操作系统原理及应用

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Chapter 9 Virtual Memory

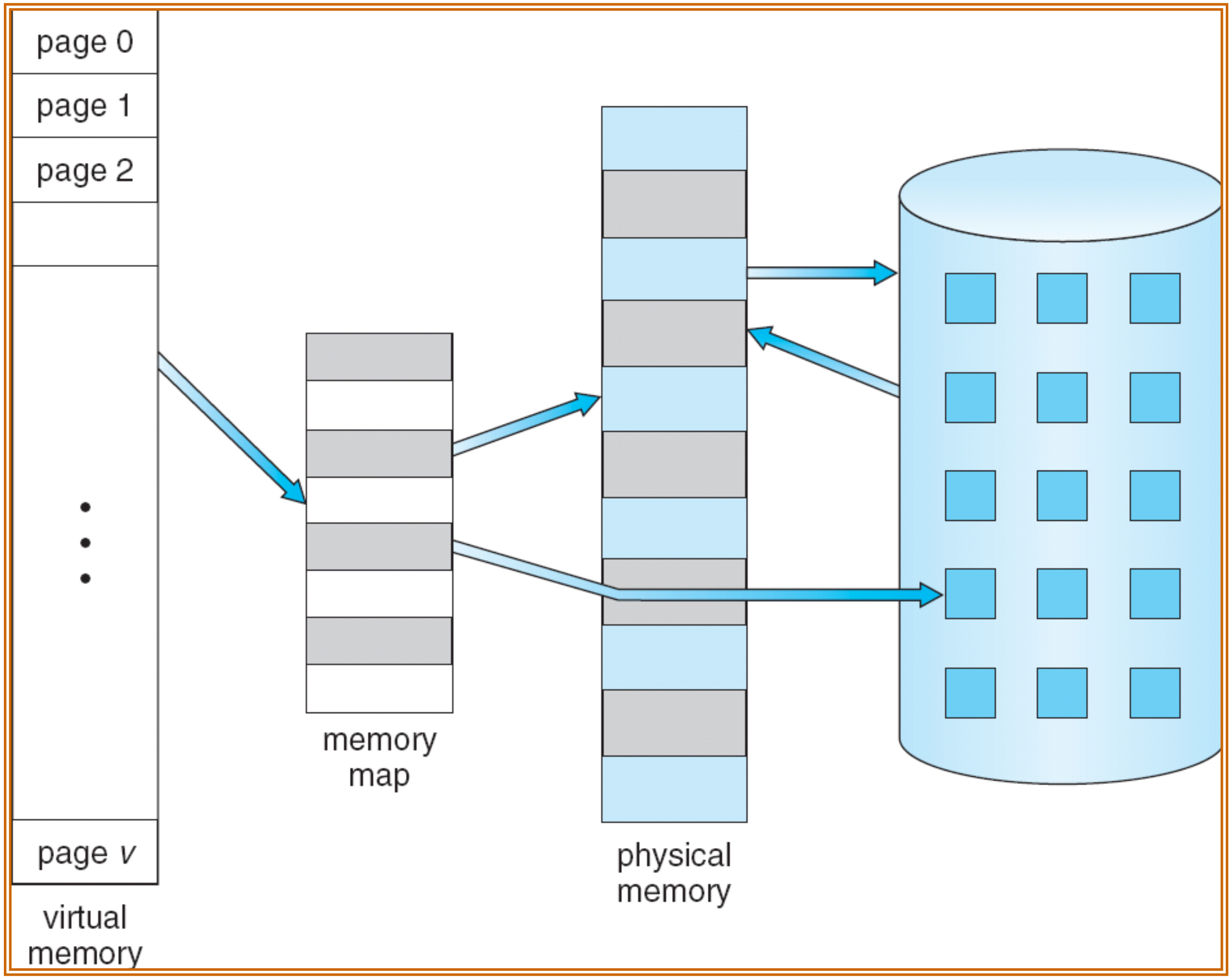
Outline

- Background
- Demand Paging
- Page Replacement
- Allocation of Frames
- Thrashing
- Memory-Mapped Files
- Allocating Kernel Memory
- Other Considerations
- Operating-System Examples

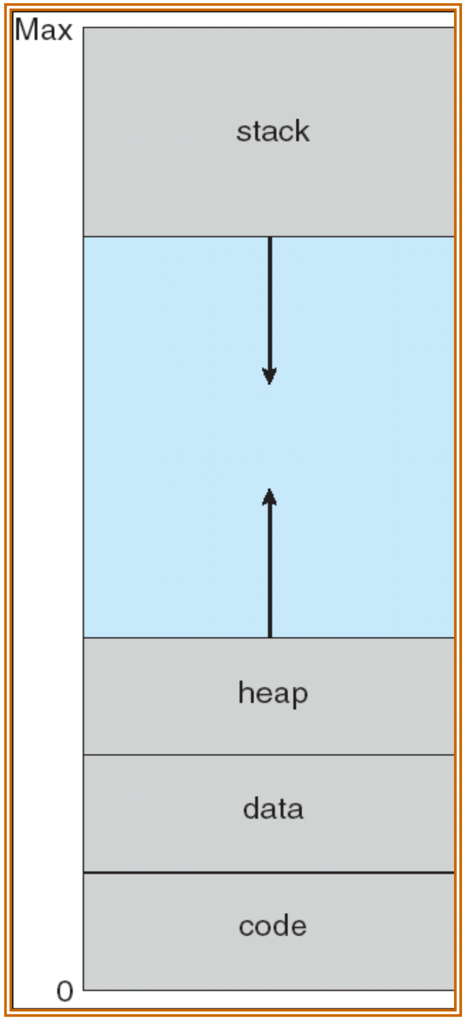
Background

- **Virtual memory – separation of user logical memory from physical memory.**
  - **Only part of the program needs to be in memory for execution.**
  - **Logical address space can therefore be much larger than physical address space.**
  - **More programs can be run at the same time**
  - **Less I/O be needed to load or swap**

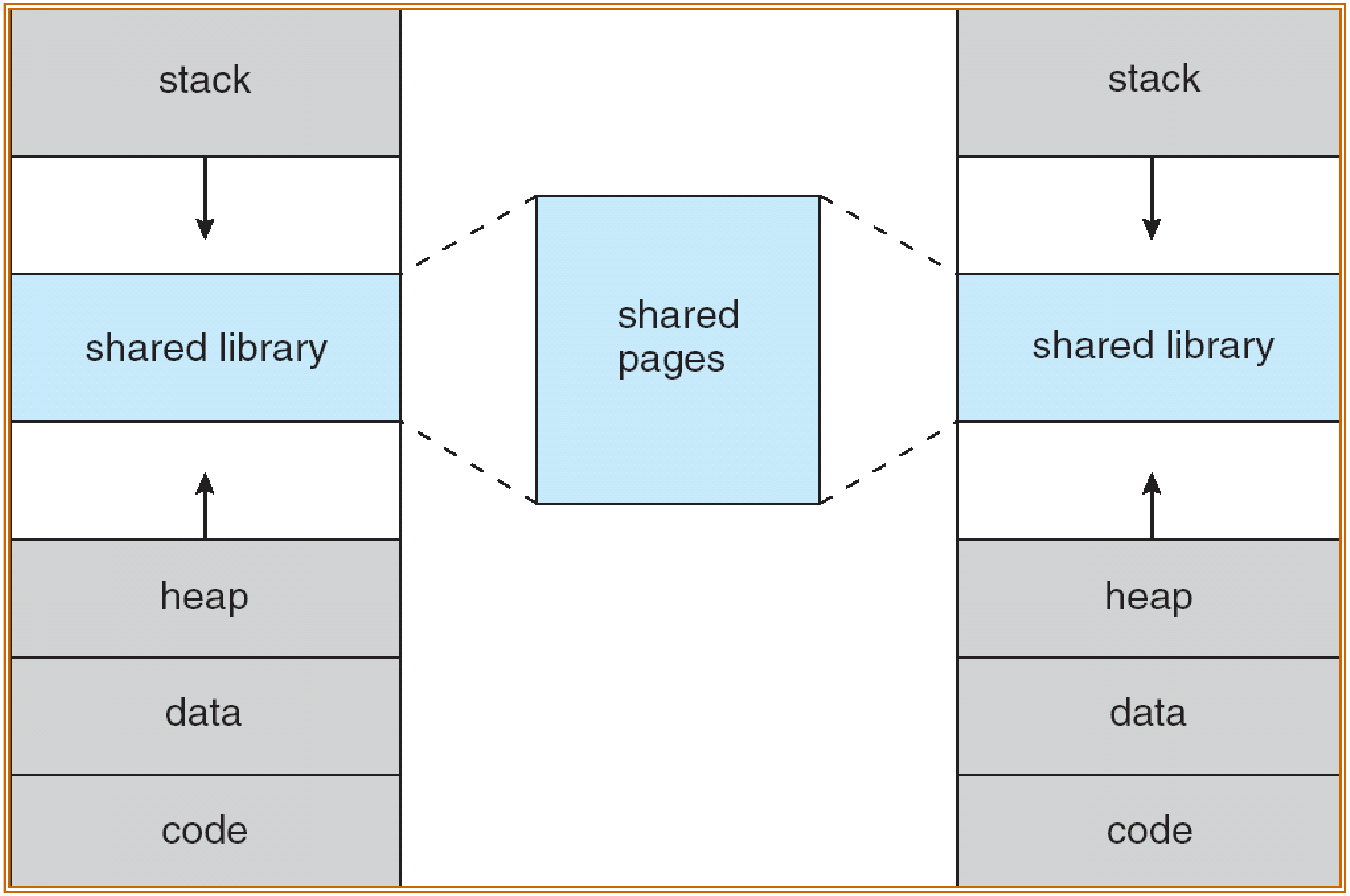
Virtual Memory is Larger than Physical Memory



Virtual-address Space



Shared Library Using Virtual Memory



Copy-on-Write

- **Process Creation**
- **Copy-on-Write (COW) allows both parent and child processes to initially *share* the same pages in memory.**
- **If either process modifies a shared page, then only the page is copied.**
- **COW allows more efficient process creation as only modified pages are copied.**
- **Free pages are allocated from a *pool* of zeroed-filled pages.**

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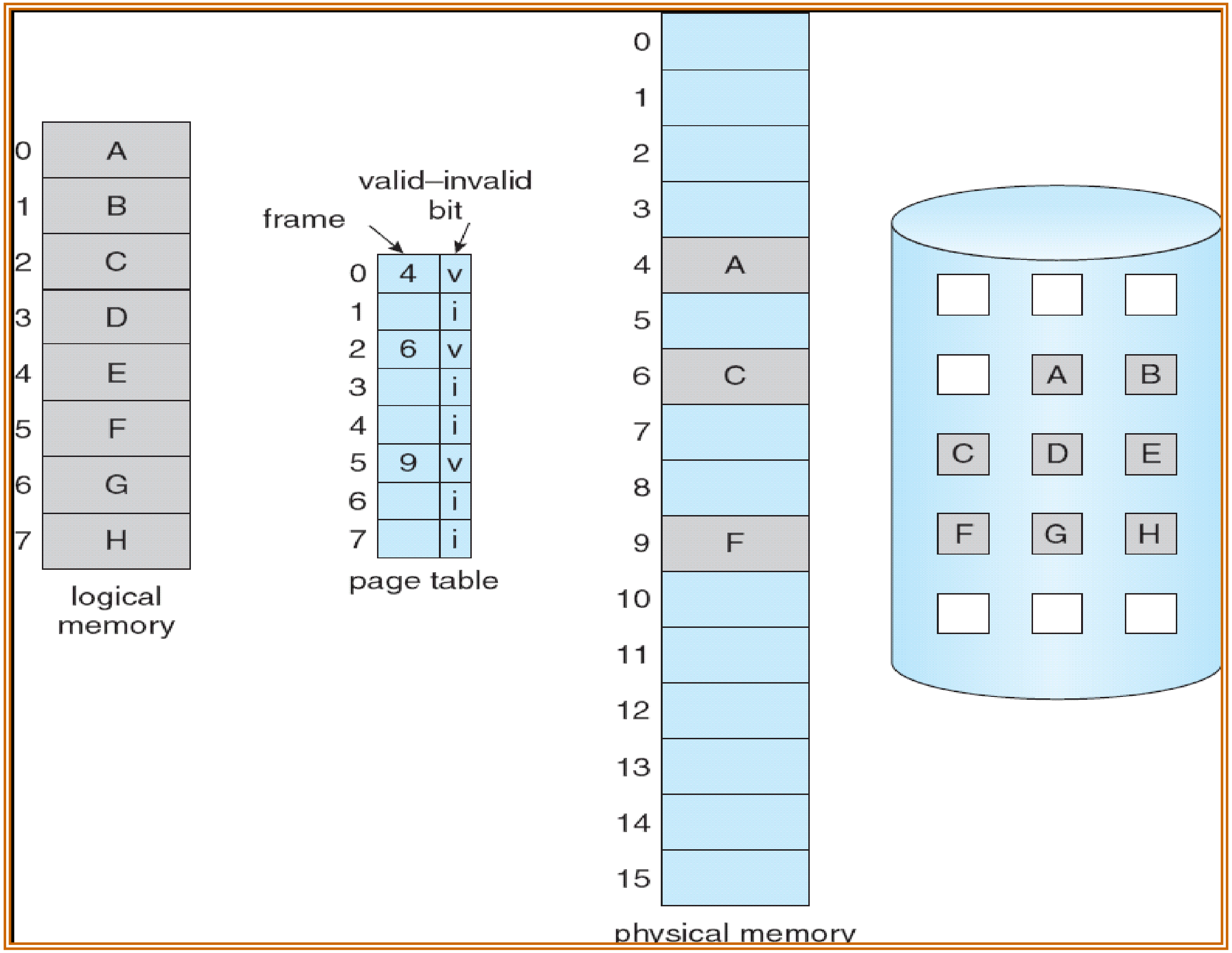
Demand Paging

- Bring a page into memory only when it is needed.
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users
- Page is needed $\Rightarrow$ reference to it
  - invalid reference $\Rightarrow$ abort
  - not-in-memory $\Rightarrow$ bring to memory
- Lazy Swapper (Pager) – never swaps a page into memory unless page will be needed

Valid-Invalid Bit

- **A valid–invalid bit is associated with each page table entry**
  - **1 $\Rightarrow$ valid and in-memory**
  - **0 $\Rightarrow$ invalid or not-in-memory**
- **Initially valid–invalid bit is set to 0 on all entries.**
- **During address translation, if valid–invalid bit in page table entry is 0 $\Rightarrow$ page fault.**

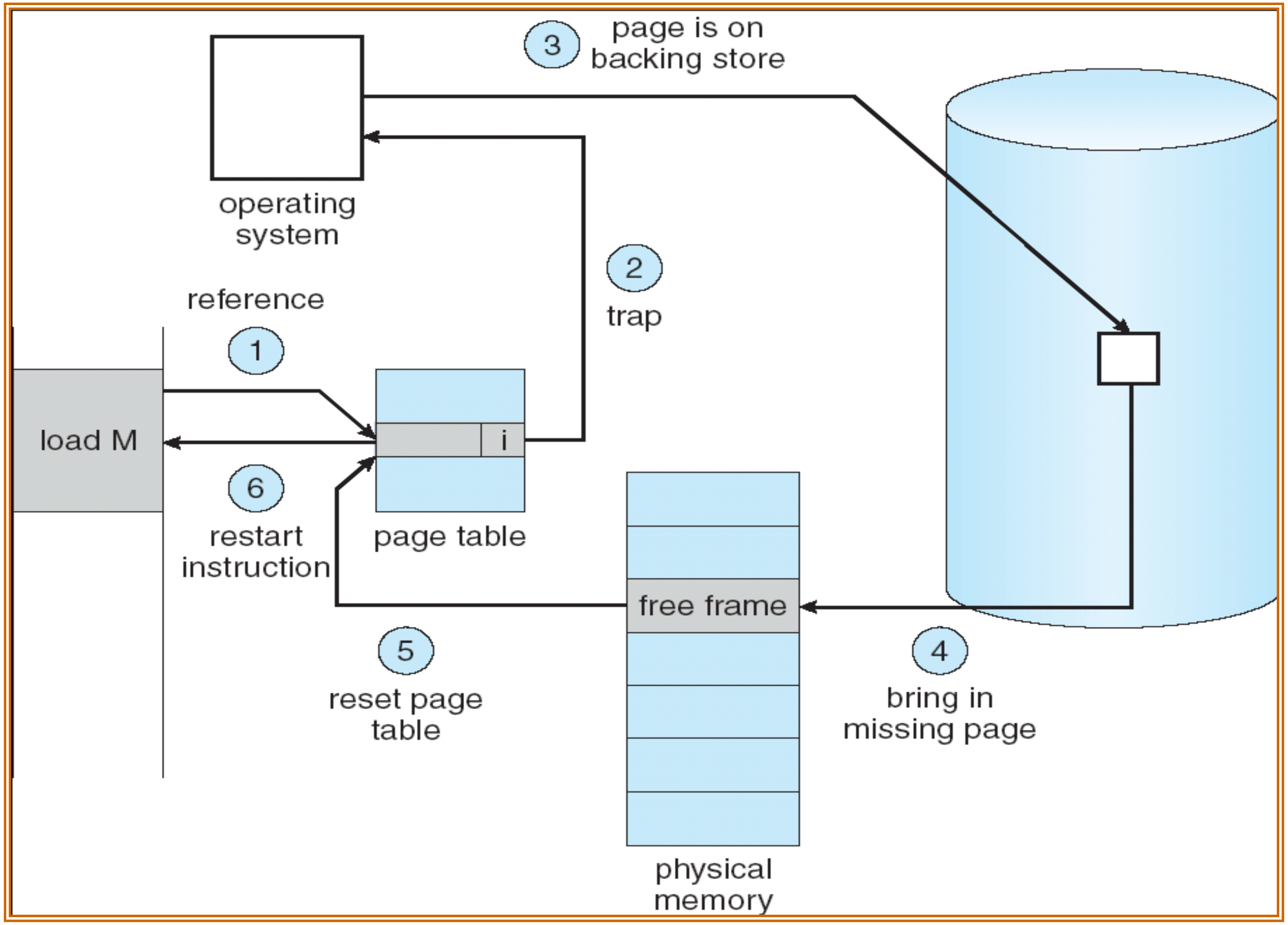
Page Table When Some Pages Are Not in Main Memory



Page Fault

- If there is ever a reference to a page, first reference will trap to OS $\Rightarrow$ page fault
  - OS looks at internal table to decide:
    - Invalid reference $\Rightarrow$ abort.
    - Just not in memory.
  - Get empty frame.
  - Swap page into frame.
  - Reset tables, validation bit = 1.
  - Restart instruction

Steps in Handling a Page Fault



Performance of Demand Paging

- **Page Fault Rate** $0 \leq p \leq 1$
  - if $p = 0$ no page faults
  - if $p = 1$, every reference is a fault
- **Effective Access Time (EAT)**

  EAT = (1 – p) x memory access time

  + p (page fault overhead)

  page fault overhead = service the page-fault interrupt

  + [swap page out]

  + swap page in

  + restart overhead

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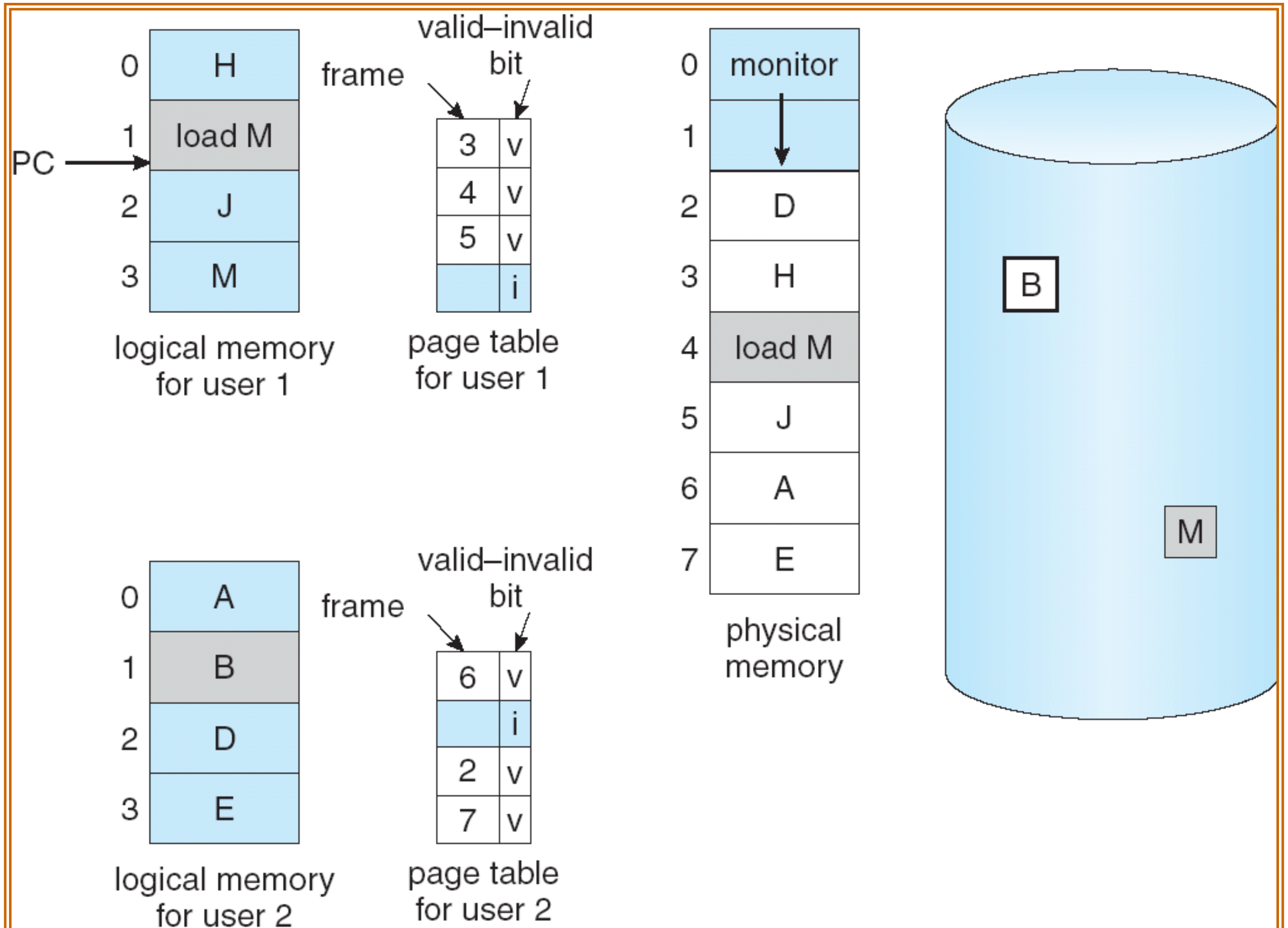
What happens if there is no free frame?

- Prevent over-allocation of memory by modifying page-fault service routine to include page replacement.
- Page replacement – find some page in memory, but not really in use, swap it out
  - algorithm

Page Replacement

- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory.
- Same page may be brought into memory several times
  - performance – want an algorithm which will result in minimum number of page faults

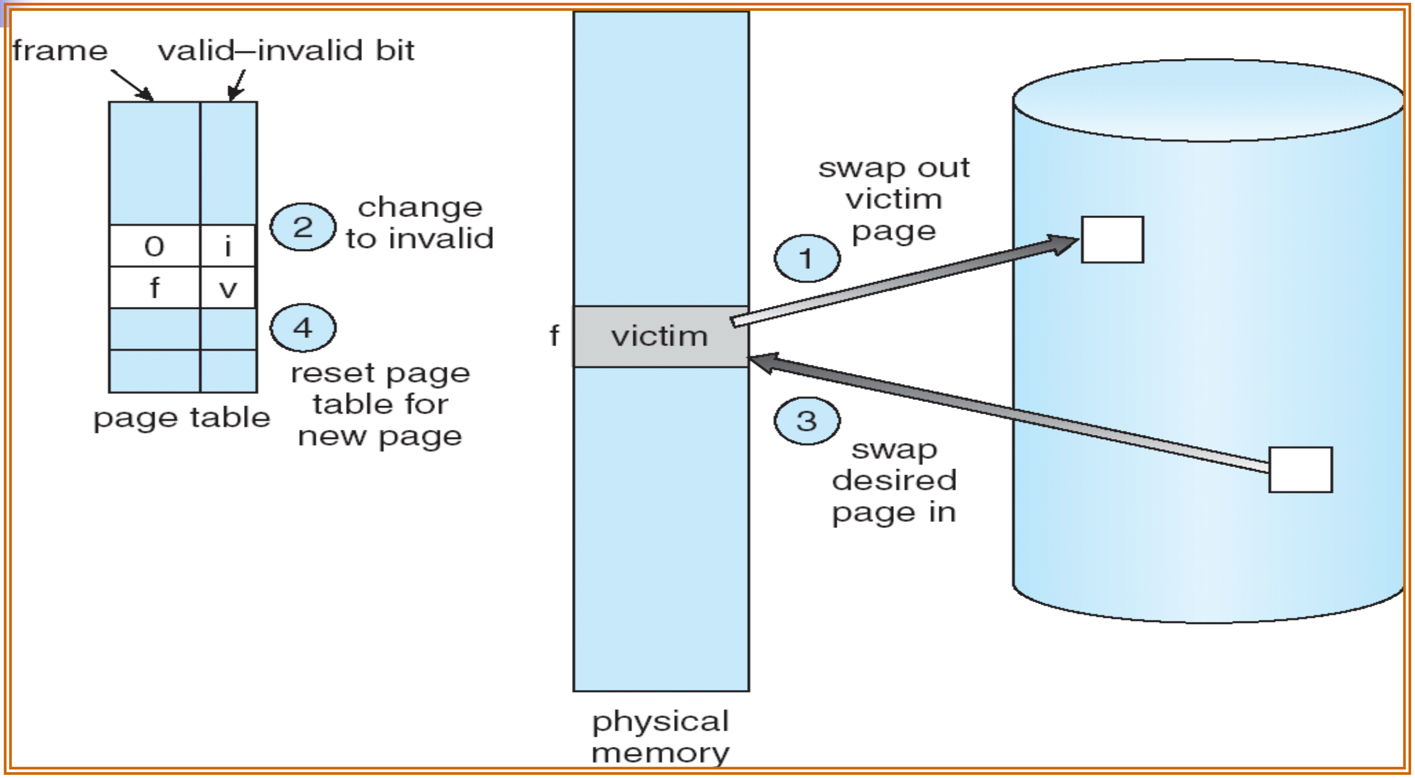
Need For Page Replacement



Basic Page Replacement

- **Find the location of the desired page on disk.**
- **Find a free frame**
  - **If there is a free frame, use it.**
  - **If there is no free frame, use a page replacement algorithm to select a *victim* frame.**
  - **Write the victim frame to the disk and change the page and frame tables.**
- **Read the desired page into the free frame. Update the page and frame tables.**
- **Restart the process.**

Basic Page Replacement

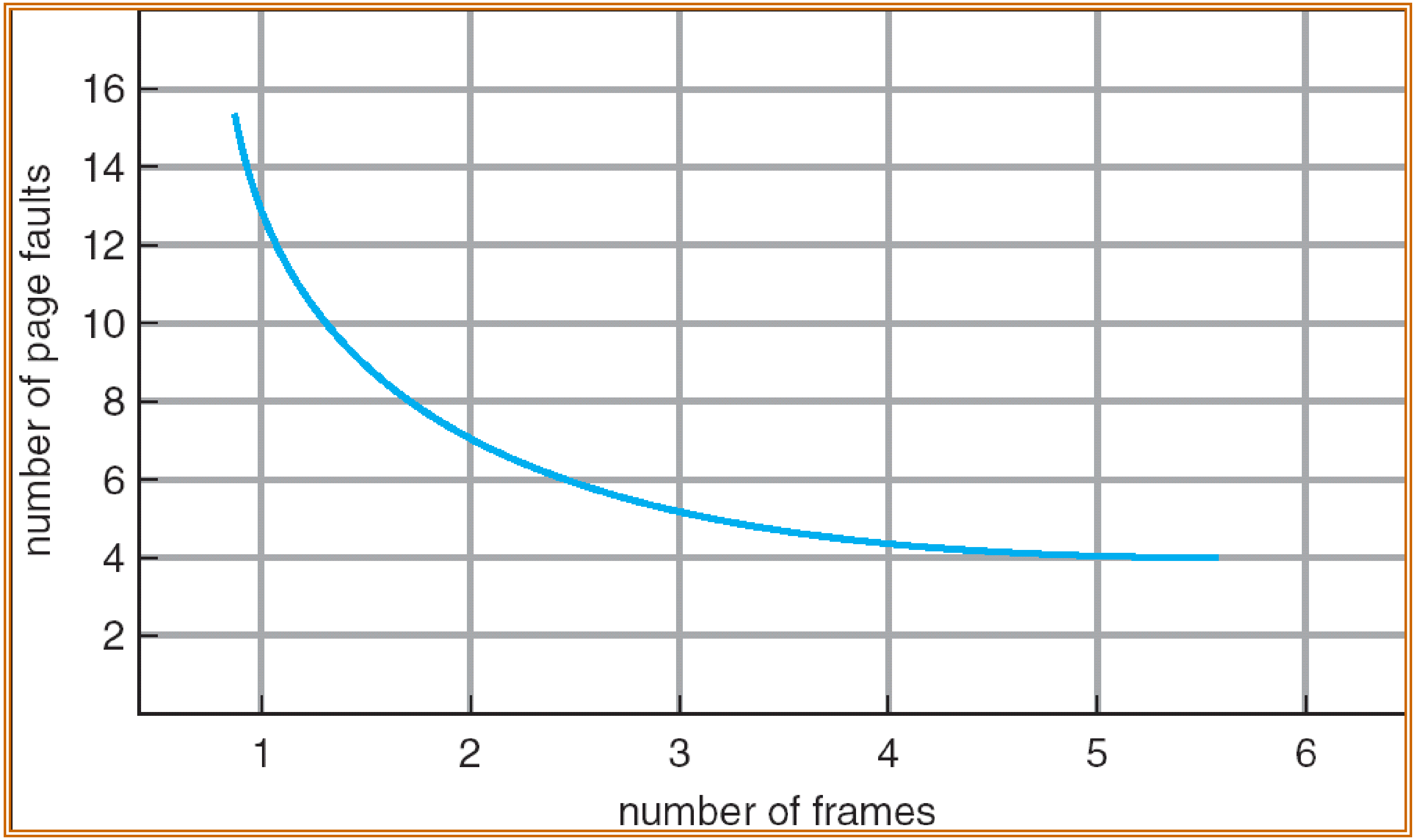


Use *modify (dirty) bit* to reduce overhead of page transfers – only modified pages are written to disk.

Page Replacement Algorithms

- Want lowest page-fault rate.
- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string.

Graph of Page Faults Versus The Number of Frames



First-In-First-Out (FIFO) Algorithm

- Reference string
  - 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 frames (3 pages can be in memory at a time per process)

1	4	5
2	1	3
3	2	4

9 page faults

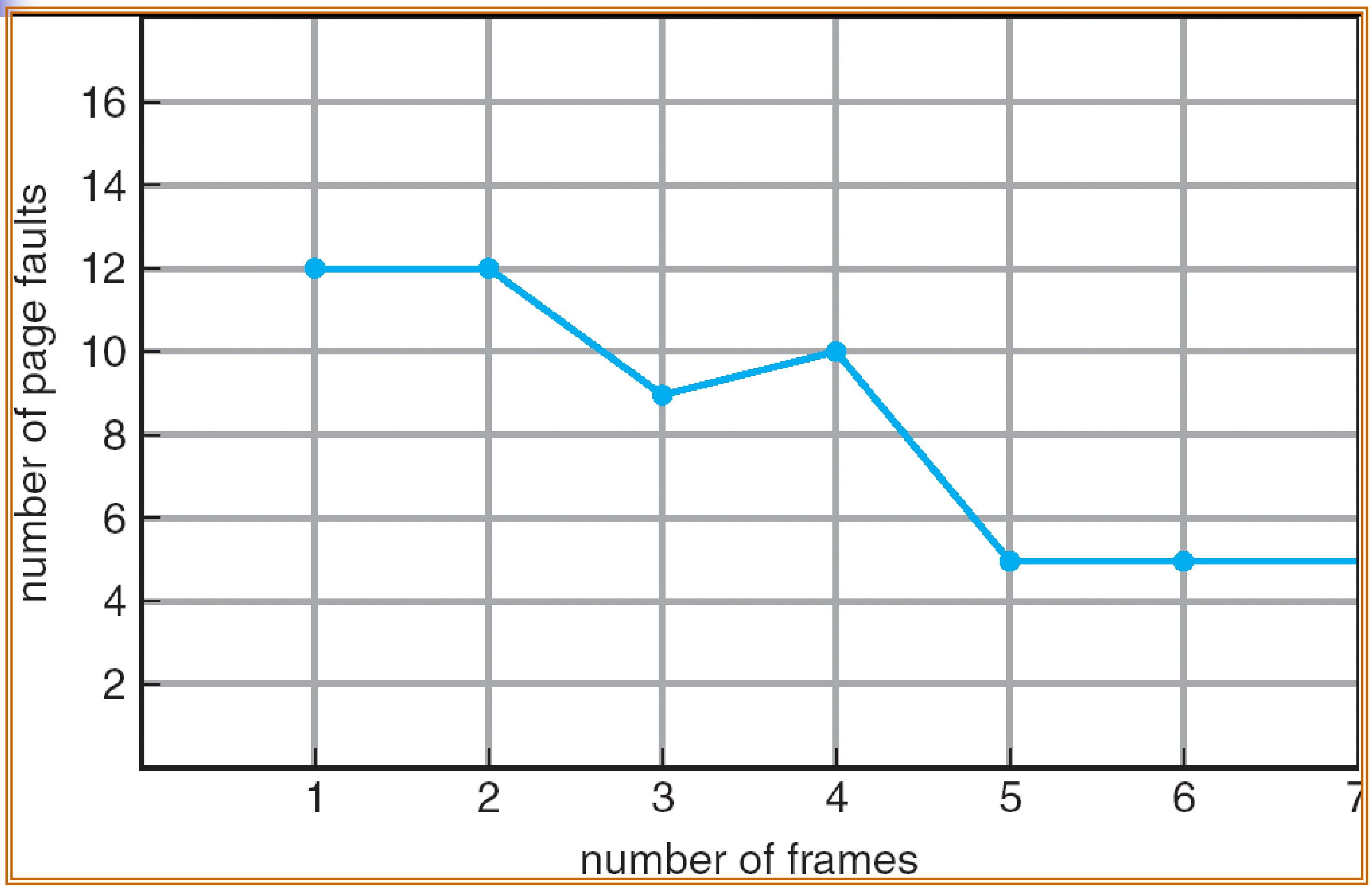
First-In-First-Out (FIFO) Algorithm

- 4 frames

1	5	4	
2	1	5	10 page faults
3	2		
4	3		

- FIFO Replacement – Belady’s Anomaly
  - more frames $\Rightarrow$ more page faults

FIFO Illustrating Belady's Anamoly



Optimal Algorithm

- **Replace page that will not be used for longest period of time.**
- **4 frames example ——1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5**

1	4
2	
3	
4	5

6 page faults

- **How do you know this?**
- **Used for measuring how well your algorithm performs.**

Least Recently Used (LRU) Algorithm

- **Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5**

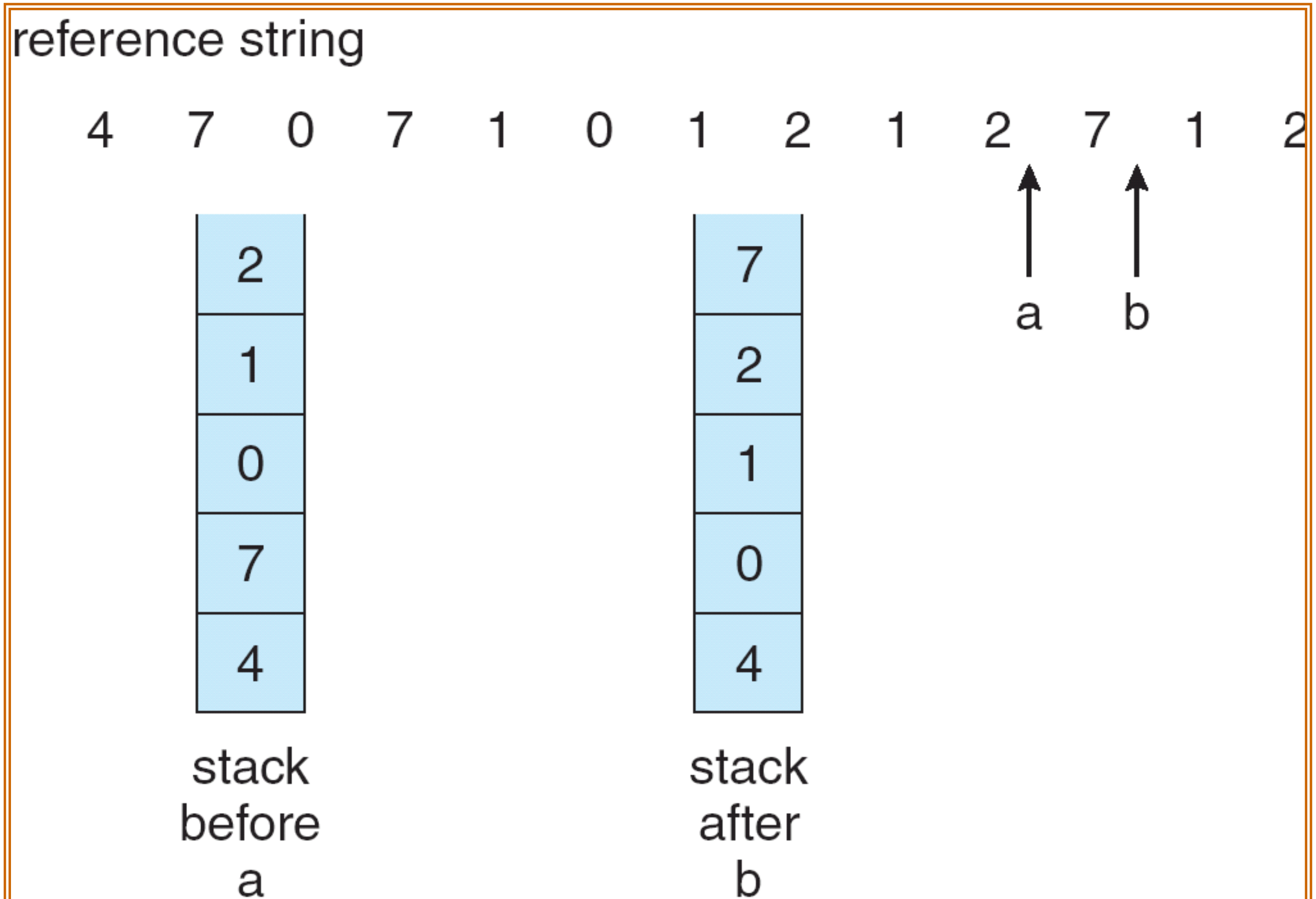
1		5
2		
3	5	4
4	3	

- **Counter implementation**
  - **Every page entry has a counter; every time page is referenced through this entry, the clock is copied into the counter.**
  - **Replace the page with the smallest time value.**

LRU Algorithm

- **Stack implementation – keep a stack of page numbers in a double link form**
  - **Page referenced**
    - **remove it from the stack and put it on the top**
    - **LRU page is always at the bottom**
    - **requires 6 pointers to be changed at worst**
  - **No search for replacement**
- **Optimal replacement and LRU replacement do not suffer from Belady's anomaly**

Use of a Stack to Record the Most Recent Page References



LRU Approximation Algorithms

- Reference bit
  - With each entry in the page table associate a bit, initially = 0
  - When page is referenced, the bit will be set to 1.
  - Replace the one which bit is 0 (if one exists). We do not know the order of use, however we can determine which pages have been used and which have not been used.

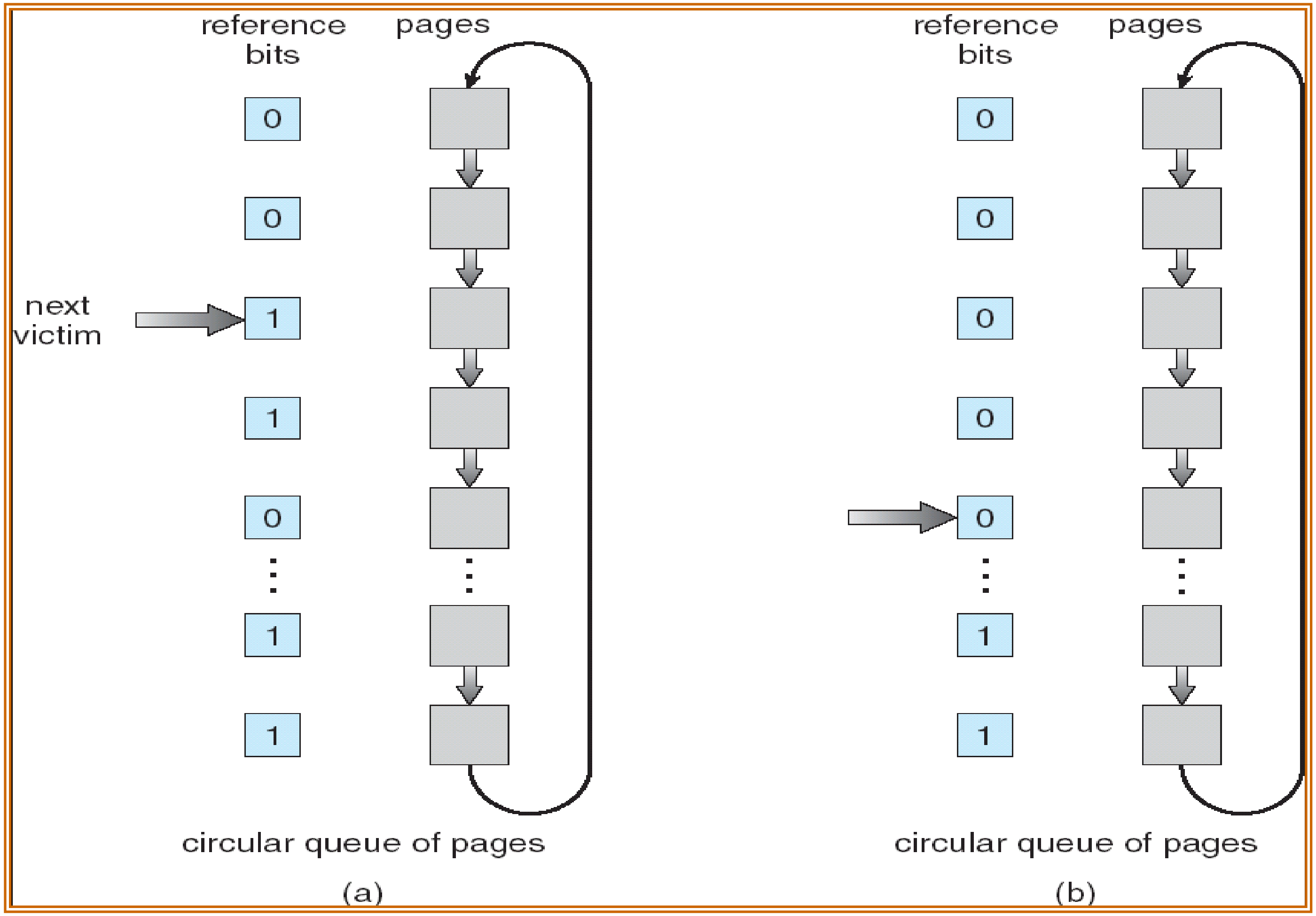
LRU Approximation Algorithms

- Additional-Reference-Bits Algorithm
  - Keep an 8-bit bytes for each page
  - At regular intervals shifts the bits right 1 bit, shift the reference bit into the high-order bit
  - Interpret these 8-bit bytes as unsigned integers, the page with lowest number is the LRU page

LRU Approximation Algorithms

- Second-Chance Algorithm
  - Need reference bit.
  - Clock replacement (FIFO).
  - If page to be replaced (in clock order) has reference bit = 1. then:
    - set reference bit 0.
    - leave page in memory.
    - replace next page (in clock order), subject to same rules.

Second-Chance Page-Replacement Algorithm



Counting Algorithms

- Keep a counter of the number of references that have been made to each page.
- LFU Algorithm: replaces page with smallest count.
- MFU Algorithm: based on the argument that the page with the smallest count was probably just brought in and has yet to be used.

作业1

- 在某请求分页管理系统中，一个作业共**5**页，作业执行时依次访问如下页面：**1**、**4**、**3**、**1**、**2**、**5**、**1**、**4**、**2**、**1**、**4**、**5**，若分配给该作业的主存块数为**3**，分别采用**FIFO**、**LRU**、**OPT**页面置换算法，试求出缺页中断的次数及缺页率。

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Allocation of Frames

- Each process needs minimum number of pages, which is decided by the given computer architecture.
- Example: IBM 370 MVC instruction:
  - instruction is 6 bytes, might span 2 pages.
  - 2 pages to handle from.
  - 2 pages to handle to.
- Two major allocation schemes.
  - fixed allocation
  - priority allocation

Fixed Allocation

- **Equal allocation – e.g., if 100 frames and 5 processes, give each 20 frames.**
- **Proportional allocation – Allocate according to the size of process.**

$$s_i = \text{size of process } p_i$$

$$S = \sum s_i$$

$$m = \text{total number of frames}$$

$$a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m$$

Priority Allocation

- **Use a proportional allocation scheme using priorities rather than size.**
- **If process P_i generates a page fault,**
  - **select for replacement one of its frames.**
  - **select for replacement a frame from a process with lower priority number.**

Global vs. Local Allocation

- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another.
- **Local replacement** – each process selects from only its own set of allocated frames.

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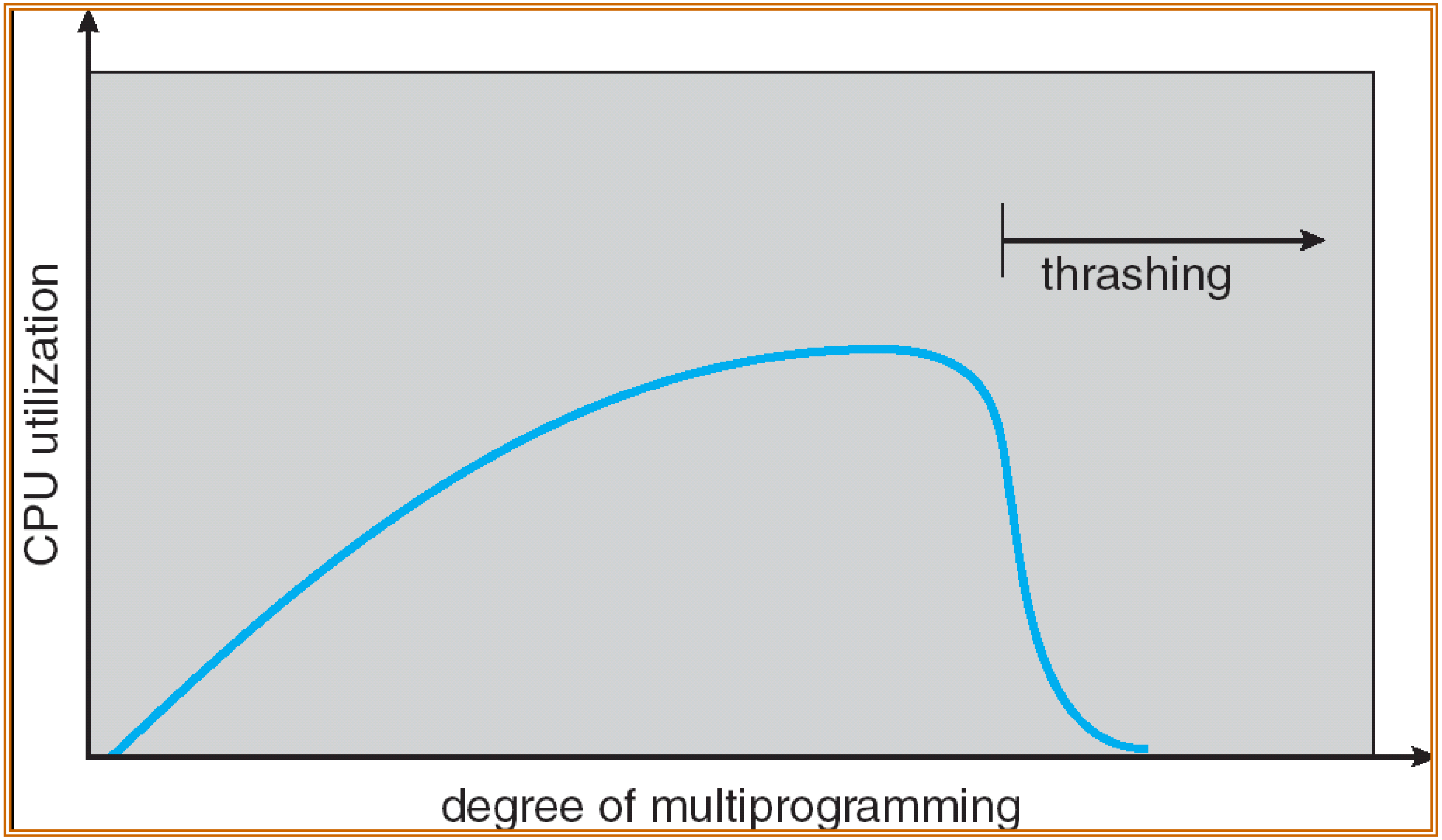
Thrashing（颠簸）

- If a process does not have “enough” frames, the page-fault rate is very high.
  - low CPU utilization.
  - operating system thinks that it needs to increase the degree of multiprogramming.
  - another process is added to the system.
- Thrashing —— a process is busy swapping pages in and out.

Thrashing



Thrashing

- Why does paging work?

  Locality model

  - A locality is a set of pages that are actively used together.
  - Process migrates from one locality to another.
  - Localities may overlap.
- Why does thrashing occur?

  size of locality > allocated memory size

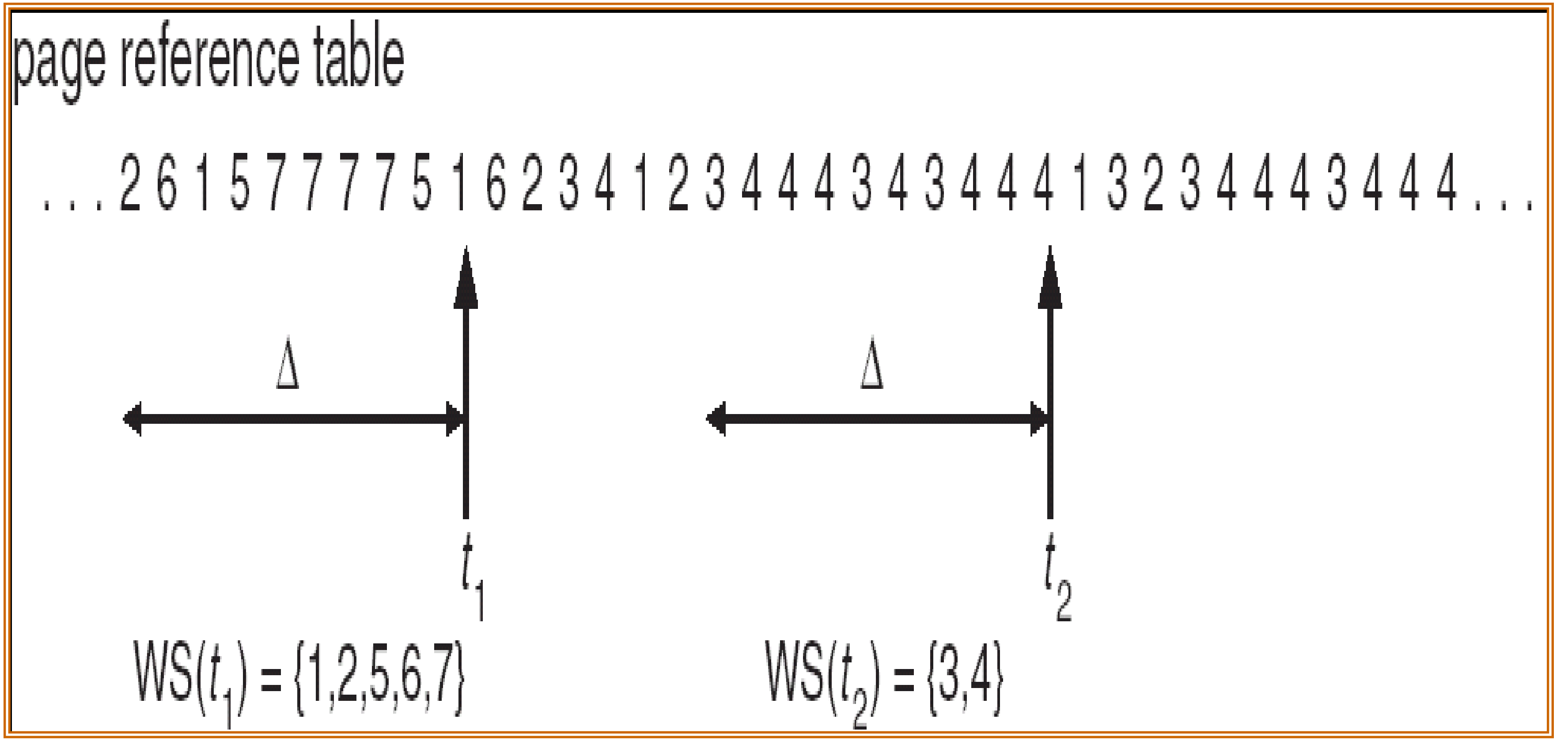
Working-Set Model

- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
  Example: 10,000 instruction
- WSS_i (working set of Process P_i) =
  total number of pages referenced in the most recent Δ (varies in time)
  - if Δ too small will not encompass entire locality.
  - if Δ too large will encompass several localities.
  - if $\Delta = \infty \Rightarrow$ will encompass entire program.

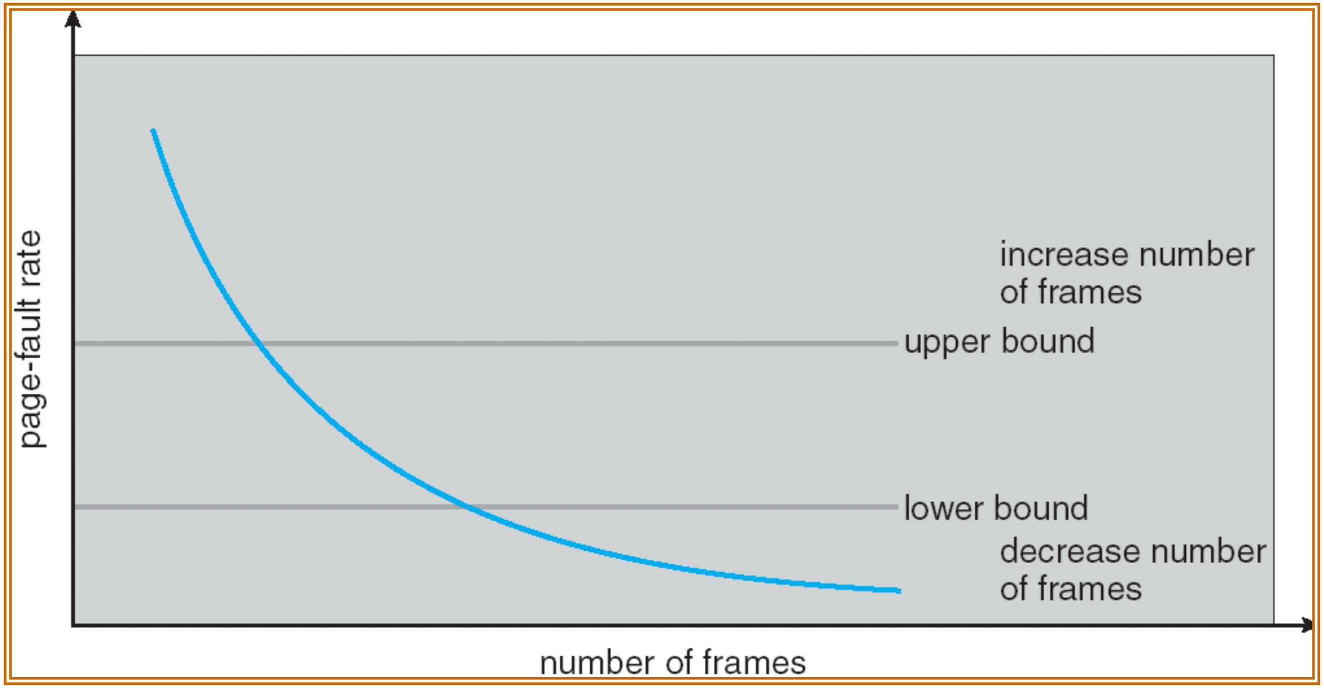
Working-Set Model

- The working set is an approximation of the program's locality.
- $D = \Sigma\, WSS_i \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing $\Rightarrow$ Suspend one of the processes

Working-set model



Page-Fault Frequency



- **Establish "acceptable" page-fault rate.**
  - **If actual rate too low, process loses frame.**
  - **If actual rate too high, process gains frame.**

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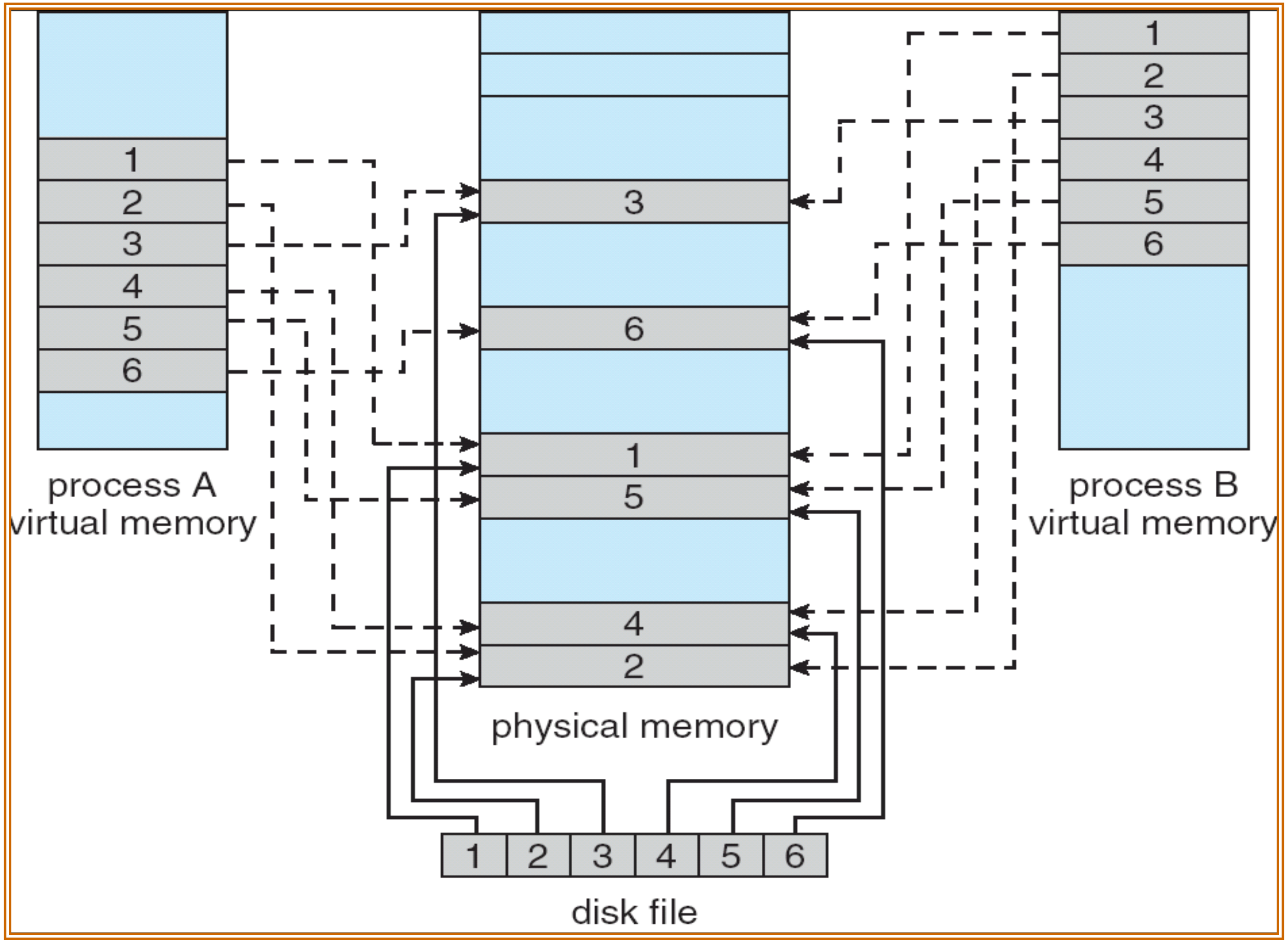
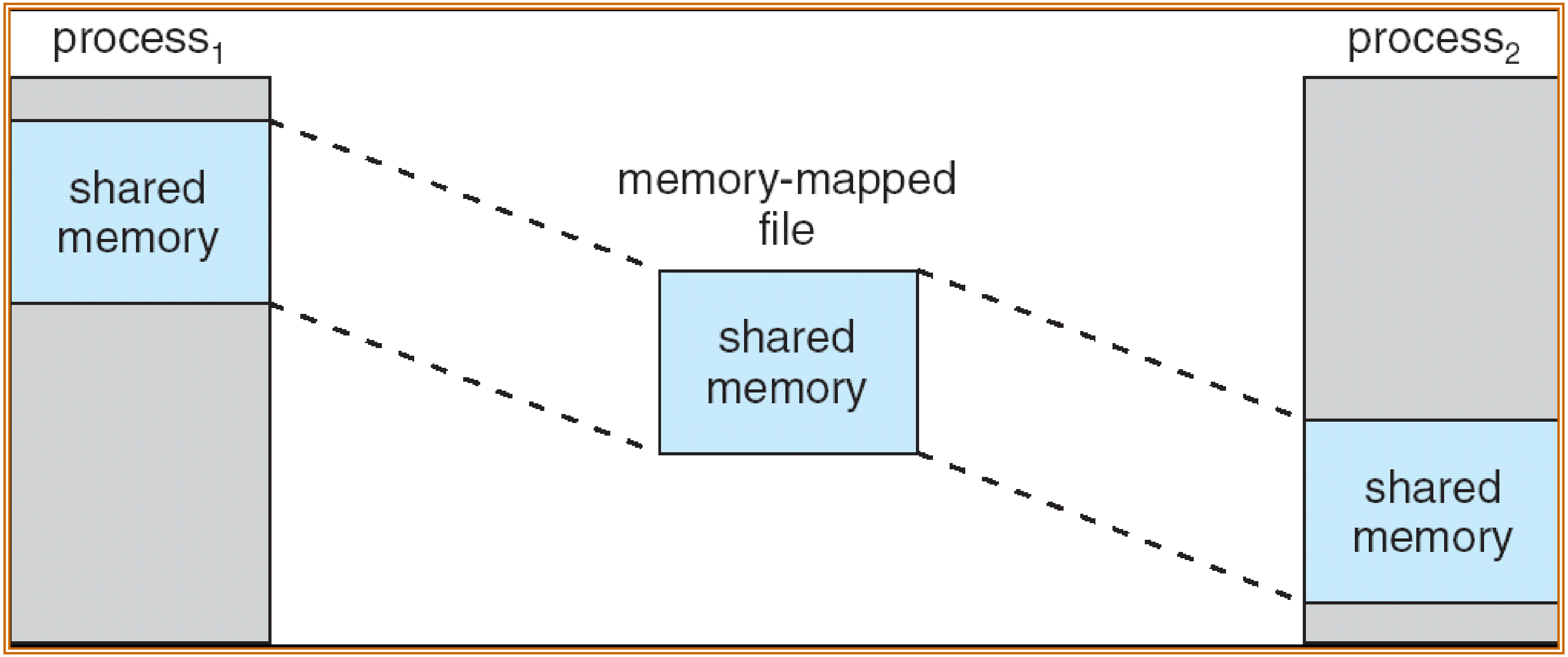
Memory-Mapped Files

- **Memory-mapped file I/O allows file I/O to be treated as routine memory access by *mapping* a disk block to a page in memory.**
- **A file is initially read using demand paging. A page-sized portion of the file is read from the file system into a physical frame. Subsequent reads/writes to/from the file are treated as ordinary memory accesses.**
- **Simplifies file access by treating file I/O through memory rather than read()/write() system calls.**
- **Also allows several processes to map the same file allowing the pages in memory to be shared.**

Memory-Mapped Files



Memory-Mapped Shared Memory in Windows



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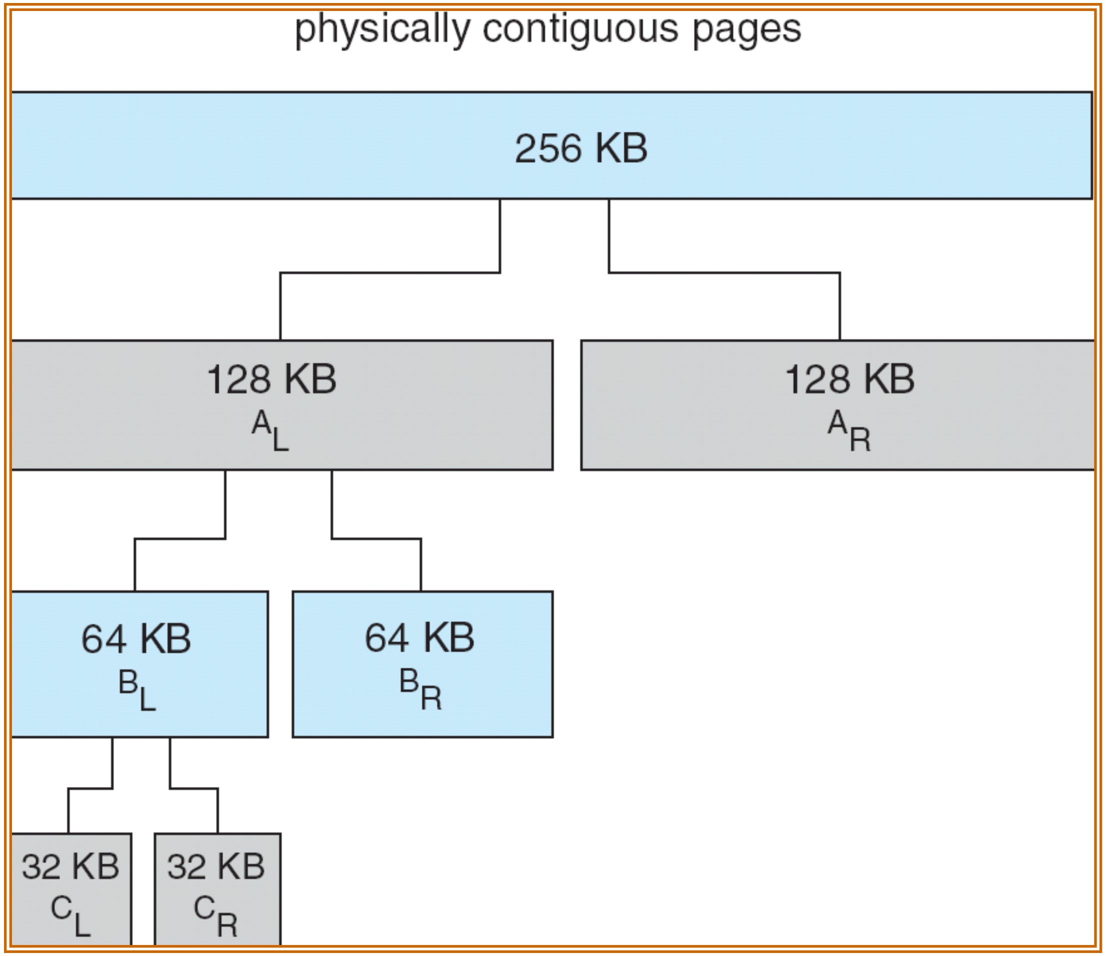
Allocating Kernel Memory

- Treated differently from user memory
- Often allocated from a free-memory pool
  - Kernel requests memory for structures of varying sizes
  - Some kernel memory needs to be contiguous

Buddy System

- Allocates memory from fixed-size segment consisting of physically-contiguous frames
- Memory allocated using power-of-2 allocator
  - Satisfies requests in units sized as power of 2
  - Request rounded up to next-highest power of 2
  - When smaller allocation needed than is available, current chunk split into two buddies of next-lower power of 2
    - Continue until appropriate sized chunk available

Buddy System Allocator



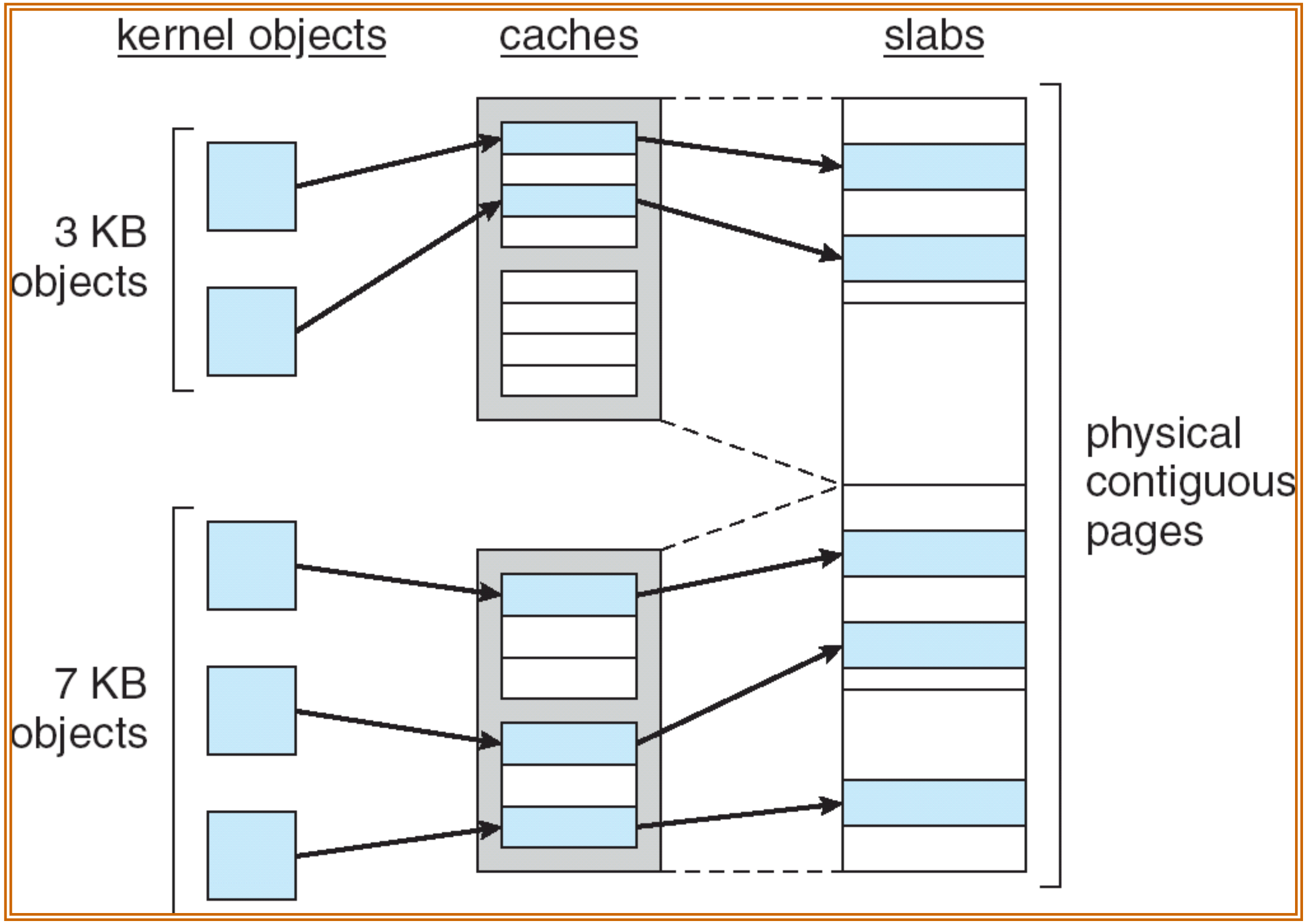
Slab Allocator

- Alternate strategy
- **Slab** is one or more physically contiguous pages
- **Cache** consists of one or more slabs
- Single cache for each unique kernel data structure
  - Each cache filled with objects – instantiations of the data structure

Slab Allocator

- When cache created, filled with objects marked as free
- When structures stored, objects marked as used
- If slab is full of used objects, next object allocated from empty slab
  - If no empty slabs, new slab allocated
- Benefits include no fragmentation, fast memory request satisfaction

Slab Allocation



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Other Issues -- Prepaging

- **Prepaging**
  - **To reduce the large number of page faults that occurs at process startup**
  - **Prepaging all or some of the pages a process will need, before they are referenced**
  - **But if prepaged pages are unused, I/O and memory was wasted**
  - **Assume *s* pages are prepaged and *α percent* of the pages is used**
    - **Is cost of *s * α* save pages faults > or < the cost of *s * (1- α)* unnecessary pages*?***
    - ***α* near 0 / 1 ⇒ prepaging loses / success**

Other Issues – Page Size

- Page size selection must take into consideration
  - fragmentation (small page)
  - table size (large page)
  - I/O overhead (large page)
  - locality (small page)

Other Issues – TLB Reach

- TLB Reach - The amount of memory accessible from the TLB
- TLB Reach = (TLB Size) X (Page Size)
- Ideally, the working set of each process is stored in the TLB. Otherwise there is a high degree of page faults
- Increase the Page Size
- Provide Multiple Page Sizes
  - This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation

Other Issues – Program Structure

- Program structure
  - **int A[][] = new int[1024][1024];**
  - Each row is stored in one page
  - Program 1

```
for (j = 0; j < A.length; j++)
    for (i = 0; i < A.length; i++)
        A[i,j] = 0;
```

    1024 x 1024 page faults

  - Program 2

```
for (i = 0; i < A.length; i++)
    for (j = 0; j < A.length; j++)
        A[i,j] = 0;
```

  - 1024 page faults

Other Issues – I/O interlock

- I/O Interlock – Pages must sometimes be locked into memory
- Consider I/O - Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm

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Operating System Examples

- Windows XP
- Solaris

Windows XP

- **Uses demand paging with clustering. Clustering brings in pages surrounding the faulting page.**
- **Processes are assigned working set minimum and working set maximum**
- **Working set minimum is the minimum number of pages the process is guaranteed to have in memory**

Windows XP

- A process may be assigned as many pages up to its working set maximum
- When the amount of free memory in the system falls below a threshold, automatic working set trimming is performed to restore the amount of free memory
- Working set trimming removes pages from processes that have pages in excess of their working set minimum

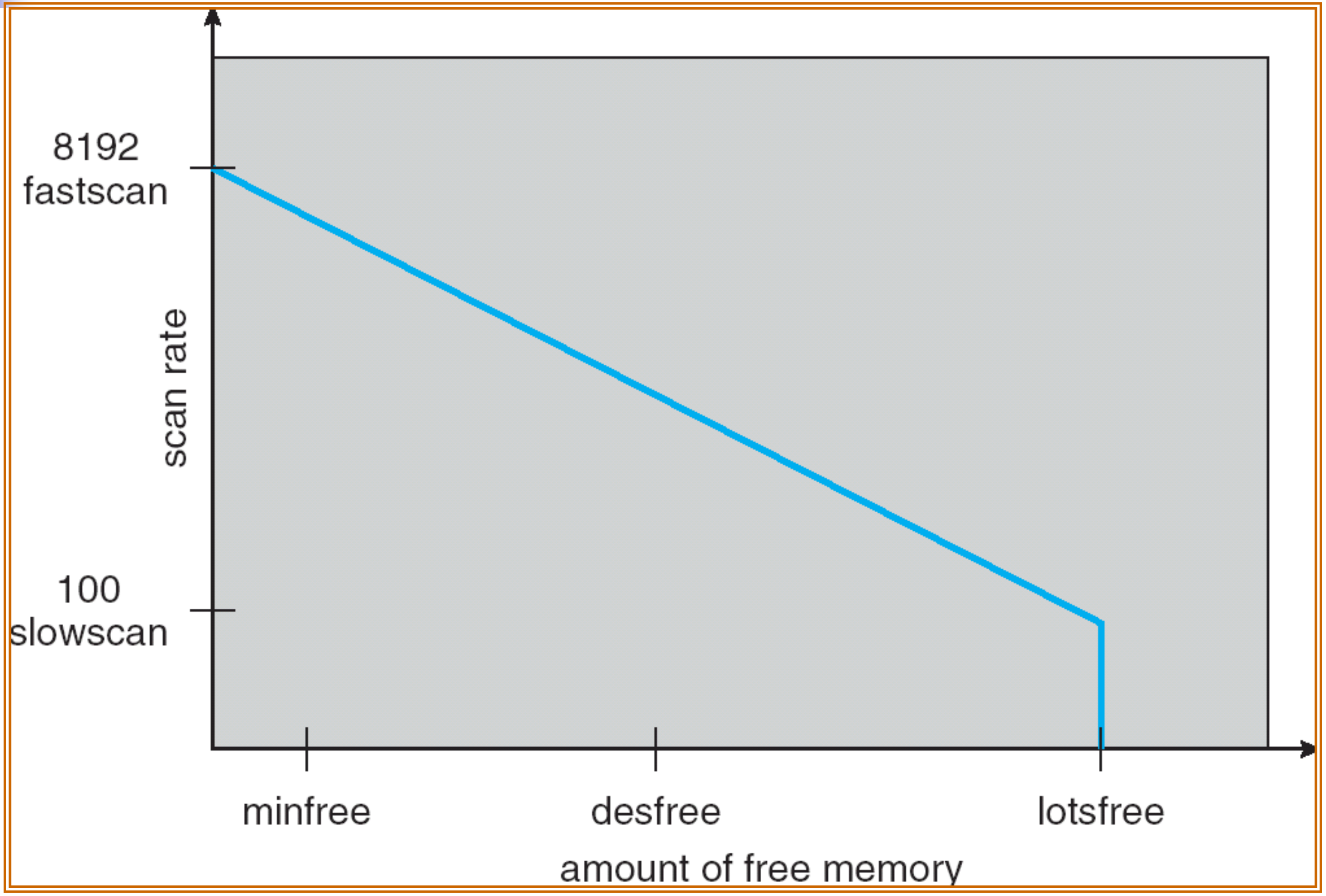
Solaris

- Paging is performed by *pageout* process
- Pageout scans pages using modified clock algorithm
- *Scanrate* is the rate at which pages are scanned. This ranges from *slowscan* to *fastscan*
- Pageout is called more frequently depending upon the amount of free memory available

Solaris

- **Maintains a list of free pages to assign faulting processes**
- *Lotsfree* – **threshold parameter (amount of free memory) to begin paging**
- *Desfree* – **threshold parameter to increasing paging**
- *Minfree* – **threshold parameter to being swapping**

Solaris 2 Page Scanner



Part 3 小结

- 基本概念：内存保护（基址寄存器+界限地址寄存器）、地址绑定、逻辑地址空间与物理地址空间、动态加载、动态链接、交换
- 连续分配：固定分区、可变分区（动态分配问题，3种方法）、碎片（内、外）
- 分页：页（页大小取值因素）、帧、页表、逻辑地址结构、页表实现（寄存器、PTBR、TLB）、Hit Radio（命中率）、内存保护、共享页、页表结构（层次、哈希、反向）、分段
- 按需调页（有效访问时间）、写时复制、页置换算法（FIFO（Belady异常）、最优OPT、LRU、近似LRU、计数）、
- 帧分配（平均、按比例）、系统颠簸（含义、原因、解决方法）、内存映射文件、内核内存分配