CS 370: OPERATING SYSTEMS
[VIRTUAL MEMORY]

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Frequently asked questions from the previous class survey

- Contents of page table entries in multilevel page table?

Topics covered in this lecture

- Demand Paging
- Performance of Demand Paging
- Page Replacement
- Belady's anomaly
- Stack algorithms

DEMAND PAGING

Demand Paging: Basic concepts

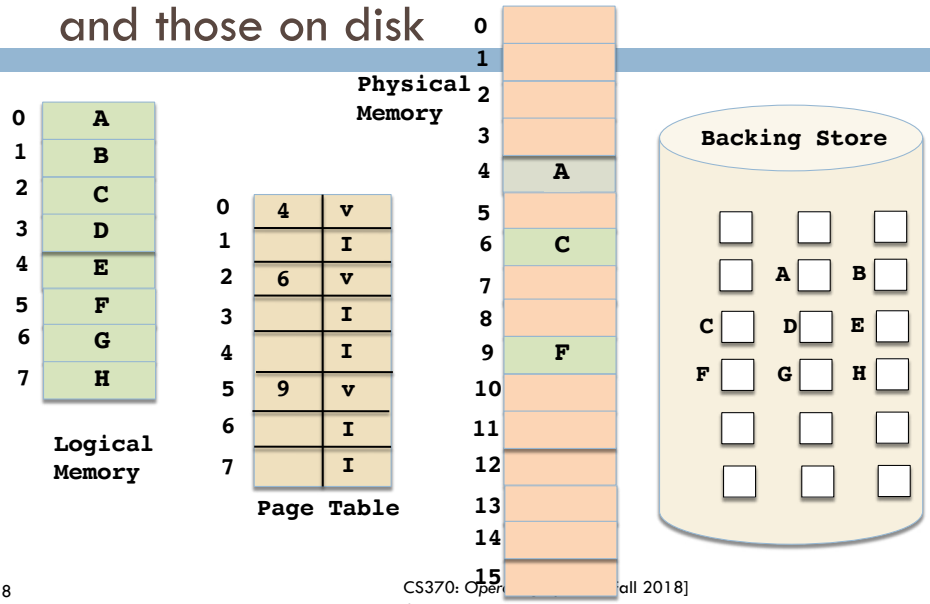
- When a process is to be swapped in, **guess** which pages will be utilized by process
  - Before the process will be swapped out again
- **Avoid** reading unused pages
  - Better physical memory utilization
  - Reduced I/O
    - Lower swap times

Distinguishing between pages in memory and those on disk

- Valid-Invalid bits
  - Associated with entries in the page table
- **Valid**
  - Page is both legal and in memory
- **Invalid**
  1. Page is *not in logical address space* of process

     OR
  2. Valid BUT currently *on disk*

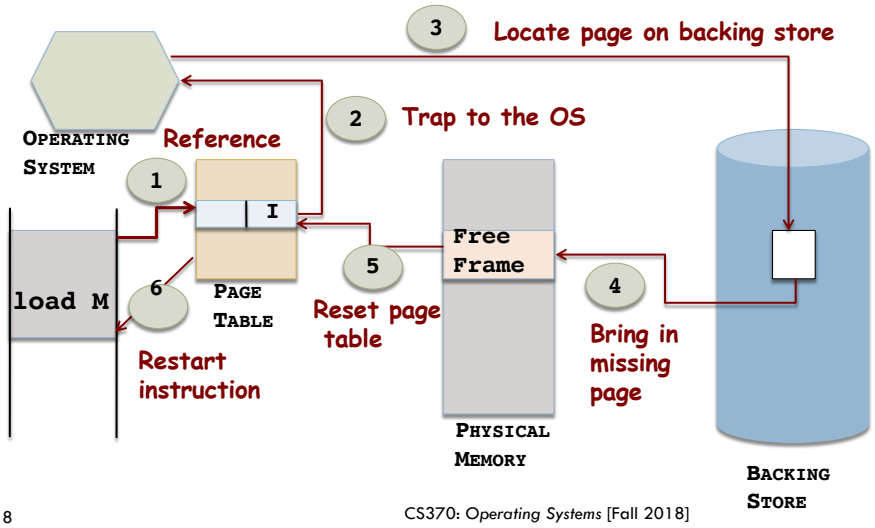
Distinguishing between pages in memory and those on disk



Handling Valid-invalid entries in the page table

- If process never attempts to access an invalid page?
  - No problems
- If process accesses page that is not memory resident?
  - **Page fault**

Handling page faults



Pure demand paging

- Never bring a page into memory unless it is required
- Execute process with no pages in memory
  - First instruction of process will fault for the page
- Page fault to load page into memory and execute

Potential problems with pure demand paging

- Multiple page faults per instruction execution
  - One fault for instruction
  - Many faults for data
- Multiple page faults per instruction are **rare**
  - **Locality of reference**

Hardware requirements to support demand paging

- Page Table
- Secondary memory
  - Section of disk known as **swap space** is used

Restarting instructions after a page fault

- Page faults occur at **memory reference**
- Use PCB to save state of the interrupted process
- Restart process in *exactly* the same place
  - Desired page is now in memory and accessible

Restarting processes after a page fault has been serviced

- If fault occurred during an instruction fetch
  - During restart, refetch the instruction
- If fault occurred while fetching operands
  1. Fetch and decode instruction
  2. Fetch the operand

Worst case example

- Add operands **A** and **B**
  - Place sum in **C**
- If we fault while storing **C**
  - Service page fault
  - Update page table
  - Restart instruction
    - Decode, fetch operand and perform addition

Problems when operations modify several different memory locations

- **E.g.** Move a block from one memory location to another
- {C1} Either block straddles page-boundary
- {C2} Page fault occurs
- Move might be **partially** done
  - Uh-oh …

Approaches to fault-proofing block transfers

① Compute and access both **ends of the block**
- If a page fault were to happen: it will at this point
  - Nothing has been partially modified
- After fault servicing, block transfer completes

② Use temporary registers
- Track overwritten values

Can on-demand paging be applied anywhere without modifications?

- Paging is between CPU and physical memory
  - **Transparent** to user process
- Non-demand paging can be applied to **any system**
- *Not so* for demand paging
  - Fault processing of special instructions non-trivial

PERFORMANCE OF DEMAND PAGING

Effective access times

- **Without** page faults, effective access times are equal to memory access times
  - 200 nanoseconds approximately
- With page faults
  - Account for fault servicing with disk I/O

Calculating the effective access times with demand paging

p : probability of a page fault

ma : memory access time

Effective access time =

(1-p) x ma + p x page-fault-time

Components of page-fault servicing

Service interrupt	Read in the page	Restart process
1~100 µS	Latency : 3 mS Seek : 5 mS	1~100 µS

Effective access times

- Effective access time =

$$(1-p) \times ma + p \times \text{page-fault-time}$$

$$= (1-p) \times 200\text{ns} + p \times (8\text{mS})$$

$$= (1-p) \times 200 + p \times (8{,}000{,}000)$$

$$= 200 + 7{,}999{,}800 \times p$$

Effective access time directly proportional to page-fault rate

If performance degradation is to be less than 10%

$$220 > 200 + 7{,}999{,}800 \times p$$

$$20 > 7{,}999{,}800 \times p$$

$$p < 0.0000025$$

Fewer than 1 memory access out of 399,990 can page-fault

OTHER ISSUES IN DEMAND PAGING

Allocation of physical memory to I/O and programs is a challenge

- 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
  - 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

Demand paging is the OS' attempt to improve CPU utilization and system throughput

- Load pages into memory when they are **referenced**
  - Increases degree of **multiprogramming**
- Example
  - 40 pages of physical memory
  - 6 processes each of which is 10 pages in size
    - Each process only needs 5 pages as of now
  - Run 6 processes with 10 pages to spare

Increasing the degree of multiprogramming can be tricky

- Essentially we are **over-allocating** physical 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

Coping with over-allocation of memory

- **Terminate** a user process
  - But paging should be transparent to the user
- **Swap out** a process
  - Reduces the degree of multiprogramming
- **Page replacement**

The two core problems in demand paging

- **Frame allocation**
  - How many frames to allocate to a process
- **Page replacement**
  - Select the frame(s) for replacement
- Caveat:
  - Disk I/O is expensive so inefficient solutions can weigh things down

PAGE REPLACEMENT

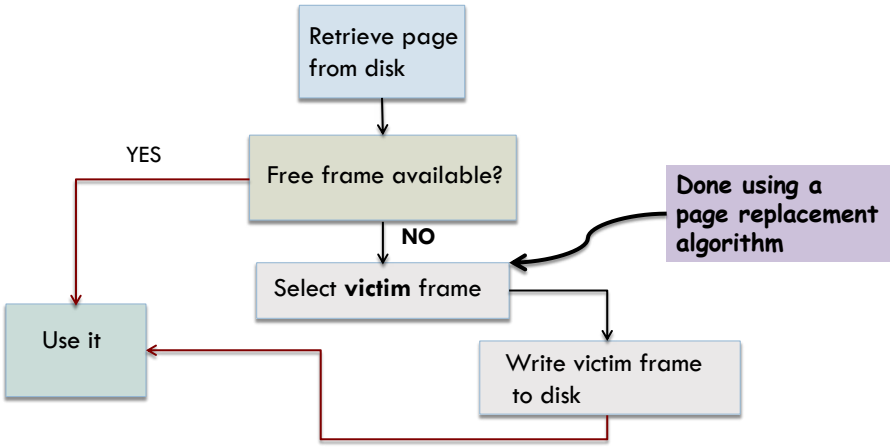
Page replacement

- If no frame is free?
  - Find one that is not currently being used
    - Use it

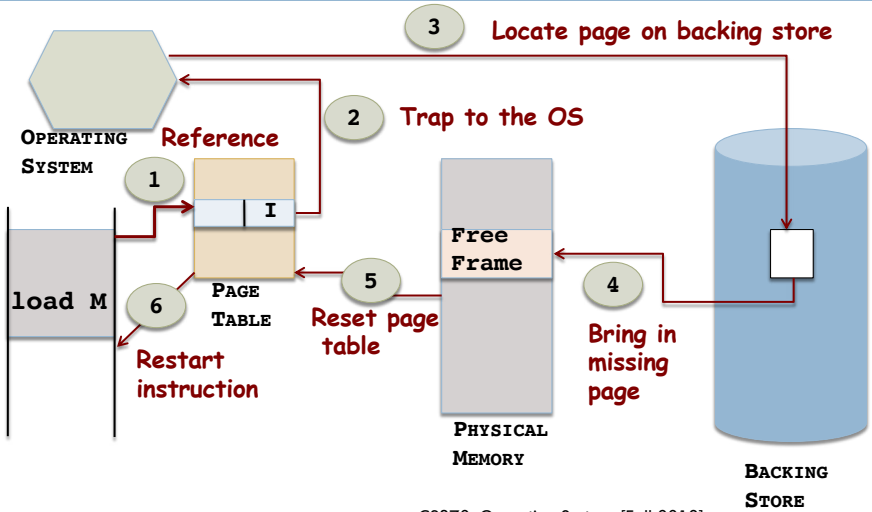
Freeing a physical memory frame

- Write frame contents to swap space
- Change page table of process
  - To reflect that page is no longer in memory
- Freed frame can now hold some other page

Servicing a page fault



Page replacement is central to demand paging



Overheads for page replacement

- If no frames are free: **2** page transfers needed
  - Victim page out
  - New page in
- No free frames?
  - Doubles page-fault service time
  - Increases effective access time

Using the modify bit to reduce page replacement overheads

- Each page/frame has a **modify** bit
  - Set by hardware when page is written into
  - Indicates if page was modified
    - Since the last time it was read from disk
- During page replacement
  - If victim page not modified, no need to write it to disk
    - Reduces I/O time by **one-half**

PAGE REPLACEMENT ALGORITHMS

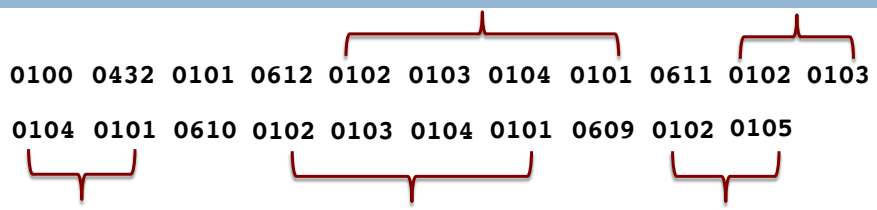
Page replacement algorithms:

- What are we looking for?
  - **Low page-fault rates**
- How do we evaluate them?
  - Run algorithm on a string of memory references
    - **Reference string**
  - Compute number of page faults

The reference string: Snapshot memory references

- We track page numbers
  - *Not* the entire address
- If we have a reference to a memory-resident page p
  - Any references to p that follow will not page fault
    - Page is already in memory

The reference string: Example Page size =100 bytes



1, 4, 1, 6, 1, 6, 1, 6, 1, 6, 1

Factors involved in determining page faults

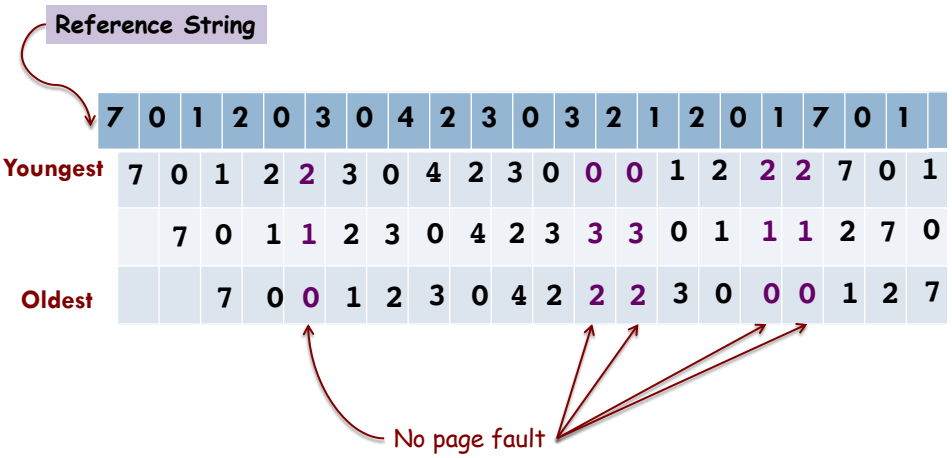
- **Reference string** of executing process
- Page **replacement algorithm**
- Number of physical memory **frames** available
- Intuitively:
  - Page faults reduce as the number of page frames increase

FIFO (FIRST IN FIRST OUT) PAGE REPLACEMENT ALGORITHM

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

FIFO example: 3 memory frames



BELADY'S ANOMALY

Intuitively the greater the number of memory frames, the lower the faults

- Surprisingly this is **not always** the case
- In 1969 Belady, Nelson and Shedler discovered counter example* in FIFO
  - FIFO caused more faults with 4 frames than 3
- This strange situation is now called **Belady's anomaly**

An anomaly in space-time characteristics of certain programs running in a paging machine.
Belady, Nelson and Shedler. Communications of the ACM. Vol. 12 (6) pp 349-353. 1969.

Belady's anomaly: FIFO
Same reference string, different frames

	0	1	2	3	0	1	4	0	1	2	3	4
Youngest	0	1	2	3	0	1	4	**4**	**4**	2	3	**3**
		0	1	2	3	0	1	**1**	**1**	4	2	**2**
Oldest			0	1	2	3	0	**0**	**0**	1	4	**4**

Numbers in this color: No page fault

9 page faults with 3 frames

	0	1	2	3	0	1	4	0	1	2	3	4
Youngest	0	1	2	3	**3**	**3**	4	0	1	2	3	4
		0	1	2	**2**	**2**	3	4	0	1	2	3
			0	1	**1**	**1**	3	3	4	0	1	2
Oldest				0	**0**	**0**	1	2	3	4	0	1

10 page faults with 4 frames

Belady's anomaly

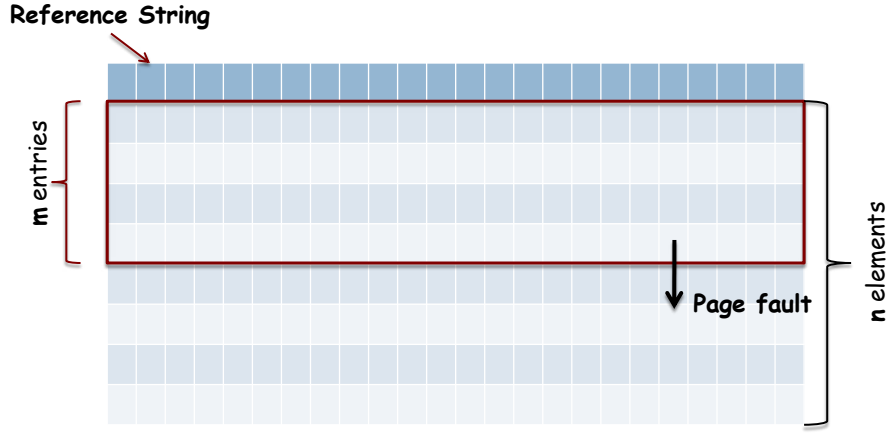
- Led to a whole theory on paging algorithms and properties
- **Stack algorithms**

STACK ALGORITHMS

The Model

- There is an array ***M***
  - Keeps track of the state of memory
- ***M*** has as many elements as pages of virtual memory
- Divided into two parts
  - Top part: ***m*** entries {Pages currently in memory}
  - Bottom part: ***n-m*** entries
    - Pages that were referenced BUT paged out

The model



Tracking the state of the array M over time

Properties of the model

- When a page is referenced
  - Move to the **top** entry of **M**
- If the referenced page is already in **M**
  - All pages above it ***moved down*** one position
  - Pages below it are not moved
- **Transition** from within box to outside of it?
  - Page eviction from main memory

The model

0	2	1	3	5	4	6	3	7	4	7	3	3	5	5	3	1	1	1	7	2	3	4	1
	0	2	1	3	5	4	6	3	7	4	7	7	3	3	5	3	3	3	1	7	2	3	4
		0	2	1	3	5	4	6	3	3	4	4	7	7	7	5	5	5	3	1	7	2	3
			0	2	1	3	5	4	6	6	6	6	4	4	4	7	7	7	5	3	1	7	2
				0	2	1	1	5	5	5	5	5	6	6	6	4	4	4	4	5	5	1	7
					0	2	2	1	1	1	1	1	1	1	1	6	6	6	6	4	4	5	5
						0	0	2	2	2	2	2	2	2	2	2	2	2	2	6	6	6	6
								0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Properties of the model

- $M(m,r)$
  - The set of pages in the top part of $\mathbf{M}$
  - m page frames
  - r memory references

A property that has some interesting implications

- $M(m, r)$ subset of $M(m+1, r)$
- Set of pages in the top part of M with m frames
  - Also included in M with $(m+1)$ frames

What the subset relationship means

- Execute a process with a set of memory frames
- If we increase memory size by one frame and re-execute
  - **At every point of execution** *all* pages in the first execution are present in the second run
- Does not suffer from Belady's anomaly
  - **Stack algorithms**

The contents of this slide-set are based on the following references

- *Avi Silberschatz, Peter Galvin, Greg Gagne. Operating Systems Concepts, 9th edition. John Wiley & Sons, Inc. ISBN-13: 978-1118063330.* [Chapter 9]
- *Andrew S Tanenbaum. Modern Operating Systems. 4th Edition, 2014. Prentice Hall. ISBN: 013359162X/ 978-0133591620. [Chapter 3]*