TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Informatik Institut für Systemarchitektur, Professur für Betriebssysteme

OPERATING-SYSTEM CONSTRUCTION

Material based on slides by Olaf Spinczyk, Universität Osnabrück

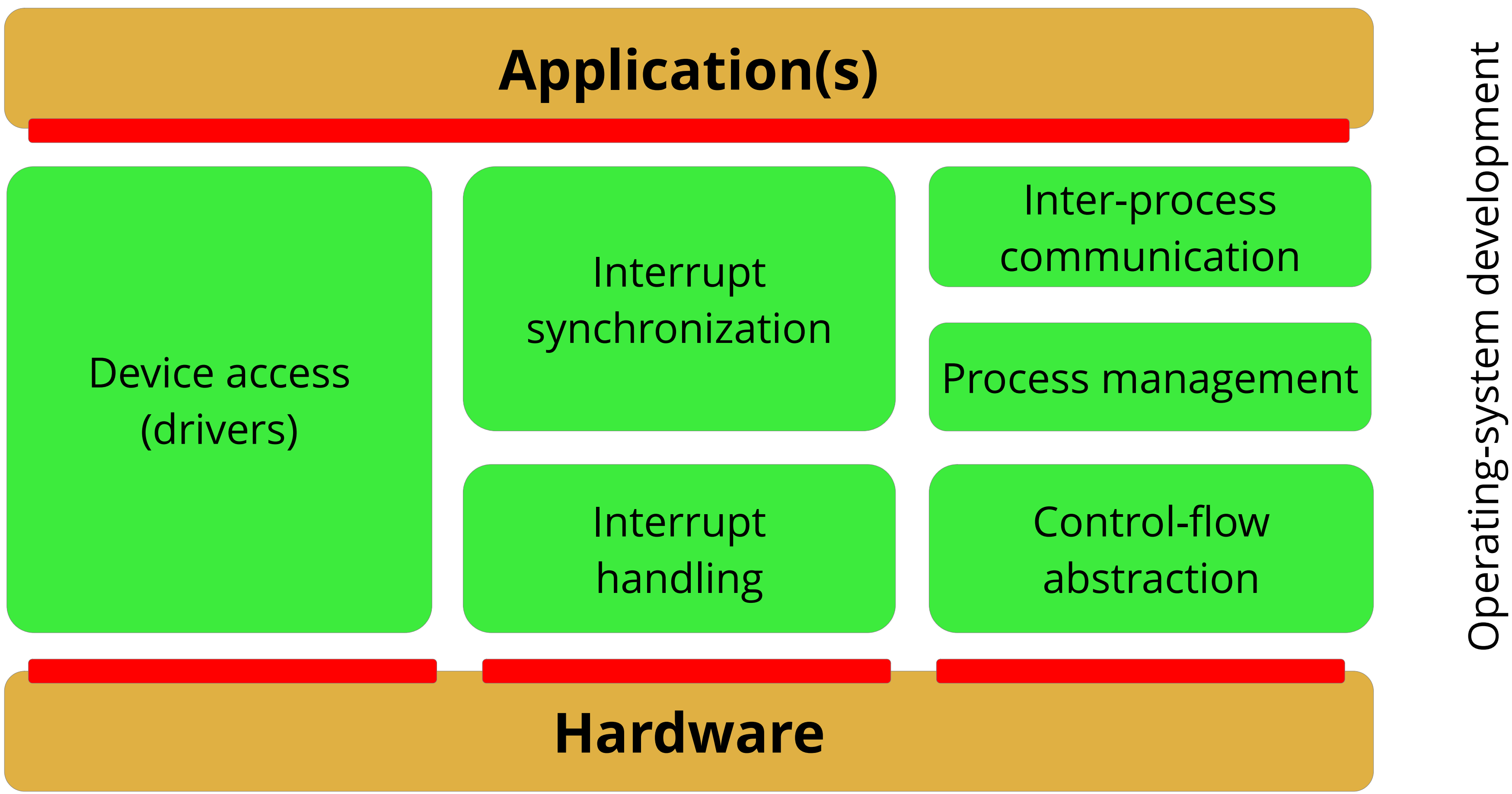
Scheduling

https://tud.de/inf/os/studium/vorlesungen/betriebssystembau

HORST SCHIRMEIER

Overview: Lectures

Structure of the "OO-StuBS" operating system:



Overview: Lectures

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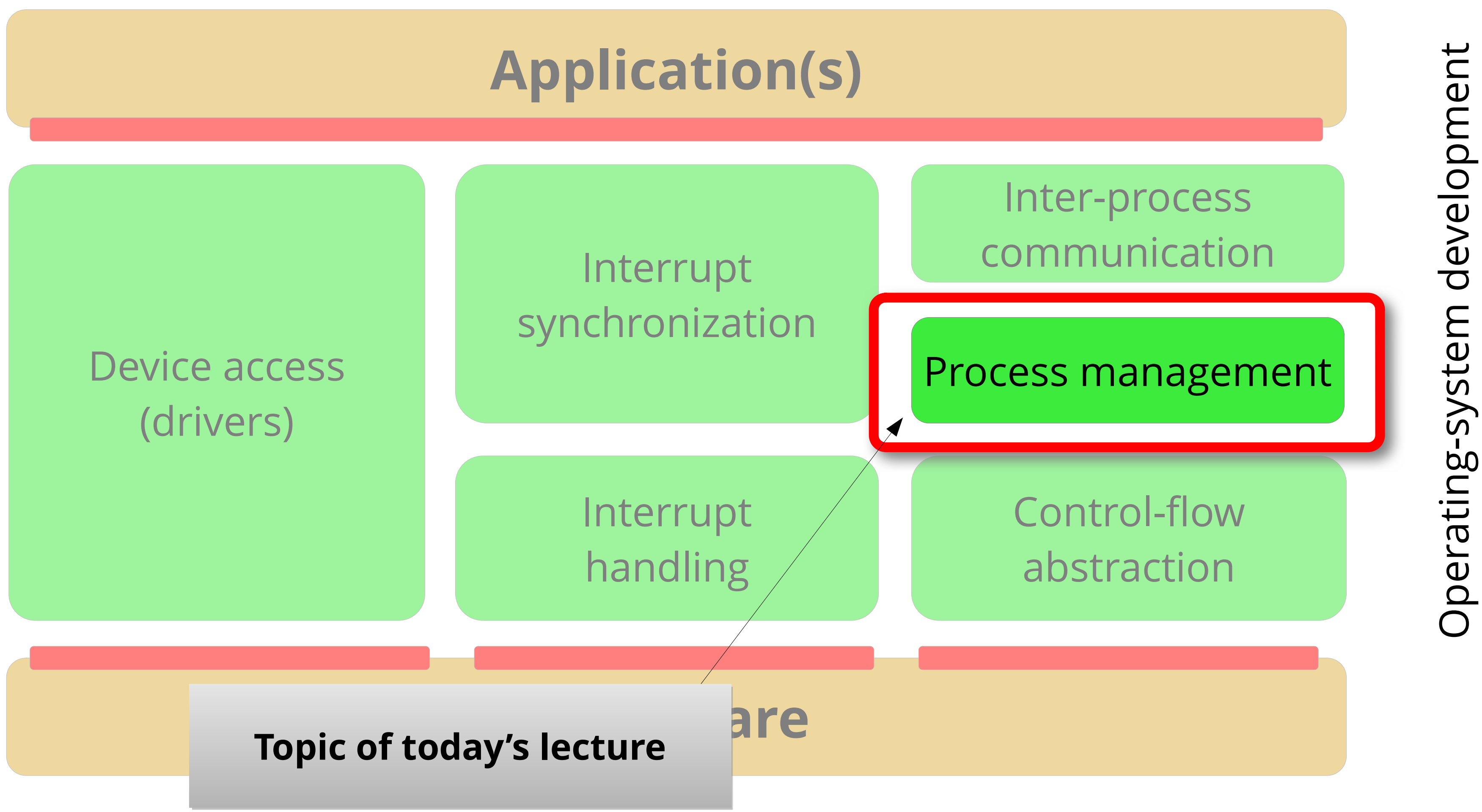

Agenda

- Kernel-Level Threads
  - Motivation
  - Cooperative Thread Switch
  - Preemptive Thread Switch
- Scheduling
  - Basic Terms and Classification
  - in Windows (XP/2000/2003)
  - in Linux
- Summary

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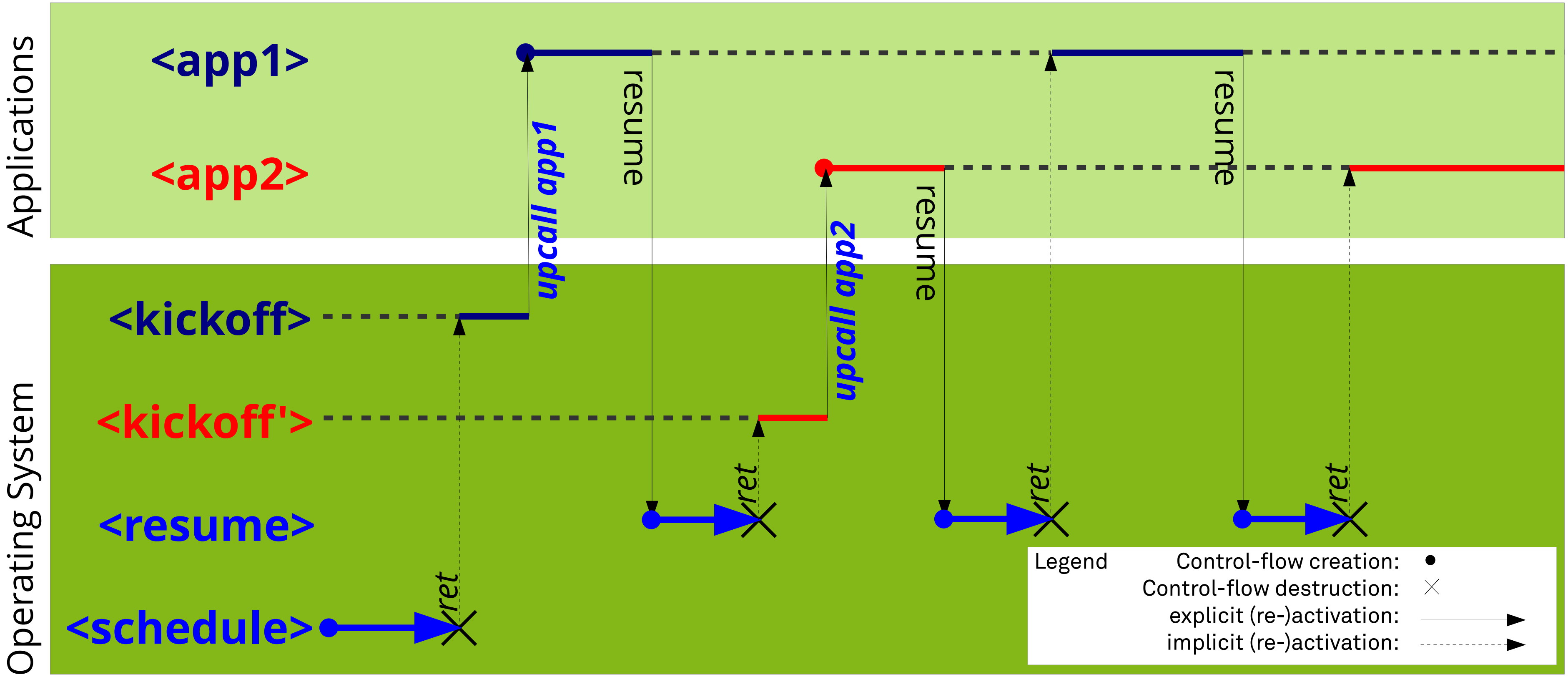
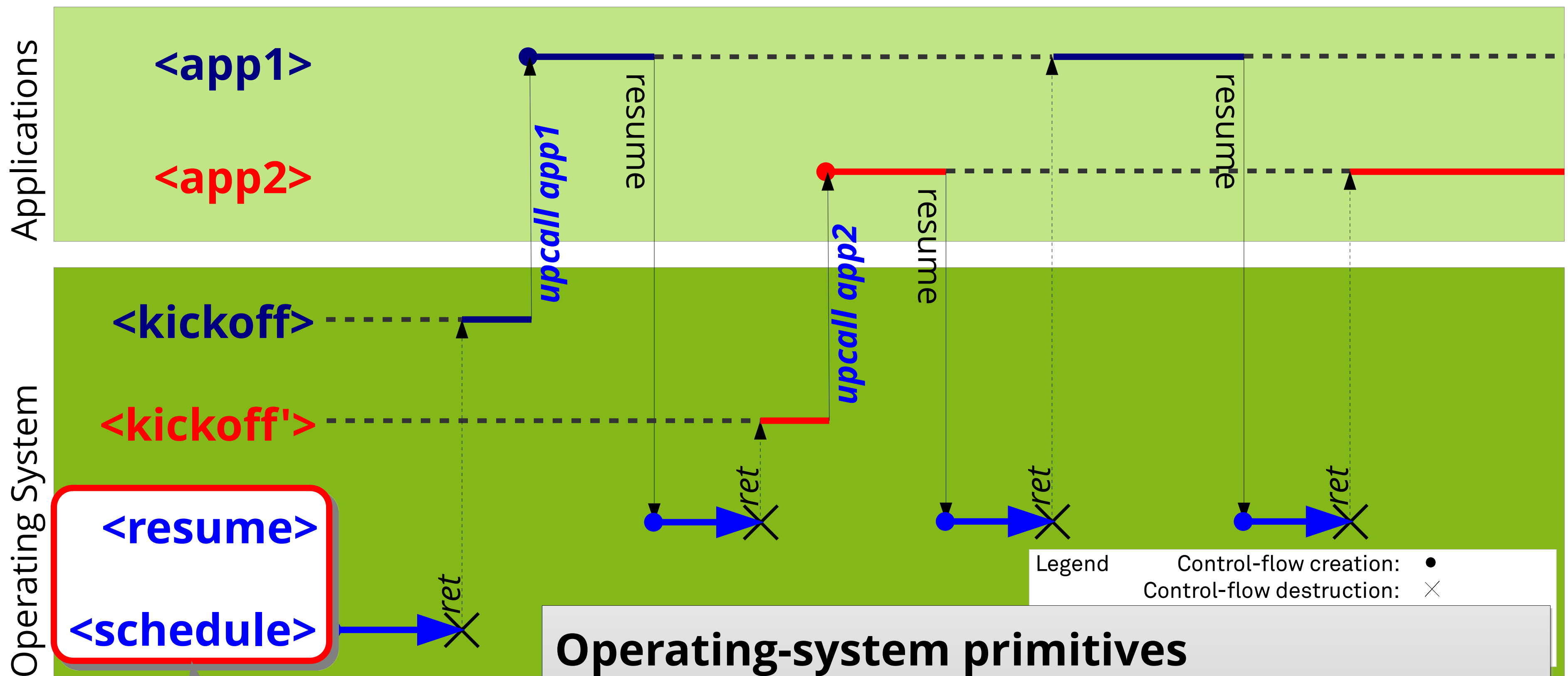
Kernel-Level Threads: Motivation

- **Approach:** Run applications “unnoticeably” as independent threads
  - One OS coroutine per application
  - Application is activated by being called
  - Coroutine switch: indirect by system call
- **Advantages:**
  - Independent application development
  - Central **scheduler** implementation
  - An application waiting for I/O can be “blocked” by the OS and “awakened” later
  - Additional **preemption mechanism** can prevent CPU monopolization

Cooperative Thread Switch



Cooperative Thread Switch

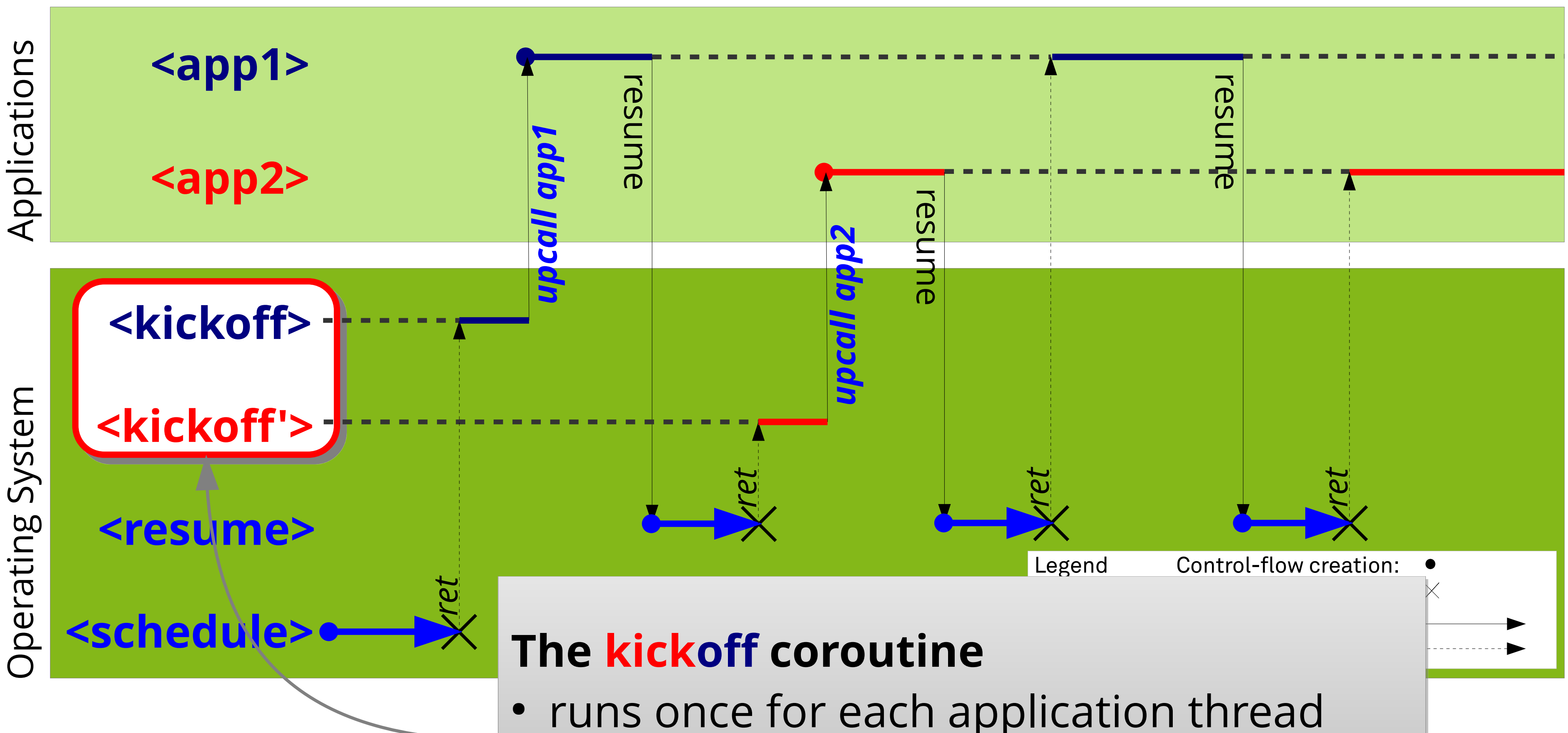


Operating-system primitives

- **schedule** (indirectly) starts the first application thread, does not return
- **resume** switches from one application thread to the next.

Both make a **scheduling decision**.

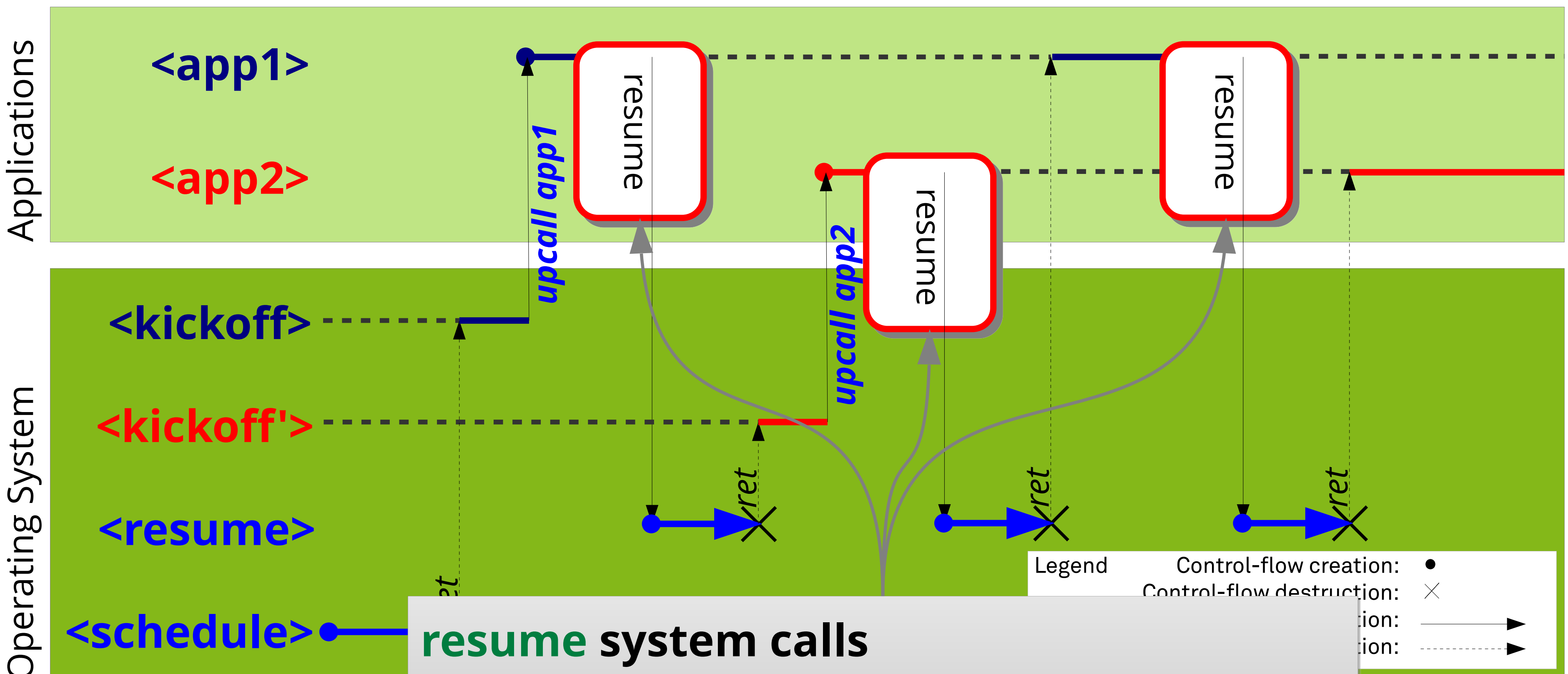
Cooperative Thread Switch



The kickoff coroutine

- runs once for each application thread
- activates the respective application through an **upcall**

Cooperative Thread Switch

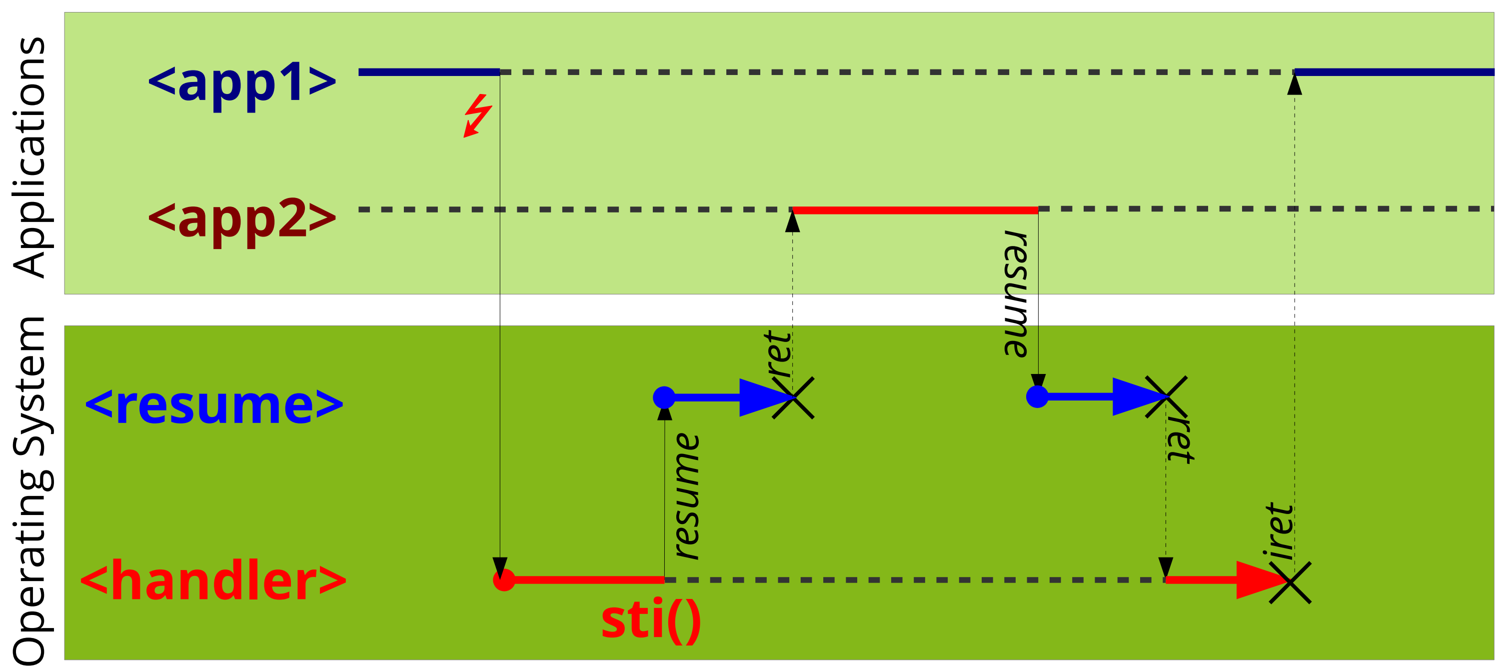


resume system calls

- the mechanism for applications to yield the CPU voluntarily
- possibly combined with a CPU mode switch (in this case we additionally need a wrapper)

Preemptive Thread Switch

- Forced CPU removal via timer interrupt
  - the interrupt is “just” an implicit call
  - handler routine can call *resume*



Careful: In general it does not work this way, because **resume** makes a **scheduling decision**. We need to apply **interrupt synchronization** for the involved data structures!

Thread Switch in the Epilogue

- Implementation
  - Scheduler data (list of ready threads) reside on the epilogue level
  - All system functions that manipulate these data must acquire the epilogue lock before (enter/leave)
    - Create thread, terminate thread, voluntary thread switch, ...
- Basic rule for thread switches:
  - the **yielding thread** requests the lock (e.g. implicitly in interrupt handling)
  - the **activated thread** must release the lock
- Tips:
  - Never call **enter** from the epilogue (double request)
  - Basic rule (see above) also holds **for the first** thread activation(!)

More on that in the exercises.

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Scheduling: Classification by …

- **Resource type** of the scheduled hardware resource
- **Operation mode** of the controlled computer system
- **Point in time** when the schedule is determined
- **Determinism** of timing and duration of process runs
- **Cooperation behavior** of (user/system) programs
- **Computer architecture** of the system
- **Decision-making level** when scheduling resources

… by Resource Type

- **CPU scheduling** of the resource "CPU"
  - Process count at times higher than CPU count
  - CPU(s) must be multiplexed for several processes
  - Admission via waiting queue
- **I/O scheduling** of the resource "device", particularly "disk"
  - Device-specific scheduling of I/O jobs generated by processes
  - e.g., **disk scheduling** usually takes into account these factors:
    - (1) Positioning time, (2) rotation time, (3) transfer time
  - Device parameters and device state determine the next I/O operation
  - Scheduling decisions possibly not conforming to CPU scheduling

… by Mode of Operation

- **Batch scheduling** of interaction-less programs
  - **non-preemptive** scheduling
    (or preemptive scheduling with long time slices)
  - Context-switch count minimization
- **Interactive scheduling** of interactive programs
  - **Event-driven**, **preemptive** scheduling with short time slices
  - Partly response-time minimization by heuristics
- **Real-time scheduling** of time-critical programs
  - Event- or time-driven **deterministic** scheduling
  - Guarantee of keeping environment-specific deadlines
  - Focus: **Timeliness**, not performance

… by Point in Time

- **Online scheduling** dynamic, during actual program execution
  - Interactive and batch systems, but also soft real-time systems
- **Offline scheduling** static, before actual program execution
  - If **complexity** prohibits scheduling at runtime
    - Guarantee keeping all deadlines: NP-hard
    - Critical if we must react to any preventable catastrophic situation
  - Result: Complete schedule (in tabular form)
    - (Half) automatically generated via source-code analysis of a specialized “compiler”
    - Often executed by a time-triggered scheduler
  - Usually limited to hard real-time systems

… by Determinism

- **Deterministic scheduling** of known, exactly pre-computed processes
  - **Process runtimes and deadlines are known**, possibly calculated offline
  - Exact prediction of CPU load is possible
  - System guarantees and enforces process runtimes/deadlines
  - Time guarantees are valid regardless of system load
- **Probabilistic scheduling** of unknown processes
  - **Process runtimes and deadlines are unknown**
  - (Probable) CPU load can only be estimated
  - System cannot give and enforce time guarantees
  - Timing guarantees conditionally achievable by application mechanisms

… by Cooperation Behavior

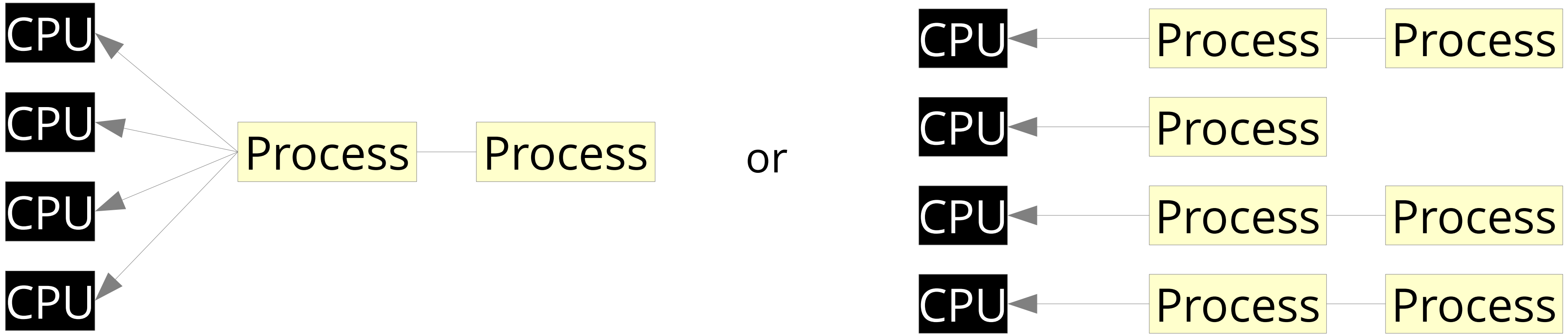
- **Cooperative scheduling** of interdependent processes
  - Processes must **voluntarily yield the CPU** in favor of other processes
  - Program execution must (directly/indirectly) trigger **system calls**
  - System calls must (directly/indirectly) activate the scheduler
- **Preemptive scheduling** of independent processes
  - Processes are forcibly **deprived of the CPU** in favor of other processes
  - **Events** can trigger preemption of the running process
  - Event processing (directly/indirectly) activates the scheduler

… by Computer Architecture

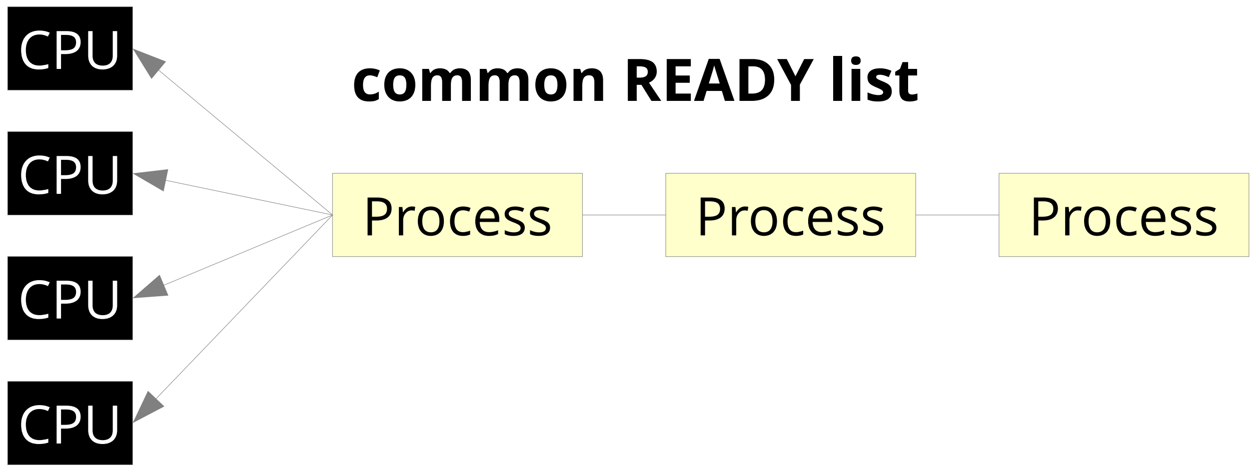
- **Uni-processor scheduling**

  in multiprogramming/processing systems
  - Process execution only pseudo parallel
- **Multi-processor scheduling**

  in shared-memory systems
  - Parallel process execution possible
    - Each processor processes its **local ready list**
    - All processors process **one global ready list**



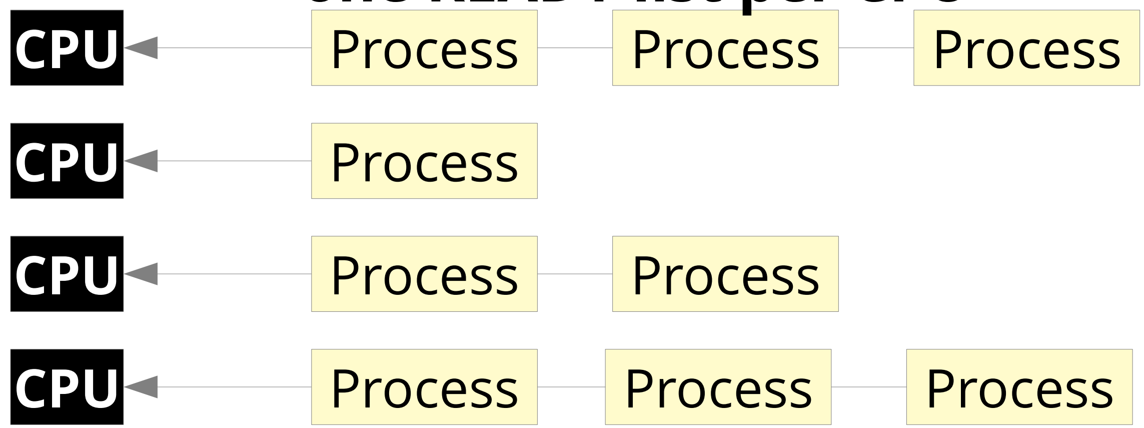
Multiprocessor CPU Scheduling



- Automatic load balancing
  - No CPU runs empty
- Processes are not bound to particular CPUs
- Accesses to the READY list must be synchronized
  - **Spinlock**
  - Conflict probability grows with CPU count!

Multiprocessor CPU Scheduling

one READY list per CPU



- Processes stay on one CPU
  - Better cache utilization
- Less synchronization costs
- CPU can drain (empty list)
  - Solution: On-demand load balancing (**pull**)
    - When a READY list is empty
  - By a load-balancer process (**push**)

> Modern PC operating systems nowadays use **separate READY lists**.

… by Decision-Making Level

- **Long-term scheduling** controls the degree of multiprogramming **[s – min]**
  - Admission for users and processes
  - Hand over processes to medium- and short-term scheduling
- **Medium-term scheduling** as part of swapping **[ms – s]**
  - Move processes back and forth between RAM and disk
  - **swapping**: swap-out, swap-in
- **Short-term scheduling** schedules processes on the CPU(s)
  - Event-driven scheduling: Interrupts, system calls, signals **[µs – ms]**
  - Blocking / preemption of the running process

Scheduling Criteria

- **Response Time** Minimizing the time from a system-service **request until the response**, while maximizing the number of interactive processes.
- **Turnaround Time** Minimizing the time between **process submission and completion**, i.e. the effective process runtime and all waiting times.
- **Timeliness** Start and/or termination of a process at **fixed points in time**.
- **Determinism** Deterministic execution of a process **regardless of the current system load**.
- **Throughput** Maximizing the number of completed processes **per predefined time unit**. A measure for the performed “work” in a system.
- **CPU Utilization** Maximizing the **percentage of time** the CPU executes processes, i.e. does useful work.
- **Fairness** Equal treatment of processes, and guarantee to schedule processes within certain time frames (no starvation).
- **Priority** Executing processes with the highest (statically/dynamically assigned) priority first.
- **Load Balancing** Uniform resource utilization, or prioritized execution of processes that rather seldomly allocate heavily utilized resources.

Scheduling Criteria

- **Response Time**
- **Turnaround Time**
- **Timeliness**
- **Determinism**
- **Throughput**
- **CPU Utilization**
- **Fairness**
- **Priority**
- **Load Balancing**

User-oriented criteria
- perceived system behavior
- determine user acceptance

influence

System-oriented criteria
- efficient resource utilization
- determine computing costs

Operating Modes and Criteria

- in general
  - Fairness
  - Load balancing
- **Batch systems**
  - Throughput
  - Turnaround time
  - CPU utilization
- **Interactive systems**
  - Response time (Proportionality – Processing time corresponds to expectation)
- **Real-time systems**
  - Priority
  - Timeliness
  - Determinism

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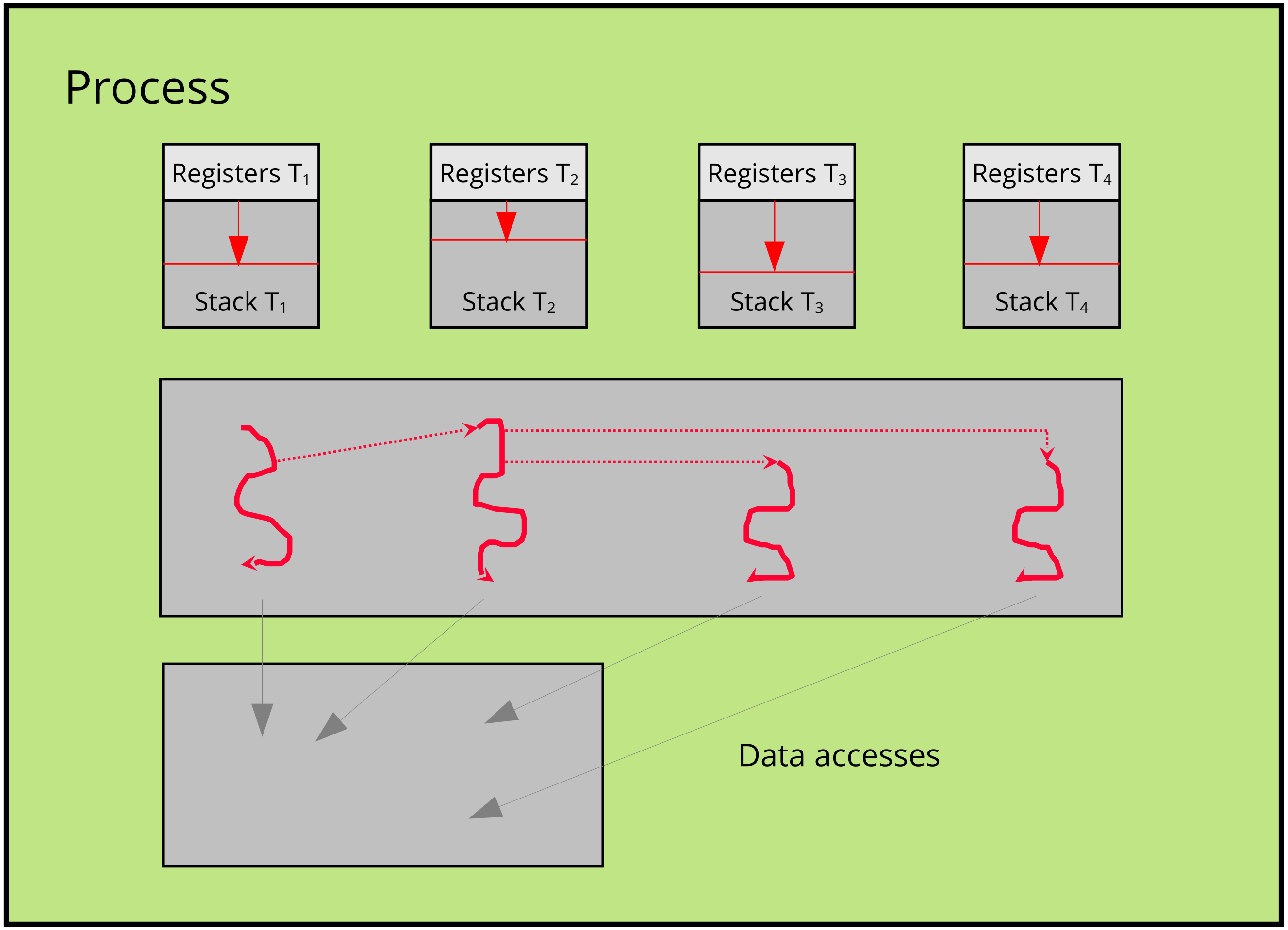
Processes and Threads in Windows NT

Stack +
Register file
(1 per thread)

Code

Global and
static data



Processes and Threads in Windows NT

- **Process:** Environment and address space for threads
  - A Win32 process always contains at least one thread
  - **Thread:** Code-executing entity
- Thread implementation by NT kernel
  - User-mode threads possible ("**fibers**"), but unusual
- Scheduler assigns processing time to threads

The NT Scheduler

- Preemptive, priority-based scheduling:
  - High-priority thread preempts thread with lower priority
    - Regardless whether thread currently in user or kernel mode
    - Most functionality of the **Executive** (“kernel”) implemented as threads, too
  - **Round-Robin** for threads with same priority
    - Round-robin assignment of one time slice (“**Quantum**”)
- Thread priorities
  - 0 to 31, subdivided in three ranges
    - **Variable Priorities**: 1 to 15
    - ***Real-time Priorities***: 16 to 31
    - Priority 0 is reserved for the Zero-Page Thread
  - Threads of the Executive maximally use priority 23

Time Slice (*Quantum*)

- *Quantum* is decreased
  - by 3 at every clock tick (every 10 or 15 ms)
  - by 1 if the thread voluntarily enters a waiting state
- Time-slice length: 20 – 180 ms

<table>
<tr><th rowspan="2"></th><th colspan="4">short Quantum values (Desktop)</th><th colspan="4">long Quantum values (Server)</th></tr>
<tr><th colspan="3">variable</th><th>fixed</th><th colspan="3">variable</th><th>fixed</th></tr>
<tr><th>Thread in backgr. process</th><td colspan="3">6</td><td>18</td><td colspan="3">12</td><td>36</td></tr>
<tr><th>Thread in FG process</th><td>6</td><td>12</td><td>18</td><td>18</td><td>12</td><td>24</td><td>36</td><td>36</td></tr>
</table>

Priority Classes, Relative Thread Priority

		Process Priority Class					
		Idle	Below Normal	Normal	Above Normal	High	Realtime
Relative Thread Priority		4	6	8	10	13	24
Time Critical	=15	15	15	15	15	15	31
Highest	+2	6	8	10	12	15	26
Above Normal	+1	5	7	9	11	14	25
Normal		**4**	**6**	**8**	**10**	**13**	24
Below Normal	-1	3	5	7	9	12	23
Lowest	-2	2	4	6	8	11	22
Idle	=1	1	1	1	1	1	16

Priorities: *Variable Priorities*

- **Variable Priorities** (1–15)
  - Scheduler strategies to prioritize “important” threads
    - **Quantum Stretching** (preference for the active GUI thread, cf. 2 slides back)
    - Dynamic **priority boost** for a few time slices at events
  - Progress guarantee
    - Every 3 to 4 seconds, up to 10 “disadvantaged” threads are raised to priority 15 for two time slices
  - Thread priority is calculated using this (simplified) formula:

Process priority class + Thread priority + Boost

Priorities: *Realtime Priorities*

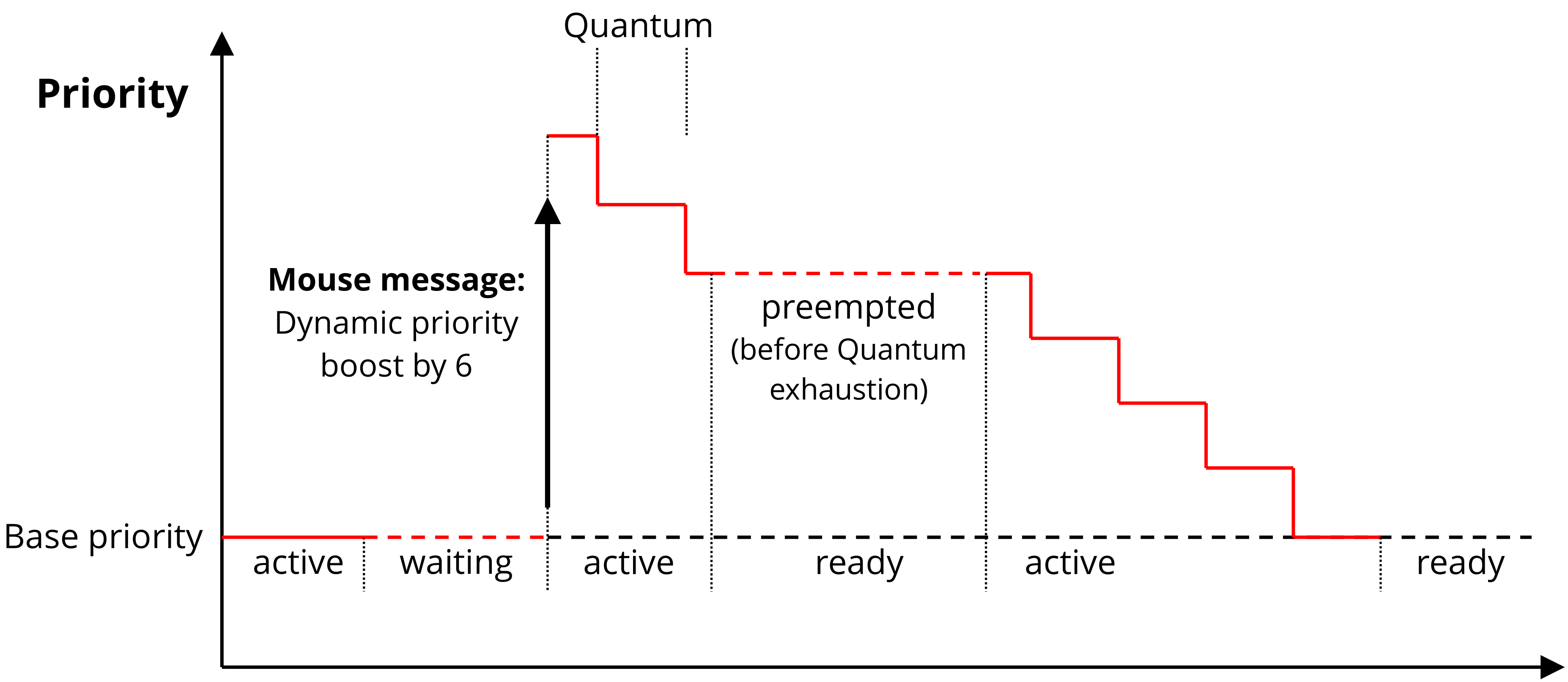
- **Realtime Priorities** (16–31)
  - Pure priority-based **Round-Robin**
    - No progress guarantee
    - No dynamic boost
    - Operating system itself can be negatively affected
    - Special user privilege necessary (`SeIncreaseBasePriorityPrivilege`)
  - Thread priority is calculated using this formula:

    REALTIME_PRIORITY_CLASS + Thread priority

Dynamic Priority Boosts

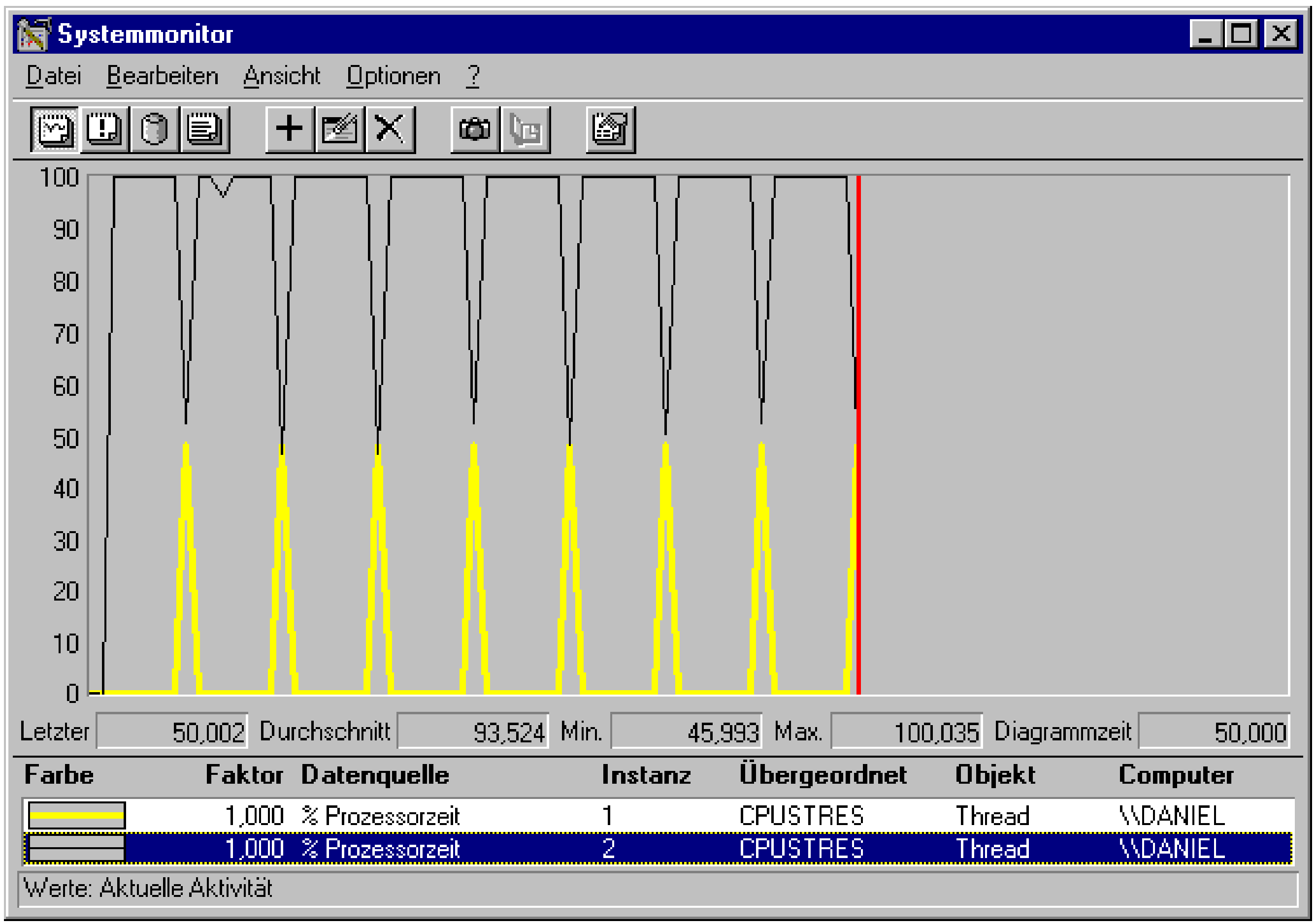
- ***Dynamic Boosts***
  - The system dynamically raises thread priorities in specific situations (not for REALTIME_PRIORITY_CLASS)
    - Disk input or output complete: +1
    - Mouse, keyboard input: +6
    - Semaphore, Event, Mutex: +1
    - Other events (network, pipe, …) +2
    - Event in the foreground application +2
  - Dynamic Boost gets “used up”
    (one level per Quantum)

Priority Change after a Boost



The *Balance-Set Manager*

- About every 3–4 seconds, up to 10 “disadvantaged” threads are raised to priority 15 for two time slices



Progress guarantee!

Selecting the Next Thread (SMP)

Goal: "fair" Round-Robin at maximum throughput

Problem: Cache effects

Affinity (mapping of CPUs to thread):

- **hard_affinity**: Fixed mapping
  → via `SetThreadAffinity()`
- **ideal_processor**: "Ideal" mapping
  → assigned at creation time ("random")
  → modifiable via `SetThreadIdealProcessor()`
- **soft_affinity**: Previous CPU the thread ran on
  → internally managed by the scheduler
- **last_run**: Point in time the thread ran last
  → internally managed by the scheduler

Selecting the Next Thread (SMP)

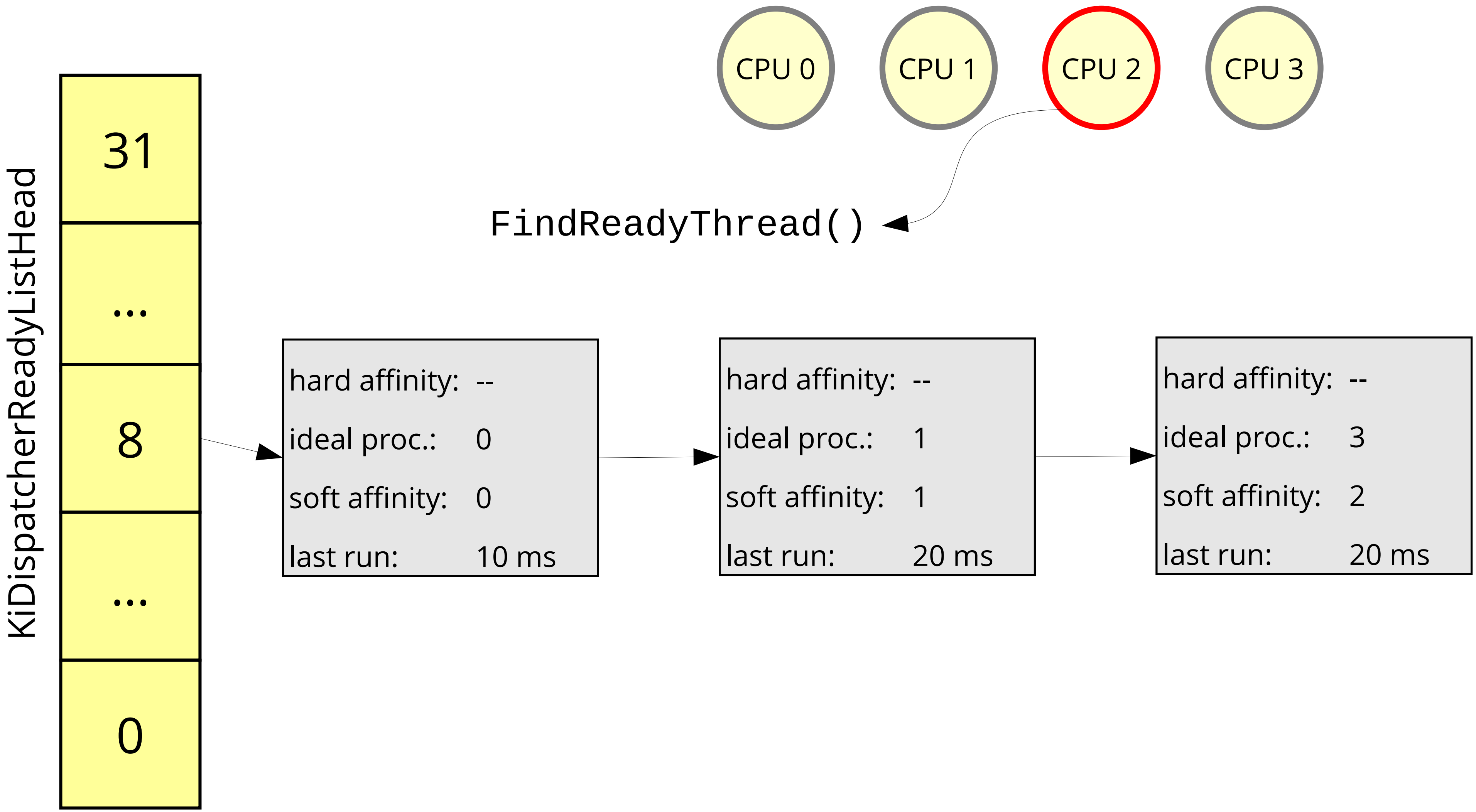
- Algorithm: CPU *n* calls `FindReadyThread()`
  - Pick highest-prioritized non-empty ready list
  - Search this ready list for a thread with
    - `soft_affinity == n`

      or
    - `ideal_processor == n`

      or
    - `currentTime()-last_run > 2 Quantum`

      or
    - `priority >= 24`
  - otherwise pick head of this ready list

Selecting the Next Thread (SMP)



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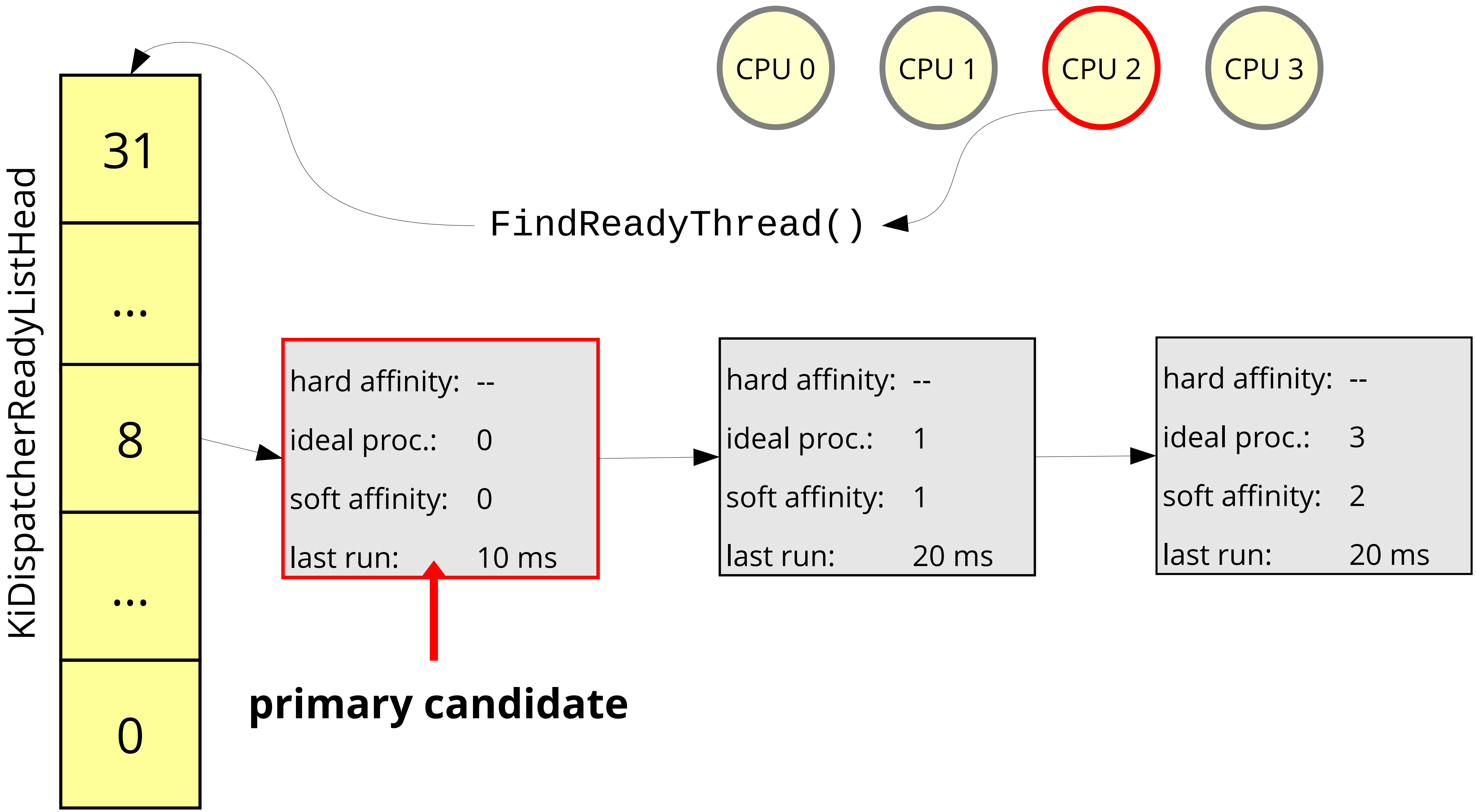

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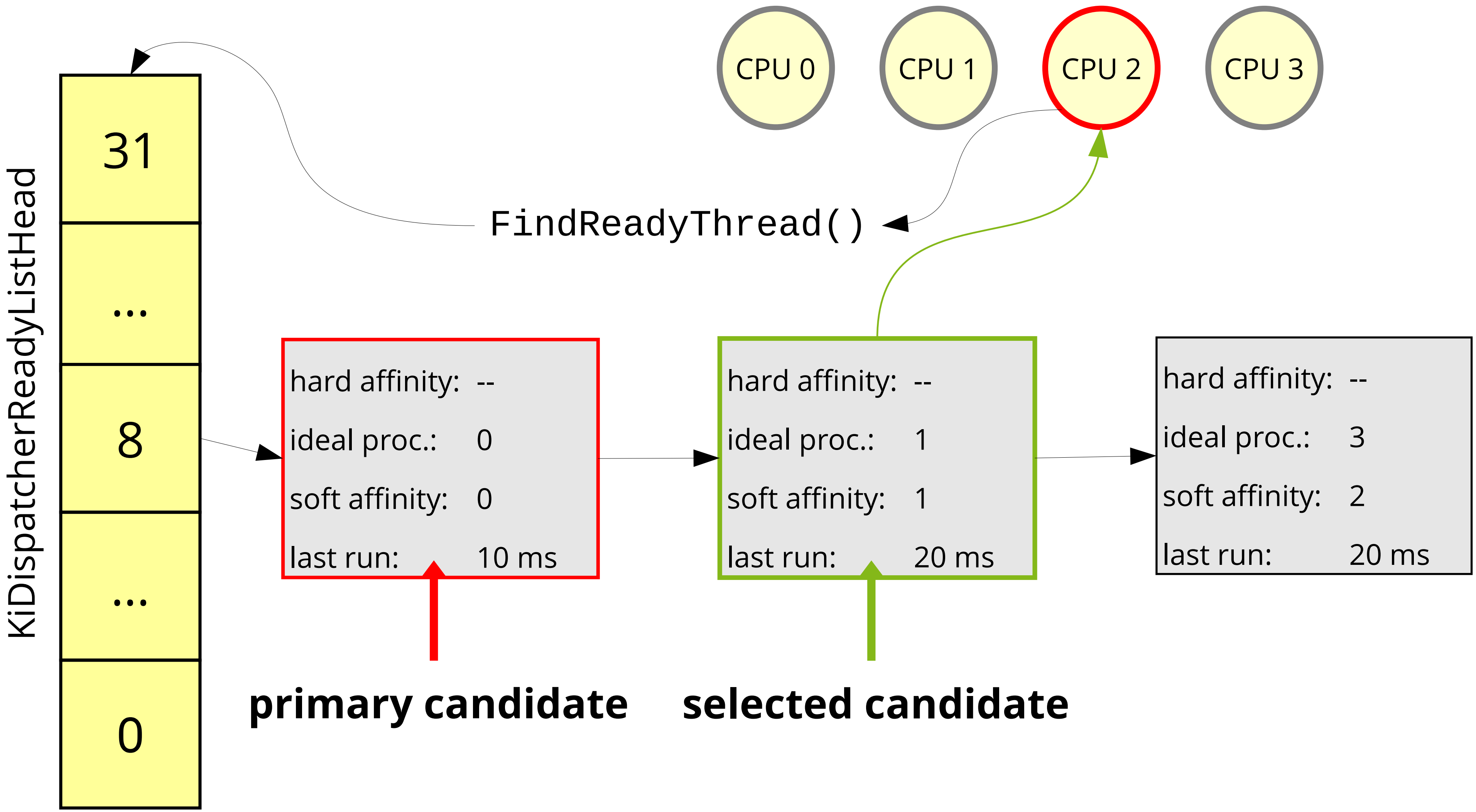

Changes in Windows 2003

- One "ready queue" per CPU
- Algorithm: CPU *n* calls `FindReadyThread()`
  - Pick highest-prioritized non-empty ready list of CPU *n*
  - Pick head of this ready list
  - If `ReadyQueue` completely empty, activate *Idle Loop*
  - In *Idle-Loop*: Search `ReadyQueue` of other CPUs

Conclusion Windows NT

- *„interactive, probabilistic, online, preemptive, multi-processor CPU scheduling“*
- Priority model allows fine-grained CPU-time allocation
  - Dynamic modifications
  - User-mode threads with high real-time priorities take precedence over all system threads!
  - Threads in the Executive are generally preemptible
- Further SMP improvements in Windows 2003
- **Heuristics** to accommodate interactive users

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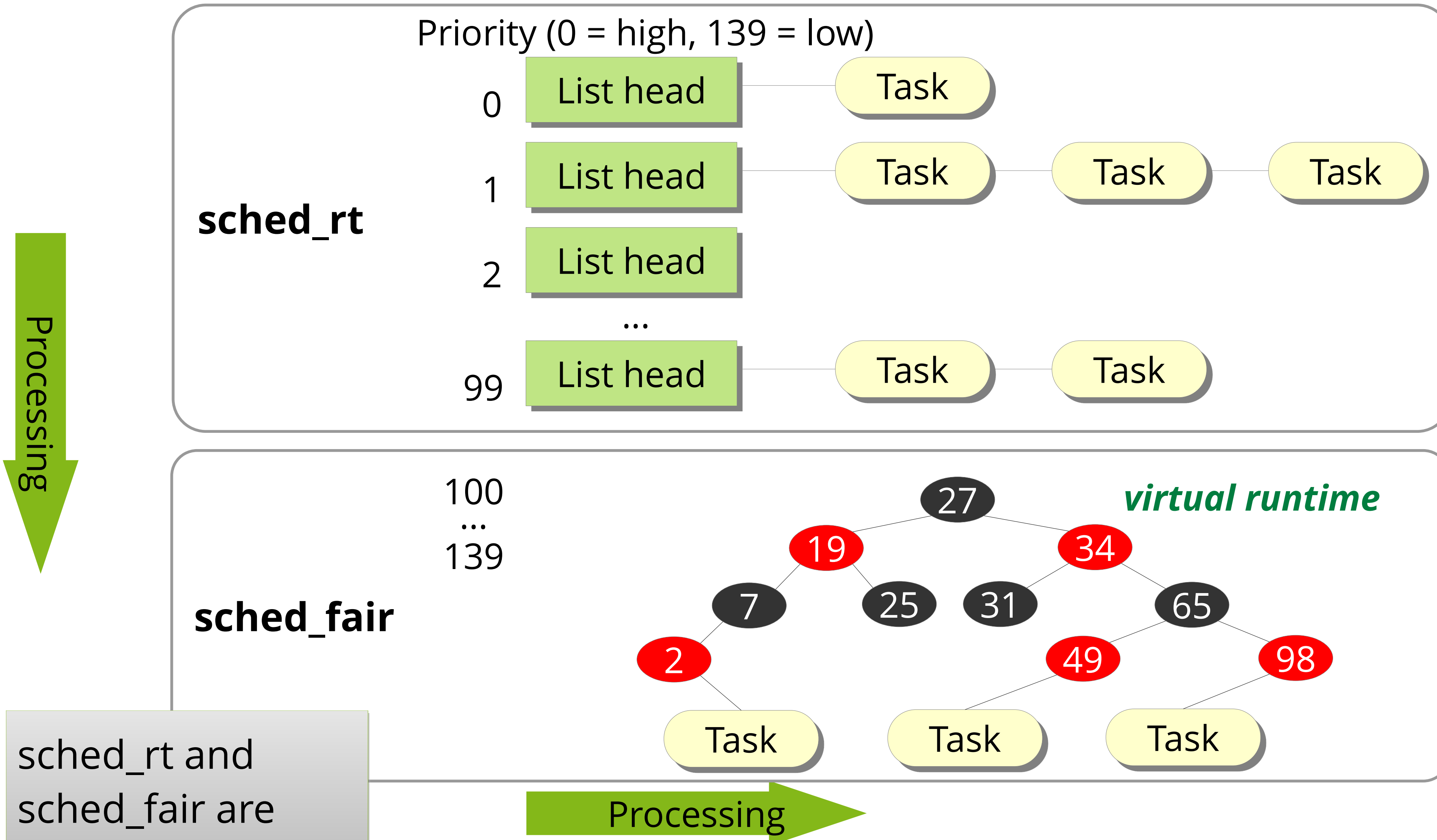
Linux *Tasks* …

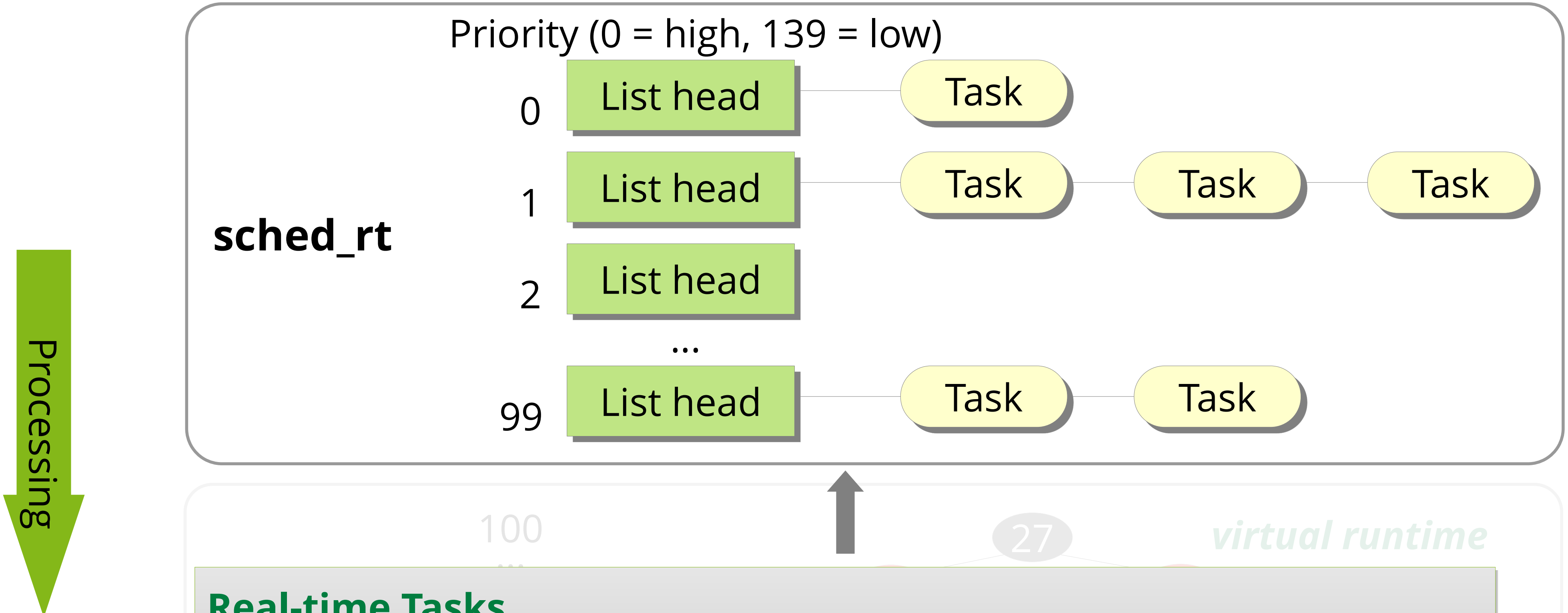
- are the **Linux-Kernel** abstraction for …
  - **UNIX processes:** one thread in one address space
  - **Linux Threads:** special process that shares its virtual address space with at least one other thread
- are the activities considered by the scheduler
  - Up to Linux 2.6.23 (introduction of CFS, the *Completely Fair Scheduler*) a program with many threads received more computation time than a single-threaded process
    - similarly a program with one process and many child processes

Linux' Modular Scheduler



sched_rt and sched_fair are ***Scheduler Classes***

Linux’ Modular Scheduler



Real-time Tasks

- SCHED_FIFO never preempted
- SCHED_RR preempted when fixed time slice expires
- Real-time tasks preempt any other regular task.
- Due to the simple strategy, the behavior in a real-time environment can be very well predicted.

Linux' Modular Scheduler

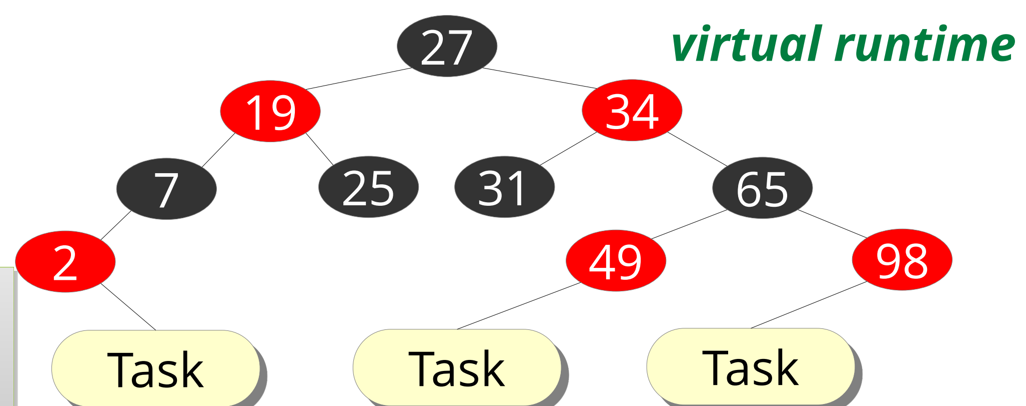
Regular tasks: **Completely Fair Scheduler (CFS)**

- Geared to an idealized "multitasking processor"
  - Infinitesimally tiny time slices
  - Runtime of two same-priority tasks distributed equally
- Quantum is not derived directly from priority (**nice value**).
  - Parameters instead: Aspired to and minimal latency; task's relative weight; group or user affiliation

Processing

100
…
139

sched_fair



Red-black Tree sorted by "virtual runtime"

- Pick task with smallest value:
  O(1) thanks to "cache"; other operations O(log N)
- Depending on task priority and number of ready tasks, virtual runtime passes with different speeds.

Processing

Multiprocessor Support

- Multiple READY lists
  - Parallel scheduler execution possible
- Support for CPU affinity
- Takes “warm” caches into account
- CPU load balancing
  - “push” by load-balancer process
    - → spin-locking still necessary
  - “pull” when a READY list runs empty

Conclusion Linux

- *„interactive, probabilistic, online, preemptive, multi-processor CPU scheduling“*
- Modular architecture
  - Arbitrary scheduler hierarchy possible
  - Support for soft real-time applications
- CFS focuses on fairness
  - Goal: Fair distribution of CPU-time **shares**
    - Fairness not guaranteed if very many processes are ready
  - Progress guarantee for all processes
  - No arbitrary heuristics
- CFS solves many problems of classic UNIX schedulers
  - CPU-time limits for users or groups
  - Provides semantics for *nice* values (+1 corresponds to CPU share * 1.25)
- Modern multiprocessor support

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Summary

- Threads are operating-system coroutines
  - OS has a preemption mechanism
- *Scheduling* has profound impact on system performance. It determines ...
  - which process wait and which progress
  - which resources are utilized how much
- There exist many variants of schedulers
  - only little differences at mainstream PC/workstation OSs
  - large differences in other application domains