

Chapter 10: Virtual Memory





Chapter 10: Virtual Memory

- Background
- Demand Paging
- Copy-on-Write
- Page Replacement
- Allocation of Frames
- Thrashing
- Memory-Mapped Files
- Allocating Kernel Memory





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.





Background

- We discussed various memory-management strategies
- All these strategies have the same goal: to keep many processes in memory simultaneously to allow multiprogramming
- One major advantage of this scheme is that programs can be larger than physical memory.
- This technique frees programmers from the concerns of memory-storage limitations
- Virtual memory also allows processes to share files and libraries, and to implement shared memory





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
 - Each program takes less memory while running -> more programs run at the same time
 - ▶ Increased CPU utilization and throughput with 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 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





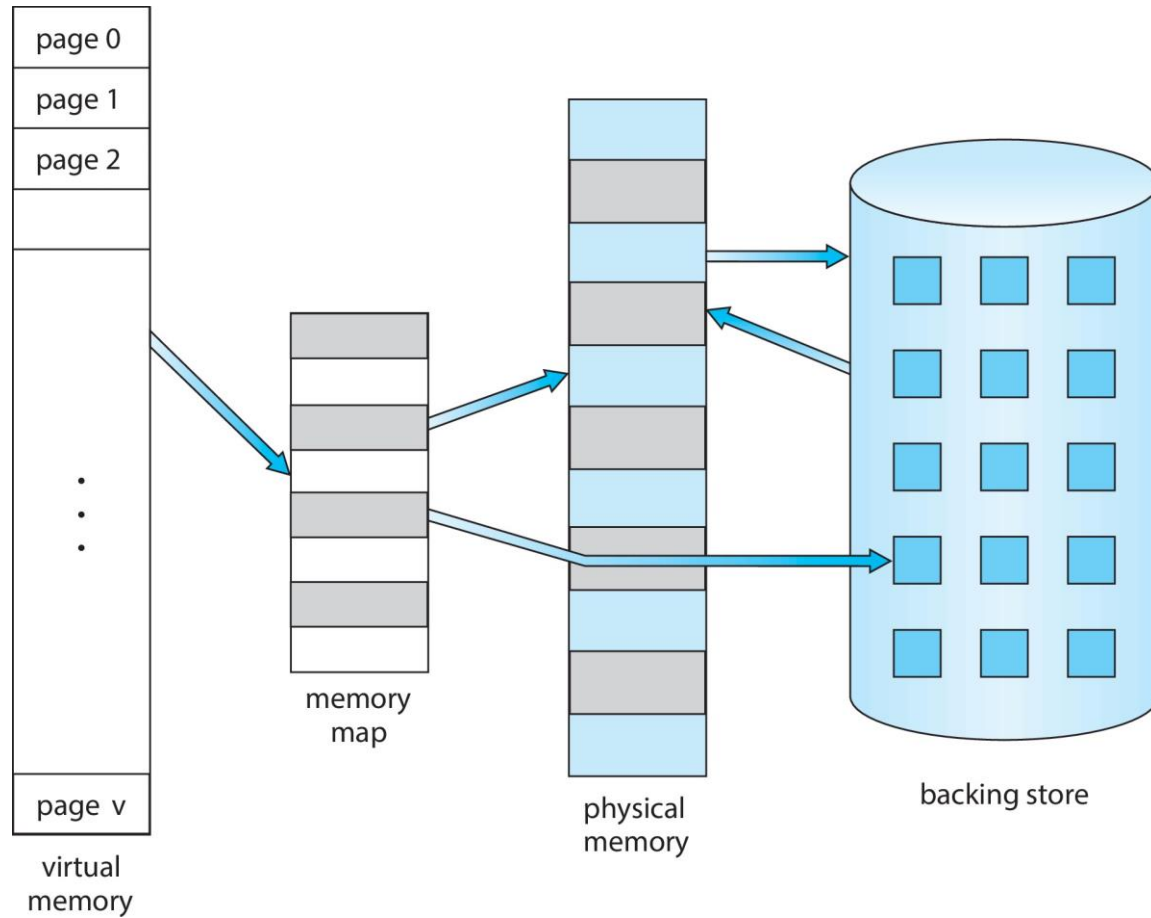
Virtual memory (Cont.)

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





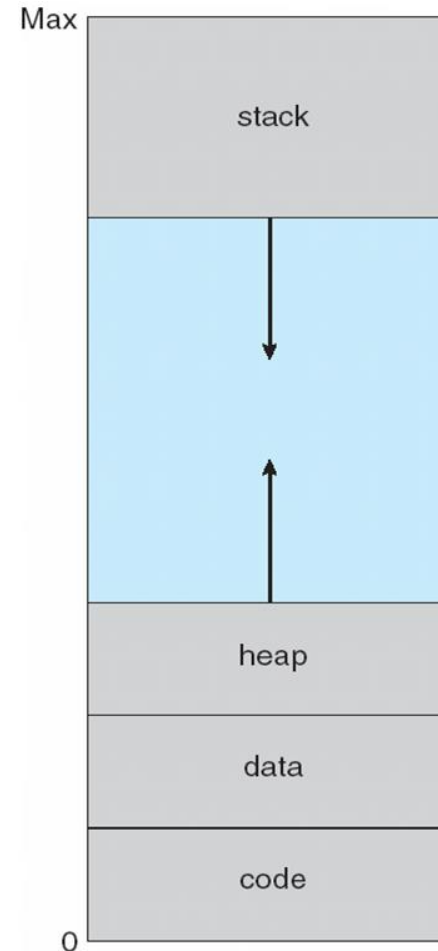
Virtual Memory That is Larger Than Physical Memory





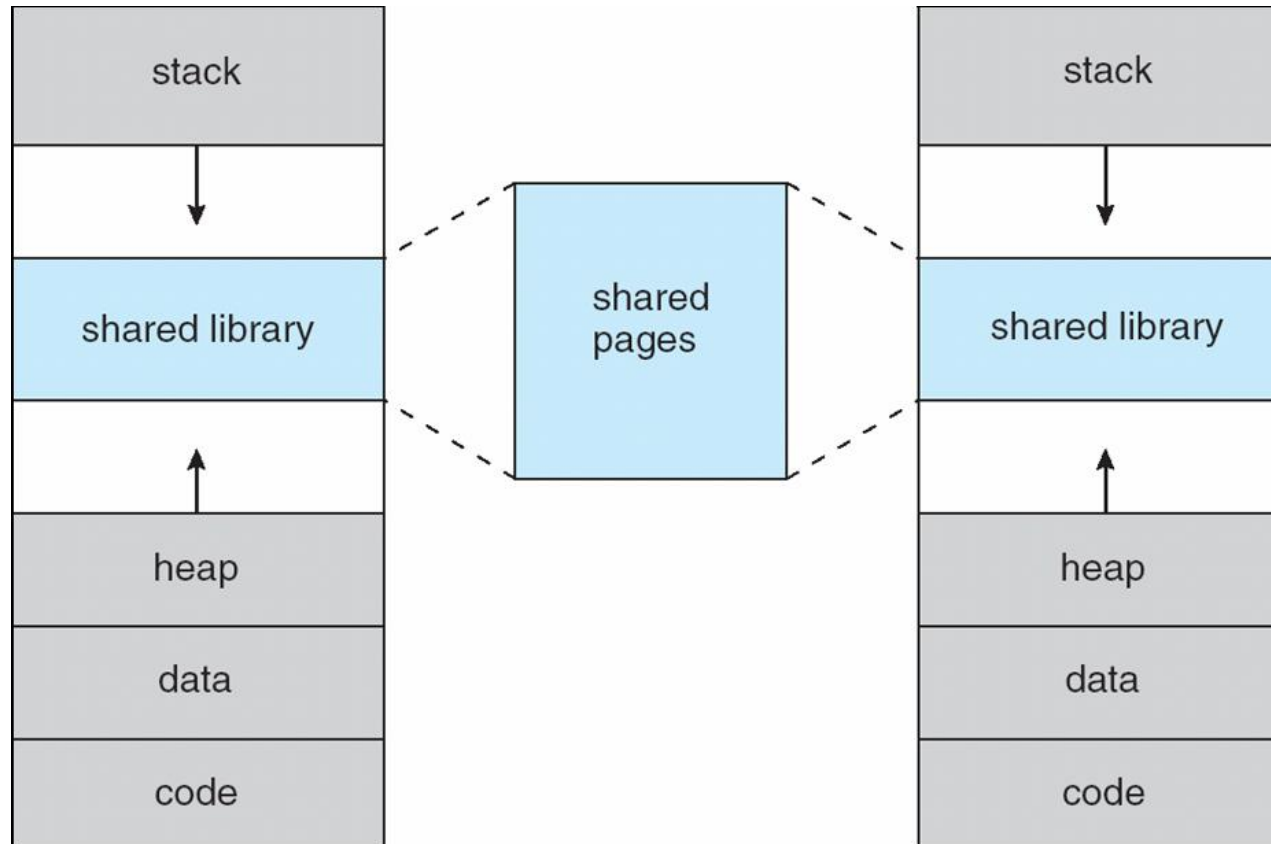
Virtual-address Space

- Usually design logical address space for stack to start at Max logical address and grow “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

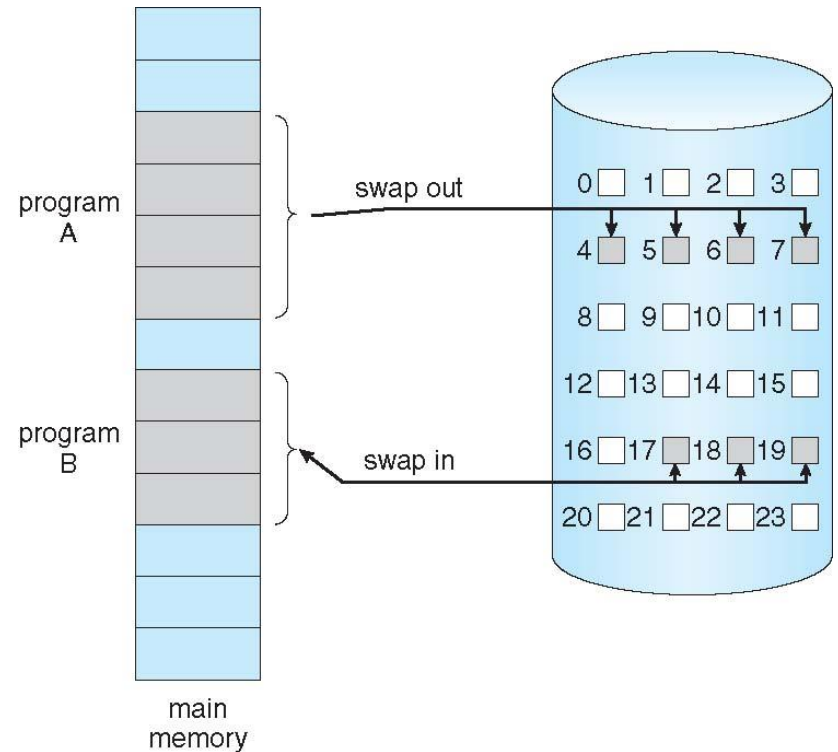
- Could bring entire process into memory at load time
- Or bring a page into memory only when it is needed
 - Less I/O needed, no unnecessary I/O
 - Less memory needed
 - Faster response
 - More users
- Similar to paging system with swapping





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 (diagram on right)





Basic Concepts

- 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 and 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

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

Frame #	valid-invalid bit
	v
	v
	v
	i
...	
	i
	i

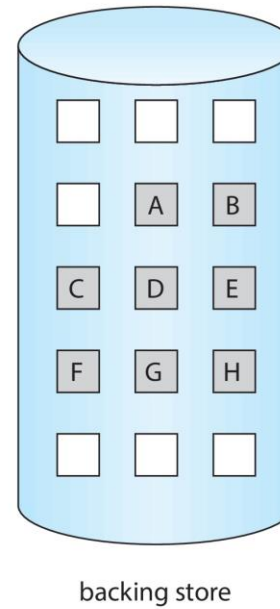
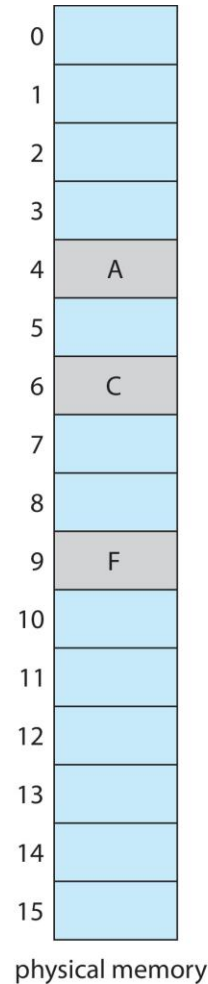
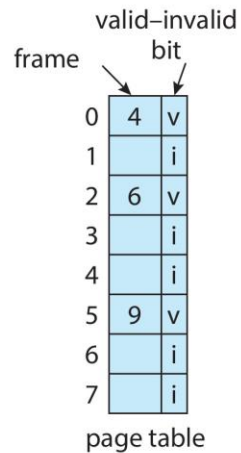
page table

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





Page Table When Some Pages Are Not in Main Memory





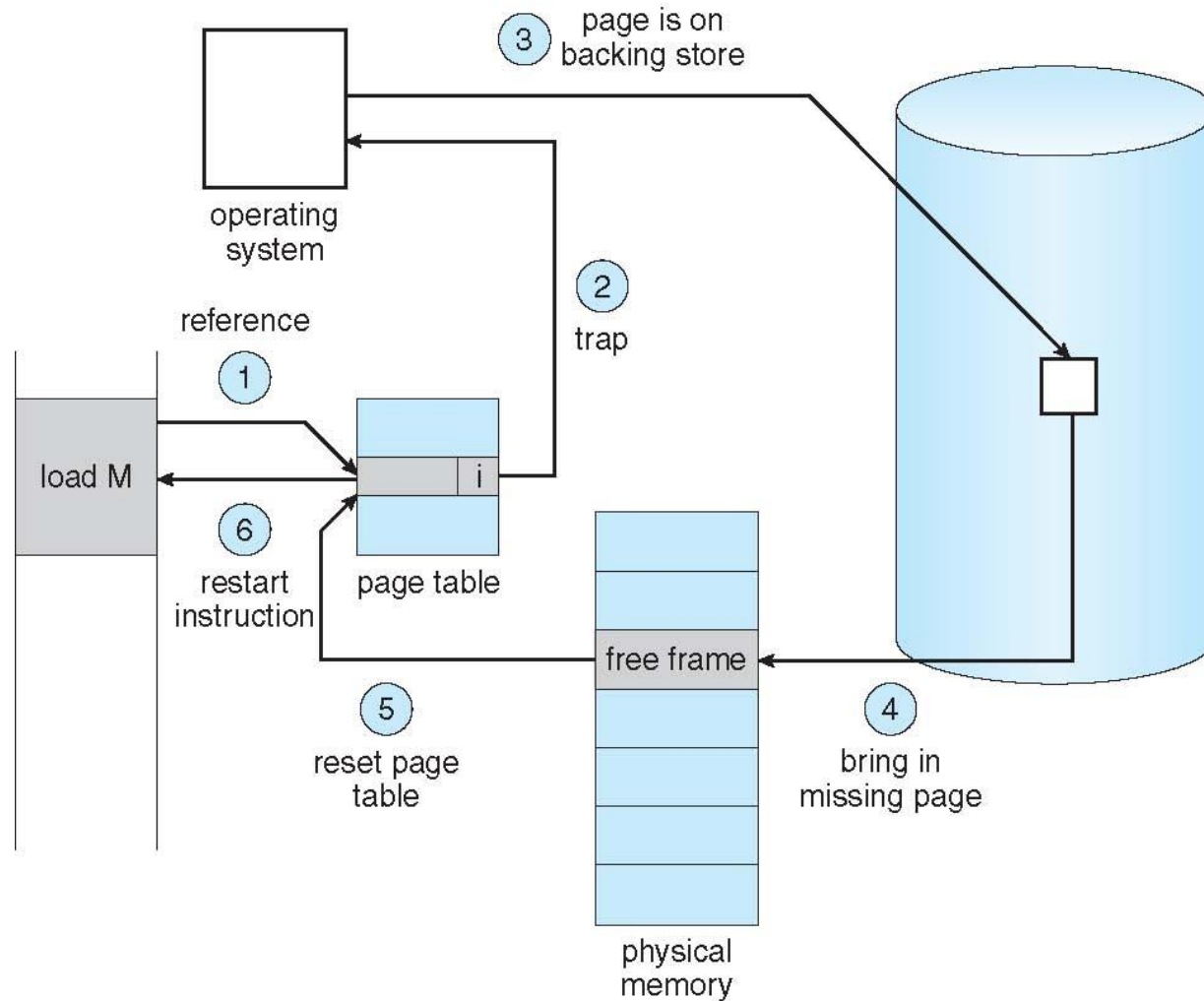
Steps in Handling Page Fault

1. If there is a reference to a page, first reference to that page will trap to operating system
 - Page fault
2. Operating system looks at another table to decide:
 - Invalid reference \Rightarrow abort
 - Just not in memory
3. Find free frame
4. Swap page into frame via scheduled disk operation
5. Reset tables to indicate page now in memory
Set validation 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
 - 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**)





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

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:
 - a) Wait in a queue for this device until the read request is serviced
 - b) Wait for the device seek and/or latency time
 - c) 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
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

- 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 $0 \leq p \leq 1$
 - if $p = 0$ no page faults
 - if $p = 1$, every reference is a fault
- Effective Access Time (EAT)
EAT = $(1 - p) \times \text{memory access}$
+ p (page fault overhead
+ swap page out
+ swap page in)





Demand Paging Example

- Memory access time = 200 nanoseconds
- Average page-fault service time = 8 milliseconds
- $EAT = (1 - p) \times 200 + p (8 \text{ milliseconds})$
 $= (1 - p) \times 200 + p \times 8,000,000$
 $= 200 + p \times 7,999,800$
- 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
 - $220 > 200 + 7,999,800 \times p$
 $20 > 7,999,800 \times p$
 - $p < .0000025$
 - < one page fault in every 400,000 memory accesses





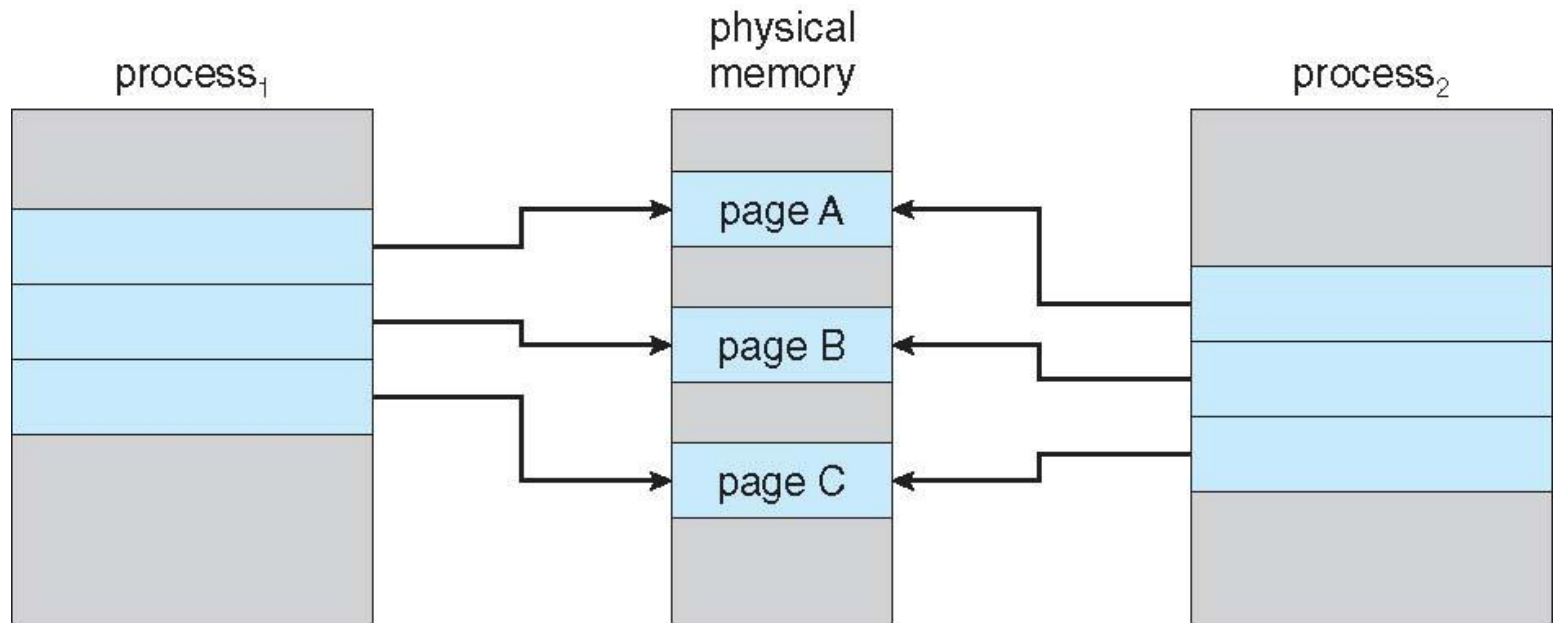
Copy-on-Write

- **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
- `vfork()` variation on `fork()` system call has parent suspend and child using address space of parent
 - Designed to have child call `exec()`
 - Very efficient



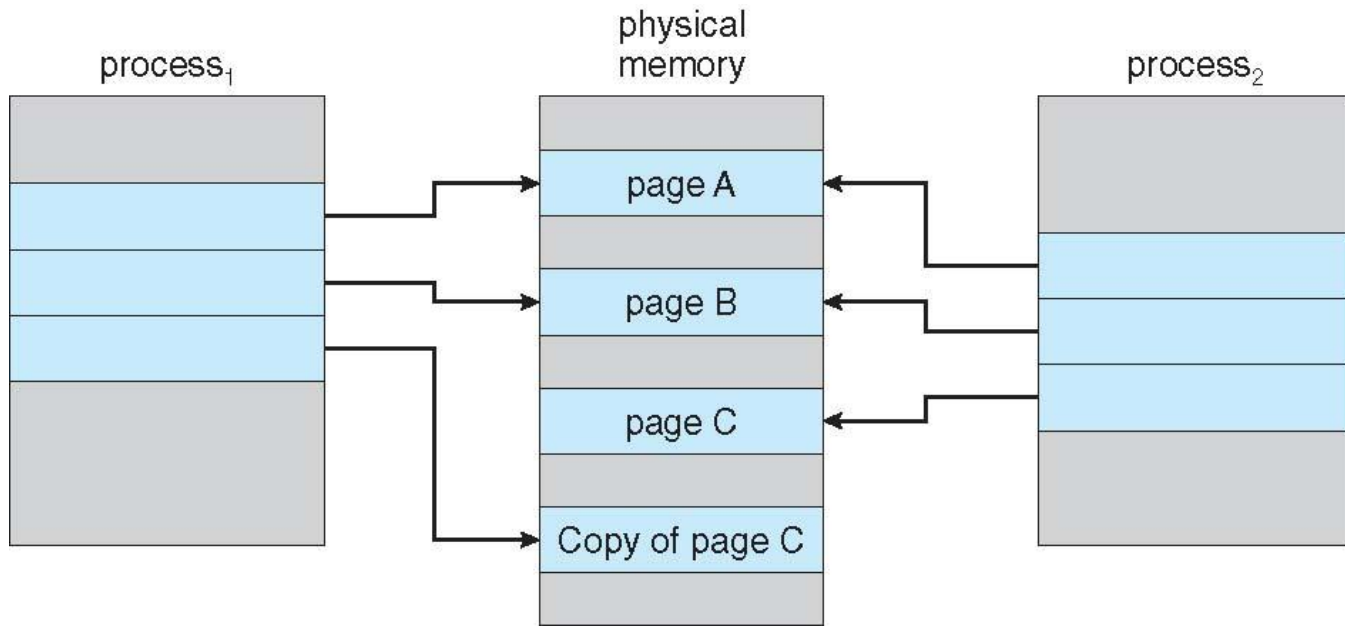


Before Process 1 Modifies Page C





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





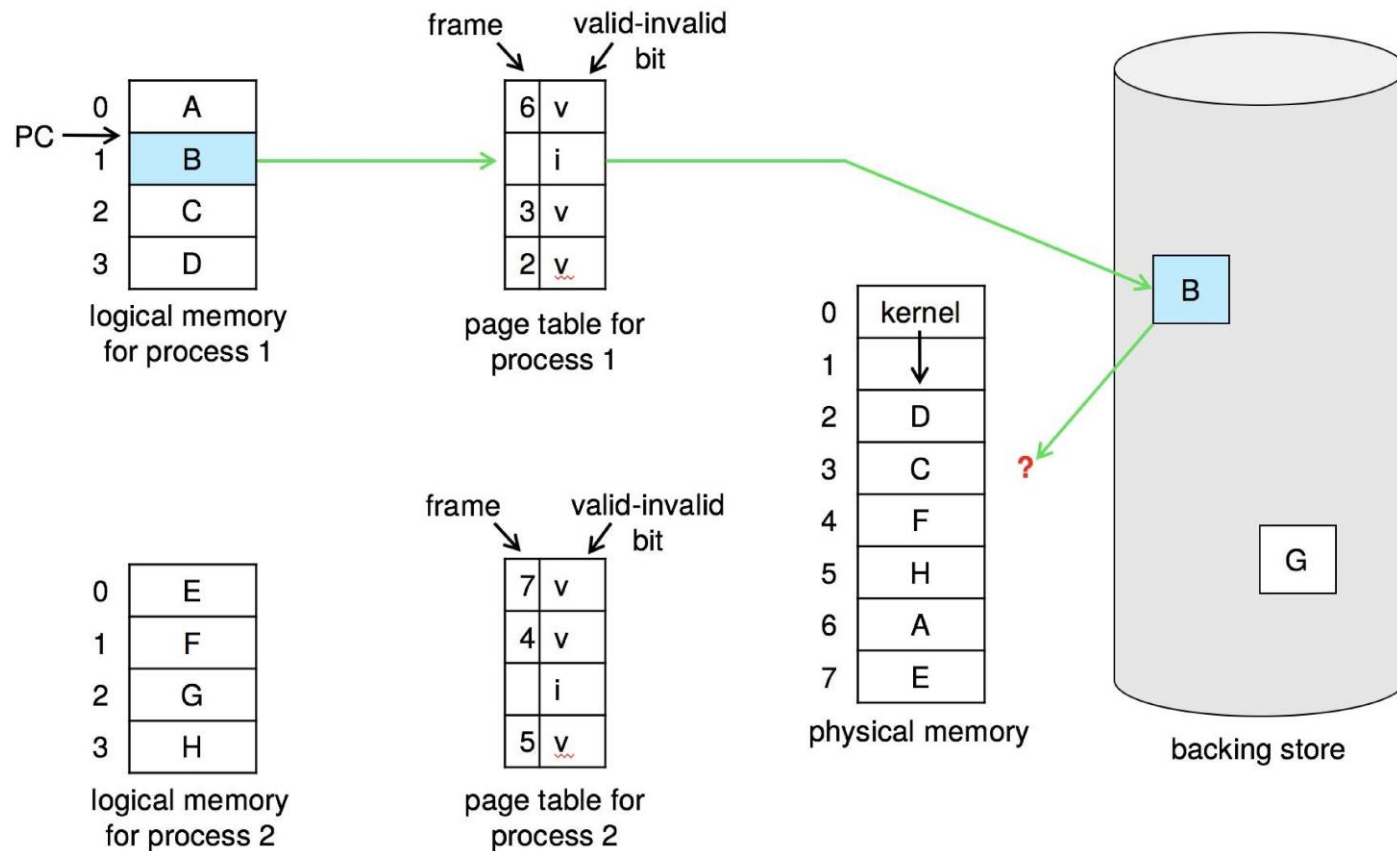
Page Replacement

- 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

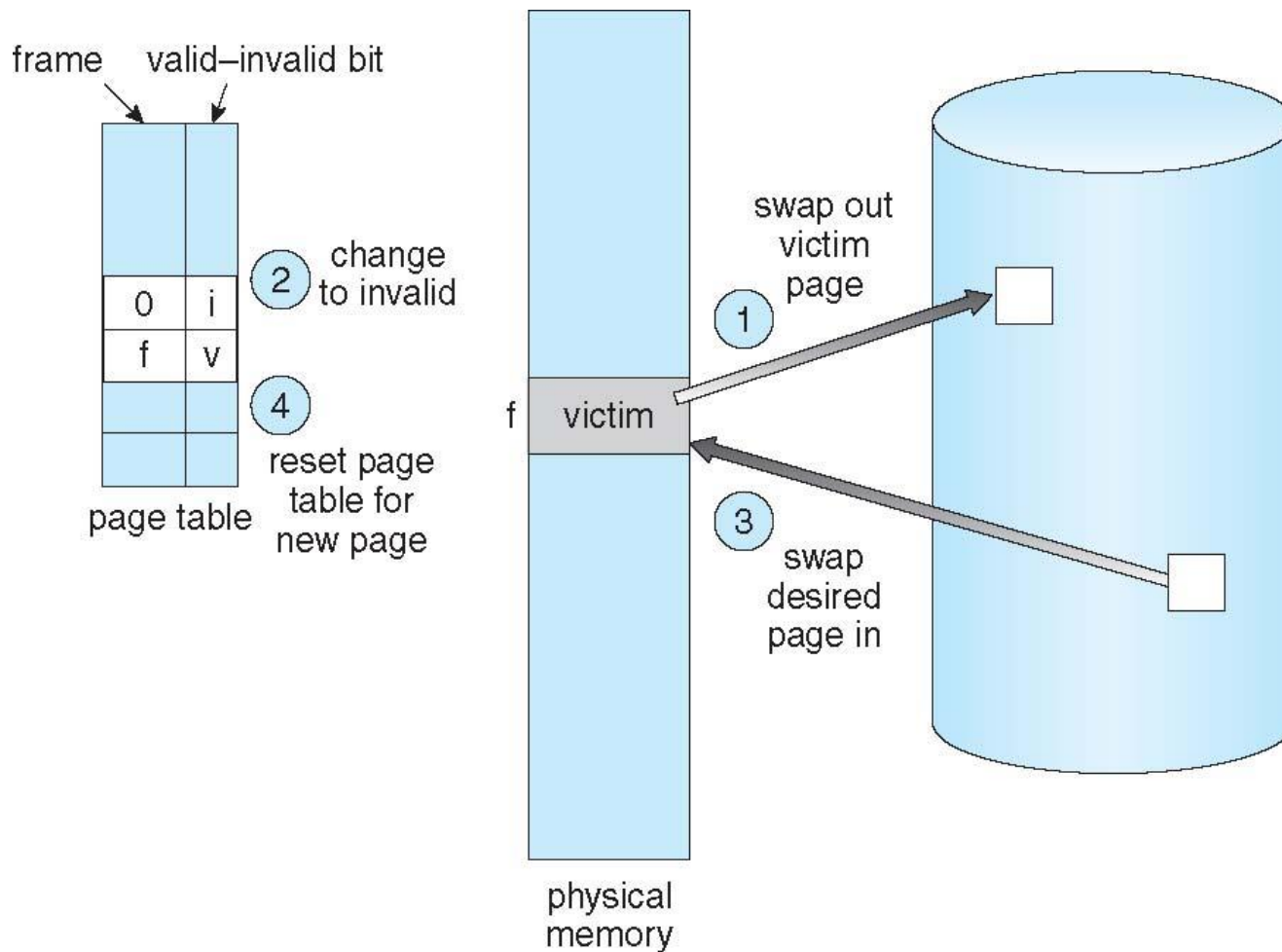
1. Find the location of the desired page on disk
2. Find a free frame:
 - If there is a free frame, use it
 - If there is no free frame, use a page replacement algorithm to select a **victim frame**
 - Write victim frame to disk if dirty
3. Bring the desired page into the (newly) free frame; update the 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 EAT





Page Replacement





Page and Frame Replacement Algorithms

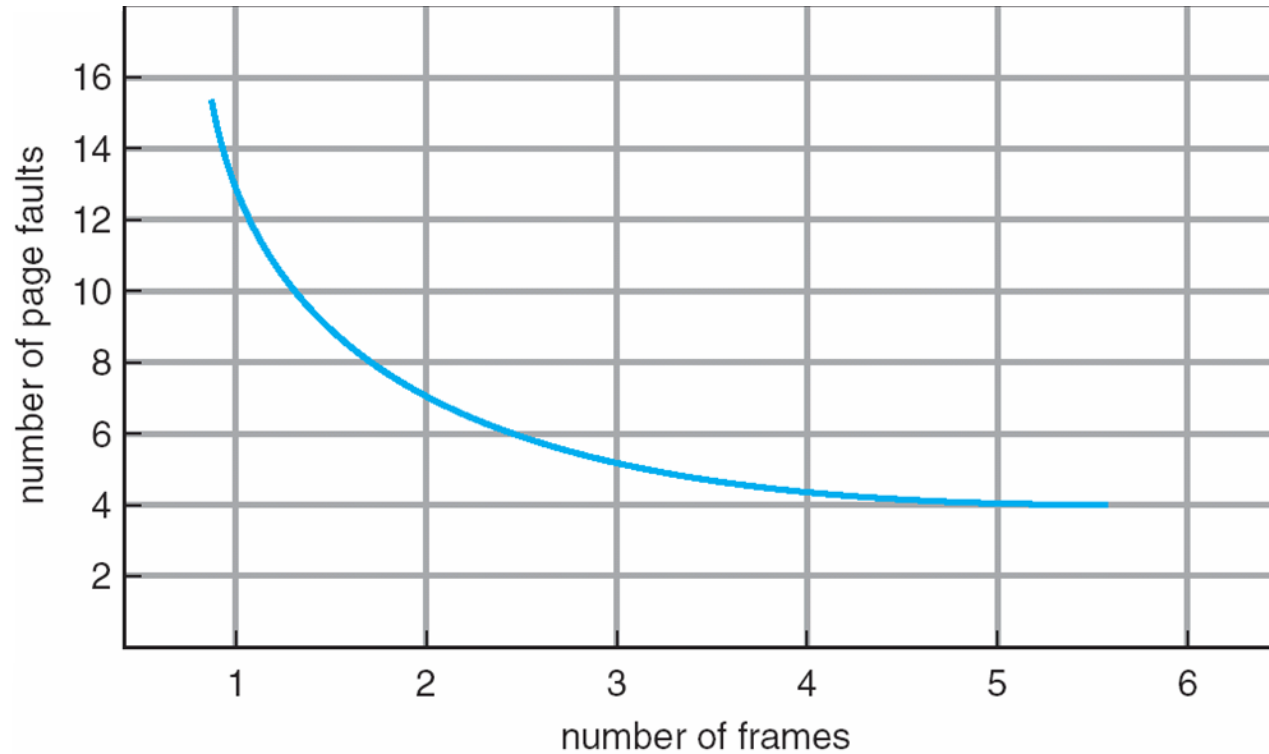
- **Frame-allocation algorithm** determines
 - How many frames to give each process
 - Which frames to replace
- **Page-replacement algorithm**
 - Want lowest page-fault rate on both first access and re-access
- Evaluate algorithm by running it on a particular string of memory references (reference string) 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: **7,0,1,2,0,3,0,4,2,3,0,3,2,1,2,0,1,7,0,1**
- 3 frames (3 pages can be in memory at a time per process)

reference string

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

7	7	7	2																
	0	0	0																
			1	1															

page frames

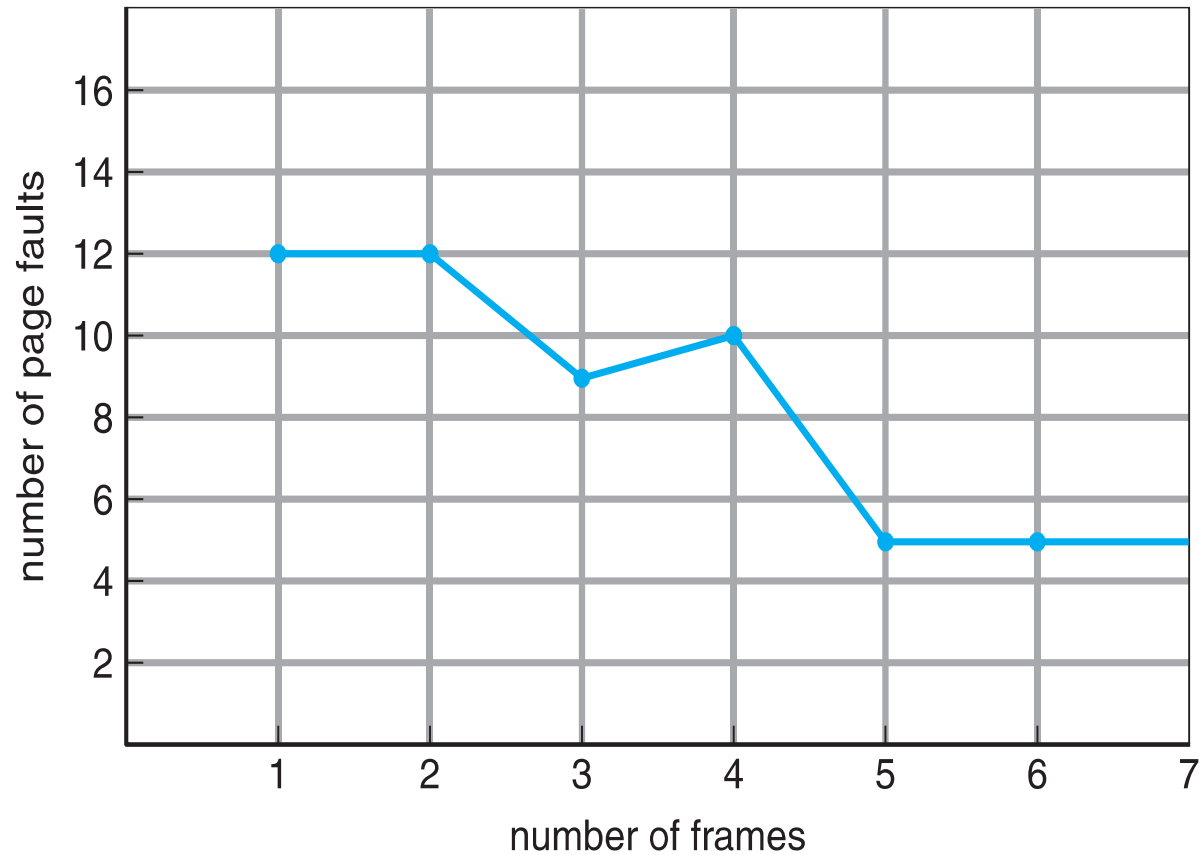
15 page faults

- 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**





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
- Used for measuring how well your algorithm performs

reference string

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

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

page frames





Least Recently Used (LRU) Algorithm

- 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

reference string

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

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

page frames

- 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 Algorithm (Cont.)

- 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

reference string

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

2
1
0
7
4

stack
before
a

7
2
1
0
4

stack
after
b

↑ ↑
a b





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





LRU Approximation Algorithms (cont.)

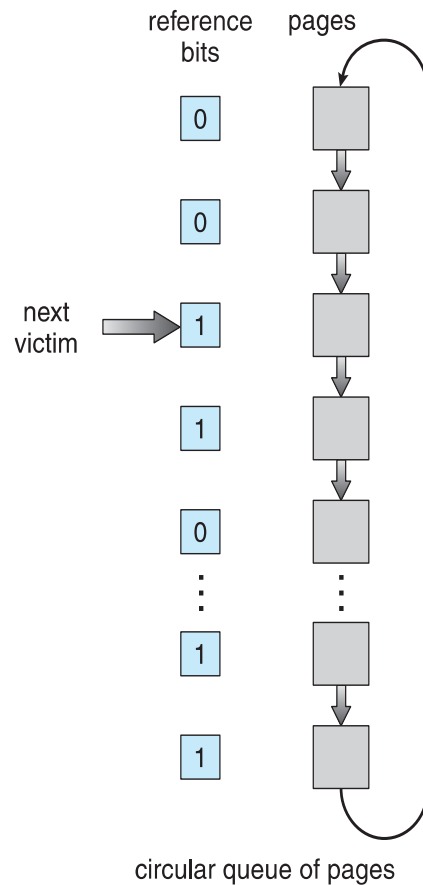
■ Second-chance algorithm

- 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

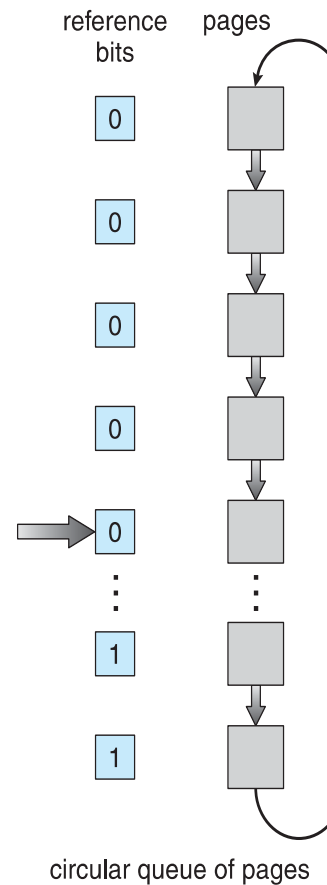




Second-chance Algorithm



(a)



(b)





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





Allocation of Frames

- Each process needs *minimum* number of frames
- *Maximum* of course is total frames in the system
- Two major allocation schemes
 - fixed allocation
 - priority allocation





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 = size of process p_i

– $S = \sum s_i$

– m = total number of frames

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

$$m = 62$$

$$s_1 = 10$$

$$s_2 = 127$$

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

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





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





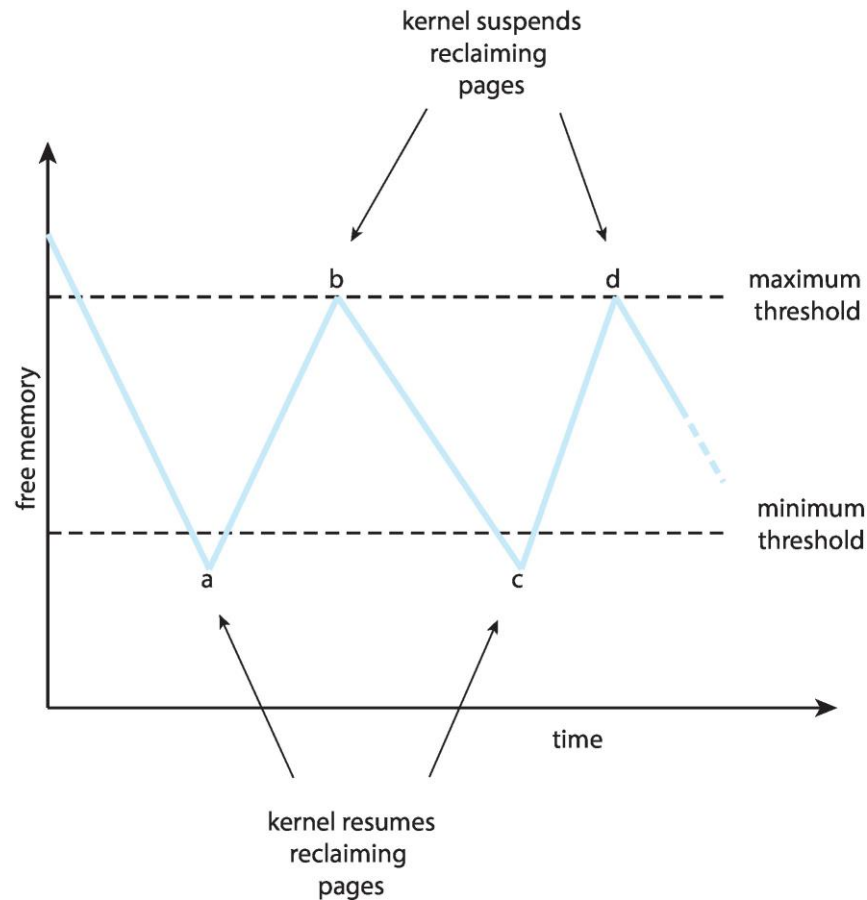
Reclaiming Pages

- A strategy to implement global page-replacement policy
- 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.





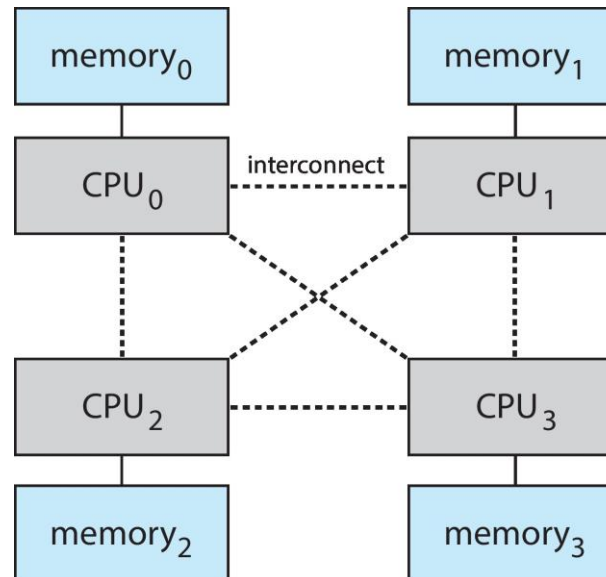
Reclaiming Pages Example

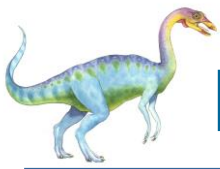




Non-Uniform Memory Access

- 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





Thrashing

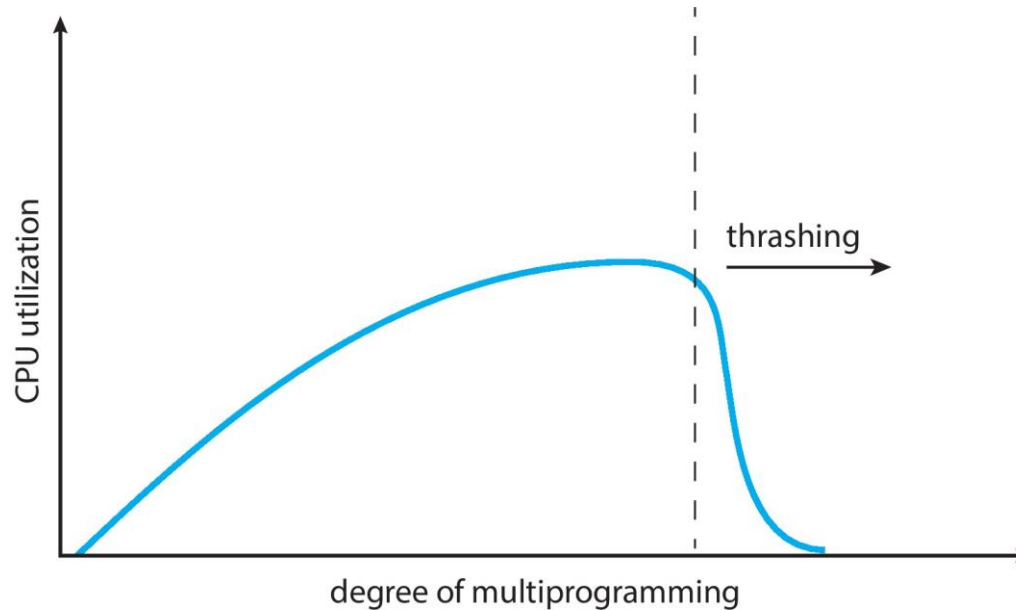
- If a process does not have “enough” pages, the page-fault rate is very high
 - Page fault to get page
 - Replace existing frame
 - But quickly need replaced frame back
 - This leads to:
 - ▶ Low CPU utilization
 - ▶ Operating system thinking that it needs to increase the degree of multiprogramming
 - ▶ Another process added to the system





Thrashing (Cont.)

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





Demand Paging and Thrashing

- Why does demand paging work?

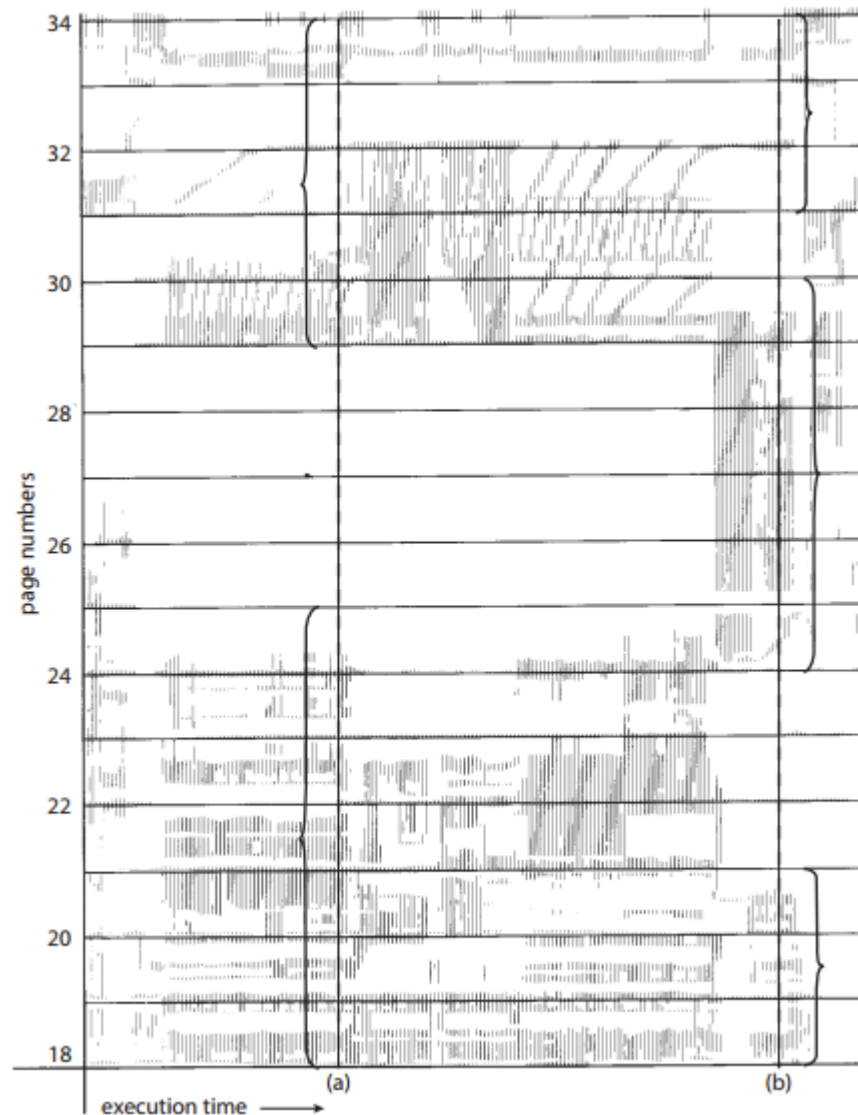
Locality model

- 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
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
- $D = \sum WSS_i \equiv$ total demand frames
 - Approximation of locality



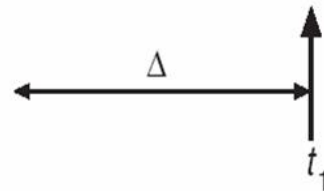


Working-Set Model (Cont.)

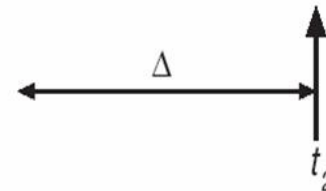
- if $D > m \Rightarrow$ Thrashing
- Policy if $D > m$, then suspend or swap out one of the processes

page reference table

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



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



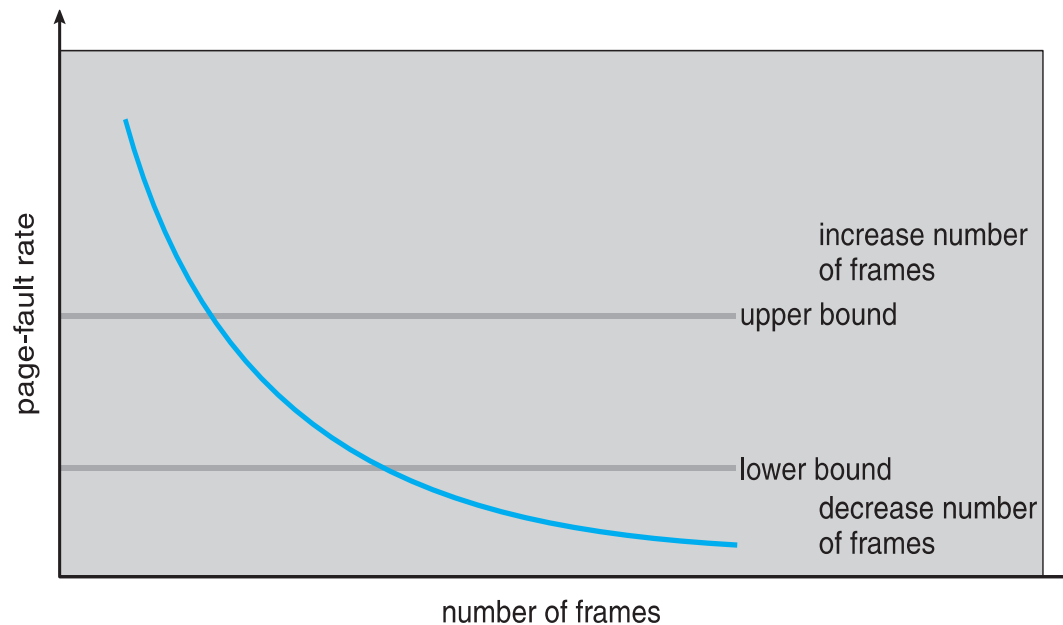
$WS(t_2) = \{3, 4\}$





Page-Fault Frequency

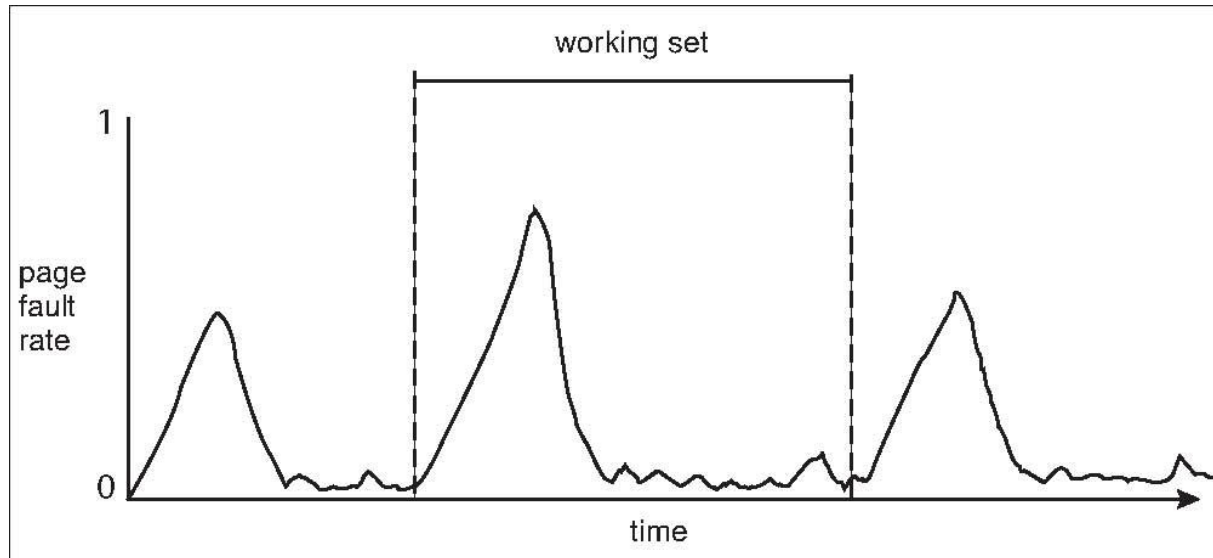
- More direct approach than WSS
- Establish “acceptable” **page-fault frequency (PFF)** rate and use local replacement policy
 - If actual rate too low, process loses frame
 - If actual rate too high, process gains frame





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





Memory Compression

- **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.
- 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, 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.

free-frame list

head → 2 → 9 → 21 → 27 → 16 → 15 → 3 → 35

modified frame list

head → 26

compressed frame list

head → 7





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





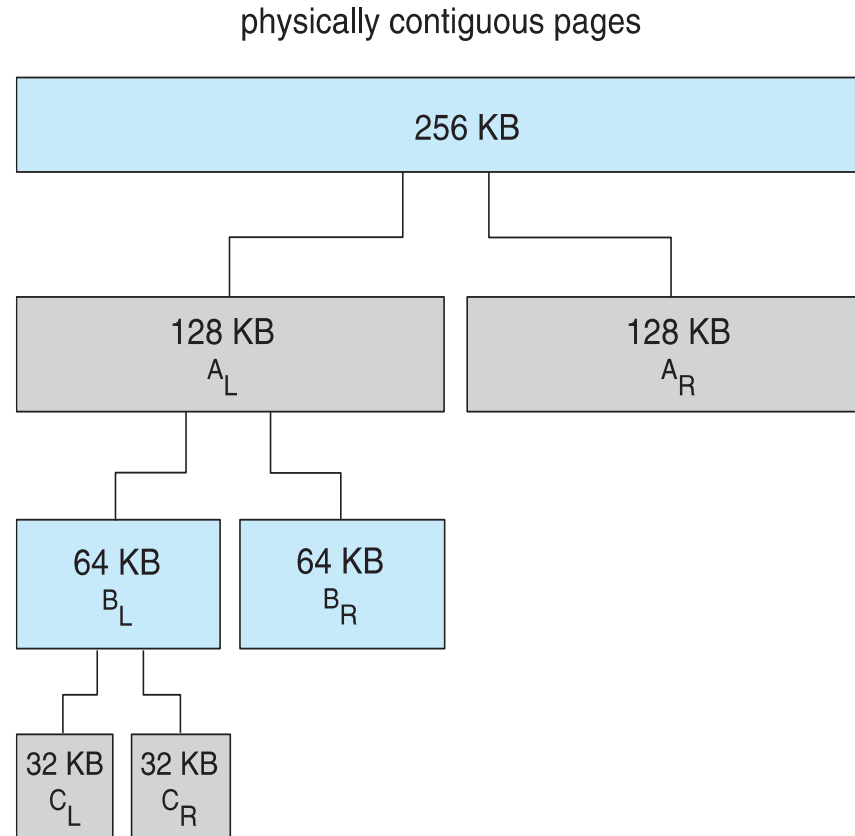
Buddy System

- 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





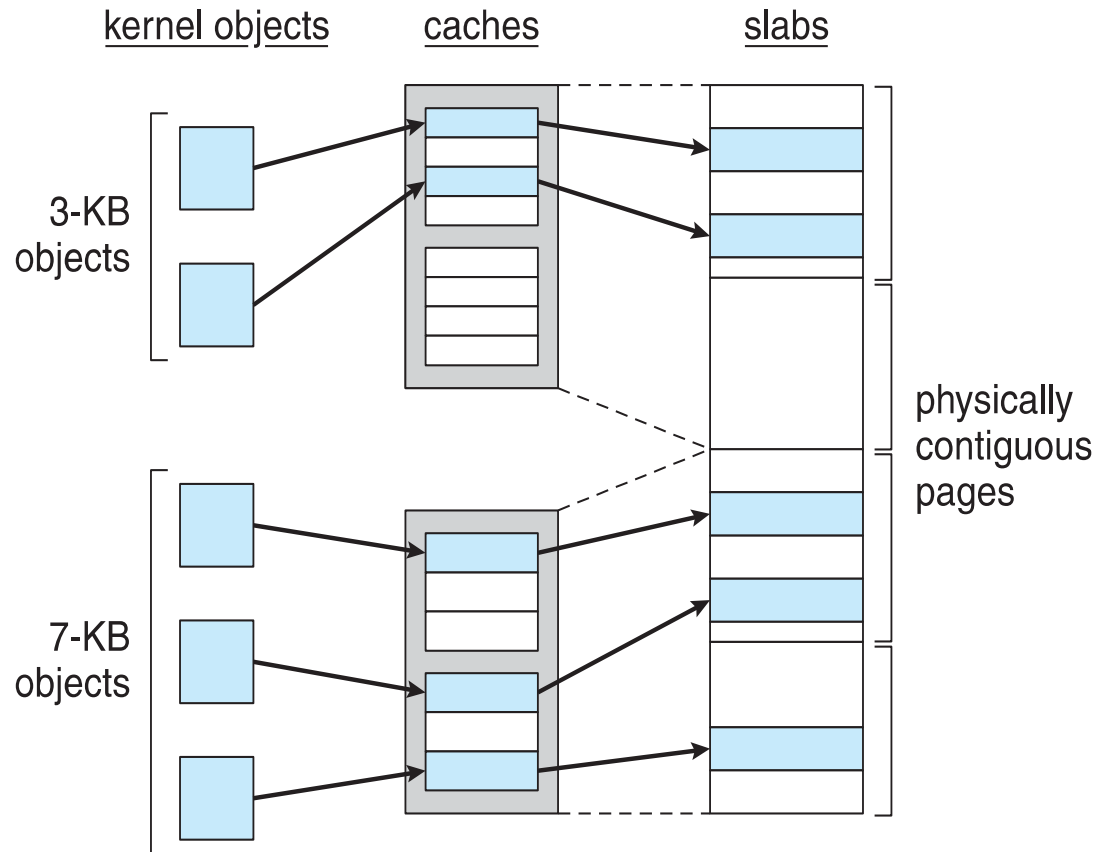
Slab Allocator

- 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
- Page size
- TLB reach
- Inverted page table
- Program structure





Prepaging

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





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





TLB Reach

- TLB Reach - The amount of memory accessible from the TLB
- $\text{TLB Reach} = (\text{TLB Size}) \times (\text{Page Size})$
- Ideally, the working set of each process is stored in the TLB
 - Otherwise there is a high degree of page faults
- Increase the Page Size
 - This may lead to an increase in fragmentation as not all applications require a large page size
- Provide Multiple Page Sizes
 - This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation





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



End of Chapter 10

