

Chapter 9: Virtual Memory





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- Background
- Demand Paging
- Process Creation
- Page Replacement
- Allocation of Frames
- Thrashing
- Demand Segmentation
- Operating System Examples





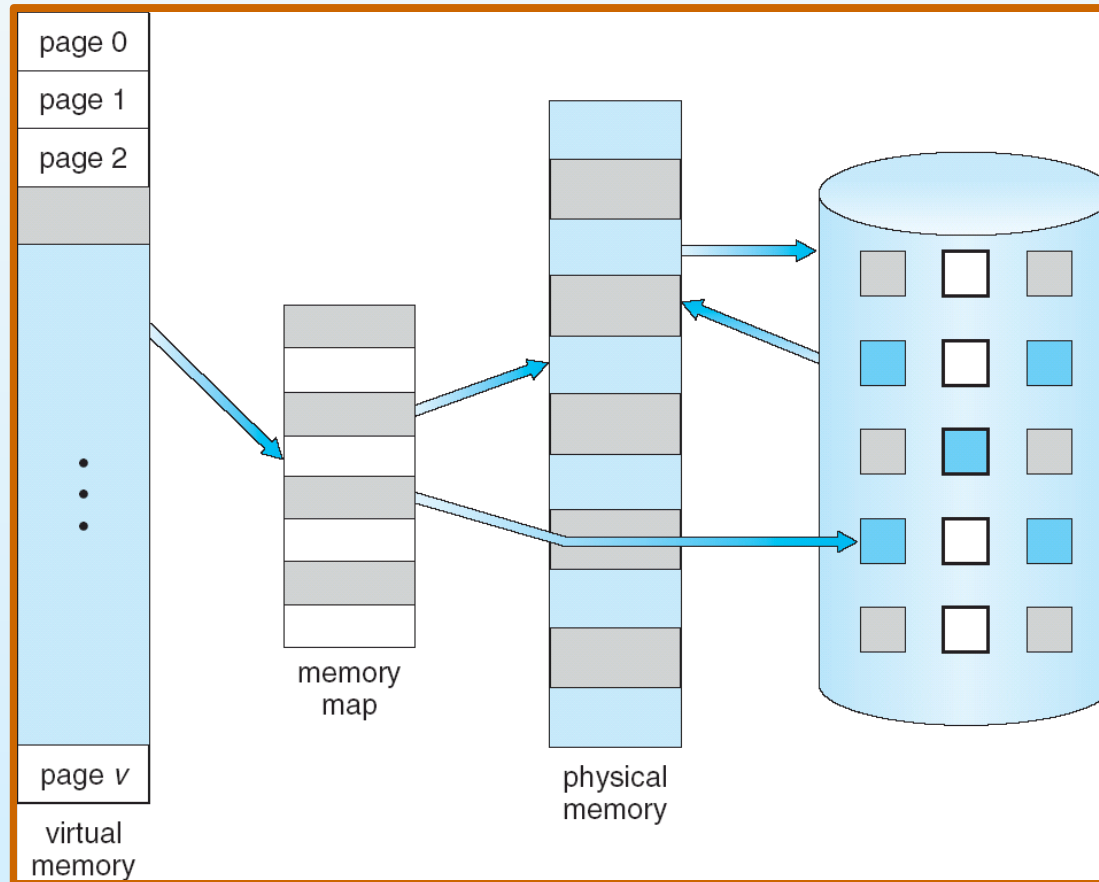
Background

- **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.
 - 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



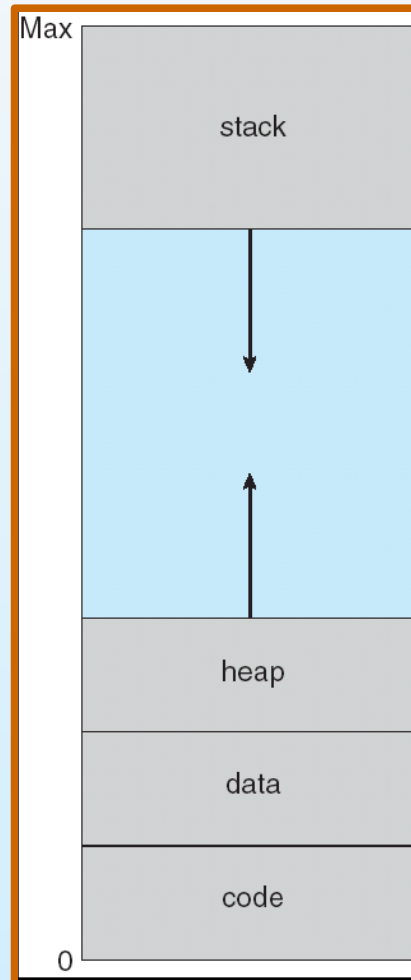


Virtual Memory That is Larger Than Physical Memory



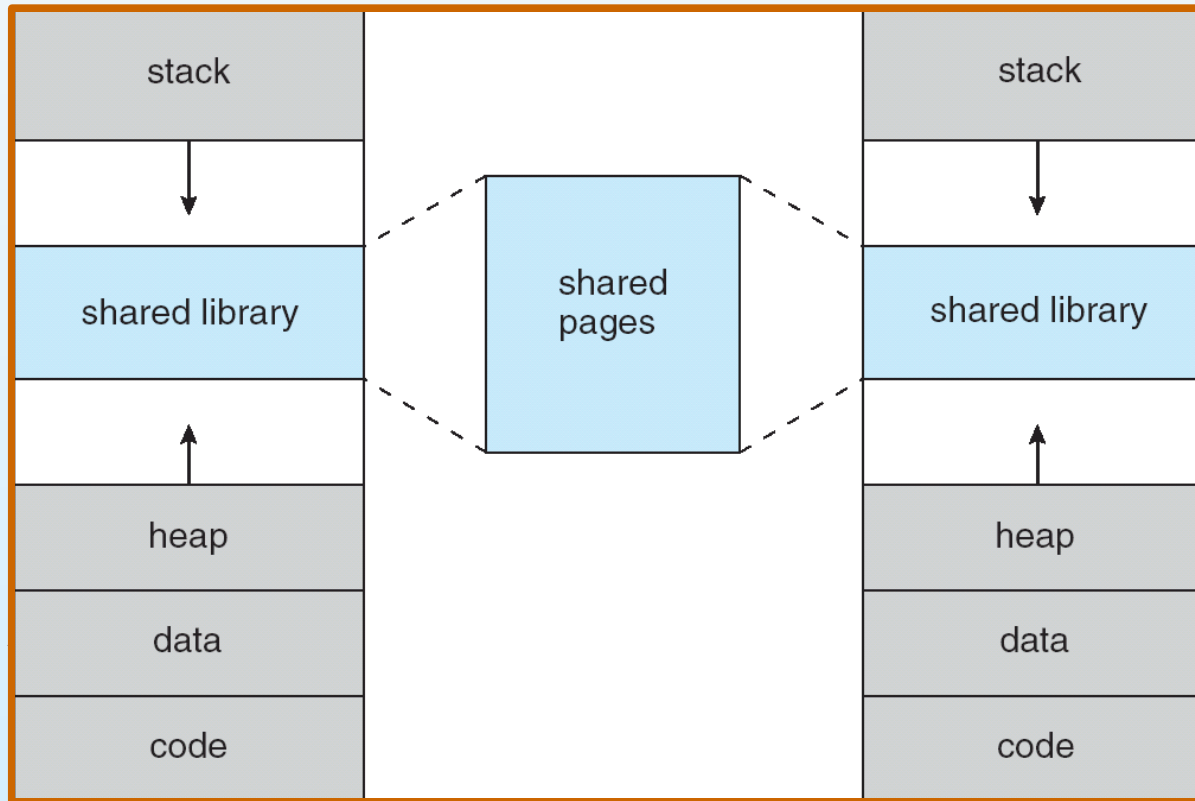


Virtual-address Space





Shared Library Using Virtual Memory





Demand Paging

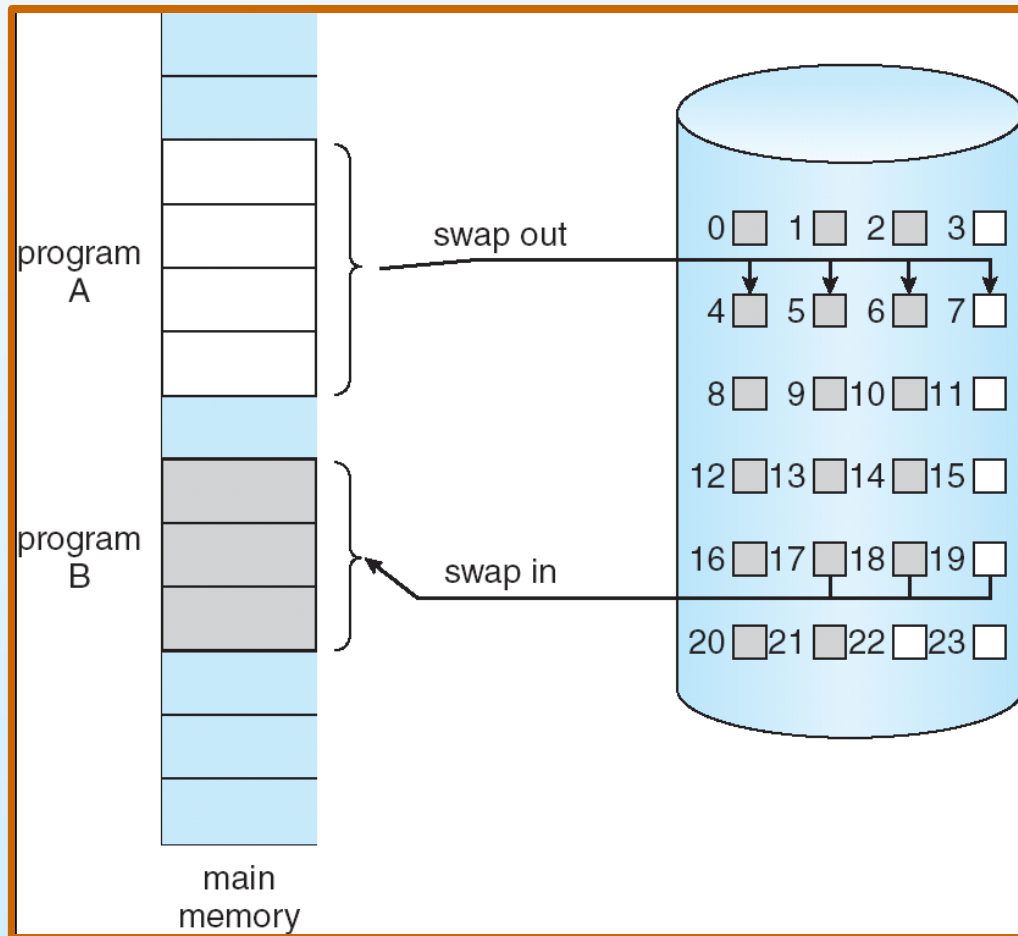
- Bring a page into memory only when it is needed
 - Less I/O needed
 - Less memory needed
 - Faster response
 - More users

- Page is needed \Rightarrow reference to it
 - invalid reference \Rightarrow abort
 - not-in-memory \Rightarrow bring to memory





Transfer of a Paged Memory to Contiguous Disk Space





Valid-Invalid Bit

- With each page table entry a valid–invalid bit is associated (1 \Rightarrow in-memory, 0 \Rightarrow not-in-memory)
- Initially valid–invalid but is set to 0 on all entries
- Example of a page table snapshot:

Frame #	valid-invalid bit
	1
	1
	1
	1
	0
⋮	
	0
	0

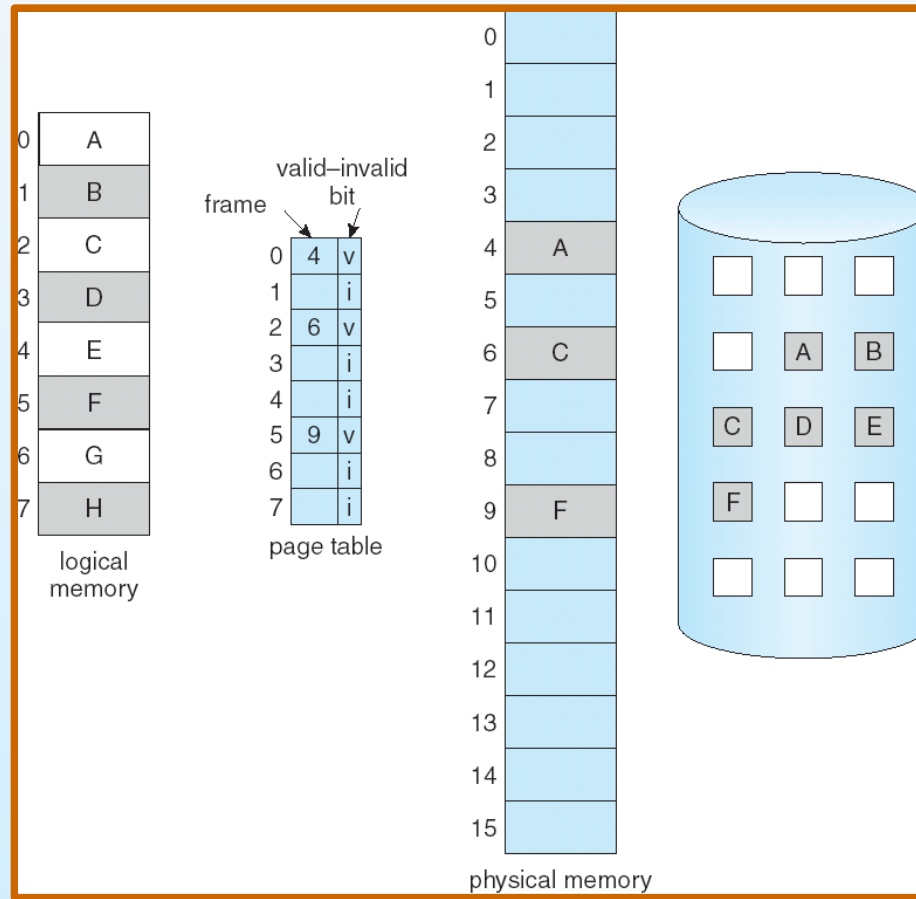
page table

- During address translation, if valid–invalid bit in page table entry is 0 \Rightarrow page fault





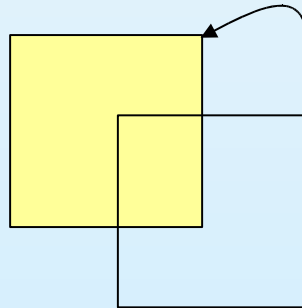
Page Table When Some Pages Are Not in Main Memory





Page Fault

- If there is ever a reference to a page, first reference will trap to OS \Rightarrow page fault
- OS looks at another 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: Least Recently Used
 - block move

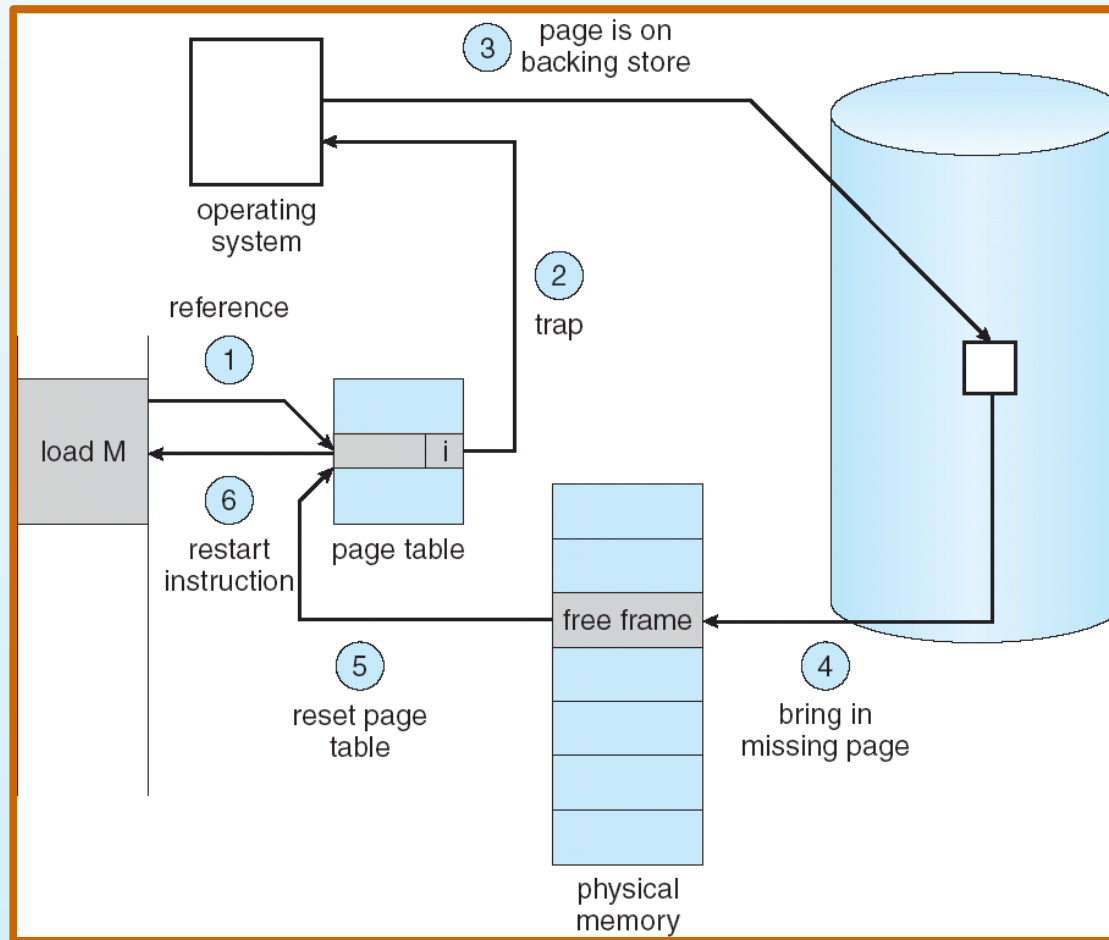


- auto increment/decrement location





Steps in Handling a Page Fault





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





Performance of Demand Paging

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

- Effective Access Time (EAT)

$$\begin{aligned} \text{EAT} = & (1 - p) \times \text{memory access} \\ & + p (\text{page fault overhead} \\ & + [\text{swap page out}] \\ & + \text{swap page in} \\ & + \text{restart overhead}) \end{aligned}$$





Demand Paging Example

- Memory access time = 1 microsecond
- 50% of the time the page that is being replaced has been modified and therefore needs to be swapped out
- Swap Page Time = 10 msec = 10,000 msec

$$\begin{aligned} \text{EAT} &= (1 - p) \times 1 + p (15000) \\ &= 1 + 15000P \quad (\text{in msec}) \end{aligned}$$





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





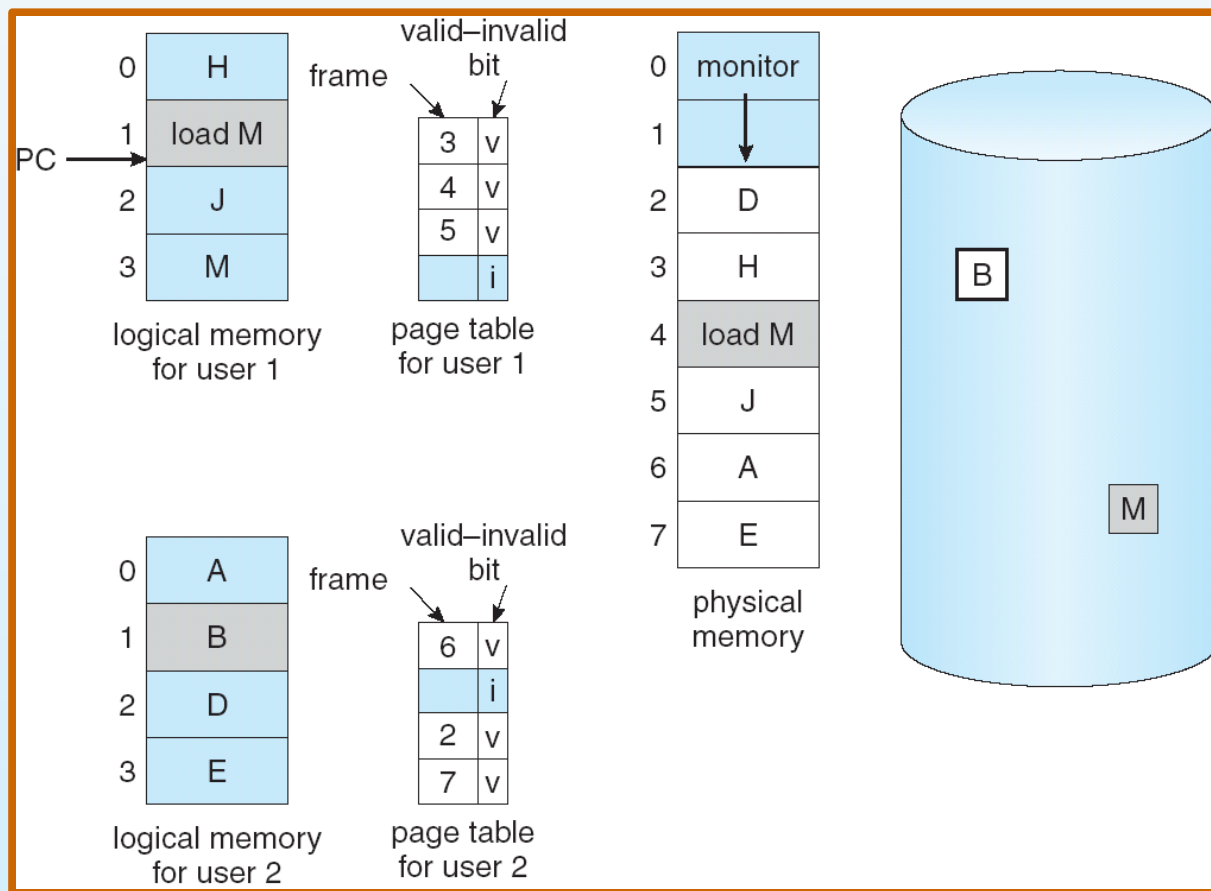
Page Replacement

- 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





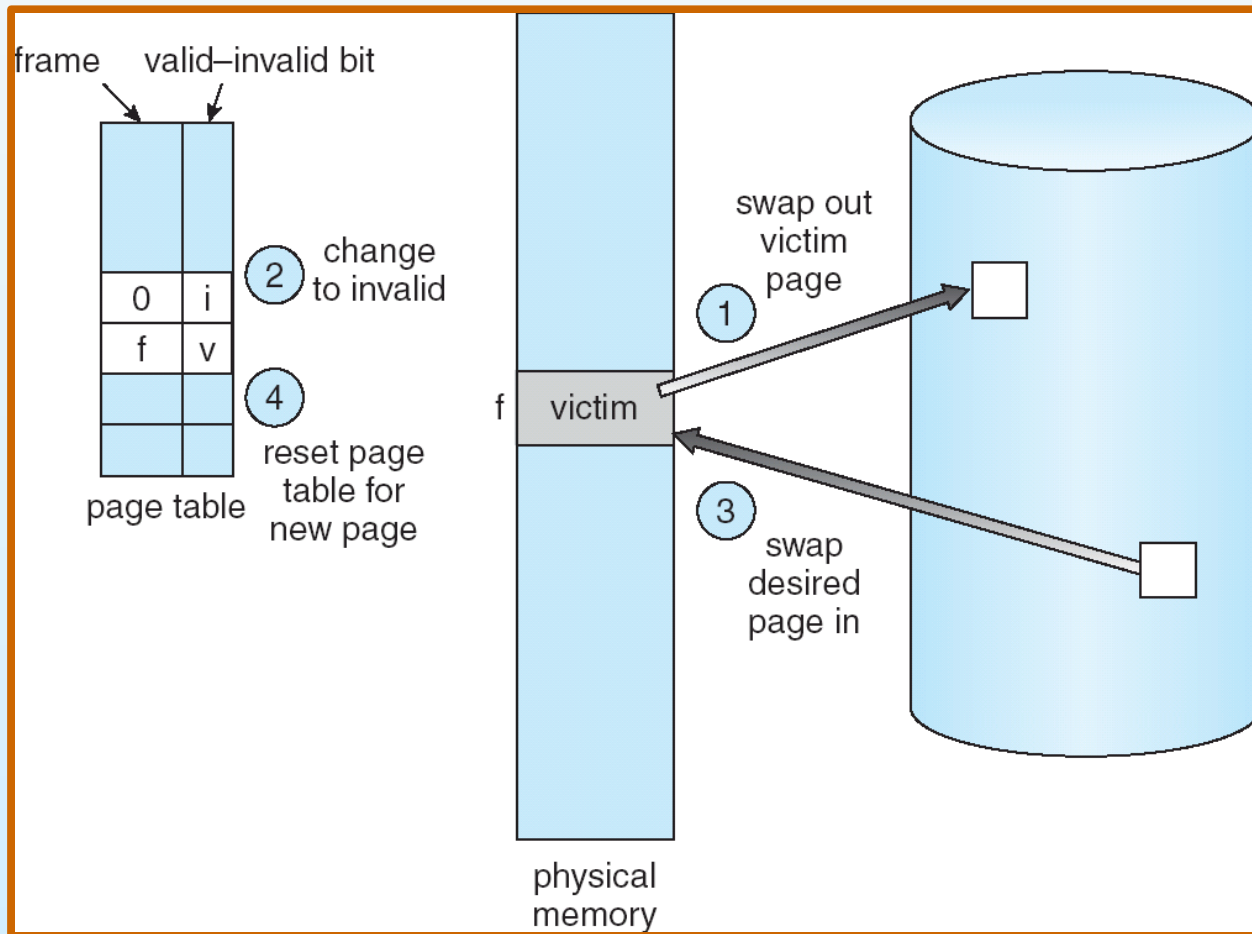
Basic Page Replacement

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. Read the desired page into the (newly) free frame. Update the page and frame tables.
4. Restart the process





Page Replacement





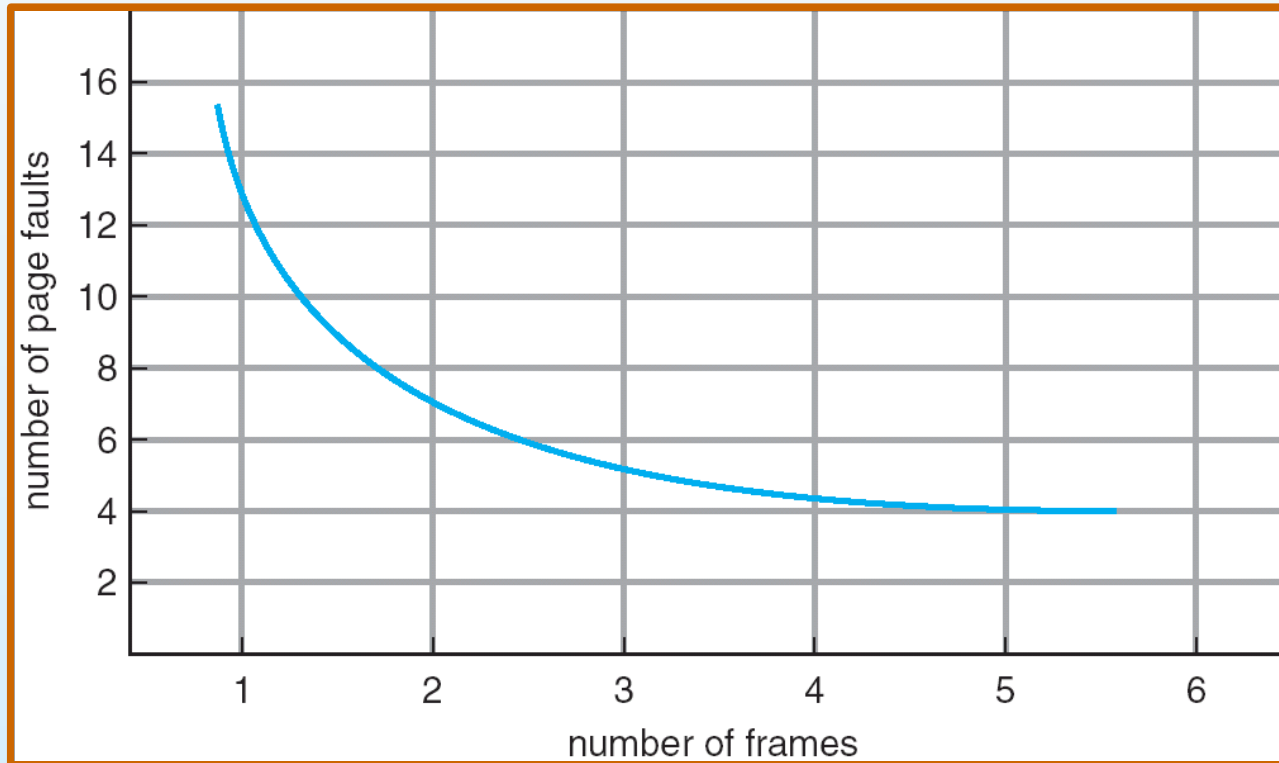
Page Replacement Algorithms

- 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





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

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





FIFO Page Replacement

reference string

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

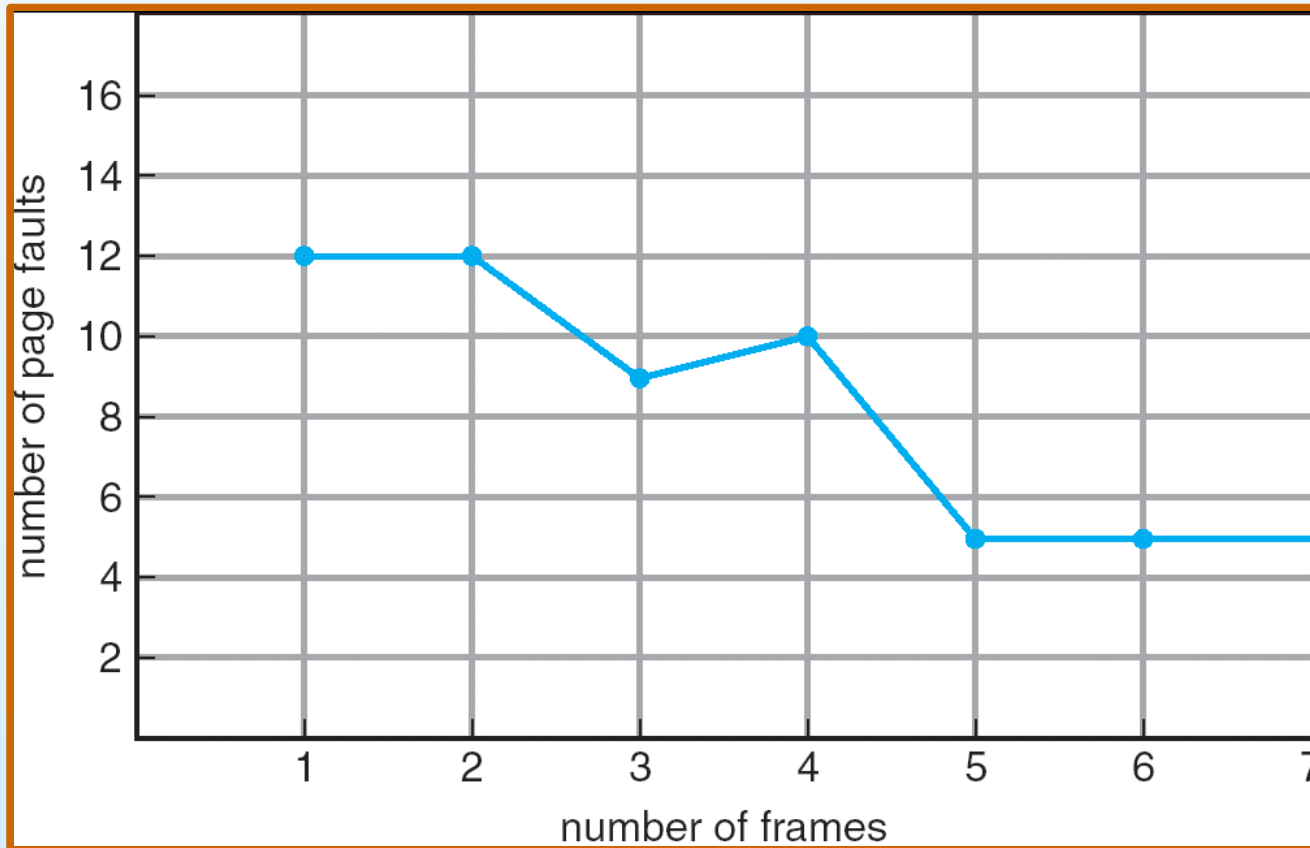
7	7	7	2			2	2	4	4	4	0			0	0			7	7	7
	0	0	0			3	3	3	2	2	2			1	1			1	0	0
		1	1			1	0	0	0	3	3			3	2			2	2	1

page frames





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

reference string

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

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

page frames





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, 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

reference string

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

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

page frames





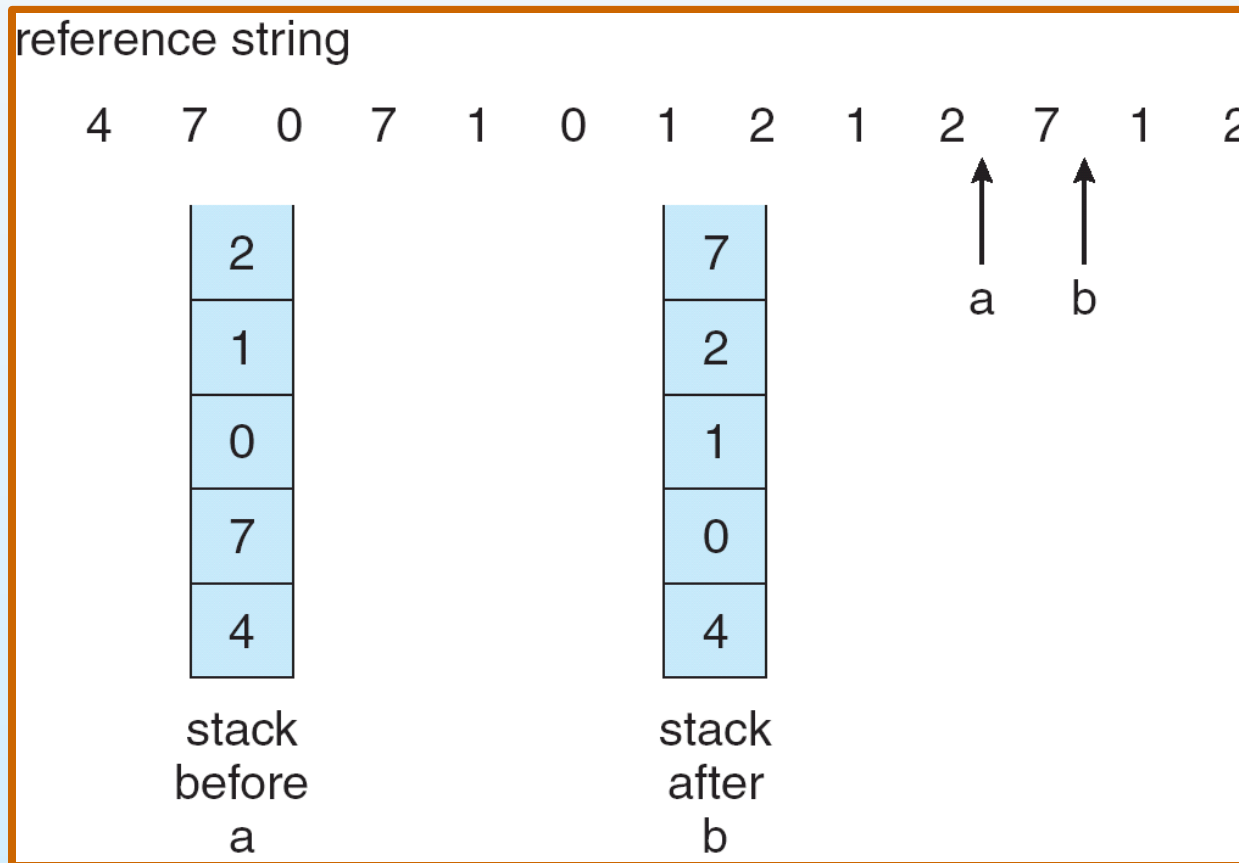
LRU Algorithm (Cont.)

- 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

■ 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.

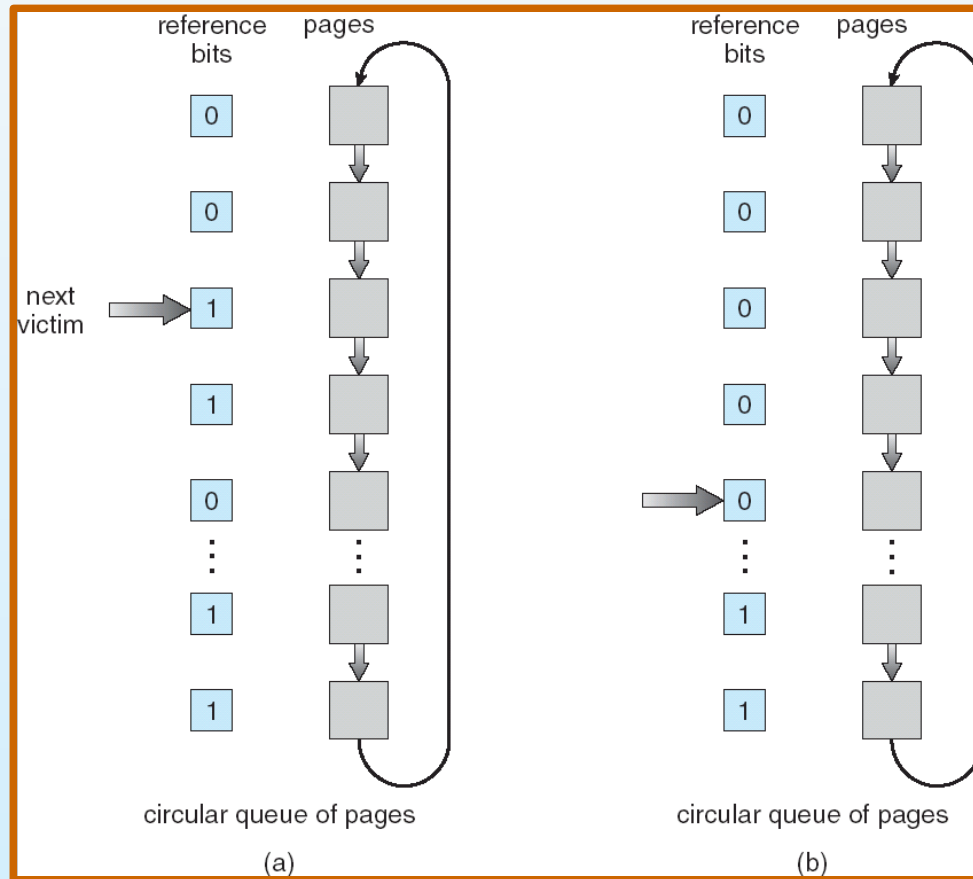
■ Second chance

- 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





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 = size of process p_i
 - $S = \sum s_i$
 - m = total number of frames
 - a_i = allocation for $p_i = \frac{s_i}{S} \times m$

$$m = 64$$

$$s_1 = 10$$

$$s_2 = 127$$

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

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





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

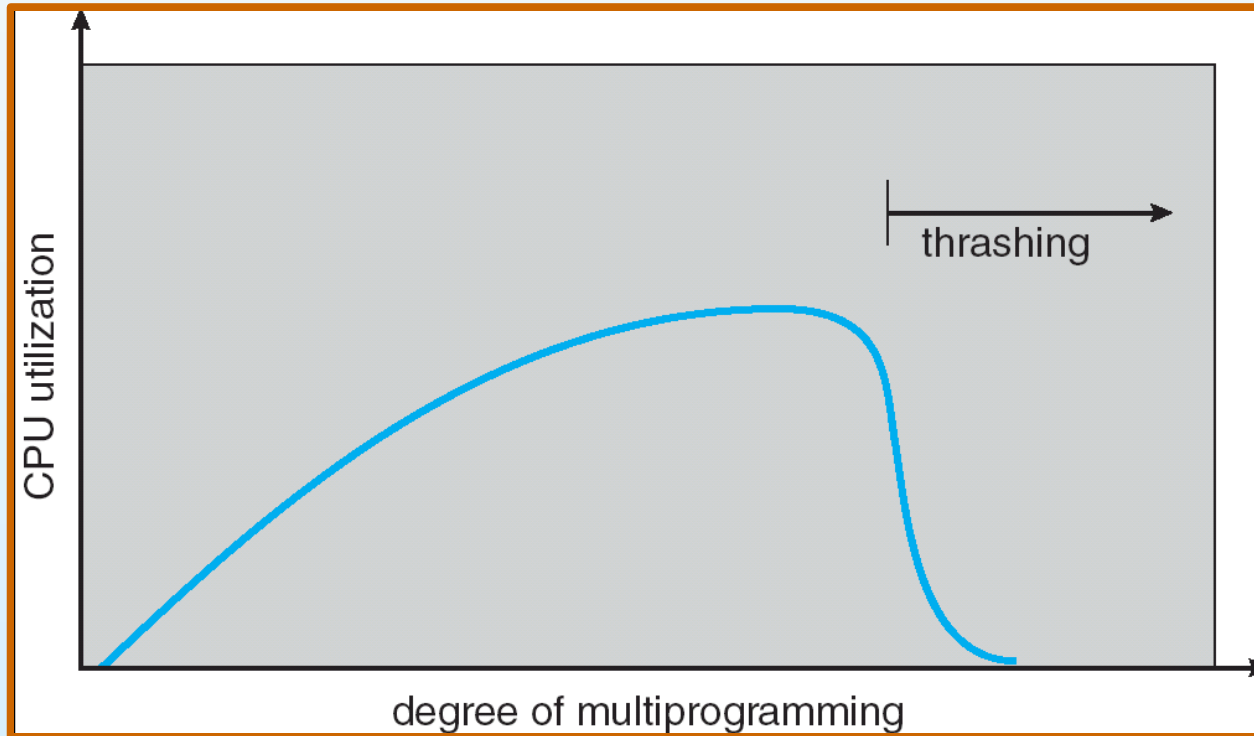
- If a process does not have “enough” pages, the page-fault rate is very high. This leads to:
 - low CPU utilization
 - operating system thinks that it needs to increase the degree of multiprogramming
 - another process added to the system

- **Thrashing** \equiv a process is busy swapping pages in and out





Thrashing (Cont.)





Demand Paging and Thrashing

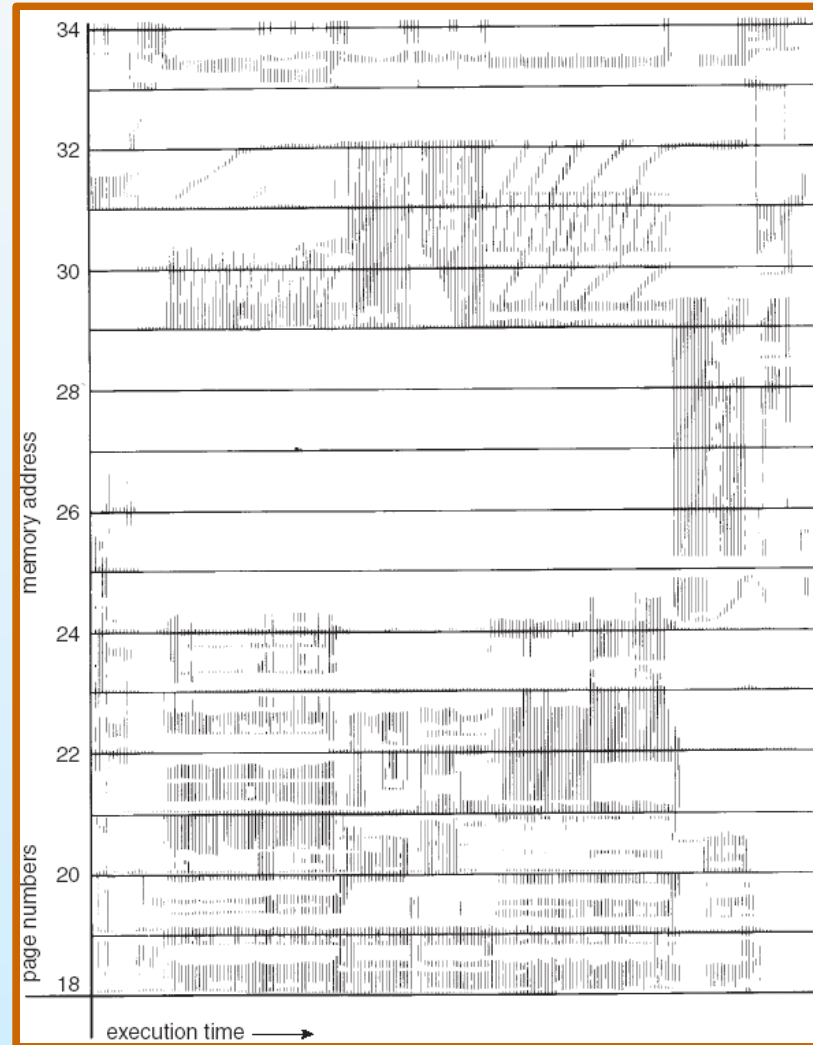
- Why does demand paging work?
Locality model
 - Process migrates from one locality to another
 - Localities may overlap

- Why does thrashing occur?
 Σ size of locality > total memory size





Locality In A Memory-Reference Pattern





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
- $D = \sum WSS_i \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing
- Policy if $D > m$, then suspend one of the processes

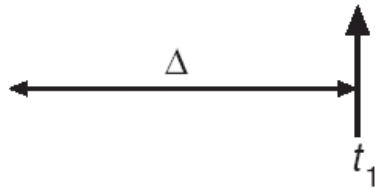




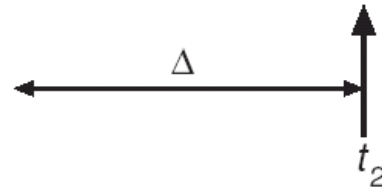
Working-set model

page reference table

. . . 2 6 1 5 7 7 7 7 5 1 6 2 3 4 1 2 3 4 4 4 3 4 3 4 4 4 4 1 3 2 3 4 4 4 3 4 4 4 . . .



$$WS(t_1) = \{1, 2, 5, 6, 7\}$$



$$WS(t_2) = \{3, 4\}$$





Keeping Track of the Working Set

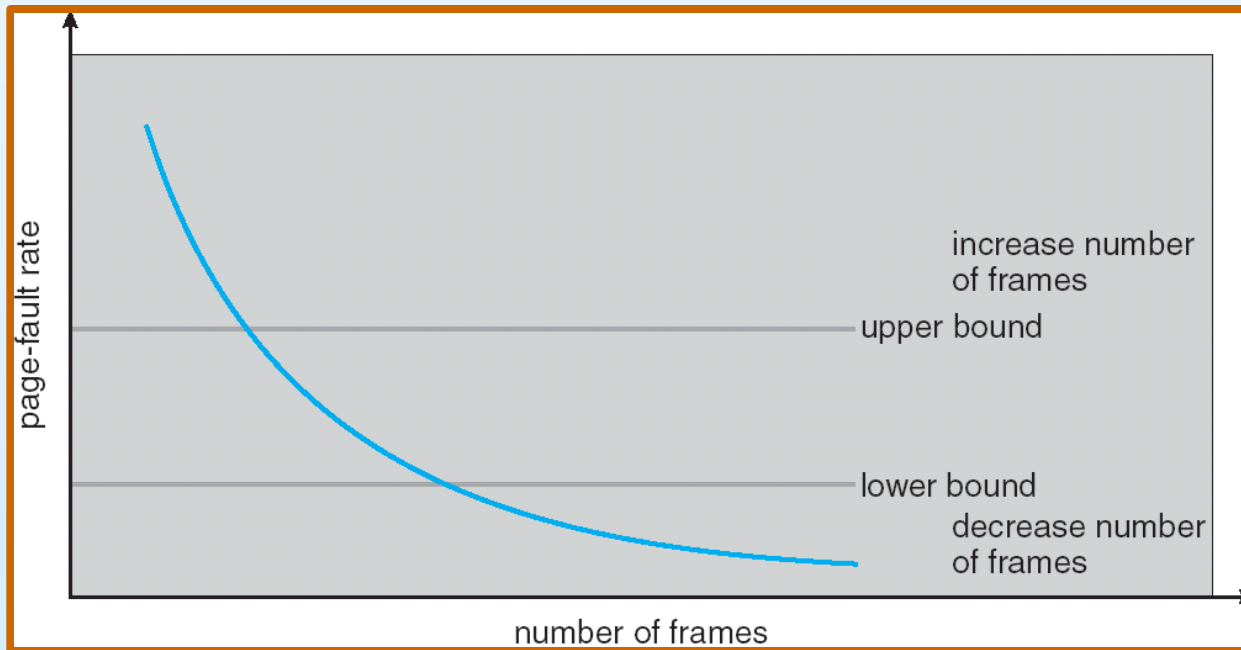
- Approximate with interval timer + a reference bit
- Example: $\Delta = 10,000$
 - Timer interrupts after every 5000 time units
 - Keep in memory 2 bits for each page
 - Whenever a timer interrupts copy and sets the values of all reference bits to 0
 - If one of the bits in memory = 1 \Rightarrow page 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
 - If actual rate too high, process gains frame





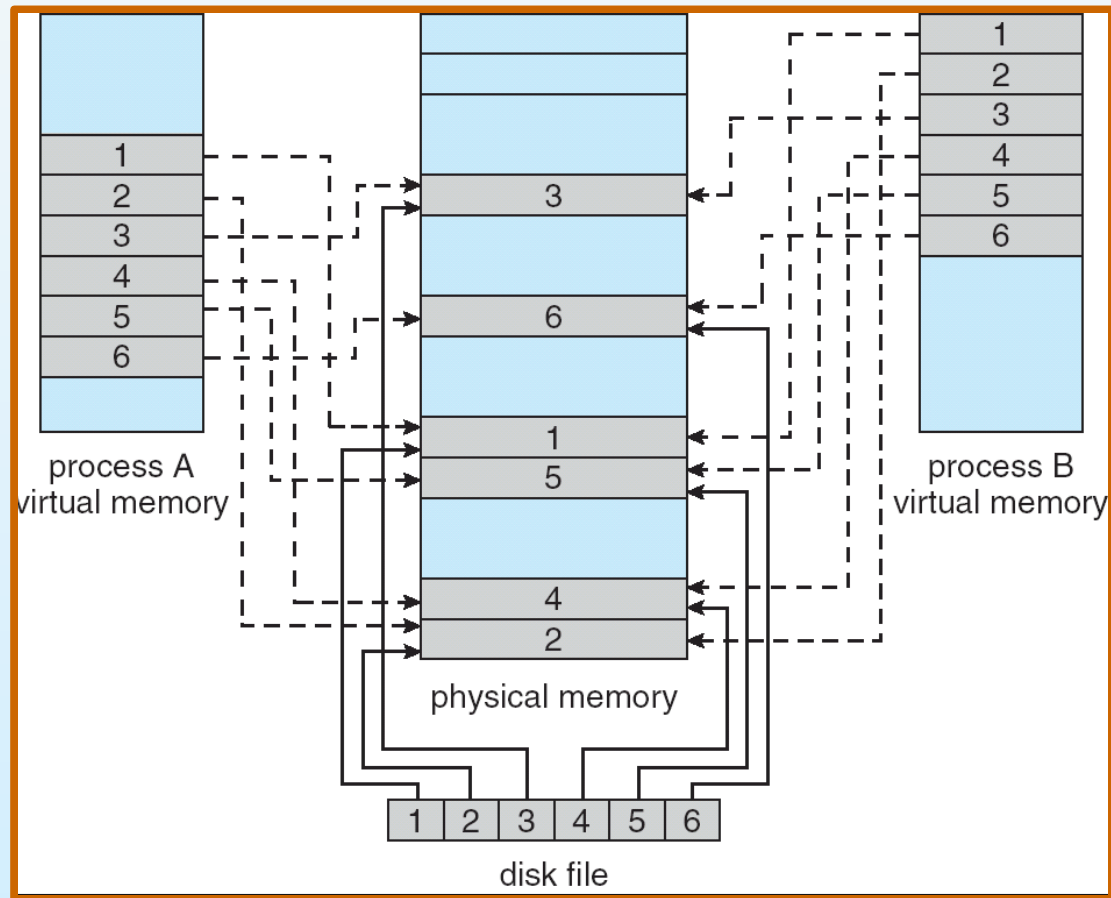
Memory-Mapped Files

- 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 Files in Java

```
import java.io.*;
import java.nio.*;
import java.nio.channels.*;
public class MemoryMapReadOnly
{
    // Assume the page size is 4 KB
    public static final int PAGE_SIZE = 4096;
    public static void main(String args[]) throws IOException {
        RandomAccessFile inFile = new RandomAccessFile(args[0], "r");
        FileChannel in = inFile.getChannel();
        MappedByteBuffer mappedBuffer =
            in.map(FileChannel.MapMode.READ_ONLY, 0, in.size());
        long numPages = in.size() / (long)PAGE_SIZE;
        if (in.size() % PAGE_SIZE > 0)
            ++numPages;
    }
}
```





Memory-Mapped Files in Java (cont)

```
// we will "touch" the first byte of every page
int position = 0;
for (long i = 0; i < numPages; i++) {
    byte item = mappedBuffer.get(position);
    position += PAGE_SIZE;
}
in.close();
inFile.close();
}
```

- The API for the `map()` method is as follows:

`map(mode, position, size)`





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 u of the pages is used
 - ▶ Is cost of $s * u$ save pages faults $>$ or $<$ than the cost of prepaging
 - ▶ $s * (1 - u)$ unnecessary pages?
 - ▶ 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
- $\text{TLB Reach} = (\text{TLB Size}) \times (\text{Page Size})$
- 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





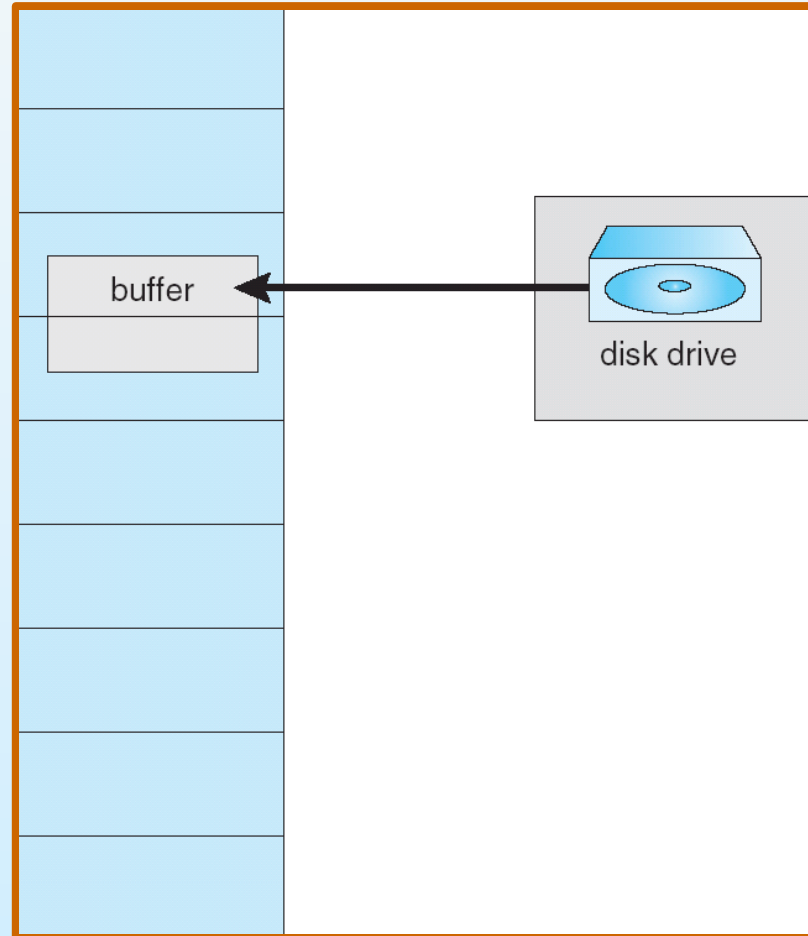
Other Issues – I/O interlock

- **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
- 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





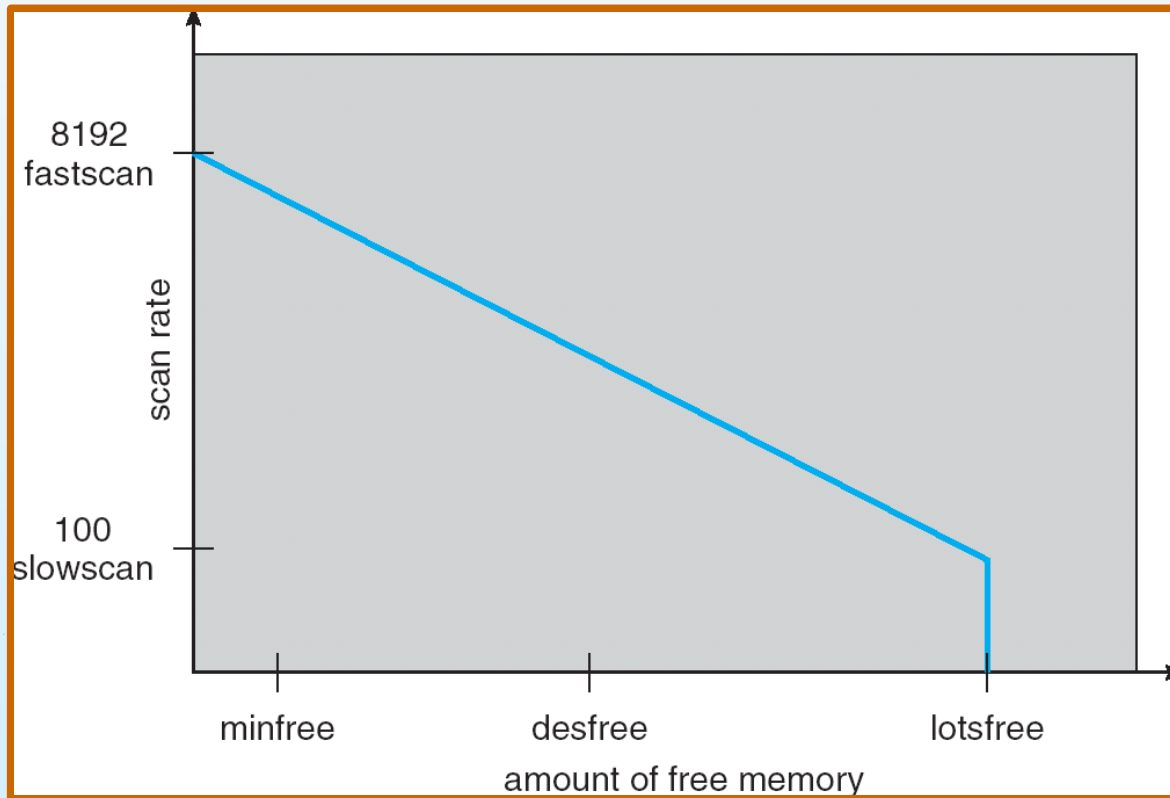
Solaris

- 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
- 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 2 Page Scanner



End of Chapter 9

