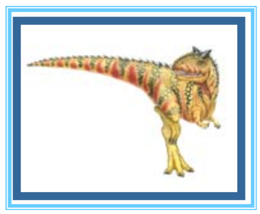
Chapter 9: Virtual Memory



(slides improved by R. Doemer, 05/27/10)

Chapter 9: Virtual Memory

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

(slide modified by R. Doemer, 05/27/10)

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

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Background

- **Virtual memory** –
  complete separation of user logical memory from physical memory.
  - Only *part* of a program needs to be in memory for its 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
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

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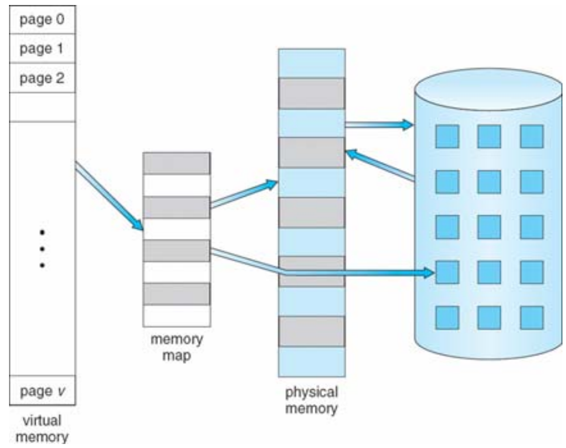
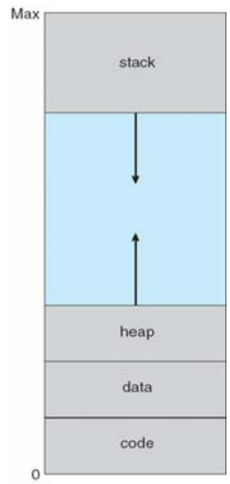
Virtual Memory That is Larger Than Physical Memory



Virtual Address Space



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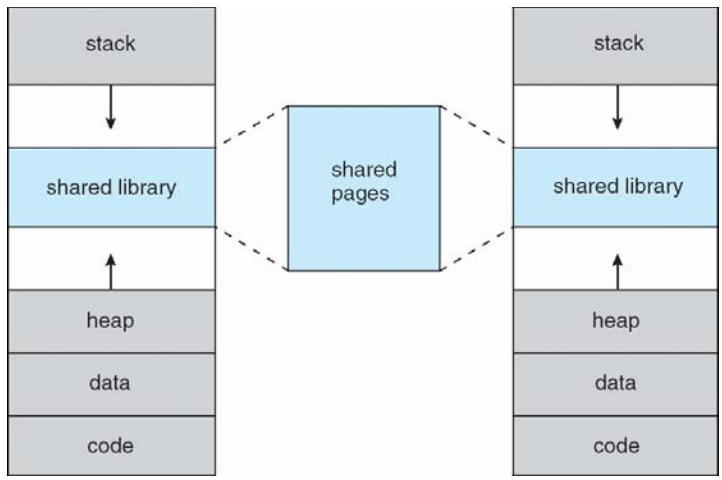
Shared Library Using Virtual Memory



Demand Paging

- Bring a page into memory *only when* it is needed
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users
- Page is *needed*
  ⇒ when a CPU instruction *references* an address in it (e.g. load, store)
- **Page Fault**
  - 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**

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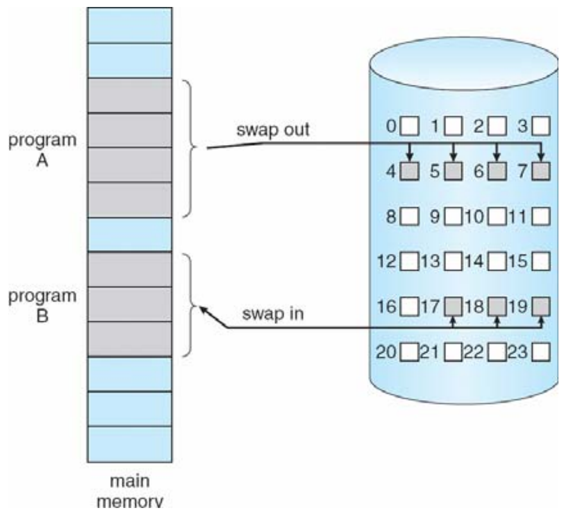
Transfer of a Paged Memory to Contiguous Disk Space



Valid-Invalid Bit

- With each page table entry a valid–invalid bit is associated (**v** ⇒ valid, in-memory, **i** ⇒ **invalid, or 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
	v
	i
….	
	i
	i

page table

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

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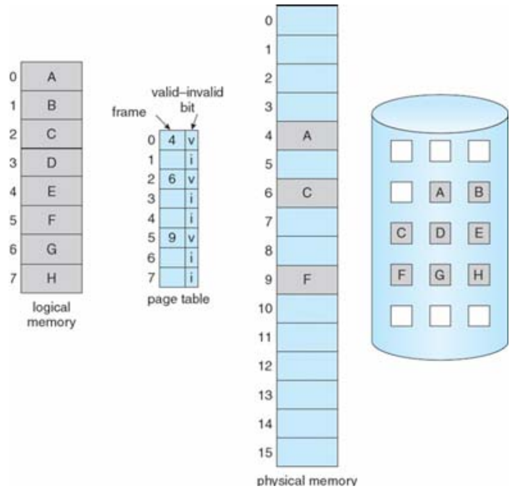
Page Table When Some Pages Are Not in Main Memory



Page Fault

- If a page is not in main memory,
  the first reference to that page will **trap** to the operating system:
  page fault

1. Operating system looks at another table to decide:
   - Invalid reference ⇒ abort
   - Just not in memory ⇒ goto step 2
2. Get empty frame
3. Swap page into frame
4. Update tables
5. Set valid-invalid bit to **v**
6. **Restart** the instruction that caused the page fault

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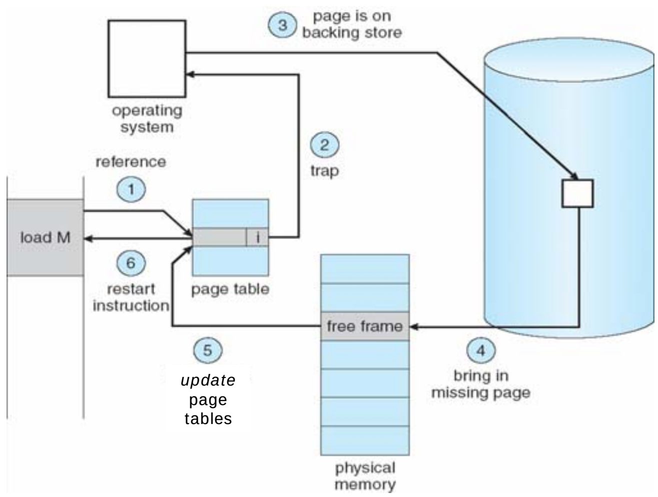
Steps in Handling a Page Fault



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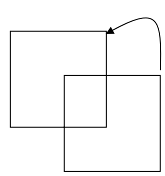
Handling a Page Fault

- Restart instruction:
  - sometimes not trivial!
  - Special care may need to be taken!
- Example 1: block move instruction where blocks span multiple pages



- Example 2: auto increment/decrement instruction

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Additional Virtual Memory Benefits

- Virtual memory allows other benefits:

  - During Process Creation: Copy-on-Write

  - Memory-Mapped Files

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Copy-on-Write

- Consider parent process forks a child process
- **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
- Free pages are allocated from a **pool** of zeroed-out pages

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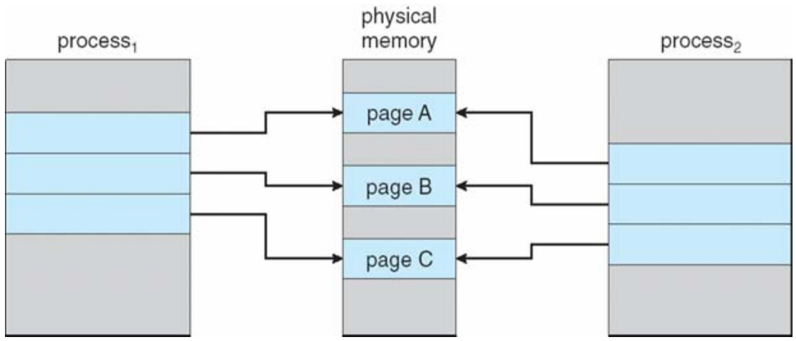
Copy-on-Write Example

- Before Process 1 Modifies Page C



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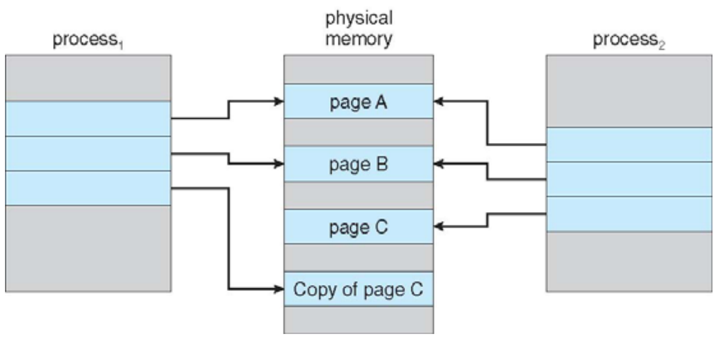
Copy-on-Write Example

- After Process 1 Modifies Page C



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Memory-Mapped Files

- Memory-mapped file I/O allows file I/O to be treated as regular 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 memory frame.
- Subsequent reads/writes to/from the file are treated as ordinary memory accesses.
- Simplifies file access by treating file I/O as ordinary memory access rather than **`read()`** and **`write()`** system calls
- Also allows several processes to map the same file allowing the pages in memory to be shared

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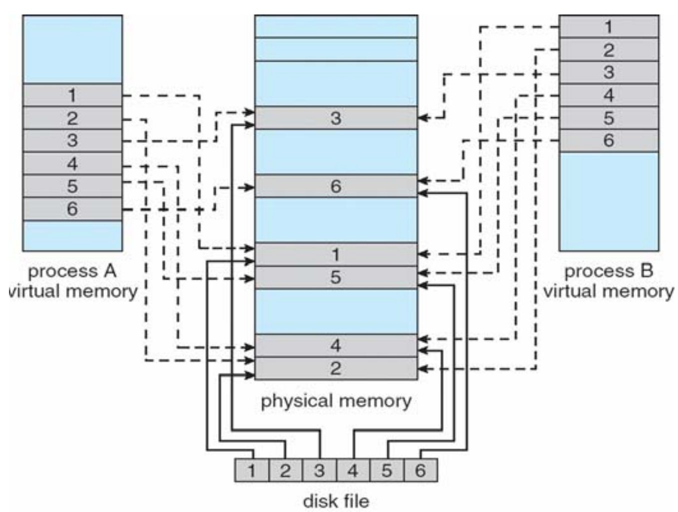
Memory-Mapped Files



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Virtual Memory

- When handling a page fault, what happens if there is no free frame?
- **Page replacement** – find some page in memory, that is not really in use, swap it out
  - Algorithm needed to find victim page
  - Performance – we want an algorithm which will result in *minimum number of page faults*
- Thus, same page may be brought into memory several times

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Page Replacement

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

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Page Replacement

Extended page fault service routine:

- Page fault, find the location of the desired page on disk
- Find a free frame:
  - If there is a free frame,
    use the free frame
  - If there is no free frame,
    use **page replacement** algorithm to select a **victim** frame
    if modified/dirty, swap out the victim page
- Bring the desired page into the (new) free frame
- *Update* the page and frame tables
- *Restart* the instruction

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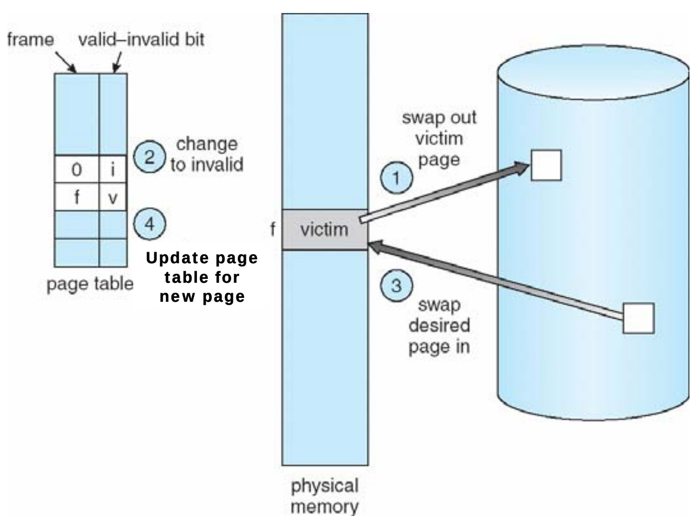
Page Replacement



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Page Replacement Algorithms

- Many page replacement algorithms are possible
- Want lowest page-fault rate

- Evaluate algorithm by running it
  on a particular string of memory references (reference string) and
  counting the number of page faults on that string

- In the following examples, the reference string is

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

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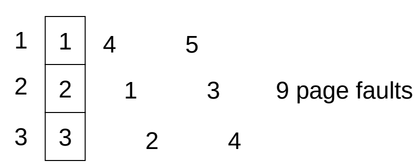
First-In-First-Out (FIFO) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 frames (3 pages can be in memory at a time per process)



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First-In-First-Out (FIFO) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 frames (3 pages can be in memory at a time per process)

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

- 4 frames

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

- **Belady's Anomaly**: more frames ⇒ more page faults

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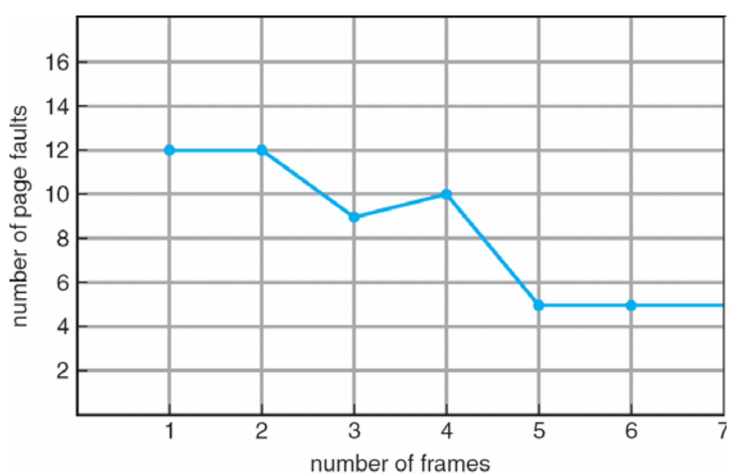
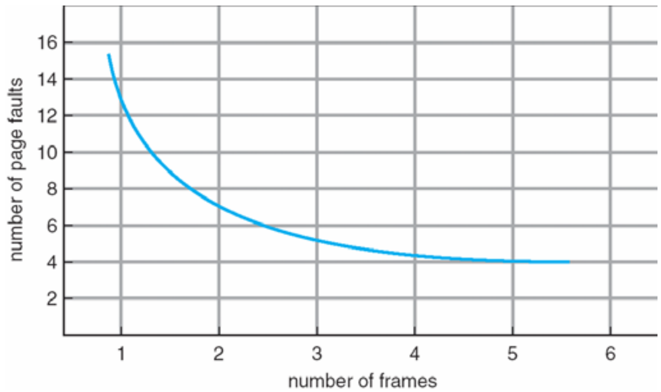
FIFO Illustrating Belady's Anomaly



Page Faults Versus The Number of Frames

General expectation:



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Optimal Algorithm

- Replace page that *will not be used* for longest period of time
- 4 frames example

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

1	4
2	
3	
4	5

6 page faults

- How do you know this?
- Optimal Algorithm: For comparison only!
  Used for measuring how well other algorithms perform.

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Least Recently Used (LRU) Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, **5**, 1, 2, **3**, **4**, **5**

1	1	1	1	**5**
2	2	2	2	2
3	**5**	5	**4**	4
4	4	**3**	3	3

8 page faults

- Possible implementation by counters/clock
  - Every page entry has a counter/clock associated with it
  - Every time a page is referenced, copy clock into its counter
  - When a page needs to be changed,
    find the smallest counter to determine which page to replace

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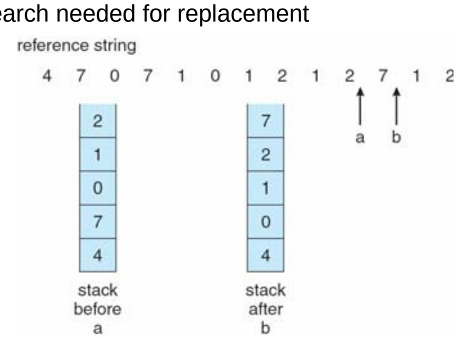
Least Recently Used (LRU) Algorithm

- Alternative implementation by use of a stack –
  keep a stack of page numbers in a doubly linked list:
  - Whenever a page is referenced
    - move it to the top
  - Requires 6 pointers to be changed
  - No search needed for replacement



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LRU Approximation Algorithms

- LRU Algorithm is quite expensive to implement
  - **LRU approximation algorithms** are often used instead
- **Reference bit**
  - With each page associate a bit, initially set to 0
  - When page is referenced, set bit to 1 (in hardware)
  - Replace a page whose bit is 0 (if one exists)
    - We do not know the order, however
- **Second chance algorithm** (aka. **Clock algorithm**)
  - Use FIFO replacement as basic algorithm
  - Add a reference bit as above
  - Consider pages to be replaced in circular order (clock order)
  - If a page is to be replaced
    - if reference bit = 1, then reset bit = 0 and leave page in memory
    - if reference bit = 0, replace this page

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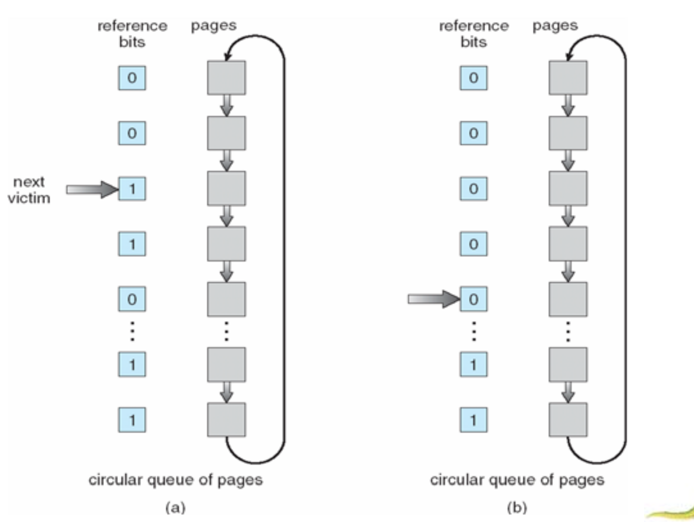
LRU Approximation Algorithms

- **Second-Chance** (**Clock**) Page Replacement Algorithm



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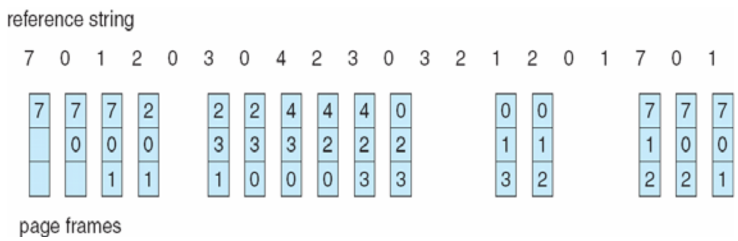
Page Replacement Algorithms

- Example: FIFO Algorithm



- 15 page faults

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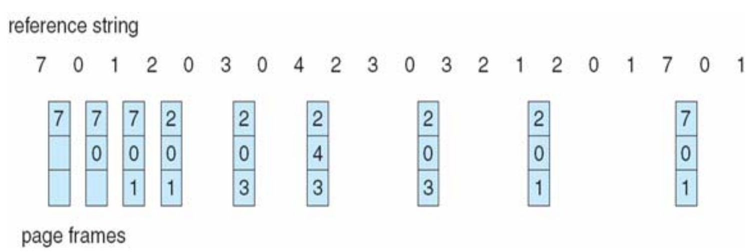
Page Replacement Algorithms

- Example: Optimal Algorithm



- 9 page faults

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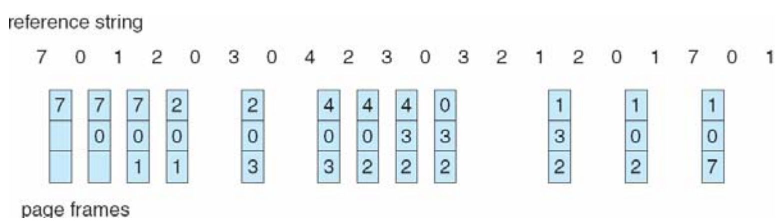
Page Replacement Algorithms

- Example: LRU Algorithm



- 12 page faults

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Page Replacement Algorithms

- Alternative Algorithms include **Counting Algorithms**
  - Keep a counter of the number of references that have been made to each page
  - **LFU Algorithm**: least-frequently used replacement
    - replaces page with smallest count
    - frequently used pages stay in memory
  - **MFU Algorithm**: most-frequently used replacement
    - replaces page with largest count
    - based on the argument that the page with the smallest count was probably just brought in and has yet to be used

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Allocation of Frames

- Each process needs a *minimum* number of pages
- Example: IBM 370 – 6 pages to handle SS MOVE instruction:
  - instruction is 6 bytes, might span 2 pages
  - 2 pages to handle *from*
  - 2 pages to handle *to*
- **Allocation of Frames**:
  Two major schemes exist
  - Fixed allocation
  - Priority allocation

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Fixed Allocation

- **Equal allocation** –
  For example, if there are 100 frames and 5 processes, give each process 20 frames.
- **Proportional allocation** –
  Allocate according to the size of the process
  Example:

$- s_i = \text{size of process } p_i$ $\quad m = 64$

$- S = \sum s_i$ $\quad s_i = 10$

$- m = \text{total number of frames}$ $\quad s_2 = 127$

$- a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m$ $\quad a_1 = \frac{10}{137} \times 64 \approx 5$

$a_2 = \frac{127}{137} \times 64 \approx 59$

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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 own frames, or
  - select for replacement a frame from a process with lower priority number
- **Global replacement** – select a replacement frame from the set of all frames; one process can take a frame from another
- **Local replacement** – select a replacement frame from only processes' own set of allocated frames

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Thrashing

- If a process has *"not enough"* pages, the page-fault rate is very high.
- This leads to:
  - low CPU utilization
  - operating system thinks that it needs to increase the degree of multiprogramming
  - another process is added to the system
  - even less pages become available…
- **Thrashing** ≡ a process is constantly swapping pages in and out

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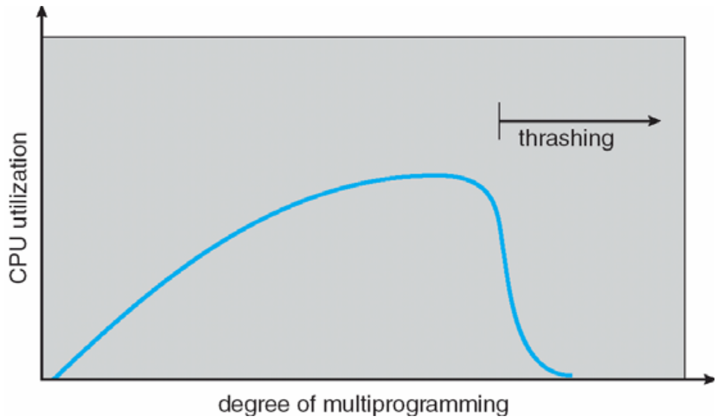
Thrashing Phenomenon



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Demand Paging and Thrashing

- Why does demand paging work?
- **Locality model**
  - Process migrates from one locality to another
  - Localities may overlap
- When does thrashing occur?
- Σ size of locality > available memory size

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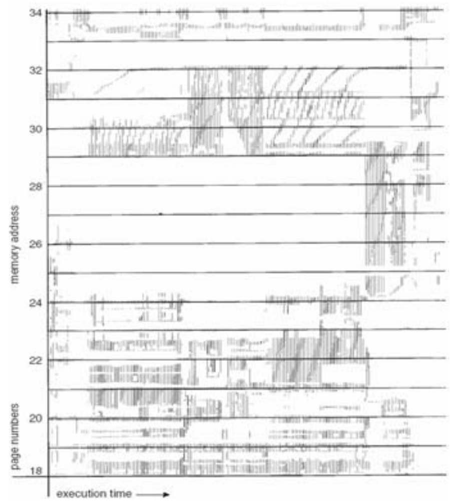
Locality In A Memory-Reference Pattern



Working-Set Model

- $\Delta \equiv$ **working-set window** $\equiv$ a fixed number of page references
  Example: sequence of 10,000 instructions
- WSS_i (**working set size** of Process P_i) =
  total number of pages referenced in the most recent Δ
  (varies in time)
  - if Δ is too small, it will not encompass the entire locality
  - if Δ is too large, it will encompass several localities
  - if $\Delta = \infty$, it will encompass the entire program
- $D = \Sigma\ WSS_i \equiv$ total demand of frames of all processes
- if $D > m \Rightarrow$ Thrashing occurs!
- Policy:
  if D > m, then suspend (swap out) one of the processes

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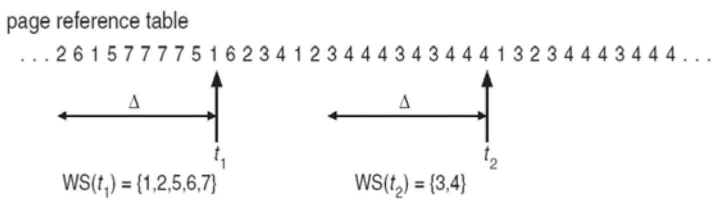
Working-Set Model



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Keeping Track of the Working Set

- Approximation with
  - interval timer
  - a reference bit in hardware
  - Set of reference bits associated with each page
- Example: Δ = 10,000 time units
  - Timer interrupts after every 5000 time units
  - Keep in memory 2 additional bits for each page
  - Whenever the timer interrupts,
    shift the bits in memory,
    copy the hardware bits to the first bit in memory, and
    set the values of all hardware reference bits to 0
  - If one of the memory bits = 1 $\Rightarrow$ page in working set
- Why is this not completely accurate?
  - Can't tell when exactly reference occurred
- Improvement: 10 bits and interrupt every 1000 time units

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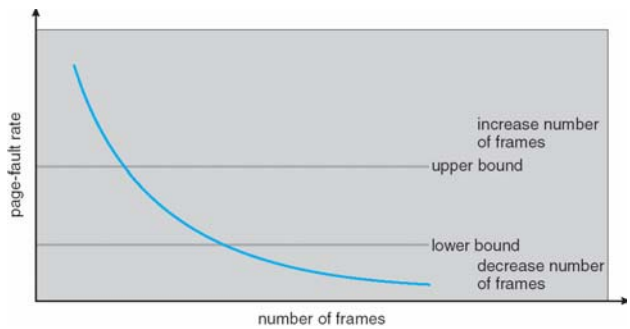
Page-Fault Frequency Scheme

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



Other Issues – Program Structure

- Program structure
  - `int data[128,128];`
  - 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

(slide fixed by R. Doemer, 02/02/09)

End of Chapter 9