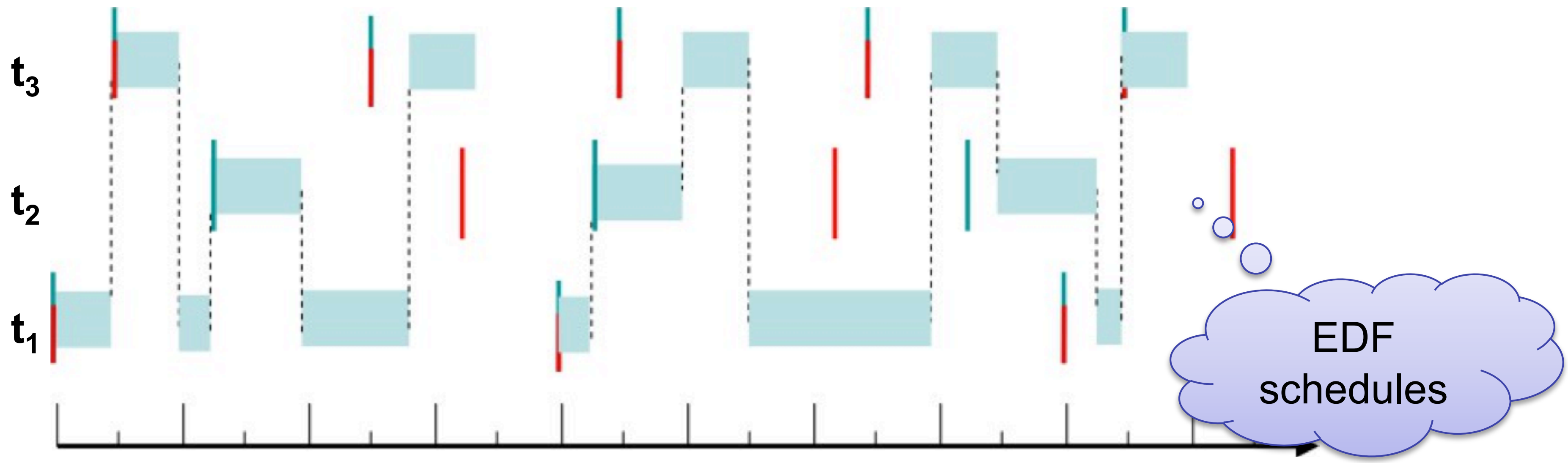
FPS vs EDF



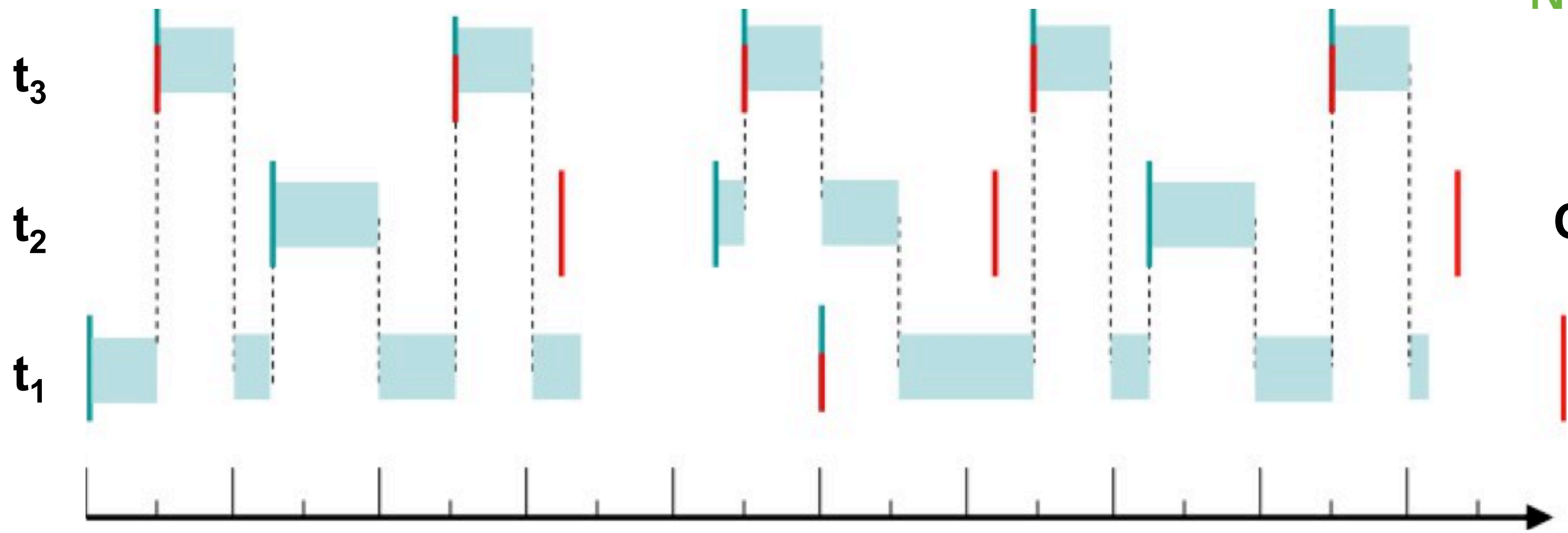
	P	C	T	D	U [%]	release
t_3	3	5	20	20	25	5
t_2	2	8	30	20	27	12
t_1	1	15	40	40	37.5	0
					89.5	

FPS vs EDF





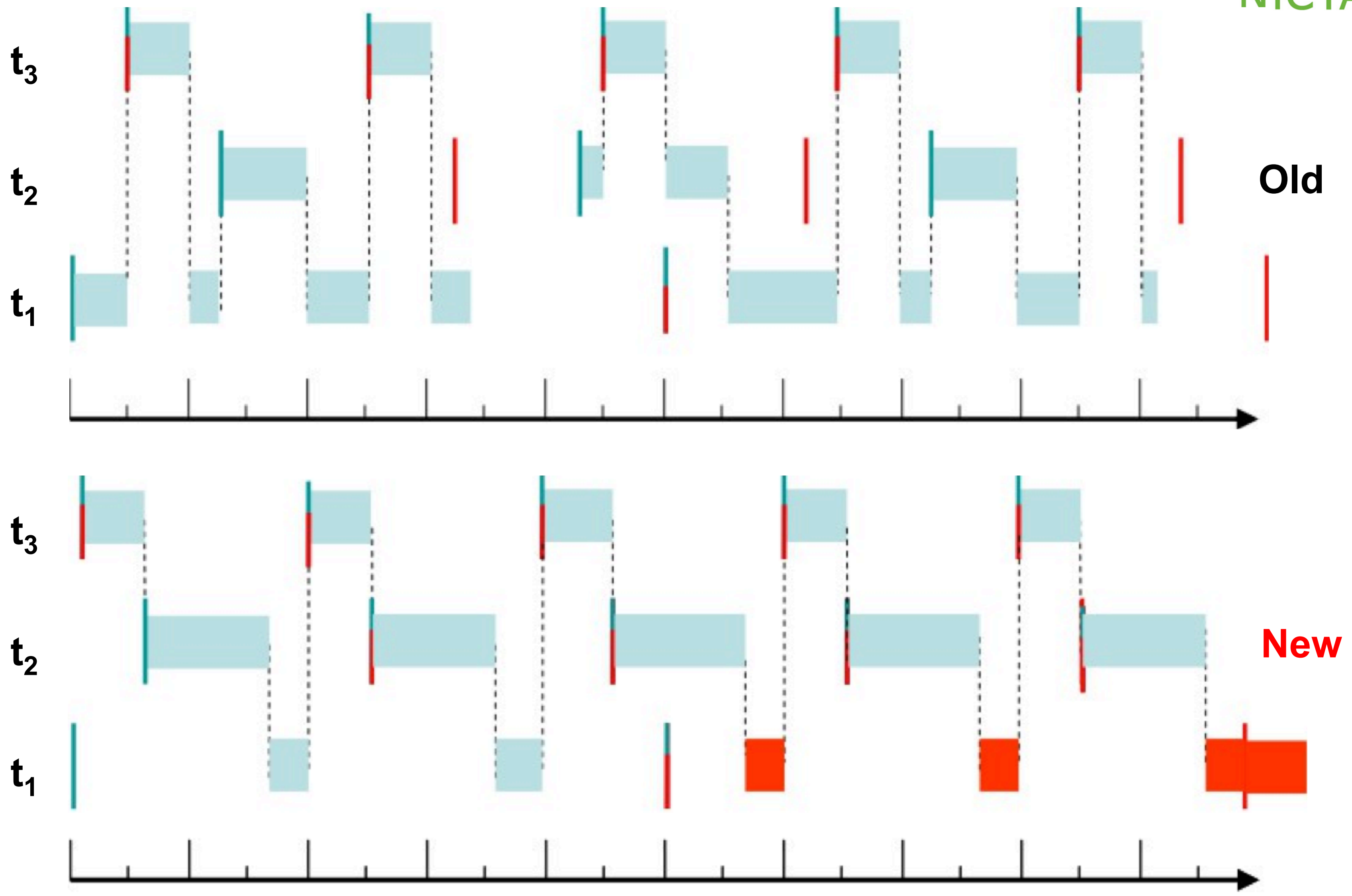
Overload: FPS



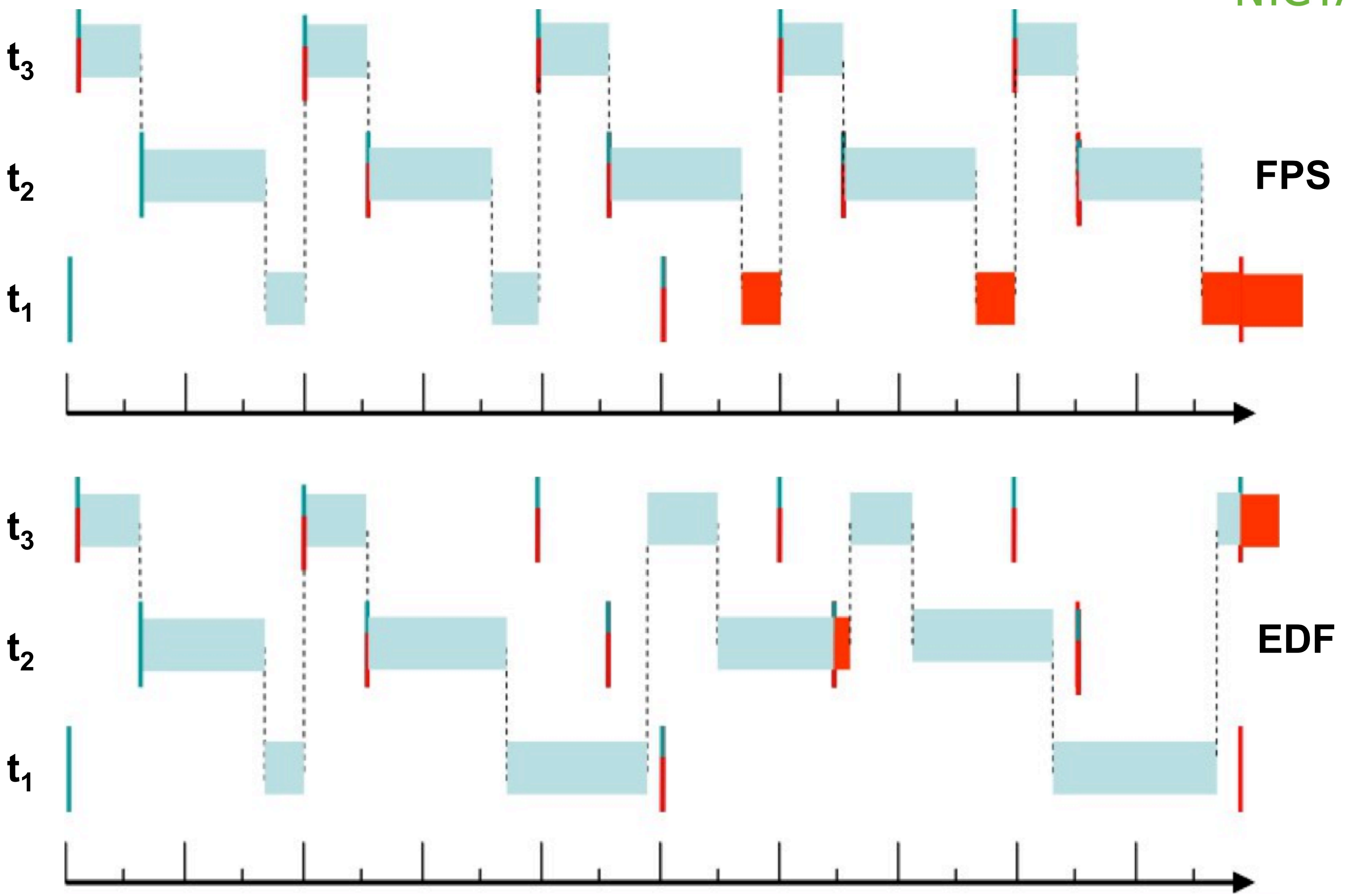
	P	C	T	D	U [%]
t_3	3	5	20	20	25
t_2	2	12	20	20	60
t_1	1	15	50	50	30
					115

New

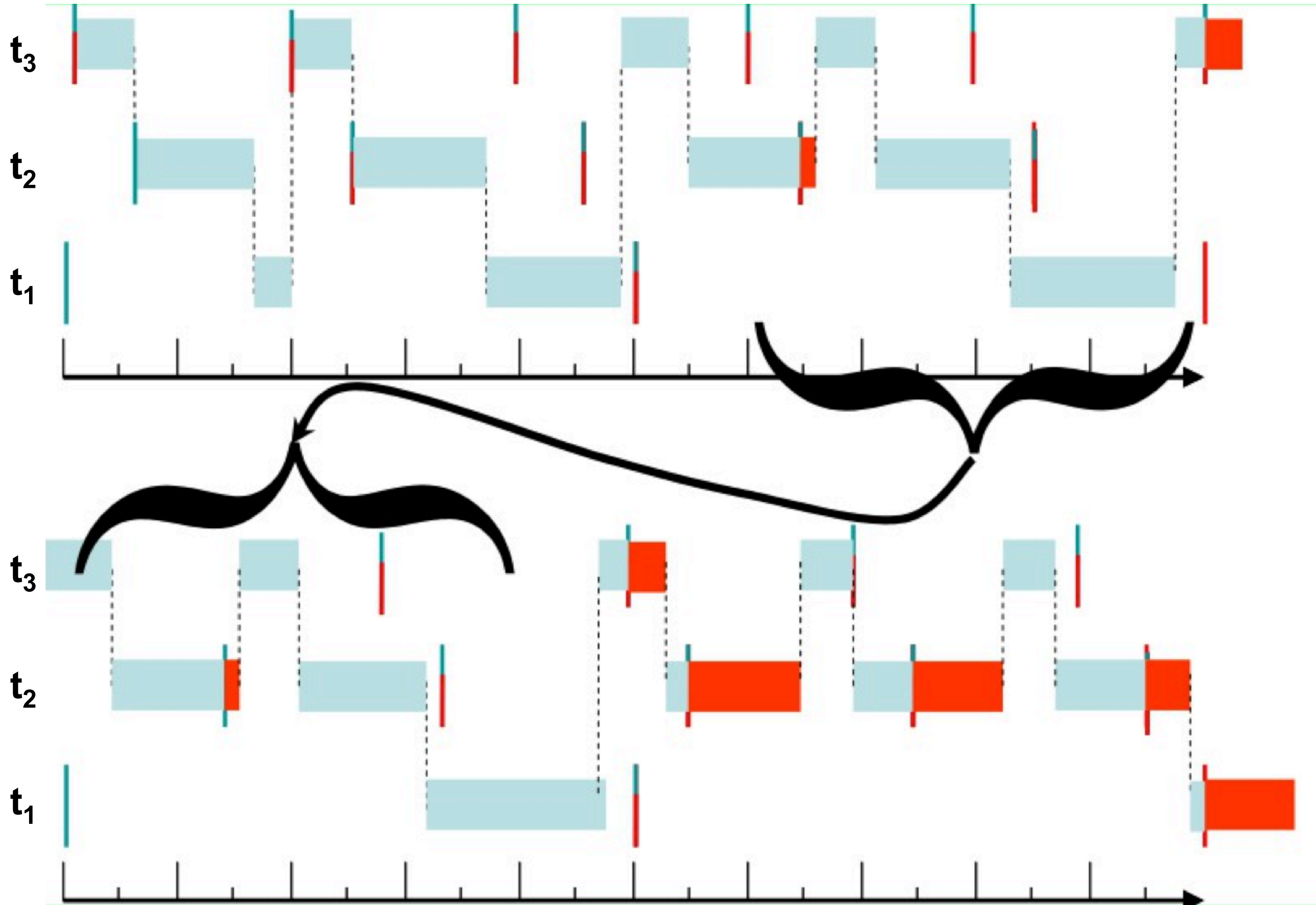
Overload: FPS



Overload: FPS vs EDF



Overload: EDF



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Overload: FPS vs EDF

On overload, (by definition!) *lowest-prio jobs miss deadlines*

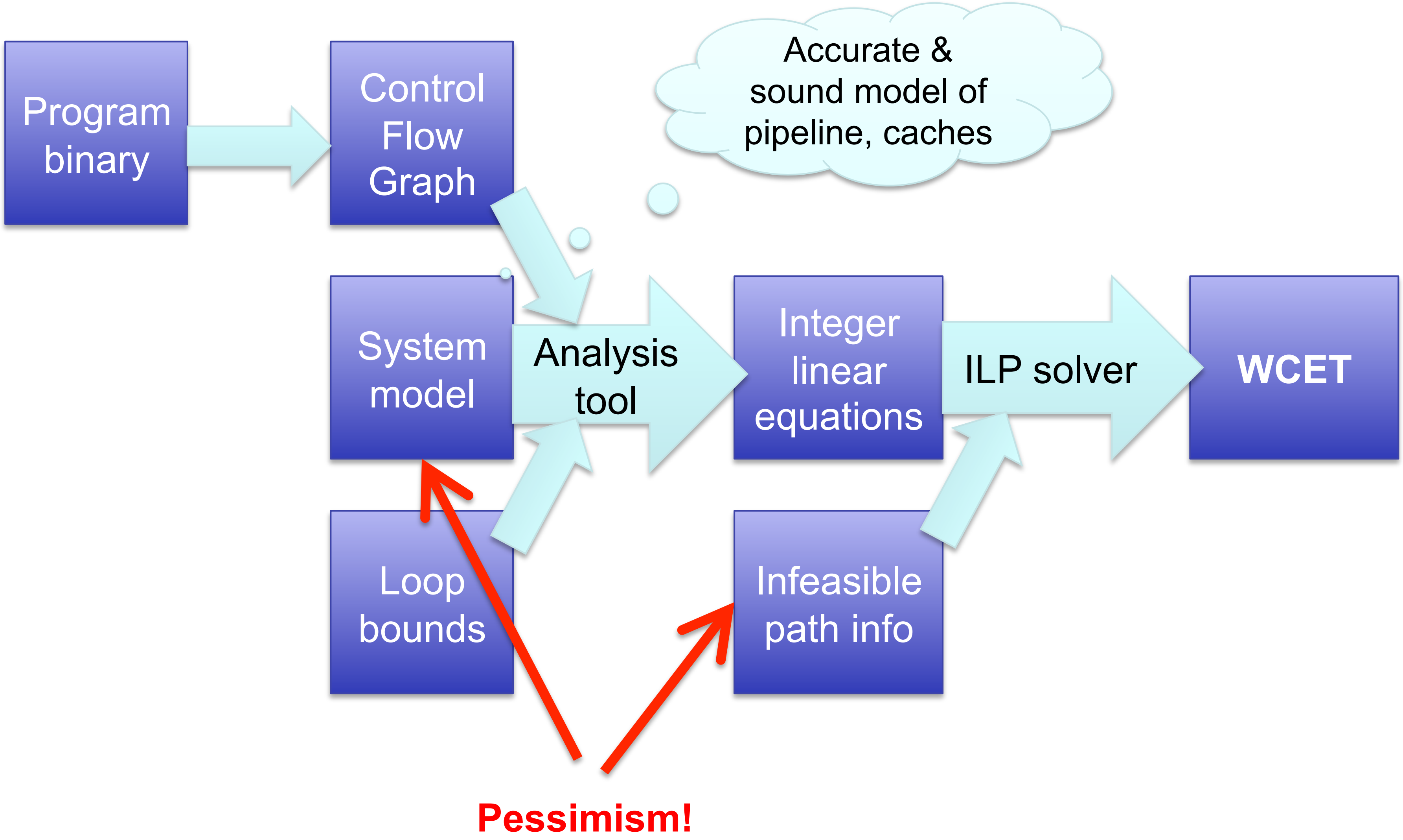
- Result is well-defined and -understood for FPS
  - Treats highest-prio task as “most important”
  - … but that may not always be appropriate!
  - Under transient overload may miss deadlines of higher-priority tasks

- Result is unpredictable (apparently random) for EDF
  - May result in all tasks missing deadlines!
  - Under constant overload will scale back all tasks
  - No concept of task “importance”
  - “EDF behaves badly under overload”
  - Main reason EDF is unpopular in industry

Why Have Overload?

- Faults (software, EMI, hardware)
- Incorrect assumptions about environment
- Optimistic WCET
  - Computing WCET of non-trivial programs is hard!
  - Safe WCET bounds tend to be highly pessimistic (orders of magnitude!)
  - WCET often very unlikely and orders of magnitude worse than “normal”
    - thanks to caches, pipelines, under-specified hardware
    - requires massive over-provisioning
  - Some systems have effectively unbounded execution time
    - e.g. object tracking

WCET Analysis



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  - WCET often very unlikely and orders of magnitude worse than “normal”
    - thanks to caches, pipelines, under-specified hardware
    - requires massive over-provisioning

Way out?

- Need explicit notion of importance: *criticality*
- Expresses effect of failure on the system mission
  - Catastrophic, hazardous, major, minor, no effect
- Orthogonal to scheduling priority

Mixed Criticality

- A mixed-criticality system supports multiple criticalities concurrently
  - Eg in avionics: consolidation of multiple functionalities
  - Higher criticality requires more pessimistic analysis, higher certification
  - Needs more than just scheduling support: strong OS-level isolation
- In overload scheduler drops lowest criticality
  - Current research issue

Must handle

Criticality	T	U_{worst}	U_{expec}	$U_{average}$
High	10	50%	50%	0.05%
Medium	1	(200%)	10%	2.5%
Low	100	(1000%)	20%	10%
		over!	**80%**	**12.55%**

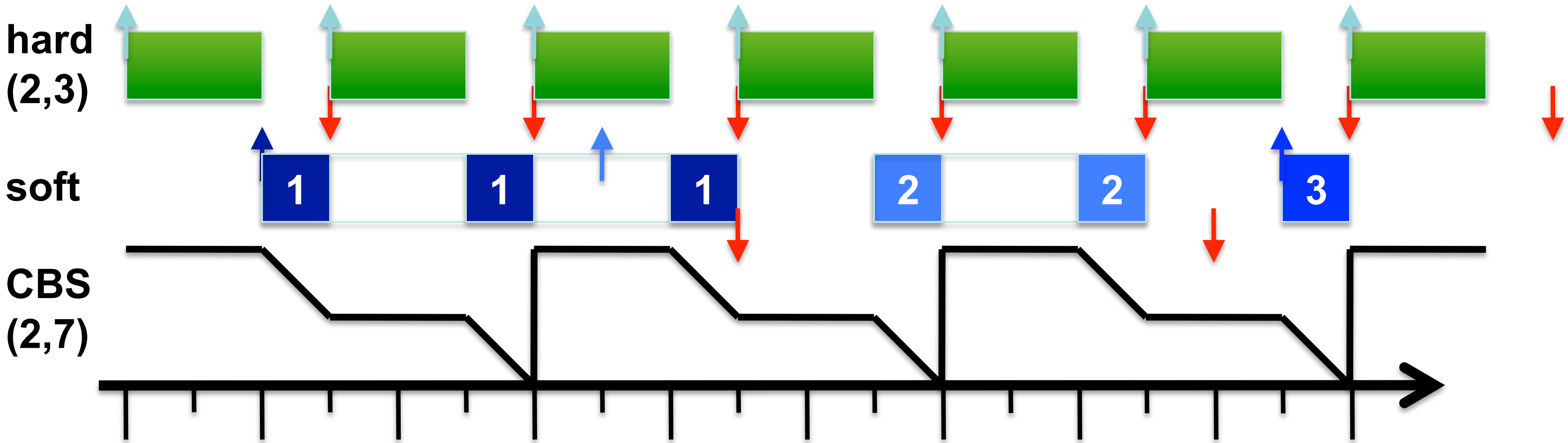
Not really known

Execution-Time Servers

- Scheduling model which
  - Allows dealing with jobs with unknown (or untrusted) deadlines
  - Allows integrating sporadic, asynchronous and soft tasks
- Core concept is a "server" which hands out time to jobs
  - effectively a simple (FIFO) sub-scheduler
- Popular: *Constant bandwidth server* (CBS) [Abeni & Buttazzo '98]

- Idea: server schedules a certain utilisation ("bandwidth")
  - server has a period, T and a *budget*, Q = U × T
  - generates appropriate absolute EDF deadlines on the fly
  - when executing a job, budget is consumed
  - when budget goes to zero, new deadline is generated with new budget

Constant Bandwidth Server



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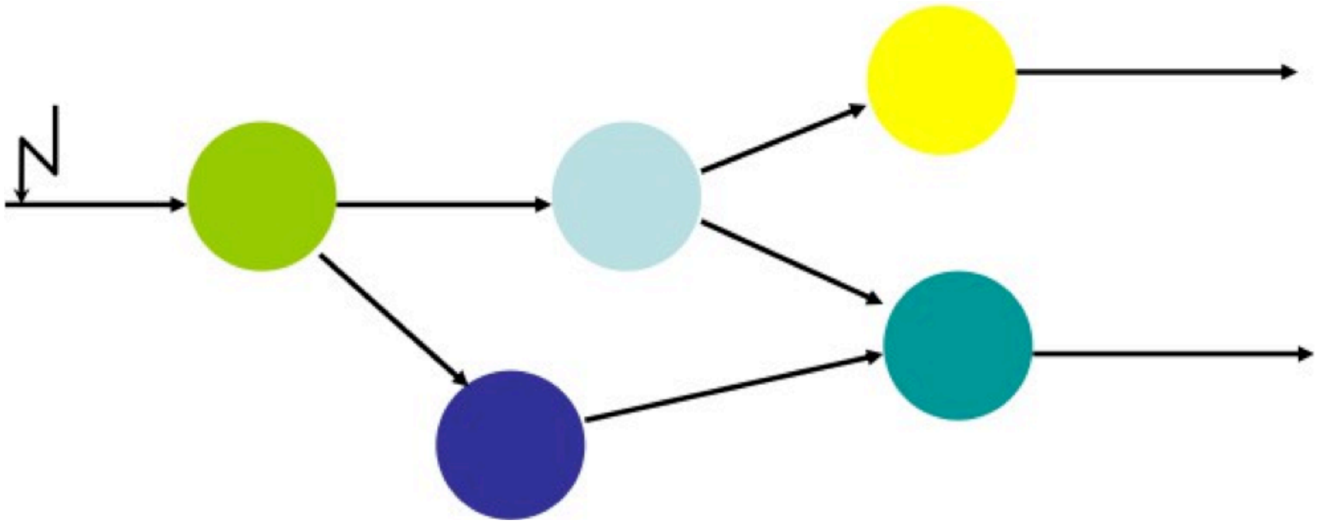
Message-Based Synchronisation

- Tasks may communicate via messages
  - blocking IPC
- Enforces precedence relations
- Tag deadlines onto messages



Shared Resources

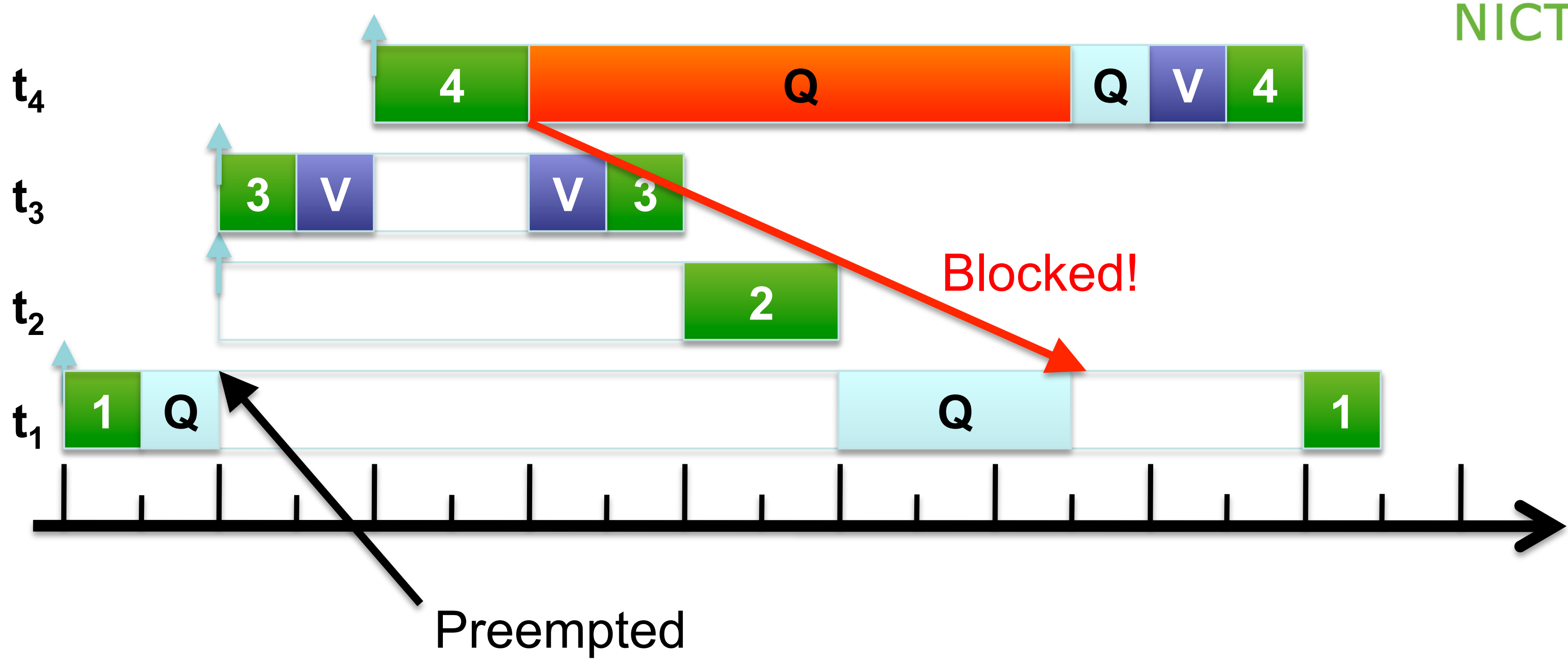
Concurrent access to shared resources

```
t_low() {
    ….
    wait(sem);
    /* critical section */
    signal(sem);
    …
}
```

```
t_high() {
    ….
    wait(sem);
    /* critical section */
    signal(sem);
    …
}
```

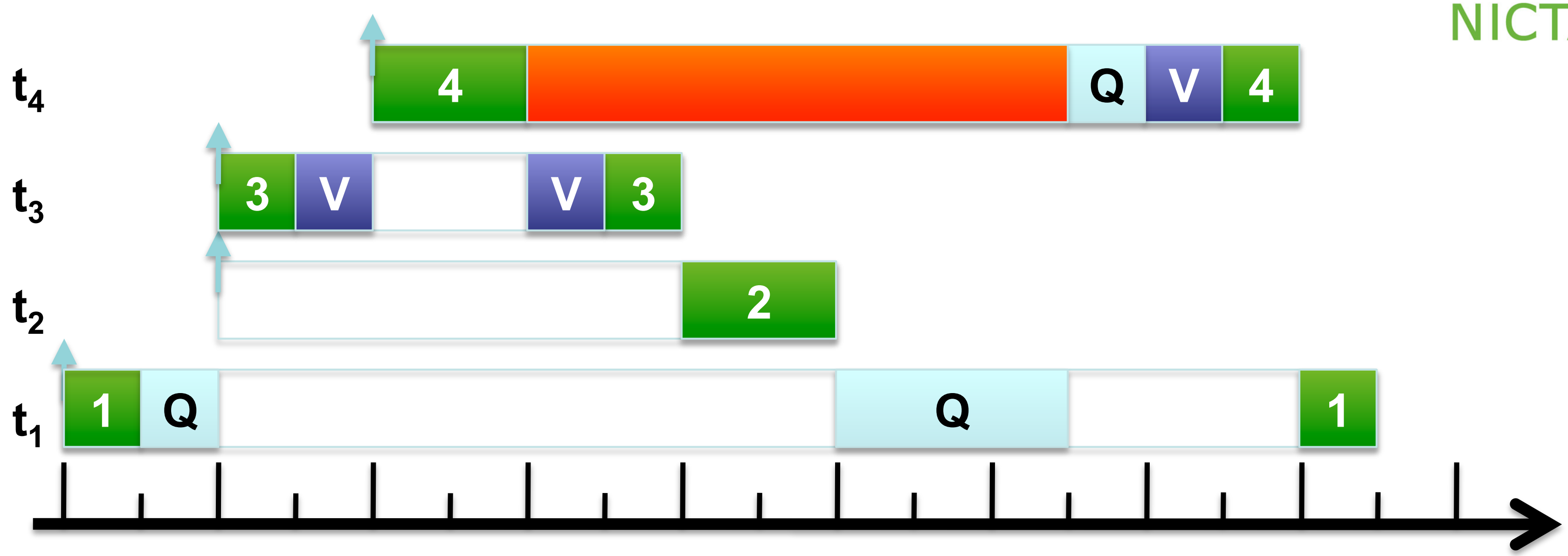
- High-priority job is blocked, waiting for low-priority job
- *Priority inversion!*
- Undermines scheduling policy
- Must limit and control enough to still allow analysis of timeliness

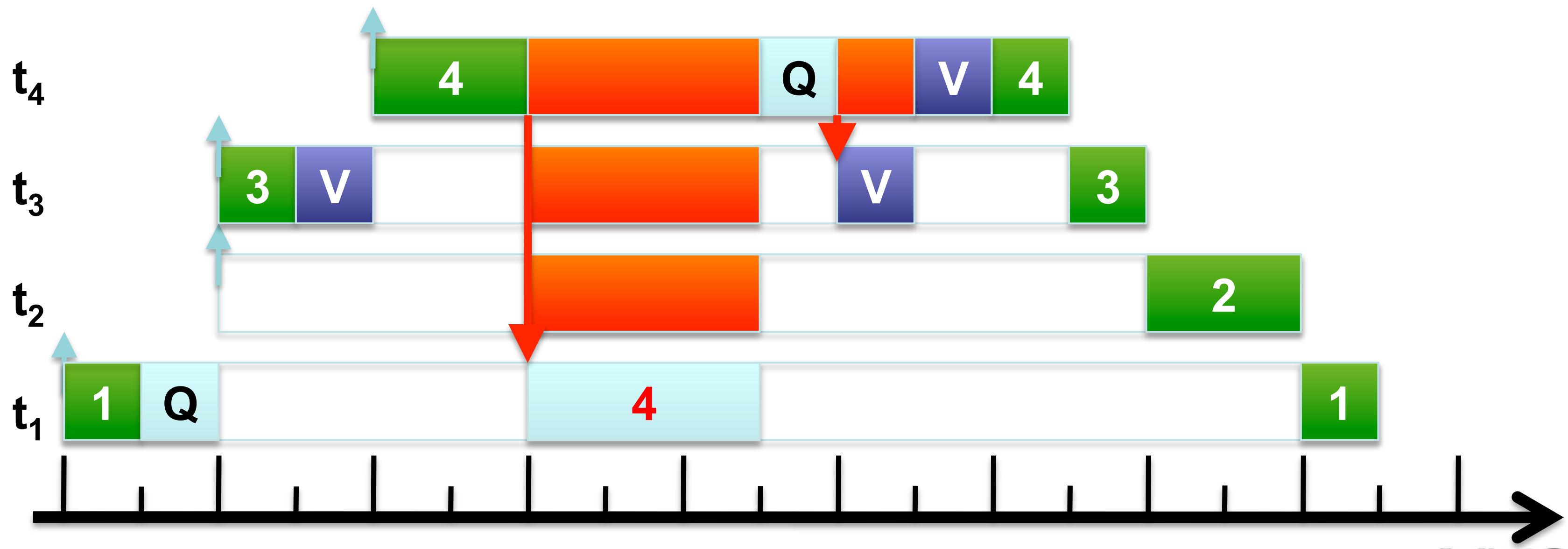
Priority Inversion



- High-priority job is blocked for a long time by a low-prio job
- Long wait chain: $t_1 \rightarrow t_4 \rightarrow t_3 \rightarrow t_2$
- Worst-case blocking time of t_1 bounded only by $C_2+C_3+C_4$!
- Must find a way to do better!

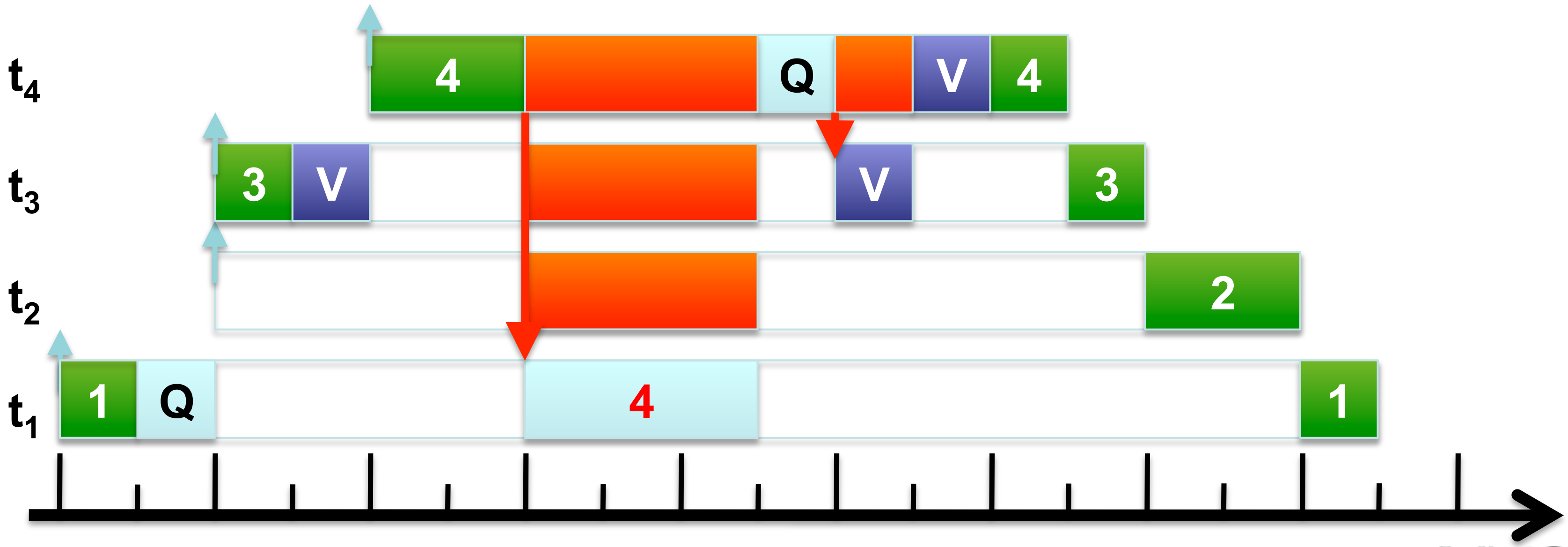
Priority Inheritance





Priority Inheritance

- If t_1 blocks on a resource held by t_2, *and* $P_1 > P_2$, then
  - t_2 is temporarily given priority P_1
  - when t_t releases the resource, its priority reverts to P_2



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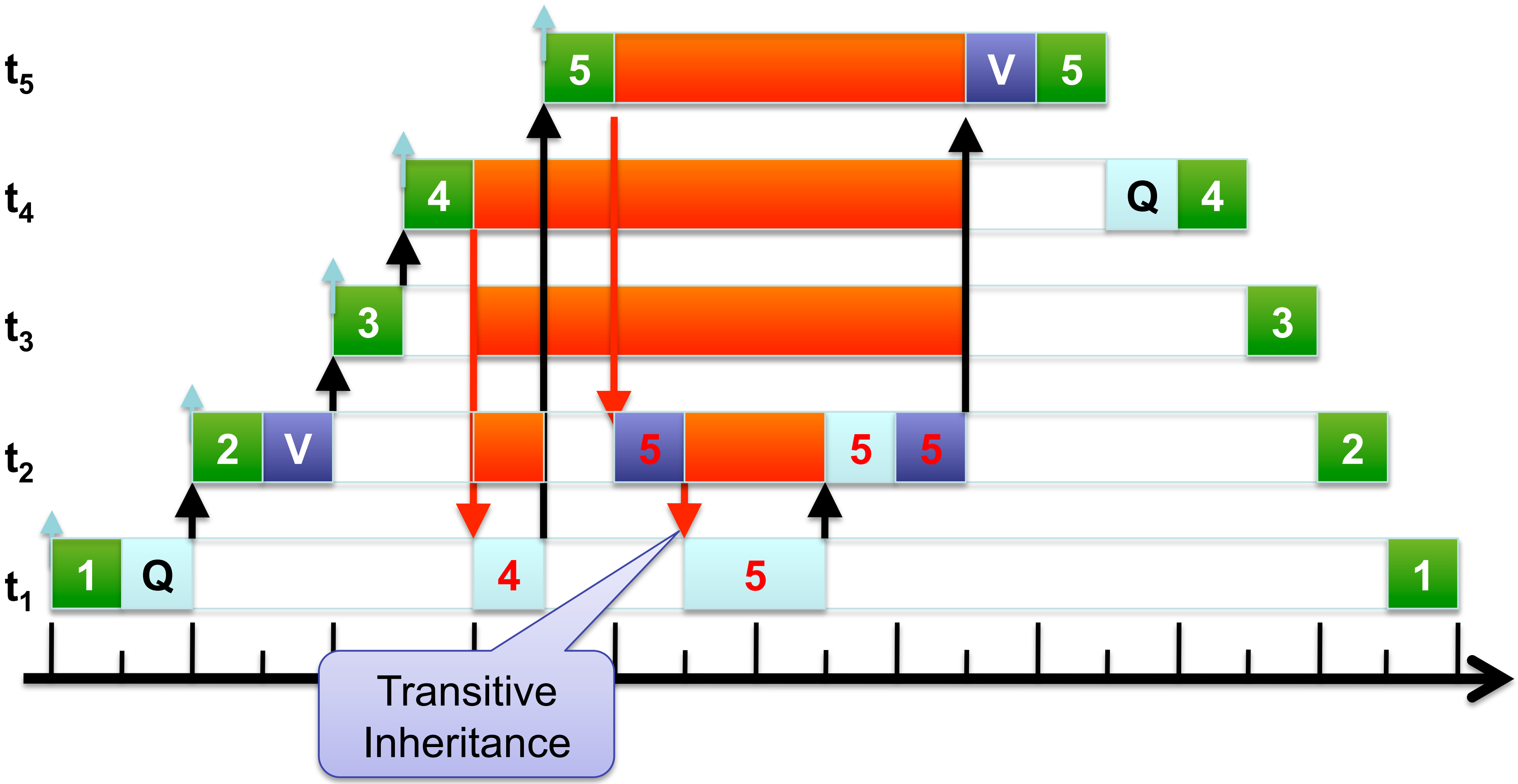

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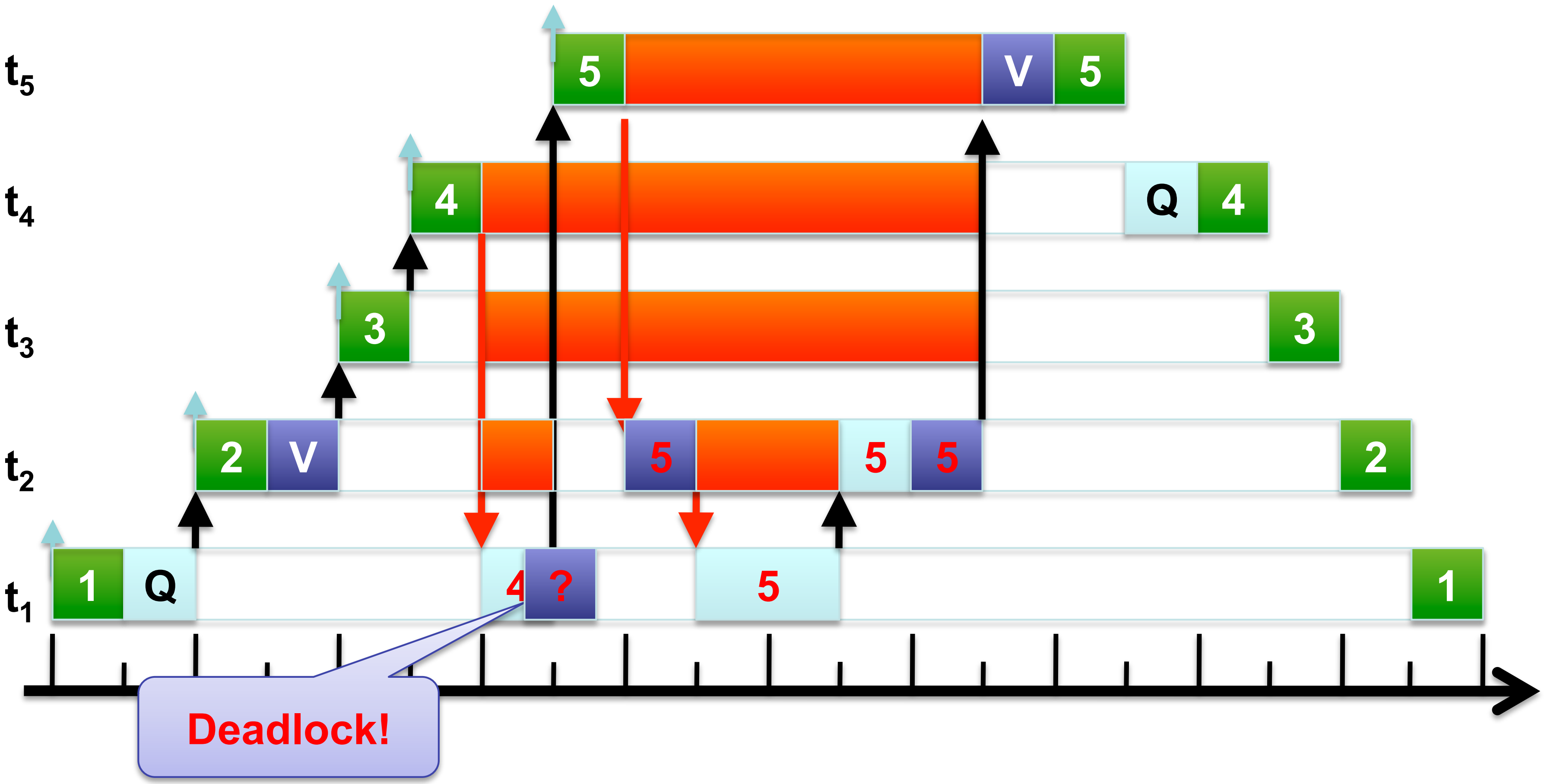


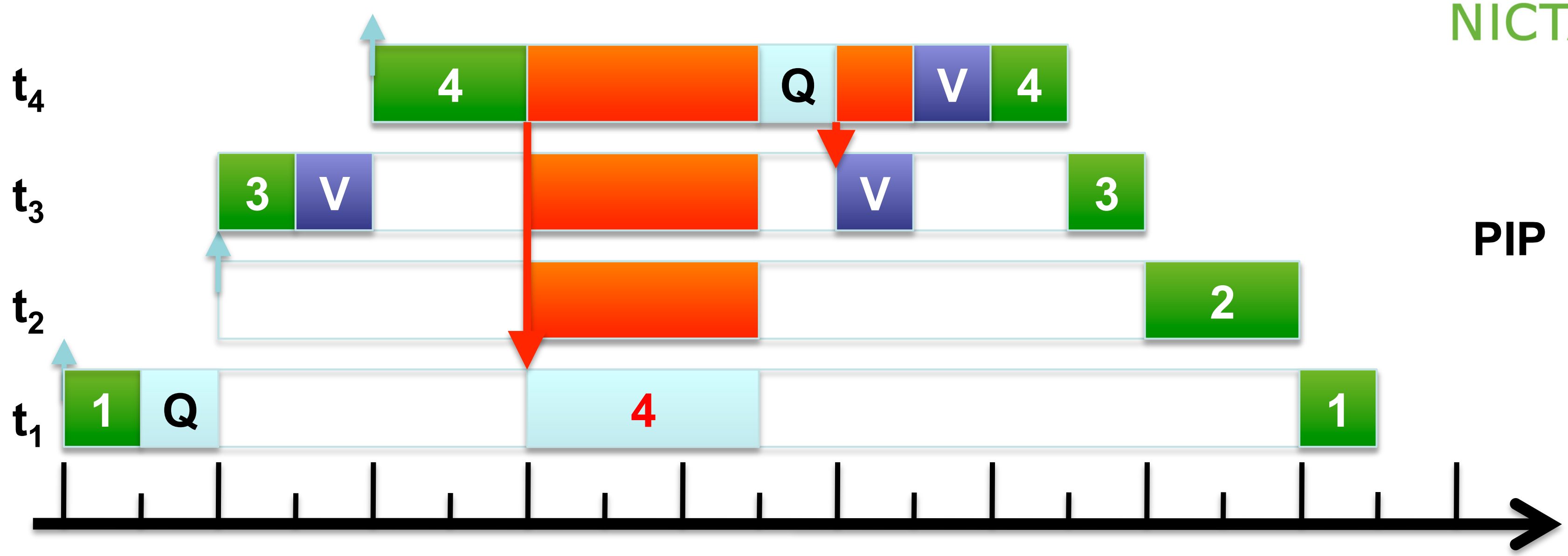
Priority Inheritance Protocol (PIP)

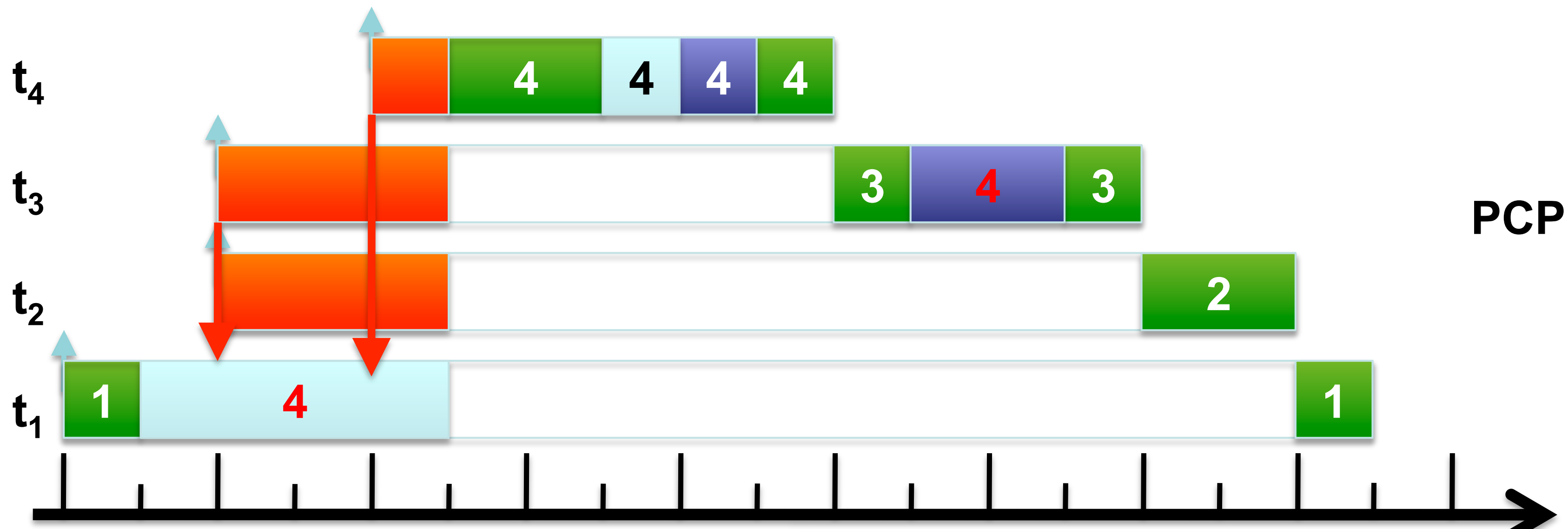
- If t_1 blocks on a resource held by t_2, *and* P_1>P_2, then
  - t_2 is temporarily given priority P_1
  - when t_t releases the resource, its priority reverts to P_2
- Transitive inheritance
  - potentially long blocking chains
  - potential for deadlock
- Frequently blocks much longer than necessary

Priority Ceiling Protocol (PCP)

- Purpose: ensure job can block at most once on a resource
  - avoid transitivity, potential for deadlocks
- Idea: associate a *ceiling priority* with each resource
  - equal to the highest priority of jobs that may use the resource
  - when job accesses its resource, immediately bump prio to ceiling!
- Also called:
  - *immediate ceiling priority protocol* (ICPP)
  - *ceiling priority protocol* (CPP)
  - *stack-based priority-ceiling protocol*
    - because it allows running all jobs on the same stack
- Improved version of the *original ceiling priority protocol* (OCPP)
  - … which is also called the *basic priority ceiling protocol*

Priority Ceiling Protocol





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  - avoid transitivity, potential for deadlocks
- Idea: associate a *ceiling priority* with each resource
  - equal to the highest priority of jobs that may use the resource
  - when job accesses its resource, immediately bump prio to ceiling!
- Properties:
  - Blocking time is limited to the duration of one critical section
  - Deadlock-free
  - Fewer context switches than OCPP
- Implementation:
  - Each task must declare all resources at admission time
    - System must maintain list of tasks associated with resource
    - Priority ceiling derived from this list
    - For EDF the "ceiling" is the *floor of relative deadlines*