

Operating Systems

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Bochum Operating Systems and System Software (BOSS)

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VII. Virtual Memory

May 24, 2023 (Summer Term 2023)



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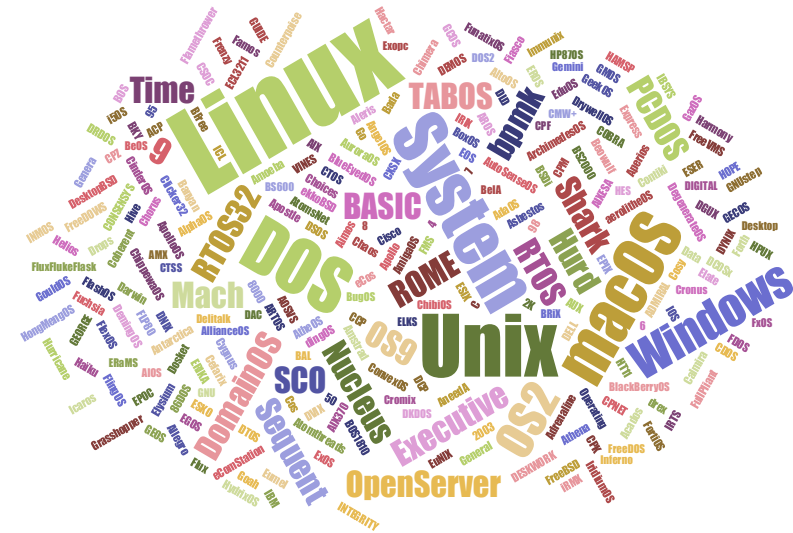
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Chair of Operating Systems and System Software

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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- ▶ **Summary and Outlook**



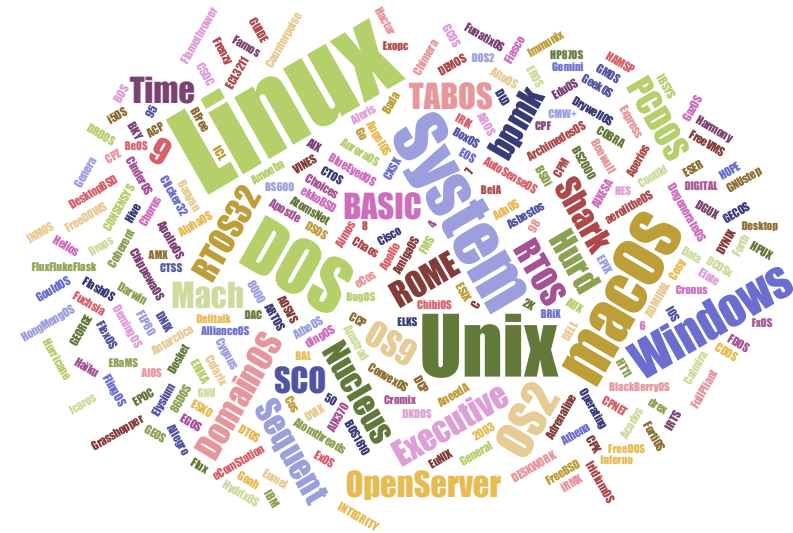
Organizational Matters

- lecture
 - Wednesday, 10:15 – 11:45
 - format: synchronous, **hybrid**
 - in presence (Room H1D, 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>



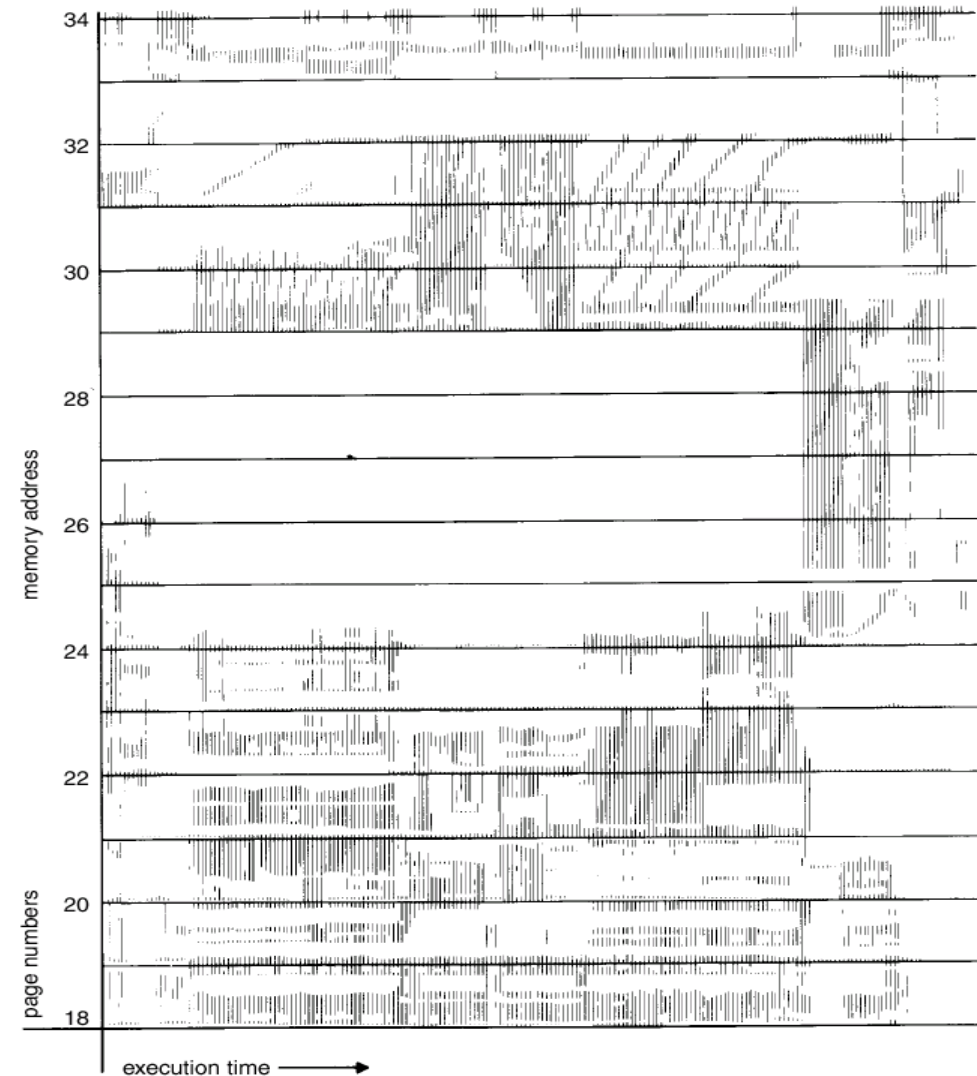
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Locality of Reference – Memory Access

- 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

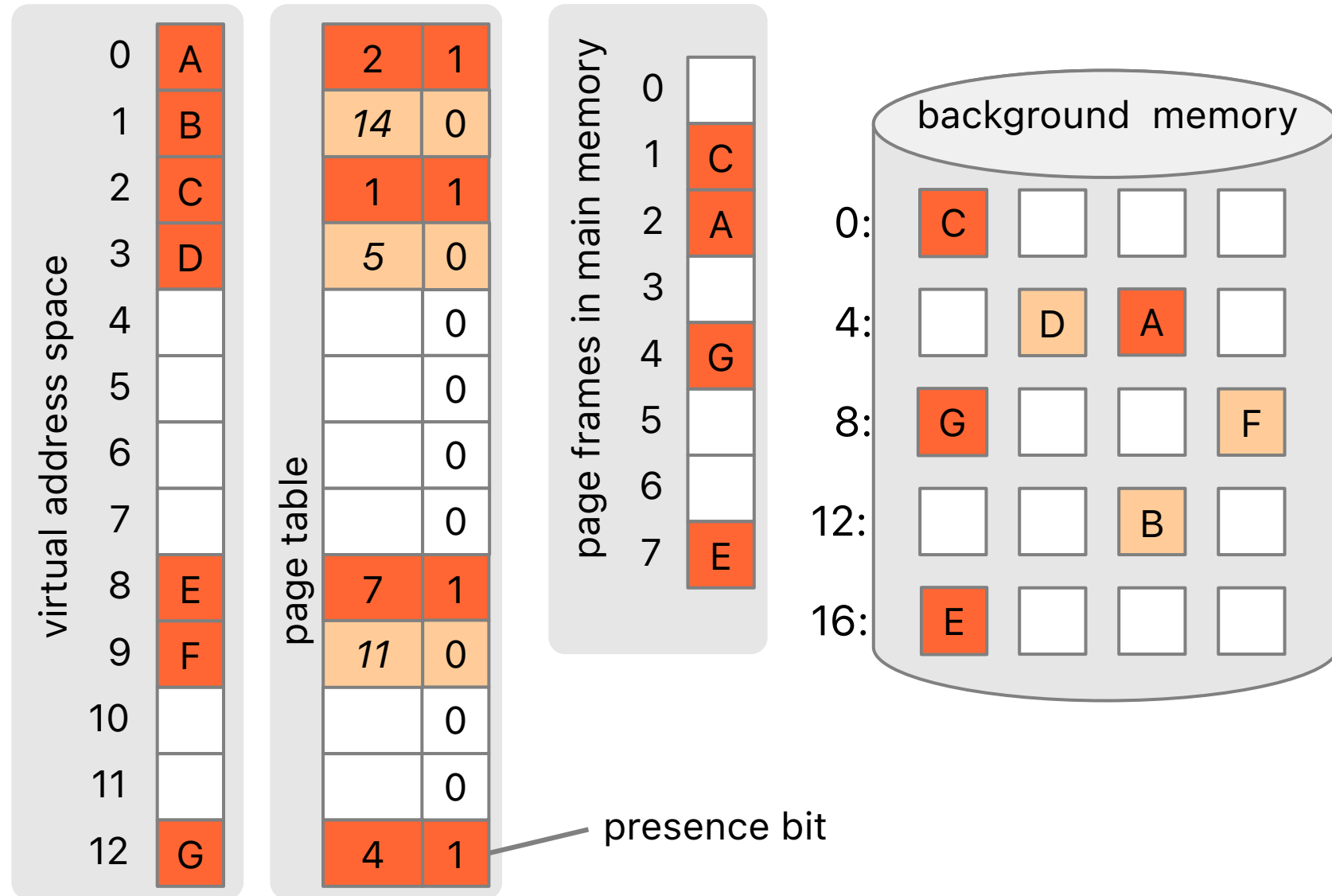
- add a system layer of indirection: decouple the memory requirement of processes from the system's main memory
 - processes do not need all memory locations equally often
 - certain functions are rarely or not at all used (e.g., error handling)
 - certain data structures are not fully populated
 - processes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

Agenda

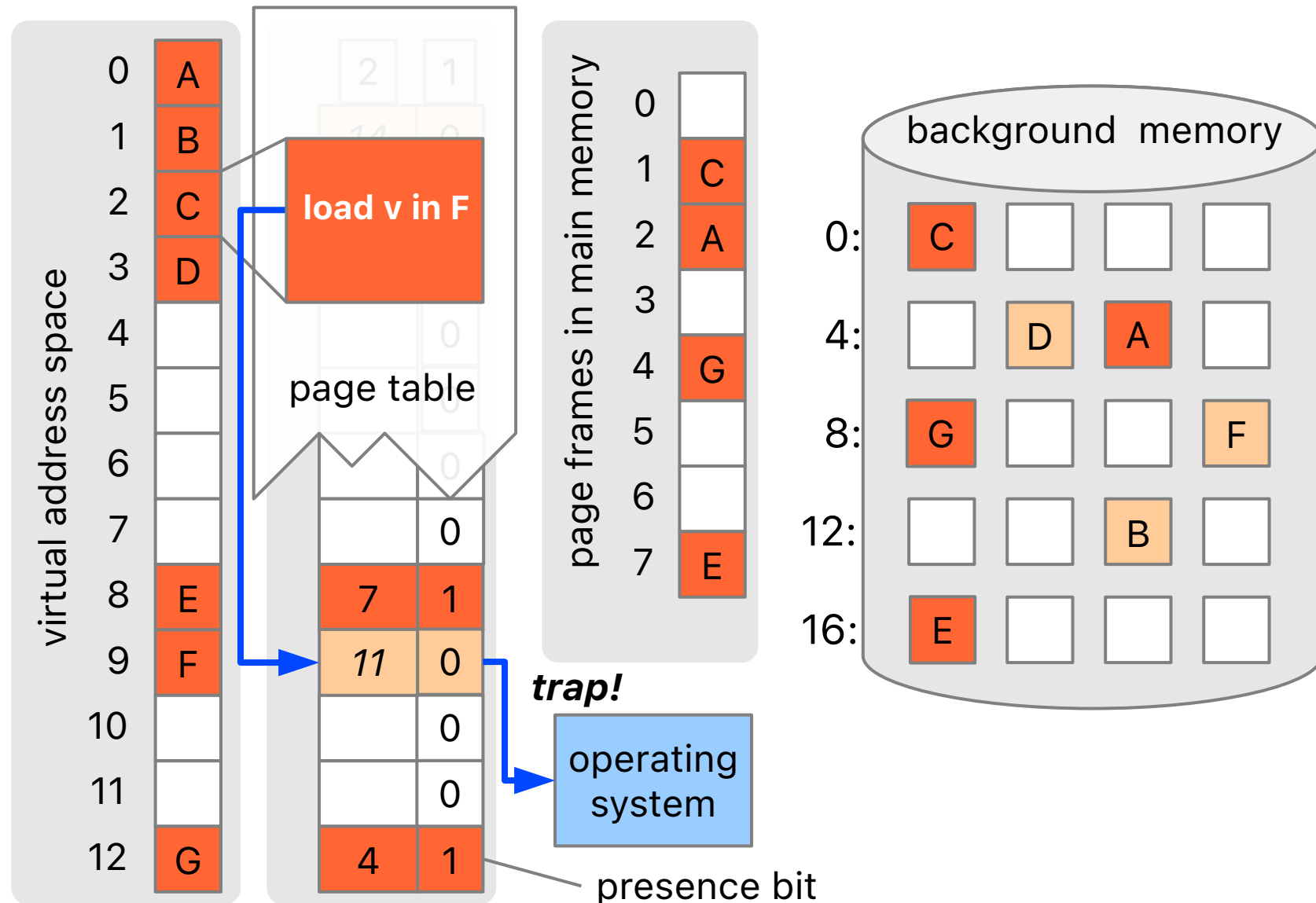
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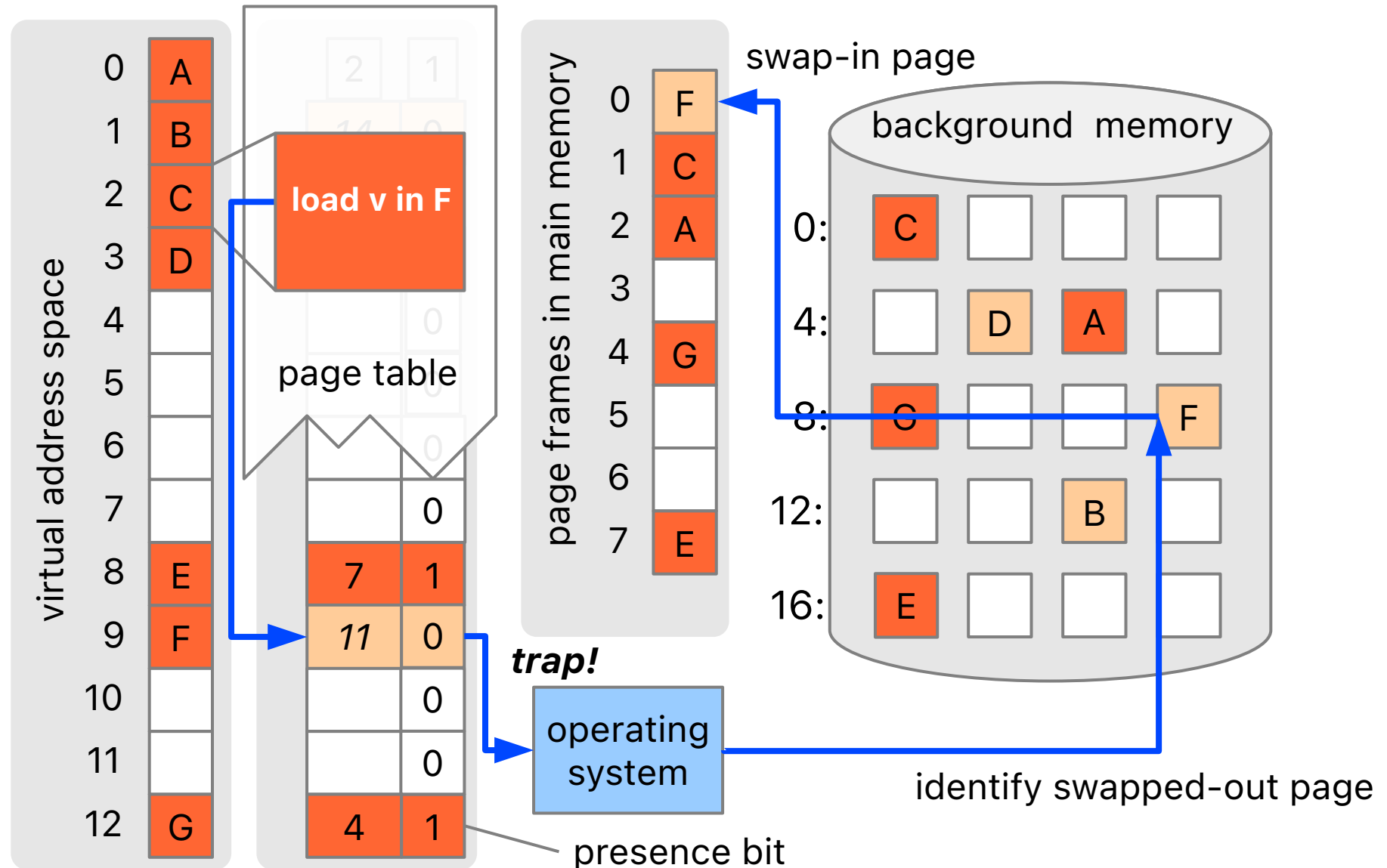
Demand Paging – Provide Pages on Demand



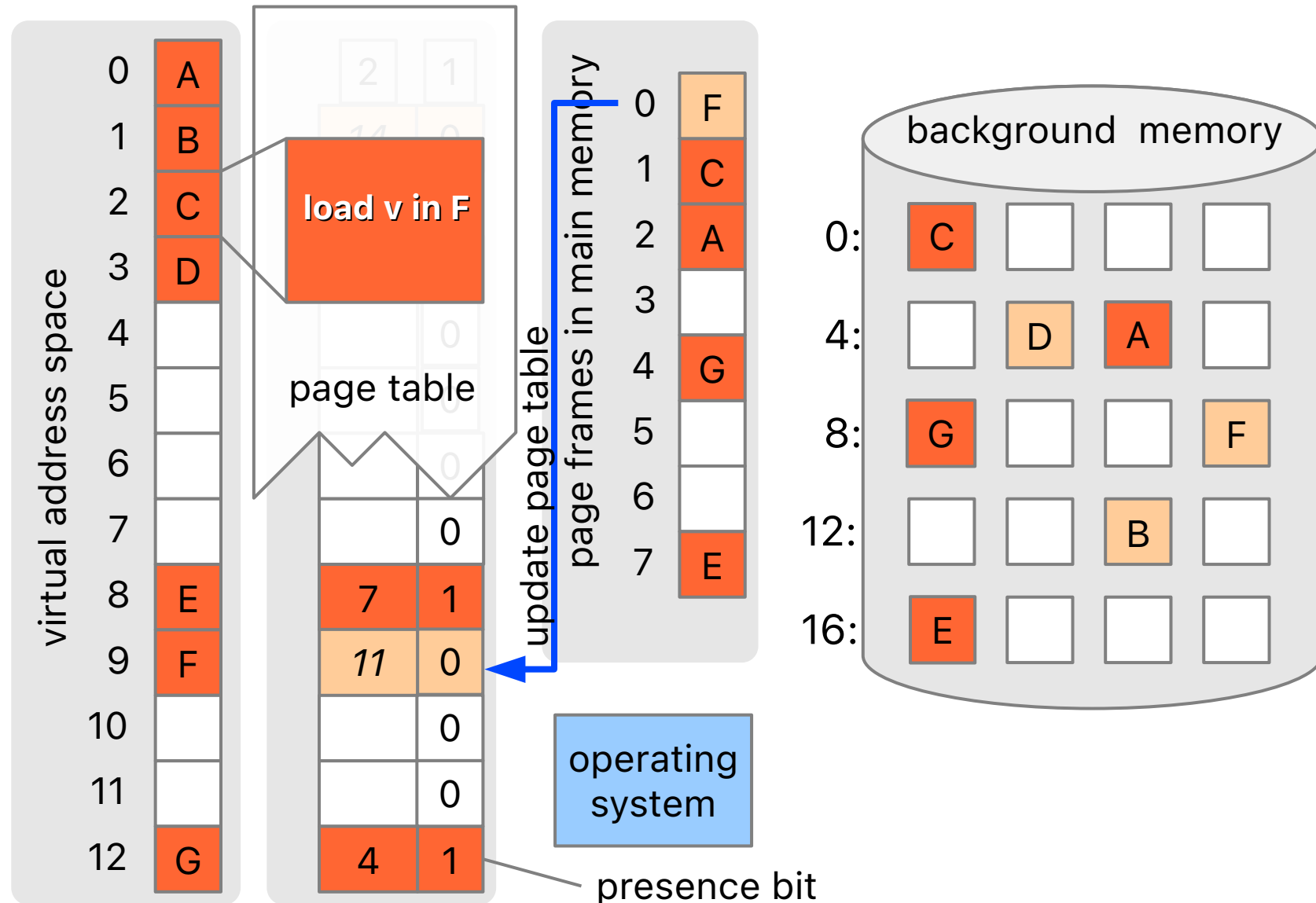
Demand Paging – Page Fault Handling



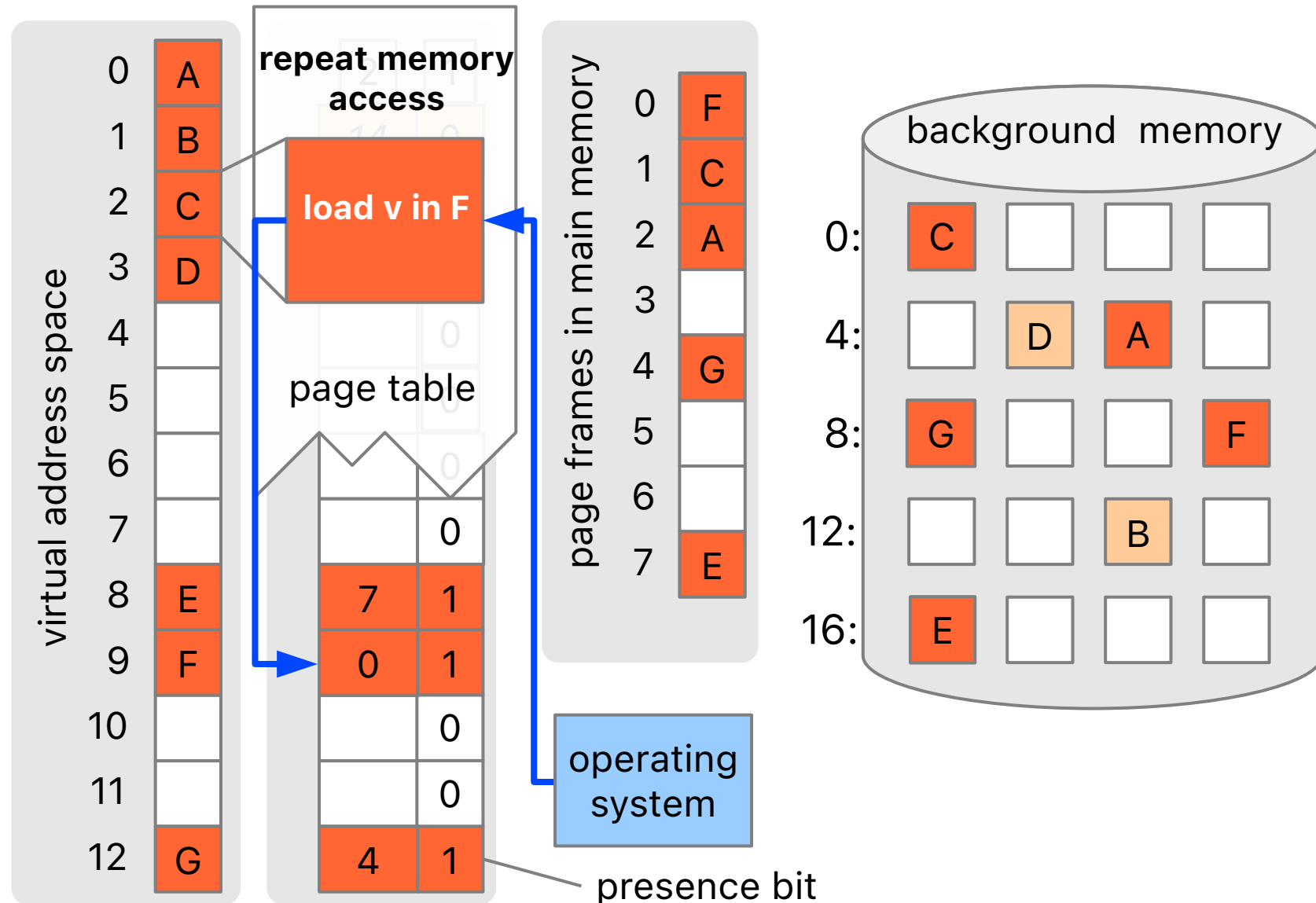
Demand Paging – Page Fault Handling



Demand Paging – Page Fault Handling



Demand Paging – Page Fault Handling



Demand Paging – Discussion

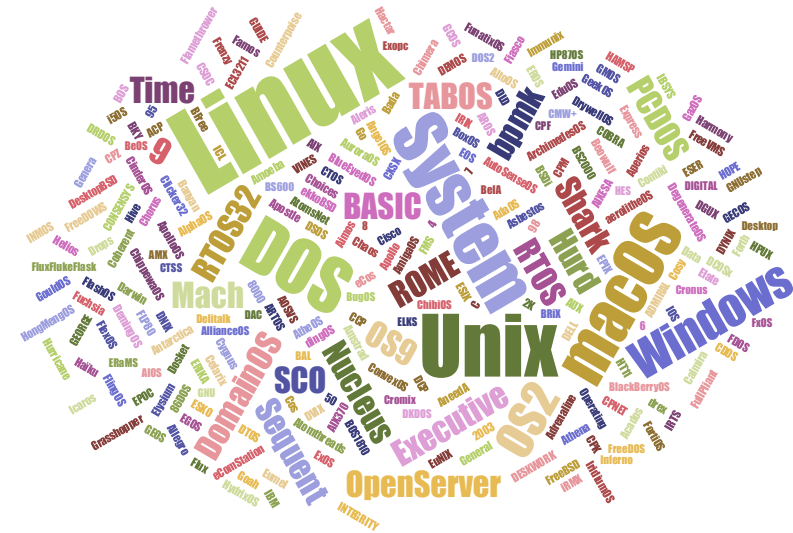
- operational costs of demand paging (i.e., performance impact)
 - without page fault
 - effective access time between 10 and 200 nanoseconds
 - with page fault
 - p : probability of a page fault
 - first assumption: time to swap-in a page from background memory is 25 milliseconds (8 ms latency, 15 ms 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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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									

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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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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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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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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
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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	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

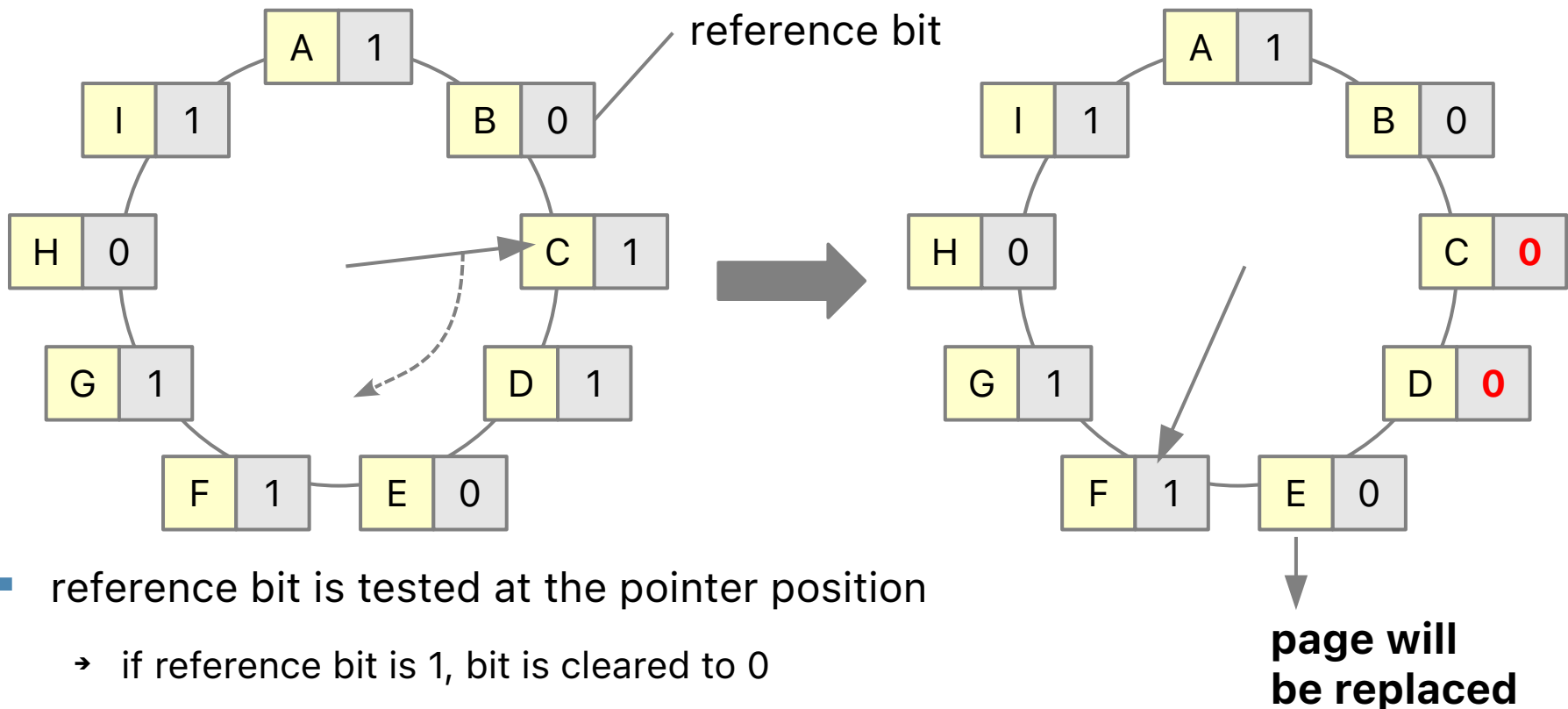
- naive idea: hardware support through counter
 - CPU has a counter that is incremented with each memory access
 - with each memory access: current counter value is written into the respective page descriptor
 - evict the page with the smallest counter reading (→ search!)
- complex implementation
 -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

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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Page Frame Allocation

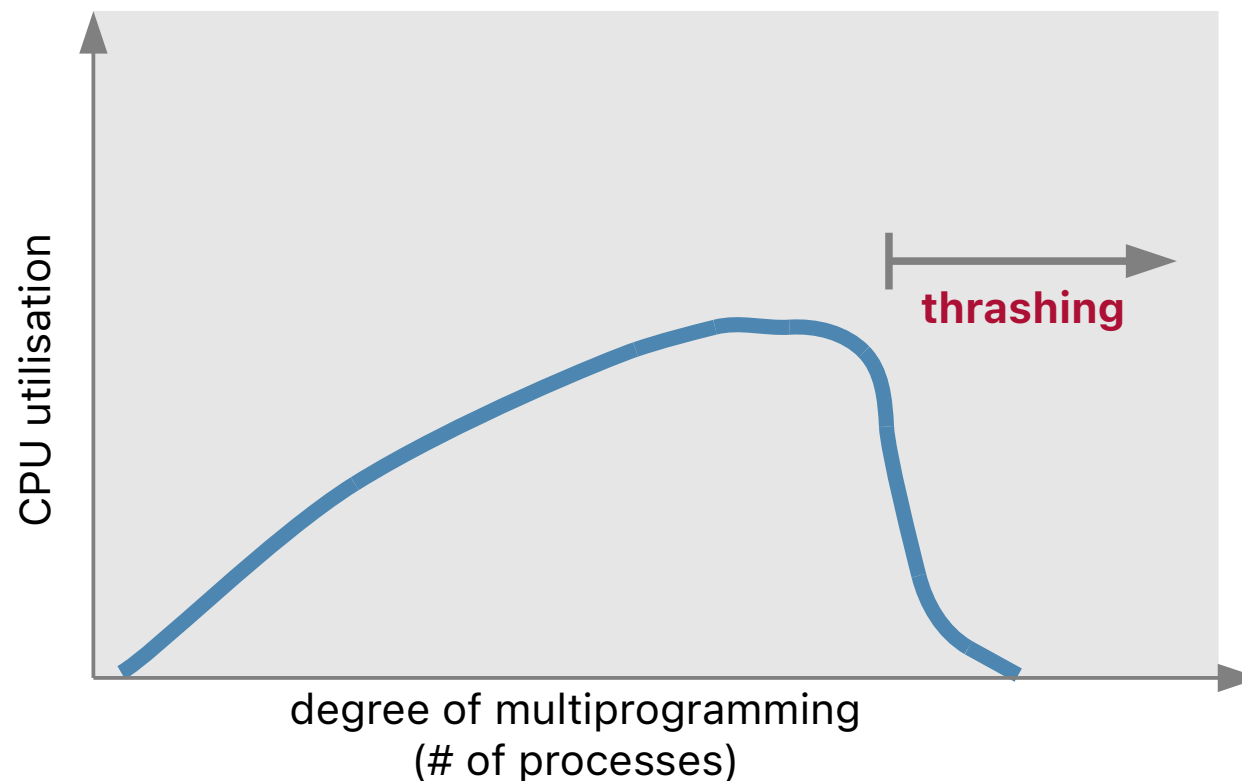
- problem: distribution of available page frames to processes
 - how many swapped-in pages should a process possess?
 - ➔ maximum: limited by size of available memory (number of page frames)
 - ➔ minimum: depends on the processor architecture
 - at least the number of pages necessary which in theory 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

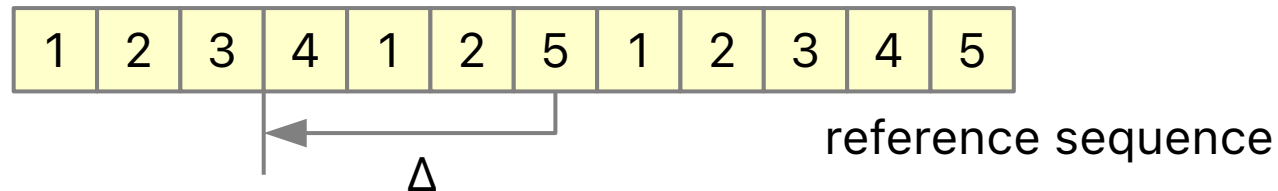
- limitation of the number of processes

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
$\Delta = 3$	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
$\Delta = 4$	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

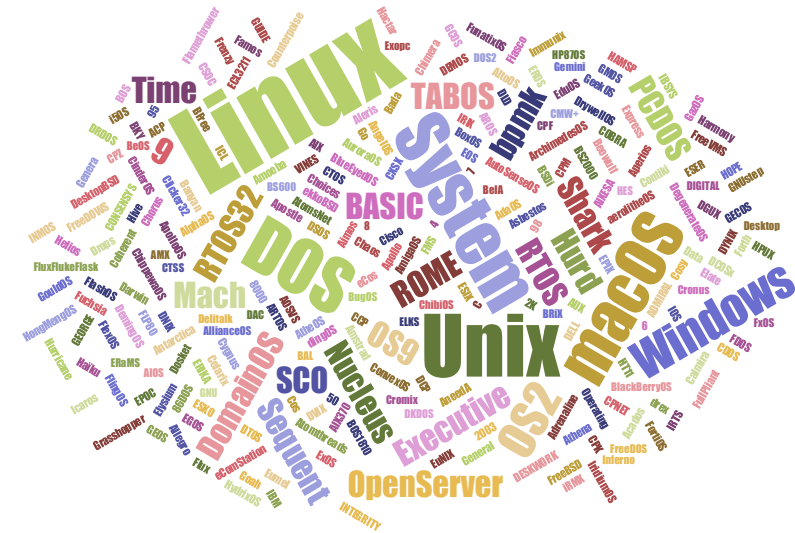
- implementation challenges similar to LRU: track how long pages have not been referenced
- algorithm with timer interrupt
 - regular interrupts update the page age information by means of the reference bit:
 - if reference bit is set (page was used), age is set to zero;
 - otherwise: age is increased
 - only the pages of the currently running process are "aged"
 - pages with age $> \Delta$ are no longer part of the working set of the respective process
- impractical 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
 - ▶ First In, First Out (FIFO)
 - ▶ Least Recently Used (LRU)
 - ▶ Second Chance (SC)
- ▶ Page Frame Allocation
 - ▶ Thrashing
 - ▶ Working Set Model
- ▶ **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

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

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