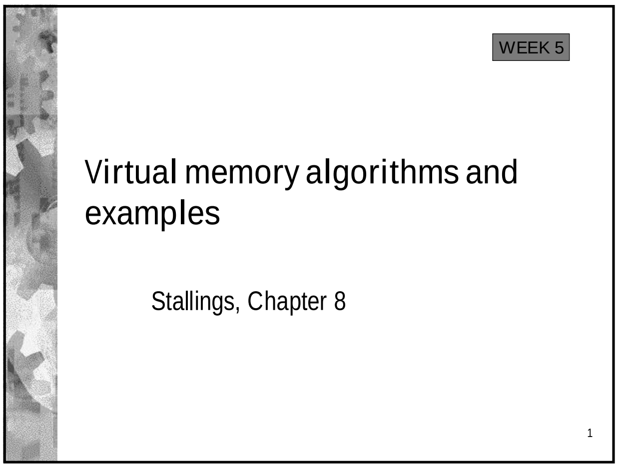
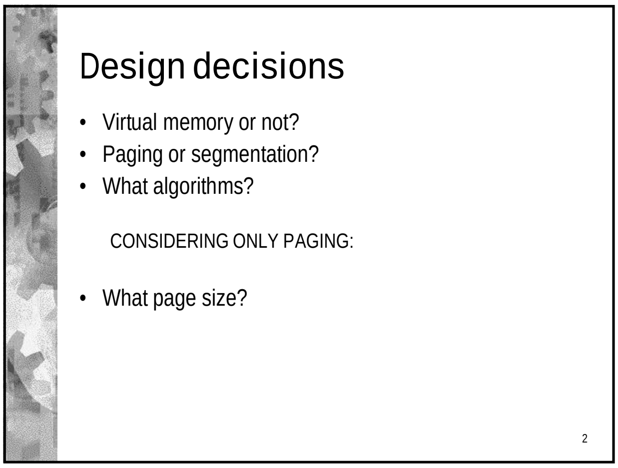


WEEK 5

Virtual memory algorithms and examples

Stallings, Chapter 8

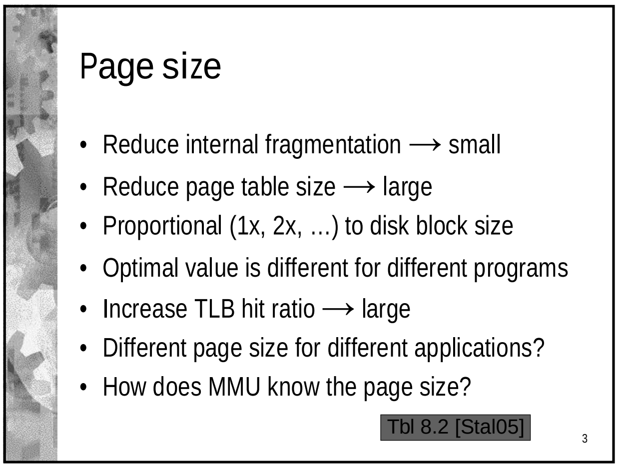


Design decisions

- Virtual memory or not?
- Paging or segmentation?
- What algorithms?

CONSIDERING ONLY PAGING:

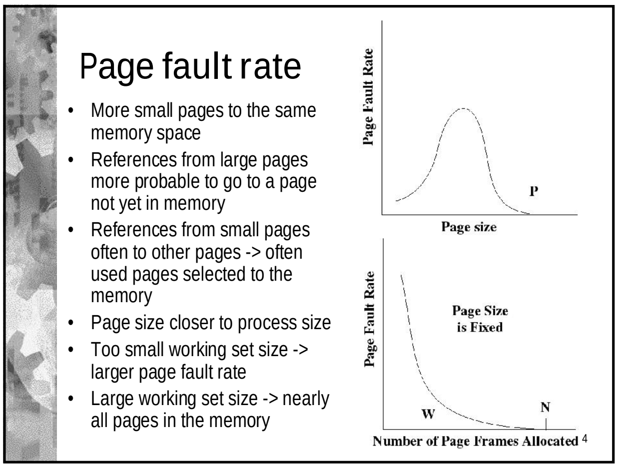
- What page size?



Page size

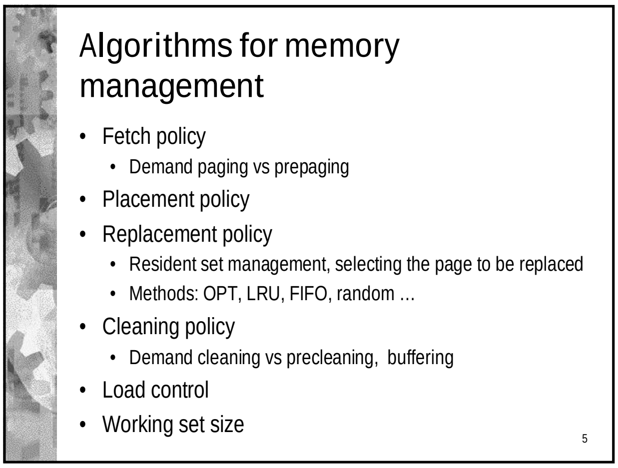
- Reduce internal fragmentation ⟶ small
- Reduce page table size ⟶ large
- Proportional (1x, 2x, …) to disk block size
- Optimal value is different for different programs
- Increase TLB hit ratio ⟶ large
- Different page size for different applications?
- How does MMU know the page size?

Tbl 8.2 [Stal05]



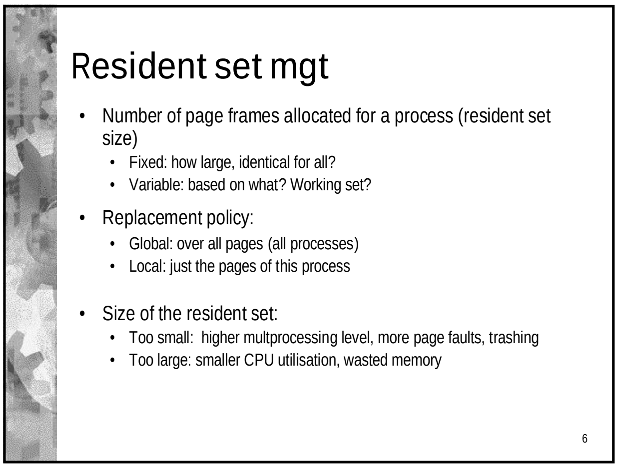
Page fault rate

- More small pages to the same memory space
- References from large pages more probable to go to a page not yet in memory
- References from small pages often to other pages -> often used pages selected to the memory
- Page size closer to process size
- Too small working set size -> larger page fault rate
- Large working set size -> nearly all pages in the memory



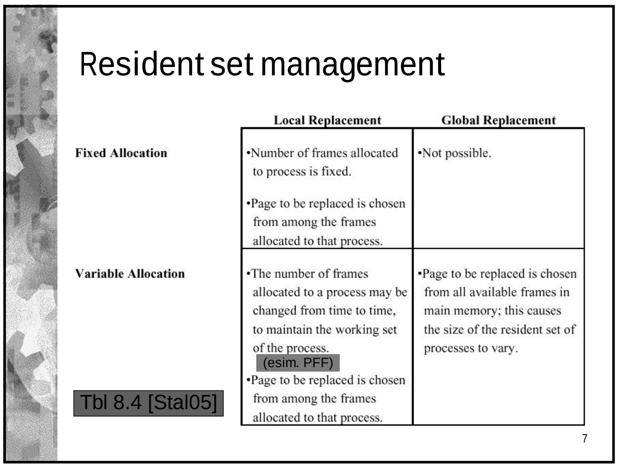
Algorithms for memory management

- Fetch policy
  - Demand paging vs prepaging
- Placement policy
- Replacement policy
  - Resident set management, selecting the page to be replaced
  - Methods: OPT, LRU, FIFO, random …
- Cleaning policy
  - Demand cleaning vs precleaning, buffering
- Load control
- Working set size



Resident set mgt

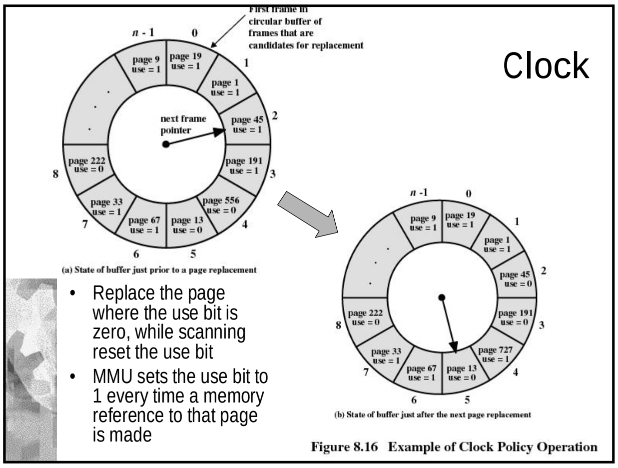
- Number of page frames allocated for a process (resident set size)
  - Fixed: how large, identical for all?
  - Variable: based on what? Working set?
- Replacement policy:
  - Global: over all pages (all processes)
  - Local: just the pages of this process
- Size of the resident set:
  - Too small: higher multprocessing level, more page faults, trashing
  - Too large: smaller CPU utilisation, wasted memory



Resident set management

	Local Replacement	Global Replacement
Fixed Allocation	•Number of frames allocated to process is fixed. •Page to be replaced is chosen from among the frames allocated to that process.	•Not possible.
Variable Allocation	•The number of frames allocated to a process may be changed from time to time, to maintain the working set of the process. (esim. PFF) •Page to be replaced is chosen from among the frames allocated to that process.	•Page to be replaced is chosen from all available frames in main memory; this causes the size of the resident set of processes to vary.

Tbl 8.4 [Stal05]



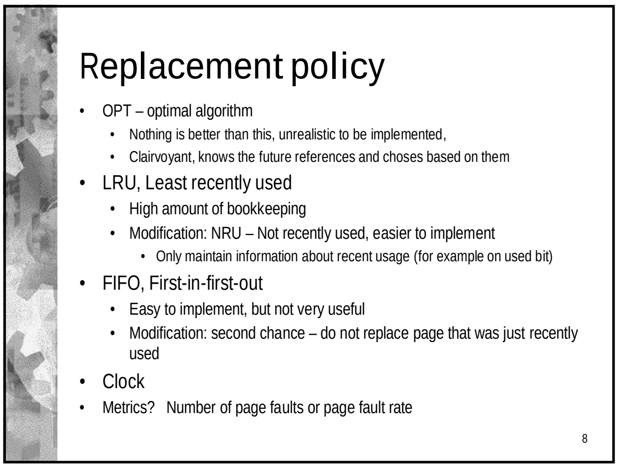
Clock

(a) State of buffer just prior to a page replacement

(b) State of buffer just after the next page replacement

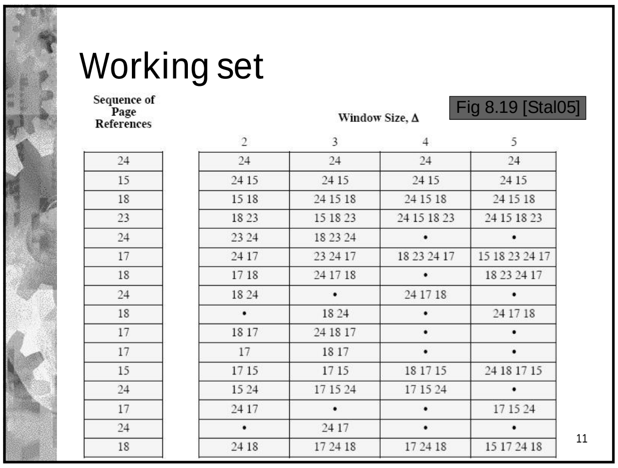
Figure 8.16 Example of Clock Policy Operation

- Replace the page where the use bit is zero, while scanning reset the use bit
- MMU sets the use bit to 1 every time a memory reference to that page is made



Replacement policy

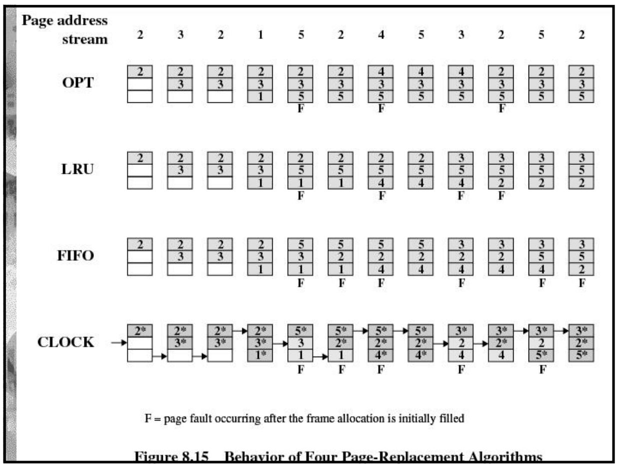
- OPT – optimal algorithm
  - Nothing is better than this, unrealistic to be implemented,
  - Clairvoyant, knows the future references and choses based on them
- LRU, Least recently used
  - High amount of bookkeeping
  - Modification: NRU – Not recently used, easier to implement
    - Only maintain information about recent usage (for example on used bit)
- FIFO, First-in-first-out
  - Easy to implement, but not very useful
  - Modification: second chance – do not replace page that was just recently used
- Clock
- Metrics? Number of page faults or page fault rate



Working set

Fig 8.19 [Stal05]

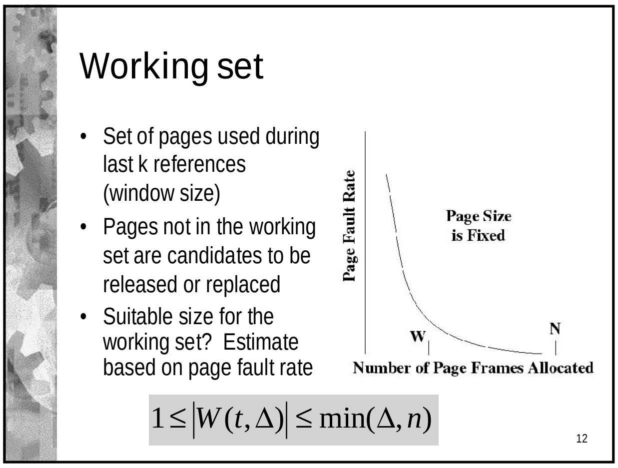
Sequence of Page References	Window Size, Δ			
	2	3	4	5
24	24	24	24	24
15	24 15	24 15	24 15	24 15
18	15 18	24 15 18	24 15 18	24 15 18
23	18 23	15 18 23	24 15 18 23	24 15 18 23
24	23 24	18 23 24	•	•
17	24 17	23 24 17	18 23 24 17	15 18 23 24 17
18	17 18	24 17 18	•	18 23 24 17
24	18 24	•	24 17 18	•
18	•	18 24	•	24 17 18
17	18 17	24 18 17	•	•
17	17	18 17	•	•
15	17 15	17 15	18 17 15	24 18 17 15
24	15 24	17 15 24	17 15 24	•
17	24 17	•	•	17 15 24
24	•	24 17	•	•
18	24 18	17 24 18	17 24 18	15 17 24 18



Page address stream	2	3	2	1	5	2	4	5	3	2	5	2
OPT	2	2 3	2 3	2 3 1	2 3 5 F	2 3 5	4 3 5 F	4 3 5	4 3 5	2 3 5 F	2 3 5	2 3 5
LRU	2	2 3	2 3	2 3 1	2 5 1 F	2 5 1	2 5 4 F	2 5 4	3 5 4 F	3 5 2 F	3 5 2	3 5 2
FIFO	2	2 3	2 3	2 3 1	5 3 1 F	5 2 1 F	5 2 4 F	5 2 4	3 2 4 F	3 2 4	3 5 4 F	3 5 2 F
CLOCK	2*	2* 3*	2* 3*	2* 3* 1*	5* 3 1 F	5* 2* 1 F	5* 2* 4* F	5* 2* 4*	3* 2 4 F	3* 2* 4	3* 2 5* F	3* 2* 5*

F = page fault occurring after the frame allocation is initially filled

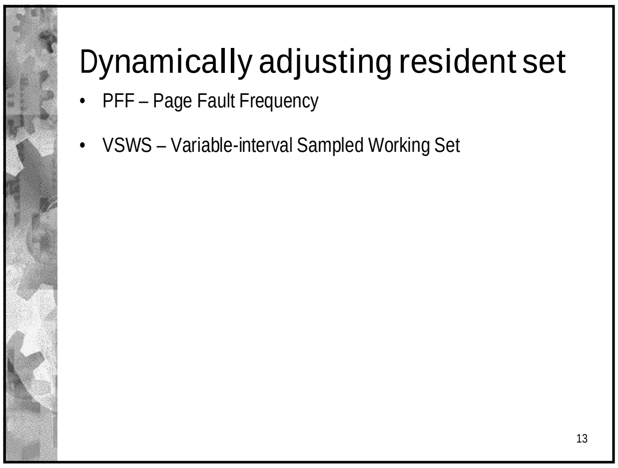
Figure 8.15 Behavior of Four Page-Replacement Algorithms



Working set

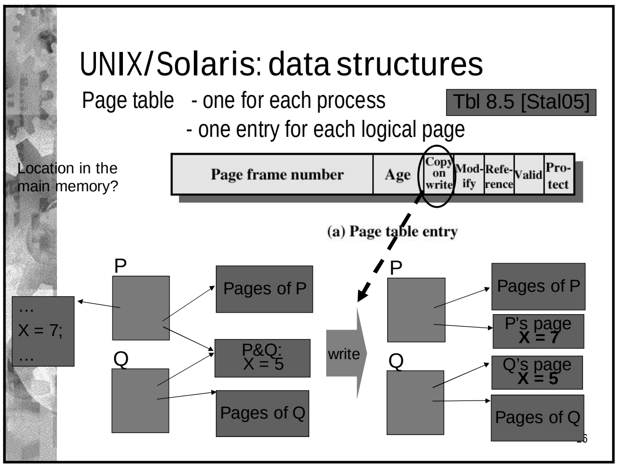
- Set of pages used during last k references (window size)
- Pages not in the working set are candidates to be released or replaced
- Suitable size for the working set? Estimate based on page fault rate

$$1 \le \left|W(t,\Delta)\right| \le \min(\Delta, n)$$



Dynamically adjusting resident set

- PFF – Page Fault Frequency
- VSWS – Variable-interval Sampled Working Set



UNIX/Solaris: data structures

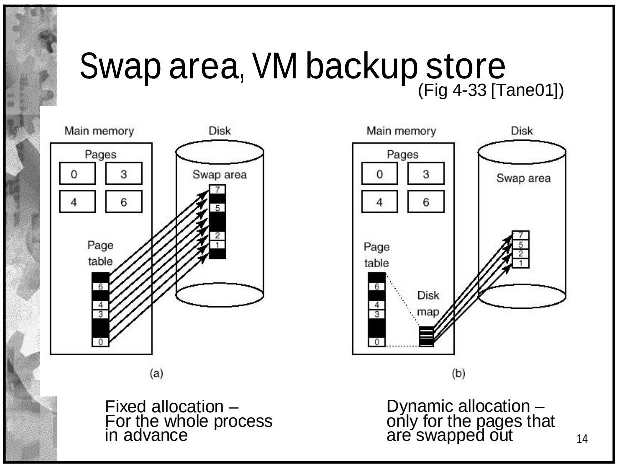
Page table - one for each process
- one entry for each logical page

Tbl 8.5 [Stal05]

Location in the main memory?

Page frame number	Age	Copy on write	Mod-ify	Refe-rence	Valid	Pro-tect

(a) Page table entry

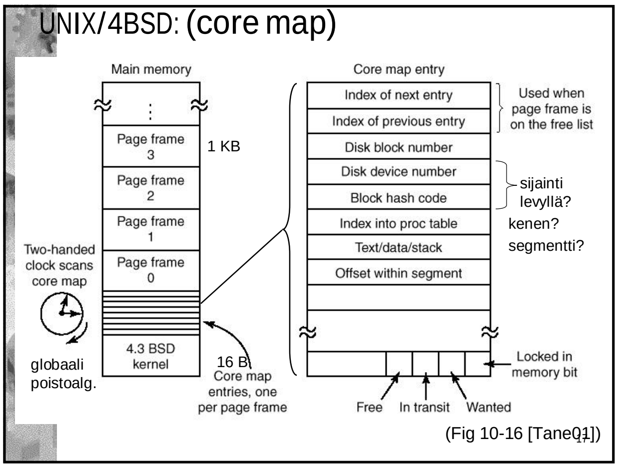


Swap area, VM backup store

(Fig 4-33 [Tane01])

Fixed allocation –
For the whole process
in advance

Dynamic allocation –
only for the pages that
are swapped out



UNIX/4BSD: (core map)

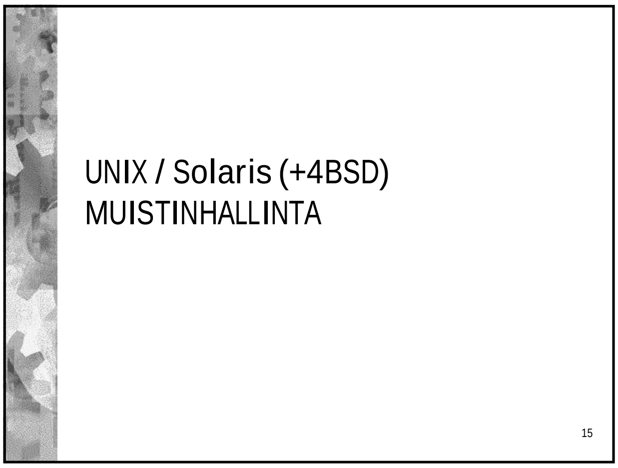
sijainti levyllä?

kenen?

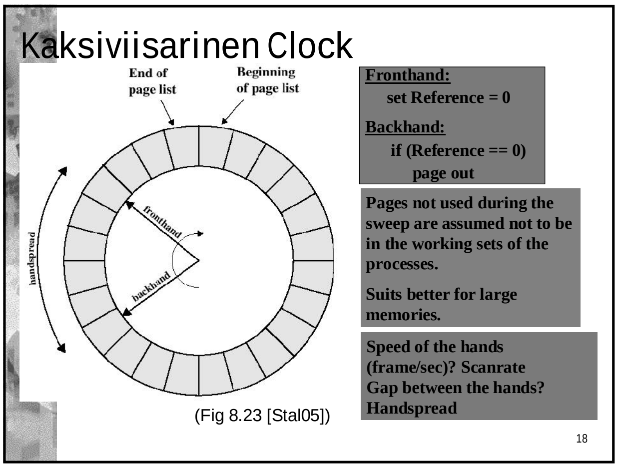
segmentti?

globaali poistoalg.

(Fig 10-16 [Tane01])



UNIX / Solaris (+4BSD)
MUISTINHALLINTA



Kaksiviisarinen Clock

(Fig 8.23 [Stal05])

Fronthand:
set Reference = 0

Backhand:
if (Reference == 0)
page out

Pages not used during the sweep are assumed not to be in the working sets of the processes.

Suits better for large memories.

Speed of the hands (frame/sec)? Scanrate
Gap between the hands? Handspread

UNIX/Solaris: Kernel memory allocation

- Based on paging
- Locking pages to memory
- Kernel allocates and deallocates all the time (large number of) small areas and buffers
    - For example: proc, vnode, file descriptor
- Kernel need to allocate and deallocate fragments of pages (not only full pages)
    - Dynamic partitioning for allocations within one page
    - => Lazy Buddy System
    - Delay combining until there are 'too many' fragments of certain size

Linux MUISTINHALLINTA

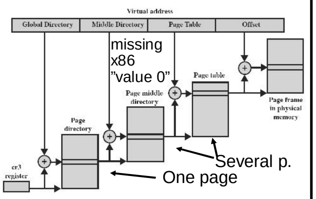
Ch 8.4 [Stal 05]

Linux: memory management

- 32-bittisissä architectures
    - 3 GB reserved for user processes
    - 1 GB for kernel (including the page tables)
        - at the beginning of the physical memory
    - Kernel mode allowed to make references to the full 4 GB
- Kernel's memory allocation based on slabs
    - Only for the kernel, efficient allocation of small memory areas, avoids allocating full pages

Linux: paging

- Architecture independent
    - Alpha: 64b addresses, full support for 3 levels,
        - Page size 8KB, offset 13 bits
    - x86: 32b address, only 2-levels,
        - Page size 4KB, offset 12 bits
- 3-level page table
    - page directory (PD), 1 page
    - page middle directory (PMD), multiple pages
    - page table (PT), multiple pages



(Fig 8.25 [Stal05])

- Page directory always in memory
    - This the page table address given to MMU at process switch
    - Other pages can be on disk

Linux: address translation

- Split address to 4 elements
    - index to page directory (PD-offset)
    - index to page middle directory (PMD-offset)
    - index to page table (PT-offset)
    - offset

```
PMD_base  = PD_base   + PD[PD_offset]
PT_base   = PMD_base  + PMD[PMD_offset]
Page_base = PT_base   + PT[PT_offset]
fyys.os   = Page-base + offset
```

- X86-trick
    - Page middle directory (PMD) reduced to one item, which compiler optimizes away.
    - MMU assumes that the page directory refers directly to the page table (PT)
    - Suitable to all architectures that support only two-level paging

Linux: placement (allocation)

- Reserves a consecutive area (region) for consecutive pages
    - More efficient fetching and storing with disks
    - Optimize the disk utilisation, with the cost of memory allocation
- Buddy System: 1, 2, 4, 8, 16 or 32 page frames
    - Allocates pages in large groups, increases internal fragmentation
    - Implementation: table with list of different sizes unallocated page regions

Linux: replacement

- Globaali Clock using M-bit + sort of LRU
  - Counter of dynamically allocated page frames
- 8 bit counter of age   vrt. U-bitti
  - MMU increases the counter at each page reference
  - Background process (kswapd) reduces the counter each second
    - if too few page frames free, deallocated unused frames
- Uses pagebuffer
  - To store deallocated pages for a short duration

Slap allocation

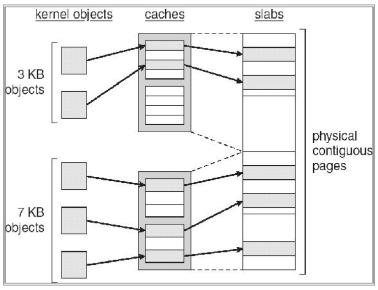
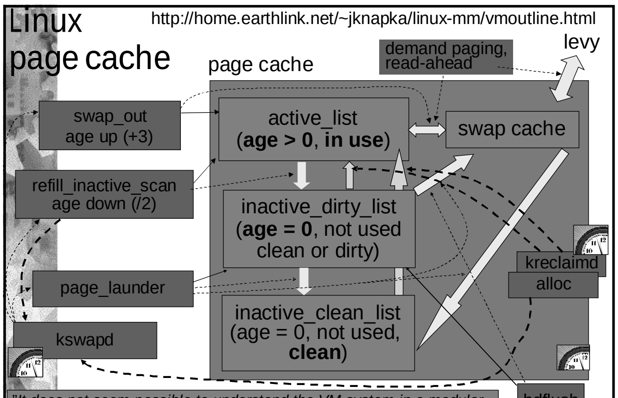


Fig 9.27 – Silberschatz, Galvin & Gagne: Operating system concepts with Java

Linux page cache

http://home.earthlink.net/~jknapka/linux-mm/vmoutline.html


levy

page cache

demand paging, read-ahead

swap_out
age up (+3)

refill_inactive_scan
age down (/2)

page_launder

kswapd

active_list
(**age > 0**, **in use**)

swap cache

inactive_dirty_list
(**age = 0**, not used clean or dirty)

inactive_clean_list
(age = 0, not used, **clean**)

kreclaimd

alloc

bdflush

”*It does not seem possible to understand the VM system in a modular way. The interfaces between, say, the zone allocator and the swap policy are many and varied… What a nightmare*” (Joe Knapka)

Windows 2000
MUISTINHALLINTA

Ch 8.5 [Stal 05]
Ch 11.5 [Tane 01]

Linux: kernel memory allocation

- Kernel memory locked to the memory
- Dynamic allocation based on pages
- Dynamically loadable modules fully to the kernel area
  - buddy system on the pages   kmalloc()
- Additional need for small, short term memory allocations -> use slab
  - One page ’cut’ to smaller areas (slabs)
  - buddy system within each page
    - x86: 32, 64, 128, 252, 508, 2040, 4080 tavua (page size 4KB)

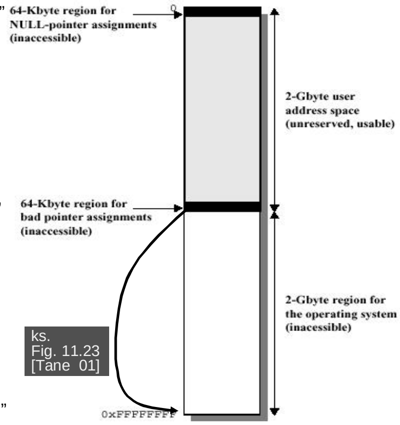
W2K

- **32-bit addresses**
  => 4 GB virt. os.
- **page size 4K - 64K**
  Pentium: 4KB
  Alpha: 8K

”0x0000????:”

”-1”

”0xFFFF????:”



(Fig 8.26 [Stal05])

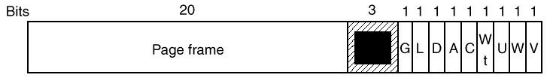
ks.
Fig. 11.23
[Tane 01]

W2K: Paging

- No segmentation
- Variable resident set size per process
  - Start with a fixed set of frames
  - If large number of free frames, process can get more frames
    - A greedy one is not allowed to allocate last 512 frames
  - If the free memory reduces, the resident set of processes can be decreased
- Demand fetch (no prefetching)
- Disk I/O using larger blocks
  - 1-8 pages at each time

W2K: paging

(Fig 11.26 [Tane01])



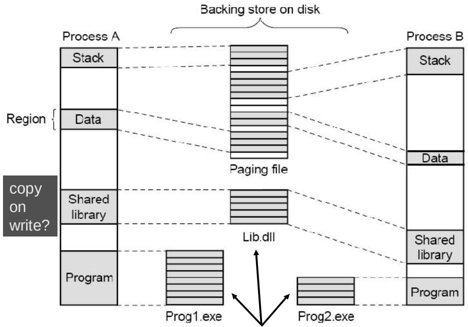
G: Page is global to all processes
L: Large (4-MB) page
D: Page is dirty
A: Page has been accessed
C: Caching enabled/disabled

Wt: Write through (no caching)
U: Page is accessible in user mode
W: Writing to the page permitted
V: Valid page table entry

Pentium

Fig 11.24 [Tane01]
(seur. kalvo)

W2K address space

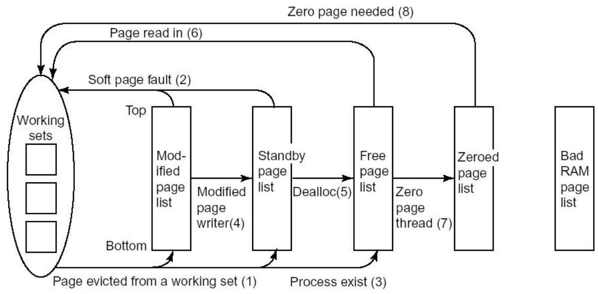


[Tane01]
Fig. 11-24. Mapped regions with their shadow pages on disk. The *lib.dll* file is mapped into two address spaces at the same time.

W2K: replacement

- Balance set manager -daemon
  - Each second 1 sec check if enough free frames
- Working set manager
  - Running when needed
  - Dynamic working set size
  - Released page frames of processes
  - Starts with large idle processes
- Swapper-daemon
  - every 4 sec: search for processes, whose threads (all of them) have been passive for long duration
- Parts of the OS and buffer pool locked to memory
- Caching of released pages

W2K: page frames



(Fig 11.27 [Tane01])

W2K

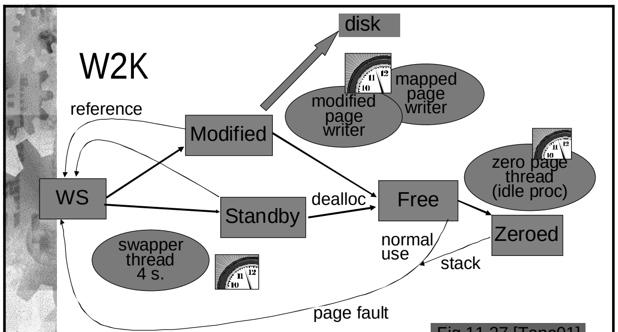


Fig 11.27 [Tane01]

Fig 11.28 [Tane01]

> ”*The code is so complex that the designers loathe to touch parts of it for fear of breaking something somewhere*”
> Andrew Tanenbaum [Tane01, p. 823]