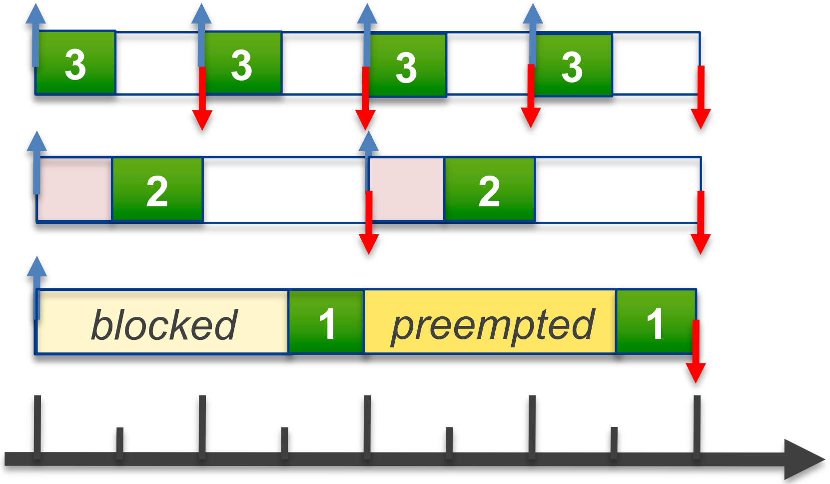
School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2023 T3 Week 07 Part 1

Real-Time Systems Basics

@GernotHeiser



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Today’s Lecture

- Real-time systems (RTS) basics
  - Types or RTS
  - Basic concepts & facts
- Resource sharing in RTS
- Scheduling overloaded RTS
- Mixed-criticality systems (MCS)

Presented by Dr Anna Lyons

Work

- 2022-23, secure kernel team @ Apple
- 2019-22, platform team @ Ghost
- 2010-18 Research Engineer @ Trustworthy Systems
- 2007-2018 Tutor - OS, AOS, COMP19**
- 2010 summer intern @ Microsoft - Bing
- 2008-10 Part-time @ Atlassian
- 2007 summer ToR @ NICTA 2007-08

Education

- 2012-2018 PhD w/ Gernot
- 2006-11 B Sci (Computer Science) / BA (Philosophy)

Presented by Dr Anna Lyons

Work at Trustworthy Systems

- Initial port of AOS to seL4 w/ Adrian Danis, then aarch64 + pico tcp + nfsv3
- Shepherd AOS from nslu2 to imx6 then odroid c2
- PhD: MCS kernel extensions
- I did AOS on the slug —> w/ OKL4

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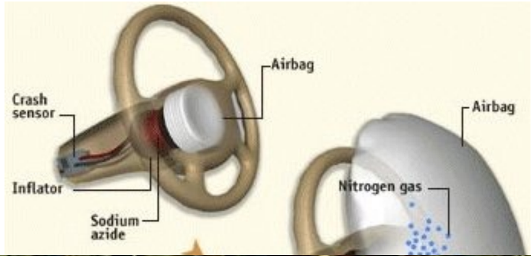
Real-Time Basics

Real-Time Systems



What’s a Real-Time System?

Aka. events

A real-time system is a system that is required to react to stimuli from the environment (including passage of physical time) within time intervals dictated by the environment.
[Randell et al., Predictably Dependable Computing Systems, 1995]

Real-time systems have timing constraints, where the correctness of the system is dependent not only on the results of computations, but on *the time at which those results arrive*. [Stankovic, IEEE Computer, 1988]

Issues:
- Correctness: What are the temporal requirements?
- Criticality: What are the consequences of failure?

Real Time → time isn't **fungible**

Fungible: replaceable by another identical item

Fungible	**Not fungible**
Chocolate chip cookies	Human Beings
Memory (e.g RAM)	The seconds after you hit the brake

Real-time = Real confusion

❌ **Real-time Applications**

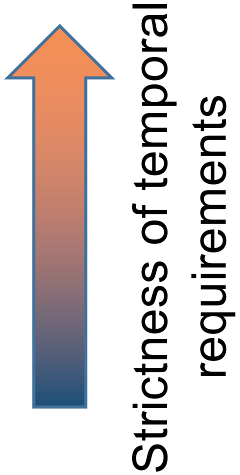
Real-time apps are those that react to changes anywhere in a connec

❌ **Real-time Processing**

They actually mean “not batch processed”

Strictness of Temporal Requirements

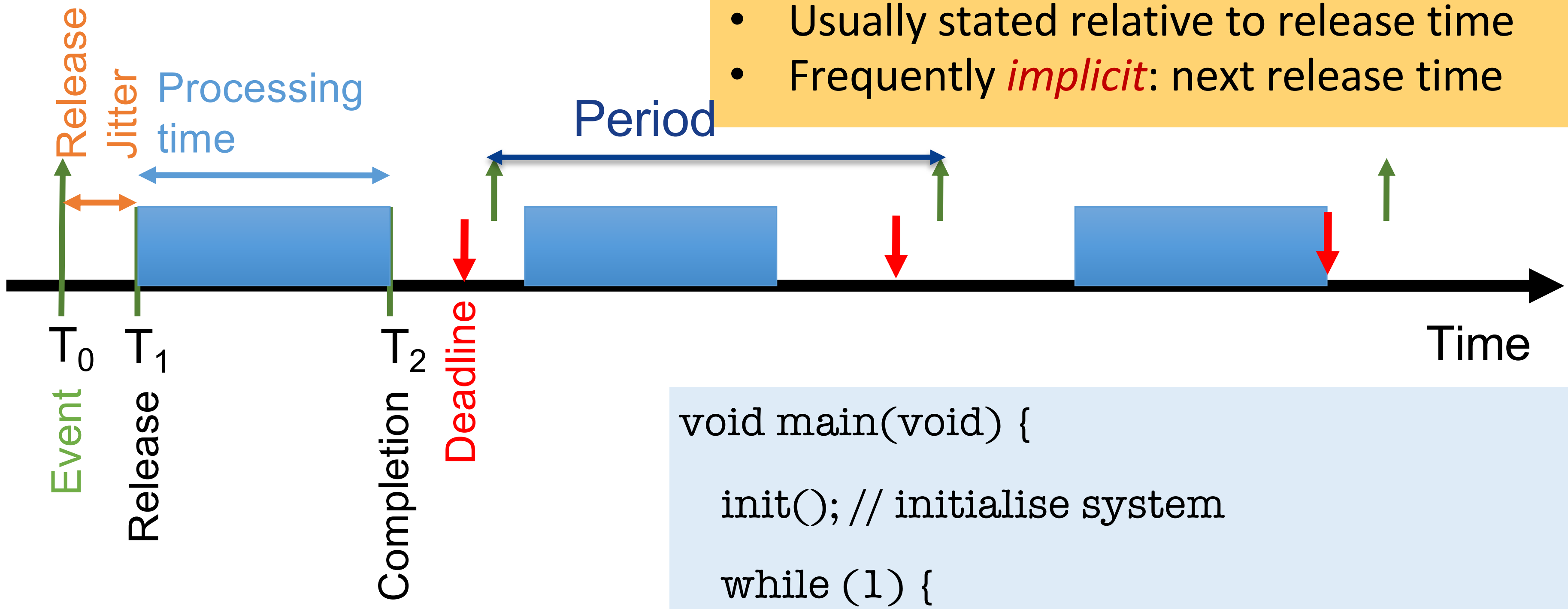
- Hard real-time systems
- Weakly-hard real-time systems
- Firm real-time systems
- Soft real-time systems
- Best-effort systems



Real-Time Tasks

Real-time tasks have deadlines

- Usually stated relative to release time
- Frequently *implicit*: next release time




```
void main(void) {
  init(); // initialise system
  while (1) {
    wait();  // timer, device interrupt, signal
    doJob();
  }
}
```

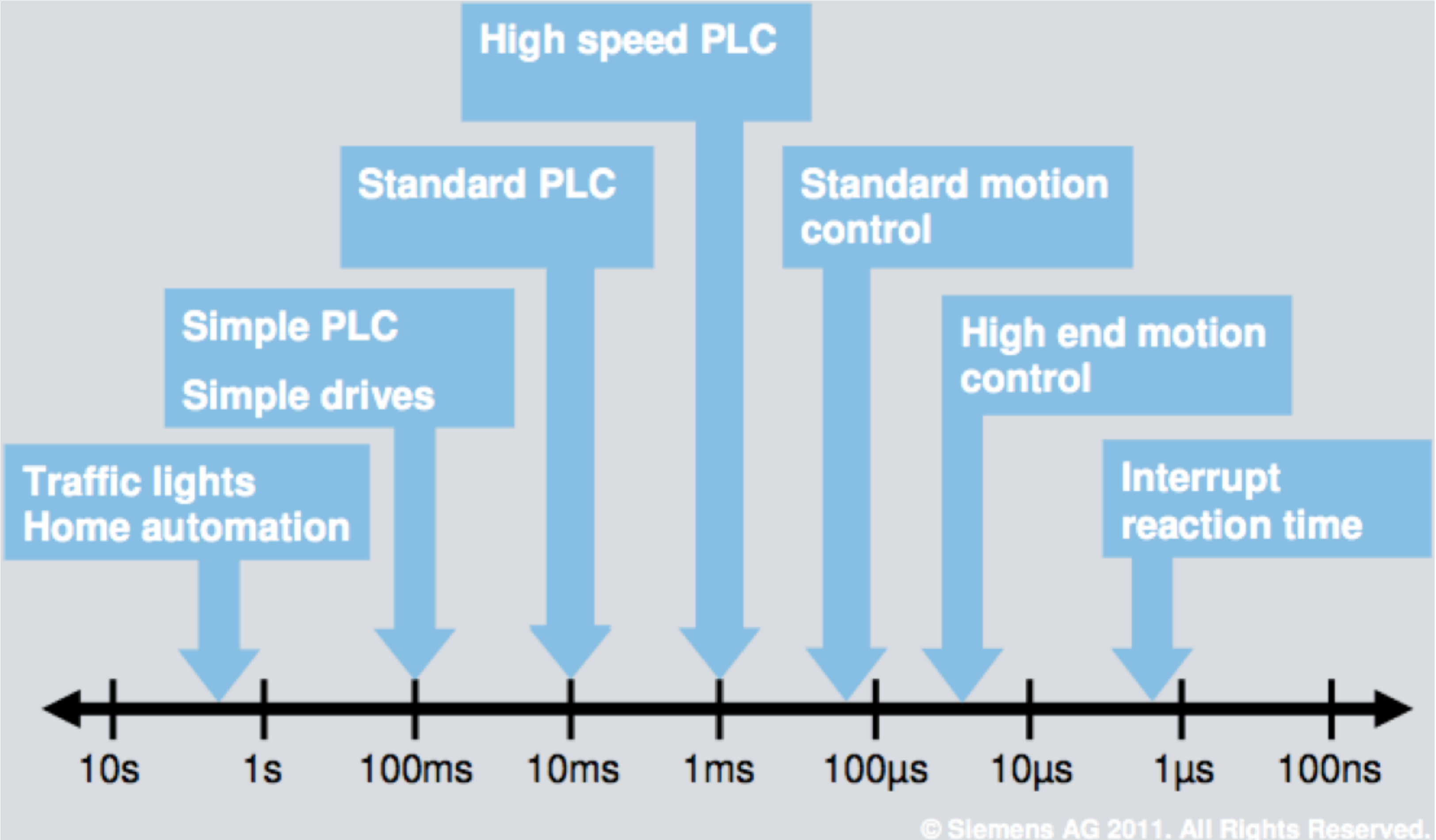
T_1 → wait();
T_2 → doJob();

Real Time ≠ Real Fast

System	Deadline	Single Miss Conseq	Ultimate Conseq.
Combustion engine ignition	2.5 ms	Catastrophic	Engine damage
Industrial robot	5 ms	Recoverable?	Machinery damage
Air bag	20 ms	Catastrophic	Injury or death
Aircraft control	50 ms	Recoverable	Crash
Industrial process	100 ms	Recoverable	Lost production, plant/ environment damage
Pacemaker	100 ms	Recoverable	Death

Criticality

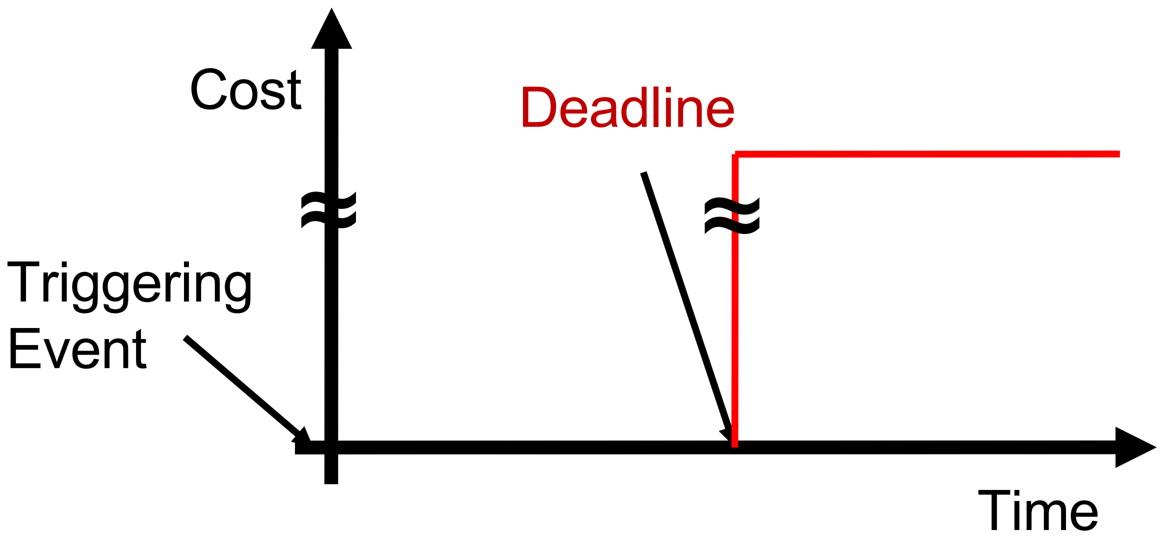
Example: Industrial Control

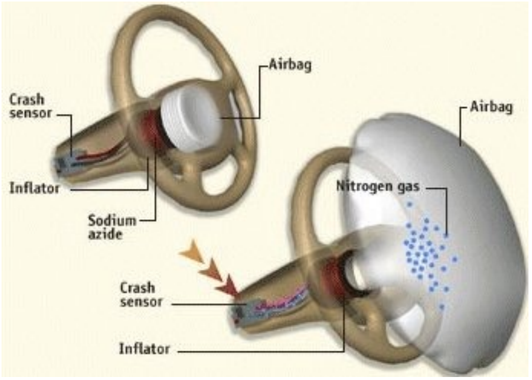


Hard Real-Time Systems

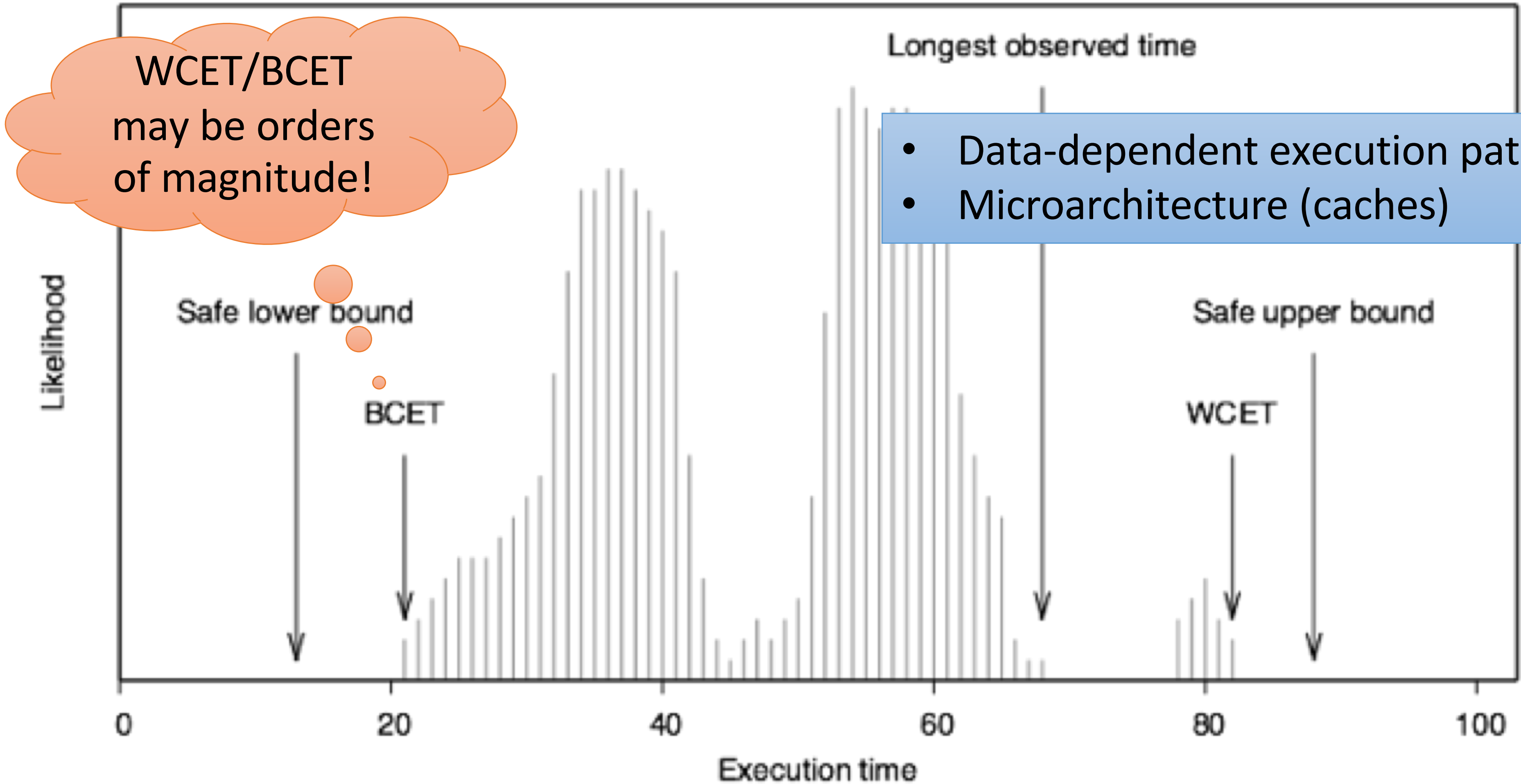
- Safety-critical: Failure ⇒ death, serious injury
- Mission-critical: Failure ⇒ massive financial damage

- Deadline miss is *catastrophic*
- Steep and real *cost* function





Challenge: Execution-Time Variance

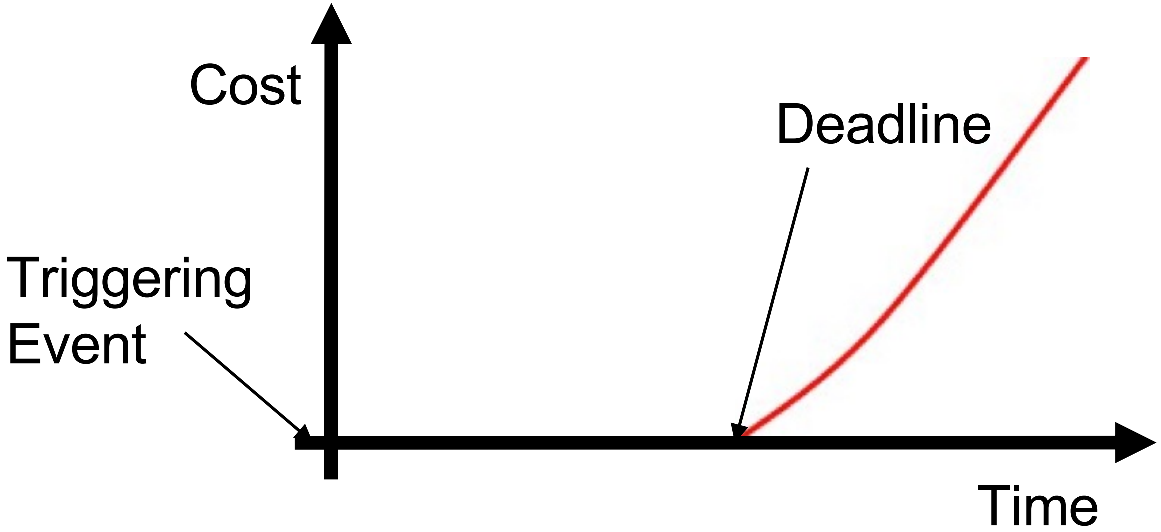


- Data-dependent execution paths
- Microarchitecture (caches)

Weakly-Hard Real-Time Systems

- Most feedback control systems (incl life-support!)
  - Control compensates for occasional miss
  - Becomes unstable if too many misses
- Typically integrated with fault tolerance for HW issues

Tolerate small fraction of deadline misses

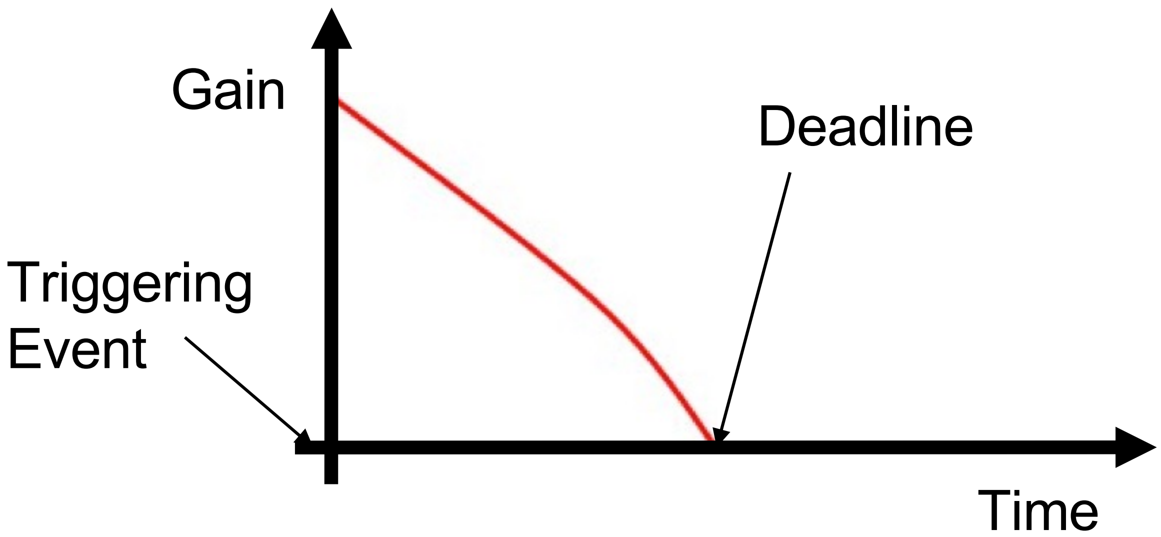


In practice, certifiers treat critical avionics as hard RT

Firm Real-Time Systems

- Forecast systems
- Trading systems

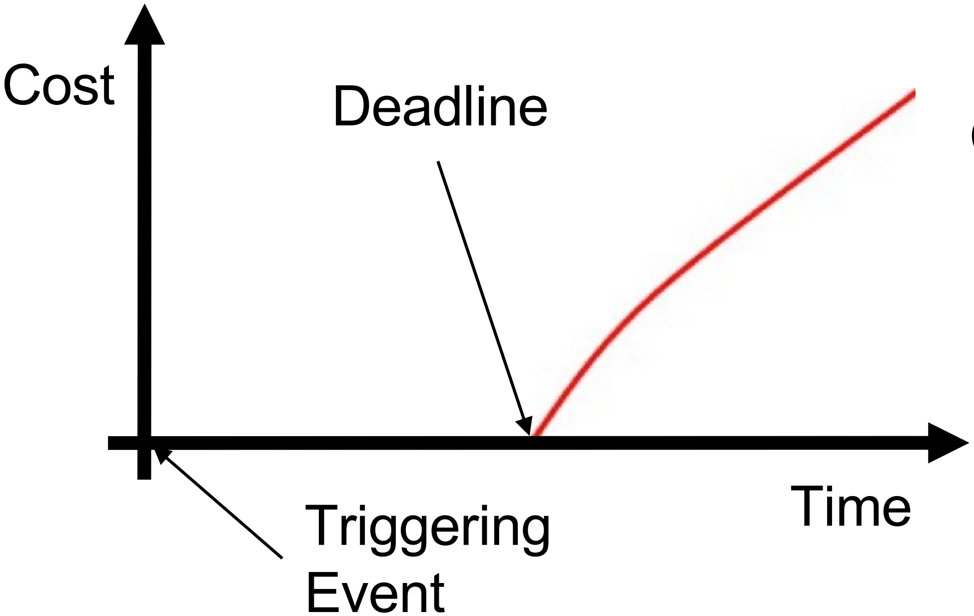
Result obsolete if deadline missed (loss of revenue)

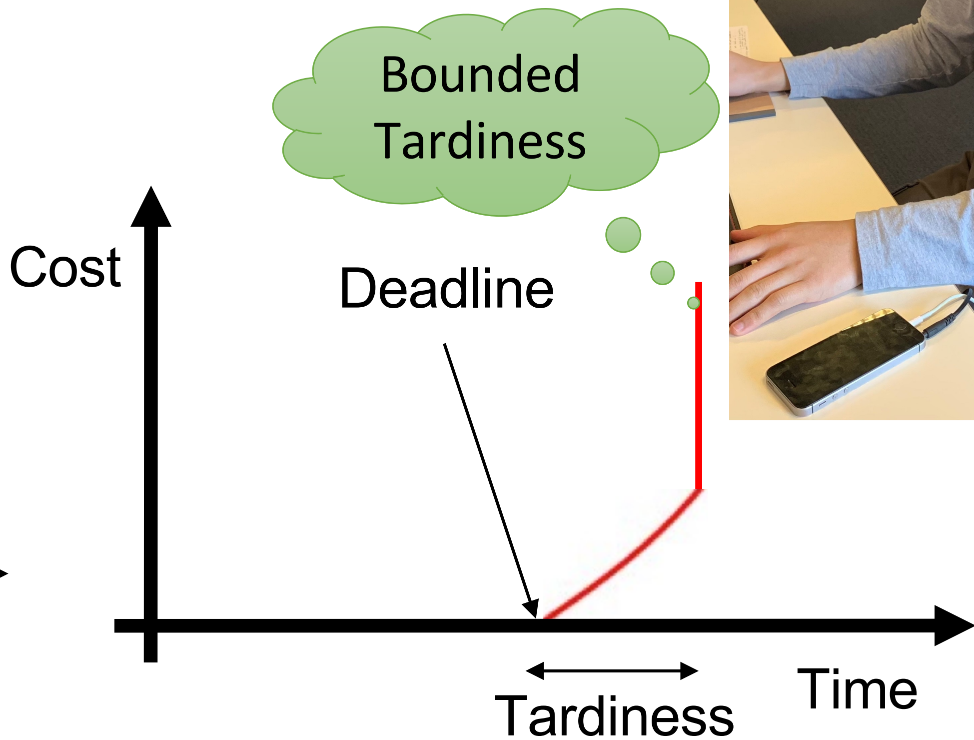


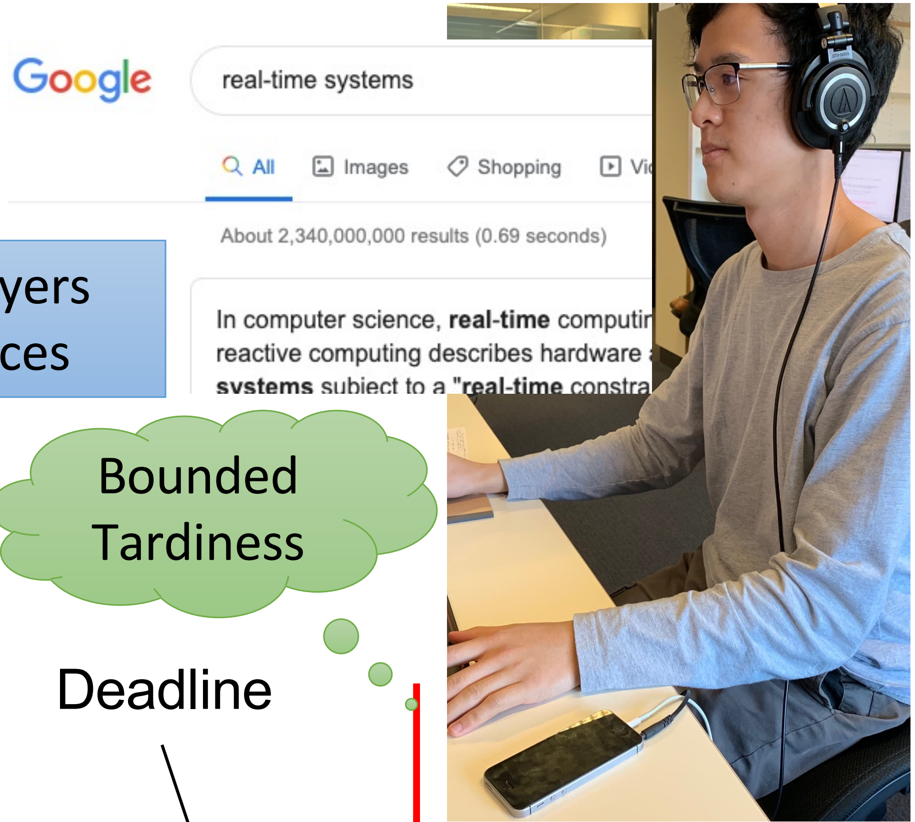
Soft Real-Time Systems

Deadline miss undesirable but tolerable, affects QoS

- Media players
- Web services







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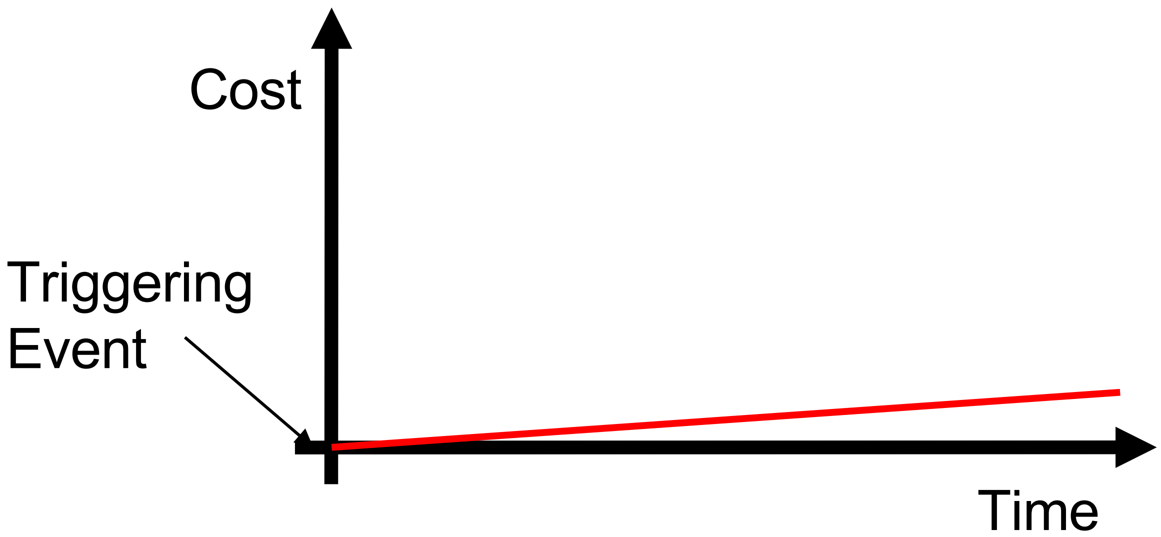
Best-Effort Systems

No deadline

In practice, duration is rarely totally irrelevant



Real-Time Operating System (RTOS)

- Designed to support real-time operation
  - Fast context switches, fast interrupt handling
  - More importantly, *predictable* response time

Requires analysis of worst-case execution time (WCET)

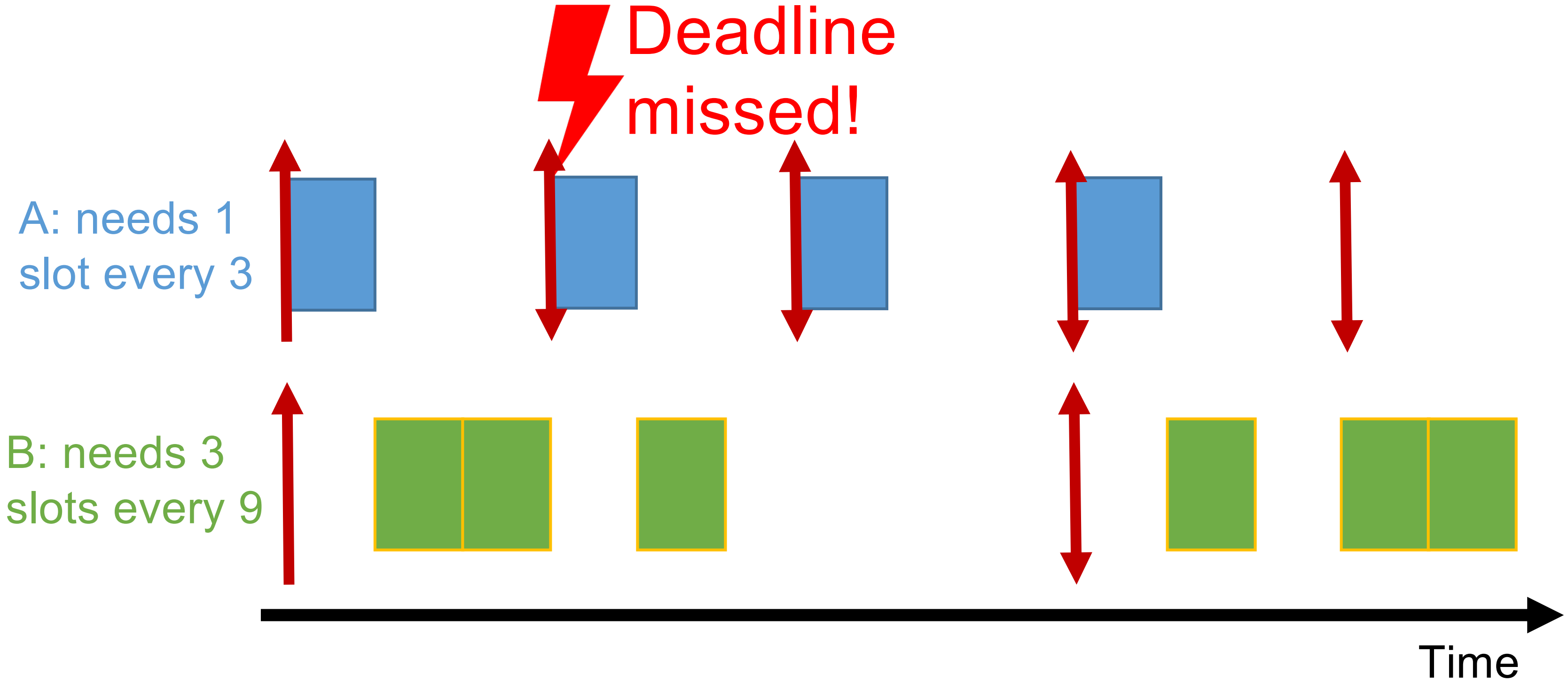
- **Main duty is scheduling tasks to meet their deadline**

Traditional RTOS is very primitive
- single-mode execution
- no memory protection
- inherently cooperative
- *all code is trusted*

RT vs OS terminology:
- "task" = thread
- "job" = execution of thread resulting from event

Real-Time Scheduling

- Ensuring all deadlines are met is harder than bin-packing
- Reason: time is not fungible



Real-Time Scheduling

- Ensuring all deadlines are met is harder than bin-packing
- Time is not fungible

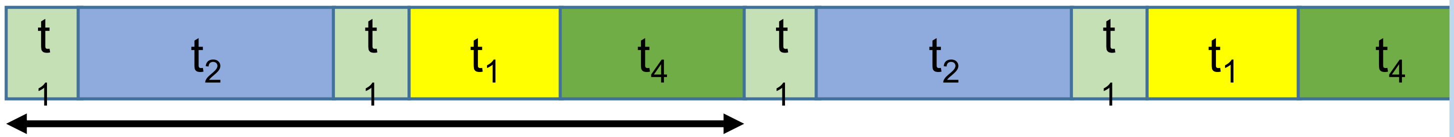
Terminology:
- A set of tasks is **feasible** if there is a known algorithm that will schedule them (i.e. all deadlines will be met).
- A scheduling algorithm is **optimal** if it can schedule all **feasible** task sets.

Cyclic Executives

- Very simple, completely static, scheduler is just table
- Deadline analysis done off-line
- Fully deterministic

Drawback: Latency of event handling is hyper-period

```
while (true) {
    wait_tick();
    job_1();
    wait_tick();
    job_2();
    wait_tick();
    job_1();
    wait_tick();
    job_3();
    wait_tick();
    job_4();
}
```

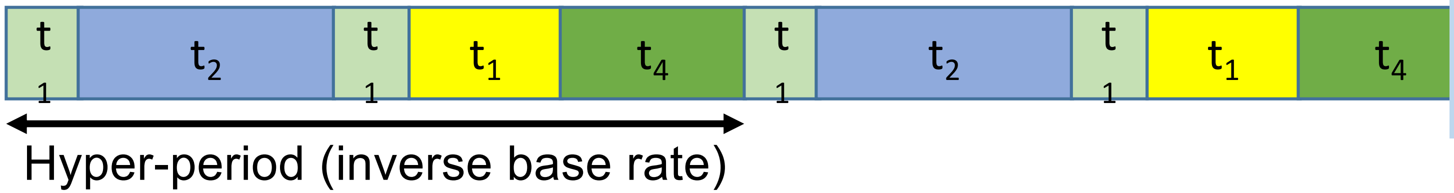


Hyper-period (inverse base rate)

Are Cyclic Executives Optimal?

- Theoretically yes if can slice (interleave) tasks
- Practically there are limitations:
  - Might require very fine-grained slicing
  - May introduce significant overhead

```
while (true) {
    wait_tick();
    job_1();
    wait_tick();
    job_2();
    wait_tick();
    job_1();
    wait_tick();
    job_3();
    wait_tick();
    job_4();
}
```



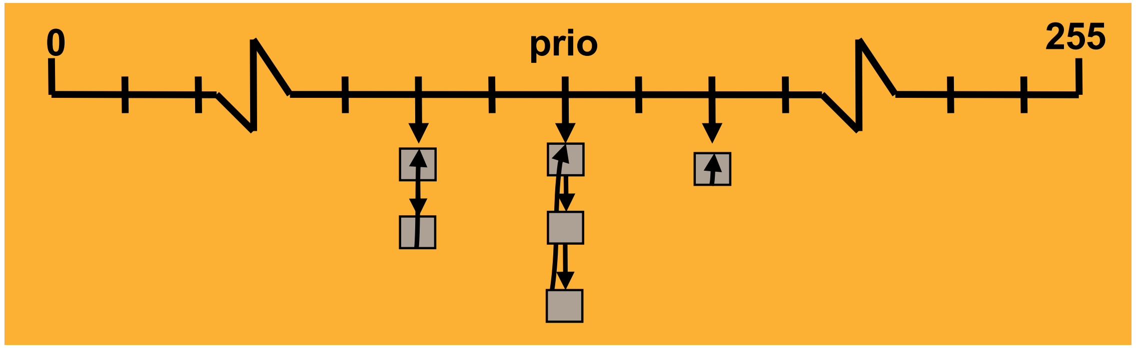
On-Line RT Scheduling

- Scheduler is part of the OS, performs scheduling decision on-demand
- Execution order not pre-determined
- Can be preemptive or non-preemptive
- Priorities can be
  - **fixed**: assigned at admission time
    - scheduler doesn't change prios
    - system may support dynamic adjustment of prios
  - **dynamic**: prios potentially different at each scheduler run

Fixed-Priority Scheduling (FPS)

- Classic L4 scheduling is a typical example:
  - always picks highest-prio runnable thread
  - round-robin within prio level
  - will preempt if higher-prio thread is unblocked or time slice depleted

FPS is not optimal, i.e. cannot schedule some feasible sets



In general may or may not:

- preempt running threads
- require unique prios

Rate Monotonic Priority Assignment (RMPA)

- Higher rate ⇒ higher priority:
  - $T_i < T_j \Rightarrow P_i > P_j$

T: period
1/T: rate
P: priority
U: utilisation

- Schedulability test: Can schedule task set with periods $\{T_1 \ldots T_n\}$ if

Assumes "*implicit*" deadlines: release time of next job

$$U \equiv \sum C_i/T_i \leq n(2^{1/n}-1)$$

RMPA is optimal for FPS

n	**1**	**2**	**3**	**4**	**5**	**10**	**∞**
U [%]	100	82.8	78.0	75.7	74.3	71.8	log(2) = 69.3

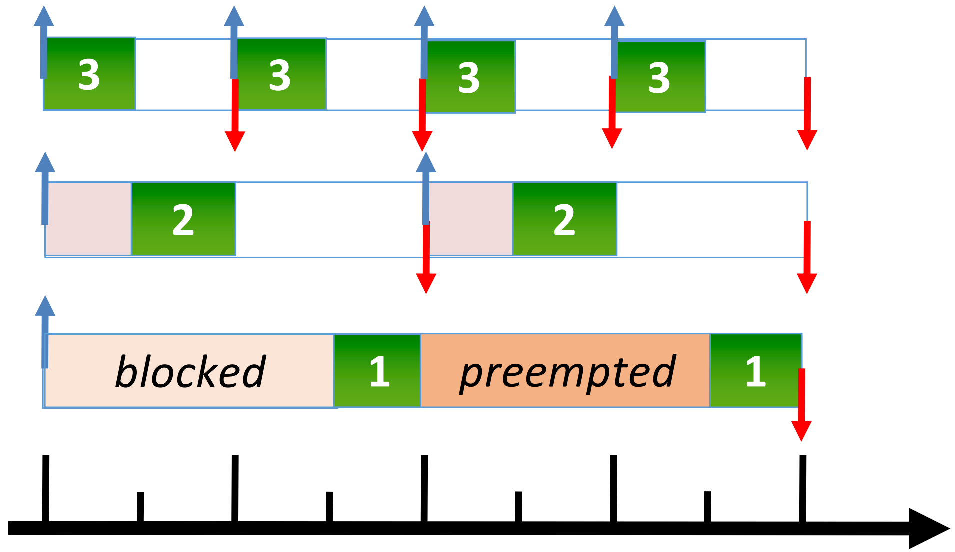
Rate-Monotonic Scheduling Example

RMPA schedulability bound is sufficient but not necessary

WCET

C/T

Task	T	P	C	U [%]
t_3	20	3	10	50
t_2	40	2	10	25
t_1	80	1	20	25
				100



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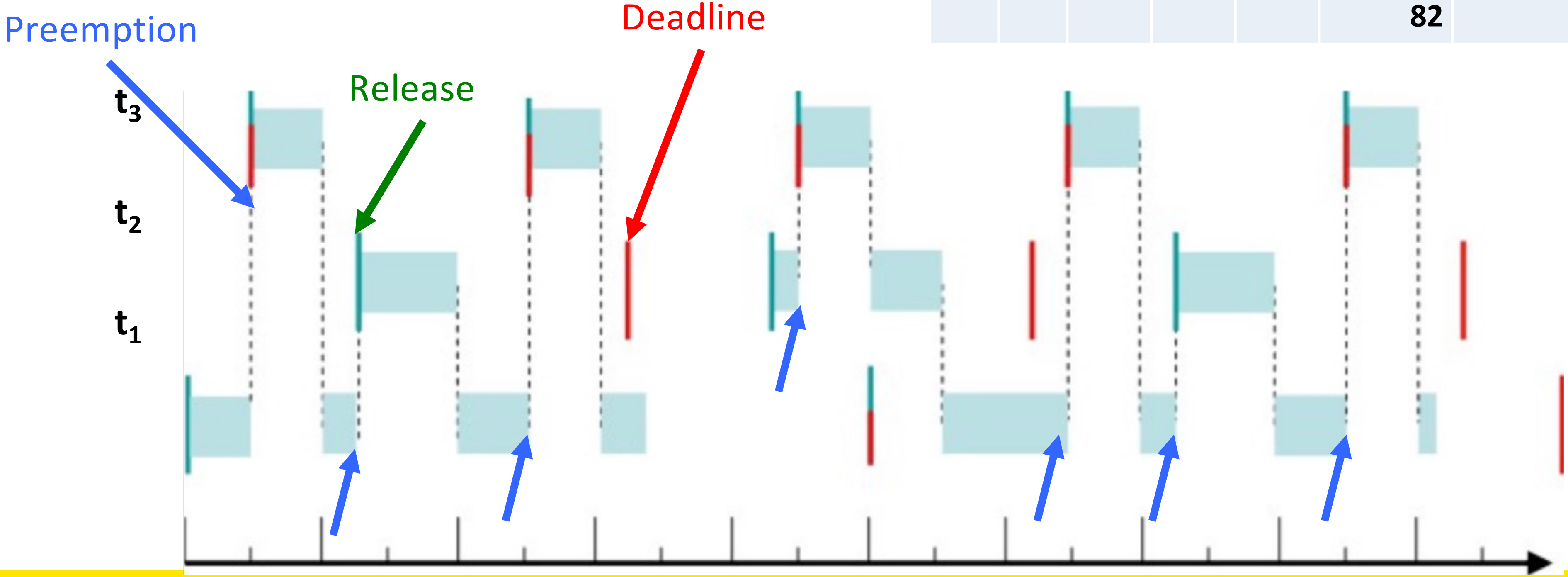
Another RMPA Example

Deadline

	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	



Dynamic Prio: Earliest Deadline First (EDF)

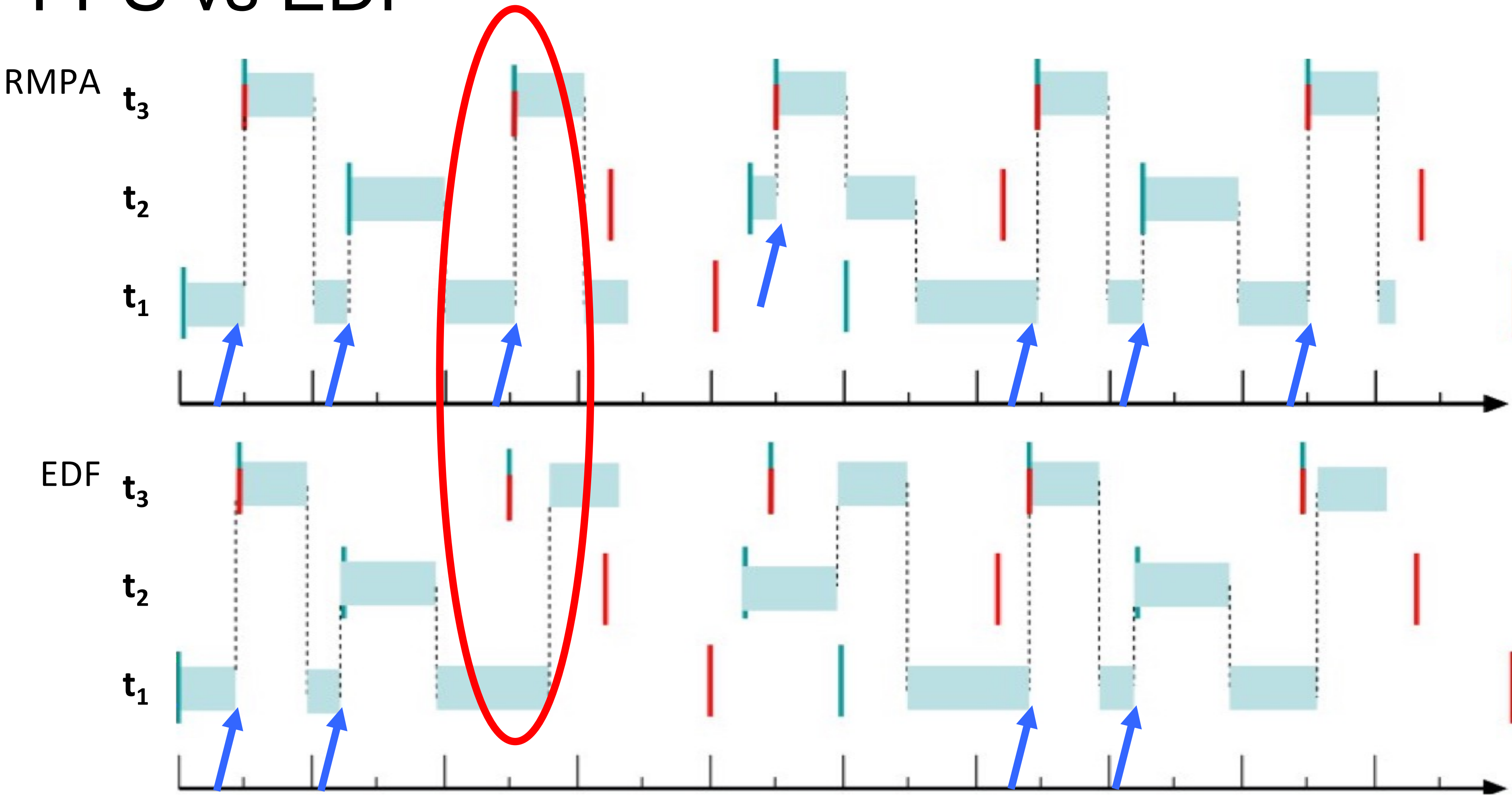
- Job with closest deadline executes
  - priority assigned at job level, not task (i.e. thread) level
  - deadline-sorted release queue

- Schedulability test: Can schedule task set with periods $\{T_1 \ldots T_n\}$ if

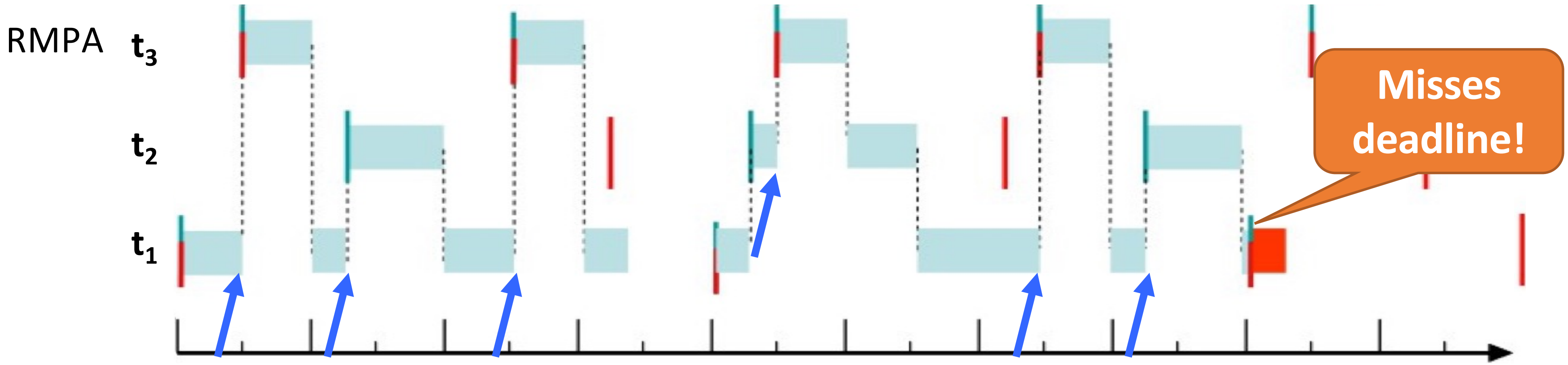
$$U \equiv \sum C_i/T_i \leq 1$$

Preemptive EDF is optimal

FPS vs EDF

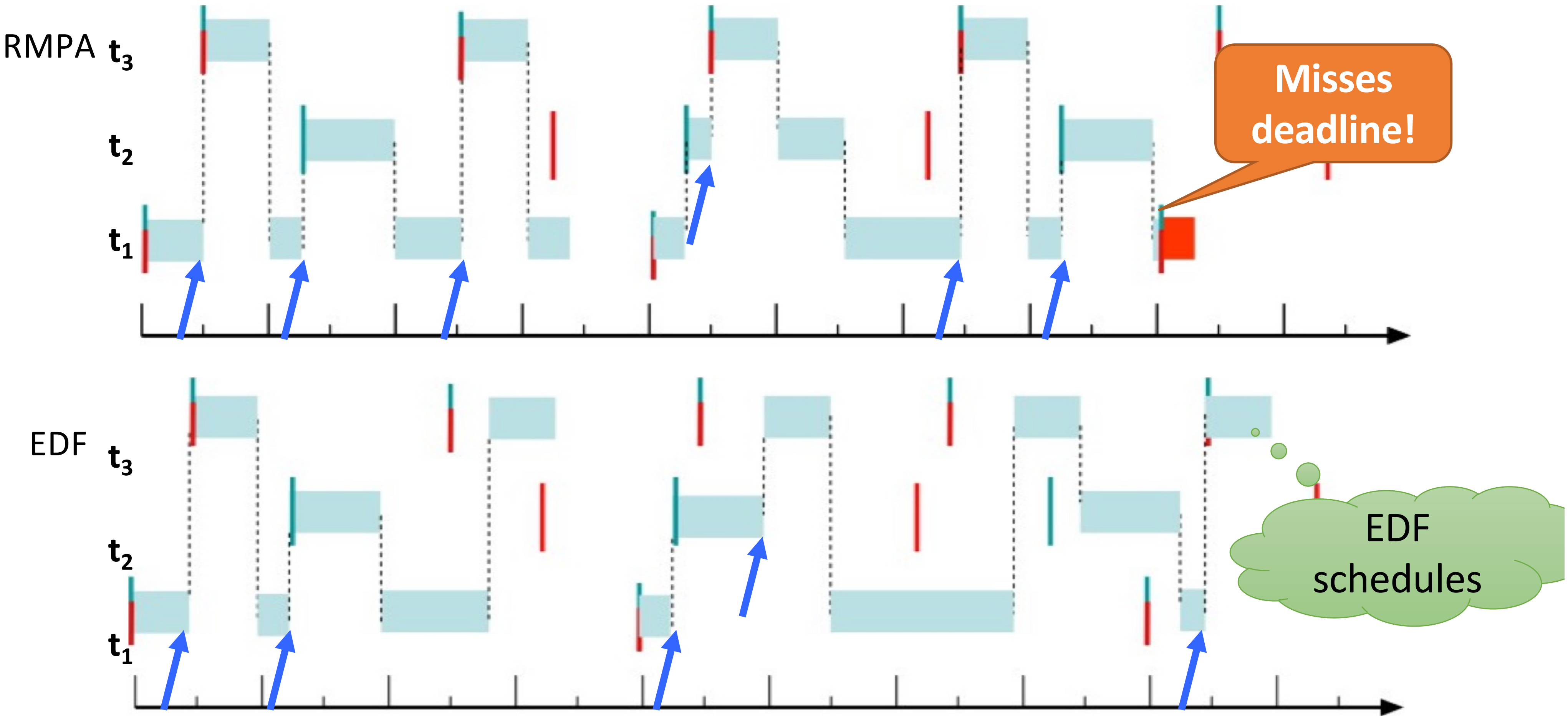


FPS vs EDF



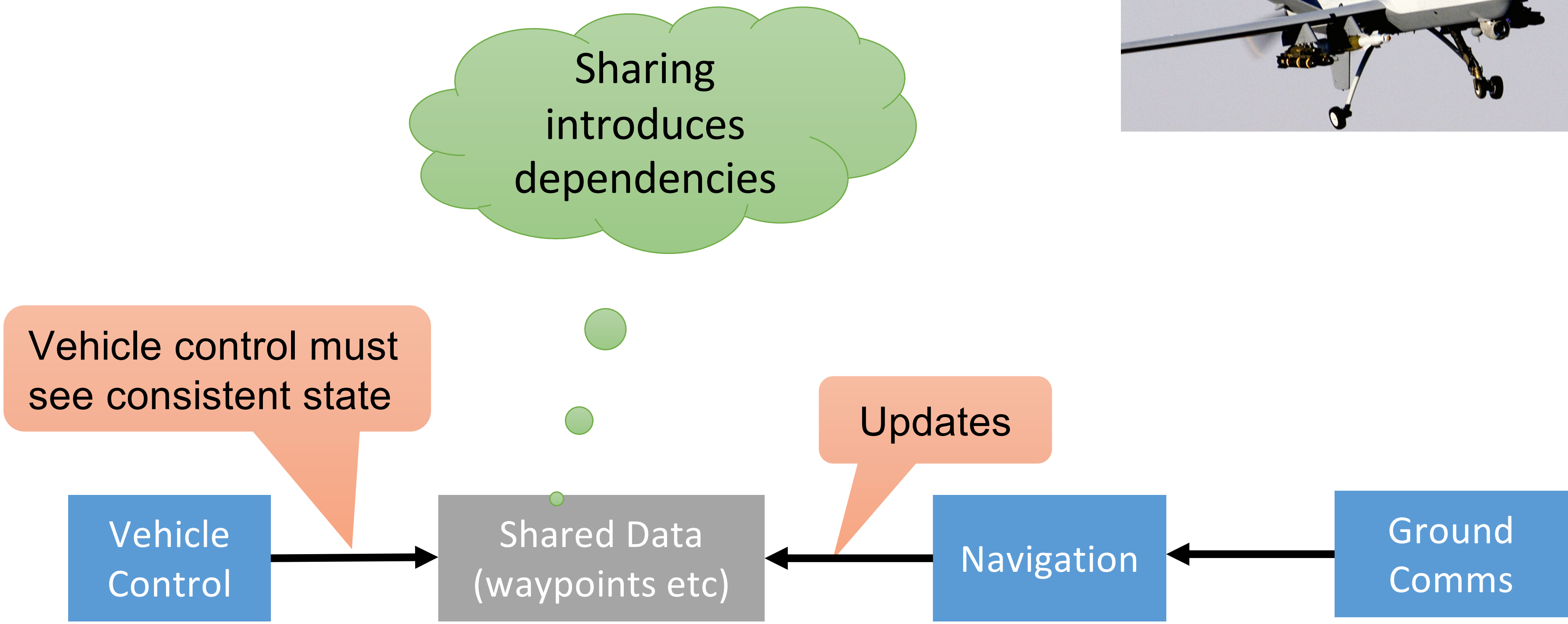
Task	P	C	T	D	U [%]	release
t_3	3	5	20	20	25	5
t_2	2	8	30	20	27	12
t_1	1	15	40	40	37.5	0
					89.5	

FPS vs EDF

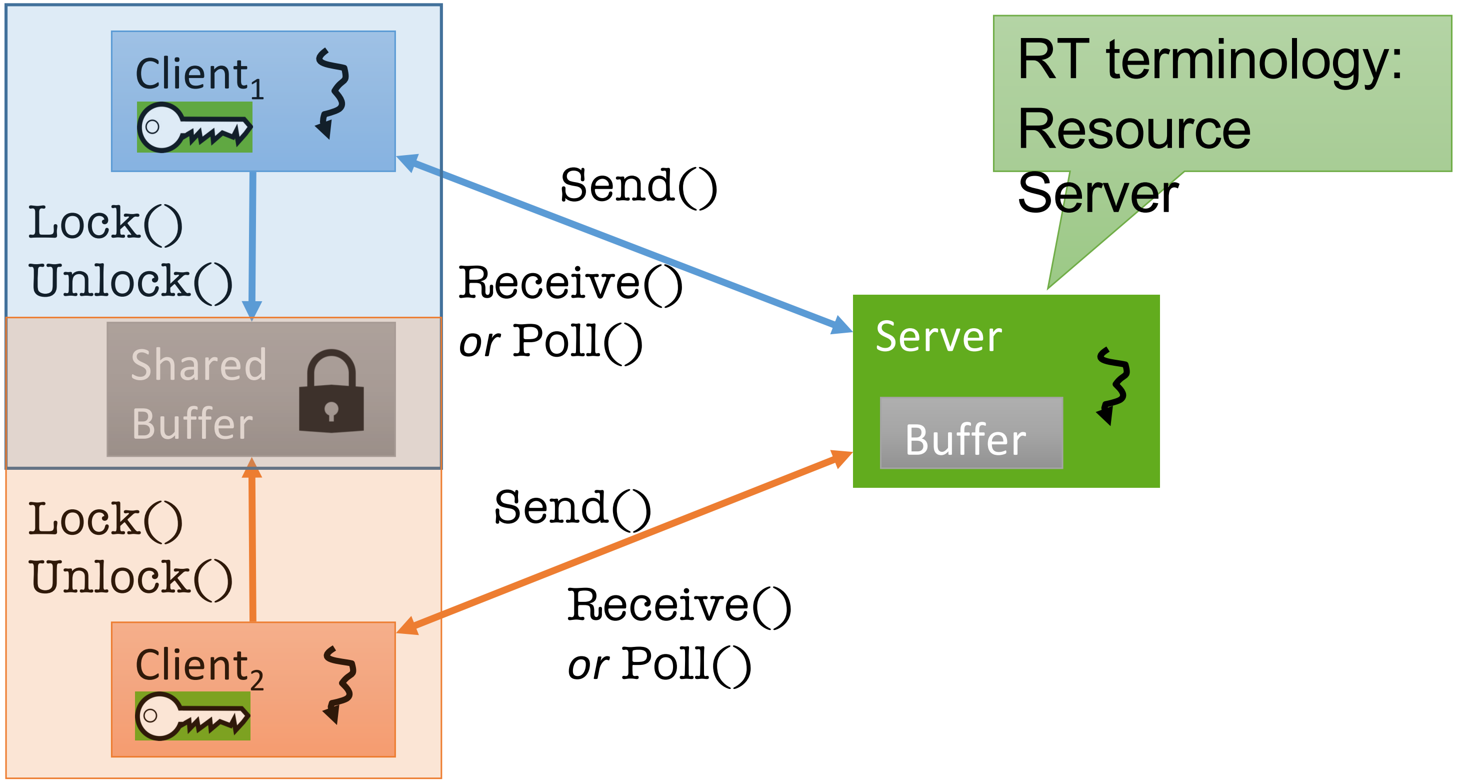


Resource Sharing

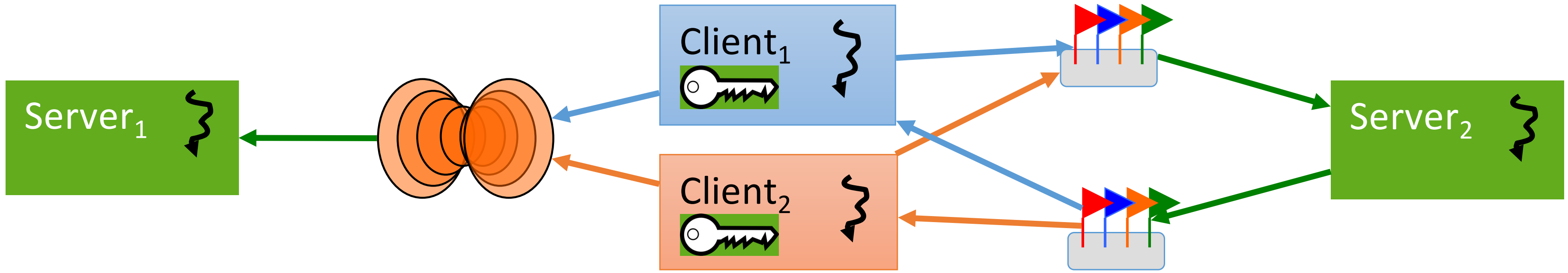
Challenge: Sharing



Critical Sections: Locking vs Delegation



seL4 Implementing Delegation




```
serv_local() {
  ...
  Wait(ep);
  while (1) {
    /* critical section */
    ReplyWait(ep);
  }
}
```

```
client() {
  while (1) {
    ...
    Call(ep);
    ...
    Signal(not_ry);
    ...
    Wait(not_rq);
  }
}
```

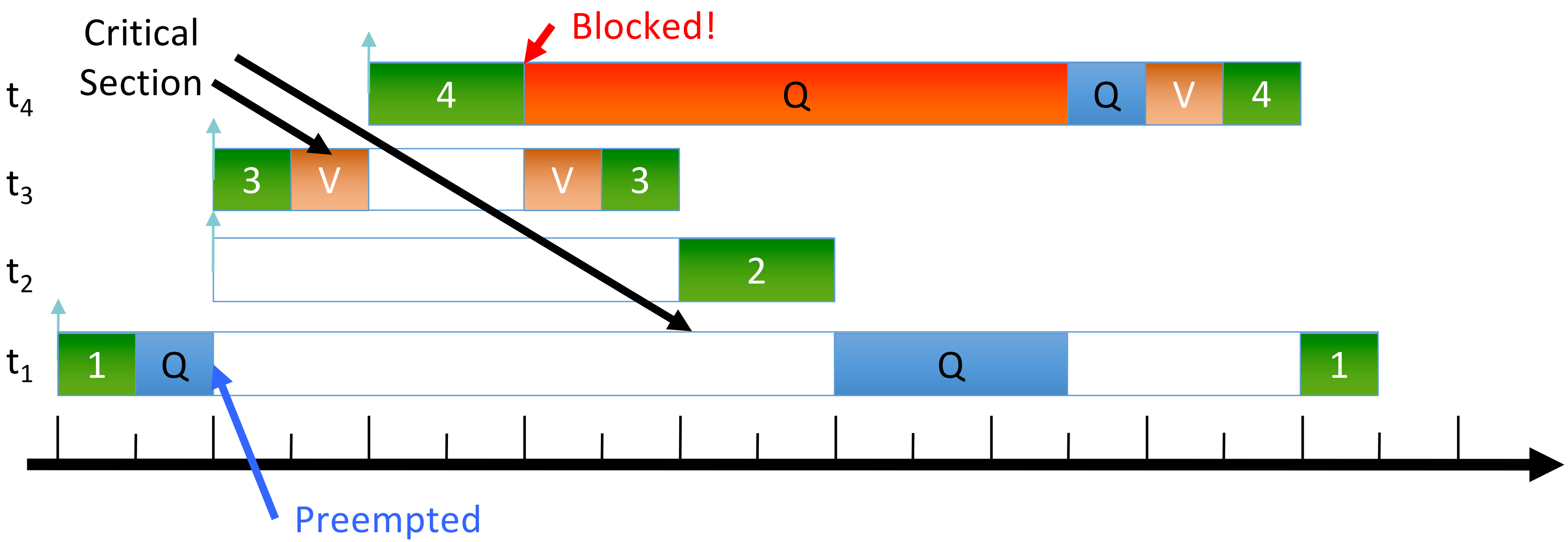
```
serv_remote() {
  ...
  while (1) {
    Wait(not_rq);
    /* critical section */
    Signal(not_ry);
  }
}
```

Hoare-style monitor
Suitable intra-core

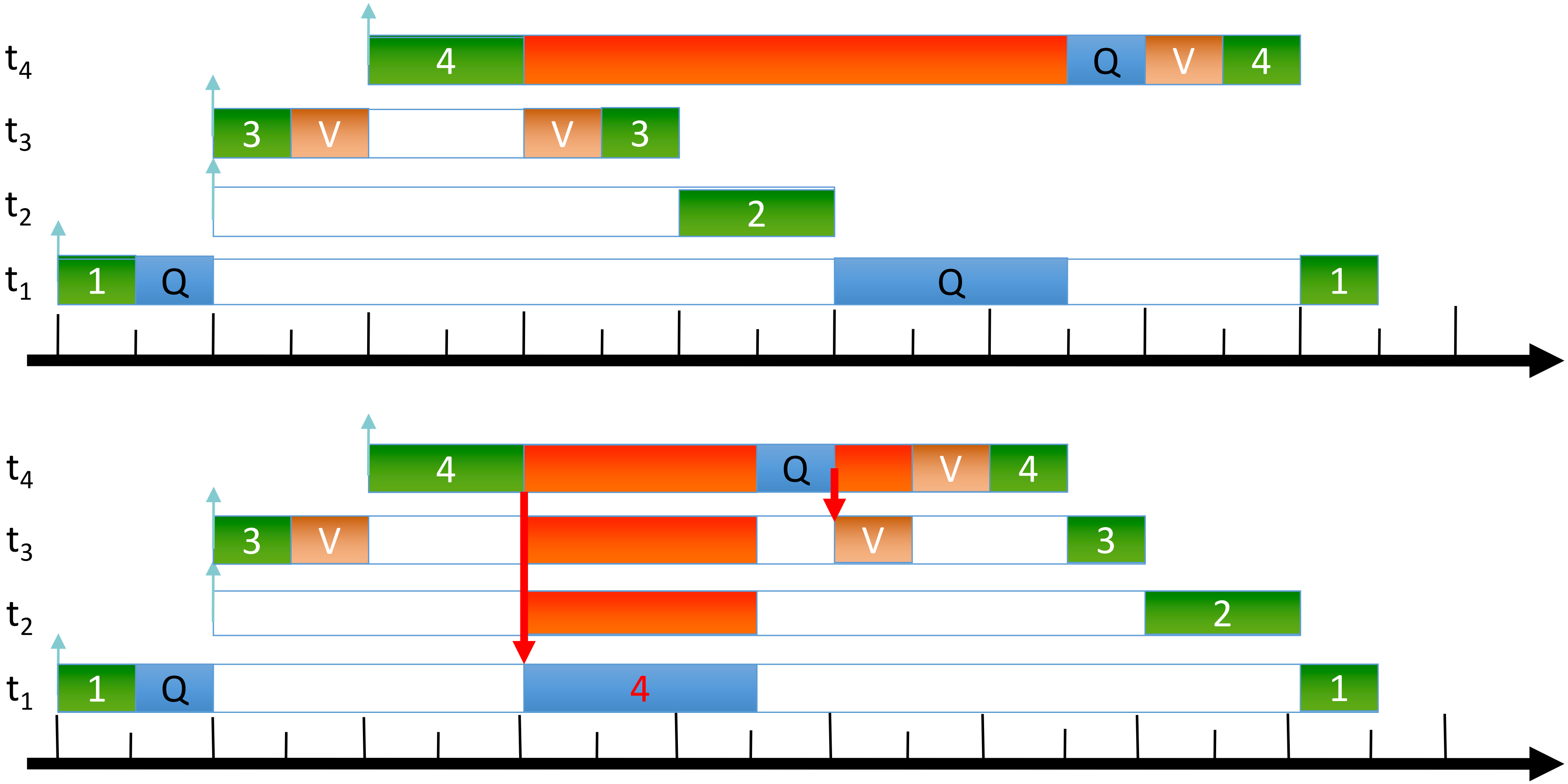
Semaphore synchronisation
Suitable inter-core

Problem: Priority Inversion

- High-priority job is blocked by low-prio for a long time
- Long wait chain: $t_4 \rightarrow t_1 \rightarrow t_3 \rightarrow t_2$
- Worst-case blocking time of t_4 bounded by total WCET: $C_1+C_2+C_3$

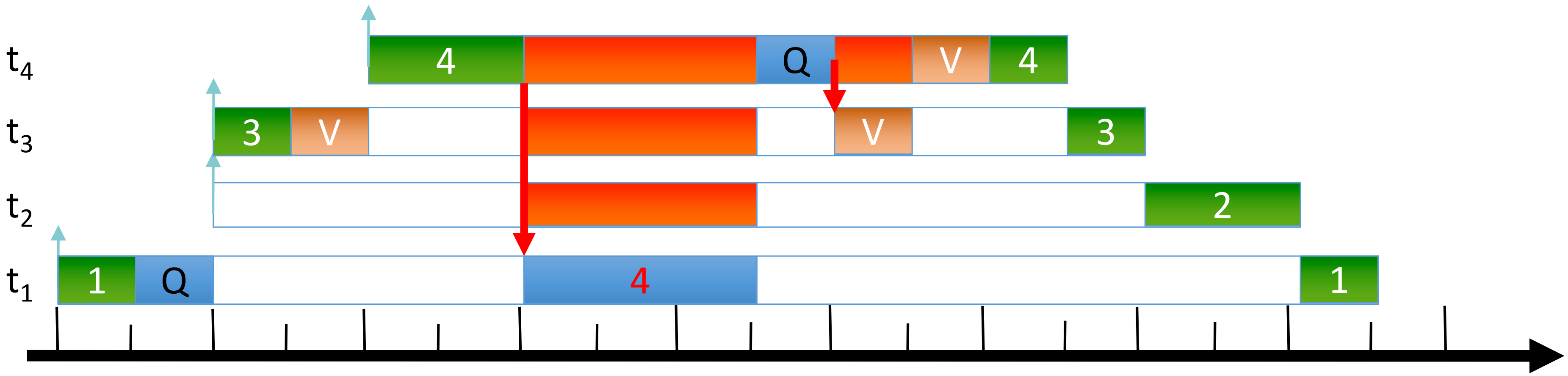


Solution 1: Priority Inheritance ("Helping")



Solution 1: Priority Inheritance ("Helping")

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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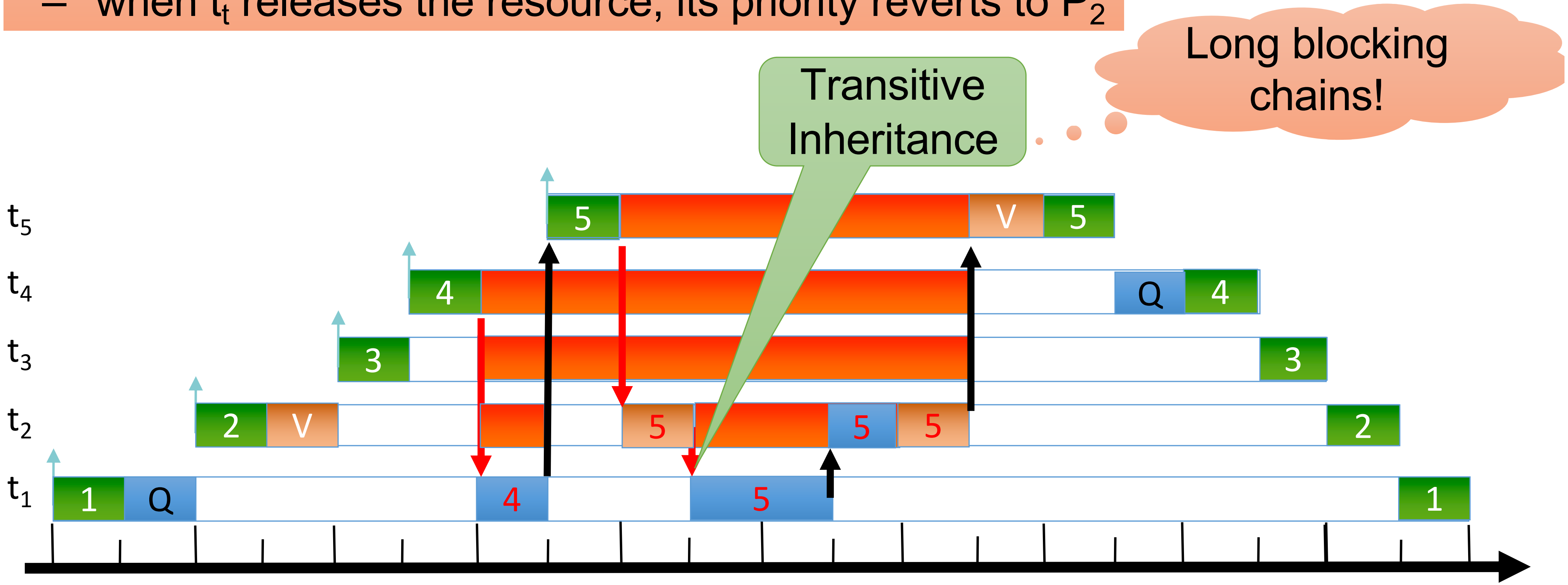
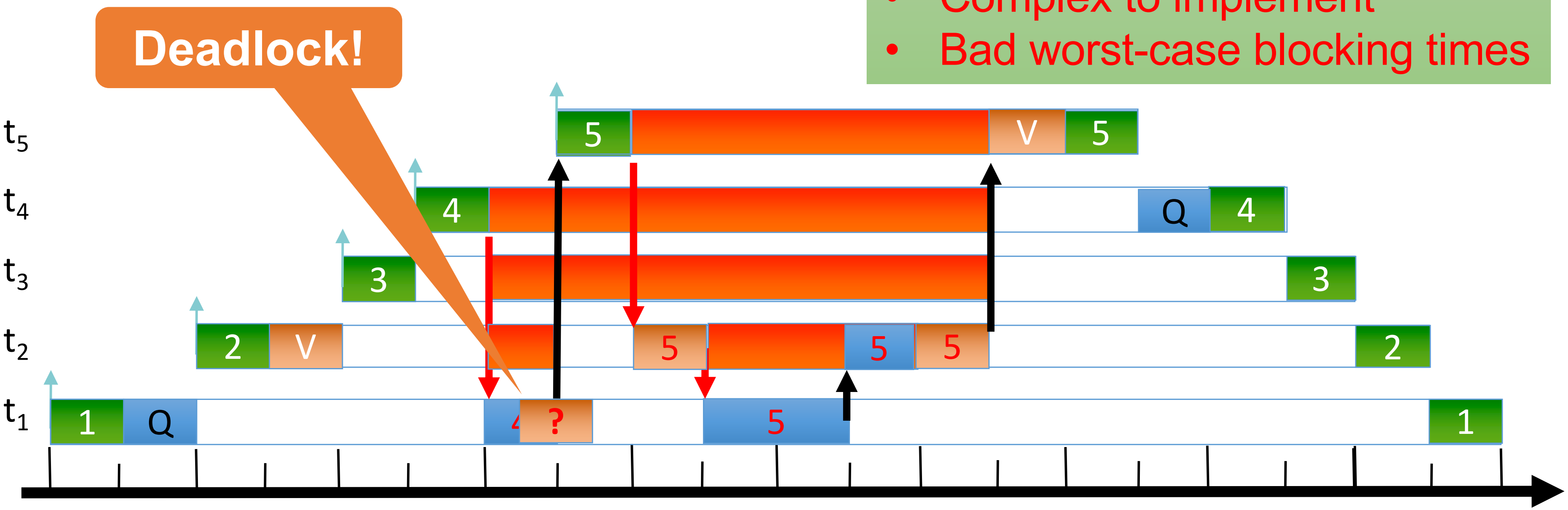


Solution 1: Priority Inheritance (“Helping”)

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

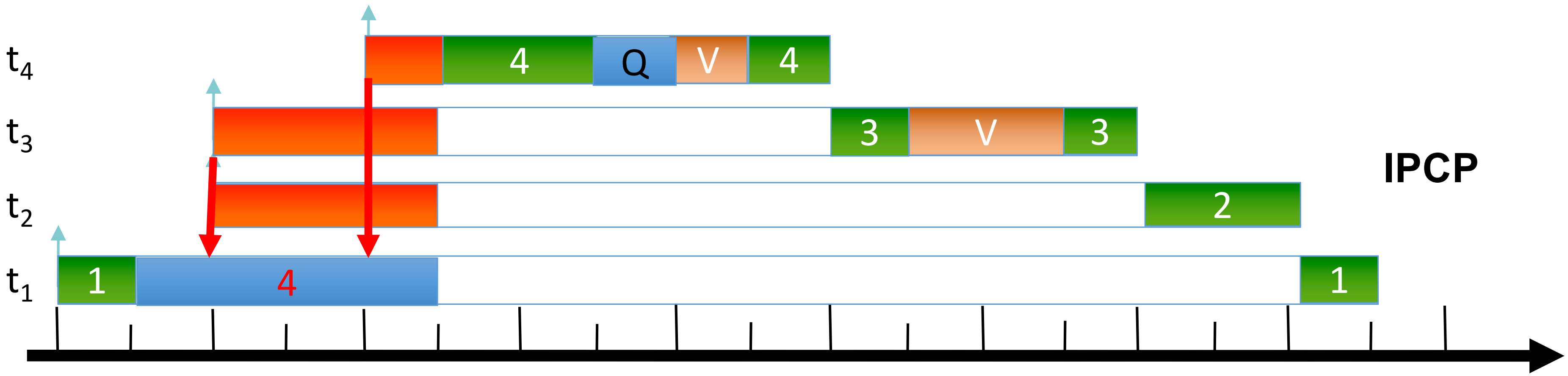
Priority Inheritance:
- Easy to use
- Potential deadlocks
- Complex to implement
- Bad worst-case blocking times



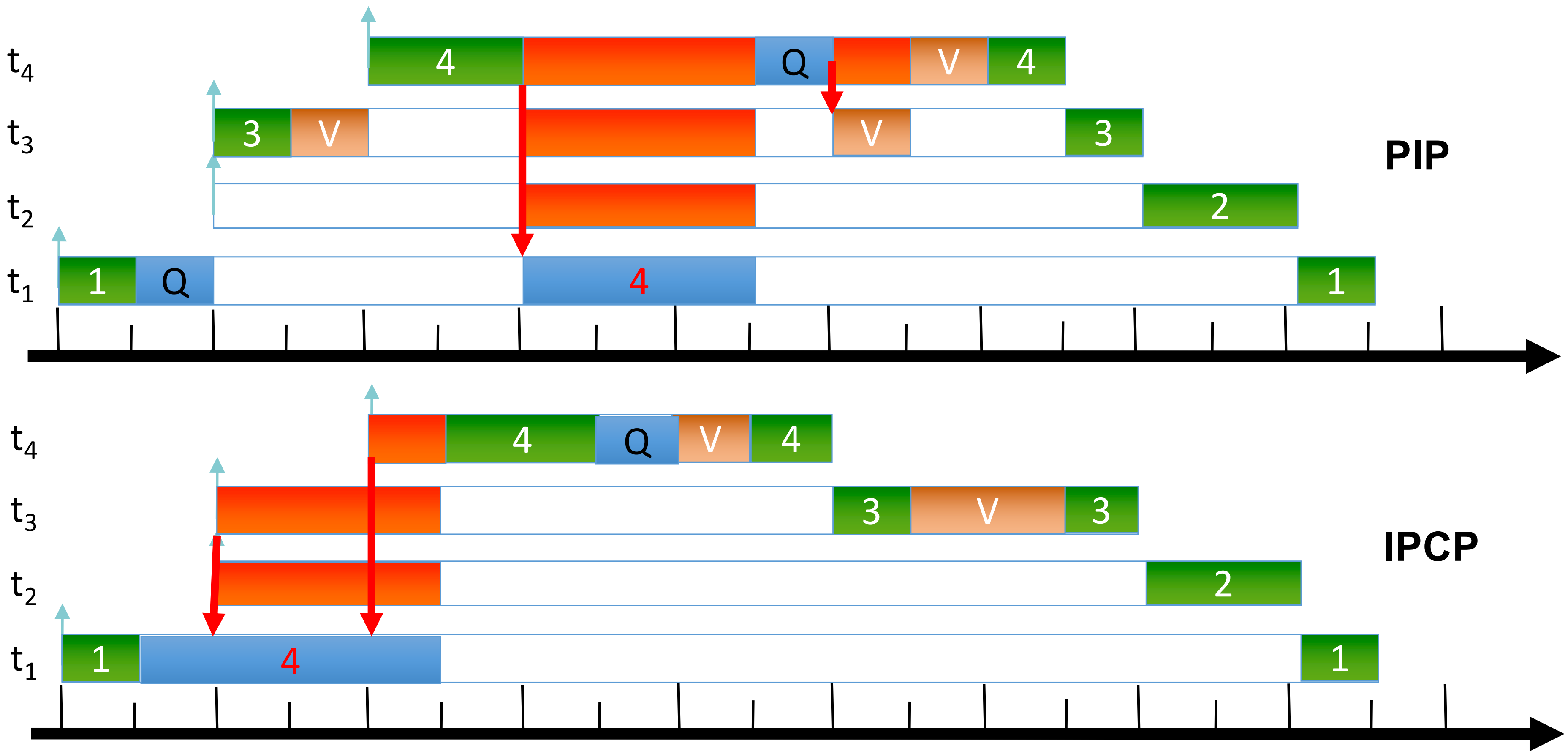
Solution 2: Priority Ceiling Protocol (PCP)

- Aim: Block at most once, avoid deadlocks
- Idea: Associate *ceiling priority* with each resource
  - Ceiling = Highest prio of jobs that may access the resource
  - On access, bump prio of job to ceiling

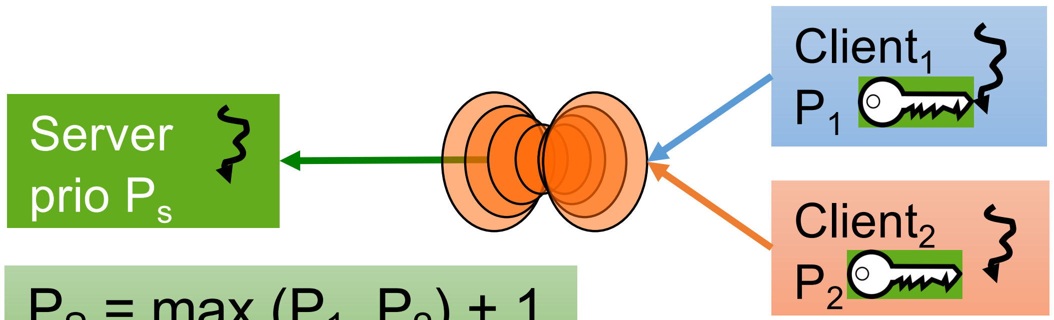
Immediate prio ceiling protocol (IPCP)



IPCP vs PIP



ICPC Implementation With Delegation



$P_S = \max(P_1, P_2) + 1$

EDF: Floor of deadlines

Immediate Priority Ceiling:

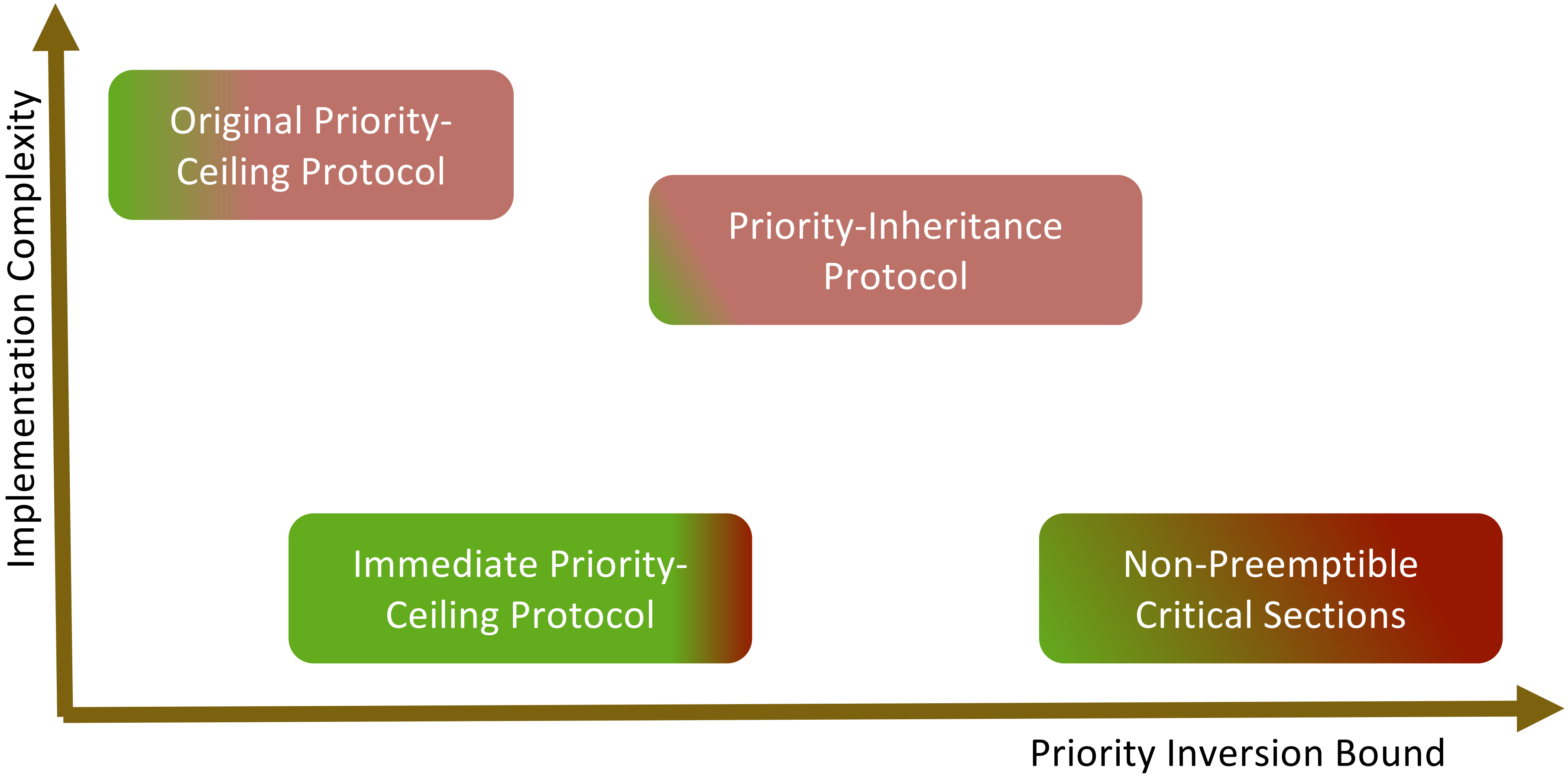
- Requires correct prio config
- Deadlock-free
- Easy to implement
- Good worst-case blocking times

Each task must declare all resources at admission time

- System must maintain list of tasks using resource
- Defines ceiling priority

Easy to enforce with caps

Comparison of Locking Protocols



Scheduling Overloaded RT Systems

Naïve Assumption: Everything is Schedulable

Standard assumptions of classical RT systems:

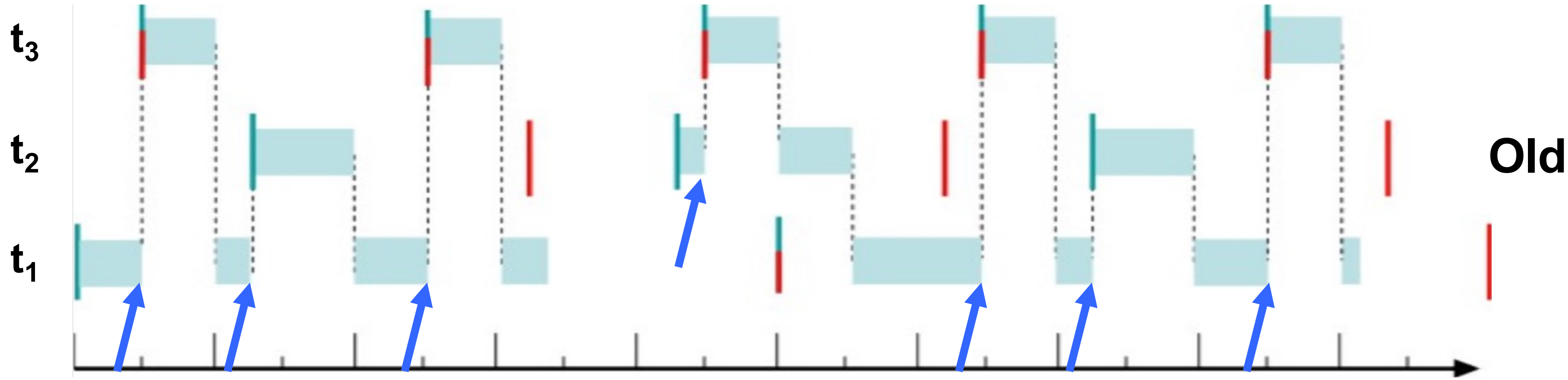
- All WCETs known
- All jobs complete within WCET
- Everything is trusted

Which job will miss its deadline?

More realistic: Overloaded system:

- Total utilisation exceeds schedulability bound
- Cannot trust everything to obey declared WCET

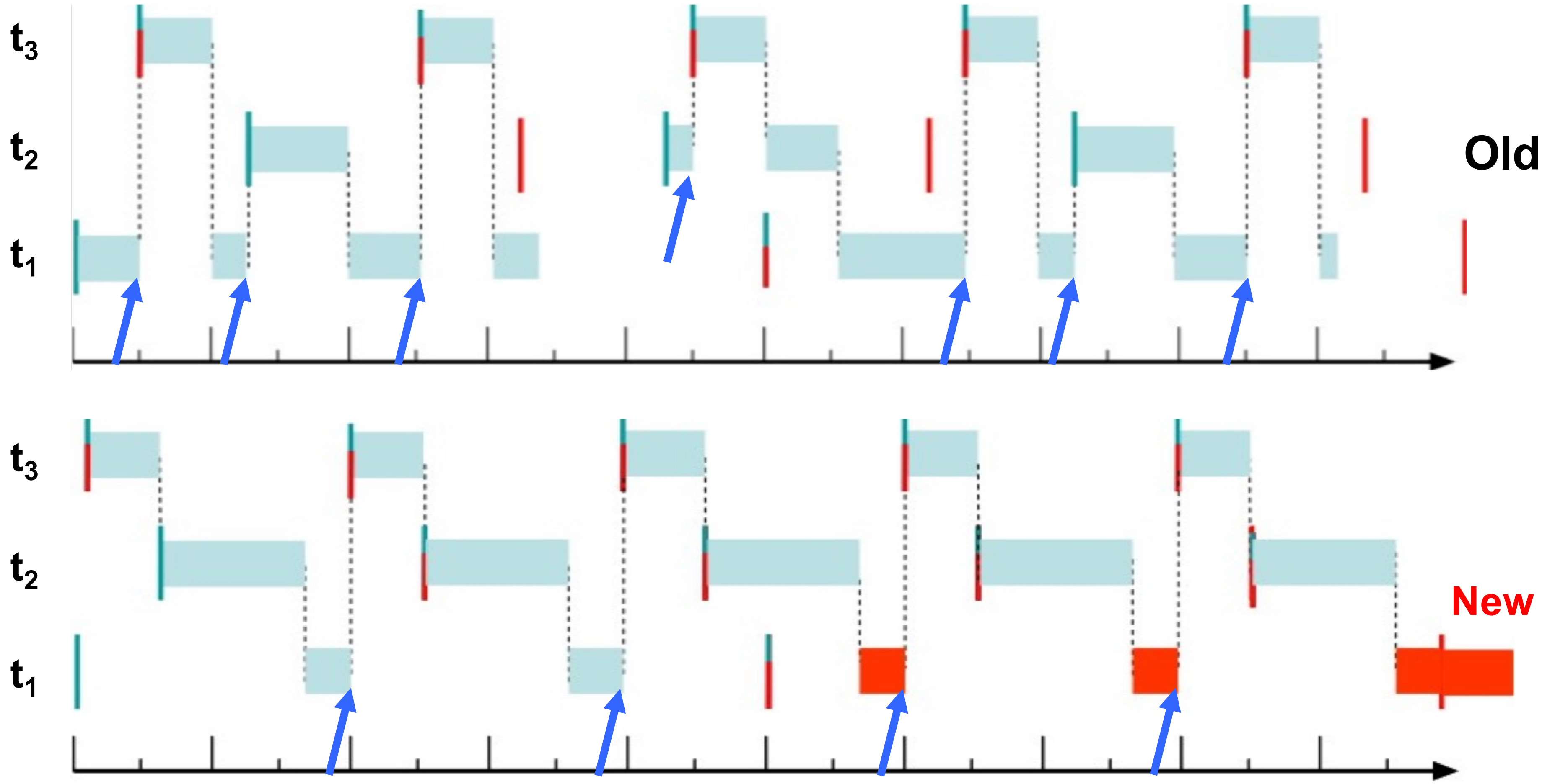
Overload: FPS



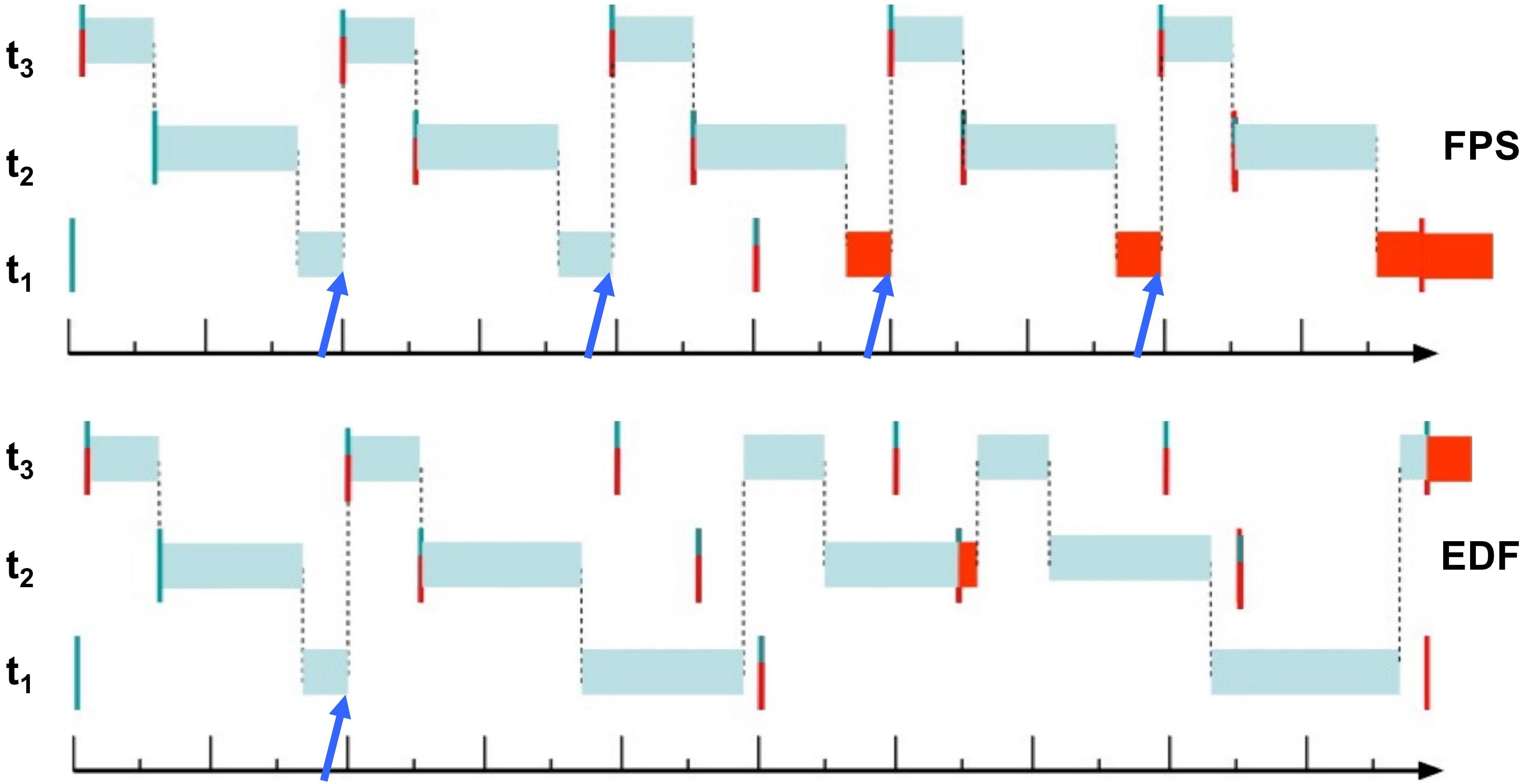
Task	P	C	T	D	U [%]
t_3	3	5	20	20	25
t_2	2	12	20	20	60
t_1	1	15	50	50	30
					115

New

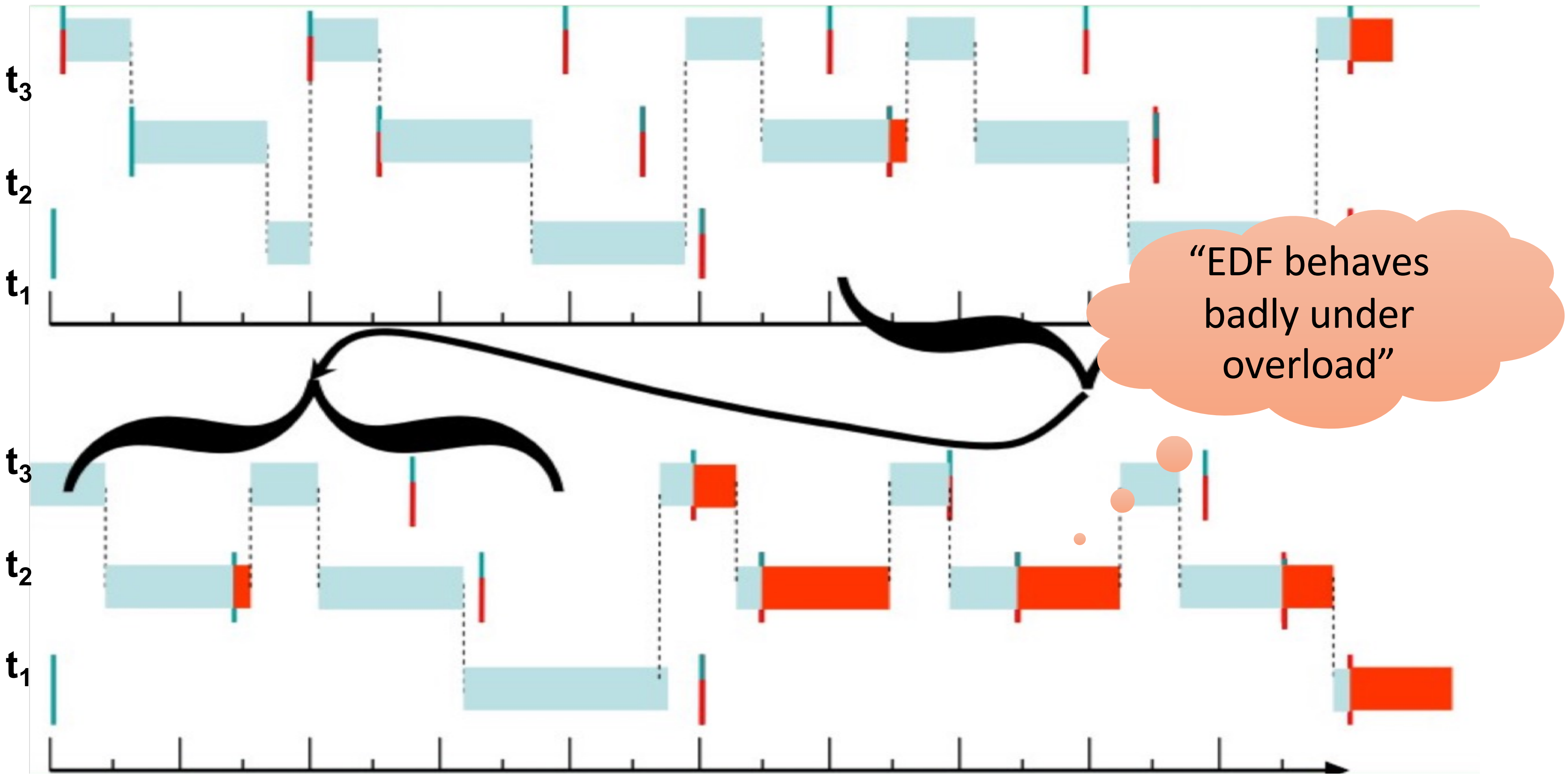
Overload: FPS



Overload: FPS vs EDF

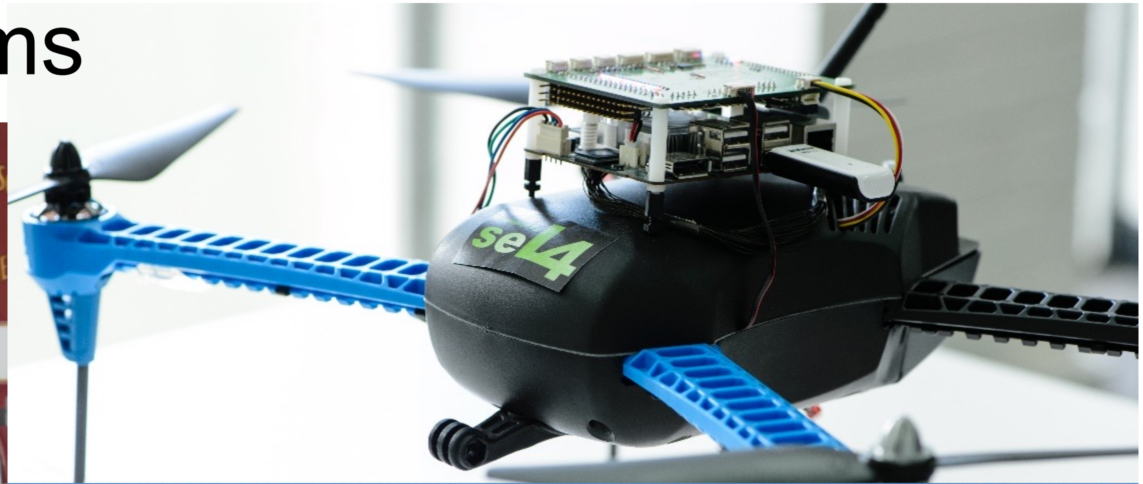


Overload: EDF



Mixed-Criticality Systems

Mixed Criticality Systems



Mixed Criticality

Need temporal isolation!

NW driver must preempt control loop

- … to avoid packet loss
- Driver must run at high prio (i.e. RMPA)
- ***Driver must not monopolise CPU***

Runs every 100 ms for a few millisecods

Runs frequently but for short time (order of μs)

Sensor readings → Control loop ↔ NW driver ← NW interrupts

Mixed Criticality

NW driver must preempt control loop
- … to avoid packet loss
- Driver must run at high prio (i.e. RMPA)
- ***Driver must not monopolise CPU***

Certification requirement: More critical components must *not* depend on any less critical ones! [ARINC-653]

Critical system certification:
- expensive
- conservative assumptions
  - eg highly pessimistic WCET

- Must minimise critical software
- Need temporal isolation: Budget enforcement

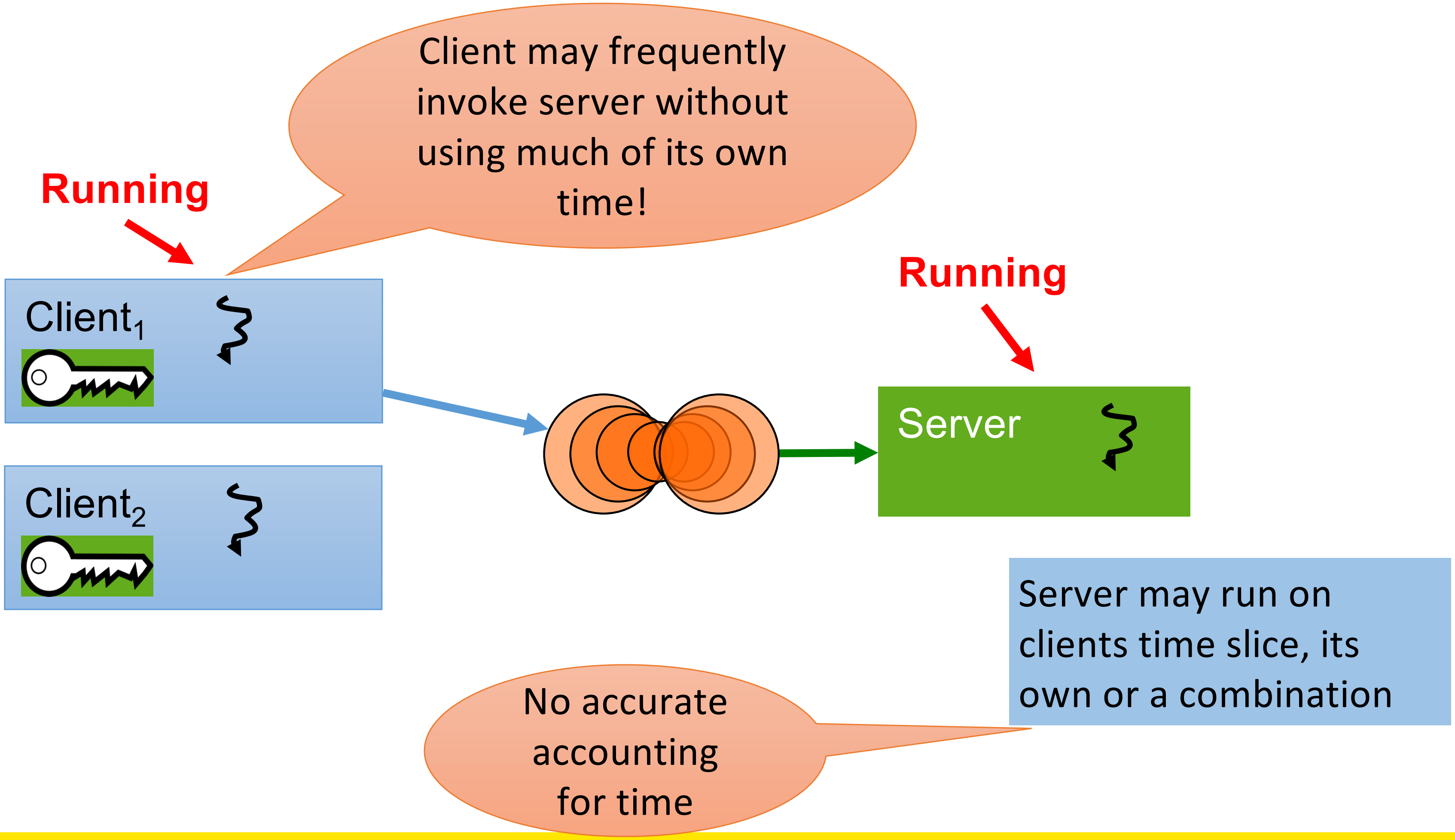
Mixed-Criticality Support

For supporting *mixed-criticality systems* (MCS), OS must provide:

- *Temporal isolation*, to force jobs to adhere to declared WCET

- Mechanisms for *safely sharing resources* across criticalities

Remember: Delegation of Critical Sections



seL4 MCS Model: Scheduling Contexts

Classical thread attributes

- Priority
- Time slice

Not runnable if null

MCS thread attributes

- Priority
- Scheduling context capability

Capability for time

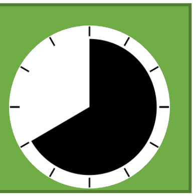
Scheduling context object

- T: period
- C: budget (≤ T)

Limits CPU access!

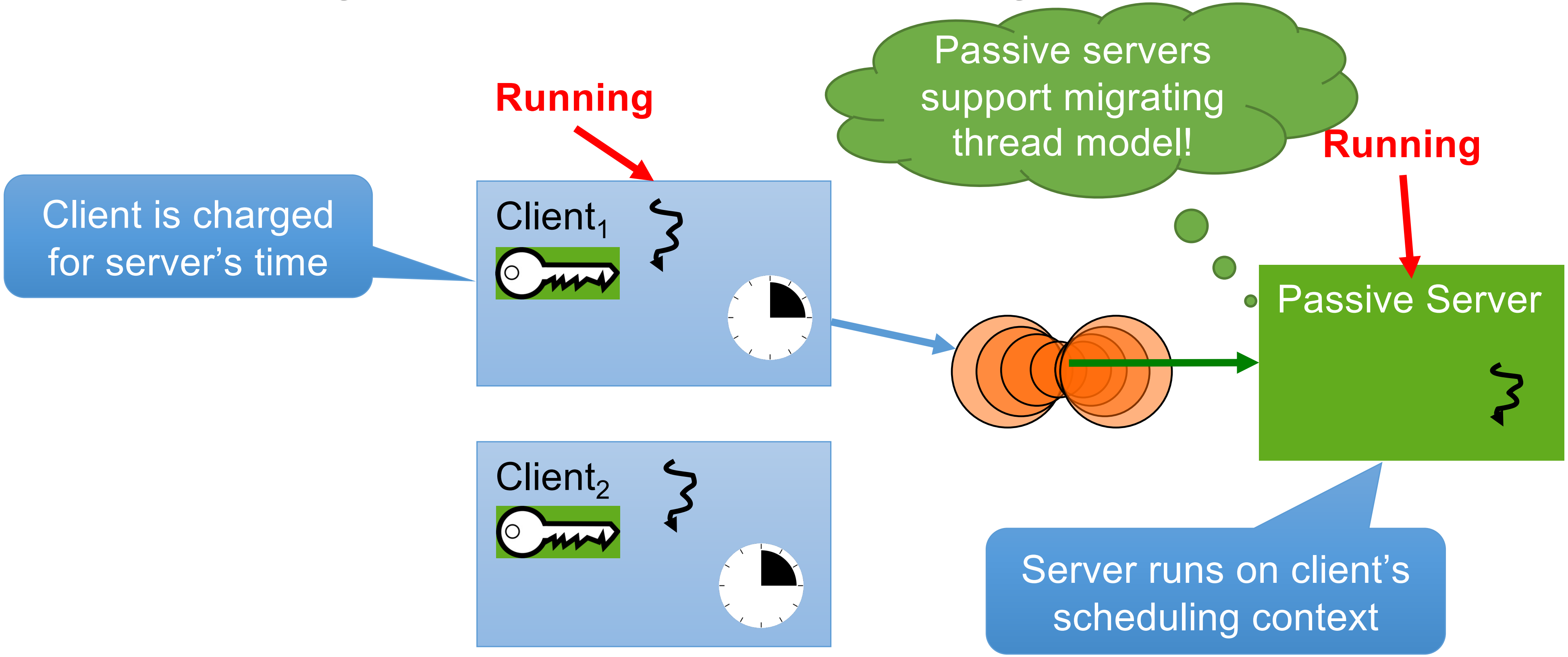
Per-core SchedControl capability conveys right to assign budgets (i.e. perform admission control)

C = 2
T = 3



C = 250
T = 1000

seL4 Delegation with Scheduling Contexts



Scheduling-context capabilities: a principled, light-weight OS mechanism for managing time [Lyons et al, EuroSys'18]

Mixed-Criticality Support

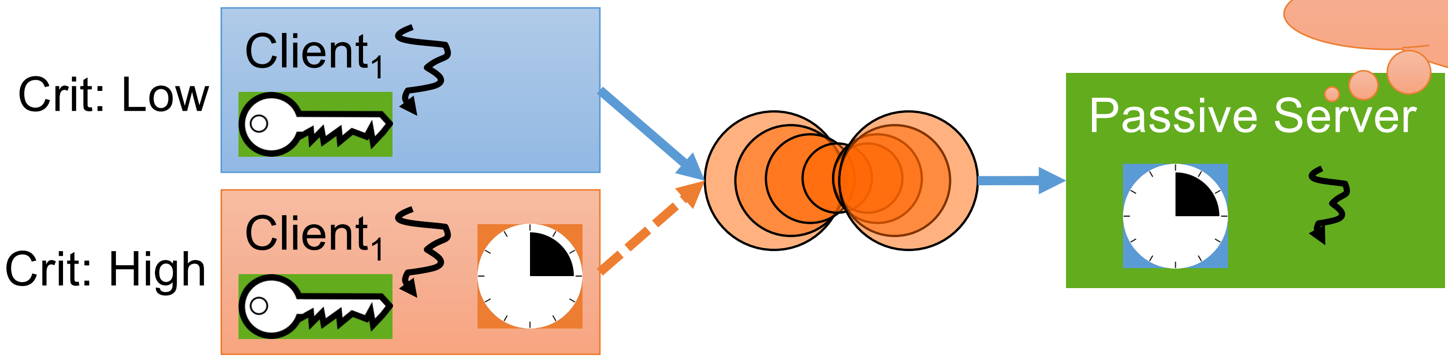
For *mixed-criticality systems* (MCS), OS must provide:

- *Temporal isolation*, to force jobs to adhere to declared WCET

Solved by scheduling contexts

- Mechanisms for *safely sharing resources* across criticalities

What if budget expires while shared server executing on Low's scheduling context?



Timeout Exceptions

Policy-free mechanism for dealing with budget depletion

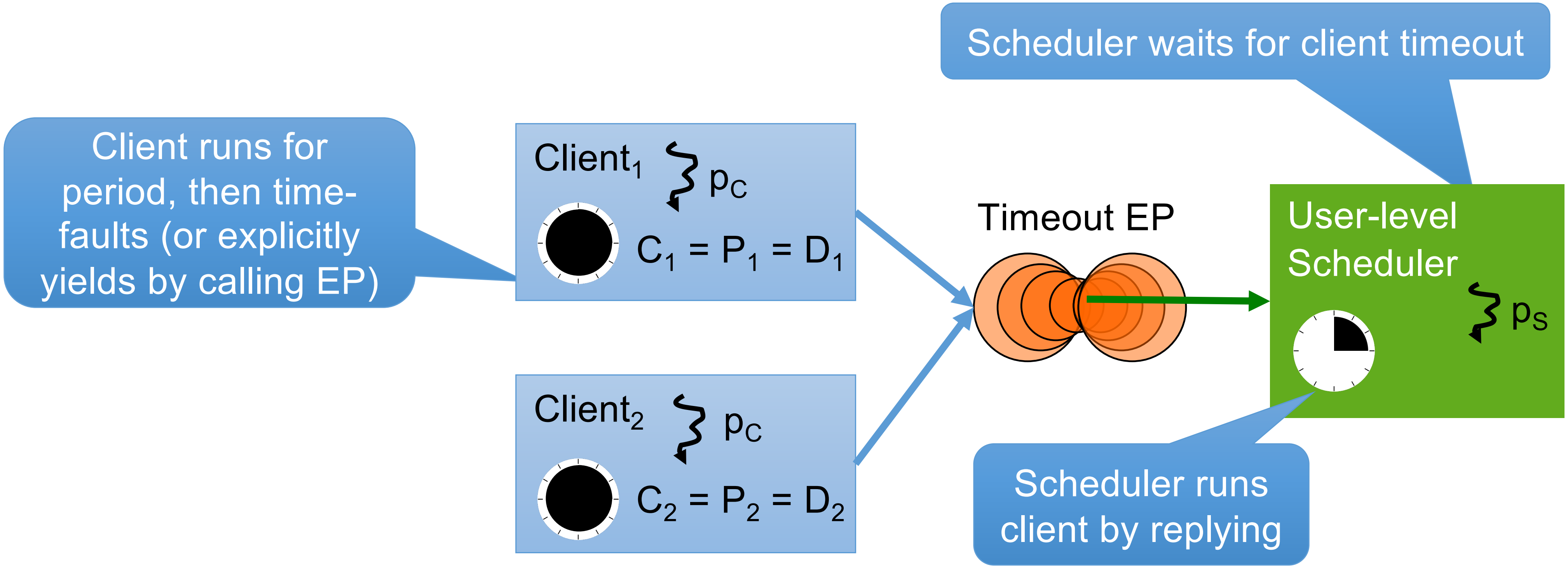
Possible actions:

- Provide emergency budget to leave critical section
- Cancel operation & roll-back server
- Reduce priority of low-crit client (with one of the above)
- Implement priority inheritance (if you must…)

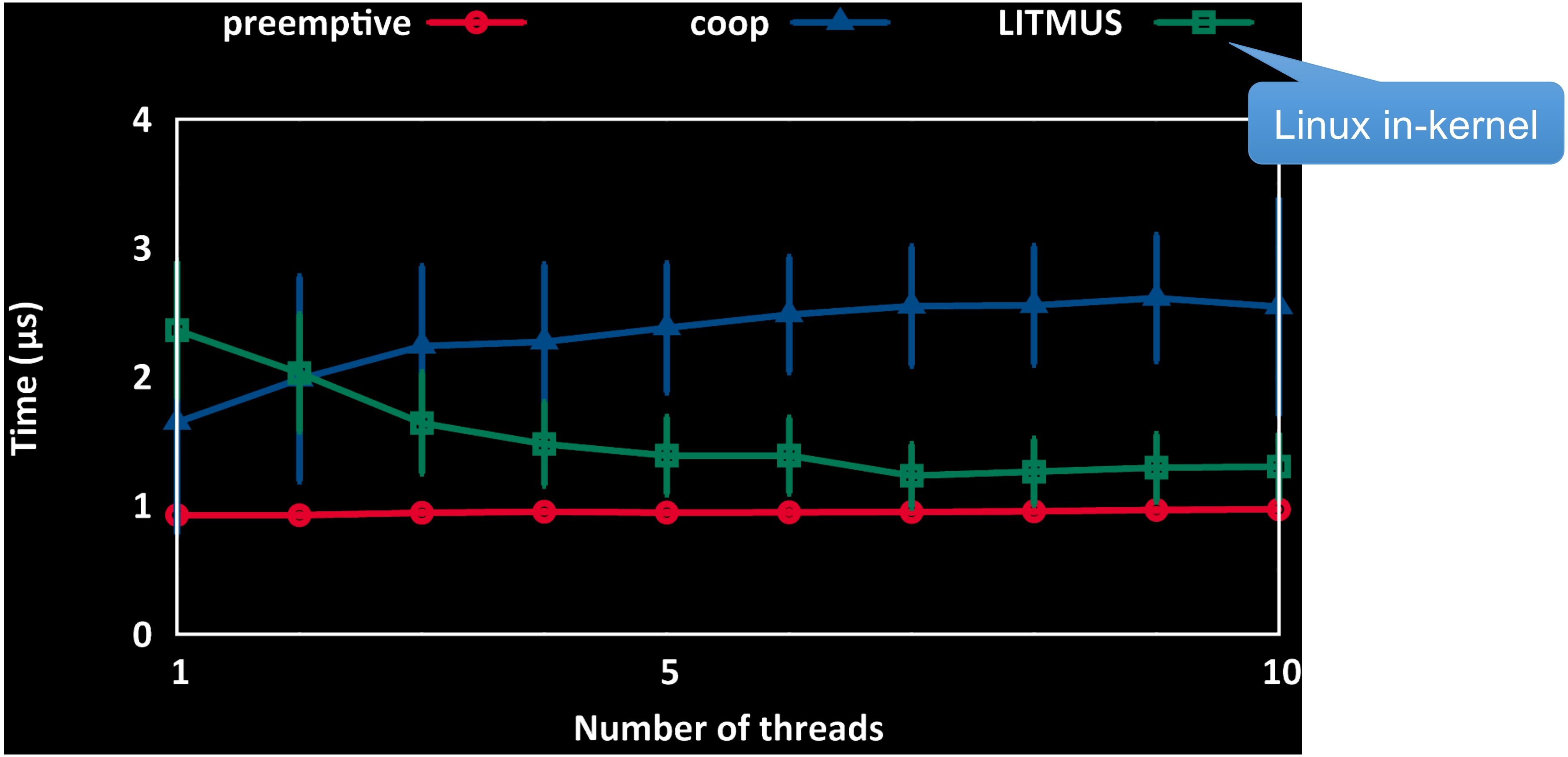
Arguable not ideal: better prevent timeout completely
RFC-14: Adding budget limit thresholds to endpoints for SC Donation

Isn't a Fixed-Prio Scheduler Policy?

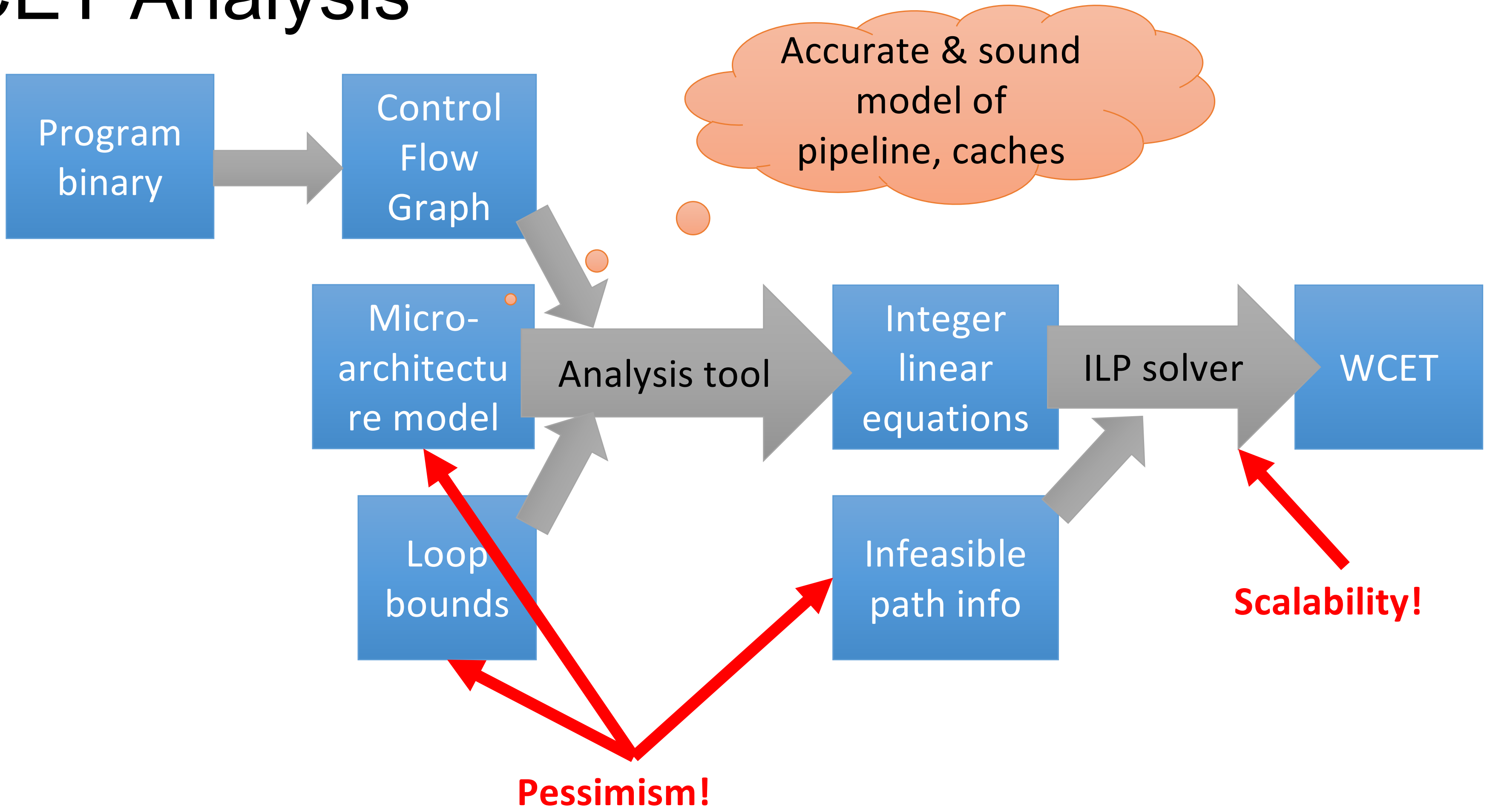
Implementing scheduling policy at user level



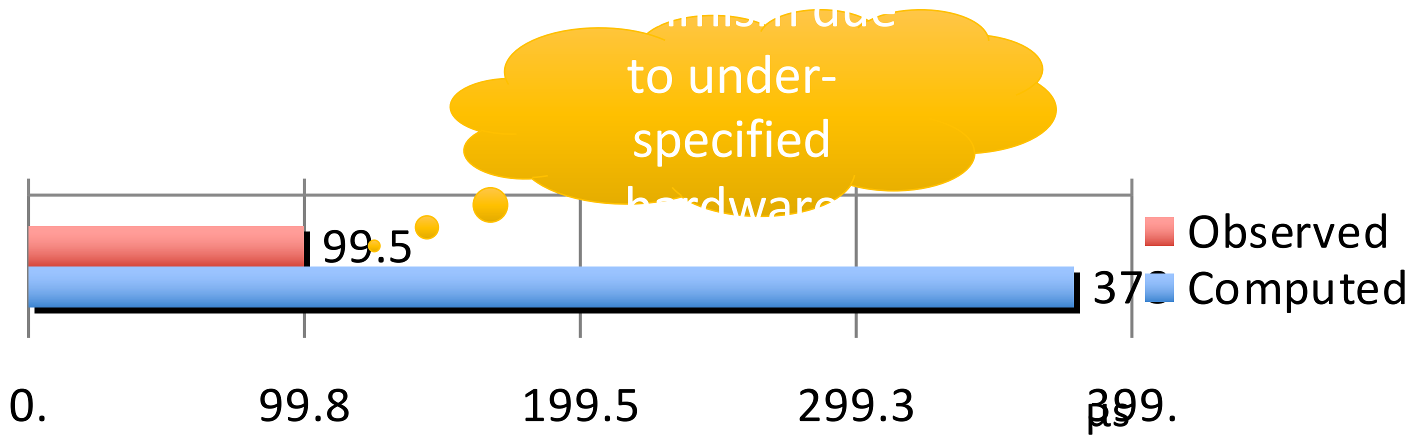
User-Level EDF Scheduler Performance



WCET Analysis



WCET Analysis on ARM11



WCET presently limited by verification practicalities

- without regard to verification achieved 50 µs
- 10 µs seem achievable
- BCET ~ 1µs
- [Blackham'11, '12] [Sewell'16]

Presented by Dr Anna Lyons

Internship!

https://jobs.apple.com/en-sg/details/200509672/secure-kernel-engineering-intern?team=SFTWR

search “secure kernel engineering intern apple”

Contact

linked in: https://www.linkedin.com/in/annamlyons/

email: anna.lyons@apple.com

Fun links

For the dark nights of AOS debugging: “The Night Watch”

https://www.usenix.org/system/files/1311_05-08_mickens.pdf

Real world priority inversion: NASA

https://www.rapitasystems.com/blog/what-really-happened-software-mars-pathfinder-spacecraft

Real world mess: (When real time is wrong) Toyota breaking

https://www.transportation.gov/briefing-room/us-department-transportation-releases-results-nhtsa-nasa-study-unintended-acceleration