NTNU | Norwegian University of Science and Technology

Operating Systems

Lecture 10: Virtual memory

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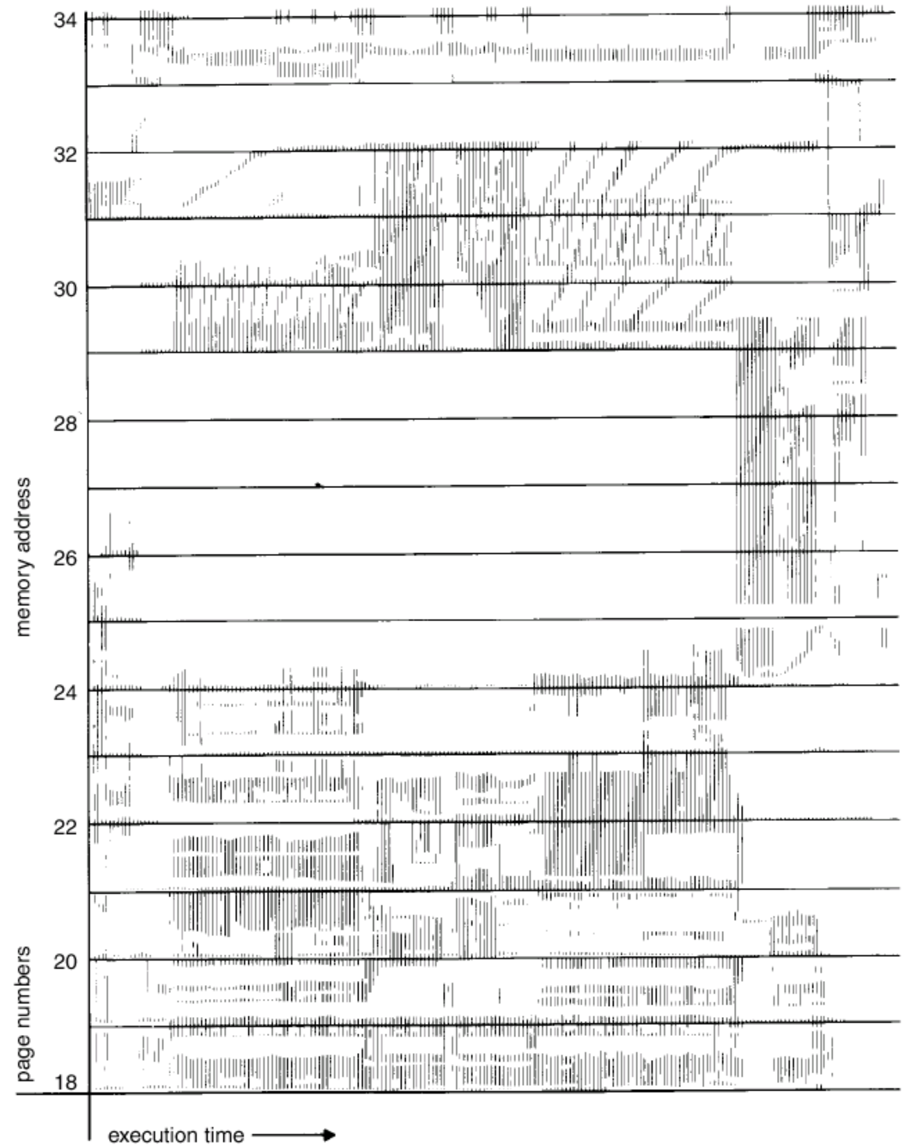
Memory management revisited

- The operating system has to collaborate closely with the hardware to enable efficient memory management
  - **Segmentation** and/or **page-based addressing**
  - The implicit indirection implemented when accessing memory enables the OS to move programs and data in memory while a program is running
- The OS additionally has to make strategic decisions
  - **Placement strategy** (first fit, best fit, Buddy, ...)
    - These differ in the resulting *fragmentation* as well as the *overhead* for memory allocation and release
    - Selection of a strategy depends on the expected *application profile*
  - When swapping segments or paging:
    - Loading strategy
    - Replacement strategy ⇒ *more on this in this lecture!*

Locality of memory accesses

- The execution of single instructions only requires the presence of very few memory pages
- This ***strong locality*** also manifests itself over longer periods of time
  - e.g., instructions are usually executed one after the other (without jumps or exceptions)
- This locality can be exploited when the system is running out of available main memory
  - e.g. using ***overlays***



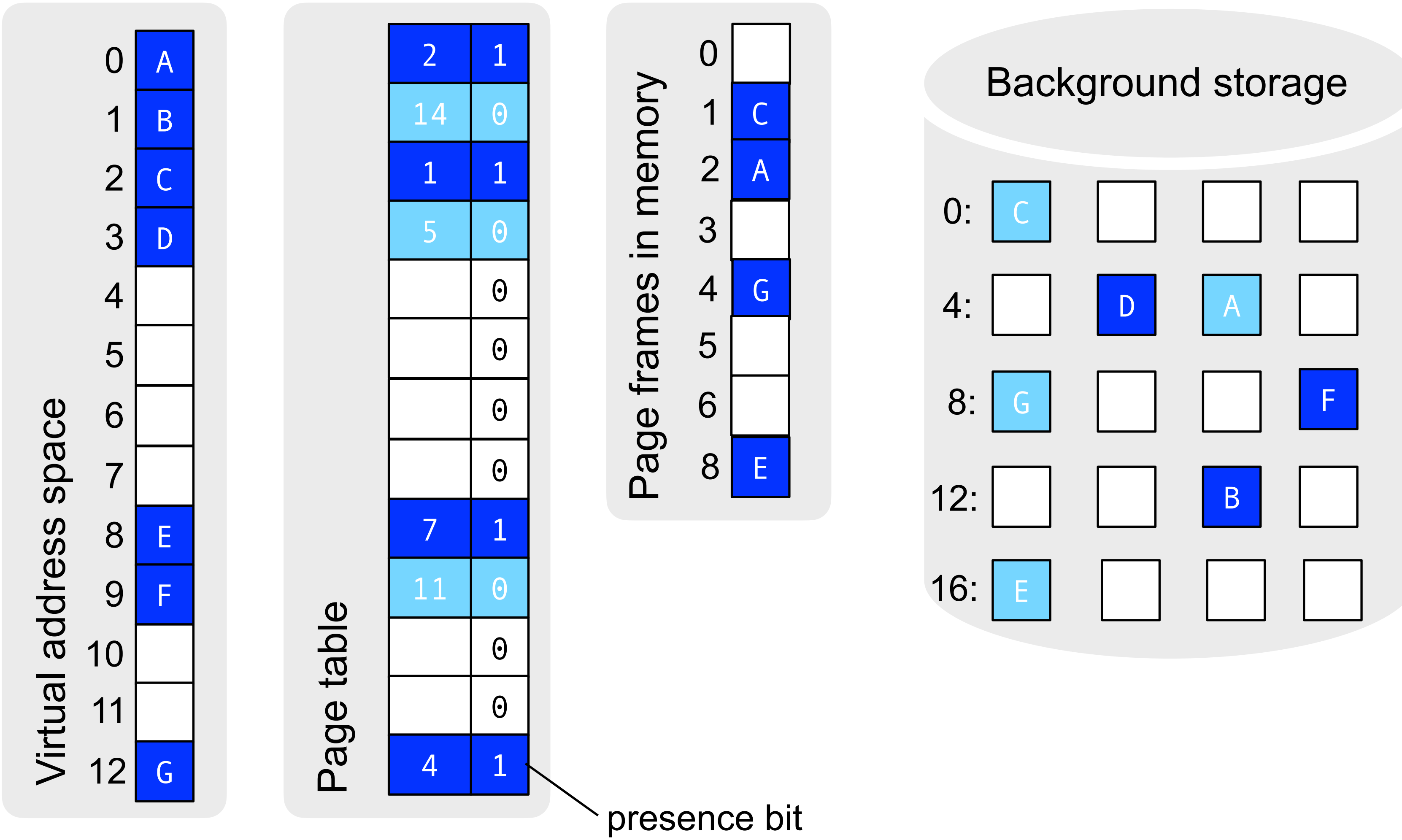
The idea of “virtual memory”

- Decouple the memory requirements from the available amount of main memory
    - Processes do not access all memory locations with the same frequency
        - certain instructions are used (executed) only very infrequently or not at all (e.g. error handling code)
        - certain data structures are not used to their full extent
    - Processes can use more memory than available as main memory

- **Idea:**
    - Create the ***illusion of a large main memory***
    - Make currently used memory areas available in main memory
    - Intercept accesses to areas currently not present in main memory
    - Provide required areas ***on demand***
    - Swap or page out areas which are (currently) not used

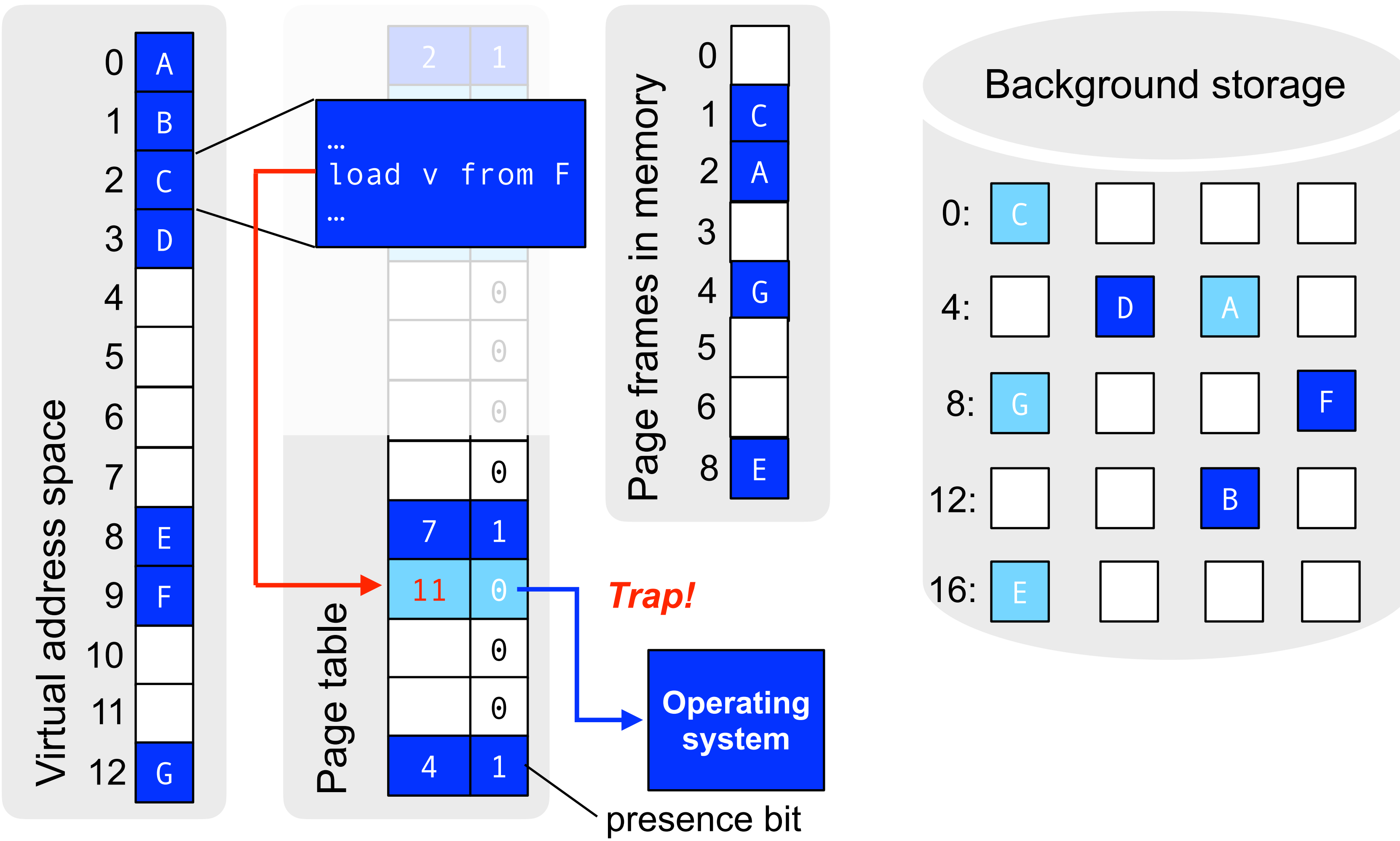
Demand paging

- Providing pages on demand



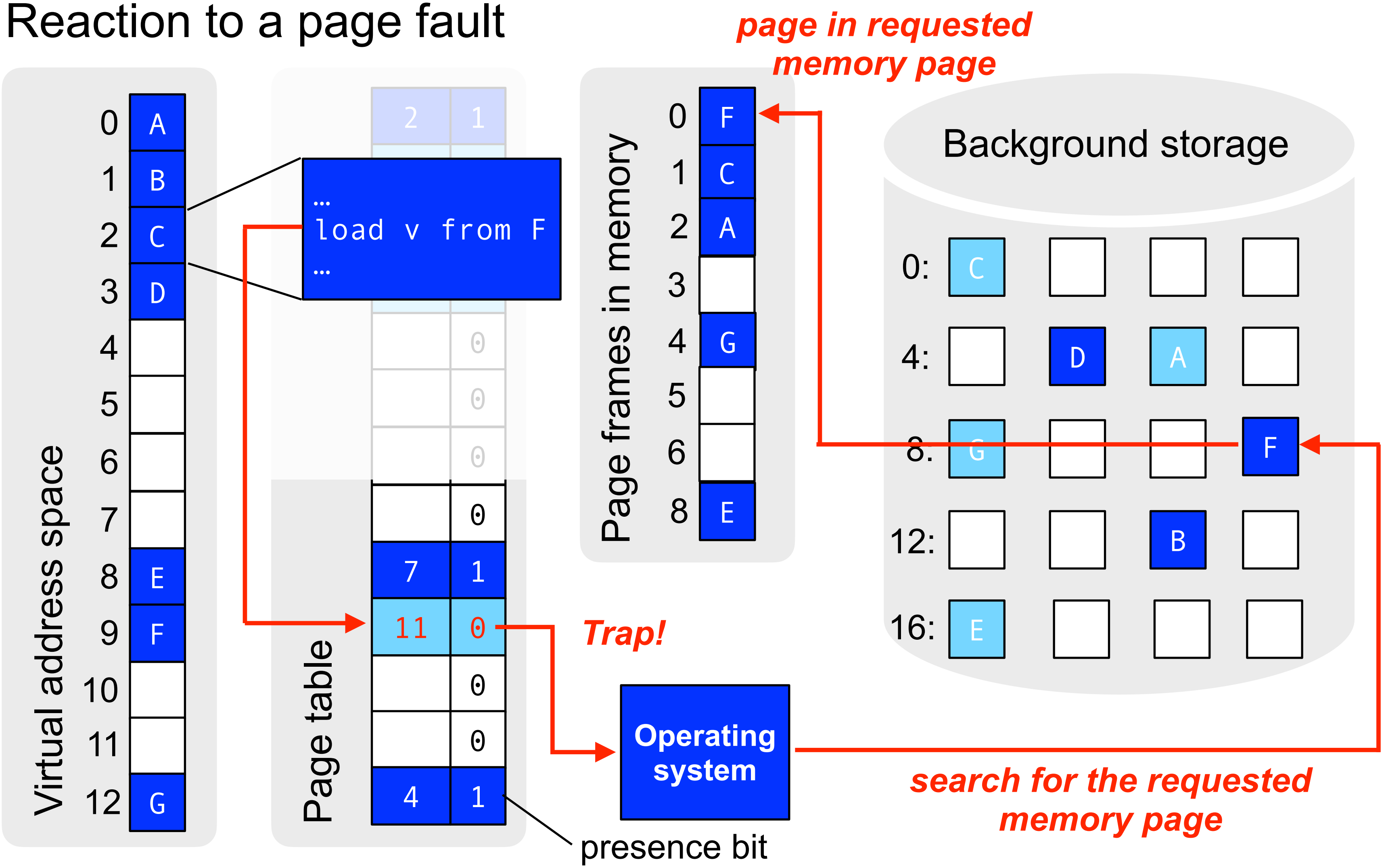
Demand paging

- Reaction to a page fault



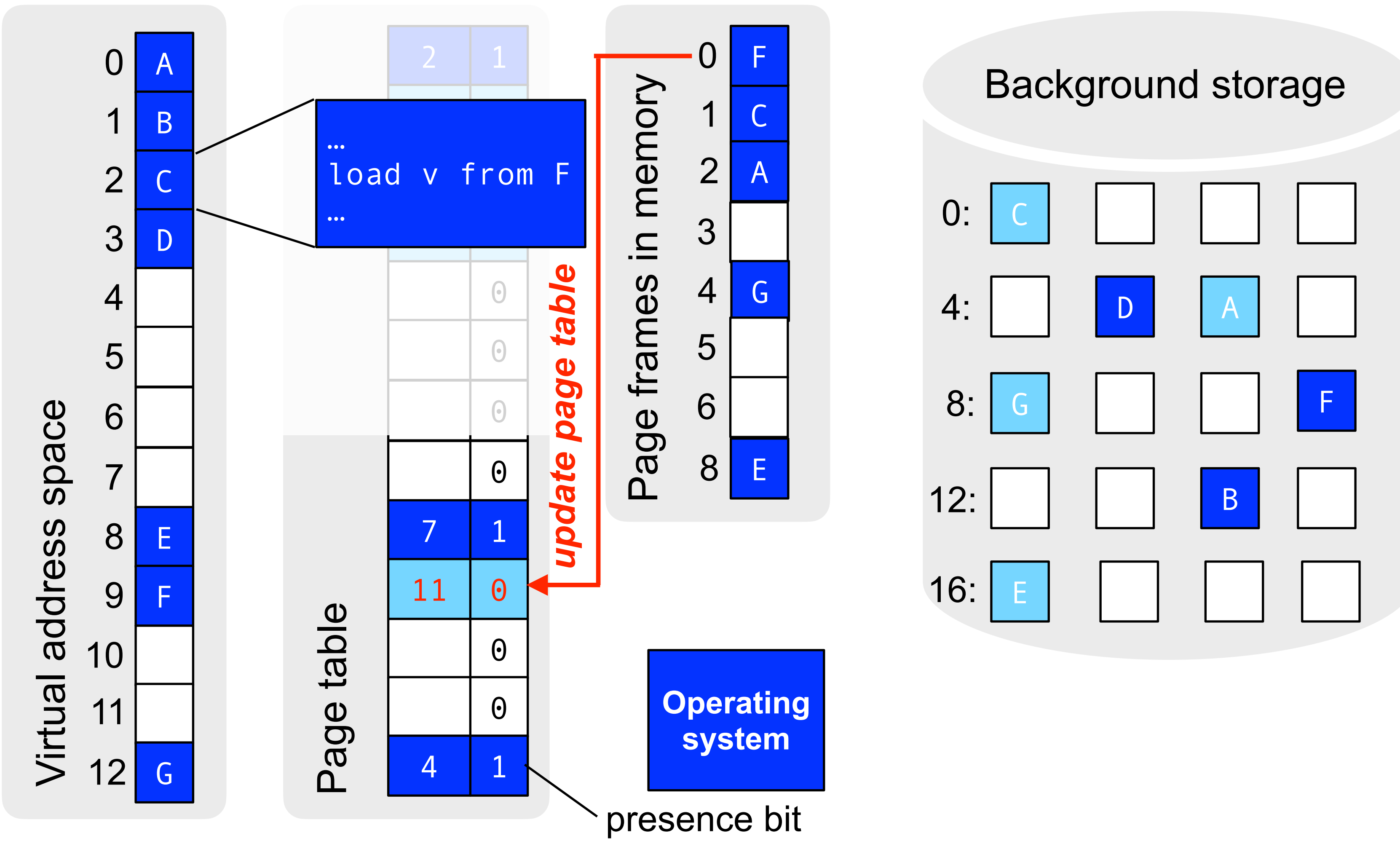
Demand paging

- Reaction to a page fault



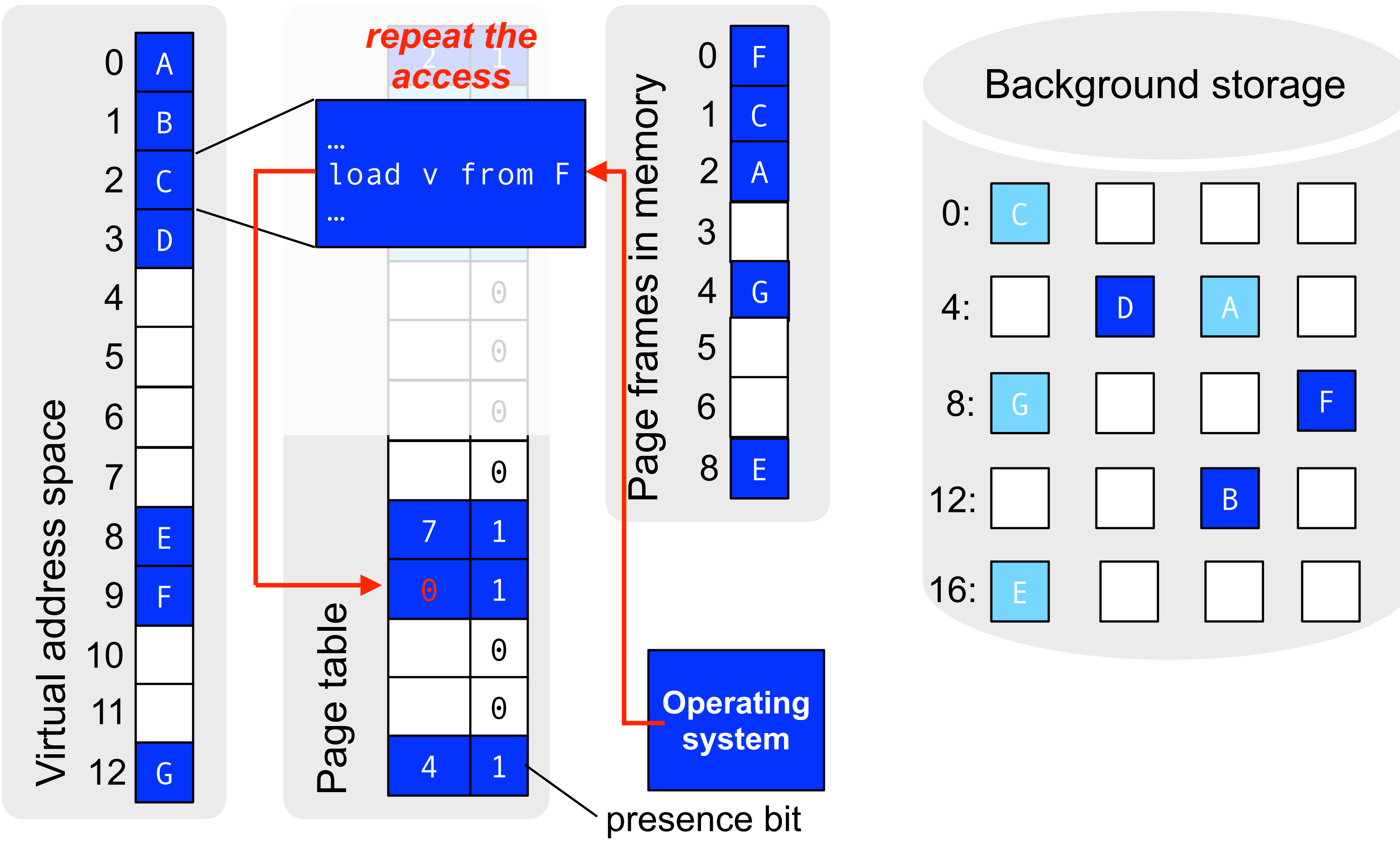
Demand paging

- Reaction to a page fault



Demand paging

- Reaction to a page fault



Discussion: *paging performance*

- Performance of *demand paging*
  - No page faults:
    - Effective access time ~10–200 ns
  - When a page fault occurs:
    - Let p be the *probability* of a page fault
    - Assume that the time required to page in a page from background memory = 25 ms
      (8 ms latency, 15 ms positioning time, 1 ms transfer time)
    - Assume a normal access time of 100 ns
    - Effective access time:
      $(1 - p) \cdot 100 + p \cdot 25000000 = 100 + 24999900 \cdot p$

➢ Page fault rate has to be extremely low

- p is close to 0

Discussion: additional properties

- Process creation
  - **Copy on write**
    - Easy to implement also using a paging MMU
    - More fine grained compared to segmentation

  - Program execution and loading can be interleaved
    - Requested pages are loaded on demand

- Locking the access to pages
  - Required for I/O operations

Discussion: *demand segmentation*

- In principle possible, but this comes with disadvantages…
  - Coarse granularity
    - e.g. code, data, stack segment
  - Difficult main memory allocation
    - With paging, all free page frames are equally useful
    - When swapping segments, the search for appropriate memory areas is more difficult
  - Background memory allocation is more difficult
    - The background memory is divided into blocks, similar to page frames (sizes = 2^n)

- Demand paging has won in practice!

Page replacement

- What is no free page frame is available when a request comes in?
  - One page has to be preempted to create space for the new page!
  - Select pages with unchanged content (refer to the *dirty bit* in the page table entries)
  - Preemption of a page implies paging it to disk if its contents were changed
- **Sequence of events:**
  - ***page fault***: trap into the OS
  - *page out* a page frame, if no free page frame is available
  - *page in* the requested page
  - Repeat the memory access
- **Problem:**
  - Which page to choose to be paged out (the “victim”)?

Replacement strategies

- We will discuss *replacement strategies* and their effect on ***access sequences*** (also: *access or reference orders)*
- *Access sequence:*
  - Sequence of page numbers which represents the ***memory access behavior*** of a process
  - Determine *access sequences*, e.g. by recording the addresses accessed by a process
    - Reduce the recorded sequence to only page numbers
    - Conflate consecutive accesses to the same page to one
  - Example access sequence:
    1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

First in, first out

- Replace the *oldest page*
- Necessary state information:
  - Age resp. page in time for each page frame

- Order of replacement (9 page ins):

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

Optimal replacement strategy

- Forward distance
  - Time until the next access to the respective page
- Strategy OPT (or MIN) is optimal (for a fixed number of frames): minimal number of page ins/replacements (here: 7)
  - “Always replace the page with the largest forward distance”

Access sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	frame 1	**1**	1	1	1	1	1	1	1	1	**3**	**4**	4
	frame 2		**2**	2	2	2	2	2	2	2	2	2	2
	frame 3			**3**	**4**	4	4	**5**	5	5	5	5	5
control states (forward dist.)	frame 1	4	3	2	1	3	2	1	>	>	>	>	>
	frame 2	>	4	3	2	1	3	2	1	>	>	>	>
	frame 3	>	>	7	7	6	5	5	4	3	2	1	>

First in, first out

- Larger main memory: 4 frames now (10 page ins)
- FIFO-anomaly (Bélády's anomaly, 1969)

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

Optimal replacement strategy

- Larger main memory: 4 frames now (6 page ins)
  - ***no anomaly***

Access sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	frame 1	**1**	1	1	1	1	1	1	1	1	1	**4**	4
	frame 2		**2**	2	2	2	2	2	2	2	2	2	2
	frame 3			**3**	3	3	3	3	3	3	3	3	3
	frame 4				**4**	4	4	**5**	5	5	5	5	5
control states (forward dist.)	frame 1	4	3	2	1	3	2	1	>	>	>	>	>
	frame 2	>	4	3	2	1	3	2	1	>	>	>	>
	frame 3	>	>	7	6	5	4	3	2	1	>	>	>
	frame 4	>	>	>	7	6	5	5	4	3	2	1	>

Optimal replacement strategy

- Implementation of OPT is practically impossible
  - …because we would have to know the access sequence *in advance!*
  - OPT is only useful to *compare strategies*

- **Wanted:** strategies which are as close to OPT as possible
  - e.g. ***Least Recently Used*** (LRU)

Least recently used (LRU)

- *Backward distance*
  - Time since the last access to the page
- LRU strategy (10 page ins)
  - “Replace the page with the largest backward distance!”

Access sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	frame 1	**1**	1	1	**4**	4	4	**5**	5	5	**3**	3	3
	frame 2		**2**	2	2	**1**	1	1	1	1	1	**4**	4
	frame 3			**3**	3	3	**2**	2	2	2	2	2	**5**
control states (backward dist.)	frame 1	0	1	2	0	1	2	0	1	2	0	1	2
	frame 2	>	0	1	2	0	1	2	0	1	2	0	1
	frame 3	>	>	0	1	2	0	1	2	0	1	2	0

Least recently used (LRU)

- Larger main memory: 4 frames now (8 page ins)

Access sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	frame 1	**1**	1	1	1	1	1	1	1	1	1	1	**5**
	frame 2		**2**	2	2	2	2	2	2	2	2	2	2
	frame 3			**3**	3	3	3	**5**	5	5	5	**4**	4
	frame 4				**4**	4	4	4	4	4	**3**	3	3
control states (backward dist.)	frame 1	0	1	2	3	0	1	2	0	1	2	3	0
	frame 2	>	0	1	2	3	0	1	2	0	1	2	3
	frame 3	>	>	0	1	2	3	0	1	2	3	0	1
	frame 4	>	>	>	0	1	2	3	4	5	0	1	2

Least recently used (LRU)

- No anomaly
  - In general: there exists a class of algorithms (**stack algorithms**) that do not show an anomaly:
    - For stack algorithms with *k* page frames, the following holds:
      At every point in time a subset of the pages is paged in that would also be paged in at the same time in a system with *k+1* page frames!
    - LRU: the most recently used *k* pages are paged in
    - OPT: the *k* pages are pages in which will be accessed next
- **Problem**
  - Implementing LRU requires hardware support
  - Every memory access has to be considered

Least recently used (LRU)

- Naive Idea: Hardware support using *counters*
  - CPU implements a counter that is incremented with every memory access
  - For every access, the current counter value is written into the respective page descriptor
  - Select the page with the lowest counter value (➛ ***search!***)

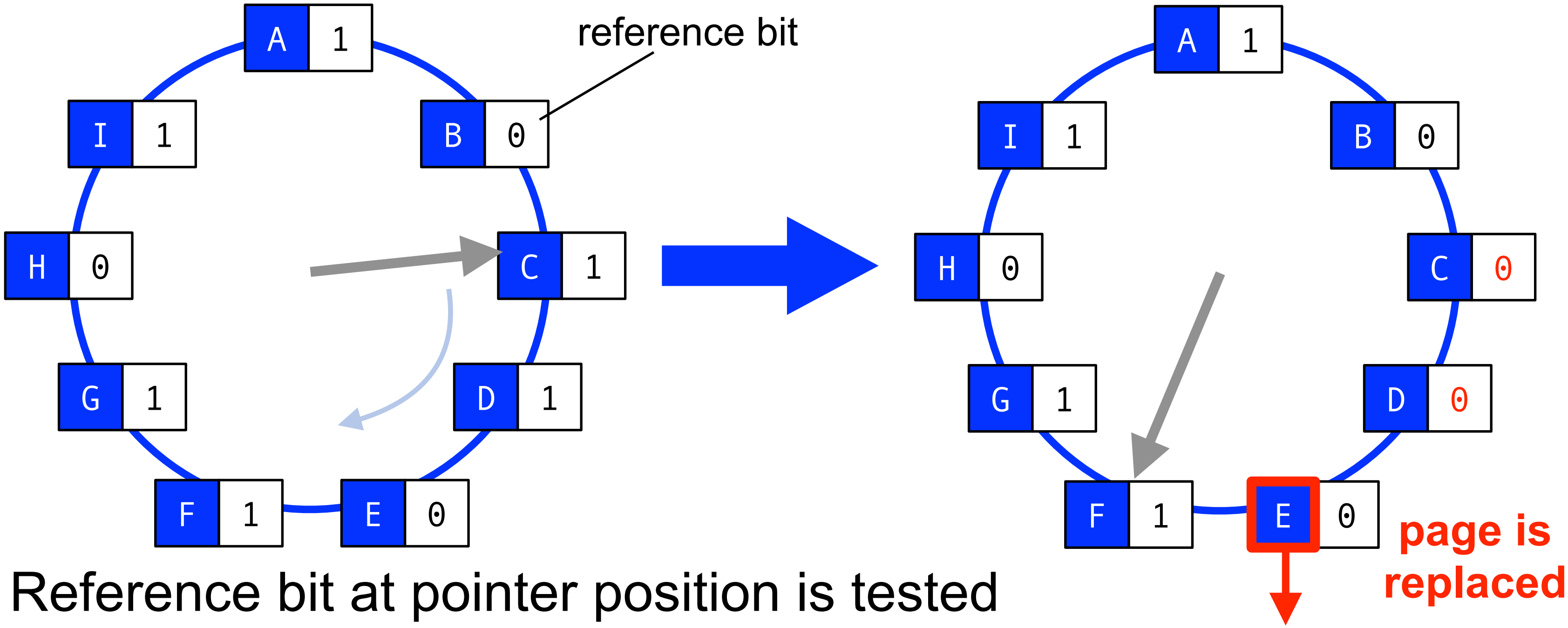
- Large implementation overhead
  - many additional memory accesses required
  - large amount of additional memory required
  - Minimum search required in the page fault handler

Second chance (clock)

- This approach works: use ***reference bits***
  - Reference bit in the page descriptor is set automatically by the hardware when a page is accessed
  - easier to implement
  - fewer additional memory accesses
- Modern processors/MMUs support reference bits (e.g. called “access bit” on x86)
- Objective: approach LRU
  - the reference bit of a newly paged in page is initially set to 1
  - when a “victim” page is needed, the reference bits are checked in order
    - if the reference bit = 1, set it to 0 (*second chance*)
    - if the reference bit = 0, replace this page!

Second chance (clock)

- Implementation using a rotating pointer (*clock*)



- Reference bit at pointer position is tested
  - if the reference bit = 1: clear it
  - if the reference bit = 0: we found a page to be replaced
  - Pointer “ticks on”: if no page could be found, then start over
- If all reference bits are = 1, then second chance is a FIFO

Second chance (clock)

- Sequence with three page frames:
  9 page ins

Access sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	frame 1	**1**	1	1	**4**	4	4	**5**	5	5	5	5	5
	frame 2		**2**	2	2	**1**	1	1	1	1	**3**	3	3
	frame 3			**3**	3	3	**2**	2	2	2	2	**4**	4
control states (reference bits)	frame 1	1	1	**1**	1	1	**1**	1	1	1	0	**0**	**1**
	frame 2	**0**	1	1	**0**	1	1	**0**	**1**	**1**	1	1	1
	frame 3	0	**0**	1	0	**0**	1	0	0	1	**0**	1	1
	pointer pos.	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**2**	**2**	**3**	**1**	**1**

Second chance (clock)

- Increase the main memory (4 page frames):
  10 page ins

Access sequence		1	2	3	4	1	2	5	1	2	3	4	5
main memory	frame 1	**1**	1	1	**1**	1	1	**5**	5	5	5	**4**	4
	frame 2		**2**	2	2	2	2	2	**1**	1	1	1	**5**
	frame 3			**3**	3	3	3	3	3	**2**	2	2	2
	frame 4				**4**	4	4	4	4	4	**3**	3	3
control states (reference bits)	frame 1	1	1	1	**1**	**1**	**1**	1	1	1	**1**	1	1
	frame 2	**0**	1	1	1	1	1	**0**	1	1	1	**0**	1
	frame 3	0	**0**	1	1	1	1	0	**0**	1	1	0	**0**
	frame 4	0	0	**0**	1	1	1	0	0	**0**	1	0	0
	pointer pos.	**2**	**3**	**4**	**1**	**1**	**1**	**2**	**3**	**4**	**1**	**2**	**3**

Second chance (clock)

- Second chance can also show the FIFO anomaly
  - If all reference bits are = 1, this is a FIFO order
- In the common case, however, second chance is close to LRU

- Extension
  - Modification bit can be considered in addition (*dirty bit*)
  - Three classes of (reference bit, modification bit) :
    (0,0), (1,0) and (1,1)
  - Search for the “lowest” class (used in macOS)

Discussion: free page buffer

…accelerates page fault handling

- Instead of replacing a page, a number of free pages is always kept in memory
  - Pageouts take place “in advance”
  - More efficient: time to replace a page is dominated by the time required for the page in (no need to find a victim and page it out)
- Page-to-page frame relation is still valid after paging out
  - In case the page is used again before it would be replaces, it can be reused with high efficiency
  - The page is no longer allocated to the free page buffer and is reallocated to its respective process

Page frame assignment

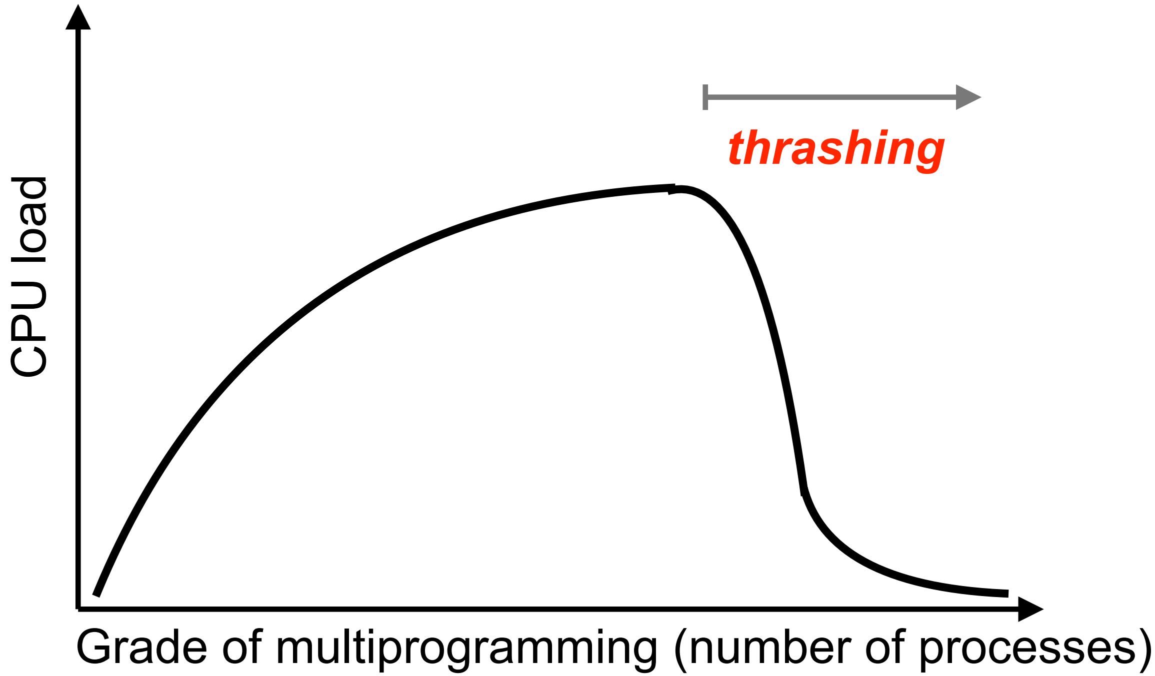
- Problem: Distribution of page frames to processes
  - How many page frames should a single process use?
    - Maximum: limited by the number of page frames
    - Minimum: depends on the processor architecture
      - At least the number of pages which is necessary to execute a machine instruction
- Identical share size
  - The number of frames allocated to a process depends on the number of processes
- Program size dependent shares
  - Program size is considered when determining the number of page frames to allocate to it

Page frame assignment

- Global and local page requests
  - local: a process only replaces its own pages
    - Page fault behavior depends only on the behavior of the process
  - global: a process can also replace pages of other processes
    - More efficient, since unused pages of other processes can be used

Thrashing

- A page that was paged out is accessed immediately after the page out happened
  - The process spends more time waiting to handle the page faults than with its own execution



Thrashing

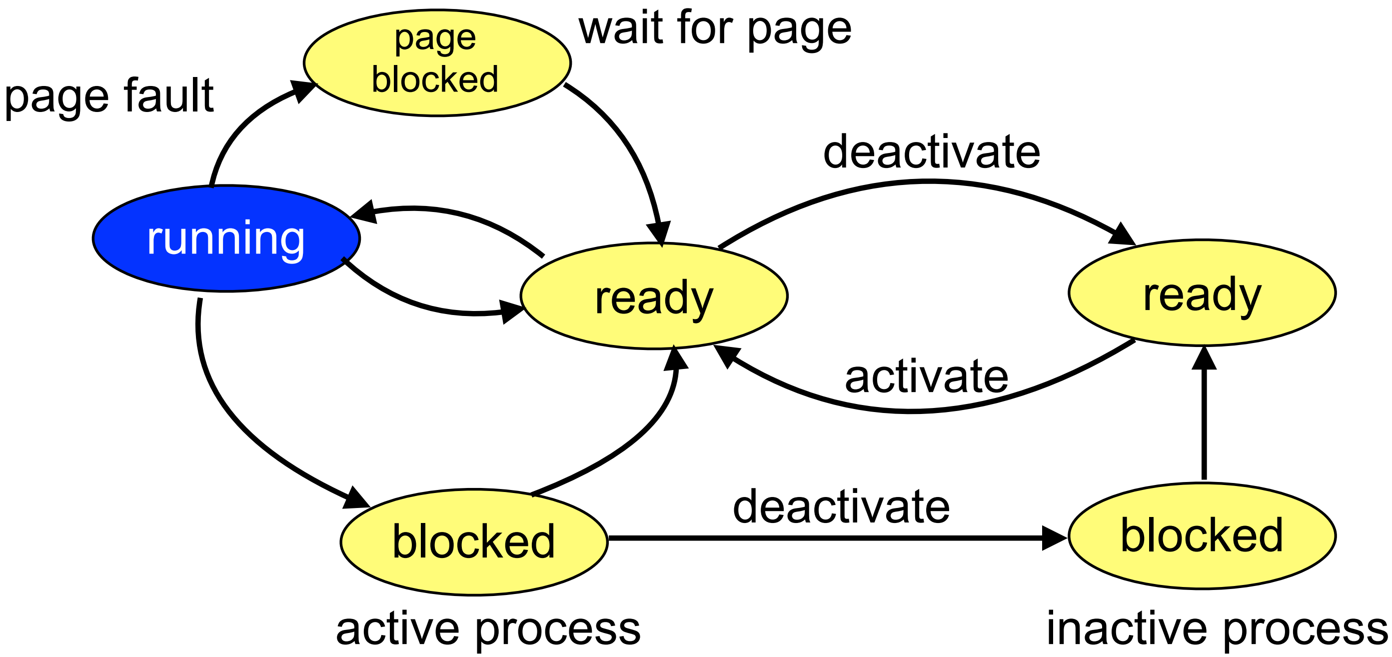
- Causes
  - A process is close to its page minimum
  - Too many processes in the system at the same time
  - Suboptimal replacement strategy

➢ Local page requests avoids ***thrashing between*** processes

➢ Allocating a sufficiently large number of page frames avoids ***thrashing within*** process pages
  - Limitation of the number of processes

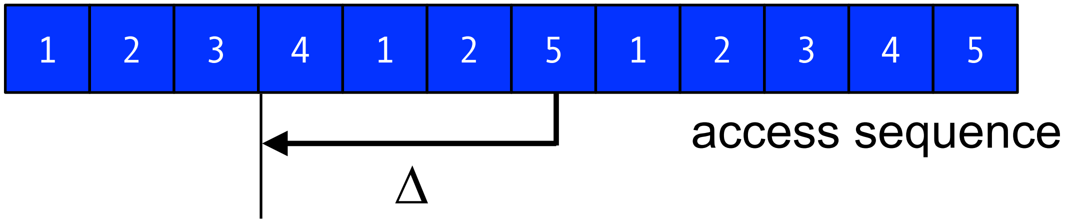
Solution 1: swapping of processes

- Inactive processes do not require page frames
  - Page frames can be distributed among fewer processes
  - Has to be combined with scheduling to…
    - avoid *starvation*
    - enable short *answer (reaction) times*



Solution 2: working set model

- Set of pages really needed by a process (working set)
  - Can only be approximated, since this is usually not predictable
- Approximation by looking at the more recently accessed Δ pages
  - Appropriate selection of a Δ
    - too large: *overlapping* of local access patterns
    - too small: working set does not contain all necessary pages



  - Notice: Δ > |*working set*|, since a single page is usually accessed multiple times in a row.

Working set model

- Example: working sets for different values of Δ

Access 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

- Approximate accesses by time values
  - A certain time interval is ~proportional to the number of memory accesses

- Requires measuring the *virtual time of the process*
  - Only that time is relevant in which the process is in state RUNNING
  - Each process has its own virtual clock

Determining the working set and timers

- Naive idea: approximate the working set using:
  - A reference bit
  - Age information per page (time interval in which the page was not used)
  - Timer interrupt (using a system timer)
- Algorithm
  - Periodic timer interrupts are used to update the age information using the reference bit:
    - reference is set (page was used) ➢ set age to zero
    - else increase the age information
    - only pages of the currently running process “age”
  - Pages with an age > Δ are no longer considered to be part of the working set of the respective process

Determining the working set and timers

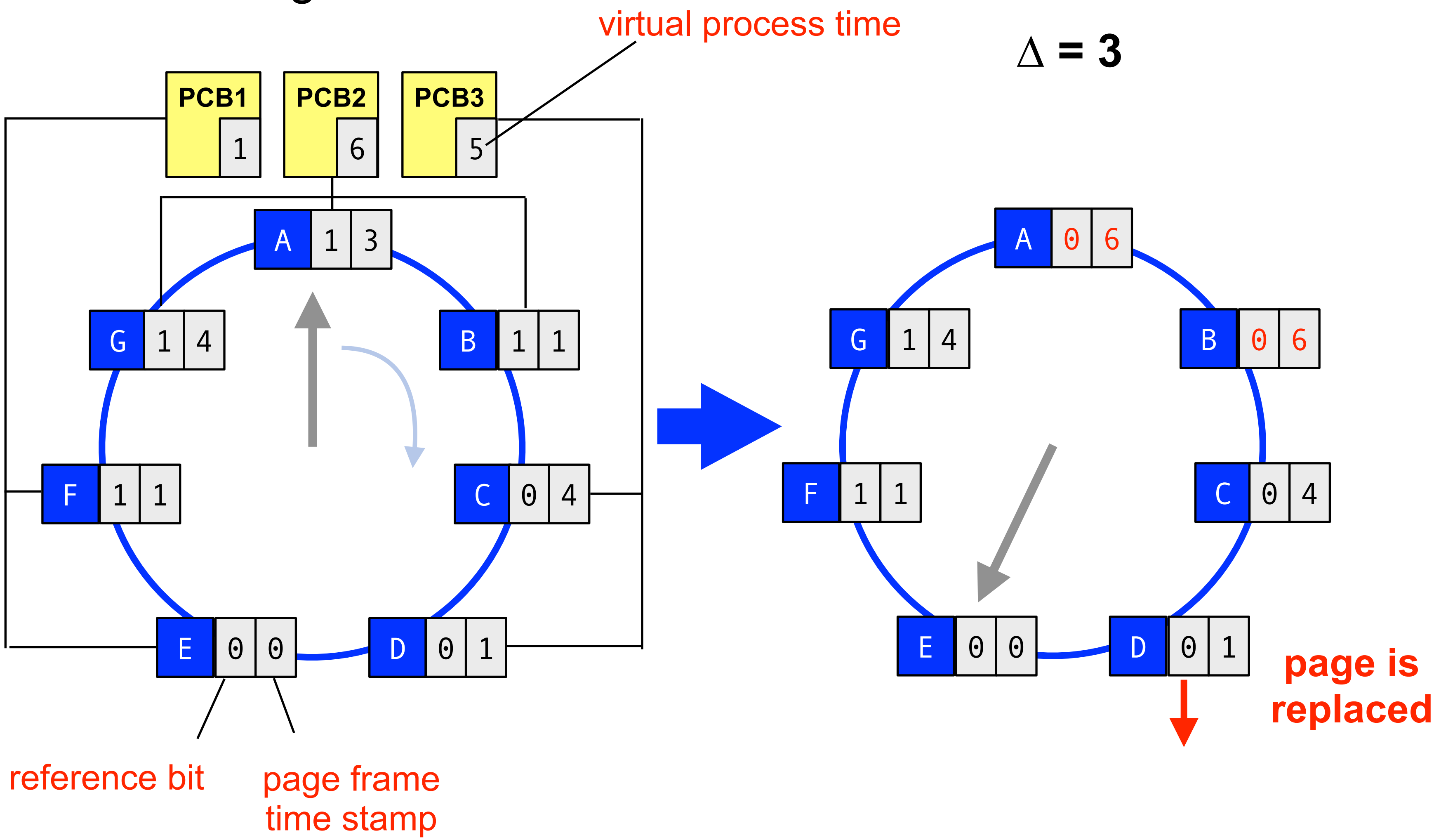
- Imprecise
  - Reduce the time intervals:
    more overhead, but more precise measurement
  - However, the system is not sensitive to this imprecision
- Inefficient
  - A large number of pages has to be checked

Determine the working set with WSclock

- This is the real solution:
  WSClock algorithm ("working set clock")
  - Works like the previous clock algorithm
  - A page is only replaced if
    - it is not an element of the working set of its process
    - or the process is deactivated
  - When resetting the reference bit, the current time of the respective process is noted
    - this time can e.g. be kept and updated in the process control block PCB
  - Determining the working set:
    - Calculate the difference between the virtual time of the process and the time stamp in the page frame

Determine the working set with WSclock

- WSClock Algorithm



Discussion: working set problems

- Time stamps also need memory
- It is not always possible to ascribe a page to a specific process
    - shared memory pages are the rule rather than an exception in modern operating systems
        - Shared libraries
        - Shared pages in the data segment (shared memory)

➢ Solution 3: Thrashing can be avoided in an easier way by directly controlling the page fault rate
- Measure per process
    - rate < limit: reduce page frame set
    - rate > limit: enlarge page frame set

Loading strategy

- **Load on demand**
  - Safe approach
- **Prefetch**
  - Difficult:
    Pages that are paged out are not used right now, only later
  - Often, one machine instruction leads to multiple page faults
    - Prefetching of these pages can be realized by interpreting the machine instruction that causes the first page fault.
      This will avoid any additional page faults for this instruction.
  - Load the complete working set in advance when a process is swapped in
  - Detect sequential access patterns and prefetch subsequent pages

Conclusions

- Virtual memory allows to use large logical address spaces even if the physical memory is small

- However, this involves some overhead
  - Hardware overhead
  - Complex algorithms in the operating system
  - “Surprising” effects (such as “thrashing”)
  - Timing behavior not predictable

➢ Simple (special purpose) systems that do not necessarily need these features should better not implement them