CS370 Operating Systems

Colorado State University

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Fall 2021 Lecture 19

Virtual Memory

Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

Microphone

Questions from last time

- TLB:
  - serves as a cache for Page Table
  - Small subset of the info in Page Table, but high hit rate
  - Can be multilevel, *may be separate for data/instruction*
  - How to find TLB hit rate? (Answer: simulation)

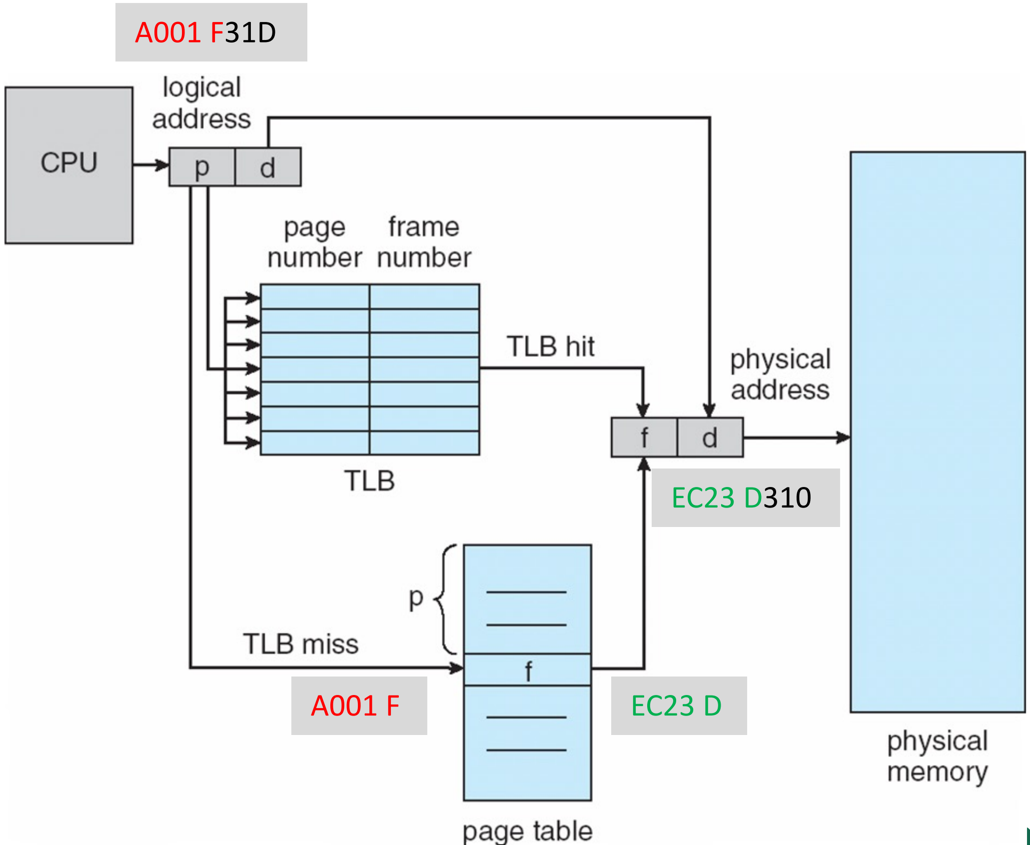
ISA knows what is being fetched

- "64-bit" chips:
  - Within the CPU, data/addresses are mostly 64 bit.
  - Externally addresses may be 48 bits. Things are not straightforward these days.
- Comment on the terminology in Operating Systems
  - Terms coined by developers of various schemes at different times
  - Terms like "TLB", "Hadoop" etc.

Questions from last time

Page table: Separate page table for each process

- Index: page number (used as an address); entry: frame number.
- Page table needs to occupy contiguous memory locations. Problem when p has too many bits (Solution: use multi-level page tables.)

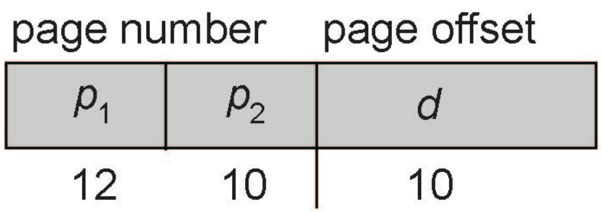


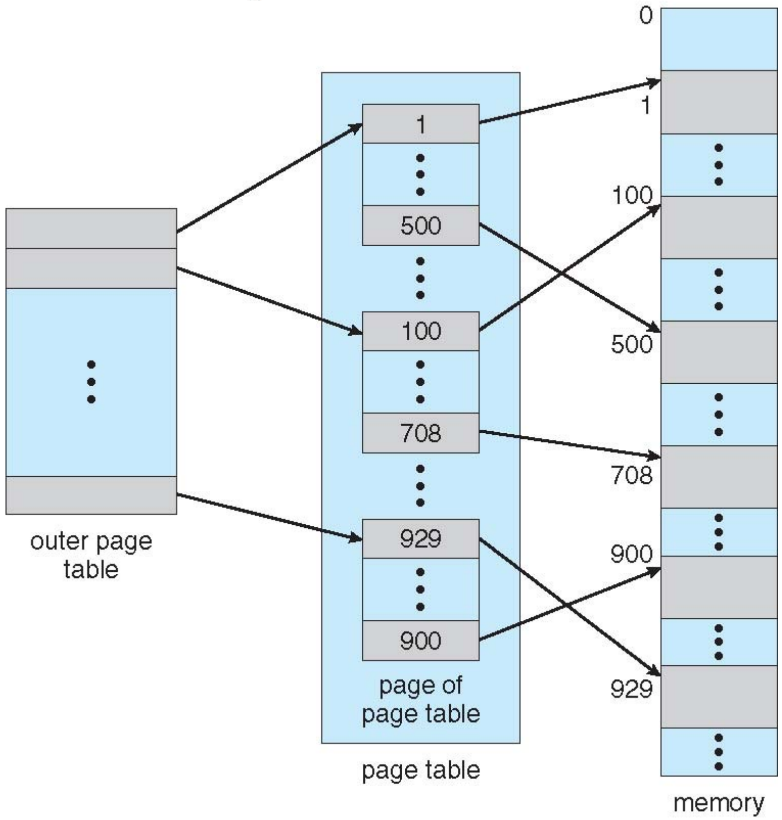
p: page number
f: frame number
Page size is the same as frame size

Where are the frames?
How big is a frame?
How many frames?

Frames are in memory.
A frame is 2^{12} bytes.
Up to 2^{20} frames.

Two-Level Page-Table Scheme





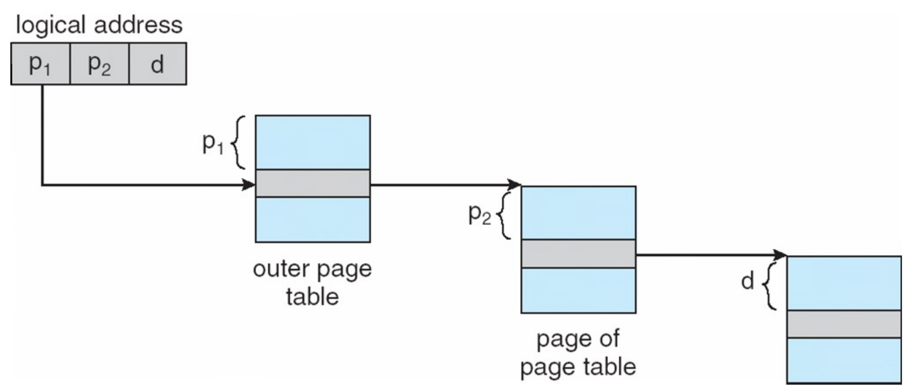
Outer page table: $2^{p1} = 2^{12}$ entries

- entry points to beginning of a page in the page table

Page Table: with 2^{12} pages, each with $2^{p2} = 2^{10}$ entries

- Entry points to a frame in physical memory

Physical memory: Many frames. *d* is the offset within the frame of size $2^{d} = 2^{10}$

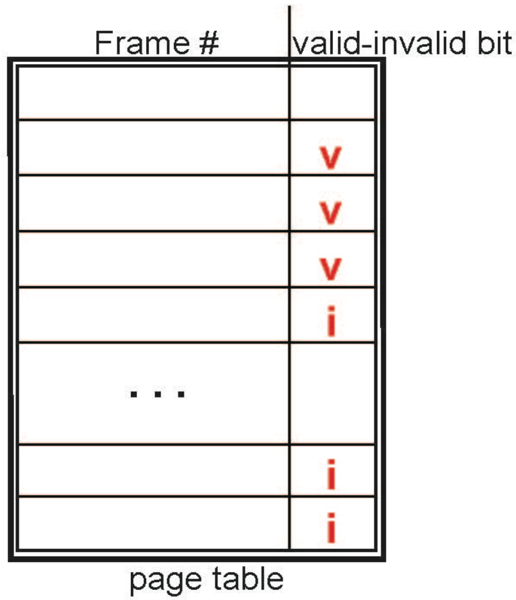


Demand paging: Basic Concepts

- Demand paging: pager brings in only those pages into memory what are needed
- 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** ⇒ in-memory – **memory resident**, **i** ⇒ not-in-memory)
- Initially valid–invalid bit is set to **i** on all entries
- Example of a page table snapshot:



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

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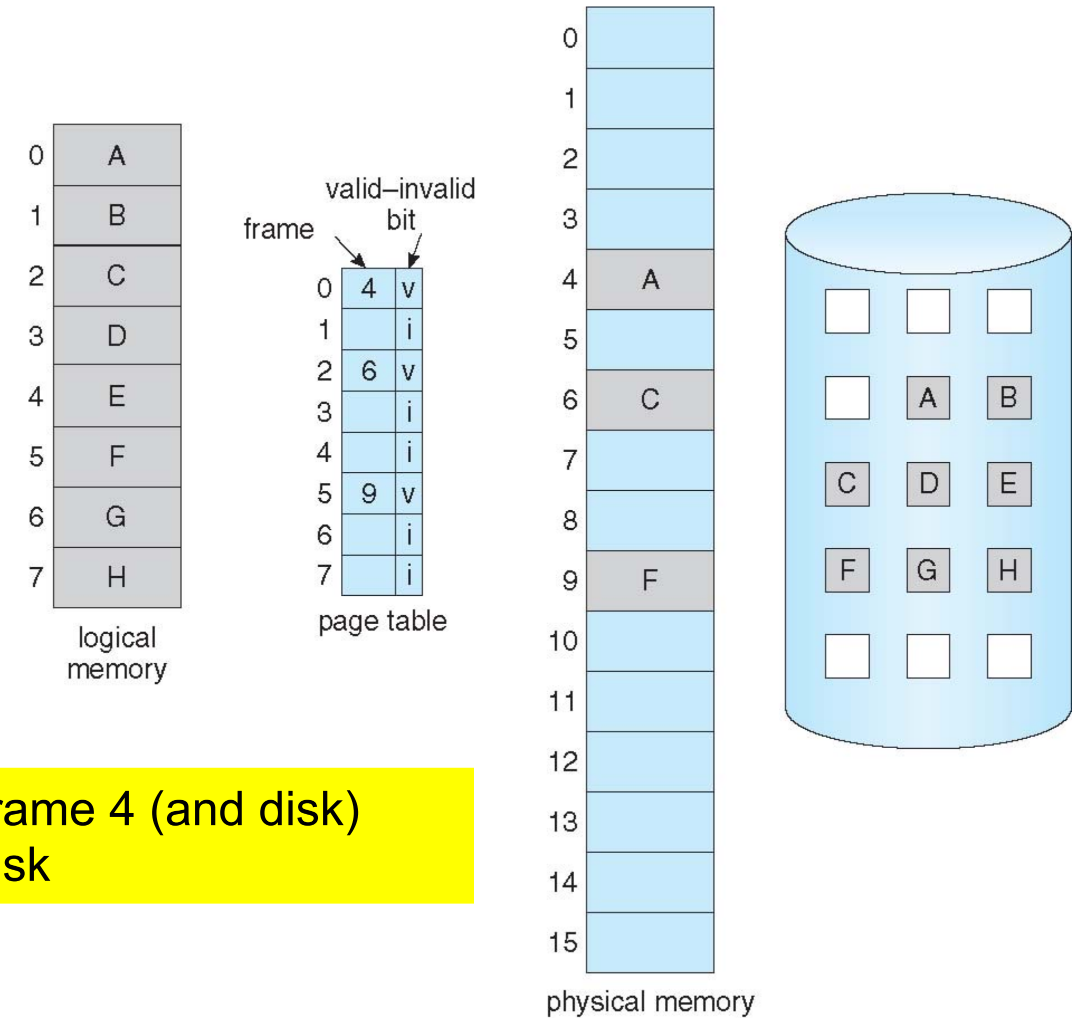
Page Table When Some Pages Are Not in Main Memory



Page 0 in Frame 4 (and disk)
Page 1 in Disk

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Page Fault

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

Page fault

1. Operating system looks at a table to decide:
   - Invalid reference $\Rightarrow$ abort
   - Just not in memory, but in *backing storage*, ->2
2. Find free frame
3. Get 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

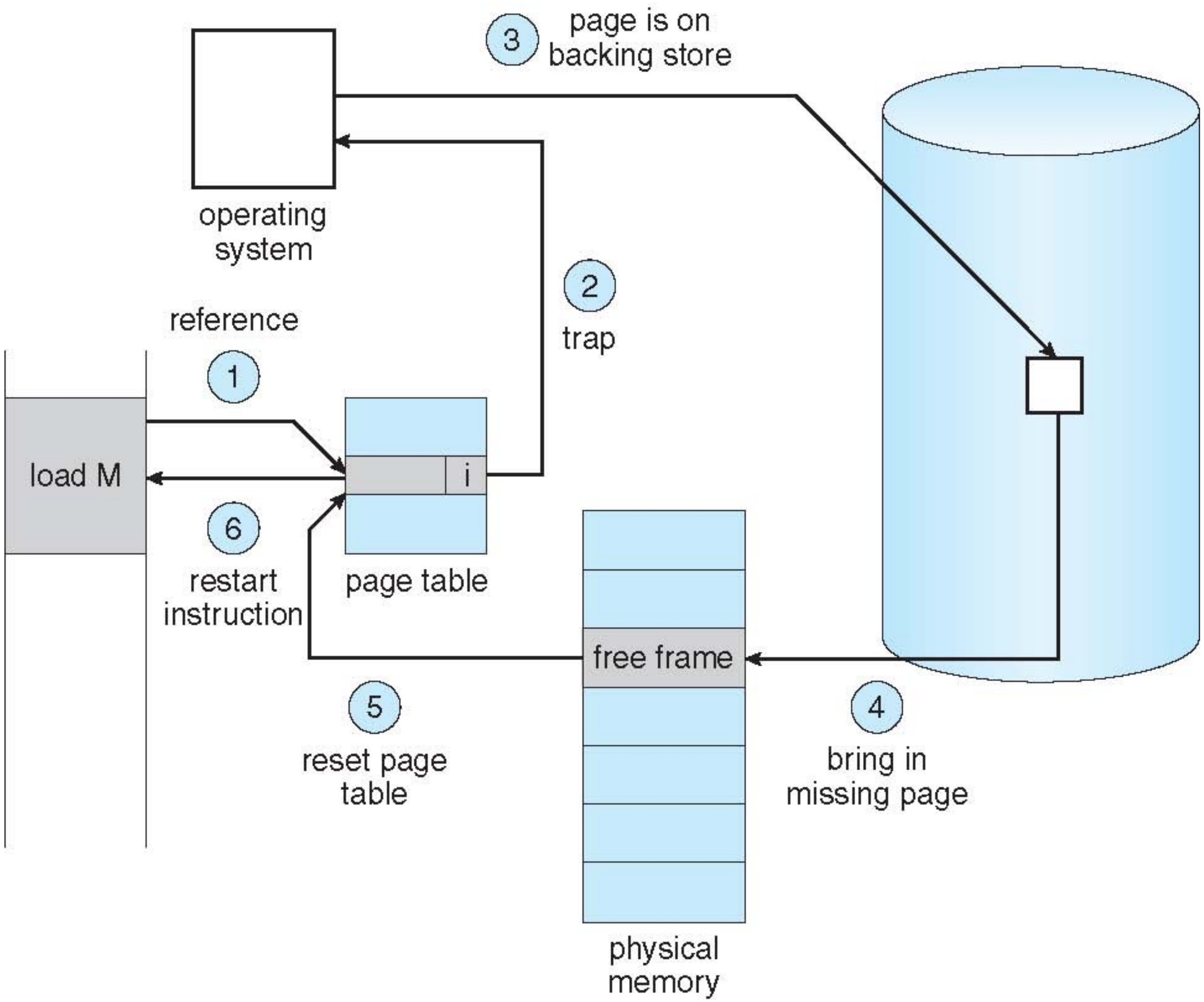
Page fault: context switch because disk access is needed

Technical Perspective: Multiprogramming

Solving a problem gives rise to a new class of problem:

- Contiguous allocation. Problem: external fragmentation
- Non-contiguous, but entire process in memory: Problem: Memory occupied by stuff needed only occasionally. Low degree of Multiprogramming.
- Demand Paging: Problem: page faults
- How to minimize page faults?

Steps in Handling a Page Fault



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**

Performance of Demand Paging (Cont.)

- Three major activities
  - Service the interrupt – careful coding means just several hundred instructions needed
  - Read the page – relatively long time
  - Restart the process – again just a small amount of time
- Page Fault Rate $0 \le p \le 1$
  - if $p = 0$ no page faults
  - if $p = 1$, every reference is a fault
- Effective Access Time (EAT)

Hopefully p <<1

EAT = $(1 - p)$ x memory access time
+ p (page fault overhead
+ swap page out + swap page in)

Page swap time = seek time + latency time

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Demand Paging Simple Numerical Example

- Memory access time = 200 nanoseconds
- Average page-fault service time = 8 milliseconds
- EAT = (1 – p) x 200 ns + p (8 milliseconds)

  = (1 – p) x 200 + p x 8,000,000 nanosec.

  = 200 + p x 7,999,800 ns

Linear with page fault rate

- 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, **p = ?**
  - 220 > 200 + 7,999,800 x p
    20 > 7,999,800 x p
  - p < .0000025
  - < one page fault in every 400,000 memory accesses

We make some simplifying assumptions here.

Issues: Allocation of physical memory to I/O and programs

- Memory used for holding **program** pages
- **I/O buffers** also consume a big chunk of memory
- Solutions:
  - Fixed percentage set aside for I/O buffers or
  - Processes and the I/O subsystem compete

Demand paging and the limits of logical memory

- Without demand paging
  - All pages of process **must be** in physical memory
  - Logical memory **limited** to size of physical memory
- With demand paging
  - All pages of process **need not be** in physical memory
  - Size of logical address space is **no longer constrained** by physical memory
- Example
  - 40 pages of physical memory
  - 6 processes each of which is 10 pages in size
    - But each process only needs 5 pages *as of now*
  - Run 6 processes with 10 pages to spare

Higher degree of multiprogramming

Coping with over-allocation of memory

Example

- Physical memory = 40 pages
- 6 processes each of which is of size 10 pages
  - But are using 5 pages each as of now
- What happens if each process needs all 10 pages?
  - 60 physical frames needed
- **Option: Terminate** a user process
  - But paging should be transparent to the user

- **Option: Swap out** a process
  - Reduces the degree of multiprogramming

- **Option: Page replacement:** selected pages. Policy?

soon

Solving the Fork mystery (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 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? (security)

For security

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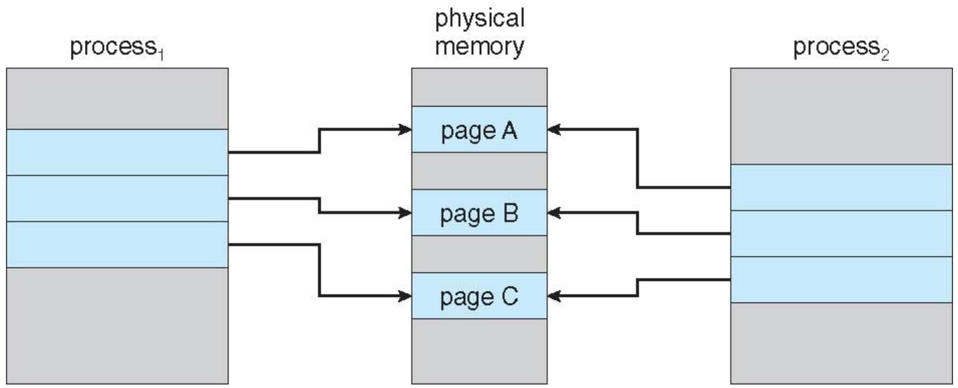
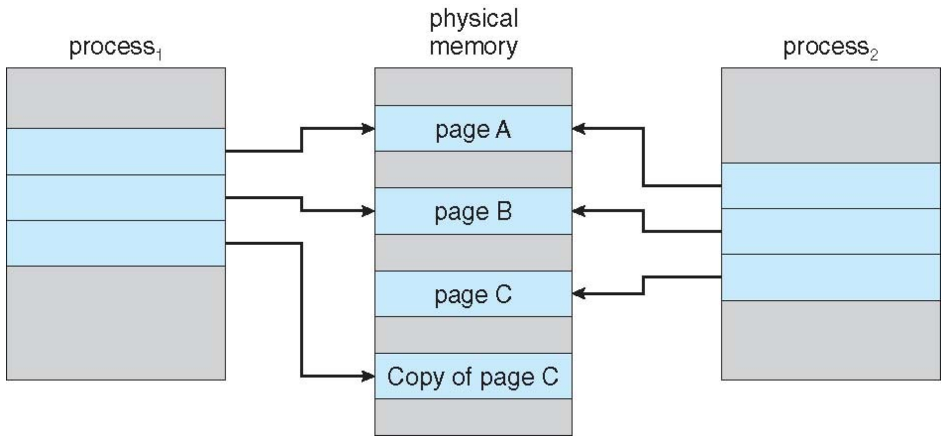
Copy-on-write

Before Process 1 Modifies Page C



After Process 1 Modifies Page C



What Happens if there is no Free Frame?

- Could be all used up by process pages or 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

Continued to Page replacement etc...

Page Replacement

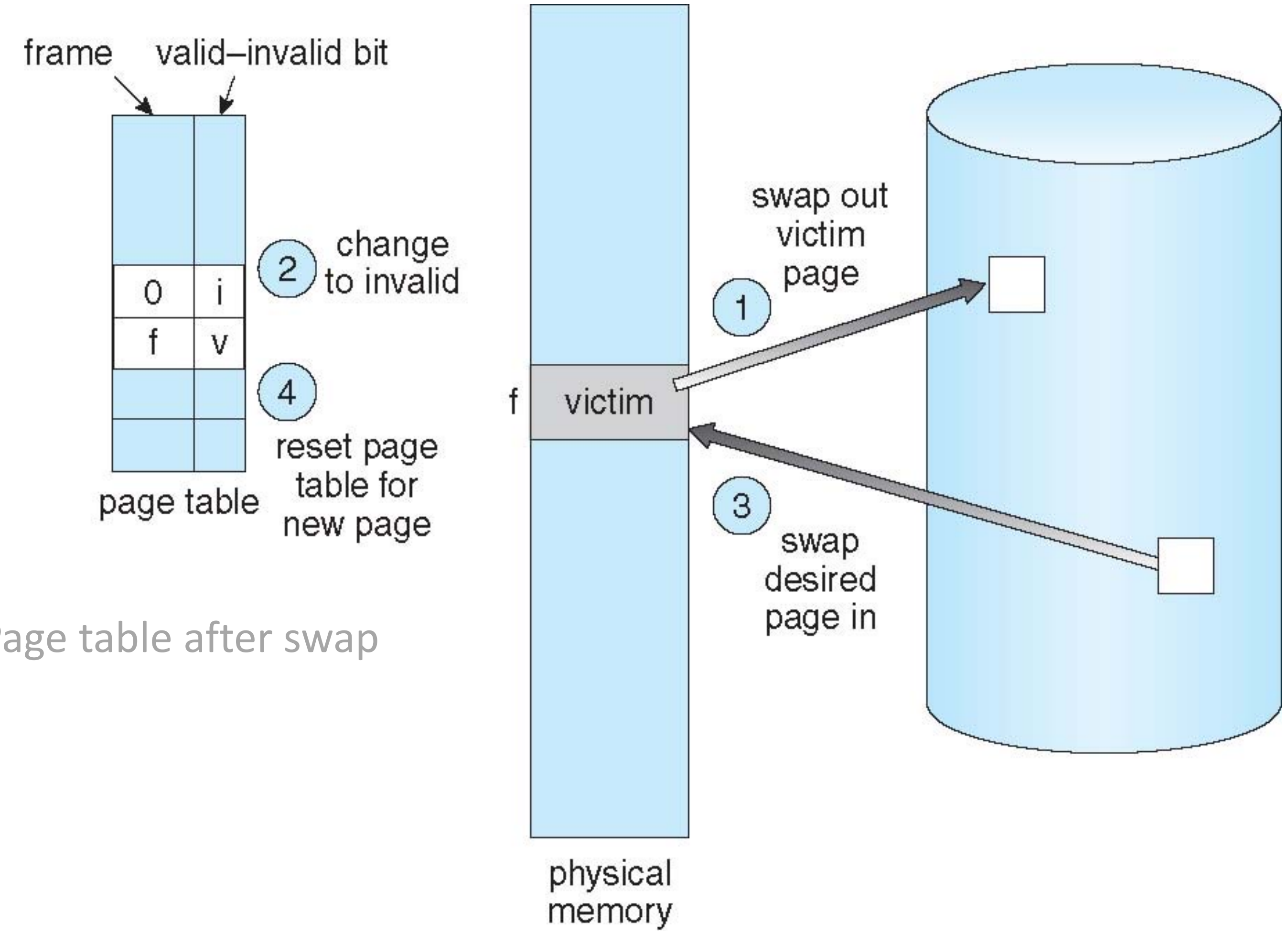
- Prevent **over-allocation** of memory by modifying page-fault service routine to include page replacement
- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory
- Use **modify** (**dirty**) **bit** to reduce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

Basic Page Replacement

1. Find the location of the desired page on disk
2. Find a free frame:
   I. If there is a free frame, use it
   II. If there is no free frame, use a page replacement algorithm to select a **victim frame**
   III. 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

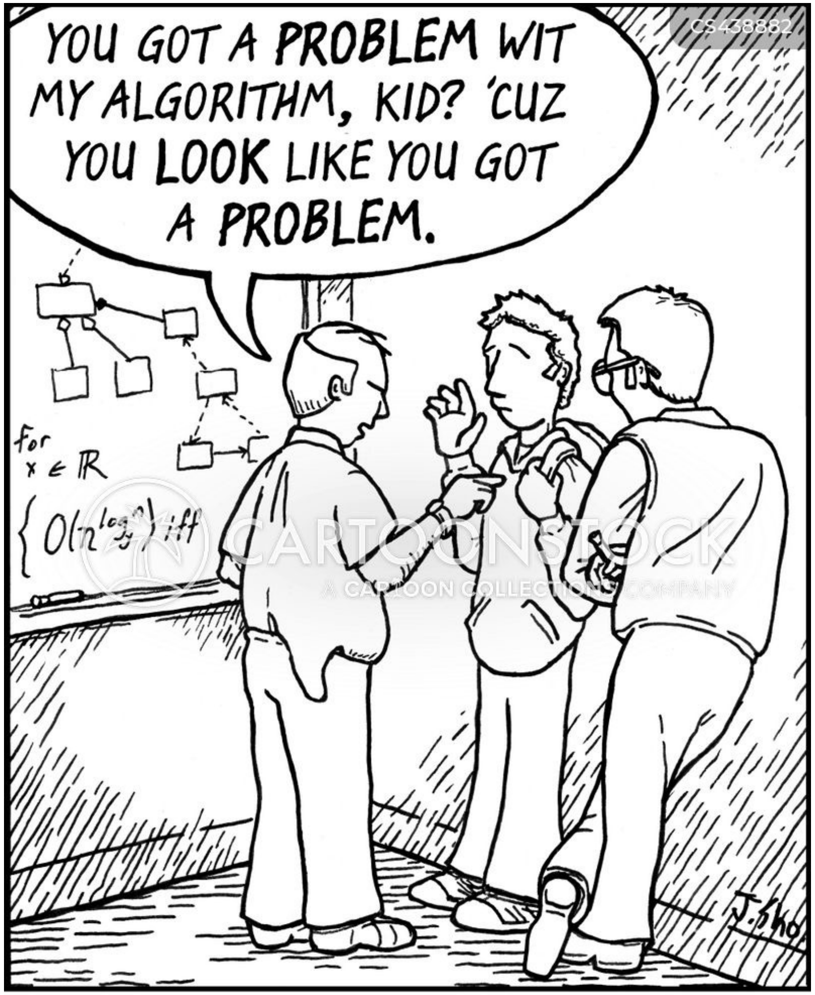
Note now potentially 2 page transfers for page fault – increasing EAT

Page Replacement



Page table after swap

More algorithms …



Jim unwittingly wanders into a rough section of the Computer Science department.

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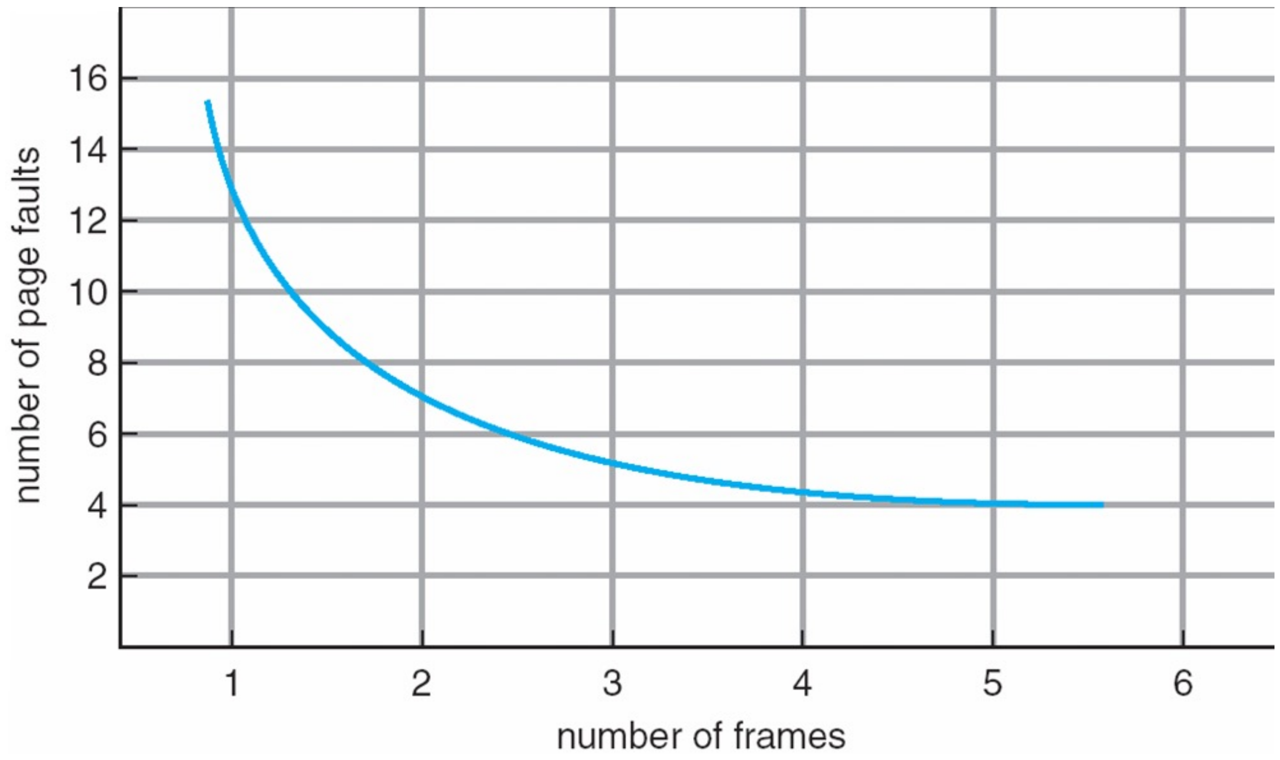
Page Replacement Algorithms

- **Page-replacement algorithm**
  - Which frames to replace
  - Want lowest page-fault rate
- **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, we use 3 frames, and the **reference string** of referenced page numbers is

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

Graph of Page Faults Versus The Number of Frames



What we would generally expect

Page Replacement Algorithms

Algorithms

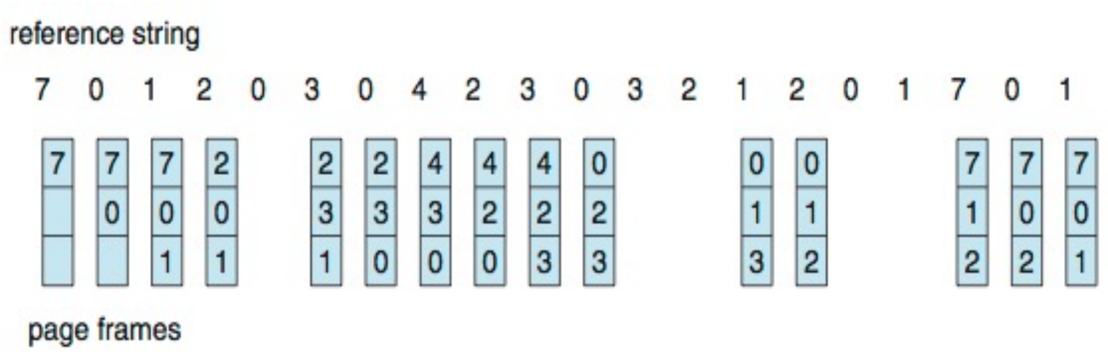
- FIFO
- "Optimal"
- The Least Recently Used (LRU)
  - Exact Implementations
    - Time of use field, Stack
  - Approximate implementations
    - Reference bit
    - Reference bit with shift register
    - Second chance: clock
    - Enhanced second chance: dirty or not?
- Other

FIFO page replacement algorithm: Out with the old; in with the new

- When a page must be replaced
  - Replace the oldest one
- OS maintains list of all pages currently in memory
  - Page at head of the list: Oldest one
  - Page at the tail: Recent arrival
- During a page fault
  - Page at the head is removed
  - New page added to the tail

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)

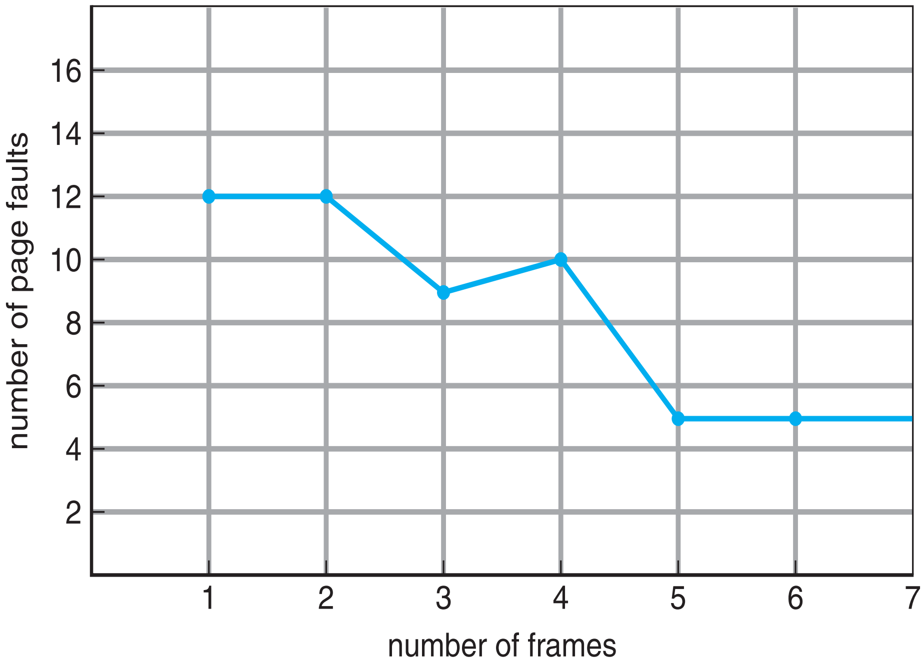


- 15 page faults (out of 20 accesses)
- Sometimes a page is needed soon after replacement 7,0,1,2,0,3 (0 out),0, ..

Belady's Anomaly

- Consider Page reference string 1,2,3,4,1,2,5,1,2,3,4,5
  - 3 frames, 9 faults, 4 frames 10 faults! Try yourself.
  - Sometimes adding more frames can cause more page faults!
    - **Belady's Anomaly**

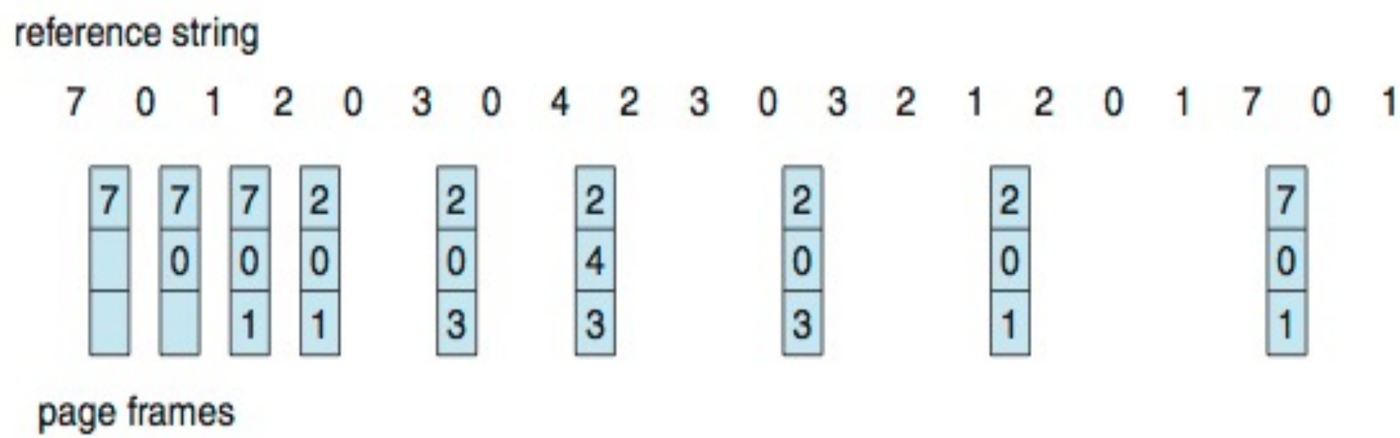
Lazlo Belady was here at CSU. Guest in my CS530!



Budapest, 1928

"Optimal" Algorithm Belady 66

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

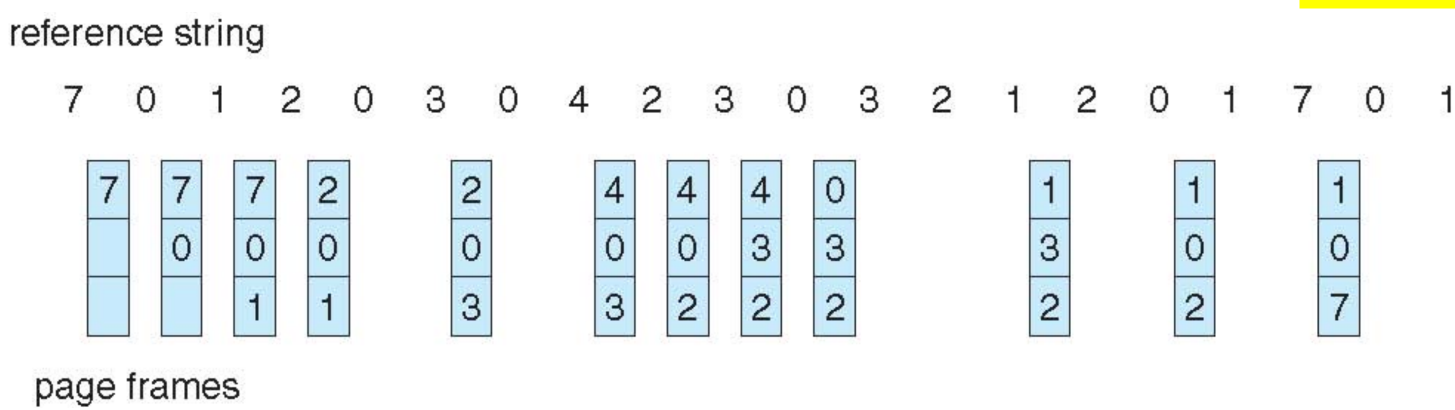


  - 4th access: replace 7 because we will not use if got the longest time…
  - 9 page replacements is optimal for the example
- But how do we know the future pages needed?
  - Can't read the future in reality.
- Used for *measuring* how well an algorithm performs.

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!

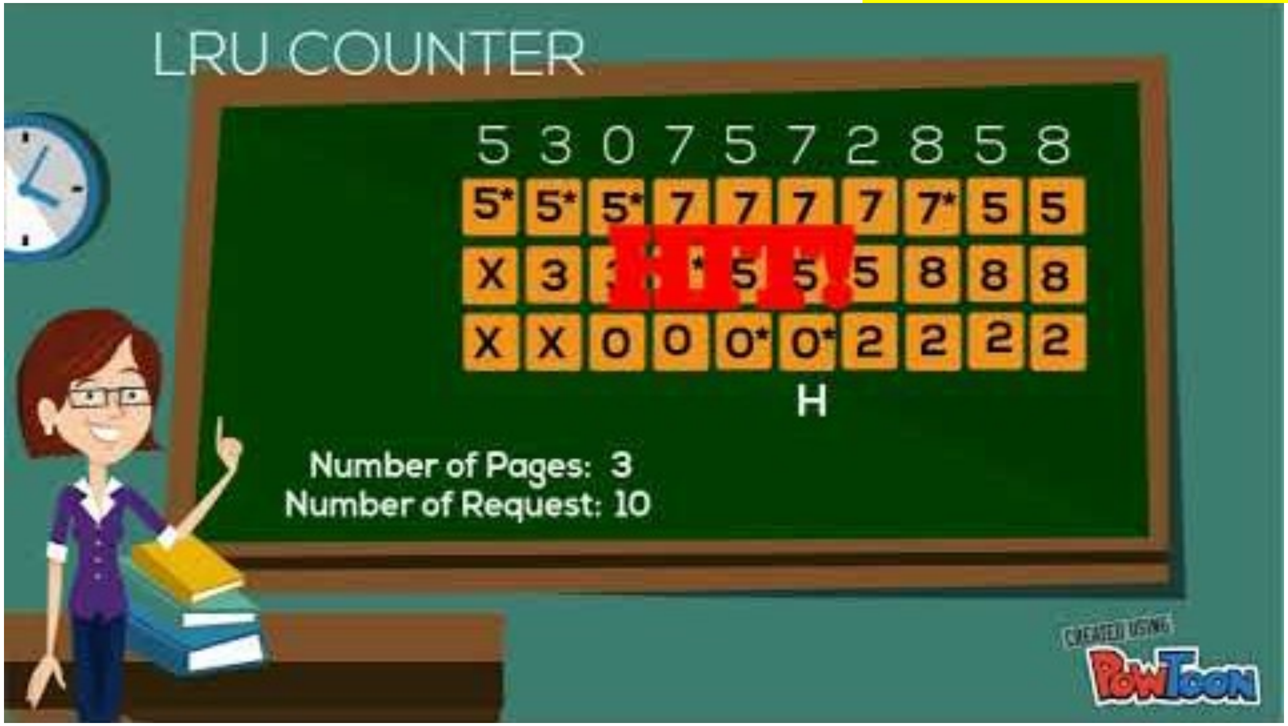


- 12 faults – better than FIFO (15) but worse than OPT (9)
- Generally good algorithm and frequently used
- But how to implement it by tracking the page usage?

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

Least Recently Used (LRU) Algorithm

LRU page number is marked (*). Unmarked if that page is accessed.



LRU applied to cache memory.

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Least Recently Used (LRU) Algorithm

* Use past knowledge rather than future

- 12 faults – better than FIFO (15) but worse than OPT (9)
- Tracking the page usage. One approach: mark least recently used page each time.

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*	4	4	4*	0	0	0*	1						
	0	0	0*	0	0	0	0	0*	3	3	3	3	3						
		1	1	1*	3	3	3*	2	2	2	2*	2	2						

- Other approach: use stack for tracking (soon)

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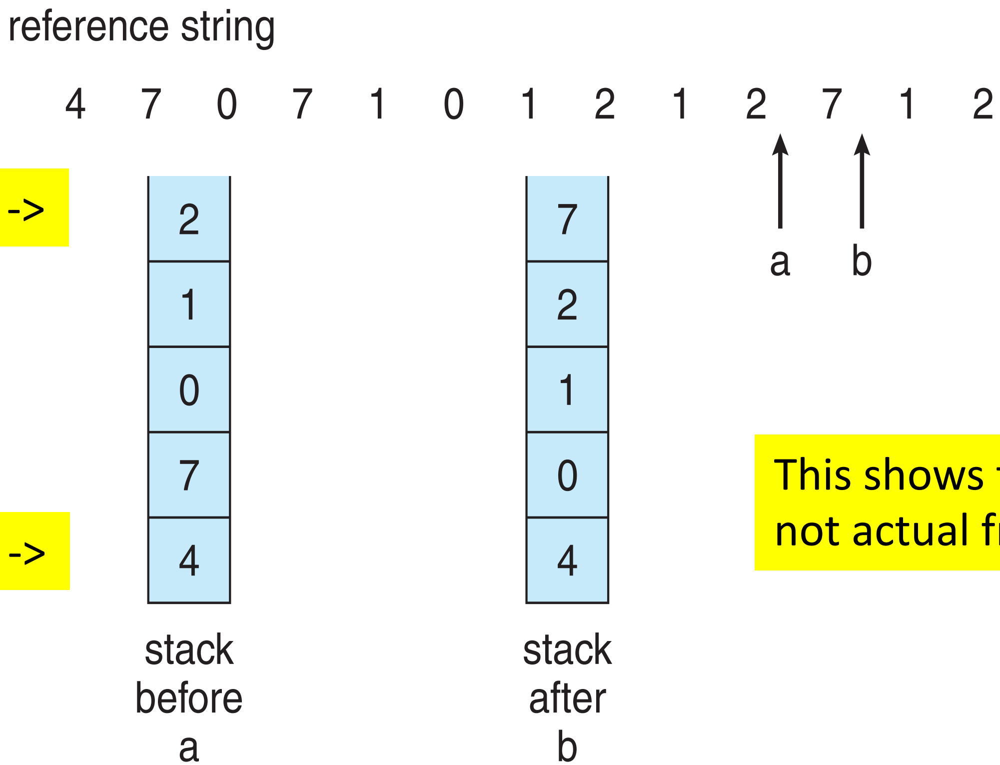
Back from ICQ

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.

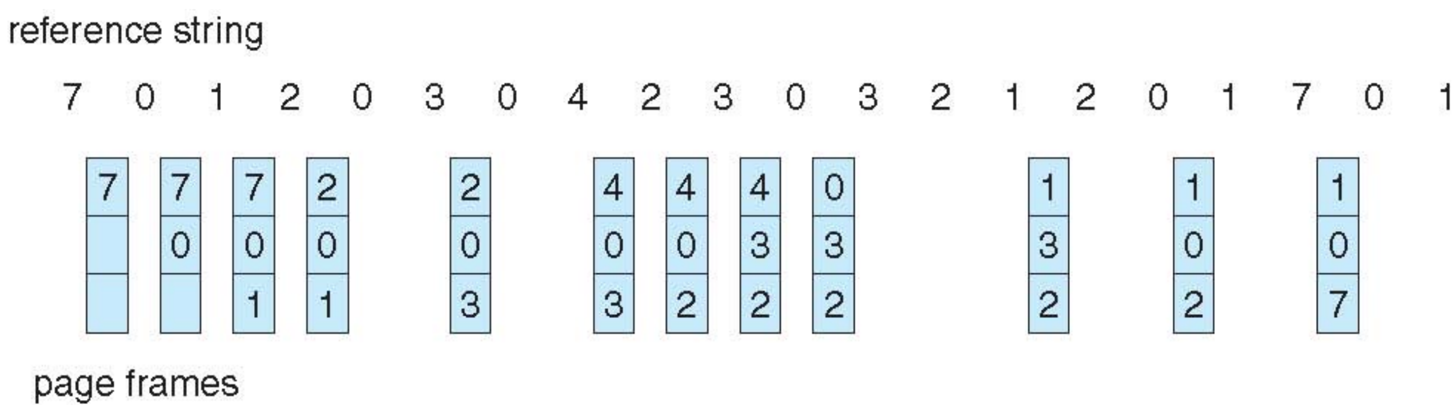
Too slow if done in software

Use Of A Stack to Record Most Recent Page References
Examine this at home.

	4	7	0	7	1	0	1	2	1	2	7	1	2
Most recently used ->	4	7	0	7	1	0	1	2	1	2	7	1	2
		4	7	0	7	1	0	1	2	1	2	7	1
			4	4	0	7	7	0	0	0	1	2	7
					4	4	4	7	7	7	0	0	0
Least recently used ->								4	4	4	4	4	4

Detailed version of previous slide.
This shows tracking stack, not actual frames.

Use Of A Stack to Record Most Recent Page References



Earlier problem (upper) revisited.
This shows tracking stack, not actual frames.

	7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
MRU->	7	0	1	2	0	3	0	4	2	3	0	3								
		7	0	1	2	0	3	0	4	2	3	0								
LRU->			7	0	1	2	2	3	0	4	2	2								

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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

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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

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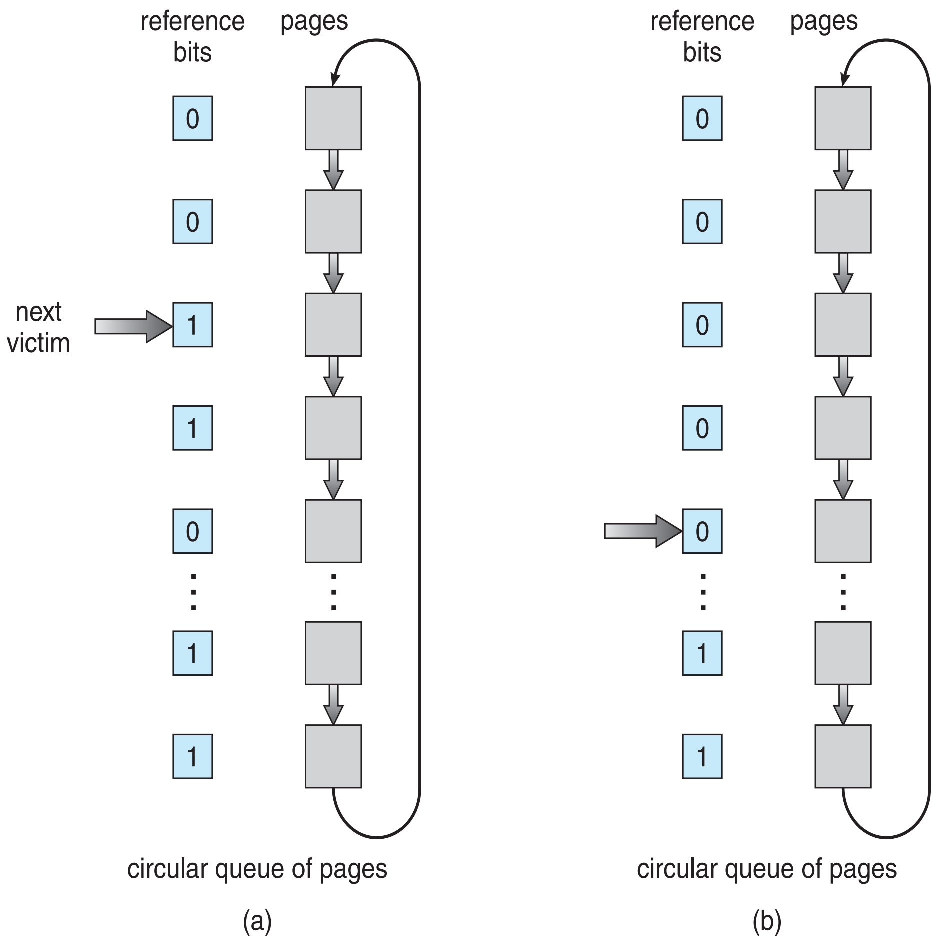
Second-chance algorithm

- **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



- **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

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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

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

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Global vs. Local Allocation

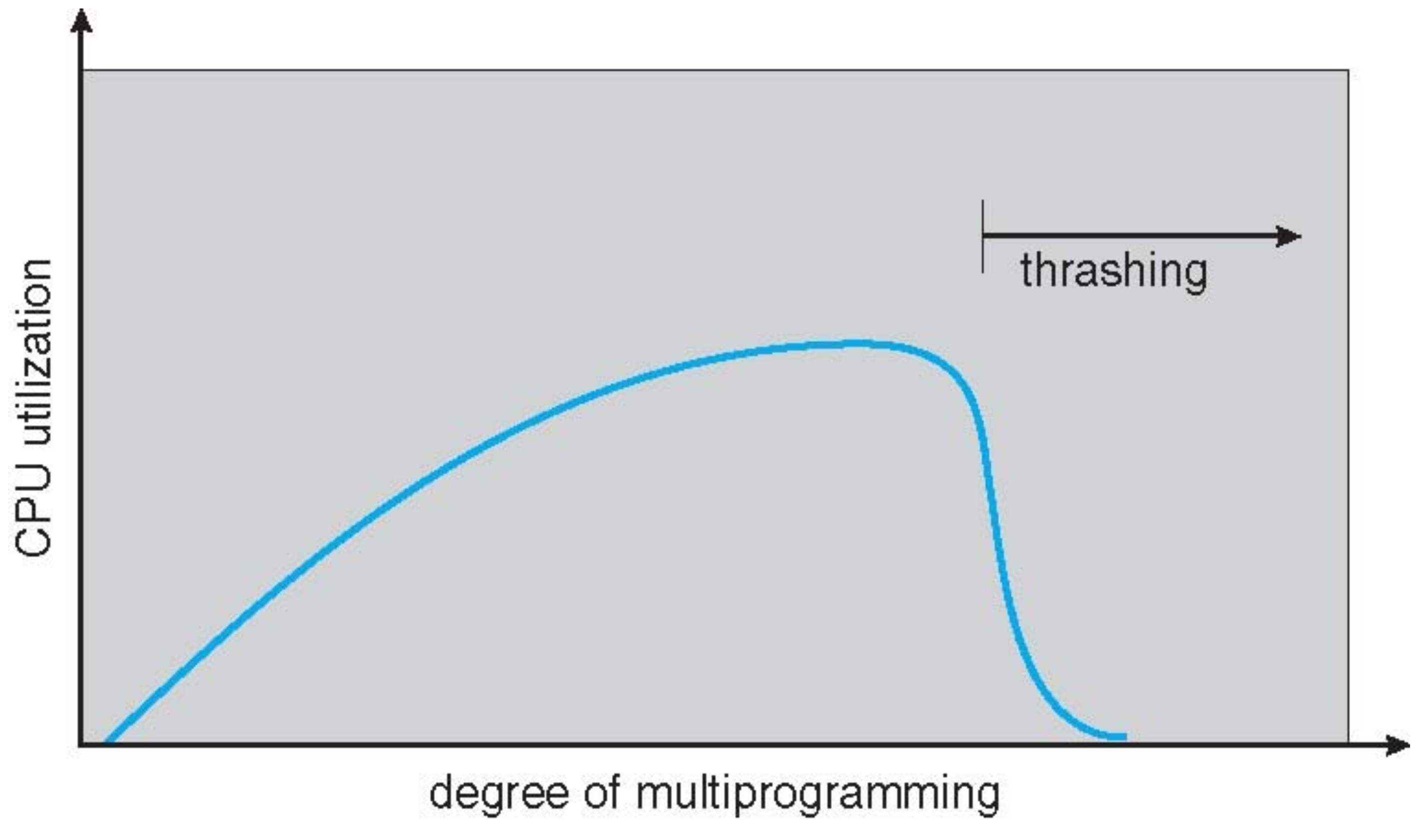
- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another
  - But then process execution time can vary greatly
  - But greater throughput, so more common
- **Local replacement** – each process selects from only its own set of 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.)



Demand Paging and Thrashing

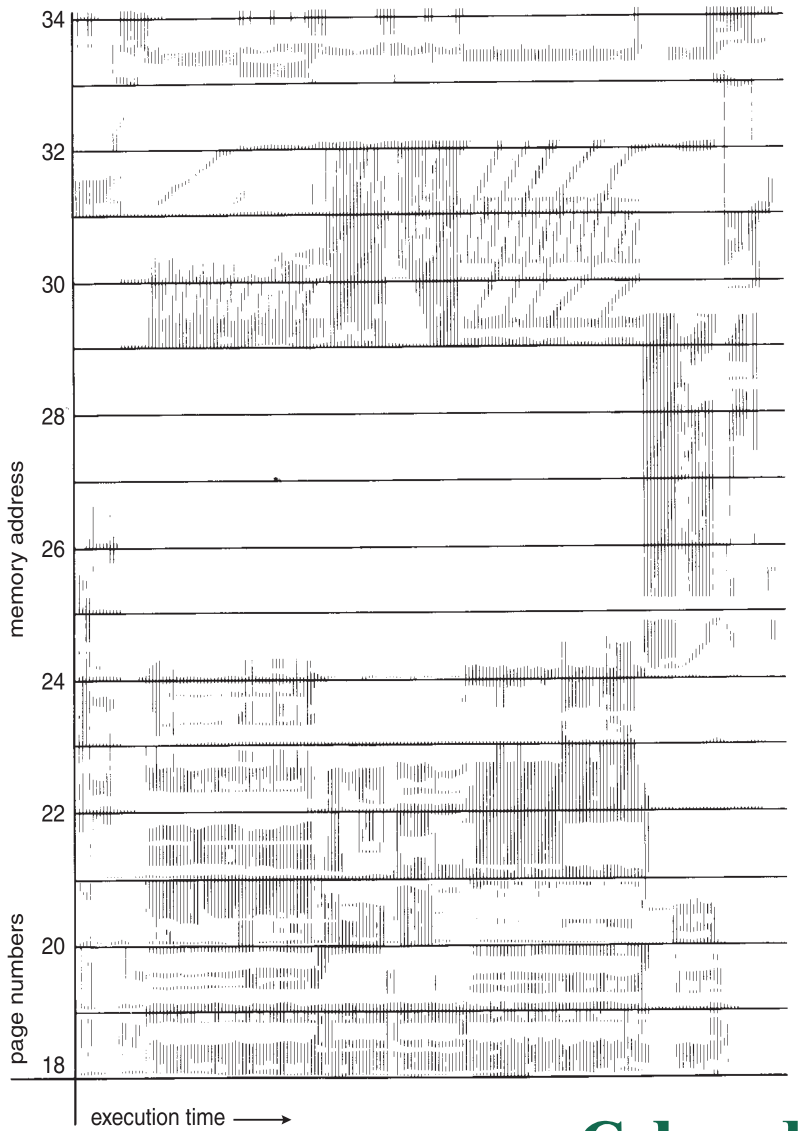
- Why does demand paging work?
  Locality model
  - Process migrates from one locality to another
  - Localities may overlap

- 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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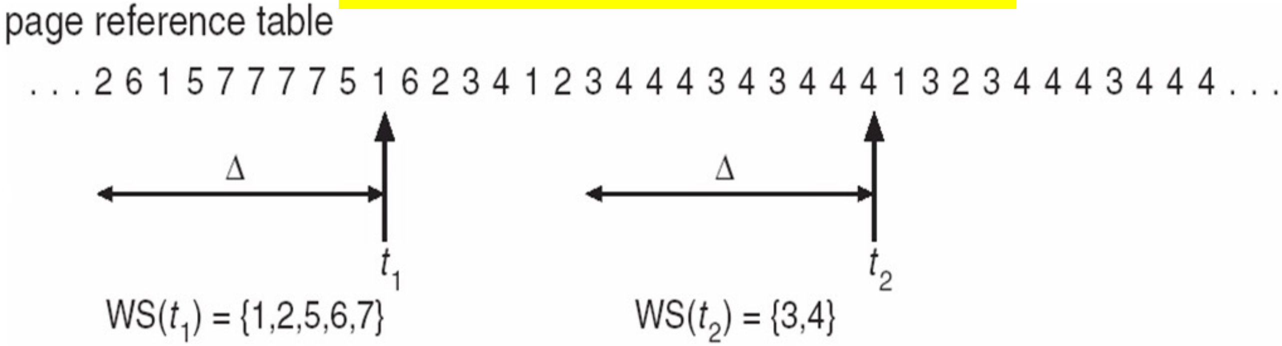
Working-Set Model

- $\Delta \equiv$ **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**
  - **Policy** if D > m, then suspend or swap out one of the processes

M is number of frames

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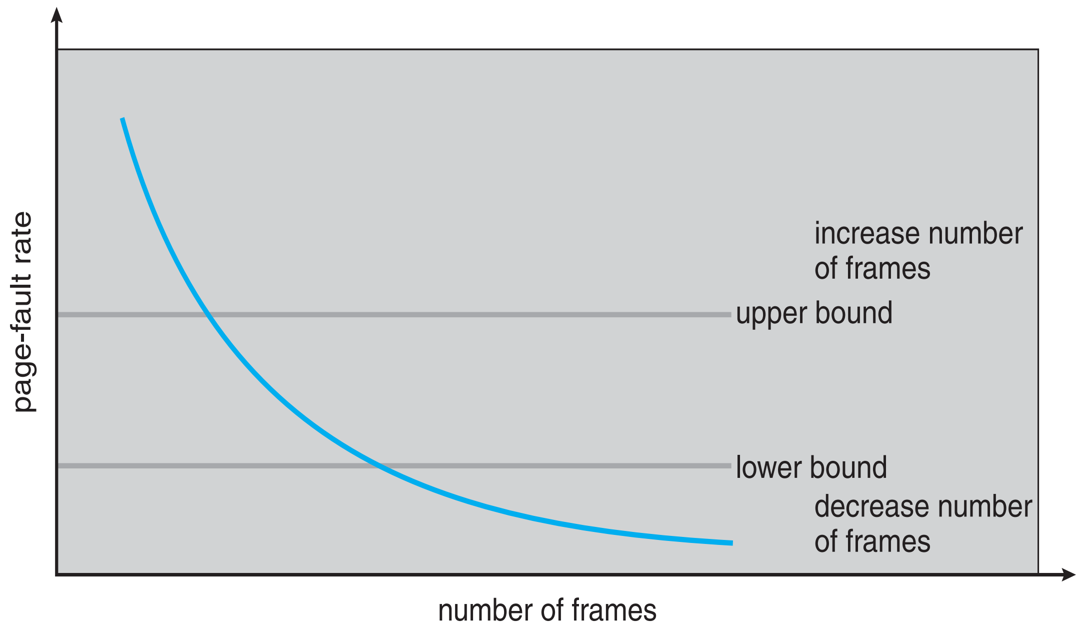
Page-Fault Frequency Approach

- 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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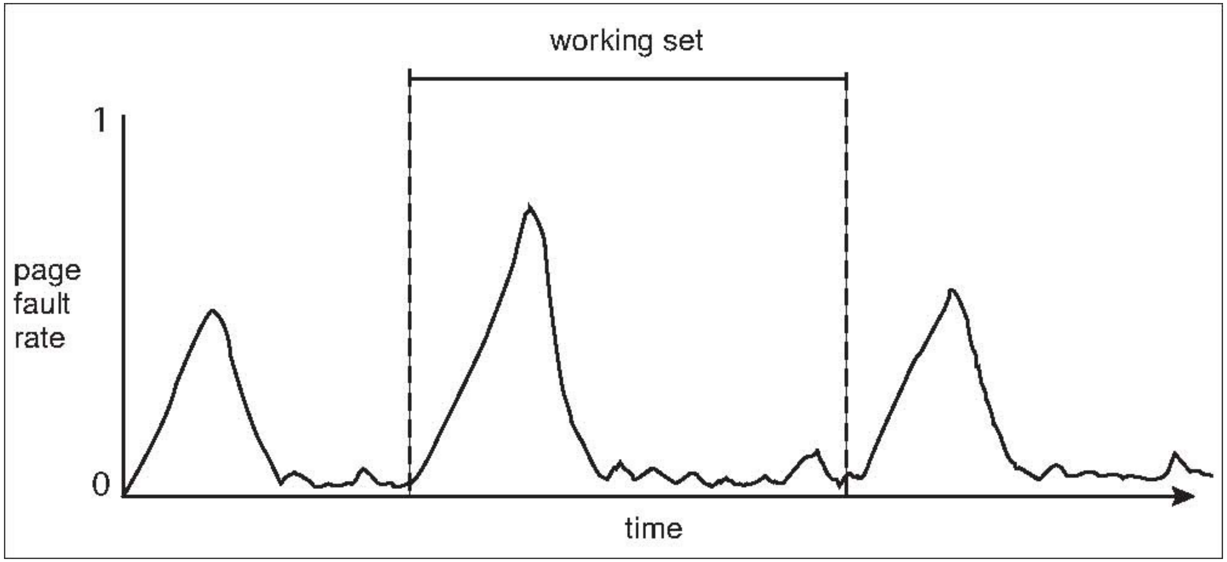
Working Sets and Page Fault Rates

- 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

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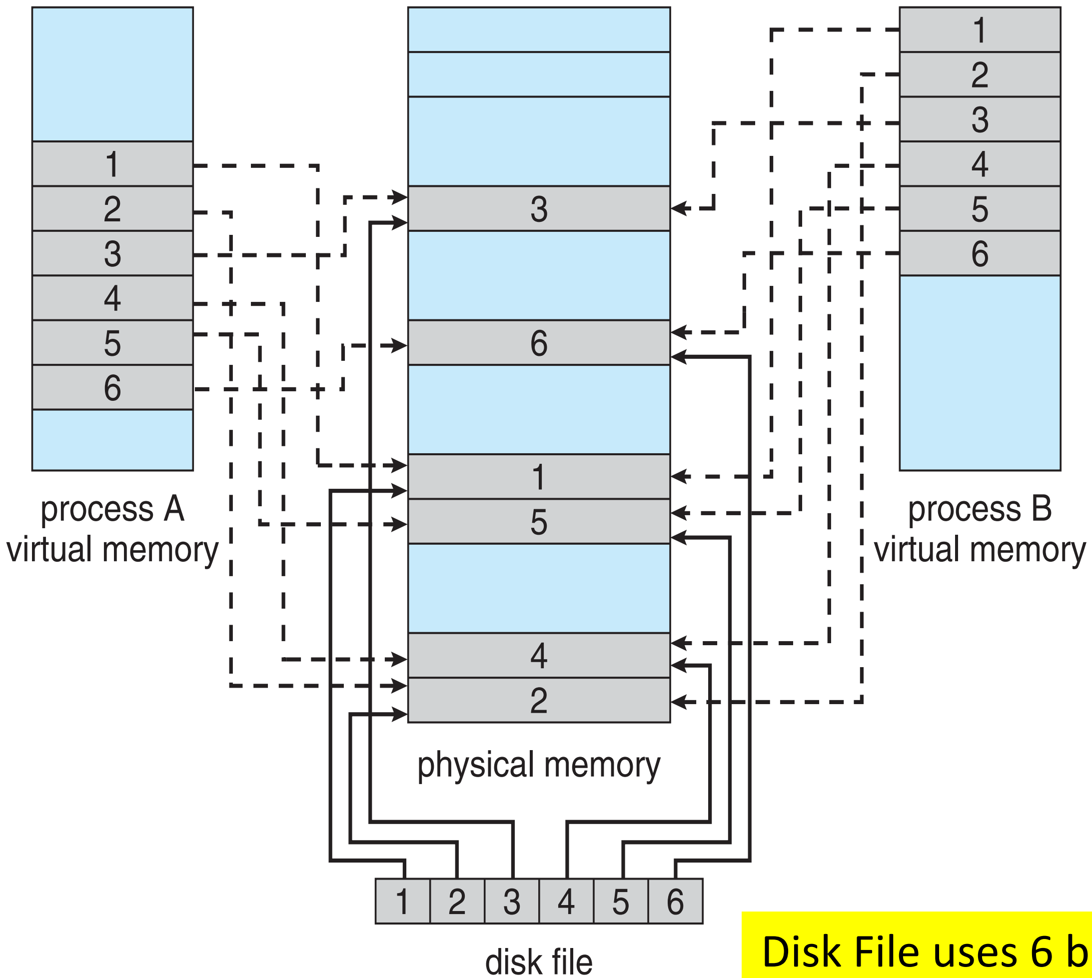
Memory-Mapped Files

- 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

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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 * α*** saved pages faults > or < than the cost of prepaging ***s * (1- α)*** unnecessary pages?
    - ***α*** near zero $\Rightarrow$ greater prepaging loses

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

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