Operating Systems Internals – Task scheduling

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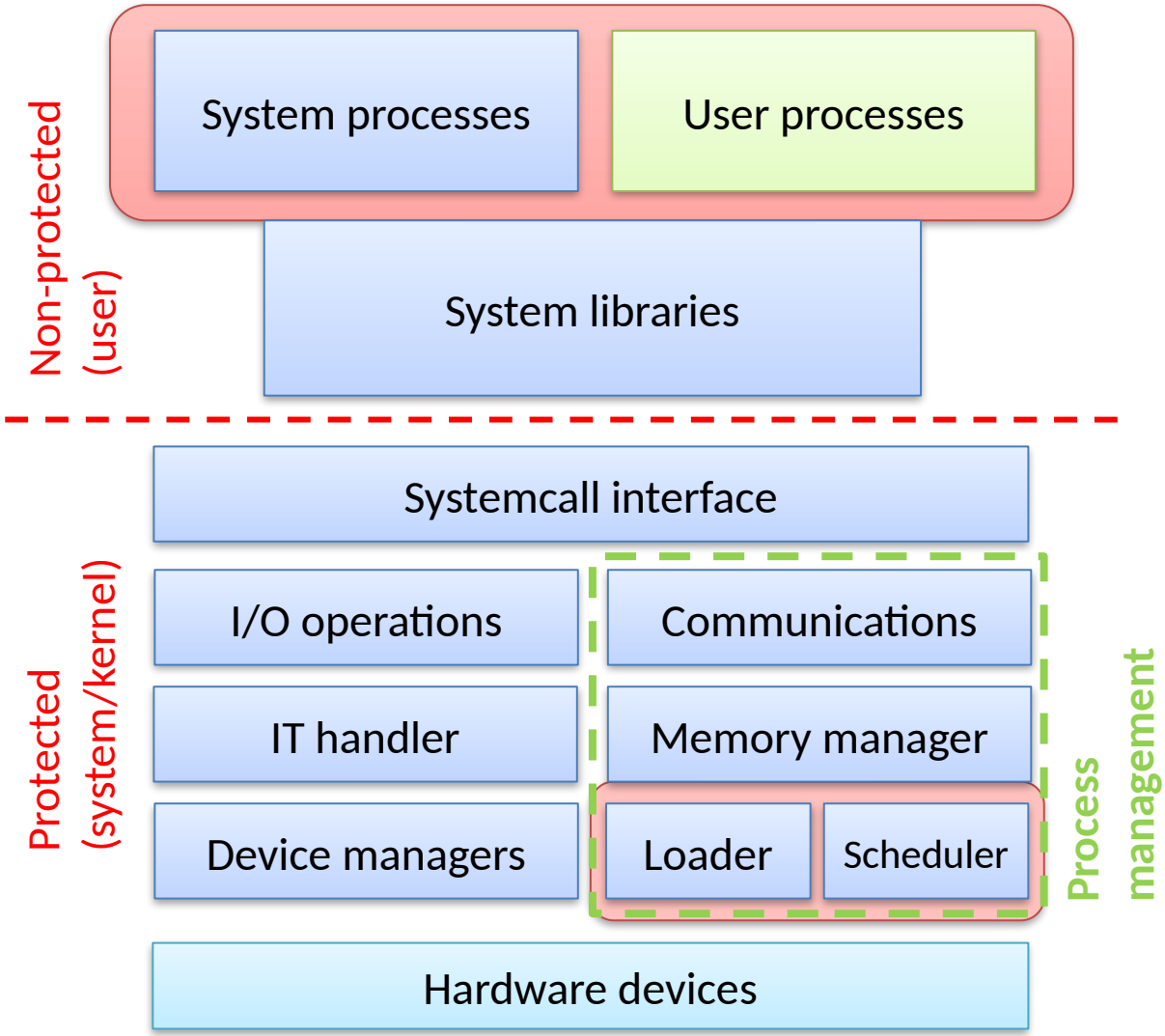
The slides of the latest lecture will be on the course page. (https://www.mit.bme.hu/eng/oktatas/targyak/vimiab00)

The basics of task scheduling (recap)

- The scheduler chooses the next task to run
  - Short term (we learned about this), medium and long term
  - Basic properties
    - Data structure
    - Considered task properties
    - Decision algorithm
    - Complexity and overhead
- Simple schedulers
  - FCFS: simple, but it may perform badly
  - RR: it is widely used, good response time, moderate overhead
  - SJF and SRTF: decision based on the task's CPU burst, optimal waiting time
  - Priority: importance shown by a number
- Complex schedulers
  - Multilevel queues
    - It can use multiple algorithms (which is suited for the tasks)

The main blocks of the OS and the kernel (recap)



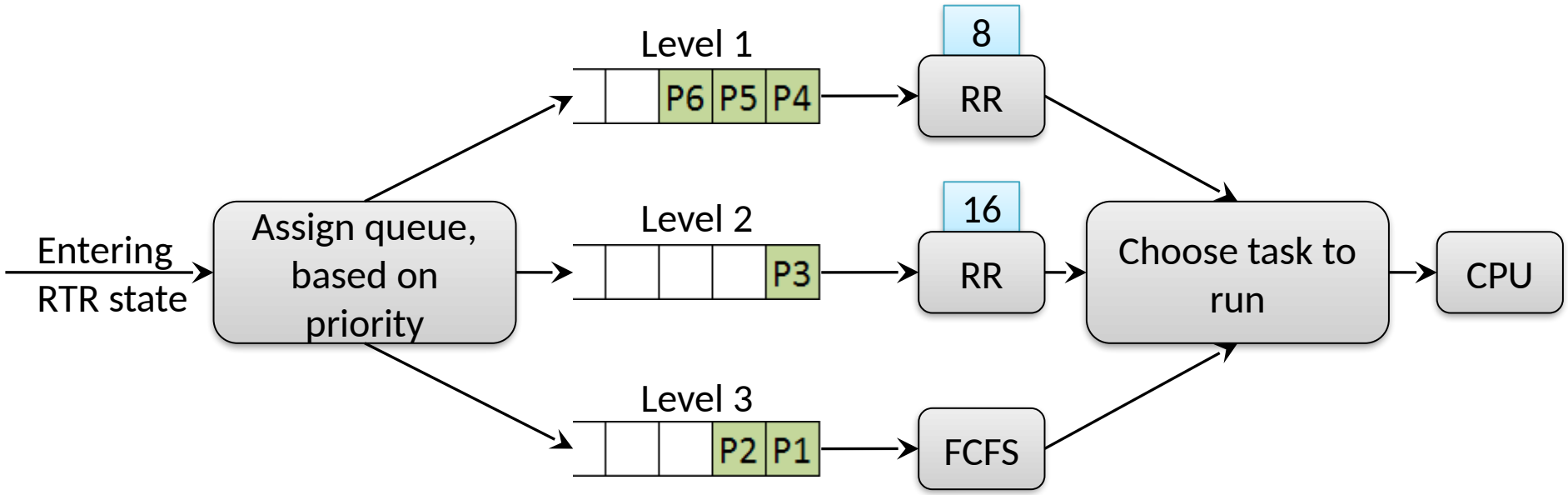
Multilevel scheduling

- Problems with the previous schedulers
  - The description capability of the priority is constrained
  - Not much information can be „crammed” in one number
  - The expectations for tasks can be different, one scheduler cannot fulfill all of them
  - The different schedulers can be optimal for different types of tasks
- Solution: Multilevel scheduling
  - If tasks can be categorized, they can be ordered in different queues. Every queue can have it’s own scheduling algorithm, which is the most appropriate for the tasks in the queue.
- The scheduling queues should also be scheduled
  - Which queue we choose the next task from?
  - Every queue may have a time slice (RR)
    - The more important level may have a longer time slice
  - Priorities can be assigned to the scheduling queues
    - Starvation may appear
  - Starvation can be avoided if the tasks are allowed to change the current scheduling queue
    - More complex: an algorithm is needed for stepping up and down the tasks

Static multilevel queues

- The tasks are assigned to a queue in a static way
  - There's no changing between queues (static priority)
  - The assignment is based on the priorities of the task
  - The priority stays the same till the completion of the task
- The different queues are defined by the nature of the tasks
  - Real-time operation
  - Serving system tasks
  - Providing interactive operation (user session in foreground)
  - Batch processing (long CPU burst, but non time critical tasks)
  - System statistics, logs, other tasks with low importance
- Advantages
  - Different levels, can be managed by different (appropriate) scheduling algorithms
  - The levels are managed in a simple way (no level changing)
- Disadvantages
  - Due to static priorities the starvation appears
  - The „nature changes" of the tasks are unmanageable
  - E.g.: a batch job may become interactive for a short time (Asks something from the user)

Static multilevel scheduler



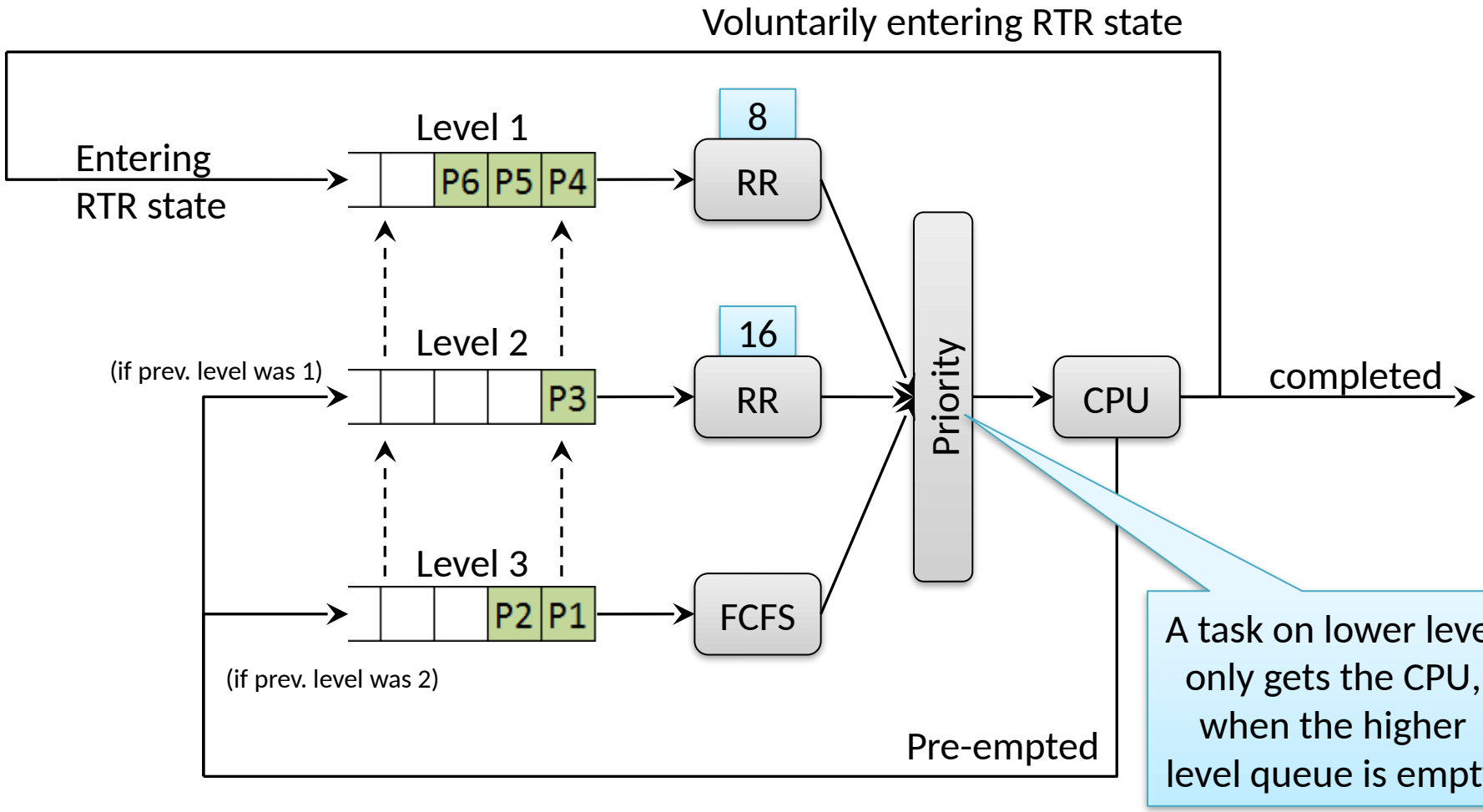
Dynamic multilevel scheduling

- The tasks assignment to queues is dynamic
  - The task's priority can change dynamically
    - Therefore the queue assignment is dynamic
  - The task can change queues
    - Upgrade: changing to a higher priority level
    - Downgrade: changing to a lower priority level
  - Beside the above, the operation is the same as static multilevel queues
- Advantages
  - Like in static multilevel queues
    - Different levels, can be managed by different (appropriate) scheduling algorithms
    - The levels are managed in a simple way: ordering the tasks by priority
  - Aging mechanism can be used to avoid starvation
  - The changing nature of the tasks can result different scheduling
- Disadvantages
  - Upgrading and downgrading makes the algorithm more complex
  - More calculations because the dynamic priorities
  - Therefore higher overhead

Multilevel Feedback Queue (MFQ)

- A basic implementation of a dynamic multilevel scheduler
  - The tasks are ordered by the estimated CPU-burst
- The basic idea: learning from the past
  - The more a task uses the CPU, the lower priority level it will get
  - If a task uses less CPU its priority gets higher and it will be upgraded to a higher level
- The scheduling algorithms
  - On the lowest level: FCFS
  - On higher levels: RR with decreasing time-slice
  - This is a globally preemptive scheduler with priorities
- Moving between levels
  - The tasks are entering on the highest level
  - The CPU intensive (using more CPU time) tasks are getting to lower priority levels through time
  - The I/O intensive (using less CPU time) tasks are stays on the higher priority levels
  - The recent CPU time of the starving task are decreasing with time, therefore their priority will rise (like aging)
- Many current scheduler based on MFQ (UNIX, Windows NT kernel)

Multilevel Feedback Queue (MFQ)



Let's design a scheduler!

- Further information and expectations for schedulers
  - Kernel mode
    - The kernel's code is running: short CPU bursts, long I/O bursts
    - The CPU burst is known in advance
      - Usually device (periphery) handling (disc, terminal, etc.)
    - No CPU intensive tasks, no convoy effect expected
    - Goal: the smallest possible overhead
  - User mode
    - Application's code is running: not known in advance
      - There are resources to wait
      - CPU intensive, I/O intensive, or changing nature tasks
      - Try to estimate the CPU burst, and schedule them accordingly
    - Convoy effect may appear (we have to manage it)
    - There may be priorities between tasks (they are not equally important)
    - It is expected: the tasks on the same priority should get equal chance to get the CPU
- The global properties of the schedulers
  - Priority (there are different importance tasks)
  - Multilevel (the kernel and user mode needs different scheduling)
  - Dynamic (the tasks nature can change, e.g. changing to kernel mode or back)

Let's design a scheduler – choosing algorithms

- Multilevel (kernel/user mode), dynamic priority scheduler
- Kernel mode
  - Small bursts ␣ let's use a cooperative scheduler
  - In a non-preemptive case static priorities are suitable
  - Because it's non-preemptive the protection of the data structures are simple
  - In summary we get small overhead
  - *How and when should the static priority determined?*
- User mode
  - Because the convoy effect, a preemptive scheduler is needed
  - The optimal solution would be the preemptive SJF (SRTF)
  - Because the user priorities, the simple SRTF is not suitable
  - The tasks with same priority should get equal chance ␣ RR scheduler
  - *How to combine SRTF and RR schedulers?*
  - *How and when should be the dynamic priority calculated?*
  - *How to manage starvation (with aging, but how)?*

Determination of static priorities in kernel mode

- The priority doesn't depend on
  - the task's priority in user mode (we are on a different level)
  - how much CPU time the task used in the past (no SJF)

- The kernel mode priority is based on
  - What resource the task is waiting for?
  - This called: sleep priority
  - For example:
    - Waiting for 20 I/O operations
    - Waiting for 10 input from the character terminal

- When calculate it?
  - After waking up from waiting, it will get the resource's sleeping priority

Determination of priorities in user mode

- Scheduling variables for the tasks
  - `p_pri` – the current priority of the task (smaller ⇒ higher priority, =>0)
  - `p_cpu` – the CPU usage in the past
  - `p_nice` – the priority modifier value, given by the user (integer, =>0)

- The CPU usage in the past is used to estimate the CPU burst
  - The `p_cpu` is incremented in every clock cycle when the task is running

- Calculation of the priority

```
p_pri = P_USER + p_cpu / 4 + 2 * p_nice
```

  - `P_USER = 50` (the kernel priorities are below 50)
  - `p_nice = 10` by default
    - The user may increase it ⇒ priority will drop
    - The root user can decrease to 0 ⇒ priority will increase

The mechanism of aging

- The `p_cpu` is incremented in every clock cycle when the task is running

  ```
  p_cpu++;
  ```

- The `p_cpu` value should be also „aged” with time
  - `p_cpu = p_cpu * CF` (correction factor < 1)
- Determination of CF
  - For example: CF = ½ (simple operation, right shift)
  - There are problems with it!

- How to create a better CF? What should it depend on?
  - If there are no RTR tasks ␣ no starvation is possible
    - In this case the value `p_cpu` can be forgotten
  - If there are few RTR tasks, the RR scheduler gives CPU to them in a short period of time
    - `p_cpu` can be aged quickly (to bound the priorities)
  - If there are many RTR tasks, the waiting time is higher in RR scheduler
    - `p_cpu` should aged slowly (to ensure lower priorities for the task which are already used the CPU in the past)
  - Use the average number of the RTR tasks: `load_avg`

```
CF = 2 * load_avg / (2 * load_avg + 1)
```

Scheduling in user mode

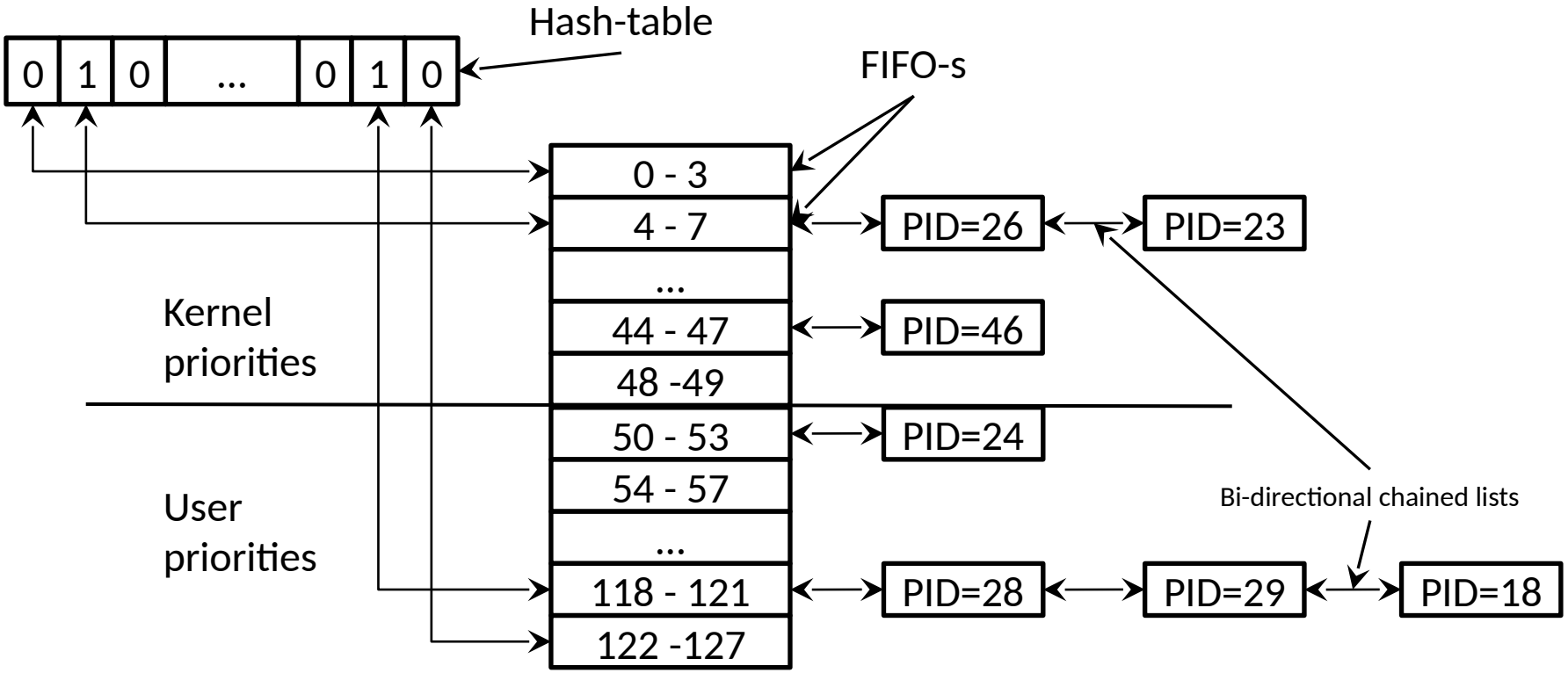
- How to combine SRTF and RR schedulers?
  - SRTF orders the tasks by their priority (optimal)
  - Priority calculation is based on the CPU-burst estimation with the `p_nice`
  - Tasks on the same priority level are scheduled with RR (time-sharing)

⇨ the user mode scheduler is also multilevel
  - Ordering tasks based on priority
  - (the adjacent priority levels can be grouped together)

- How is this scheduler has the attributes of SRTF?
  - `p_cpu` estimates the remaining CPU time
  - Priority is determined by `p_cpu`
  - The scheduler orders the tasks by their CPU bursts ⇨ SRTF

Data structures of the scheduler

- Priority is an integer: 0 – 127
  - 0 is the highest, 127 is the lowest priority
  - 0 – 49 kernel levels, 50 – 127 user levels
- The scheduler put the tasks into 32 FIFO queues based on their priority
- A hash-table is used to determine which level there are tasks on



Operation of the designed scheduler

- Multilevel scheduler with dynamic priorities
  - In kernel mode: **cooperative**, **static priorities**
    - Priorities depends on the cause of waiting (faster device ␣ higher priority)
  - In user mode: **preemptive**, **dynamic priorities, time-sharing**
    - Priorities depends on the estimated CPU-burst
- Event-based scheduling in kernel mode
  - If a task wakes up by an event, priority is set and the appropriate queue is selected
- Time-based scheduling in user mode
  - Every clock cycle
    - If there's a task on higher level ␣ preemption
  - At the end of every RR time-slice
    - If there's a task in the same priority queue as the running task ␣ preemption
    - The preempted task is put to the end of the queue
  - After every 100th time-slice
    - „Aging" `p_cpu` ␣ recalculating `p_pri` ␣ reordering queues

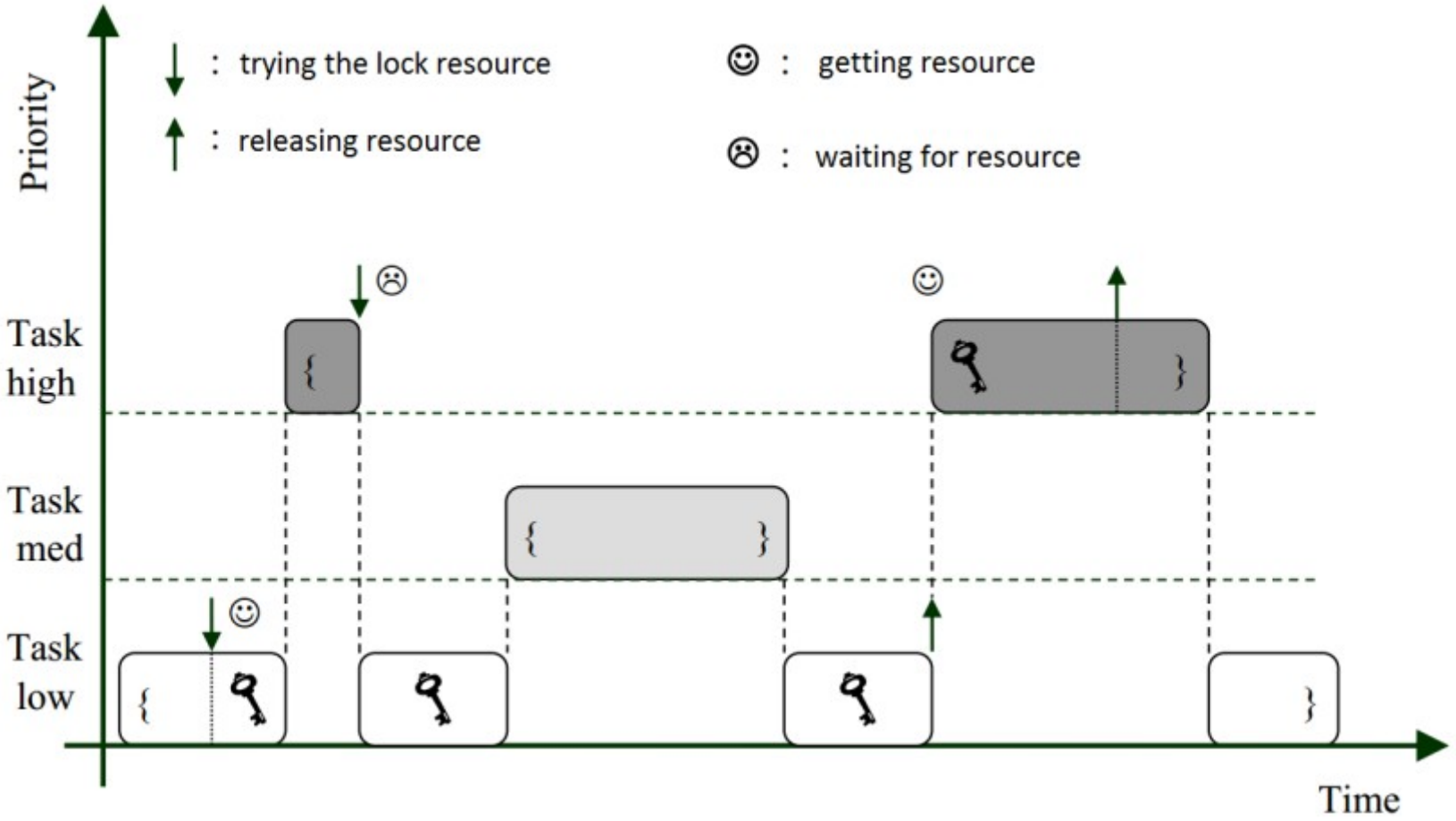
Evaluation of the designed scheduler

- This is the traditional UNIX scheduler
  - **Multilevel with priorities and time-sharing**
  - System V R3 and BSD 4.3 used this solution
  - Designed for interactive systems
  - Works good also when batch and interactive tasks are in the system simultaneously
  - Provides good response time for interactive tasks while starvation of the background tasks are avoided
- Problems
  - High overhead, when the task count is very high
  - **Which operation has the highest algorithmic complexity?**
  - There's no special tasks (e.g. real-time)
  - Many problems with the cooperative scheduler in kernel mode
    - Problems are caused by tasks with long CPU-bursts in kernel mode
    - Lower level task can hold up tasks with higher priority (no preemption)
    - This is called: **priority inversion**
    - Because the single threaded kernel: more CPUs don't solve the problem
    - How can we make manage this?
    - Can we make a preemptive kernel mode scheduler?
    - How can we use more processors?

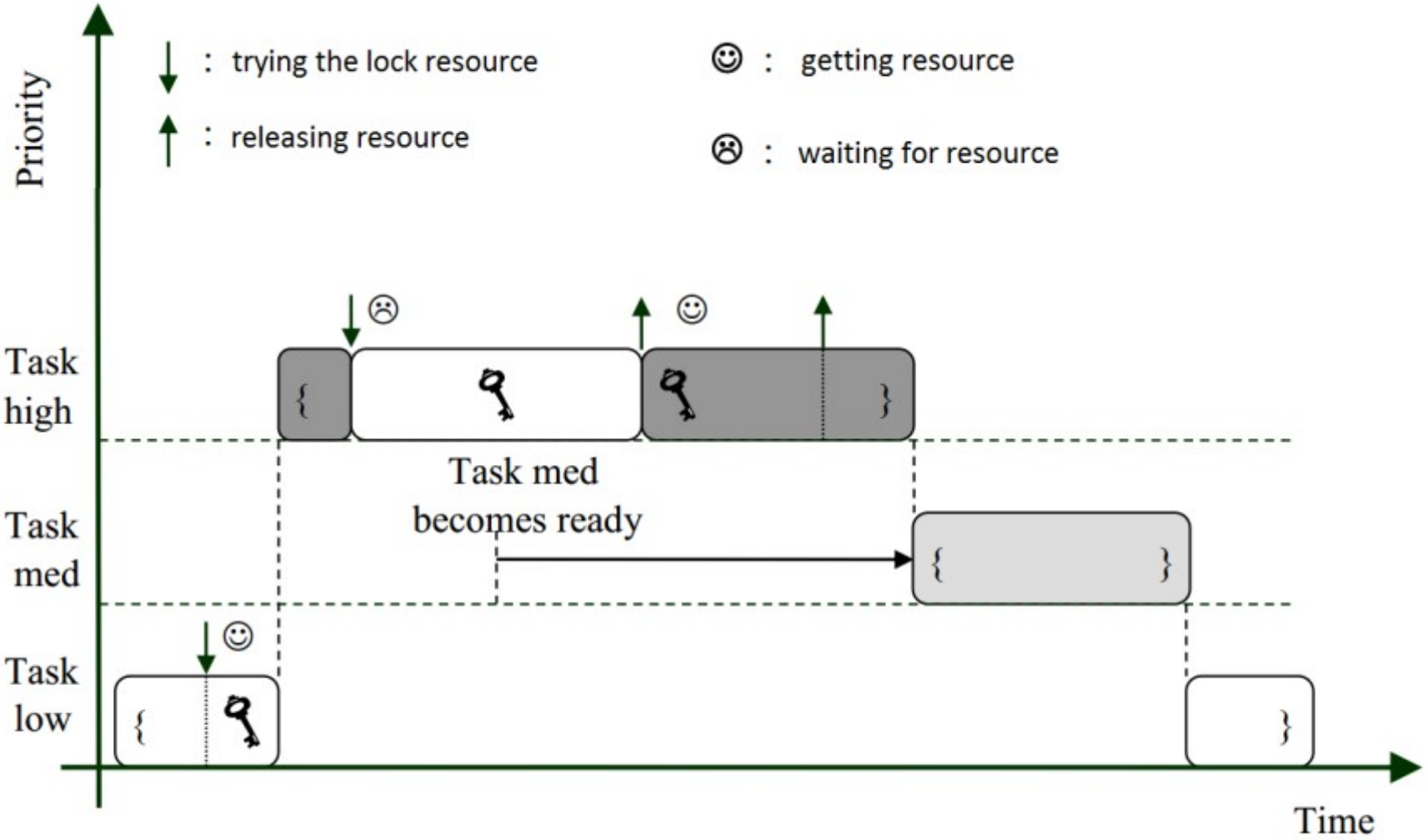
Priority inversion

- Definition: A task (A) with lower priority can hold up a task (B) with higher priority.
  - There is a dependency between the execution of A and B
  - For example: „A” is waiting for a resource in an uninterruptable way, and „B” also waits for that resource
  - It happens often! There can be dependencies between more than two tasks also
  - The result: the priority of „A” seems the same as the priority of „B”
- How it can be managed?
  - Increase the priority of „A” to the „B”’s level for a short time, to resolve the dependency
  - This is called **priority inheritance**
- The bounds of priority inheritance
  - It isn’t always known which task causing the problem
    - Complex dependency graphs, where we can’t find the cause
  - It can happen that more the one task is blocking „B”
    - Cannot increase the priority of many tasks ⇨ long-term effects (chain reaction)

Priority inversion



Priority inversion with priority inheritance



Priority inversion – other solutions

- Priority ceiling
  - The task is upgraded to the kernel level
- Priority inheritance
  - As seen before
- Random boosting
  - RTR tasks which are holding locks may randomly boosted to higher priority until they are exit the critical section
- Avoid blocking
  - If the dependencies are known in advance (e.g. real-time systems)

How to make the kernel scheduler preemptive?

- Introducing preemption points
  - During certain points of the execution of the kernel code a task change is allowed
  - At this point it is checked if there's a higher priority task ␣ if yes, preemption
  - The kernel memory consistence should be only ensured on these points
  - E.g. System V R4 (SRV4) UNIX scheduler
    - Introduces real-time tasks, which requires preemption points
    - The scheduler checks, if there is a real-time task
- Fully preemptive scheduling for kernel level
  - This is the only way, if there are multiple processors
    - Current client and server Oss using preemptive kernel
  - All data structures have to be protected (later will be discussed)
    - Problems when
      - two tasks writes the same area
      - one task read from the same area, which modified by another task
  - Non preemptive code sections can be defined
    - Preemption can be disabled in critical section, if there's no other solution

Multiprocessor scheduling

Basic questions of multiprocessor scheduling

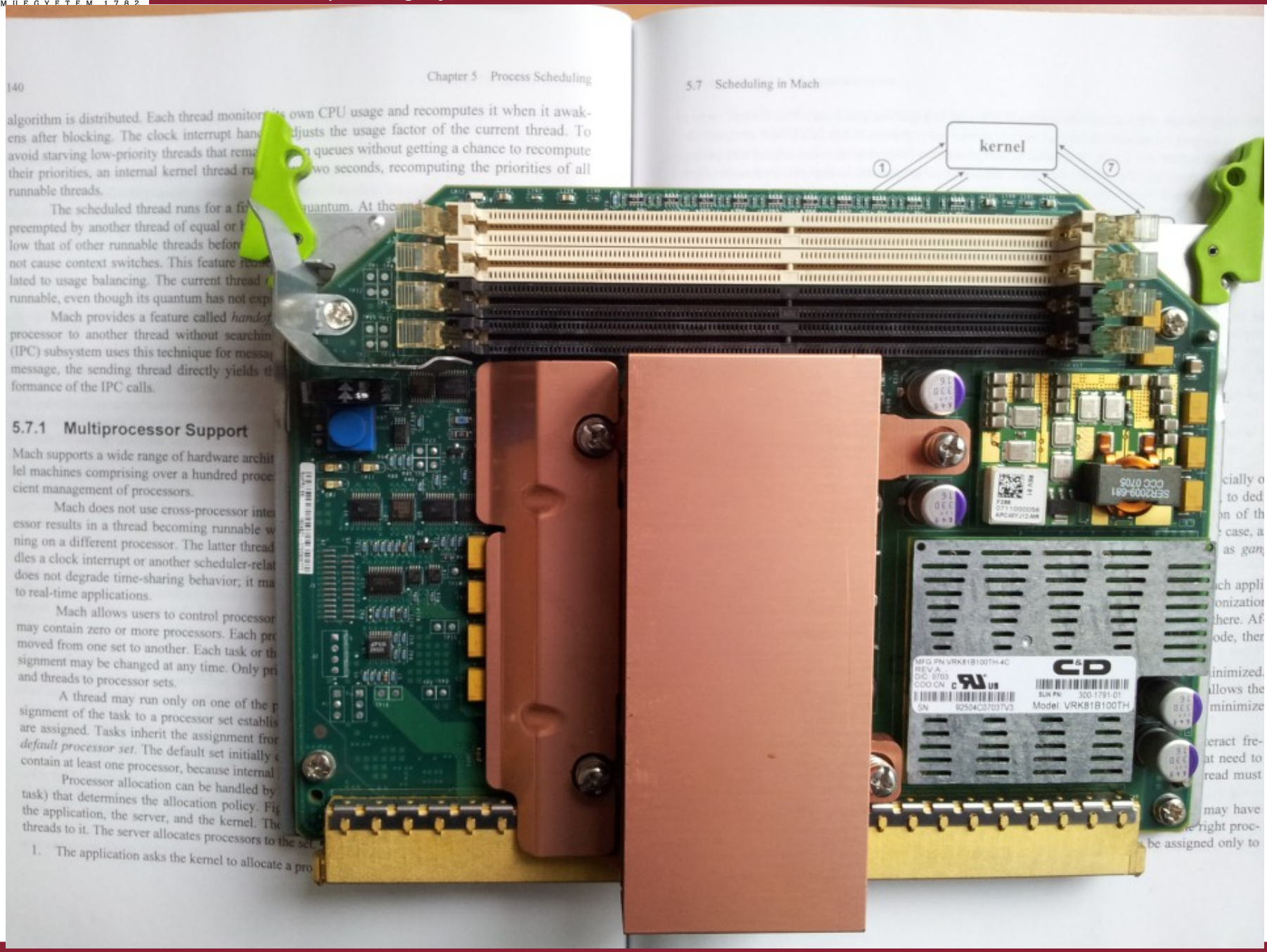
- Until now we assumed only one processor unit
  - Current HWs provide multiple CPUs, also with different capabilities (heterogeneous systems)
- Multiple tasks may run in kernel mode
  - Preemptive kernel is required with protected data structures
- Managing „remainders” during context changes
  - There are remaining data when R ⊔ (W ⊔) RTR ⊔ R state transition happen
    - In CPU registers, cache memories
    - E.g. handling an interrupt means minimal context change
  - A task should get back to the last processor
    - The scheduler should manage this
- Resource allocation for a process group
  - Processors and process groups can be bind together
  - These task get constant amount of resources even in a highly loaded system
- Load balancing
  - A suitable processor is chosen to each task
  - Not every processor has to be the same, cache sizes may also differ

Basic variants of multiprocessor scheduling

- Asymmetrical systems
  - One of the units serves the kernel task(s)
  - The user tasks are running on the other units
  - Advantages
    - Easy implementation based on the single processor codes
    - The kernel can be one task ⇒ simple to implement
  - Disadvantages
    - The utilization of the CPU assigned to kernel will be low
  - **Rarely used, may be a good solution in heterogeneous systems**
- Symmetrical systems
  - Every processor has its own scheduler
  - The RTR tasks can be in a shared queue, or in separate queues assigned to each CPU
  - Better CPU utilization
  - Risks: requires careful software development
  - **Current systems using this method**

Multiprocessor HW systems
(background knowledge from computer architectures)

- Parallel processing in single processor systems
  - Some of the HW resources is multiplied (TLB, instruction cache, etc.)
  - Fine-grained: task change in every cycle
  - Coarse-grained: task change when something is holding up the task (e.g. cache error)
- Multiprocessor system: more separate CPU
  - Communication between tasks
    - Through shared memory (monolithic system)
    - Messaging (distributed system)
  - Efficiency of memory operations
    - Uniform Memory Access (UMA): the processors using shared memory
      - Bad scalability, shared memory bus is the bottleneck
    - Non-Uniform Memory Access (NUMA)
      - The processors access the whole memory through a communication interface
      - But a smaller memory range is assigned to the CPU for direct access (much faster)
- Multiprocessor, multi-core, multi-thread systems
  - The current system using a combination of these techniques


Chapter 5 Process Scheduling
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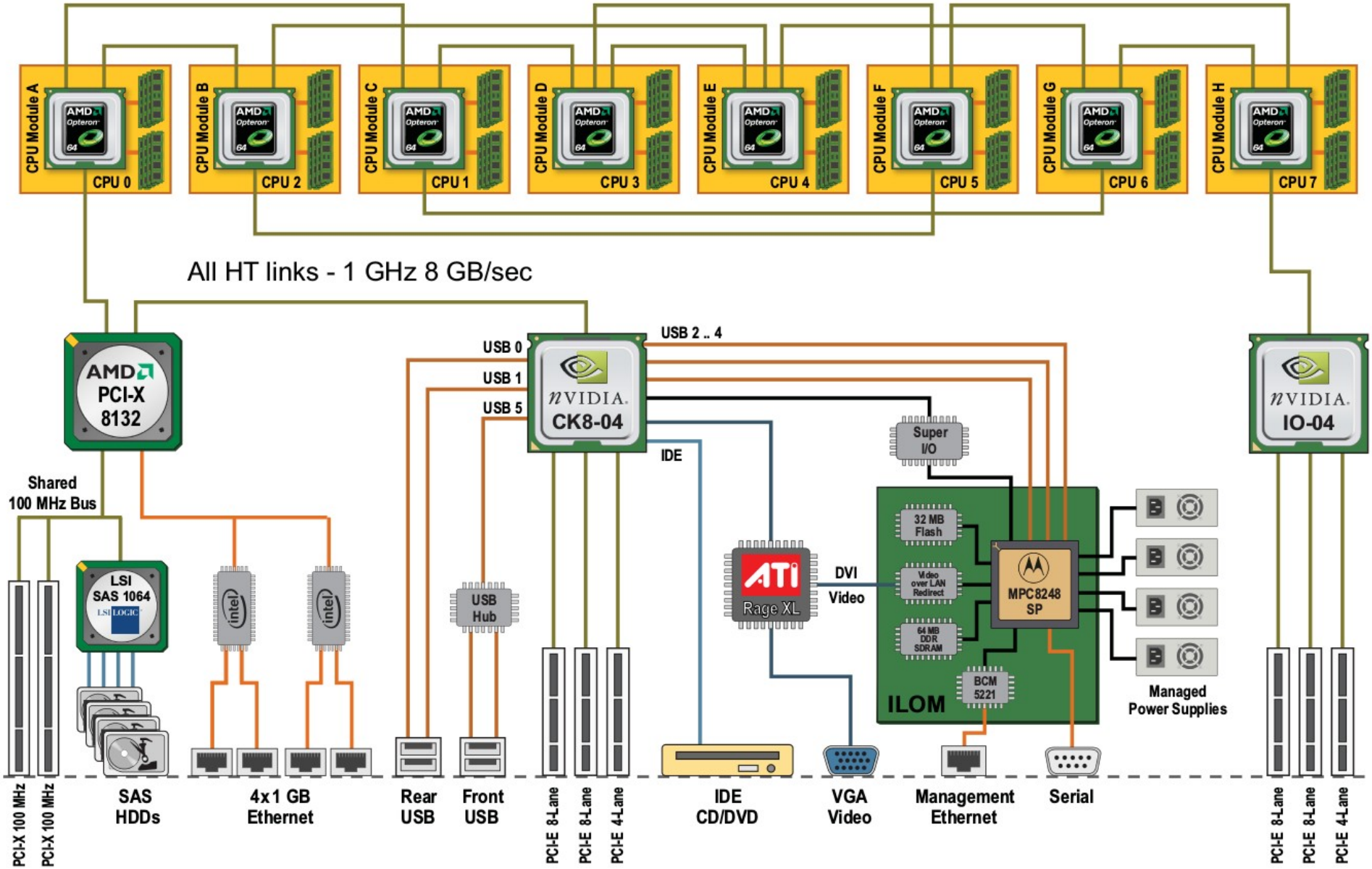
5.7 Scheduling in Mach
kernel
5.7.1 Multiprocessor Support


CPU Module A
CPU 0
CPU Module B
CPU 2
CPU Module C
CPU 1
CPU Module D
CPU 3
CPU Module E
CPU 4
CPU Module F
CPU 5
CPU Module G
CPU 6
CPU Module H
CPU 7
All HT links - 1 GHz 8 GB/sec
AMD PCI-X 8132
Shared 100 MHz Bus
USB 0
USB 1
USB 5
nVIDIA CK8-04
USB 2 .. 4
IDE
nVIDIA IO-04
Super I/O
32 MB Flash
Video over LAN Redirect
64 MB DDR SDRAM
MPC8248 SP
BCM 5221
ILOM
Managed Power Supplies
LSI SAS 1064
USB Hub
ATI Rage XL
DVI
Video
PCI-X 100 MHz
PCI-X 100 MHz
SAS HDDs
4x1 GB Ethernet
Rear USB
Front USB
PCI-E 8-Lane
PCI-E 8-Lane
PCI-E 4-Lane
IDE CD/DVD
VGA Video
Management Ethernet
Serial
PCI-E 8-Lane
PCI-E 8-Lane
PCI-E 4-Lane

Processor affinity and its types

- The scheduler has to adapt to the HW
  - The increased amount of context changes should not cause more overhead than the benefit of using multiple processors
    - UMA: maintain the cache memory contents
    - NUMA: should use the direct memory access
  - A preempted task should get the last CPU
    - It is not possible in every case: high load & high number of tasks
    - Priority of the tasks may influence this behavior
- Processor affinity
  - Binding processes to a specific CPU
  - This bond should be maintained
    - It is hard to maintain for tasks with large working set
  - Soft affinity
    - The OS tries to maintain the bond, but no guarantees
    - This is the default behavior in current operating systems
  - Hard affinity
    - The kernel guarantees the bond between the task and the CPU
    - The behavior is customizable through system calls
    - A sub-version: **processor group affinity** – a task will run on one of the CPU-s from the group

Load balancing between CPU-s

- The load should be equally distributed
- If the tasks managed in a global structure (queue)
  - Simple problem: if a processor is released the next task from the queue gets the CPU
  - In this way, the processor affinity is unmanageable
- RTR tasks are stored in separate queues assigned to each processing units
  - Local scheduling is simple like in a single processor system
  - Processor affinity is manageable: every task stays on the same unit
  - Load balancing may be a problem: one RTR queue becomes empty ⇨ other tasks should moved there
  - There will be an overhead caused by ignoring affinity
- How the tasks are moved between processors?
  - Push: a kernel task controls the processor change
  - Pull: the scheduler of an idle processor may aquire tasks for itself
- Handling grouped tasks (e.g. threads in the same process)
  - Gang scheduler: a group of tasks is bond to a group of processors
  - Important question in virtualization systems also (e.g. Vmware ESXi co-scheduling)

Summary

- Single level scheduling
  - FIFO, RR, SJF, SRTF, Priorities
  - Starvation
  - Measures: avg. waiting time, turnaround time, CPU utilization
- Multilevel scheduling
  - Multilevel static scheduling: fixed priorities (no queue change)
  - Multilevel dynamic scheduling: dynamic priorities (better in practice, because the tasks may change their nature)
- Multiprocessor scheduling
  - Processor affinity
  - Symmetric
    - Local queues for every processor
    - Push-pull task transfer
  - Asymmetric
    - Kernel gets a whole CPU