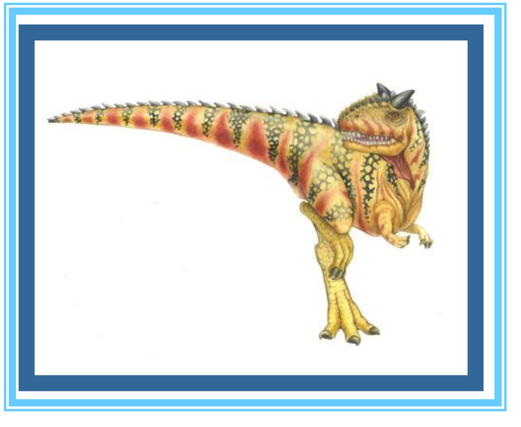
Chapter 9: Virtual-Memory Management



Chapter 9: Virtual-Memory Management

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

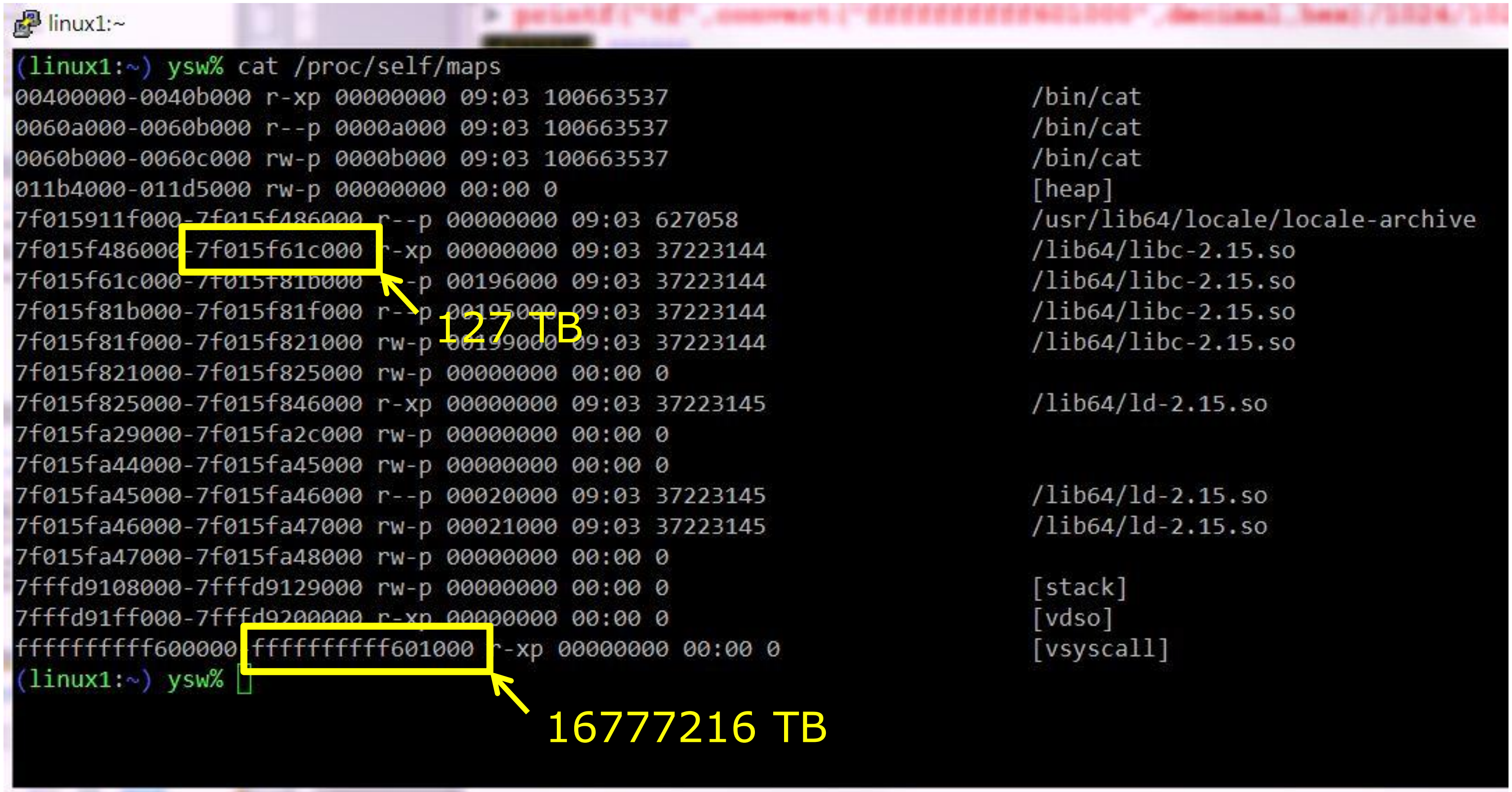
Objectives

- To describe the benefits of a virtual memory system
- To explain the concepts of demand paging, page-replacement algorithms, and allocation of page frames
- To discuss the principle of the working-set model

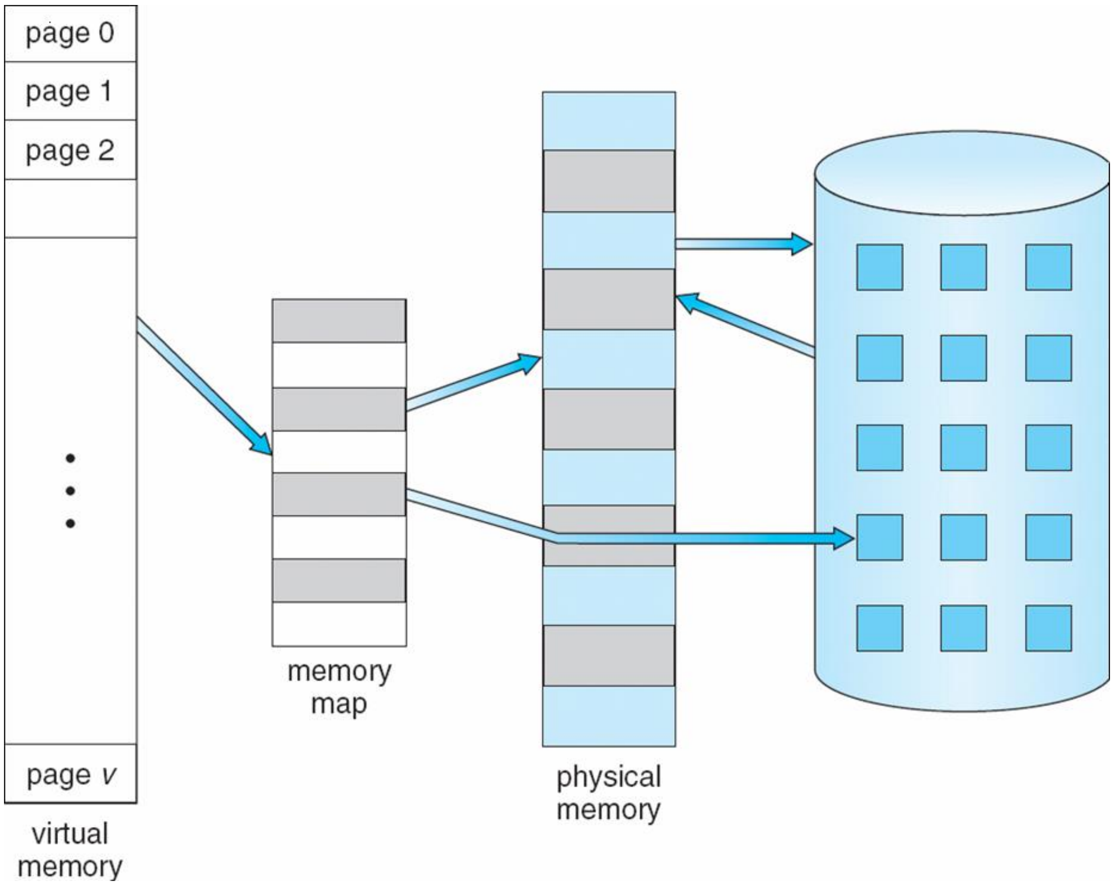
Background

- **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
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

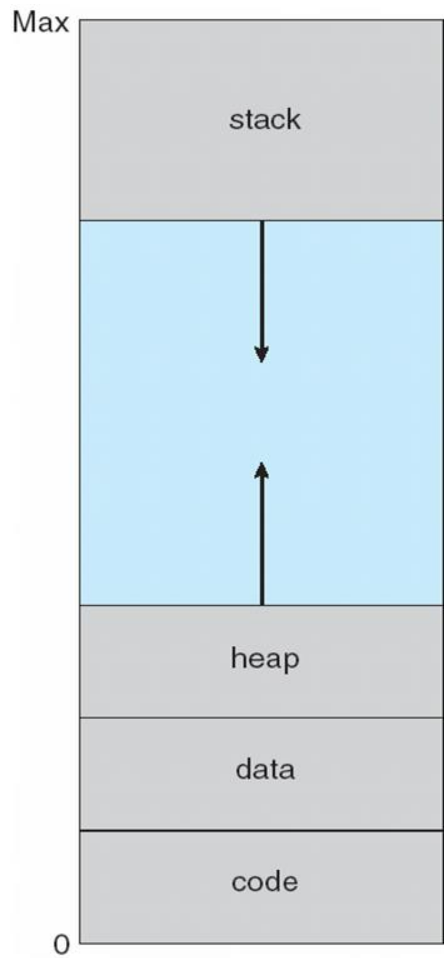
Virtual Memory That is Larger Than Physical Memory



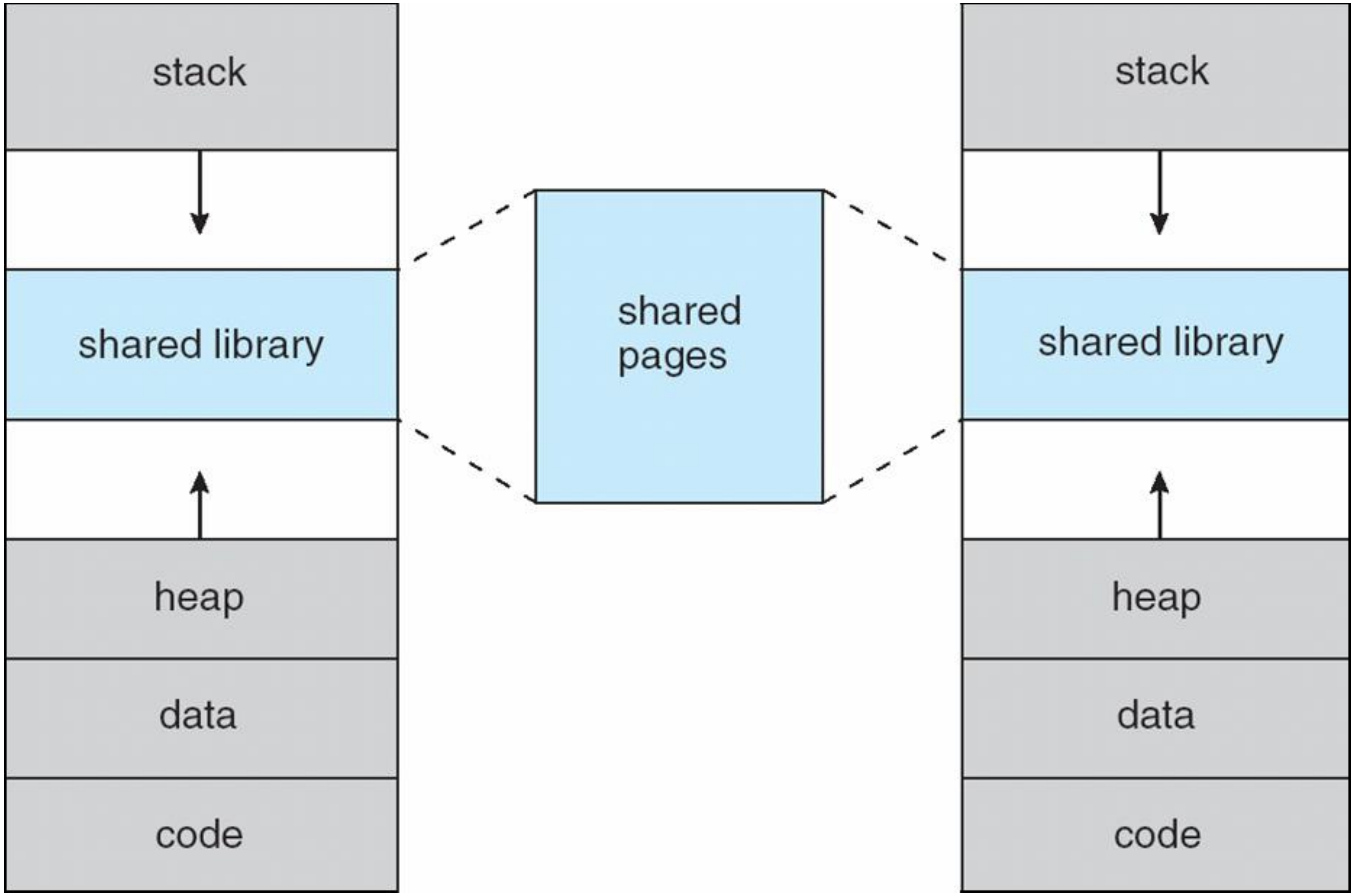
Virtual Memory That is Larger Than Physical Memory



Virtual-address Space



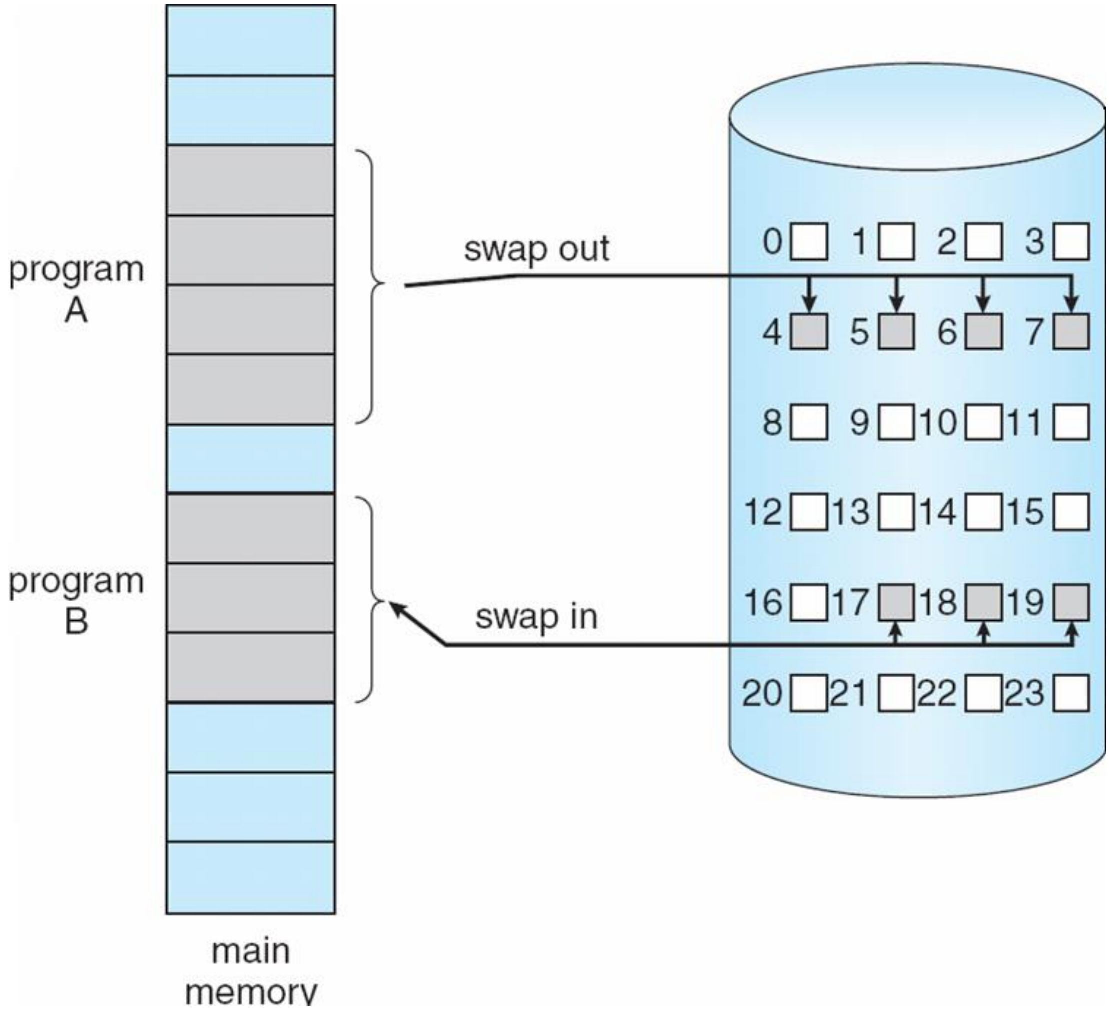
Shared Library Using Virtual Memory



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** – never swaps a page into memory unless page will be needed
  - Swapper that deals with pages is a **pager**

Transfer of a Paged Memory to Contiguous Disk Space



Valid-Invalid Bit

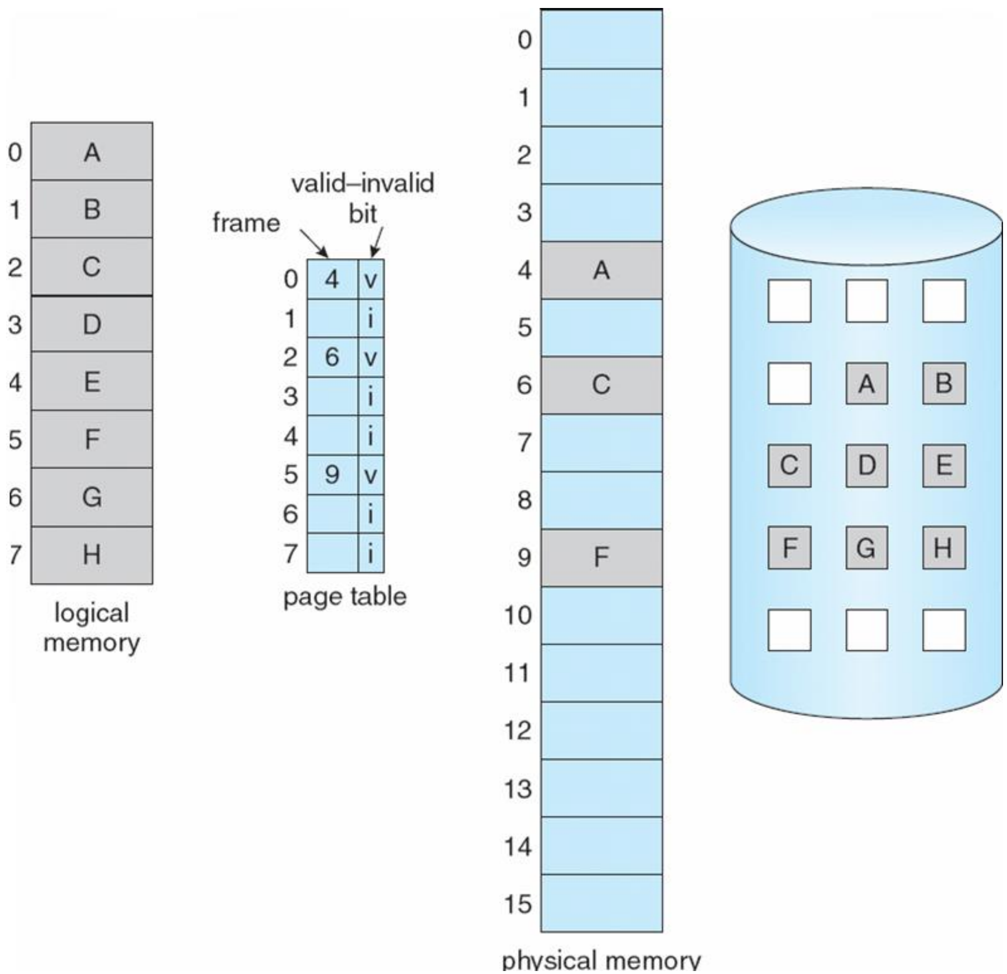
- With each page table entry a valid–invalid bit is associated
  (**v** ⇒ in-memory, **i** ⇒ not-in-memory)
- Initially valid–invalid bit is set to **i** on all entries
- Example of a page table snapshot:

Frame #	valid-invalid bit
	v
	v
	v
	v
	i
….	
	i
	i

page table

- During address translation, if valid–invalid bit in page table entry
  is **i** ⇒ page fault

Page Table When Some Pages Are Not in Main Memory



Page Fault

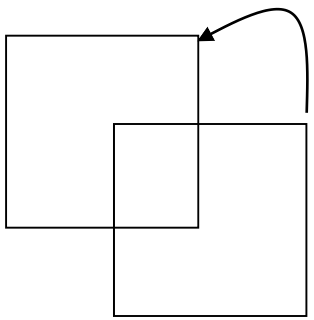
- If there is a reference to a page, first reference to that page will trap to operating system:

  page fault

1. Operating system looks at another table to decide:
   - Invalid reference $\Rightarrow$ abort
   - Just not in memory
2. Get empty frame
3. Swap page into frame
4. Reset tables
5. Set validation bit = **v**
6. Restart the instruction that caused the page fault

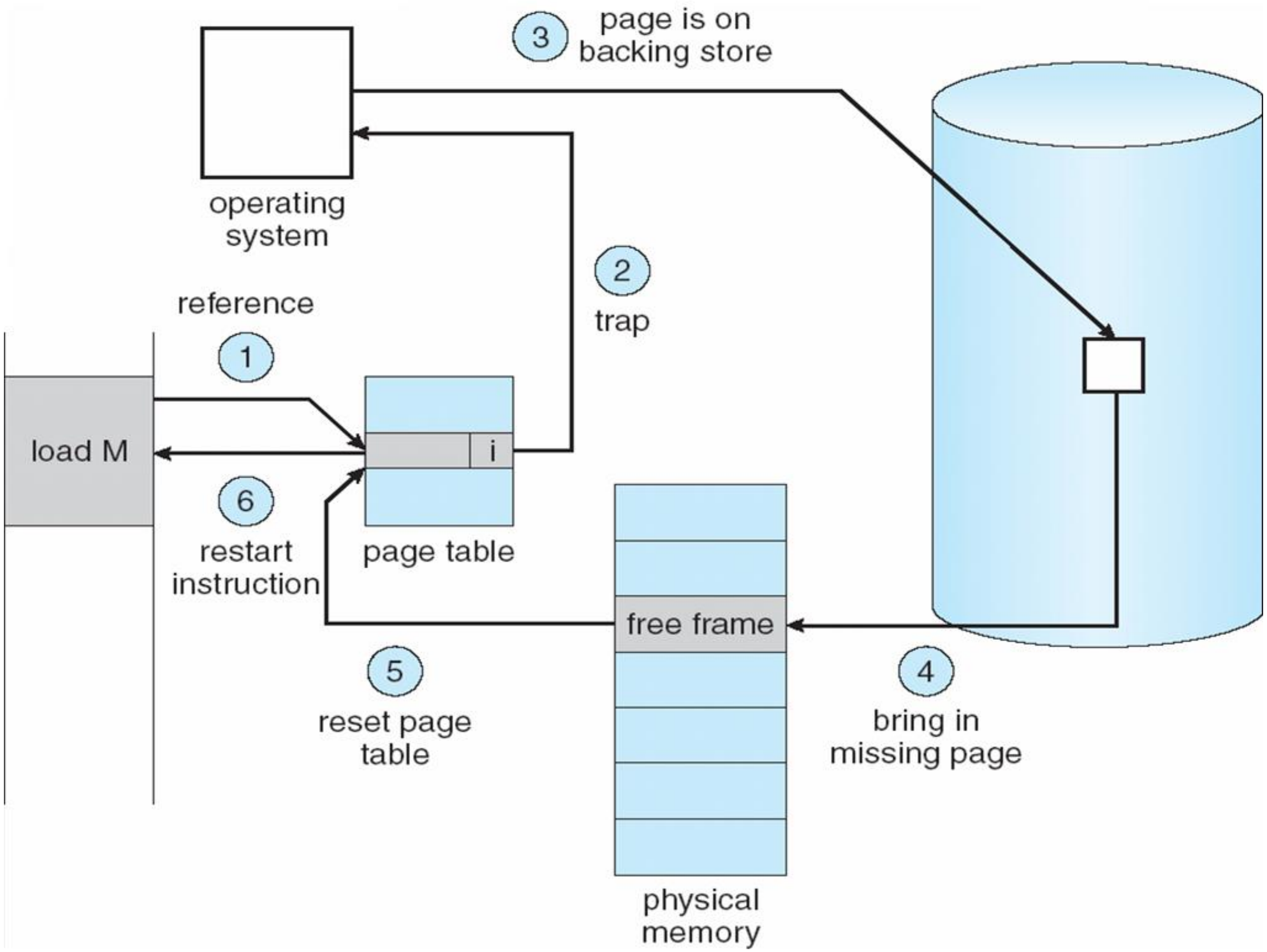
Page Fault (Cont.)

- Restart instruction
  - block move



  - auto increment/decrement location

Steps in Handling a Page Fault



Performance of Demand Paging

- Page Fault Rate $0 \le p \le 1.0$
  - if $p = 0$ no page faults
  - if $p = 1$, every reference is a fault

- Effective Access Time (EAT)

EAT = $(1 – p)$ x memory access
+ p (page fault overhead
+ swap page out
+ swap page in
+ restart overhead
)

Demand Paging Example

- Memory access time = 200 nanoseconds
- Average page-fault service time = 8 milliseconds
- EAT = (1 – p) x 200 + p (8 milliseconds)

  = (1 – p x 200 + p x 8,000,000

  = 200 + p x 7,999,800

- If one access out of 1,000 causes a page fault, then

  EAT = 8.2 microseconds.

  This is a slowdown by a factor of 40!!

Process Creation

- Virtual memory allows other benefits during process creation:

  - Copy-on-Write

  - Memory-Mapped Files (later)

Copy-on-Write

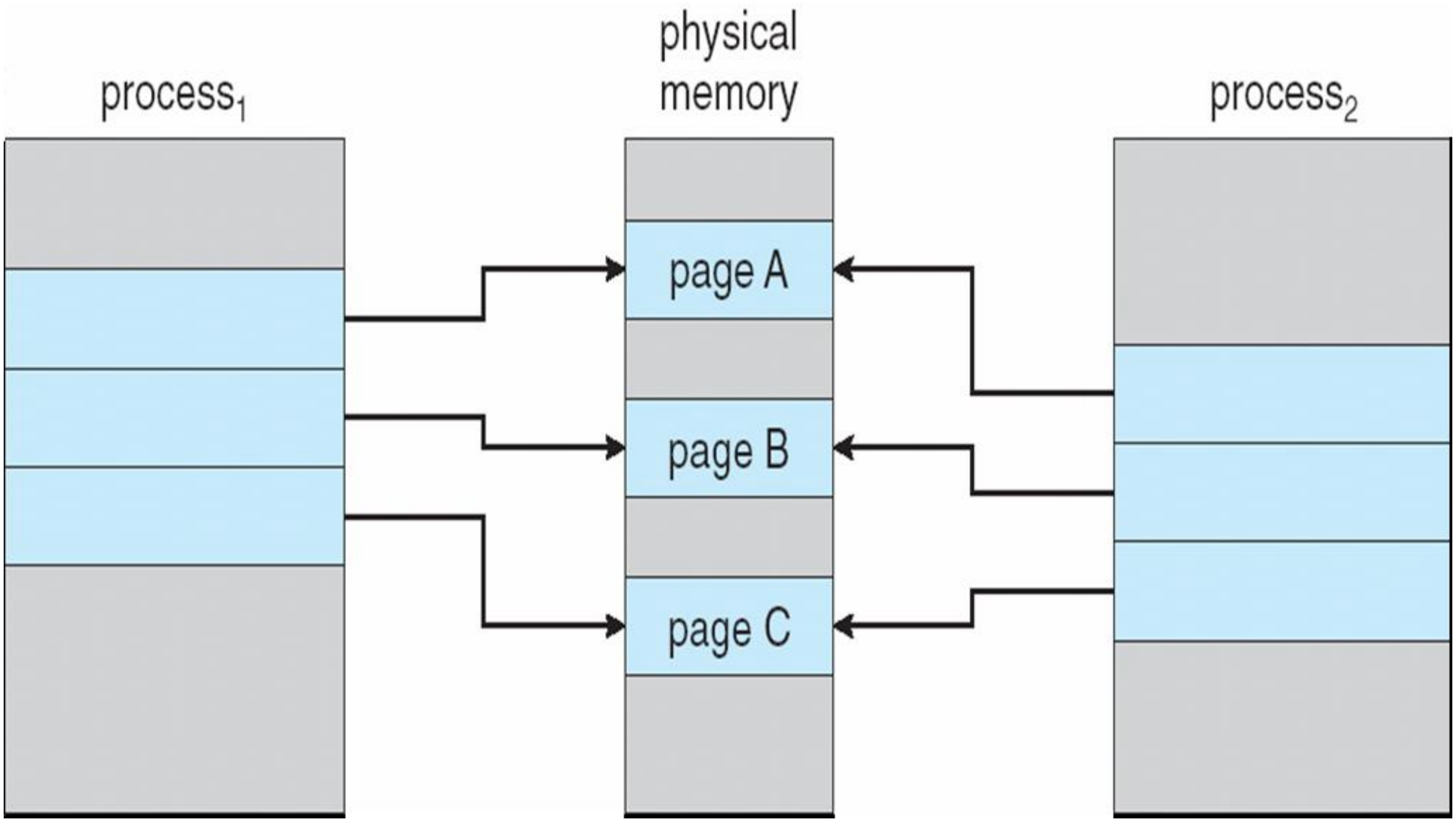
- Copy-on-Write (COW) allows both parent and child processes to initially *share* the same pages in memory

  If either process modifies a shared page, only then is the page copied

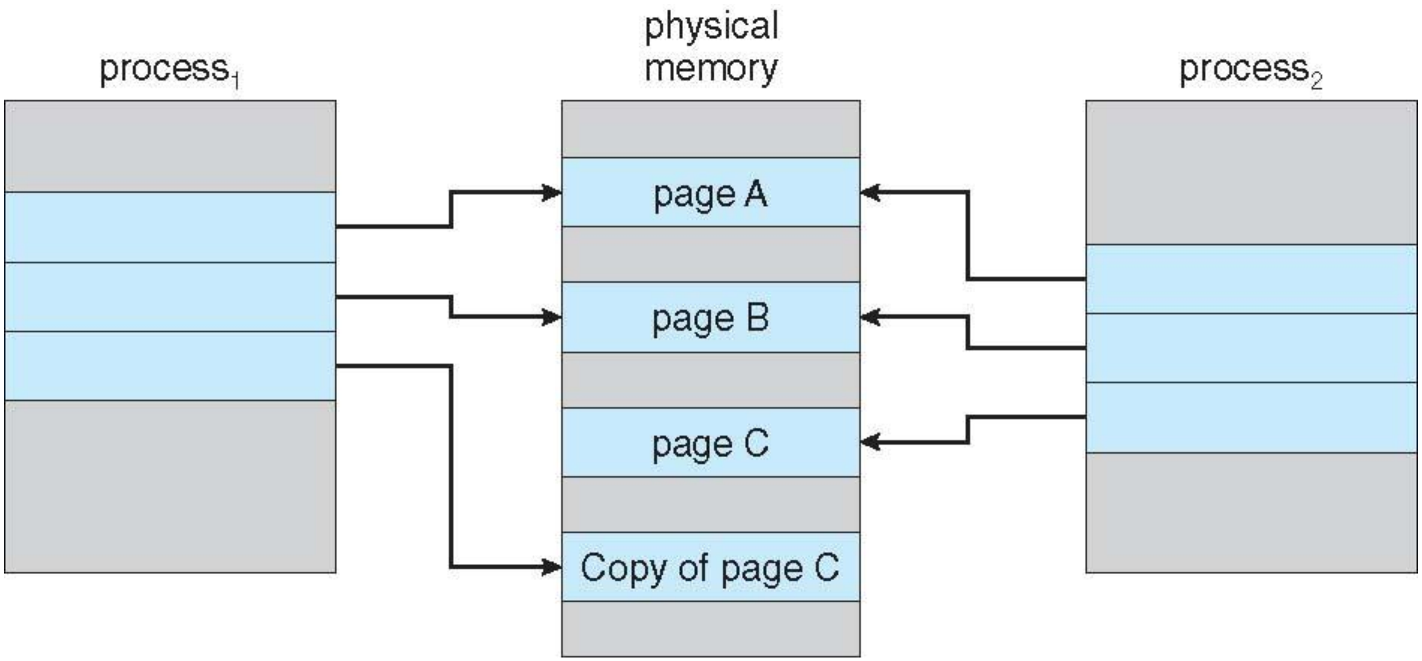
- COW allows more efficient process creation as only modified pages are copied

- Free pages are allocated from a **pool** of zeroed-out pages

Before Process 1 Modifies Page C



After Process 1 Modifies Page C



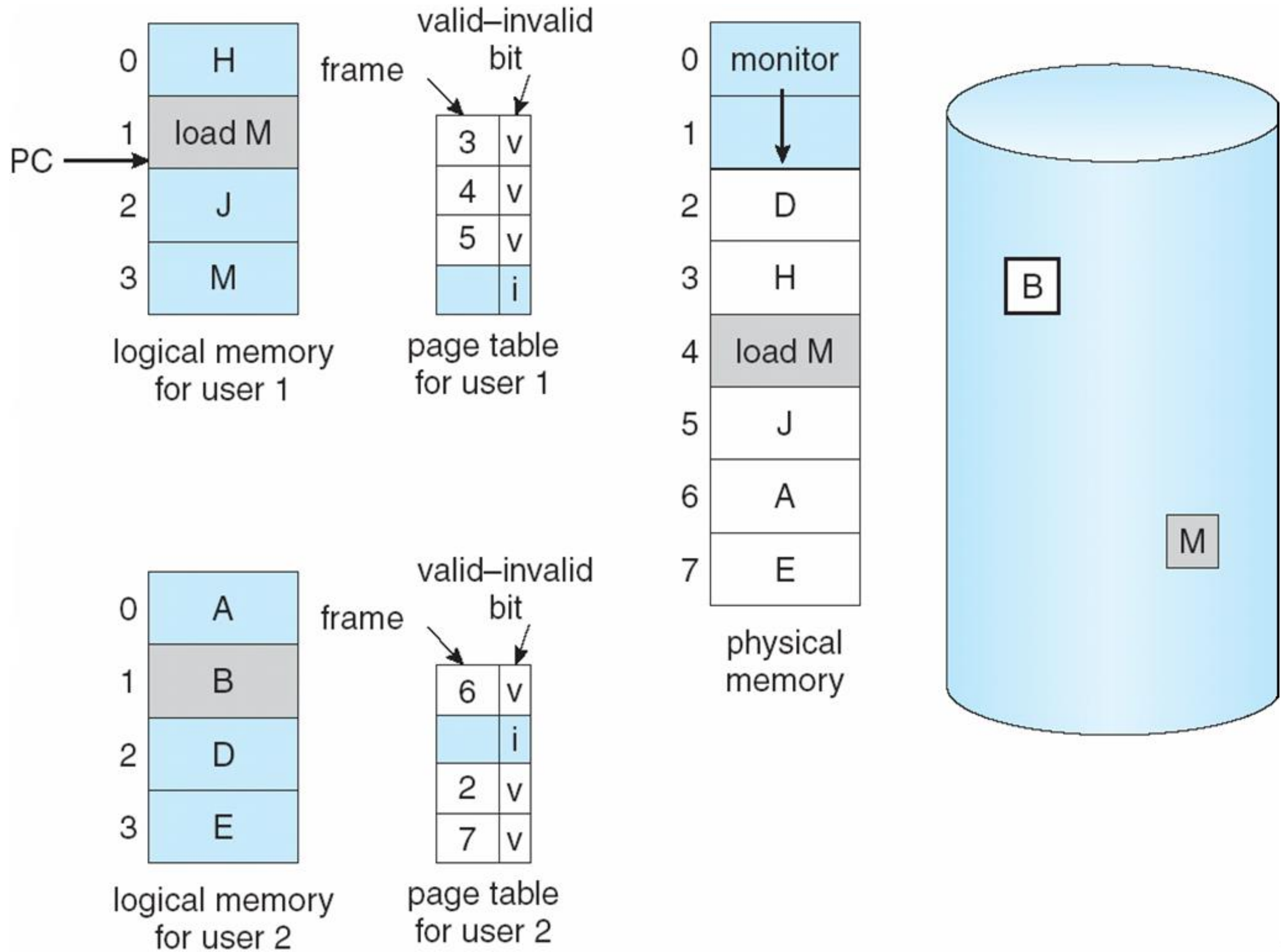
What happens if there is no free frame?

- Page replacement – find some page in memory, but not really in use, swap it out
  - algorithm
  - performance – want an algorithm which will result in minimum number of page faults
- Same page may be brought into memory several times

Page Replacement

- Prevent over-allocation of memory by modifying page-fault service routine to include page replacement
- Use **modify (dirty) bit** to reduce overhead of page transfers – only modified pages are written to disk
- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory

Need For Page Replacement



Basic Page Replacement

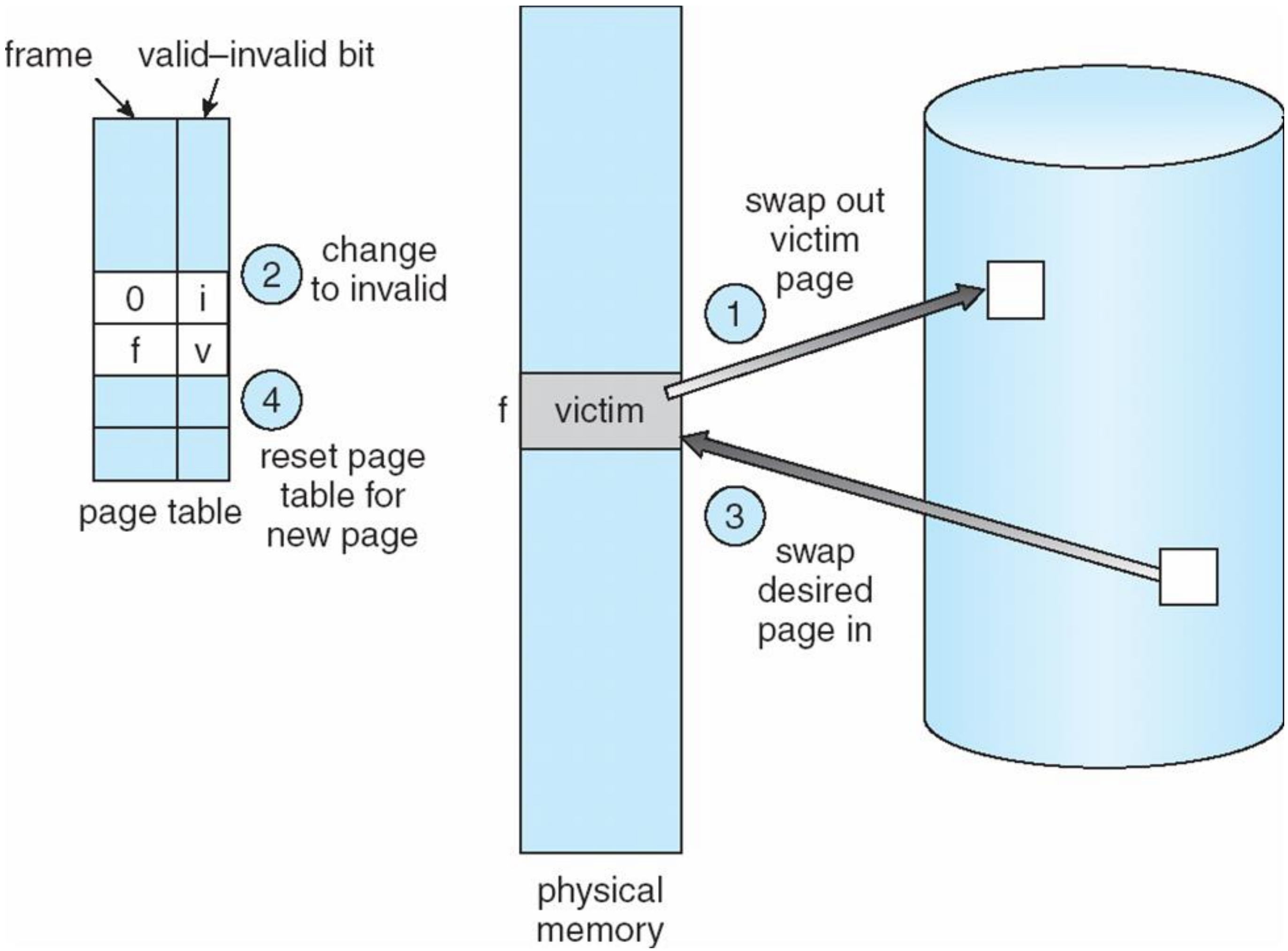
1. Find the location of the desired page on disk

2. 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

3. Bring the desired page into the (newly) free frame; update the page and frame tables

4. Restart the process

Page Replacement



Page Replacement Algorithms

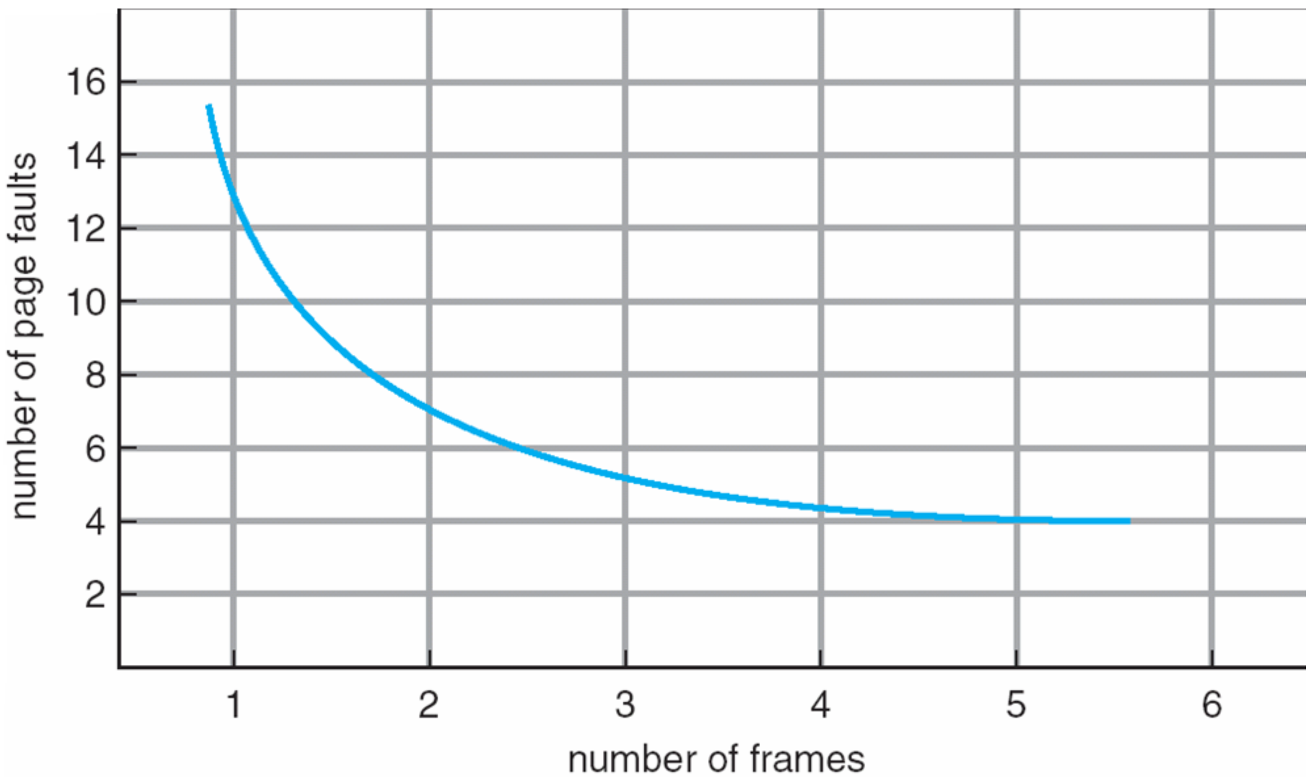
- Want lowest page-fault rate

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

- In all our examples, the reference string is

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

Graph of Page Faults Versus The Number of Frames



- One desirable property: When you add memory, # of page faults goes down
  - Does this always happen?
  - Seems like it should, right?

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	1	4	5
2	2	1	3
3	3	2	4

9 page faults

- 4 frames

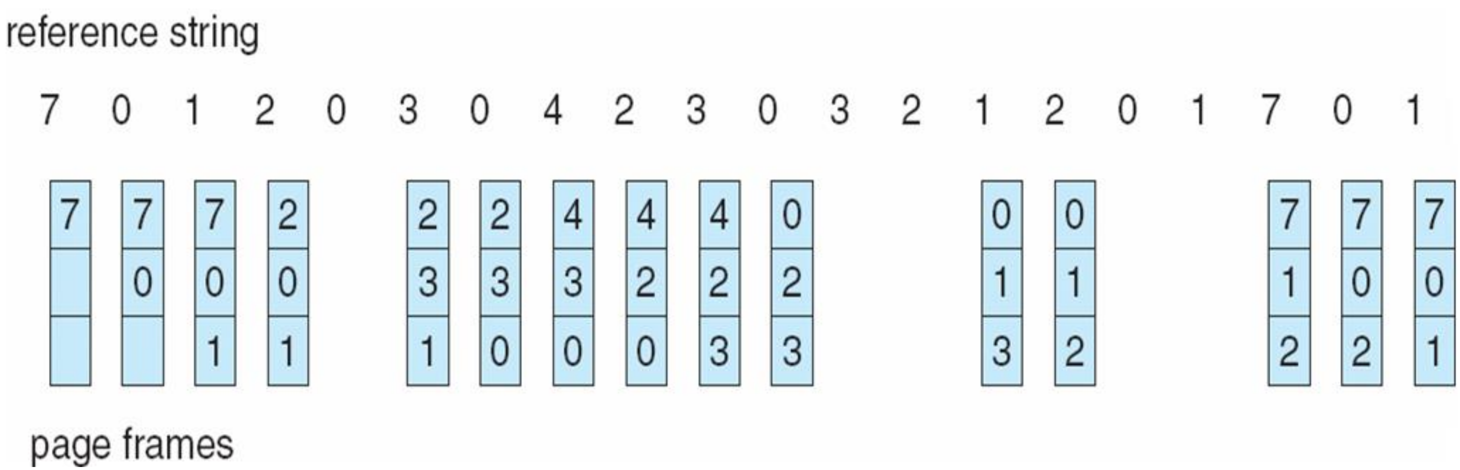
1	1	5	4
2	2	1	5
3	3	2	
4	4	3	

10 page faults

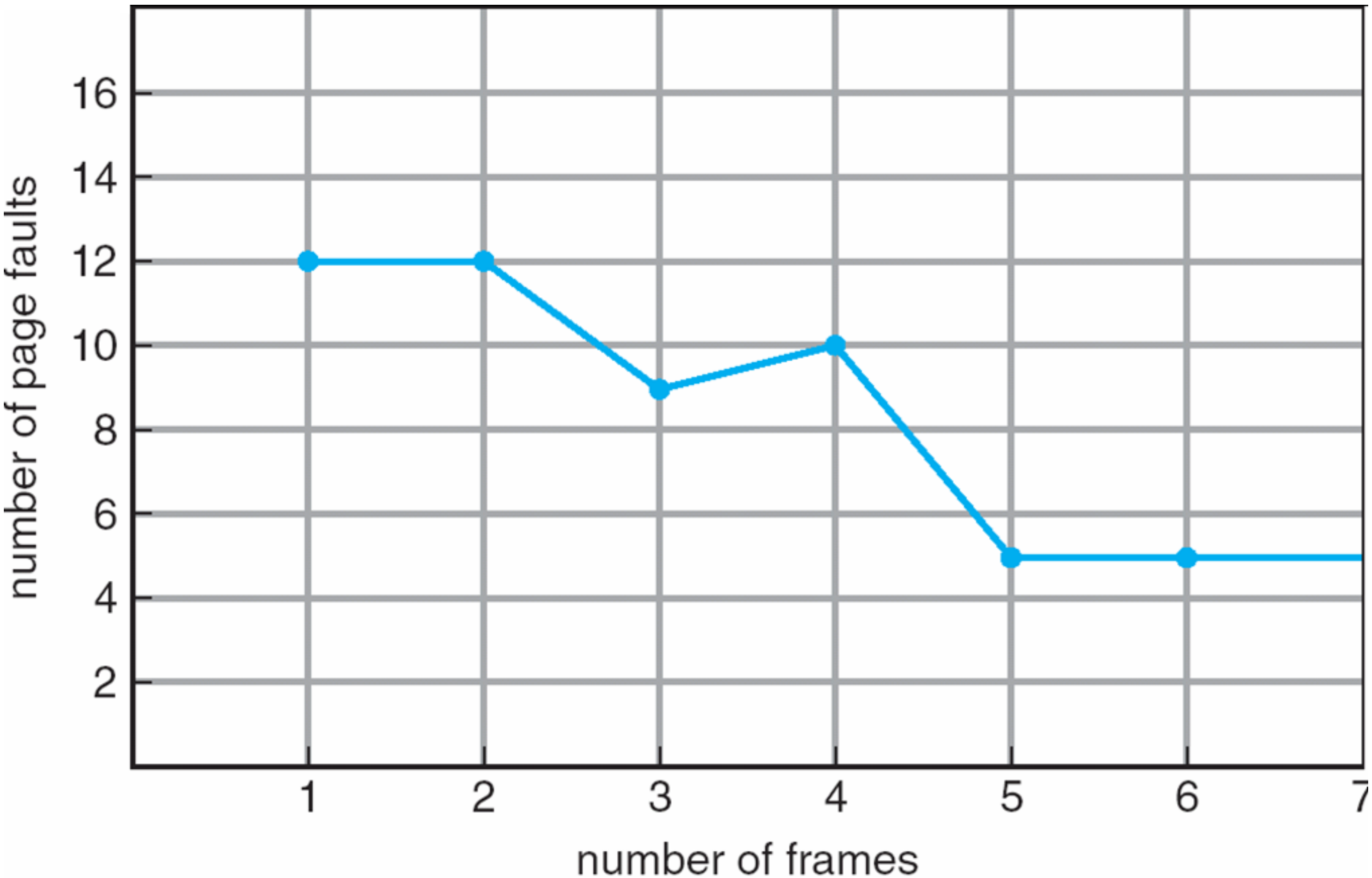
With FIFO, contents can be completely different after adding memory

- Belady’s Anomaly: more frames $\Rightarrow$ more page faults

FIFO Page Replacement



FIFO Illustrating Belady's Anomaly



Optimal Algorithm

- Replace page that will not be used for longest period of time
- 4 frames example

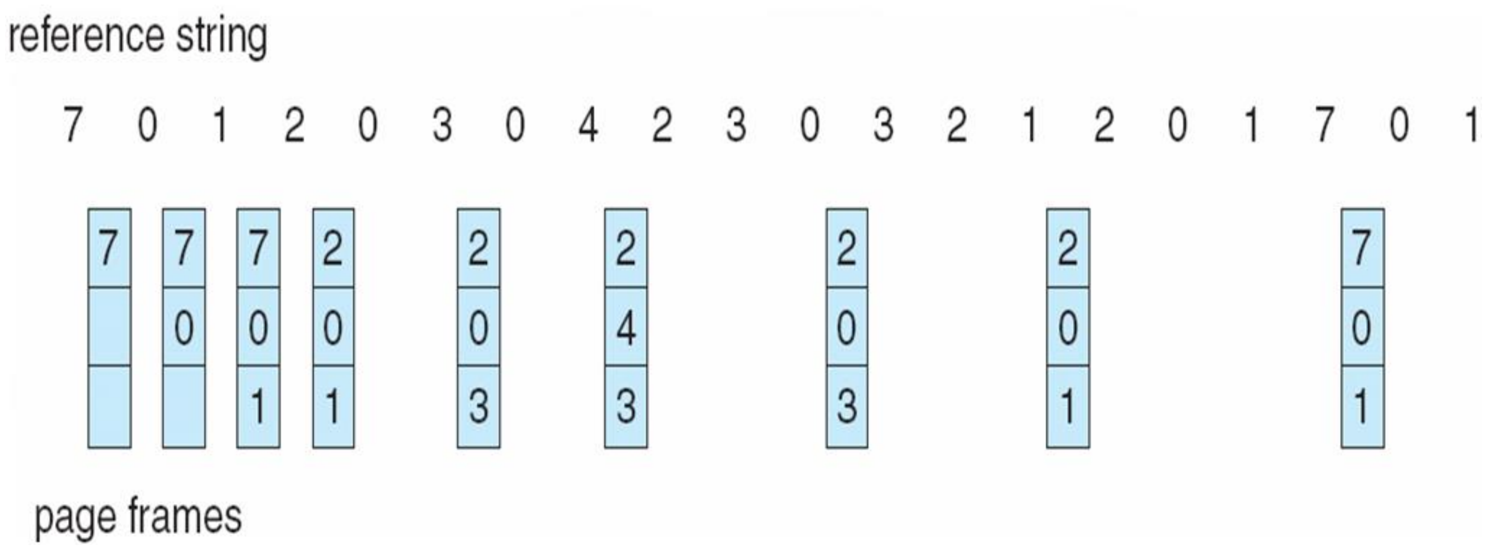
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

1	4
2	
3	
4	5

6 page faults

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

Optimal Page Replacement



With OPTIMAL, contents of memory with X pages are a subset of contents with X+1 pages after adding memory

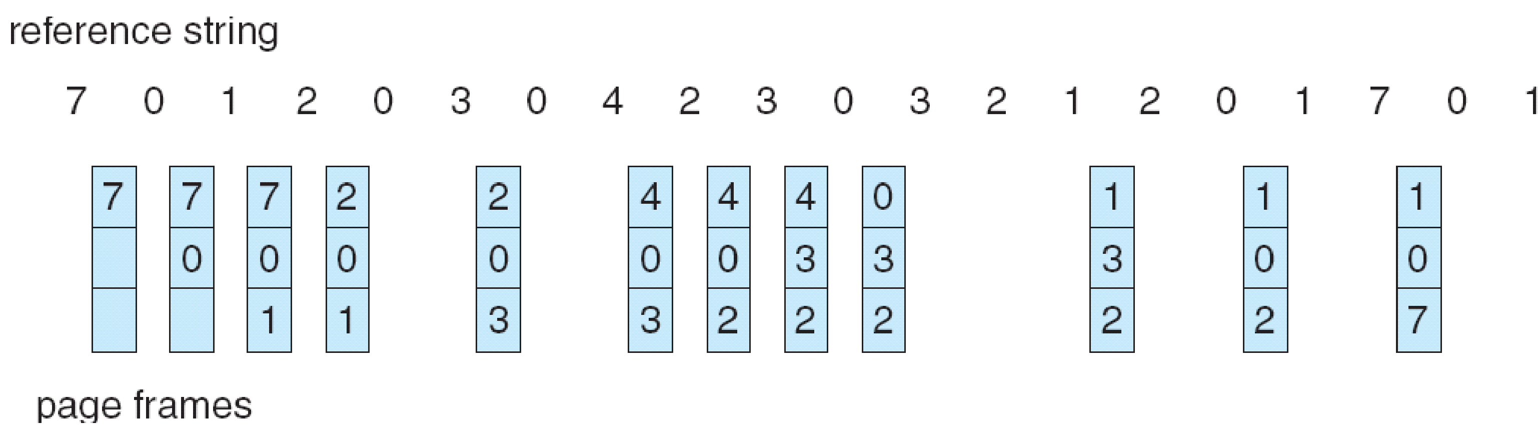
Least Recently Used (LRU) Algorithm

- Assumption: A page that has not been referenced for the longest time would wait for the longest time to be accessed again
  - Use of known history to predict unknown future
  - Does the intuition really work?
- Reference string: 1, 2, 3, 4, 1, 2, **5**, 1, 2, **3**, **4**, **5**

1	1	1	1	**5**
2	2	2	2	2
3	**5**	5	**4**	4
4	4	**3**	3	3

- Counter implementation
  - Every page entry has a counter; every time page is referenced through this entry, copy the clock into the counter
  - When a page needs to be changed, look at the counters to determine which are to change

LRU Page Replacement

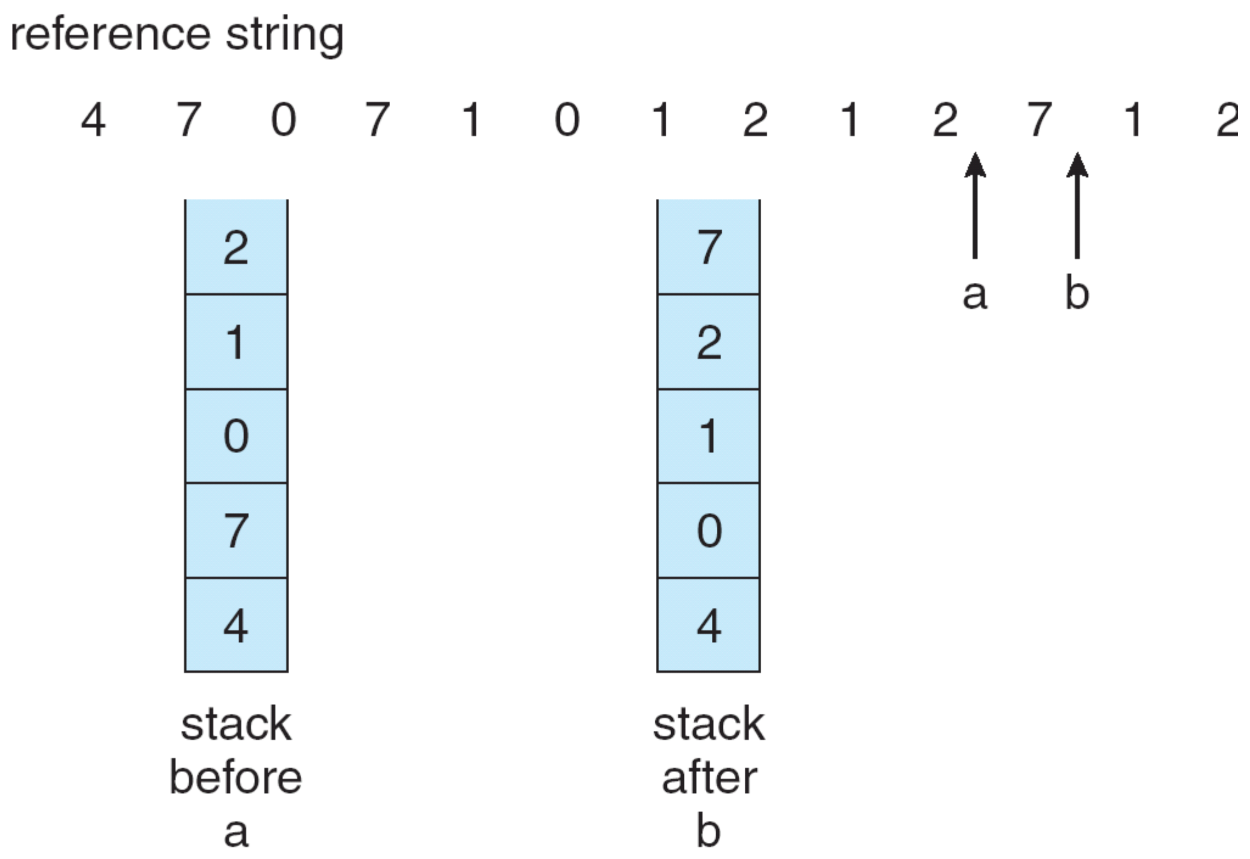


With LRU, contents of memory with X pages are a subset of contents with X+1 pages after adding memory

LRU Algorithm (Cont.)

- Stack implementation – keep a stack of page numbers in a double link form:
  - Page referenced:
    - move it to the top
    - requires 6 pointers to be changed
  - No search for replacement

Use Of A Stack to Record The Most Recent Page References

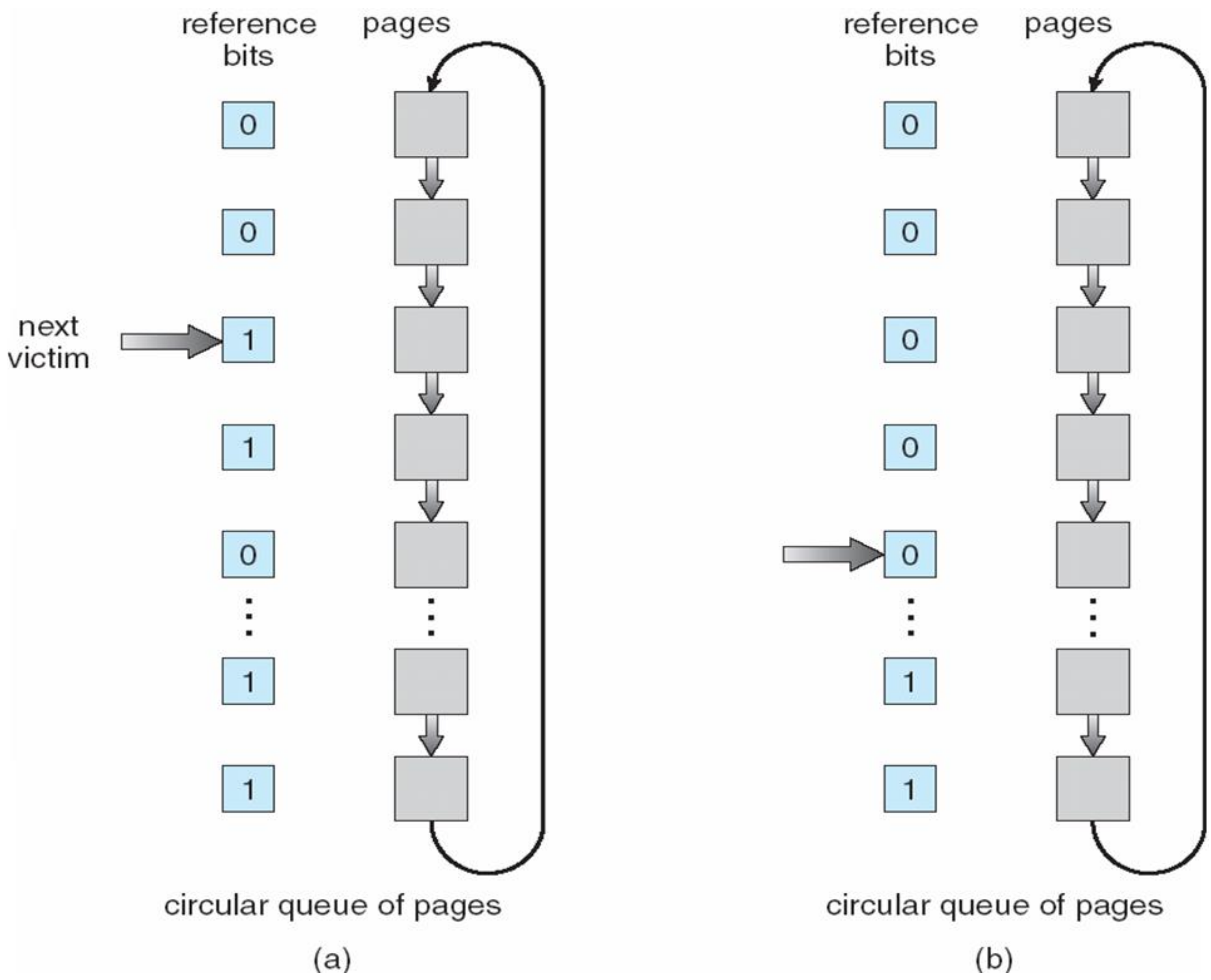


LRU Approximation Algorithms

- Both timestamp and stack implementations are too expensive to implement in practice

- Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - Replace the one which is 0 (if one exists)
    - We do not know the order, however
- Second chance
  - Need reference bit
  - Clock replacement
  - 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 (clock) Page-Replacement Algorithm



Second-Chance (clock) Page-Replacement Algorithm

- What if all reference bits are set?
  - The original victim will be selected after looping around
  - The clock algorithm degenerates into FIFO

- The clock algorithm replaces an old page, not the oldest page
- What if hand moves slowly?
  - Not many page faults
  - Or, victim page can be found quickly
- What if hand moves quickly?
  - Lots of page faults
  - Or, lots of reference bits set
- One way to view clock algorithm
  - Crude partitioning of pages into two groups: young and old
  - Why not partition into more than 2 groups?

N^{th} Chance version of Clock Algorithm

- N^{th} chance algorithm: Give page N chances
  - OS keeps counter per page: # sweeps
  - On page fault, OS checks reference bit:
    - 1⇒clear reference bit and also clear counter (used in last sweep)
    - 0⇒increment counter; if count=N, replace page
  - Means that clock hand has to sweep by N times without page being used before page is replaced
- How do we pick N?
  - Why pick large N? Better approximation to LRU
    - If N ~ 1K, really good approximation
  - Why pick small N? More efficient
    - Otherwise might have to look a long way to find free page
- What about dirty pages?
  - Takes extra overhead to replace a dirty page, so give dirty pages an extra chance before replacing?
  - Common approach:
    - Clean pages, use N=1
    - Dirty pages, use N=2

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

Allocation of Frames

- Each process needs *minimum* number of pages
- Example: IBM 370 – 6 pages to handle SS MOVE 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 – For example, if there are 100 frames and 5 processes, give each process 20 frames.
- Proportional allocation – Allocate according to the size of process

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

$$-\, S = \sum s_i$$

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

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

$$m = 64$$

$$s_i = 10$$

$$s_2 = 127$$

$$a_1 = \frac{10}{137} \times 64 \approx 5$$

$$a_2 = \frac{127}{137} \times 64 \approx 59$$

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

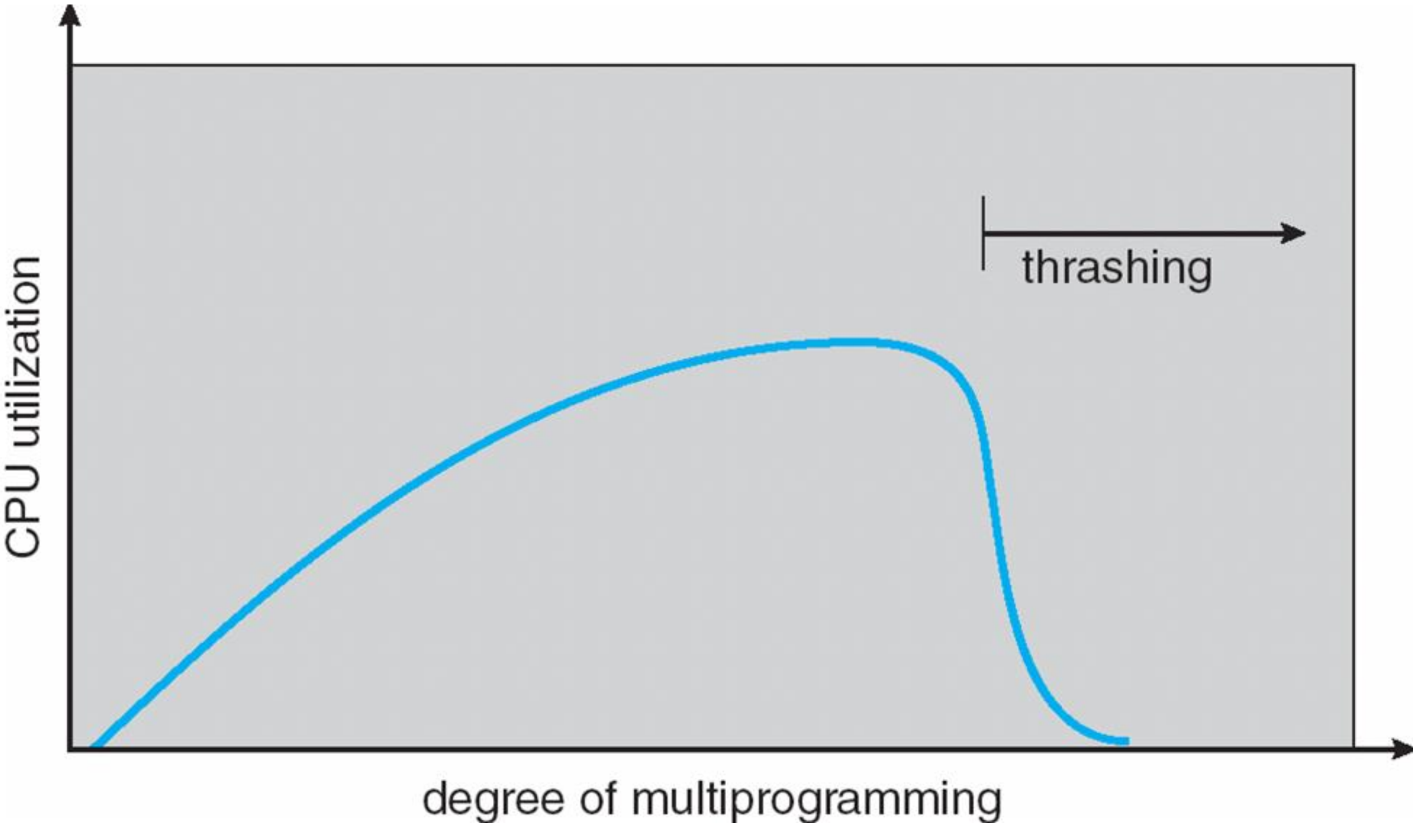
Global vs. Local Allocation

- **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

Thrashing

- If a process does not have "enough" pages, the page-fault rate is very high. This leads to:
  - low CPU utilization
  - operating system thinks that it needs to increase the degree of multiprogramming
  - another process added to the system
  - Even worse thrashing
- **Thrashing** ≡ a system experiences a high degree of paging activity
  - Each process is busy swapping pages in and out

Thrashing (Cont.)



Demand Paging and Thrashing

- Pages should only be brought into memory if the executing process demands them
  - As opposed to anticipatory paging
  - Many page faults will occur until most of a process's working set of pages is located in physical memory
- Why does demand paging work?
  Locality model
  - Process migrates from one locality to another
  - Localities may overlap

Locality In A Memory-Reference Pattern

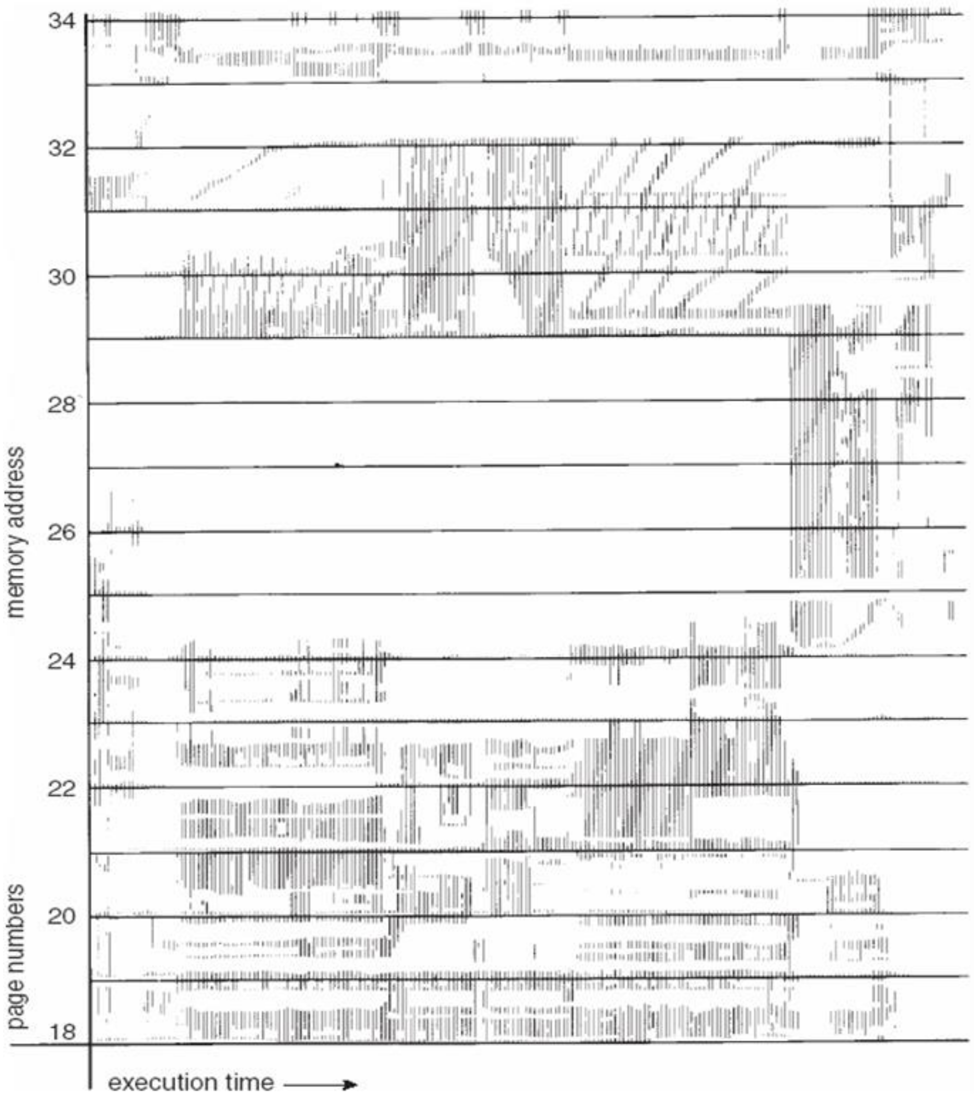
why does paging work?

locality model

- a locality is a set of pages that are actively used together
- program is composed of several different localities, which may overlap
- process migrates from one locality to another.
- if we allocate enough frames to accommodate the locality, faults will only occur when transitioning

why does thrashing occur?

Σ locality sizes > total memory size



Demand Paging and Thrashing

- Why does thrashing occur?
  size of locality > total memory size
  - Could be a process is too large for memory
    - There is nothing the OS can do
  - Could also be the sum of several processes is too large
    - Figure out how much memory each process needs and schedule them accordingly
- Thrashing occurs because the system doesn’t know when it has taken on more work than it can handle
- LRU-type mechanism, such as clock, order pages in terms of last access, but don’t give absolute numbers indicating pages that mustn’t be thrown out

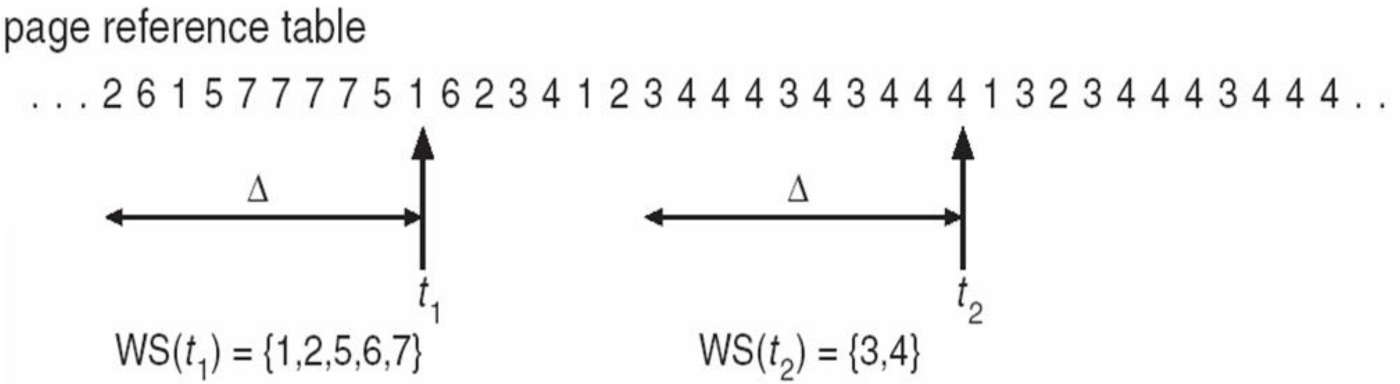
Working-Set Model

- A conceptual model by Peter Denning to prevent thrashing
- Informal definition of working set
  - The collection of pages that a process is working with, and which must thus be resident if the process is to avoid thrashing
- $\Delta \equiv$ 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

- Use the recent needs of a process to predict its future needs
  - At any given time, all pages referenced by a process in the last working-set window are considered to comprise its working set
- A process will never be executed unless its working set is resident in memory
- Pages outside the working set may be swapped out at any time
- $D = \Sigma\, WSS_i \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing
- Policy if D > m, then suspend one of the processes (swap it out if needed)

Working-set model



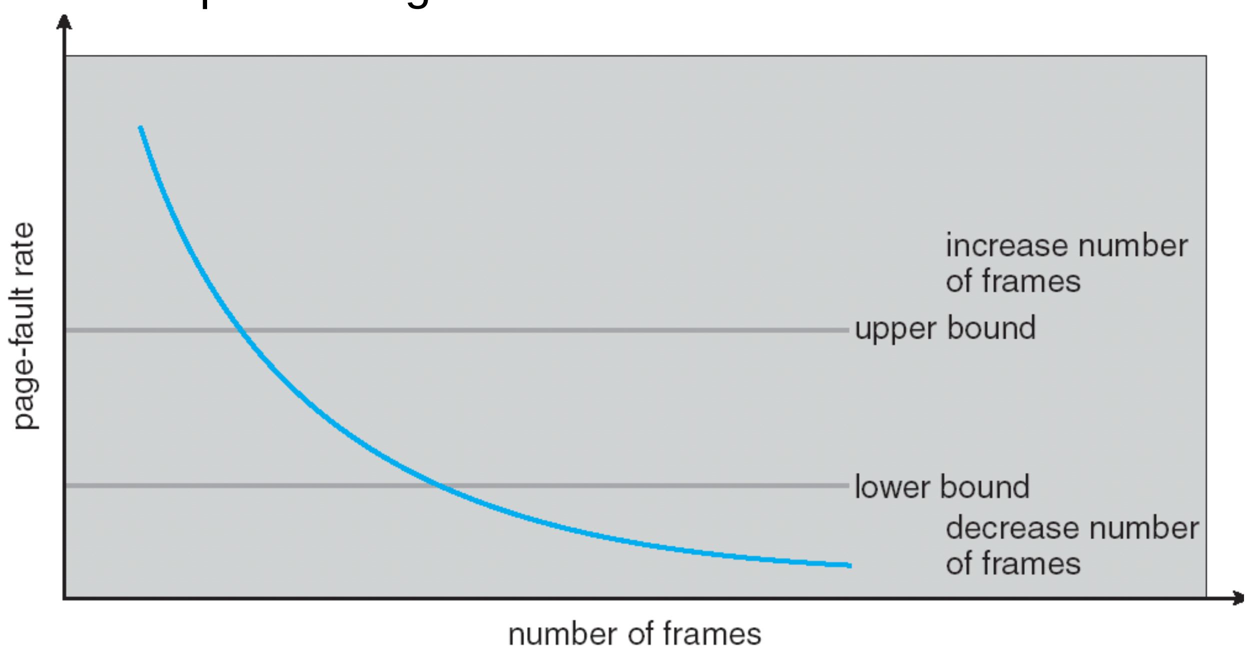
Keeping Track of the Working Set

- How to determine when a page was last accessed?

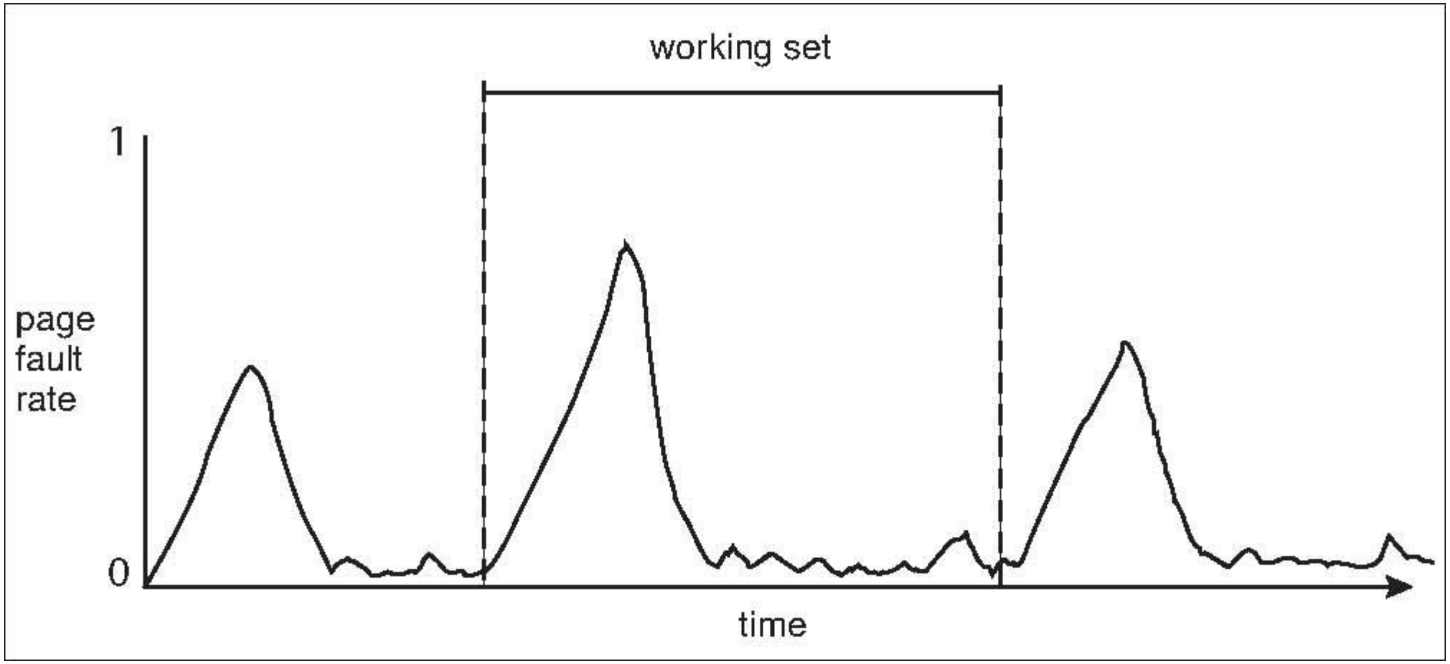
- Approximate with interval timer + a reference bit
- Example: $\Delta = 10{,}000$
  - Timer interrupts after every 5000 time units
  - Keep in memory 2 bits for each page
  - Whenever a timer interrupts copy and sets the values of all reference bits to 0
  - If one of the bits in memory = 1 $\Rightarrow$ page in working set
- Why is this not completely accurate?
- Improvement = 10 bits and interrupt every 1000 time units

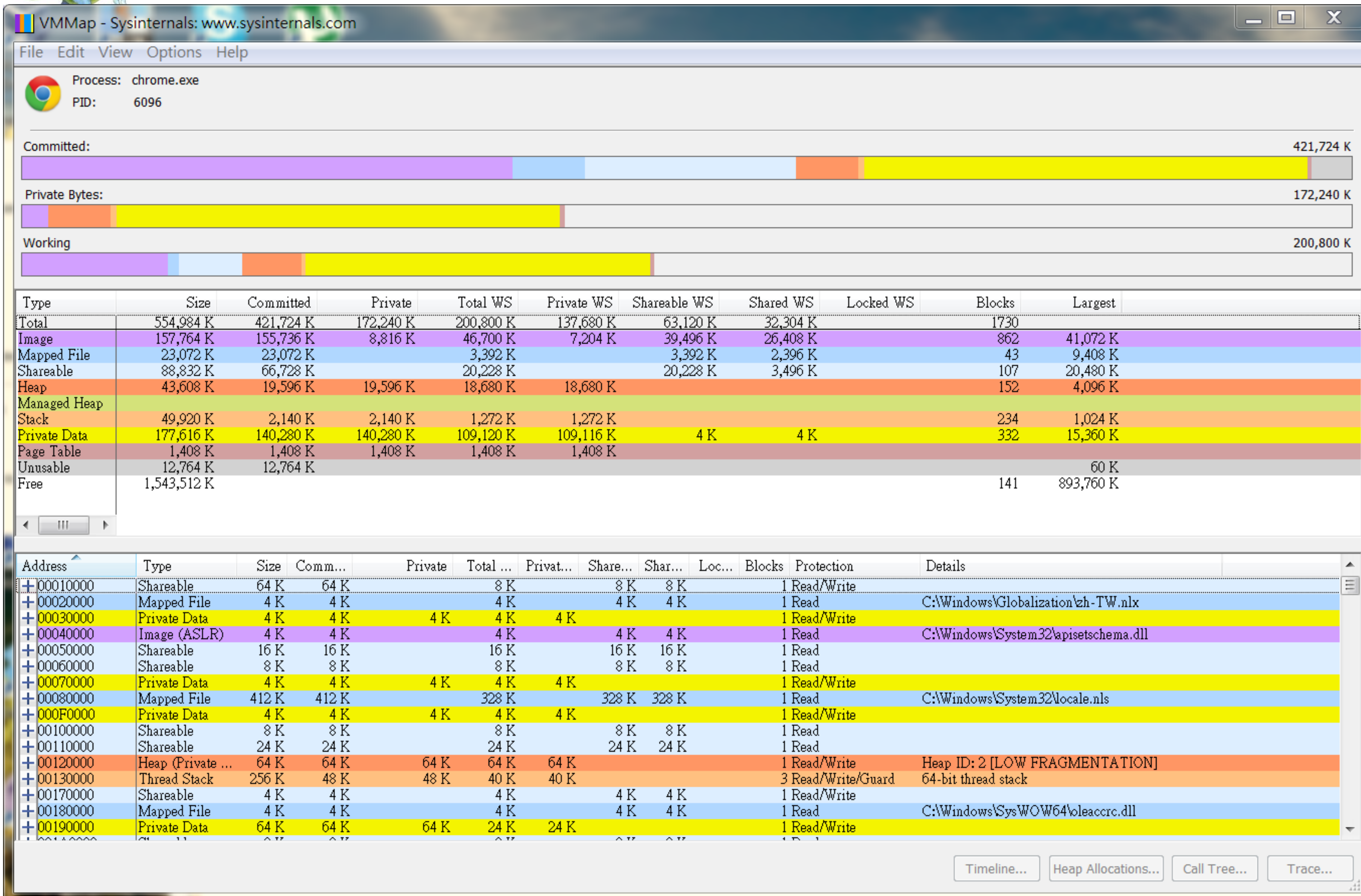
Page-Fault Frequency Scheme

- Establish “acceptable” page-fault rate
  - If actual rate too low, process loses frame
    - Suspend processes to decrease degree of multiprocessing
  - If actual rate too high, process gains frame
    - Restart suspended processes to increase degree of multiprocessing



Working Sets and Page Fault Rates





VMMap - Sysinternals: www.sysinternals.com

File Edit View Options Help

Process: chrome.exe

PID: 6096

Committed: 421,724 K

Private Bytes: 172,240 K

Working 200,800 K

Type	Size	Committed	Private	Total WS	Private WS	Shareable WS	Shared WS	Locked WS	Blocks	Largest
Total	554,984 K	421,724 K	172,240 K	200,800 K	137,680 K	63,120 K	32,304 K		1730	
Image	157,764 K	155,736 K	8,816 K	46,700 K	7,204 K	39,496 K	26,408 K		862	41,072 K
Mapped File	23,072 K	23,072 K		3,392 K		3,392 K	2,396 K		43	9,408 K
Shareable	88,832 K	66,728 K		20,228 K		20,228 K	3,496 K		107	20,480 K
Heap	43,608 K	19,596 K	19,596 K	18,680 K	18,680 K				152	4,096 K
Managed Heap										
Stack	49,920 K	2,140 K	2,140 K	1,272 K	1,272 K				234	1,024 K
Private Data	177,616 K	140,280 K	140,280 K	109,120 K	109,116 K	4 K	4 K		332	15,360 K
Page Table	1,408 K	1,408 K	1,408 K	1,408 K	1,408 K					
Unusable	12,764 K	12,764 K								60 K
Free	1,543,512 K								141	893,760 K

Address	Type	Size	Comm...	Private	Total ...	Privat...	Share...	Shar...	Loc...	Blocks	Protection	Details
00010000	Shareable	64 K	64 K		8 K		8 K	8 K		1	Read/Write	
00020000	Mapped File	4 K	4 K		4 K		4 K	4 K		1	Read	C:\Windows\Globalization\zh-TW.nlx
00030000	Private Data	4 K	4 K	4 K	4 K	4 K				1	Read/Write	
00040000	Image (ASLR)	4 K	4 K		4 K		4 K	4 K		1	Read	C:\Windows\System32\apisetschema.dll
00050000	Shareable	16 K	16 K		16 K		16 K	16 K		1	Read	
00060000	Shareable	8 K	8 K		8 K		8 K	8 K		1	Read	
00070000	Private Data	4 K	4 K	4 K	4 K	4 K				1	Read/Write	
00080000	Mapped File	412 K	412 K		328 K		328 K	328 K		1	Read	C:\Windows\System32\locale.nls
000F0000	Private Data	4 K	4 K	4 K	4 K	4 K				1	Read/Write	
00100000	Shareable	8 K	8 K		8 K		8 K	8 K		1	Read	
00110000	Shareable	24 K	24 K		24 K		24 K	24 K		1	Read	
00120000	Heap (Private ...	64 K	64 K	64 K	64 K	64 K				1	Read/Write	Heap ID: 2 [LOW FRAGMENTATION]
00130000	Thread Stack	256 K	48 K	48 K	40 K	40 K				3	Read/Write/Guard	64-bit thread stack
00170000	Shareable	4 K	4 K		4 K		4 K	4 K		1	Read/Write	
00180000	Mapped File	4 K	4 K		4 K		4 K	4 K		1	Read	C:\Windows\SysWOW64\oleaccrc.dll
00190000	Private Data	64 K	64 K	64 K	24 K	24 K				1	Read/Write	

Timeline... Heap Allocations... Call Tree... Trace...

Memory-Mapped Files

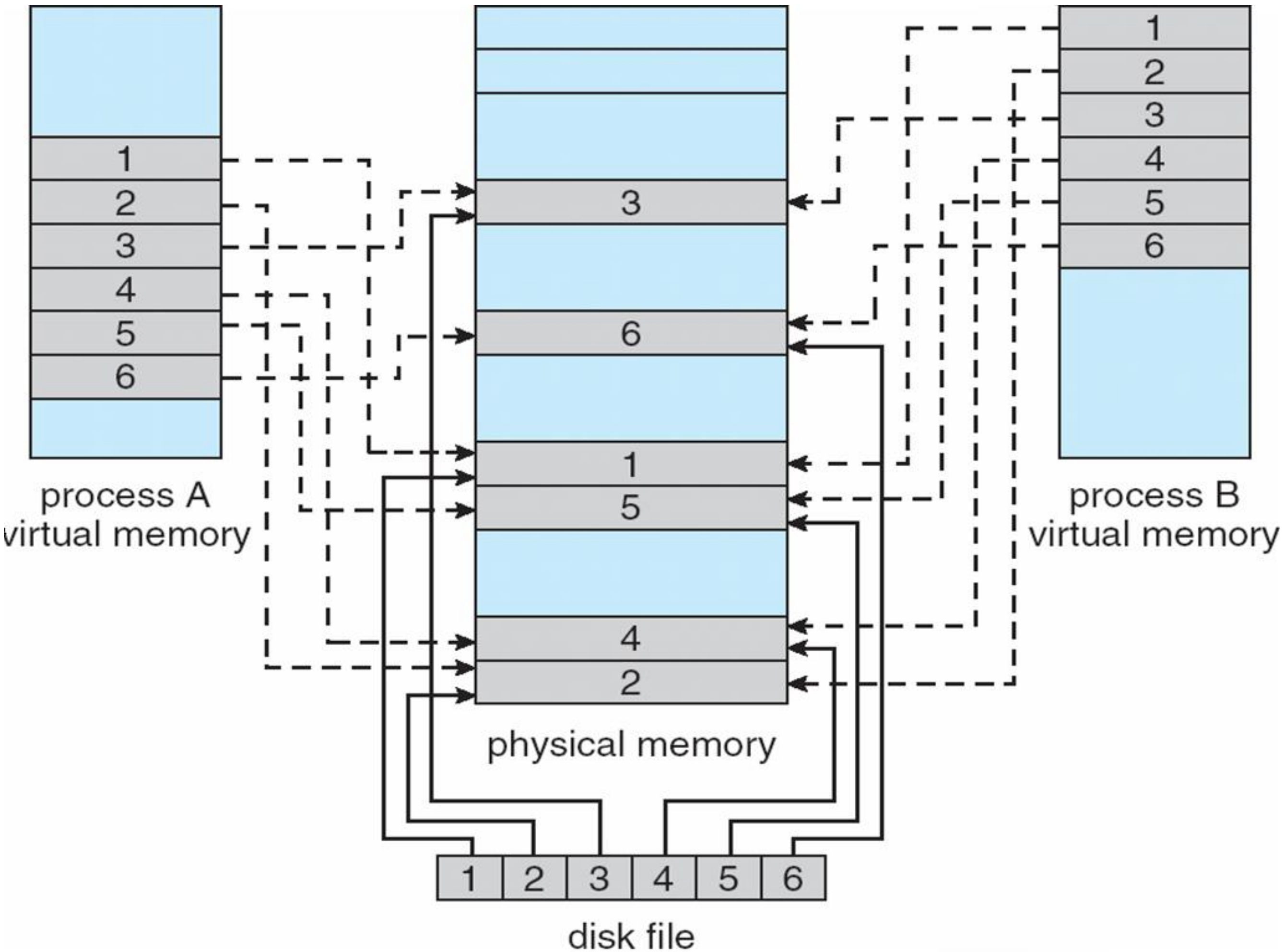
- Memory-mapped file I/O allows file I/O to be treated as routine memory access by **mapping** a disk block to a page in memory

- A file is initially read using demand paging. A page-sized portion of the file is read from the file system into a physical page. Subsequent reads/writes to/from the file are treated as ordinary memory accesses.

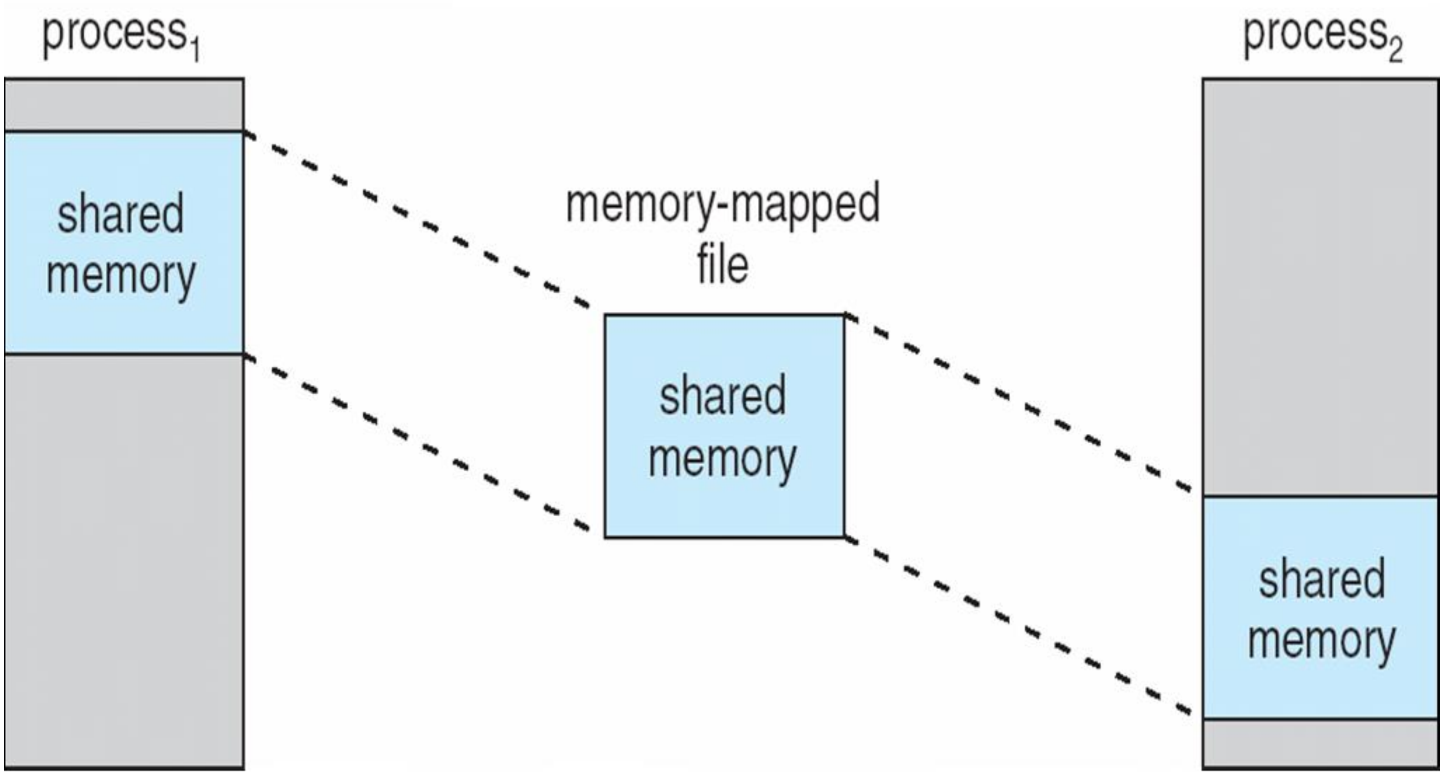
- Simplifies file access by treating file I/O through memory rather than **`read()`** **`write()`** system calls

- 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



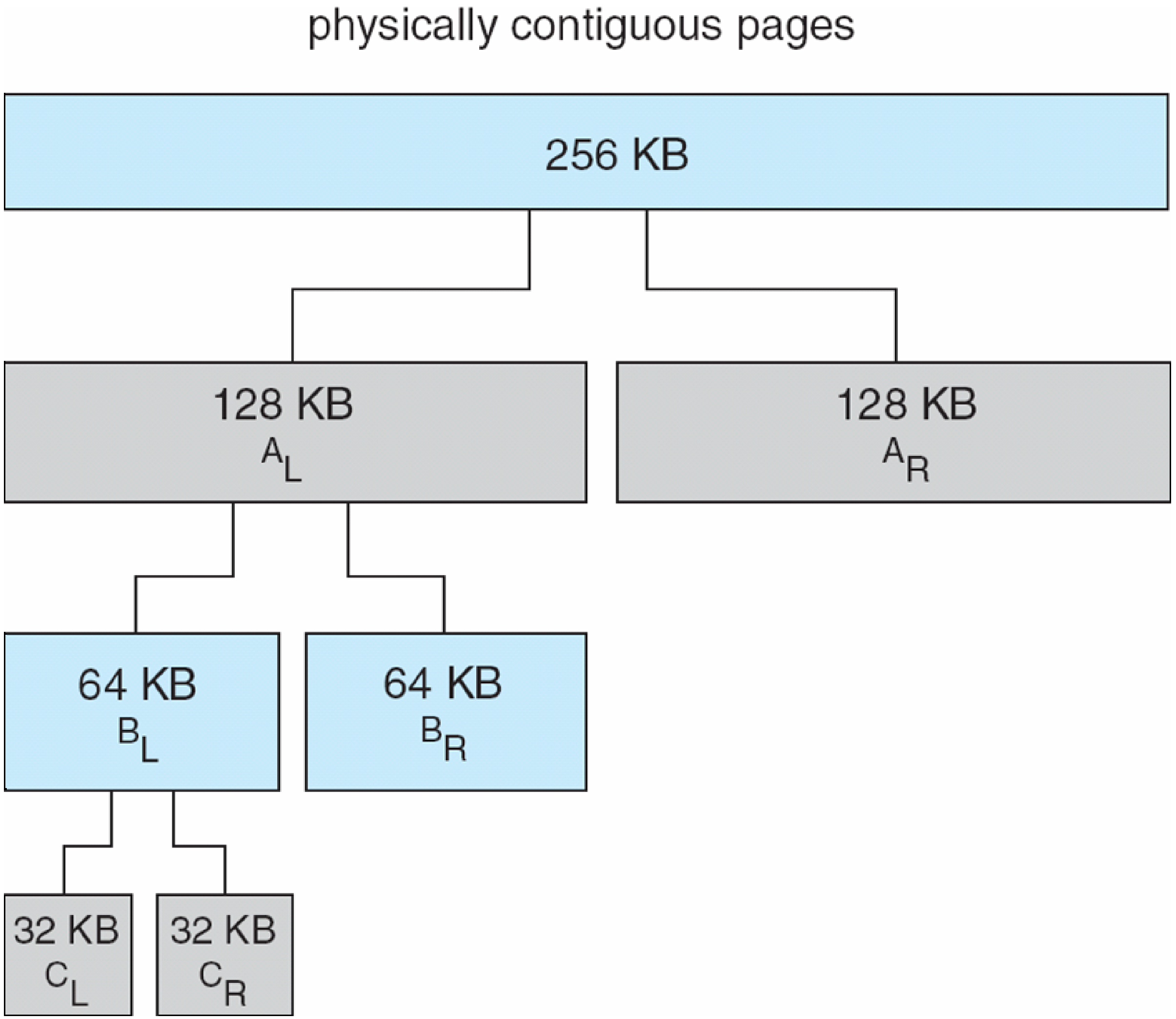
Allocating Kernel Memory

- 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
    - Memory buffer will be accessed by a DMA device on a physically addressed bus (like PCI)
    - Base kernel is placed on a contiguous block that can fit into one page
      - Reduce chance of TLB miss
    - Contiguous page frame allocation leaves kernel page tables unchanged, preserving TLB and reducing effective access time
  - kmalloc

Buddy System

- Allocates memory from fixed-size segment consisting of physically-contiguous pages
- 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



Buddy System Allocator

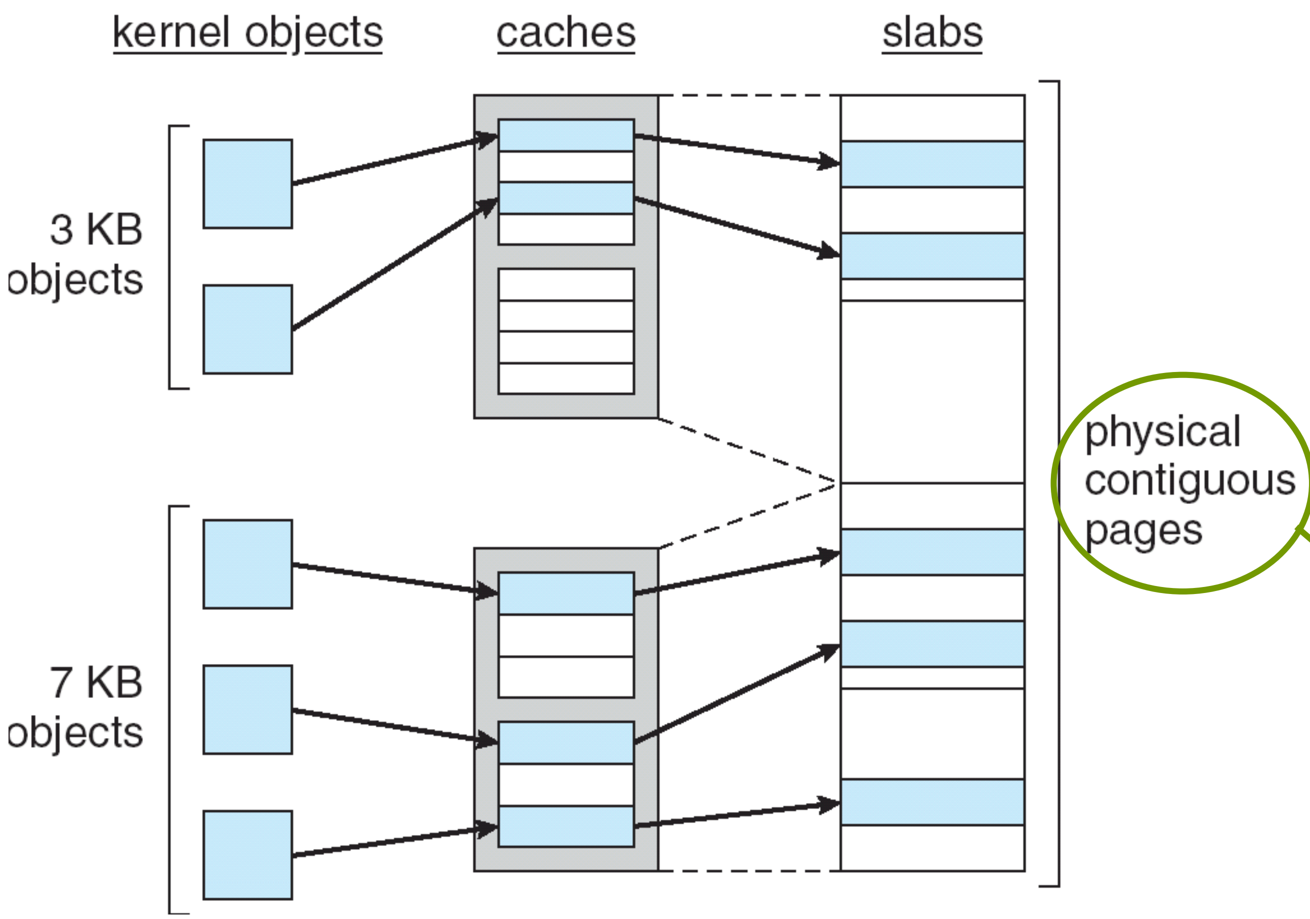
- Buddy system addresses external fragmentation
- How about internal fragmentation?
  - i.e. when allocating a 65 bytes structure, buddy system returns a 128 bytes block
    - 128-65 = 63 bytes are wasted
- http://utcc.utoronto.ca/~cks/space/blog/linux/KernelMemoryZones

```
linux1:~
(linux1:~) ysw% ls /proc/buddyinfo
/proc/buddyinfo
(linux1:~) ysw% cat /proc/buddyinfo
Node 0, zone      DMA      0      0      1      0      2      1      1      0      1      1      3
Node 0, zone    DMA32   1100   1384    709    358    161     89     56     55     46     27     72
Node 0, zone   Normal    401      0      0      0      0      0      0      0      0      0      0
Node 1, zone   Normal   1361   1936    755    487    493    413    381    247    142    166    758
(linux1:~) ysw%
```

Slab Allocator

- Introduced in Linux 2.2 kernel to deal with internal fragmentation
- Kernel functions often request small objects of the same type repeatedly
  - Process descriptors, file descriptors, etc.
- **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
- 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



Each slab is allocated by buddy system

Slab Allocator

```
linux1:~
(linux1:~) ysw% slabtop
 Active / Total Objects (% used)    : 796954 / 892955 (89.2%)
 Active / Total Slabs (% used)      : 20248 / 20248 (100.0%)
 Active / Total Caches (% used)     : 73 / 108 (67.6%)
 Active / Total Size (% used)       : 217238.22K / 230534.95K (94.2%)
 Minimum / Average / Maximum Object : 0.01K / 0.26K / 8.00K

  OBJS ACTIVE  USE OBJ SIZE  SLABS OBJ/SLAB CACHE SIZE NAME
138474 138009  99%    0.19K   3297       42     26376K dentry
122421 122413  99%    0.10K   3139       39     12556K buffer_head
102200 101492  99%    0.07K   1825       56      7300K selinux_inode_security
 62310  61882  99%    1.02K   2010       31     64320K nfs_inode_cache
 55904  55871  99%    0.25K   1747       32     13976K kmalloc-256
 50496  24688  48%    0.06K    789       64      3156K kmalloc-64
 35840  22299  62%    0.02K    140      256       560K kmalloc-16
 35374  25868  73%    0.17K    769       46      6152K vm_area_struct
 35328  35089  99%    0.01K     69      512       276K kmalloc-8
 34300  34292  99%    0.55K   1225       28     19600K radix_tree_node
 31290  27748  88%    0.19K    745       42      5960K kmalloc-192
 28050  19053  67%    0.05K    330       85      1320K shared_policy_node
 22784   9567  41%    0.03K    178      128       712K kmalloc-32
 17416  12381  71%    0.07K    311       56      1244K anon_vma
 16779  16665  99%    0.08K    329       51      1316K sysfs_dir_cache
 11184  10037  89%    0.65K    466       24      7456K proc_inode_cache
```

Noncontiguous Memory Area Allocation

- In the Linux kernel, we try to avoid allocating noncontiguous memory areas
- But there are occasions when we want to create a large buffer in the kernel that can't fit into a contiguous kernel memory area
  - We can use paging for the allocation
  - Linux uses most of the reserved addresses above PAGE_OFFSET to map non-contiguous memory area
  - vmalloc

Other Issues -- Prepaging

- Prepaging
  - To reduce the large number of page faults that occurs at process startup
  - Prepage 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 of the pages is used
    - Is cost of $s * \alpha$ save pages faults > or < than the cost of prepaging
      $s * (1- \alpha)$ unnecessary pages?
    - α near zero $\Rightarrow$ prepaging loses

Other Issues – Page Size

- Page size selection must take into consideration:
  - fragmentation
  - table size
  - I/O overhead
  - locality

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
  - This may lead to an increase in fragmentation as not all applications require a large 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[128,128] data;`
  - Each row is stored in one page
  - Program 1

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

128 x 128 = 16,384 page faults

  - Program 2

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

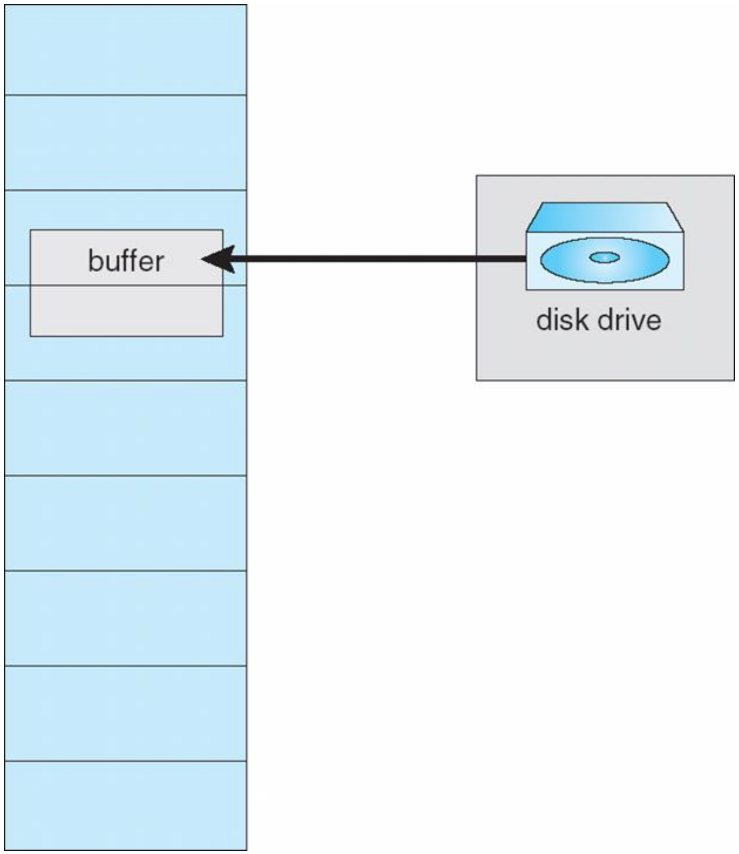
128 page faults

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

Reason Why Frames Used For I/O Must Be In Memory



Operating System Examples

- Windows XP
- Solaris

Windows XP

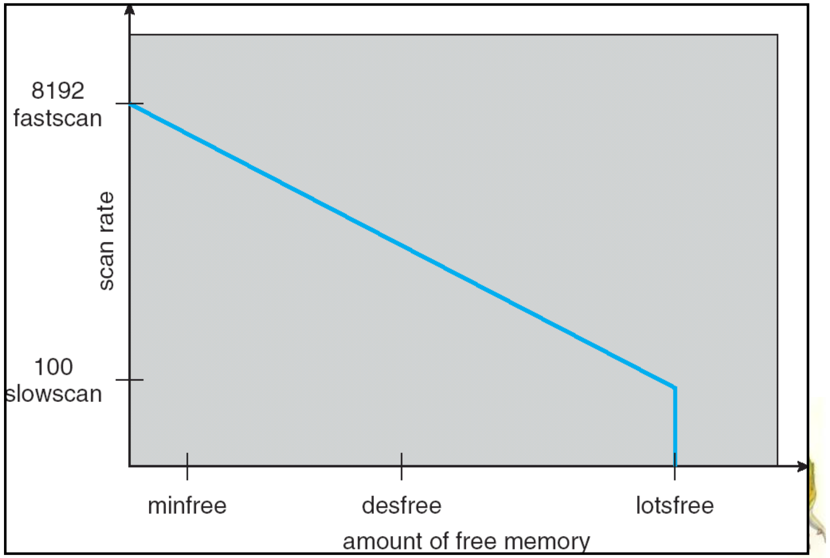
- uses demand paging with *clustering*
  - clustering brings in pages surrounding the faulting page
- processes are assigned *working set minimum* and *working set maximum*
  - working set minimum is the minimum number of pages the process is guaranteed to have in memory (for most apps, 50…345)
  - a 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
- page replacement algorithm varies depending on processor
  - single processor Intel CPU: variation of the clock (timestamp) algorithm
  - multiprocessor or Alpha CPU: variation of FIFO

Solaris

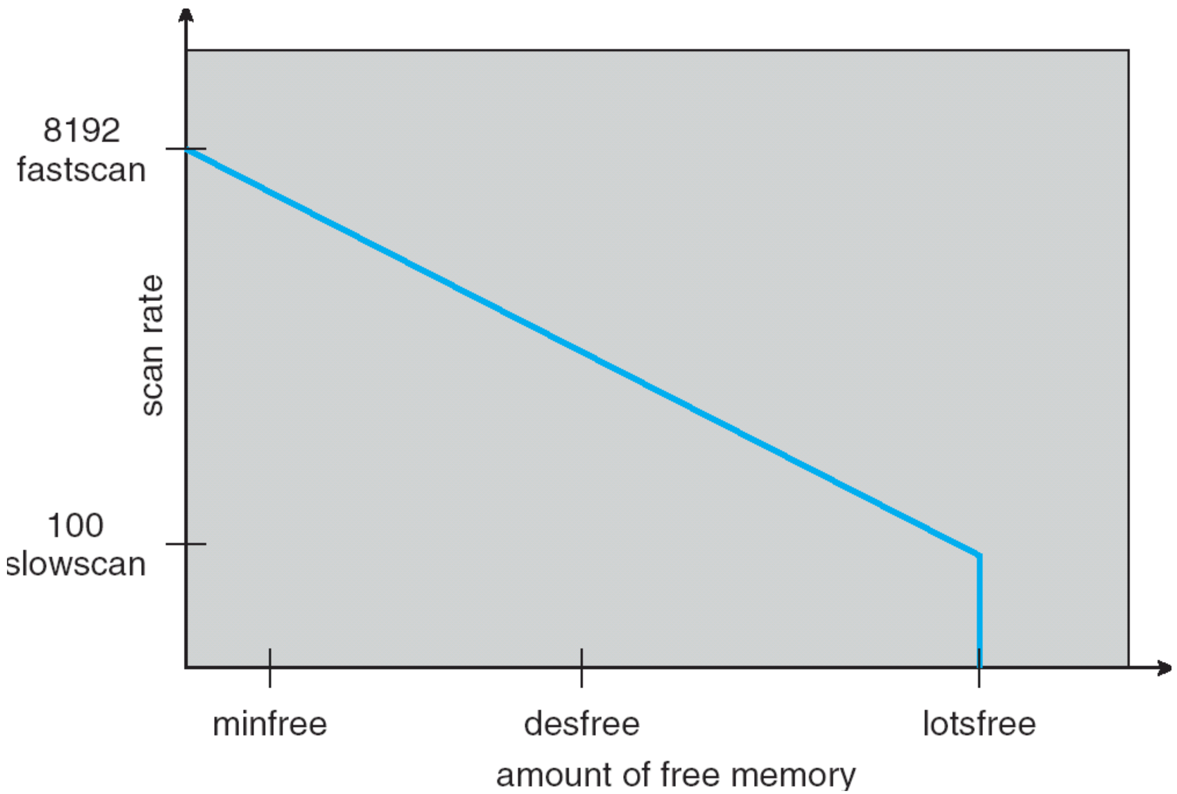
- system maintains a list of free pages
  - paging occurs when the number of free pages drops below a threshold (e.g., 1/64 size of physical memory)

- paging is performed by a *pageout* process
  - pageout scans pages using a modified clock algorithm
  - pages not referenced since last scan are returned to free list
  - the smaller the free list, the more frequent scanning occurs

lotsfree – threshold parameter to begin paging
desfree – threshold parameter to increase paging
minfree – threshold parameter to begin swapping



Solaris 2 Page Scanner



End of Chapter 9