

Chapter 9: Virtual Memory





Chapter 9: 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





Background (Cont.)

- **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





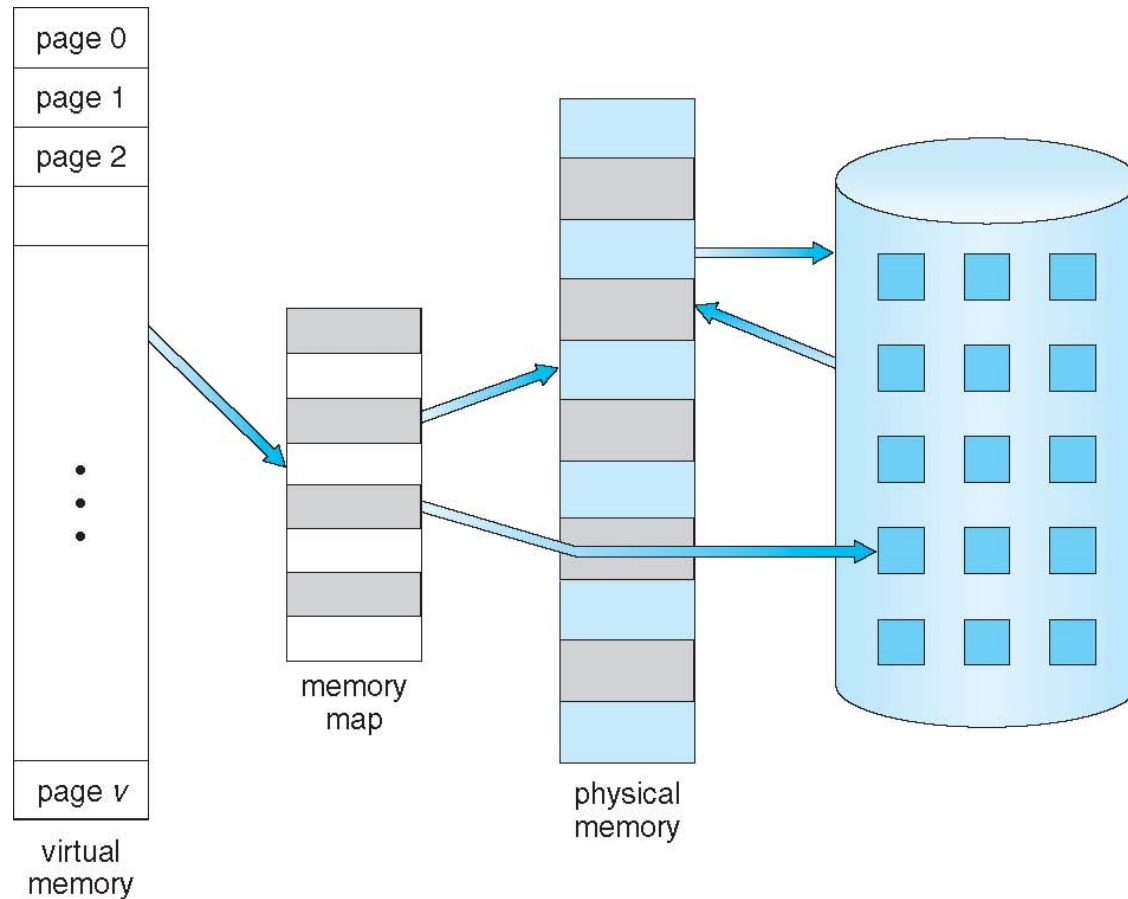
Background (Cont.)

- **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





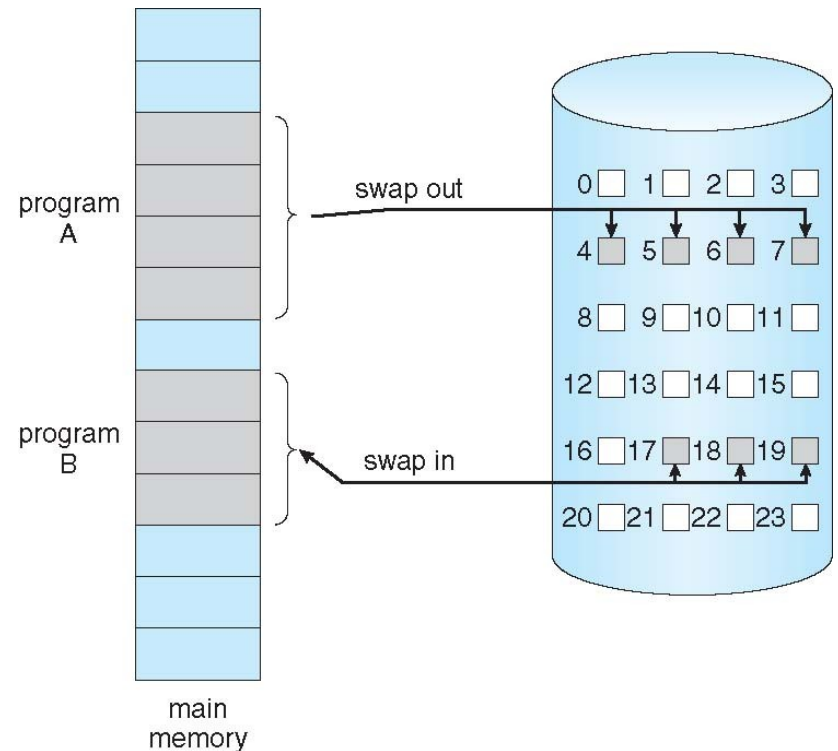
Virtual Memory That is Larger Than Physical Memory





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)
- Page is needed \Rightarrow reference to it
 - invalid reference \Rightarrow abort
 - not-in-memory \Rightarrow bring to memory
- **Lazy swapper** – never swaps a page into memory unless page will be needed
 - Swapper that deals with pages is a **pager**





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





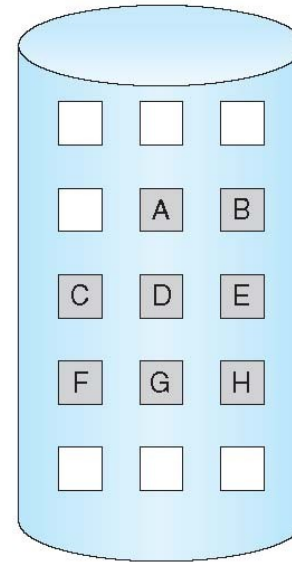
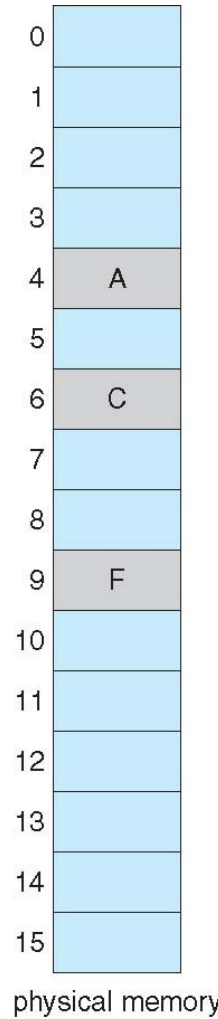
Page Table When Some Pages Are Not in Main Memory

0	A
1	B
2	C
3	D
4	E
5	F
6	G
7	H

logical
memory

valid-invalid bit		
frame		
0	4	v
1		i
2	6	v
3		i
4		i
5	9	v
6		i
7		i

page table





Page Fault

- If there is a reference to a page, first reference to that page will trap to operating system:

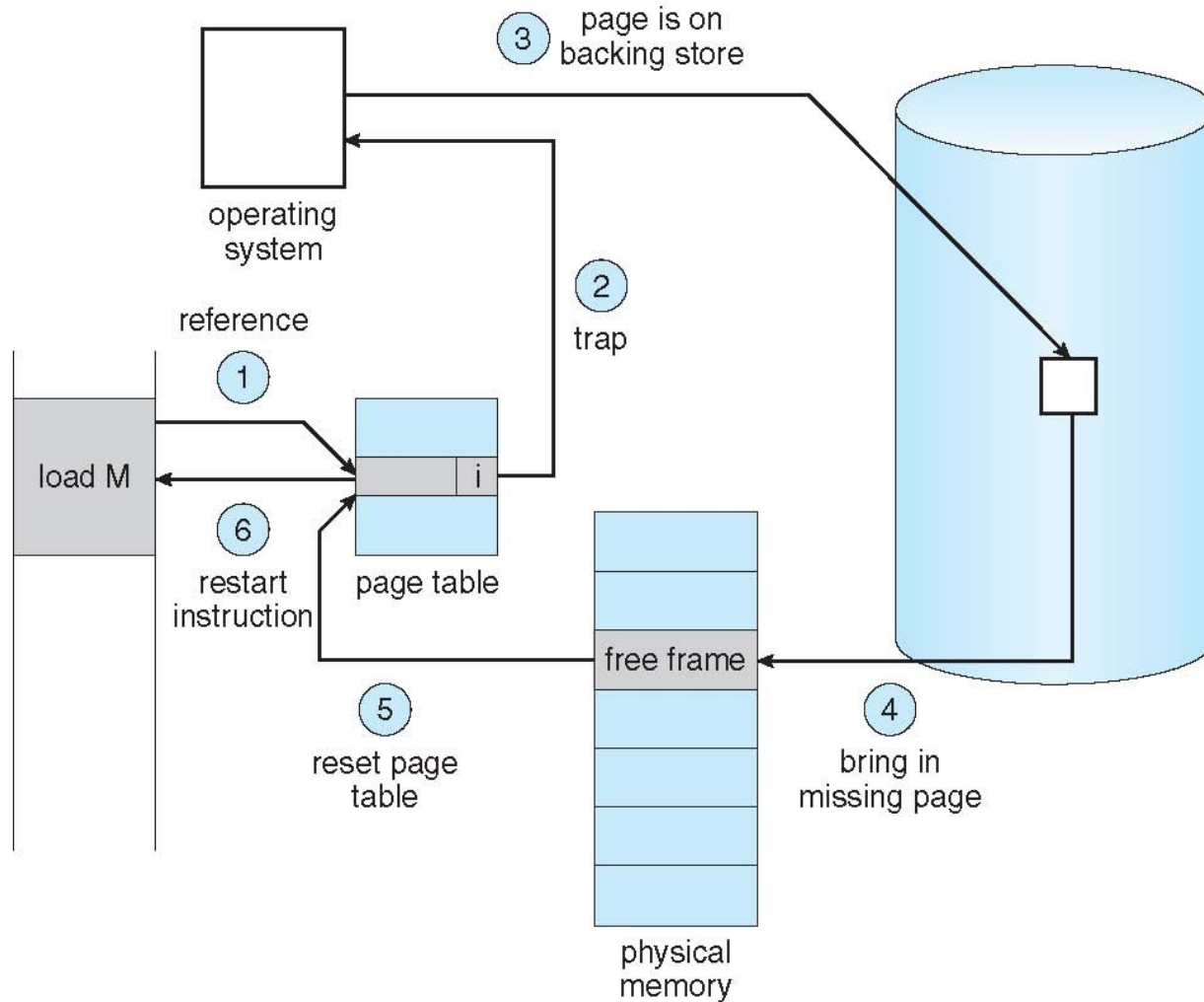
page fault

1. Operating system looks at another table to decide:
 - Invalid reference \Rightarrow abort
 - Just not in memory
2. Find free frame
3. Swap page into frame via scheduled disk operation
4. Reset tables to indicate page now in memory
Set validation bit = **v**
5. Restart the instruction that caused the page fault





Steps in Handling a 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
 - Consider fetch and decode of instruction which adds 2 numbers from memory and stores result back to memory
 - Pain decreased because of **locality of reference**
- Hardware support needed for demand paging
 - Page table with valid / invalid bit
 - Secondary memory (swap device with **swap space**)
 - Instruction restart





Performance of Demand Paging

■ Stages in Demand Paging (worse case)

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





Demand Paging Optimizations

- Swap space I/O faster than file system I/O even if on the same device
 - Swap allocated in larger chunks, less management needed than file system
- Copy entire process image to swap space at process load time
 - Then page in and out of swap space
 - Used in older BSD Unix
- Demand page in from program binary on disk, but discard rather than paging out when freeing frame
 - Used in Solaris and current BSD
 - Still need to write to swap space
 - Pages not associated with a file (like stack and heap) – **anonymous memory**
 - Pages modified in memory but not yet written back to the file system
- Mobile systems
 - Typically don't support swapping
 - Instead, demand page from file system and reclaim read-only pages (such as code)





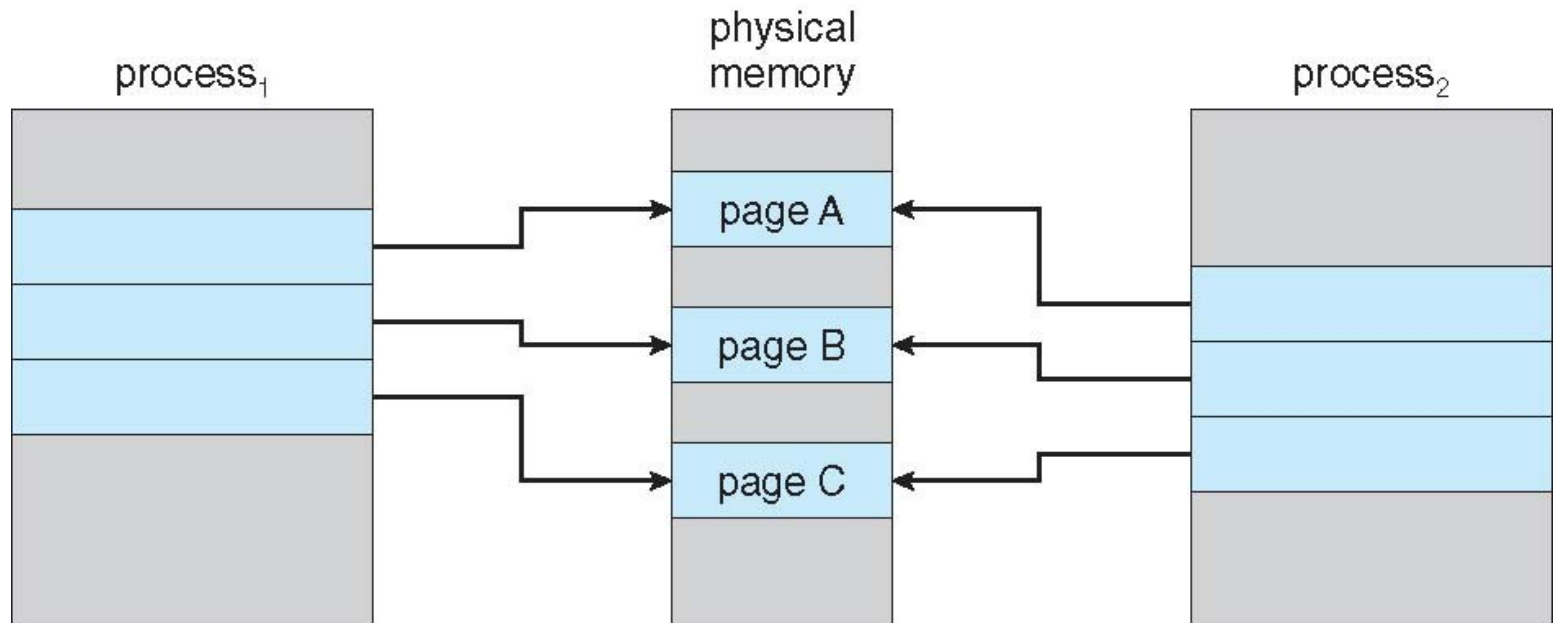
Copy-on-Write

- **Copy-on-Write** (COW) allows both parent and child processes to initially **share** the same pages in memory
 - If either process modifies a shared page, only then is the page copied
- COW allows more efficient process creation as only modified pages are copied
- In general, free pages are allocated from a **pool** of **zero-fill-on-demand** pages
 - Pool should always have free frames for fast demand page execution
 - ▶ Don't want to have to free a frame as well as other processing on page fault
 - Why zero-out a page before allocating it?
- `vfork()` variation on `fork()` system call has parent suspend and child using copy-on-write address space of parent
 - Designed to have child call `exec()`
 - Very efficient



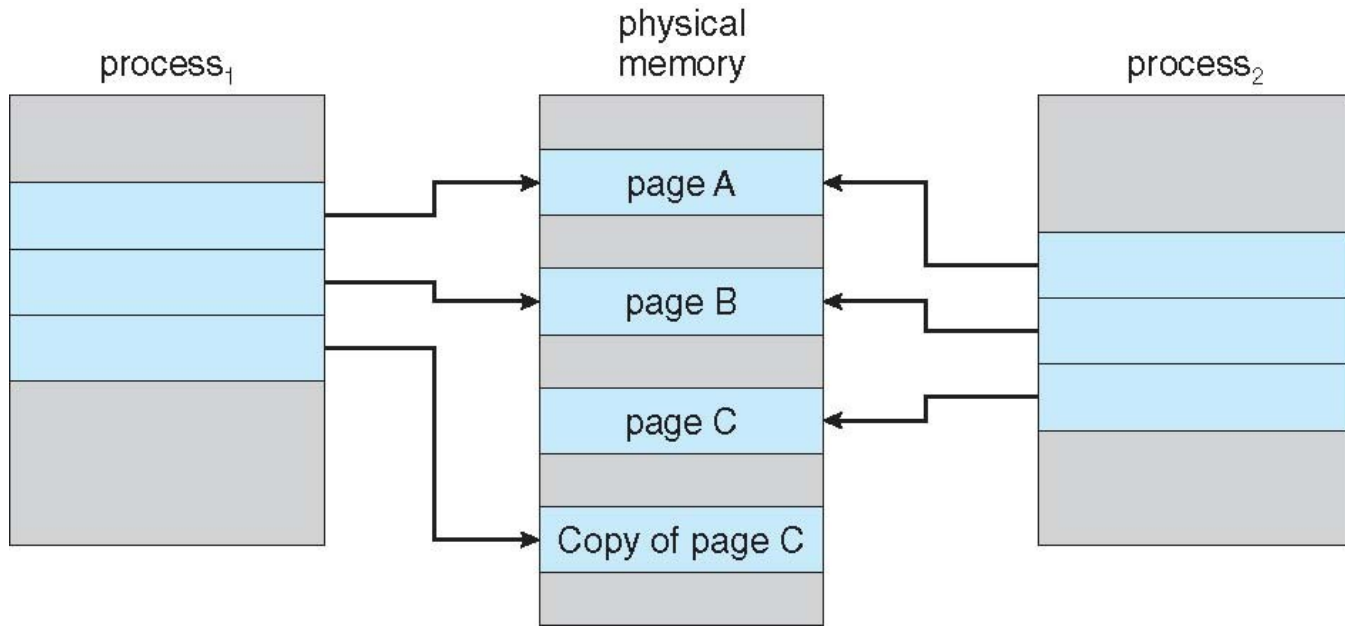


Before Process 1 Modifies Page C





After Process 1 Modifies Page C





What Happens if There is no Free Frame?

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





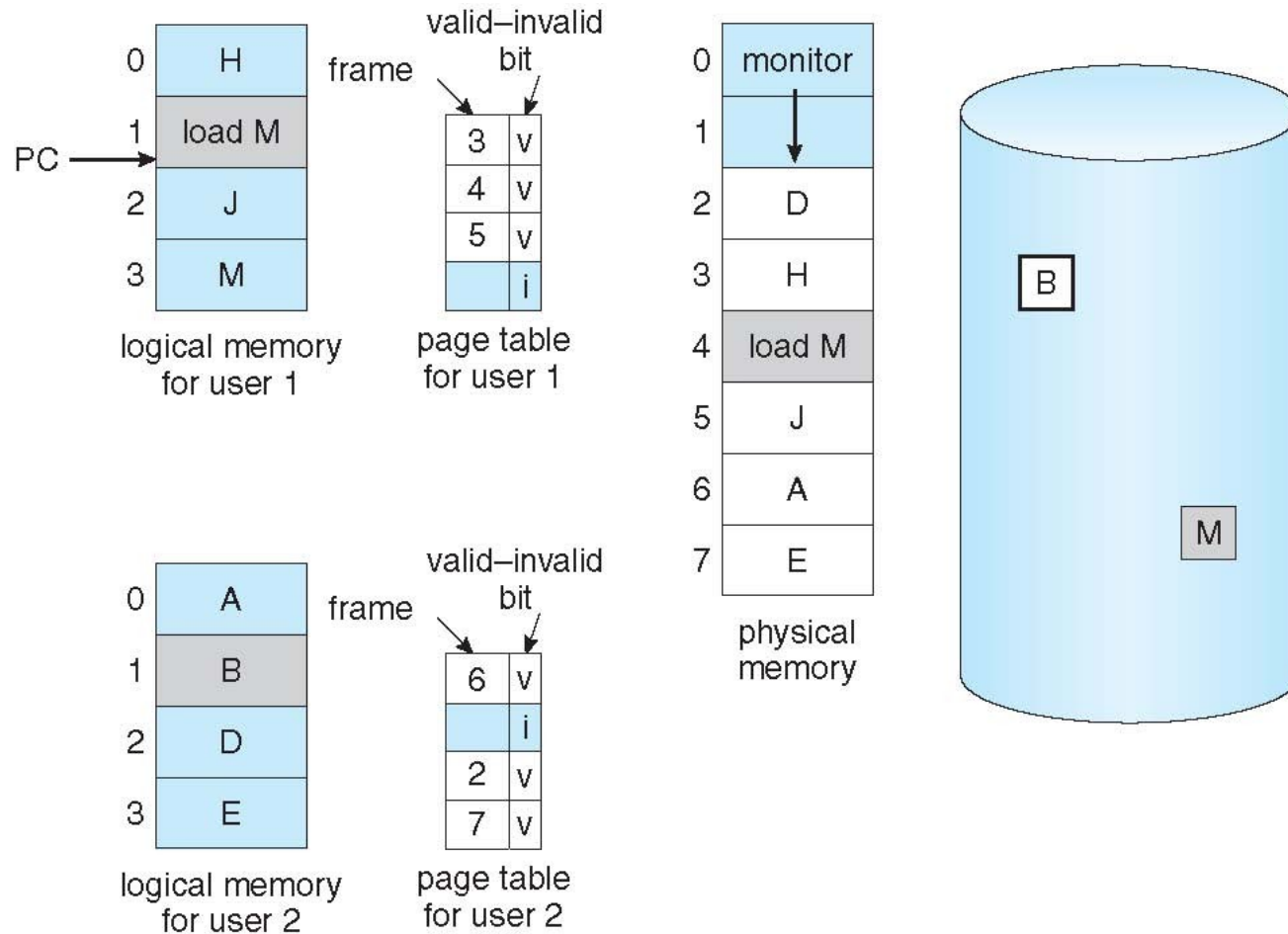
Page Replacement

- Prevent **over-allocation** of memory by modifying page-fault service routine to include page replacement
- Use **modify (dirty) bit** to reduce overhead of page transfers – only modified pages are written to disk
- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory





Need For Page Replacement





Basic Page Replacement

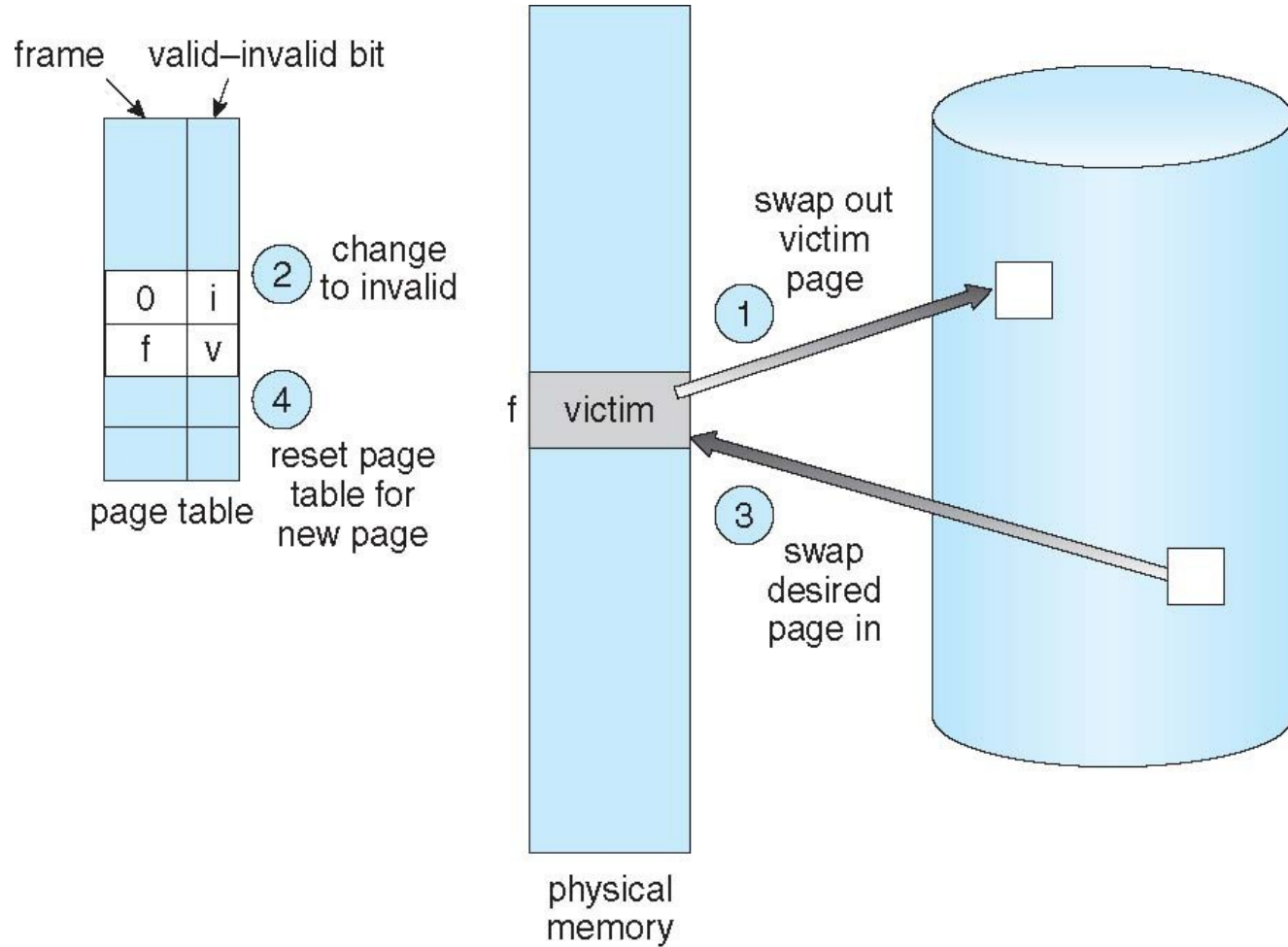
1. Find the location of the desired page on disk
2. Find a free frame:
 - If there is a free frame, use it
 - If there is no free frame, use a page replacement algorithm to select a **victim frame**
 - Write victim frame to disk if dirty
3. Bring the desired page into the (newly) free frame; update the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





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

page frames

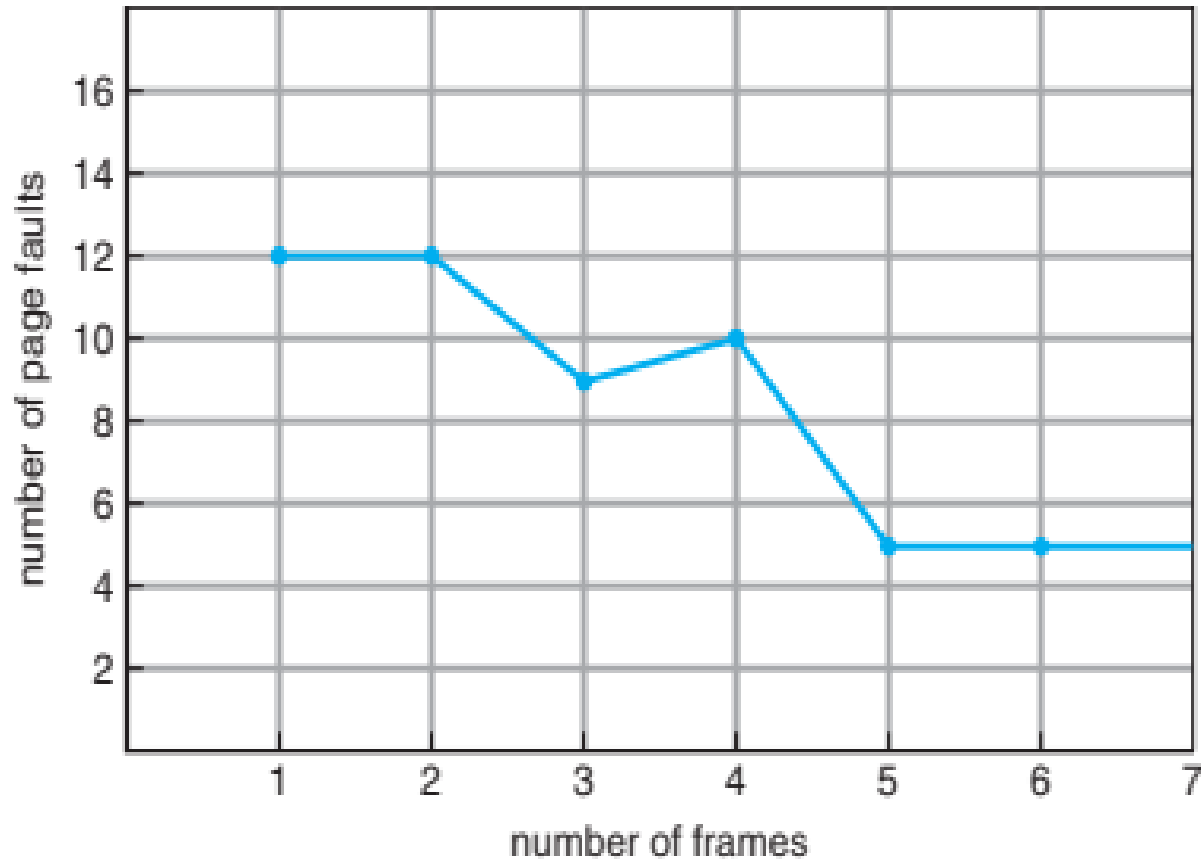
15 page faults

- 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**
- How to track ages of pages?
 - Just use a FIFO queue





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



stack
before
a



stack
after
b





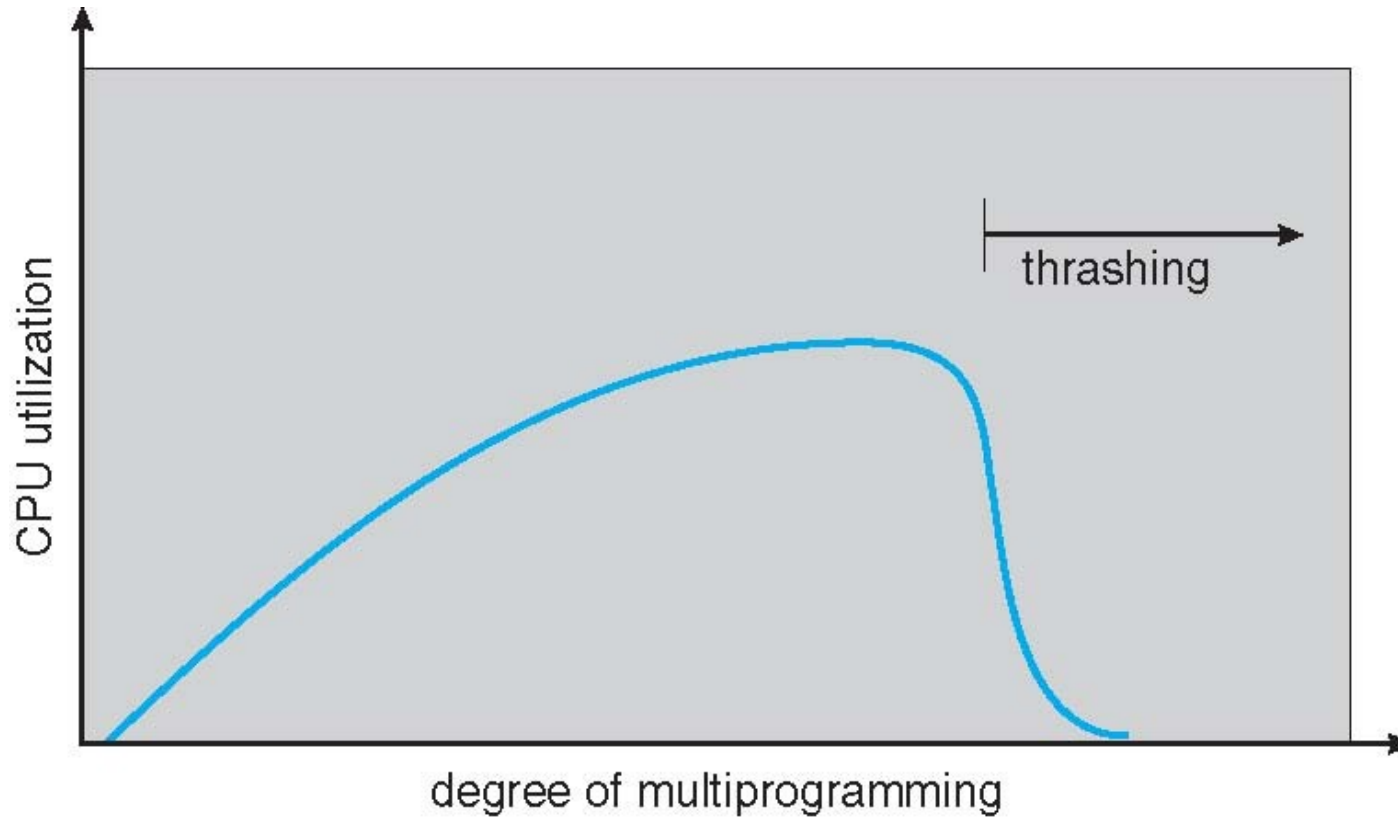
Thrashing

- 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





Virtual Machine





Overview

- Fundamental idea – abstract hardware of a single computer into several different execution environments, thereby creating the illusion that each separate execution environment is running its own private computer.
- Single physical machine can run multiple operating systems concurrently, each in its own virtual machine







Chapter 11: File-System Interface





File Concept

- Contiguous logical address space
- Types:
 - Data
 - ▶ numeric
 - ▶ character
 - ▶ binary
 - Program
- Contents defined by file's creator
 - Many types
 - ▶ Consider **text file, source file, executable file**





File Attributes

- **Name** – only information kept in human-readable form
- **Identifier** – unique tag (number) identifies file within file system
- **Type** – needed for systems that support different types
- **Location** – pointer to file location on device
- **Size** – current file size
- **Protection** – controls who can do reading, writing, executing
- **Time, date, and user identification** – data for protection, security, and usage monitoring
- Information about files are kept in the directory structure, which is maintained on the disk
- Many variations, including extended file attributes such as file checksum
- Information kept in the directory structure





File Operations

- File is an **abstract data type**
- **Create**
- **Write** – at **write pointer** location
- **Read** – at **read pointer** location
- **Reposition within file - seek**
- **Delete**
- **Truncate**
- ***Open(F_i)*** – search the directory structure on disk for entry F_i , and move the content of entry to memory
- ***Close (F_i)*** – move the content of entry F_i in memory to directory structure on disk





Open Files

- Several pieces of data are needed to manage open files:
 - **Open-file table**: tracks open files
 - File pointer: pointer to last read/write location, per process that has the file open
 - **File-open count**: counter of number of times a file is open – to allow removal of data from open-file table when last processes closes it
 - Disk location of the file: cache of data access information
 - Access rights: per-process access mode information





Open File Locking

- Provided by some operating systems and file systems
 - Similar to reader-writer locks
 - **Shared lock** similar to reader lock – several processes can acquire concurrently
 - **Exclusive lock** similar to writer lock
- Mediates access to a file
- Mandatory or advisory:
 - **Mandatory** – access is denied depending on locks held and requested
 - **Advisory** – processes can find status of locks and decide what to do





File Types – Name, Extension

file type	usual extension	function
executable	exe, com, bin or none	ready-to-run machine-language program
object	obj, o	compiled, machine language, not linked
source code	c, cc, java, pas, asm, a	source code in various languages
batch	bat, sh	commands to the command interpreter
text	txt, doc	textual data, documents
word processor	wp, tex, rtf, doc	various word-processor formats
library	lib, a, so, dll	libraries of routines for programmers
print or view	ps, pdf, jpg	ASCII or binary file in a format for printing or viewing
archive	arc, zip, tar	related files grouped into one file, sometimes compressed, for archiving or storage
multimedia	mpeg, mov, rm, mp3, avi	binary file containing audio or A/V information





Tree-Structured Directories

