Chapter 9: Virtual Memory

Chapter 9: Outline

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

Objectives

- Define *virtual memory* and describe its *benefits*.
- Illustrate how pages are loaded into memory using *demand paging*.
- Apply the *FIFO*, *optimal*, and *LRU page-replacement algorithms*.
- Describe the *working set of a process*, and explain how it is related to *program locality*.
- Describe how **Windows 10** manage virtual memory.

Background

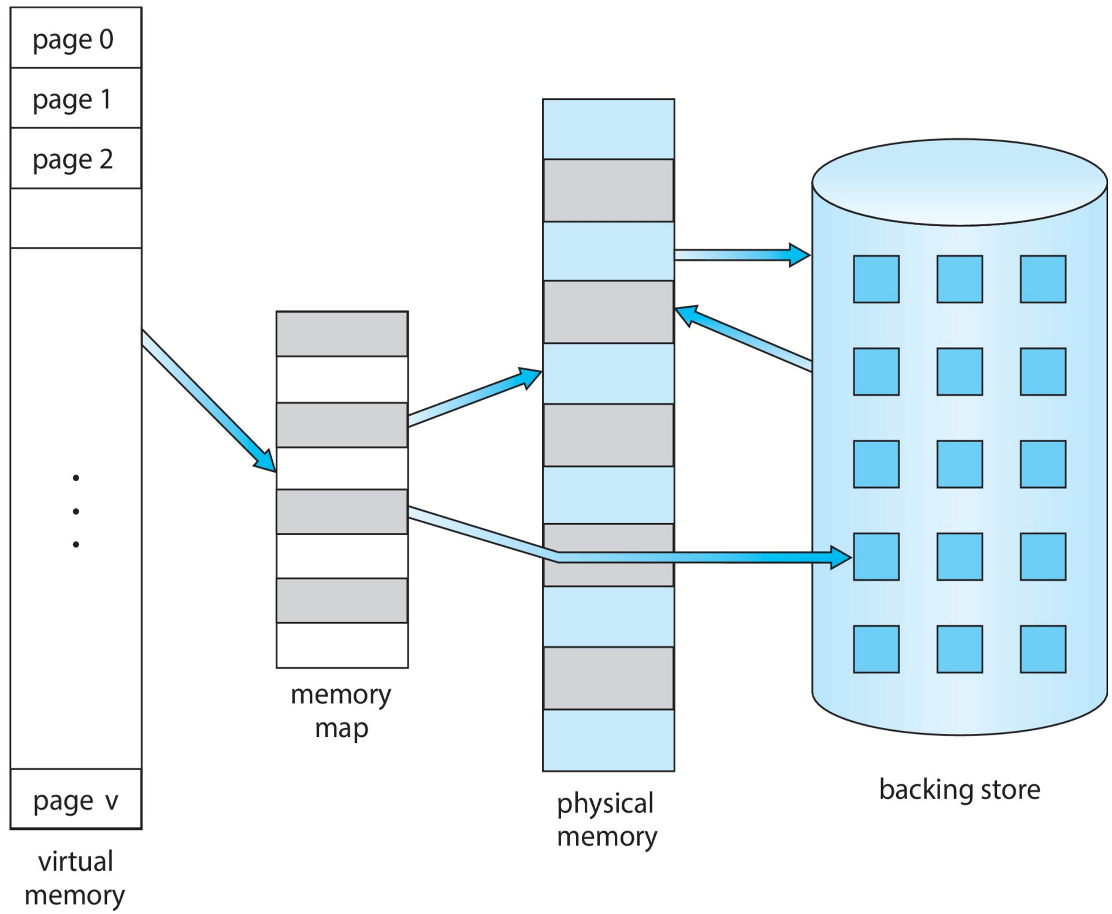
- **Observation**
  - *Code* needs to be in memory to be executed, but entire *program* rarely used. E.g., Error code, unusual routines, large data structures
  - *Entire program code* are not needed at same time
- **Motivation**: consider ability to execute *partially-loaded program*
  - Program no longer *constrained by limits* of physical memory
  - Each program takes *less memory* while running
    ➢ more programs run at the same time
    - Increase *CPU utilization* and *throughput*
    - No increase in *response time* or *turnaround time*
  - *Less I/O* needed to load or swap programs into memory
    ➢ each user program runs faster

Virtual memory

- **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 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*

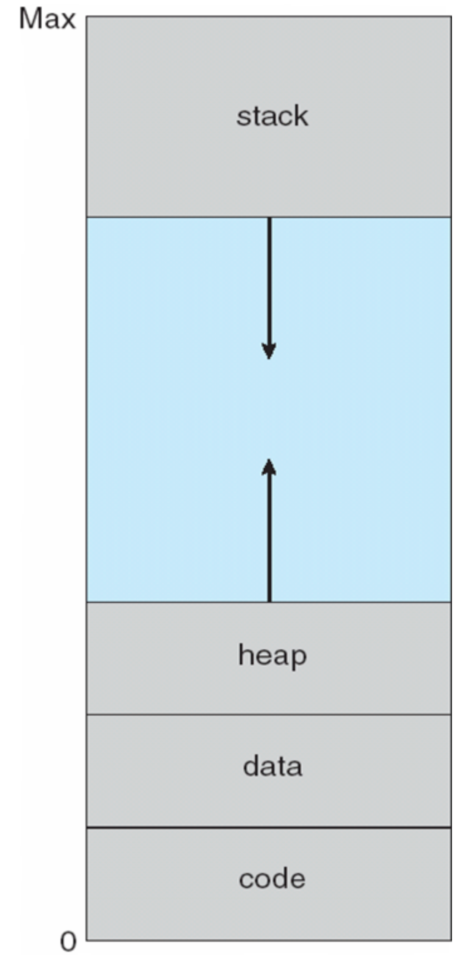
Virtual Address Space

- *Virtual address space* – logical view of how process is stored in memory
  - Usually start at address **0**, contiguous addresses until *end of space*
  - Meanwhile, physical memory organized in *page frames*
  - **MMU** must *map* logical to physical addresses

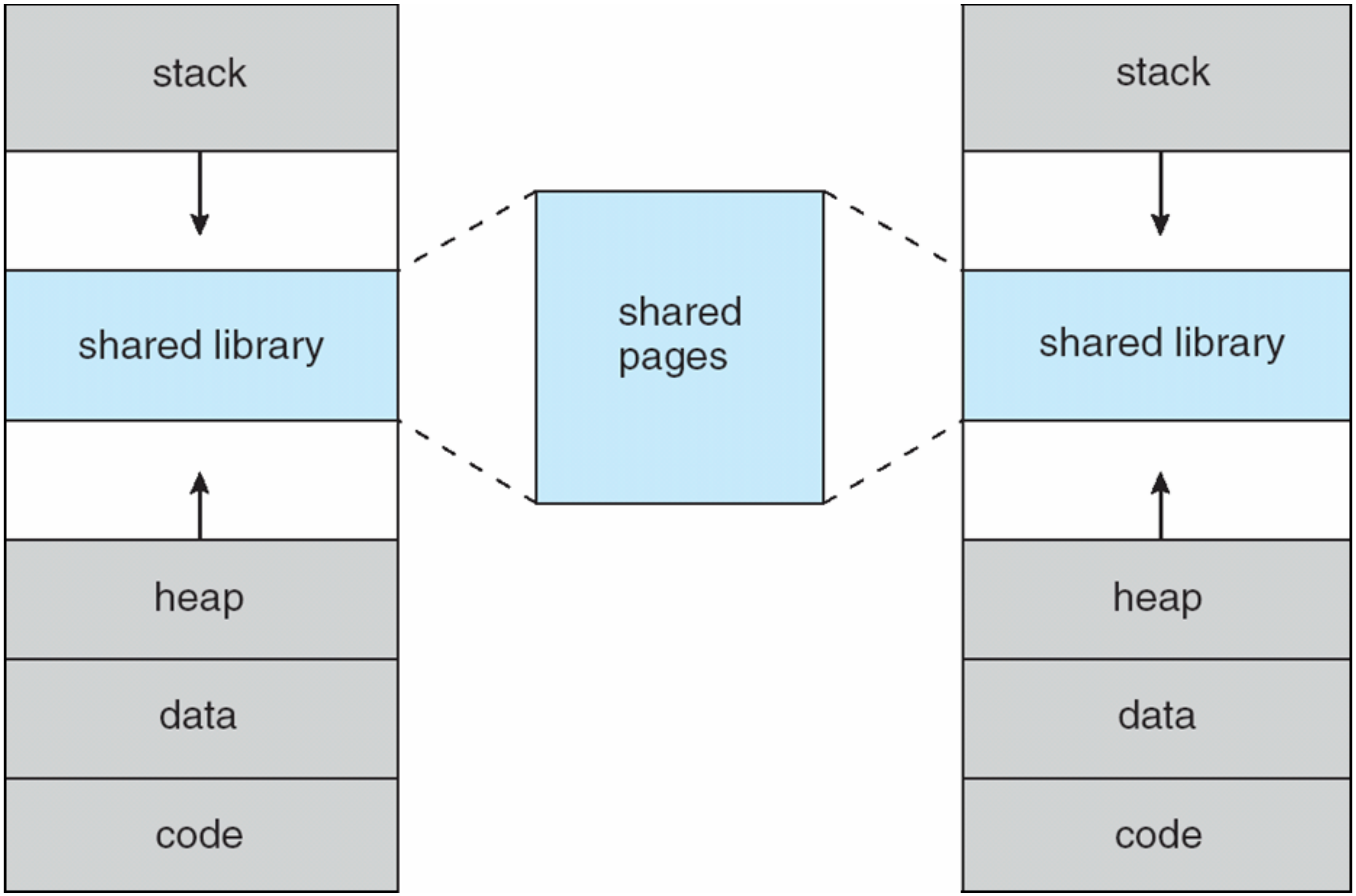


Virtual Address Space (Cont.)

- Usually *design logical address space* for *stack* to start at Max logical address and grows "down" while *heap* grows "up"
  - Maximizes address space use
  - Unused address space between the two is *hole*
    - No physical memory needed until *heap* or *stack* grows to a given new page
- 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

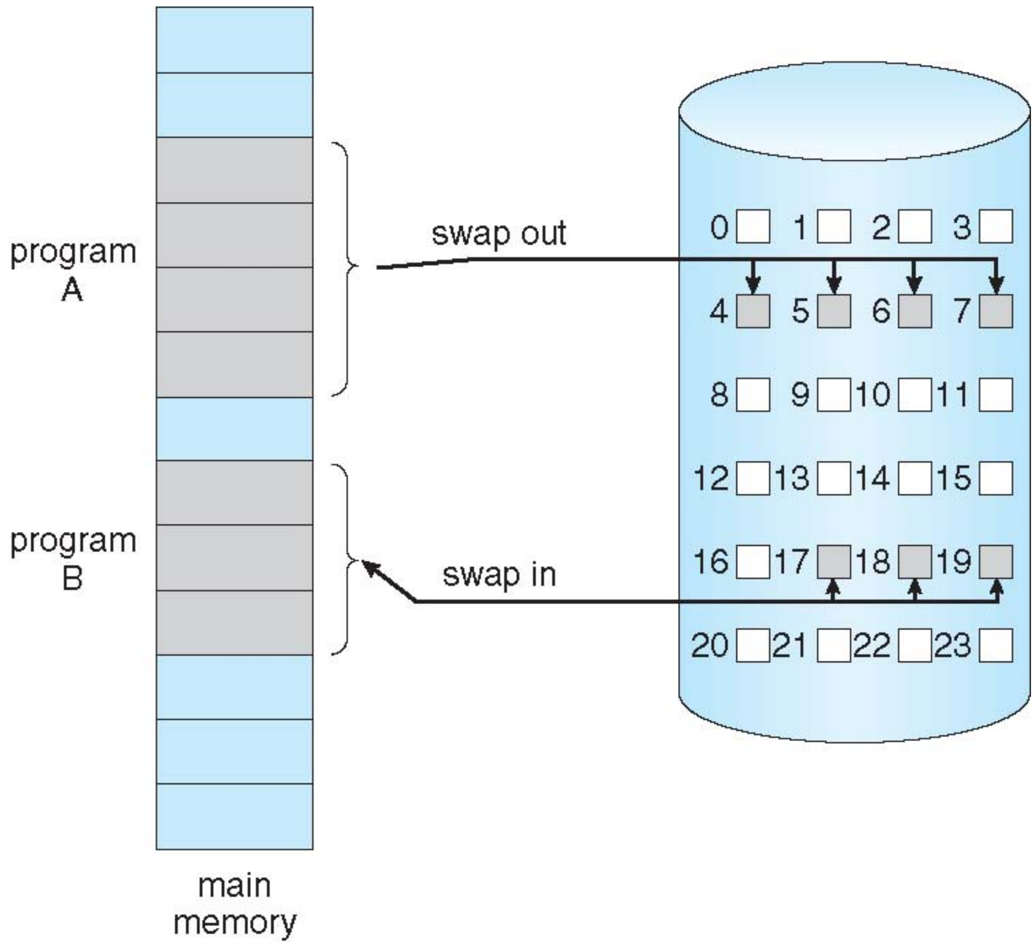


Shared Library Using Virtual Memory



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
- Similar to *paging system with swapping*



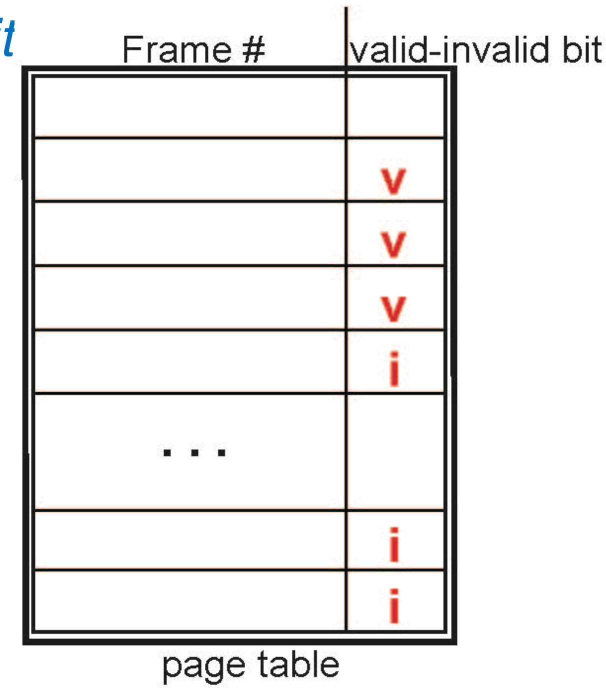
Basic Concepts

- *Lazy swapper* – never swaps a page into memory unless page will be needed (Swapper that deals with pages is a *pager*)
- With swapping, pager *guesses* which pages will be used before swapping out again
  - Instead, pager brings in only those pages into memory
- How to determine that set of pages?
  - Need new **MMU** functionality to implement *demand paging*
- If pages needed are already *memory resident*
  - No difference from non demand-paging
- If page needed are not memory resident
  - *Need to detect and load the page into memory from storage*
    - Without changing program behavior
    - Without programmer needing to change code

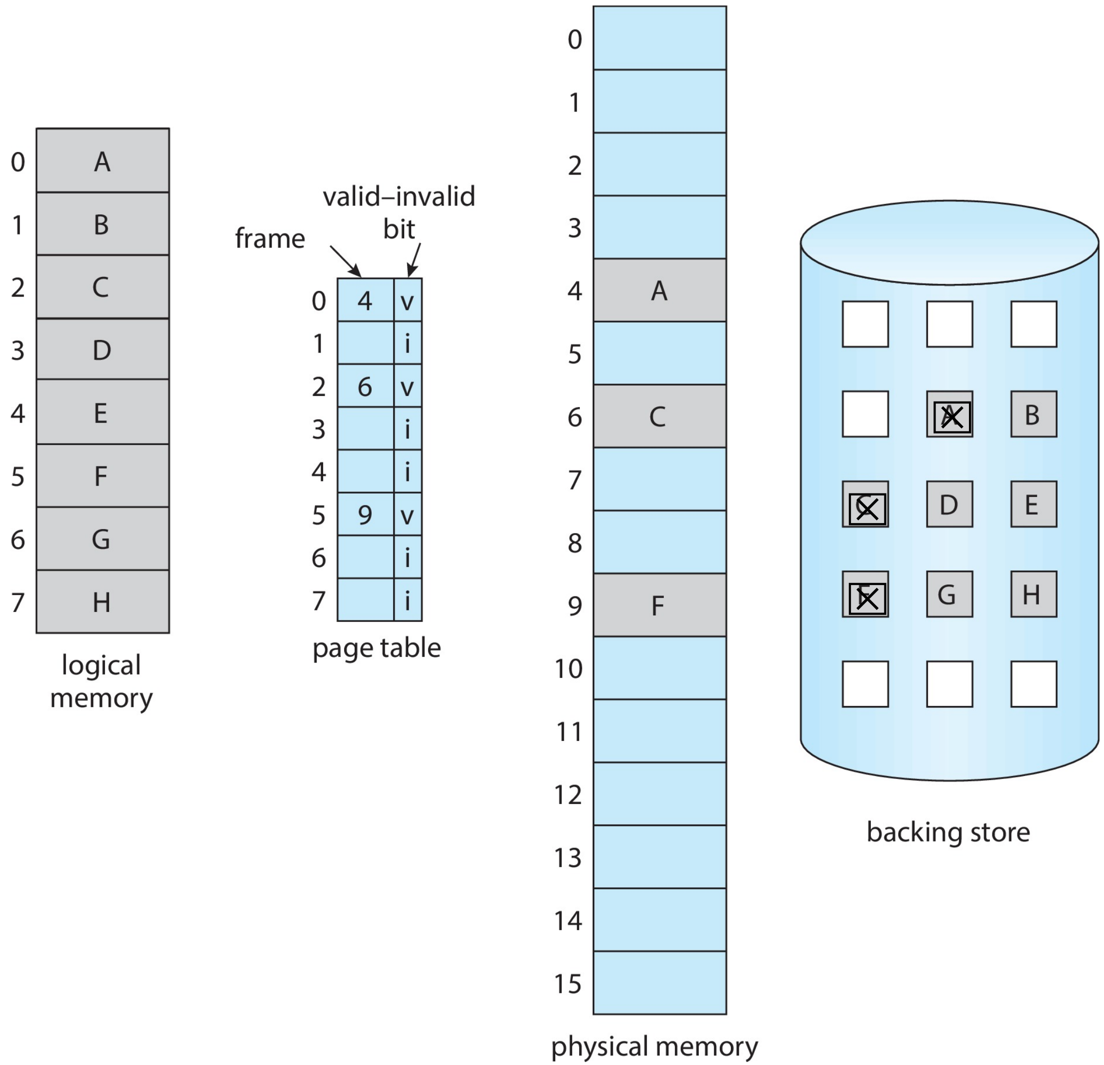
Valid-Invalid Bit

- Page is needed ⇒ reference to it
  - invalid reference? ⇒ abort
  - If valid, but not-in-memory? ⇒ bring to memory
- 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)
- During **MMU** address translation, if valid-invalid bit in page-table entry is **i**

  ⇒ *page fault*
- Example of a page-table snapshot is shown



Page Table When Some Pages Are Not in Main Memory



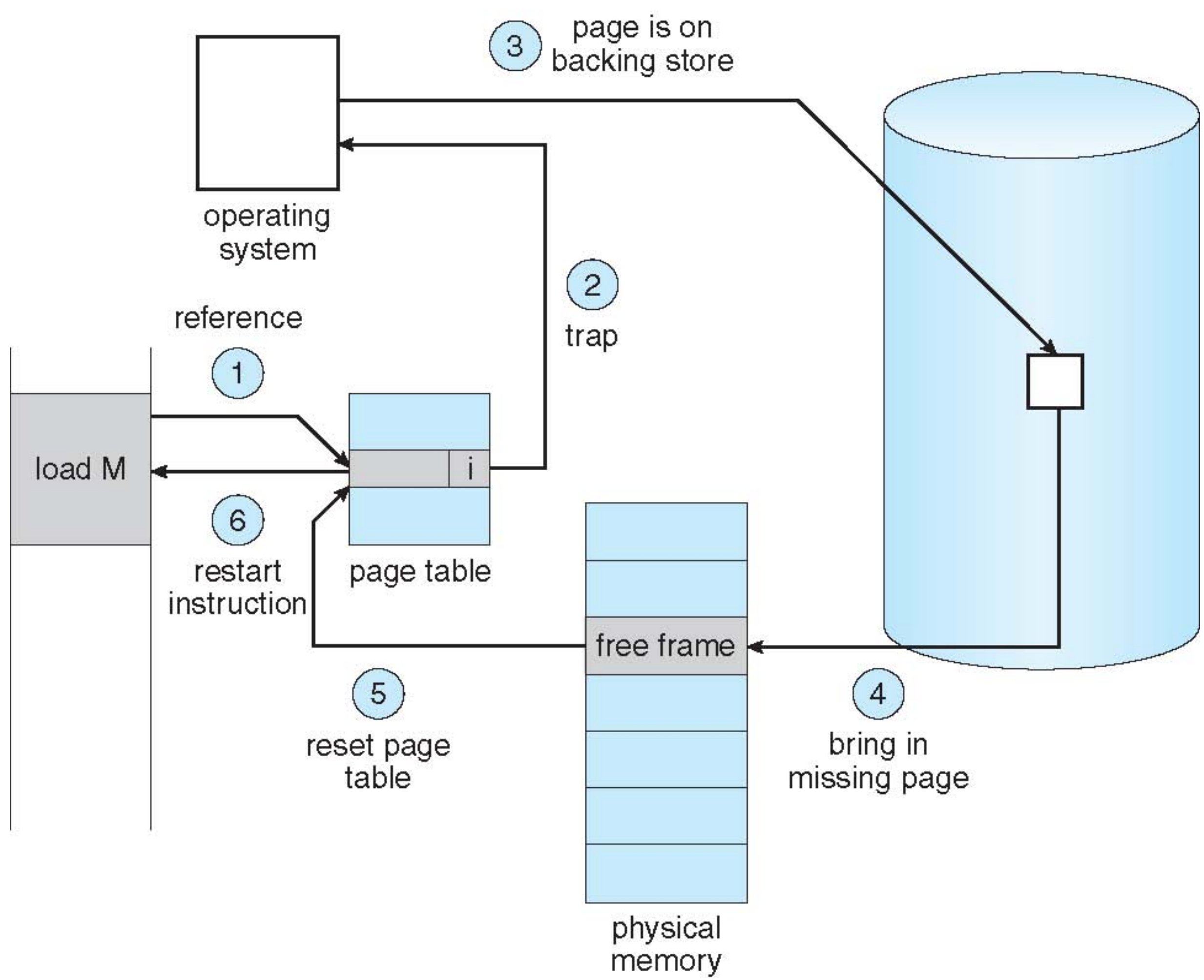
Steps in Handling Page Fault

1. If there is a reference to a *missed page*, first reference to that page will trap to operating system

   ⇒ *Page fault*

2. Operating system looks at another table to decide:
   - Invalid reference? ⇒ abort
   - Or just not-in-memory?
3. Find *free* frame
4. Swap page into frame via *scheduled disk operation*
5. Reset page tables to indicate that page now is in memory
   - Set valid-invalid bit = **v**
6. Restart the instruction that caused the page fault

Steps in Handling a Page Fault (Cont.)

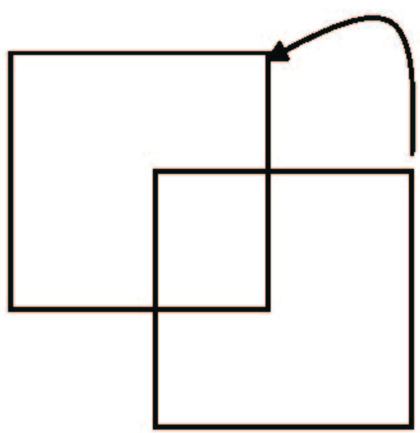


Aspects of Demand Paging

- 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*
  - E.g., 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

Instruction Restart

- Consider an instruction that could access several different locations, e.g.,
  - Block move
  - Auto increment/decrement location
- Restart the whole operation?
  - What if source and destination overlap?



Free-Frame List

- When a page fault occurs, the operating system must bring the desired page from secondary storage into main memory
- Most operating systems maintain a *free-frame list* – a pool of free frames for satisfying such requests

- Operating system typically allocate free frames using a technique known as *zero-fill-on-demand* – the content of the frames zeroed-out before being allocated
- When a system starts up, all available memory is placed on the free-frame list

Stages in Demand Paging – Worse Case

1. Trap to the operating system
2. Save the 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 (disk)
    3. Begin the transfer of the page to a free frame

Stages in Demand Paging (Cont.)

6. While waiting, allocate the CPU to some other user processes
7. Receive an interrupt from the disk I/O subsystem (I/O completed)
8. Save the registers and process state for the other user processes
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

- Three major activities
  - *Service the interrupt* – careful coding means just several hundred instructions needed
  - Read the page – lots of time
  - Restart the process – again just a small amount of time
- Page fault rate ***p***, $0 \le p \le 1$
  - 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 x (page fault overhead

  + swap page out + swap page in)

Example of Demand Paging

- Memory access time = *200 nanoseconds*
- Average page-fault service time = *8 milliseconds*
- EAT = (1 – p) x 200 + p x (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 we want performance degradation < 10 percent
  - $220 > 200 + 7{,}999{,}800 \times p \Rightarrow 20 > 7{,}999{,}800 \times p$
  - $\Rightarrow p < 0.0000025$
  - $\Rightarrow$ < one page fault in every 400,000 memory accesses

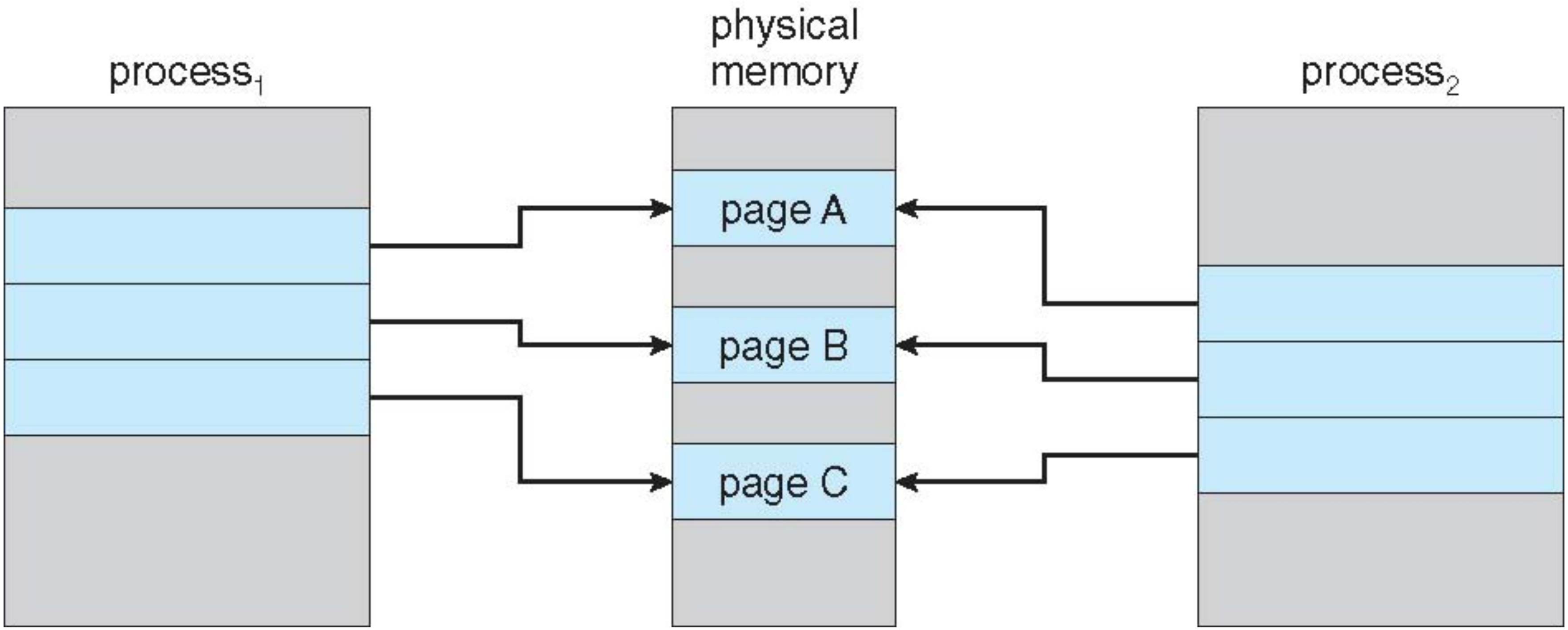
Demand Paging Optimizations

- *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)

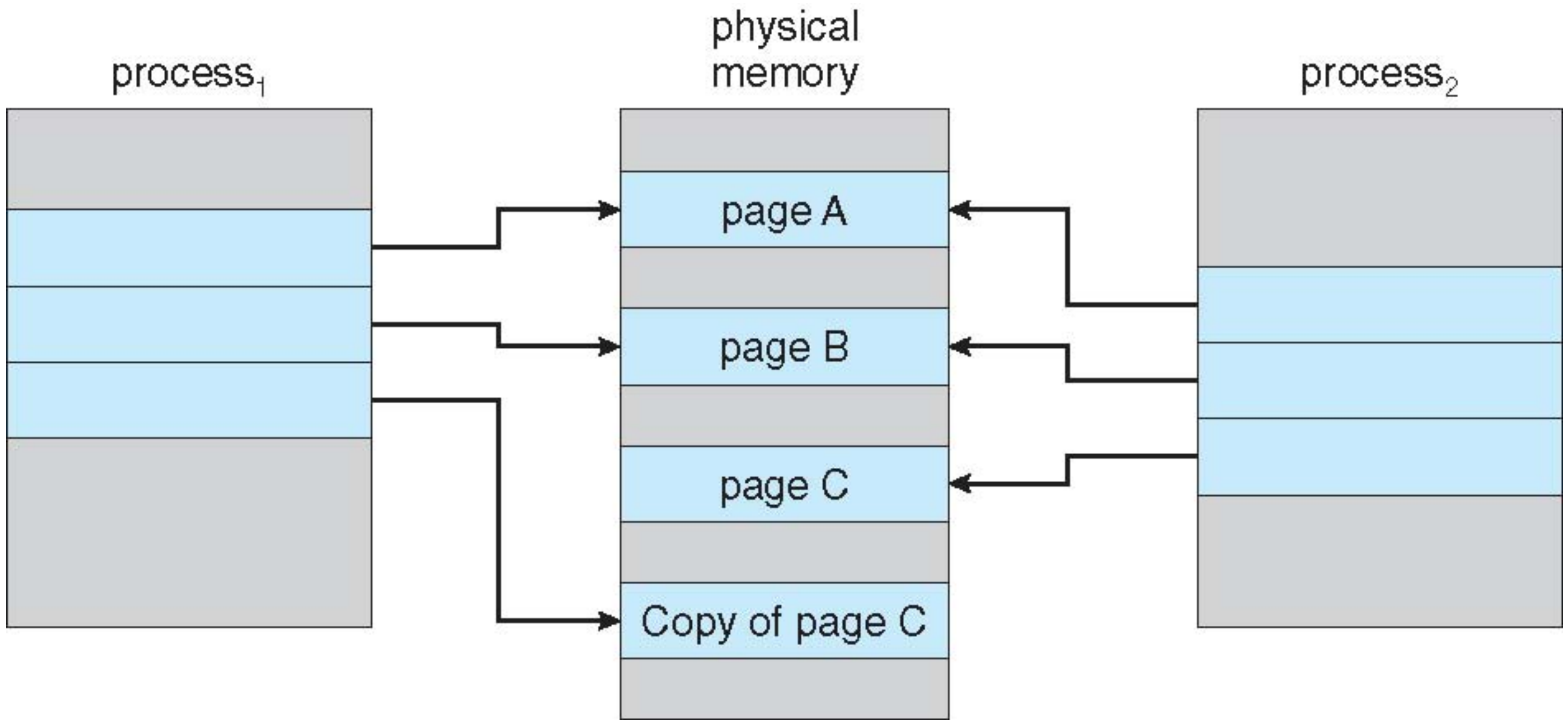
Copy-on-Write

- *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 and child suspend 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 Modified Page C



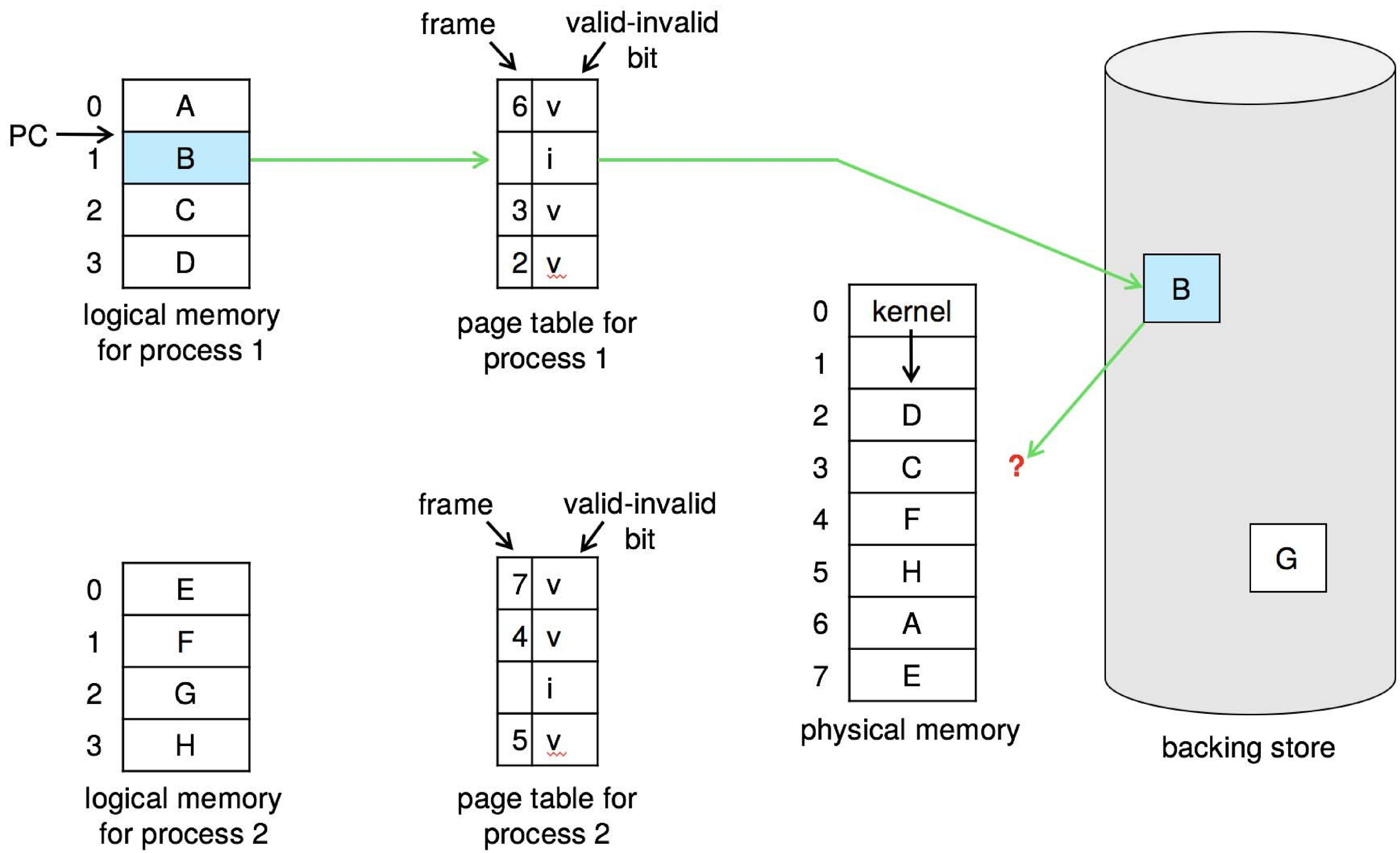
What Happens if There is no Free Frame?

- 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

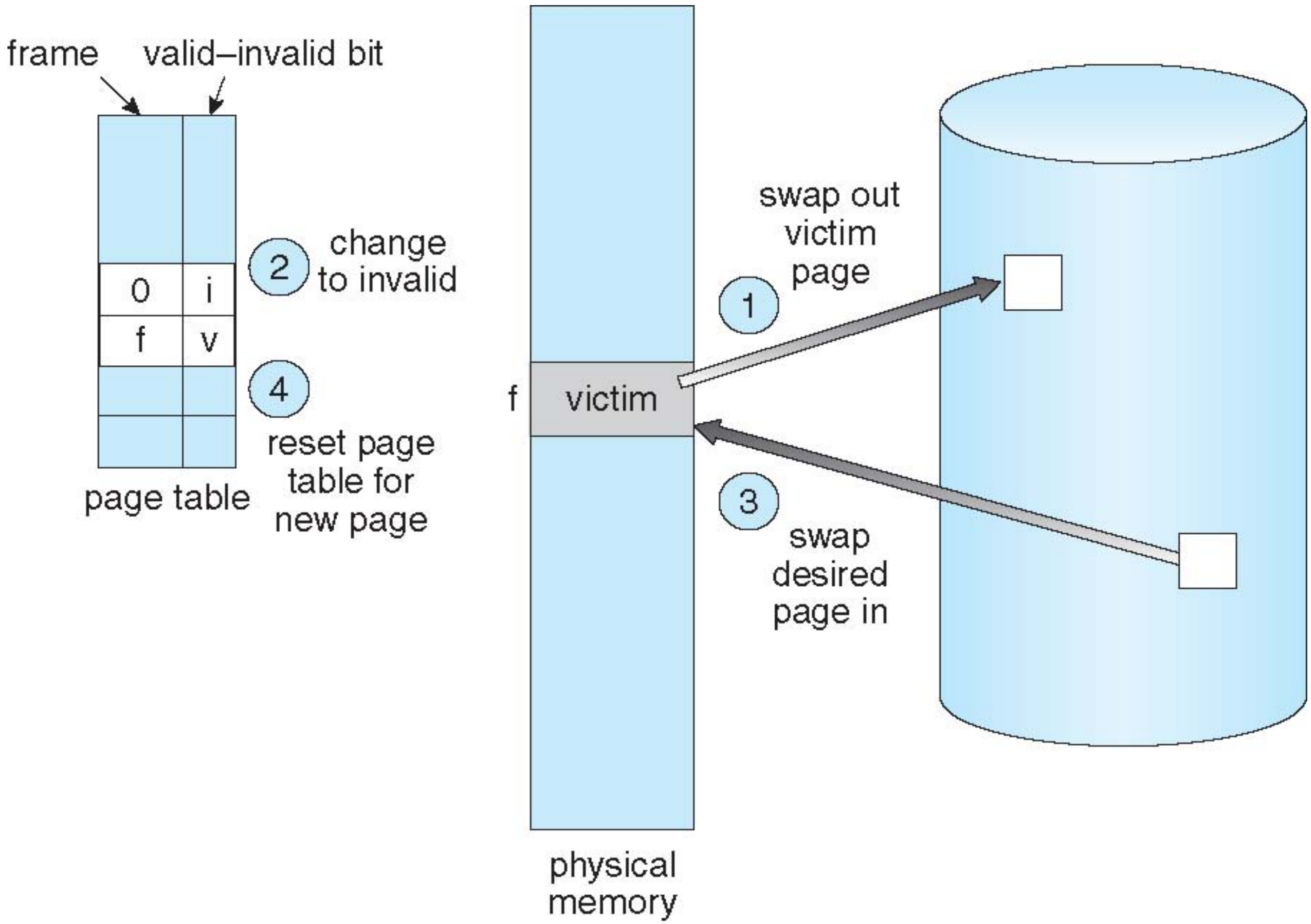


Basic Page Replacement

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 $\Rightarrow$ increasing EAT

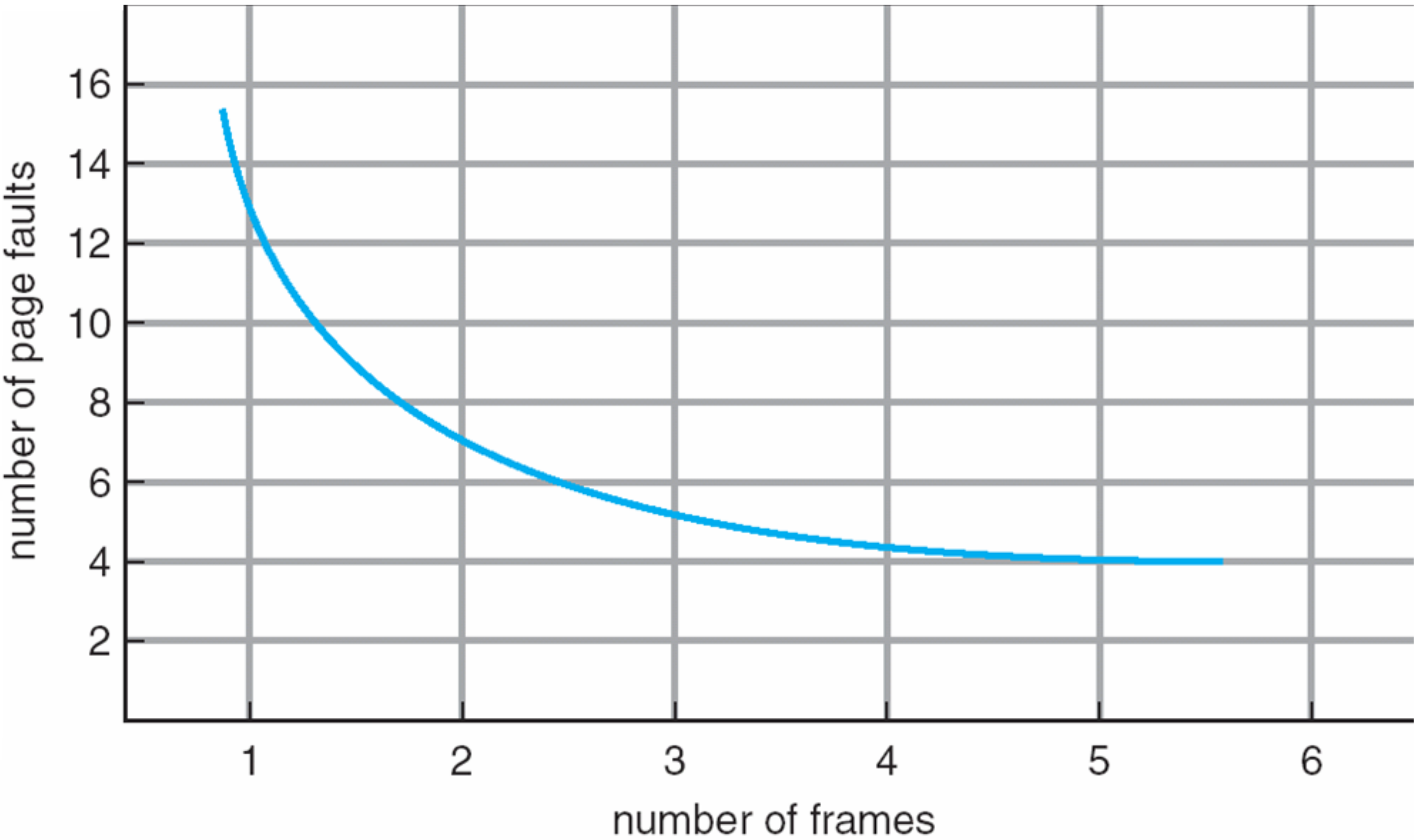
Page Replacement



Page and Frame Replacement Algorithms

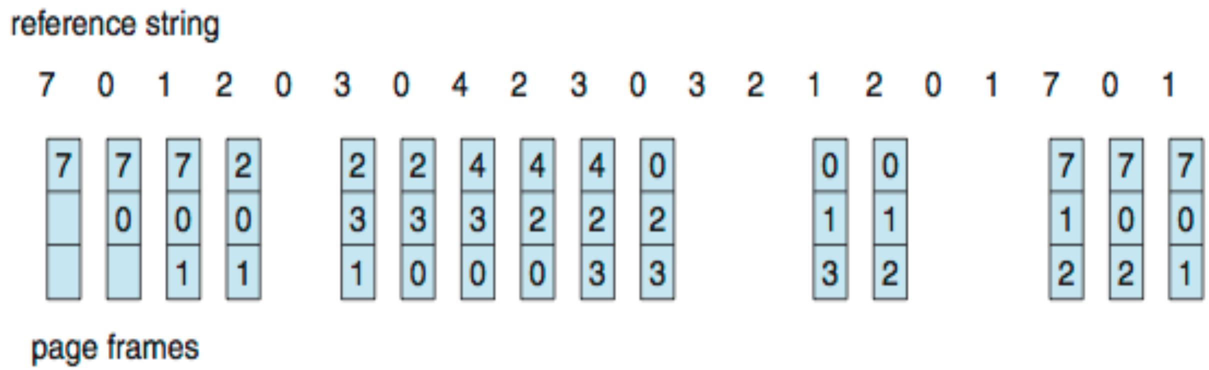
- *Frame-allocation algorithm* determines
  - How many frames to give each process
  - Which frames to replace
- *Page-replacement algorithm*
  - Want *lowest page-fault rate* on both first access and re-access
- Evaluate algorithm by running it on a particular *string of memory references* (reference 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
  - Results depend on number of frames available
- In all our examples, the *reference string* of referenced page numbers 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

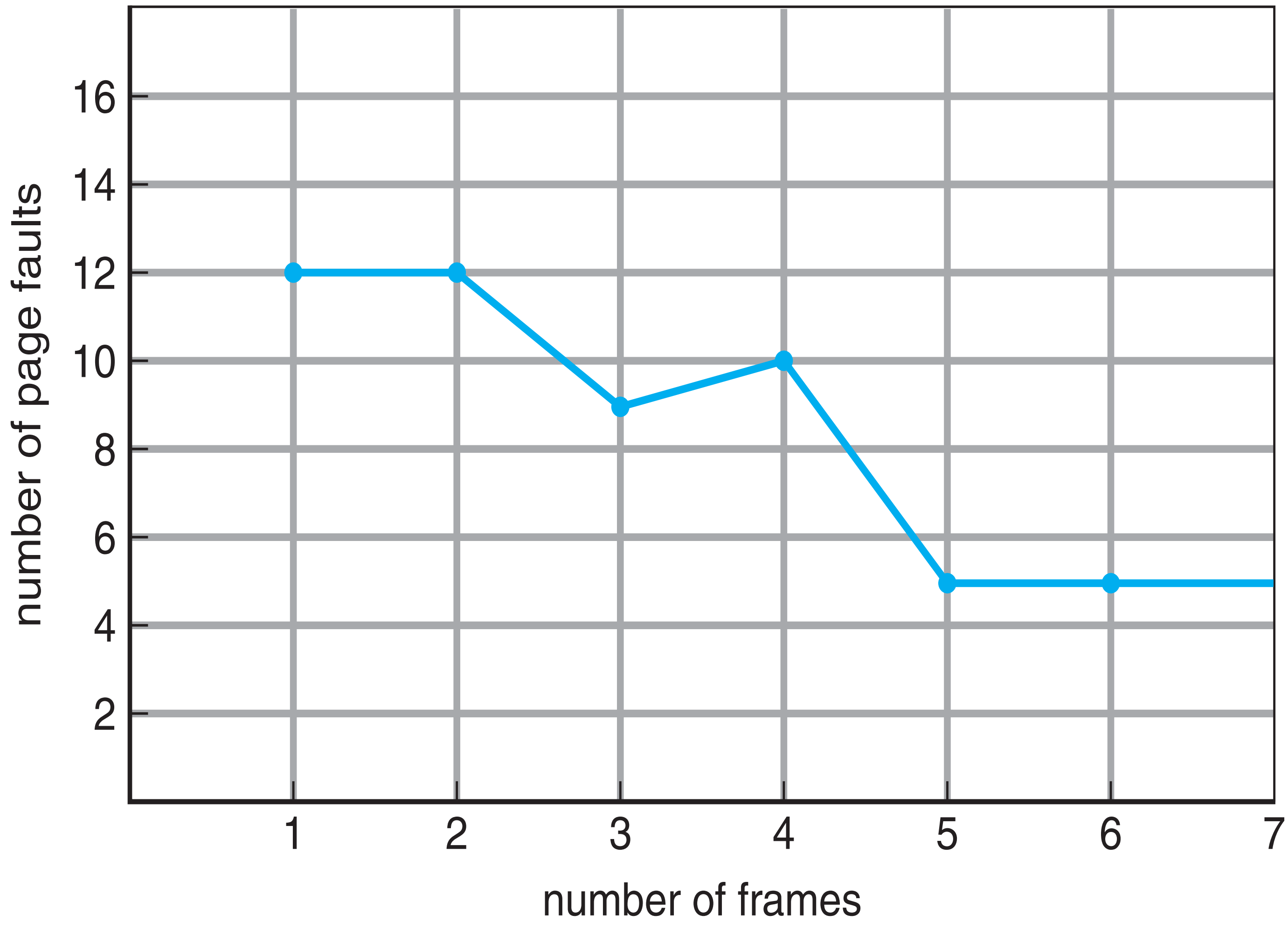
- Reference string: **7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1**
- 3 frames (3 pages can be in memory at a time per process)



15 page faults

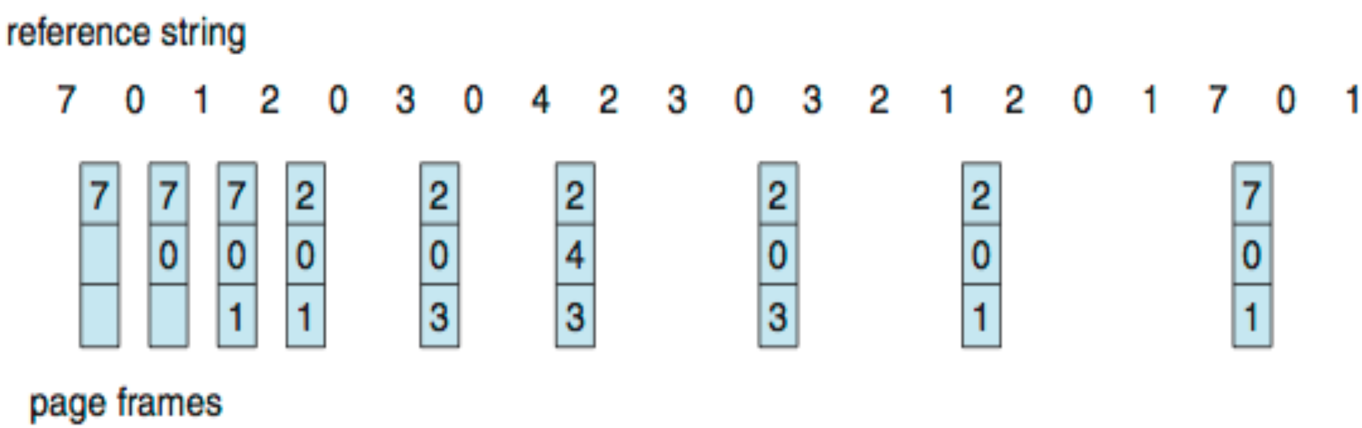
- Can vary by reference string: consider 1,2,3,4,1,2,5,1,2,3,4,5
  - *Adding more frames can cause more page faults!*
    - **Belady's Anomaly**
- How to track ages of pages?
  - Just use a FIFO queue

FIFO Illustrating Belady's Anomaly



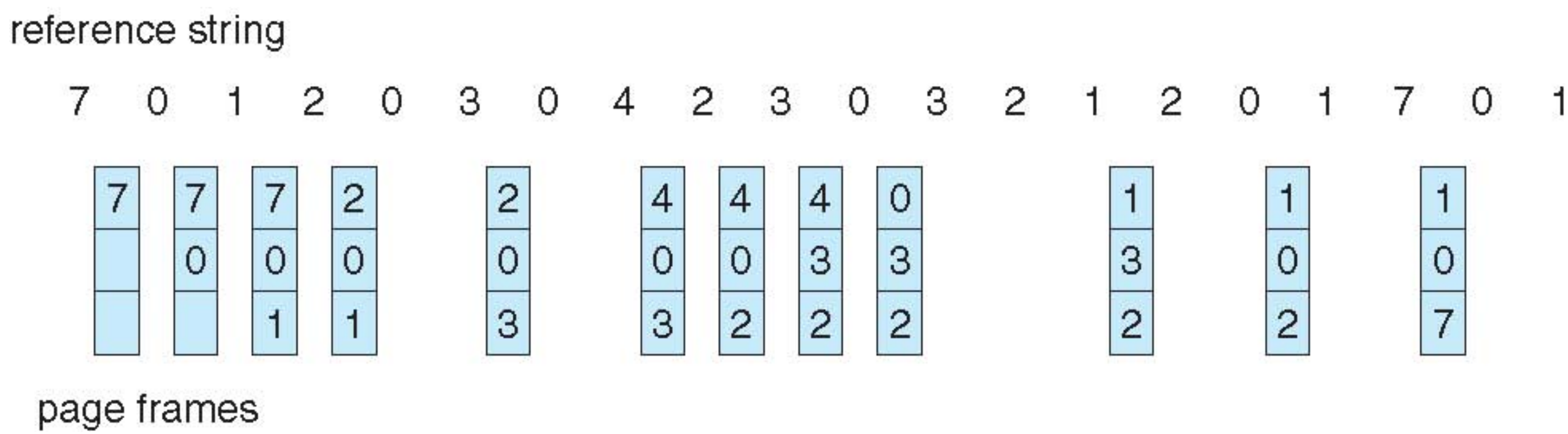
Optimal (OPT) Algorithm

- *Replace page that will not be used for longest period of time*
  - *9* is optimal for the example
- How do you know this?
  - Can't read the future
- Used for measuring how well your algorithm performs



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

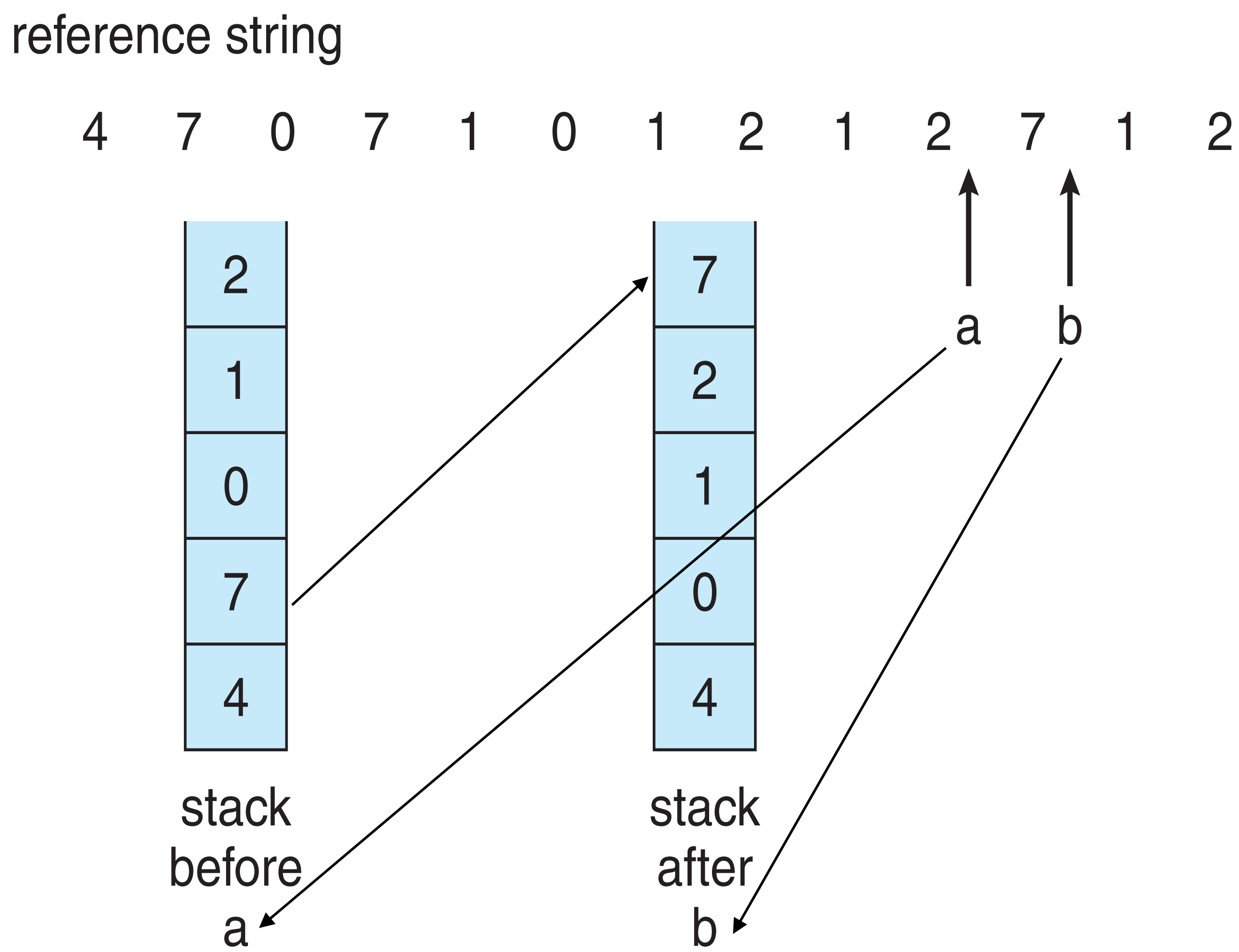


- *12* faults – better than FIFO but worse than OPT
- *Generally good algorithm and frequently used*
- But how to implement?

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, check 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 (for the example of reference string)
  - But each update more expensive
  - No search for replacement
- LRU and OPT are cases of stack algorithms that don't have Belady's Anomaly

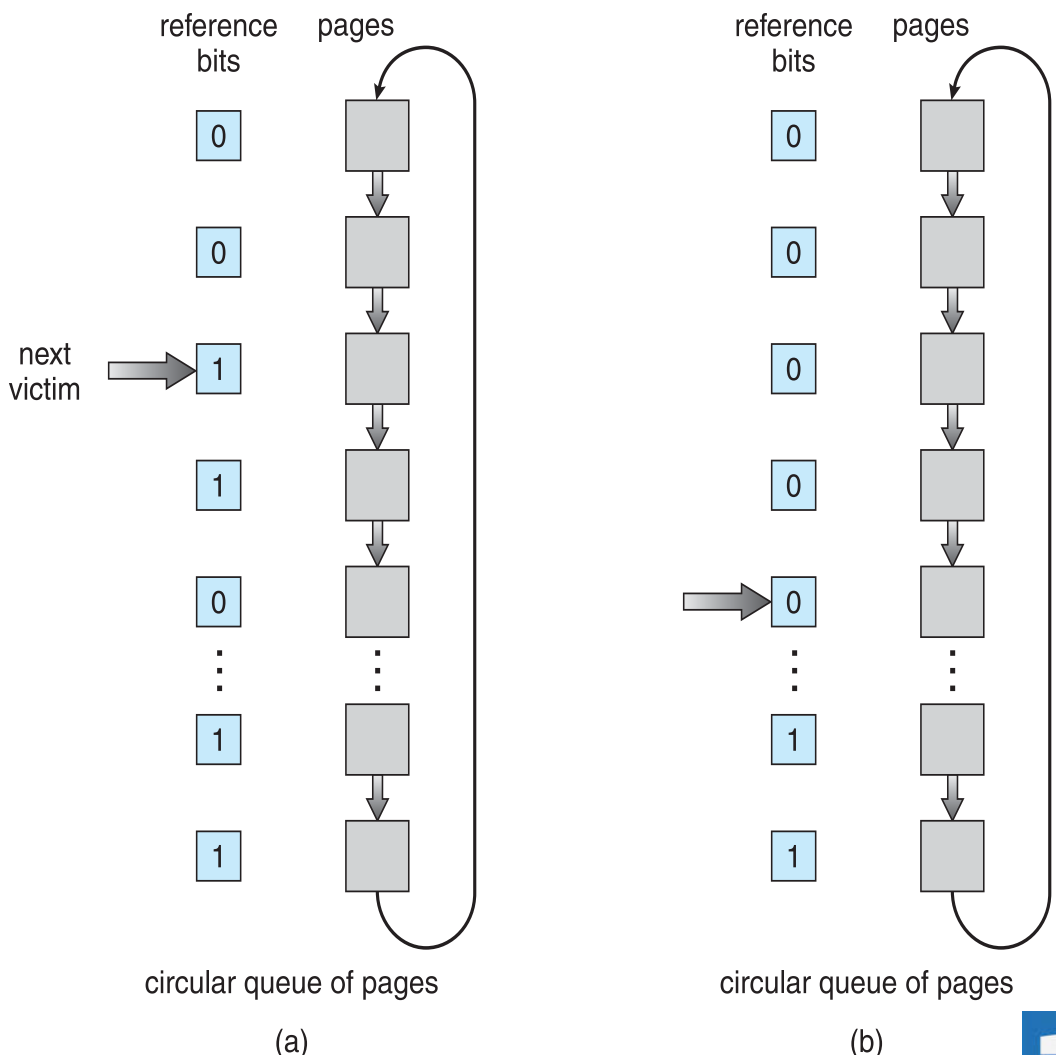
Use Of A Stack to Record Most Recent Page References



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 page 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



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 nor 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
  - Not common
- *Least Frequently Used (LFU) Algorithm*: replaces page with smallest count
- *Most Frequently Used (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
- And any 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

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

$$S = \quad s_i$$

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

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

$$m = 64$$

$$s_1 = 10$$

$$s_2 = 127$$

$$a_1 = \frac{10}{137} \times 62 \approx 4$$

$$a_2 = \frac{127}{137} \times 62 \approx 57$$

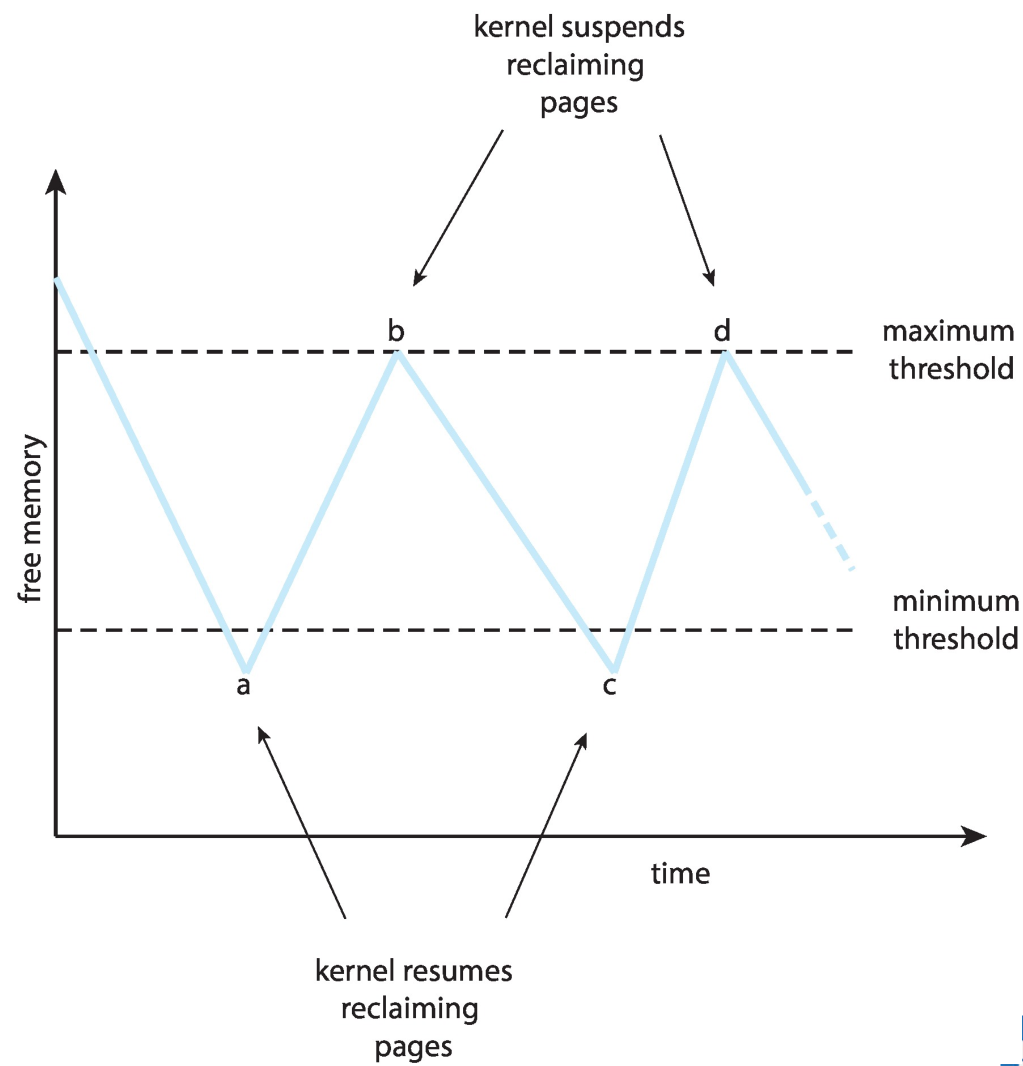
Global vs. Local Allocation

- *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

Reclaiming Pages

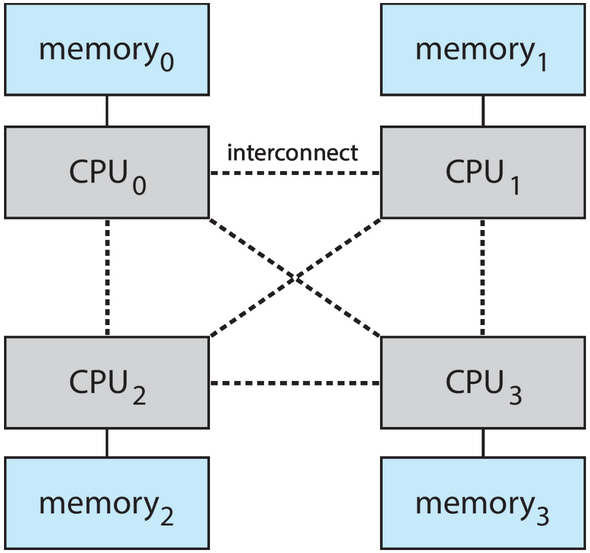
- A strategy to implement *global page-replacement policy*
- **Motivation**: All memory requests are satisfied from the free-frame list, rather than waiting for the list to drop to zero before we begin selecting pages for replacement
- *Page replacement is triggered when the list falls below a certain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

Reclaiming Pages Example



Non-Uniform Memory Access (NUMA)

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



Non-Uniform Memory Access (Cont.)

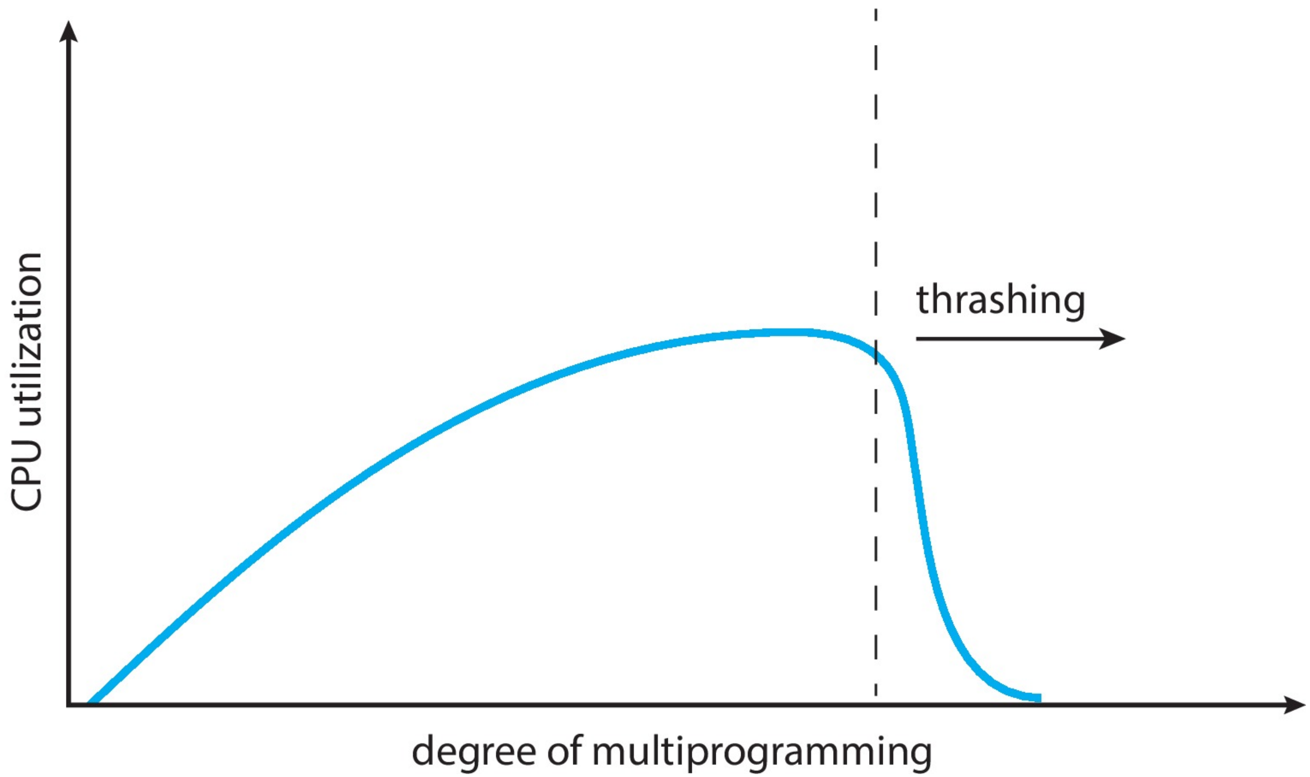
- Optimal performance comes from allocating memory *"close to" the CPU* on which the thread is scheduled
  - And modifying the scheduler to schedule the thread on the same system board when possible
  - E.g., Solved by creating **lgroups** on Solaris
    - Structure to track CPU / Memory *low latency groups*
    - Used scheduler 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" frames, the page-fault rate is very high
  - Page fault to get frame
  - Replace existing frame
  - But, quickly need replaced frame back
  - More processes have page faults
  - 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 (Cont.)

- *Thrashing*. A process is busy swapping pages in and out



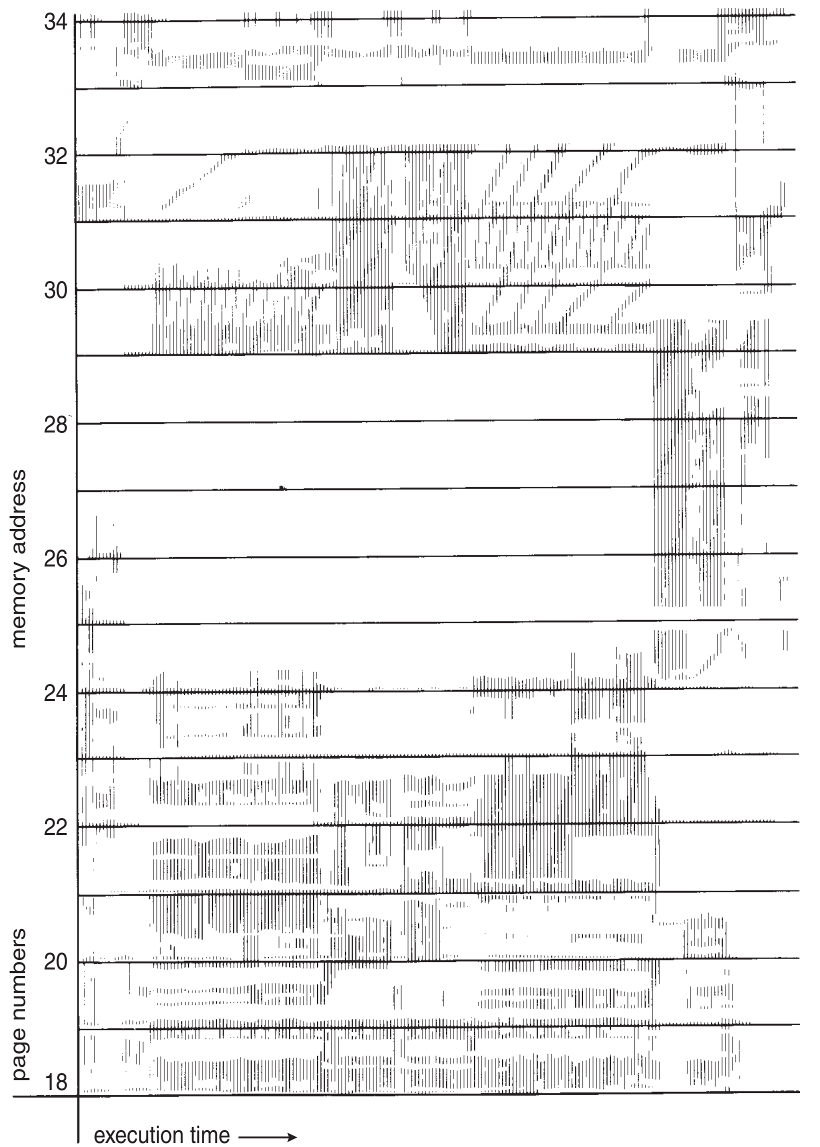
Demand Paging and Thrashing

- 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

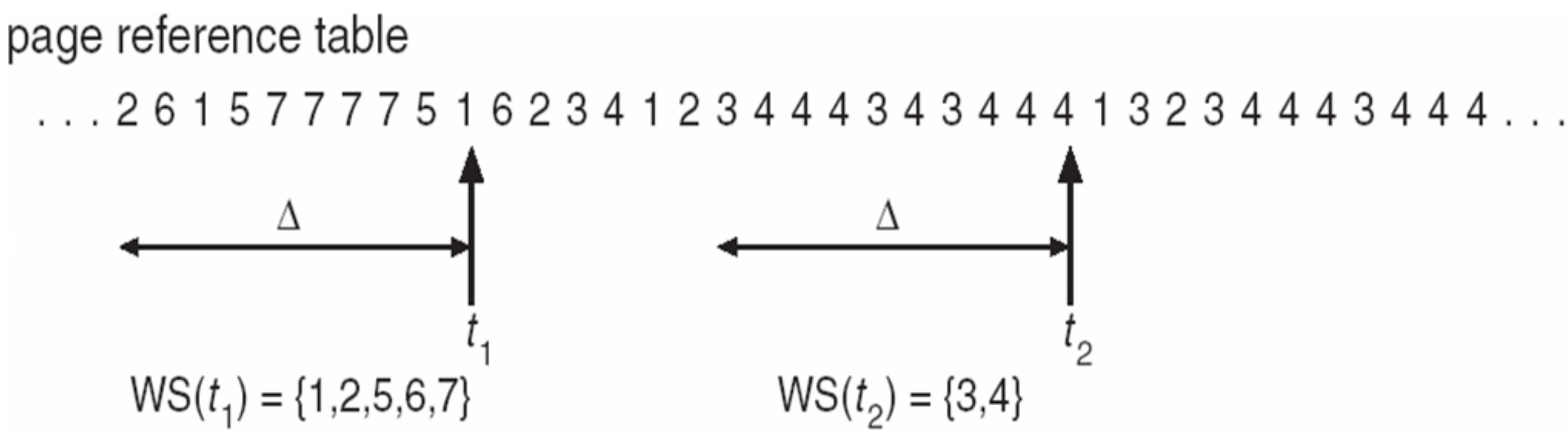
- Limit effects by using *local* or *priority page replacement*

Locality In A Memory-Reference Pattern



Working-Set Model

- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
  - E.g., 10,000 instructions
- **WSS_i** (working set of Process P_i) = total number of pages referenced in the most recent Δ (varies in time)



Working-Set Model (Cont.)

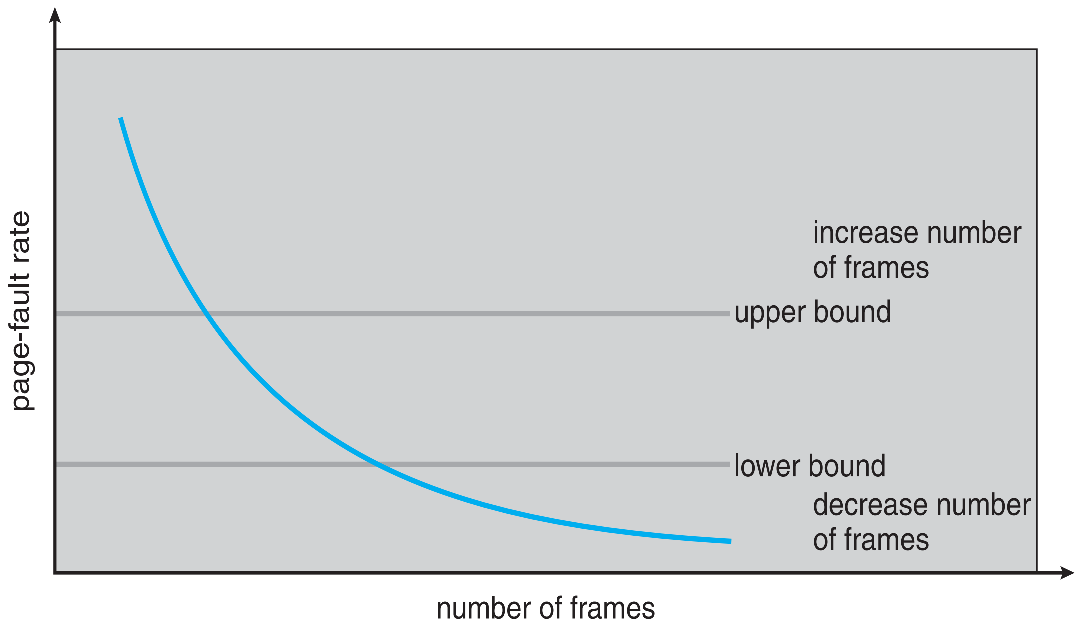
- Working-set window (Δ) and locality
  - if Δ too small will not encompass entire locality
  - if Δ too large will encompass several localities
  - if $\Delta = \infty \Rightarrow$ will encompass entire program
- **$D = \Sigma\ WSS_i$** $\equiv$ total demand frames
  - Approximation of locality
- **m** $\equiv$ total number of available frames
- if ***D > m*** $\Rightarrow$ Thrashing
  - One policy: *if D > m, then suspend or swap out one of the processes*

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 this is not completely accurate?
- Improvement = 10 bits and interrupt every 1000 time units

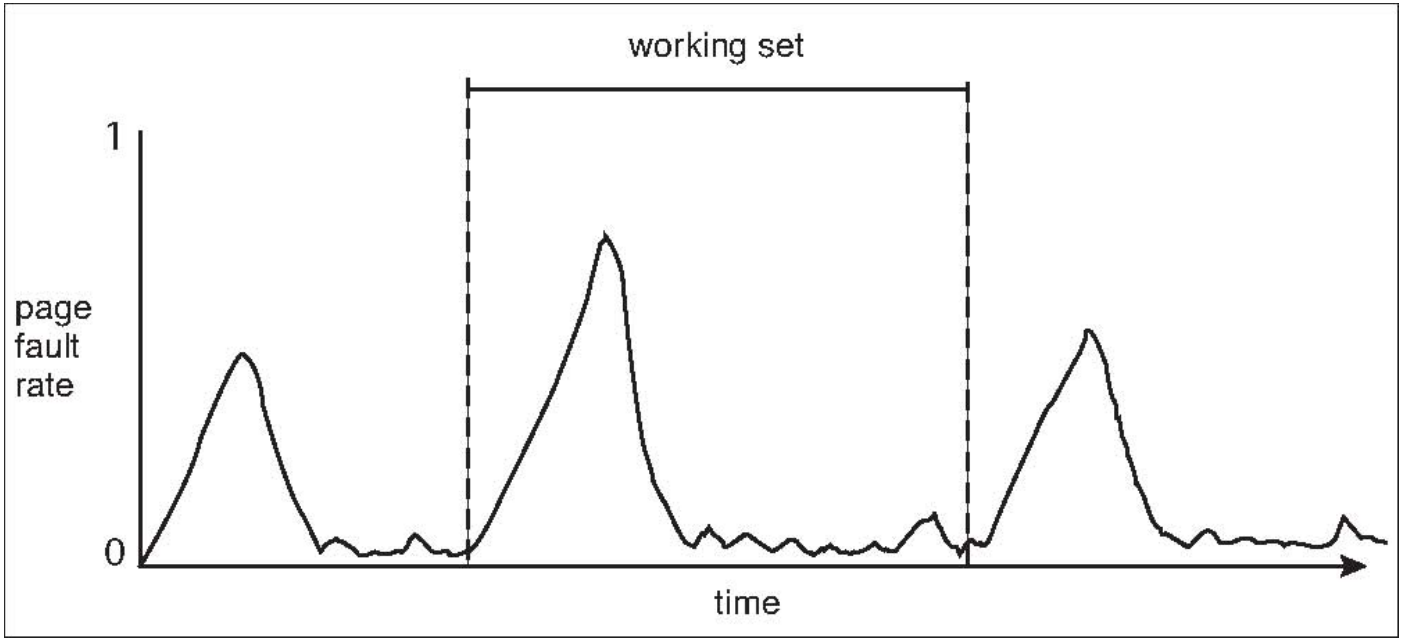
Page-Fault Frequency

- More direct approach than WSS
- Establish "acceptable" *page-fault frequency* (**PFF**) *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

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



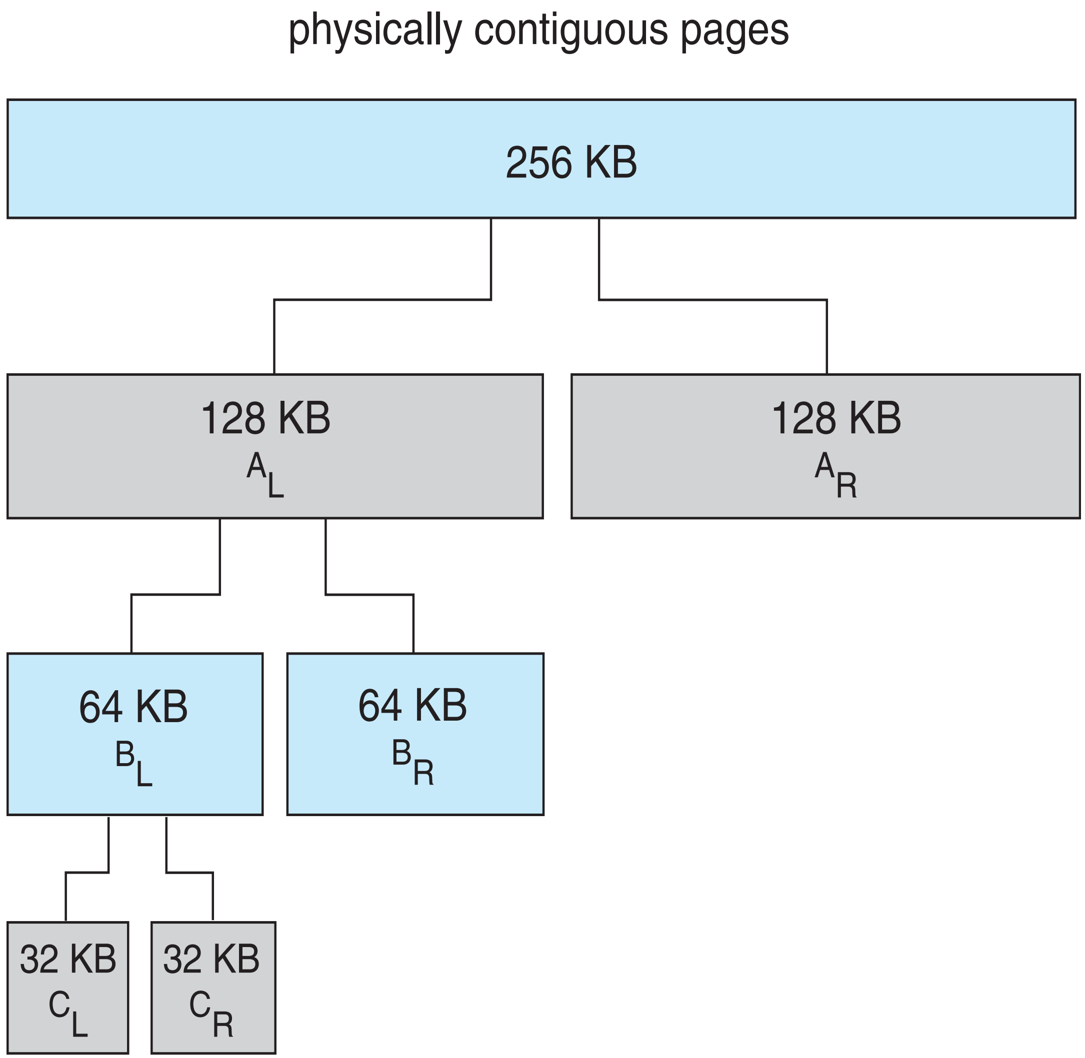
Allocating Kernel Memory

- 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*
    - E.g., for device I/O

Buddy System (power-of-2 Allocator)

- 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

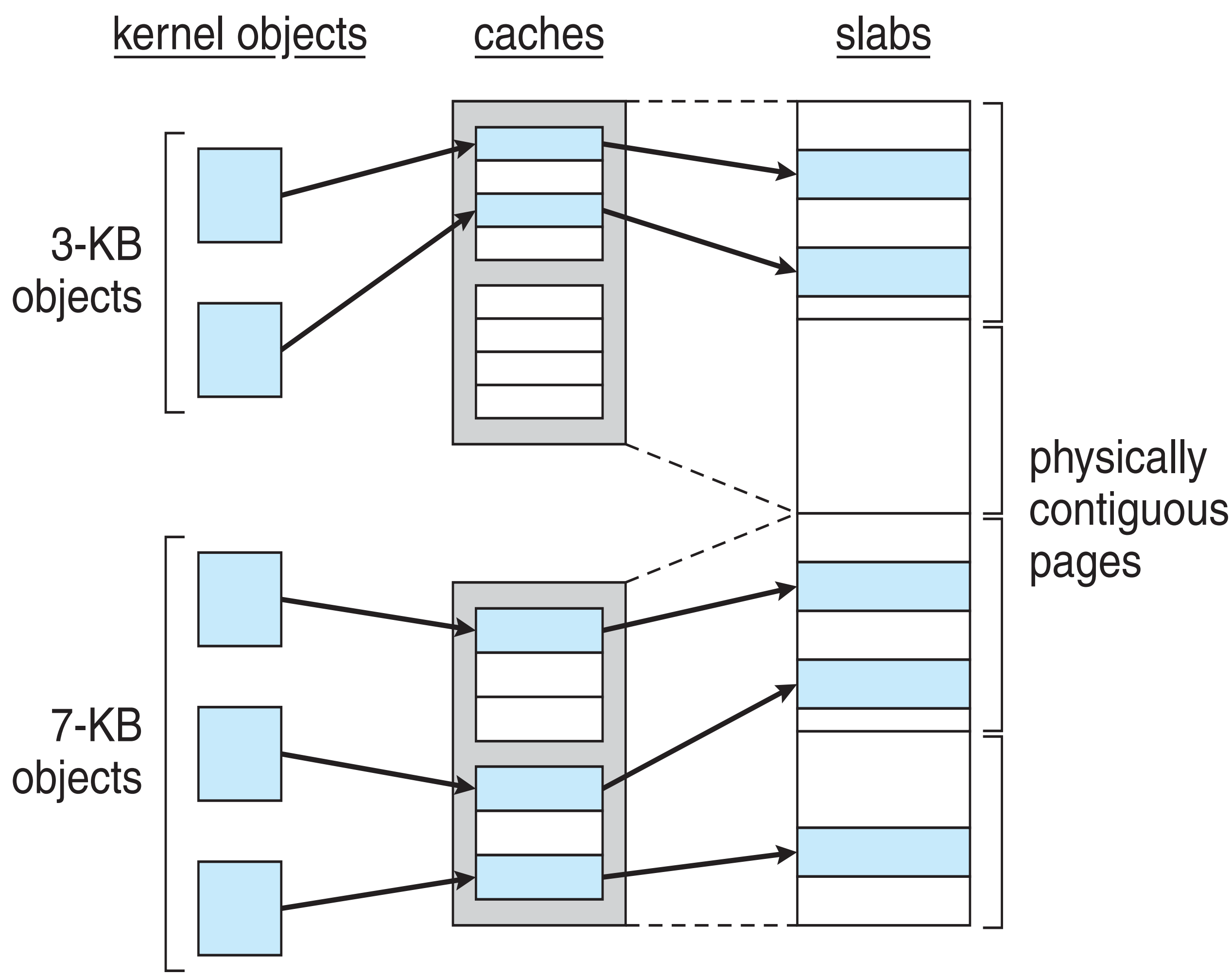
Buddy System Allocator



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



Slab Allocator in Linux

- For example, process descriptor is of type `struct task_struct`
- Approx. 1.7KB of memory
- New task => allocate new struct from cache
  - Will use existing free `struct task_struct`
- Slab can be in three possible states
  1. Full – all used
  2. Empty – all free
  3. Partial – mix of free and used
- Upon request, slab allocator
  1. Uses free struct in partial slab
  2. If none, takes one from empty slab
  3. If no empty slab, create new empty

Slab Allocator in Linux (Cont.)

- Slab started in **Solaris**, now wide-spread for both kernel mode and user memory in various OSes
- Linux 2.2 had **SLAB**, now has both **SLOB** and **SLUB** allocators
  - SLOB (Simple List of Blocks) for systems with limited memory
    - maintains 3 list objects for small, medium, large objects
  - SLUB is performance-optimized SLAB removes per-CPU queues, metadata stored in page structure

Other Considerations

- Pre-paging
- Page size
- TLB reach
- Inverted page table
- Program structure
- I/O interlock and page locking

Pre-paging

- To reduce the large number of page faults that occurs at process startup
- Pre-page all or some of the pages a process will need, before they are referenced
- But if pre-paged pages are unused, I/O and memory was wasted
- Assume ***s*** pages are pre-paged and ***α*** of the pages is used
  - Is cost of $s * \alpha$ save pages faults > or < than the cost of pre-paging $s * (1 - \alpha)$ unnecessary pages?
  - α near zero $\Rightarrow$ pre-paging loses

Page Size

- Sometimes OS designers have a choice of page size
  - 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

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

Example of a 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*

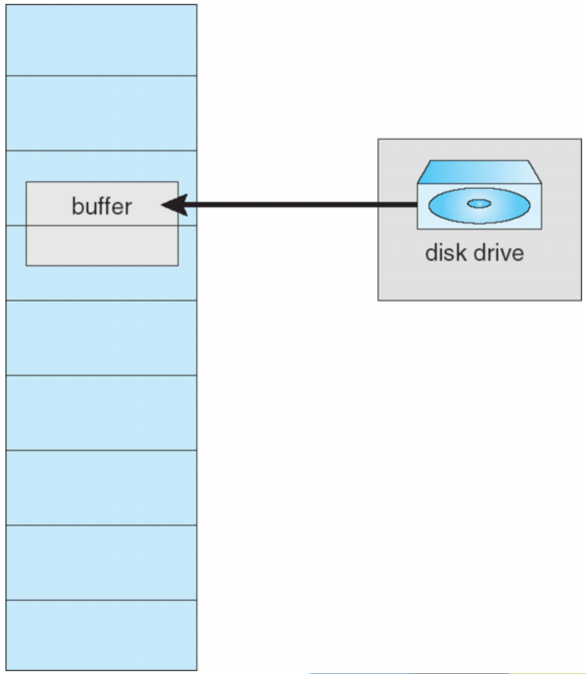
  - *Program 2*

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

128 page faults

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
- *Pinning* of pages to lock into memory



Operating System Examples

- Windows

Windows

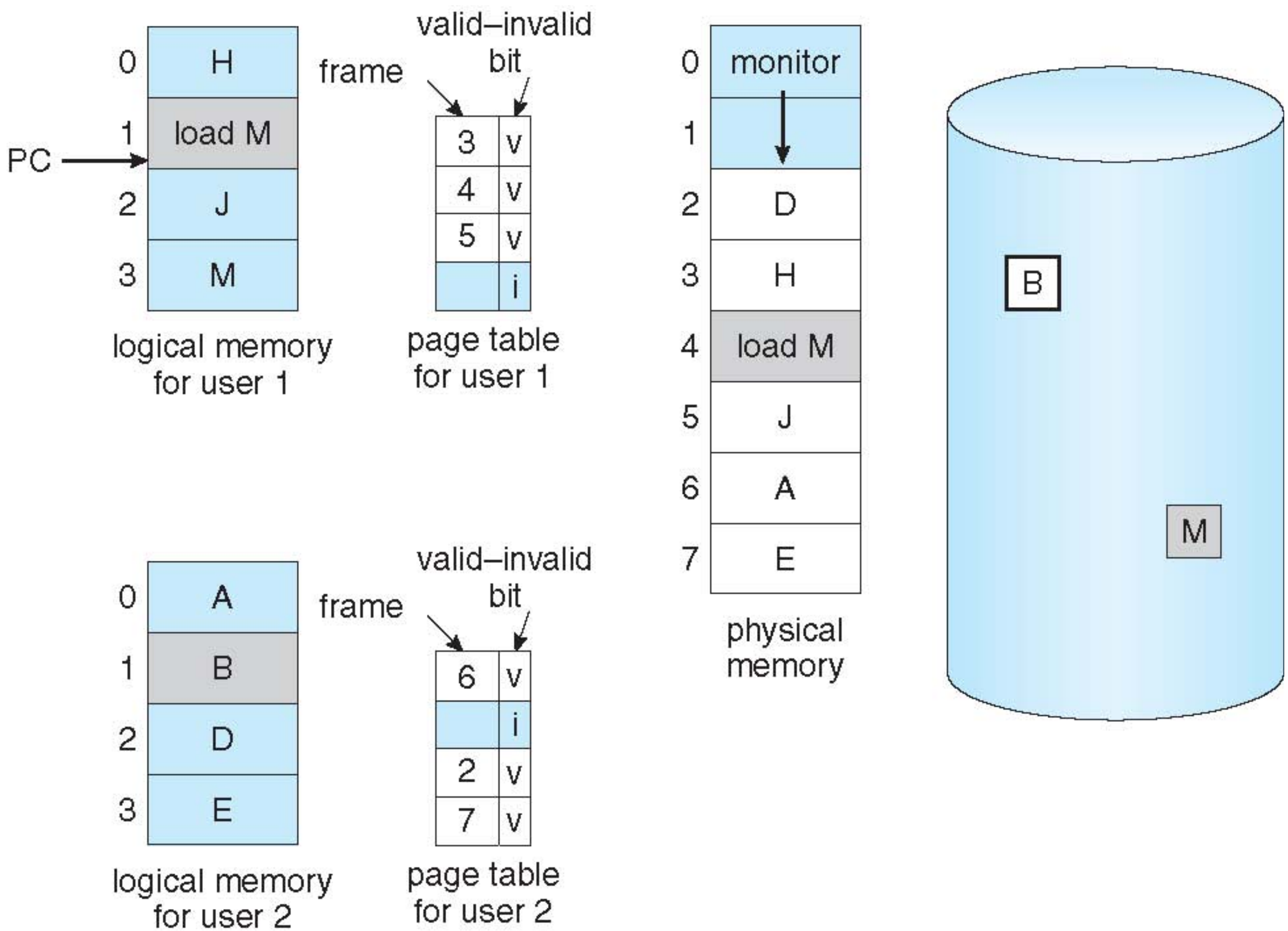
- Uses demand paging with *clustering*. Clustering brings in pages surrounding the faulting page
- Processes are assigned *working set minimum* and *working set maximum*
  - *Working set minimum* is the minimum number of pages the process is guaranteed to have in memory
  - A process may be assigned 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

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

Need For Page Replacement



Priority Allocation

- Apply 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

Memory Compression

- Consider the following free-frame-list consisting of 6 frames

free-frame list

head → 7 → 2 → 9 → 21 → 27 → 16

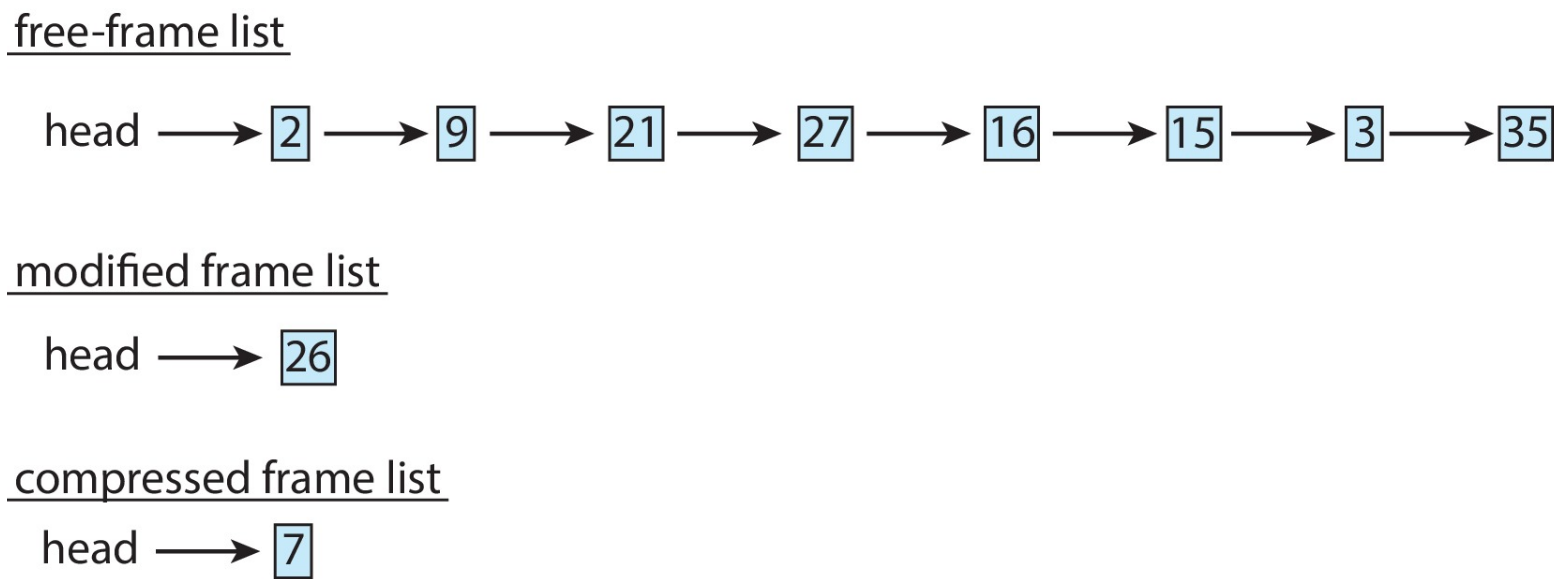
modified frame list

head → 15 → 3 → 35 → 26

  - Assume that this number of free frames falls below a certain threshold that triggers page replacement. The replacement algorithm (say, an LRU approximation algorithm) selects four frames - **15, 3, 35**, and **26** - to place on the free-frame list. It first places these frames on a modified-frame list. Typically, the modified-frame list would next be written to swap space, making the frames available to the free-frame list. An alternative strategy is to *compress a number of frames*, say three, and *store their compressed versions in a single page frame.*

Memory Compression (Cont.)

- An alternative to paging is *memory compression*
- Rather than paging out modified frames to swap space, we *compress several frames into a single frame*, enabling the system to reduce memory usage without resorting to swapping pages



Summary

- *Virtual memory* abstracts physical memory into an extremely large uniform array of storage.
- The *benefits* of virtual memory include the following: (1) a program can be larger than physical memory, (2) a program does not need to be entirely in memory, (3) processes can share memory, and (4) processes can be created more efficiently.
- *Demand paging* is a technique whereby pages are loaded only when they are demanded during program execution. Pages that are never demanded are thus never loaded into memory.
- A *page fault* occurs when a page that is currently not in memory is accessed. The page must be brought from the backing store into an available page frame in memory.

Summary (Cont.)

- *Copy-on-write* allows a child process to share the same address space as its parent. If either the child or the parent process writes (modifies) a page, a copy of the page is made.
- When available memory runs low, a *page-replacement algorithm* selects an existing page in memory to replace with a new page. Page-replacement algorithms include FIFO, optimal, and LRU. Pure LRU algorithms are impractical to implement, and most systems instead use LRU-approximation algorithms.
- *Global page-replacement algorithms* select a page from any process in the system for replacement, while *local page-replacement algorithms* select a page from the faulting process.
- *Thrashing* occurs when a system spends more time paging than executing.

Summary (Cont.)

- A *locality* represents a set of pages that are actively used together. As a process executes, it moves from locality to locality. *A working set* is based on locality and is defined as the set of pages currently in use by a process.
- *Memory compression* is a memory-management technique that compresses a number of pages into a single page. Compressed memory is an alternative to paging and is used on mobile systems that do not support paging.
- *Kernel memory* is allocated differently than user-mode processes; it is allocated in contiguous chunks of varying sizes. Two common techniques for allocating kernel memory are (1) the buddy system and (2) slab allocation.

Summary (Cont.)

- *TLB reach* refers to the amount of memory accessible from the TLB and is equal to the number of entries in the TLB multiplied by the page size. One technique for increasing TLB reach is to increase the size of pages.
- **Linux**, **Windows**, and **Solaris** manage virtual memory similarly, using demand paging and copy-on-write, among other features. Each system also uses a variation of LRU approximation known as the clock algorithm.

End of Chapter 10