Virtual Memory Management

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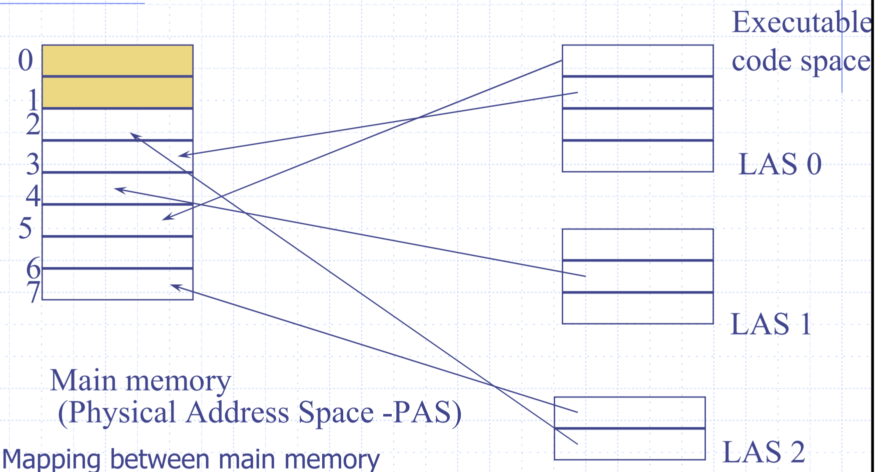
Demand Paging

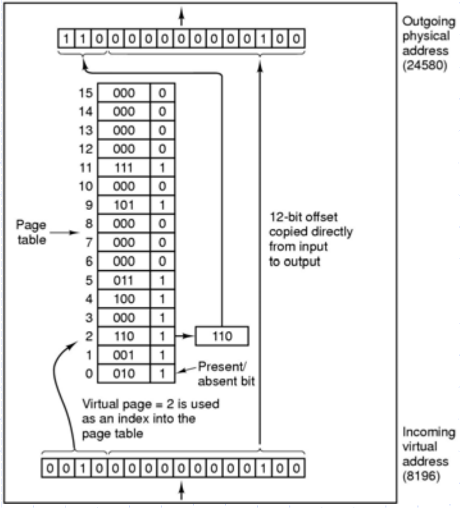


Main memory
(Physical Address Space -PAS)

Mapping between main memory and virtual memory is given by a page table

LAS - Logical Address Space
Virtual address space

Page Tables (1)

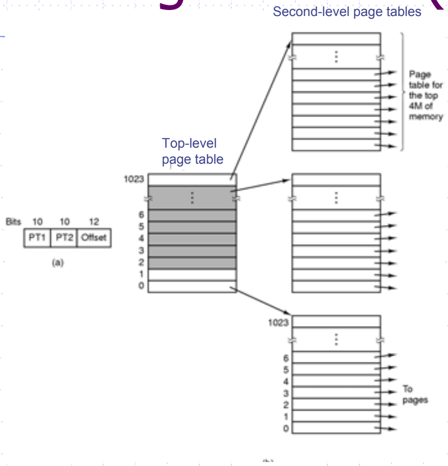


1 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0
Outgoing physical address (24580)
Page table
110
Present/ absent bit
12-bit offset copied directly from input to output
Virtual page = 2 is used as an index into the page table
0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0
Incoming virtual address (8196)

15	000	0
14	000	0
13	000	0
12	000	0
11	111	1
10	000	0
9	101	1
8	000	0
7	000	0
6	000	0
5	011	1
4	100	1
3	000	1
2	110	1
1	001	1
0	010	1

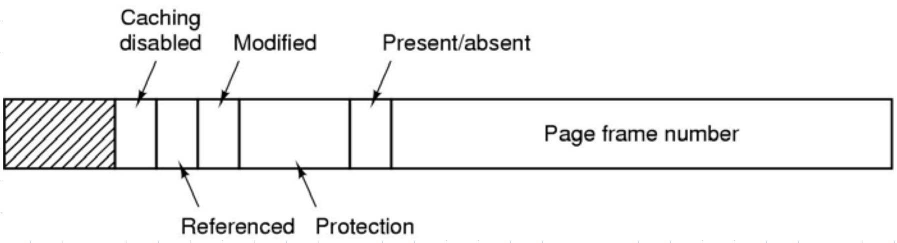
Internal operation of MMU with 16 4 KB pages

Page Tables (2)



- 32 bit address with 2 page table fields
- Two-level page tables

Page Tables (3)



Typical page table entry

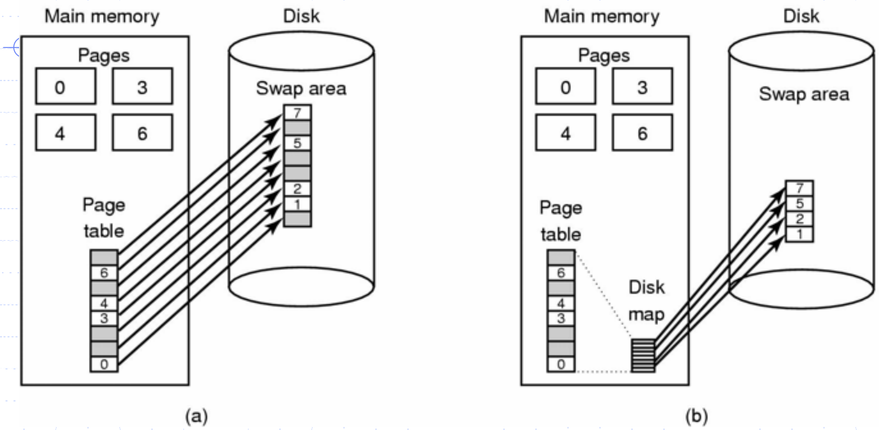
Page Fault Handling (1)

- Hardware traps to kernel
- General registers saved
- OS determines which virtual page needed
- OS checks validity of address, seeks page frame
- If selected frame is dirty, write it to disk

Page Fault Handling (2)

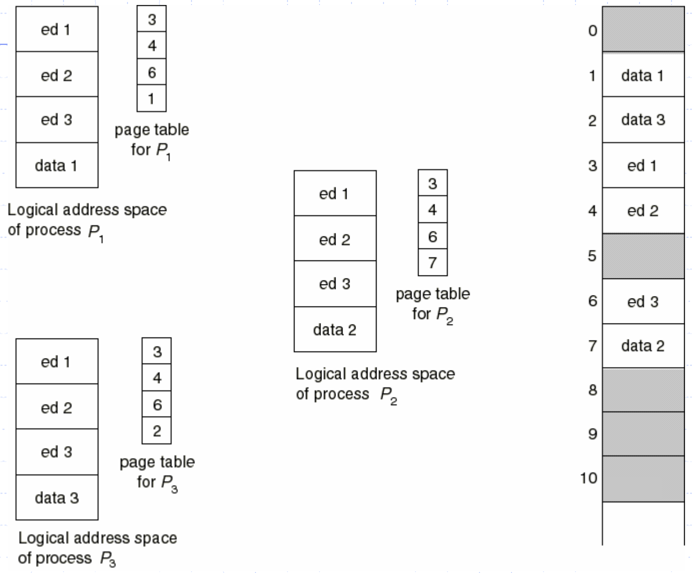
- OS brings schedules new page in from disk
- Page tables updated
- Faulting instruction backed up to when it began
- Faulting process scheduled
- Registers restored
- Program continues

Backing Store



(a) Paging to static swap area
(b) Backing up pages dynamically

Sharing Pages: a text editor



ed 1
ed 2
ed 3
data 1

3
4
6
1

page table for P_1

Logical address space of process P_1

ed 1
ed 2
ed 3
data 2

3
4
6
7

page table for P_2

Logical address space of process P_2

ed 1
ed 2
ed 3
data 3

3
4
6
2

page table for P_3

Logical address space of process P_3

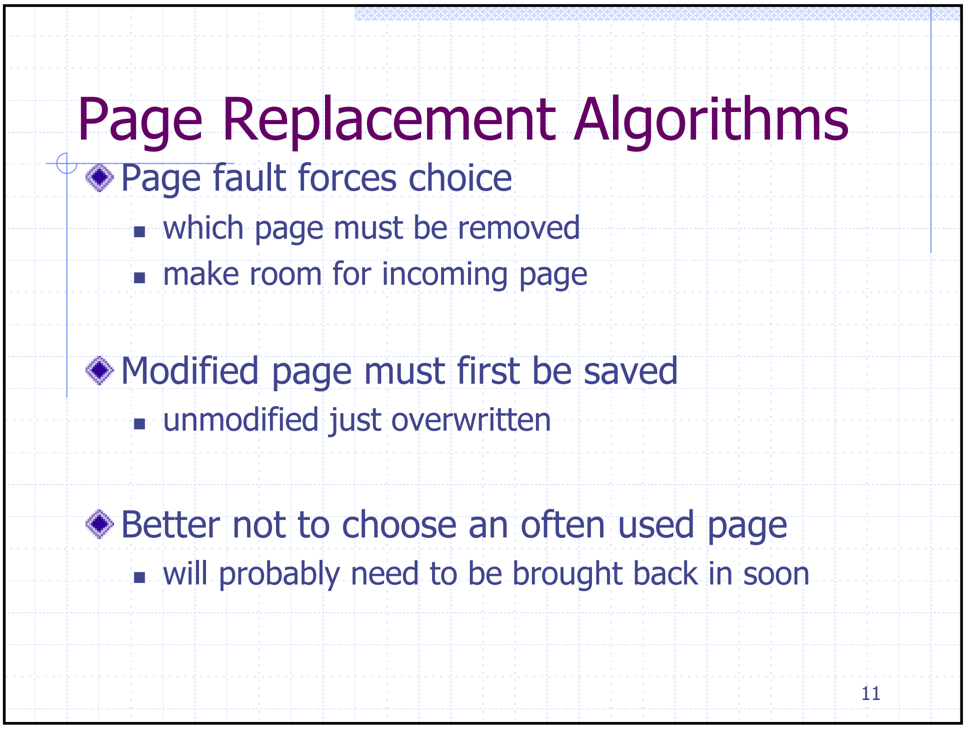
0	
1	data 1
2	data 3
3	ed 1
4	ed 2
5	
6	ed 3
7	data 2
8	
9	
10	

Implementation Issues

Operating System Involvement with Paging

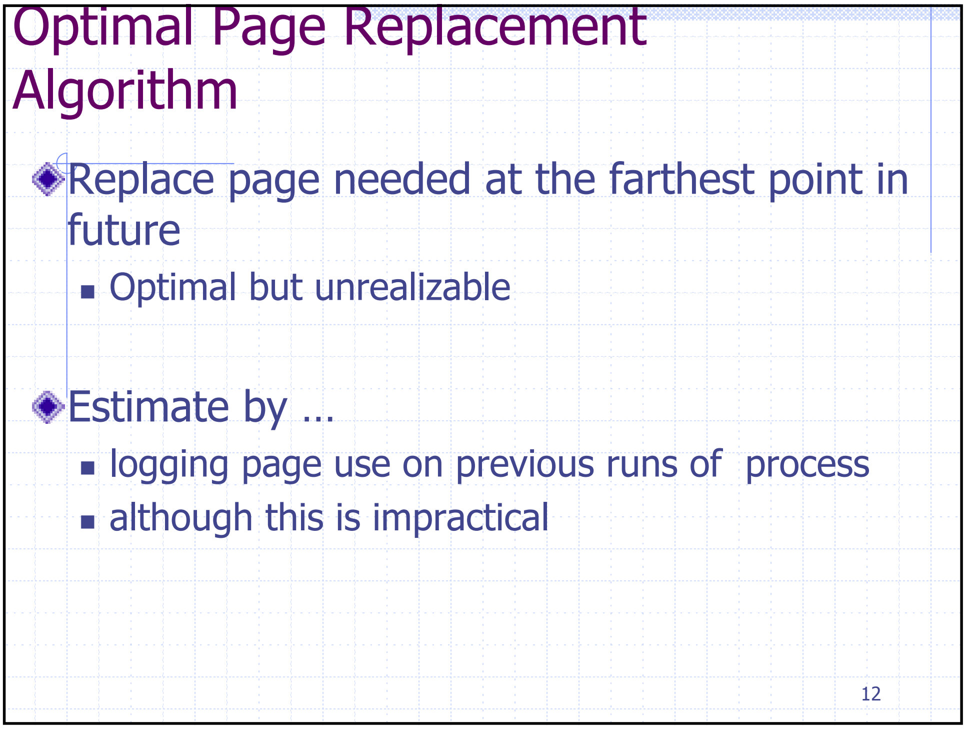
Four times when OS involved with paging

1. Process creation
   - determine program size
   - create page table
2. Process execution
   - MMU reset for new process
   - TLB flushed
3. Page fault time
   - determine virtual address causing fault
   - swap target page out, needed page in
4. Process termination time
   - release page table, pages



Page Replacement Algorithms

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



Optimal Page Replacement Algorithm

- Replace page needed at the farthest point in future
  - Optimal but unrealizable
- Estimate by …
  - logging page use on previous runs of process
  - although this is impractical

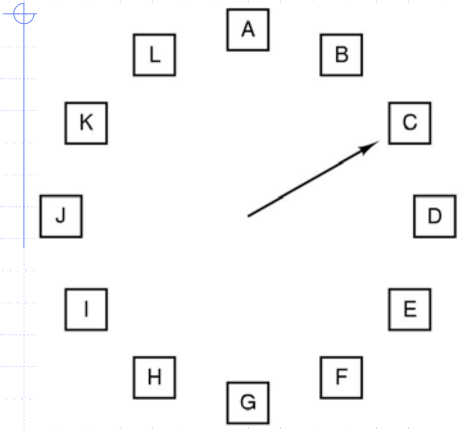
Not Recently Used Page Replacement Algorithm

- Each page has Reference bit, Modified bit
  - bits are set when page is referenced, modified
- Pages are classified
  1. not referenced, not modified
  2. not referenced, modified
  3. referenced, not modified
  4. referenced, modified
- NRU removes page at random
  - from lowest numbered non empty class

FIFO Page Replacement Algorithm

- Maintain a linked list of all pages
  - in order they came into memory
- Page at beginning of list replaced
- Disadvantage
  - page in memory the longest may be often used

The Clock Page Replacement Algorithm

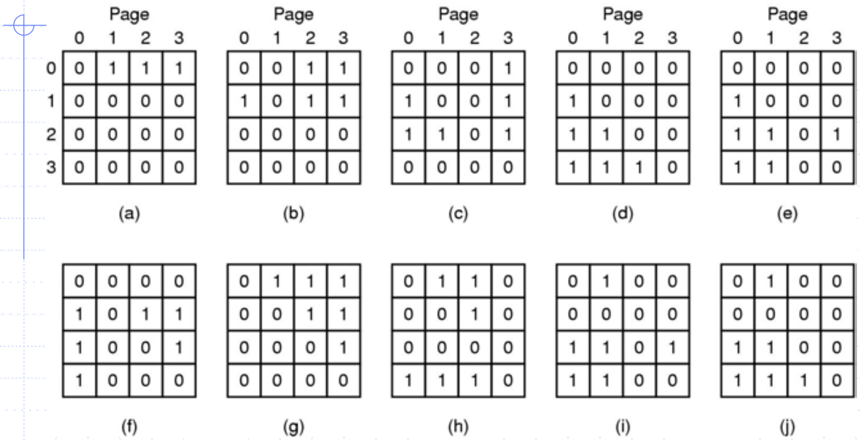


When a page fault occurs,
the page the hand is
pointing to is inspected.
The action taken depends
on the R bit:
R = 0: Evict the page
R = 1: Clear R and advance hand

Least Recently Used (LRU)

- Assume pages used recently will used again soon
  - throw out page that has been unused for longest time
- Must keep a linked list of pages
  - most recently used at front, least at rear
  - update this list every memory reference !!
- Alternatively keep counter in each page table entry
  - choose page with lowest value counter
  - periodically zero the counter

Simulating LRU in Software (1)



Page

(a)	0	1	2	3
0	0	1	1	1
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0

(b)	0	1	2	3
0	0	0	1	1
1	1	0	1	1
2	0	0	0	0
3	0	0	0	0

(c)	0	1	2	3
0	0	0	0	1
1	1	0	0	1
2	1	1	0	1
3	0	0	0	0

(d)	0	1	2	3
0	0	0	0	0
1	1	0	0	0
2	1	1	0	0
3	1	1	1	0

(e)	0	1	2	3
0	0	0	0	0
1	1	0	0	0
2	1	1	0	1
3	1	1	0	0

(f)			
0	0	0	0
1	0	1	1
1	0	0	1
1	0	0	0

(g)			
0	1	1	1
0	0	1	1
0	0	0	1
0	0	0	0

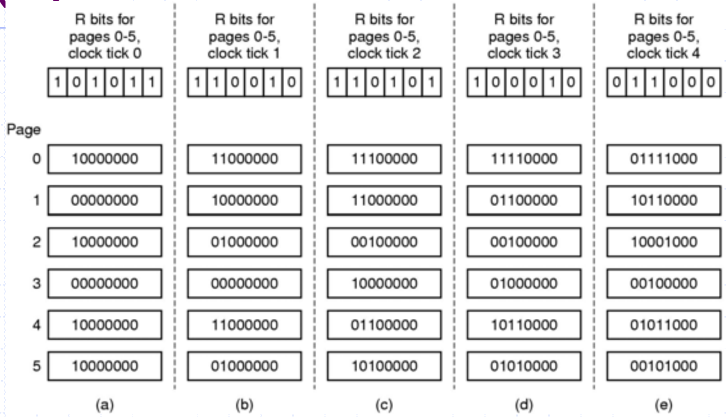
(h)			
0	1	1	0
0	0	1	0
0	0	0	0
1	1	1	0

(i)			
0	1	0	0
0	0	0	0
1	1	0	1
1	1	0	0

(j)			
0	1	0	0
0	0	0	0
1	1	0	0
1	1	1	0

LRU using a matrix – pages referenced in order 0,1,2,3,2,1,0,3,2,3

Simulating LRU in Software (2)



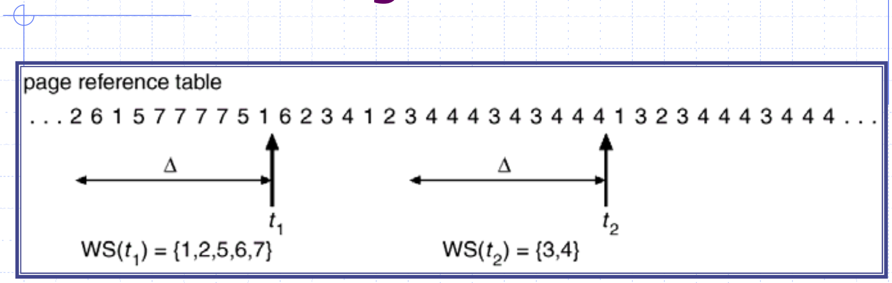
Page	(a)	(b)	(c)	(d)	(e)
R bits for pages 0-5	clock tick 0 1 0 1 0 1 1	clock tick 1 1 1 0 0 1 0	clock tick 2 1 1 0 1 0 1	clock tick 3 1 0 0 0 1 0	clock tick 4 0 1 1 0 0 0
0	10000000	11000000	11100000	11110000	01111000
1	00000000	10000000	11000000	01100000	10110000
2	10000000	01000000	00100000	00100000	10001000
3	00000000	00000000	10000000	01000000	00100000
4	10000000	11000000	01100000	10110000	01011000
5	10000000	01000000	10100000	01010000	00101000

- The aging algorithm simulates LRU in software
- Note 6 pages for 5 clock ticks, (a) – (e)

Working-Set Model

- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
  Example: 10,000 instruction
- 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 will not encompass entire locality.
  - if Δ too large will encompass several localities.
  - if $\Delta = \infty \Rightarrow$ will encompass entire program.
- $D = \Sigma\ WSS_i \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing
- Policy if $D >$ m, then suspend one of the processes.

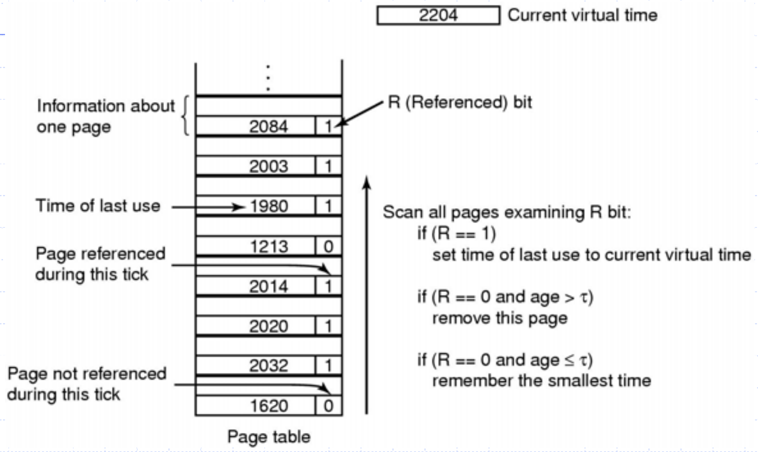
Working-set model



Keeping Track of the Working Set

- Approximate with interval timer + a reference bit
- Example: Δ = 10,000
  - Timer interrupts after every 5000 time units.
  - Keep in memory 2 bits for each page.
  - Whenever a timer interrupts copy and sets the values of all reference bits to 0.
  - If one of the bits in memory = 1 ⇒ page in working set.
- Why is this not completely accurate?
- Improvement = 10 bits and interrupt every 1000 time units.

The Working Set Page Replacement Algorithm (2)



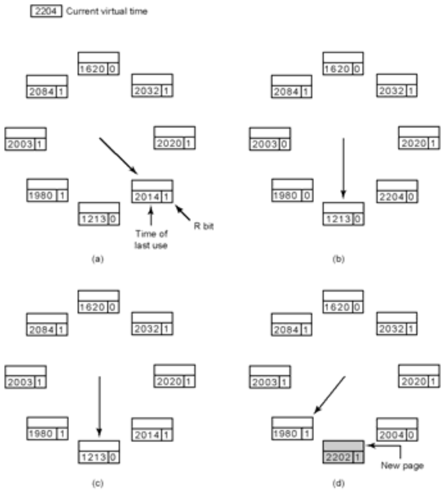
```
Scan all pages examining R bit:
    if (R == 1)
      set time of last use to current virtual time

    if (R == 0 and age > τ)
      remove this page

    if (R == 0 and age ≤ τ)
      remember the smallest time
```

The working set algorithm

The WSClock Page Replacement Algorithm



Operation of the WSClock 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 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

(a)

		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

(b)

- FIFO with 3 page frames
- FIFO with 4 page frames
- *P*s show which page references show page faults

Stack Algorithms

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	
Distance string		∞	∞	∞	∞	∞	∞	∞	4	∞	4	2	3	1	5	1	2	6	1	1	4	**7**	**4**	**6**	**5**

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

Page Size (1)

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 (2)

- Overhead due to page table and internal fragmentation

page table space

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

internal fragmentation

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

Optimized when

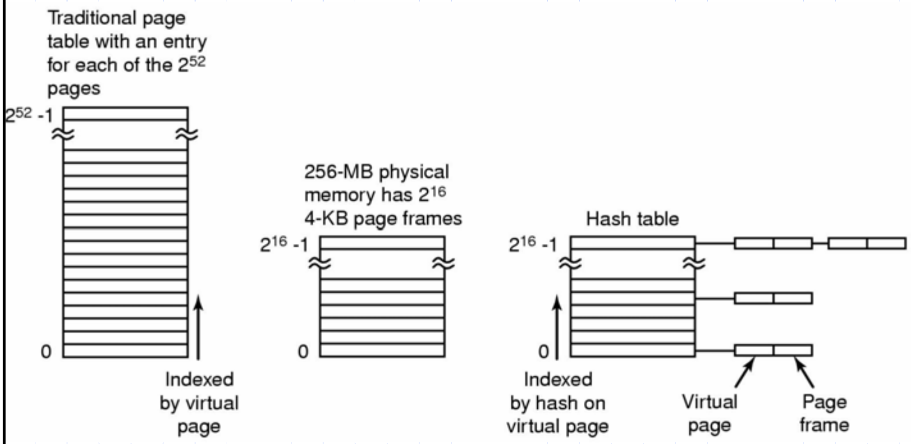
$$p = \sqrt{2se}$$

TLBs – Translation Lookaside 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

A TLB to speed up paging

Inverted Page Tables


Traditional page table with an entry for each of the 2^{52} pages
2^{52} -1
0
Indexed by virtual page
256-MB physical memory has 2^{16} 4-KB page frames
2^{16} -1
0
Hash table
2^{16} -1
0
Indexed by hash on virtual page
Virtual page
Page frame

Comparison of a traditional page table with an inverted page table