Memory Management (Virtual Memory)

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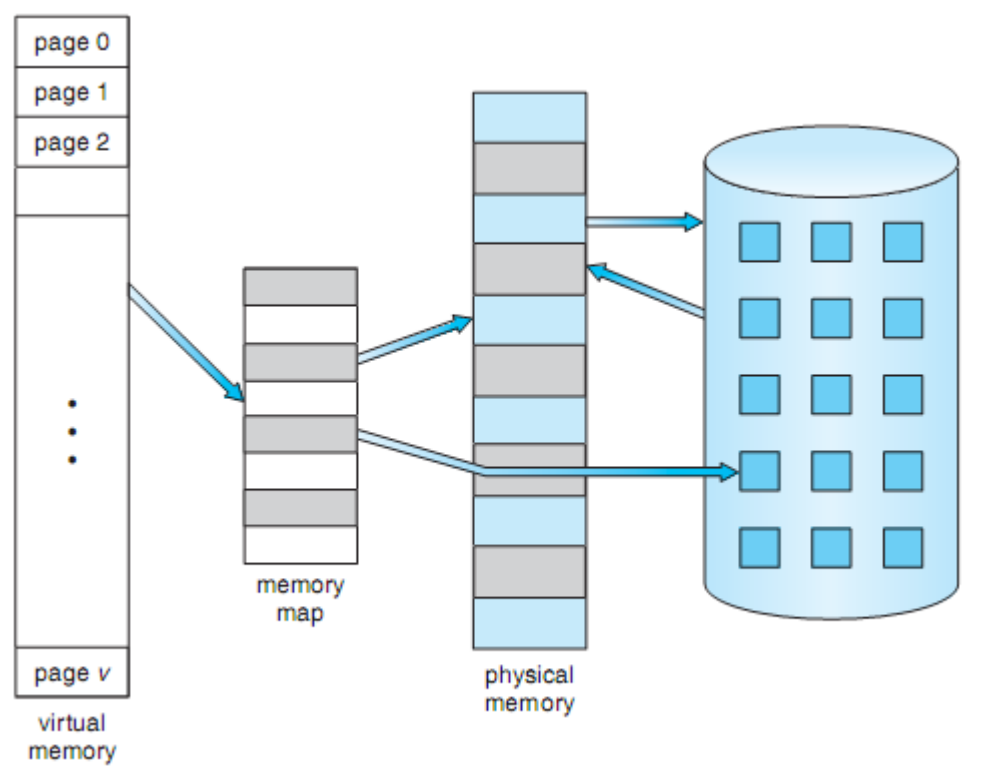
Summer 2016

Background

- It is not required to load all the program into main memory
- Virtual memory separates logical memory from physical memory



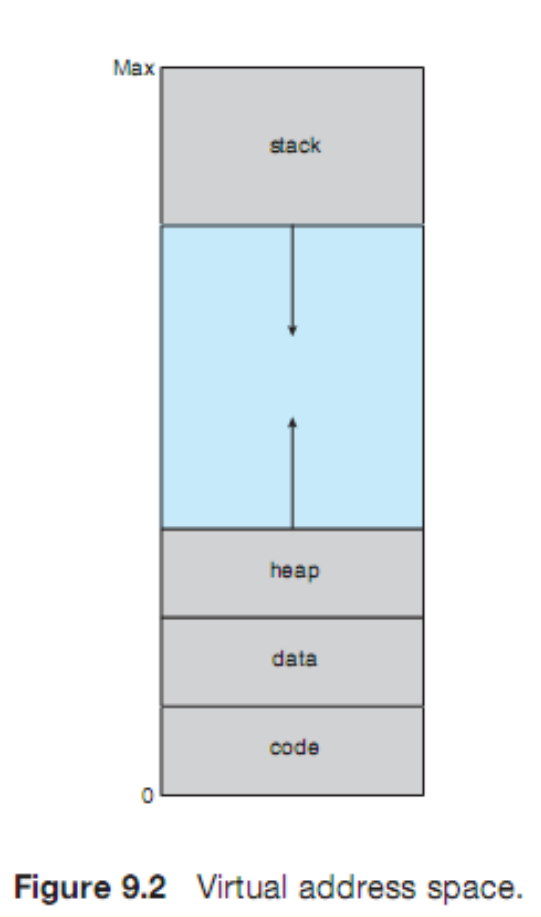
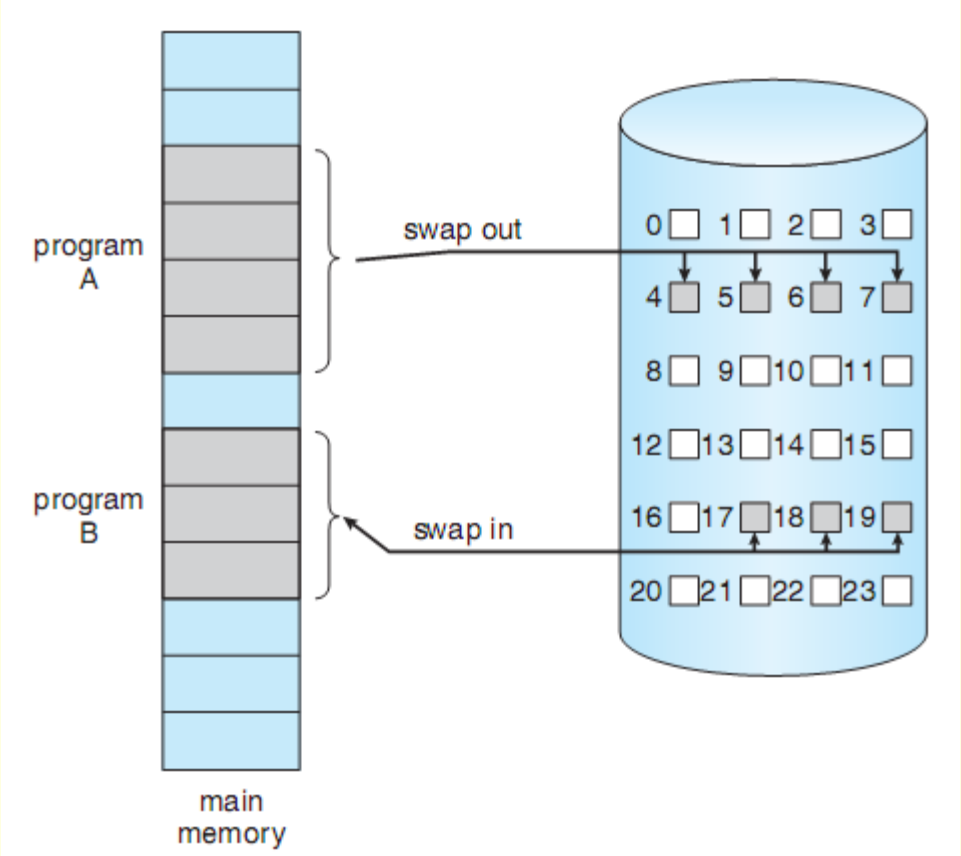


Figure 9.2 Virtual address space.

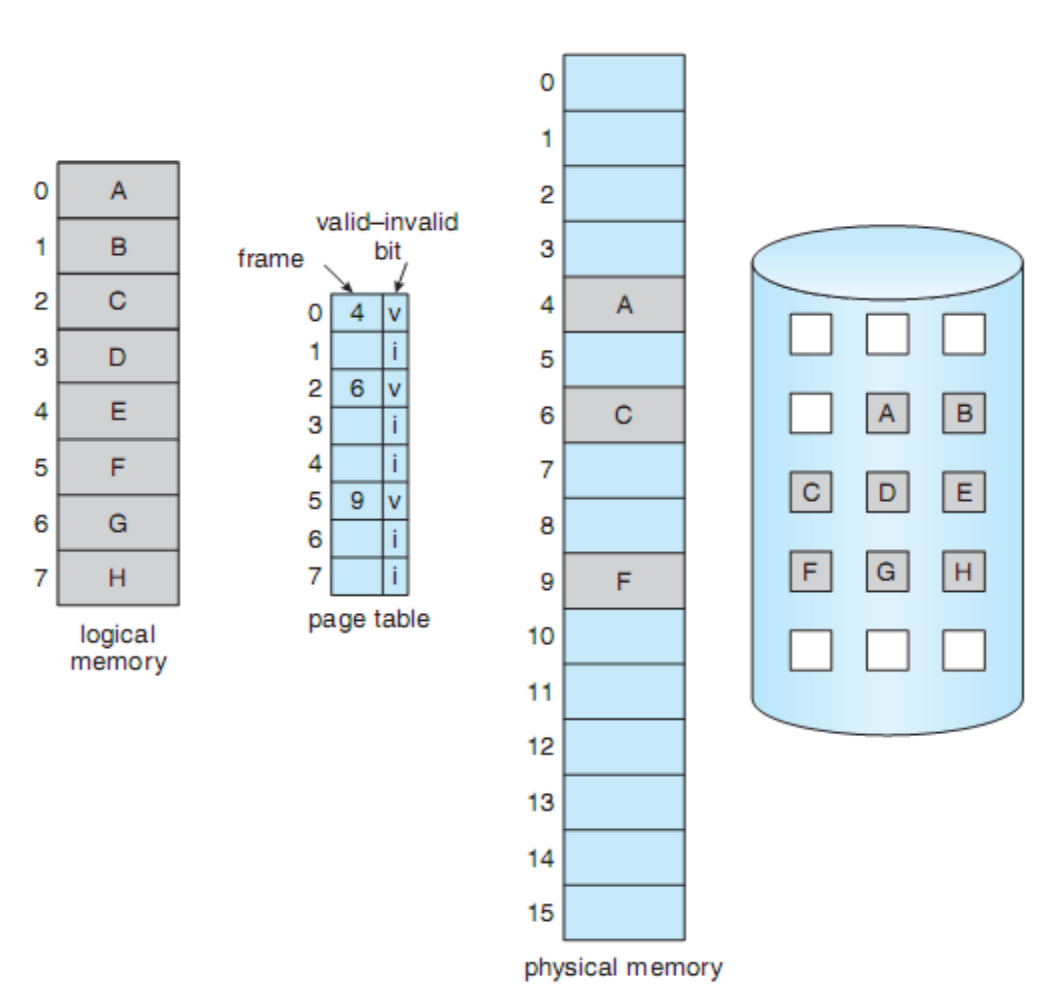
Demand Paging

- Pages are only loaded when they are demanded during program execution (using a *pager*)
- Swapper: manipulates entire processes
- Pager: manipulates individual pages of a process

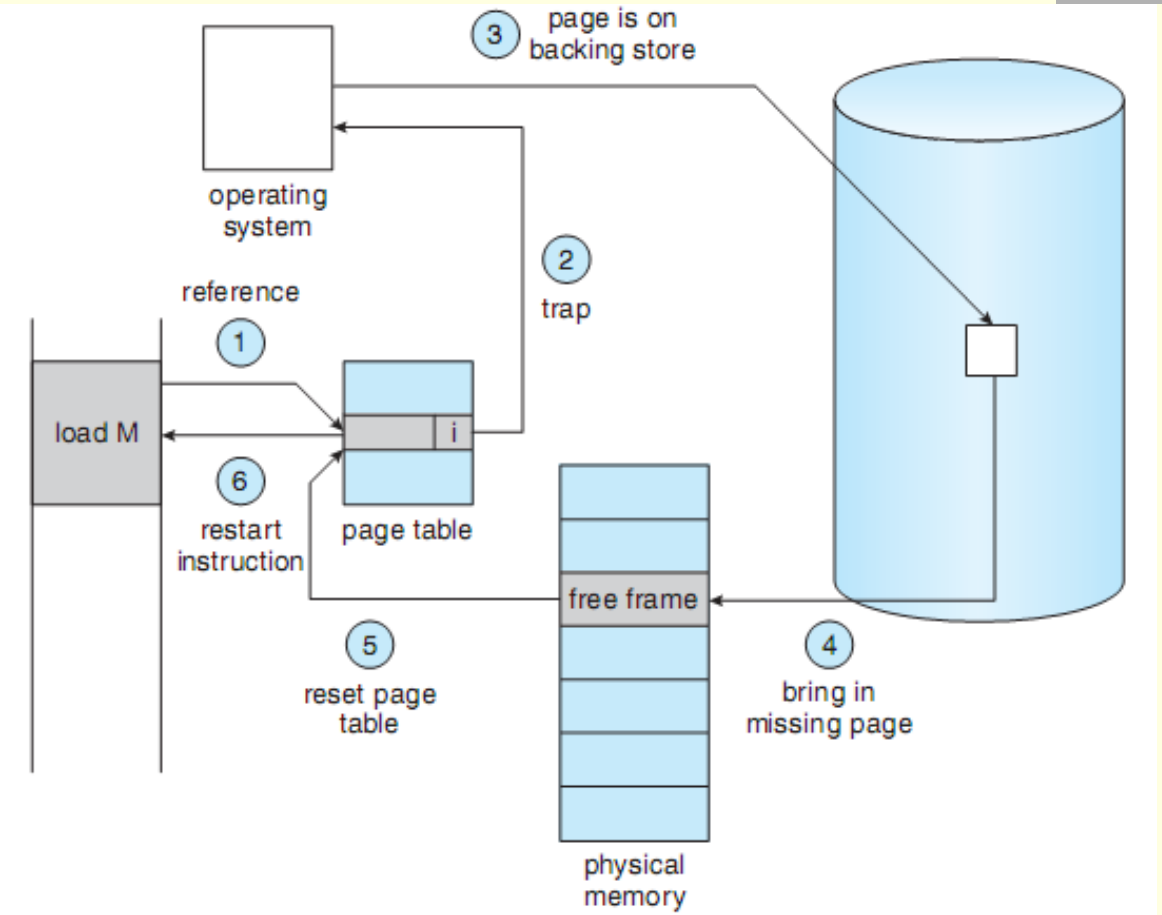


Demand Paging

- If the pager guesses right the required pages at load time the execution can proceed normally



Handling a Page Fault



Handling a Page Fault

- Whether are all instructions restartable?
  - IBM 370→ MVC with overlapping addresses
  - VAX & Motorola 68000→ MOV (R2)+, -(R3)
    - The microcode computes and attempts to access both ends of source and destination blocks
    - Using temporary registers to hold the values of overwritten locations
- *Locality of reference* for instructions
- The performance of demand paging can highly affect the feasibility of using paging in a system

Performance of Demand Paging

- *Effective access time = (1-p)× ma + p× page fault time*
- Major components of page fault service time
  - Service the page fault interrupt
  - Read in the page
  - Restart the process

Effective access time = (1-p)× ma + p× page fault time

Computing the page fault time

1. Trap to the operating system.
2. Save the user registers and process state.
3. Determine that the interrupt was a page fault.
4. Check that the page reference was legal and determine the location of the page on the disk.
5. Issue a read from the disk to a free frame:
   a. Wait in a queue for this device until the read request is serviced.
   b. Wait for the device seek and/or latency time.
   c. Begin the transfer of the page to a free frame.
6. While waiting, allocate the CPU to some other user (CPU scheduling, optional).
7. Receive an interrupt from the disk I/O subsystem (I/O completed).
8. Save the registers and process state for the other user (if step 6 is executed).
9. Determine that the interrupt was from the disk.
10. Correct the page table and other tables to show that the desired page is now in memory.
11. Wait for the CPU to be allocated to this process again.
12. Restore the user registers, process state, and new page table, and then resume the interrupted instruction.

Performance of Demand Paging

- *Effective access time = (1-p)× ma + p× page fault time*
- Major components of page fault service time
  - Service the page fault interrupt (1 to 100 μs)
  - Read in the page: 8 ms (ignoring device queueing time)
    - Hard disk latency: 3 ms
    - Seek time: 5 ms
    - Transfer time: 0.05 ms
  - Restart the process (1 to 100 μs)
  - Assuming ma = 200 ns

$$\begin{aligned}\text{effective access time} &= (1-p) \times (200) + p\ (8 \text{ milliseconds}) \\ &= (1-p) \times 200 + p \times 8{,}000{,}000 \\ &= 200 + 7{,}999{,}800 \times p.\end{aligned}$$

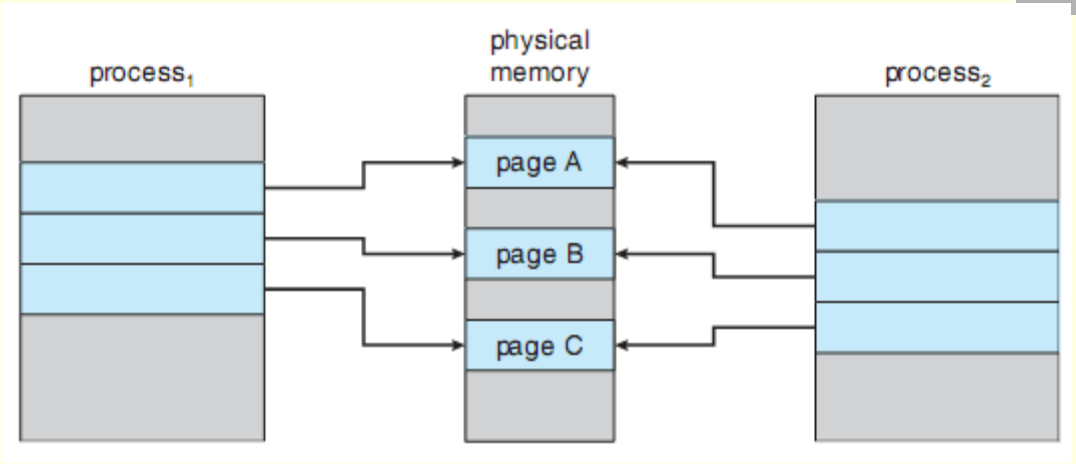
  - P= 0.001 ➔ eat = 8.2 μs ➔ computer is slowed down by a factor of 40
  - For 10% slow down: $220 > 200 + 7{,}999{,}800 \times p,$ ➔ $p < 0.0000025.$

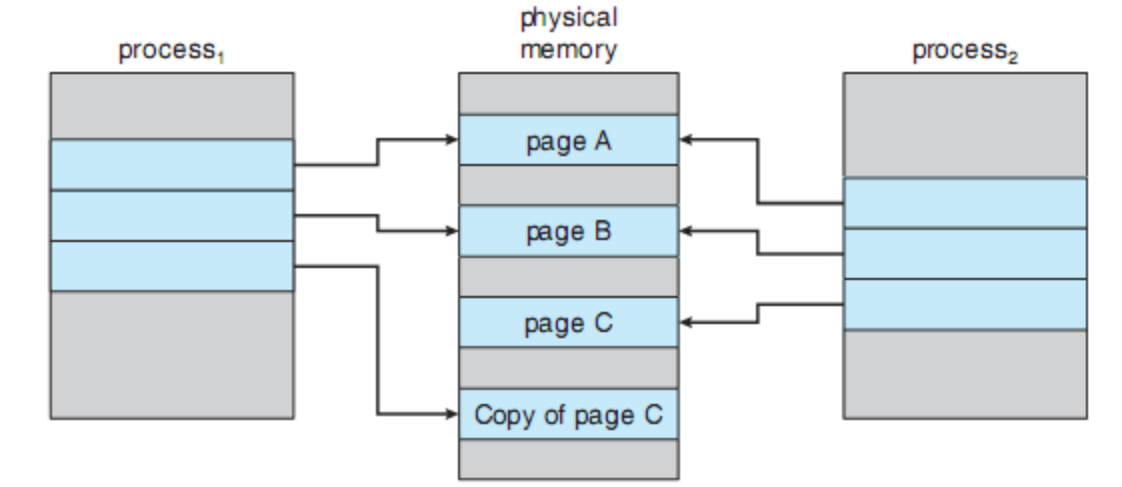
How demand paging can be improved?

An additional aspect of demand paging is the handling and overall use of swap space. Disk I/O to swap space is generally faster than that to the file system. It is faster because swap space is allocated in much larger blocks, and file lookups and indirect allocation methods are not used (Chapter 12). The system can therefore gain better paging throughput by copying an entire file image into the swap space at process startup and then performing demand paging from the swap space. Another option is to demand pages from the file system initially but to write the pages to swap space as they are replaced. This approach will ensure that only needed pages are read from the file system but that all subsequent paging is done from swap space.

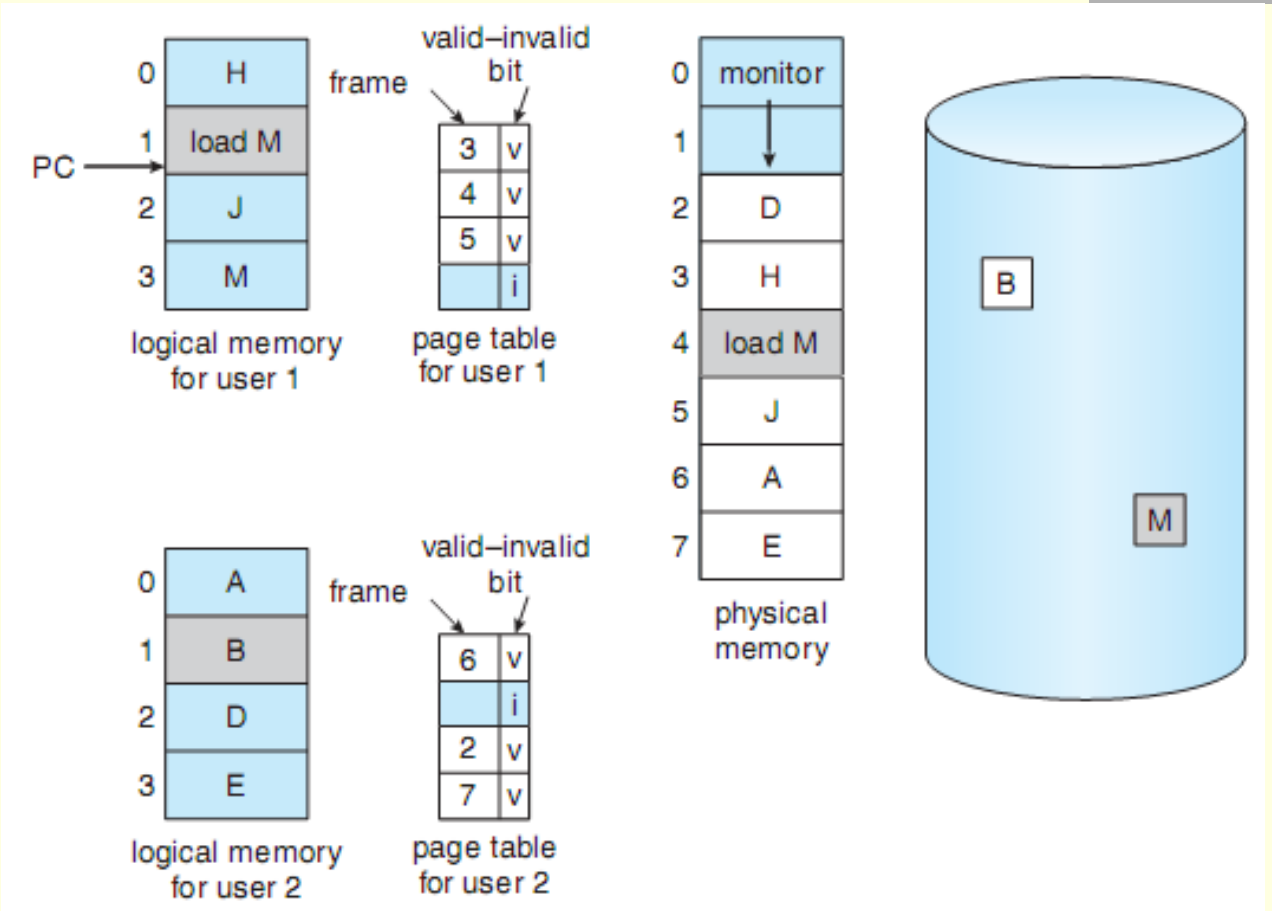
Some systems attempt to limit the amount of swap space used through demand paging of binary files. Demand pages for such files are brought directly from the file system. However, when page replacement is called for, these frames can simply be overwritten (because they are never modified), and the pages can be read in from the file system again if needed. Using this approach, the file system itself serves as the backing store. However, swap space must still be used for pages not associated with a file; these pages include the stack and heap for a process. This method appears to be a good compromise and is used in several systems, including Solaris and BSD UNIX.

Copy-On-Write



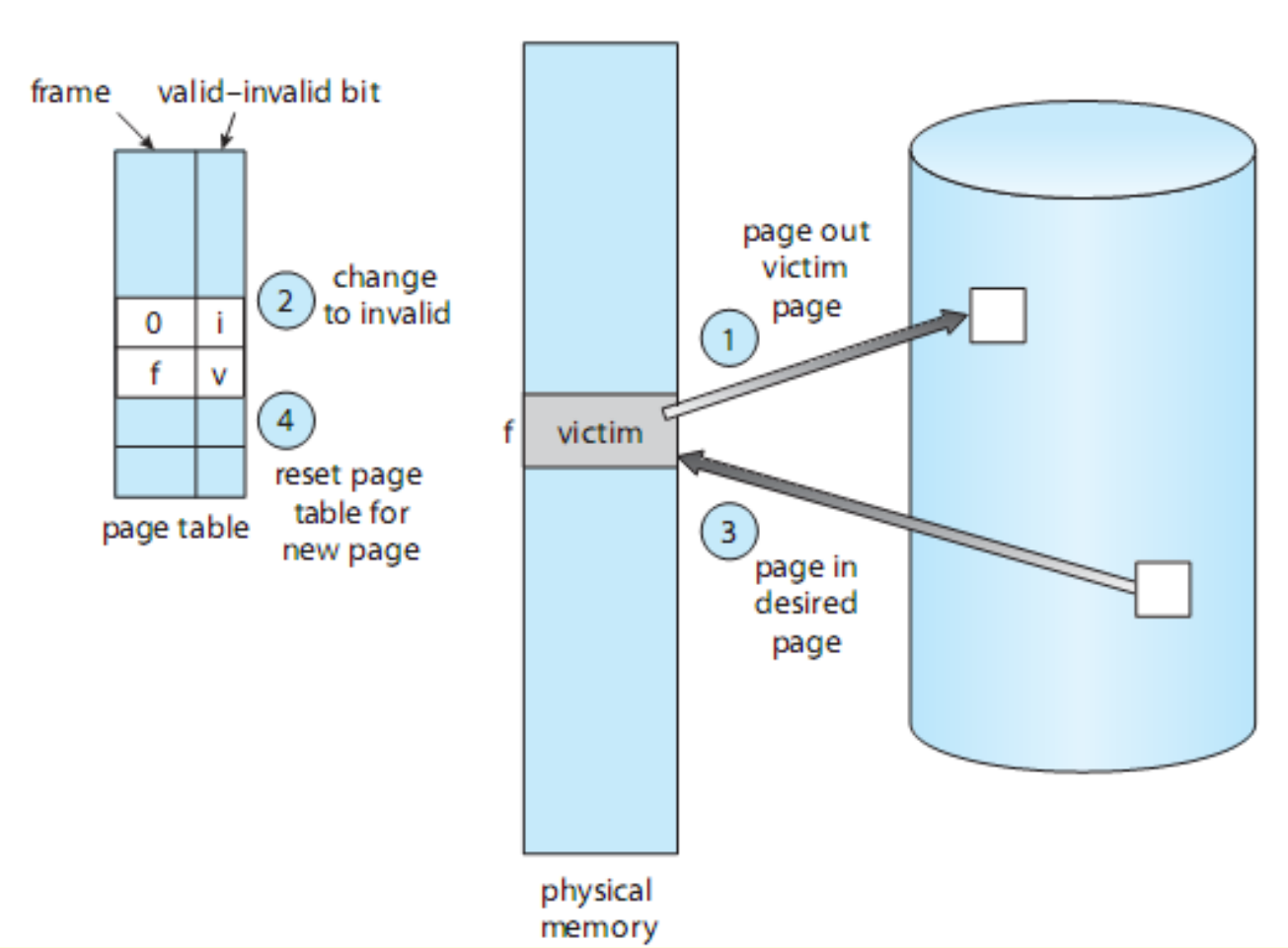


Need for Page Replacement



Basic Page Replacement

- Pa



Basic Page Replacement

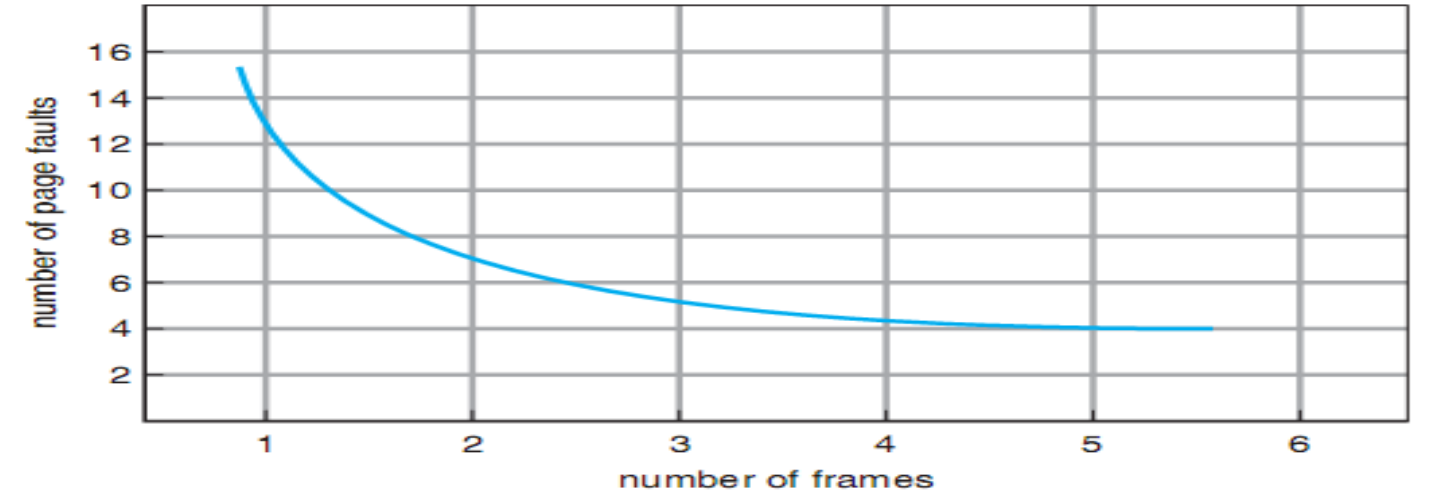
- Reducing the overhead
  - Modify (Dirty) bit: Pages not modified and read-only pages need not be written to the disk
- Two important matters
  - How many frames should be allocated to each process?
  - Which page should be replaced to reduce the page fault probability?
- Reference string

Reference String

- Address sequence

  0100, 0432, 0101, 0612, 0102, 0103, 0104, 0101, 0611, 0102, 0103, 0104, 0101, 0610, 0102, 0103, 0104, 0101, 0609, 0102, 0105

- Page size: 100 bytes
- Reference string: 1, 4, 1, 6, 1, 6, 1, 6, 1, 6, 1
- 3 frames for the process ➔ 3 page faults
- 1 frame ➔ 11 page faults

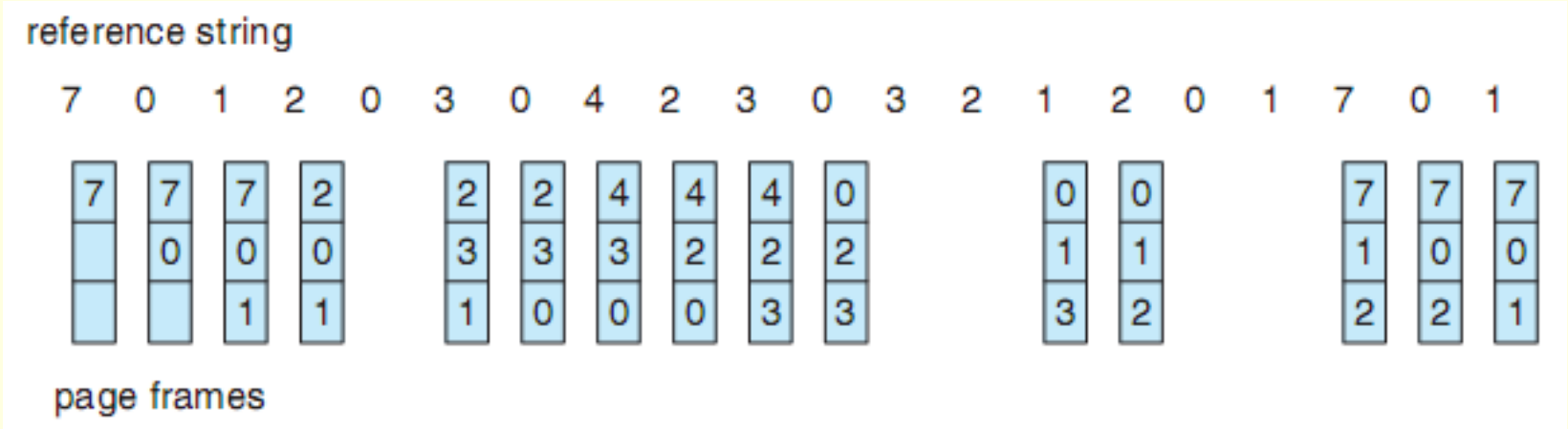


Page Replacement Algorithms

- Sample reference string:

7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2, 1, 2, 0, 1, 7, 0, 1

- FIFO page replacement



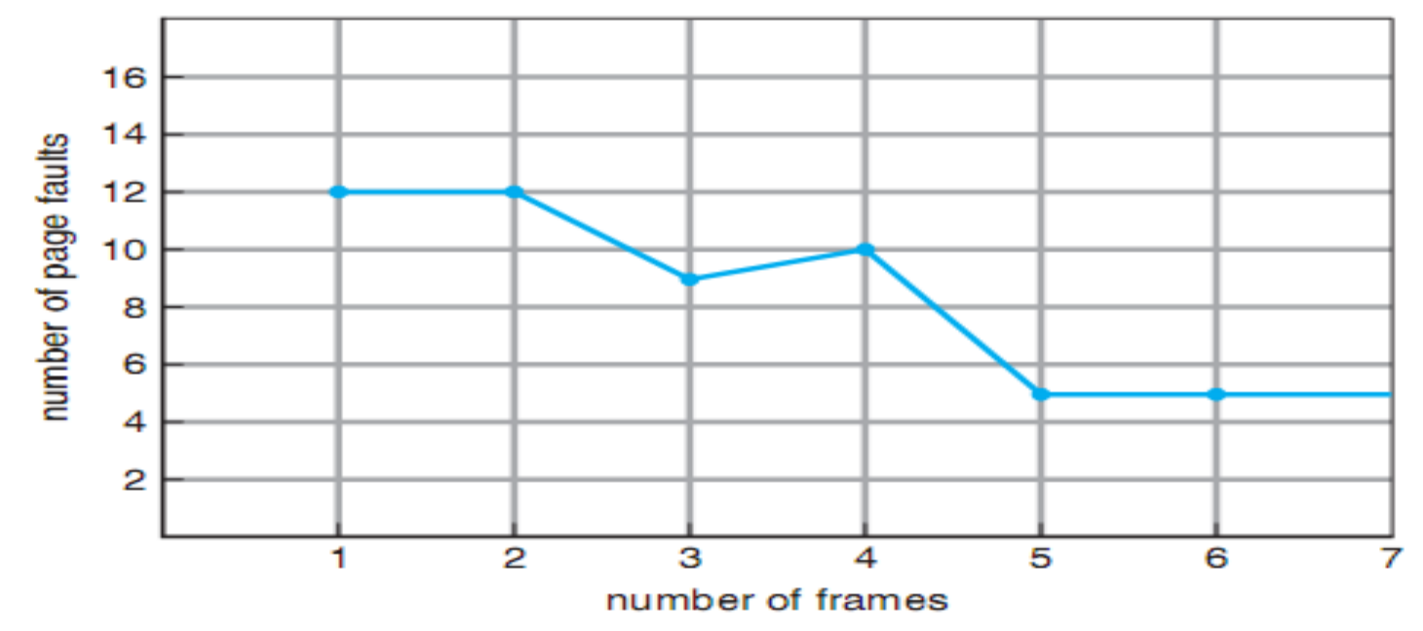
- 15 page faults

Belady's Anomaly and FIFO Page Replacement

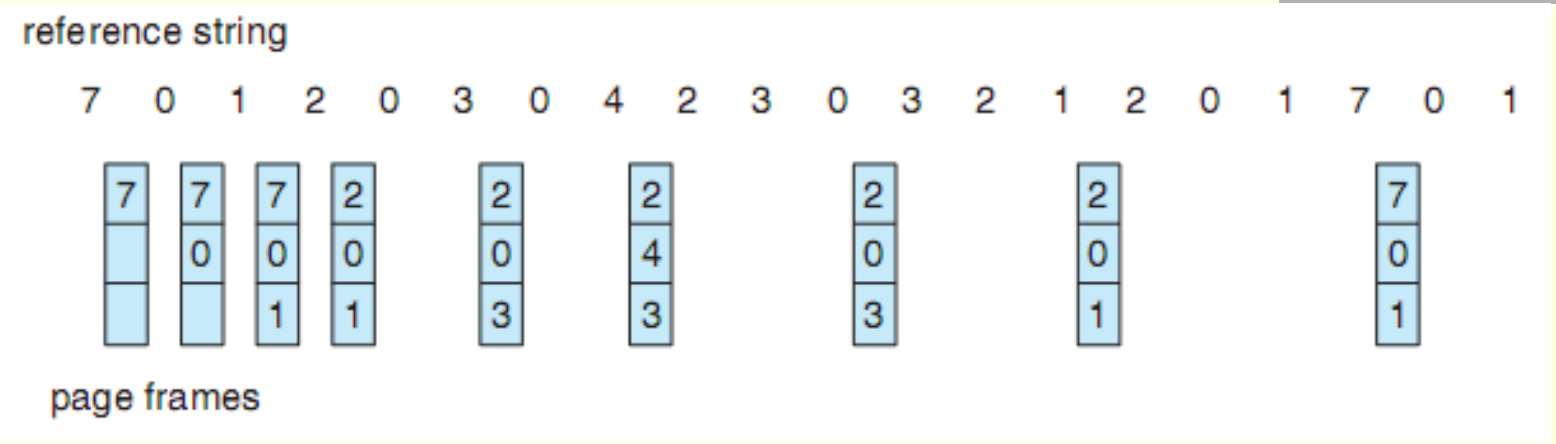
- Sample reference string:

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

- Page faults with 1, 2, 3, 4, 5, and 6 frames?



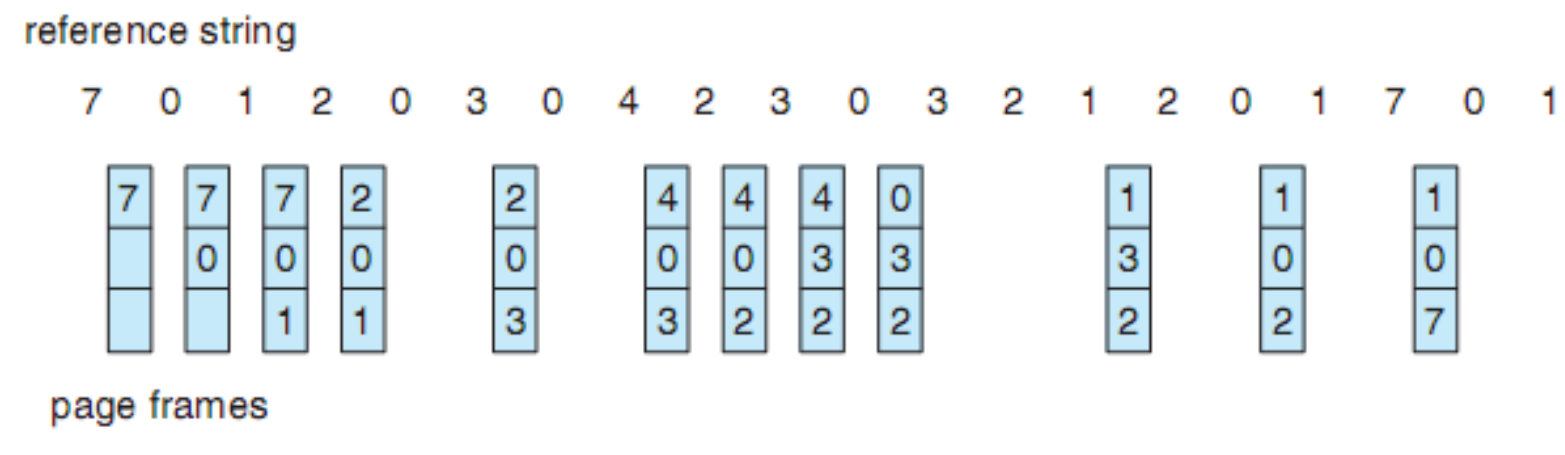
Optimal Page Replacement



- Reduces 15 page faults of FIFO to 9 page faults
- Difficult to implement
- Mainly used for comparison study
- Belady's anomaly?

LRU Page Replacement

- LRU: Least-Recently Used



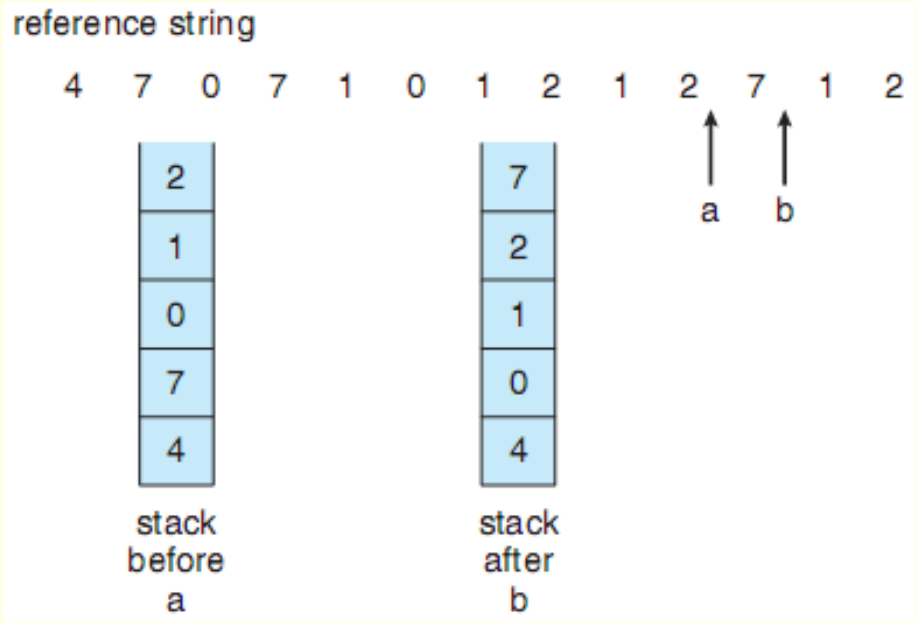
- 12 page faults
- Implementation: according to the last time of access to each page!!!

LRU Implementation

- Hardware support is required
- Counters
  - A logical clock or counter is incremented on each memory access
  - This value is copied in the time-of-use field in the page table entry
  - Problems
    - Search for the smallest time value
    - A write to memory for each memory access
    - Maintaining the information when the page table is changed due to CPU scheduling
    - Clock overflow

LRU Implementation

- Stack



- Stack is implemented as a doubly linked-list
- Each update requires changing 6 pointers
- The page number at the bottom of the stack is the LRU page
- Belady's anomaly?
  - The set of pages in *n* frames is a subset of the set of pages in *n*+1 frames

LRU-Approximation Page Replacement

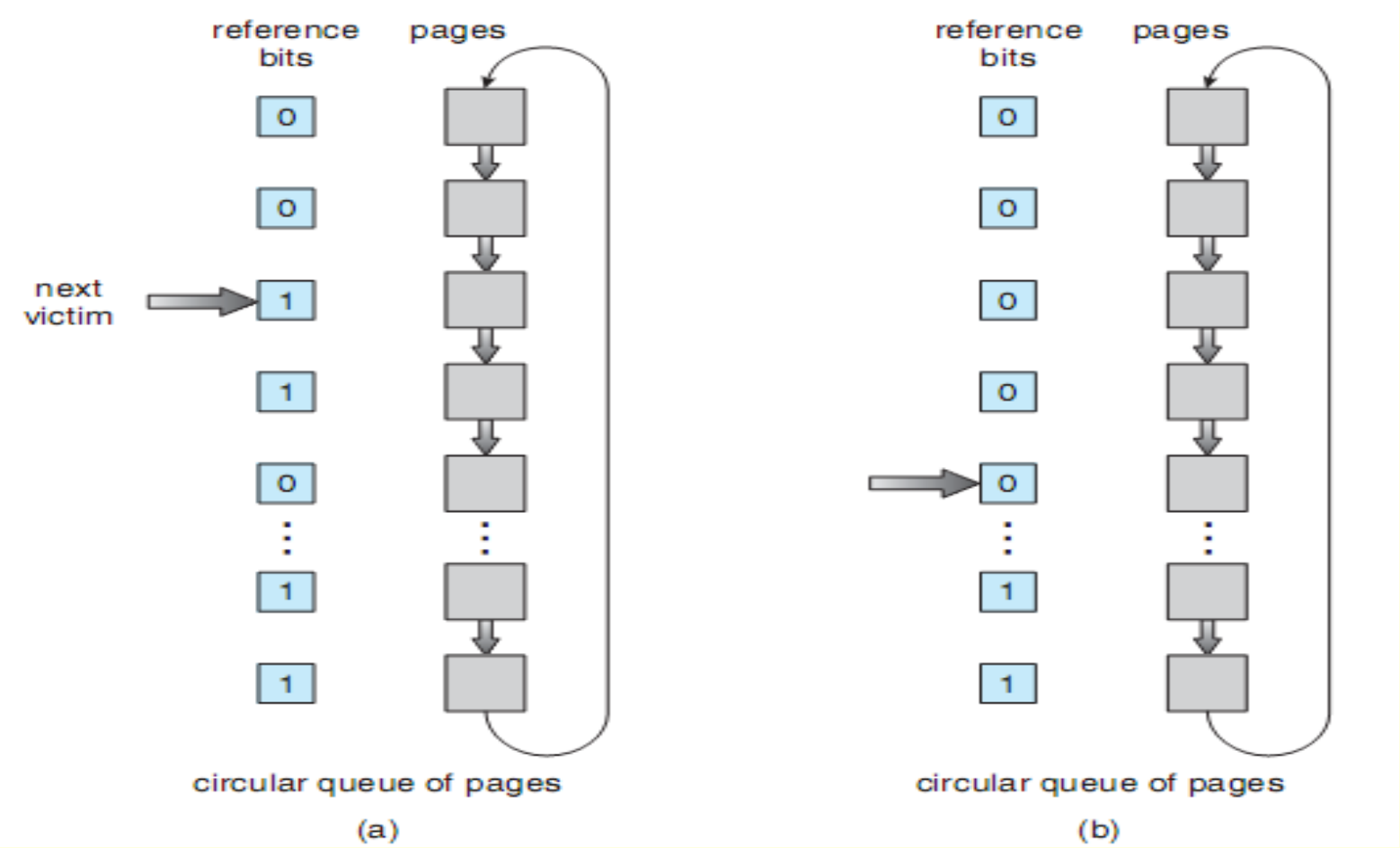
- The updating of clock fields or stack for every memory reference requires an interrupt!!
- Few computers provide sufficient hardware for implementing LRU
- A basic method
  - Using a reference bit
    - Hardware should set this bit on each access
    - This method does not specify the order of using the pages

Additional-Reference-Bits Algorithm

- Recording the reference bits at regular intervals
- Assume an 8-bit byte for each page in a table in memory
- At regular intervals, a timer interrupt activates the OS to shifts the reference bit into the high-order bit of each page
- The corresponding register contains the history of accessing the page for the last 8 time periods
- The smaller the unsigned value of the register, the LRU page
- Problems
  - Searching among the values
  - Equal values will result an approximation of LRU
    - Replace all equal smallest values or according to FIFO order

Second-Chance Algorithm

- Degenerates to FIFO if all bit are set



Enhanced Second-Chance Algorithm

- Considering both reference-bit and modify-bit

1. (0, 0) neither recently used nor modified—best page to replace
2. (0, 1) not recently used but modified—not quite as good, because the page will need to be written out before replacement
3. (1, 0) recently used but clean—probably will be used again soon
4. (1, 1) recently used and modified—probably will be used again soon, and the page will be need to be written out to disk before it can be replaced

- The circular queue may have to be scanned several times before finding a page to be replaced

Counting-Based Page Replacement

- LFU (Least-Frequently Used)
  - *Problem*: A page is used heavily during the initial phase but then is never used again
  - *Solution*: Shift the counts right by one bit at regular intervals
- MFU (Most-Frequently Used)
  - The page with the smallest count was probably just brought in and has yet to be used
- Properties
  - Expensive to implement
  - Weakly approximate OPT

Page-Buffering Algorithms

- Beside page-replacement algorithms
- Systems commonly keep a pool of frames
  - Page fault ➔ Selecting a victim frame ➔ Read in the page into a free frame before writing out the victim to restart the process sooner ➔ When the victim is later written out, the free frame is added to the pool
  - *Expansion*: Maintaining a list of modified pages ➔ Writing out a modified page whenever the paging device is idle and reset the modify bit ➔ Higher probability that a page will be clean.

Frame Allocation

- The minimum number of frames for each process depends strongly on the system architecture:
  - A machine that all memory-reference instructions have only one memory address
    - Requires 2 pages, at least
  - A machine that all memory-reference instructions can have one indirect memory address
    - At least 3 pages is required
  - A machine that memory-reference instructions can have two indirect memory address
    - At least 6 pages is needed
  - What if the instructions can be of more than one word?
  - What about multiple levels of indirection? Any limit?
  - Minimum number of frames/process is defined by the architecture
  - Maximum number of frames/process is defined by the amount of available physical memory (If all memory is used for indirection)

Frame Allocation Algorithms

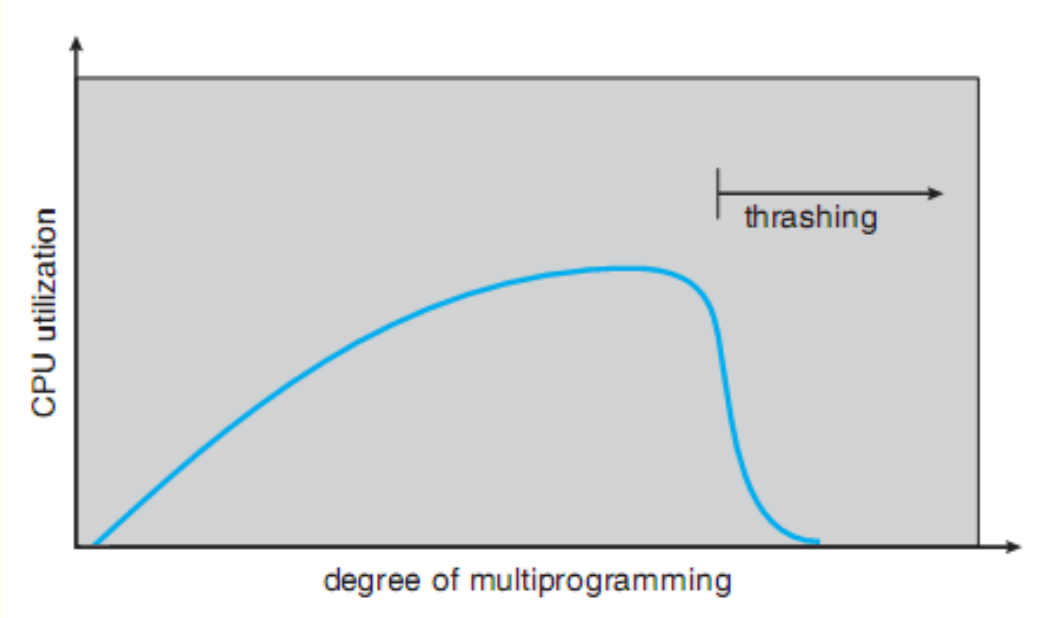
- *m* frames, *n* processes
- *Equal allocation*: *m*/*n* frames per process
- *Proportional allocation*:
  - s_i: size of the virtual memory for process p_i
  - $S = \Sigma s_i$
  - $a_i = s_i/S \times m$
  - a_i should be larger than minimum number of frames per process
- Priority can also be a parameter for frame allocation

Global vs. Local Allocation

- Global replacement: replaces a page among all pages in the memory
  - A process cannot manage its own page fault rate
  - Higher throughput
- Local replacement: replaces a page of itself
  - Does not use less used pages of memory

Thrashing

- A process is thrashing if it is spending more time paging than executing
- If the number of frames of a process falls below the number of required frames by the computer architecture, it will thrash



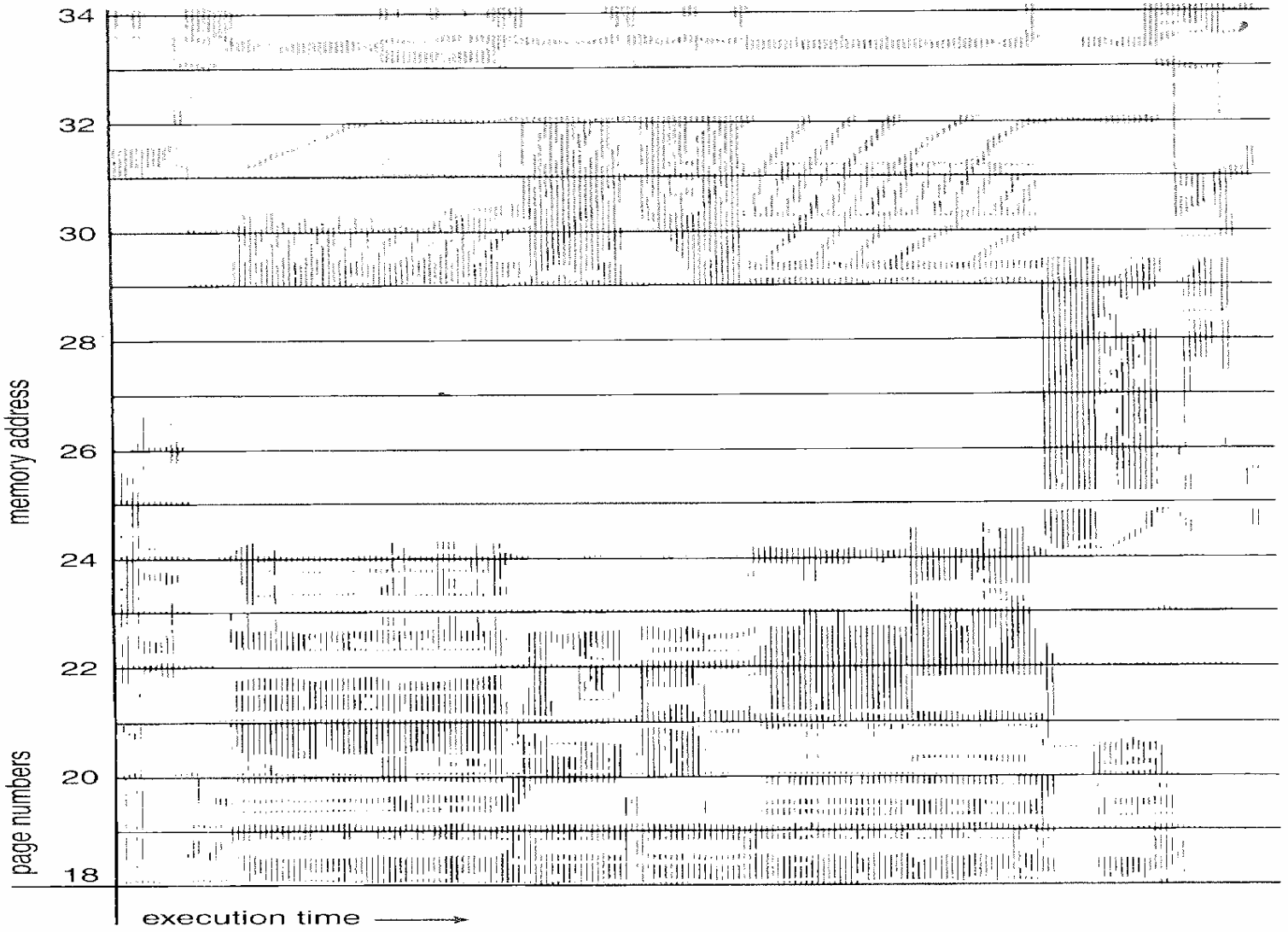
Example

1. Assume global page replacement
2. Assume that page faults result in some processes to wait on the paging device
3. CPU utilization decreases
4. Increasing the degree of multiprogramming
5. The new process requires page and encounters page fault, therefore waits on the paging device
6. CPU utilization decreases …

Solution

- Using local page replacement, if one process starts thrashing, it cannot steal frames from other processes
- Thrashing results in increased waiting time on the paging device which affects the effective access time of memory even for processes which are not thrashing
- To prevent thrashing a process should have its required frames
- How do we know how many frames it needs?
  - Working-Set Model
  - Page-Fault Frequency

Locality in a Memory Reference Pattern

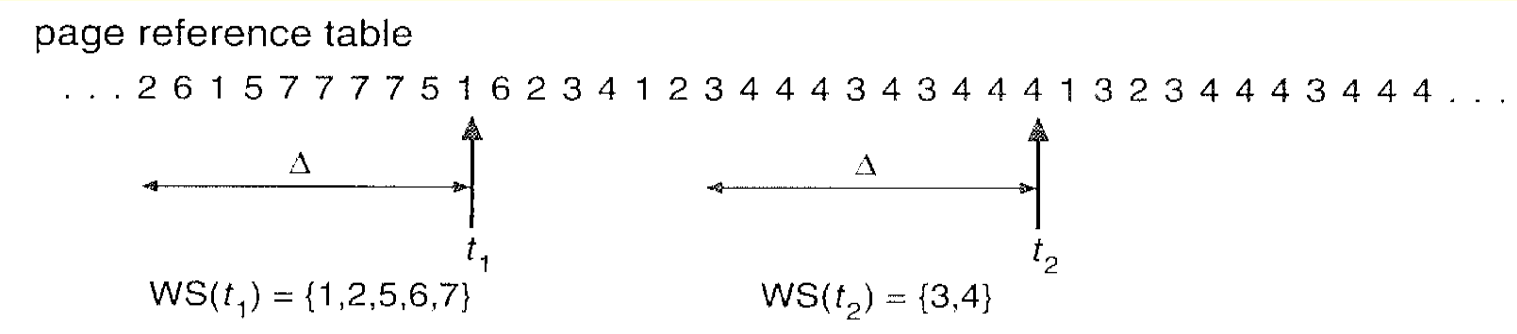


Locality in a Memory Reference Pattern

- If we allocate fewer frames than the size of the current locality, the process will thrash, since it cannot keep in memory all the pages that it is actively using

Working-Set Model

- Δ: Working-set window
- Working set: the most recent Δ page references
  - An approximation of the program's locality
  - Ex.: Δ=10



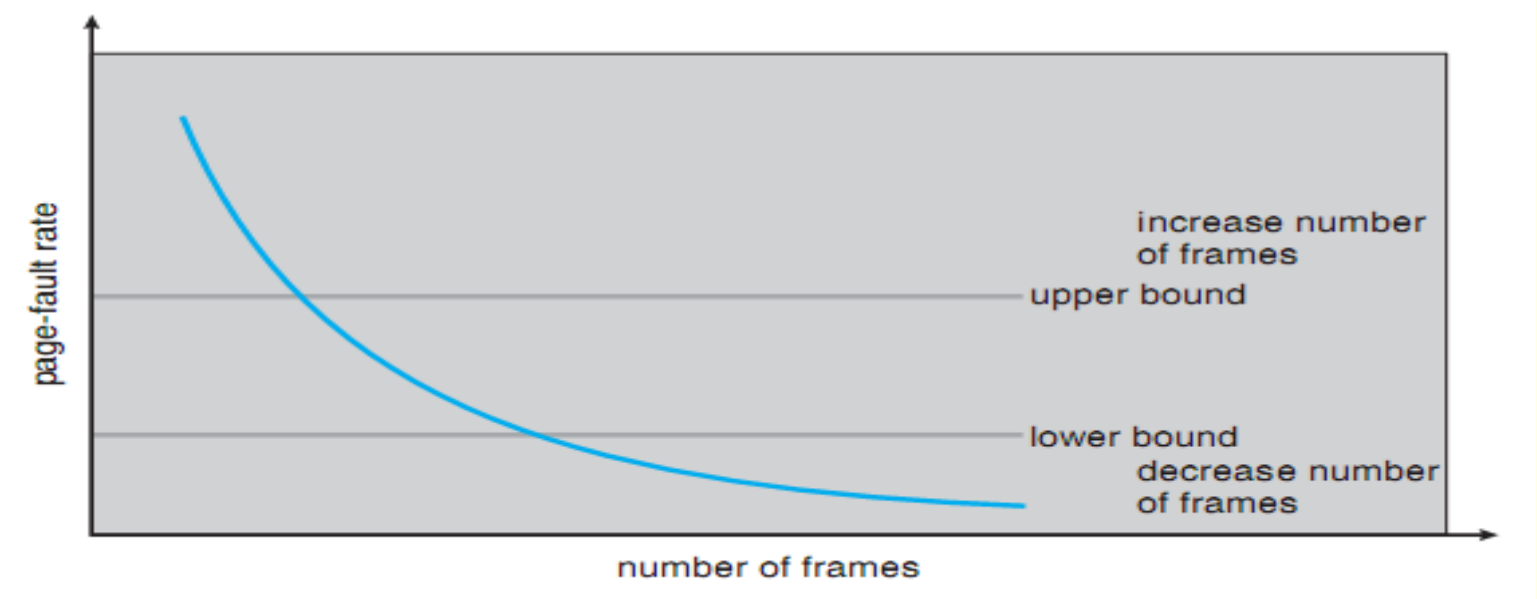
  - Large Δ: overlapping several localities
  - Small Δ: Doesn't show the entire locality

Working-Set Model

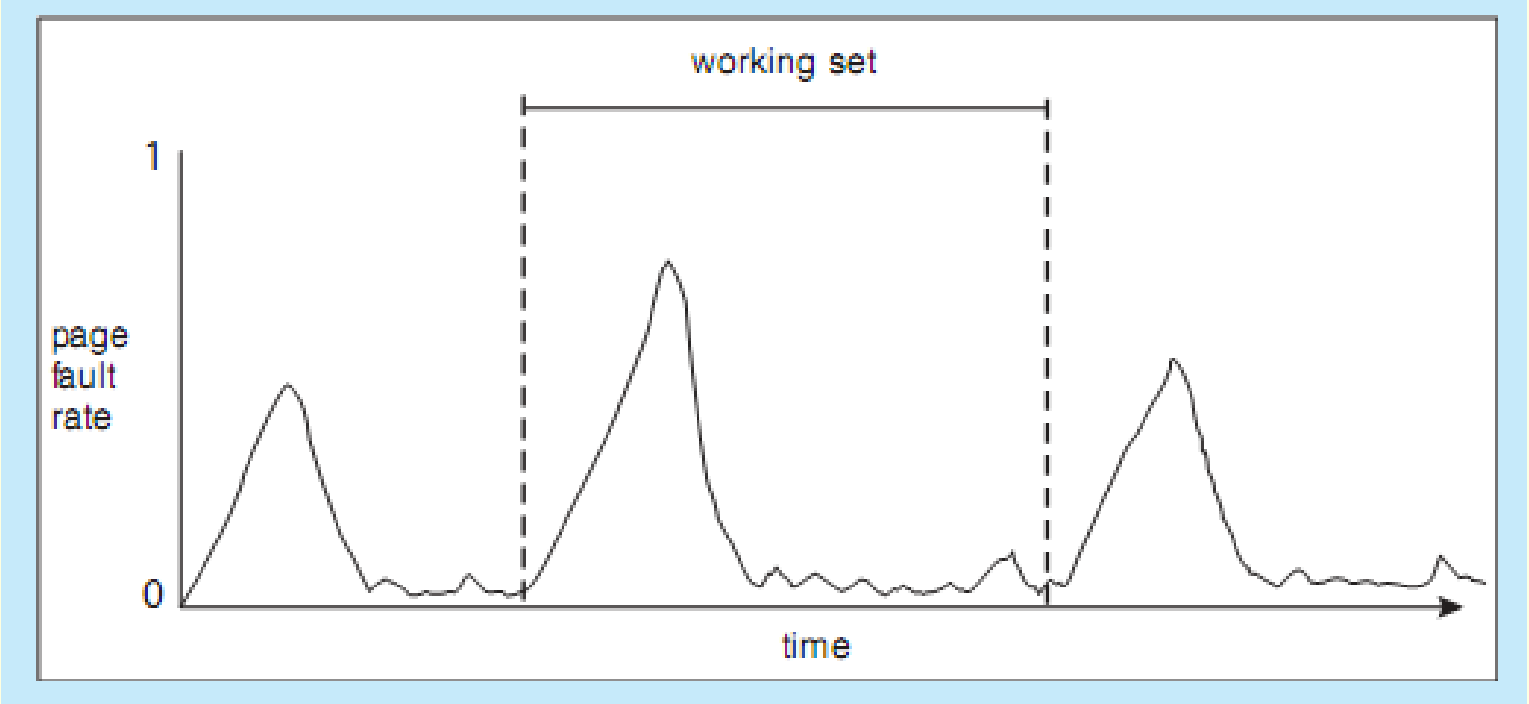
- WSS_i: Working-set size of process p_i
- Total demand for frames➔ $D = \Sigma\ WSS_i$
- D>m ➔ Thrashing
- The OS will assign frames to each process according to its working-set size which can be obtained by looking at Δ
- If free frames are ready ➔ another process can be initiated
- If D>m ➔ the OS should suspend some processes

Page-Fault Frequency (PFF)

- Page-fault rate > upper bound ➔ increasing the frames of this process
- Page-fault rate < lower bound ➔ decreasing the frames of this process

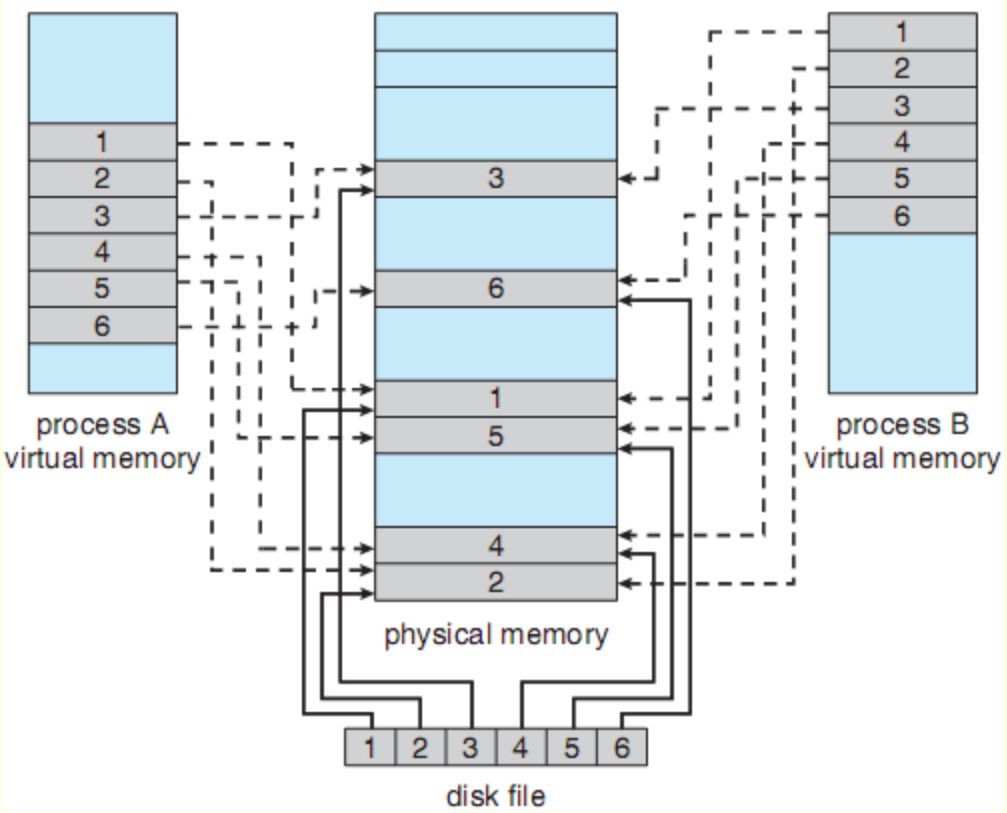


Page-Fault Rate over Time



Memory-Mapped Files

- Mapping disk blocks to pages for memory-mapped files



Memory-Mapped I/O

- Memory-mapped I/O:
  - Setting ranges of memory addresses to special device registers
    - E.g., a few device registers are called I/O ports (serial and parallel)
    - Polling a control bit in the memory words to check if the I/O device has received the data: Programmed I/O
    - Using interrupts to do so: Interrupt-driven

Allocating Kernel Memory

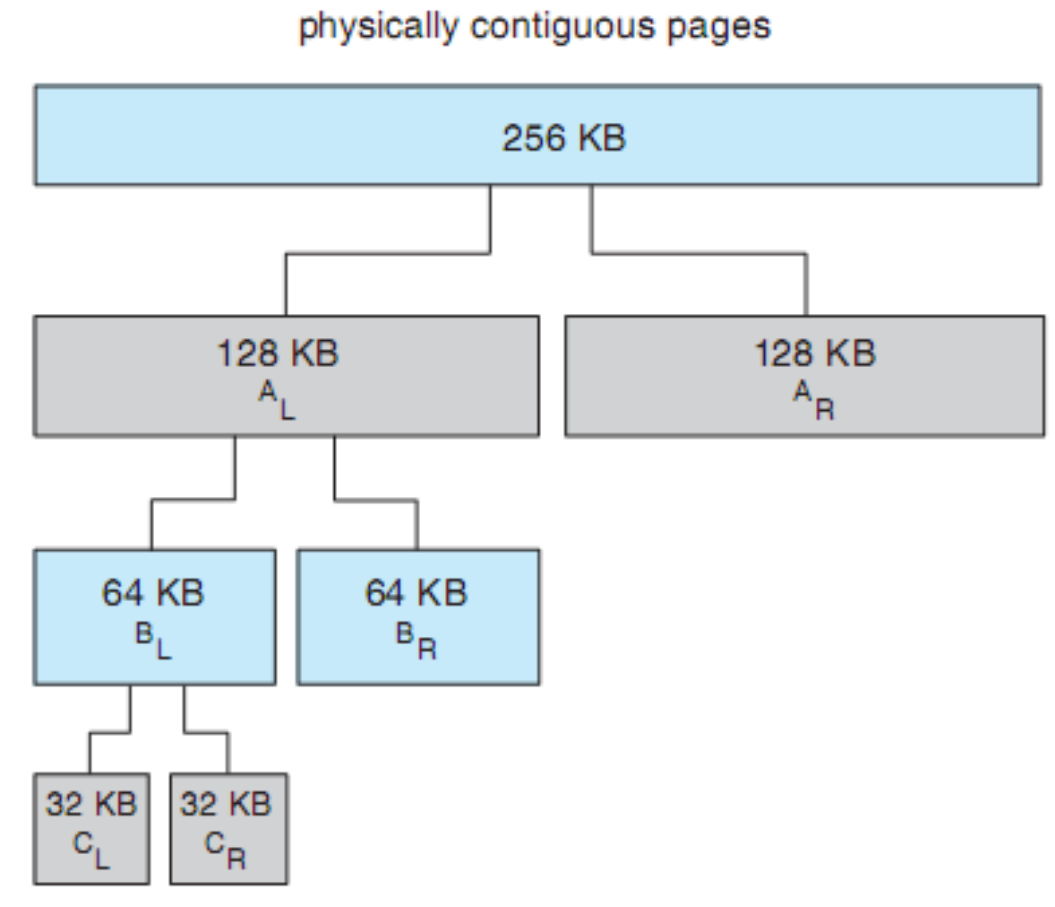
- Kernel memory is often allocated from a free memory pool, in a different manner with respect to user-mode processes.
  - Kernel requests memory for data structures of varying size
    - Fragmentation should be minimized to prevent wasting
  - Due to the direct interaction of certain hardware devices with physical memory, usually contiguous memory is required (in spite of paging for user-mode processes)

Strategies for Managing Free Memory that is Assigned to Kernel Processes

- Buddy system
- Slab allocation

Buddy System

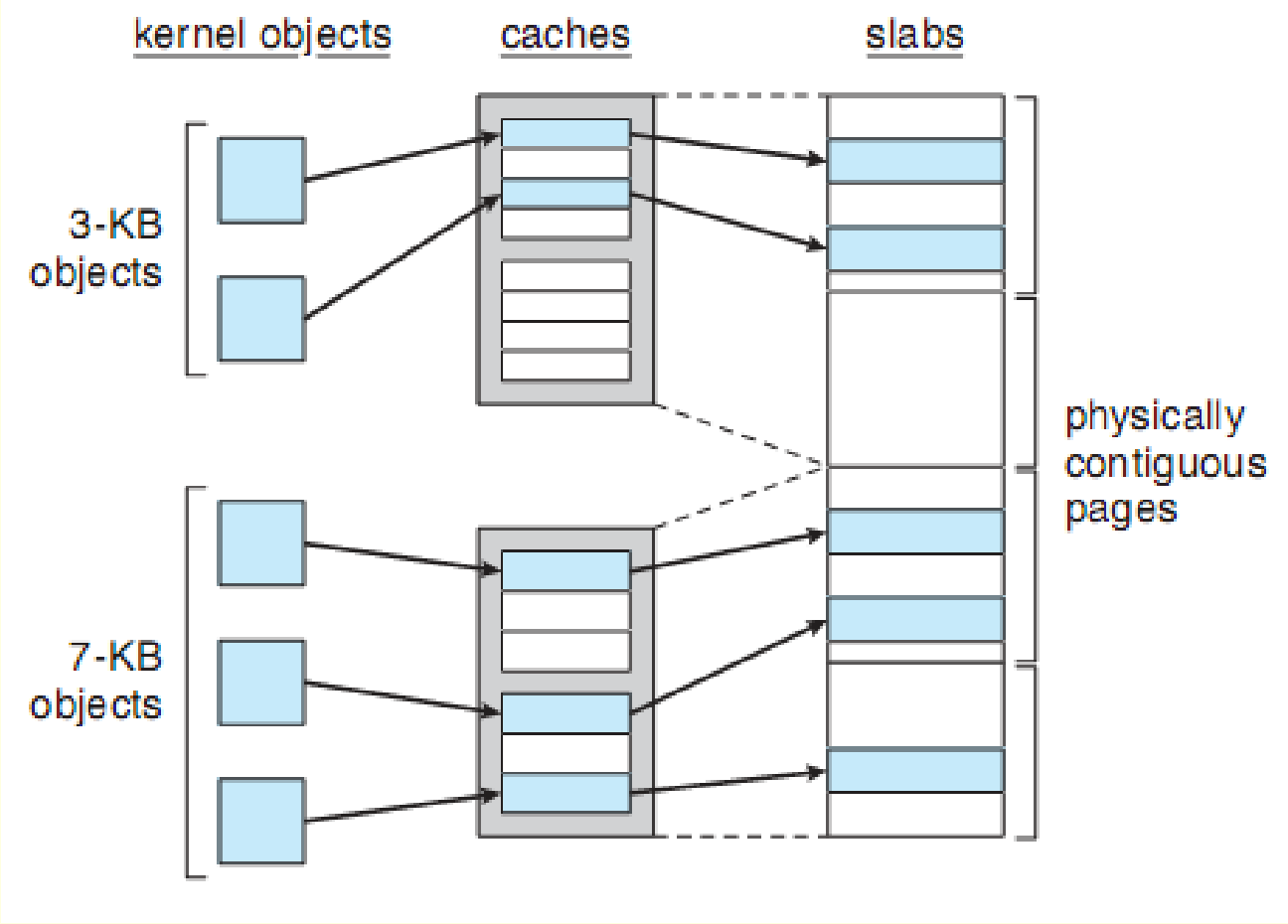
- Power-of-2 allocator
- Internal fragmentation
- Coalescing



Slab Allocation

- Slab: One or more physically contiguous pages
- Cache: One or more slabs
- There is a single cache for each unique kernel data structure, e.g., PCBs, file objects, semaphores, …
  - E.g., in Linux, a slab may be in one of the following three states:
    - Full: All objects in the slab are marked as used
    - Empty: All objects in the slab are marked as free
    - Partial: The slab consists of both used and free objects

Slab Allocation



Slab Allocation

- Benefits
  - No memory is wasted due to fragmentation
  - Memory requests can be satisfied quickly
- Slab allocator is used in Solaris 2.4 kernel as well as certain user-mode memory requests in Solaris

Other Considerations

- Prepaging
  - Prepaging s pages
  - The fraction of α is used
  - The cost that have been saved with α*s page faults should be greater than prepaging (1-α)*s pages
- Page size
  - Page table size
  - Memory is better used with smaller pages
  - Time needed to read or write a page
  - Smaller page size improves locality and reduces I/O
  - The relationship between page size and sector size of the paging device

Other Considerations

- TLB Reach
  - TLB size * page size
  - Page size can affect the TLB reach
  - TLB in systems with more than one page size can be managed by software (Alpha, MIPS, UltraSPARC) or hardware (Pentium, PowerPC)
- Inverted page table

Other Considerations

- Program structure

```
int i, j;
int[128][128] data;

for (j = 0; j < 128; j++)
    for (i = 0; i < 128; i++)
        data[i][j] = 0;
```

```
int i, j;
int[128][128] data;

for (i = 0; i < 128; i++)
    for (j = 0; j < 128; j++)
        data[i][j] = 0;
```

- I/O interlock