CSMC 412

Operating Systems

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Set 9

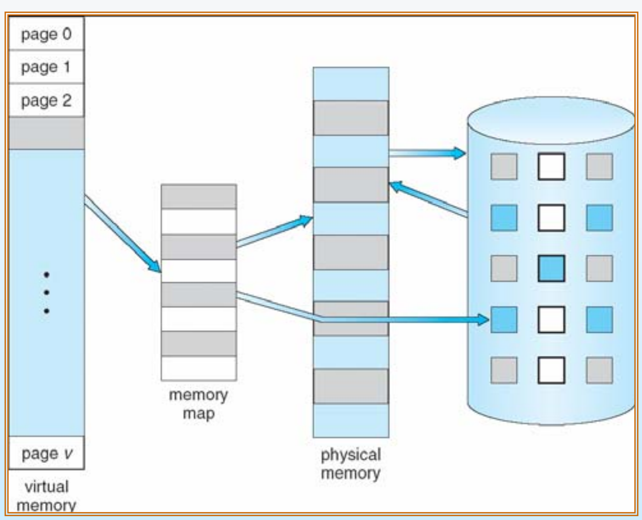
Virtual Memory

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

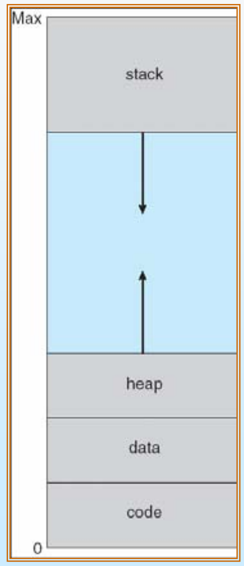
Background

- **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

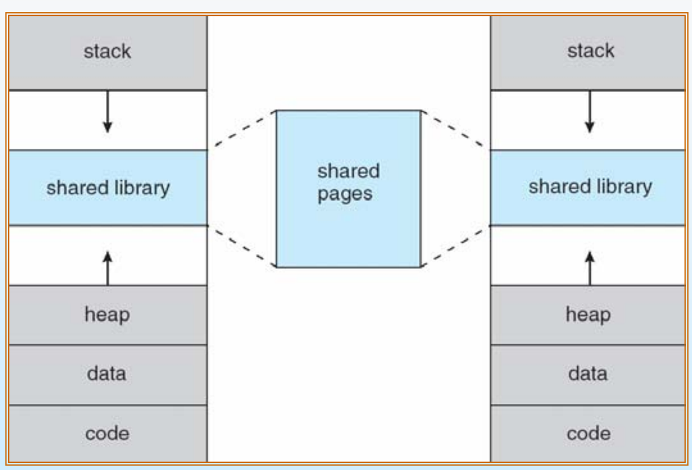


Virtual-address Space



hole

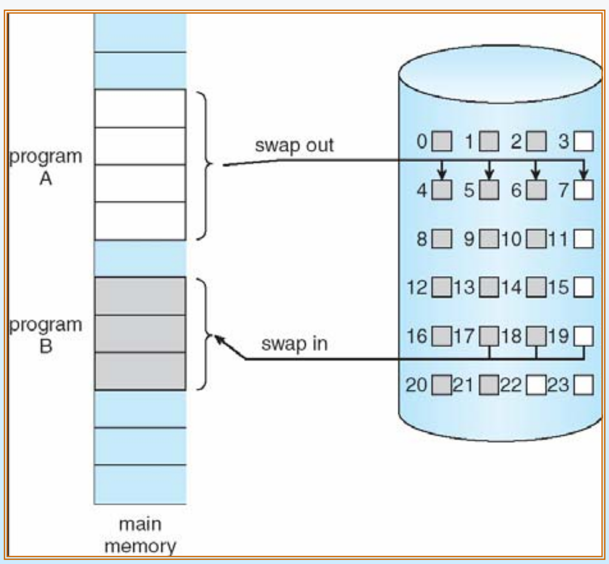
Shared Library Using Virtual Memory



Demand Paging

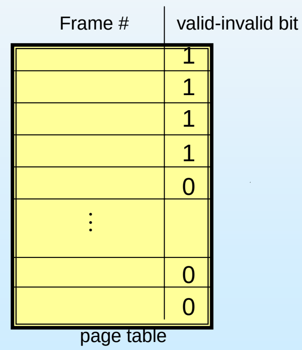
- Bring a page into memory only when it is needed
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users
- Page is needed $\Rightarrow$ reference to it
  - invalid reference $\Rightarrow$ abort
  - not-in-memory $\Rightarrow$ bring to memory

Transfer of a Paged Memory to Contiguous Disk Space



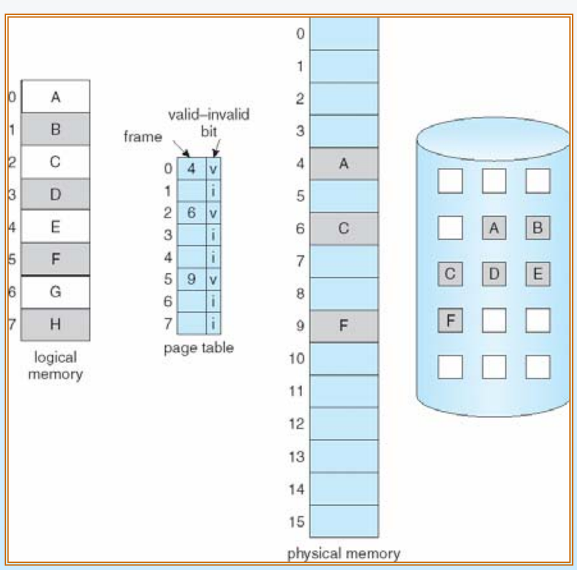
Valid-Invalid Bit

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



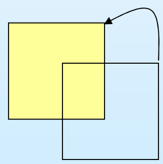
- During address translation, if valid–invalid bit in page table entry is 0 ⇒ page fault

Page Table When Some Pages Are Not in Main Memory



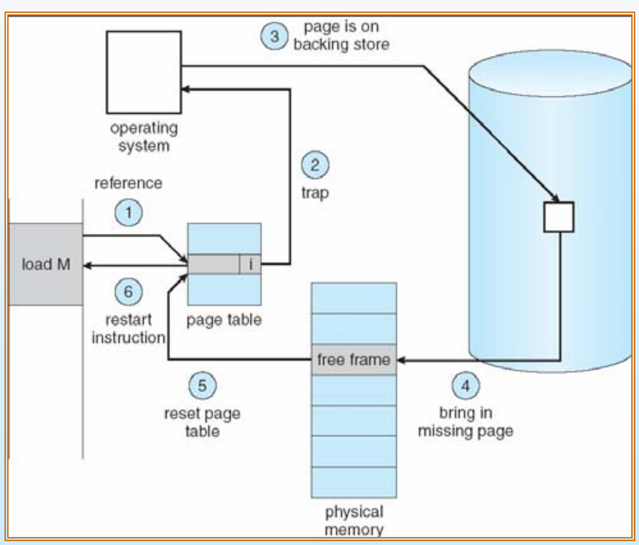
Page Fault

- If there is ever a reference to a page, first reference will trap to OS ⇒ page fault
- OS looks at another table to decide:
  - Invalid reference ⇒ 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 $0 \le p \le 1.0$
  - 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)

Steps in Handling Page faults

- Trap to the OS
- Save the user registers and process state
- Determine that the Interrupt was a page fault
- Check that the page reference was legal and determine the location of the page on the disk
- Issue a read from the dist to a free frame:
  - Wait in a queue for this devie until the read request is serviced
  - Wait for the device to seek and/ or latency time
  - Begin the transfer of the page to the selected free frame
- While waiting, allocate the CPU to some other user
- Receive an interrut from the disk subsystem on I/O completion
- Save the registers and process state for the process running
- Determine that the interrupt was from the disk
- Correct the page table and other tables to show that the desired page is in the memory now
- Wait for the CPU to be allocated to this process again
- Restore the user registers, process state, and new page table, and resume the interrupted instruction

Demand Paging Example

- Memory access time = 200 ns
- Disk access time = 8 ms = 8,000,000 ns
- 50% of the time the page that is being replaced has been modified and therefore needs to be swapped out
- EAT = (1 – p) x 200 + p (8,000,000) + 4,000,000)
  = 200+7,999,800p
  11,
- What should p be for EAT to be <220 ns ?
  220 > 200 + 7999800p
  or p<0.0000025

Process Creation

- Virtual memory allows other benefits during process creation:

  - Copy-on-Write

  - Memory-Mapped Files (later)

Copy-on-Write

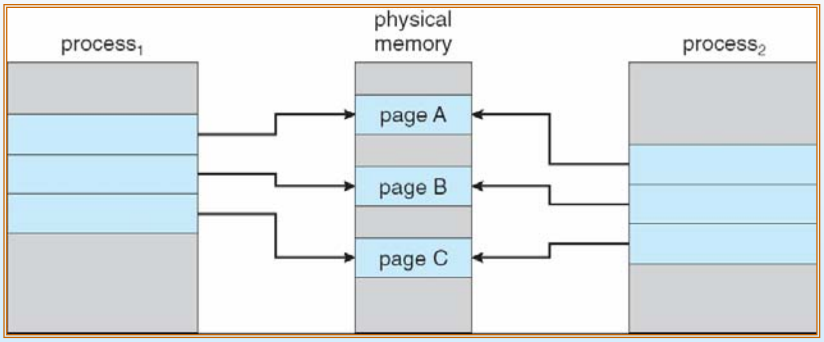
- Copy-on-Write (COW) allows both parent and child processes to initially *share* the same pages in memory

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

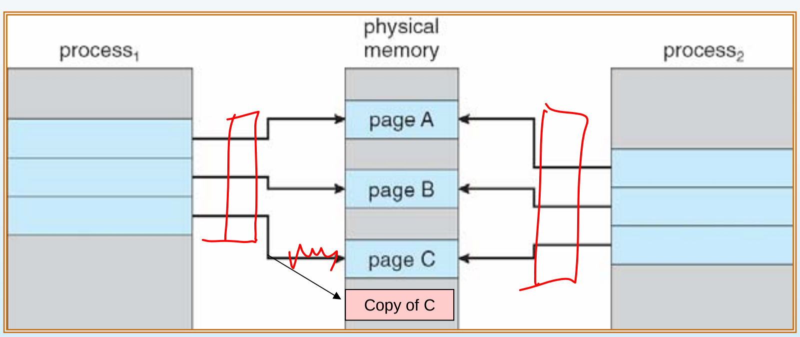
- COW allows more efficient process creation as only modified pages are copied

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

Before process 1 modifies page C



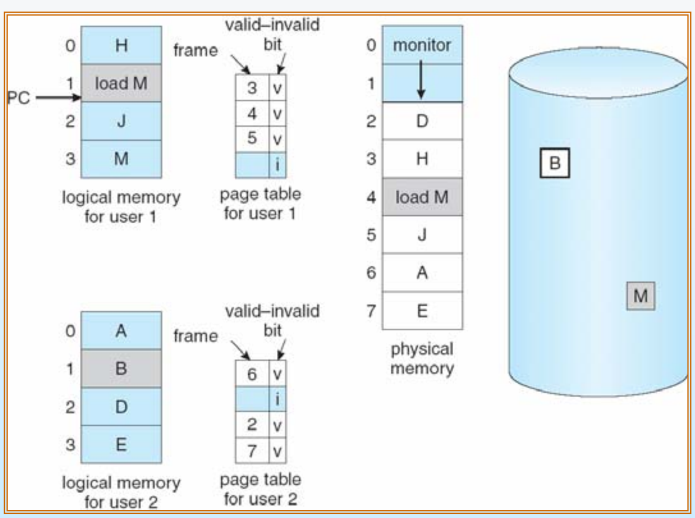
After Process 1 Modifies page C



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

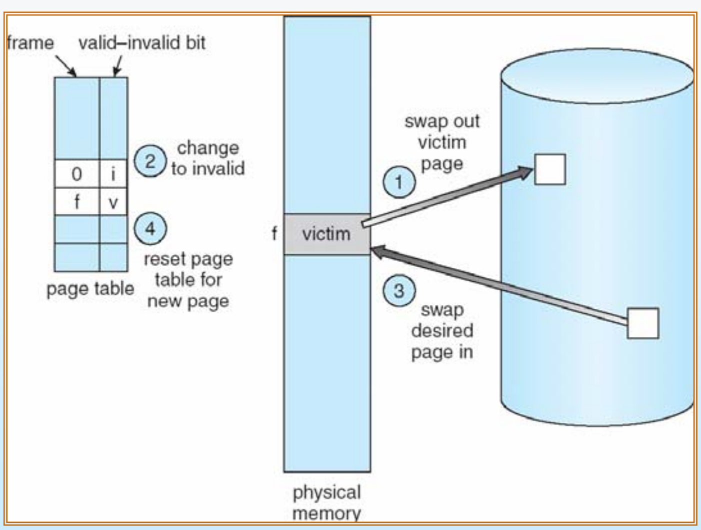
1. Find the location of the desired page on disk

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

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

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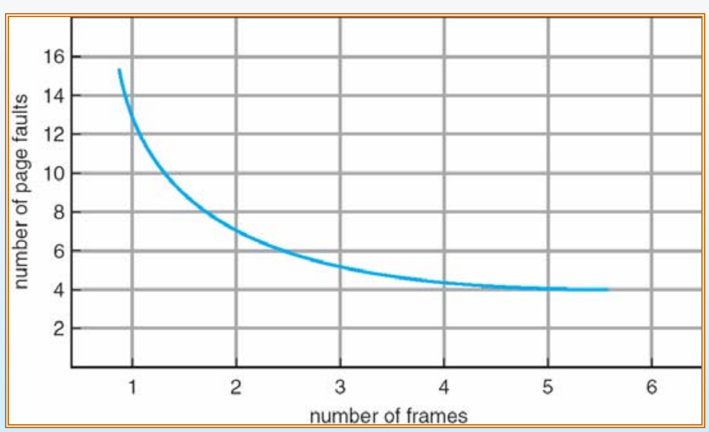
Graph of Page Faults Versus The Number of Frames



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)

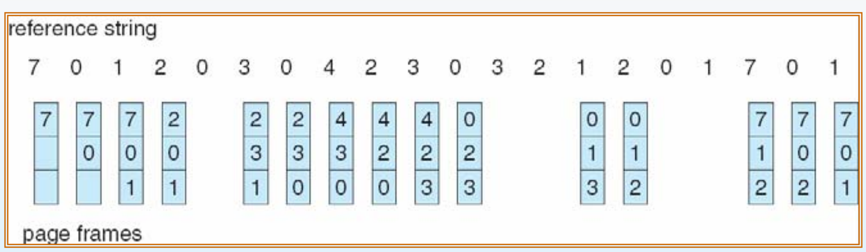
1	1	4	5	
2	2	1	3	9 page faults
3	3	2	4	

- 4 frames

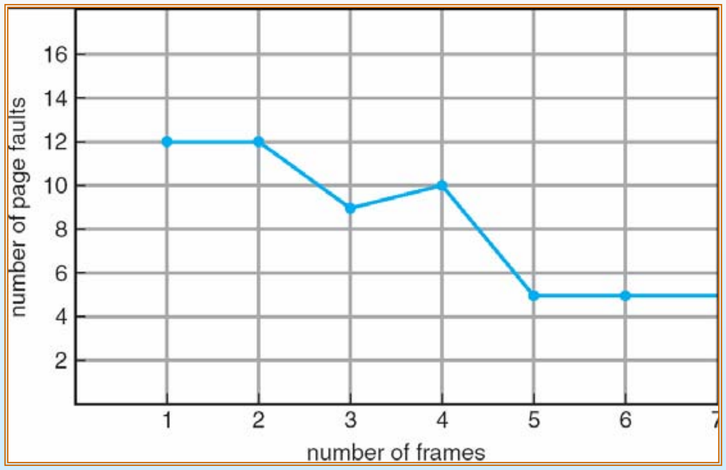
1	1	5	4	
2	2	1	5	10 page faults
3	3	2		
4	4	3		

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

FIFO Page Replacement



FIFO Illustrating Belady's Anomaly



Optimal Algorithm

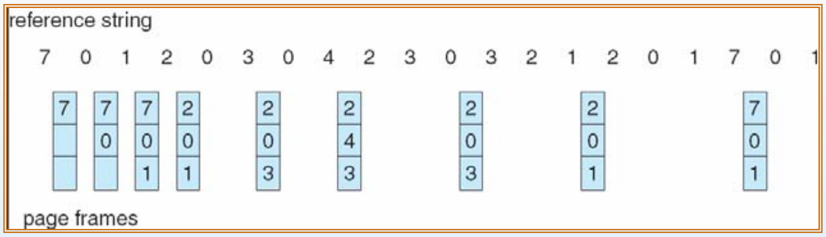
- Replace page that will not be used for longest period of time
- 4 frames example

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

1	4	
2		6 page faults
3		
4	5	

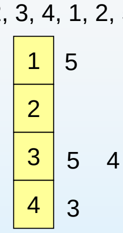
- How do you know this?
- Used for measuring how well your algorithm performs

Optimal Page Replacement



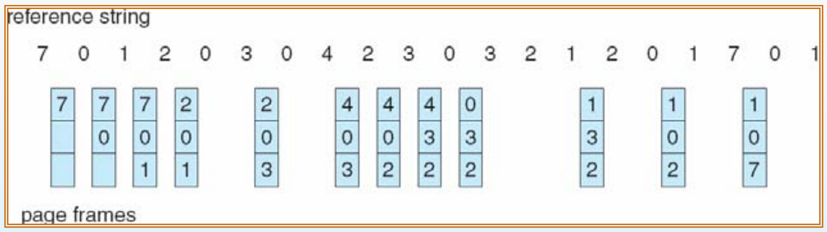
Least Recently Used (LRU) Algorithm

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



- 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

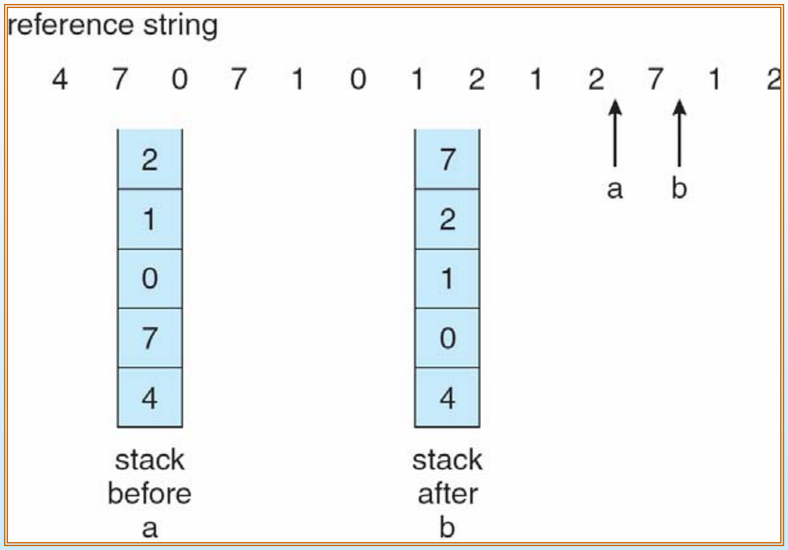
LRU Page Replacement



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

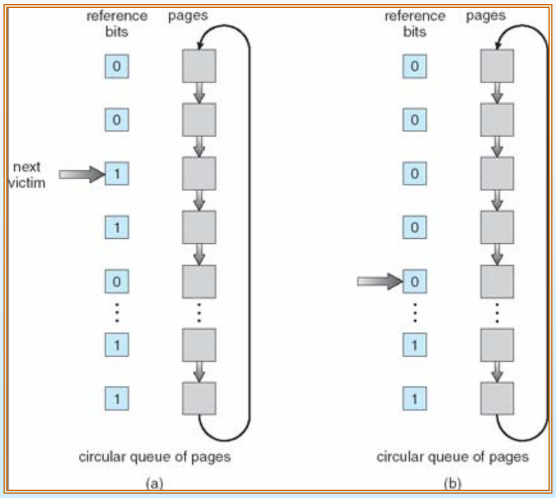
Use Of A Stack to Record The Most Recent Page References



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 – e.g., if 100 frames and 5 processes, give each 20 pages
- 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 $p_i = \frac{s_i}{S} \times m$

$m = 64$

$s_i = 10$

$s_2 = 127$

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

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

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

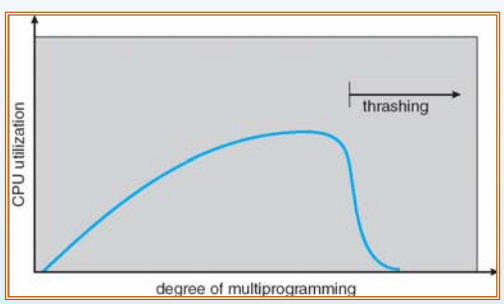
Global vs. Local Allocation

- **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

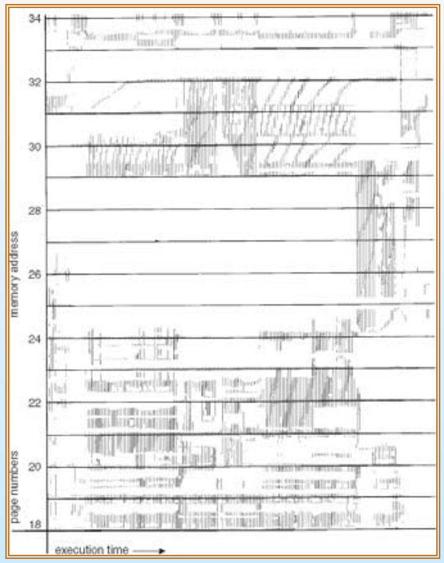
- If a process does not have “enough” pages, the page-fault rate is very high. This leads to:
  - low CPU utilization
  - operating system thinks that it needs to increase the degree of multiprogramming
  - another process added to the system
- **Thrashing** ≡ a process is busy swapping pages in and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

Thrashing



- Why does 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

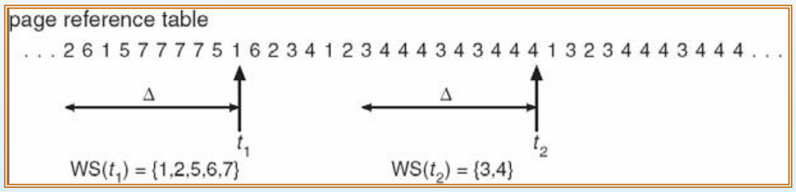
Locality In A Memory-Reference Pattern



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

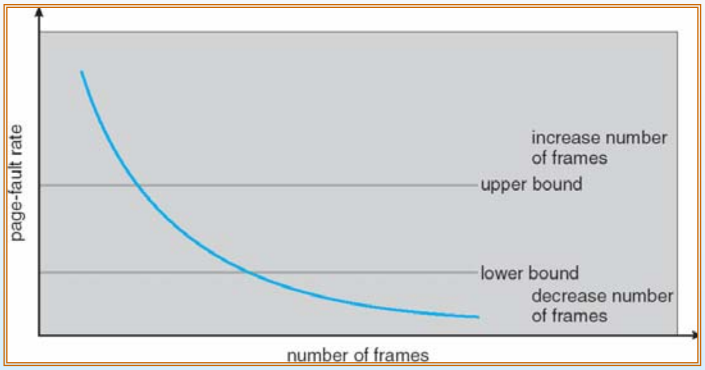
Working-set model



Keeping Track of the Working Set

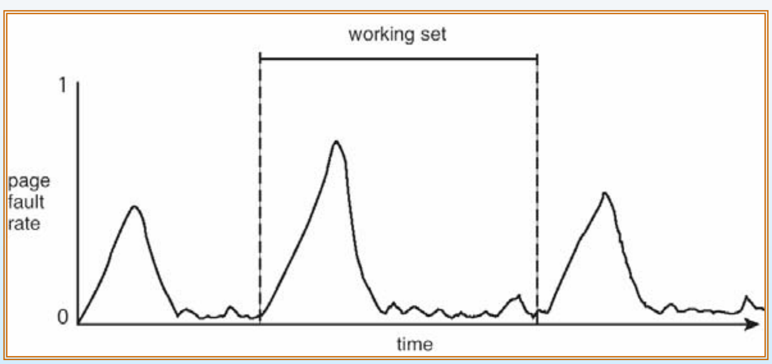
- Approximate with interval timer + a reference bit
- Example: Δ = 10,000
  - Timer interrupts after every 5000 time units
  - Keep in memory 2 bits for each page
  - Whenever a timer interrupts copy and sets the values of all reference bits to 0
  - If one of the bits in memory = 1 $\Rightarrow$ page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

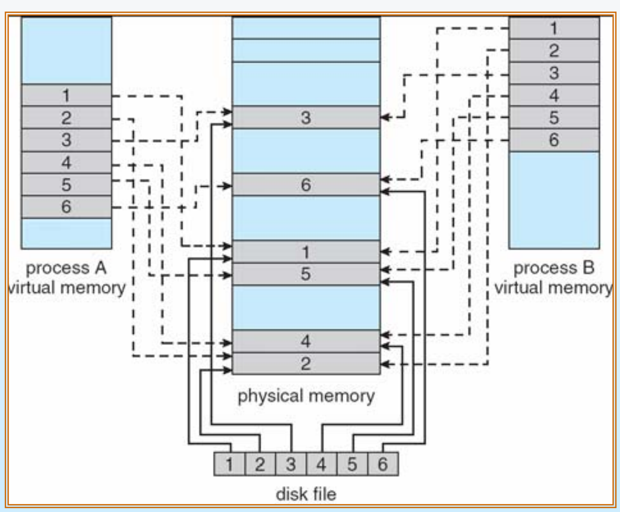
Page Fault Rates over Time



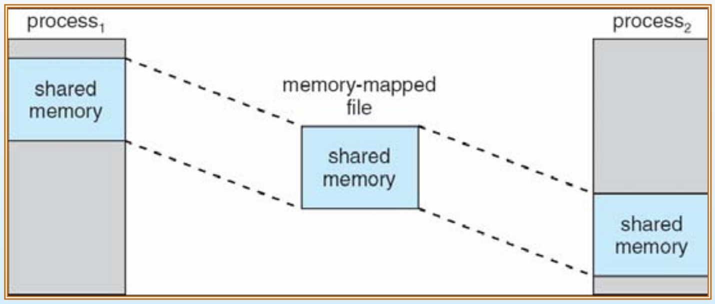
Memory-Mapped Files

- 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



Shared Memory in the WIN32 API



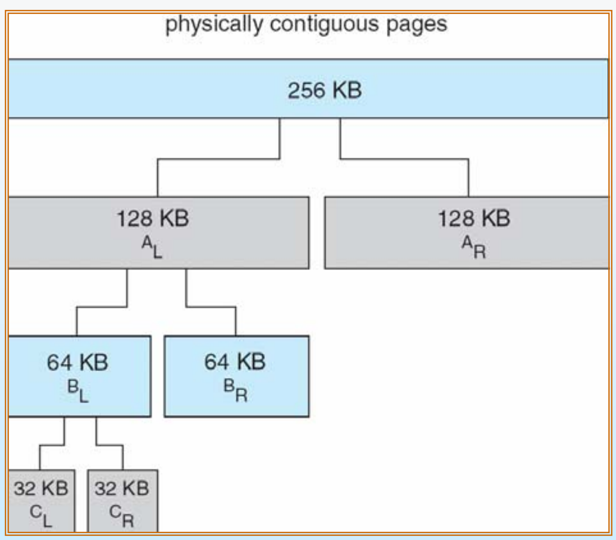
Allocating Kernel Memory

- The kernel requests memory for data structures of varying sizes, some much smaller than a page
  - Must use memory conservatively
  - Minimize waste due to fragmentation
    - Kernel memory may not be paged
- Pages allocated to user-mode processes do not necessarily have to be in contiguous memory. Some devices interact directly with physical memory and may require allocation of contiguous pages.

Buddy System Allocation

- Allocate memory from fixed size segments of physically contiguous pages.
- Use “Power of 2” Allocator
  - Satisfy requests in units of powers of 2
  - Round up to the next higher size
- Advantage
  - Adjacent buddies can be combines to form larger segment – called Coalescing
- Disadvantage
  - Fragmentation

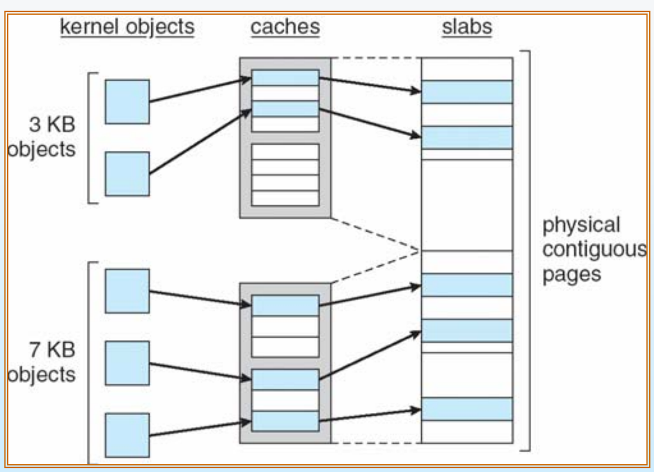
Buddy System Allocation



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
  - Separate cache for
    - Data structure for process descriptors
    - File objects
    - Semaphores
    - …
- Each cache is populated with objects that are instantiations of the kernel data structures
- Advantages
  - No memory is wasted due to fragmentation
  - Memory requests can be satisfied quickly

Slab Allocation



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

Other Issues (Cont.)

- **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.

Other Issues (Cont.)

- **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 (Cont.)

- 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

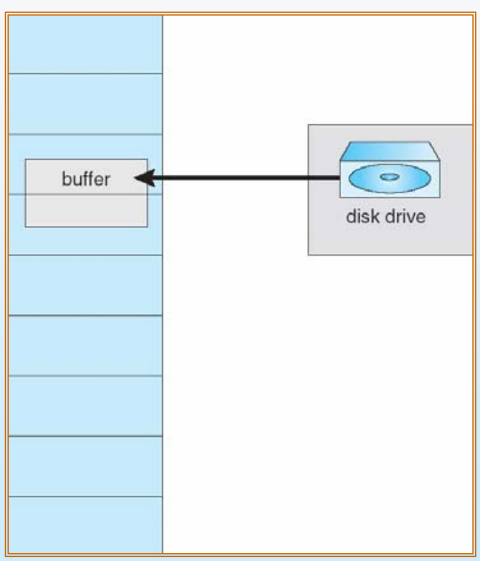
```
for (i = 0; i < A.length; i++)
    for (j = 0; j < A.length; j++)
        A[i,j] = 0;
```

    1024 page faults

Other Considerations (Cont.)

- **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



Demand Segmentation

- Used when insufficient hardware to implement demand paging.
- OS/2 allocates memory in segments, which it keeps track of through segment descriptors
- Segment descriptor contains a valid bit to indicate whether the segment is currently in memory.
  - If segment is in main memory, access continues,
  - If not in memory, segment fault.

Operating System Examples

- Windows NT
- Solaris 2

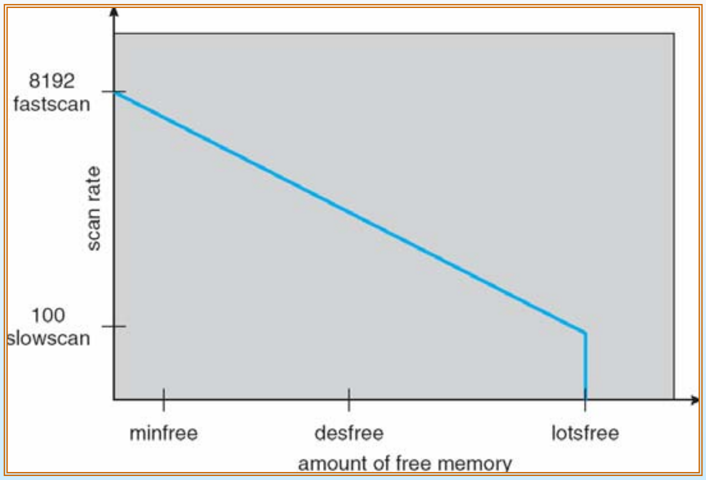
Windows XP

- 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 – Typically 1/64 of the physical memory
- *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



Solaris

- Two Hands
  - Second hand is about 1024 pages behind the first hand
- Freed pages added to Free page list from where they can be reclaimed
- Pageout process activated 4 times a second
  - If free memory below desfree then 100 times a second
- If free memory is less than desfree for 30 seconds – swapping starts
  - Swaps processes idle for a long time
- If free memory is below minfree, pageout process is called for every new page request
- New enhancements – recognize shared library pages, etc.