Operating Systems

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X. Scheduling
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RUHR UNIVERSITÄT BOCHUM RUB

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Chair of Operating Systems and System Software

Agenda

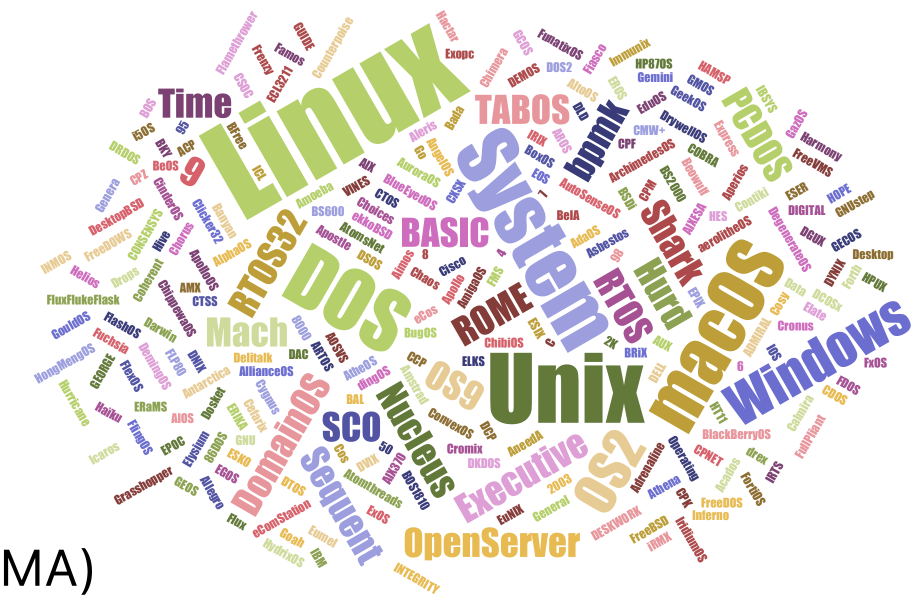
- Recap
- Organizational Matters
- Scheduling, State Transitions
- CPU Scheduling Strategies
  - Basic (First-Come First-Served)
  - Time-slice Driven (Round Robin, Virtual Round Robin)
  - Prediction Driven (Shortest Process Next, Highest Response Ratio Next)
  - Priority Driven (Multilevel Feedback Queues)
- Discussion: Reflection and Comparison
- Scheduling in Practice: The Linux O(1) Scheduler
- Summary and Outlook

Literature References

Silberschatz, Chapters 3.2, 5

Tanenbaum, Chapters 2.4

⏮ Recap



- **input/output** with **hardware devices** in operating systems
  - classification (character-based, block-based, and others)
  - operating principals (interrupts, DMA)
- device programming
  - address space models
  - operating modes: polling, interrupt- and DMA-driven
- I/O in practice: UNIX system services
  - UNIX **system calls** (i.e., open/read/write/close)
  - improve efficiency with buffers

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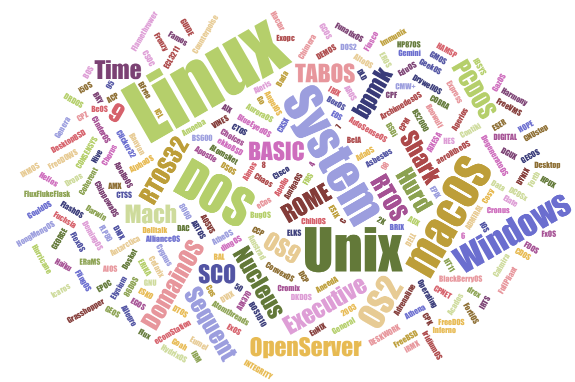
Organizational Matters



- lecture
  - Wednesday, 10:15 – 11:45
  - format: synchronous, **hybrid**
    - → in presence (Room HID, Building ID)
    - → online lecture (Zoom)
  - **exam:** August 7, 2023 (first appointment)
    September 25, 2023 (retest appointment)

  - **evaluation is live!**

    `https://tinyurl.com/25twb8qr`

- manage course material, asynchronous communication: Moodle
- `https://moodle.ruhr-uni-bochum.de/course/view.php?id=50698`

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Scheduling

- definition: „scheduling concerns the allocation of limited resources to processes over time"
  → **maximize CPU utilisation**

- depending on the **scheduling level**, each process is assigned a logical state that specifies its processing state at a point in time:
- **short-term scheduling**
- **medium-term scheduling**
- **long-term scheduling**

Rule of thumb for the frequency of **scheduler decisions** or **process state changes**:

- **short term**: µs ... ms
- **medium term**: ms ... min
- **long term**: min ... hrs

Long-Term Scheduling

Controls the degree of multiprogramming. Dynamically at runtime or in extreme cases statically within the operating system.

- **NEW** (dt. erzeugt): ready for program processing via `fork(2)`
  - the process is instantiated, a program has been assigned to it
  - however, the allocation of necessary operating resources (e.g., memory, devices) may still be pending

- **EXIT** (dt. beendet): termination via `exit(2)/wait(2)` is expected
  - the process is terminated, its resources are (to be) released
  - if necessary, another process must complete the "cleanup"

Medium-Term Scheduling

A process is completely **swapped out**: the contents of its entire address space have been moved to background memory (swap-out) and the foreground memory occupied by the process has been freed. The swap-in of the address space must be awaited.

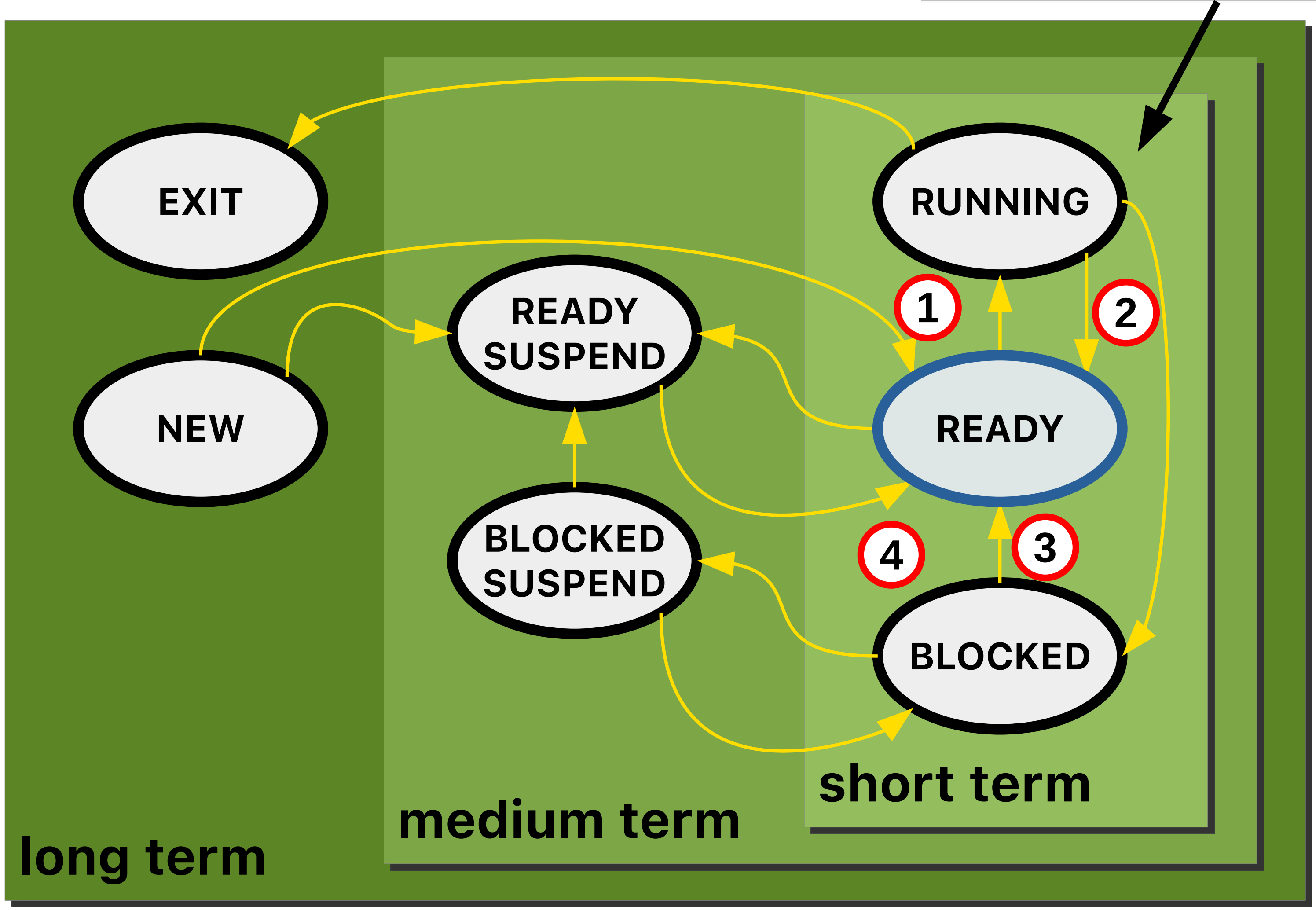
- **READY SUSPEND** (dt. ausgelagert bereit)
  - the CPU allocation ("ready") is disabled
  - the process is on the waiting list for memory allocation
- **BLOCKED SUSPEND** (dt. ausgelagert blockiert)
  - the process still expects an event (BLOCKED)
  - once the event occurs, the process is READY SUSPEND

Short-Term Scheduling

- **READY** (dt. bereit) for execution by the processor (the CPU)
  - the process is on the waiting list for CPU allocation (**ready list**)
  - list position is determined by the scheduling procedure
- **RUNNING** (dt. laufend) the resource CPU has been allocated
  - the process performs **calculations**, it completes its CPU burst
  - for each processor there is only one running process at a time
- **BLOCKED** (dt. blockiert) blocks on a specific event
  - the process performs **input/output operations**, it performs its I/O burst
  - it expects the fulfillment of at least one condition

State Transitions

focus:
short-term scheduling



Process Dispatching: Time and Selection

- transitions to the ready state (READY) <u>update</u> the CPU ready list
  - a decision regarding the **placement** of the **process control block** is made
  - the result depends on the system's **CPU scheduling strategy**
- scheduling or rescheduling (dt. Einplanung/Umplanung) occurs, ...
  - 1 after a process has been created
  - 2 when a process yields control of the CPU
  - 3 if the event which is expected by a process has occurred
  - 4 as soon as an swapped-out process is resumed

A process can be **forced** to release the CPU → **preemptive scheduling**

- for example, by a timer interrupt 2

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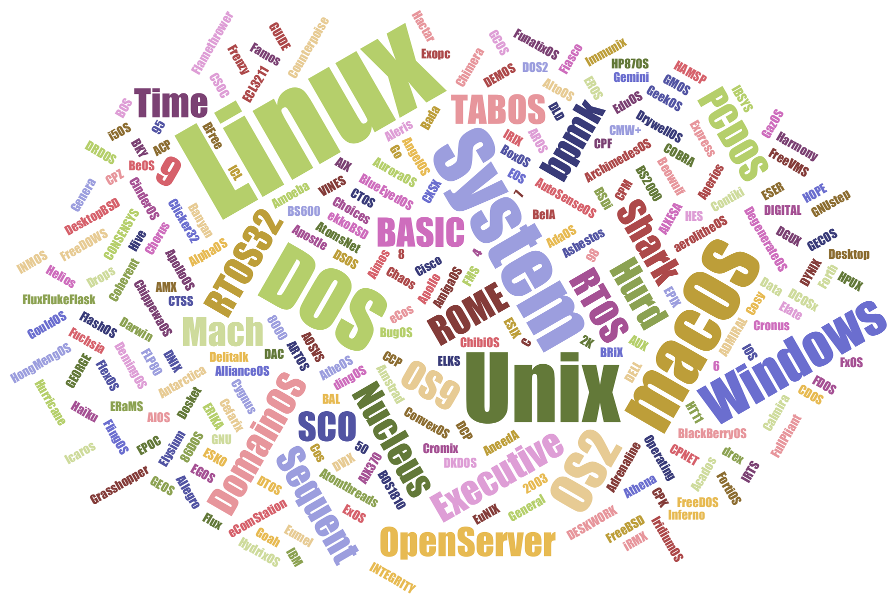

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Basic: First-Come First-Served (FCFS)

- First-Come First-Served: a simple and fair procedure?
  - queuing criterion is the **arrival time** of a process
  - **non-preemptive**, thus requires cooperative processes
- Example:

Process	Times					
	Arrival	Service T_s	Start	End	Turnaround T_r	T_r/T_s
A	0	1	0	1	1	1.00
B	1	100	1	101	100	1.00
C	2	1	101	102	100	**100.00**
D	3	100	102	202	199	1.99
Average					100	26.00

  - discussion: **service time** (dt. Bedienzeit) vs. **turnaround time** (dt. Durchlaufzeit)
  - wanted: proportionality between service time and turnaround time
  - example: the normalized execution time (T_r/T_s) of process C is very poorly in comparison to its service time T_s

Discussion: FCFS – The Convoy Effect

- the problem is faced by short-running **I/O-heavy processes** that follow long-running **CPU-heavy processes**
  - processes with **long CPU bursts** are **favored**
  - processes with **short CPU bursts** are **penalized**
- FCFS **minimizes** the number of **context switches**. However, the convoy effect causes the following problems:
  - high response times
  - low I/O throughput
- FCFS is therefore unsuitable for a mixed workloads (CPU- and I/O-heavy processes)
- typically, FCFS is only in used in batch processing systems

Time-slice Driven: Round Robin (RR)

- reduces the **penalization of processes with short CPU bursts** that occurs with FCFS:
  - the processor time is divided into **time slices** (dt. Zeitscheiben)
- when the time slice expires, a process change <u>may</u> take place
  - the interrupted process is pushed to the end of the ready list
  - the next process is taken from the ready list according to FCFS
- basis for CPU protection: timer interrupt enforces end of time slice
- the **time slice length** determines the effectiveness of this scheduling method
  - time slice
    - ➔ too long: degeneration of RR to FCFS
    - ➔ too short: high scheduling overhead
  - rule of thumb: slightly longer than the duration of a "typical interaction"

Discussion: Round Robin – Performance Issues

- **I/O-heavy** processes finish CPU burst within their time slice
  - they block and return to the ready list at the end of their I/O burst
  - it is likely that their time slice has not yet been exhausted
- **CPU-heavy** processes, on the other hand, make full use of their time slice
  - they are preempted and immediately return to the ready list
- result: **CPU time is unevenly distributed** in favor of CPU-heavy processes
  - causal link: I/O-heavy processes are poorly operated and thus devices poorly utilized
  - response time of I/O-heavy processes increases

Time-slice Driven: Virtual Round Robin (VRR)

- VRR addresses the uneven distribution of CPU times that is possible with RR
  - processes are added to a *preferred list* at the end of their I/O bursts
  - scheduler processes *preferred list* **before** the *ready list*
- the method works with **time slices of variable lengths**
  - processes on the *preferred list* are **not** allocated a full time slice
  - instead, they are granted the remaining term of their previously not fully used time
  - if their CPU burst takes longer, they are preempted and put back to the ready list
- process handling more complex compared to RR → overhead

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Prediction Driven: Shortest Process Next (SPN)

- reduces the disadvantage of short CPU bursts that occurs with FCFS: "the little ones to the front"
  - necessary basis: knowledge of the process execution times
  - preemption does **not** happen
- the main problem is the **estimation** of the CPU burst time
  - batch operation: programmers **specify** the required **time limit***
  - interactive operation: **estimation** based of the **previous bursts** lengths of the process
- response times are significantly reduced and overall performance increases
  - but: risk of **starvation** of CPU-heavy processes

* the execution time within which the job will (probably/hopefully) be completed before it is canceled

Discussion: SPN – Estimate CPU Burst Time (I)

- estimate next CPU burst (S_{n+1}): calculate average over all previous CPU bursts lengths (T_i) of a process

$$S_{n+1} = \frac{1}{n} \cdot \sum_{i=1}^{n} T_i$$

- **challenge** of this calculation is the equal **weighting** of all CPU bursts
  - however, recent CPU bursts are more important than older ones
  - hence, greater weighting for more recent process behavior
- cause is the **principle of locality**

Discussion: SPN – Estimate CPU Burst Time (II)

- the CPU bursts further back are to be given less weight:

$$S_{n+1} = \alpha \cdot T_n + (1-\alpha) \cdot S_n$$

  - for the constant **weighting factor α** holds: $0 < \alpha < 1$
  - it reflects the **relative weighting** of the of individual CPU bursts of the time series

Exponential Smoothing

- recursive insertion leads to...

$$S_{n+1} = \alpha T_n + (1-\alpha) \alpha T_{n-1} + \ldots + (1-\alpha)^i \alpha T_{n-i} + \ldots + (1-\alpha)^n S_1$$

$$S_{n+1} = \alpha \cdot \sum_{i=0}^{n-1} (1-\alpha)^i T_{n-i} + (1-\alpha)^n S_1$$

- for α = 0.8:

$$S_{n+1} = 0.8 T_n + 0.16 T_{n-1} + 0.032 T_{n-2} + 0.0064 T_{n-3} + \ldots$$

Problem: Starvation!

Prediction Driven: Highest Response Ratio Next (HRRN)

- **prevents** the **starvation** of CPU-heavy processes
  - scheduler considers **aging (i.e., the waiting time)** of processes

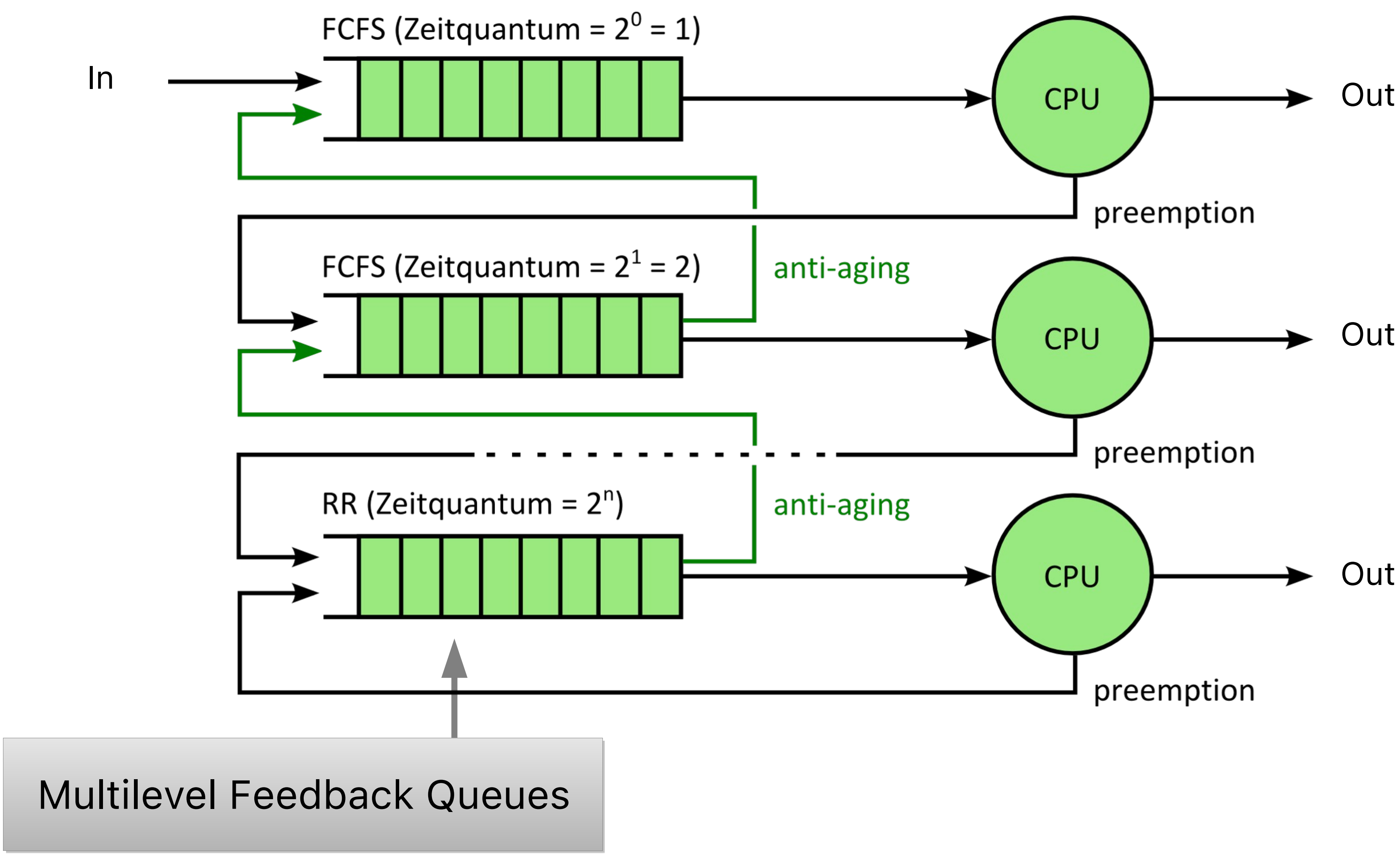
$$R = \frac{w+s}{s}$$

  - w is the "waiting time of the process" so far
  - s is the "expected service time"
  - R is the **response ratio**
- the process with the **highest response ratio is chosen**
- based again on the estimate of the CPU burst time

Priority Driven: Multilevel Feedback Queues

- favors short processes **without estimating** the CPU burst time of the processes
  - principle: "punishment" (dt. Bestrafung) of processes with long execution time
  - processes are subject to preemption
- **multiple** ready lists, depending on the number of **priority levels**
  - when a process first arrives, it runs at the highest level
  - with the expiration of its time slice, he comes to the next lower level
  - the lowest level operates according to RR
- processes with short execution time complete relatively quickly
- processes with long execution time are prone to starvation
  - the waiting time can be considered to regain higher levels (**anti-aging**)

Priority Driven: Multilevel Feedback Queues



Discussion: Priority Driven

- process priority := a process "precedence" that significantly influences scheduling decisions by the operating system

- **static priorities** are set at the time of process generation
  - the priority level is **not** changed during execution
  - this method enforces a deterministic order between processes

- **dynamic priorities** are calculated and updated during the process execution
  - updates takes place in the operating system, but also from the user
  - SPN, HRRN, and MFQ are special cases of this method

Discussion: Priority Inversion

- priority inversion: scheduler dispatches a **process with lower priority** while another process with **higher priority is blocked** (on a resource held by a process with low priority)
- cross-cutting concerns of OS scheduler and OS process synchronisation primitives and protocols
- possible solutions:
  - appropriate synchronisation methods to protect critical sections
    - → non-blocking synchronisation
  - priority ceiling protocols

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Scheduler Evaluation Criteria and Goals

- goals from perspective of a **user**:
  - **processing time** – time between arrival and completion of a process including waiting time(s) → **batch processing**
  - **response time** – time between user input and system response → **interactive systems**
  - **deadline adherence** – deadlines *should* be met for the interaction with external physical processes → **real-time systems**
  - **predictability** – processes are always handled the same regardless of the load → **hard real-time systems**
- goals from the perspective of the **system**:
  - **throughput** – process as many processes as possible per time unit
  - **CPU utilization** – CPU should always be busy, if possible. Overhead (scheduling decisions, context switches) should be minimised.
  - **fairness** – no process should be penalized (avoid starvation)
  - **load balancing** – I/O devices should also be evenly utilized

Comparison – Quantitative Evaluation

	Process	A	B	C	D	E	
	Arrival	0	2	4	6	8	**Average**
	Service T_s	3	6	4	5	2	
FCFS	Finish	3	9	13	18	20	
	Turnaround T_r	3	7	9	12	12	8.60
	T_r/T_s	1.00	1.17	2.25	2.40	6.00	2.56
RR	Finish	4	18	17	20	15	
q=1	Turnaround T_r	4	16	13	14	7	10.80
	T_r/T_s	1.33	2.67	3.25	2.80	3.50	2.71
SPN	Finish	3	9	15	20	11	
	Turnaround T_r	3	7	11	14	3	**7.60**
	T_r/T_s	1.00	1.17	2.75	2.80	1.50	**1.84**
HRRN	Finish	3	9	13	20	15	
	Turnaround T_r	3	7	9	14	7	8.00
	T_r/T_s	1.00	1.17	2.25	2.80	3.50	2.14
MFQ	Finish	4	20	16	19	11	
q=1	Turnaround T_r	4	18	12	13	3	10.00
	T_r/T_s	1.33	3.00	3.00	2.60	1.50	2.29

Based on William Stallings, „Operating Systems – Internals and Design Principles"

Service T_s: Bedienzeit
Turnaround T_r: Durchlaufzeit
T_r/T_s: Größenverhältnis von Bedien- und Durchlaufzeit (kleiner ist besser)

Comparison – Qualitative Evaluation

scheduling strategy	preemptive/ cooperative	prediction necessary?	implementation effort	prone to starvation?	impact on processes
FCFS	cooperative	no	minimal	no	convoi effect
RR	preemptive (timer)	no	small	no	fair, but puts I/O-heavy processes at a disadvantage
SPN	cooperative	yes	big	yes	puts CPU-heavy processes at a disadvantage
HRRN	cooperative	yes	big	no	good load balancing
MFQ	preemptive (timer)	no	huge	yes	may favor I/O-heavy processes

Based on William Stallings, „Operating Systems – Internals and Design Principles“

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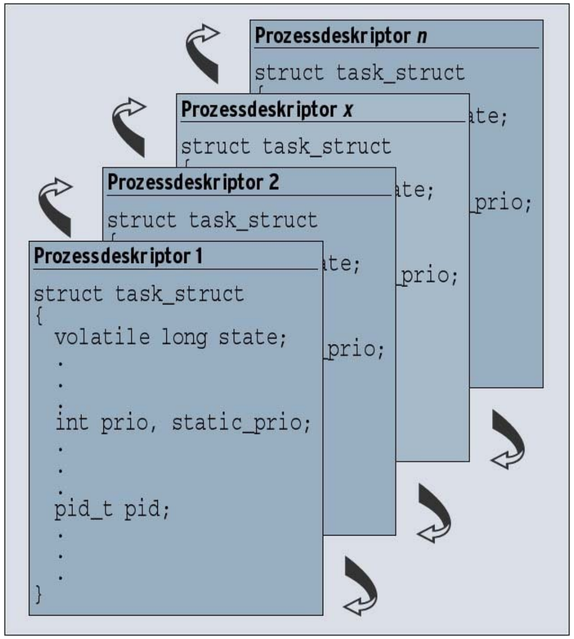
The Linux O(1) Scheduler

- **motivation**
  - runtime complexity of Linux 2.4 scheduler (until 2002): $O(n)$
  - thus, poor performance with increasing number of processes
  - issue: **overhead scales linear** with **number of processes**

- ***O*(1) process scheduler**
  - Linux 2.6 (2002-2007): improved scheduler which reduces process **scheduling efforts** to a **constant** amount of work ($O(1)$) – independent of the number of processes
  - **goals:** reduce scheduling overhead, improve system responsiveness for interactive processes

The Linux O(1) Scheduler

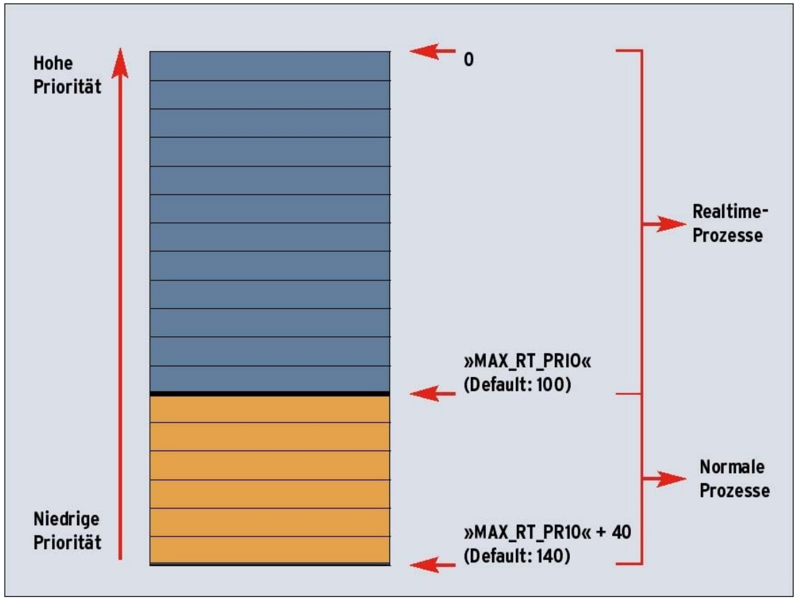
- operating principle and implementation
  - each CPU: individual ready lists, avoiding concurrent access by different CPUs
  - each run queue consists of two lists:
    active list (ready processes, time available)
    expired list (ready processes, expired time)
  - preemptive scheduling, process priorities



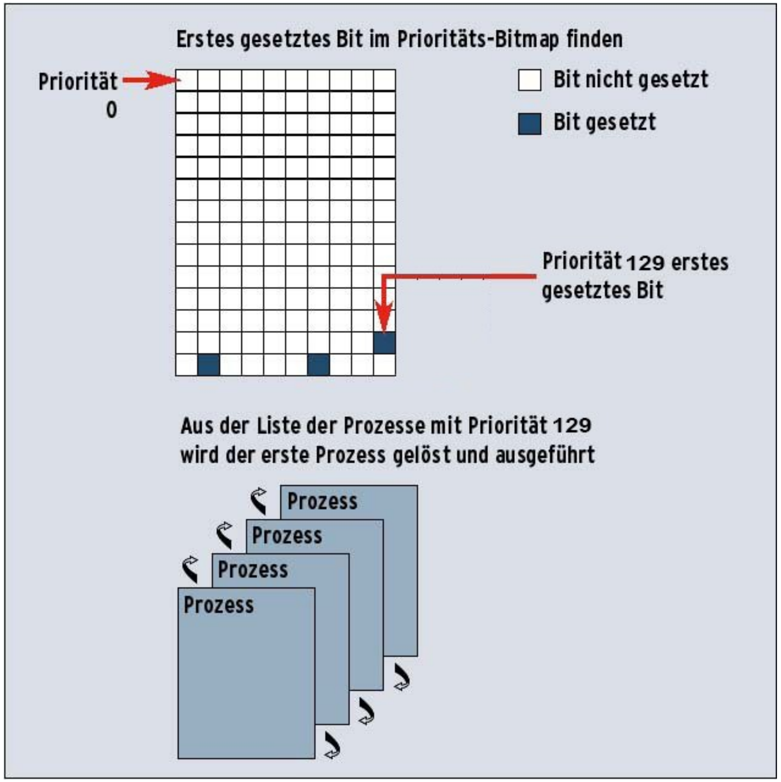
- reduced overhead, improve performance
  - decreased memory pressure on the kernel stack
  - bitmaps for implementing process priorities
  - variable time slices (10 ... 200 ms)

The Linux O(1) Scheduler

- process priorities
  - highest priority: 0
    lowest priority: 139
  - priority is based on **nice** value of each process (100 … 139)
  - additional priorities of **real-time** processes (0 … 99)
- tracking processes and priorities
  - bitmap tracks for which **priority** at least one **ready process exists**, references **double linked** list of corresponding processes
  - scheduler handles each priority level with **RR**



The Linux O(1) Scheduler



- when the last **process** of a given priority **terminates**, the corresponding **field in the bitmap** is set to **null**
- scheduler moves to **next** (lower) **priority level** and continues
- when **active** run queue is empty:
  - exchange **active** and **expired** run queue
  - repeat until processes exhaust their time slices, again
- O(1): scheduling effort is constant (proportional to the size of the bitmap)

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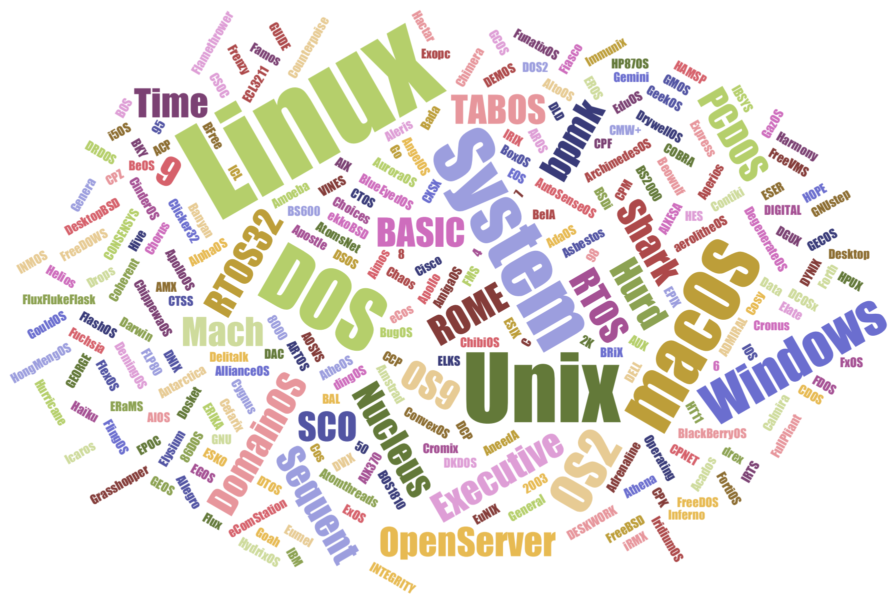

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⏭ Summary and Outlook

- **summary**
  - operating systems make **CPU scheduling** decisions at three scheduling levels:
    - **long-term** scheduling: allowance of processes to the system
    - **medium-term** scheduling: swap-out and swap-in of processes
    - **short-term** scheduling: allocation of CPU time for the execution of processes
  - **short-term scheduling methods**
    - **basic**
    - **advanced** algorithms based on time slices, prediction, priorities
  - the Linux O(1) scheduler – **practical process scheduler** to improve system responsiveness
- **outlook: inter-process communication**
  - **communication between process** to exchange data (e.g., for cooperation)
  - methods: shared memory and messages

References and Acknowledgments

Lecture

- Systemnahe Programmierung in C (SPiC), Betriebssysteme (Jürgen Kleinöder, Wolfgang Schröder-Preikschat)
- Betriebssysteme und Rechnernetze (Olaf Spinczyk, Embedded Software Systems Group, Universität Osnabrück)

Teaching Books and Reference Book

[1] Avi Silberschatz, Peter Baer Galvin, Greg Gagne: *Operating System Concepts*, John Wiley & Sons, 2018.

[2] Andrew Tanenbaum, Herbert Bos: *Modern Operating Systems*, Pearson, 2015.

[3] Wolfgang Schröder-Preikschat: *Grundlage von Betriebssystemen – Sachwortverzeichnis*, 2023.
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