8. Virtual Memory

8.1 Principles of Virtual Memory

8.2 Implementations of Virtual Memory

- Paging
- Segmentation
- Paging With Segmentation
- Paging of System Tables
- Translation Look-aside Buffers

8.3 Memory Allocation in Paged Systems

- Global Page Replacement Algorithms
- Local Page Replacement Algorithms
- Load Control and Thrashing
- Evaluation of Paging

Principles of Virtual Memory

- For each process, the system creates the illusion of large contiguous memory space(s)
- Relevant portions of *Virtual Memory (VM)* are loaded automatically and transparently
- *Address Map* translates Virtual Addresses to Physical Addresses

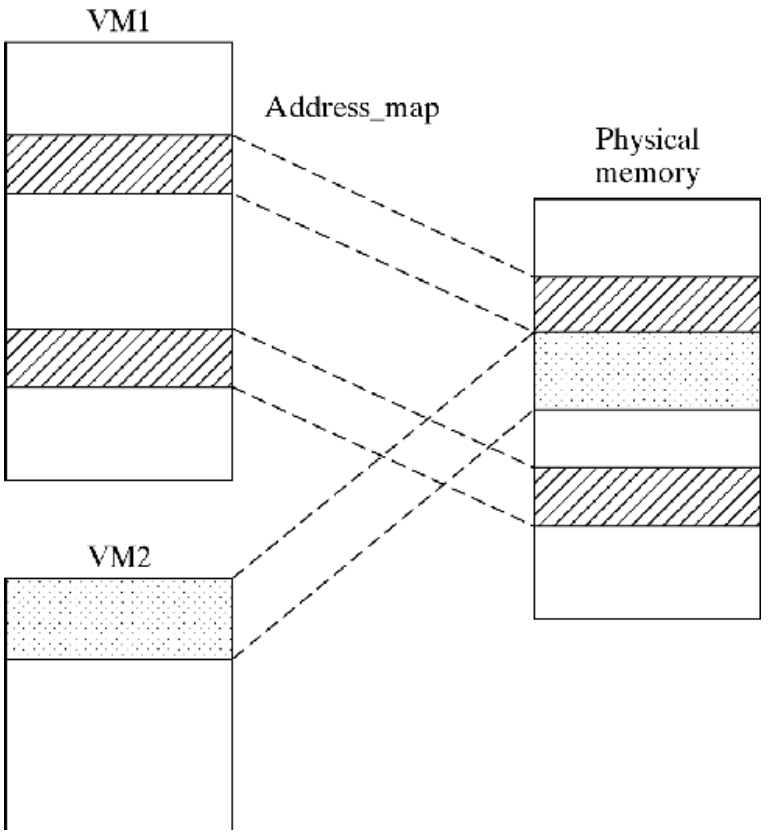


Figure 8-11

Principles of Virtual Memory

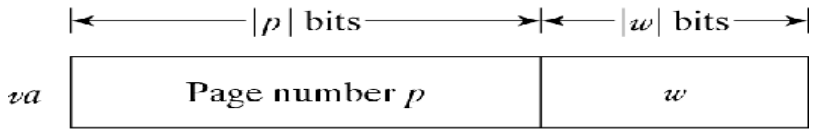
- Single-segment Virtual Memory:
  - One area of 0..n-1 words
  - Divided into fix-sized pages
- Multiple-Segment Virtual Memory:
  - Multiple areas of up to 0..n-1 (words)
  - Each holds a *logical segment* (e.g., function, data structure)
  - Each logical segment
    - may be contiguous is contiguous, or
    - may be divided into pages

Main Issues in VM Design

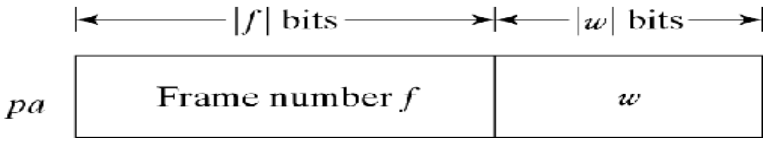
1. Address mapping
   - How to translate virtual addresses to physical addresses
2. Placement
   - Where to place a portion of VM needed by process
3. Replacement
   - Which portion of VM to remove when space is needed
4. Load control
   - How much of VM to load at any one time
5. Sharing
   - How can processes share portions of their VMs

VM Implementation via Paging

- **VM** is divided into fix-sized pages : page_size=$2^{|w|}$
- **PM** (physical memory) is divided into $2^{|f|}$ *page frames* : frame_size=page_size=$2^{|w|}$
- System loads pages into frames and translates addresses
- Virtual address: va = (p,w)



- Physical address: pa = (f,w)



- |p|, |f|, and |*w*|
  - |p| determines number of pages in VM, $2^{|p|}$
  - |f| determines number of frames in PM, $2^{|f|}$
  - |w| determines page/frame size, $2^{|w|}$

Figure 8-2

Paged Virtual Memory

- Virtual address: va = (p,w) Physical address: pa = (f,w)
- $2^{|p|}$ pages in VM; $2^{|w|}$ = page/frame size; $2^{|f|}$ frames in PM

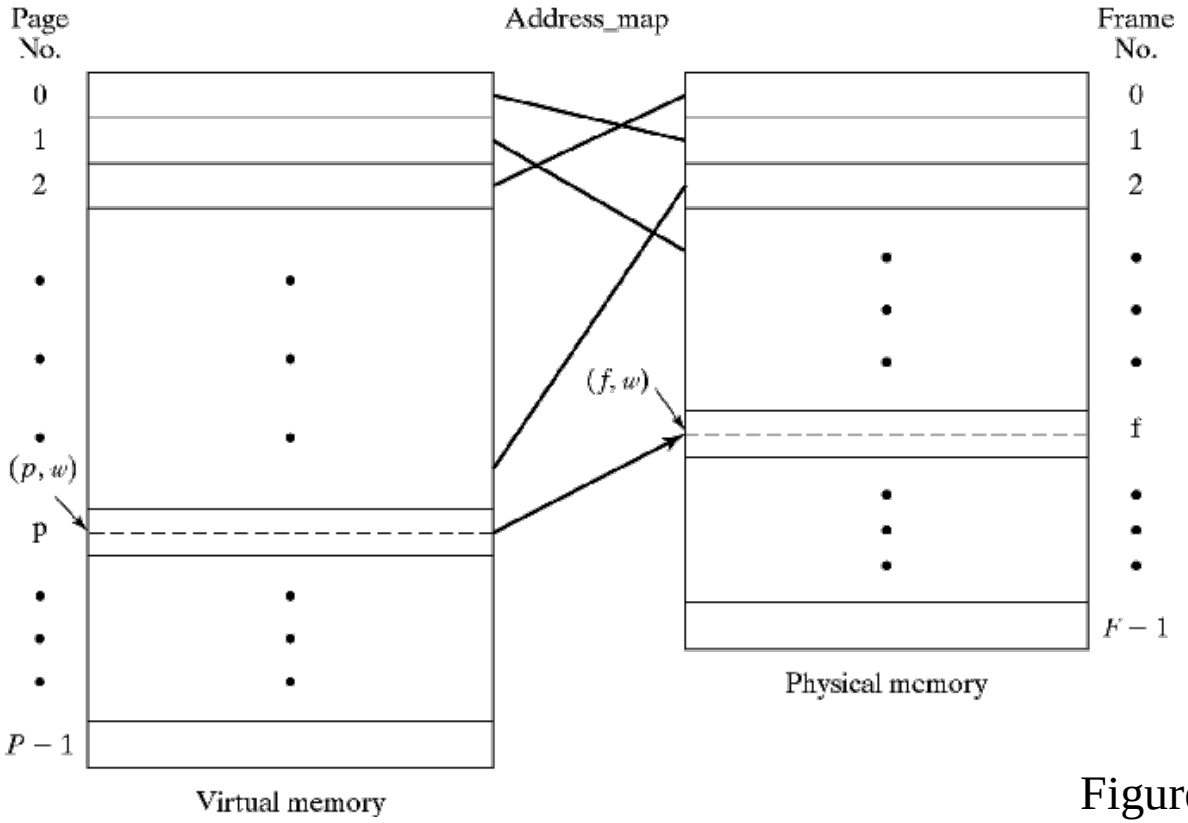


Figure 8-3

Paged VM Address Translation

- Given (p,w), how to determine f from p ?
- One solution: *Frame Table* :
  - One entry, FT[i], for each frame
    FT[i].pid records process ID
    FT[i].page records page number **p**
  - Given (id,p,w), search for a match on (id,p)
    f is the i for which (FT[i].pid, FT[i].page)=(id,p)
  - Pseudocode for Frame Table lookup:

```
address_map(id,p,w)
{
  pa = UNDEFINED;
  for (f=0; f<F; f++)
     if (FT[f].pid==id && FT[f].page==p) pa=f+w;
  return pa;
}
```

Address Translation via Frame Table

```
address_map(id,p,w) {
  pa = UNDEFINED;
  for (f=0; f<F; f++)
    if (FT[f].pid==id &&
          FT[f].page==p)
                pa=f+w;
    return pa;
  }
```

- Drawbacks
  - Costly: Search must be done in parallel in hardware
  - Sharing of pages: difficult or not possible

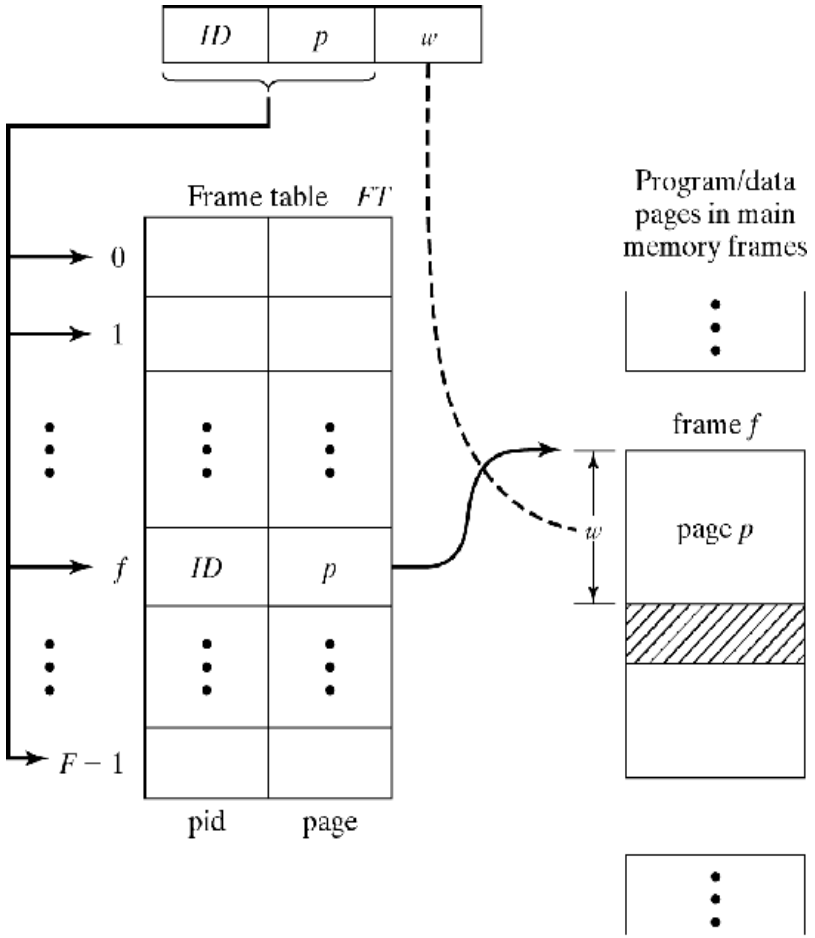


Figure 8-4

Page Table for Paged VM

- *Page Table (PT)* is associated with each VM (not PM)
- *Page table register* PTR points at PT at run time
- Entry p of PT holds frame number of page p :
  - *(PTR+p) points to frame f
- Address translation:

```
address_map(p, w) {
  pa = *(PTR+p)+w;
  return pa }
```

- Drawback:

  Extra memory access

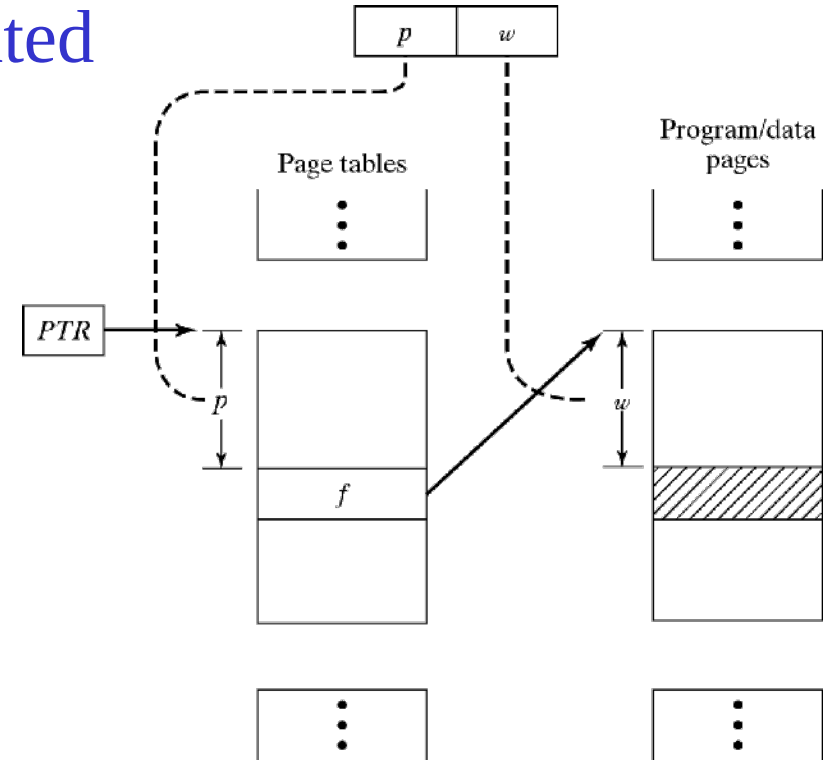


Figure 8-5

Demand Paging

- All pages of VM can be loaded initially
  - Simple, but maximum size of VM = size of PM
- Pages a loaded as needed: on demand
  - Additional bit in PT indicates a page's presence/absence in memory
  - *Page fault* occurs when page is absent

```
address_map(p, w)
{
    if (resident(*(PTR+p))) {
       pa = *(PTR+p)+w; return pa; }
    else page_fault;
}
```

VM using Segmentation

- Multiple contiguous spaces: *segments*
  - More natural match to program/data structure
  - Easier sharing (Chapter 9)
- Virtual address (s,w) mapped to physical address (but no frames)
- Where/how are segments placed in physical memory?
  - Contiguous
  - Paged

Contiguous Allocation

- Each segment is contiguous in physical memory
- *Segment Table (ST)* tracks starting locations
- *Segment Table Register* STR points to segment table
- Address translation:

```
address_map(s, w)
{
    if (resident(*(STR+s))) {
       pa = *(STR+s)+w;
       return pa; }
    else segment_fault;
}
```

- Drawback: External fragmentation

Paging with segmentation

- Each segment is divided into fix-size pages
- va = (s,p,w)
  - |s| determines # of segments (size of ST)
  - |p| determines # of pages per segment (size of PT)
  - |w| determines page size
- pa = *(*(STR+s)+p)+w
- Drawback:
  2 extra memory references

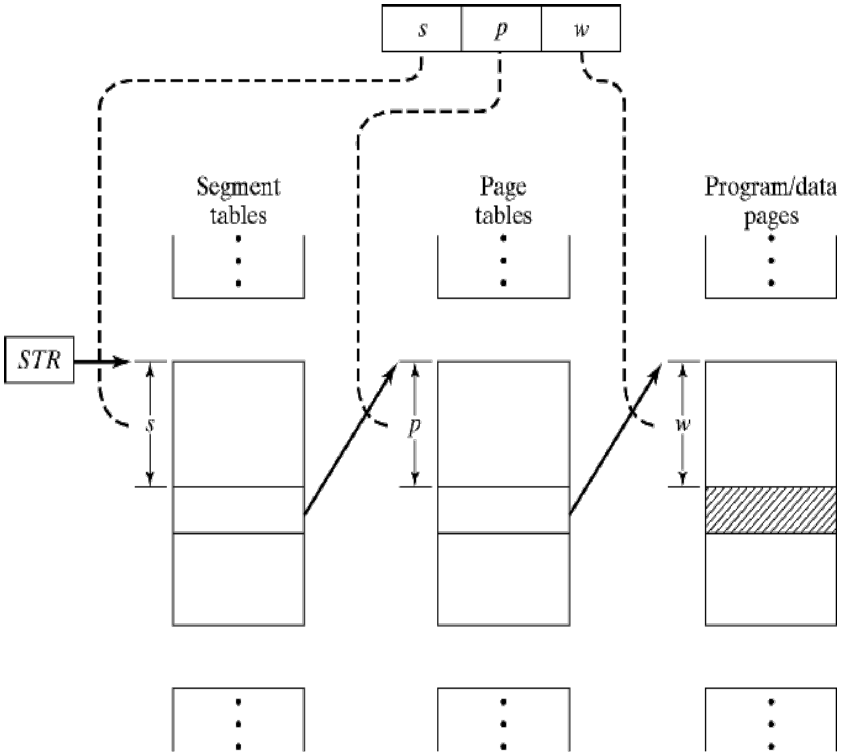


Figure 8-7

Paging of System Tables

- ST or PT may be too large to keep in PM
  - Divide ST or PT into pages
  - Keep track by additional page table
- Paging of ST
  - ST divided into pages
  - Segment directory keeps track of ST pages
  - va = (s1,s2,p,w)
  - pa = *(*(*(STR+s1)+s2)+p)+w
- Drawback: 3 extra memory references

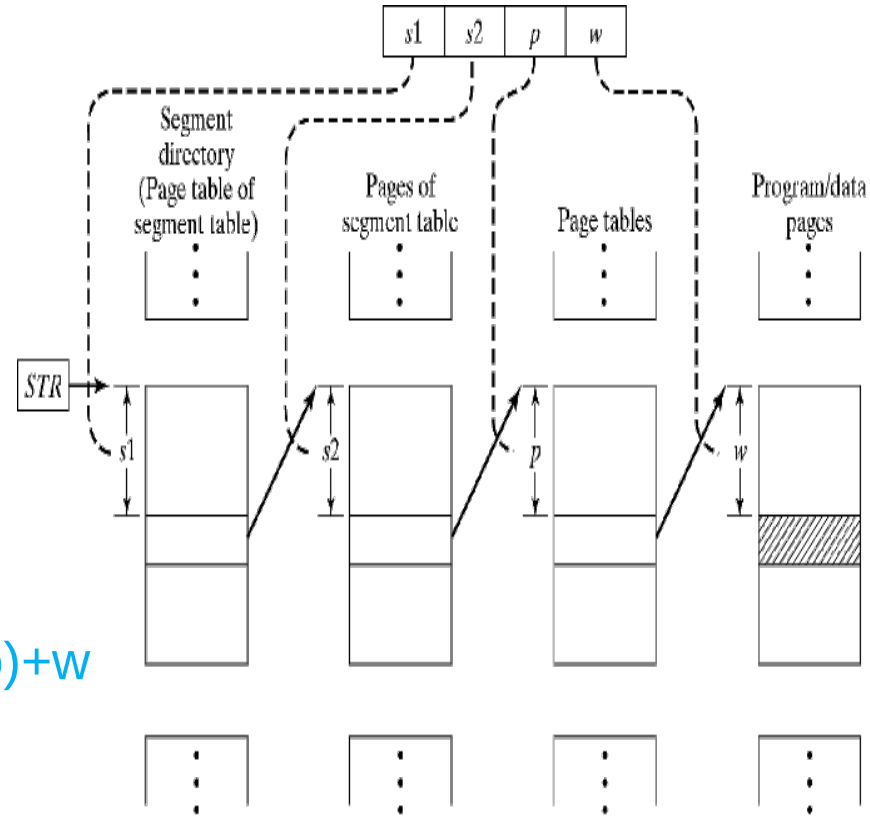


Figure 8-8

Translation Look-aside Buffers

- *Translation Lookaside Buffer (TLB)* avoids some additional memory accesses
  - Keep most recently translated page numbers in associative memory:
    For any (s,p,*) ; keep (s,p) and frame number f
  - Bypass translation if match found on (s,p)
- TLB ≠ cache
  - TLB keeps only frame numbers
  - Cache keeps data values

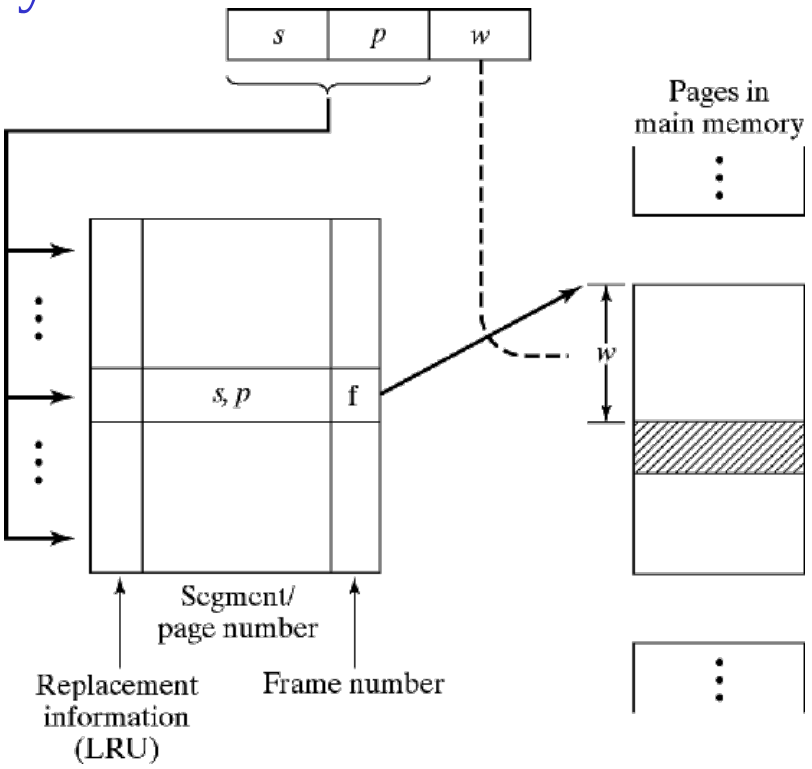


Figure 8-10

Memory Allocation with Paging

- Placement policy: Any free frame is OK
- Replacement: Goal is to minimize data movement between physical memory and secondary storage
- Two types of replacement strategies:
  - Global replacement: Consider *all* resident pages, regardless of owner
  - Local replacement: Consider *only* pages of *faulting* process
- How to compare different algorithms:
  - Use *Reference String (RS)* : $r_0\ r_1 \ldots r_t \ldots$

    r_t is the (number of the) page referenced at time t
  - Count number of page faults

Global page replacement

- *Optimal (MIN):* Replace page that will not be referenced for the longest time in the future

Time t	0	1	2	3	4	5	6	7	8	9	10
RS		c	a	d	b	e	b	a	b	c	d
Frame 0	a	a	a	a	a	a	a	a	a	a	d
Frame 1	b	b	b	b	b	b	b	b	b	b	b
Frame 2	c	c	c	c	c	c	c	c	c	c	c
Frame 3	d	d	d	d	d	e	e	e	e	e	e
IN						e					d
OUT						d					a

- Problem: Need entire reference string (i.e.,need to know the future)

Global Page Replacement

- *Random Replacement:* Replace a randomly chosen page
  - Simple but
  - Does not exploit *locality of reference*
    - Most instructions are sequential
    - Most loops are short
    - Many data structures are accessed sequentially

Global page replacement

- *First-In First-Out (FIFO):* Replace oldest page

Time t	0	1	2	3	4	5	6	7	8	9	10
RS		c	a	d	b	e	b	a	b	c	d
Frame 0	>a	>a	>a	>a	>a	e	e	e	e	>e	d
Frame 1	b	b	b	b	b	>b	>b	a	a	a	>a
Frame 2	c	c	c	c	c	c	c	>c	b	b	b
Frame 3	d	d	d	d	d	d	d	d	>d	c	c
IN						e		a	b	c	d
OUT						a		b	c	d	e

- Problem:
  - Favors recently loaded pages, but
  - Ignores when program returns to old pages

Global Page Replacement

- *LRU:* Replace Least Recently Used page

Time t	0	1	2	3	4	5	6	7	8	9	10
RS		c	a	d	b	e	b	a	b	c	d
Frame 0	a	a	a	a	a	a	a	a	a	a	a
Frame 1	b	b	b	b	b	b	b	b	b	b	b
Frame 2	c	c	c	c	c	e	e	e	e	e	d
Frame 3	d	d	d	d	d	d	d	d	d	c	c
IN						e				c	d
OUT						c				d	e
Q.end	d	c	a	d	b	e	b	a	b	c	d
	c	d	c	a	d	b	e	b	a	b	c
	b	b	d	c	a	d	d	e	e	a	b
Q.head	a	a	b	b	c	a	a	d	d	e	a

Global page replacement

- LRU implementation
  - Software queue: too expensive
  - Time-stamping
    - Stamp each referenced page with current time
    - Replace page with oldest stamp
  - Hardware capacitor with each frame
    - Charge at reference
    - Charge decays exponentially
    - Replace page with smallest charge
  - ***n***-bit aging register with each frame
    - Shift all registers to right periodically (or at every reference to any page)
    - Set left-most bit of referenced page to 1
    - Replace page with smallest value
  - Simpler algorithms that approximate LRU algorithm

Global Page Replacement

- *Second-chance algorithm*
  - Approximates LRU
  - Implement *use-bit* u with each frame
  - Set u=1 when page referenced
  - To select a page:
    - If u==0, select page
    - Else, set u=0 and consider next frame
  - Used page gets a second chance to stay in PM
- Algorithm is called *clock algorithm*:
  - Search cycles through page frames

Global page replacement

- Second-chance algorithm

…	4	5	6	7	8	9	10
…	b	e	b	a	b	c	d
…	>a/1	e/1	e/1	e/1	e/1	>e/1	d/1
…	b/1	>b/0	>b/1	b/0	b/1	b/1	>b/0
…	c/1	c/0	c/0	a/1	a/1	a/1	a/0
…	d/1	d/0	d/0	>d/0	>d/0	c/1	c/0
…		e		a		c	d

Global Page Replacement

- *Third-chance algorithm*
  - Second chance algorithm does not distinguish between read and write access
    - Write access more expensive
  - Give modified pages a third chance:
    - *use-bit* u set at every reference (read and write)
    - *write-bit* w set at write reference
    - *dirty-bit* needed to keep track of whether page has been modified
    - to select a page, cycle through frames, resetting bits, until uw==00:

u w	→	u w	
1 1		0 1	
1 0		0 0	
0 1		0 0 *	(set dirty bit to remember modification)
0 0	(select page for replacement)		

Global Page Replacement

- Third-chance algorithm

  Read->10->00->Select

  Write->11->01->00*->Select

... 0	1	2	3	4	5	6	7	8	9	10 .
…	c	a^w	d	b^w	e	b	a^w	b	c	d .
>a/10	>a/10	>a/11	>a/11	>a/11	a/00*	a/00*	a/11	a/11	>a/11	a/00*
… b/10	b/10	b/10	b/10	b/11	b/00*	b/10*	b/10*	b/10*	b/10*	d/10
… c/10	c/10	c/10	c/10	c/10	e/10	e/10	e/10	e/10	e/10	>e/00
… d/10	d/10	d/10	d/10	d/10	>d/00	>d/00	>d/00	>d/00	c/10	c/00 .
… IN					e				c	d
… OUT					c				d	b

Local Page Replacement

- Measurements indicate that every program needs a minimum set of pages to be resident in memory
  - If too few, *thrashing* occurs
  - If too many, page frames are wasted
- The size of the minimum set varies over time
- Goal: attempt to maintain an optimal resident set of pages for each active process
  - Number of resident pages for each process changes over time

Local Page Replacement

- *Optimal (VMIN)*
  - Define a sliding window $(t,t+\tau)$
  - τ is a parameter (constant)
  - At any time t, maintain as resident all pages visible in window
- Guaranteed to generate smallest number of page faults
- Requires knowledge of future

Local page replacement

- Optimal (VMIN) with τ=3

Time t	0	1	2	3	4	5	6	7	8	9	10
RS	d	c	c	d	b	c	e	c	e	a	d
Page a	-	-	-	-	-	-	-	-	-	x	-
Page b	-	-	-	-	x	-	-	-	-	-	-
Page c	-	x	x	x	x	x	x	x	-	-	-
Page d	x	x	x	x	-	-	-	-	-	-	x
Page e	-	-	-	-	-	-	x	x	x	-	-
IN		c			b		e			a	d
OUT					d	b			c	e	a

- Unrealizable without entire reference string (knowledge of future)

Local Page Replacement

- *Working Set Model:*
  - Uses *principle of locality:* Memory requirement for a process in the near future is closefly approximated by the process's memory requirement in the recent past
  - Use trailing window (instead of future window)
  - Working set $W(t,\tau)$ is all pages referenced during the interval $(t-\tau,t)$
  - At time t:
    - Remove all pages not in $W(t,\tau)$
    - Process may run only if entire $W(t,\tau)$ is resident

Local Page Replacement

- Working Set Model with τ=3

Time t	0	1	2	3	4	5	6	7	8	9	10
RS	a	c	c	d	b	c	e	c	e	a	d
Page a	x	x	x	x	-	-	-	-	-	x	x
Page b	-	-	-	-	x	x	x	x	-	-	-
Page c	-	x	x	x	x	x	x	x	x	x	x
Page d	x	x	x	x	x	x	x	-	-	-	x
Page e	x	x	-	-	-	-	x	x	x	x	x
IN		c			b		e			a	d
OUT			e		a			d	b		.

- Drawback: costly to implement
- Approximate (aging registers, time stamps)

Local Page Replacement

- *Page fault frequency (PFF)*
- Goals
  - Keep frequency of page faults acceptably low
  - Keep resident page set from growing unnecessarily large
- Uses a parameter τ
- Only adjust resident set when a page fault occurs
- Rule: When a page fault occurs
  - If time between page faults $\leq \tau$
    - Add new page to resident set
  - If time between page faults $> \tau$
    - Add new page to resident set
    - Remove all pages not referenced since last page fault

Local Page Replacement

- Page Fault Frequency with τ=2

Time t	0	1	2	3	4	5	6	7	8	9	10
RS		c	c	d	b	c	e	c	e	a	d
Page a	x	x	x	x	-	-	-	-	-	x	x
Page b	-	-	-	-	x	x	x	x	x	-	-
Page c	-	x	x	x	x	x	x	x	x	x	x
Page d	x	x	x	x	x	x	x	x	x	-	x
Page e	x	x	x	x	-	-	x	x	x	x	x
IN		c			b		e			a	d
OUT					ae					bd	

Load Control and Thrashing

- Main issues:
  - How to choose the amount/degree of multiprogramming?
  - When level decreased, which process should be deactivated?
  - When new process reactivated,which of its pages should be loaded?
  - *Load Control:* Policy setting
    number and type of concurrent processes
  - *Thrashing:* Effort moving pages
    between main and secondary memory

Load Control and Thrashing

- Choosing degree of multiprogramming
- Local replacement:
  - Working set of any process must be resident
  - This automatically imposes a limit
- Global replacement
  - No working set concept
  - Use CPU utilization as a criterion
  - With too many processes, thrashing occurs

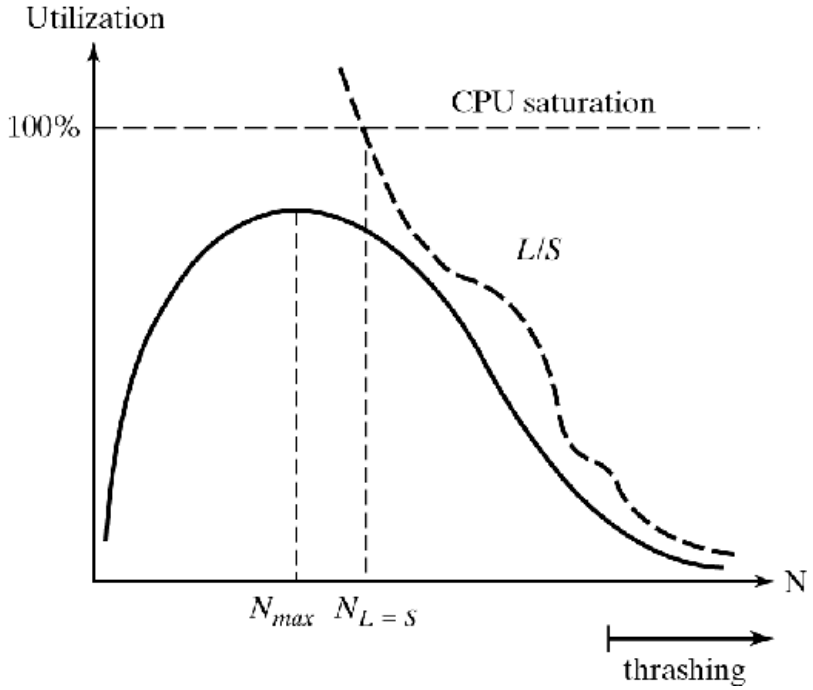


Figure 8-11
L=mean time between faults
S=mean page fault service time

Load Control and Thrashing

- How to find N_{max}?
  - L=S criterion:
    - *Page fault service time* S needs to keep up with *mean time between page faults* L
  - 50% criterion:
    - CPU utilization is highest when paging disk is 50% busy (found experimentally)

Load Control and Thrashing

- Which process to deactivate
  - Lowest priority process
  - Faulting process
  - Last process activated
  - Smallest process
  - Largest process
- Which pages to load when process activated
  - Prepage last resident set

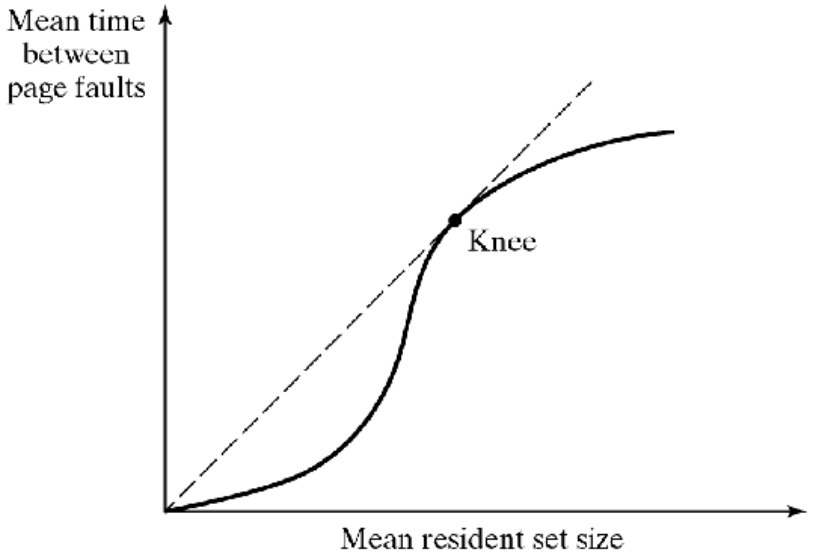


Figure 8-12

Evaluation of Paging

Prepaging is important

- Initial set can be loaded more efficiently than by individual page faults

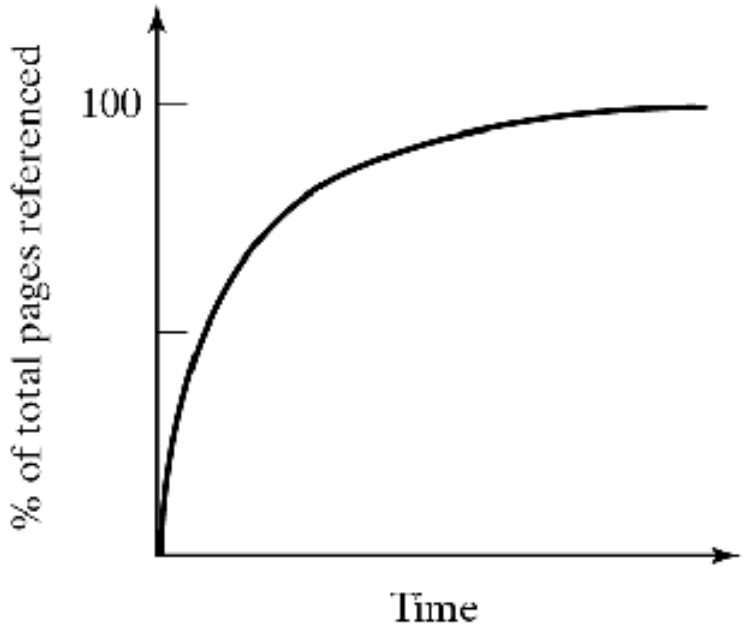


Figure 8-13(a)

Evaluation of Paging

Page size should be small. However, small pages need

- Larger page tables
- More hardware
- Greater I/O overhead

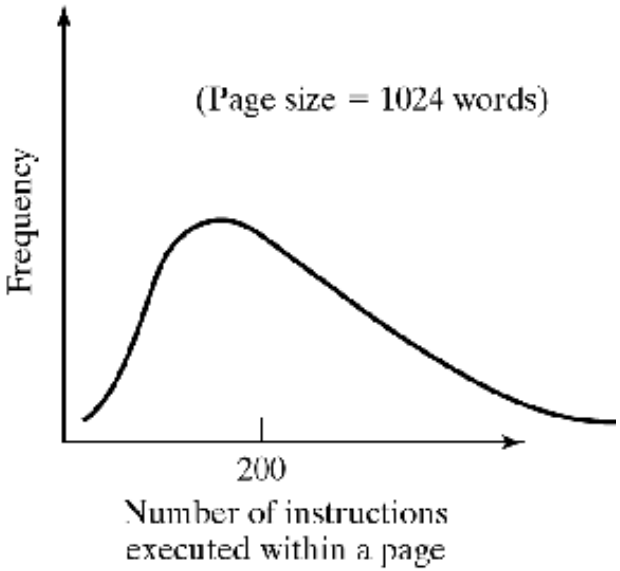


Figure 8-13(b)

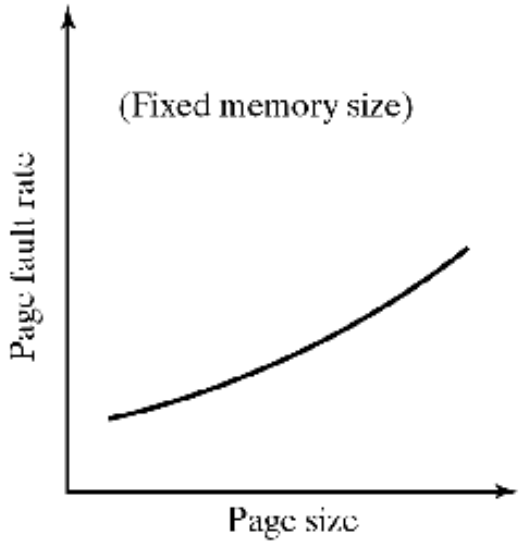


Figure 8-13(c)

Evaluation of Paging

Load control is important

W = Minimum amount of memory to avoid thrashing.

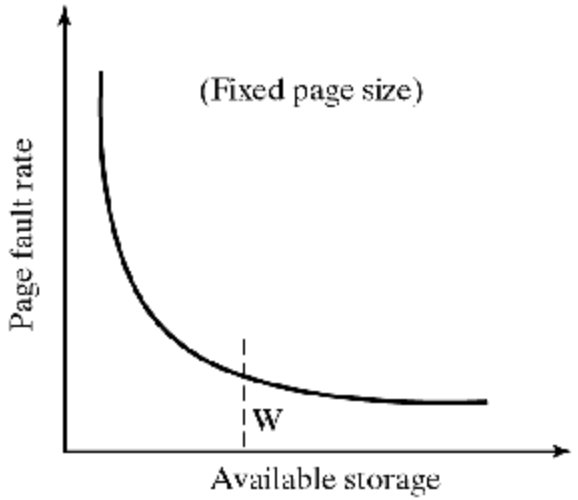


Figure 8-13(d)

History

- Originally developed by Steve Franklin
- Modified by Michael Dillencourt, Summer, 2007
- Modified by Michael Dillencourt, Spring, 2009
- Modified by Michael Dillencourt, Winter, 2010