TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Computer Science Institute of System Architecture, Operating Systems Group

REAL-TIME

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OVERVIEW

SO FAR

- talked about in-kernel building blocks:
  - threads
  - memory
  - IPC

COURSE EIP

Applications

System Services

Basic Abstractions

RESOURCES

Disk Bandwidth

Network I/O

TCP/IP Sessions

Windows

Files

Semaphores

Memory

Threads

Communication Rights

COMPARISON

Memory	Time
discrete, limited	continuous, infinite
hidden in the system	user-perceivable
managed by pager	managed by scheduler
page-granular partitions	arbitrary granularity
all pages are of equal value	value depends on workload
active policy decisions, passive enforcement	active policy decisions, active enforcement
hierarchical management	Fiasco: flattened in-kernel view

TIME

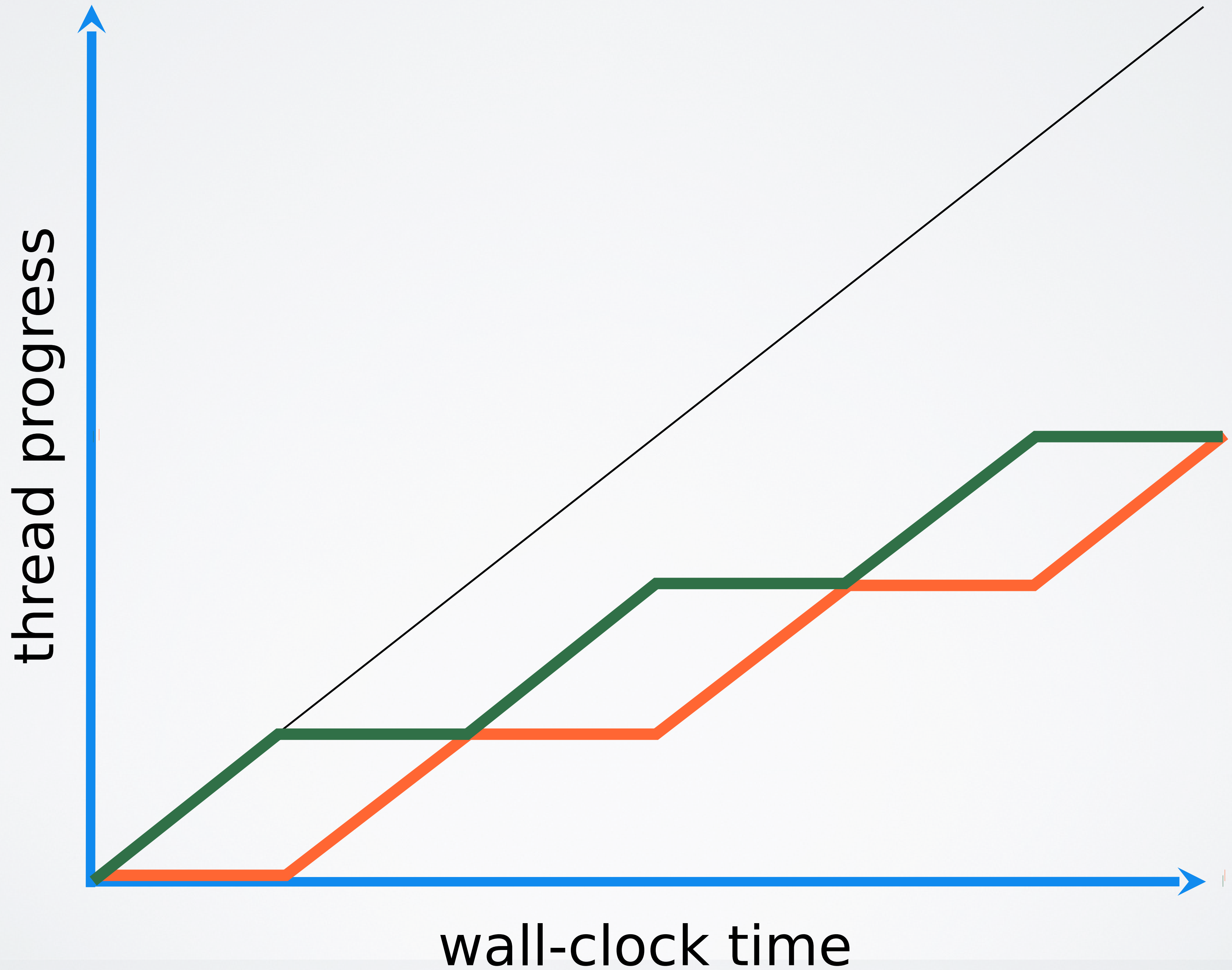
HISTORY

- in the early years of computing: time coarsely managed by batch systems
  - jobs receive the entire machine or a dedicated part of it for a given time
  - accounting, budgeting
  - no preemption
  - no interaction, good utilization
- still prevalent in HPC systems

THREADS

- today: threads provide a CPU abstraction
- each thread should observe its own time as continuous
- if there are more threads than physical CPU cores, we have to multiplex
- enforced by preemption
- implemented with timer interrupt

PROGRESS



REAL-TIME

DEFINITION

- a real-time system denotes a system, whose correctness depends on the timely delivery of results
- “it matters, when a result is produced”
- real-time denotes a predictable relation between system progress and wall-clock time

INTUITION

- real-time is about
  - predictability
  - guarantees
  - timeliness
  - responsiveness
- real-time is not about
  - being fast
  - live calculations

EXAMPLES

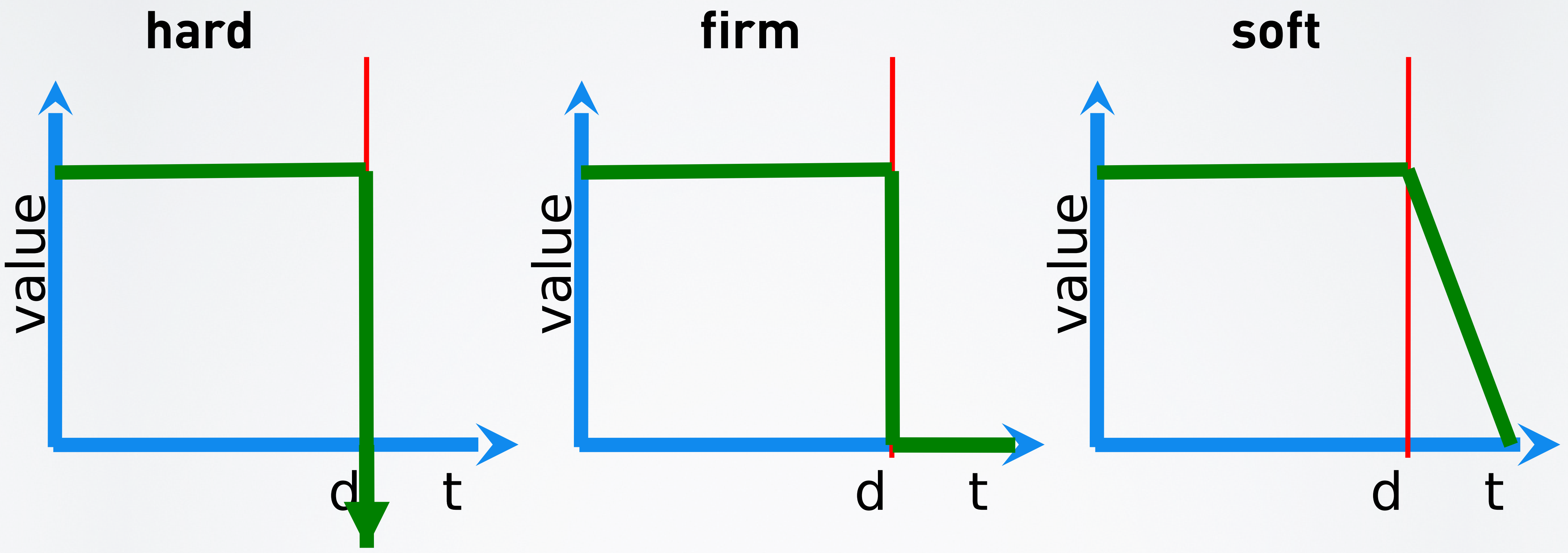
- engine control in a car
- break-by-wire
- avionics
- railway control

focused
catastrophic failures

- set-top box DVD player
- GSM-stack in your cell phone

benign failures
complex

VALUE FUNCTION

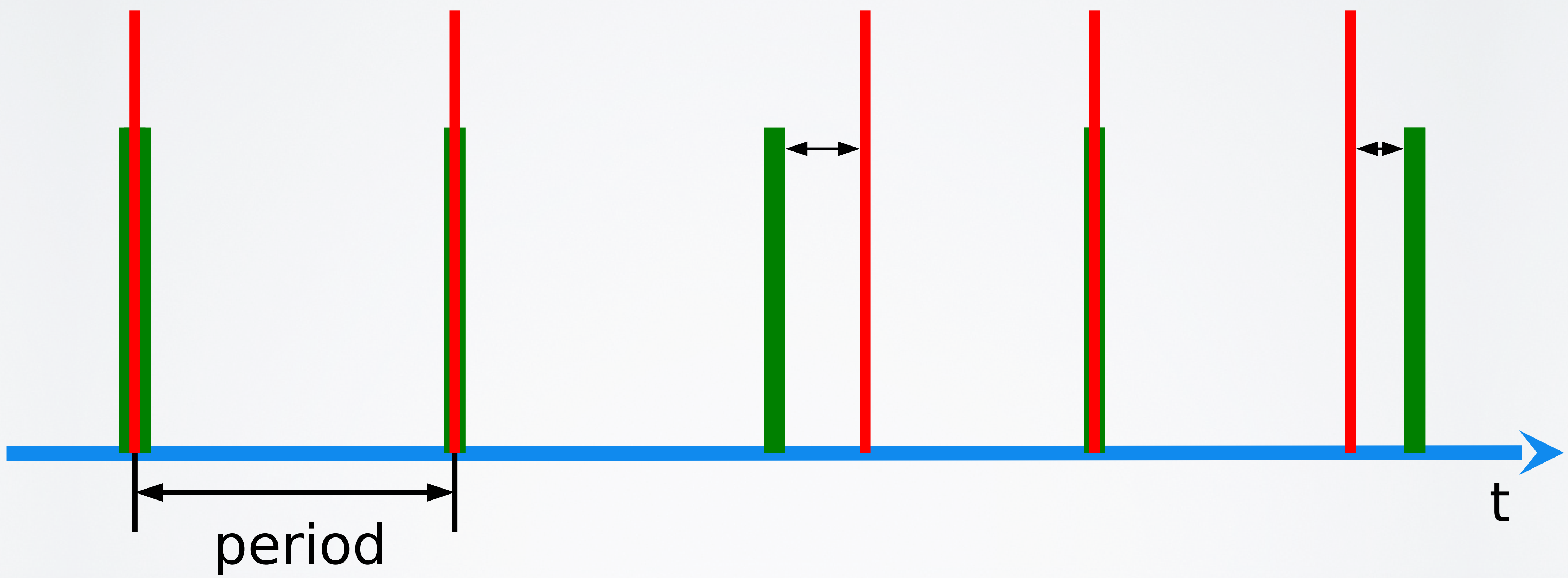


airbag | lung ventilator | video stream

FLAVORS

	hard real-time	firm real-time	soft real-time
missing some deadlines is tolerable	✗	✓	✓
a result delivered after its deadline is still useful	✗	✗	✓

JITTER



THEMES

① Predictability

② Guarantees

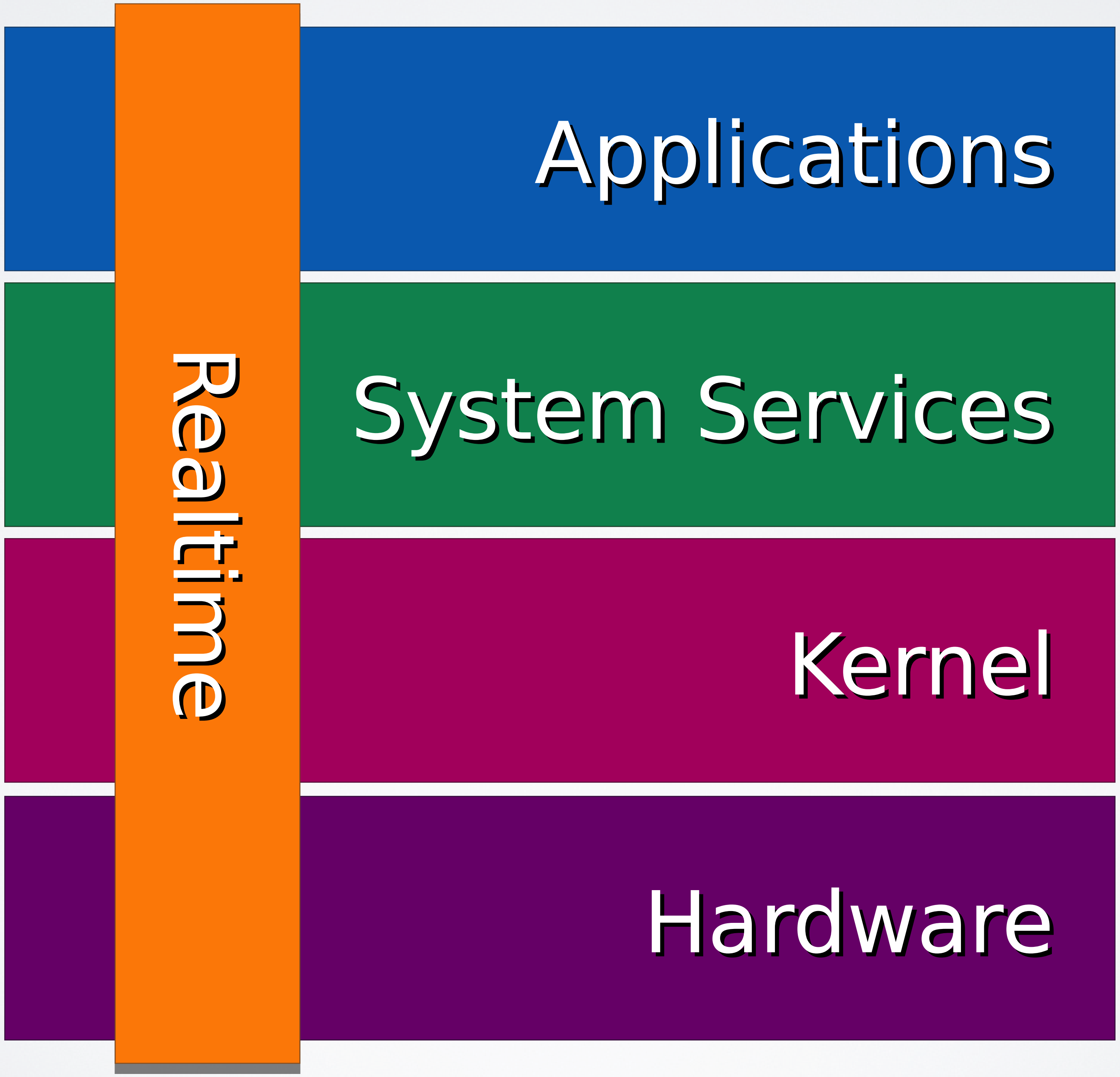
③ Enforcement

PREDICTABILITY

ENEMIES

- gap between worst and average case
  - memory caches, disk caches, TLBs
- “smart” hardware
  - system management mode
  - disk request reordering
- cross-talk from resource sharing
  - servers showing O(n) behavior
  - SMP
- unpredictable external influences
  - interrupts

CROSSCUTTING

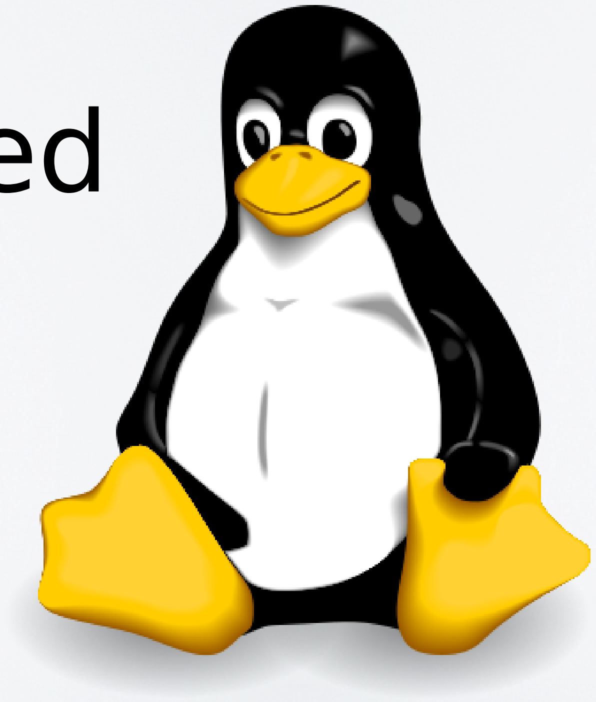


CUSTOM RTOS

- small real-time executives
  tailor-made for specific applications
- fixed workload known a priori
- pre-calculated time-driven schedule
- used on small embedded controllers
- benign hardware

RTLINUX

- full Linux kernel and real-time processes run side-by-side
- small real-time executive underneath supports scheduling and IPC
- real-time processes implemented as kernel modules
- all of this runs in kernel mode
- no isolation



XNU

- the kernel used in Mac OS X
- offers a real-time priority band above the priority of kernel threads
- interface: “I need X time with a Y period.”
- threads exceeding their assignment will be demoted
- all drivers need to handle interrupts correctly

FIASCO

- static thread priorities
- O(1) complexity for most system calls
- fully preemptible in kernel mode
  - bounded interrupt latency
- lock-free synchronization
  - uses atomic operations
- wait-free synchronization
  - locking with helping instead of blocking

be Afraid

- architecture for those afraid of touching the OS
- example: Real-Time Java

RESOURCES

- a real-time kernel alone is not enough
- microkernel solution: temporal isolation
  - eliminates cross-talk through system calls
  - interrupt handling controlled by scheduler
- user-level servers on top act as resource managers
  - implement real-time views on specific resources
  - real-time is not only about CPU

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GUARANTEES

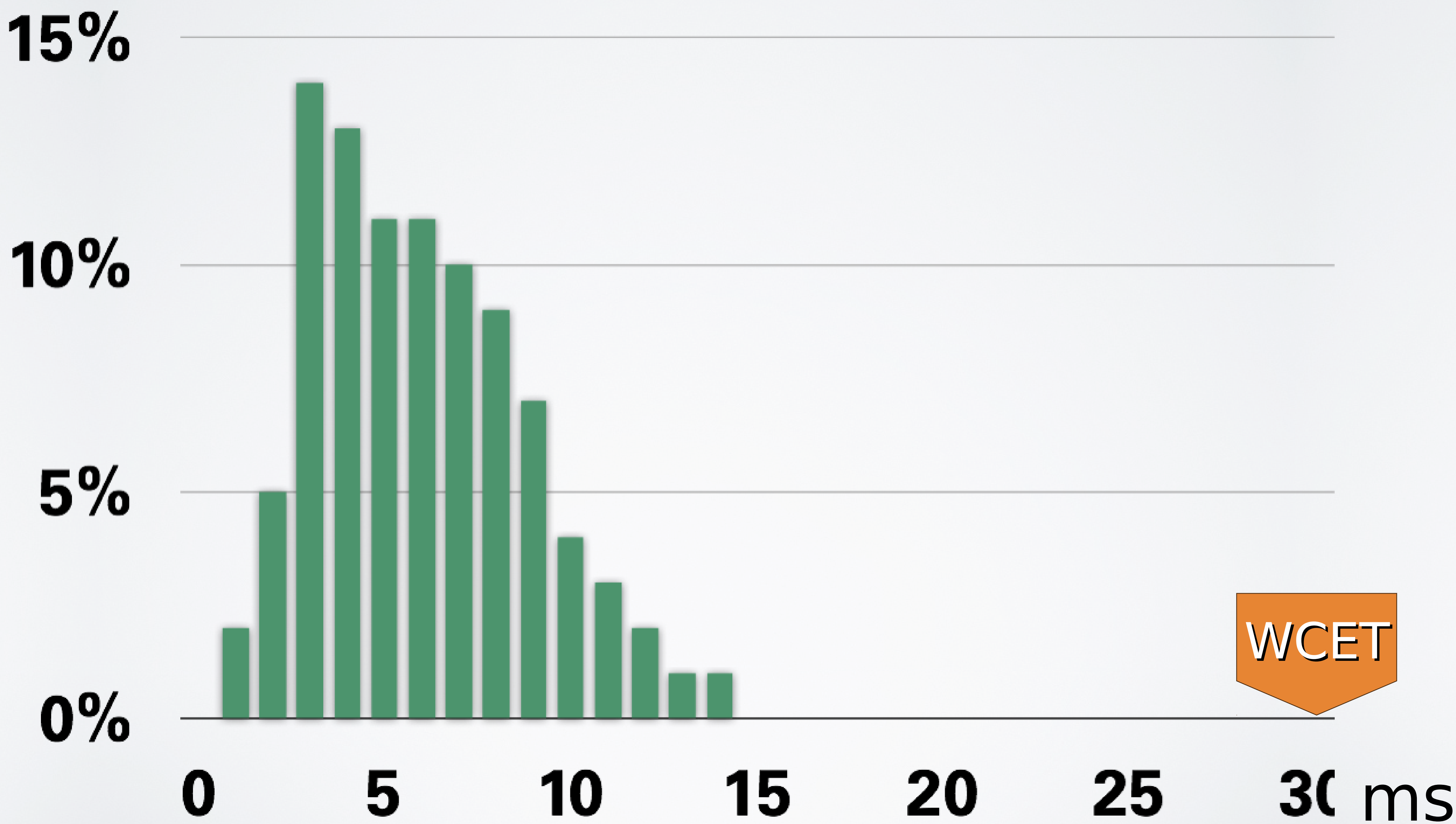
PROBLEM

- worst case execution time (WCET) largely exceeds average case
- offering guarantees for the worst case will waste lots of resources
- missing some deadlines can be tolerated with the firm and soft real-time flavors

MOTIVATION

- desktop real-time
- there are no hard real-time applications on desktops
- there is a lot of firm and soft real-time
  - low-latency audio processing
  - smooth video playback
  - desktop effects
  - user interface responsiveness

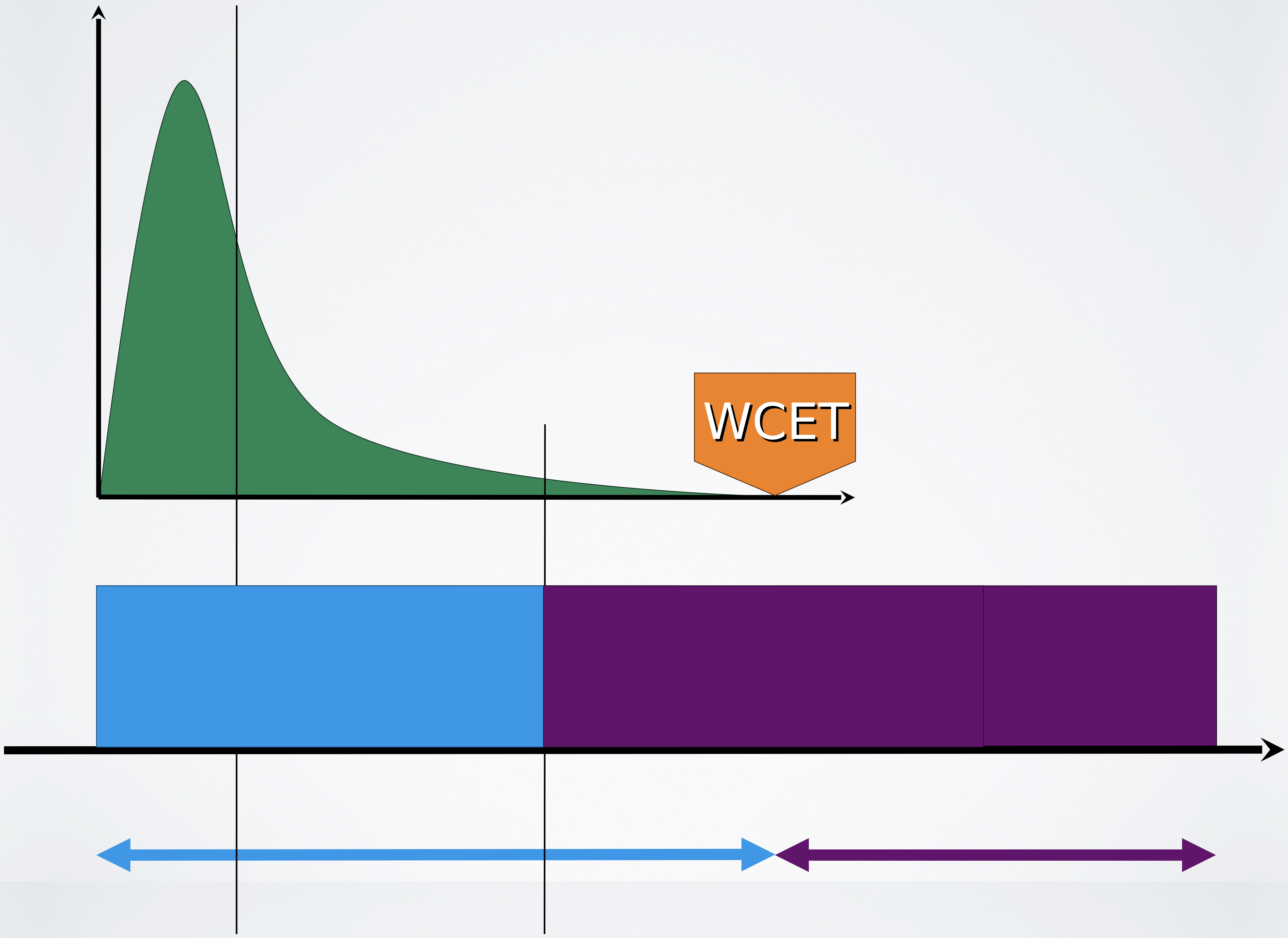
H.264 DECODING



KEY IDEA

- guarantees even slightly below 100% of WCET can dramatically reduce resource allocation
- unused reservations will be used by others at runtime
- use probabilistic planning to model the actual execution
- quality q: fraction of deadlines to be met

KEY IDEA



RESERVATION

$$r'_i = \min(r \in \mathbb{R} \mid \sum_{k=1}^{m_i} \mathbf{P}(X_i + k \cdot Y_i \leq r) \geq q_i m_i)$$

$$r_i = \max(r'_i, w_i) \quad i = 1, \ldots, n$$

- to fully understand this (or not): see real-time systems lecture
- good for microkernel: reservation can be calculated by a userland service
- kernel only needs to support static priorities

SCHEDULING

- scheduling = admission + enforcement
- admission = scheduling analysis
  - verifies the feasibility of client requests
  - formal task model
  - calculates task parameters
  - can reject requests
- enforcement
  - executing the schedule
  - preempt when reservation expires

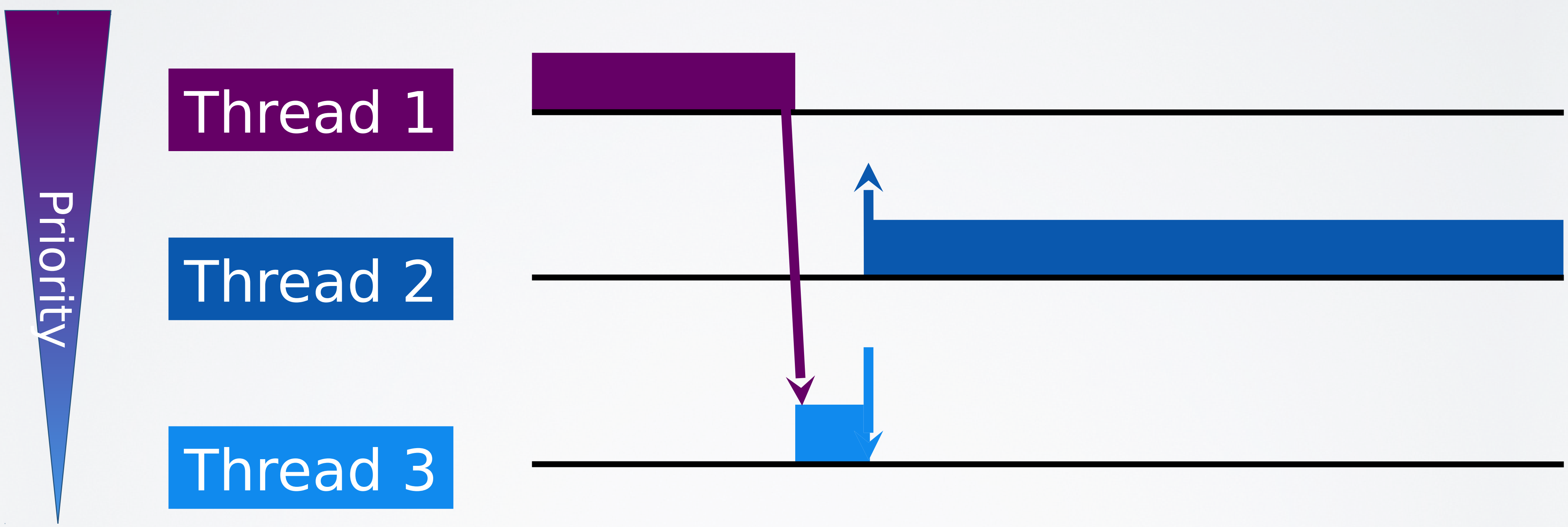
ENFORCEMENT

DISPATCHER

- executed at specific events
- enforces task parameters by preemption
  - e.g. on deadline overrun
- picks the next thread
  - static priorities (e.g. RMS, DMS)
  - dynamic priorities (e.g. EDF)
- seems simple…

PROBLEM

- high priority thread calls low priority service with a medium priority thread interfering:



1 waits for 3 ✓

3 waits for 2 ✓

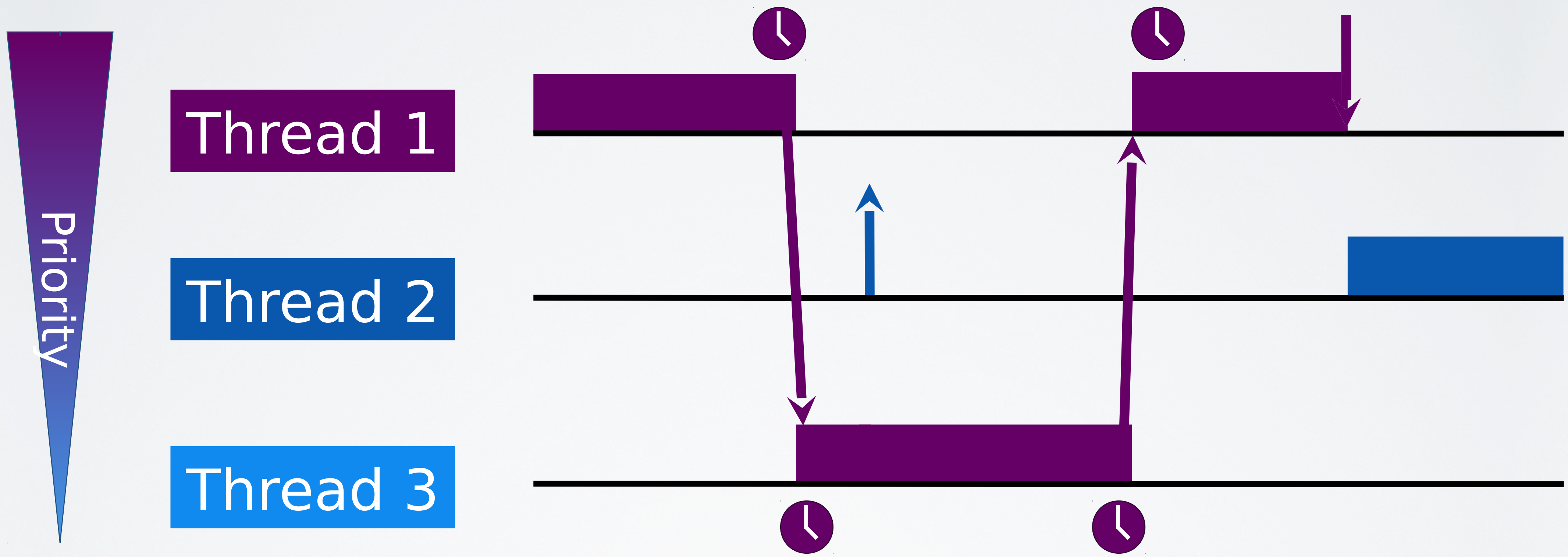
= 1 waits for 2 ✗

Priority Inversion

SOLUTION

- priority inheritance, priority ceiling
- nice mechanism for this in Fiasco, NOVA: timeslice donation
- implemented by splitting thread control block
  - execution context: holds CPU state
  - scheduling context: time and priority
- on IPC-caused thread switch, only the execution context is switched

DONATING CALL



- IPC receiver runs on the sender’s scheduling context
- priority inversion problem solved with priority inheritance

ACCOUNTING

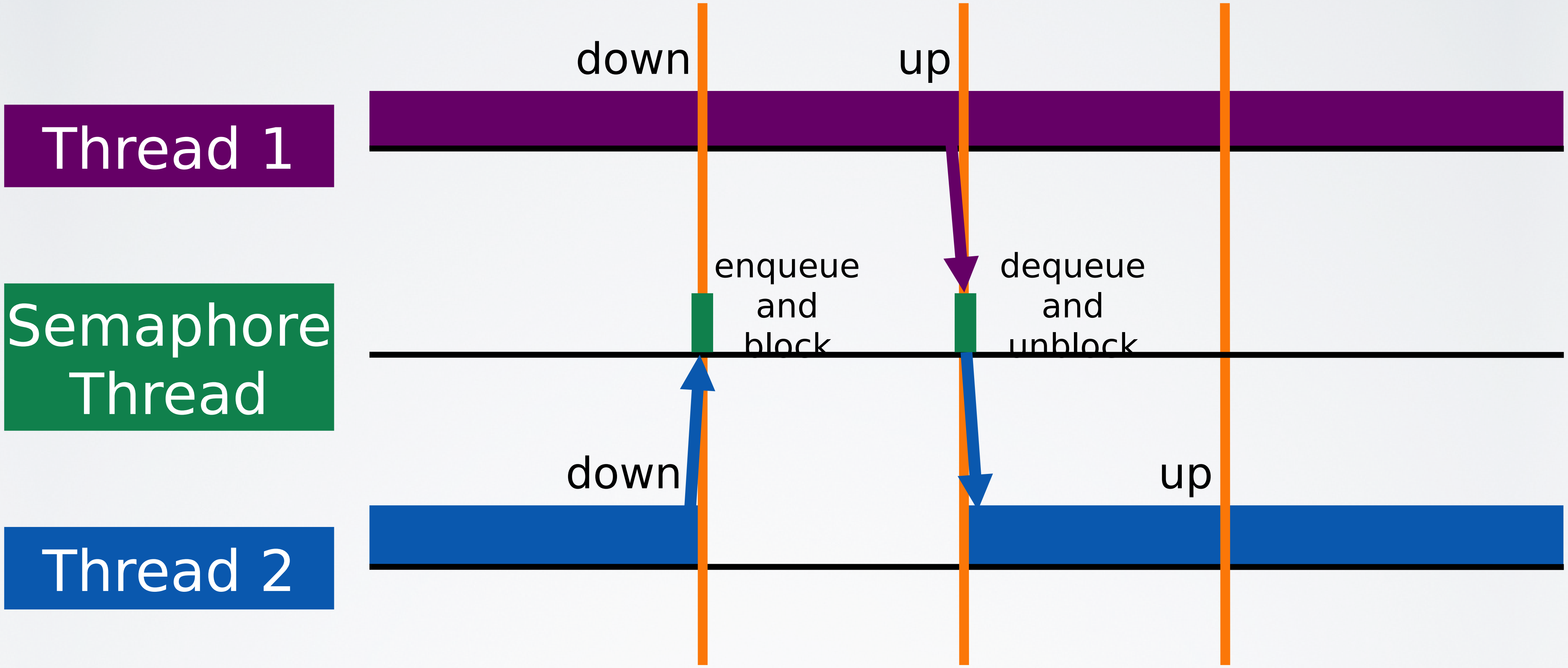
- servers run on their clients’ time slice
  - when the server executes on behalf of a client, the client pays with its own time
- this allows for servers with no scheduling context
  - server has no time or priority on its own
  - can only execute on client‘s time
  - relieves scheduler from dealing with servers

Open Issues

- servers could be malicious, so you need timeouts to get your time back
  - now, malicious clients can call the server with a very short timeout
  - on what time will the server do cleanup?
- donation does not work across processors
  - would thwart admission; one CPU cannot execute on behalf of another
  - migrate servers or clients?

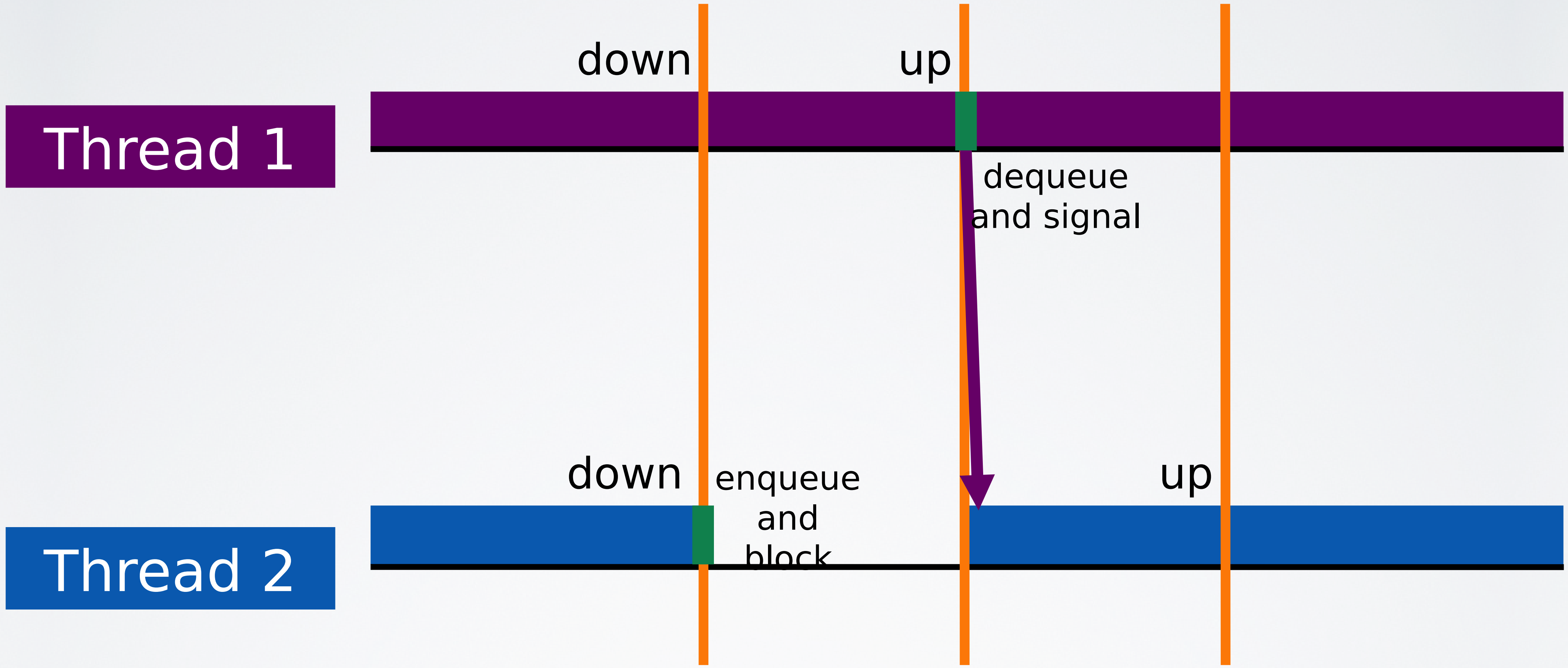
OPTIMIZATION

SEMAPHORES



- IPC only in the contention case
- optimized for low contention
- bad for producer-consumer (high contention)

SEMAPHORES



- reduce from 2 IPCs to one
- how to protect the short critical section?
- spinlocks suffer from lockholder preemption

IDEA

- allow threads to have short periods where they are never preempted
  - like a low cost global system lock
  - like a userland flavor of disabling interrupts
- delayed preemption
- threads set “don’t preempt” flag in UTCB
  - very low cost
  - not a lock, no lockholder preemption

PROBLEMS

- unbounded delay
  - kernel honors the delayed preemption flag only for a fixed maximum delay
  - what delay is useful?
- delay affects all threads
  - effect can be limited to a priority band
  - must be included in real-time analysis
- does not work across multiple CPUs

SUMMARY

- managing time is necessary
  - we interact with the system based on time
- real-time is a cross-cutting concern
- "hard real-time is hard, soft real-time is even harder" (E. Douglas Jensen)
- priority inheritance by timeslice donation
- synchronisation, delayed preemption
- next week: drivers