Operating Systems

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VII. Virtual Memory
May 24, 2023 (Summer Term 2023)

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RUHR UNIVERSITÄT BOCHUM RUB

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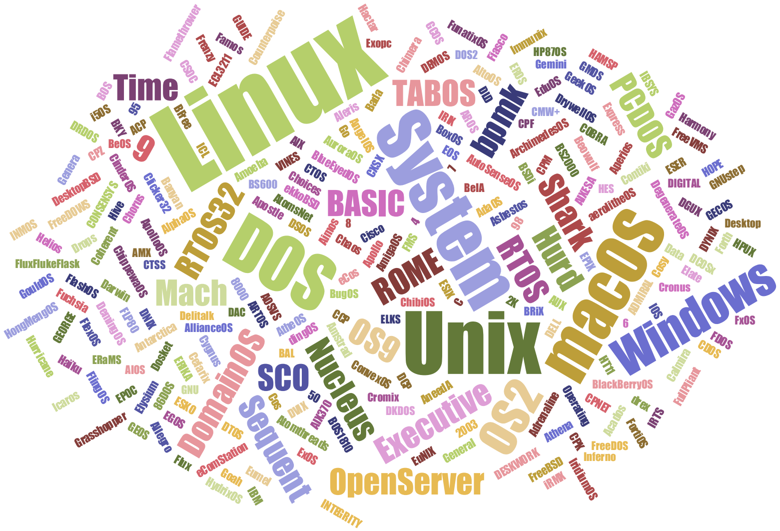
Chair of Operating Systems and System Software

Agenda

- Recap
- Organizational Matters
- Motivation
  - Locality of Reference
  - Virtual Memory
- Demand Paging
- Page Replacement Algorithms
  - First In, First Out (FIFO),
  - Least Recently Used (LRU)
  - Second Chance (SC)
- Page Frame Allocation
  - Thrashing
  - Working Set Model
- Summary and Outlook

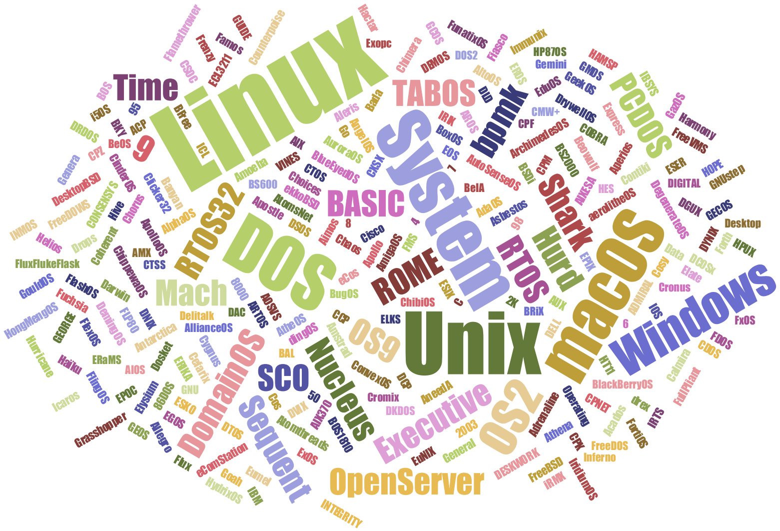


Literature References

Silberschatz, Chapter 10

Tanenbaum, Chapter 3.3

⏮ Recap



- for memory management, the operating system works very closely with the hardware
  - **segmentation** or/and **paging**
  - implicit indirection in memory access allows segments and pages of programs to be moved arbitrarily during operation
- several strategic decisions have to be made
  - placement strategies (First Fit, Best Fit, Buddy, ...)
  - different characteristics with regards to fragmentation, time overhead
  - choice of strategy depends on the expected memory access patterns

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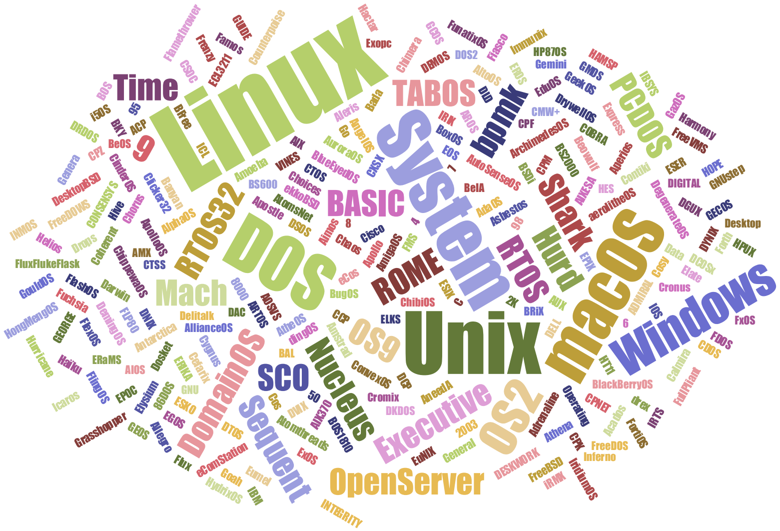

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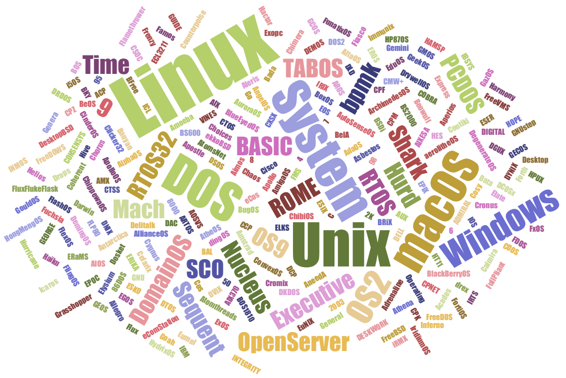
Organizational Matters



- 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)
- exercises: **group allocation ~~almost~~ complete**
  - make use of group work - for your own benefit!
- manage course material, asynchronous communication: Moodle
- `https://moodle.ruhr-uni-bochum.de/course/view.php?id=50698`

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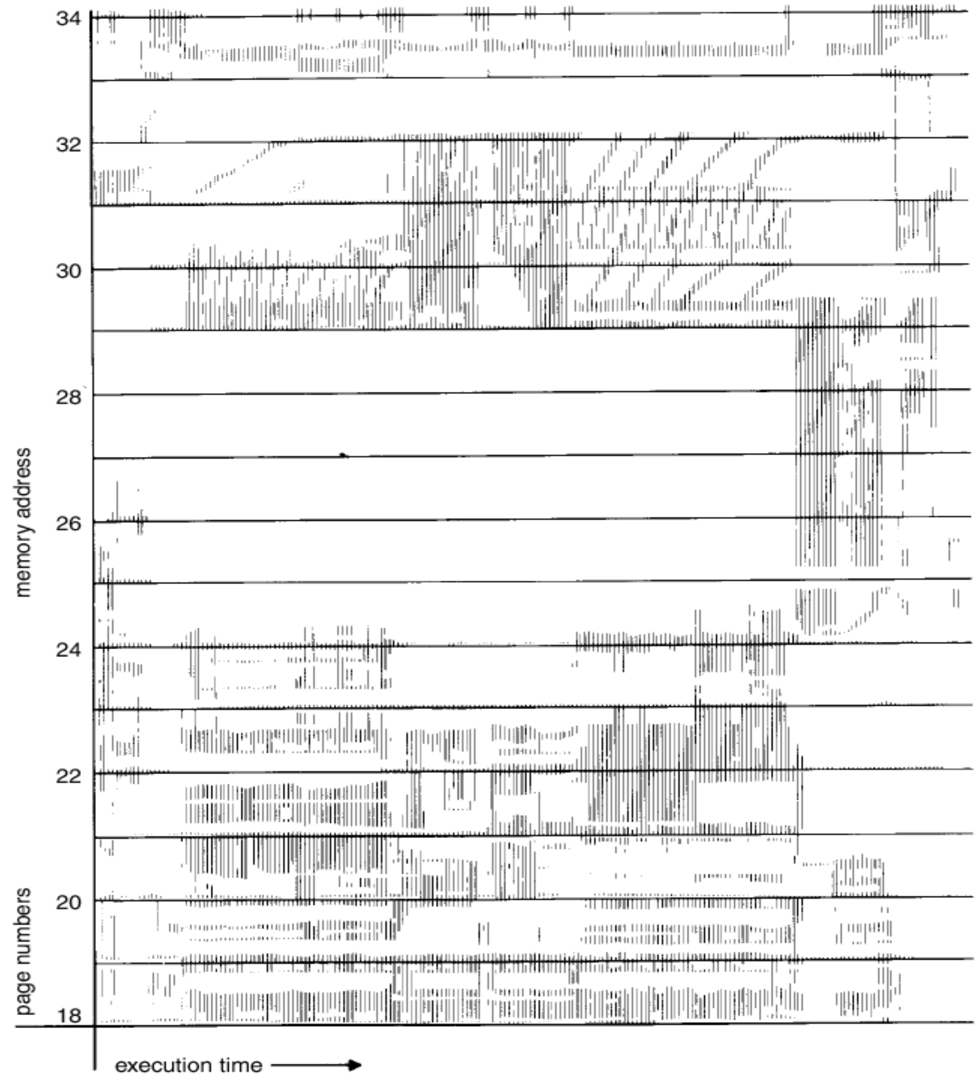
Locality of Reference – Memory Access

- single instructions require only a few memory pages
- even over longer periods of time: strong locality of reference
  - instructions are executed, for example, one after the other

➔ locality can be exploited if primary memory is not large enough to keep pages of all processes at the same time

  - for example, overlay technique



Source: Silberschatz, „Operating System Concepts“

Virtual Memory – Main Idea

- add a system layer of indirection: decouple the memory requirement of processes from the system's main memory
  - processes do not need all memory locations equally often
    - → certain functions are rarely or not at all used (e.g., error handling)
    - → certain data structures are not fully populated
  - processes may require more memory than main memory is available

- main idea
  - delude the existence of a (unlimited) large main memory
  - swap out unused memory areas from primary to secondary storage

    byte-addressable main memory (e.g., RAM) →
    block-addressable background storage/memory (e.g., SSD, HDD)
  - provide the required memory areas on demand → demand paging

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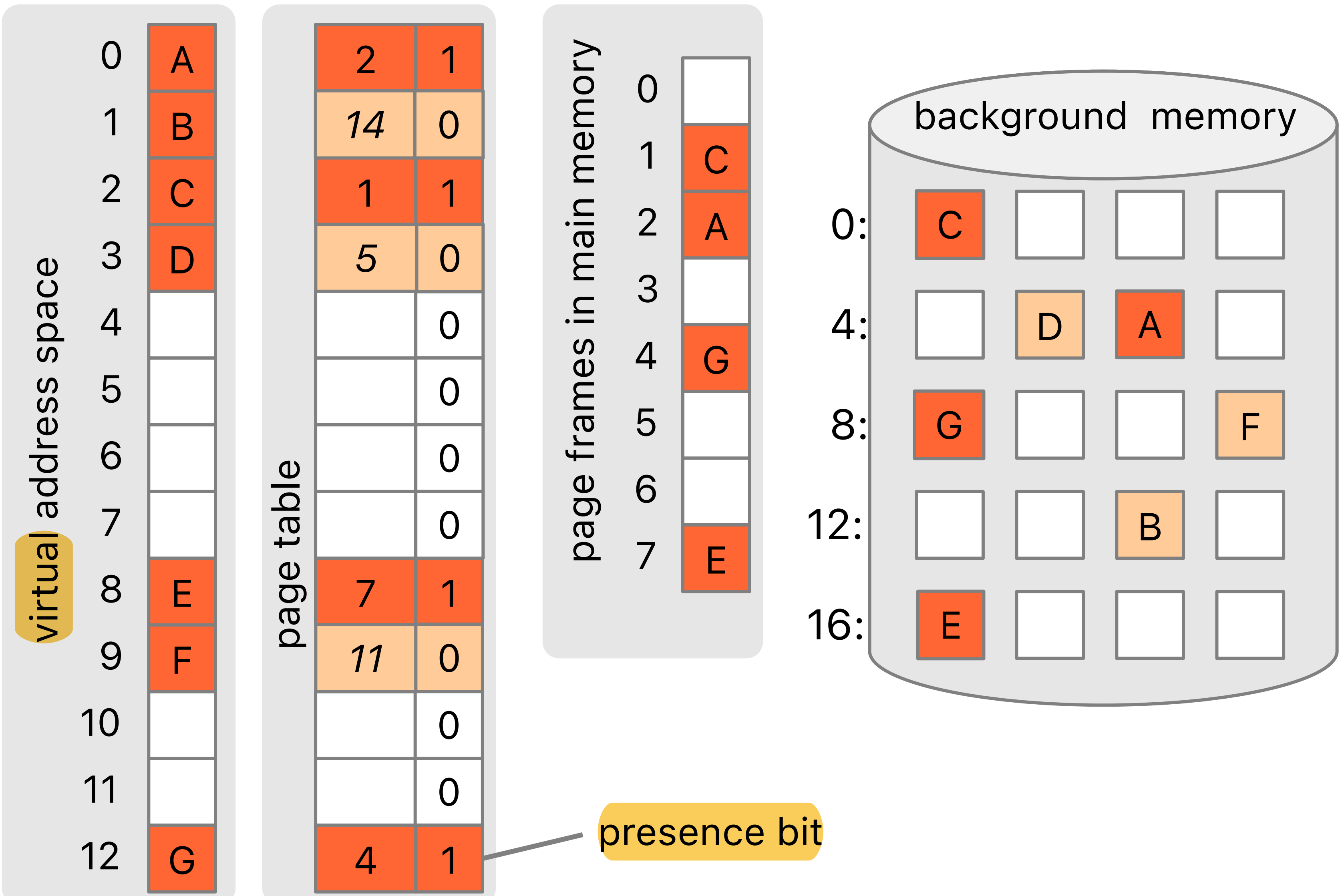
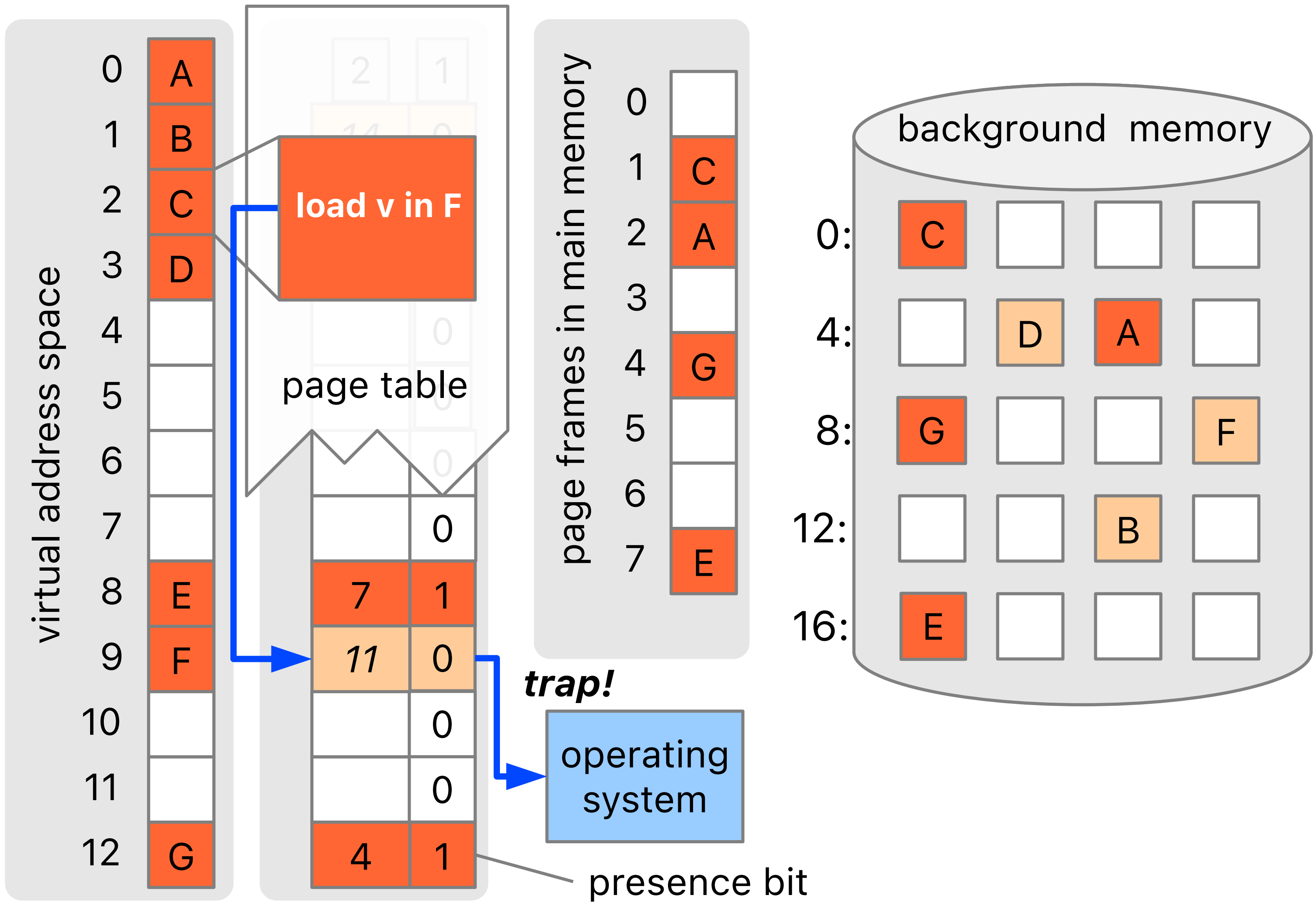
Demand Paging – Provide Pages on Demand



Demand Paging – Page Fault Handling



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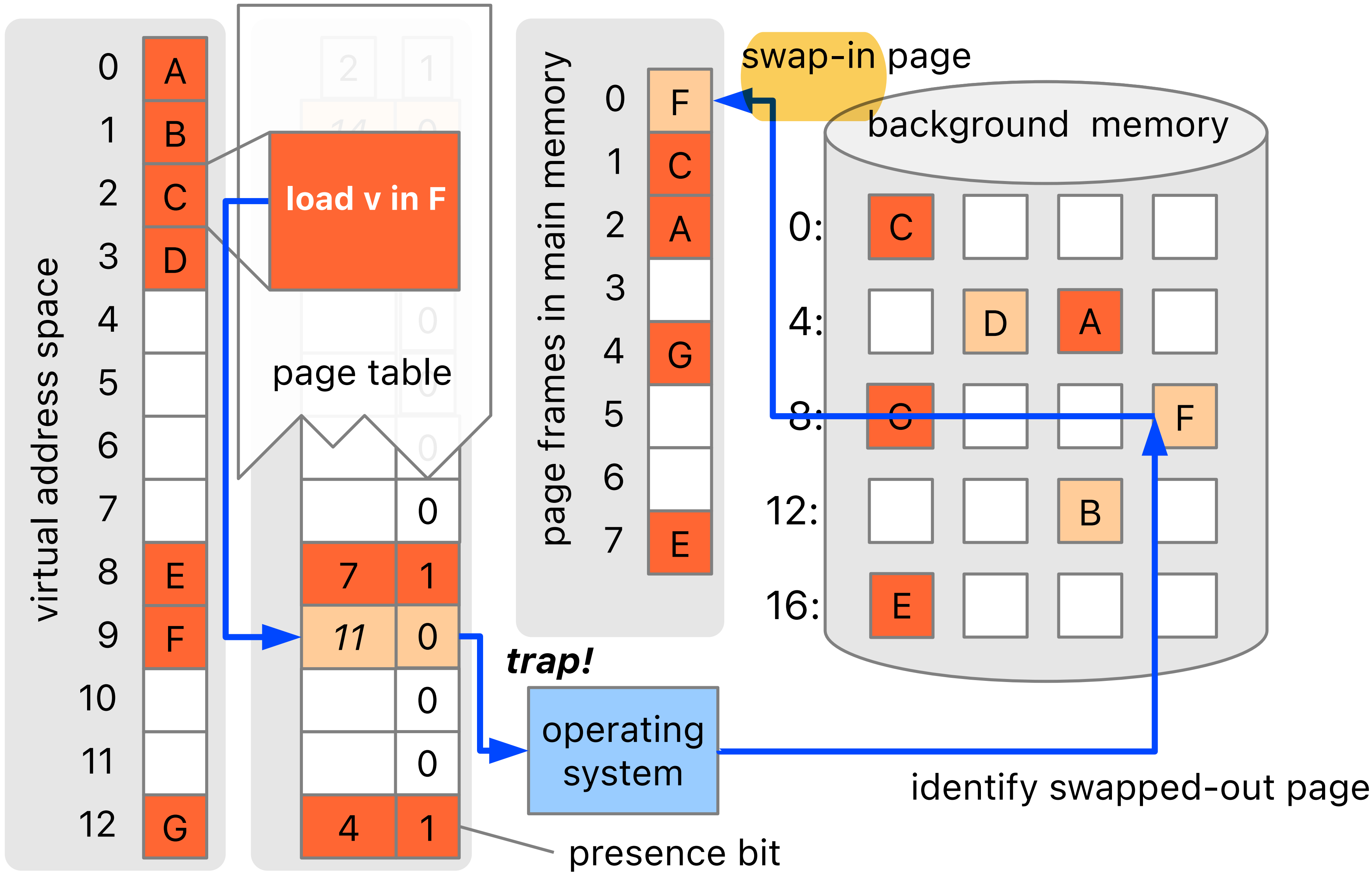

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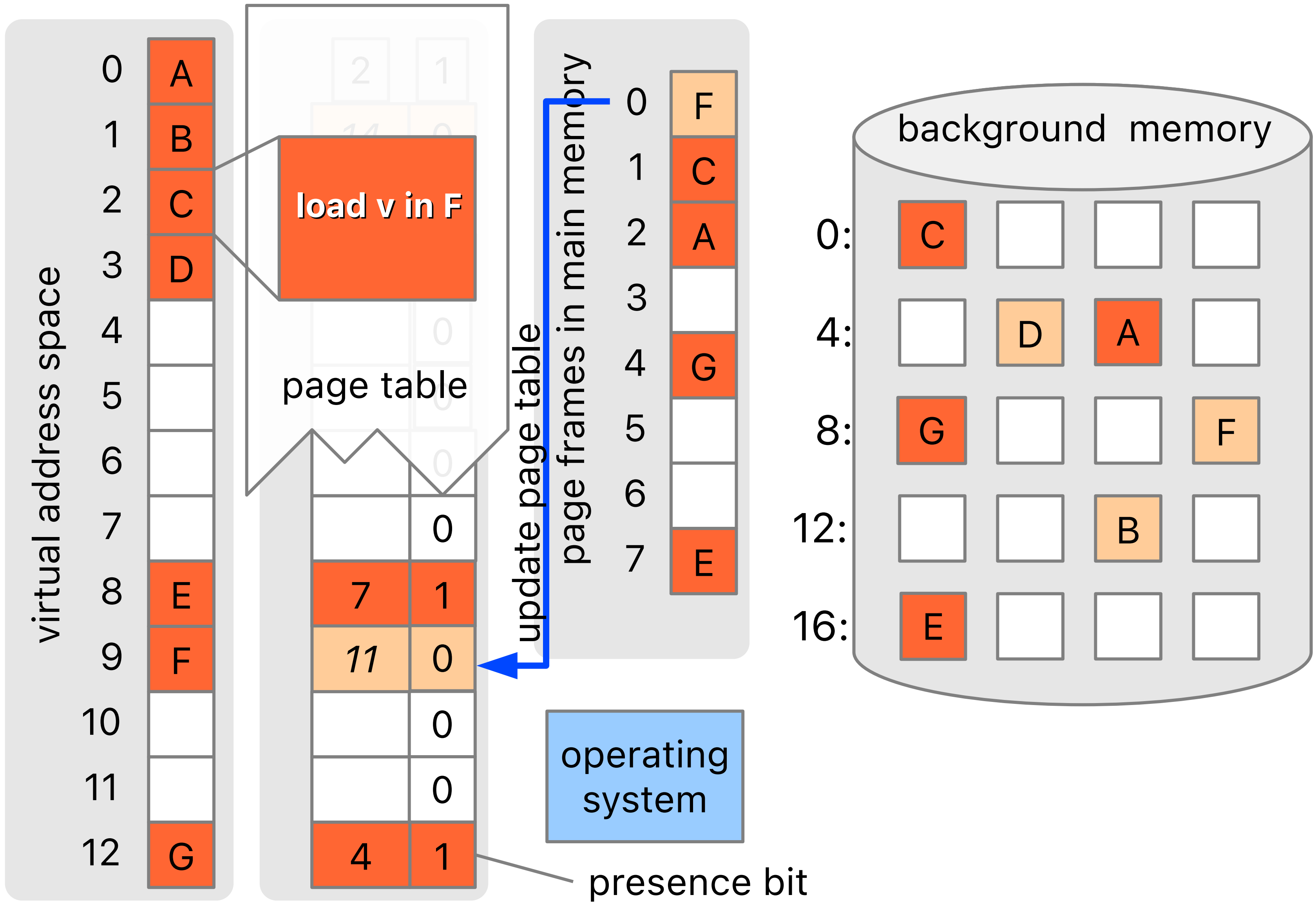
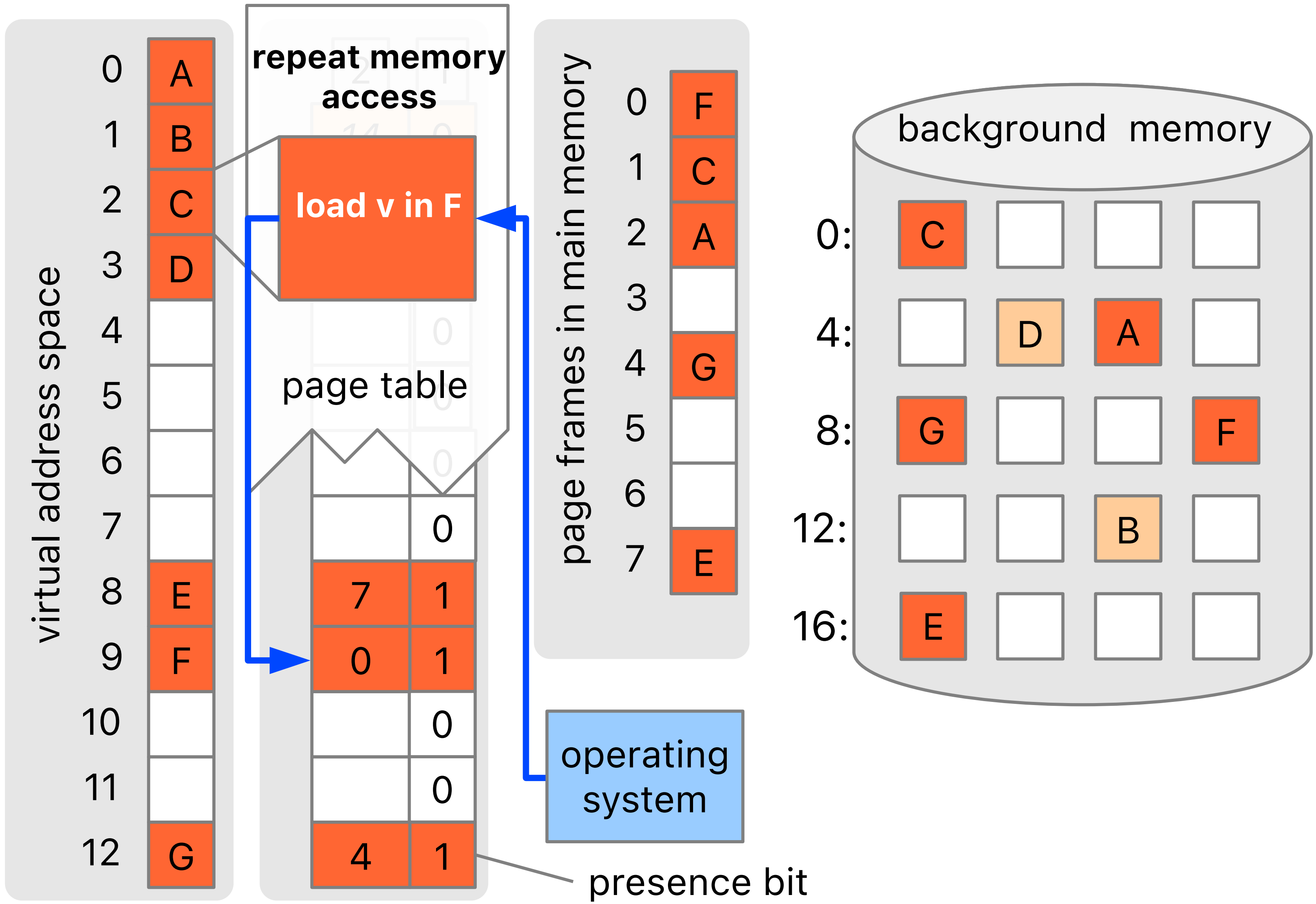


Demand Paging – Page Fault Handling



Demand Paging – Discussion

- operational costs of demand paging (i.e., performance impact)
  - without page fault
    - ➔ effective access time between 10 and 200 nanoseconds
  - with page fault
    - ➔ *p*: probability of a page fault
    - ➔ first assumption: time to swap-in a page from background memory is 25 milliseconds (8 ms latency, 15 ms positioning time, 1 ms transmission time)
    - ➔ second assumption: main memory access time is 100 ns
    - ➔ effective access time:
      $(1 - p) \cdot 100 + p \cdot 25000000 = 100 + 24999900 \cdot p$

➔ rate of page faults must be *very* low
  - *p* close to zero
  - realistic only due to data locality

Demand Paging – Characteristics

- operational concerns on process generation (e.g., fork)
  - **copy-on-write**
    - → also easy to implement with paging MMU
    - → finer granularity than with segmentation
  - program execution and memory accesses are interleaved
    - → required pages are loaded only as they are needed

- page locking
  - lock pages that are used by DMA during trap (i.e., page fault handling)
  - necessary for input/output operations

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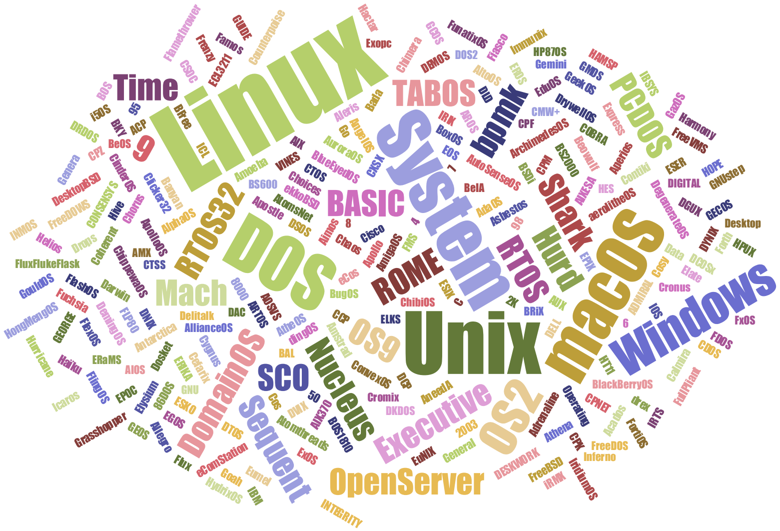

Page Replacement Algorithms

- demand paging: need for free page frame(s)
- modus operandi:
  - page fault: exception handling via trap into the operating system
  - if no free page frame is available: swap-out a page
  - swap-in the required page
  - repeat memory access
- what to do if there is no free page frame?
  - a page must be swapped-out to the background memory to free up space for a new page in main memory
  - pages that have not been changed (dirty bit in page table)
  - if page was changed: process preemption requires swapping
- problem
  - which page ("victim") should be swapped-out?

Page Replacement Algorithms

- consideration of replacement strategies and their effect on reference sequences
- reference sequence
  - sequence of page numbers that model the memory access behavior of a process
  - determination of reference sequences, for example, by recording the accessed addresses
    - → reduce the recorded sequence to page numbers
    - → group accesses to the same page in immediate succession
  - reference sequence: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

First-In, First-Out (FIFO)

- oldest page is replaced
- necessary states:
  - age (time of swap-in) for each page frame
- sequence of replacement

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**											
	page frame 2												
	page frame 3												
control states (age per page frame)	page frame 1	0											
	page frame 2	>											
	page frame 3	>											

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reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1										
	page frame 2		**2**										
	page frame 3												
control states (age per page frame)	page frame 1	0	1										
	page frame 2	>	0										
	page frame 3	>	>										

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- sequence of replacement

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1									
	page frame 2		**2**	2									
	page frame 3			**3**									
control states (age per page frame)	page frame 1	0	1	2									
	page frame 2	>	0	1									
	page frame 3	>	>	0									

First-In, First-Out (FIFO)

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  - age (time of swap-in) for each page frame
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reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	**4**								
	page frame 2		**2**	2	2								
	page frame 3			**3**	3								
control states (age per page frame)	page frame 1	0	1	2	0								
	page frame 2	>	0	1	2								
	page frame 3	>	>	0	1								

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  - age (time of swap-in) for each page frame
- sequence of replacement

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	**4**	4							
	page frame 2		**2**	2	2	**1**							
	page frame 3			**3**	3	3							
control states (age per page frame)	page frame 1	0	1	2	0	1							
	page frame 2	>	0	1	2	0							
	page frame 3	>	>	0	1	2							

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- sequence of replacement

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	**4**	4	4						
	page frame 2		**2**	2	2	**1**	1						
	page frame 3			**3**	3	3	**2**						
control states (age per page frame)	page frame 1	0	1	2	0	1	2						
	page frame 2	>	0	1	2	0	1						
	page frame 3	>	>	0	1	2	0						

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reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	**4**	4	4	**5**					
	page frame 2		**2**	2	2	**1**	1	1					
	page frame 3			**3**	3	3	**2**	2					
control states (age per page frame)	page frame 1	0	1	2	0	1	2	0					
	page frame 2	>	0	1	2	0	1	2					
	page frame 3	>	>	0	1	2	0	1					

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- oldest page is replaced
- necessary states:
  - age (time of swap-in) for each page frame
- sequence of replacement

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	**4**	4	4	**5**	5				
	page frame 2		**2**	2	2	**1**	1	1	1				
	page frame 3			**3**	3	3	**2**	2	2				
control states (age per page frame)	page frame 1	0	1	2	0	1	2	0	1				
	page frame 2	>	0	1	2	0	1	2	3				
	page frame 3	>	>	0	1	2	0	1	2				

First-In, First-Out (FIFO)

- oldest page is replaced
- necessary states:
  - age (time of swap-in) for each page frame
- sequence of replacement

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	**4**	4	4	**5**	5	5	5	5	5
	page frame 2		**2**	2	2	**1**	1	1	1	1	**3**	3	3
	page frame 3			**3**	3	3	**2**	2	2	2	2	**4**	4
control states (age per page frame)	page frame 1	0	1	2	0	1	2	0	1	2	3	4	5
	page frame 2	>	0	1	2	0	1	2	3	4	0	1	2
	page frame 3	>	>	0	1	2	0	1	2	3	4	0	1

- 9 swap-in operations

First-In, First-Out (FIFO)

- larger main memory with 4 page frames
  - → 10 swap-in operations
- FIFO anomaly (Bélády's anomaly, 1969)

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	1	1	1	**5**	5	5	5	**4**	4
	page frame 2		**2**	2	2	2	2	2	**1**	1	1	1	**5**
	page frame 3			**3**	3	3	3	3	3	**2**	2	2	2
	page frame 4				**4**	4	4	4	4	4	**3**	3	3
control states (age per page frame)	page frame 1	0	1	2	3	4	5	0	1	2	3	0	1
	page frame 2	>	0	1	2	3	4	5	0	1	2	3	0
	page frame 3	>	>	0	1	2	3	4	5	0	1	2	3
	page frame 4	>	>	>	0	1	2	3	4	5	0	1	2

Optimal Replacement Strategy (OPT)

- longest forward distance (LFD, dt. Vorwärtsabstand)
  - time interval until next access to the corresponding page
- strategy OPT (or MIN) is optimal (with fixed number of page frames): minimum number of swap-in/replacements (here: 7)
  - always replace the page with the longest forward distance

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	1	1	1	1	1	1	**3**	**4**	4
	page frame 2		**2**	2	2	2	2	2	2	2	2	2	2
	page frame 3			**3**	**4**	4	4	**5**	5	5	5	5	5
control states (LFD)	page frame 1	4	3	2	1	3	2	1	>	>	>	>	>
	page frame 2	>	4	3	2	1	3	2	1	>	>	>	>
	page frame 3	>	>	7	7	6	5	5	4	3	2	1	>

Optimal Replacement Strategy (OPT)

- increase the size of the main memory (4 page frames): 6 swap-in operations
  - no anomaly

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	1	1	1	1	1	1	1	**4**	4
	page frame 2		**2**	2	2	2	2	2	2	2	2	2	2
	page frame 3			**3**	3	3	3	3	3	3	3	3	3
	page frame 4				**4**	4	4	**5**	5	5	5	5	5
control states (LFD)	page frame 1	4	3	2	1	3	2	1	>	>	>	>	>
	page frame 2	>	4	3	2	1	3	2	1	>	>	>	>
	page frame 3	>	>	7	6	5	4	3	2	1	>	>	>
	page frame 4	>	>	>	7	6	5	5	4	3	2	1	>

Optimal Replacement Strategy – Discussion

- implementation of OPT practically impossible
  - reference sequence would have to be known in advance (oracle)
  - OPT is only useful for comparing strategies
- research for strategies that are as close to OPT as possible
  - for example: **Least Recently Used** (LRU)

Least Recently Used (LRU)

- longest backward distance
  - time interval since the last access to the corresponding page
- LRU strategy (10 swap-in operations)
  - always replace the page that has not been used for the longest time

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	**4**	4	4	**5**	5	5	**3**	3	3
	page frame 2		**2**	2	2	**1**	1	1	1	1	1	**4**	4
	page frame 3			**3**	3	3	**2**	2	2	2	2	2	**5**
control states (oldest access time)	page frame 1	0	1	2	0	1	2	0	1	2	0	1	2
	page frame 2	>	0	1	2	0	1	2	0	1	2	0	1
	page frame 3	>	>	0	1	2	0	1	2	0	1	2	0

Least Recently Used (LRU)

- increase the size of the main memory (4 page frames)
- 8 swap-in operations

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	1	1	1	1	1	1	1	1	**5**
	page frame 2		**2**	2	2	2	2	2	2	2	2	2	2
	page frame 3			**3**	3	3	3	**5**	5	5	5	**4**	4
	page frame 4				**4**	4	4	4	4	4	**3**	3	3
control states (oldest access time)	page frame 1	0	1	2	3	0	1	2	0	1	2	3	0
	page frame 2	>	0	1	2	3	0	1	2	0	1	2	3
	page frame 3	>	>	0	1	2	3	0	1	2	3	0	1
	page frame 4	>	>	>	0	1	2	3	4	5	0	1	2

Least Recently Used (LRU) – Discussion

- no anomaly
  - in general, there is a class of algorithms (stack algorithms) for which no anomaly occurs:
    - with stack algorithms, if there are *k* page frames at any time, a subset of the pages is swapped-in that would also be swapped-in if there were *k+1* page frames at the same time
    - LRU: there are always the last *k* used pages swapped-in
    - OPT: the *k* already used pages are swapped-in, which will be accessed next
- problem
  - implementation of LRU only possible with hardware support
  - every memory access must be considered

Least Recently Used (LRU) – Discussion

- naive idea: hardware support through counter
  - CPU has a counter that is incremented with each memory access
  - with each memory access: current counter value is written into the respective page descriptor
  - evict the page with the smallest counter reading (→ search!)

- complex implementation
  - many additional memory accesses
  - high memory requirements
  - minimum search in page-fault handling

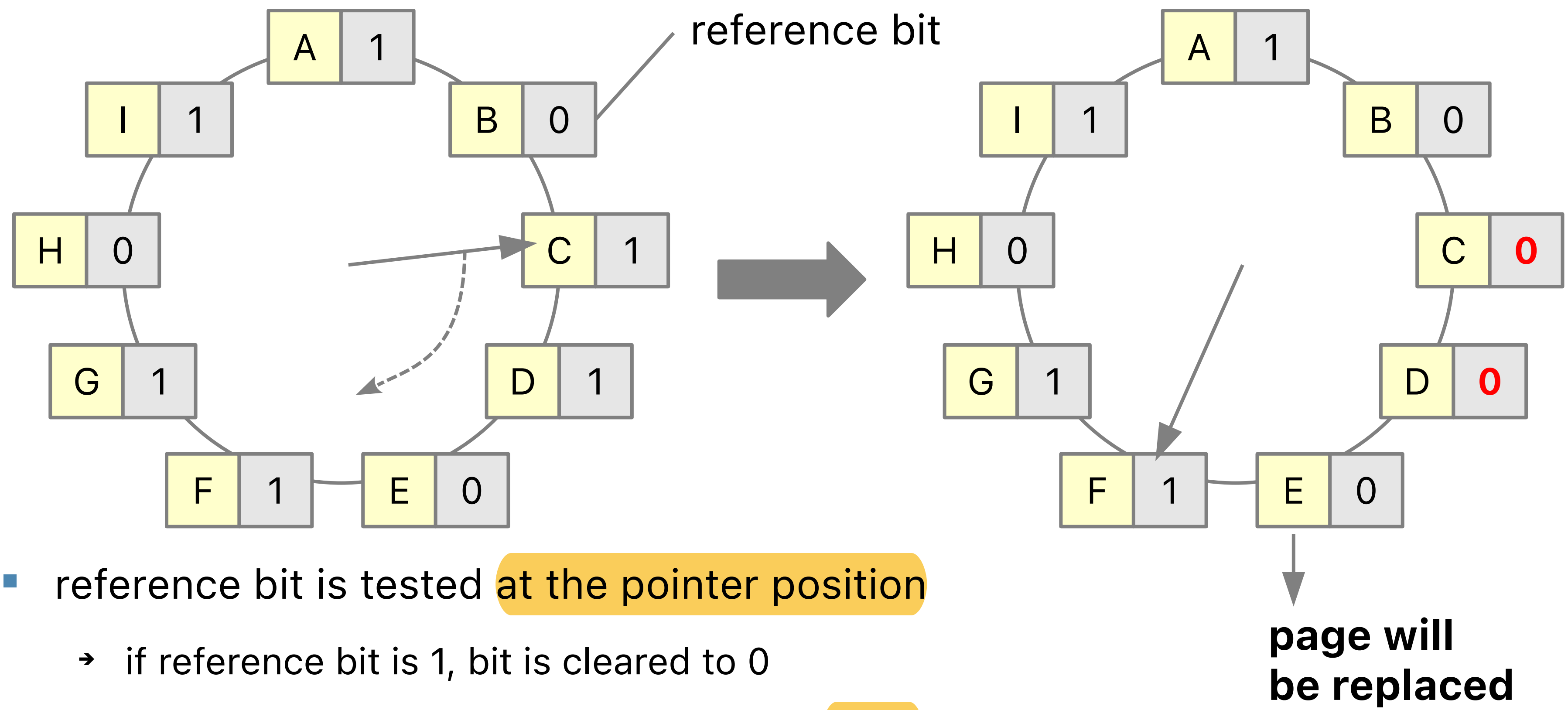
Second Chance (SC)

- core idea: use of reference bits
  - reference bit in page descriptor is automatically set by hardware when page is accessed
    - ➔ easy to implement
    - ➔ reduced number of additional memory accesses
    - ➔ supported by modern processors and MMUs (e.g., x86: access bit)

- goal: approximation of LRU
  - reference bit is is initially set to 1 for a freshly swapped-in page
  - when a victim page is searched, reference bits in the page table are inspected in turn
    - ➔ if inspected reference bit is 1, it is set to 0 (second chance)
    - ➔ else: if inspected reference bit is 0, the page is chosen as victim and swapped-out

Second Chance (SC)

- implementation with a circulating pointer (clock)



- reference bit is tested at the pointer position
  - if reference bit is 1, bit is cleared to 0
  - if reference bit is 0, replaceable page is found
  - pointer is incremented; if no victim page is found: repeat
- if all reference bits are set to 1: Second Chance degrades to FIFO

Second Chance (SC)

- modus operandi with 3 page frames
- 9 swap-in operations

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	1	1	1	4	4	4	5	5	5	5	5	5
	page frame 2		2	2	2	1	1	1	1	1	3	3	3
	page frame 3			3	3	3	2	2	2	2	2	4	4
control states (reference bits)	page frame 1	1	1	1	1	1	1	1	1	1	0	0	1
	page frame 2	0	1	1	0	1	1	0	1	1	1	1	1
	page frame 3	0	0	1	0	0	1	0	0	1	0	1	1
	circulating pointer	2	3	1	2	3	1	2	2	2	3	1	1

不用替换时，指针不变，
但是更新ref bit

Second Chance (SC)

- increase the size of the main memory (4 page frames)
- 10 swap-in operations

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	page frame 1	**1**	1	1	1	1	1	**5**	5	5	5	**4**	4
	page frame 2		**2**	2	2	2	2	2	**1**	1	1	1	**5**
	page frame 3			**3**	3	3	3	3	3	**2**	2	2	2
	page frame 4				**4**	4	4	4	4	4	**3**	3	3
control states (reference bits)	page frame 1	1	1	1	1	1	1	1	1	1	1	1	1
	page frame 2	0	1	1	1	1	1	0	1	1	1	0	1
	page frame 3	0	0	1	1	1	1	0	0	1	1	0	0
	page frame 4	0	0	0	1	1	1	0	0	0	1	0	0
	circulating pointer	**2**	**3**	**4**	**1**	**1**	**1**	**2**	**3**	**4**	**1**	**2**	**3**

Second Chance (SC)

- second chance may lead to FIFO anomaly
  - if all reference bits are set, the decision is made according to FIFO
- however, normally Second Chance comes close to LRU

- enhanced Second Chance variant
  - modification bit can be considered additionally (dirty bit)
  - four classes (reference bit, modification bit):
    - → (0,0): neither recently used nor modified
    - → (0,1): not recently used but modified
    - → (1,0): recently used and unmodified
    - → (1,1): recently used and modified
  - search for the lowest class

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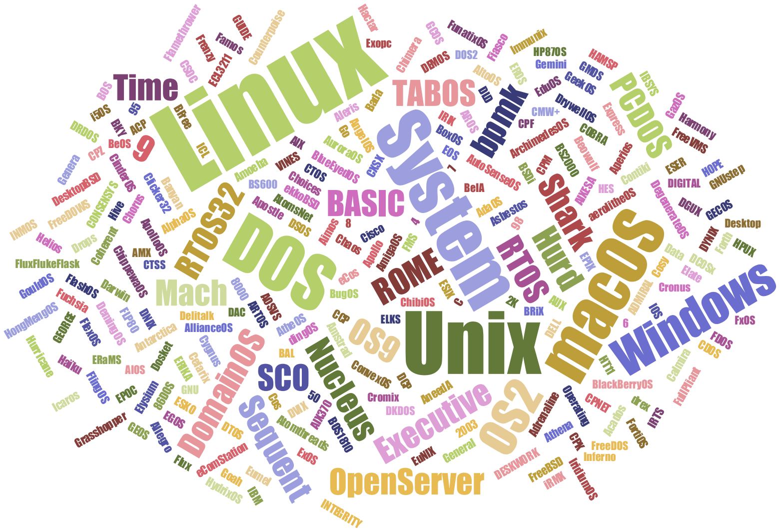

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- Demand Paging
- Page Replacement Algorithms
  - First In, First Out (FIFO)
  - Least Recently Used (LRU)
  - Second Chance (SC)
- Page Frame Allocation
  - Thrashing
  - Working Set Model
- Summary and Outlook

Page Frame Allocation

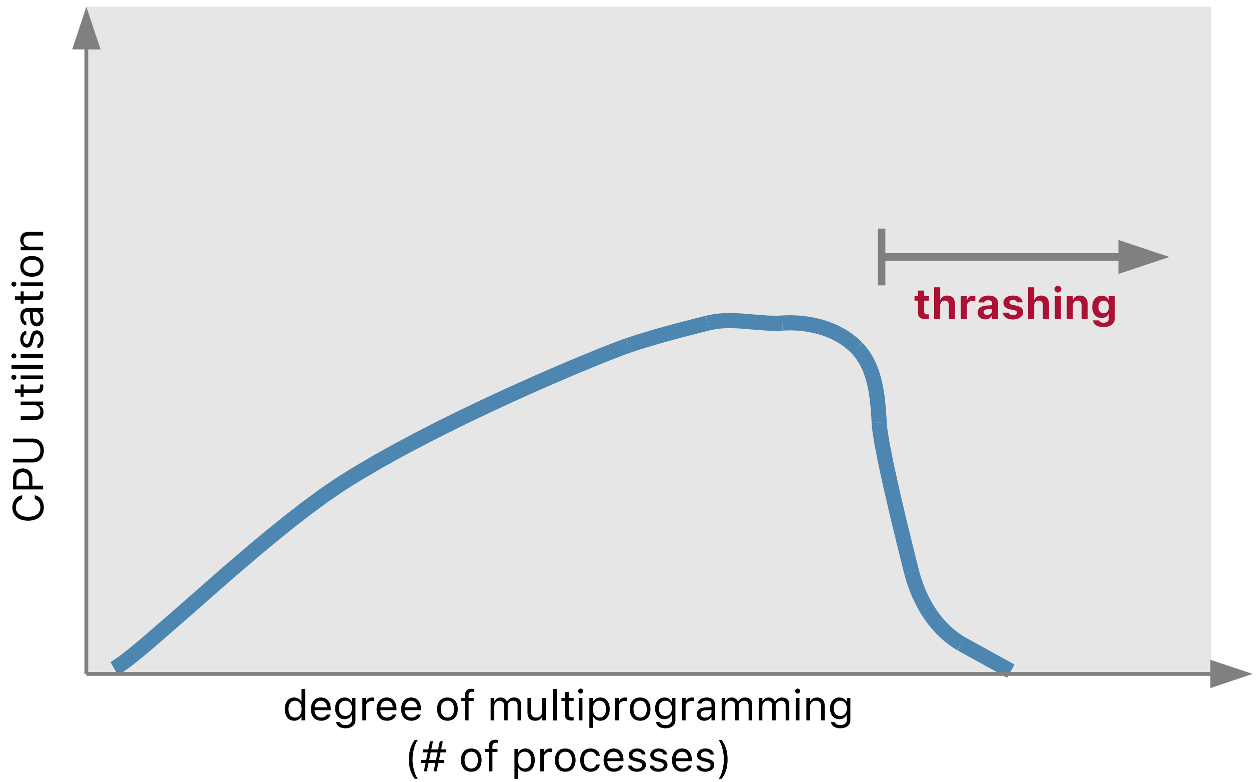
- problem: distribution of available page frames to processes
  - how many swapped-in pages should a process possess?
    - → maximum: limited by size of available memory (number of page frames)
    - → minimum: depends on the processor architecture
      - – at least the number of pages necessary which in theory are required for executing a single instruction
      - – for example: 2 pages for instructions, 4 pages for the data
- homogenous allocation
  - number of processes determines how many page frames each process can possess
- size-based allocation
  - process size influences page frame allocation

Page Frame Allocation

- global and local page frame allocation
  - **local**: processes always replace their own pages
    - ➔ page fault handling: responsibility of the individual process, only
  - **global**: processes can also displace pages of other processes
    - ➔ better efficiency, as unused pages can be used by other processes

Thrashing

- thrashing (dt. Seitenflattern) happens when swapped-out pages are immediately addressed again
  - process spends more time waiting for page faults handled than actually executing its own code



Thrashing

- causes
  - process operates with a number of page frames close to the necessary minimum
  - too many processes in the system at the same time
  - poor replacement strategy

➔ local page allocation resolves thrashing between processes

➔ allocation of a sufficiently large number of page frames resolves thrashing within the pages of a process

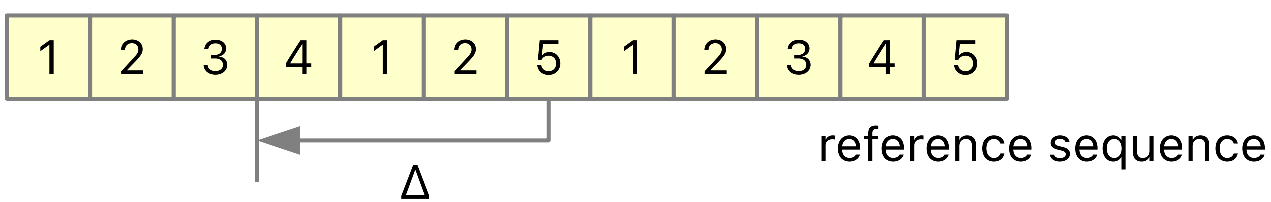
- limitation of the number of processes

Thrashing – Solution 1

- solution 1: swap-out processes
- inactive processes do not need page frames
  - page frames are distributed to a smaller number of processes
  - needs to be interlinked with scheduling
    - ➔ prevent starvation of processes
    - ➔ achieve good response times (low latency)

Thrashing – Solution 2

- solution 2: working set model
- working set: amount of pages that a process really needs
  - can only be approximated, as usually not predictable
- approach by looking at the last Δ pages that were referenced
  - appropriate choice of Δ
    - → too large: overlapping of local access patterns
    - → too small: work set does not contain all necessary pages



Working Set Model

- example: working set model for different Δ

reference sequence		1	2	3	4	1	2	5	1	2	3	4	5
Δ = 3	page 1	X	X	X		X	X	X	X	X	X		
	page 2		X	X	X		X	X	X	X	X	X	
	page 3			X	X	X					X	X	X
	page 4				X	X	X					X	X
	page 5							X	X	X			X
Δ = 4	page 1	X	X	X	X	X	X	X	X	X	X	X	
	page 2		X	X	X	X	X	X	X	X	X	X	X
	page 3			X	X	X	X				X	X	X
	page 4				X	X	X	X				X	X
	page 5							X	X	X	X		X

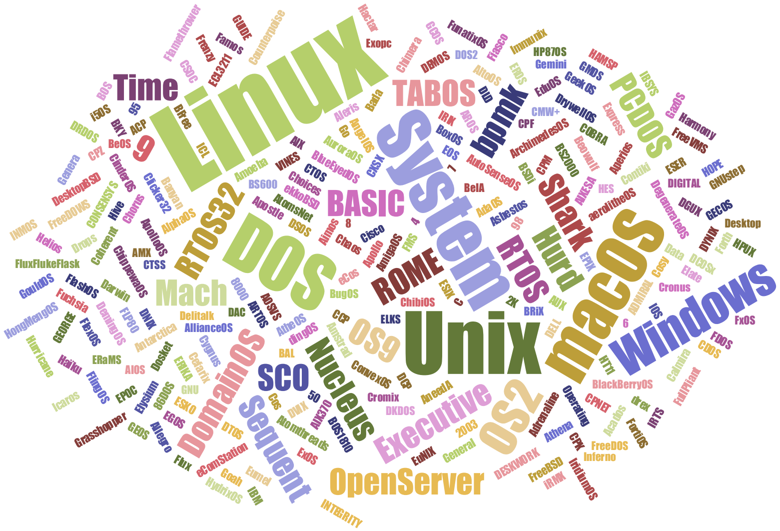
Working Set Model with Timer

- implementation challenges similar to LRU: track how long pages have not been referenced
- algorithm with timer interrupt
  - regular interrupts update the page age information by means of the reference bit:
    - ➔ if reference bit is set (page was used), age is set to zero;
    - ➔ otherwise: age is increased
    - ➔ only the pages of the currently running process are "aged"
  - pages with age > Δ are no longer part of the working set of the respective process
- <u>impractical</u> as to run-time overhead

Thrashing – Solution 3

- solution 3: react on rate of page faults
- thrashing can be more easily avoided by directly controlling the page fault rate
  - page-fault logging per process
  - page-fault rate < threshold: decrease number of page frames
  - page-fault rate > threshold: increase number of page frames

Agenda



- Recap
- Organizational Matters
- Motivation
  - Locality of Reference
  - Virtual Memory
- Demand Paging
- Page Replacement Algorithms
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- **Summary and Outlook**

⏭ Summary and Outlook

- **summary**
  - virtual memory enables the use of large logical address spaces despite limitations of the main memory
  - but: comfort comes at a price
    - ➔ increased complexity and effort at the hardware level
    - ➔ complex algorithms in the operating system → runtime overhead
    - ➔ strategy selection depends on the usage pattern
  - more simple (special-purpose) operating systems that do not necessarily need this "luxury" are better off without it
- **outlook: filesystems**
  - abstraction methods to represent data blocks as files and directories
  - data management and storage, error handling and recovery

References and Acknowledgments

Lecture

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