Operating Systems

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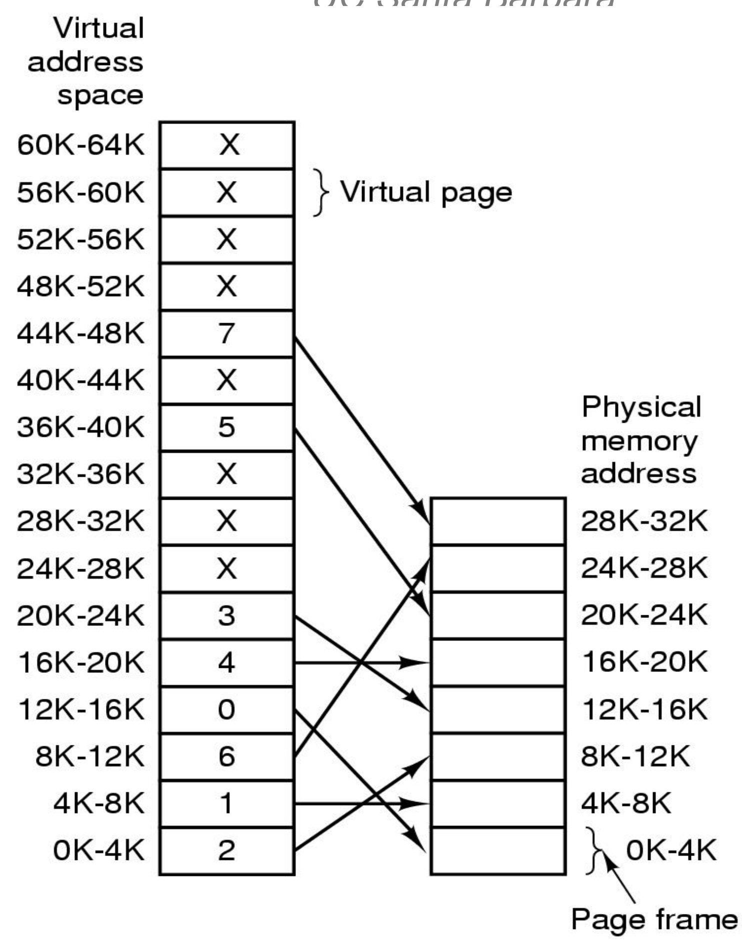
Virtual Memory and Paging

- What if a program is too big to be loaded in memory
- What if a higher degree of multiprogramming is desirable
- Physical memory is split in *page frames*
- Virtual memory is split in pages
- OS (with help from the hardware) manages the mapping between pages and page frames

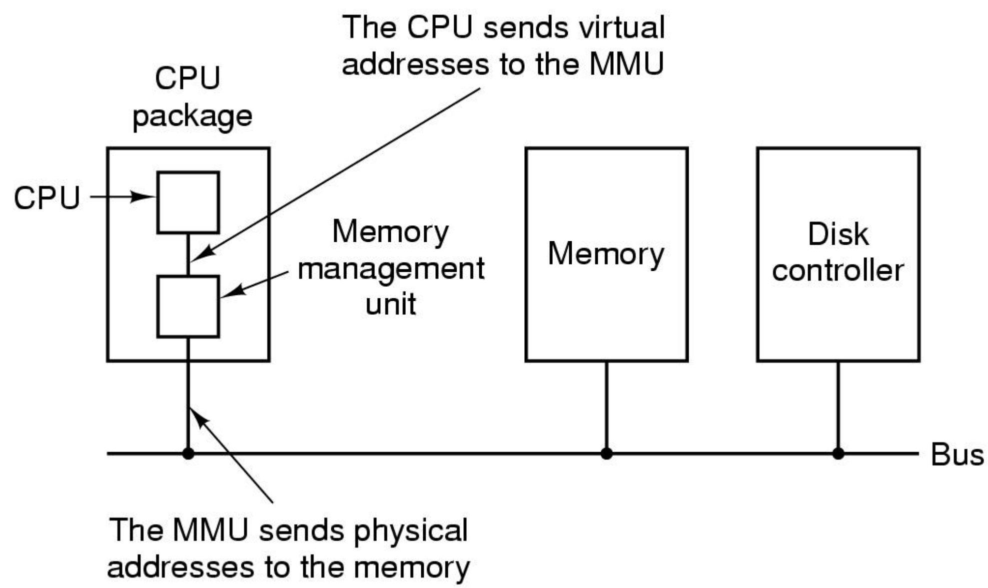
Mapping Pages to Page Frames

- Virtual memory: 64KB
- Physical memory: 32KB
- Page size: 4KB
- Virtual memory pages: 16
- Physical memory pages: 8



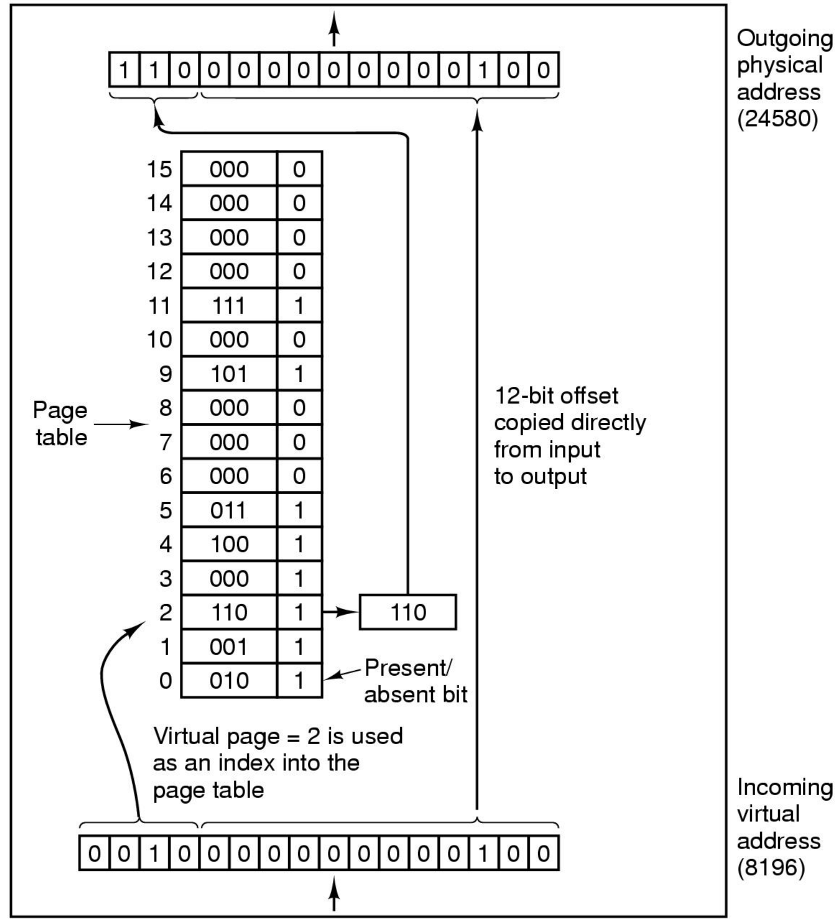
Memory Management Unit

- Automatically performs the mapping from virtual addresses into physical addresses



Memory Management Unit

- Addresses are split into a page number and an offset
- Page numbers are used to look up a table in the MMU with as many entries as the number of virtual pages
- Each entry in the table contains a bit that states if the virtual page is actually mapped to a physical one
- If it is so, the entry contains the number of physical page used
- If not, a *page fault* is generated and the OS has to deal with it



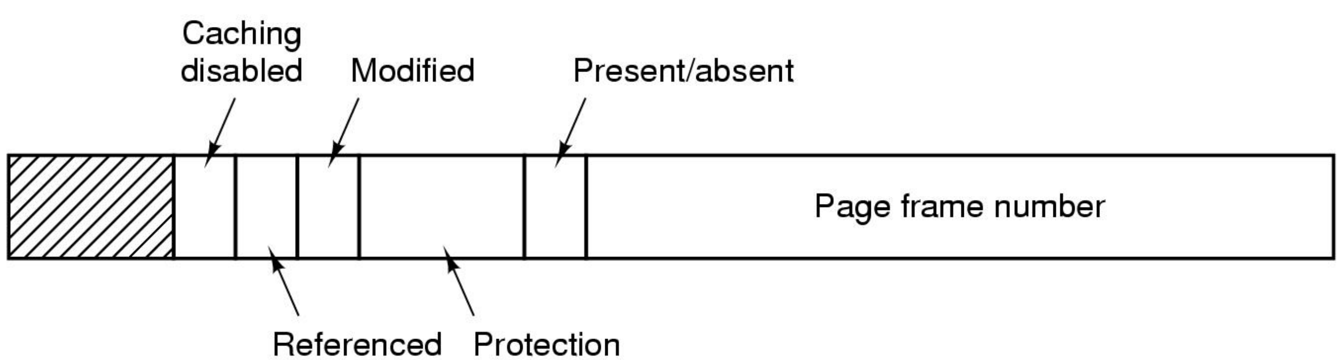
Page Tables

- Page tables contain an entry for each virtual table
- If virtual memory is big (e.g., 32 bit and 64 bit addresses) the table can become of unmanageable size
- Solution: instead of keeping them in the MMU move them to main memory
- Problem: page tables are used each time an access to memory is performed. Adding a level of indirection, may kill performance
- Another solution: multilevel tables

Multilevel Page Tables

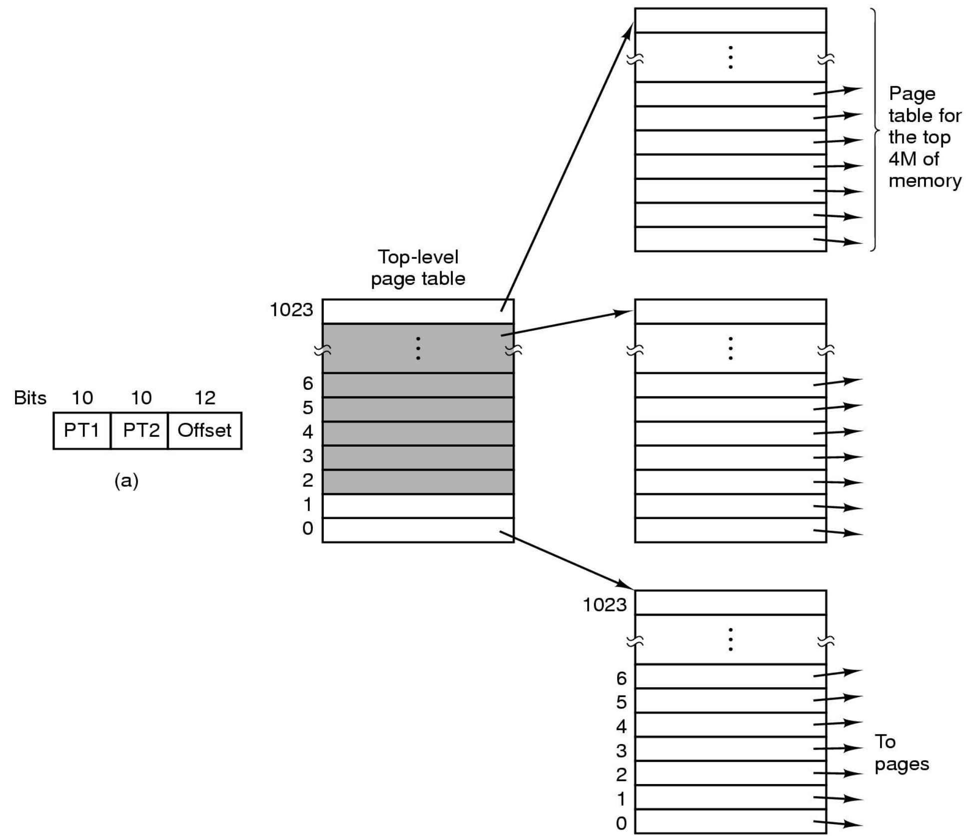
- Two types of tables
  - Top-level (in MMU)
  - Second-level (in a page frame)
- Virtual address split in three parts
  - Top-level page index
  - Second-level page index
  - Offset

- Each entry in a table contains
  - Page frame number
  - Present/absent bit
  - Protection bits (RWX)
  - Modified bit (or “dirty bit”)
  - Referenced bit
  - Caching disabled bit (for memory mapped I/O)



Multilevel Page Tables

- 32 bit virtual address
- PT1: Top-level index, 10 bits
- PT2: Second-level index, 10 bits
- Offset: 12 bits
- Page size: 4KB
- Second-level maps 4MB (1024 entries of 4KB)
- Top-level maps 4GB (1024 entries of 4MB)
- Process is 12 MB



Locality of Reference

- Multilevel tables can hold many pages but they still require multiple index lookups for each memory access

- Most programs use a subset of their memory pages (loops, sequential executions, updates to the same data structures, etc) and the set changes slowly
  - *Locality of reference*
  - *Working set*

Translation Look-aside Buffers

- Translation Look-aside Buffer (TLB)
  - hardware device that allows fast access without using the page table

- Small number of entries (e.g., 8) accessible as an associative memory
- Checked before doing a page table mapping
- If lookup succeeds (hit), the page is accessed directly
- If TLB lookup fails (miss), the page table is used and the corresponding entry in TLB is added
- When an entry is taken out of the TLB, the modified bit is updated in the corresponding entry of the page table
- TLB management can be done both in hardware (MMU) or in software (by the OS)

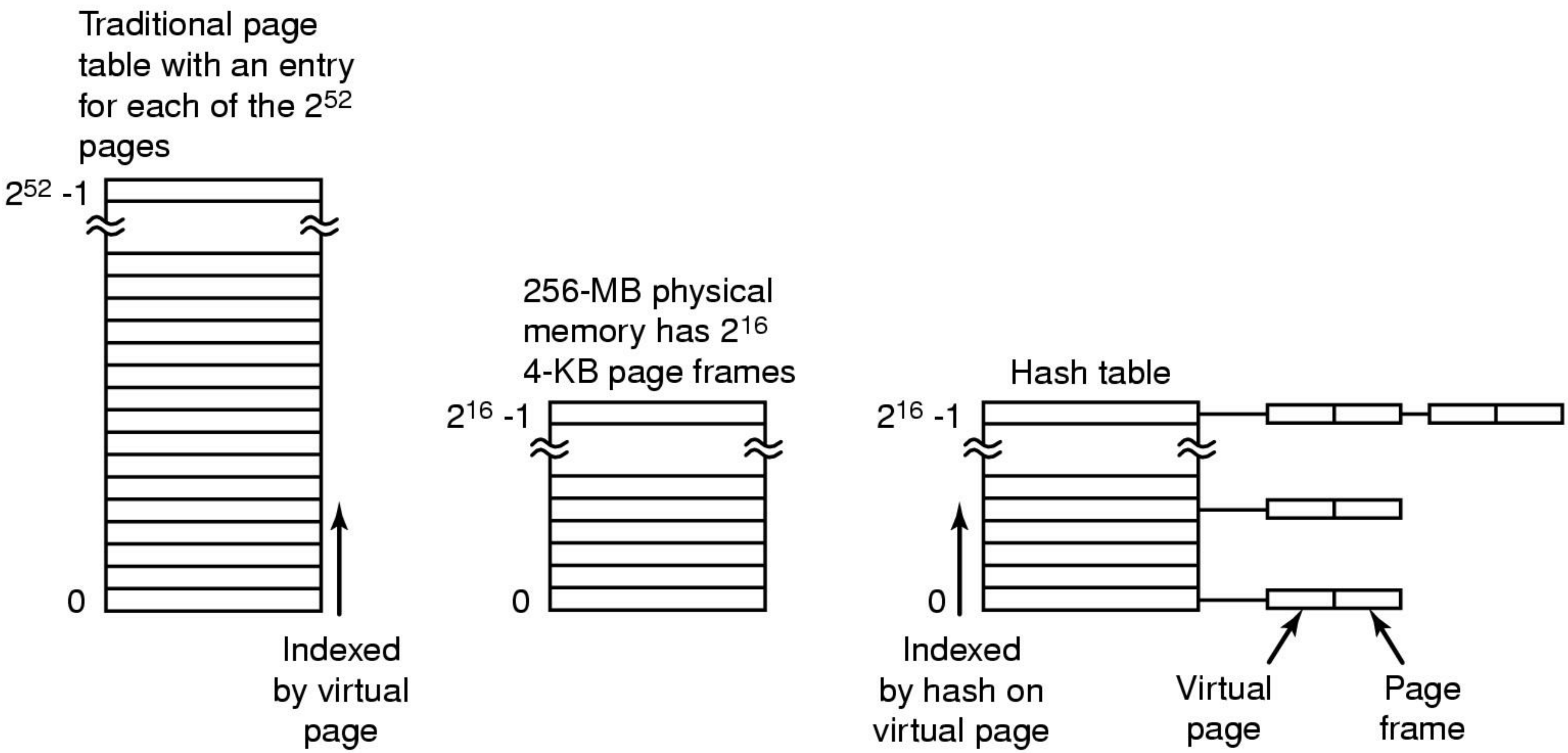
Translation Look-aside Buffers

Valid	Virtual page	Modified	Protection	Page frame
1	140	1	RW	31
1	20	0	R X	38
1	130	1	RW	29
1	129	1	RW	62
1	19	0	R X	50
1	21	0	R X	45
1	860	1	RW	14
1	861	1	RW	75

Inverted Page Table

- When virtual pages are too many, maintaining a page table is not feasible
- Solution: Inverted Page Table
  - One entry per physical page frame
  - Each entry contains a pair <process, virtual page>
- Address cannot be resolved simply by looking for an index in a table
- When process n accesses page p, the table must be scanned for an entry <n, p>
- Solution
  - TLB should catch most of the accesses
  - Table hashed on virtual addressed to resolve the mapping

Inverted Page Table



Page Replacement Algorithms

- Page fault forces choice
  - Which page must be removed to make room for an incoming page?
- Criteria:
  - Modified page must first be saved
  - Unmodified just overwritten
  - Better not to choose an often used page that will probably need to be brought back in soon

R and M Bits

- Each page has a Reference (R) bit and a Modified (M) bit

- R and M bits can be provided by the hardware or can be managed in software
  - Initial process with no pages in memory
  - When page is loaded
    - R bit is set
    - READONLY mode is set
  - When modification is attempted a fault is generated
    - M bit is set
    - READ/WRITE mode is set

Optimal Page Replacement Algorithm

- Determine how far in the execution of the program a page will be hit

- Replace page needed at the farthest point in the future
  - Optimal but unrealizable

- Useful to compare with other algorithms
  - Log page use on first execution of the program
  - Develop a scheduling for following executions (with same inputs)

Not Recently Used Page Replacement Algorithm

- When process starts, R and M bit are set to 0
- Periodically R bit is cleared to take into account for pages that have not been referenced recently
- Pages are classified according to R and M
  - Class 0: not referenced, not modified
  - Class 1: not referenced, modified (R bit has been cleared!)
  - Class 2: referenced, not modified
  - Class 3: referenced, modified
- NRU removes page at random from lowest numbered non empty class
- Easy to implement but not terribly effective

FIFO
Page Replacement Algorithm

- Maintain a linked list of all pages
- List is ordered by loading time
- The page at the beginning is replaced
  - Oldest one

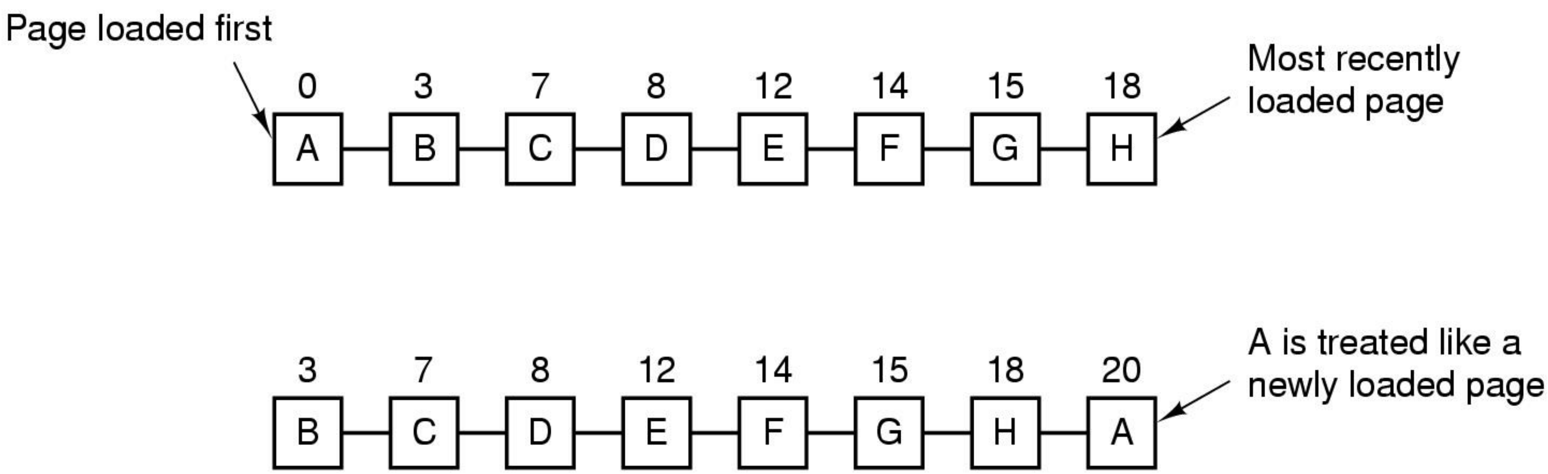
- Advantage
  - Easy to manage
- Disadvantage
  - Page in memory the longest may be often used

Second Chance Page Replacement Algorithm

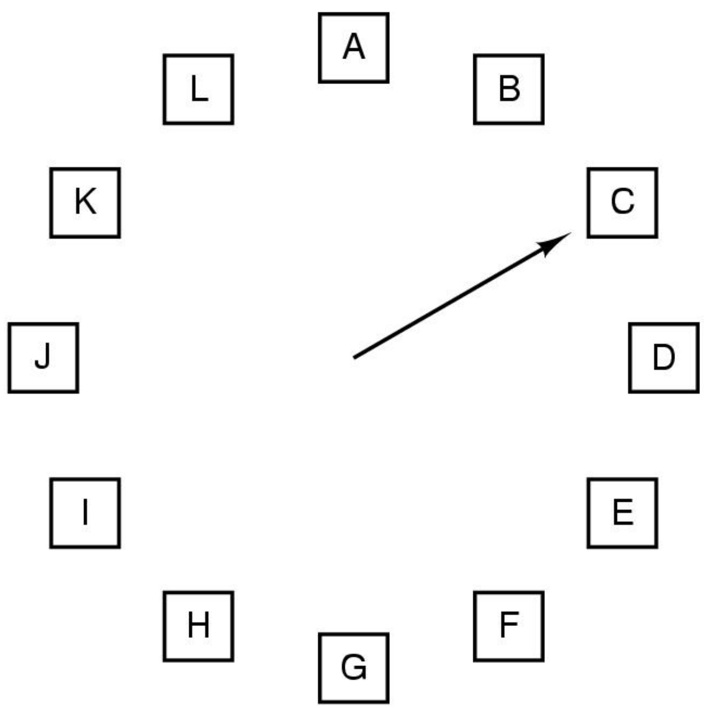
- Pages in list are sorted in FIFO order
- R bits are cleared regularly
- If the R bit of the oldest page is set it is put at the end of the list
- If all the pages in the list have been referenced the page that was “recycled” will reappear with the R bit cleared and will be thrown away

Second Chance Page Replacement Algorithm

- Page list if fault occurs at time 20, A has R bit set



Clock Page Replacement Algorithm



- Same concept as Second Chance, different implementation
- Hand points to oldest page
- When a page fault occurs
  - If R=0: evict the page
  - If R=1: clear R and advance hand

Least Recently Used (LRU) Page Replacement Algorithm

- Assumption: pages used recently will be used again soon
  - Throw out page that has been unused for longest time
- Very expensive: Must keep a linked list of pages
  - Most recently used at front, least at rear
  - Update this list every memory reference !!
- Alternative
  - Maintain global counter that is incremented at each instruction execution
  - Maintain similar counter in each page table entry
  - If page is referenced copy global counter in page counter
  - Choose page with lowest value counter

Least Recently Used (LRU) Page Replacement Algorithm

Another alternative:

- Maintain matrix with *n* x *n* bits, where *n* is the number of page frames
- If page *j* is accessed
  - set to 1 all the bits in the corresponding row
  - set to 0 all the bits in the corresponding column
- At any moment the page with the row containing the lowest value is the least recently used

Least Recently Used (LRU) Page Replacement Algorithm

Page

	0	1	2	3
0	0	1	1	1
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0

Page 0

Page

0	1	2	3
0	0	1	1
1	0	1	1
0	0	0	0
0	0	0	0

Page 1

Page

0	1	2	3
0	0	0	1
1	0	0	1
1	1	0	1
0	0	0	0

Page 2

Page

0	1	2	3
0	0	0	0
1	0	0	0
1	1	0	0
1	1	1	0

Page 3

Page

0	1	2	3
0	0	0	0
1	0	0	0
1	1	0	1
1	1	0	0

Page 2

0	0	0	0
1	0	1	1
1	0	0	1
1	0	0	0

Page 1

0	1	1	1
0	0	1	1
0	0	0	1
0	0	0	0

Page 0

0	1	1	0
0	0	1	0
0	0	0	0
1	1	1	0

Page 3

0	1	0	0
0	0	0	0
1	1	0	1
1	1	0	0

Page 2

0	1	0	0
0	0	0	0
1	1	0	0
1	1	1	0

Page 3

Not Frequently Used (NFU) Page Replacement Algorithm

- A counter is associated with each page
- At each clock interval, the counter is incremented if the page has been referenced (R=1)
- The page with the lowest counter is removed
- Problem: pages that have been heavily used in the past will always maintain high counter values
- Need for an aging mechanism
  - First shift the counter
  - Then set bit in most significant position if referenced

Not Frequently Used (NFU) Page Replacement Algorithm

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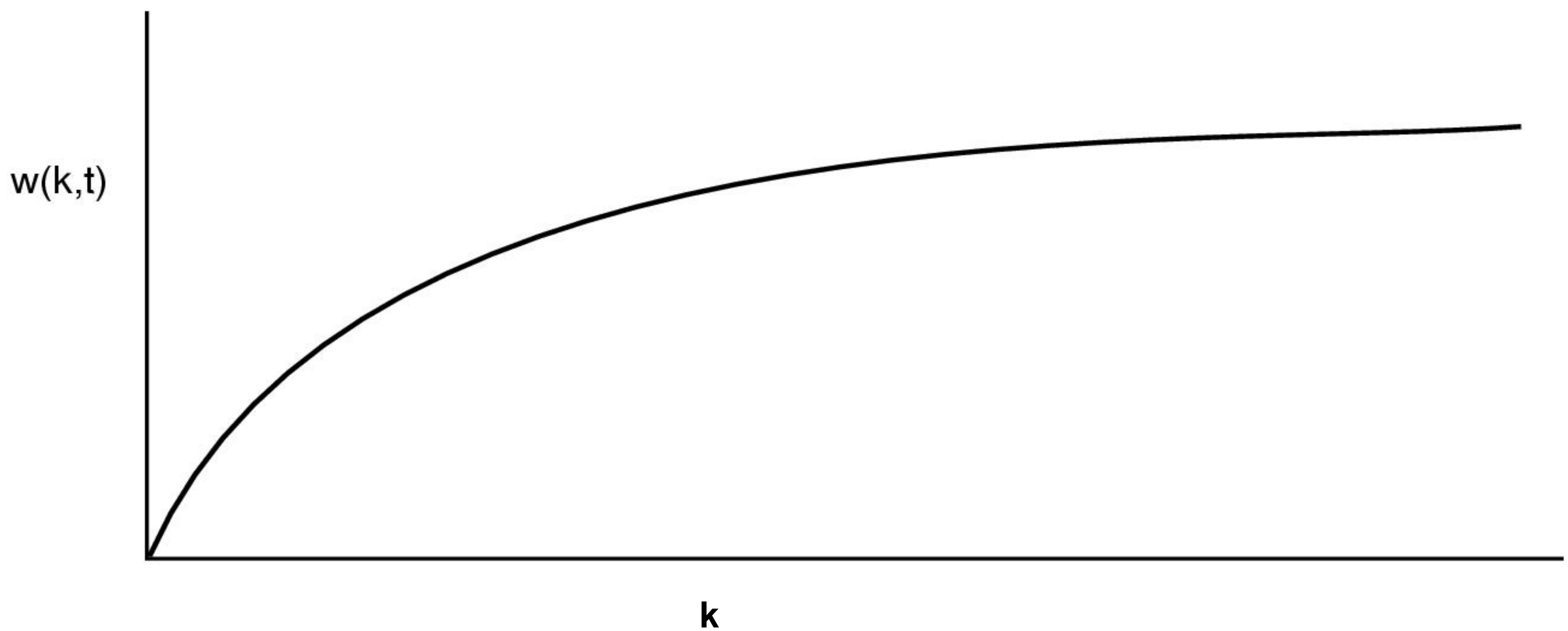
Page	R bits for pages 0-5, clock tick 0	R bits for pages 0-5, clock tick 1	R bits for pages 0-5, clock tick 2	R bits for pages 0-5, clock tick 3	R bits for pages 0-5, clock tick 4
	1 0 1 0 1 1	1 1 0 0 1 0	1 1 0 1 0 1	1 0 0 0 1 0	0 1 1 0 0 0
0	10000000	11000000	11100000	11110000	01111000
1	00000000	10000000	11000000	01100000	10110000
2	10000000	01000000	00100000	00100000	10001000
3	00000000	00000000	10000000	01000000	00100000
4	10000000	11000000	01100000	10110000	01011000
5	10000000	01000000	10100000	01010000	00101000

Working Set Page Replacement Algorithm

- Locality of reference: Most programs use a subset of their memory pages (loops, sequential executions, updates to the same data structures, etc) and the set changes slowly
- The working set is the set of pages used by the k most recent memory references
- For a reasonable value of k, the number of page faults is reduced and the process does not *thrash*
- If the working set can be determined it can be preloaded at context switch to minimize the initial demand of pages

Working Set
Page Replacement Algorithm

- w(k,t) is the size of the working set at time, t



Working Set
Page Replacement Algorithm

- Algorithm:

  when a page has to be evicted, find one that is not in the working set

- Use a shift register of size k

- At every reference
  - Right-shift the register
  - Insert page in left most position

- At replacement time
  - Remove duplicates and obtain working set
  - Remove page not in working set

- Problem: too heavy to maintain

Working Set
Page Replacement Algorithm

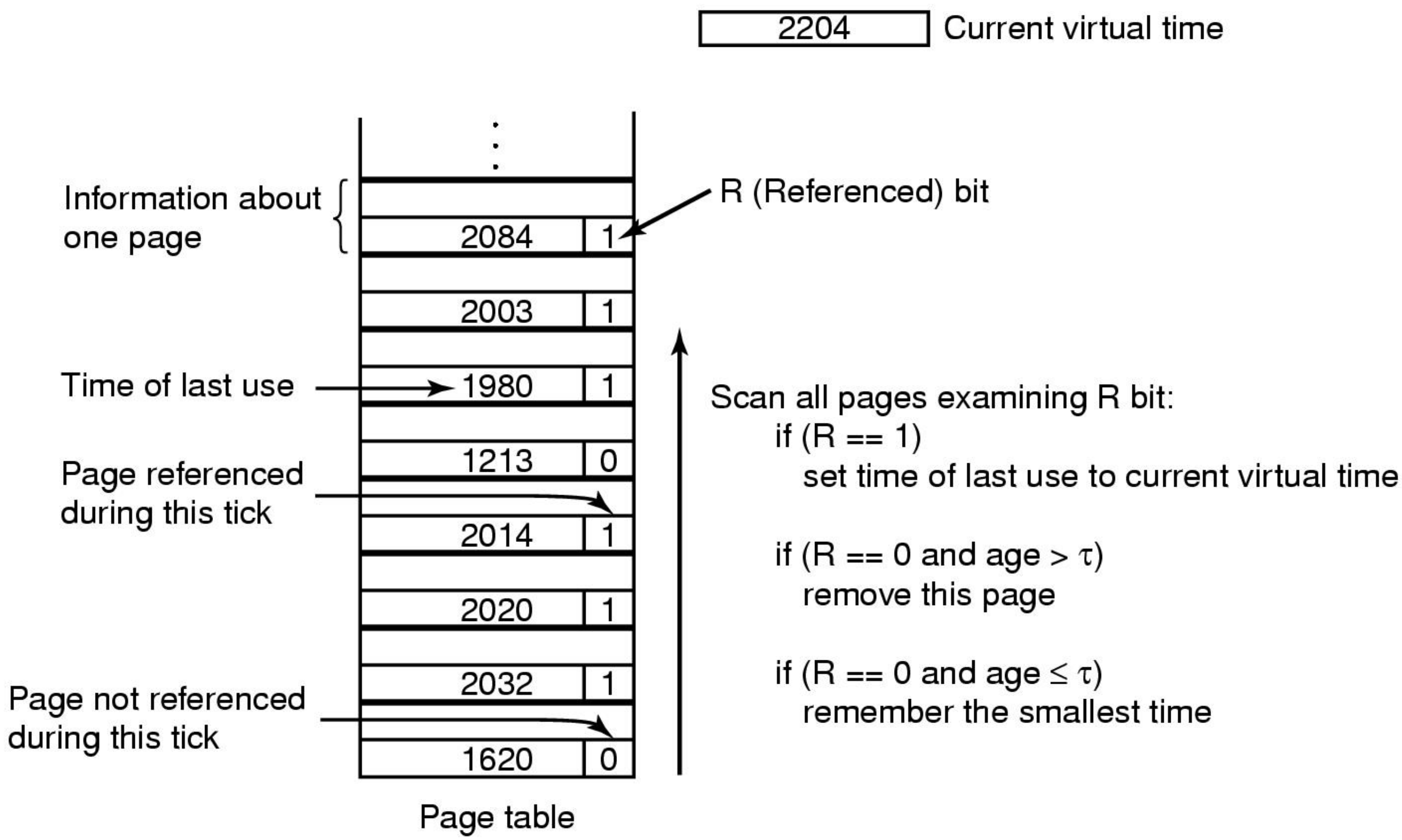
- Use execution time instead of references
- Working set composed of pages referenced in the last t msec of execution
- Each entry contains
  - The time the page was last used
  - The reference bit, R

Working Set Page Replacement Algorithm

- At every page fault
  - If R=1 the current time is written in the page entry
  - If R=0
    - If the "age" (current time - time of last reference) is smaller than t, the page is spared (but the page with the highest age/smallest time of last usage in the working set is recorded)
    - If the "age" is greater than t, the page is a candidate
  - If there is one or more candidates, the candidate with highest age is evicted
  - If there are no candidates the oldest page in the working set is evicted

- Problem: whole page table must be scanned

Working Set Page Replacement Algorithm



WSClock
Page Replacement Algorithm

- Every time a page is loaded is added to a circular list
- Each page is marked with the time of last use
- At page fault:
  - Examine page pointed by hand
    - If R=1: R is cleared, time is updated and hand advanced
    - If R=0:
      - If age is greater than t
        - » If page is clean (M=0) then evict
        - » If page is dirty (M=1) page is scheduled for writing to disk and hand advanced
      - If age is less than t the hand is advanced
  - If hand returns to initial position
    - If no writes are scheduled choose a random clean page
    - If writes have been scheduled continue until a clean, old page is found

WSClock
Page Replacement Algorithm

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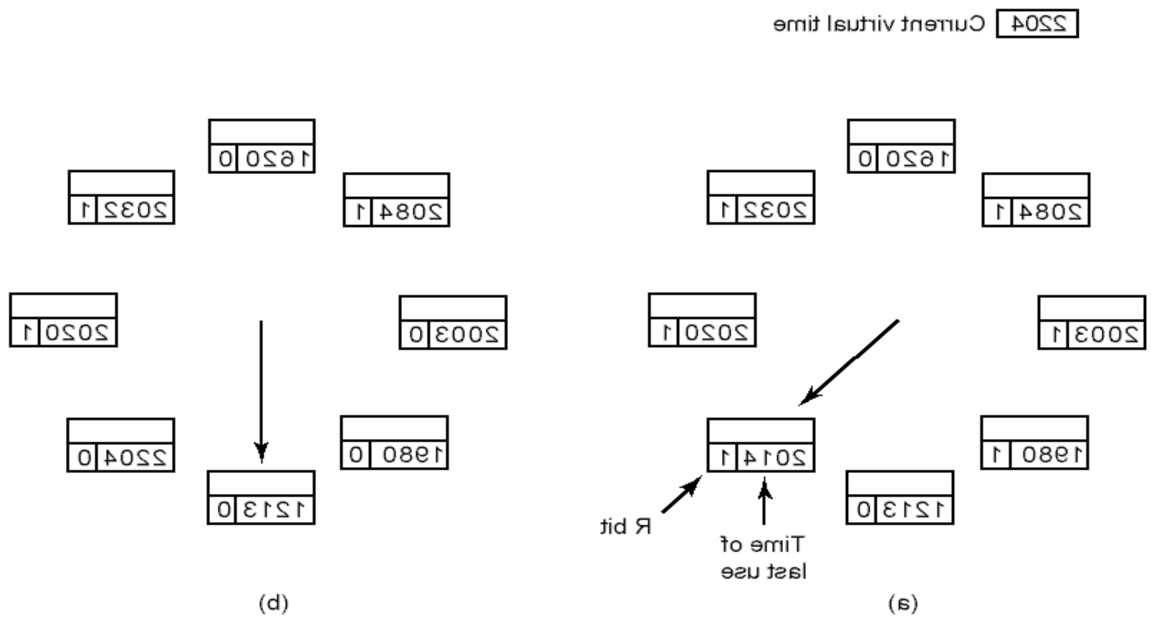
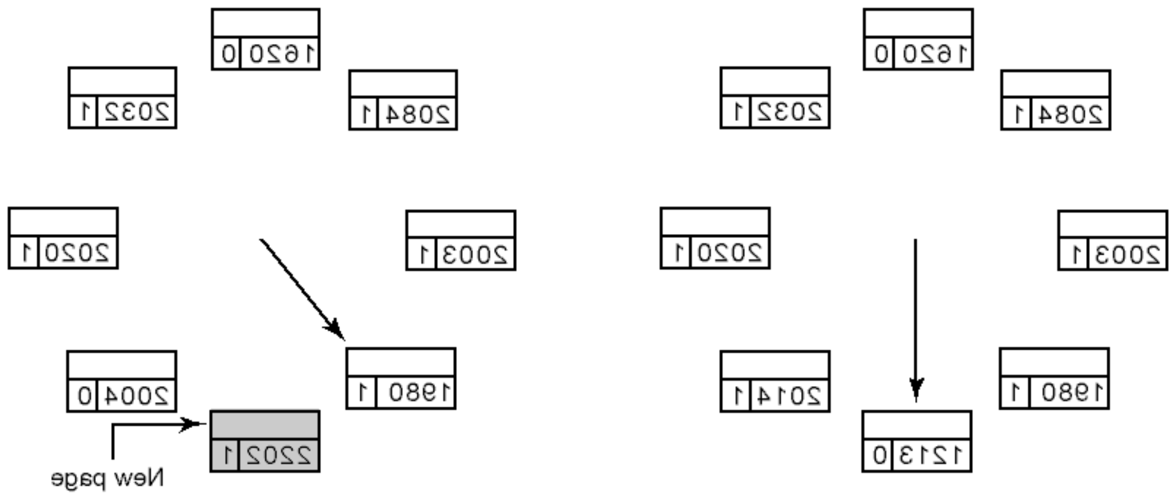


WSClock
Page Replacement Algorithm



Review of Page Replacement Algorithms

Algorithm	Comment
Optimal	Not implementable, but useful as a benchmark
NRU (Not Recently Used)	Very crude
FIFO (First-In, First-Out)	Might throw out important pages
Second chance	Big improvement over FIFO
Clock	Realistic
LRU (Least Recently Used)	Excellent, but difficult to implement exactly
NFU (Not Frequently Used)	Fairly crude approximation to LRU
Aging	Efficient algorithm that approximates LRU well
Working set	Somewhat expensive to implement
WSClock	Good efficient algorithm

Modeling Page Replacement Algorithms

- Program memory access is characterized as a string of referenced page numbers, called *reference string*

- Memory has n virtual pages and $m < n$ page frames

- Memory is modeled as an array M divided in two portions:
  - Top m rows are the actual mapping
  - Bottom $n - m$ rows represent swapped pages

- As the reference string is examined
  - the top portion is checked to see if the reference page is present
    - If not, a page fault is generated
  - In any case the chosen algorithm algorithm is used to determine the configuration of the next column

Example with LRU

- State of memory array, M, after each item in reference string is processed

Reference string	0	2	1	3	5	4	6	3	7	4	7	3	3	5	5	3	1	1	1	7	1	3	4	1
	0	2	1	3	5	4	6	3	7	4	7	3	3	5	5	3	1	1	1	7	1	3	4	1
		0	2	1	3	5	4	6	3	7	4	7	7	3	3	5	3	3	3	1	7	1	3	4
			0	2	1	3	5	4	6	3	3	4	4	7	7	7	5	5	5	3	3	7	1	3
				0	2	1	3	5	4	6	6	6	6	4	4	4	7	7	7	5	5	5	7	7
					0	2	1	1	5	5	5	5	5	6	6	6	4	4	4	4	4	4	5	5
						0	2	2	1	1	1	1	1	1	1	1	6	6	6	6	6	6	6	6
							0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
									0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Page faults	P	P	P	P	P	P	P		P					P			P						P	

Belady's Anomaly

All pages frames initially empty

		0	1	2	3	0	1	4	0	1	2	3	4	
Youngest page		0	1	2	3	0	1	4	4	4	2	3	3	
			0	1	2	3	0	1	1	1	4	2	2	
Oldest page				0	1	2	3	0	0	0	1	4	4	
		P	P	P	P	P	P	P			P	P		9 Page faults

		0	1	2	3	0	1	4	0	1	2	3	4	
Youngest page		0	1	2	3	3	3	4	0	1	2	3	4	
			0	1	2	2	2	3	4	0	1	2	3	
Oldest page				0	1	1	1	2	3	4	0	1	2	
					0	0	0	1	2	3	4	0	1	
		P	P	P	P			P	P	P	P	P	P	10 Page faults

Stack Algorithms

- Algorithms that satisfy
  M(m,r) is in M(m+1,r)
  are called stack algorithms

- Stack algorithms do not suffer from the Belady's anomaly

- This means: if the same reference string is run on two memories with frame pages *m* and *m+1* respectively, the set of pages loaded in memory in corresponding points in the reference string are one a subset of the other

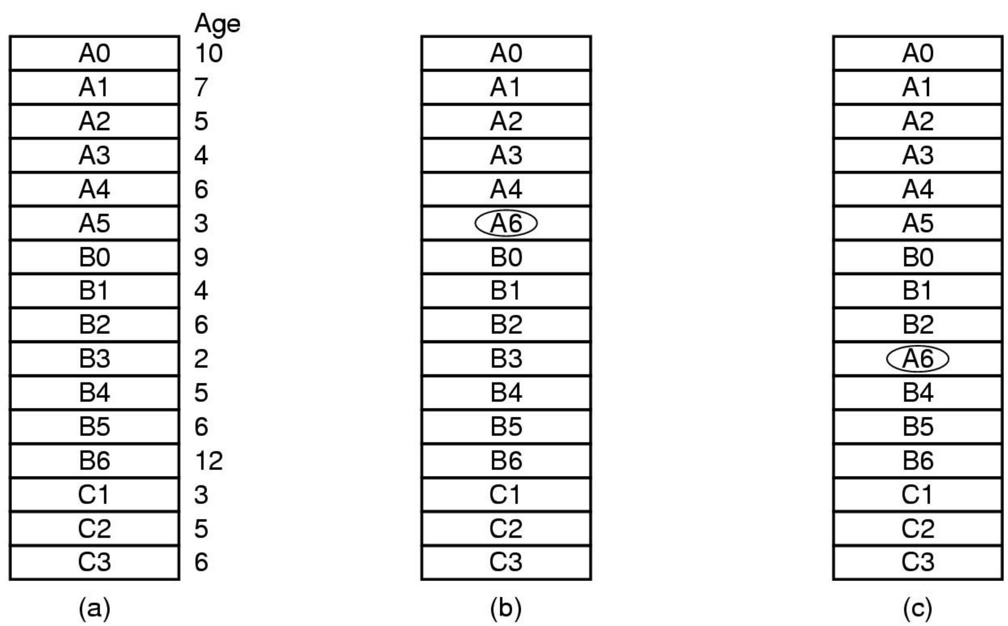
- Violated at the seventh reference in previous example

Design Issues

- Local vs. global allocation policies
- Load control
- Page size and internal fragmentation
- Sharing pages
- Locking pages
- Separating policy and mechanism

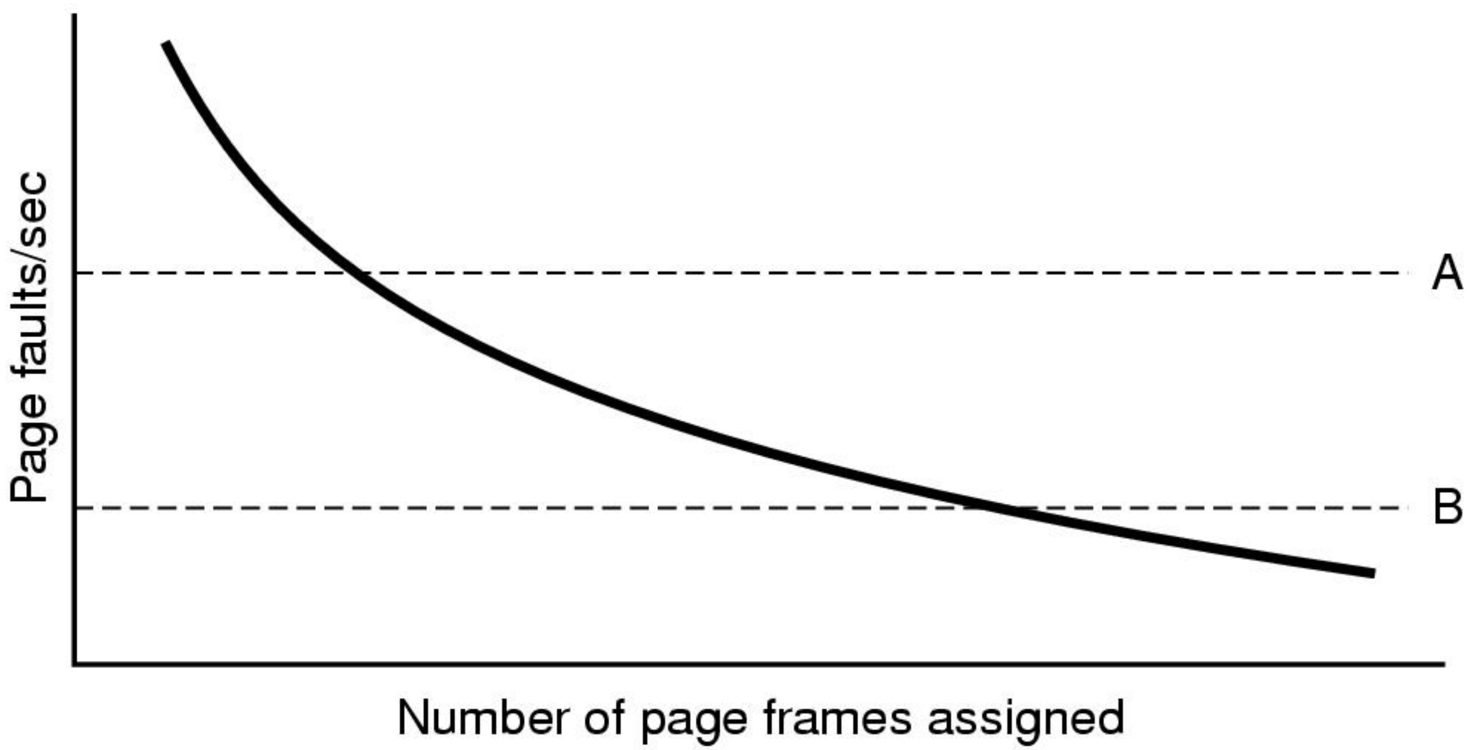
Local versus Global Allocation Policies

- (a) Original configuration
- (b) Local page replacement
- (c) Global page replacement



Local versus Global Allocation Policies

- Page fault rate as a function of the number of page frames assigned



Load Control

- Despite good designs, system may still thrash

- The Page Fault Frequency algorithm uses page faults frequency to determine
  - Which processes need more memory
  - Which processes need less

- Reduce number of processes competing for memory
  - Swap one or more to disk, divide up pages they held
  - Reconsider degree of multiprogramming

Page Size

Small page size

- Advantages
  - Less internal fragmentation
  - Better fit for various data structures, code sections
  - Less unused program in memory
- Disadvantages
  - Programs need many pages, larger page tables

Page Size

- Overhead due to page table and internal fragmentation

$$overhead = \frac{s \cdot e}{p} + \frac{p}{2}$$

page table space

internal fragmentation

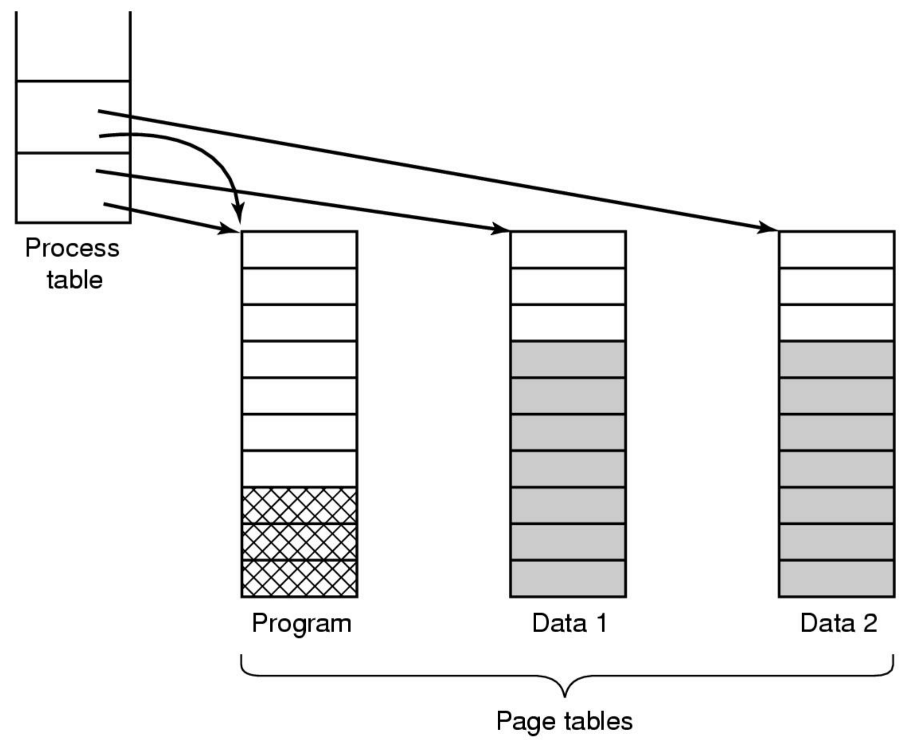
- Where
  - s = average process size in bytes
  - p = page size in bytes
  - e = page entry

Optimized when

$$p = \sqrt{2se}$$

Shared Pages

- Two processes sharing same program, sharing its page table



Locking Pages in Memory

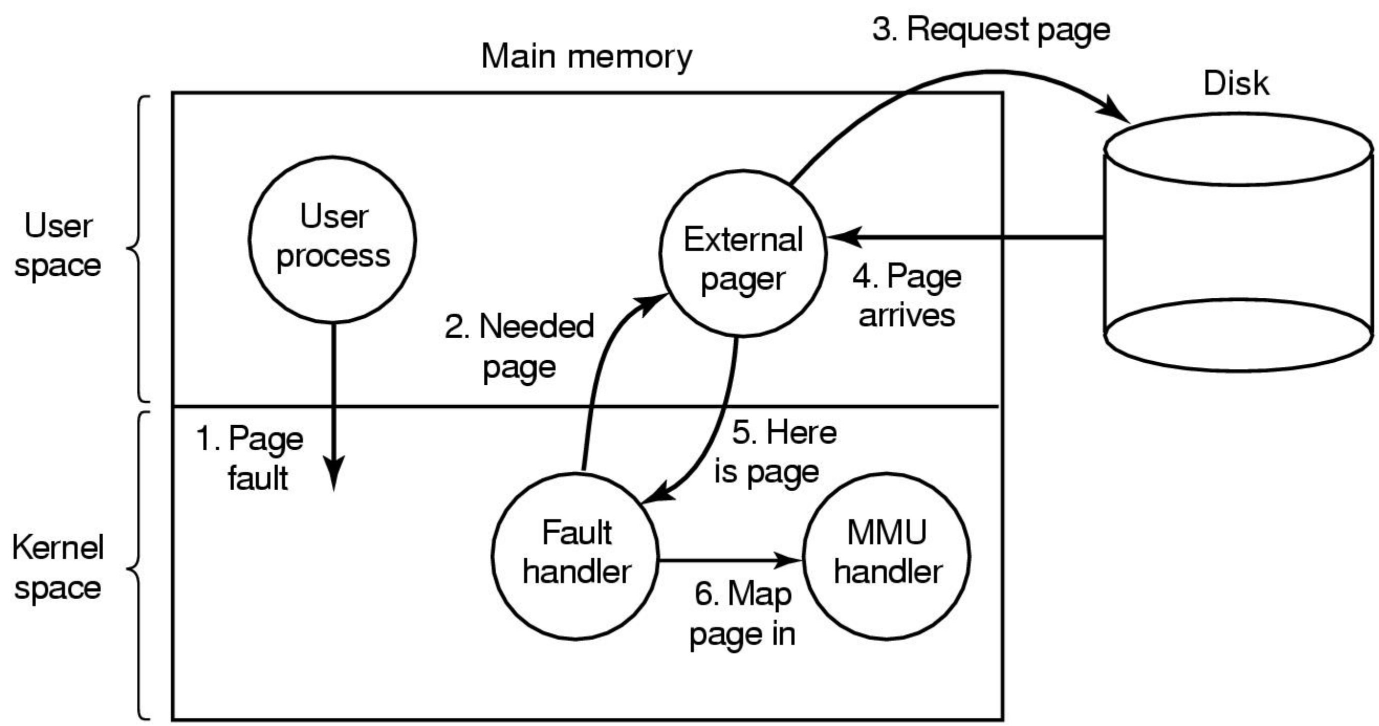
- Virtual memory and I/O occasionally interact

- Process issues call for read from device into buffer
  - While waiting for I/O, another processes starts up
  - New process has a page fault
  - Buffer for the first process may be chosen to be paged out

- Need to specify some pages locked
  - Exempted from being target pages

Separation of Policy and Mechanism

- Page fault handling with an external pager



Operating System Involvement

- Process creation
  - Determine program size
  - Create page table
  - Allocate swap
- Process execution
  - MMU reset for new process
  - TLB flushed
  - Make page table current
- Page fault time
  - Determine virtual address causing fault
  - Swap target page out, needed page in
- Process termination time
  - Release page table, pages