Advanced Operating Systems

Real-Time Systems

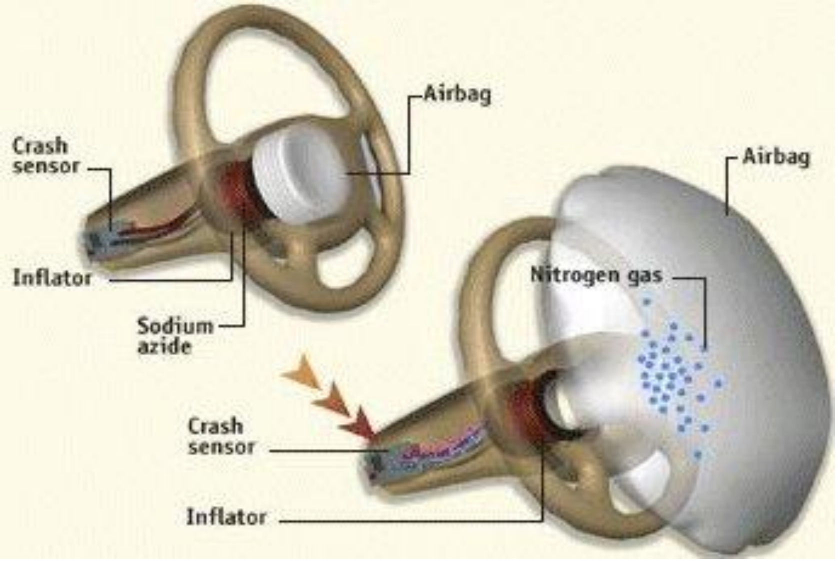
Lecture 6

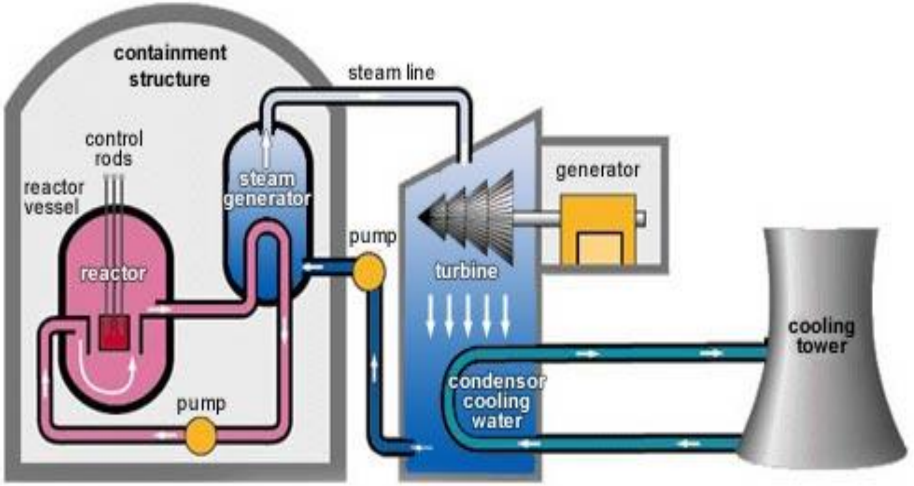
Real-Time System: Definition

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*:

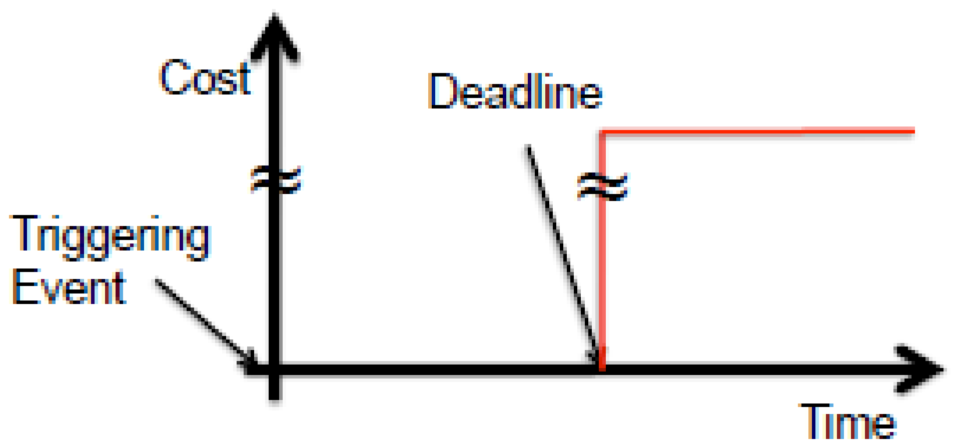
– A deadline is a time instant by which a response has to be completed

– 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

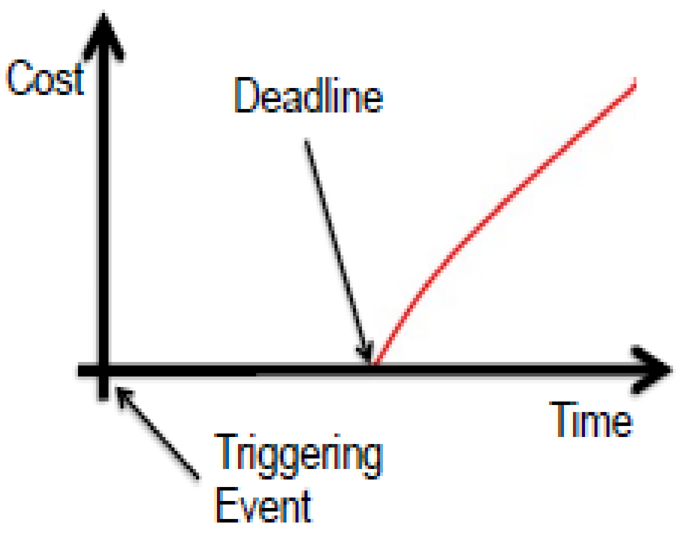
Hard Real-Time Systems

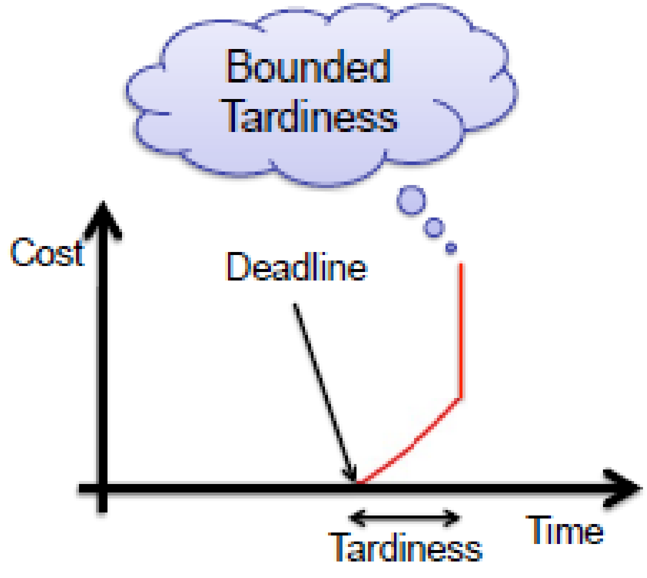
- Deadline miss is “catastrophic”
  – safety-critical system: failure results in death, severe injury
  – mission-critical system: failure results in massive financial damage
- Steep and real “cost” function



Soft Real-Time Systems

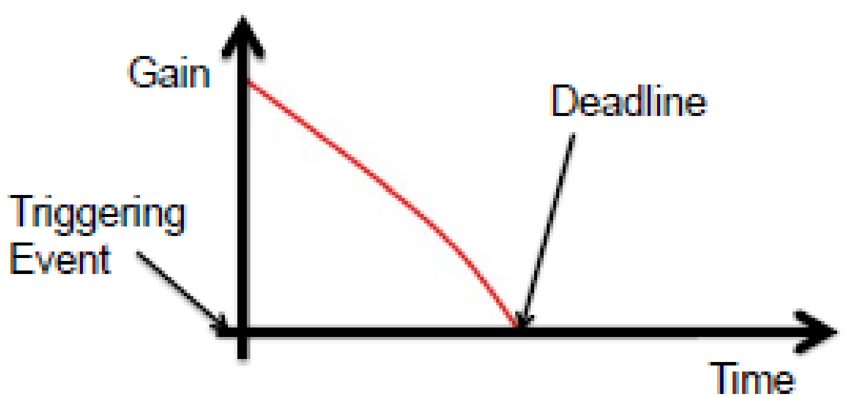
- Deadline miss is undesired but tolerable
  - Frequently results on quality-of-service (QoS) degradation
    - eg audio, video rendering
    - Steep “cost” function
- Cost of deadline miss may be abstract





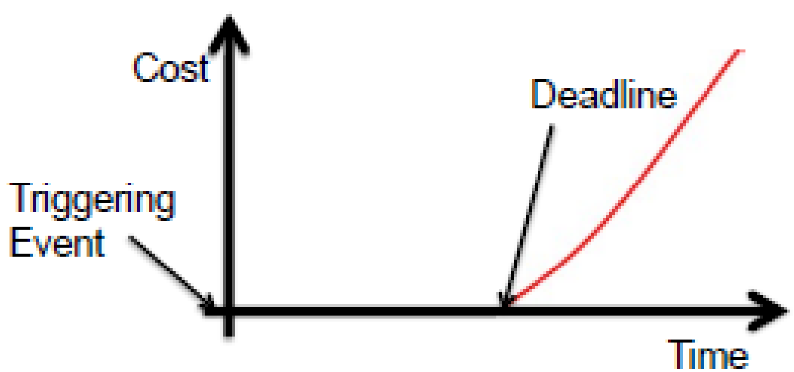
Firm Real-Time Systems

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



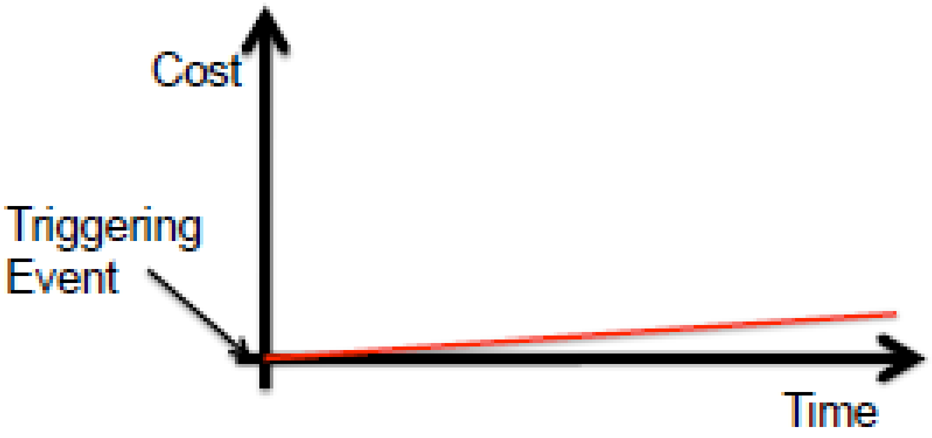
Weakly-Hard Real-Time Systems

- 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"
  - inherently cooperative
- 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

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

Real-Time Task Model

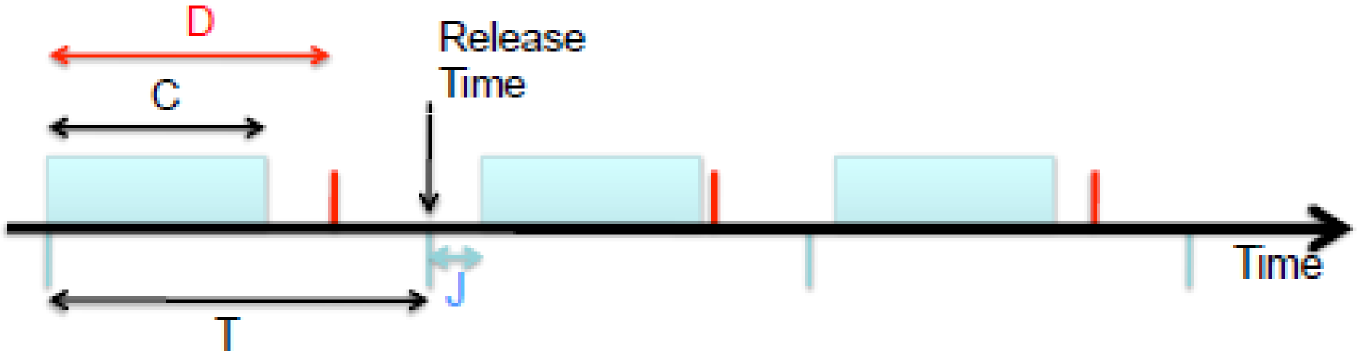
- **Job**: unit of work to be executed
  - … resulting from an event or time trigger
- **Task**: set of related jobs which provide some system function
  - A *task* is a sequence of *jobs* (typically executing same function)
  - Job *i+1* of a task cannot start until job *i* is completed/aborted

- 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 means higher priority
- B: Worst-case blocking time
- R: Worst-case response time
- U: Utilisation; U=C/T

OS terminology:
- "task" = thread
- "job" = event-based activation of thread



Task Constraints

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

    t1 ⇨ t2: t2 execution cannot start until t1 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 priority) or job-level (jobs change priorities)

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

- Note: “Fixed” in the sense that system doesn’t change them
  - OS may support dynamic adjustment
  - Requires on-the-fly (re-)admission control

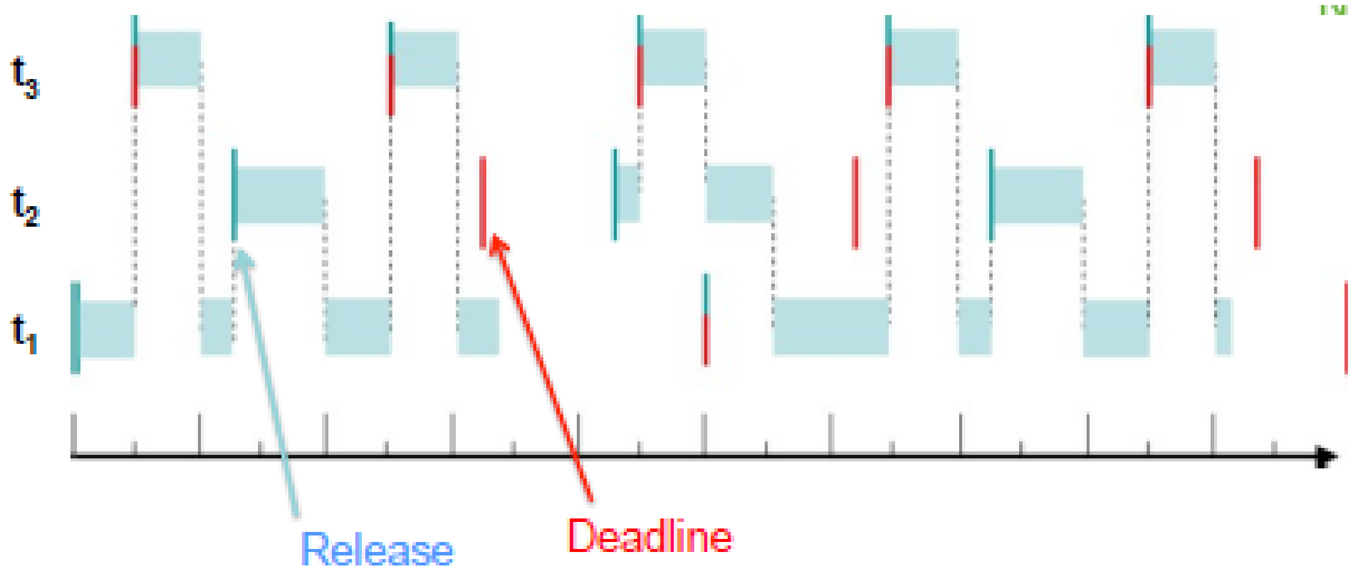
Rate-Monotonic (RM) Scheduling

- 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
  - $U \equiv \Sigma C_i/T_i \leq n(2^{1/n}-1)$; $\lim_{n\to\infty} U = \log 2$
    - 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	

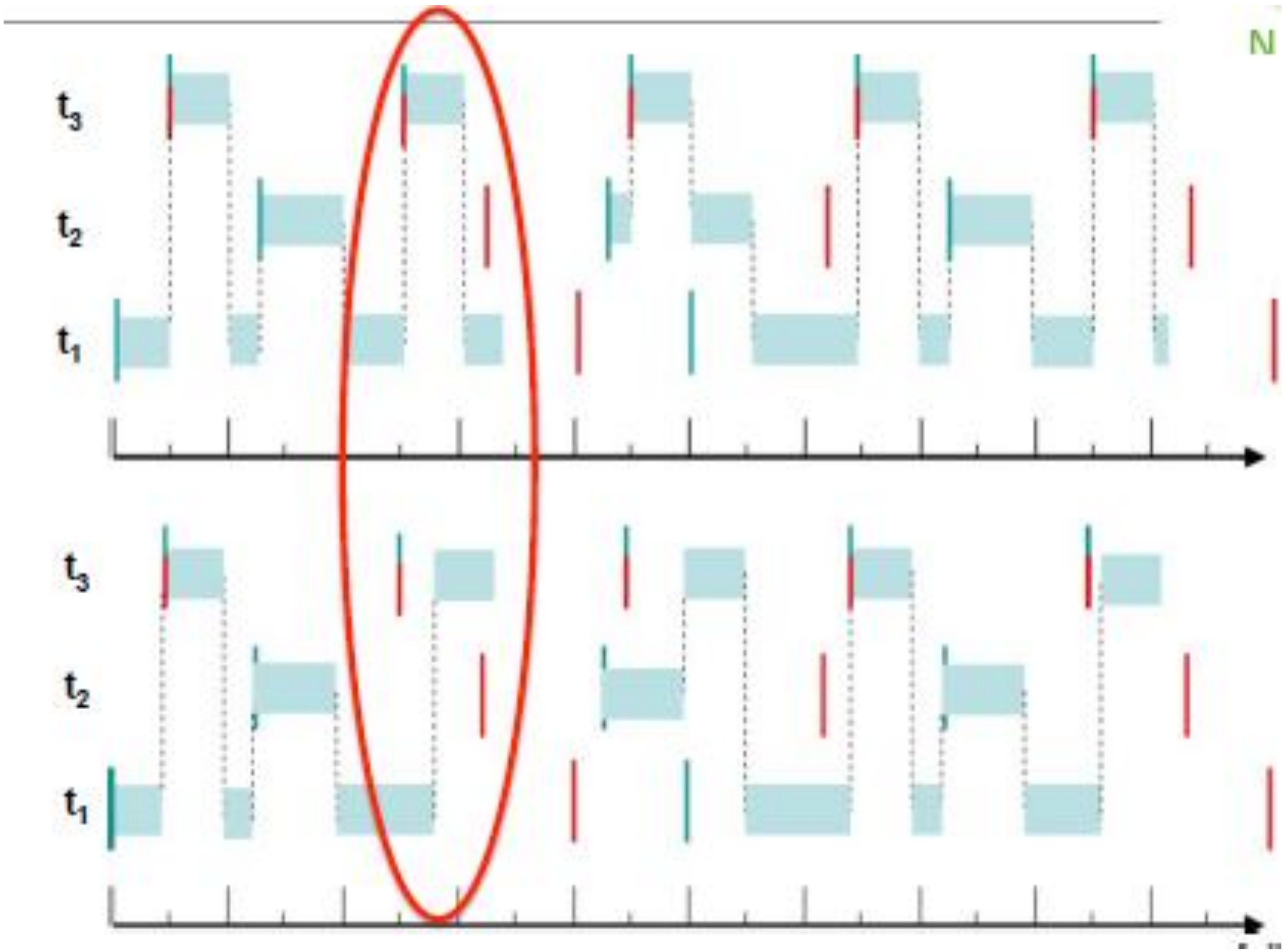
Earliest Deadline First (EDF)

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

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

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

FPS vs EDF



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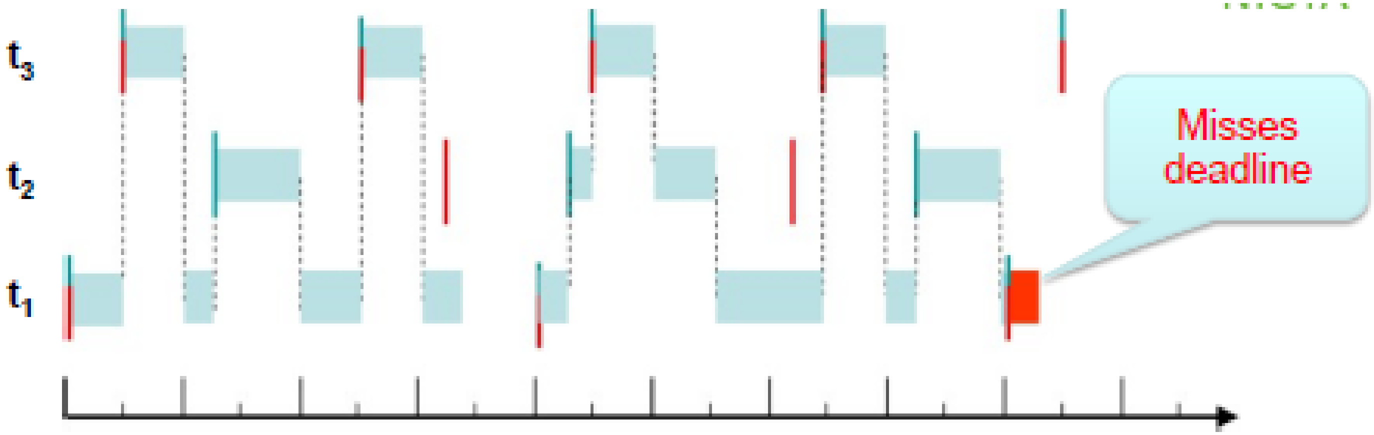
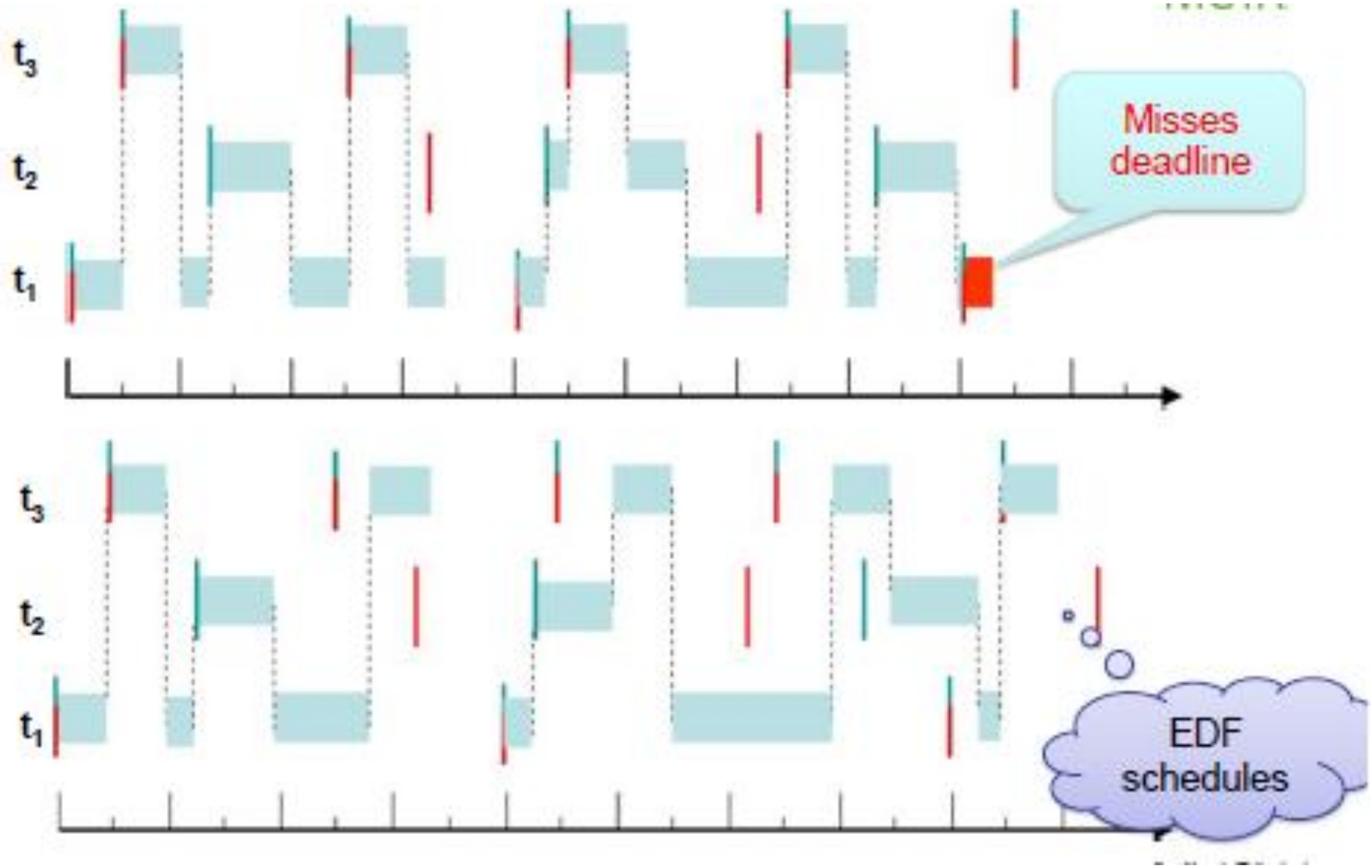
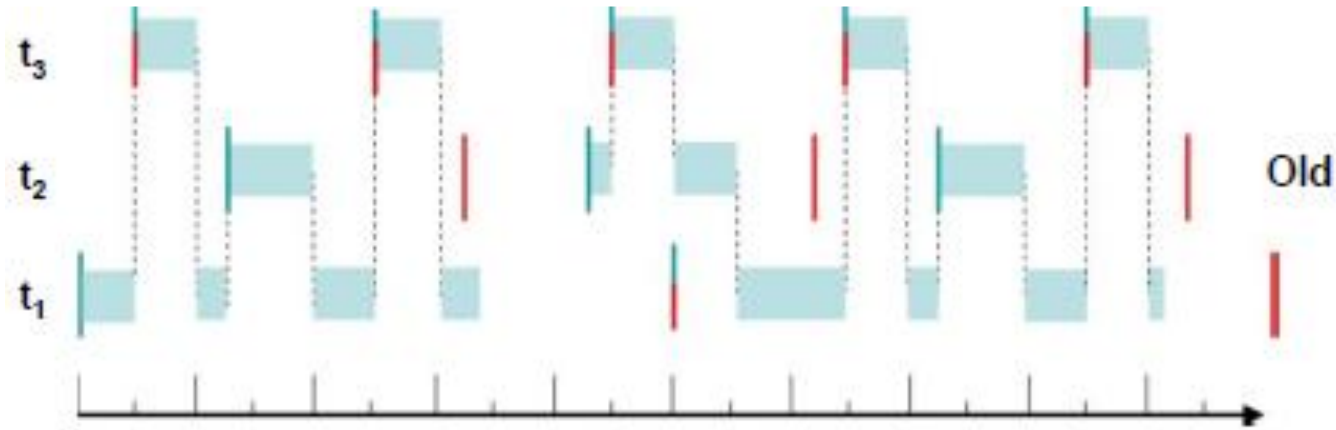


	P	C	T	D	U [%]	release
t_3	3	5	20	20	25	5
t_2	2	8	30	20	27	12
t_1	1	15	40	40	37.5	0
					89.5	

FPS vs EDF



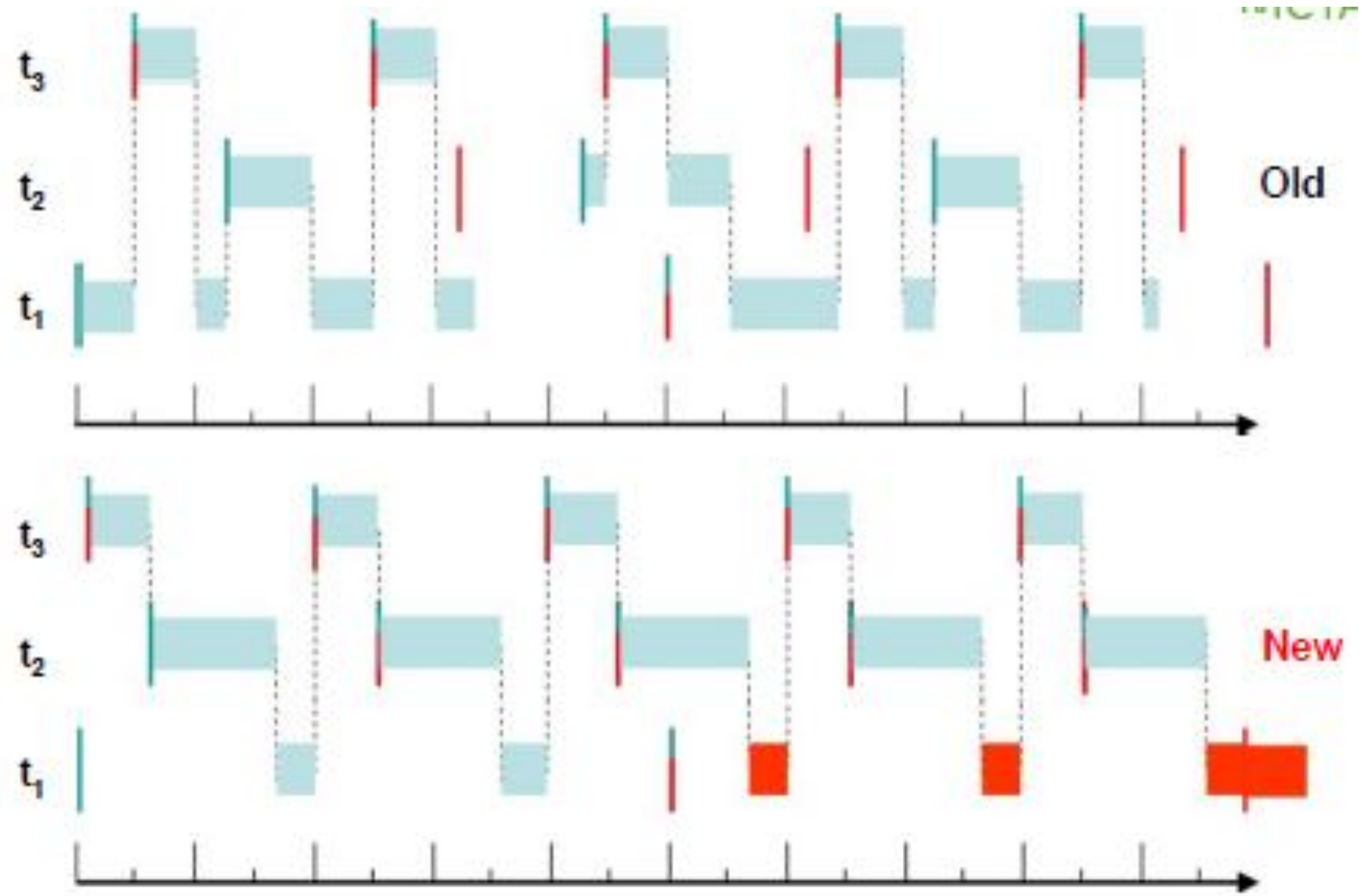
Overload: FPS



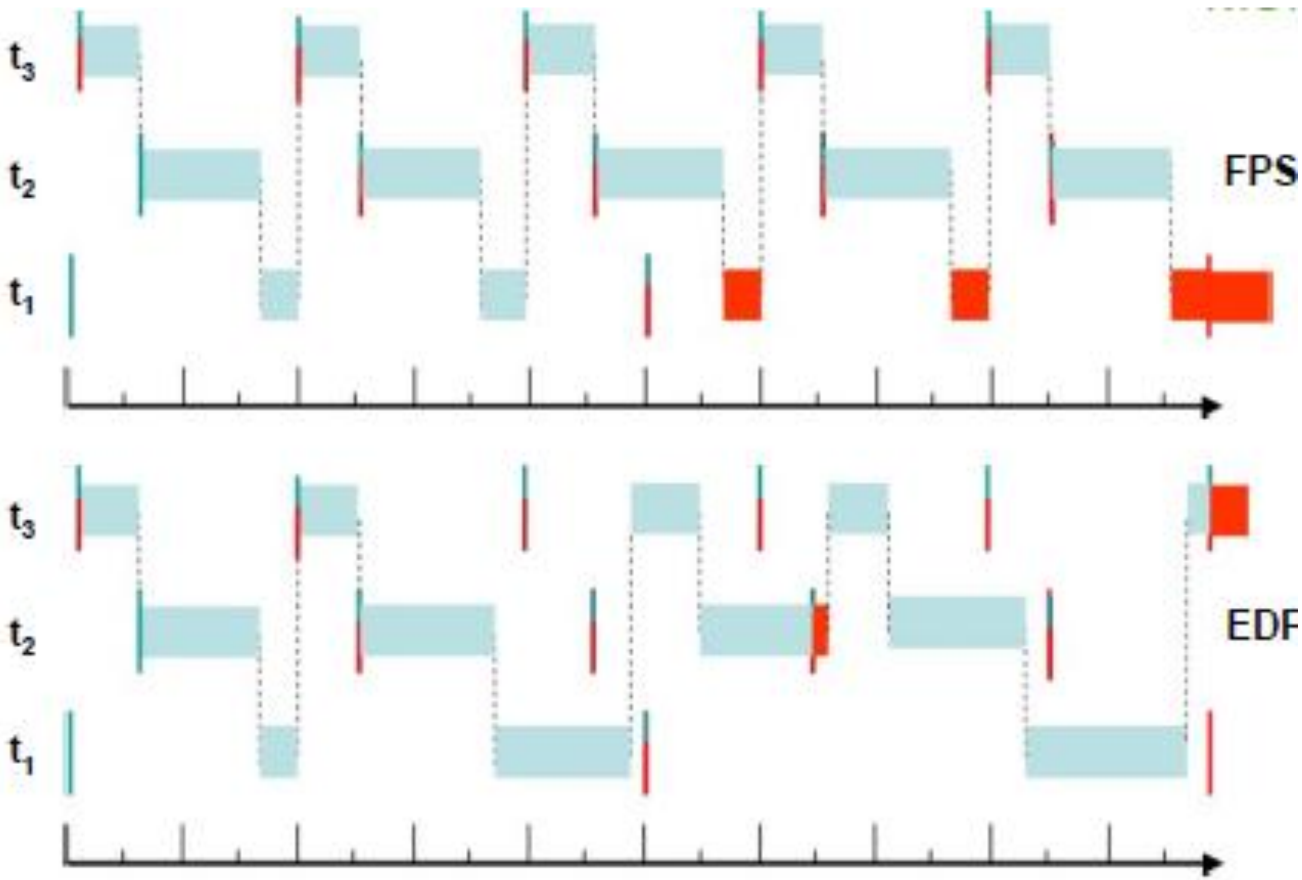
	P	C	T	D	U [%]
t_3	3	5	20	20	25
t_2	2	12	20	20	60
t_1	1	15	50	50	30
					115

New

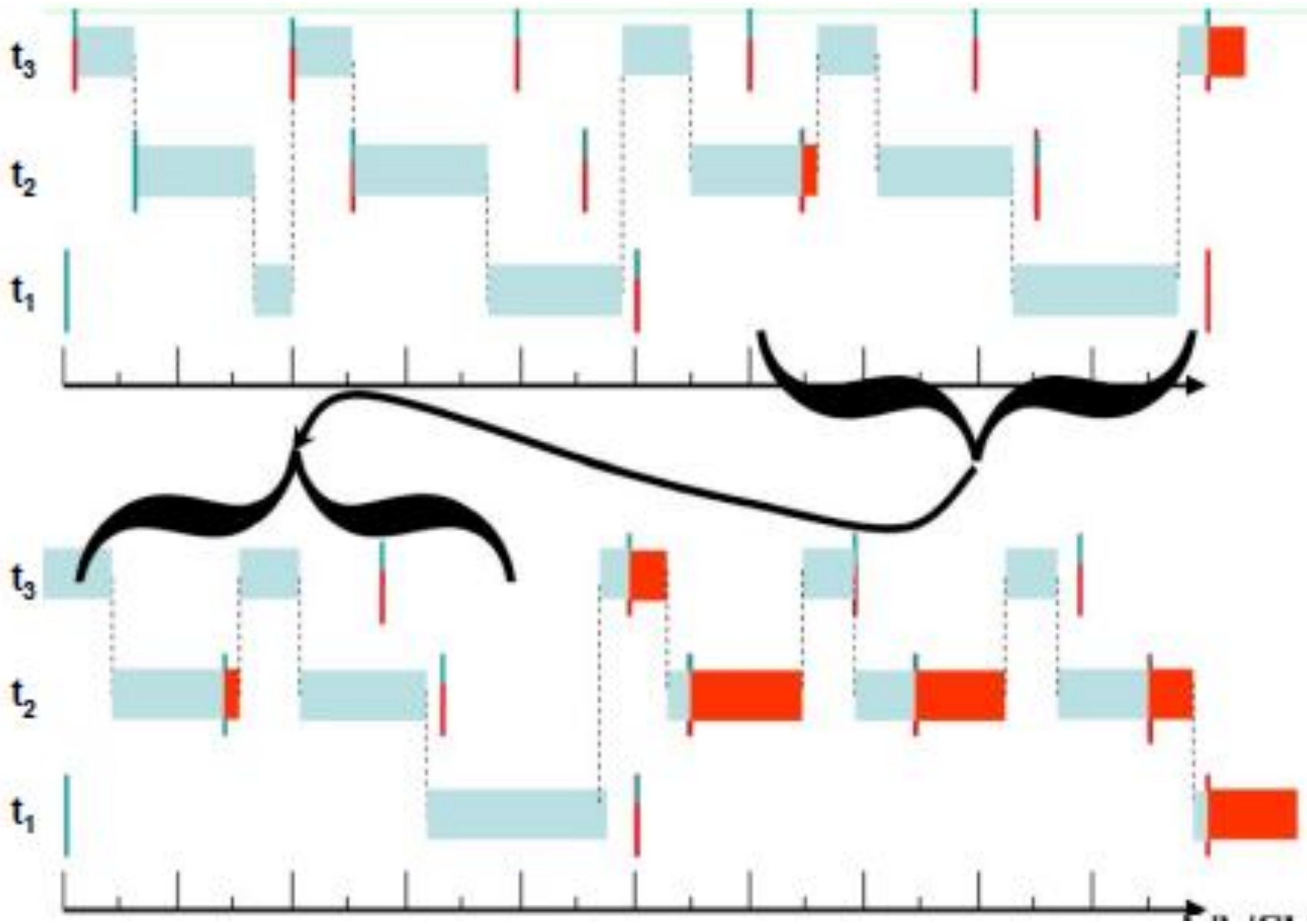
Overload: FPS



Overload: FPS vs EDF



Overload: EDF



Overload: FPS vs EDF

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

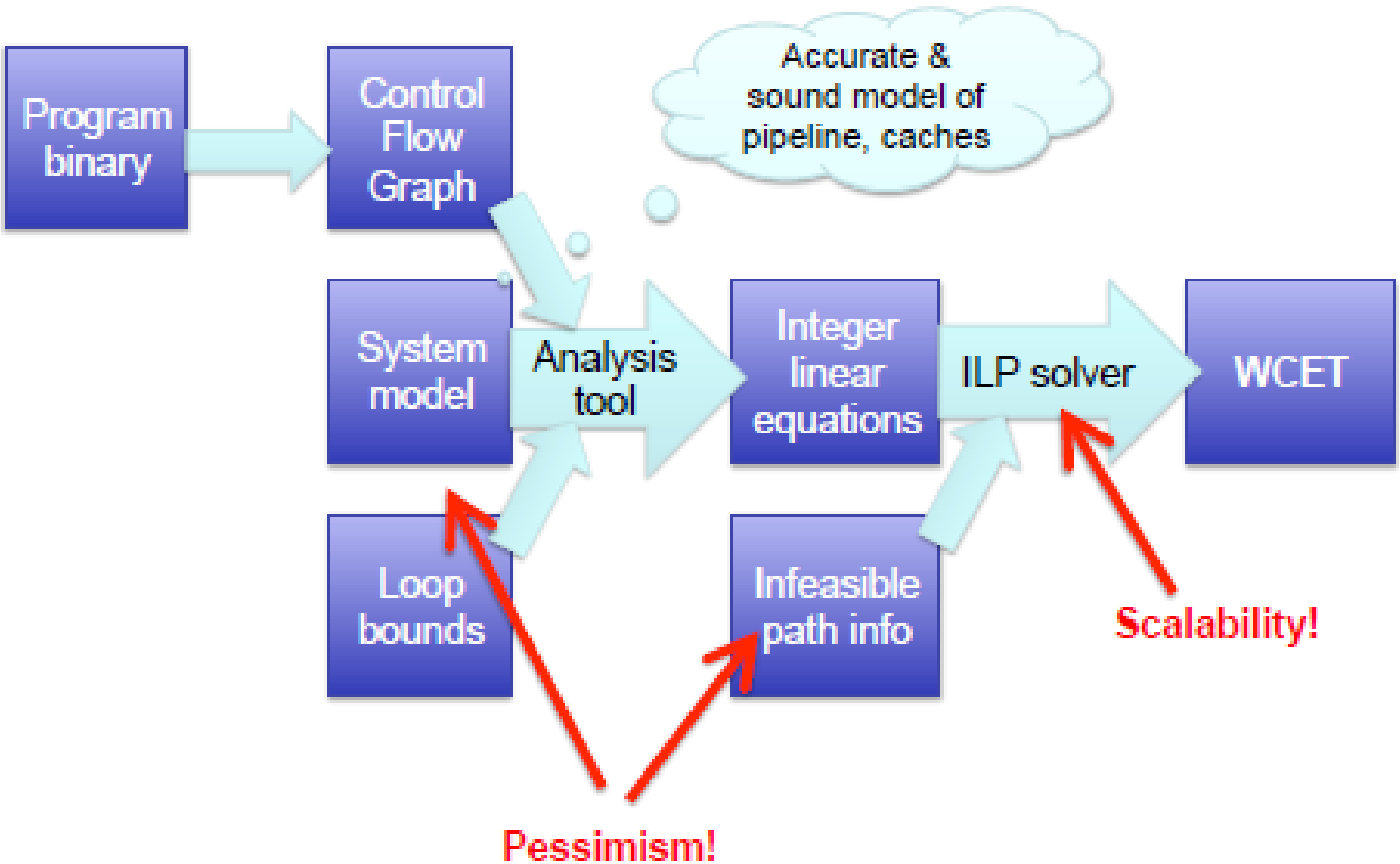
- Result is well-defined and -understood for FPS
  - Treats highest-prio task as "most important"
  - … but that may not always be appropriate!
  - Under transient overload may miss deadlines of higher-priority tasks

- 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, often infeasible!
  - 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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    - 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

Mixed Criticality Implementation

- Whenever running low job, ensure no high job misses deadline
- Switch to *critical mode* when not assured
  - Various approaches to determine switch
  - eg. *zero slack*: high job's deadline = its WCET

- Criticality-mode actions:
  - FP: temporarily drop all low jobs' prios below that of critical high!
    - Simply preempting present job won't help!
  - EDF: drop all low deadlines earlier than next high deadline
- Issues:
  - Treatment of low jobs still rather indiscriminate
  - Need to determine when to switch to normal mode, restore prios

- Alternative: use *reservations*

CPU Bandwidth Reservations

- Idea: Utilisation U = C/T can be seen as required CPU *bandwidth*
  - Account time use against reservation C
  - Not runnable when reservation exhausted
  - Replenish every T

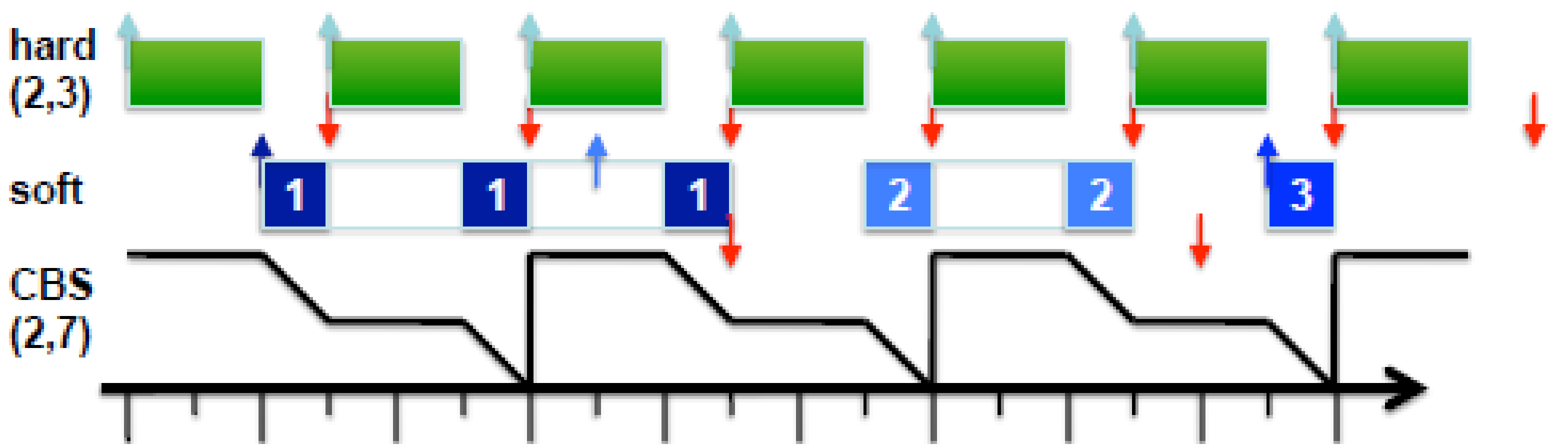
- Can support over-committing
  - Reduce low reservations if high reservations fully used

- Advantages:
  - Allows dealing with jobs with unknown (or untrusted) deadlines
  - Allows integrating sporadic, asynchronous and soft tasks

- Modelled as a “server” which hands out time to jobs
  - effectively a simple (FIFO) sub-scheduler

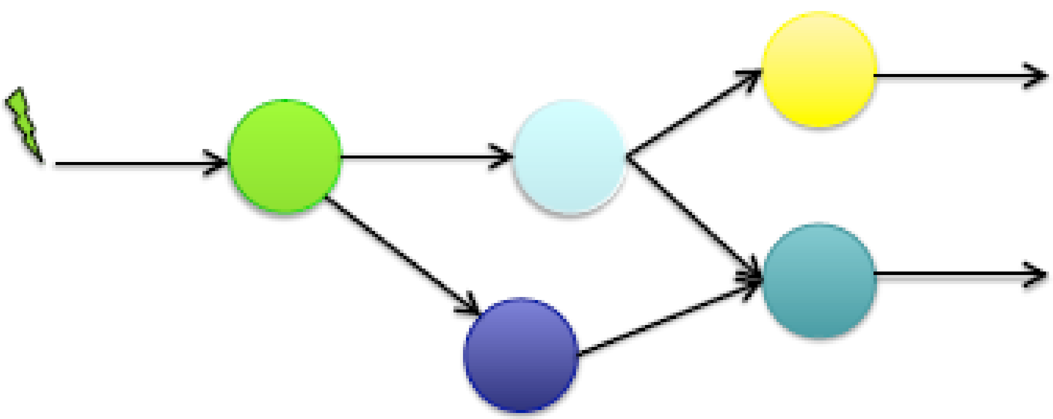
Constand Bandwidth Server (CBS)

- Popular theoretical model suitable for EDF [Abeni & Buttazzo '98]
- CBS schedules specified 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
    - $D_{i+1} = D_i + T$
    - Schedulability: $\Sigma U_i \leq 1$



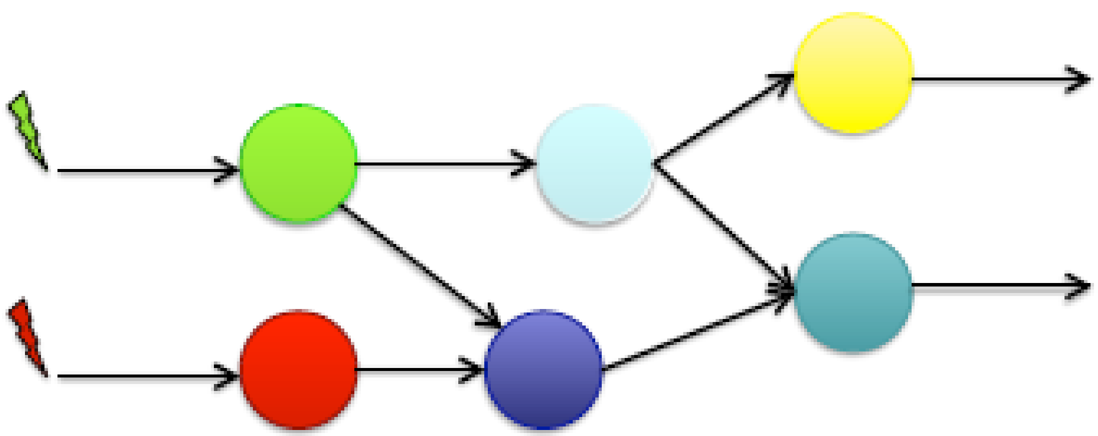
Message-Based Synchronisation

- Tasks may communicate via messages
  - blocking IPC
- Enforces precedence relations
- Allows sharing resources (services)
- Tag prios/deadlines onto messages
  - Classical L4 approach: timeslice donation:
    - Receiver continues on sender's time slice (and prio)
    - Avoids scheduler invocation



Synchronisation Issues

- Thread invoked by IPC is essentially a Hoare-style *monitor*
  - Typical in client-server scenario
  - Blocks other threads IPCing to same thread
  - How long?
- Time-slice preemption during monitor?
- Worse: priority inversion – general issue with shared resources



Shared Resources

Problem is not restricted to synchronous communication

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

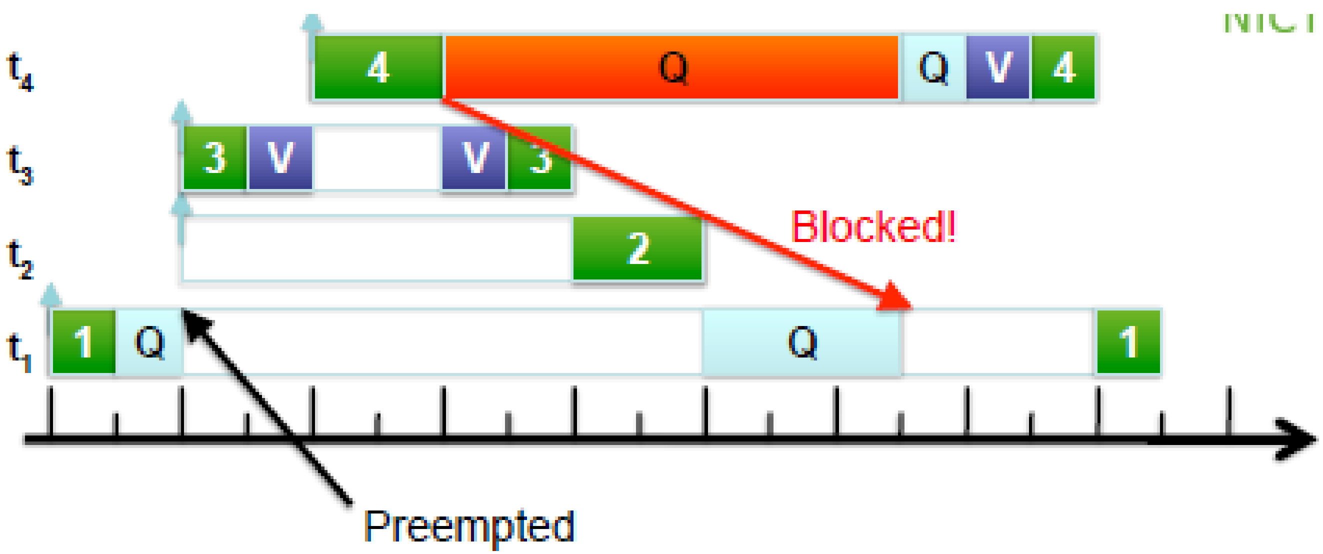
Async EP

seL4_Notify

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

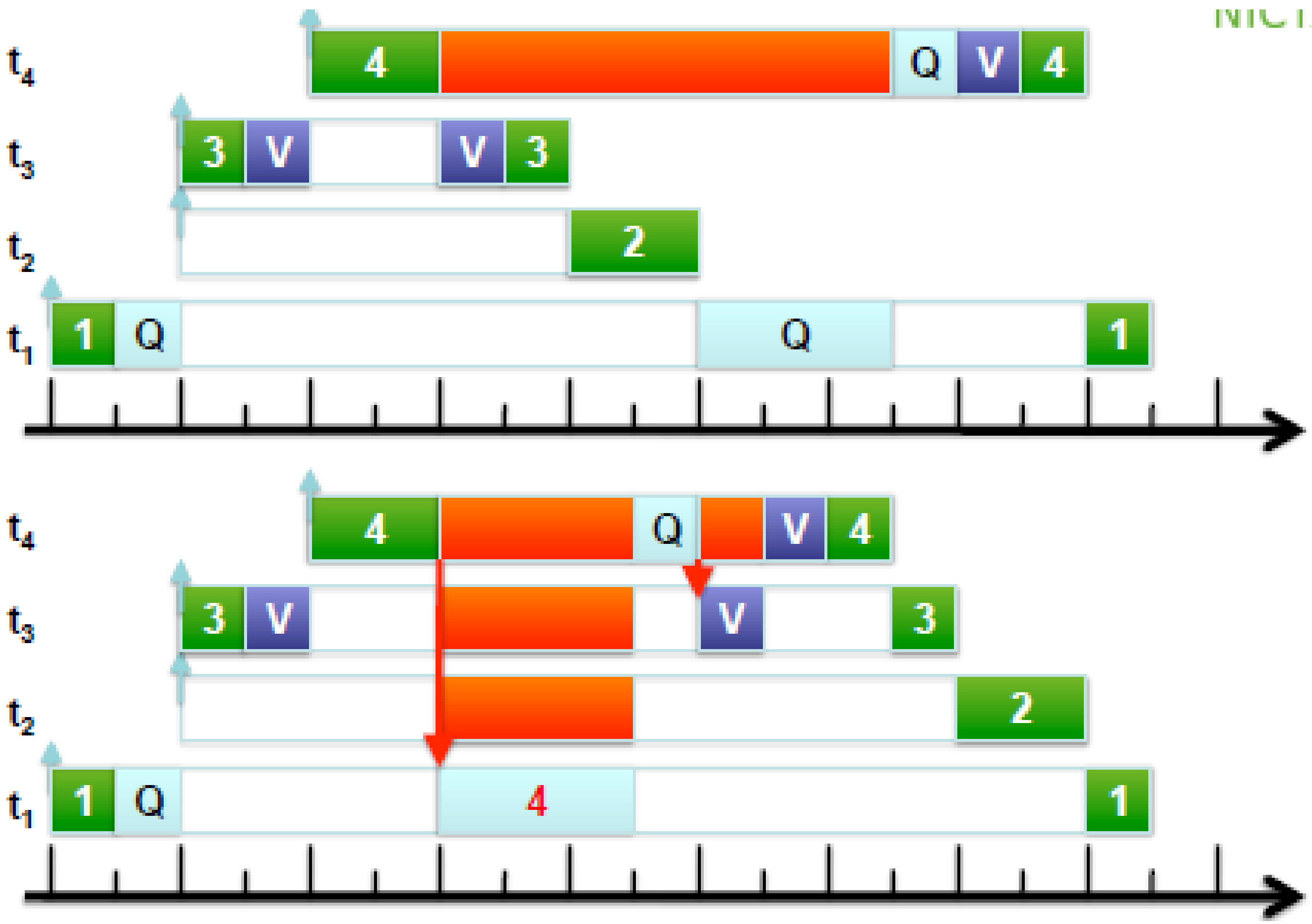
- High-priority job is blocked, waiting for low-priority job
- *Priority inversion!*
- Undermines scheduling policy
- Must limit and control enough to still allow analysis of timeliness

Priority Inversion



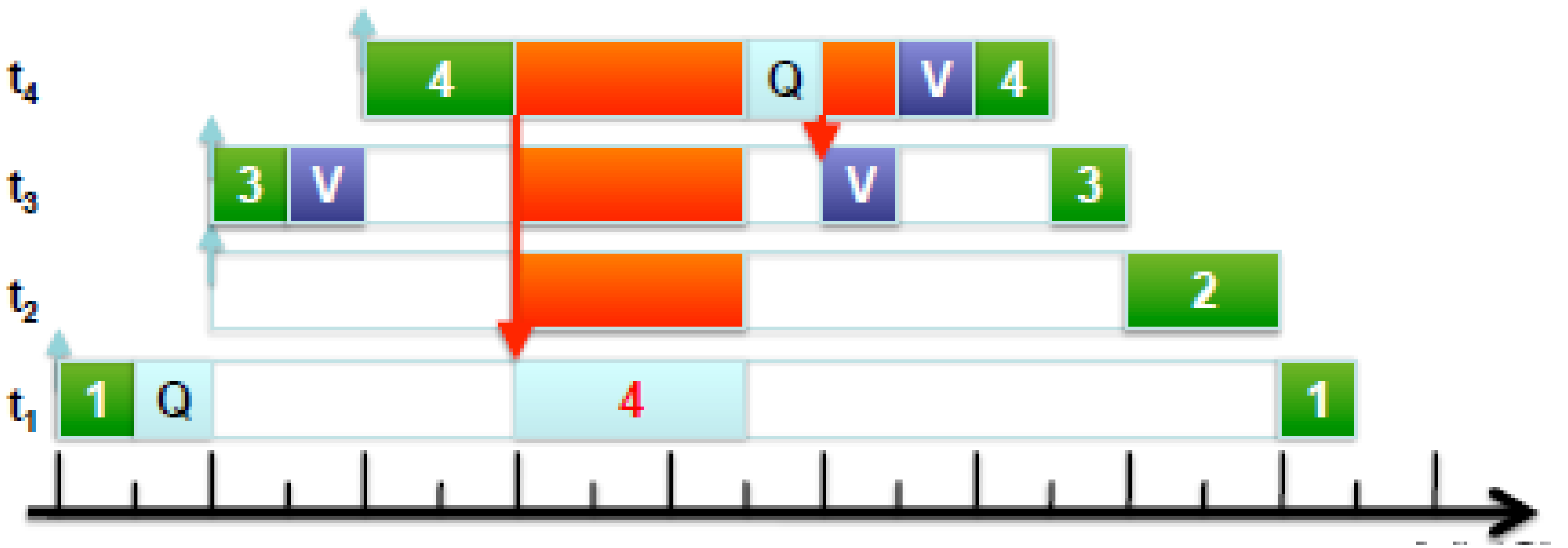
- High-priority job is blocked for a long time by a low-prio job
- Long wait chain: $t_1 \rightarrow t_4 \rightarrow t_3 \rightarrow t_2$
- Worst-case blocking time of t_1 bounded only by WCET of $C_2+C_3+C_4$
- Must find a way to do better!

Priority Inheritance ("Helping")



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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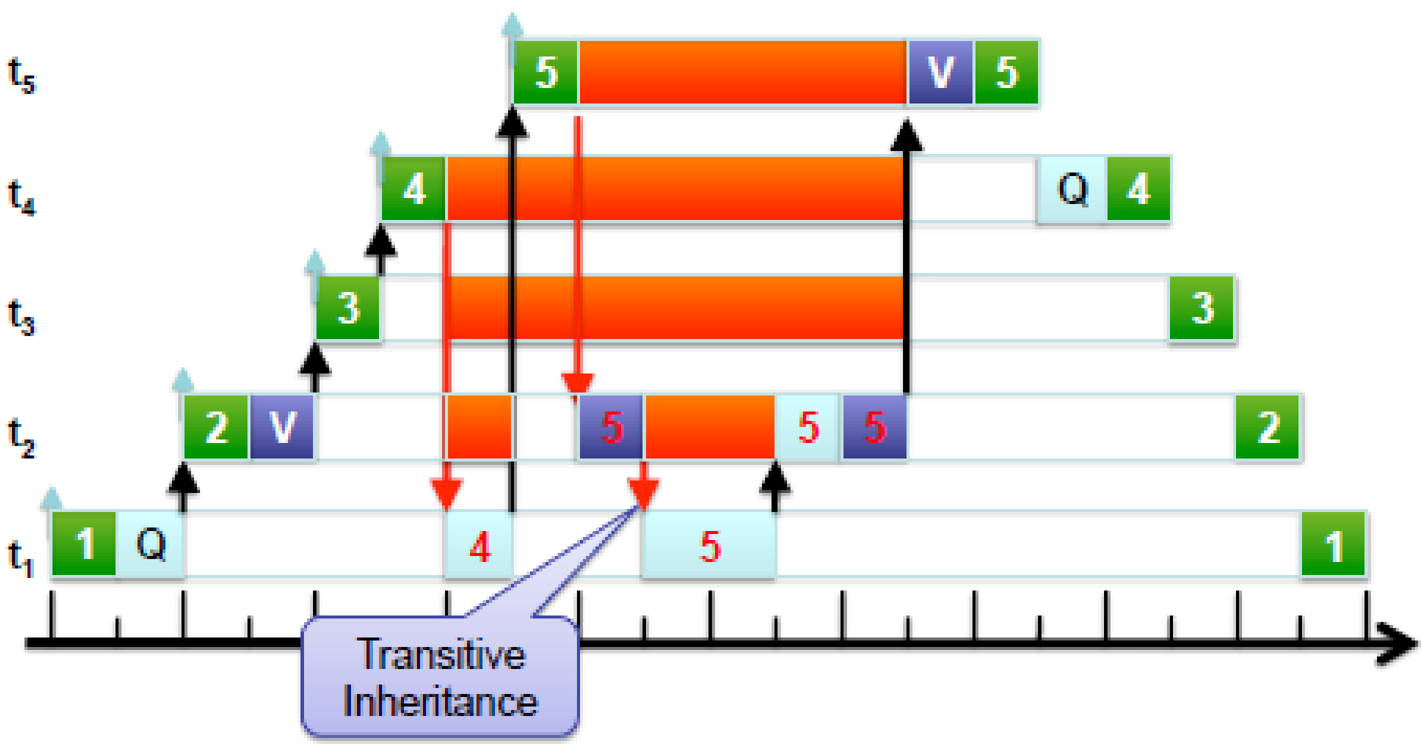

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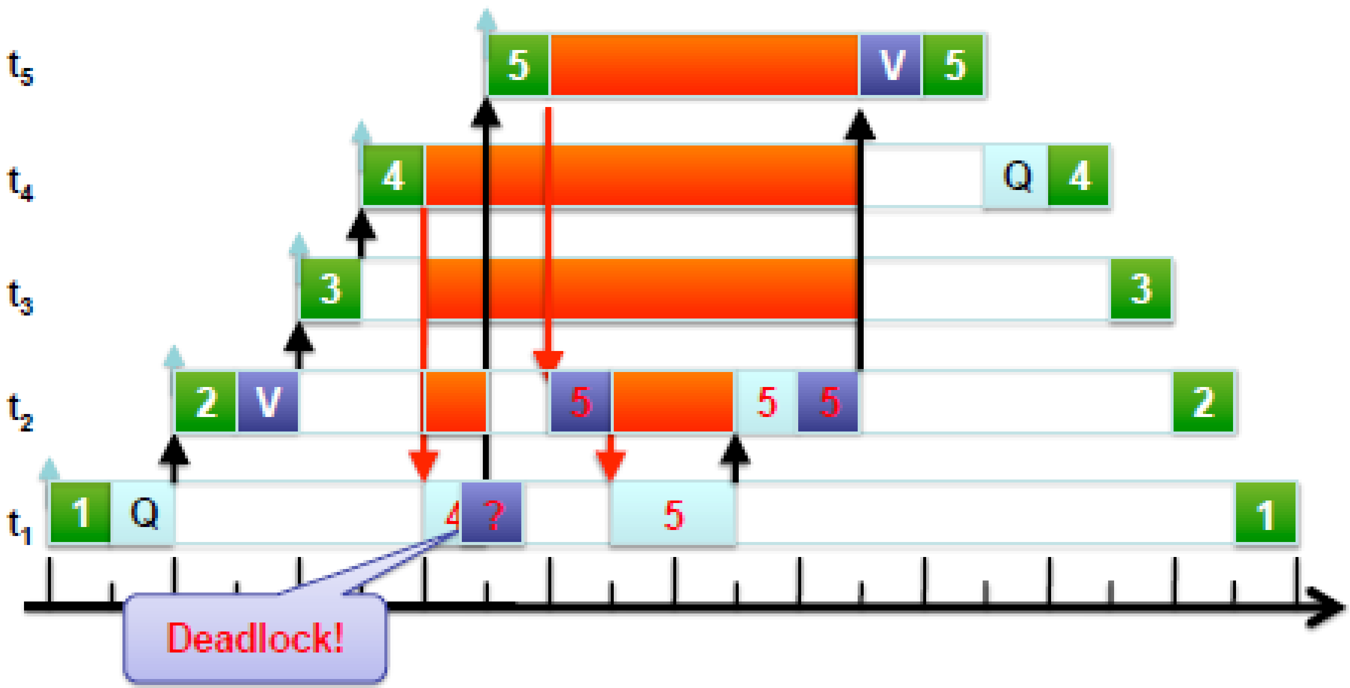


Priority Inheritance Protocol (PIP)

- 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

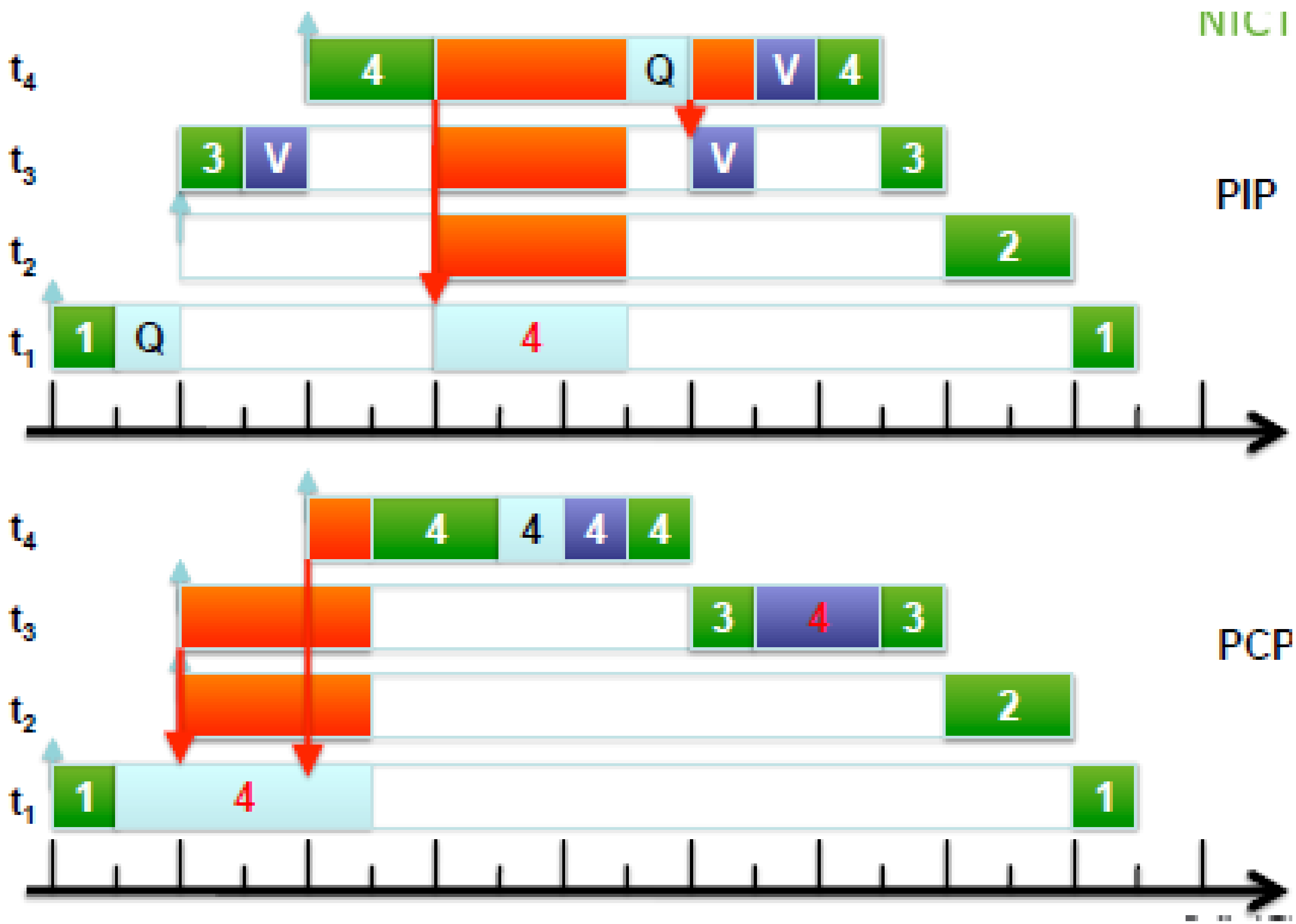
Priority Inheritance:

- Easy to use, potential deadlocks
- Complex to implement
- Bad worst-case blocking times

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*
  - Requires global tracking of ceiling prios

(Immediate) Priority Ceiling Protocol



PCP 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*
- In seL4:
  - Have the server run at the ceiling prio
  - Ceiling is max prio of threads holding a send cap on server EP
    - Obviously hard to determine automatically at admission time
    - Could use trusted server to hand out caps
    - In any case a user-level (system design) problem
- Challenge: proper time accounting not supported by present seL4
  - Work in progress – stay tuned!