# IF2230 Virtual Memory

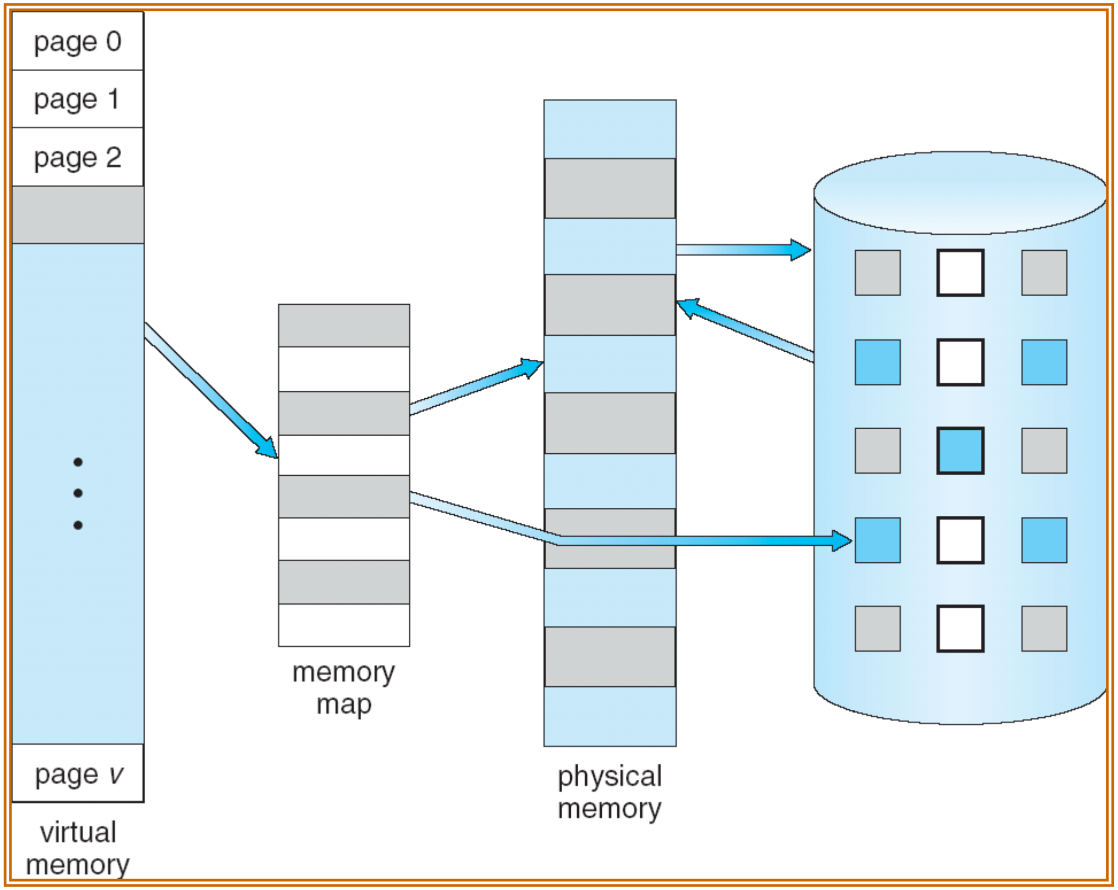
# Chapter 9: Virtual Memory

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

# Background

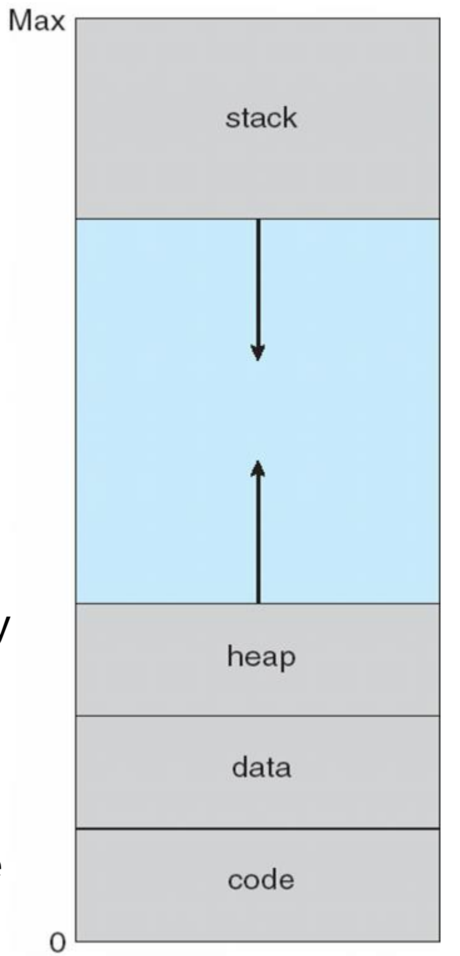
- **Virtual memory** – Pemisahan logical memory yang digunakan user dengan physical/real memory.
  - Hanya Sebagian dari program saja yang perlu ada di memori saat eksekusi
  - Logical address space dapat berukuran jauh lebih besar dibandingkan physical address space.
  - Memungkinkan address spaces digunakan bersama oleh proses lain.
  - Memungkinkan pembuatan proses yang lebih efisien
- Virtual memory dapat diimplementasikan sebagai:
  - Demand paging
  - Demand segmentation

# Virtual Memory That is Larger Than Physical Memory

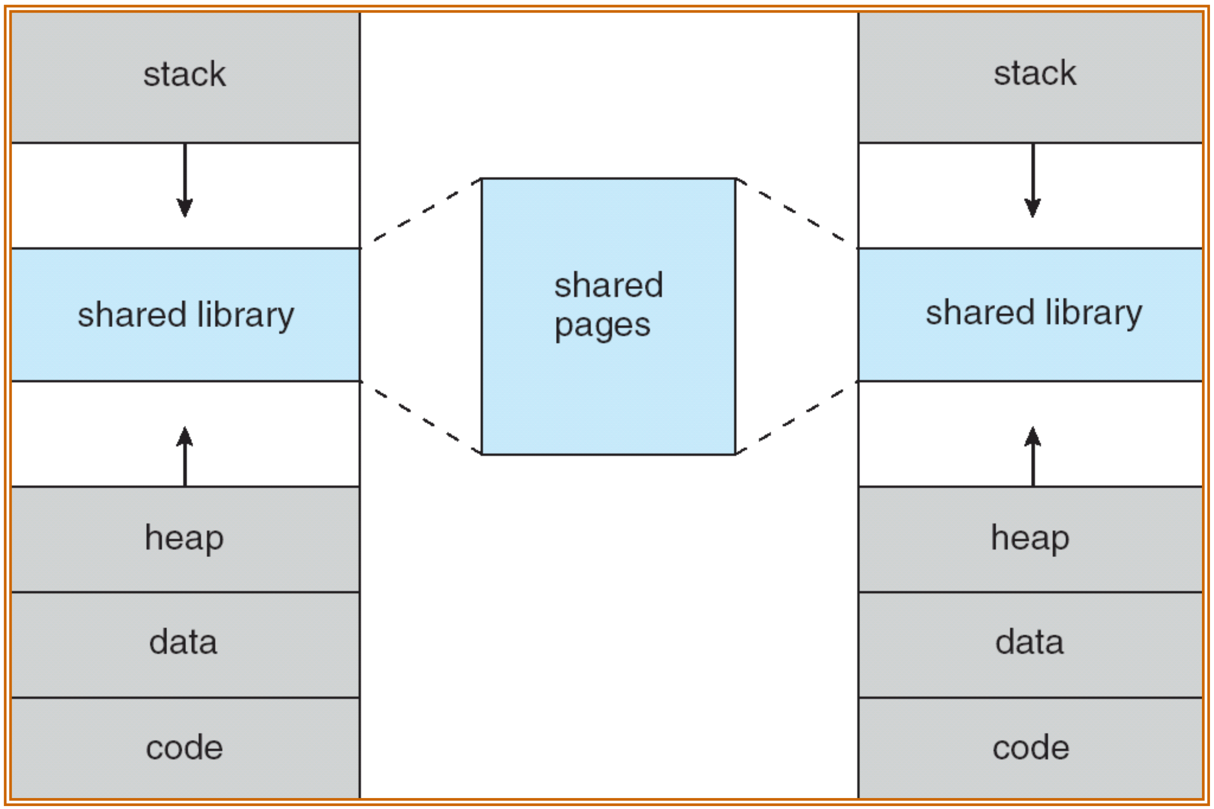


# Virtual-address Space

- Umumnya desain logical address space stack dimulai pada Max logical address dan tumbuh “ke bawah” sementara heap tumbuh “ke atas”
  - Me-maksimalkan penggunaan address space
  - address space yang tidak digunakan di antara keduanya menjadi hole
    - Tidak memerlukan physical memory hingga heap atau stack tumbuh sehingga memerlukan page baru
- Memungkinkan **sparse** address spaces dengan holes yang tersisa untuk pertumbuhan, dynamically linked libraries, etc
- System libraries di shared via mapping ke virtual address space
- Shared memory dengan mapping pages read-write ke virtual address space
- Pages dapat di-shared saat `fork()`, mempercepat process creation



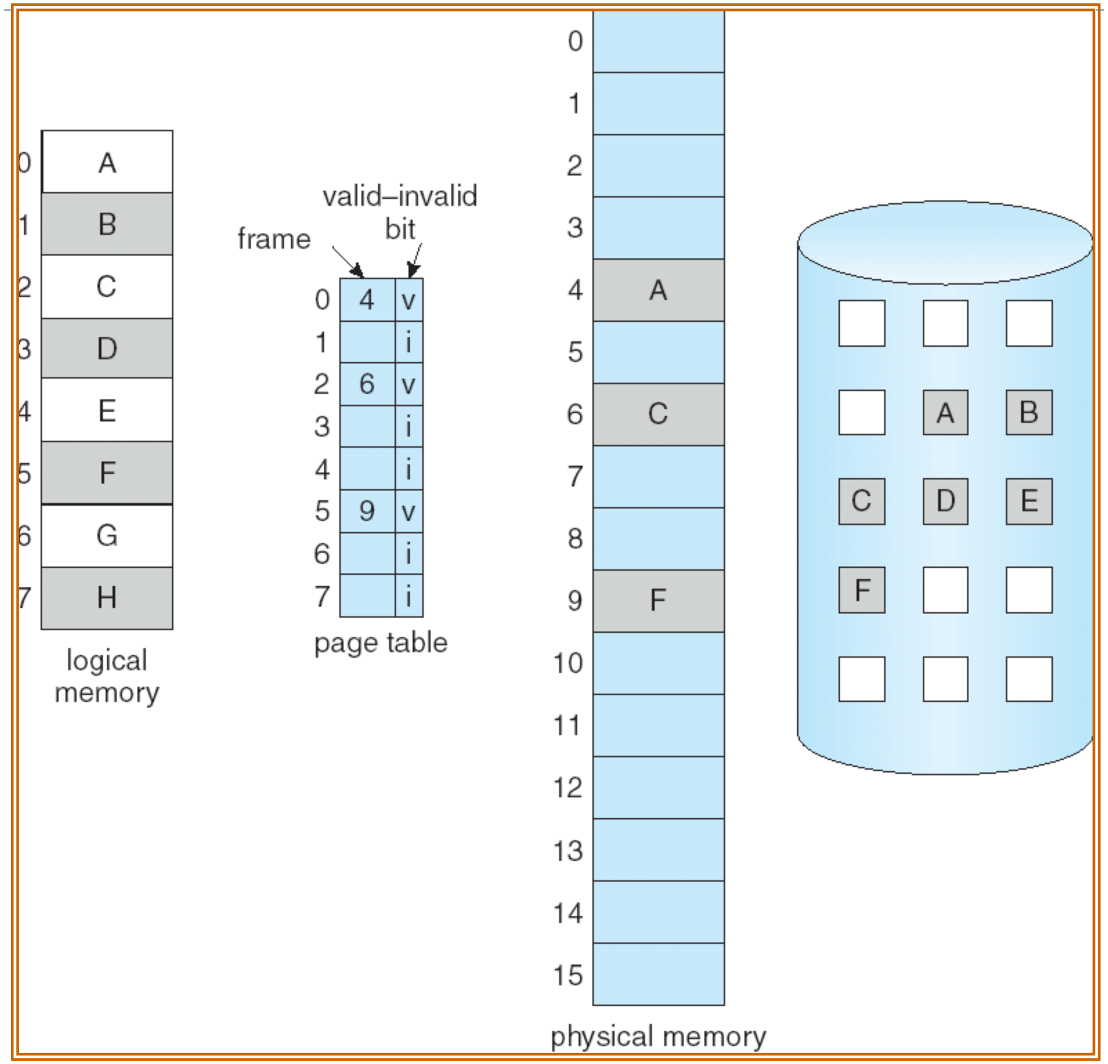
# Shared Library Using Virtual Memory



# Demand Paging

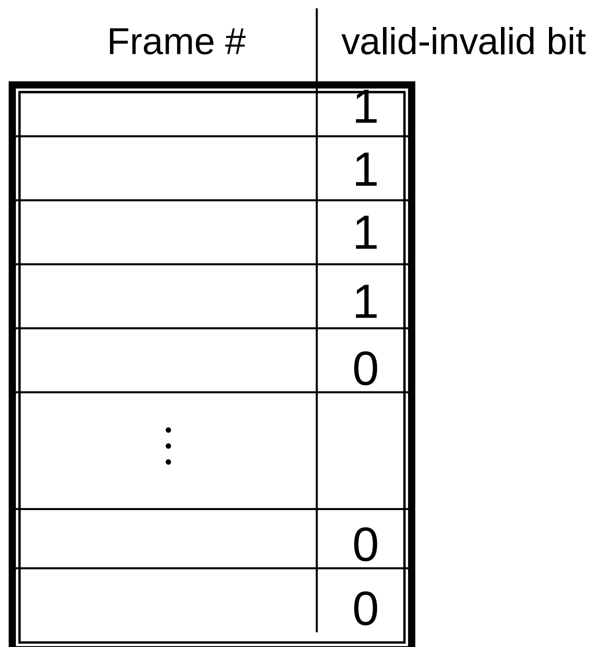
- Mengalokasikan page ke memory hanya pada saat dibutuhkan
  - Membutuhkan I/O yang lebih sedikit
  - Membutuhkan memori yang lebih sedikit
  - Respons yang lebih cepat
  - Users lebih banyak
- Page dibutuhkan $\Rightarrow$ jika ada reference ke page tsb
  - invalid reference $\Rightarrow$ abort
  - not-in-memory $\Rightarrow$ bring to memory

# Page Table When Some Pages Are Not in Main Memory



# Valid-Invalid Bit

- Dalam setiap page table entry, ada valid–invalid bit
  (1 ⇒ in-memory, 0 ⇒ not-in-memory)
- Awalnya,valid–invalid bit di set 0 untuk semua entries
- Contoh page table snapshot:



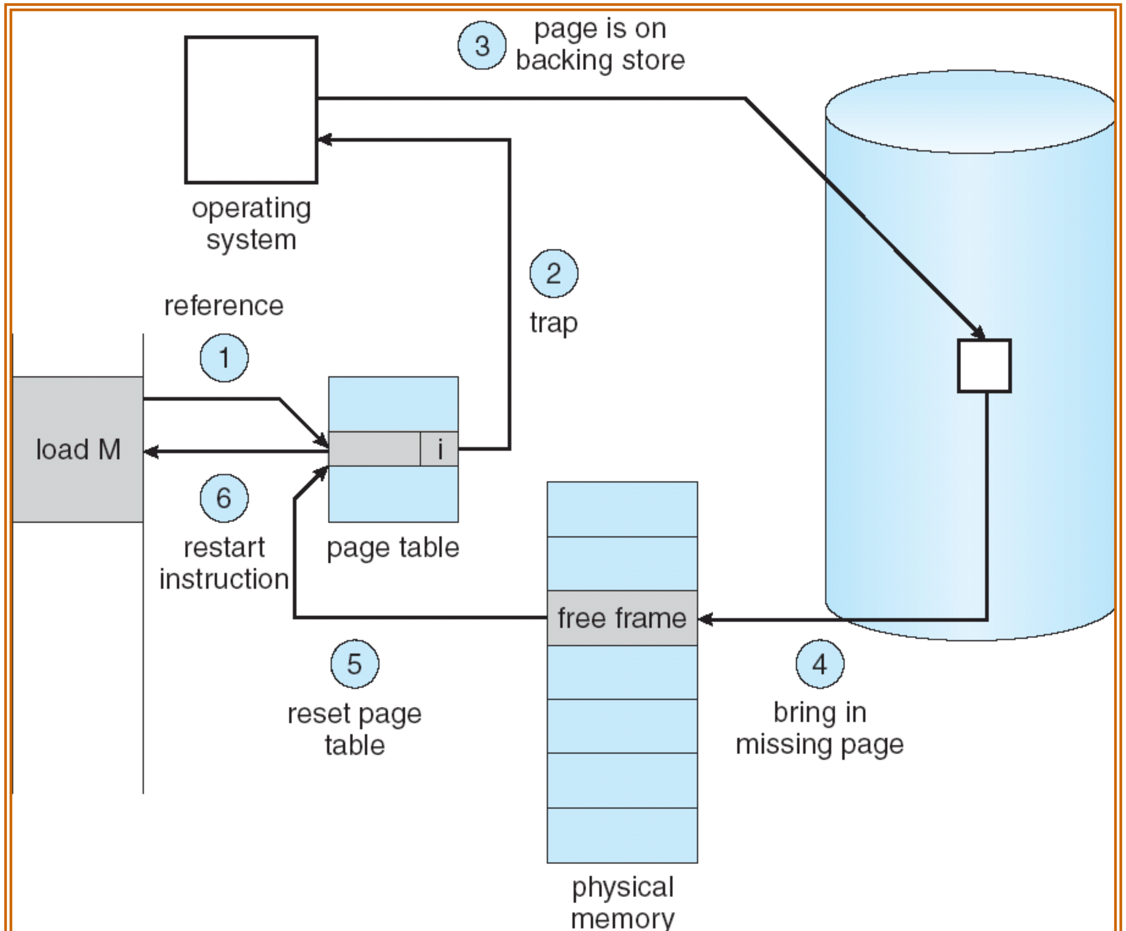
page table

- Saat address translation, jika valid–invalid bit dalam page table entry 0 ⇒ page fault

# Page Fault

- Jika ada reference ke page, reference akan menghasilkan trap ke
  OS $\Rightarrow$ page fault
- OS mencek pada table lain untuk memutuskan:
  - Invalid reference $\Rightarrow$ abort.
  - Memang sedang tidak ada di memory.
- Ambil empty frame.
- Swap page ke frame.
- Reset tables, validation bit = 1.
- Restart instruction

# 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

# Aspects of Demand Paging

- Extreme case – start process with *no* pages in memory
  - OS sets instruction pointer to first instruction of process, non-memory-resident -> page fault
  - And for every other process pages on first access
  - **Pure demand paging**

- Actually, a given instruction could access multiple pages -> multiple page faults
  - Consider fetch and decode of instruction which adds 2 numbers from memory and stores result back to memory
  - Pain decreased because of **locality of reference**

- Hardware support needed for demand paging
  - Page table with valid / invalid bit
  - Secondary memory (swap device with **swap space**)
  - Instruction restart

# Performance of Demand Paging

- Stages in Demand Paging (worse case)

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

# Performance of Demand Paging

- 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)

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

# Demand Paging Example

- Memory access time = 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!!
- If want performance degradation < 10 percent
  - 220 > 200 + 7,999,800 x p
    20 > 7,999,800 x p
  - p < .0000025
  - < one page fault in every 400,000 memory accesses

# Demand Paging Optimizations

- Swap space I/O faster than file system I/O even if on the same device
  - Swap allocated in larger chunks, less management needed than file system

- Copy entire process image to swap space at process load time
  - Then page in and out of swap space
  - Used in older BSD Unix

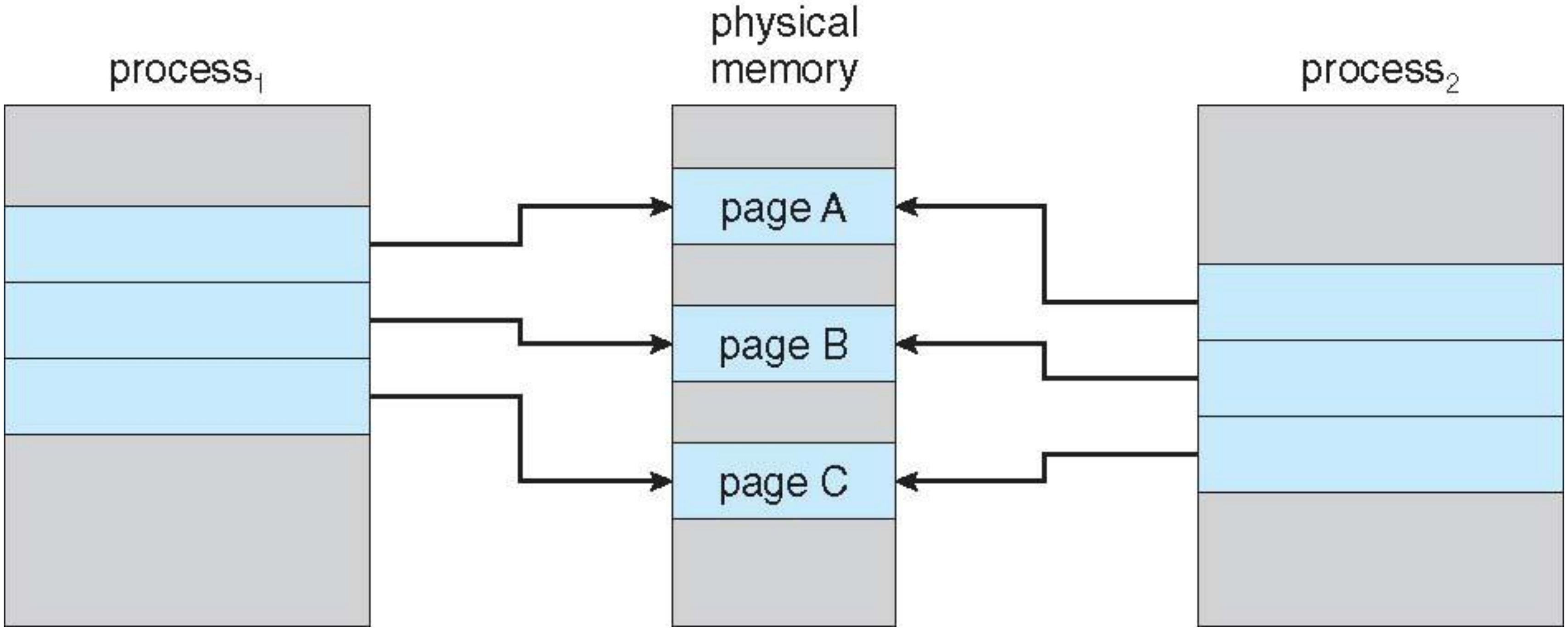
- Demand page in from program binary on disk, but discard rather than paging out when freeing frame
  - Used in Solaris and current BSD
  - Still need to write to swap space
    - Pages not associated with a file (like stack and heap) – **anonymous memory**
    - Pages modified in memory but not yet written back to the file system

- Mobile systems
  - Typically don't support swapping
  - Instead, demand page from file system and reclaim read-only pages (such as code)

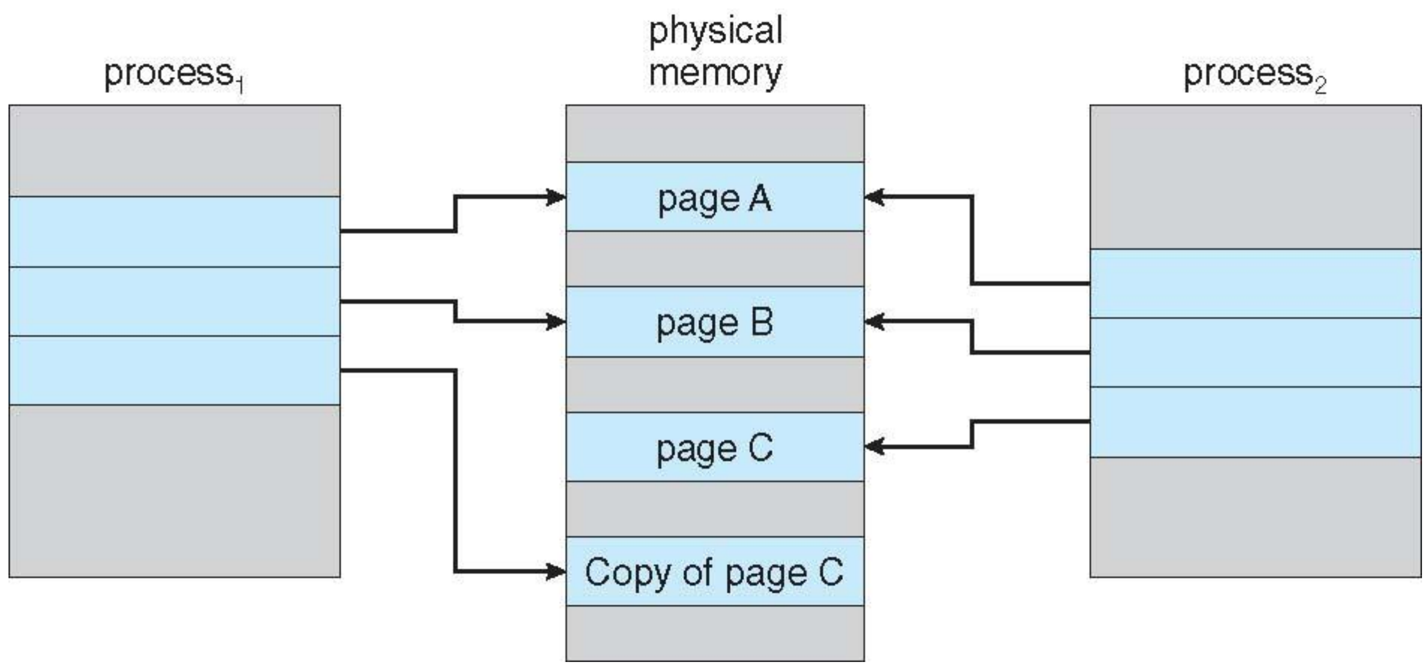
# Copy-on-Write

- **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
- In general, free pages are allocated from a **pool** of **zero-fill-on-demand** pages
  - Pool should always have free frames for fast demand page execution
    - Don't want to have to free a frame as well as other processing on page fault
  - Why zero-out a page before allocating it?
- `vfork()` variation on `fork()` system call has parent suspend and child using copy-on-write address space of parent
  - Designed to have child call `exec()`
  - Very efficient

# Before Process 1 Modifies Page C



# After Process 1 Modifies Page C



# What Happens if There is no Free Frame?

- Used up by process pages
- Also in demand from the kernel, I/O buffers, etc
- How much to allocate to each?
- Page replacement – find some page in memory, but not really in use, page it out
  - Algorithm – terminate? swap out? replace the page?
  - Performance – want an algorithm which will result in minimum number of page faults
- Same page may be brought into memory several times

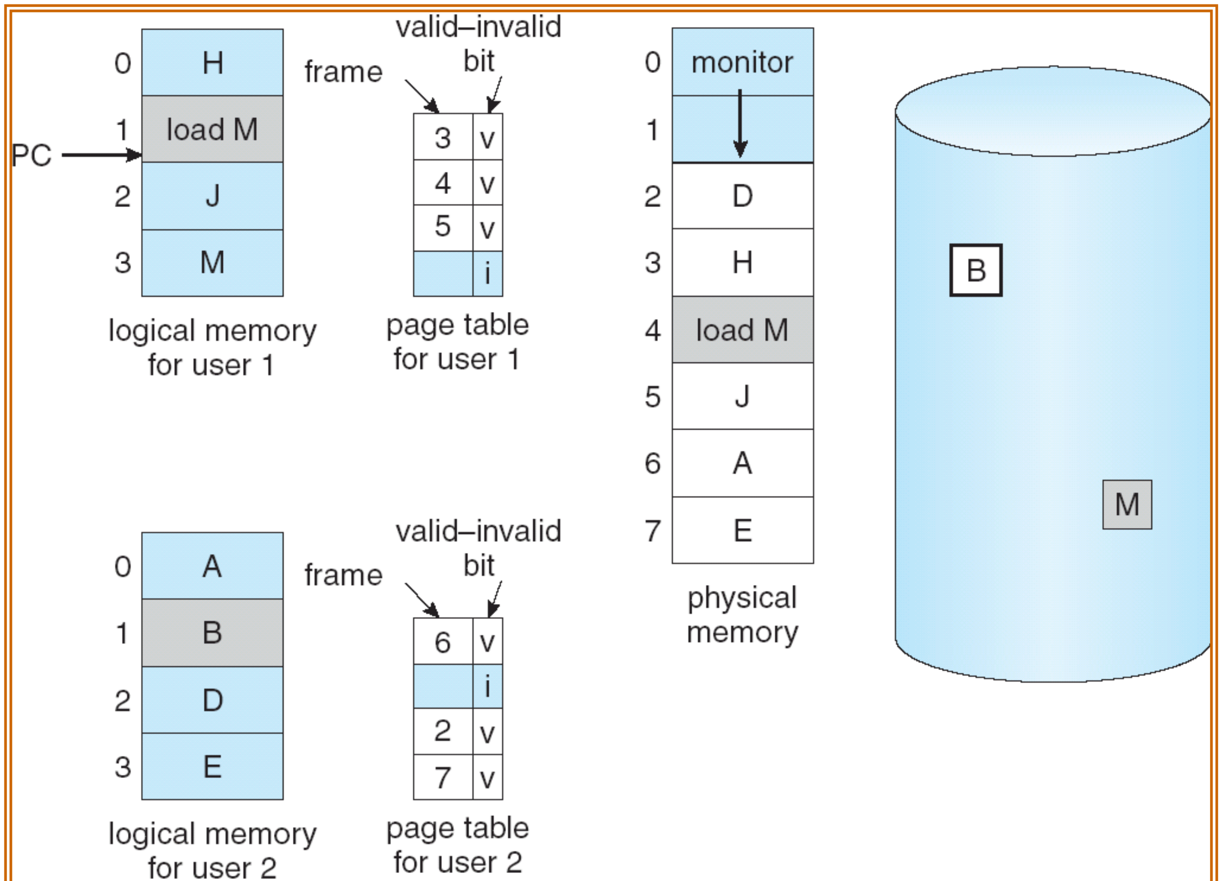
# Page Replacement

- 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

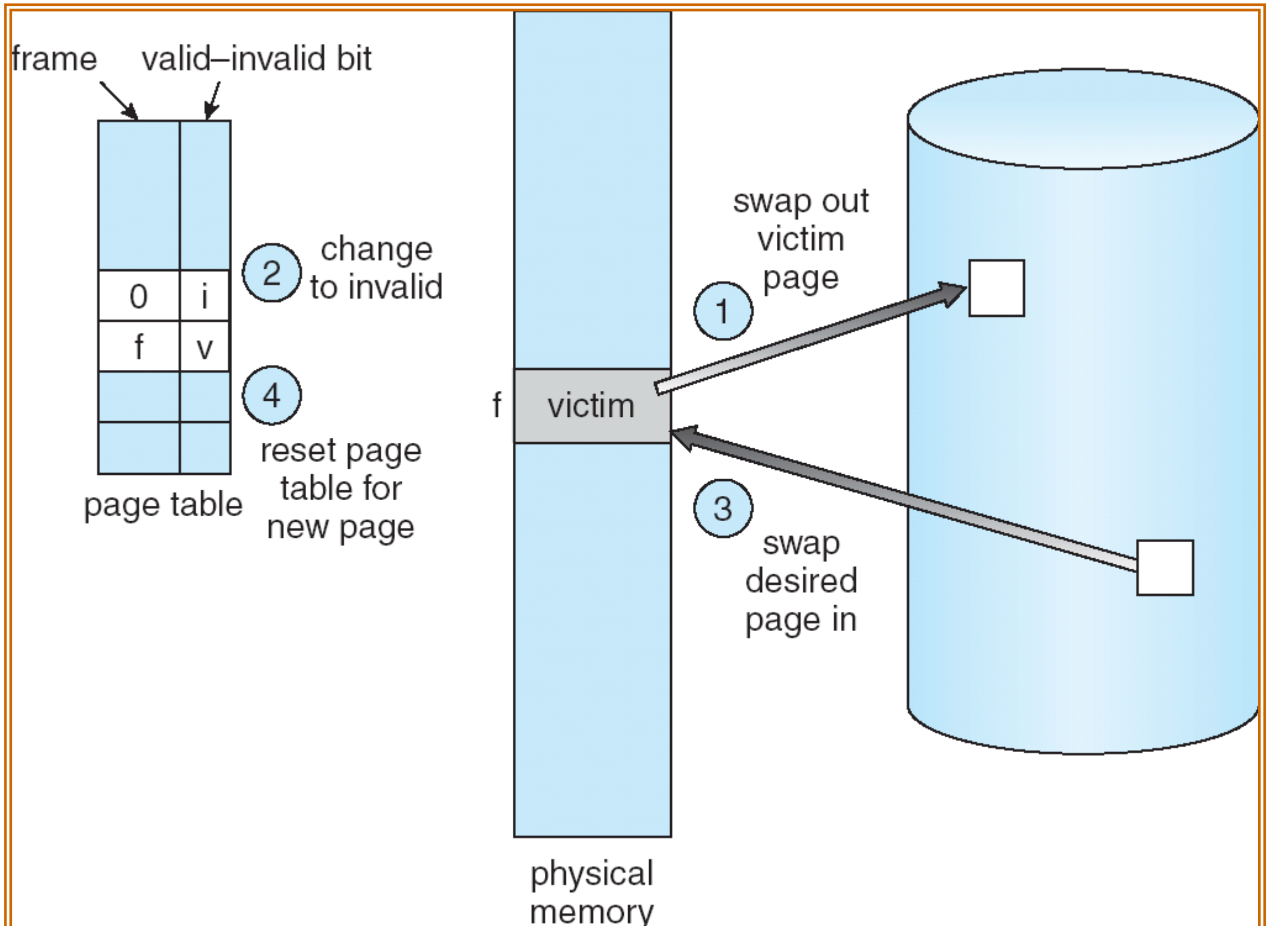
1. Find the location of the desired page on disk

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

4. Restart the process

# Page Replacement

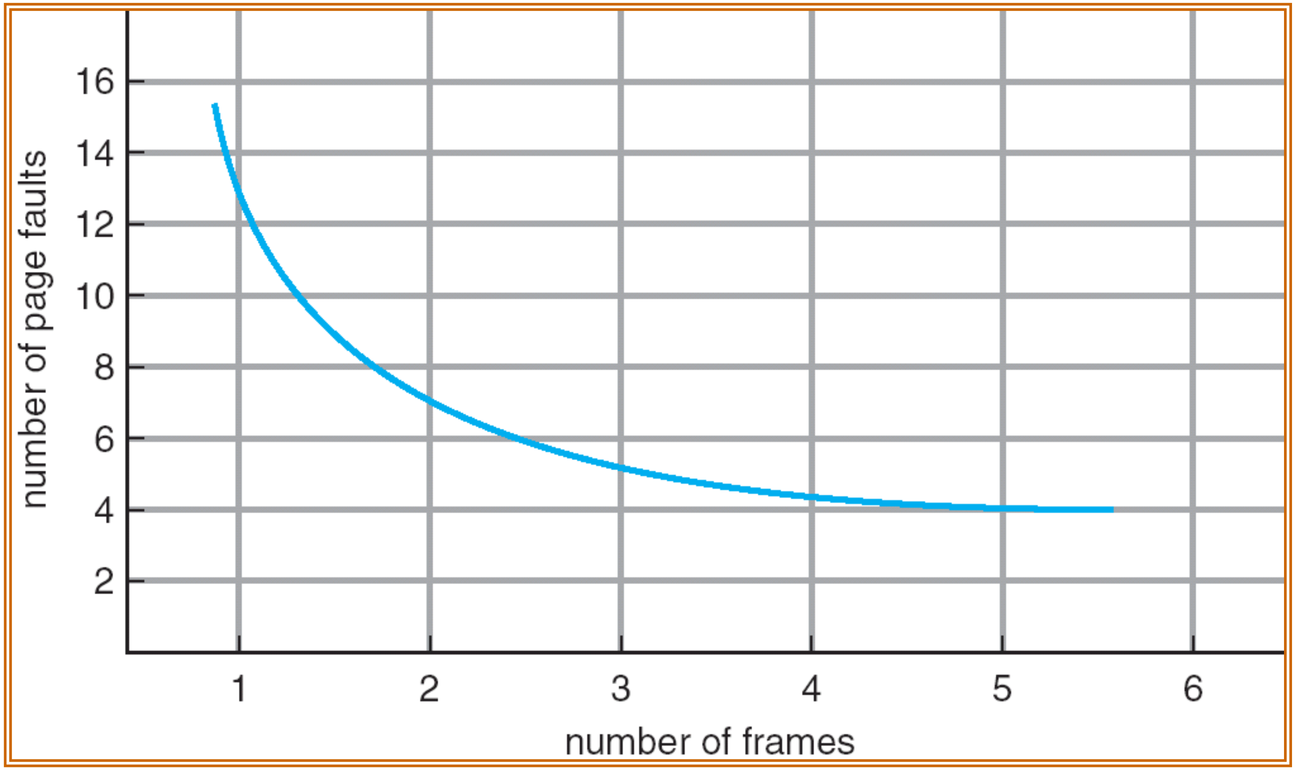


# Page Replacement Algorithms

- **Frame-allocation algorithm** determines
  - How many frames to give each process
  - Which frames to replace
- 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)

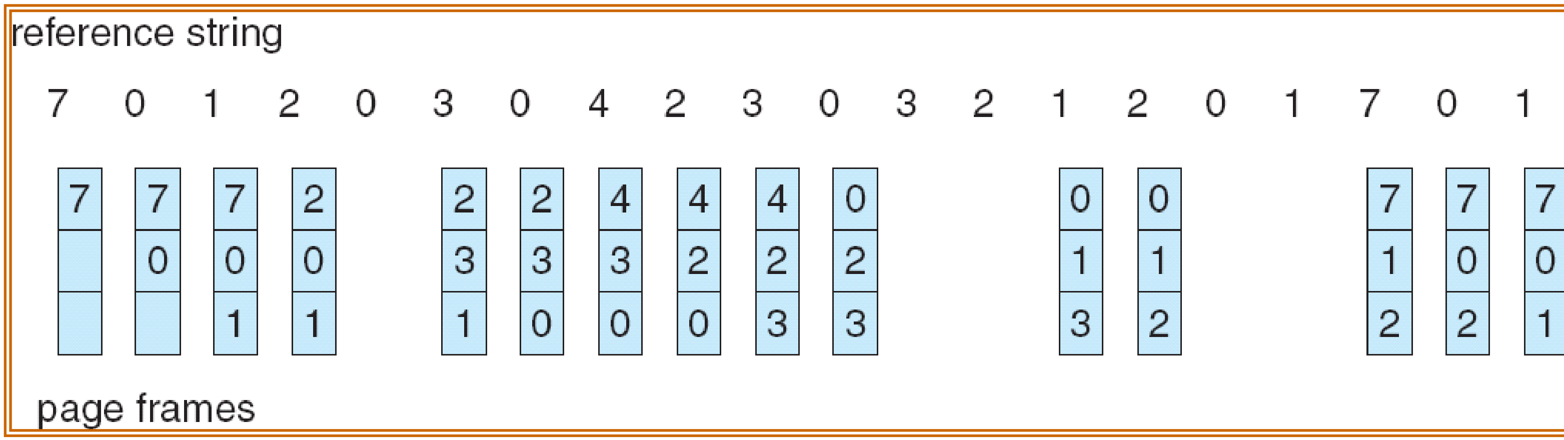
| | | | | |
|---|---|---|---|---|
| 1 | 1 | 4 | 5 | |
| 2 | 2 | 1 | 3 | 9 page faults |
| 3 | 3 | 2 | 4 | |

- 4 frames

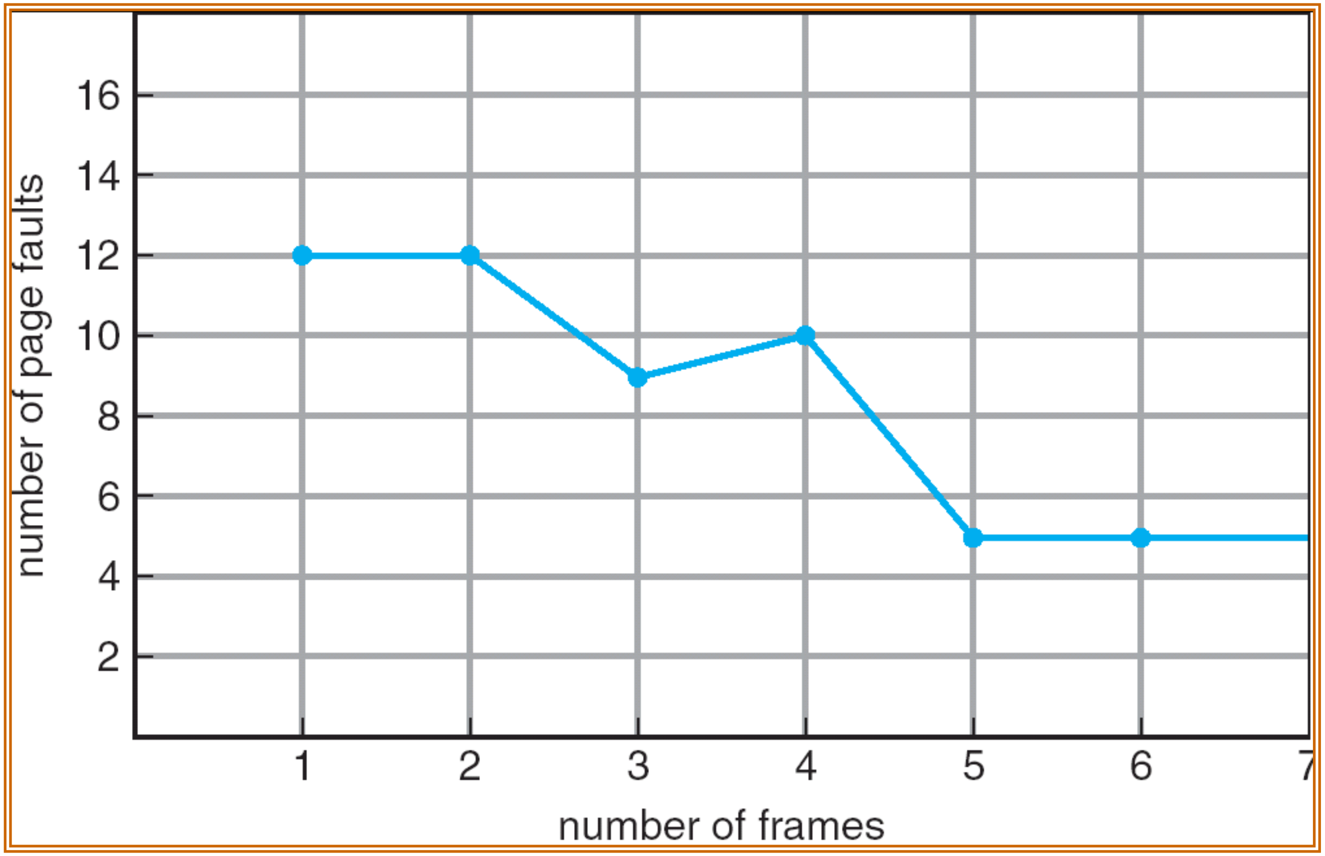
| | | | | |
|---|---|---|---|---|
| 1 | 1 | 5 | 4 | |
| 2 | 2 | 1 | 5 | 10 page faults |
| 3 | 3 | 2 | | |
| 4 | 4 | 3 | | |

- FIFO Replacement – Belady's Anomaly
  - more frames ⇒ 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

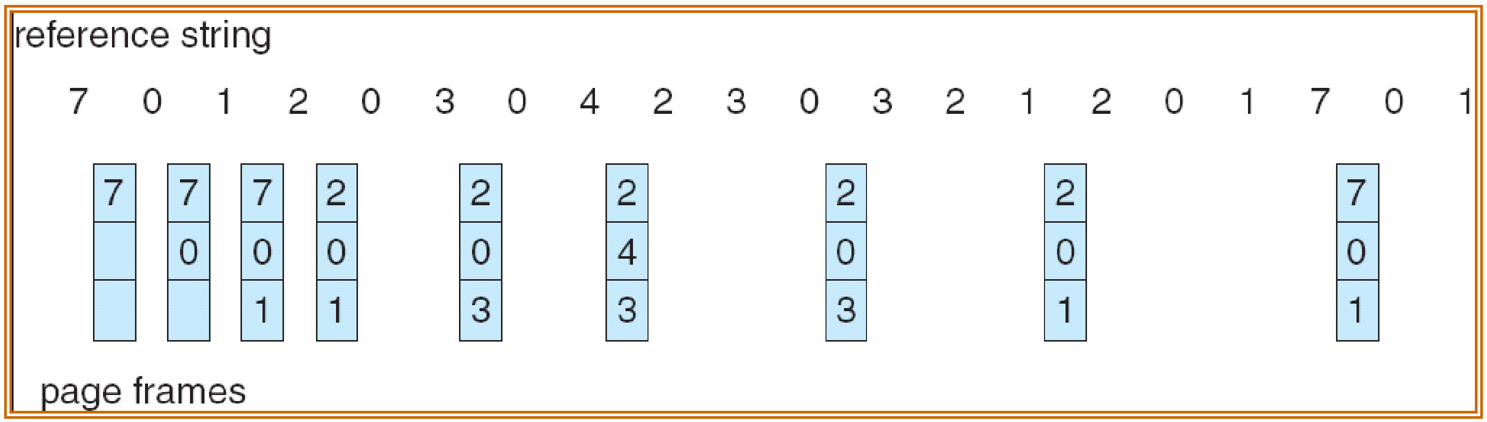
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

| | |
|---|---|
| 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



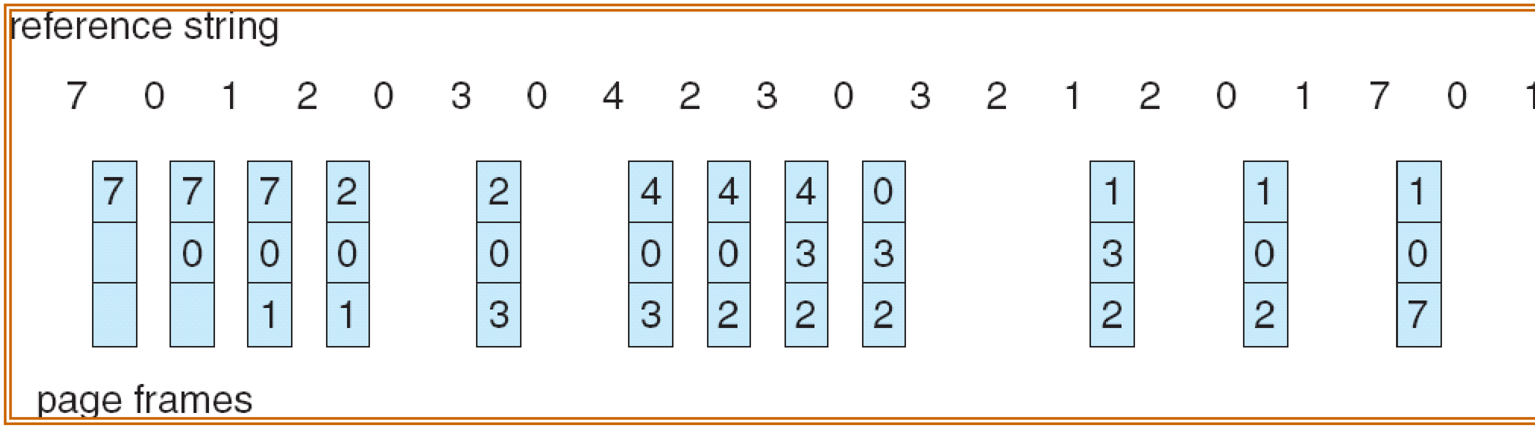
# Least Recently Used (LRU) Algorithm

- 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

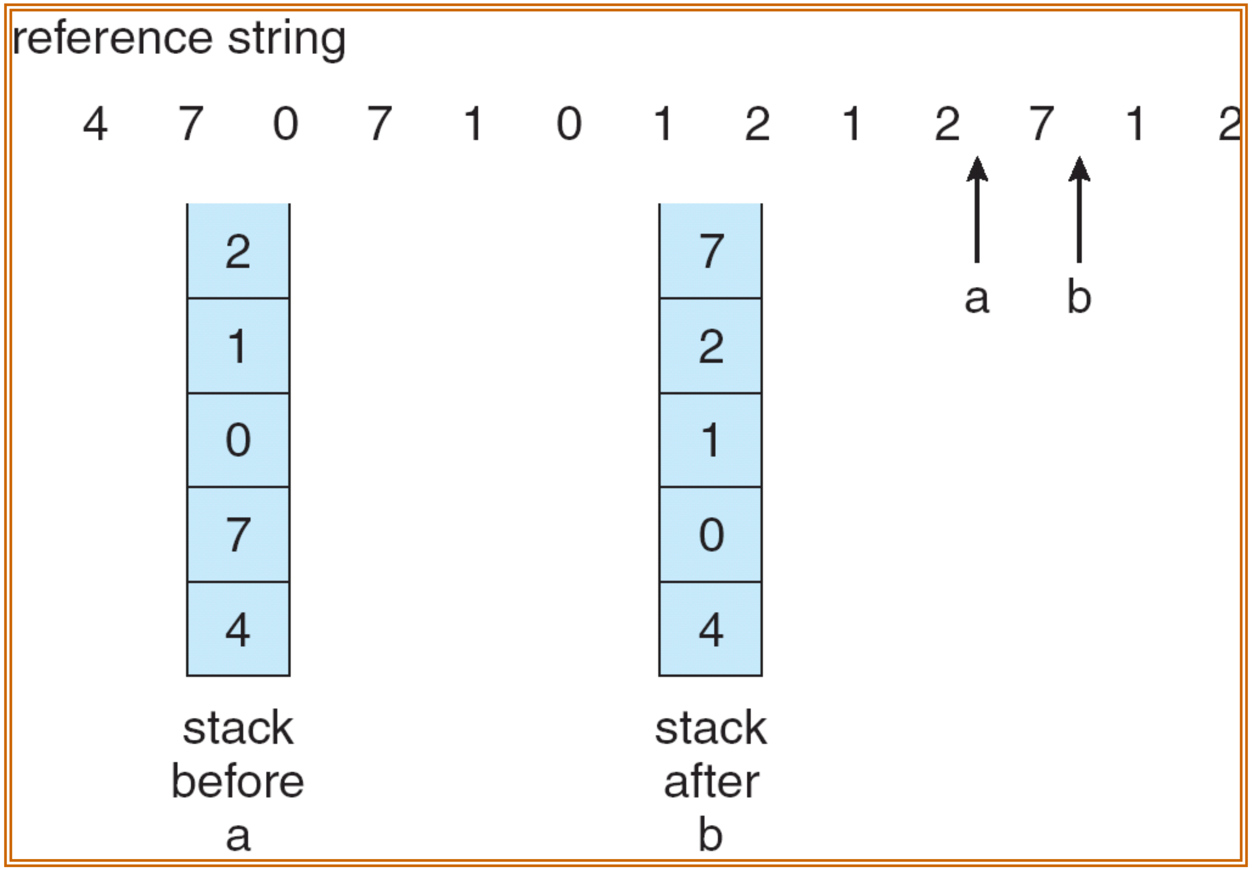
# LRU Page Replacement



# 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

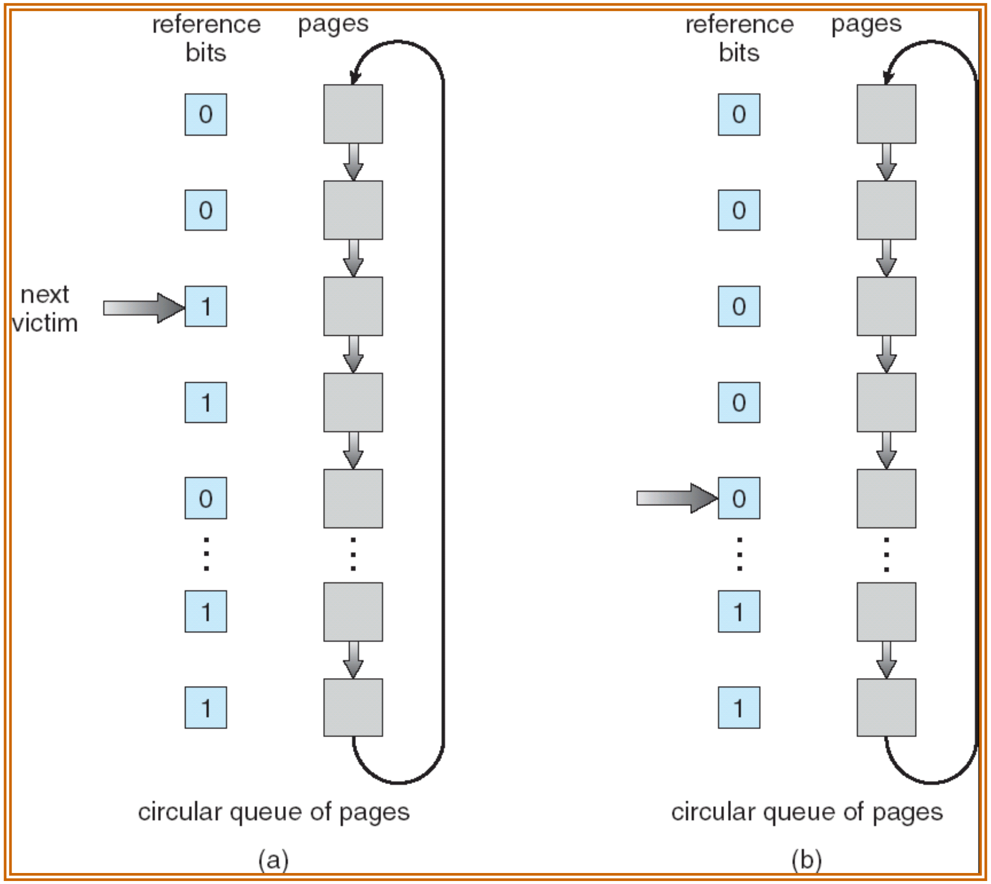
# Use Of A Stack to Record The Most Recent Page References



# 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



# Enhanced Second-Chance Algorithm

- Improve algorithm by using reference bit and modify bit (if available) in concert
- Take ordered pair (reference, modify):
  - (0, 0) neither recently used not modified – best page to replace
  - (0, 1) not recently used but modified – not quite as good, must write out before replacement
  - (1, 0) recently used but clean – probably will be used again soon
  - (1, 1) recently used and modified – probably will be used again soon and need to write out before replacement
- When page replacement called for, use the clock scheme but use the four classes replace page in lowest non-empty class
  - Might need to search circular queue several times

# 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

# Page-Buffering Algorithms

- Keep a pool of free frames, always
  - Then frame available when needed, not found at fault time
  - Read page into free frame and select victim to evict and add to free pool
  - When convenient, evict victim
- Possibly, keep list of modified pages
  - When backing store otherwise idle, write pages there and set to non-dirty
- Possibly, keep free frame contents intact and note what is in them
  - If referenced again before reused, no need to load contents again from disk
  - Generally useful to reduce penalty if wrong victim frame selected

# Applications and Page Replacement

- All of these algorithms have OS guessing about future page access
- Some applications have better knowledge – i.e. databases
- Memory intensive applications can cause double buffering
  - OS keeps copy of page in memory as I/O buffer
  - Application keeps page in memory for its own work
- Operating system can given direct access to the disk, getting out of the way of the applications
  - **Raw disk** mode
- Bypasses buffering, locking, etc.

# 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 $p_i = \frac{s_i}{S} \times m$

$$m = 64$$
$$s_i = 10$$
$$s_2 = 127$$
$$a_1 = \frac{10}{137} \times 64 \approx 5$$
$$a_2 = \frac{127}{137} \times 64 \approx 59$$

# 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

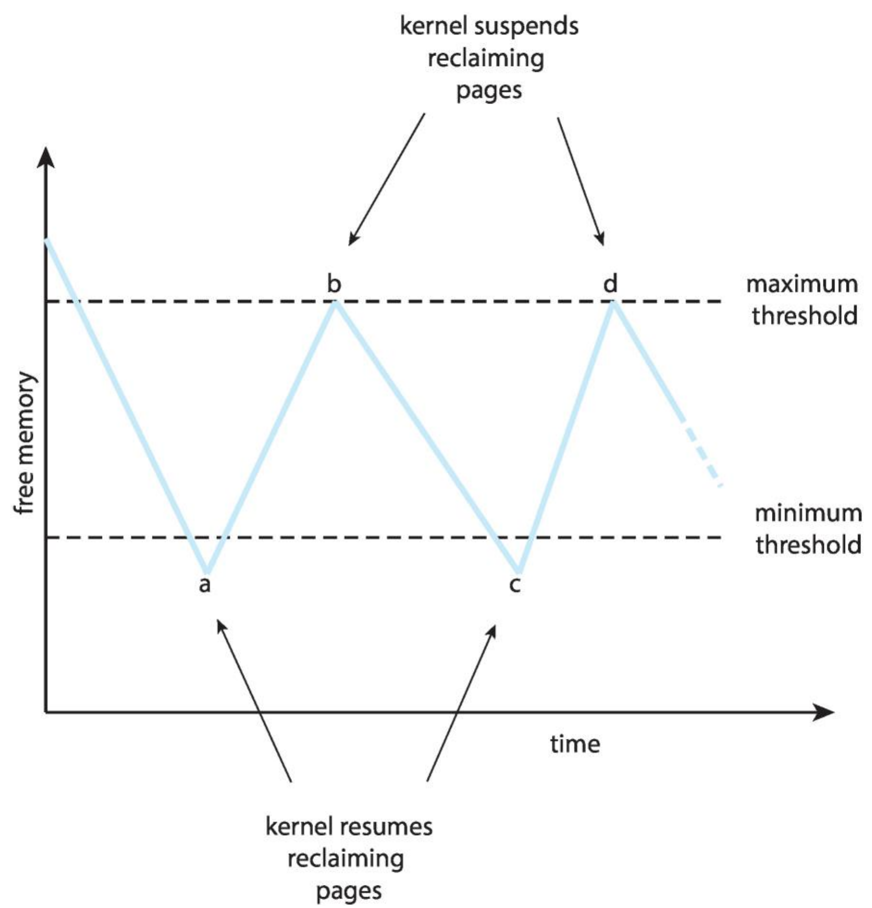
# Global vs. Local Allocation

- **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

# Reclaiming Pages

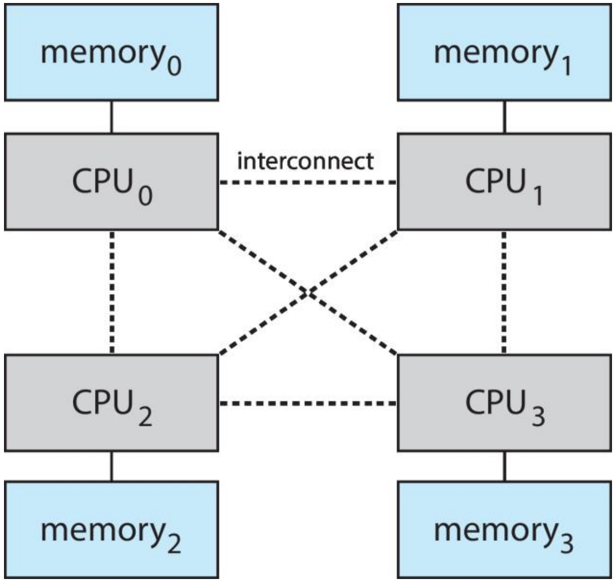
- A strategy to implement global page-replacement policy
- All memory requests are satisfied from the free-frame list, rather than waiting for the list to drop to zero before we begin selecting pages for replacement,
- Page replacement is triggered when the list falls below a certain threshold.
- This strategy attempts to ensure there is always sufficient free memory to satisfy new requests.

# Reclaiming Pages Example



# Non-Uniform Memory Access

- So far, we assumed that all memory accessed equally
- Many systems are **NUMA** – speed of access to memory varies
  - Consider system boards containing CPUs and memory, interconnected over a system bus
- NUMA multiprocessing architecture



# Non-Uniform Memory Access (Cont.)

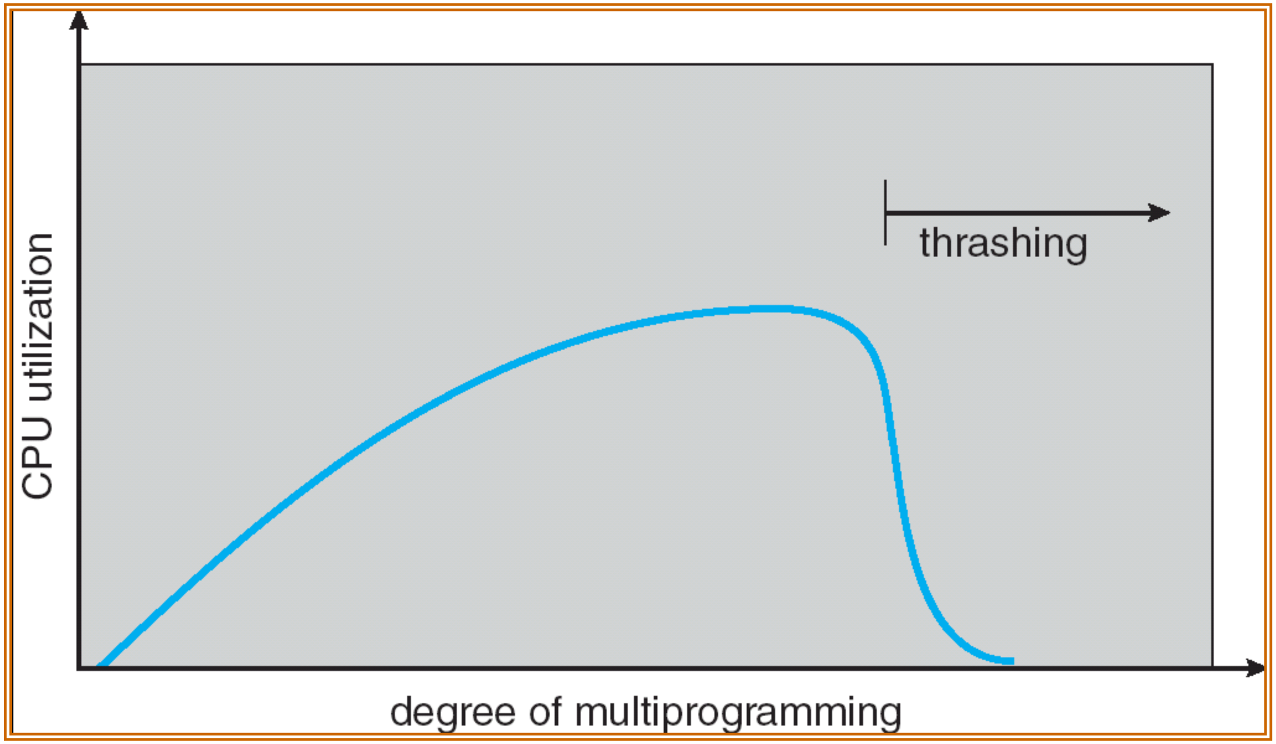
- Optimal performance comes from allocating memory "close to" the CPU on which the thread is scheduled
  - And modifying the scheduler to schedule the thread on the same system board when possible
  - Solved by Solaris by creating **lgroups**
    - Structure to track CPU / Memory low latency groups
    - Used my schedule and pager
    - When possible schedule all threads of a process and allocate all memory for that process within the lgroup

# 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 (Cont.)

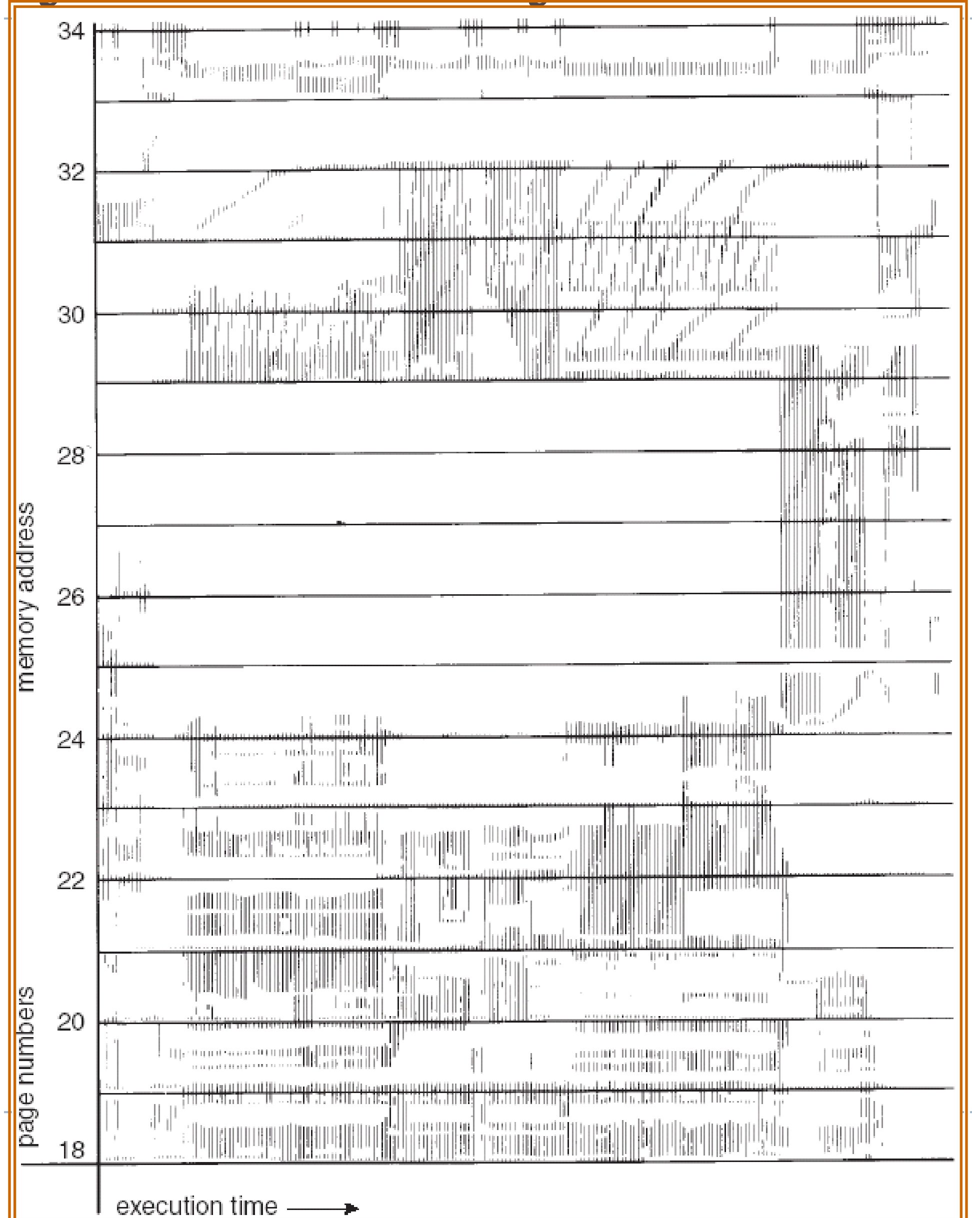


# Demand Paging and Thrashing

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

- Why does thrashing occur?
  $\Sigma$ size of locality > total memory size

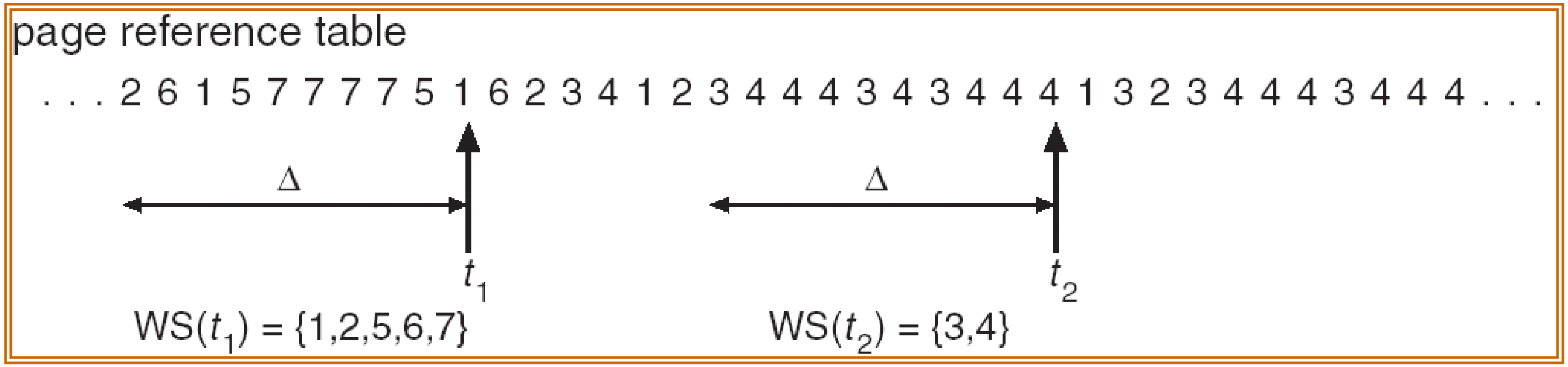
# Locality In A Memory-Reference Pattern



# 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 $\Delta$ (varies in time)
  - if $\Delta$ too small will not encompass entire locality
  - if $\Delta$ 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

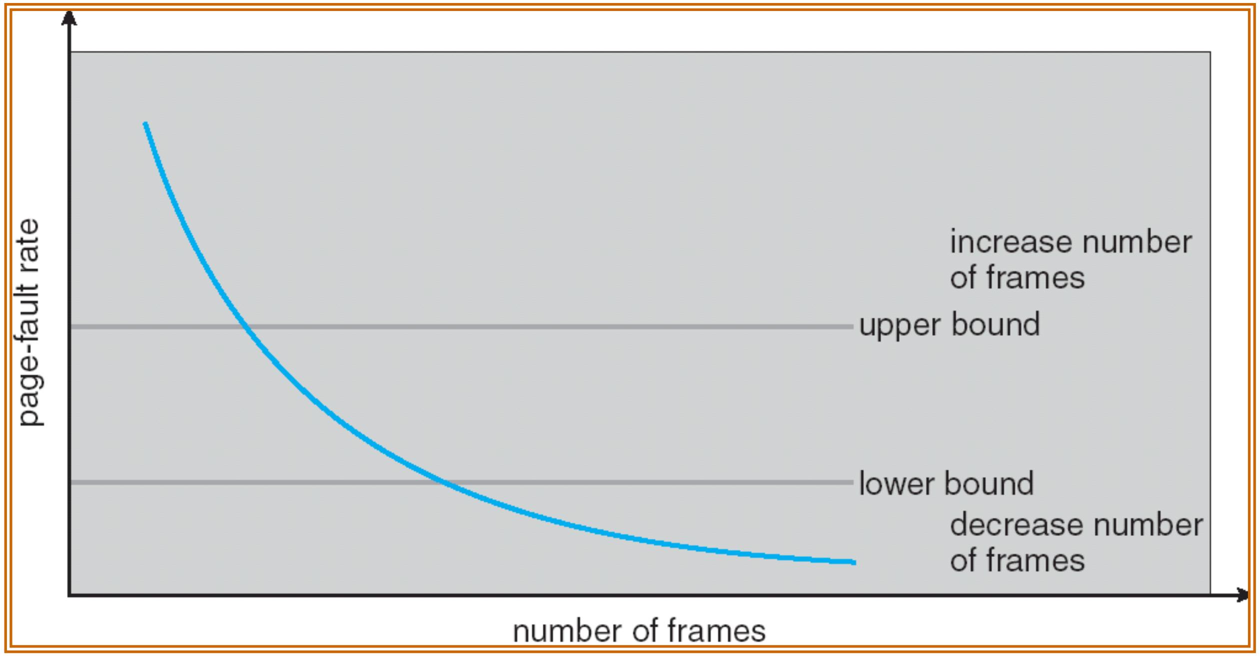


# Keeping Track of the Working Set

- Approximate with interval timer + a reference bit
- Example: $\Delta$ = 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

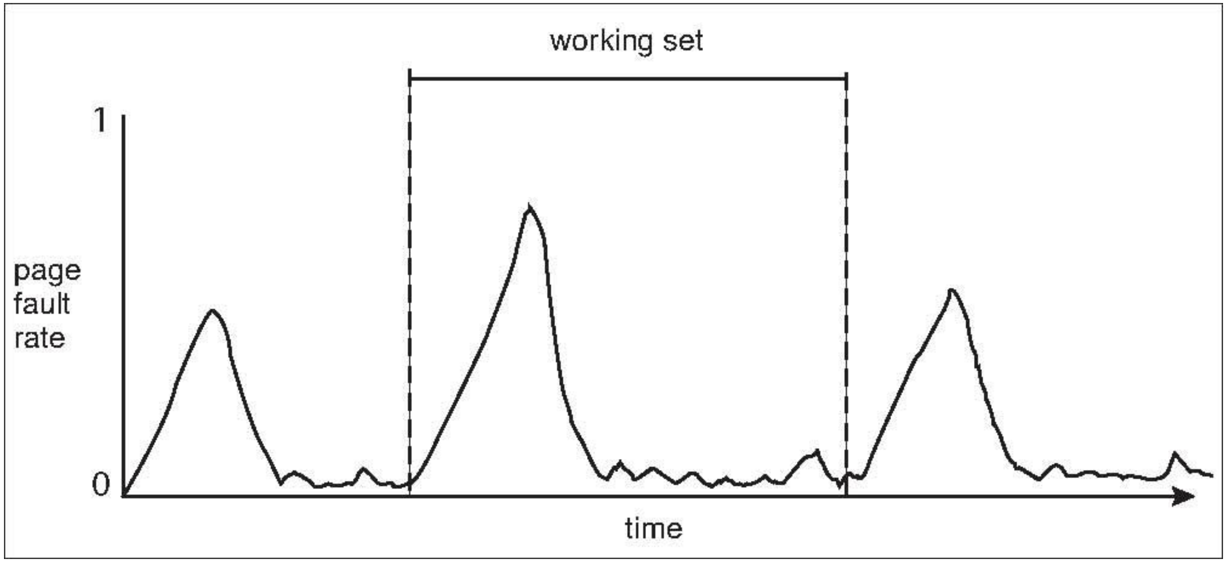
# Page-Fault Frequency Scheme

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



# Working Sets and Page Fault Rates

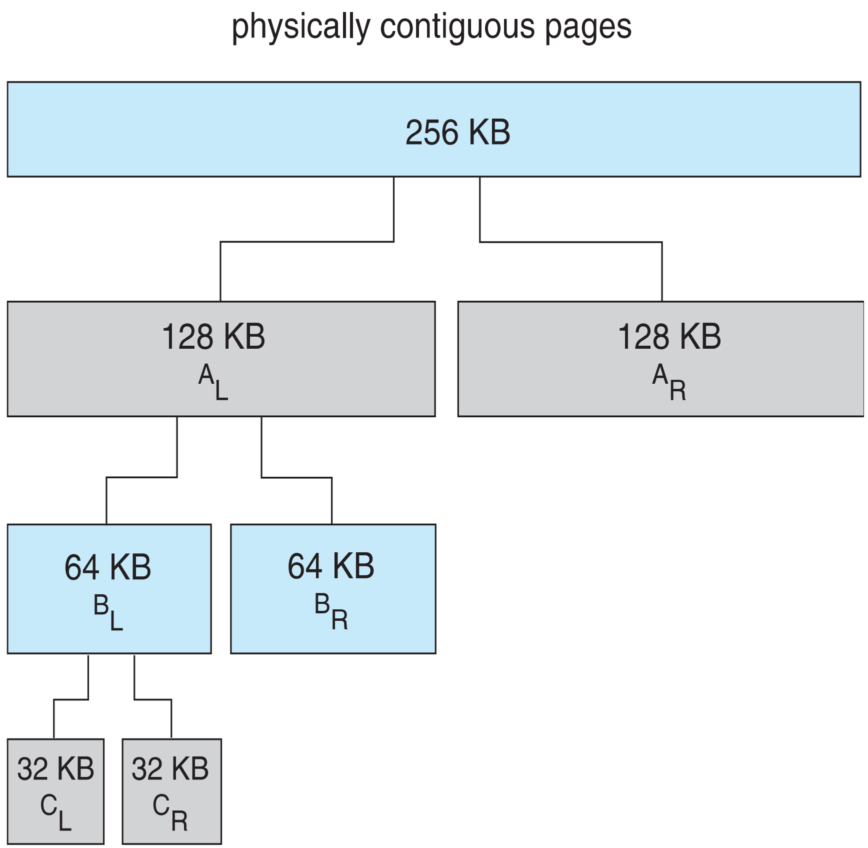
- Direct relationship between working set of a process and its page-fault rate
- Working set changes over time
- Peaks and valleys over time



# 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
- For example, assume 256KB chunk available, kernel requests 21KB
  - Split into $A_L$ and $A_R$ of 128KB each
    - One further divided into $B_L$ and $B_R$ of 64KB
      - One further into $C_L$ and $C_R$ of 32KB each – one used to satisfy request
- Advantage – quickly **coalesce** unused chunks into larger chunk
- Disadvantage - fragmentation

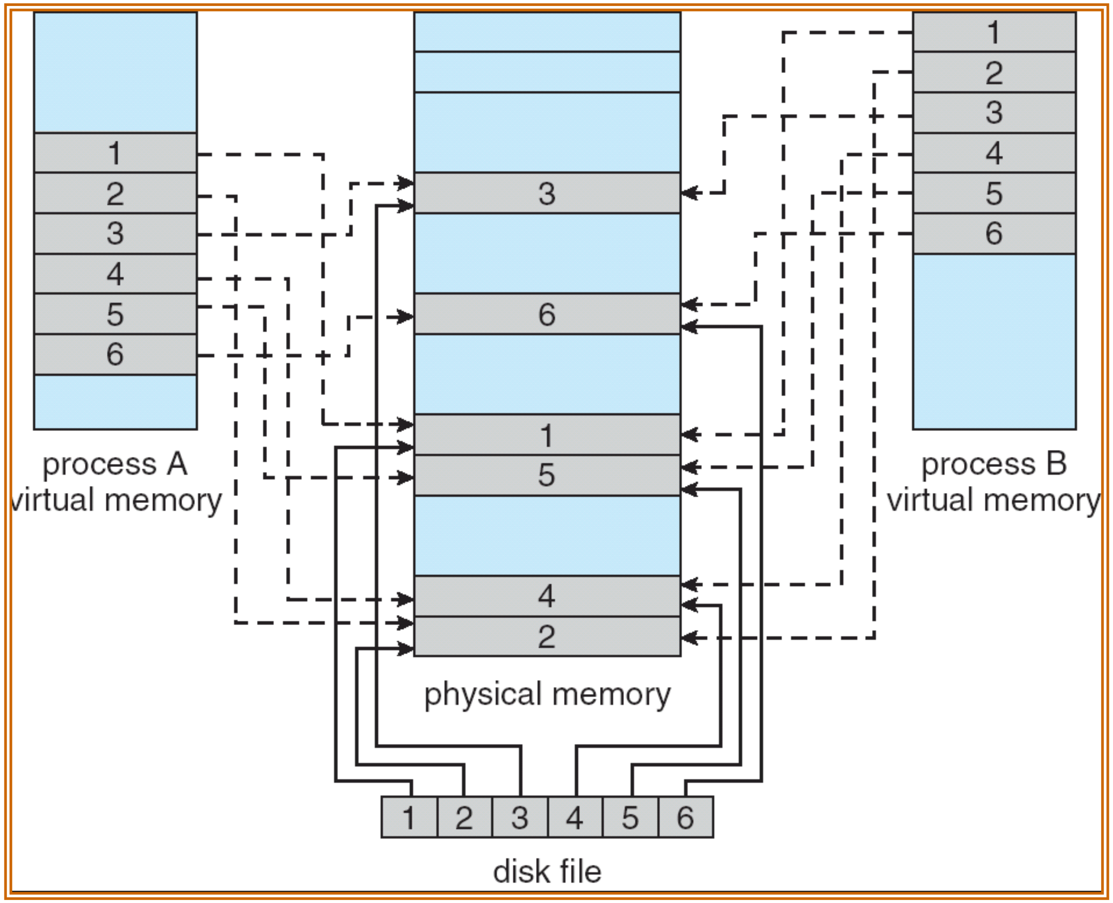
# Buddy System Allocator



# 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 $\alpha$ of the pages is used
    - Is cost of $s * \alpha$ save pages faults > or < than the cost of prepaging
      $s * (1- \alpha)$ unnecessary pages?
    - $\alpha$ 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;
```

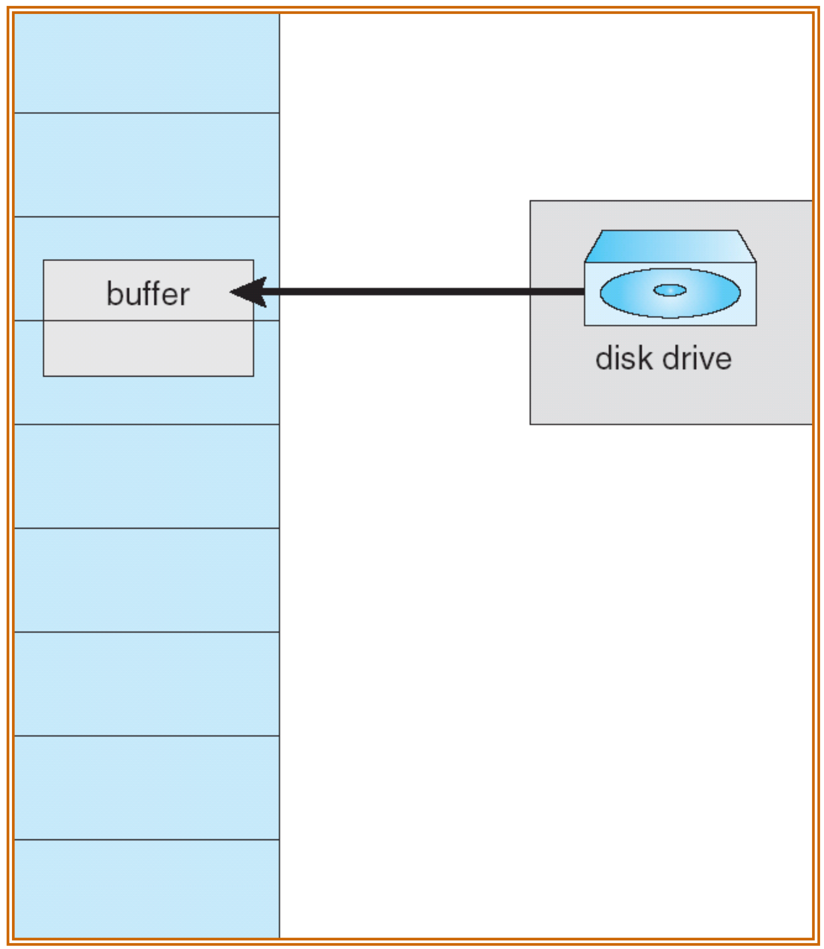
128 page faults

# 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
- 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