GMIT

INSTITIÚID TEICNEOLAÍOCHTA NA GAILLIMHE-MAIGH EO

GALWAY-MAYO INSTITUTE OF TECHNOLOGY

Operating Systems

Virtual Memory

Virtual Memory

- 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

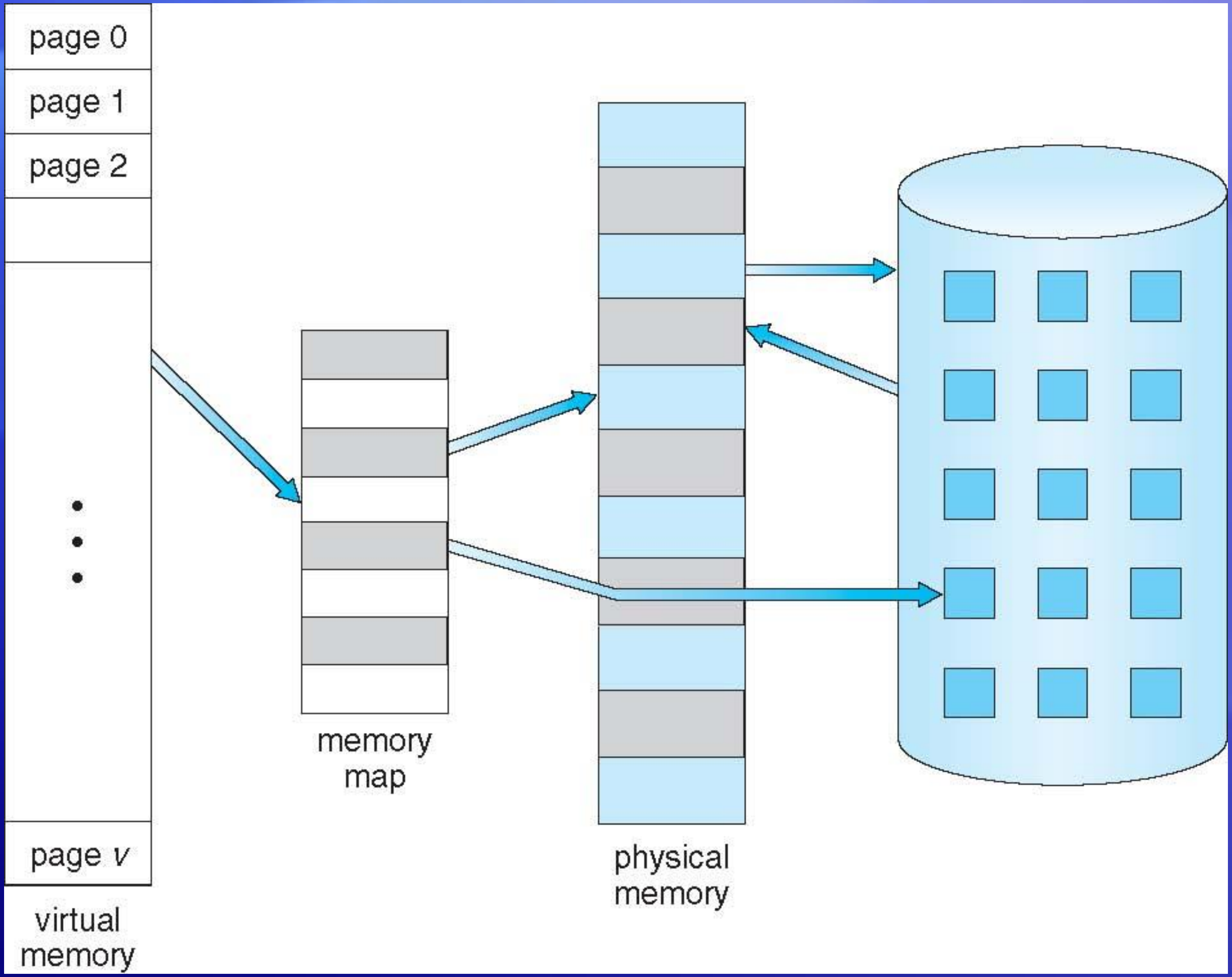
- Code needs to be in memory to execute, but entire program rarely used
    - Error code, unusual routines, large data structures
- Entire program code not needed at same time
- Consider ability to execute partially-loaded program
    - Program no longer constrained by limits of physical memory
    - Program and programs could be larger than physical memory

Background

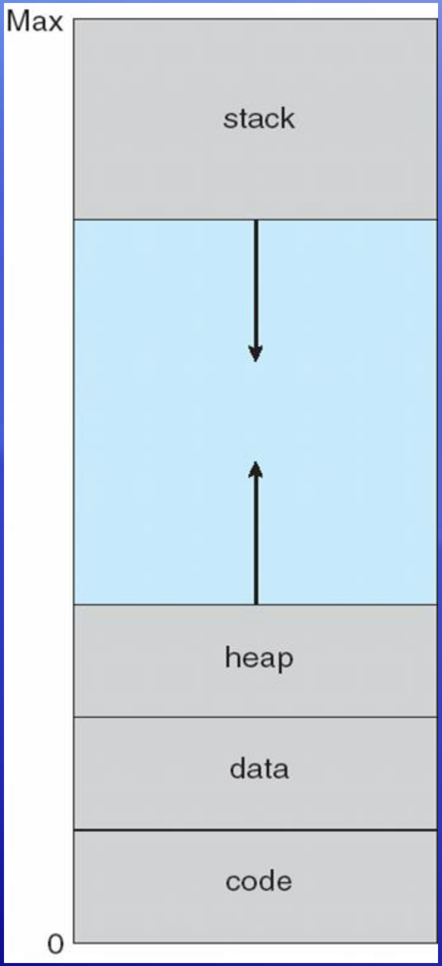
- **Virtual memory** – separation of user logical memory from physical memory
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation
  - More programs running concurrently
  - Less I/O needed to load or swap processes

- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

Virtual Memory That is Larger Than Physical Memory



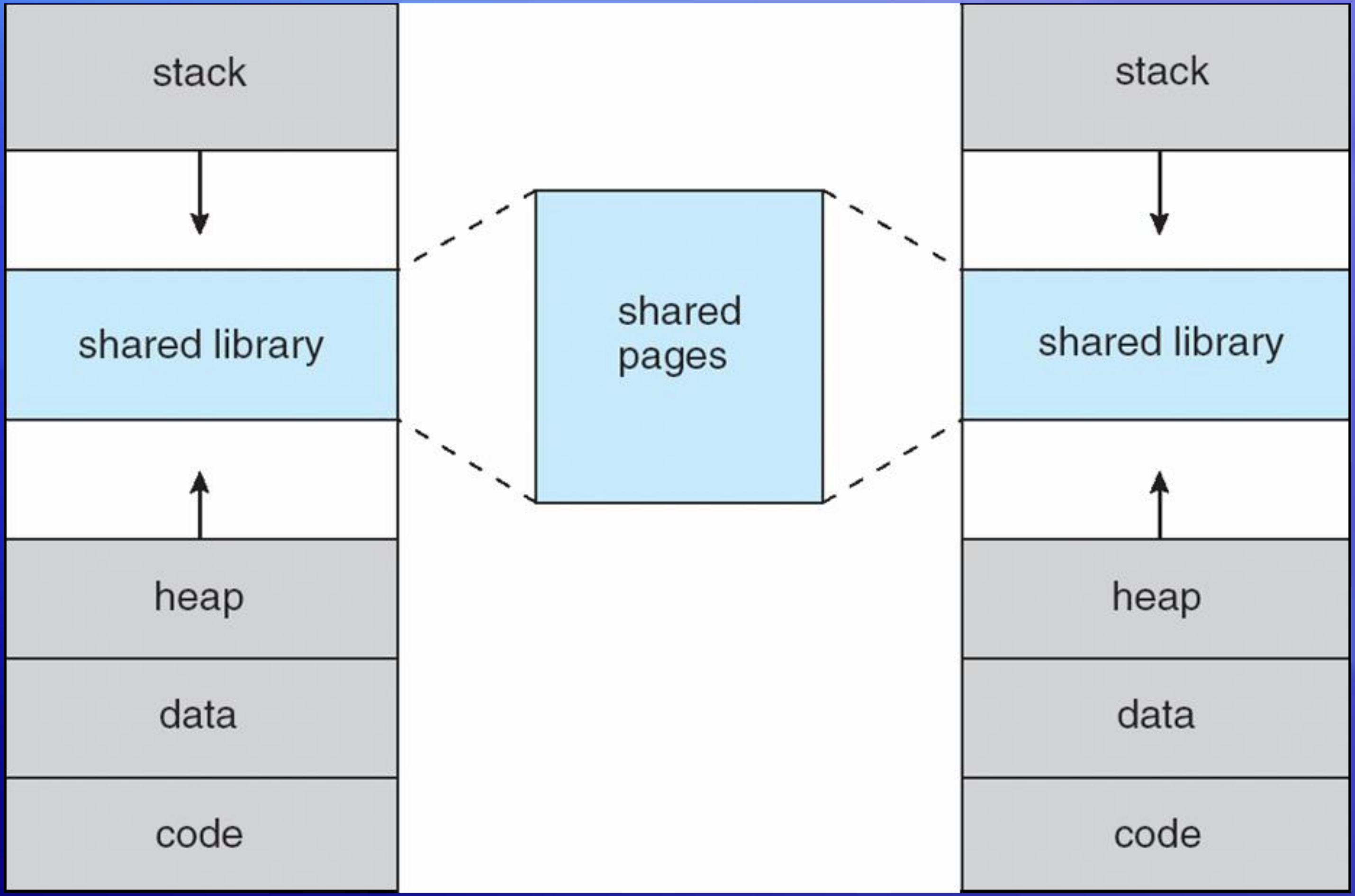
Virtual-address Space



Virtual Address Space

- Enables **sparse** address spaces with holes left for growth, dynamically linked libraries, etc
- System libraries shared via mapping into virtual address space
- Shared memory by mapping pages read-write into virtual address space
- Pages can be shared during `fork()`, speeding process creation

Shared Library Using Virtual Memory



Demand Paging

Could bring entire process into memory at load time

Or bring a page into memory only when it is needed

- Less I/O needed, no unnecessary I/O
- Less memory needed
- Faster response
- More users

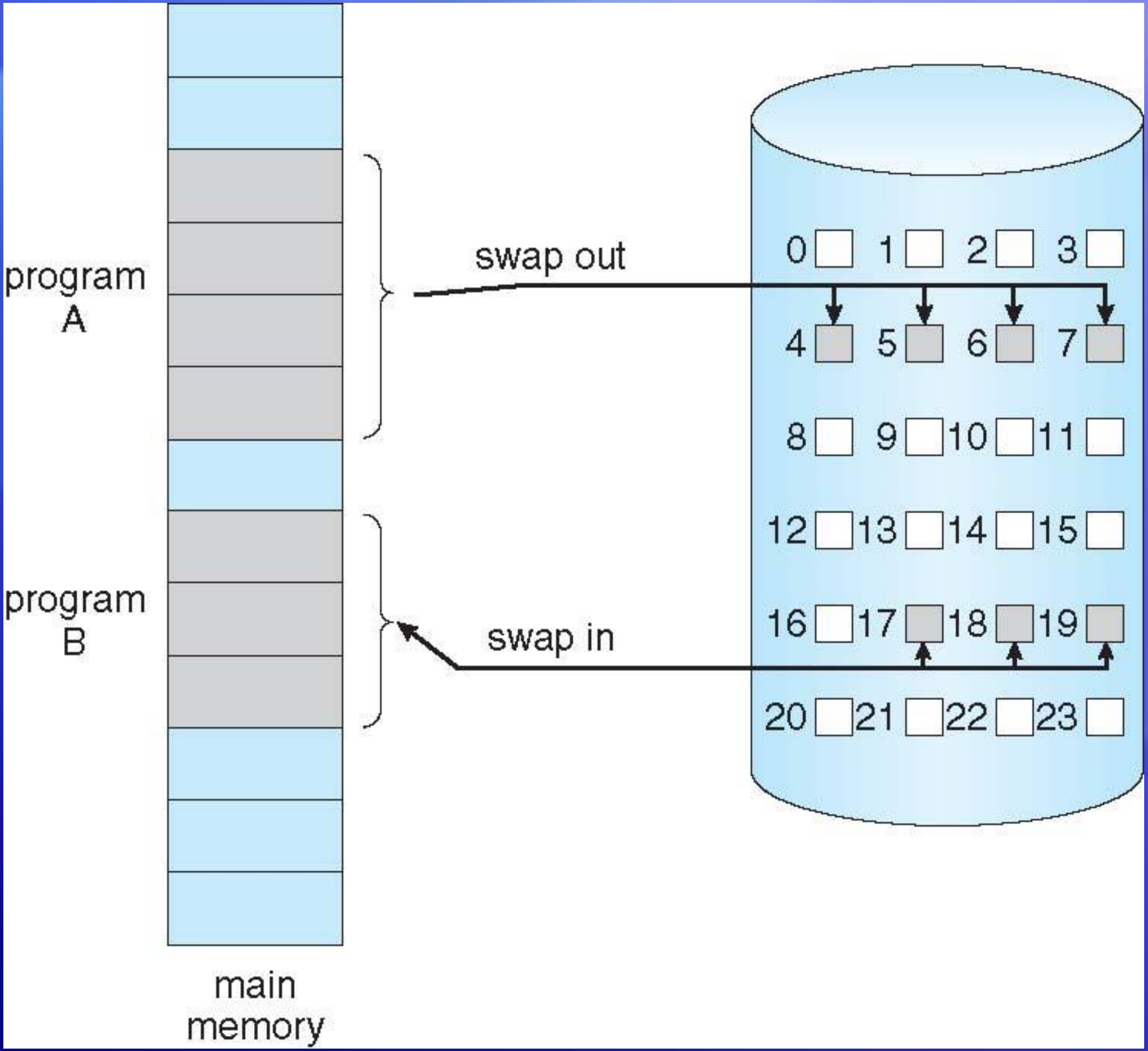
Page is needed ⇒ reference to it

- invalid reference ⇒ abort
- not-in-memory ⇒ 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

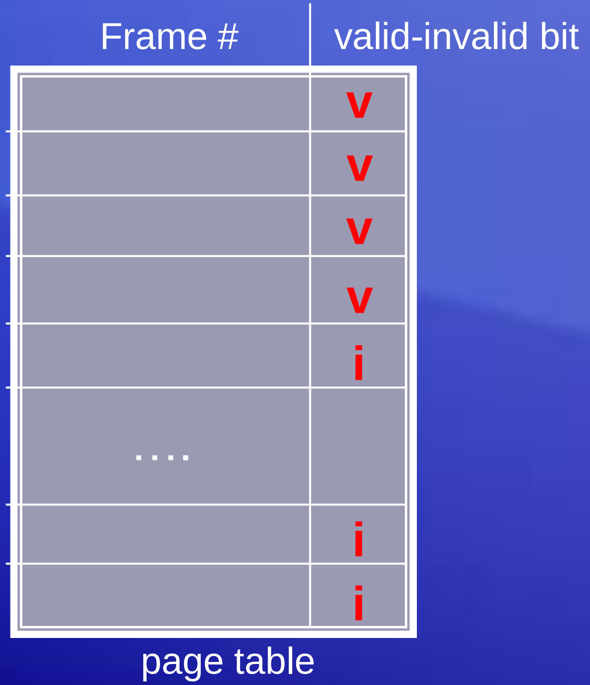


Valid-Invalid Bit

With each page table entry a valid–invalid bit is associated
(**v** ⇒ in-memory – **memory resident**, **i** ⇒ not-in-memory)

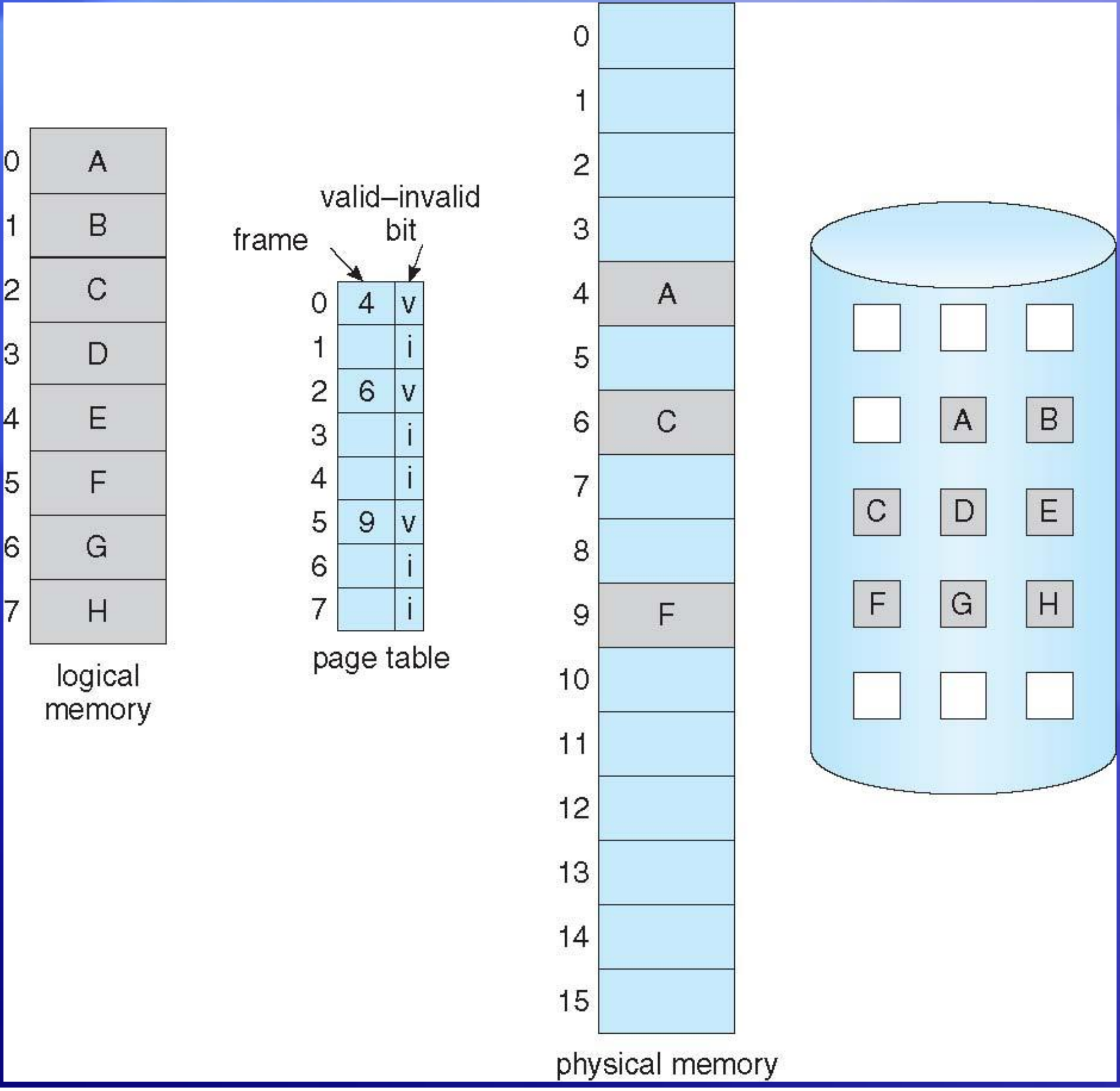
Initially valid–invalid bit is set to **i** on all entries

Example of a page table snapshot:



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

Operating system looks at another table to decide:

- Invalid reference $\Rightarrow$ abort
- Just not in memory

Get empty frame

Swap page into frame via scheduled disk operation

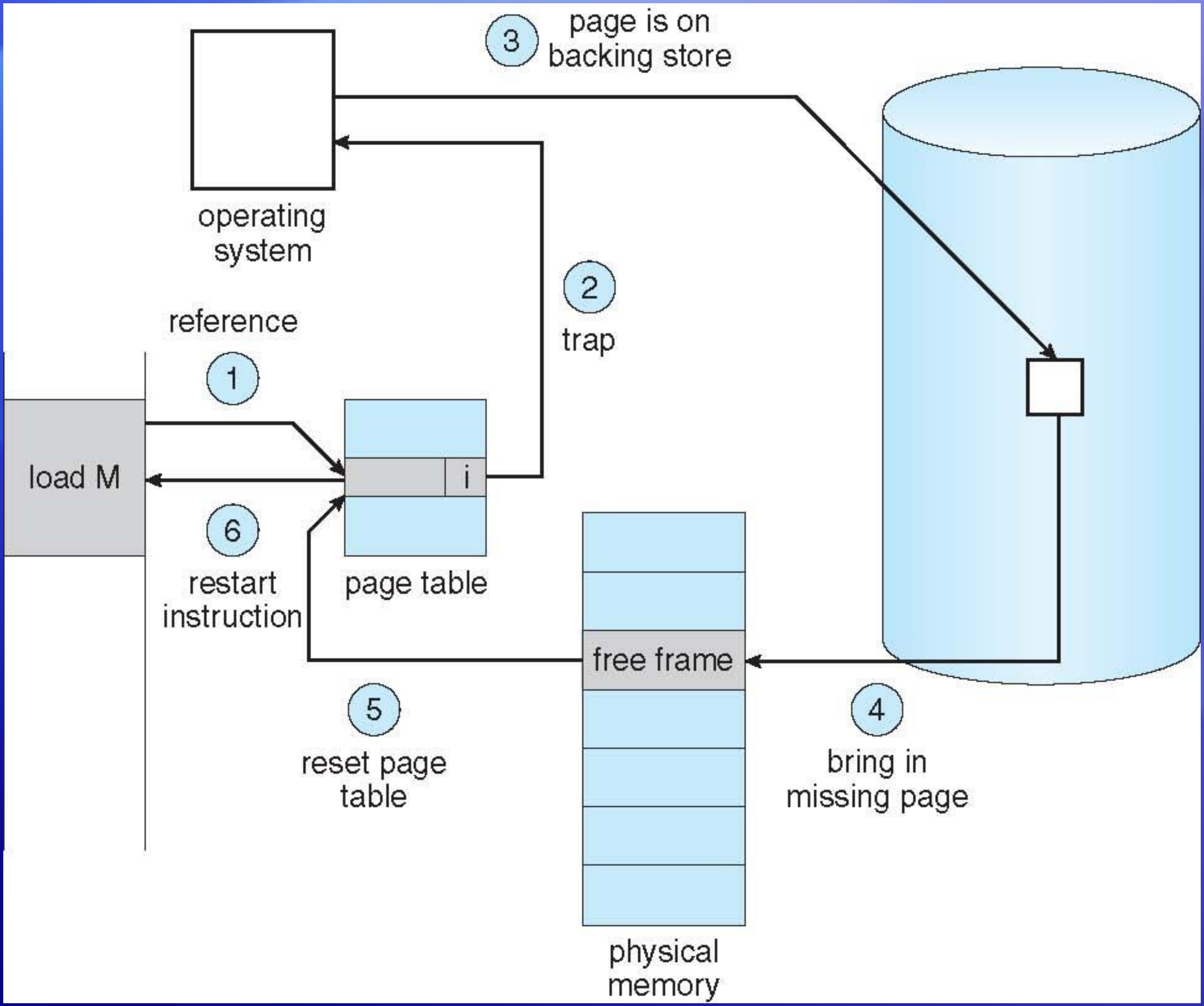
Reset tables to indicate page now in memory
Set validation bit = **v**

Restart the instruction that caused the page fault

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
  - 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

Steps in Handling a Page Fault



Performance of Demand Paging

Stages in Demand Paging

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 (Cont.)

Page Fault Rate $0 \le p \le 1$

  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

Copy entire process image to swap space at process load time

- Then page in and out of swap space
- Used in older BSD Unix

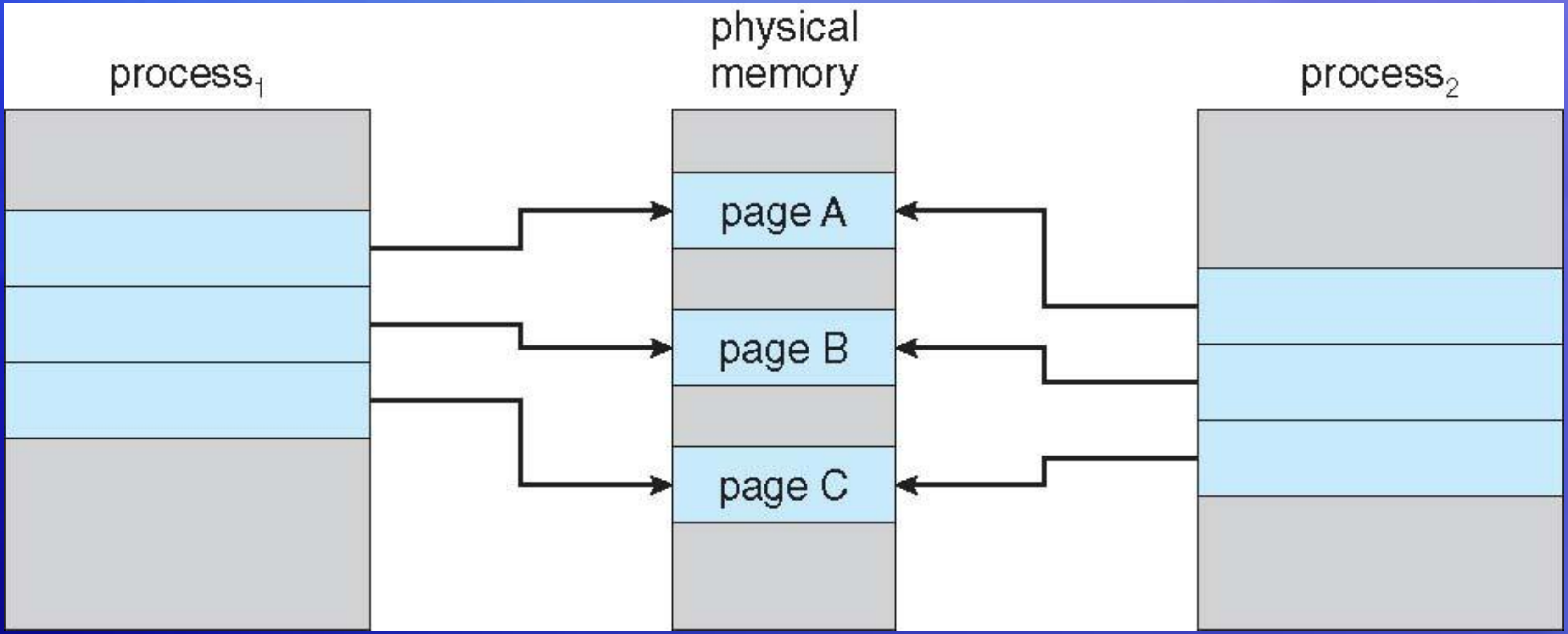
Demand page in from program binary on disk, but discard rather than paging out when freeing frame

- Used in Solaris and current BSD

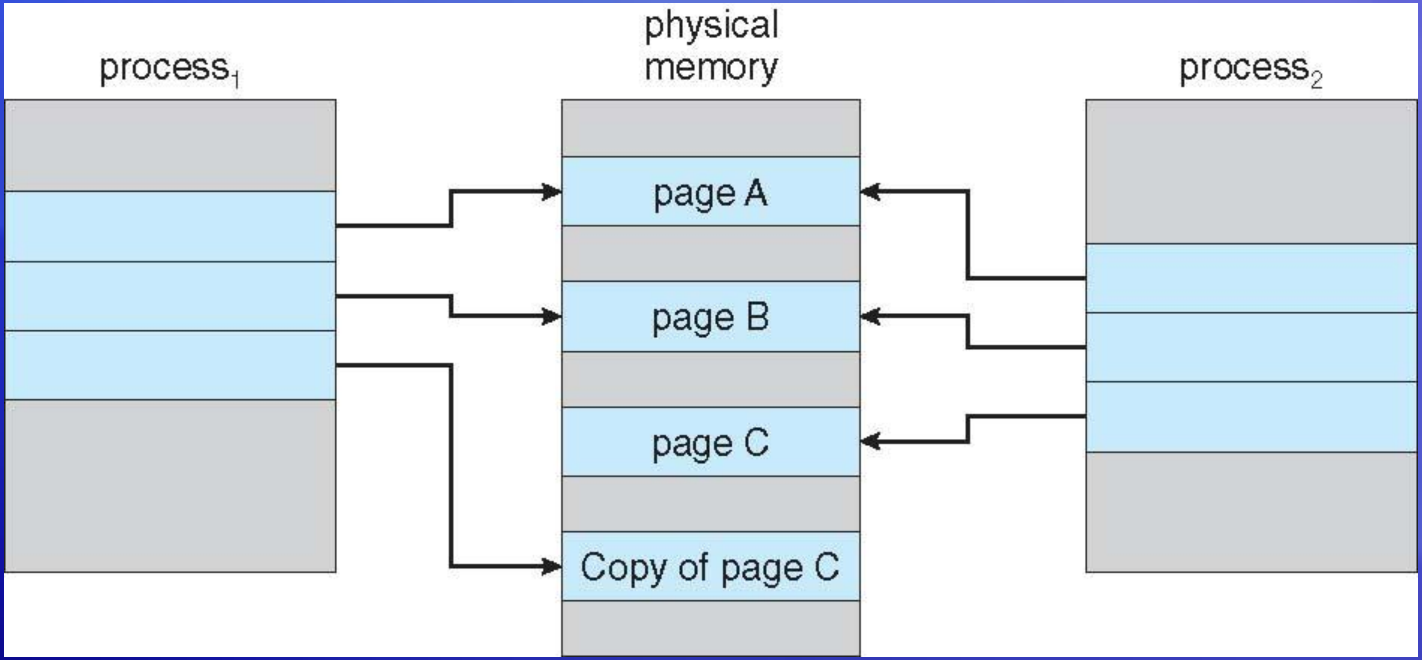
Copy-on-Write

- **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
  - 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

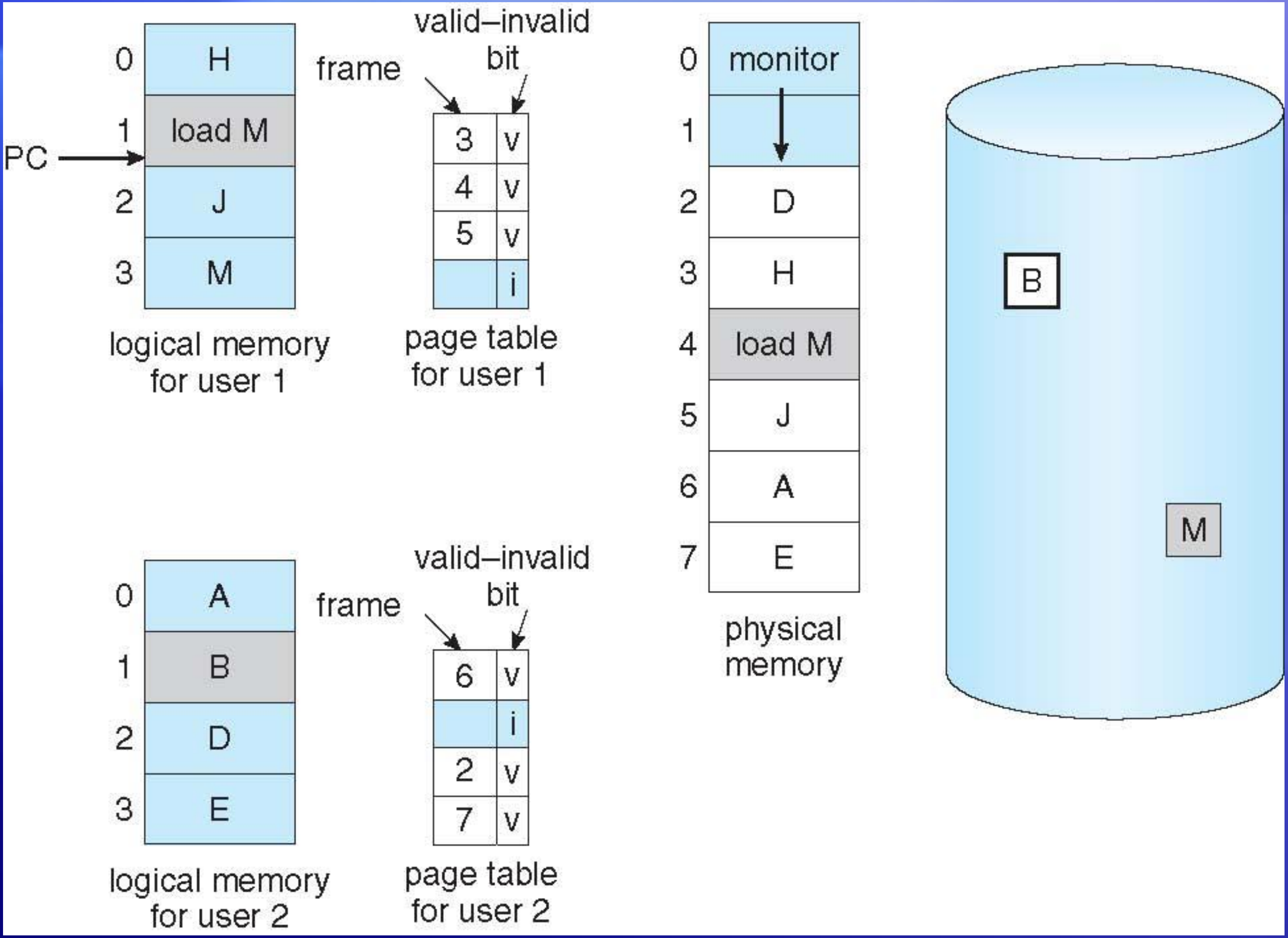
Page Replacement

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

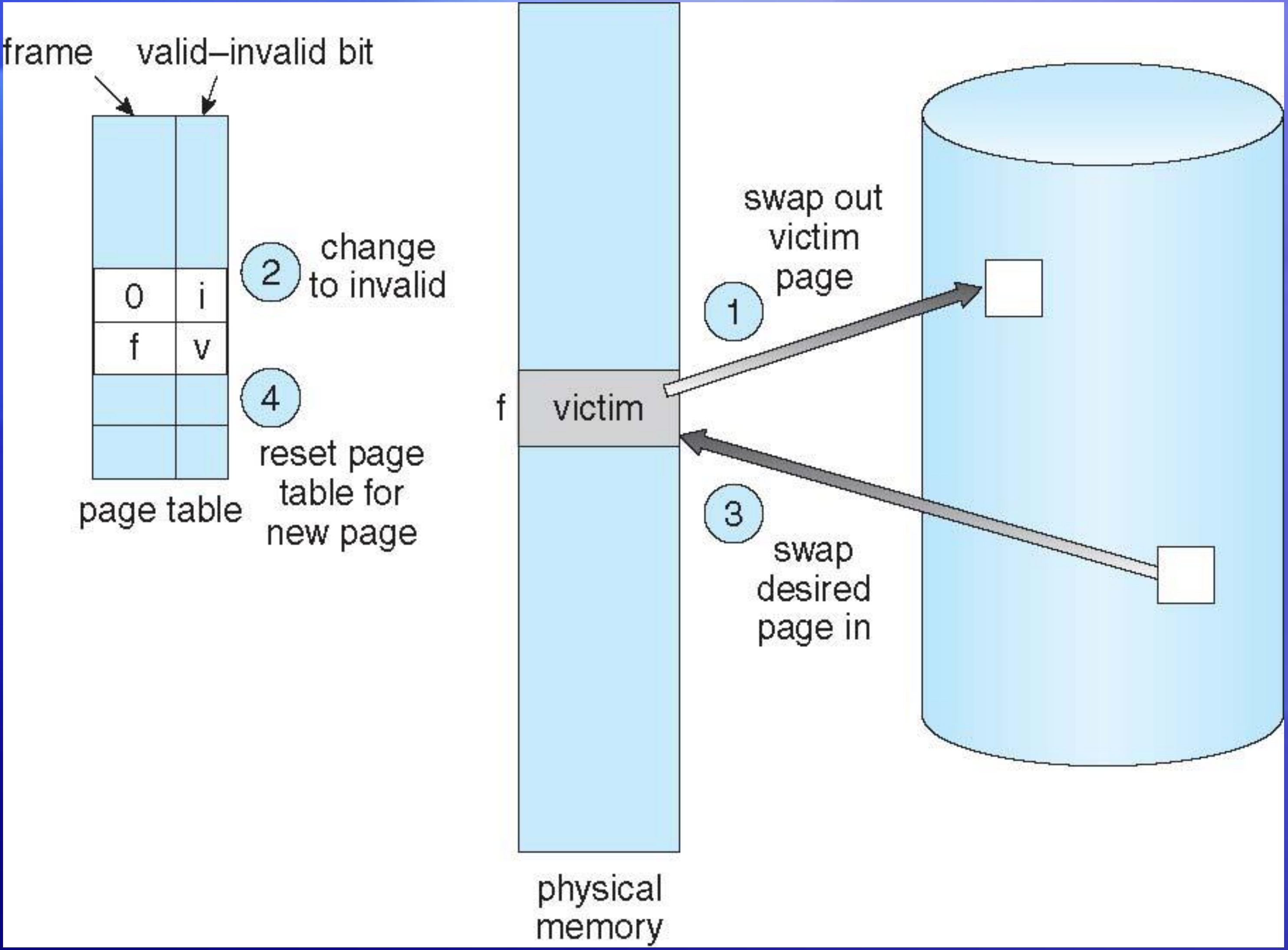
2. Find a free frame:
   - If there is a free frame, use it
   - If there is no free frame, use a page replacement algorithm to select a **victim frame**
     - Write victim frame to disk if dirty

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

4. Continue the process by restarting the instruction that caused the trap

Note now potentially 2 page transfers for page fault – increasing

Page Replacement



Page and Frame Replacement Algorithms

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

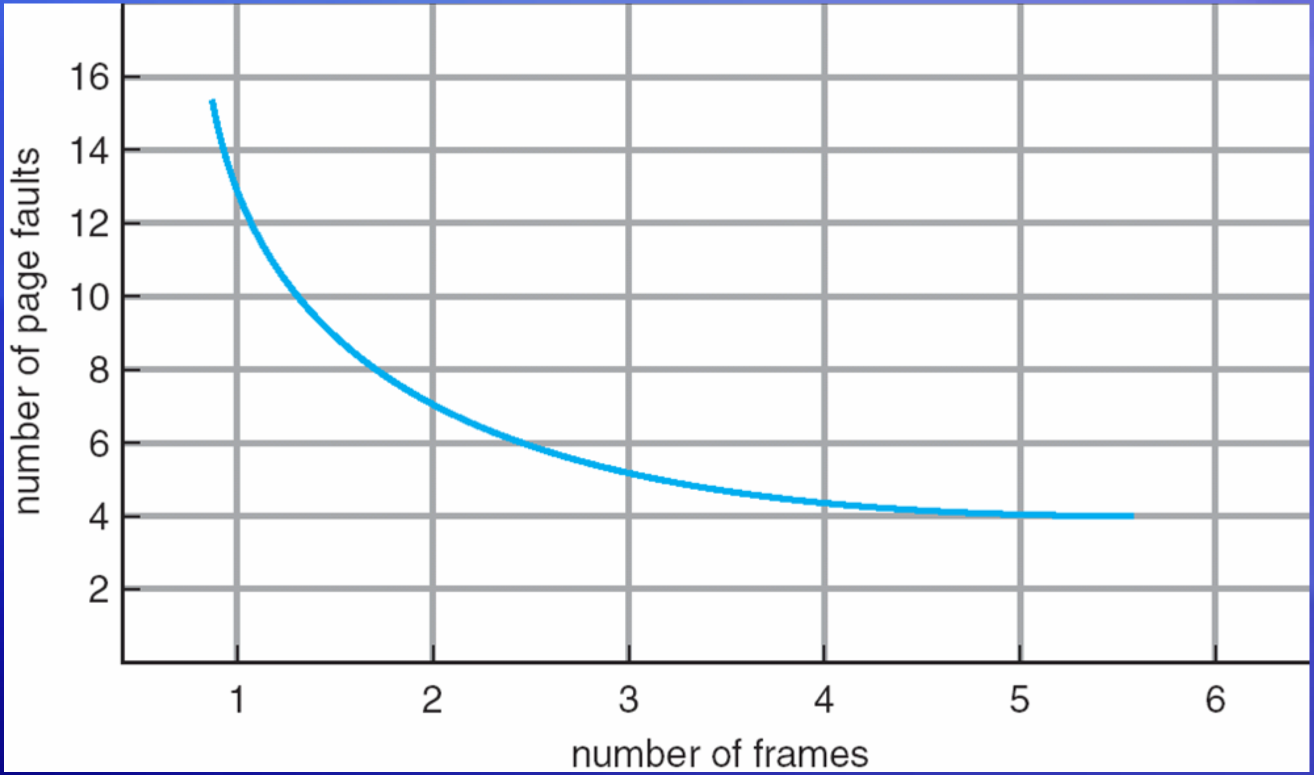
Page-replacement algorithm
- Want lowest page-fault rate on both first access and re-access

Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string
- String is just page numbers, not full addresses
- Repeated access to the same page does not cause a page fault

In all our examples, the reference string is

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

Graph of Page Faults Versus The Number of Frames



First-In-First-Out (FIFO) Algorithm

Reference string: **7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1**

3 frames (3 pages can be in memory at a time per process)

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

15 page faults

Can vary by reference string: consider 1,2,3,4,1,2,5,1,2,3,4,5

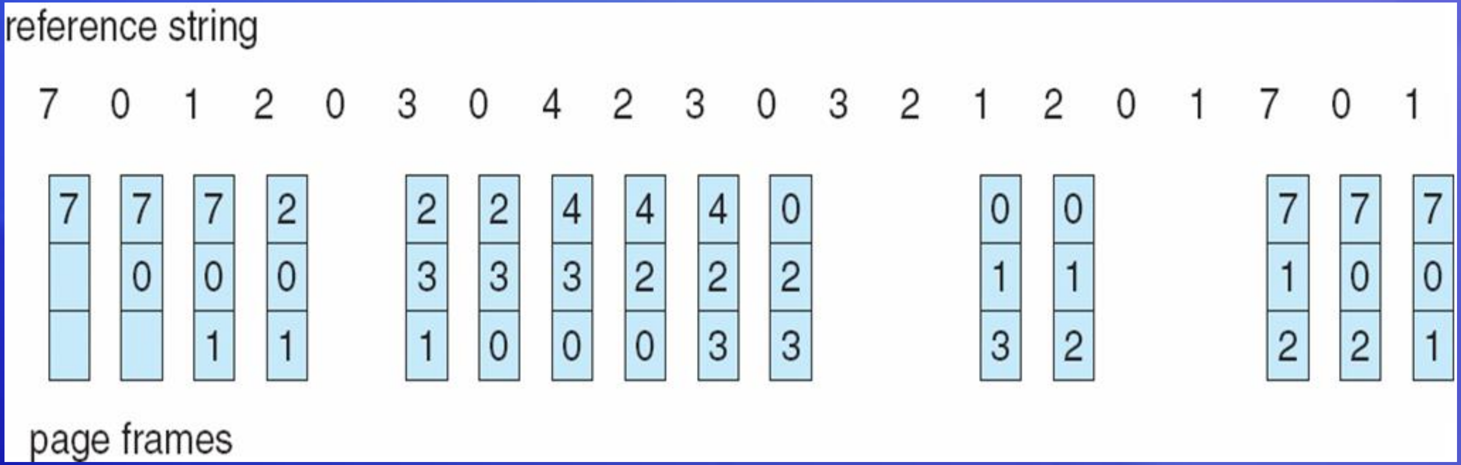
Adding more frames can cause more page faults!

Belady's Anomaly

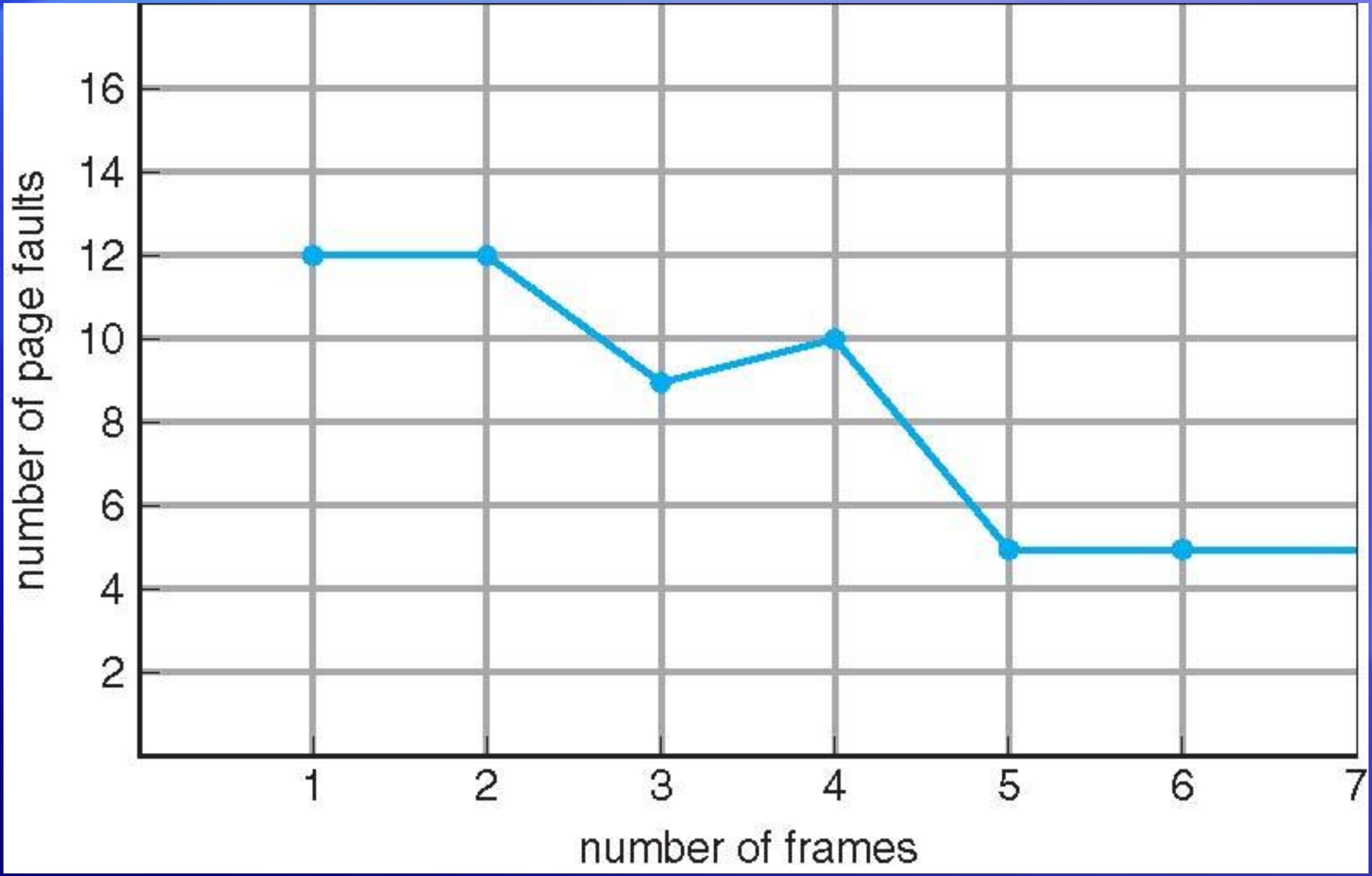
How to track ages of pages?

Just use a FIFO queue

FIFO Page Replacement



FIFO Illustrating Belady's Anomaly



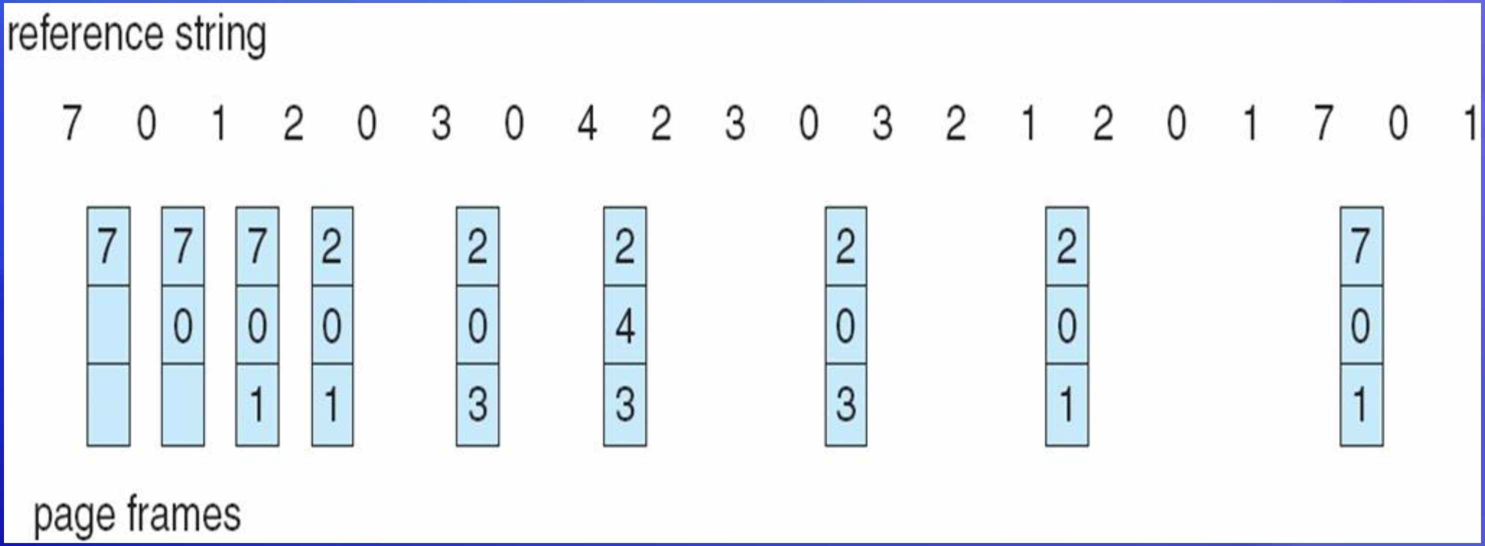
Optimal Algorithm

- Replace page that will not be used for longest period of time
  - 9 is optimal for the example on the next slide

- How do you know this?
  - Can’t read the future

- Used for measuring how well your algorithm performs

Optimal Page Replacement

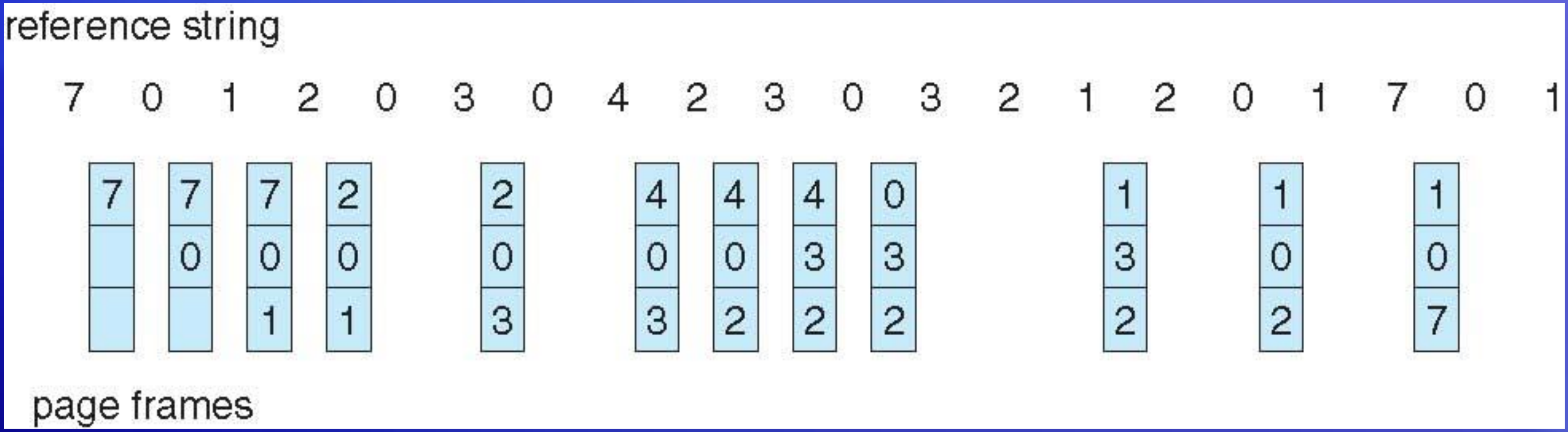


Least Recently Used (LRU) Algorithm

Use past knowledge rather than future

Replace page that has not been used in the most amount of time

Associate time of last use with each page



12 faults – better than FIFO but worse than OPT

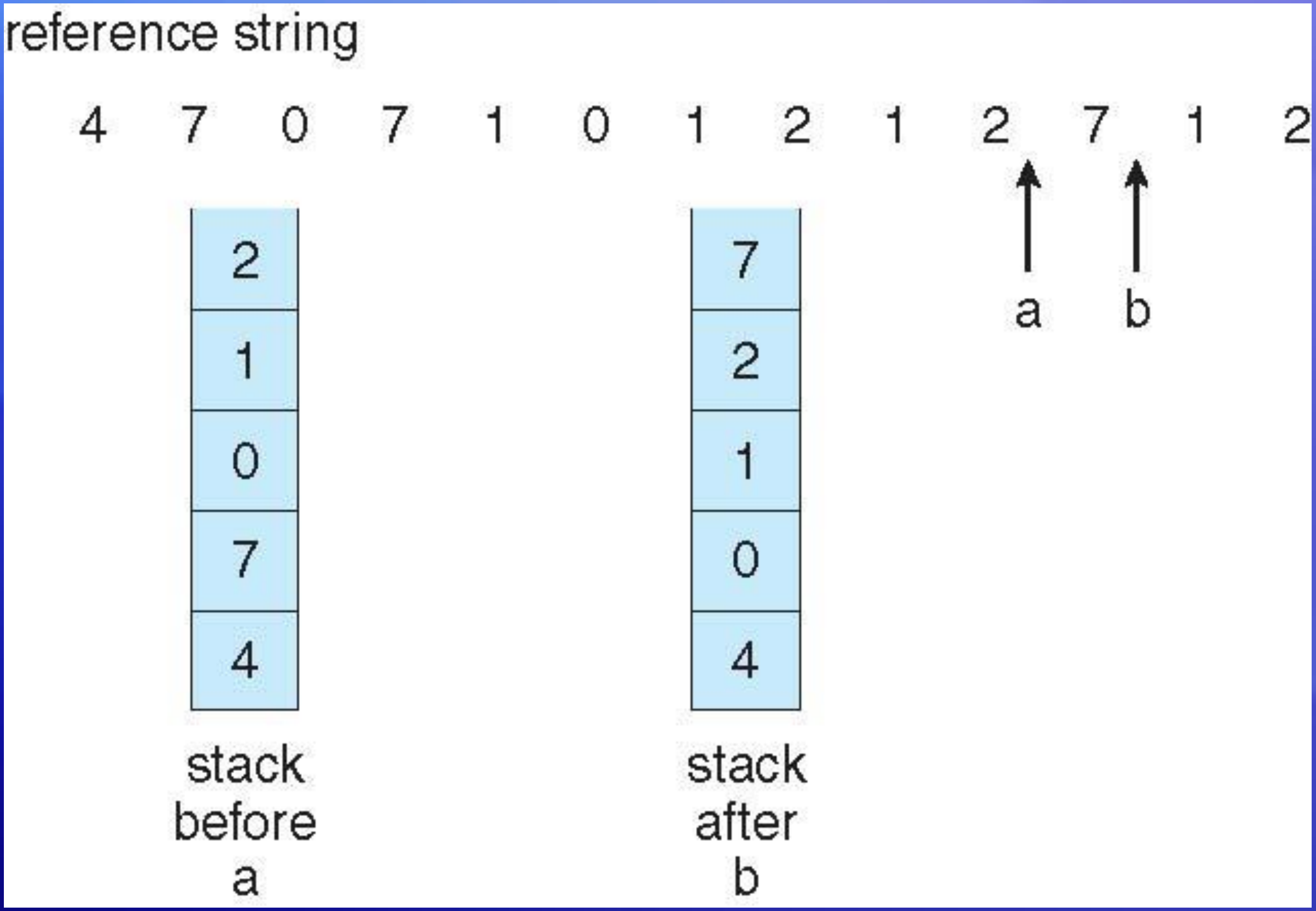
Generally good algorithm and frequently used

But how to implement?

LRU Algorithm (Cont.)

- 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 find smallest value
    - Search through table needed
- 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
  - But each update more expensive
  - No search for replacement
- LRU and OPT are cases of **stack algorithms** that don’t have Belady’s Anomaly

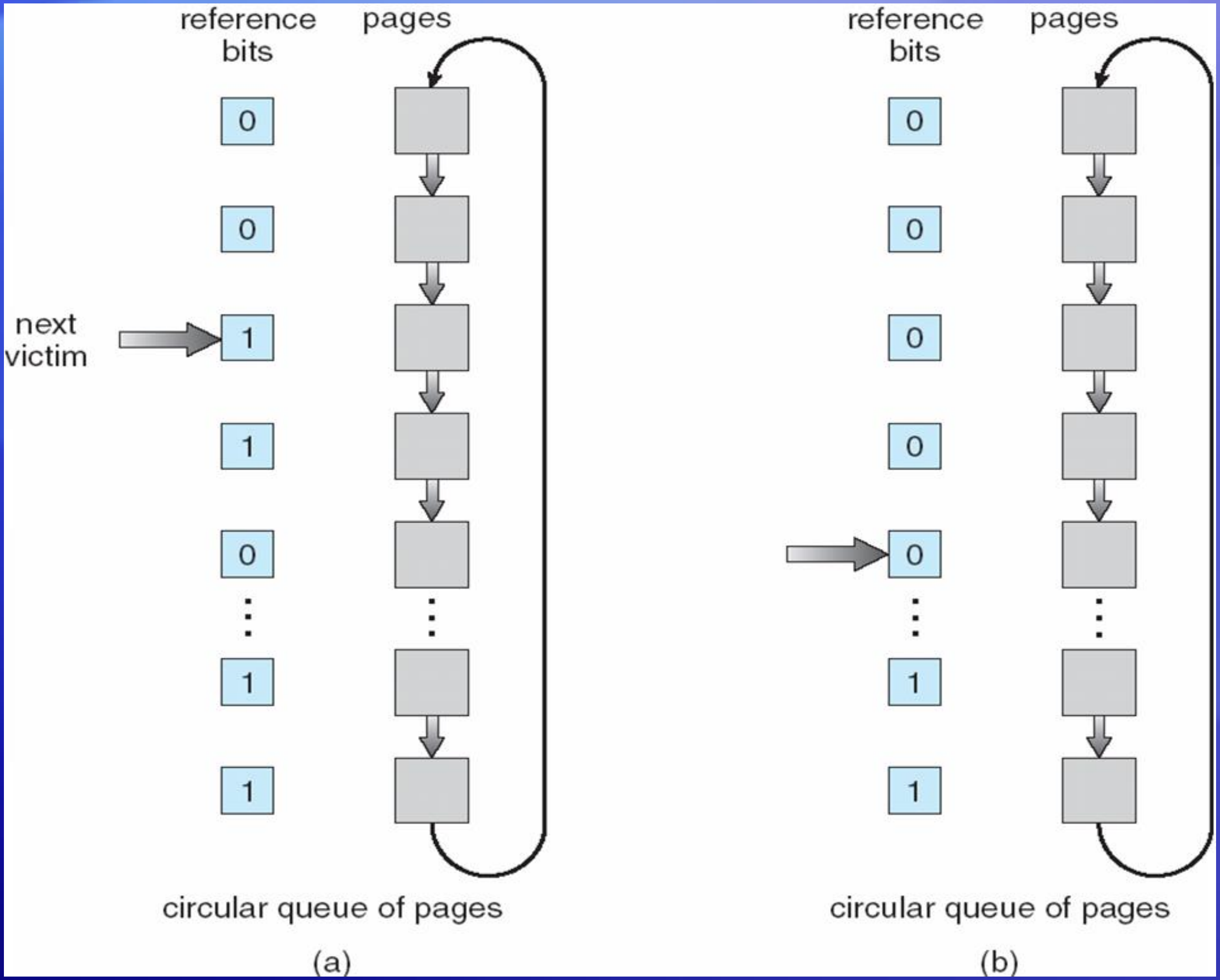
Use Of A Stack to Record The Most Recent Page References



LRU Approximation Algorithms

- LRU needs special hardware and still slow
- **Reference bit**
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - Replace any with reference bit = 0 (if one exists)
    - We do not know the order, however
- **Second-chance algorithm**
  - Generally FIFO, plus hardware-provided reference bit
  - Clock replacement
  - If page to be replaced has
    - Reference bit = 0 -> replace it
    - reference bit = 1 then:
      - set reference bit 0, leave page in memory
      - replace next page, 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

- Not common

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 frames
- 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*
- *Maximum* of course is total frames in the system
- Two major allocation schemes
  - fixed allocation
  - priority allocation
- Many variations

Fixed Allocation

- Equal allocation – For example, if there are 100 frames (after allocating frames for the OS) and 5 processes, give each process 20 frames
  - Keep some as free frame buffer pool
- Proportional allocation – Allocate according to the size of process
  - Dynamic as degree of multiprogramming, process sizes change
    - $s_i = \text{size of process } p_i$

      $S = \sum s_i$
    - $m = \text{total number of frames}$

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

$$m = 64$$
$$s_1 = 10$$
$$s_2 = 127$$
$$a_1 = \frac{10}{137} \times 64 \approx 5$$
$$a_2 = \frac{127}{137} \times 64 \approx 59$$

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

- But then process execution time can vary greatly
- But greater throughput so more common

Local replacement – each process selects from only its own set of allocated frames

- More consistent per-process performance
- But possibly underutilized memory

Non-Uniform Memory Access

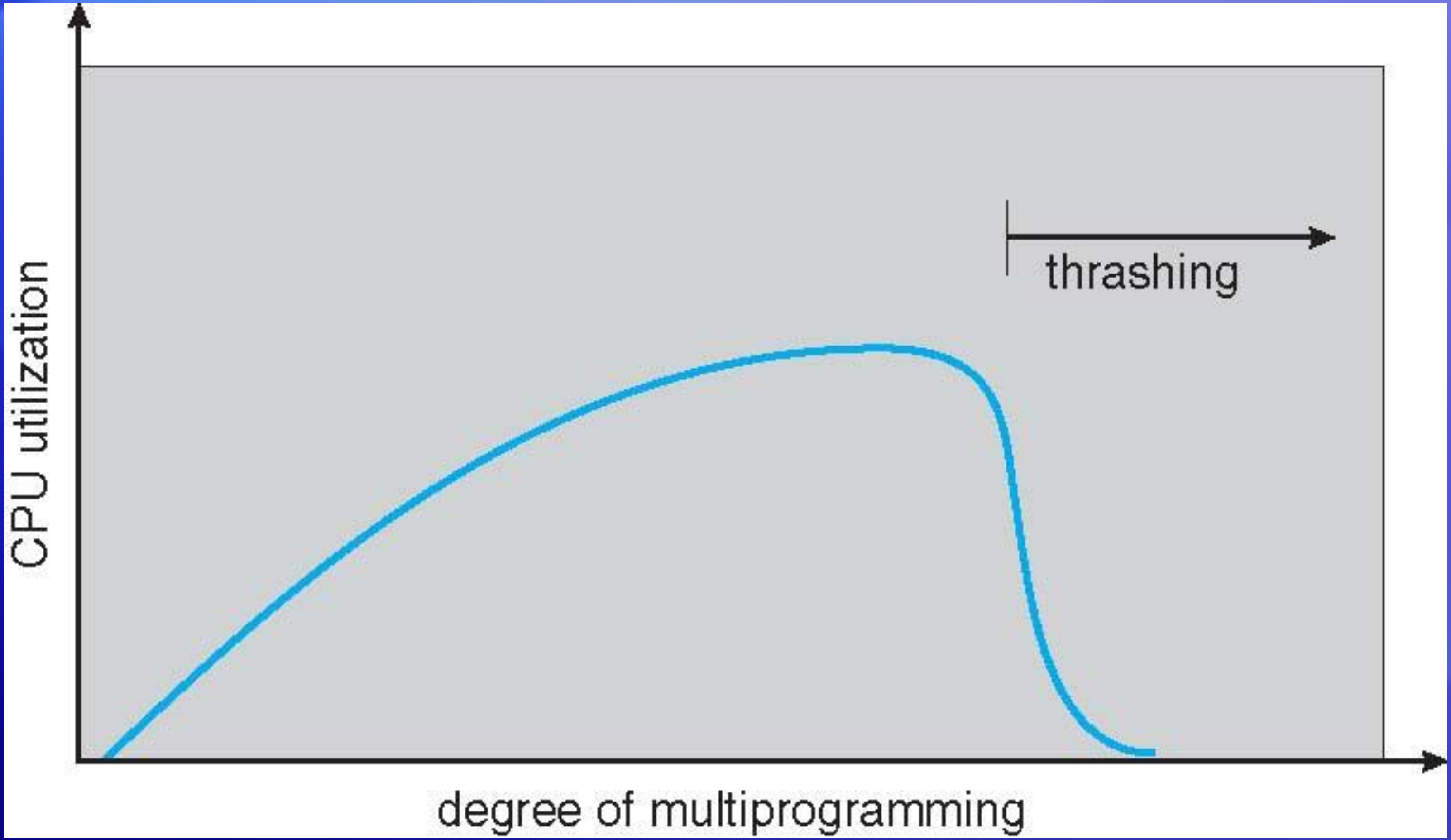
- So far all memory accessed equally
- Many systems are NUMA – speed of access to memory varies
  - Consider system boards containing CPUs and memory, interconnected over a system bus
- Optimal performance comes from allocating memory "close to" the CPU on which the thread is scheduled
  - And modifying 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
  - Page fault to get page
  - Replace existing frame
  - But quickly need replaced frame back
  - This leads to:
    - Low CPU utilization
    - Operating system thinking 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

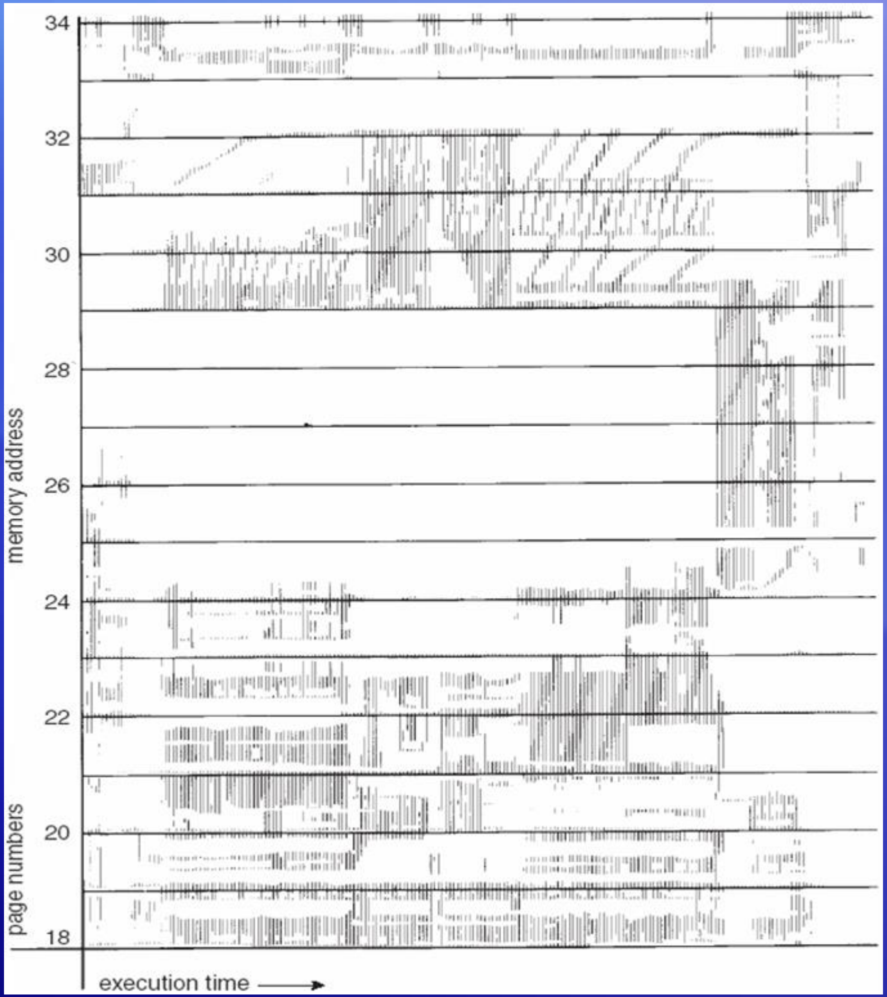
Why does demand paging work?

- **Locality model**
  - Process migrates from one locality to another
  - Localities may overlap

Why does thrashing occur?

- Σ size of locality > total memory size
  - Limit effects by using local or priority page replacement

Locality In A Memory-Reference Pattern



Working-Set Model

$\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
Example: 10,000 instructions

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

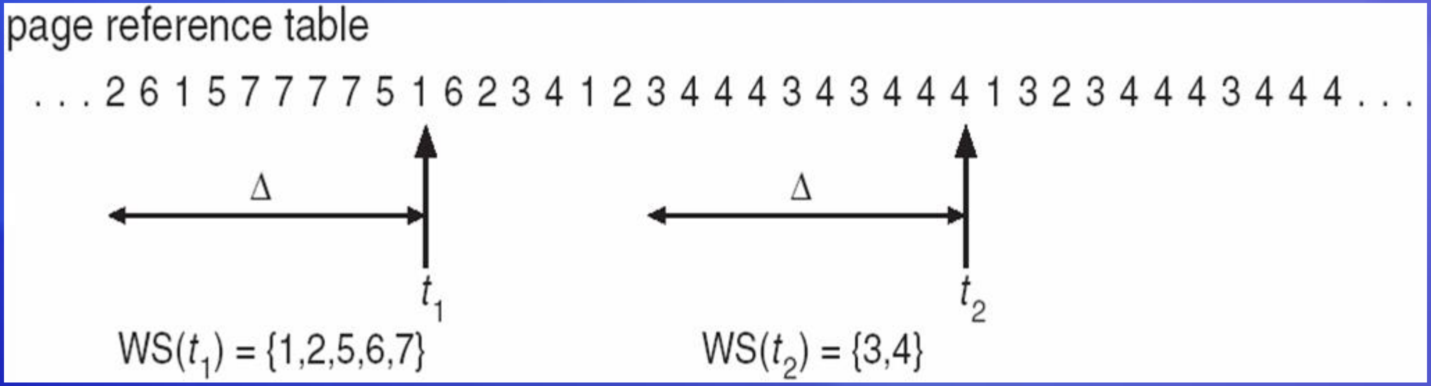
$D = \Sigma\, WSS_i \equiv$ total demand frames

Approximation of locality

if $D > m \Rightarrow$ Thrashing

Policy if D > m, then suspend or swap out one of the processes

Working-set model



Keeping Track of the Working Set

Approximate with interval timer + a reference bit

Example: $\Delta = 10{,}000$

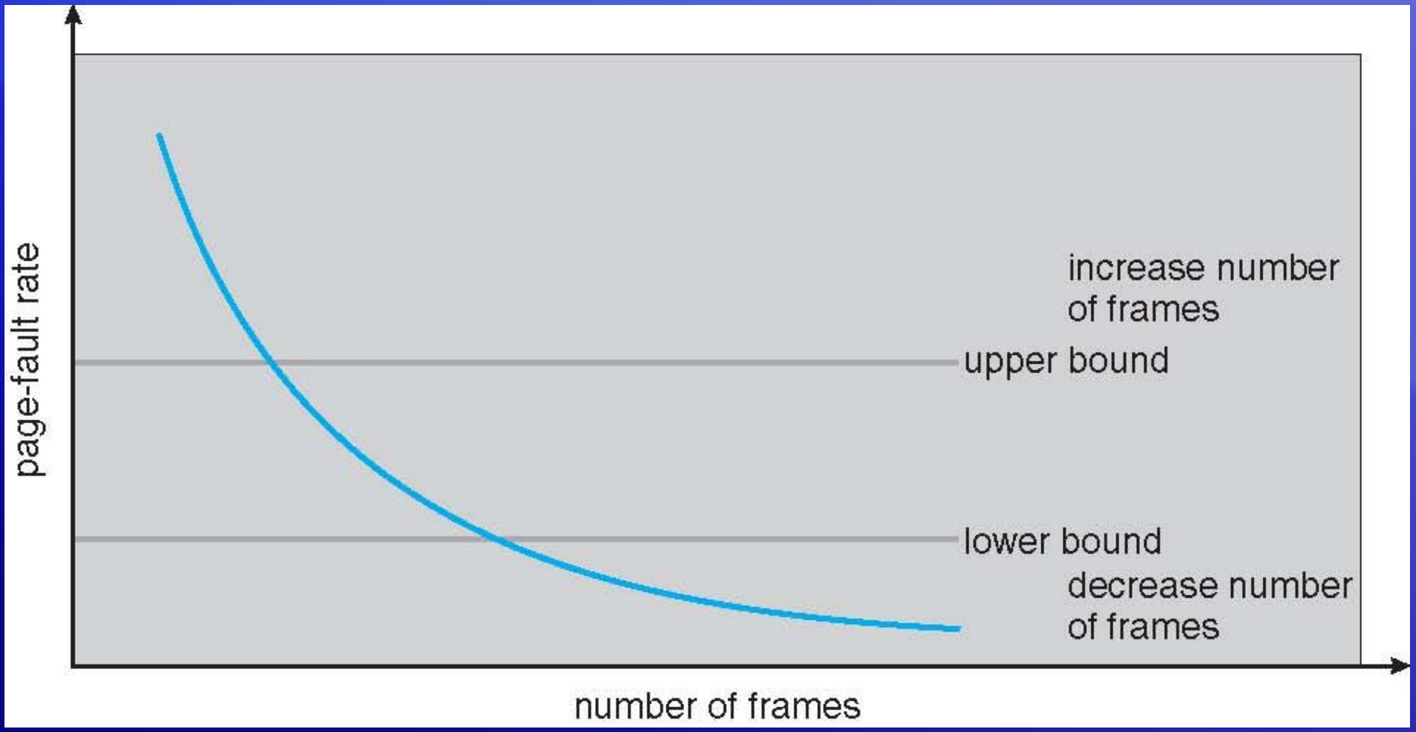
- Timer interrupts after every 5000 time units
- Keep in memory 2 bits for each page
- Whenever a timer interrupts copy and sets the values of all reference bits to 0
- If one of the bits in memory = 1 $\Rightarrow$ page in working set

Why is this not completely accurate?

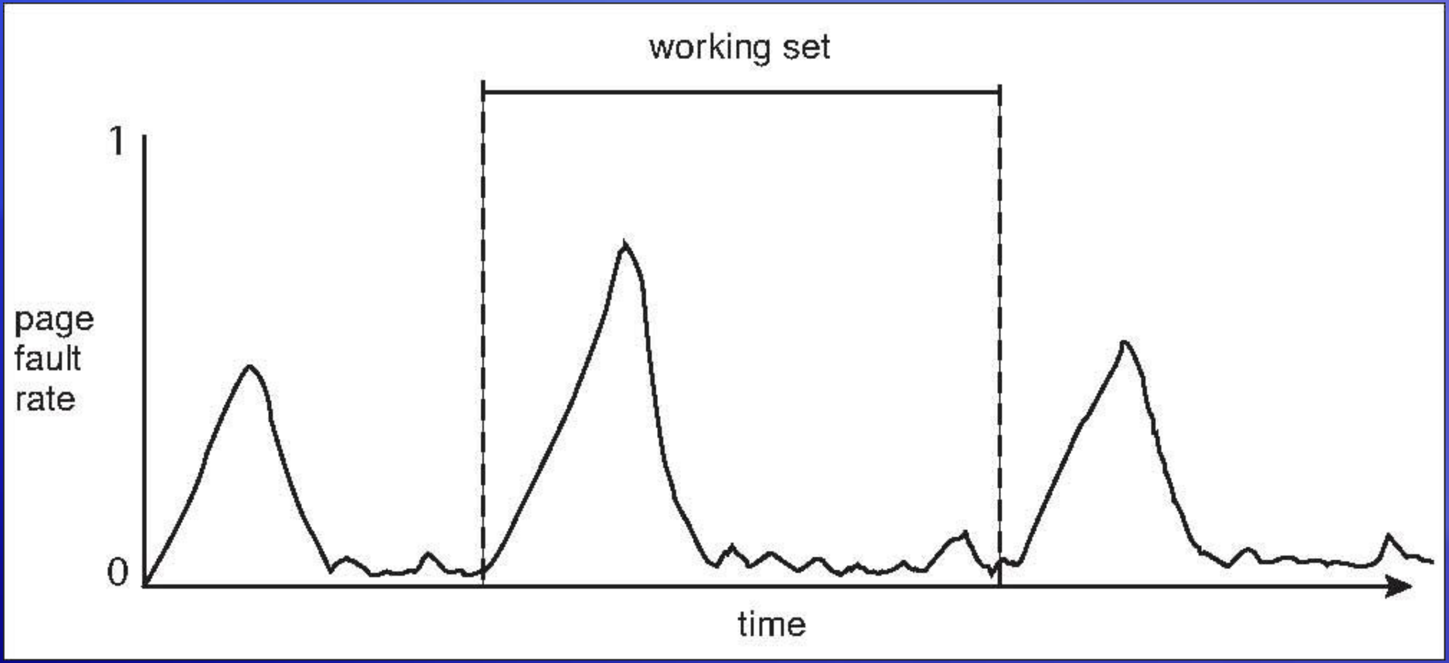
Improvement = 10 bits and interrupt every 1000 time units

Page-Fault Frequency

- More direct approach than WSS
- Establish “acceptable” **page-fault frequency** rate and use local replacement policy
  - If actual rate too low, process loses frame
  - If actual rate too high, process gains frame



Working Sets and Page Fault Rates



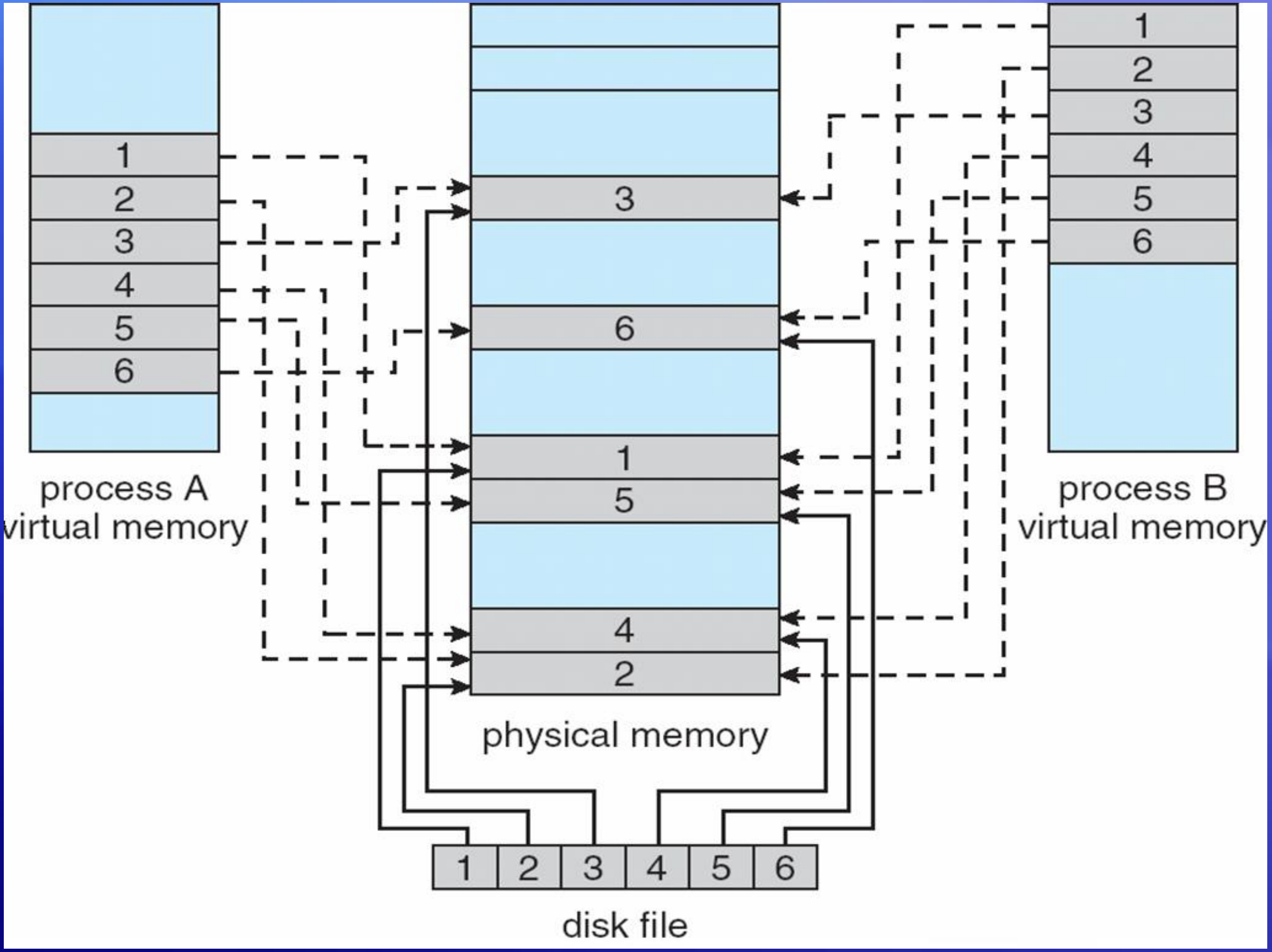
Memory-Mapped Files

- 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 and speeds file access by driving file I/O through memory rather than `read()` and `write()` system calls
- Also allows several processes to map the same file allowing the pages in memory to be shared
- But when does written data make it to disk?
  - Periodically and / or at file `close()` time
  - For example, when the pager scans for dirty pages

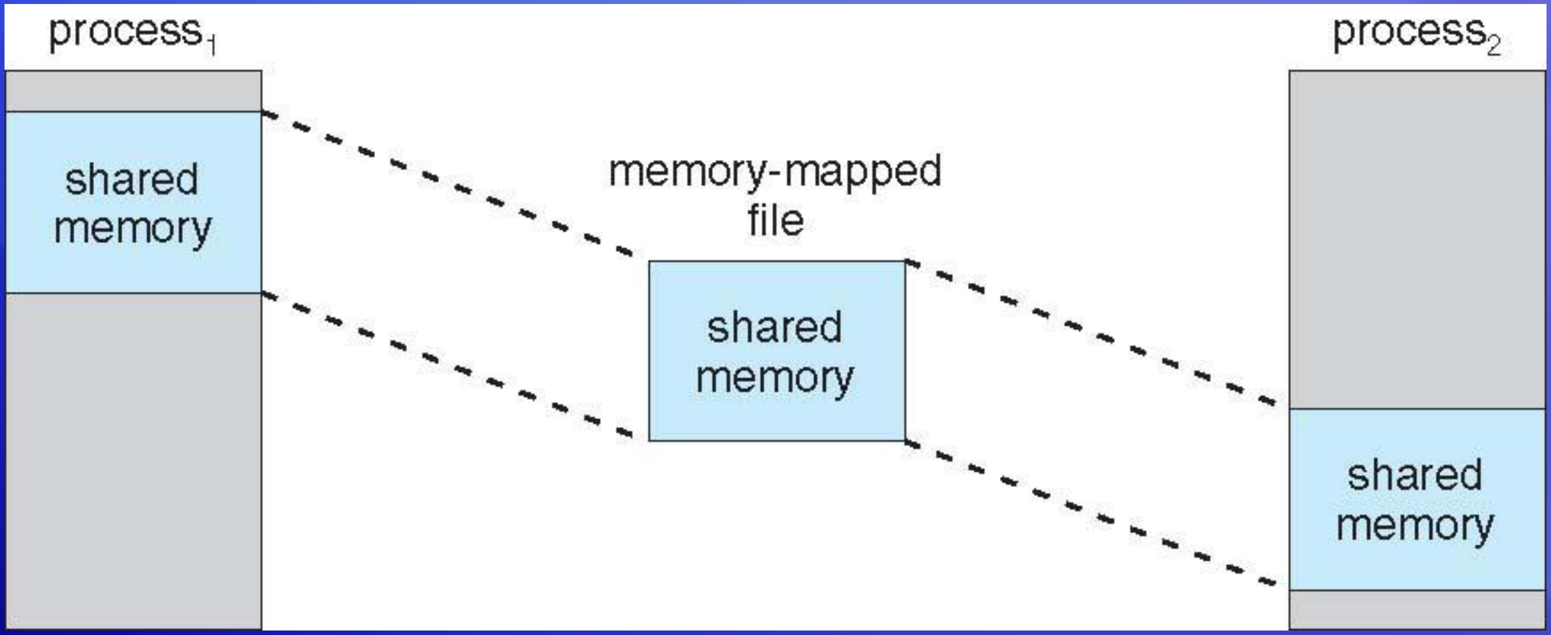
Memory-Mapped File Technique for all I/O

- Some OSes uses memory mapped files for standard I/O
- Process can explicitly request memory mapping a file via `mmap()` system call
  - Now file mapped into process address space
- For standard I/O (`open()`, `read()`, `write()`, `close()`), mmap anyway
  - But map file into kernel address space
  - Process still does read() and write()
    - Copies data to and from kernel space and user space
  - Uses efficient memory management subsystem
    - Avoids needing separate subsystem
- COW can be used for read/write non-shared pages
- Memory mapped files can be used for shared memory (although again via separate system calls)

Memory Mapped Files



Memory-Mapped Shared Memory in Windows



Allocating Kernel Memory

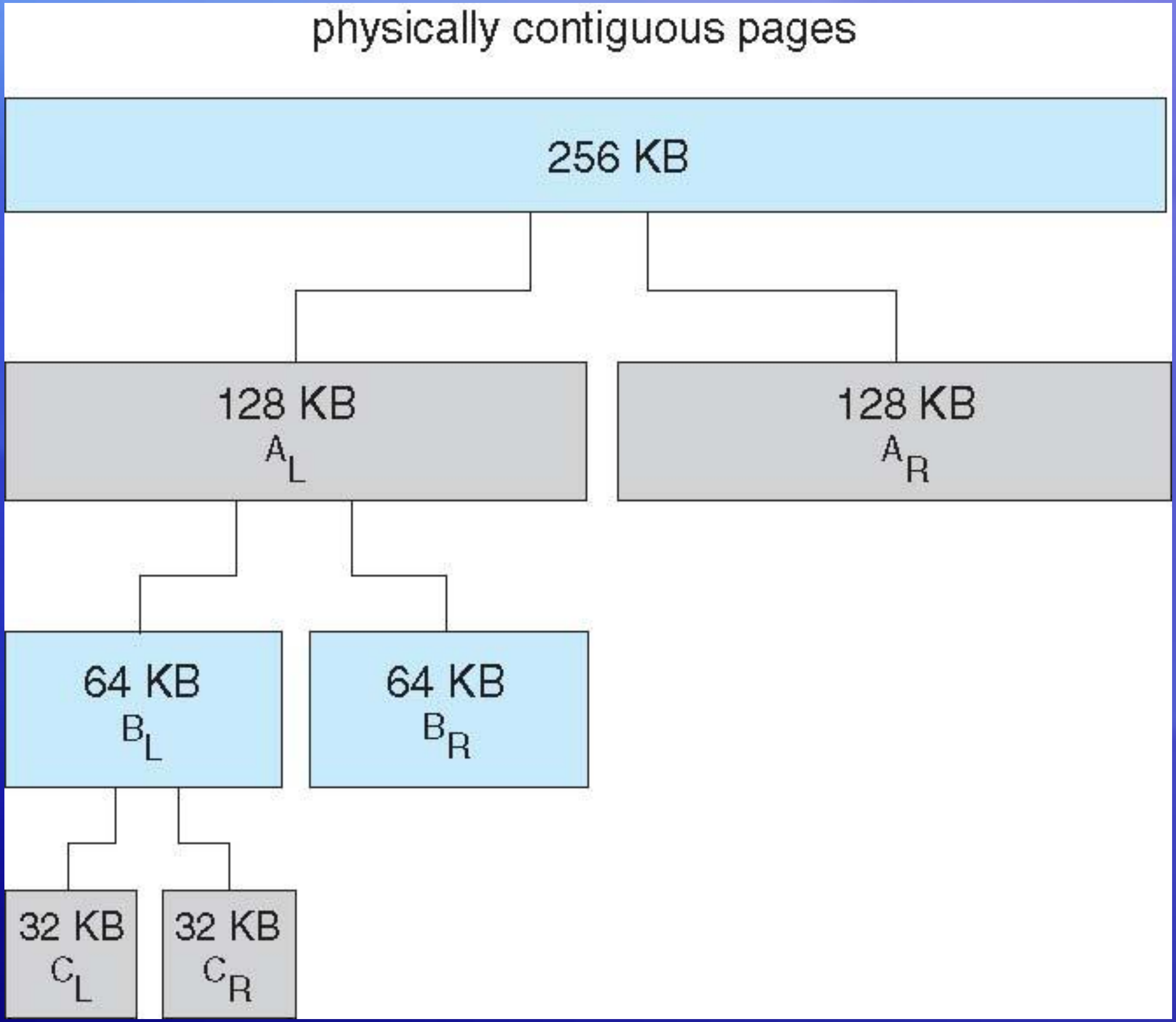
- Treated differently from user memory

- Often allocated from a free-memory pool
  - Kernel requests memory for structures of varying sizes
  - Some kernel memory needs to be contiguous
    - I.e. for device I/O

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

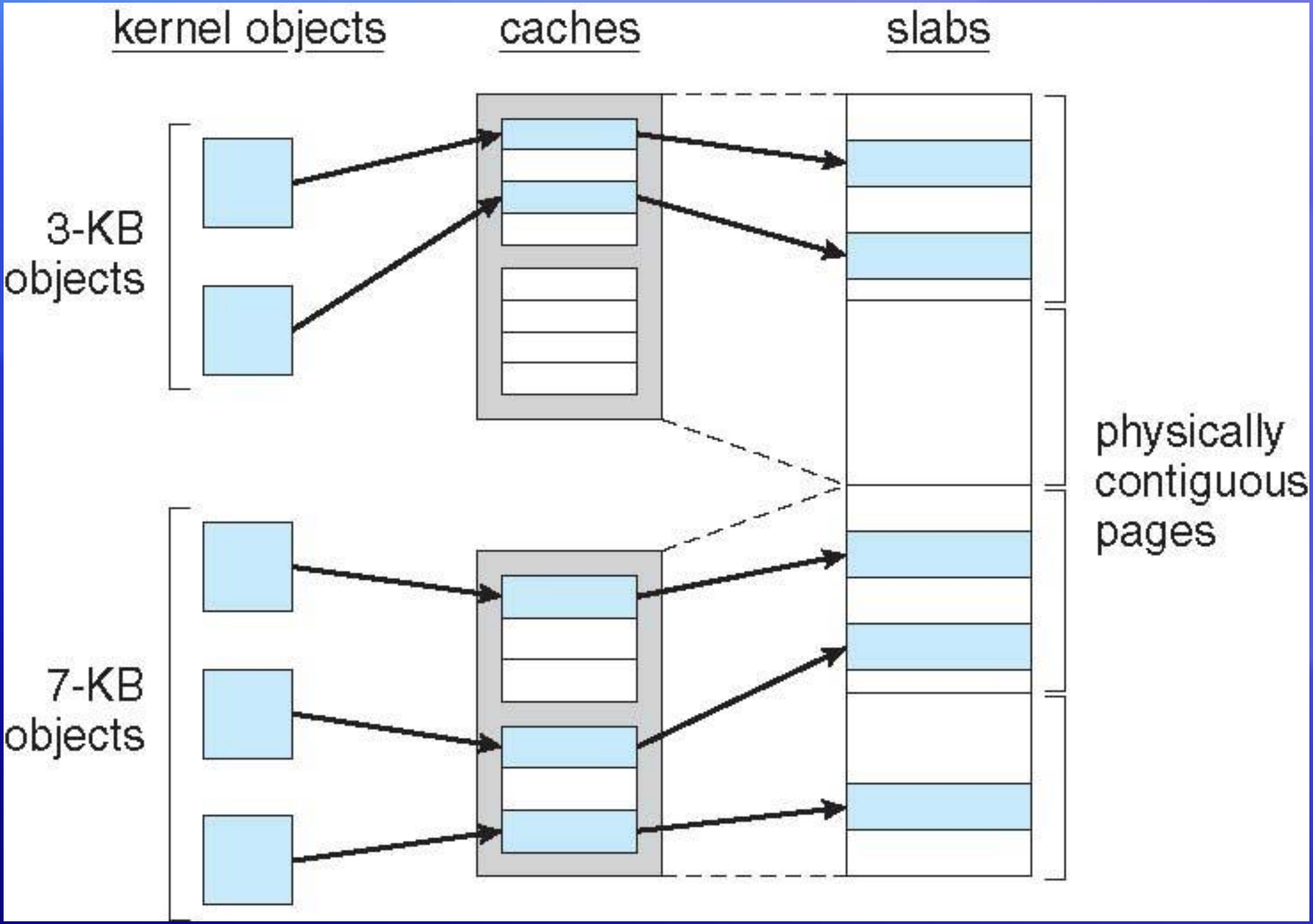
Buddy System Allocator



Slab Allocator

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



Other Considerations -- 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 * α* save pages faults > or < than the cost of prepaging
      *s * (1- α)* unnecessary pages?
    - *α* near zero ⇒ prepaging loses

Other Issues – Page Size

- Sometimes OS designers have a choice
  - Especially if running on custom-built CPU
- Page size selection must take into consideration:
  - Fragmentation
  - Page table size
  - Resolution
  - I/O overhead
  - Number of page faults
  - Locality
  - TLB size and effectiveness
- Always power of 2, usually in the range 2^{12} (4,096 bytes) to 2^{22} (4,194,304 bytes)
- On average, growing over time

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;
```

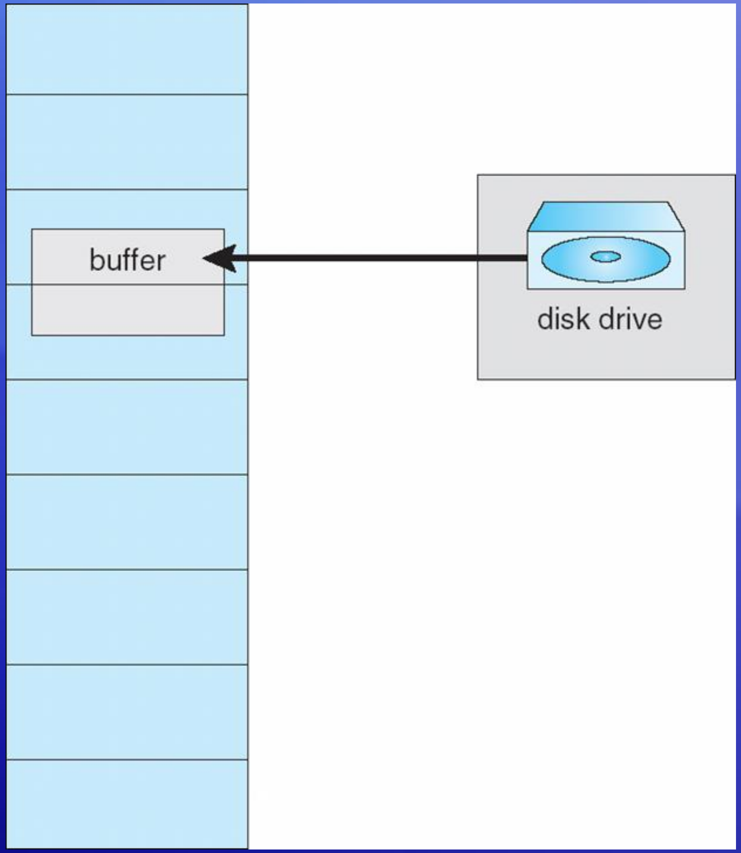
128 page faults

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



Reference Book

“Operating System Concepts” by Silberchartz, Galvin, Gagne, Wiley India Publications.