CS370 Operating Systems

Colorado State University
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Fall 2024 L20
Virtual Memory

Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

Please be considerate

- Allow other students to focus
  - No talking (except for iClicker sessions), humming, etc.
  - No cell phone use (except for iClicker)
  - No laptop/handheld use, unless pledge submitted, and rules followed.
  - No leaving in the middle of the class or just after an iClicker session.

Project D2 Progress report

- Your group has been assigned a Canvas Group (Research or Development).
- One person will submit the report on behalf of the group. Due Oct 31.
  - Use the format specifications for the Final report, with about half the size.
- When graded, all persons will automatically receive the score. Note: A groups involving both students from section needs special attention. One sec 1 students has joined a Sec 801 group.
- All members of a group are expected to contribute their fair share of effort. We will check.

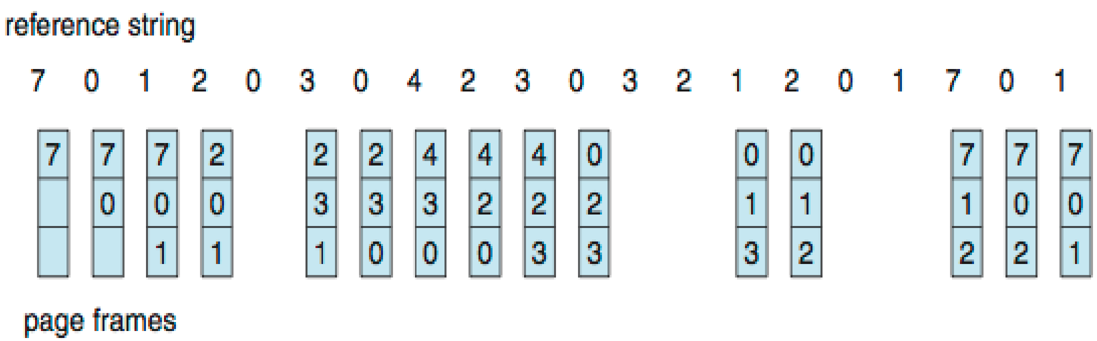
Page Replacement Algorithms

Algorithms

- FIFO
- "Optimal"
- The Least Recently Used (LRU)
  - Exact Implementations
    - Time of use field, Stack
  - Approximate implementations
    - Reference bit
    - Reference bit with shift register
    - Second chance: clock
    - Enhanced second chance: dirty or not?
- Other

First-In-First-Out (FIFO) Algorithm

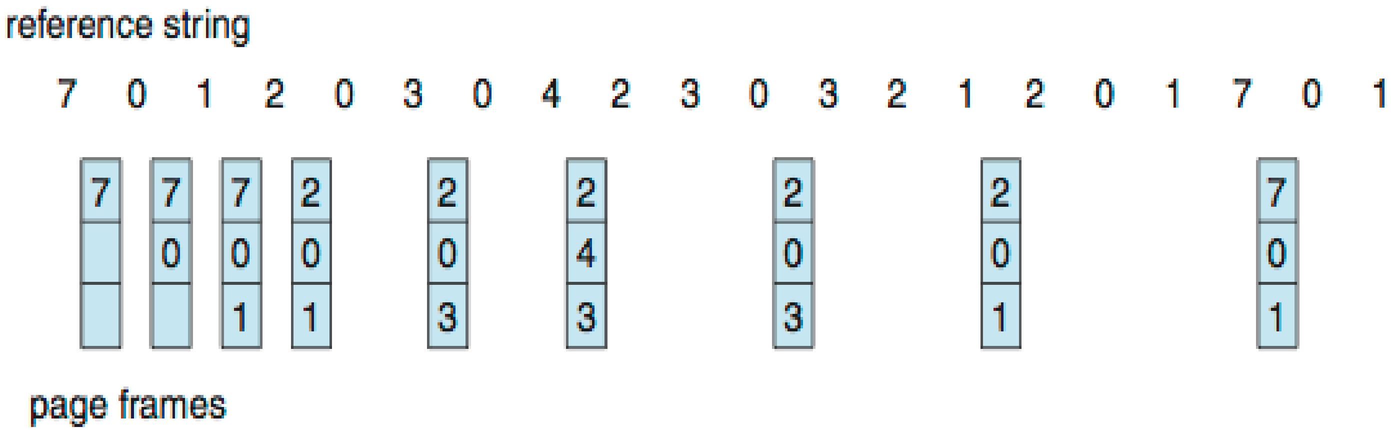
- Reference string:
  7,0,1,2,0,3,0,4,2,3,0,3,2,1,2,0,1,7,0,1
- 3 frames (3 pages can be in memory at a time per process)



- 15 page faults (out of 20 accesses)
- Sometimes a page is needed soon after replacement 7,0,1,2,0,3 (0 out),0, ..

"Optimal" Algorithm Belady 66

- Replace page that will not be used for longest period of time



  - 4th access: replace 7 because we will not use if got the longest time…
  - 9 page replacements is optimal for the example
- But how do we know the future pages needed?
  - Can't read the future in reality.
- Used for *measuring* how well an algorithm performs.

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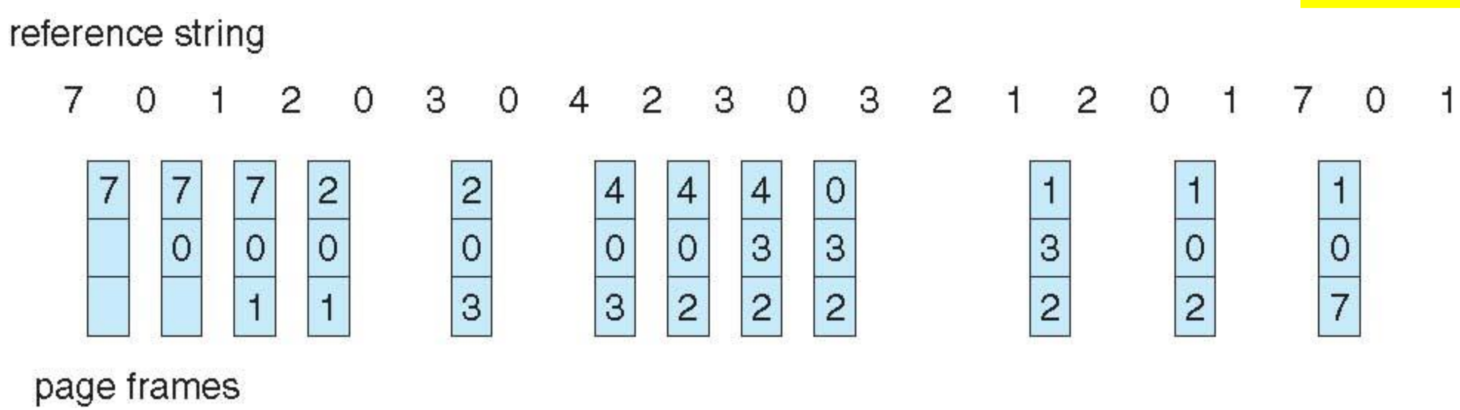
Least Recently Used (LRU) Algorithm

- Use past knowledge rather than future
- Replace page that has not been used in the most amount of time (4th access – page 7 is least recently used …_)
- Associate time of last use with each page

Track usage carefully!



- 12 faults – better than FIFO (15) but worse than OPT (9)
- Generally good algorithm and frequently used
- But how to implement it by tracking the page usage?

LRU and OPT are cases of *stack algorithms* that don't have Belady's Anomaly

LRU Algorithm: Implementations

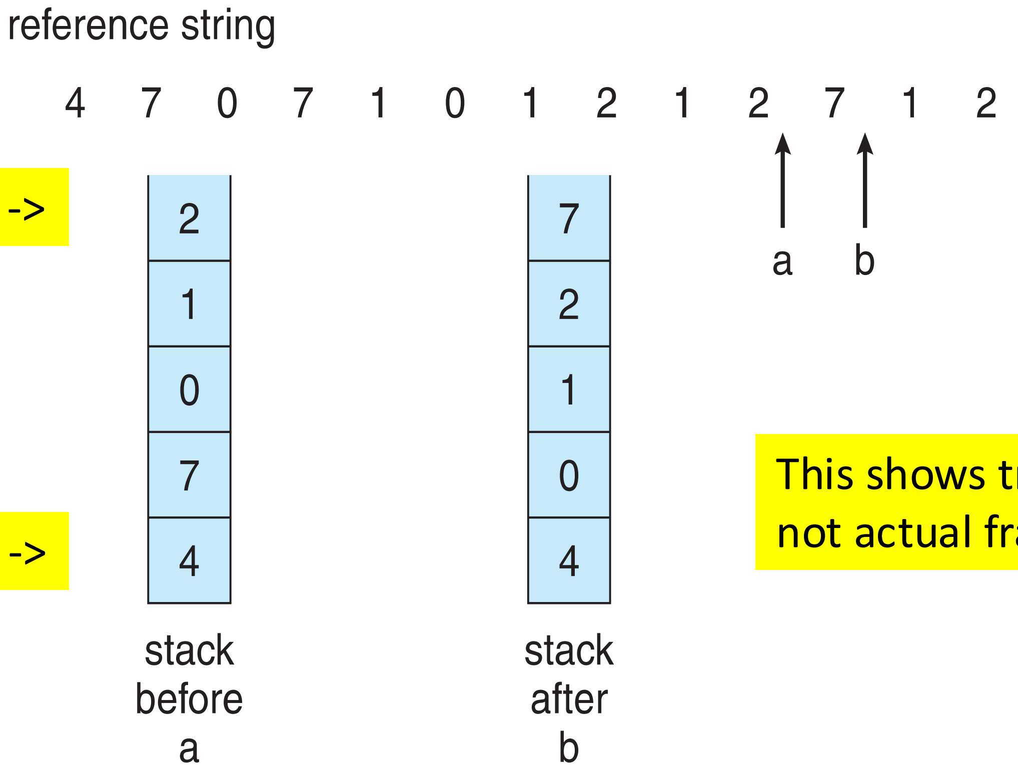
Possible tracking implementations

- 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
  - Each update expensive
  - No search for replacement needed (bottom is least recently used)

Use Of A Stack to Record Most Recent Page References

Most recently used ->

Least recently used ->



This shows tracking stack, not actual frames.

Too slow if done in software

LRU Approximation Algorithms

- LRU needs special hardware and still slow
- **Reference** **1 bit per frame to track history**
  - With each page associate a bit, initially = 0
  - When the page is referenced, bit set to 1
  - Replace any page with reference bit = 0 (if one exists)
    - 0 implies not used since initialization
    - We do not know the order, however.
- Advanced schemes using more bits: preserve more information about the order

Ref bit + history shift register

LRU approximation 9 bits per frame to track history

Ref bit: 1 indicates used, Shift register records history. Examples:

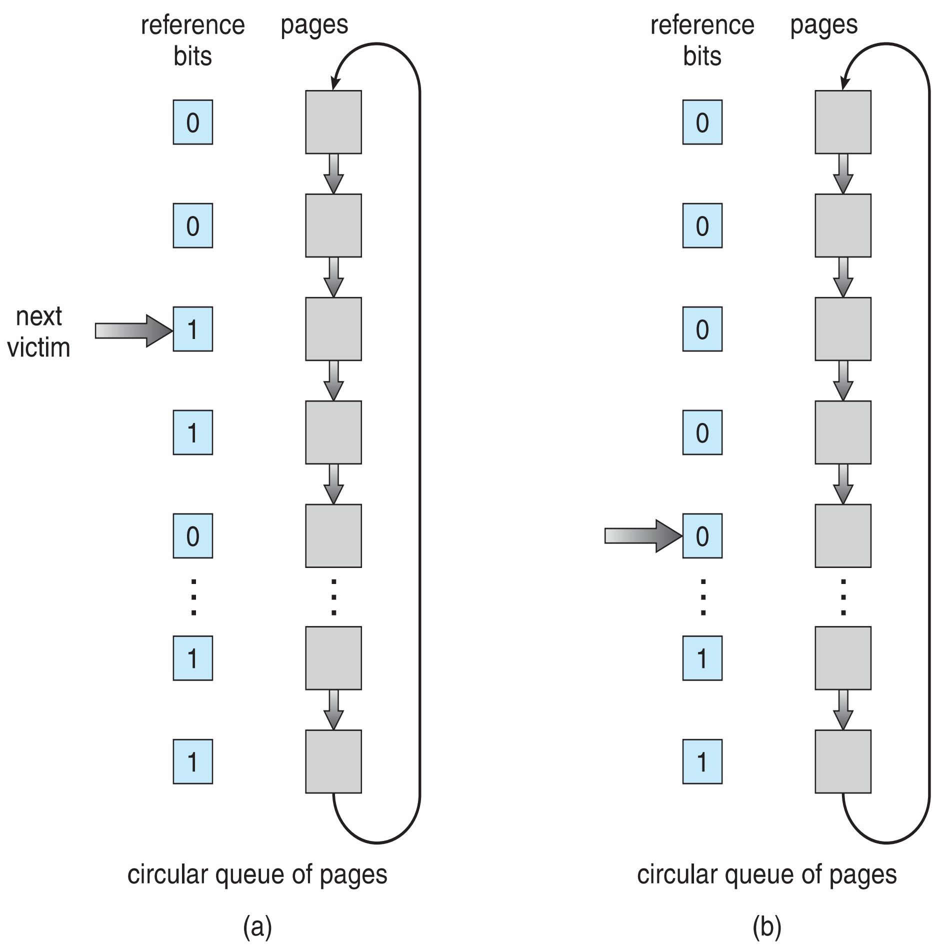
Ref Bit	Shift Register	Shift Register after OS timer interrupt
1	0000 0000	1000 0000
1	1001 0001	1100 1000
0	0110 0011	0011 0001

- Interpret 8-bit bytes as **unsigned integers**
- Page with the lowest number is the LRU page: replace.
  Examples:
  - 00000000 : Not used in last 8 periods
  - 01100101 : Used 4 times in the last 8 periods
  - 11000100 used more recently than 01110111

Second-chance algorithm

- **Second-chance algorithm**
  - Generally FIFO, plus hardware-provided reference bit
  - Avoid throwing out a heavily used page
  - **"Clock"** replacement (using circular queue): hand as a pointer
  - Consider next page
    - Reference bit = 0 -> replace it
    - reference bit = 1 then: give it another chance
      - set reference bit 0, leave page in memory
      - consider next page, subject to same rules

Second-Chance (clock) Page-Replacement Algorithm



- **Clock** replacement: hand as a pointer
- Consider next page
  - Reference bit = 0 -> replace it
  - reference bit = 1 then:
    - set reference bit 0, leave page in memory
    - consider next page, subject to same rules

Example:

(a) Change to 0, give it another chance

(b) Already 0. Replace page

Enhanced Second-Chance Algorithm

Improve algorithm by using reference bit and modify bit (if available) in concert clean page: better replacement candidate

- Take ordered pair (reference, modify)

1. (0, 0) neither recently used not modified – best page to replace
2. (0, 1) not recently used but modified – not quite as good, must write out before replacement
3. (1, 0) recently used but clean – probably will be used again soon
4. (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

Clever Techniques for enhancing Perf

- Keep a buffer (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
- Keep list of modified pages
  - When backing store is otherwise idle, write pages there and set to non-dirty (being proactive!)
- Keep free frames' previous 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

Buffering and applications

- Some applications (like databases) often understand their memory/disk usage better than the OS
  - Provide their own buffering schemes
  - If both the OS and the application were to buffer
    - Twice the I/O is being utilized for a given I/O
  - OS may provide “raw access” disk to special programs without file system services.

Allocation of Frames

How to allocate frames to processes?

- Each process needs ***minimum*** number of frames

  Depending on specific needs of the process
- ***Maximum*** of course is total frames in the system

- Two major allocation schemes
  - fixed allocation
  - priority allocation
- Many variations

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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 (need based)
  - Dynamic as degree of multiprogramming, process sizes change

s_j= size of process p_j

$S = \sum s_j$

m = total number of frames

$a_j = allocation\ for\ p_j = \frac{s_j}{S} \times m$

Example:
Processes P1,P2

m = 62

s_1 =10

s_2 =127

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

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

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Priority Allocation

- Use a proportional allocation scheme using priorities rather than size
- If process $\boldsymbol{P_i}$ generates a page fault,
  - select for replacement one of its frames or
  - select for replacement a frame from a process with lower priority number

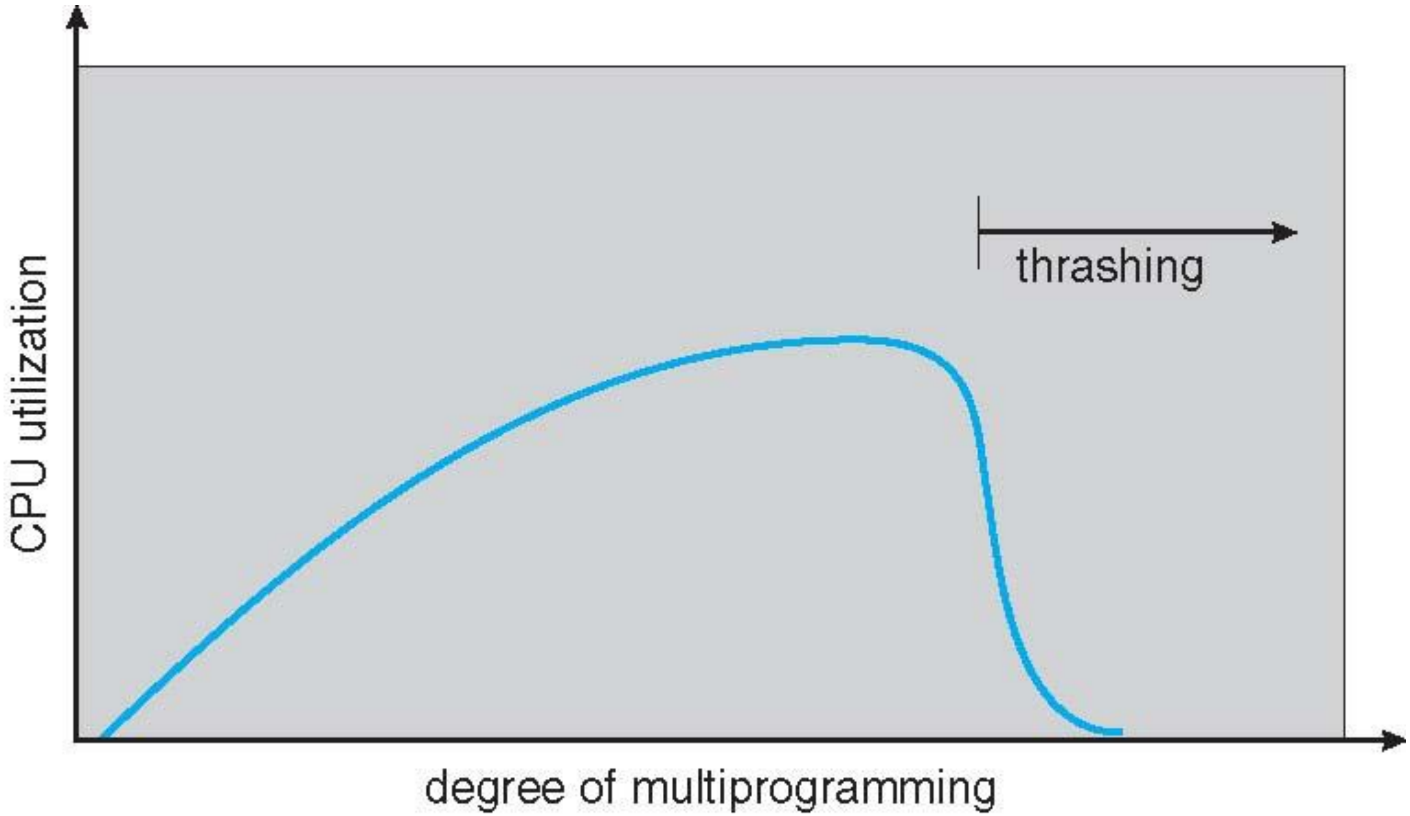
Global vs. Local Allocation

- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another
  - But then process execution time can vary greatly
  - But greater throughput, so more common
- **Local replacement** – each process selects from only its own set of allocated frames
  - More consistent per-process performance
  - But possibly underutilized memory

Problem: 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, leading to
    - Operating system thinking that it needs to increase the degree of multiprogramming leading to
    - Another process added to the system
- **Thrashing** ≡ a process is busy swapping pages in and out

Thrashing (Cont.)



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Demand Paging and Thrashing

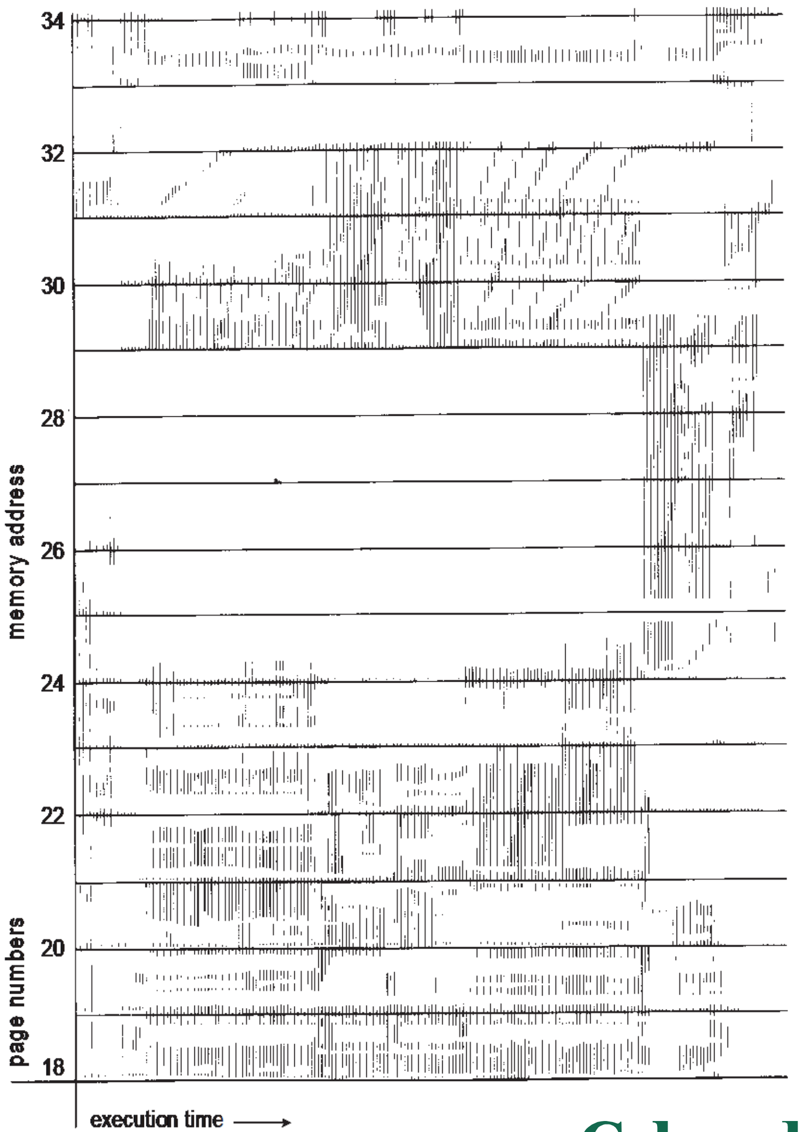
- Why does demand paging work?
  Locality model
  - Process migrates from one locality to another
  - Localities may overlap

- Why does thrashing occur in a process?

  size of locality > total memory size allocated

  - Limit effects by using local or priority page replacement

Locality In A Memory-Reference Pattern



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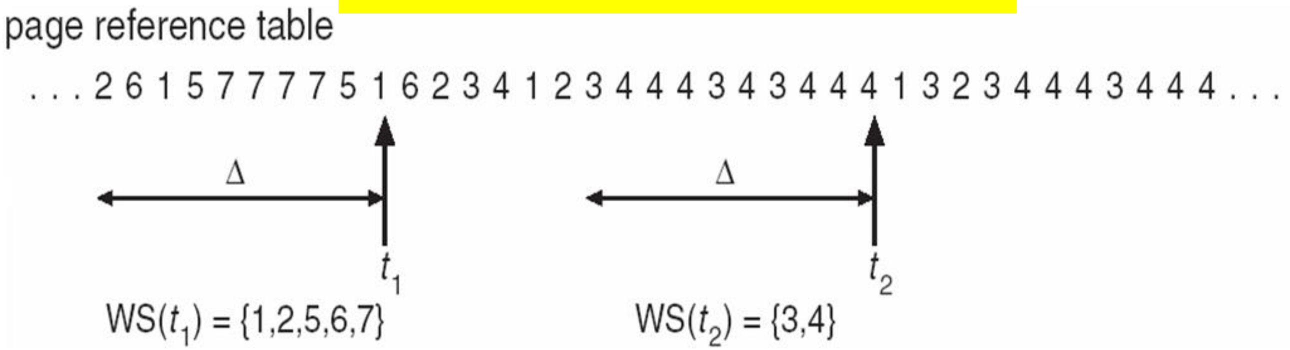
Working-Set Model

- $\Delta \equiv$ **working-set window** $\equiv$ a fixed number of page references

Example: Δ = 10 page references



- ***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, working set will not encompass entire locality
  – if Δ too large, working set will encompass several localities
  – ws is an approximation of locality

- **$D = \Sigma\, WSS_i \equiv$ total demand for frames** for all processes
  – **if $D > m \Rightarrow$ Thrashing**

M is number of frames

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

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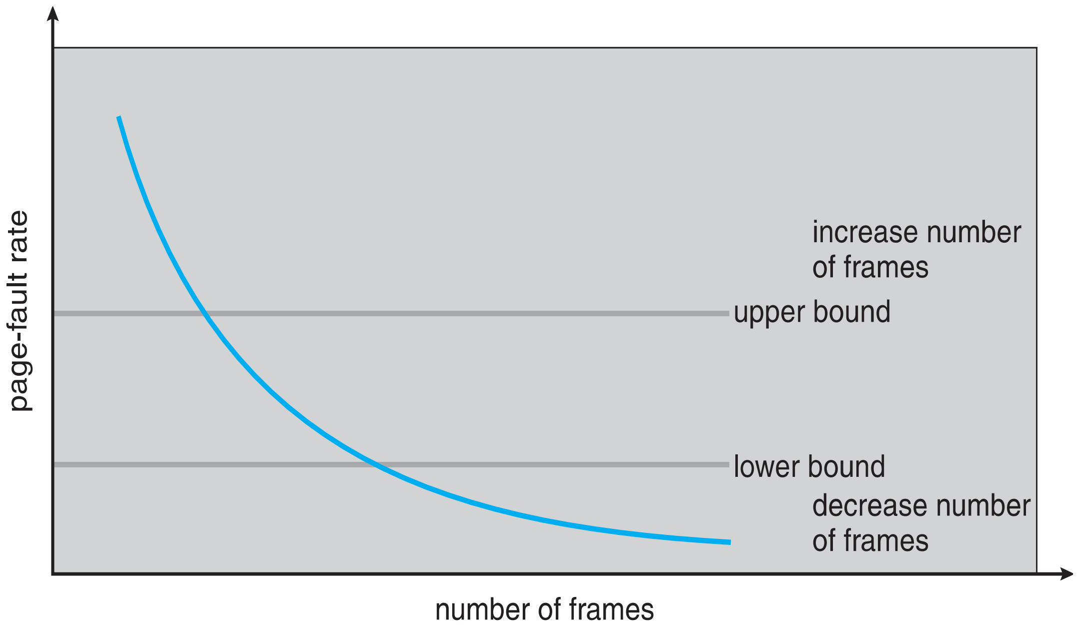
Page-Fault Frequency Approach

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



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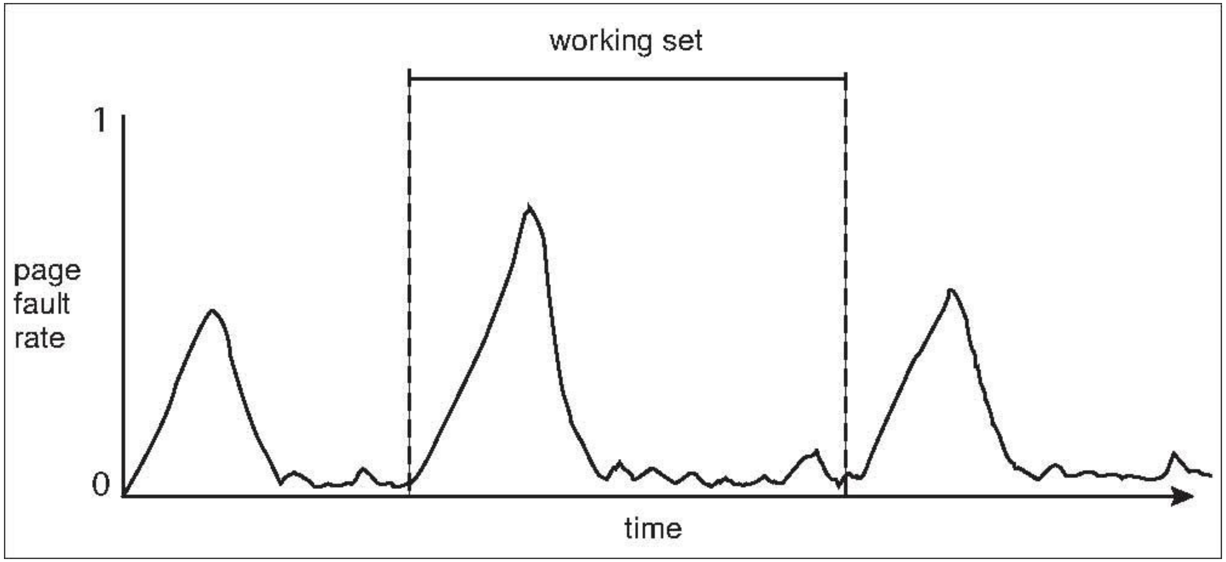
Working Sets and Page Fault Rates

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

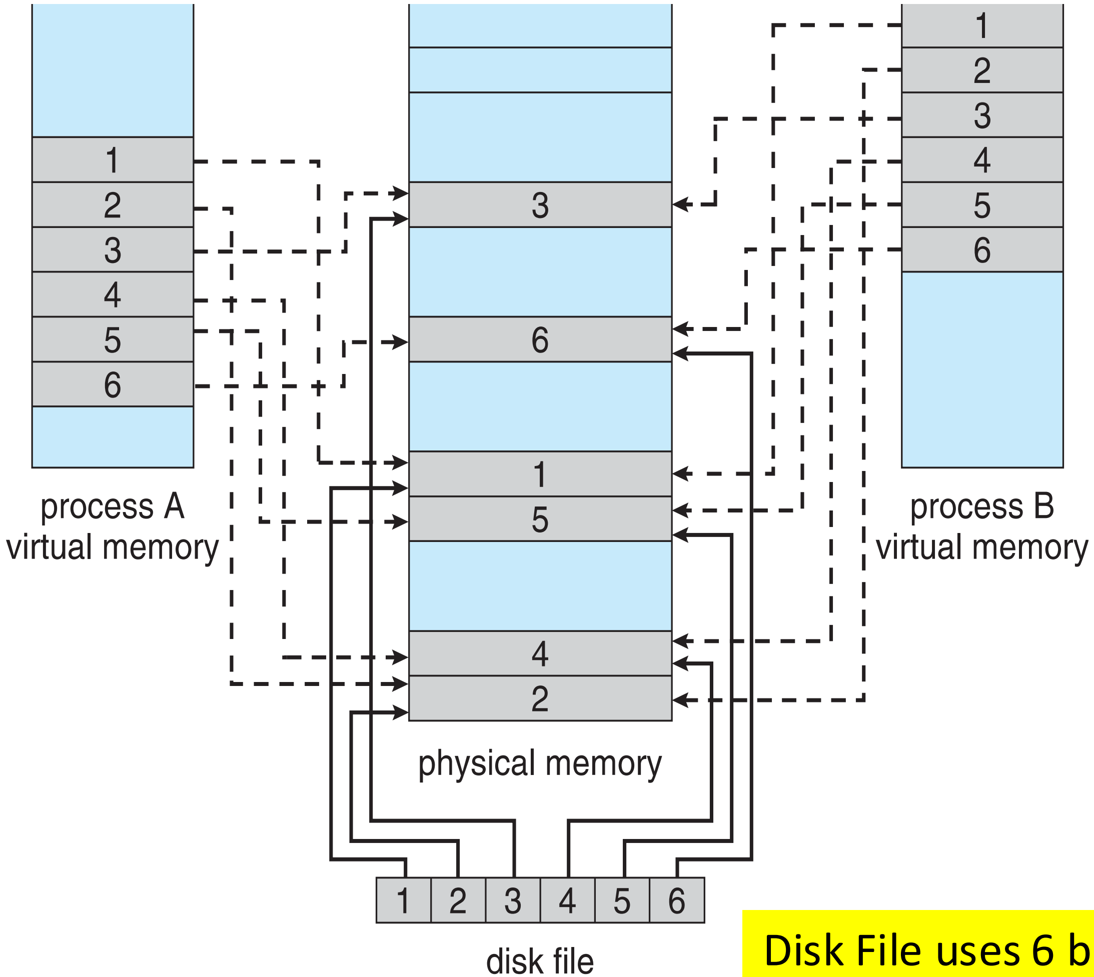


Peaks occur at locality changes: 3 working sets

Memory-Mapped Files

- Memory-mapped file I/O allows file I/O to be treated as routine memory access by **mapping** a disk block to a page in memory
- File is then in memory instead of disk
- A file is initially read using demand paging
  - A page-sized portion of the file is read from the file system into a physical page
  - Subsequent reads/writes to/from the file are treated as ordinary memory accesses
- Simplifies and speeds file access by driving file I/O through memory rather than `read()` and `write()` system calls
- Also allows several processes to map the same file allowing the pages in memory to be shared
- But when does written data make it to disk?
  - Periodically and / or at file `close()` time
  - For example, when the pager scans for dirty pages

Memory Mapped Files



Disk File uses 6 blocks
Page tables used for mapping

Allocating Kernel Memory

- Treated differently from user memory
- Often allocated from a free-memory pool
  - Kernel requests memory for structures of varying sizes
    - Process descriptors, semaphores, file objects etc.
    - Often much smaller than page size
  - Some kernel memory needs to be contiguous
    - e.g. for device I/O
  - approaches (skipped)

Other Considerations -- Prepaging

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

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Other Issues – Page Size

- Sometimes OS designers have a choice
  - Especially if running on custom-built CPU
- Page size selection must take into consideration:
  - Fragmentation
  - Page table size
  - 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

Page size issues – TLB Reach

- TLB Reach - The amount of memory accessible from the TLB
- TLB Reach = (TLB Size) X (Page Size)
- Ideally, the working set of each process is stored in the TLB
  - Otherwise there is a high degree of page faults

Other Issues – Program Structure

- Program structure
  - `int[128,128] data;` i: row, j: column
  - Each row is stored in one page
  - Program 1

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

128 x 128 = 16,384 page faults

  - Program 2 inner loop = 1 row = 1 page

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

128 page faults

Example: MS 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 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

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File-system

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File-Systems

Ch 13: File system interface

- File Concept, types
- Attributes, Access Methods, operations, Protection
- Directory Structure, namespace, File-System Mounting, File Sharing

Ch 14: File system implementation

Ch 15: File system internals

- **Storage abstraction**: File system metadata (size, free lists), File metadata(attributes, disk block maps), data blocks
- **Allocation of blocks to files**: contiguous, sequential, linked list allocation, indexed
- **In memory info**: Mount table, directory structure cache, open file table, buffers
- **Unix**: inode numbers for directories and files

Ch 11: Mass storage: technology specific details

File Systems

"MS. GRIMMETT, I SORT OF LIKED THE OLD FILING SYSTEM...IN THE FILE CABINETS."

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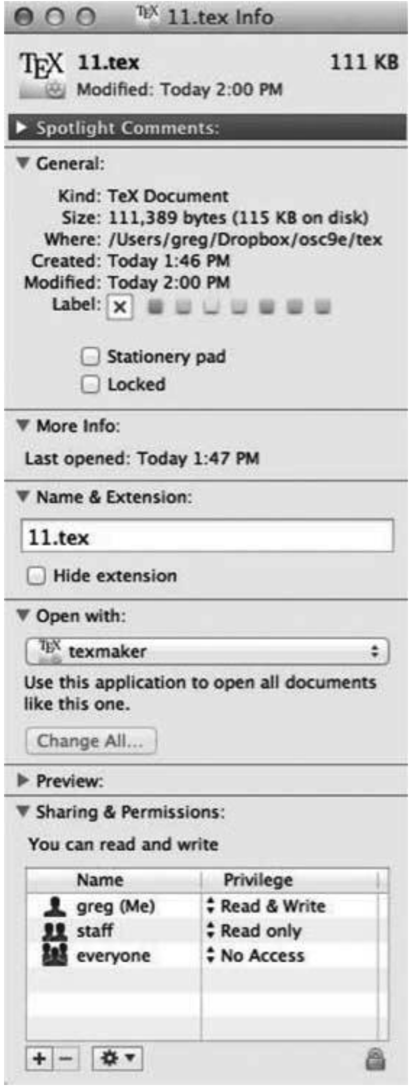
File types

Type used by programs *not OS*

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

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



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Disk Structure

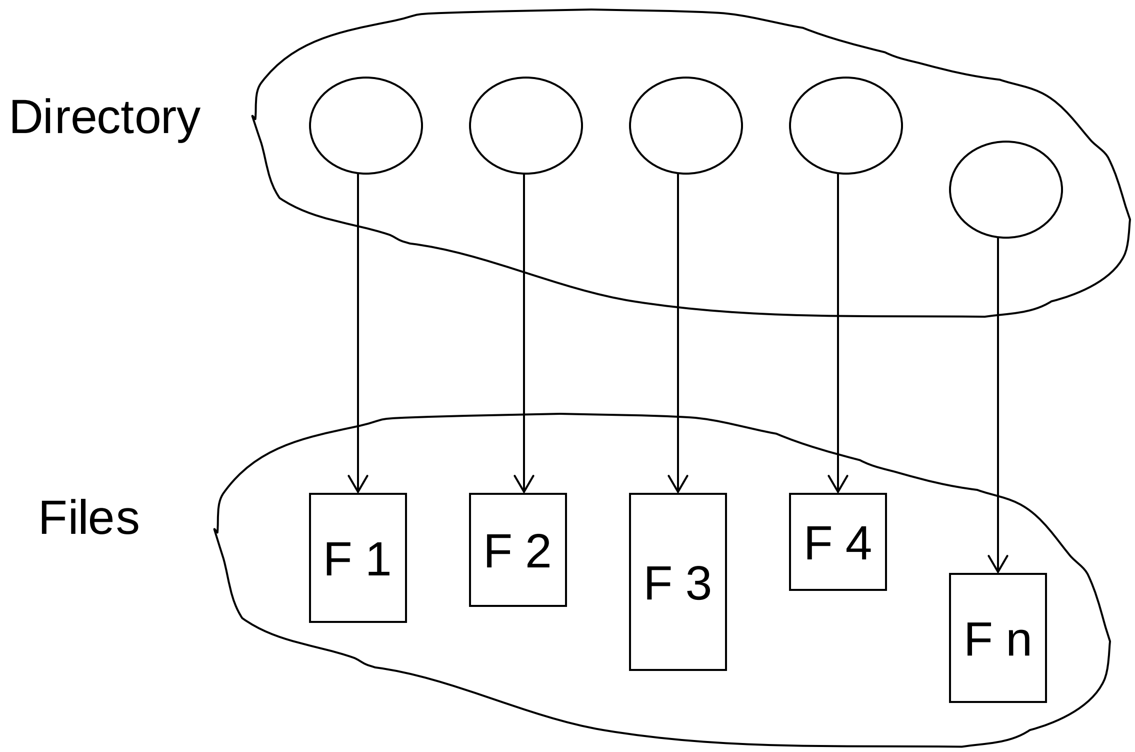
Disk can be subdivided into **partitions**

- Disks or partitions can be **RAID** protected against failure
- Partition can be **formatted** with a file system. Different partitions can host different file systems.
- Entity containing file system known as a **volume**
- Each volume containing file system also tracks that file system's info in **device directory** or **volume table of contents**

As well as **general-purpose file systems** there are many **special-purpose file systems**, frequently all within the same operating system or computer

Directory Structure

Directory: A collection of nodes containing information about all files



Both the directory structure and the files reside on disk

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Operations Performed on Directory

- Traverse the file system
- List a directory
- Search for a file
- Create/Delete/Rename a file

Directory Organization

- All files within a directory must have a unique name. But ..

Evolution of directory structure

- Single level directory
- Two-level directory
- Tree-structured directories:
  - efficient grouping, searching,
  - absolute or relative path names
- Acyclic graph directories
  - Shared sub-directory, files