Systems and Networking – Unit 1

B.Sc. in Applied Computer Science and Artificial Intelligence

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SAPIENZA
UNIVERSITÀ DI ROMA

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Paging + Segmentation

- Paging (OS' view of memory)
  - Divide memory into fixed-size pages and map them to physical frames
- Segmentation (compiler's view of memory)
  - Divide process into logical segments (e.g., code, data, stack, heap)
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So far, the entire virtual address space of a process was assumed to fit and be all in memory

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Virtual Memory uses backing storage (i.e., disk) to store unused pages and give the illusion of infinite virtual address space

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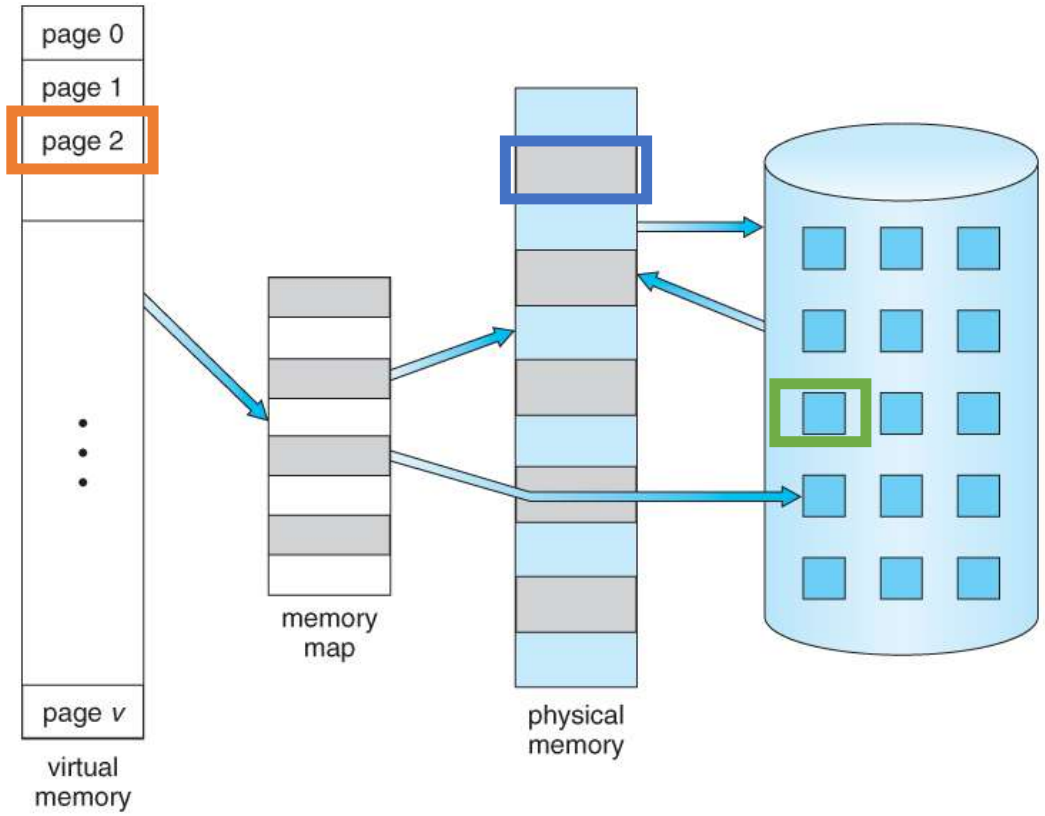
  - More memory is left for other programs, improving CPU utilization
  - Less I/O is needed for swapping processes in and out of memory, speeding things up

Virtual Memory: The Big Picture



At any given time, each page can be:

in memory (physical frame)

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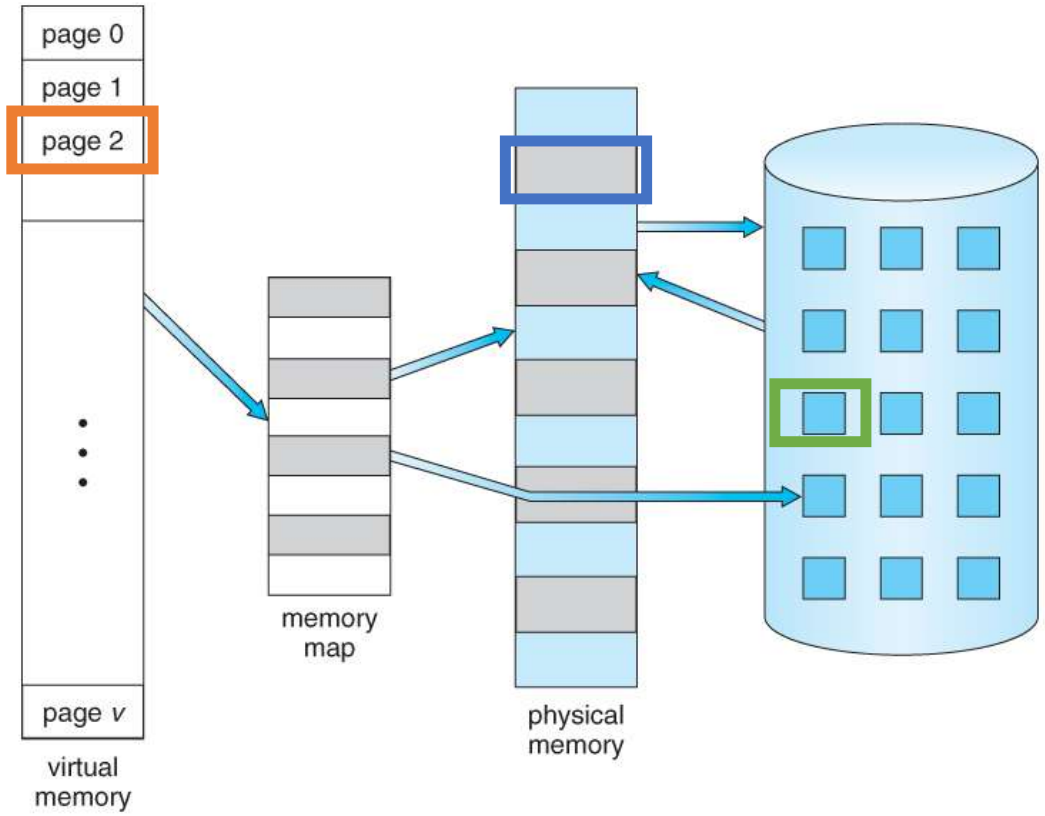
Virtual Memory: The Big Picture

virtual memory can be much larger than physical memory



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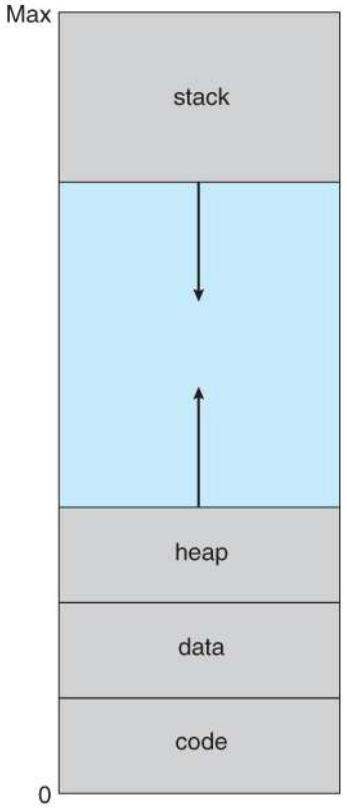
The Sparseness of Virtual Address Space



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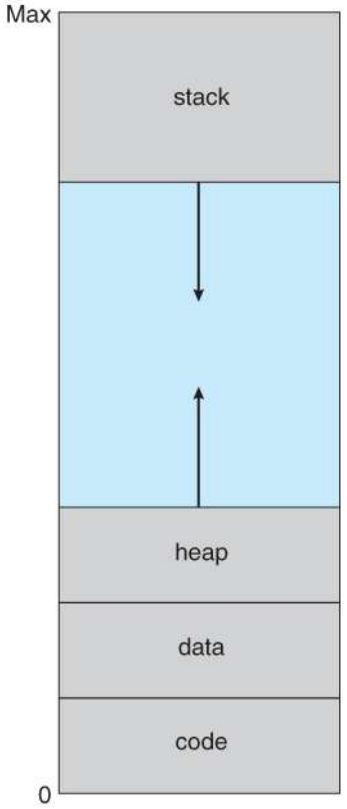

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A lot of virtual memory addresses remain unreferenced

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- Remember: access to disk is extremely slower than access to memory
- Therefore, memory accesses must reference pages that are in memory with high probability

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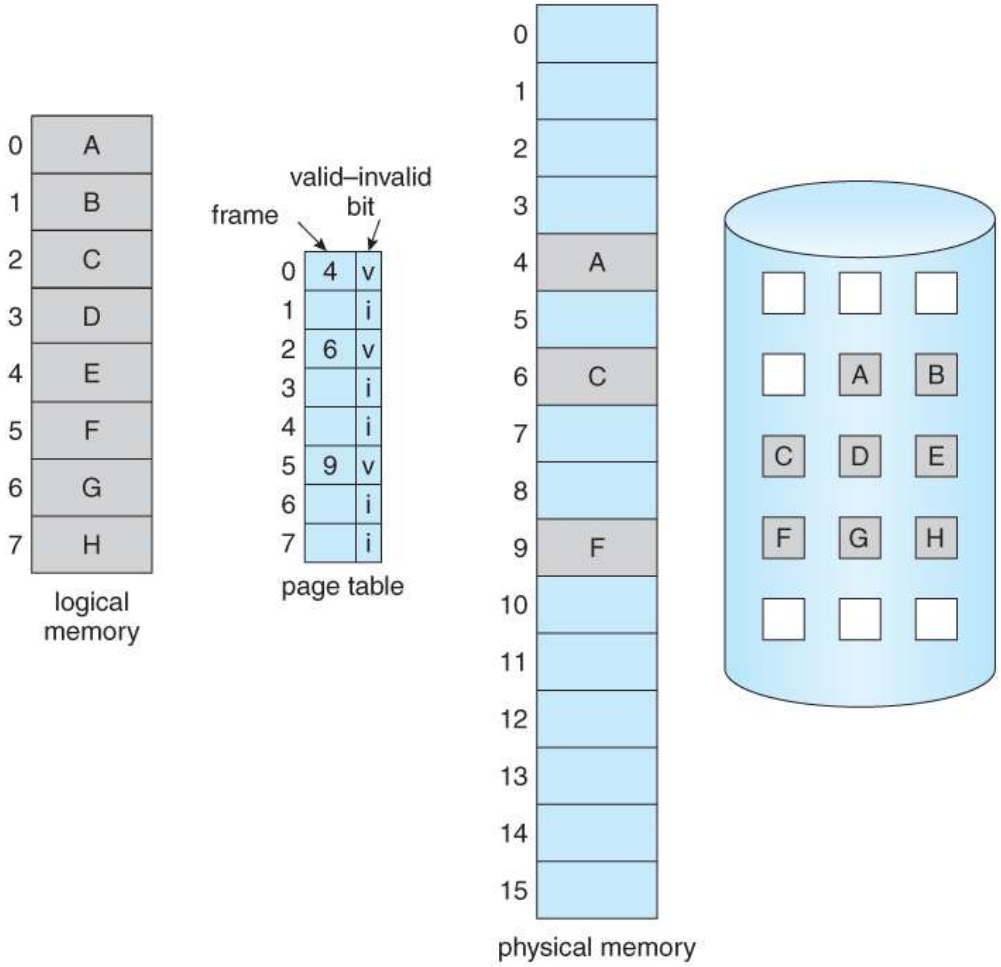
Virtual Memory: Basic Concepts



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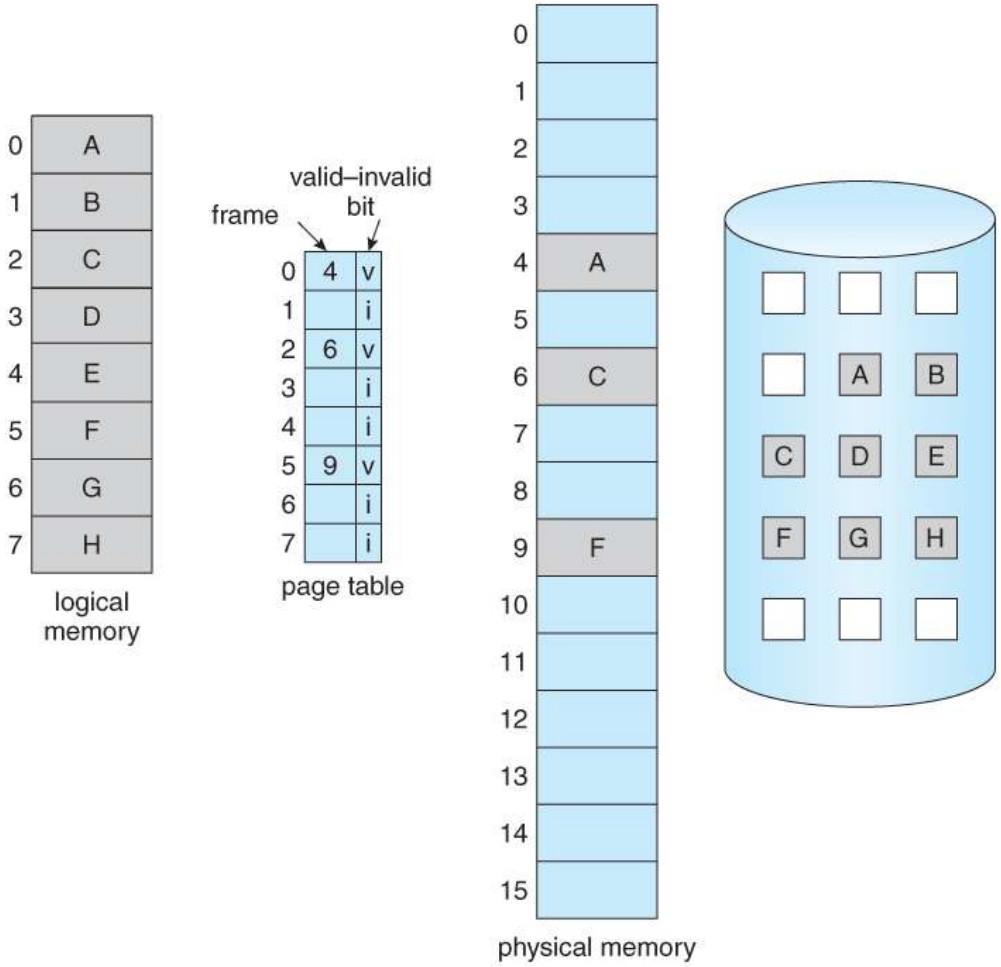

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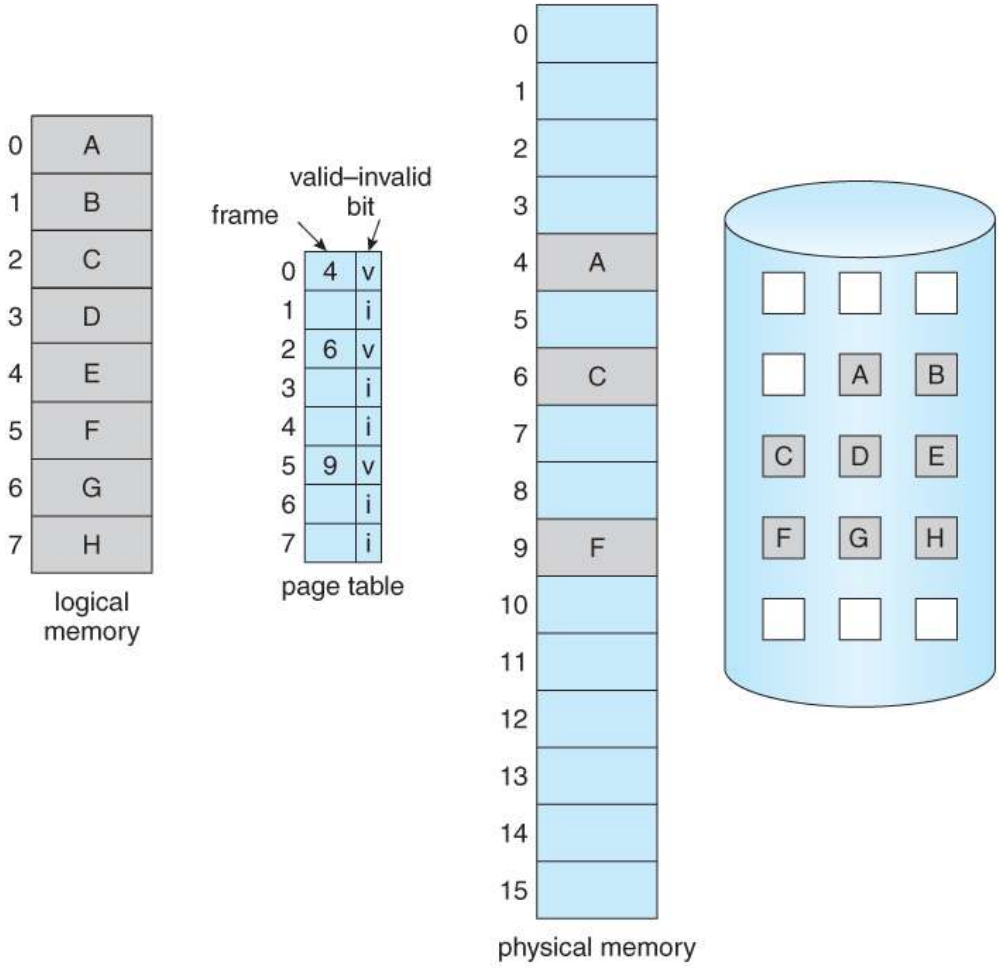

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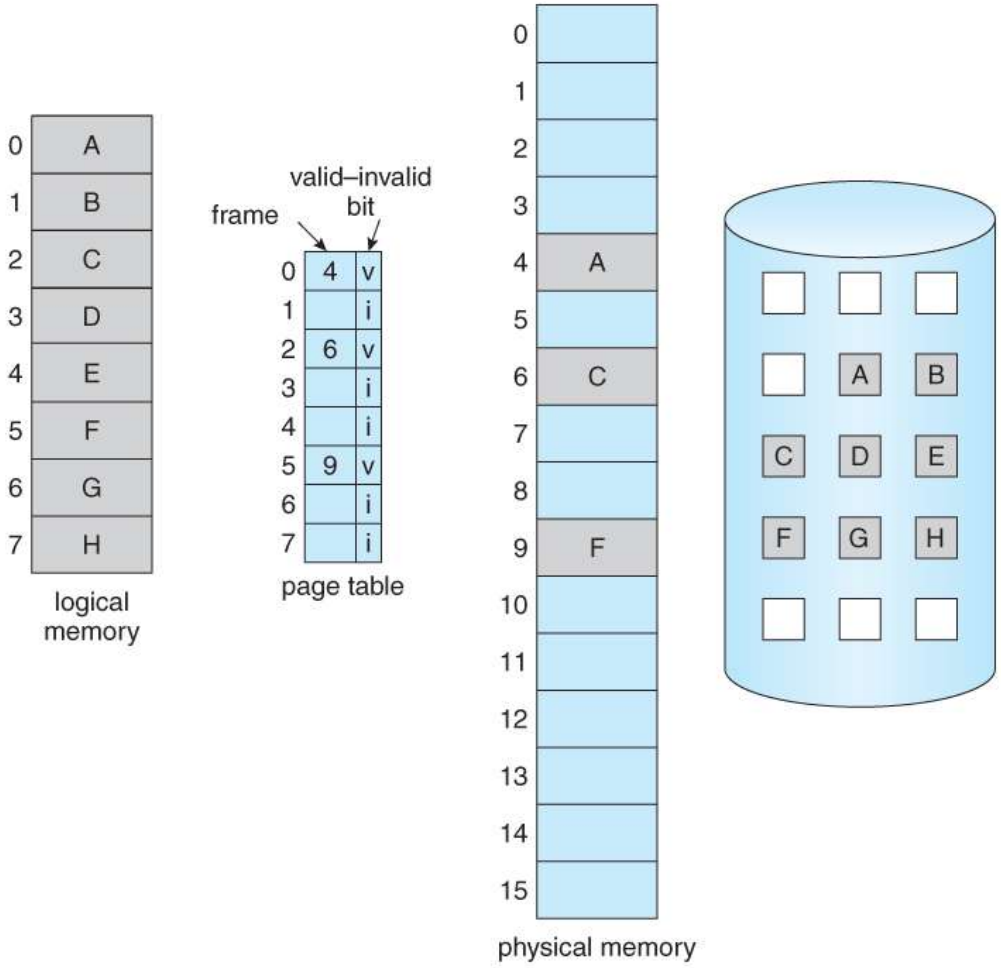

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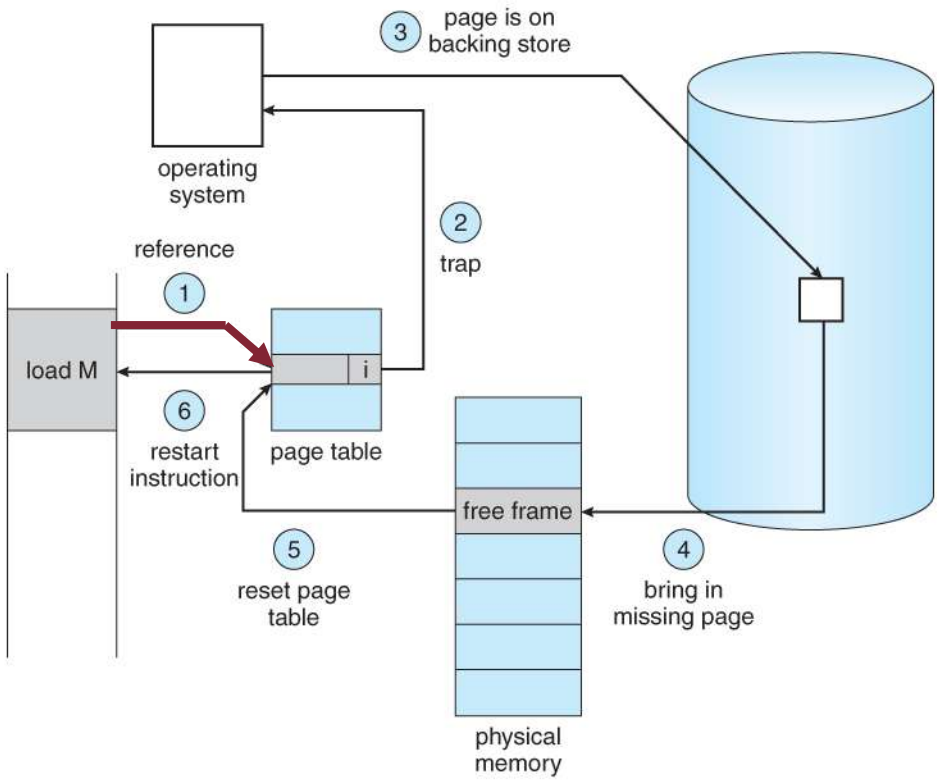
If the bit is set to 1 it means the page entry is valid (i.e., the requested page is in memory)

Otherwise, a page fault trap occurs, and the page has to be loaded (i.e., fetched) from disk

Page Fault Handling

1. The memory address is first checked, to see if it is legitimate



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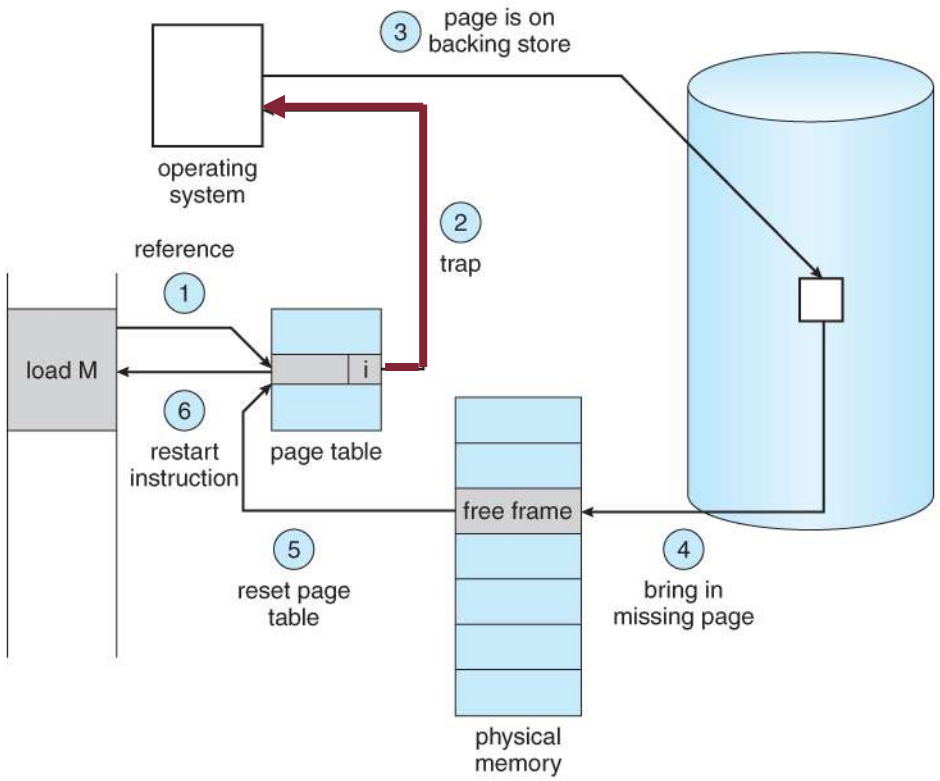

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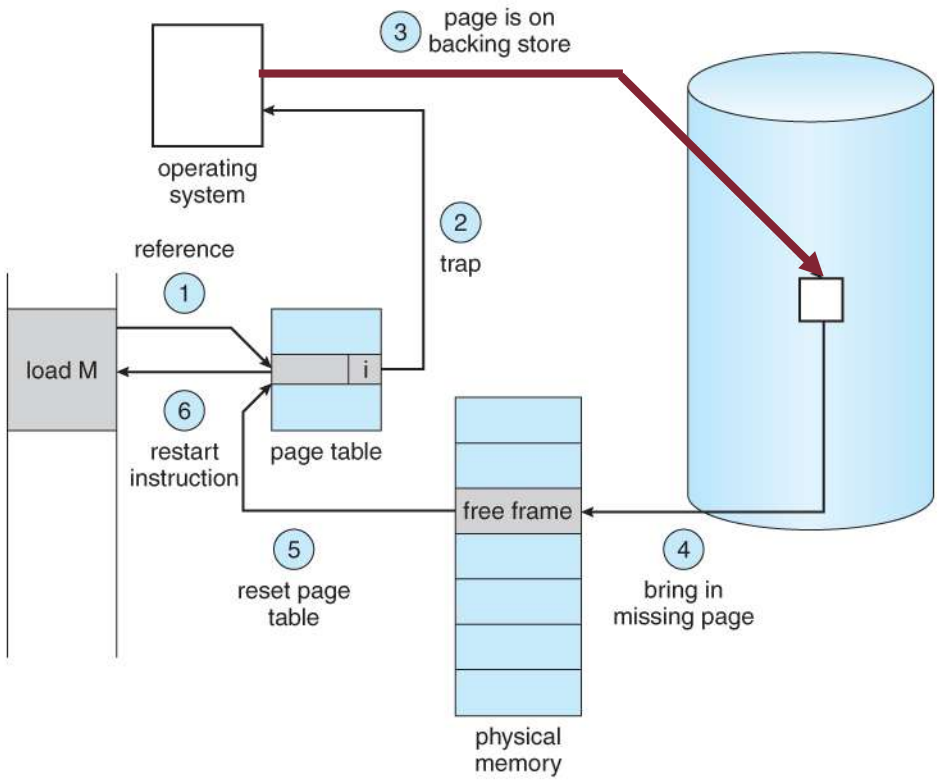

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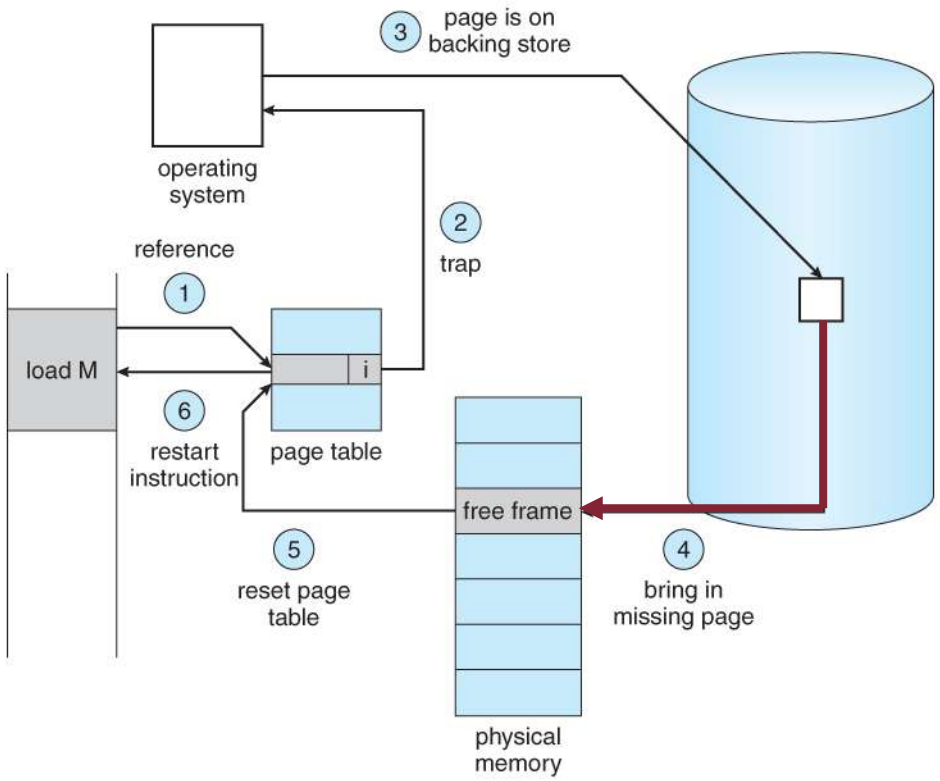

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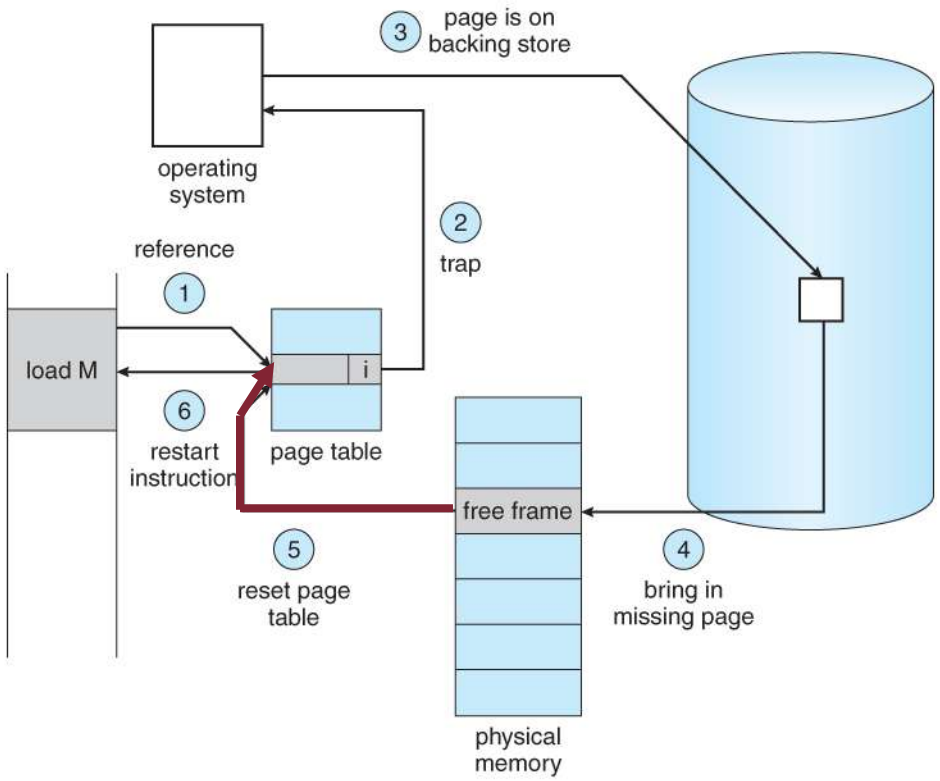

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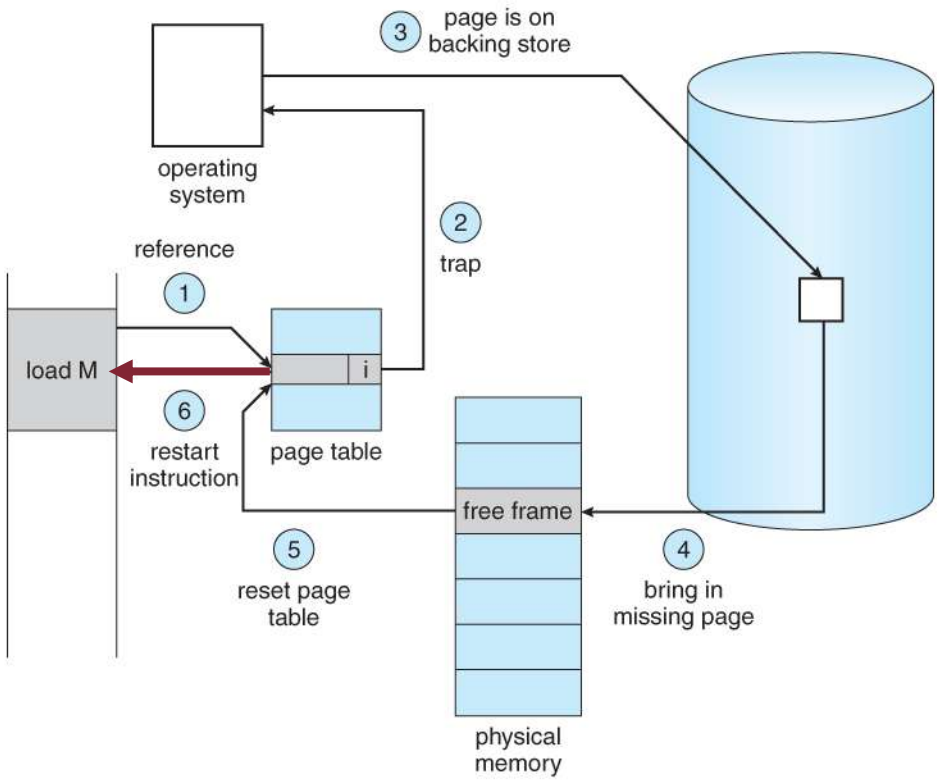

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6. The current process gets interrupted and the instruction that caused the page fault must be restarted from the beginning

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- TLB hit means the requested page entry is in the cache and the referenced frame is also in memory

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  - The OS picks a TLB entry to replace and fills it with the new entry as follows
    - invalidates the TLB entry
    - performs page fault trap operations
    - updates the TLB entry
    - restarts the faulting instruction

Page Fault Handling: Faulty Address

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- Architecture-dependent:
  - x86: hardware saves the virtual address that caused the fault (`CR2` register)
  - On some platforms, OS gets only address of faulting instruction, must simulate the instruction and try every address to find the one that generated the fault

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- To restart (from scratch) a faulty instruction the OS needs hardware support for saving:
  - The faulting instruction
  - The CPU state

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- idempotent → just restart the faulting instruction (hardware saves instruction address during page fault)
- non-idempotent → much more difficult to restart
  - `MOV [%R1], +(%R2)` → increment the value of `R2` and store it to memory address in `R1`
  - What if memory address `[%R1]` causes the page fault?
  - Cannot naively redo the instruction from scratch, otherwise `R2` gets incremented twice

Page Fault Handling: Transparency

- Even harder when using instructions that are not easily undoable
  - E.g., instructions that are used to move a block of memory at once
  - The block may span multiple pages: some of them can be in memory while some others not
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How to unwind those complicated side-effects?

Make sure all the addresses within the block to be transferred are in memory before starting executing the instruction

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  - spatial → if a process accesses an item in memory, it will tend to reference a close item again soon
- Still, an overhead must be paid every time a page fault occurs as the OS needs to interact with slower disk

Virtual Memory: Performance

t_{MA} = physical memory access time
t_{FAULT} = time to handle a page fault
$p \in [0, 1]$ = probability of page fault
t_{ACCESS} = effective time for each memory reference

$$t_{ACCESS} = (1 - p) * t_{MA} + p * t_{FAULT}$$

Let's assume: $t_{MA} = 100$ nsec and $t_{FAULT} = 20$ msec $= 20,000,000$ nsec

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This heavily depends on *p*!

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The access time increases from just 100 nsec up to ~20.1 microsec

200 times slowdown factor

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$$1.1 * 100 = 100 - 100p + 20,000,000p =$$
$$19,999,900p = 110 - 100 =$$

$$p = \frac{10}{19,999,900} = \frac{1}{1,999,990} \approx 0,0000005 = 5 * 10^{-7}$$

To achieve that goal, we can tolerate at most 1 page fault every about 2 million accesses!

Virtual Memory: Performance Example

More generally, given t_{MA}, t_{FAULT}, and a threshold $\varepsilon > 0$ if we want to find p s.t.:

$$t_{ACCESS} = (1 + \epsilon) * t_{MA}$$

We substitute t_{ACCESS} and solve for p the resulting equation:

$$(1 - p) * t_{MA} + p * t_{FAULT} = (1 + \epsilon) * t_{MA} =$$
$$t_{MA} - p * t_{MA} + p * t_{FAULT} = t_{MA} + \epsilon * t_{MA}$$
$$p(t_{FAULT} - t_{MA}) = \epsilon * t_{MA} =$$

$$p = \frac{\epsilon * t_{MA}}{t_{FAULT} - t_{MA}}$$

Virtual Memory: Considerations

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- So far, we have described how the OS (with the support of HW) manages page faults
- Still, the OS has to answer 2 fundamental questions:
  - When to load process' pages into main memory (page fetching)
  - Which page to remove from memory if this gets filled (page replacement)

Page Fetching Goals

- The overall goal is still to make physical memory look larger than it is
- Exploiting the locality reference of programs
- Keep in memory only those pages that is being used
- Keep on disk those pages that are unused
- Ideally, producing a memory system with the performance of main memory and the cost/capacity of disk!

Page Fetching Strategies

3 page fetching strategies

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Startup

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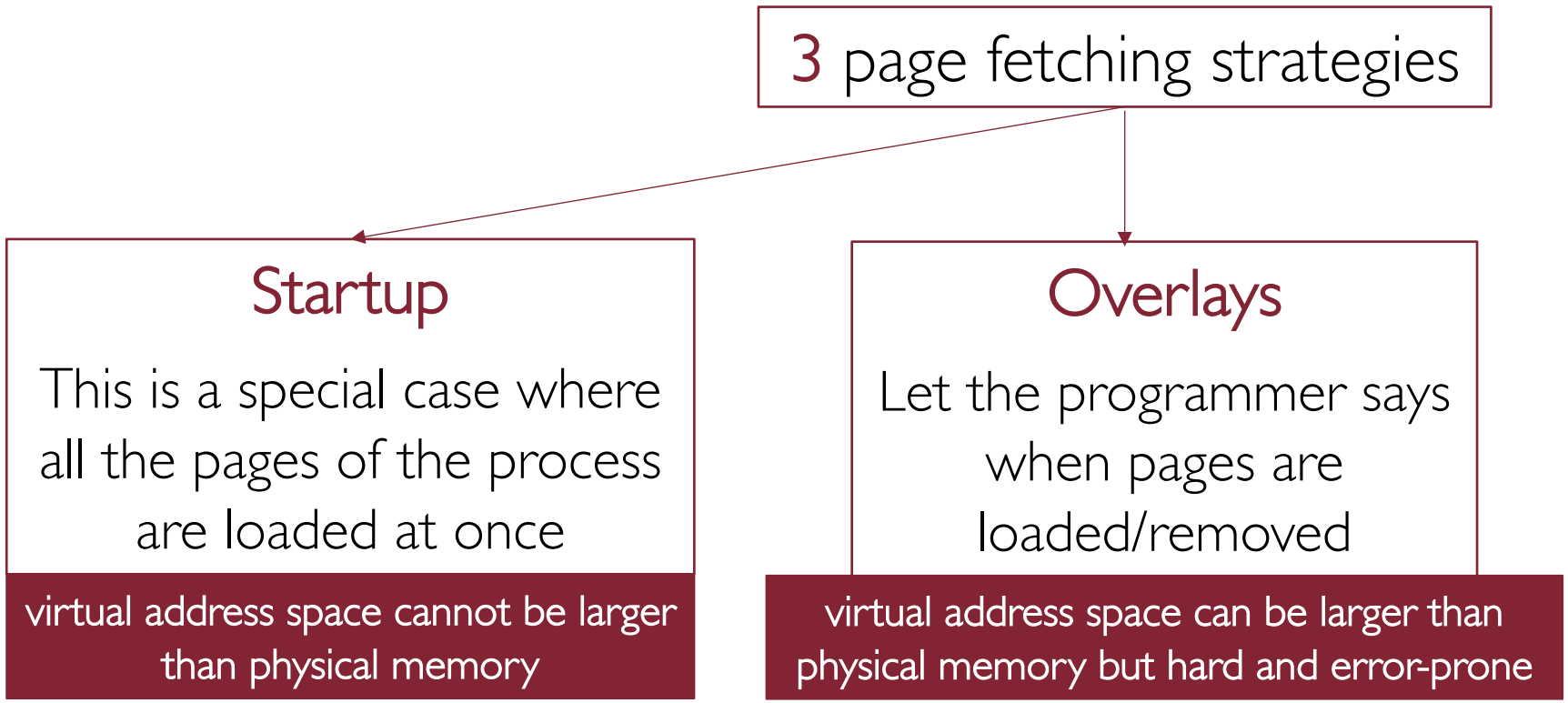
virtual address space cannot be larger than physical memory

Page Fetching Strategies



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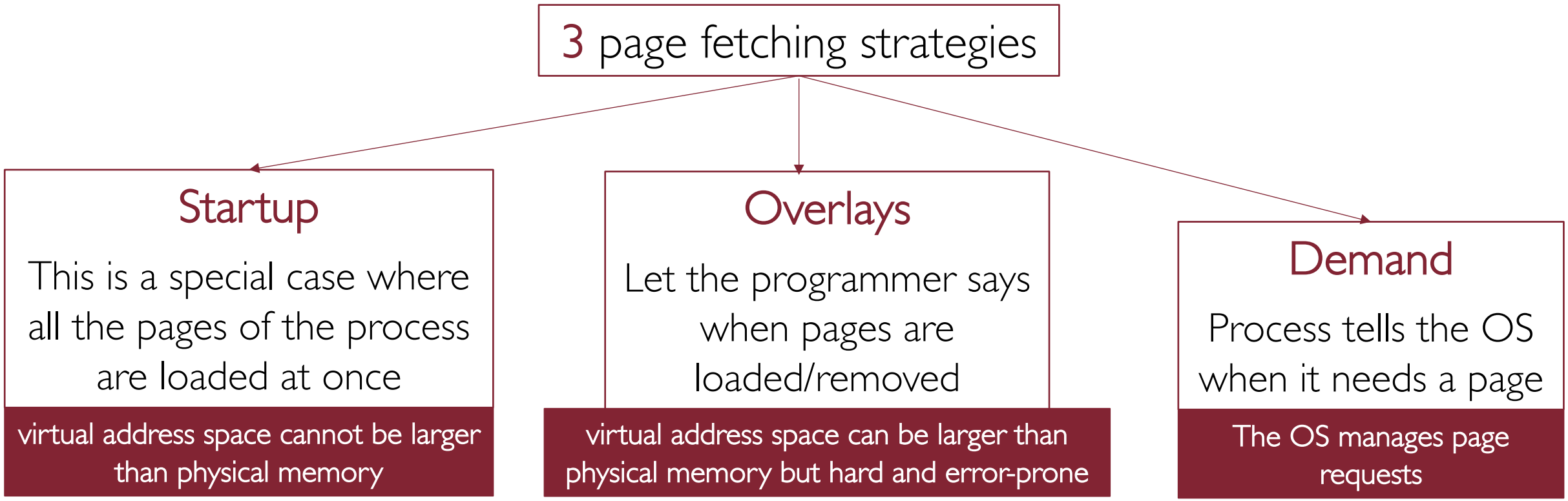

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Overlays

Let the programmer says when pages are loaded/removed

virtual address space can be larger than physical memory but hard and error-prone

Demand

Process tells the OS when it needs a page

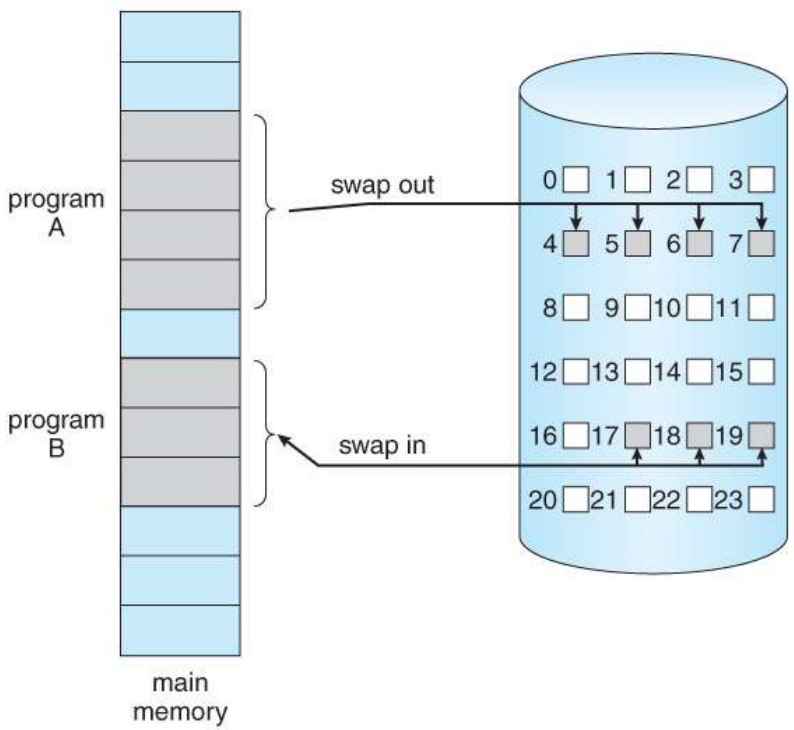
The OS manages page requests

Most modern OSs use demand fetching

(Pure) Demand Paging

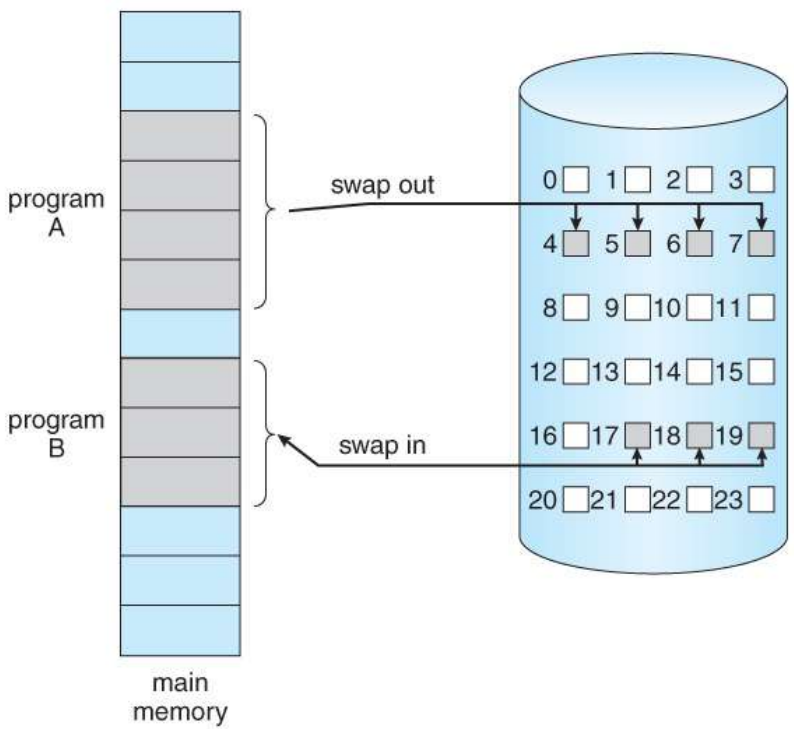
- When a process starts up, none of its pages are loaded
- Rather, a page is swapped in only when the process references it (upon a page fault)
- This is termed a lazy swapper or pager
- Opposite of loading all the pages at process startup!

Prefetching



The pager guesses when pages will be needed and load them ahead of time

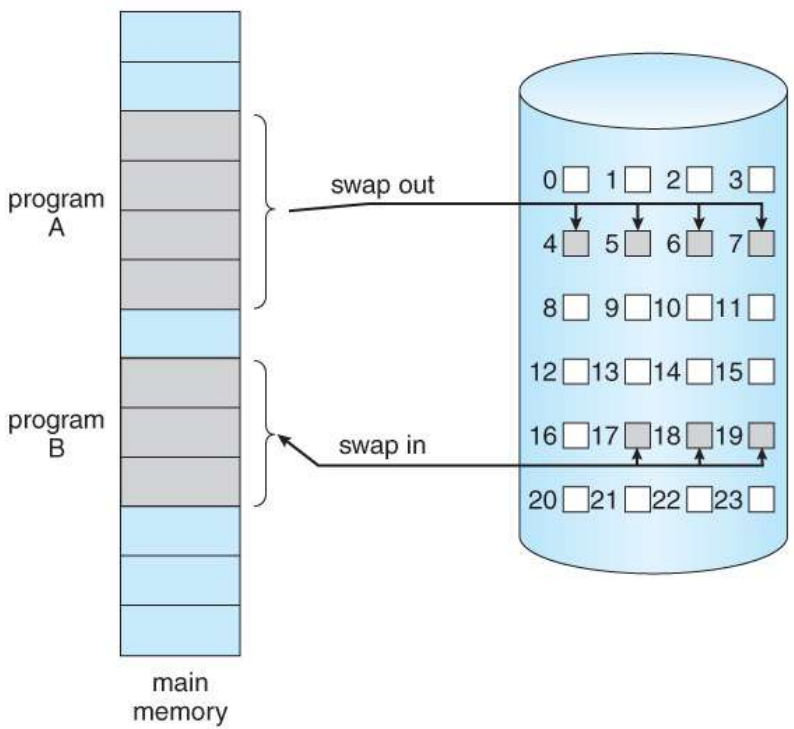
Prefetching



The pager guesses when pages will be needed and load them ahead of time

Trying to avoid page faults

Prefetching



The pager guesses when pages will be needed and load them ahead of time

Trying to avoid page faults

Requires predicting the future → very hard!

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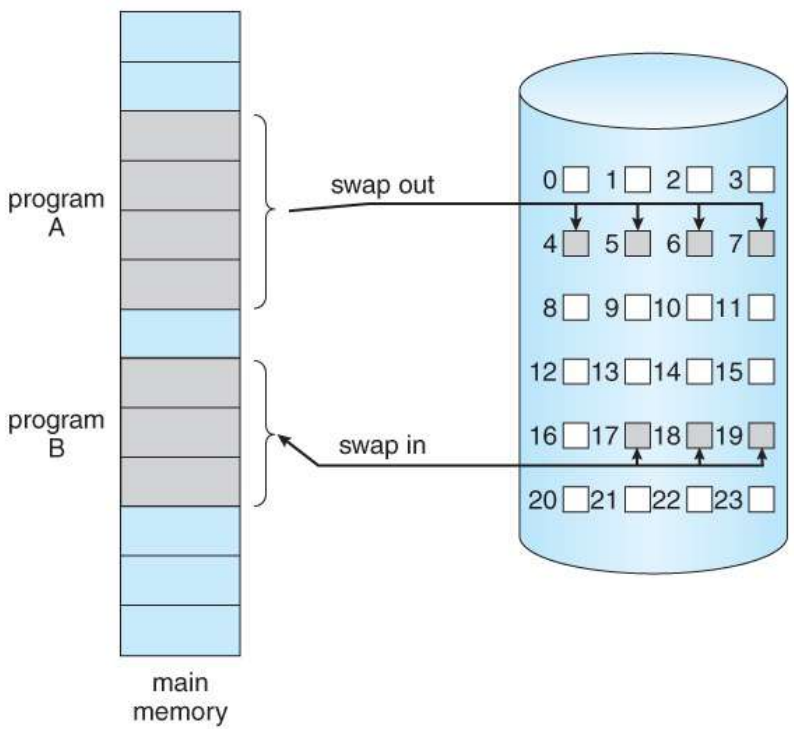

The pager guesses when pages will be needed and load them ahead of time

Trying to avoid page faults

Requires predicting the future → very hard!

Possible approach: upon page fault, load many pages instead of only the faulty one

works if program accesses memory sequentially

Swap Space

- A portion of the disk reserved for storing pages that are evicted from memory

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Swap Space

- A portion of the disk reserved for storing pages that are evicted from memory
- May be not part of the actual disk file system
- On Linux there exists a dedicated swap partition (on disk)
  - no actual files are stored in that partition
- On Mac, instead, swap space is part of the file system
  - swapfiles

Swap Out

- When a page needs to be swapped out, it will be generally copied to disk

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- When a page needs to be swapped out, it will be generally copied to disk
- The pages for a process are divided into 2 groups:
  - Code (read-only)
  - Data (initialized/uninitialized)
- Depending on which kind of page is removed, different optimizations may apply upon page swap-out

Swap Out Optimizations

- Code page (read-only):
  - Code content does not change!
  - Just remove it and re-load it back from executable file stored on disk
  - Make use of the filesystem

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- Code page (read-only):
  - Code content does not change!
  - Just remove it and re-load it back from executable file stored on disk
  - Make use of the filesystem
- Data page:
  - Data content does actually change!
  - Save it to a separate paging file, so that no changes are lost when it will be loaded in the future
  - Need to use the dedicated swap space

Page Replacement: Motivation

- On a page fault, we need to load a page from disk into memory
- If physical memory has still free frames, the page can be safely loaded into one of those
- However, if physical memory is full (i.e., all of its frames are loaded) a frame must be swapped out to make room for the swap-in page
- Several algorithms to select the page to evict from memory

Page Replacement Algorithms

- Random: pick any page at random (works surprisingly well!)

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  - Easy to implement but may remove frequently accessed pages

Page Replacement Algorithms

- Random: pick any page at random (works surprisingly well!)
- FIFO (First-In-First-Out): throw out the page that has been in memory for longest time (i.e., the oldest)
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- MIN (OPT): remove the page that will not be accessed for the longest time (provably optimal [Belady 1966])
  - Needs to predict the future → very hard!

Page Replacement Algorithms

- Random: pick any page at random (works surprisingly well!)
- FIFO (First-In-First-Out): throw out the page that has been in memory for longest time (i.e., the oldest)
  - Easy to implement but may remove frequently accessed pages
- MIN (OPT): remove the page that will not be accessed for the longest time (provably optimal [Belady 1966])
  - Needs to predict the future → very hard!
- LRU (Least Recently Used): approximation of MIN, remove the page that has not been used in the longest time
  - Assumes the past is a good predictor of the future (not always true!)

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1											
F_2											
F_3											

How many page faults (denoted by *)?

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1											
F_2											
F_3											

Initially, no frame is loaded in memory at all (pure demand paging)

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1											
F_2											
F_3											

Virtual address within page A is referenced

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1											
F_2											
F_3											

Virtual address within page A is referenced ⇨ page fault

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*										
F_2											
F_3											

Virtual address within page A is referenced → page fault → A loaded

FIFO = A

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A									
F_2											
F_3											

Virtual address within page B is referenced

FIFO = A

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A									
F_2											
F_3											

Virtual address within page B is referenced ⇒ page fault

FIFO = A

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A									
F_2		B*									
F_3											

Virtual address within page B is referenced → page fault → B loaded

FIFO = A → B

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A								
F_2		B*	B								
F_3											

Virtual address within page C is referenced

FIFO = A → B

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A								
F_2		B*	B								
F_3											

Virtual address within page C is referenced ⇨ page fault

FIFO = A → B

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A								
F_2		B*	B								
F_3			C*								

Virtual address within page C is referenced → page fault → C loaded

FIFO = A → B → C

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A							
F_2		B*	B	B							
F_3			C*	C							

Virtual address within page A is referenced ⇒ A is already loaded

FIFO = A → B → C

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A						
F_2		B*	B	B	B						
F_3			C*	C	C						

Virtual address within page B is referenced ⇒ B is already loaded

FIFO = A → B → C

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	C					

Virtual address within page D is referenced

FIFO = A → B → C

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	C					

Virtual address within page D is referenced → page fault

FIFO = A → B → C

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	D*					
F_2		B*	B	B	B	B					
F_3			C*	C	C	C					

Virtual address within page D is referenced → page fault → A replaced, D loaded

FIFO = B → C → D

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	D*	D				
F_2		B*	B	B	B	B	B				
F_3			C*	C	C	C	C				

Virtual address within page A is referenced

FIFO = B → C → D

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	D*	D				
F_2		B*	B	B	B	B	B				
F_3			C*	C	C	C	C				

Virtual address within page A is referenced ⇒ page fault

FIFO = B → C → D

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	D*	D				
F_2		B*	B	B	B	B	A*				
F_3			C*	C	C	C	C				

Virtual address within page A is referenced → page fault → B replaced, A loaded

FIFO = C → D → A

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	D*	D	D			
F_2		B*	B	B	B	B	A*	A			
F_3			C*	C	C	C	C	C			

Virtual address within page D is referenced ⇒ D is already loaded

FIFO = C → D → A

FIFO Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	D*	D	D	D	C*	C
F_2		B*	B	B	B	B	A*	A	A	A	A
F_3			C*	C	C	C	C	C	B*	B	B

Eventually, we get a total of 7 page faults

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1											
F_2											
F_3											

How many page faults (denoted by *)?

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1											
F_2											
F_3											

Initially, no frame is loaded in memory at all (pure demand paging)

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A						
F_2		B*	B	B	B						
F_3			C*	C	C						

Up to this point, the same as FIFO

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	C					

Virtual address within page D is referenced

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	C					

Virtual address within page D is referenced → page fault

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	C					

Virtual address within page D is referenced → page fault

What's the page that will be requested the furthest away?

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	D*					

Virtual address within page D is referenced → page fault → C replaced, D loaded

C is the page that will be requested the furthest away

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A		
F_2		B*	B	B	B	B	B	B	B		
F_3			C*	C	C	D*	D	D	D		

Up to this point, no more page faults

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	A	
F_2		B*	B	B	B	B	B	B	B	B	
F_3			C*	C	C	D*	D	D	D	D	

Virtual address within page C is referenced

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	A	
F_2		B*	B	B	B	B	B	B	B	B	
F_3			C*	C	C	D*	D	D	D	D	

Virtual address within page C is referenced → page fault

What's the page that will be requested the furthest away?

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	A	
F_2		B*	B	B	B	B	B	B	B	C*	
F_3			C*	C	C	D*	D	D	D	D	

Virtual address within page C is referenced → page fault → B replaced, C loaded

B or D will be requested the furthest away (surely not A): pick one (e.g., B)

MIN Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	A	A
F_2		B*	B	B	B	B	B	B	B	C*	C
F_3			C*	C	C	D*	D	D	D	D	D

Eventually, we get a total of 5 page faults

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1											
F_2											
F_3											

How many page faults (denoted by *)?

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1											
F_2											
F_3											

Initially, no frame is loaded in memory at all (pure demand paging)

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A						
F_2		B*	B	B	B						
F_3			C*	C	C						

Up to this point, the same as FIFO

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	C					

Virtual address within page D is referenced ⇒ page fault

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	C					

Virtual address within page D is referenced → page fault

We can't look forward anymore!

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A					
F_2		B*	B	B	B	B					
F_3			C*	C	C	D*					

Virtual address within page D is referenced → page fault → C replaced, D loaded

C is the page that has not been used for the longest time in the past

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A		
F_2		B*	B	B	B	B	B	B	B		
F_3			C*	C	C	D*	D	D	D		

Up to this point, no more page faults

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	A	
F_2		B*	B	B	B	B	B	B	B	B	
F_3			C*	C	C	D*	D	D	D	D	

Virtual address within page C is referenced

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	A	
F_2		B*	B	B	B	B	B	B	B	B	
F_3			C*	C	C	D*	D	D	D	D	

Virtual address within page C is referenced ⇒ page fault

We can't look forward anymore!

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	C*	
F_2		B*	B	B	B	B	B	B	B	B	
F_3			C*	C	C	D*	D	D	D	D	

Virtual address within page C is referenced → page fault → A replaced, C loaded

A is the page that has not been used for the longest time in the past

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	C*	C
F_2		B*	B	B	B	B	B	B	B	B	B
F_3			C*	C	C	D*	D	D	D	D	D

Virtual address within page A is referenced

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	C*	C
F_2		B*	B	B	B	B	B	B	B	B	B
F_3			C*	C	C	D*	D	D	D	D	D

Virtual address within page A is referenced ⇒ page fault

We can't look forward anymore!

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	C*	C
F_2		B*	B	B	B	B	B	B	B	B	B
F_3			C*	C	C	D*	D	D	D	D	A*

Virtual address within page A is referenced → page fault → D replaced, A loaded

D is the page that has not been used for the longest time in the past

LRU Page Replacement: Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, A, B, D, A, D, B, C, A

	A	B	C	A	B	D	A	D	B	C	A
F_1	A*	A	A	A	A	A	A	A	A	C*	C
F_2		B*	B	B	B	B	B	B	B	B	B
F_3			C*	C	C	D*	D	D	D	D	A*

Eventually, we get a total of 6 page faults

LRU Page Replacement: (An Unlucky) Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, D, A, B, C, D, A, B, C

	A	B	C	D	A	B	C	D	A	B	C
F_1											
F_2											
F_3											

How many page faults (denoted by *)?

LRU Page Replacement: (An Unlucky) Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, D, A, B, C, D, A, B, C

	A	B	C	D	A	B	C	D	A	B	C
F_1	A*	A	A								
F_2		B*	B								
F_3			C*								

LRU Page Replacement: (An Unlucky) Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, D, A, B, C, D, A, B, C

	A	B	C	D	A	B	C	D	A	B	C
F_1	A*	A	A	D*							
F_2		B*	B	B							
F_3			C*	C							

LRU Page Replacement: (An Unlucky) Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, D, A, B, C, D, A, B, C

	A	B	C	D	A	B	C	D	A	B	C
F_1	A*	A	A	D*	D						
F_2		B*	B	B	A*						
F_3			C*	C	C						

LRU Page Replacement: (An Unlucky) Example

3 physical frames: F_1, F_2, F_3

4 virtual pages: A, B, C, D

Reference sequence of pages: A, B, C, D, A, B, C, D, A, B, C

	A	B	C	D	A	B	C	D	A	B	C
F_1	A*	A	A	D*	D	D					
F_2		B*	B	B	A*	A					
F_3			C*	C	C	B*					

LRU Page Replacement: (An Unlucky) Example

3 physical frames: F_1, F_2, F_3

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Reference sequence of pages: A, B, C, D, A, B, C, D, A, B, C

	A	B	C	D	A	B	C	D	A	B	C
F_1	A*	A	A	D*	D	D	C*				
F_2		B*	B	B	A*	A	A				
F_3			C*	C	C	B*	B				

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Reference sequence of pages: A, B, C, D, A, B, C, D, A, B, C

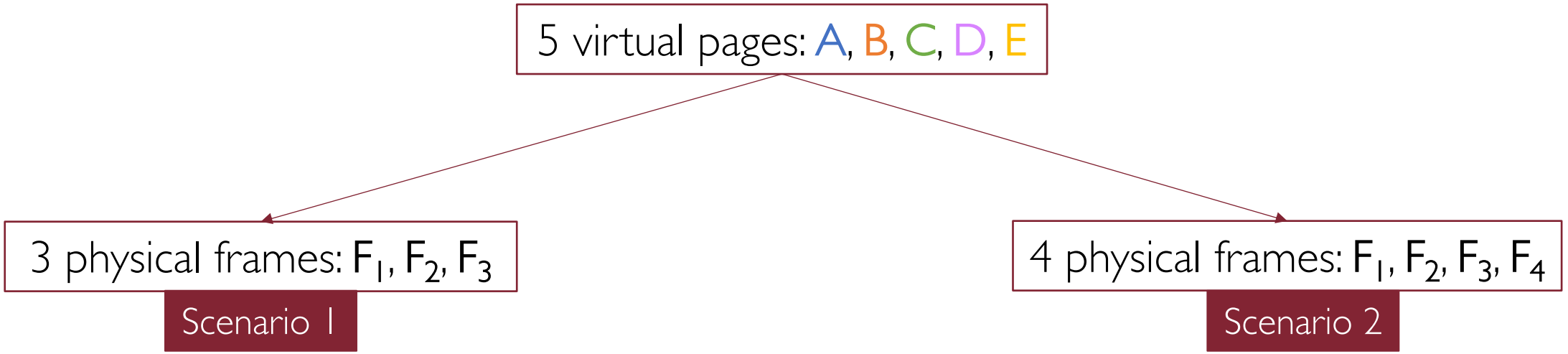
	A	B	C	D	A	B	C	D	A	B	C
F_1	A*	A	A	D*	D	D	C*	C	C	B*	B
F_2		B*	B	B	A*	A	A	D*	D	D	C*
F_3			C*	C	C	B*	B	B	A*	A	A

Eventually, we get a total of 11 page faults

Page Replacement: What If We Add Memory?

- Does adding memory always reduce the number of page faults?
- Intuitively, it would seem so…
- The answer, in fact, depends on the page replacement algorithm
- Let's see this with an example, using FIFO page replacement

FIFO Page Replacement: Example



Reference sequence of pages: A, B, C, D, A, B, E, A, B, C, D, E

FIFO Page Replacement: Example

	A	B	C	D	A	B	E	A	B	C	D	E
F_1	A*	A	A	D*	D	D	E*	E	E	E	E	E
F_2		B*	B	B	A*	A	A	A	A	C*	C	C
F_3			C*	C	C	B*	B	B	B	B	D*	D
F_1	A*	A	A	A	A	A	E*	E	E	E	D*	D
F_2		B*	B	B	B	B	B	A*	A	A	A	E*
F_3			C*	C	C	C	C	C	B*	B	B	B
F_4				D*	D	D	D	D	D	C*	C	C

FIFO Page Replacement: Example

	A	B	C	D	A	B	E	A	B	C	D	E
F_1	A*	A	A	D*	D	D	E*	E	E	E	E	E
F_2		B*	B	B	A*	A	A	A	A	C*	C	C
F_3			C*	C	C	B*	B	B	B	B	D*	D

10 page faults

	A	B	C	D	A	B	E	A	B	C	D	E
F_1	A*	A	A	A	A	A	E*	E	E	E	D*	D
F_2		B*	B	B	B	B	B	A*	A	A	A	E*
F_3			C*	C	C	C	C	C	B*	B	B	B
F_4				D*	D	D	D	D	D	C*	C	C

11 page faults

Belady's Anomaly

Adding page frames may cause more page faults with some algorithms

LRU Page Replacement: Example

	A	B	C	D	A	B	E	A	B	C	D	E
F_1	A*	A	A	D*	D	D	E*	E	E	C*	C	C
F_2		B*	B	B	A*	A	A	A	A	A	D*	D
F_3			C*	C	C	B*	B	B	B	B	B	B

9 page faults

F_1	A*	A	A	A	A	A	A	A	A	A	A	E*
F_2		B*	B	B	B	B	B	B	B	B	B	B
F_3			C*	C	C	C	E*	E	E	E	D*	D
F_4				D*	D	D	D	D	D	C*	C	C

8 page faults

With LRU, adding page frames always decreases the number of page faults

LRU Page Replacement: Example

	A	B	C	D	A	B	E	A	B	C	D	E
F_1	A*	A	A	D*	D	D	E*	E	E	C*	C	C
F_2		B*	B	B	A*	A	A	A	A	A	D*	D
F_3			C*	C	C	B*	B	B	B	B	B	B

9 page faults

F_1	A*	A	A	A	A	A	A	A	A	A	A	E*
F_2		B*	B	B	B	B	B	B	B	B	B	B
F_3			C*	C	C	C	E*	E	E	E	D*	D
F_4				D*	D	D	D	D	D	C*	C	C

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With LRU, adding page frames always decreases the number of page faults

Why?

LRU Page Replacement: Example

	A	B	C	D	A	B	E	A	B	C	D	E
F_1	A*	A	A	D*	D	D	E*	E	E	C*	C	C
F_2		B*	B	B	A*	A	A	A	A	A	D*	D
F_3			C*	C	C	B*	B	B	B	B	B	B
F_1	A*	A	A	A	A	A	A	A	A	A	A	E*
F_2		B*	B	B	B	B	B	B	B	B	B	B
F_3			C*	C	C	C	E*	E	E	E	D*	D
F_4				D*	D	D	D	D	D	C*	C	C

At each point in time 4-frame memory contains a subset of 3-frame

Can't do any worst!

Page Replacement: Summary

- FIFO is easy to implement but may lead to too many page faults
  - May suffer from Belady's Anomaly

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- FIFO is easy to implement but may lead to too many page faults
  - May suffer from Belady's Anomaly
- MIN is the optimal choice but cannot be used in practice since future memory references are never known in advance
- LRU is a fair approximation of MIN assuming the past is a good predictor of the future
  - Exploits the locality reference (small working set that fits in memory)
  - Works poorly when the locality reference doesn't hold (large working set)

LRU: Implementation Details

How could we implement LRU page replacement algorithm?

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First Idea

Keep a timestamp for each page with the time it has been last accessed
Remove the page with the highest difference w.r.t. current timestamp

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Every time a page is accessed its timestamp must be updated

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Remove the page with the highest difference w.r.t. current timestamp

Problems?

Every time a page is accessed its timestamp must be updated

Linear scan of all the pages to select the one to be removed

LRU: Implementation Details

How could we implement LRU page replacement algorithm?

Second Idea

Keep a list of pages with the most recently used in front and the least recently used at the end: every time a page is accessed move it to front

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How could we implement LRU page replacement algorithm?

Second Idea

Keep a list of pages with the most recently used in front and the least recently used at the end: every time a page is accessed move it to front

Problems?

Still too expensive as the OS must change multiple pointers on each memory access

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- Many systems provide some HW support which is enough to approximate LRU fairly well
- Single-Reference Bit → Maintain 1 bit for each page table entry
  - Initially, all bits for all pages are set to 0
  - On each access to a page, the HW sets the reference bit to 1
  - Enough to distinguish pages that have been accessed since the last clear
  - No total order of page access

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- Additional-Reference-Bits → Maintain 8 bits for each page table entry

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- The specific number of bits used and the frequency with which the reference byte is updated are adjustable

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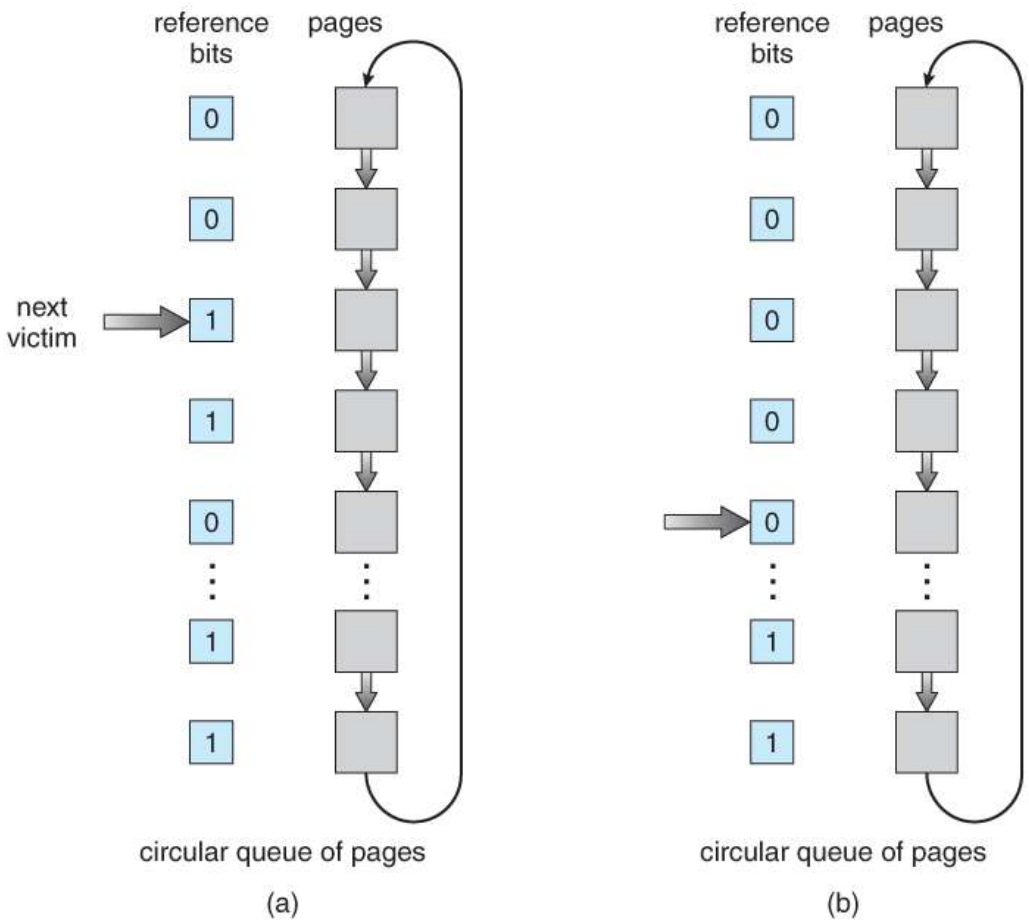
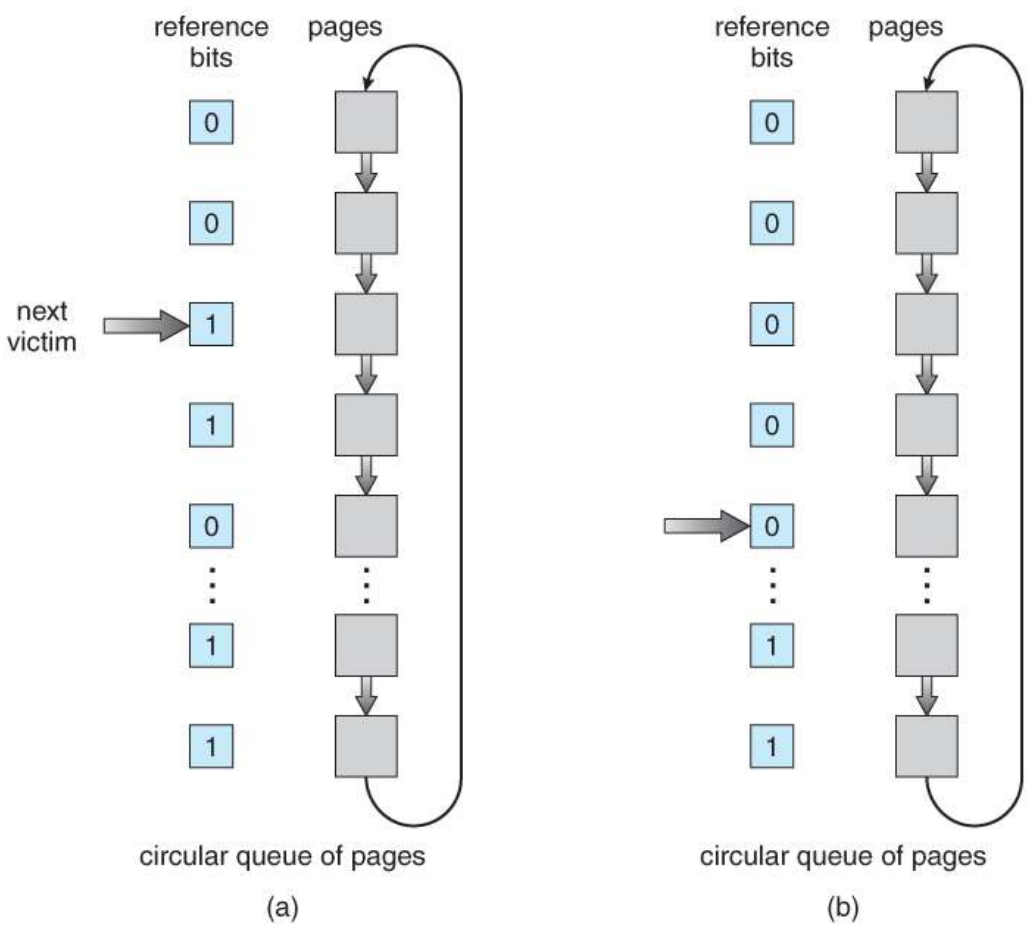
- OS keeps frames in a FIFO circular list
- On every memory access, the reference bit is set to 1
- On a page fault, the OS scans the list of page table, checking the reference bit of the frame:
  - If this is 0, it replaces the page and sets it to 1
  - If this is 1, it sets it to 0 (second chance) and move to the next frame

Second Chance Algorithm (Clock)



A raw partitioning into: young vs. old frames

Second Chance Algorithm (Clock)



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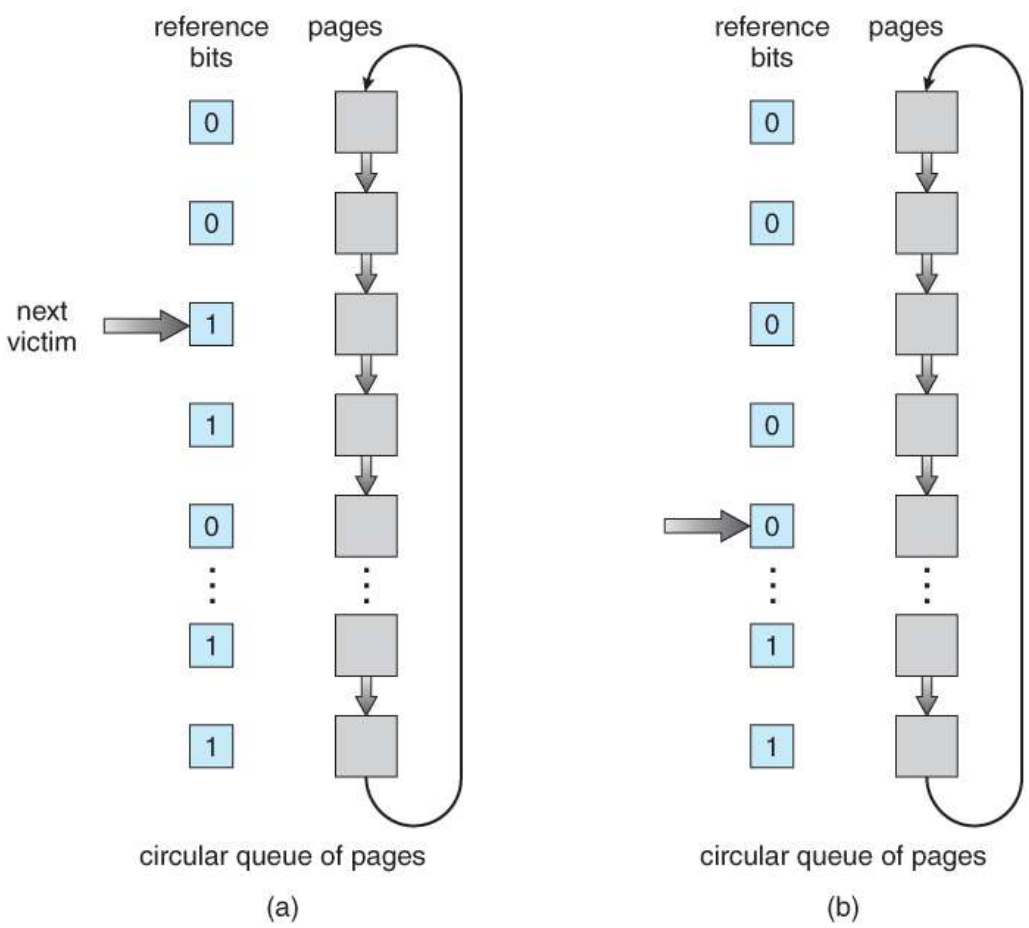

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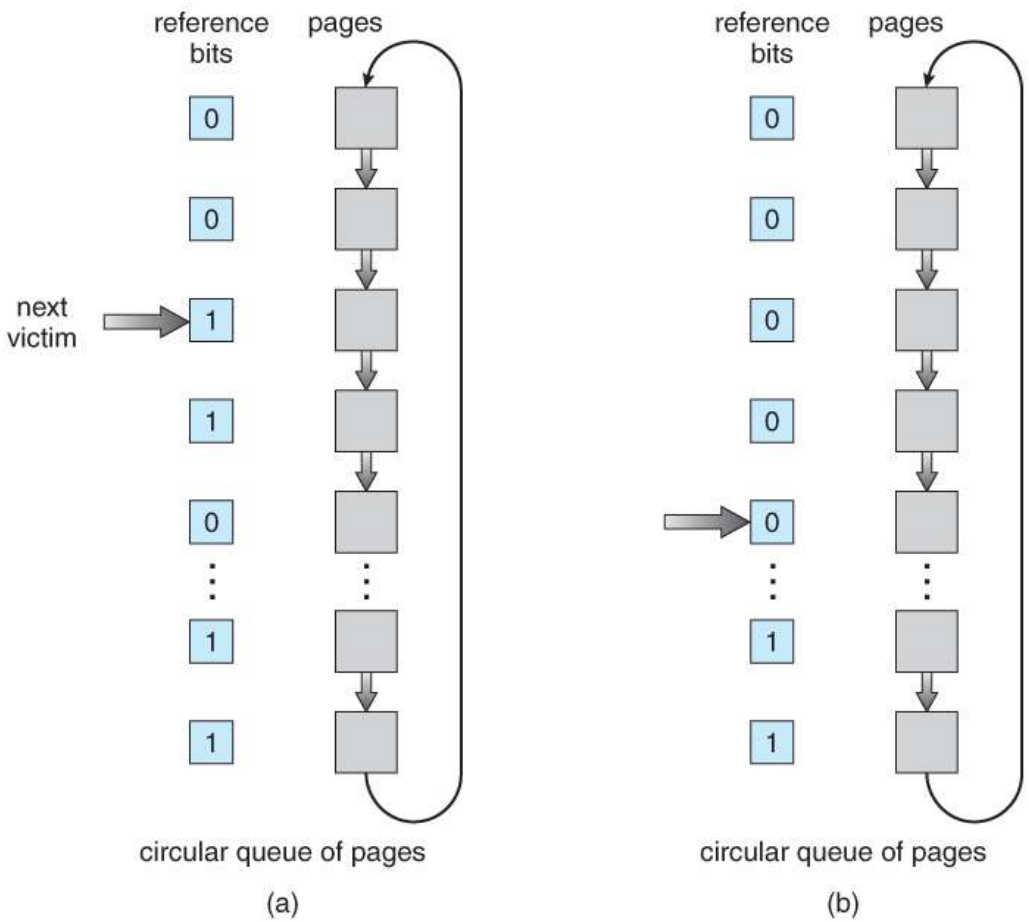

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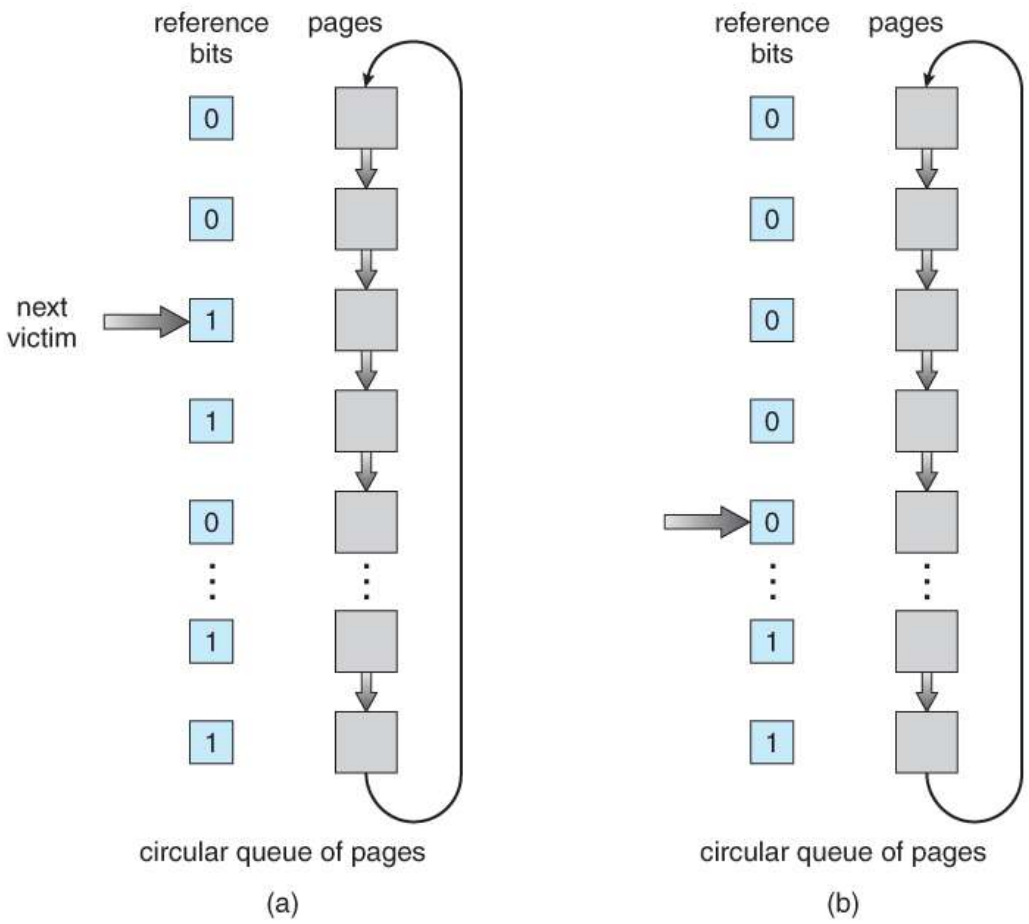

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This algorithm is also known as clock because it mimics the hands of a clock

Enhanced Second Chance Algorithm

- Page replacement generally involves 2 I/O operations:
  - write the evicted page back to disk
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- Page replacement generally involves 2 I/O operations:
  - write the evicted page back to disk
  - read the newly referenced page from disk
- Intuition: It is cheaper to replace a page which has not been modified, since the OS does not need to write this back to disk
- OS should give preference to paging-out un-modified frames
  - Yet, it can proactively write to disk modified frames for later

Enhanced Second Chance Algorithm

- HW keeps a modify bit (in addition to the reference bit)
  - 1 means the page has been modified (different from the copy on disk)
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Enhanced Second Chance Algorithm

- HW keeps a modify bit (in addition to the reference bit)
  - 1 means the page has been modified (different from the copy on disk)
  - 0 means the page is the same as the one stored on disk
- Use both the reference and modify bits (r, m) to classify pages into:
  - (0, 0): neither recently used nor modified;
  - (0, 1): not recently used, but modified;
  - (1, 0): recently used, but clean
  - (1, 1): recently used and modified

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- First, it looks for a (0, 0) frame, and if it can't find one, it makes another pass looking for a (0, 1), etc.
- The first page with the lowest numbered category is replaced
- The main difference between this algorithm and the standard clock is the preference for replacing clean pages if possible

Multiprogramming and Thrashing

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- Multiple processes can however run concurrently on a single-CPU system
- The degree of multiprogramming is not fixed apriori, yet it is driven by the locality reference (a.k.a. 90÷10 rule)
- This allows a system to load the working set (i.e., few pages) of many processes, thereby increasing the degree of multiprogramming

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- When the degree of multiprogramming is too high, active working sets of running processes may saturate the whole memory capacity

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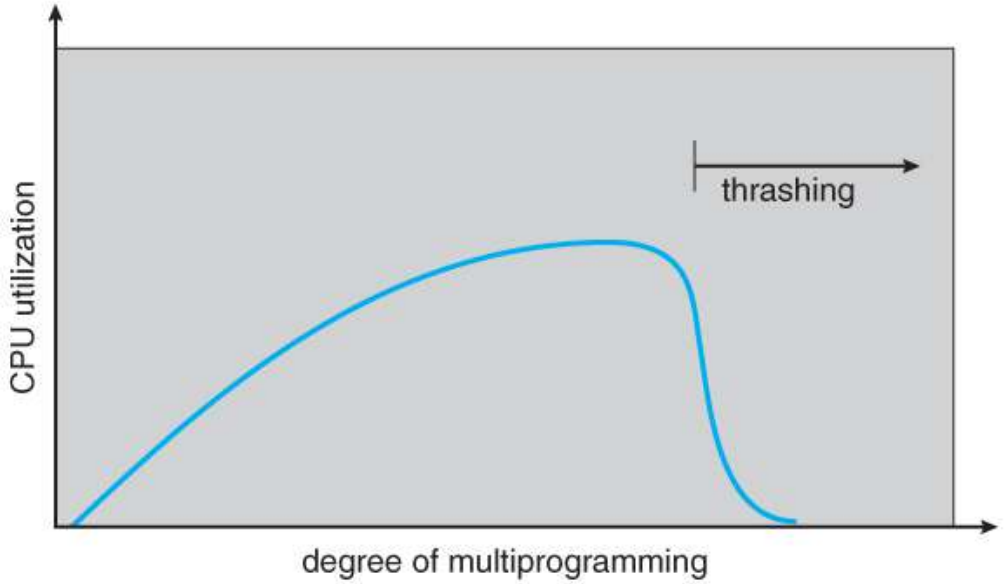
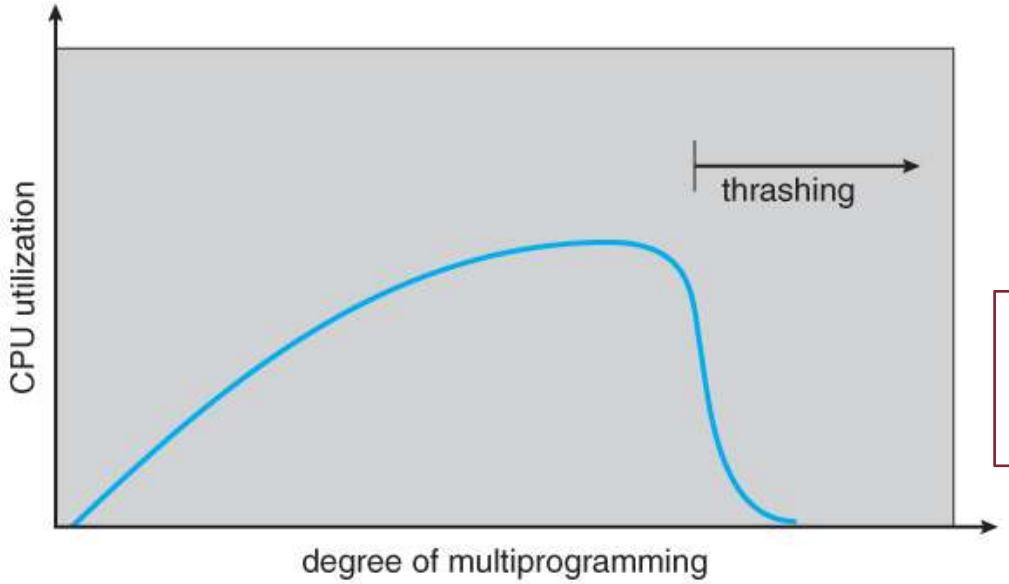
- When the degree of multiprogramming is too high, active working sets of running processes may saturate the whole memory capacity
- Thrashing → Memory is over-committed and pages are continuously tossed out while they are still in use
  - Memory access time approaches disk access time due to many page faults
  - Drastic degradation of performance

Multiprogramming and Thrashing



CPU utilization drops after a certain degree of multiprogramming

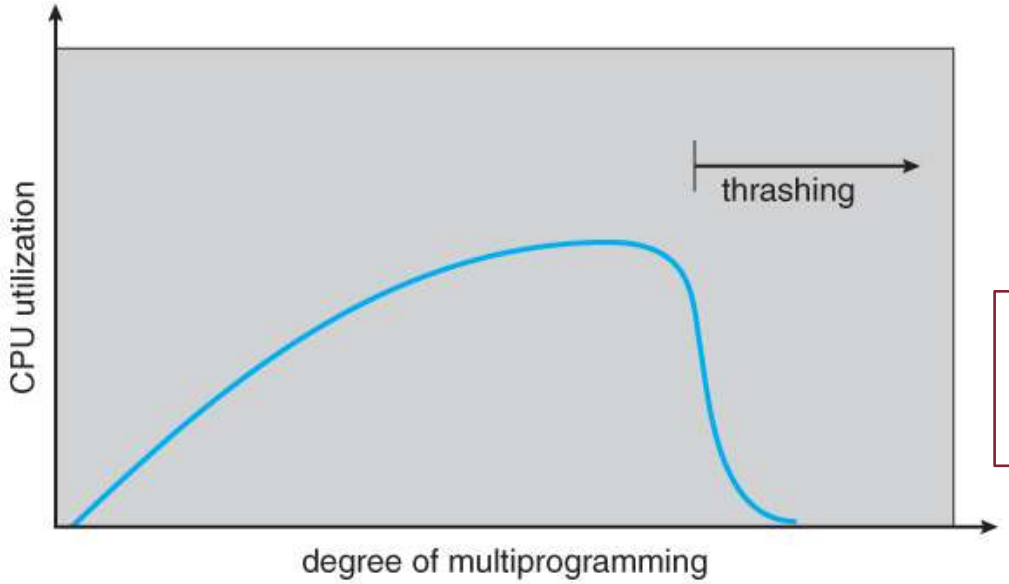
Multiprogramming and Thrashing



CPU utilization drops after a certain degree of multiprogramming

Eventually, also CPU-bound processes turn into I/O-bound ones (due to page faults)

Multiprogramming and Thrashing



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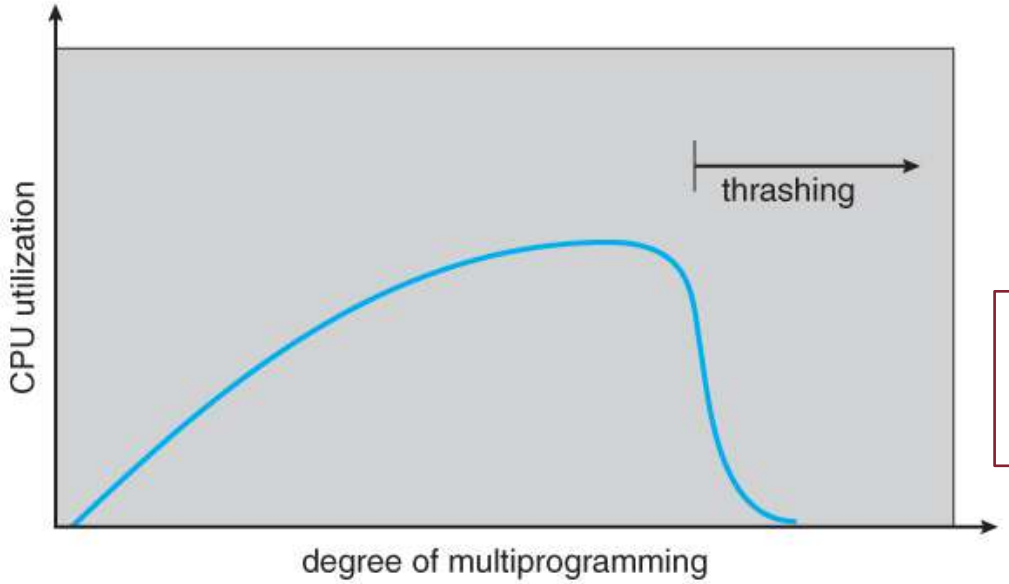

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Fixing the degree of multi-programming apriori may be a too inflexible option

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Global Allocation/Replacement

- All pages from all processes are in a single pool (single LRU queue)
- Upon page replacement, any page may be a potential victim, whether it currently belongs to the process seeking a free frame or not
- PRO: flexibility
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Local Allocation/Replacement

- Each process has its own fixed pool of frames
- Run only group of processes that fits in memory
- LRU replacement affects only each process' frames
- PRO: isolation
- CON: performance (a process may not be given enough memory)

Local Allocation/Replacement

m = number of available physical page frames

n = number of processes

S_i = size of the i-th process; $S = \sum_{i=1}^{n} S_i =$ total size of all processes

Equal Allocation/Replacement: $\frac{m}{n}$

Proportional Allocation/Replacement: $\frac{m*S_i}{S}$

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As allocations fluctuate over time, so does *m*
(processes must either be swapped out or not allowed to start if not enough frames)

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- In other words, the working set of a process may not be correlated with its memory footprint

Matching the Working Set

- Goal → Give each process enough frames to contain its working set
  - Informally, the working set is the set of pages the process is using "right now"
  - More formally, it is the set of all pages that the process has referenced during the past T units of time (e.g., seconds)

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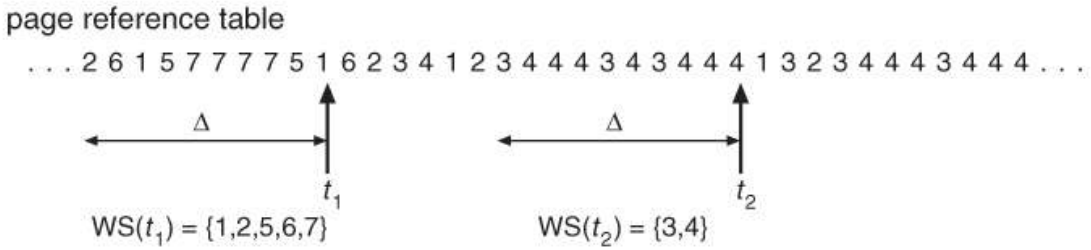
  - More formally, it is the set of all pages that the process has referenced during the past T units of time (e.g., seconds)
- How does the OS pick T?
  - 1 page fault takes order of 10 msecs to be served
  - 10 msecs ~ 10 million instructions
  - T needs to account for a lot more than 10 million instructions

Determining the Working Set



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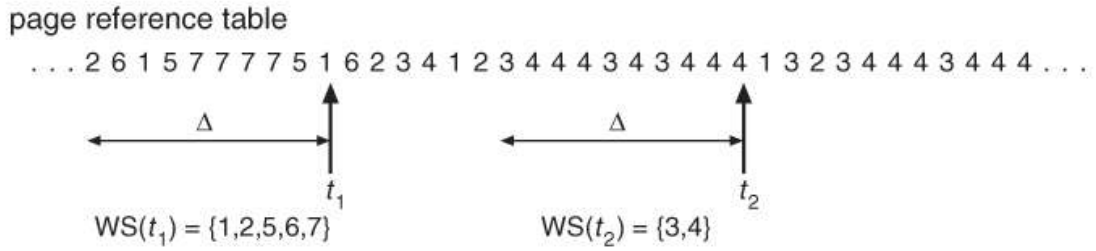

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it does not encompass all of the pages of the current locality

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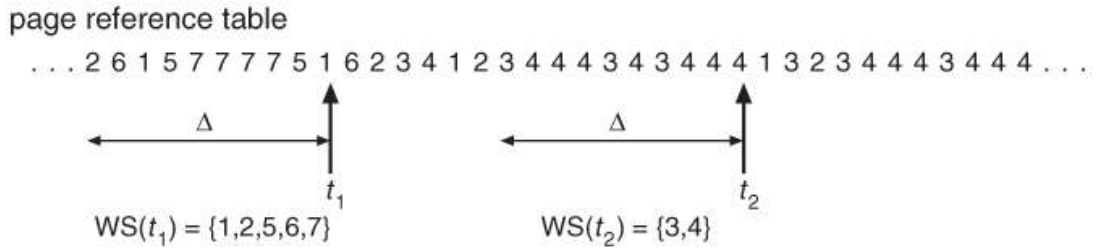

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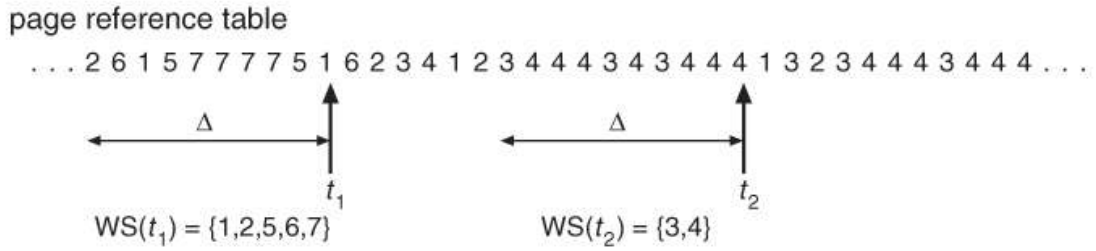

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Exact tracking is expensive: update the working set at each memory access

Approximating the Working Set

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- To avoid the overhead of keeping a list of the last Δ referenced pages, the working set is often implemented with sampling
- Every k memory references (e.g., $k = 1{,}000$), consider the working set to be all pages referenced within *that* period of time

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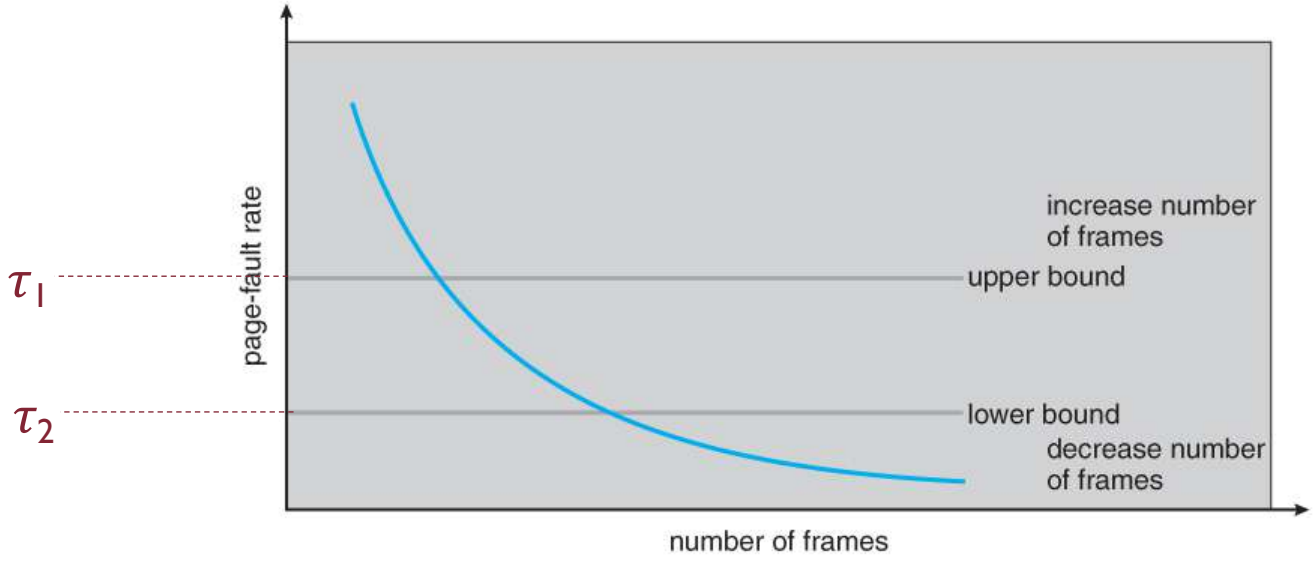

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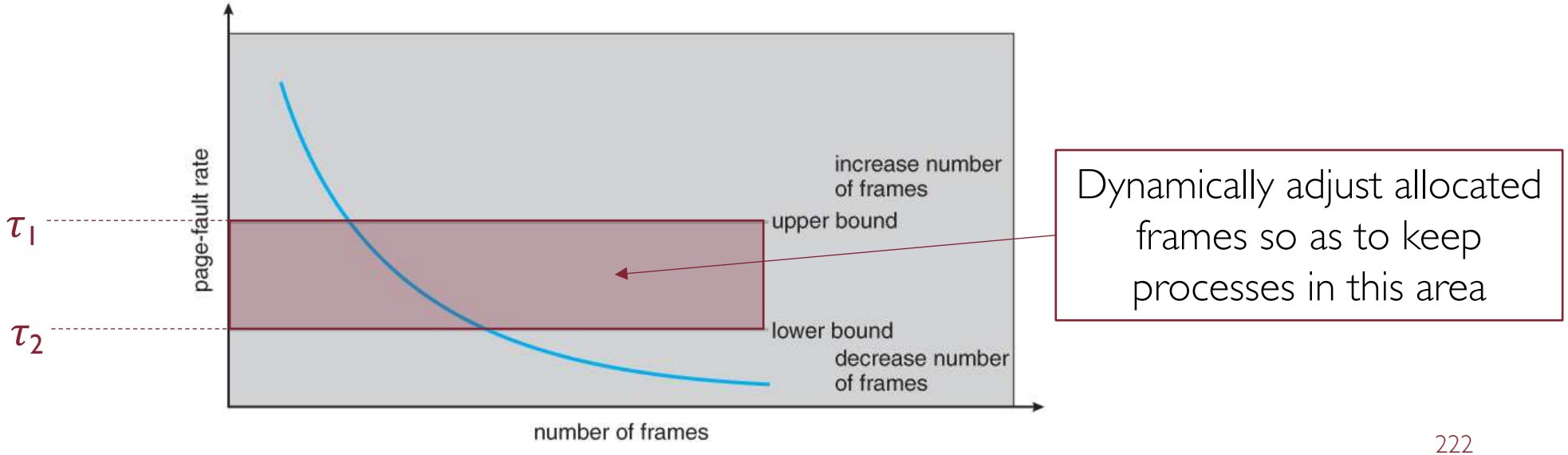


Kernel Memory

- So far, we only considered memory allocation for user processes
- But kernel needs memory to store things too: code and data structures like PCB, page tables, etc.
- Kernel does not use any of the advanced mechanisms seen so far
  - No paging → what if a page fault occurs for the kernel?

Kernel Memory: Buddy Allocator

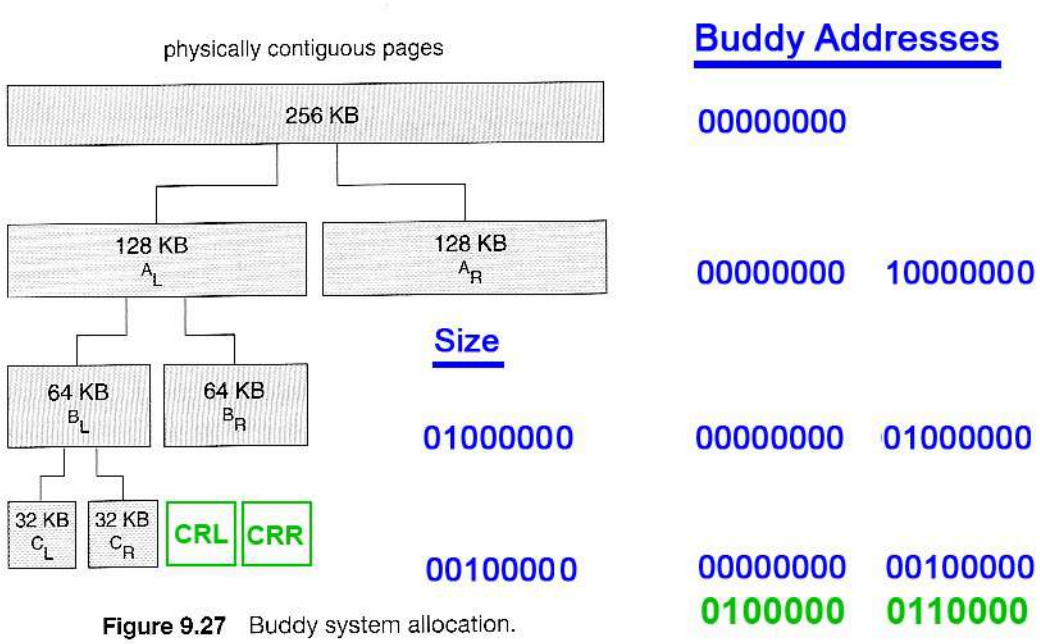
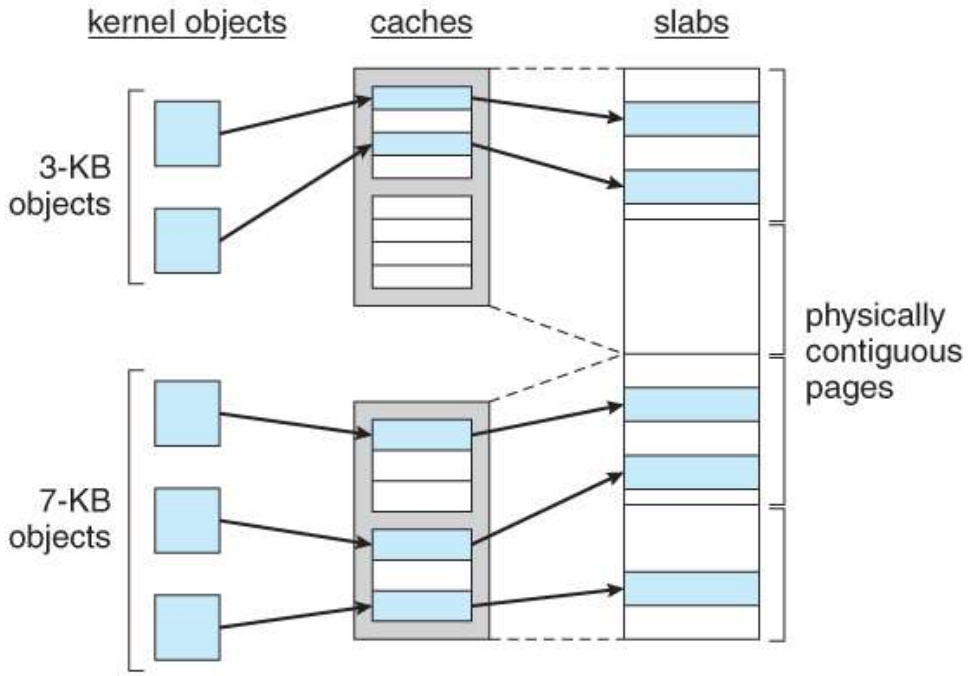


Figure 9.27 Buddy system allocation.

- Allocates memory using a power of 2 allocator (e.g., 4KiB, 8KiB, 16KiB), rounding up to the next nearest power of two if necessary
- If a block of the correct size is not available, then one is formed by (repeatedly) splitting the next larger block in two
- Can lead to internal fragmentation

Kernel Memory: Slab Allocator



- Group of objects of the same size in a slab
- Object cache points to one or more slabs
- Separate cache for each kernel data structure (e.g., PCB)
- No internal fragmentation
- Used in Solaris and Linux

Page Sizes

- Reasons for small pages?

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  - Higher degree of multiprogramming
- Reasons for large pages?
  - Smaller page table size (i.e., smaller number of page table entries)
  - Fewer page faults (locality reference)
  - Amortizes disk overhead (reading a 1 KiB page from disk takes approximately the same as reading an 8KiB one)

Summary of Page Replacement

- The choice of page replacement algorithm is crucial when physical memory is limited
  - All algorithms approach to the optimum as the physical memory allocated to a process approaches to the virtual memory size

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  - All algorithms approach to the optimum as the physical memory allocated to a process approaches to the virtual memory size
- The more processes running concurrently, the less physical memory each one can have
- The OS must choose how many processes (and the number of frames per process) can share memory simultaneously