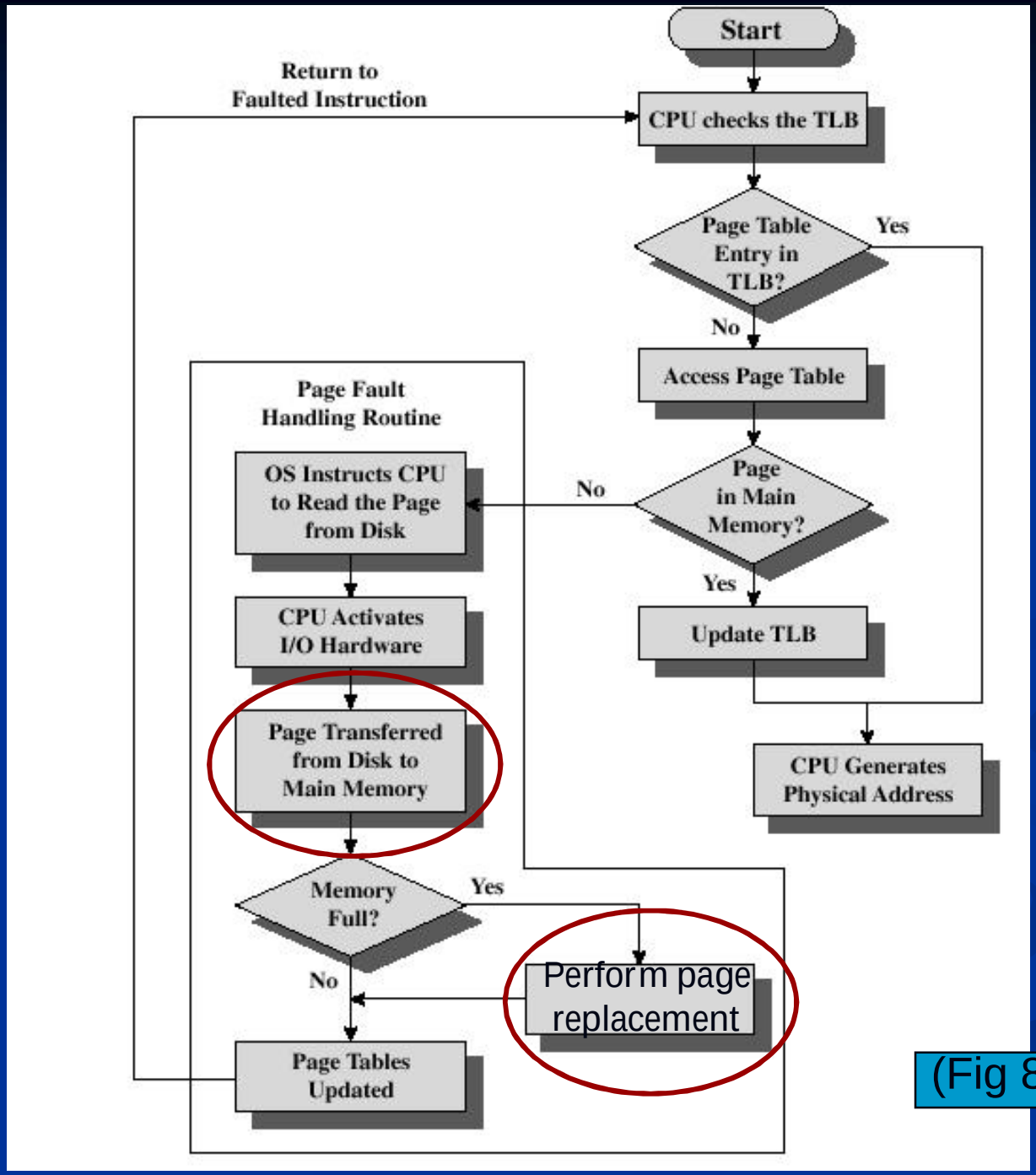
# Virtual memory Operations and policies

Chapters 3.4. – 3.7

# Policies and methods

- Fetch policy *(Noutopolitiikka)*
  - When to load page to memory?
- Placement policy *(Sijoituspolitiikka )*
  - Where to place the new page?
- Replacement policy *(Korvaus/poistopolitiikka)*
  - Which page to be evicted and replaced
- cleaning policy *(Levylle kirjoitus –politiikka)*
  - When to evict a modified page?
- Multiprogramming, load control *(Moniajoaste)*
  - How many processes in the system at the same time?
  - How much memory, how many pages per process?
- Working set *(Käyttöjoukko)*
  - How many page frames allocated for one process? (resident set)
  - Which areas have been referenced recently?




(Fig 8.8 [Stal05])

# Page fault *(Sivun puutos)*

- If the requested page is not in memory, MMU causes interrupt
- OS process the interrupt and notice a page fault
  - Move the process to blocked state
  - Allocate page frame for the new page
  - Start page load from disk using controller
  - Switch another process for execution
- After the driver interrupt
  - OS notices the termination of page transfer
  - Move process to ready state
  - Continue the process now or later (scheduling decision)

# Locking pages

- To avoid page fault, page can be locked to memory
  - Kernel pages
  - Key data structures of OS
  - I/O buffers  (at least during the transfer)
  - Process pages (at least in real time systems)
- How?
  - Page frame table? has a lock bit on the frame
    - Per frame
  - Or page table entry has the lock bit
    - Per process

# Page replacement

- When?
  - Page fault
  - Memory too full, no free frames (usually some kept free!)
  - Not enough free unallocated frames (limit value)
- Which page to replace?
  - One, that is not needed in the (near) future
    - Predict based on the past behaviour
    - Locality principle helps: no more references to the page, process passed that phase
    - Some time mistakes happen

See Fig 8.1 [Stal05]

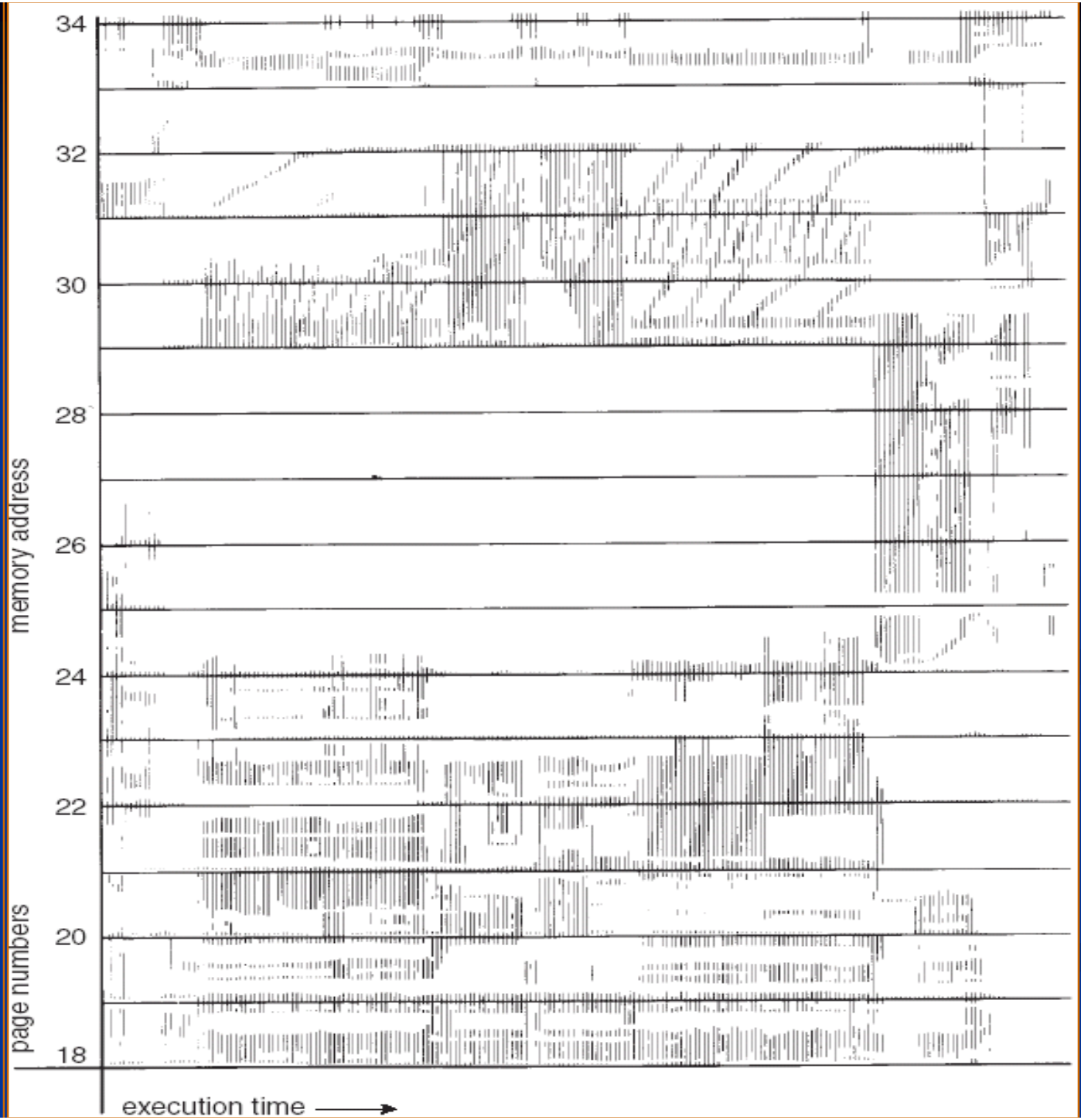



Fig 8.1 [Sta05]

Fig. 9.19 [SGG07]

# 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

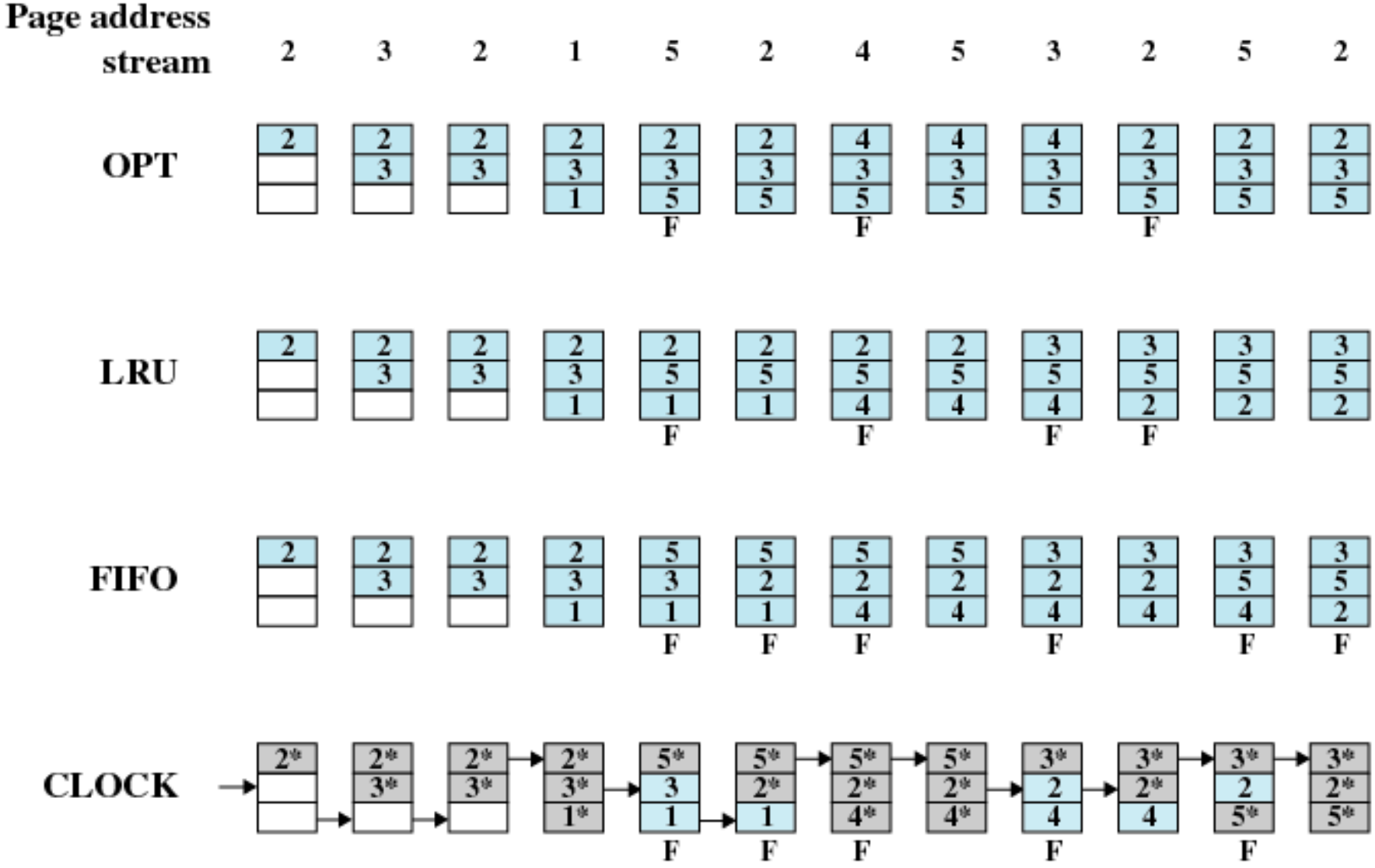



**Figure 8.15 Behavior of Four Page-Replacement Algorithms**

# Optimal Page Replacement Algorithm

- Replace page needed at the farthest point in future
  - Optimal but unrealizable
  - Clairvoyant (not possible!)
  - can be found afterwards from trace
- Used as a reference point for other algorithms
  - Nothing is better that optimal!
- Estimate by …
  - logging page use on previous runs of process
  - although this is impractical

# Least Recently Used (LRU)

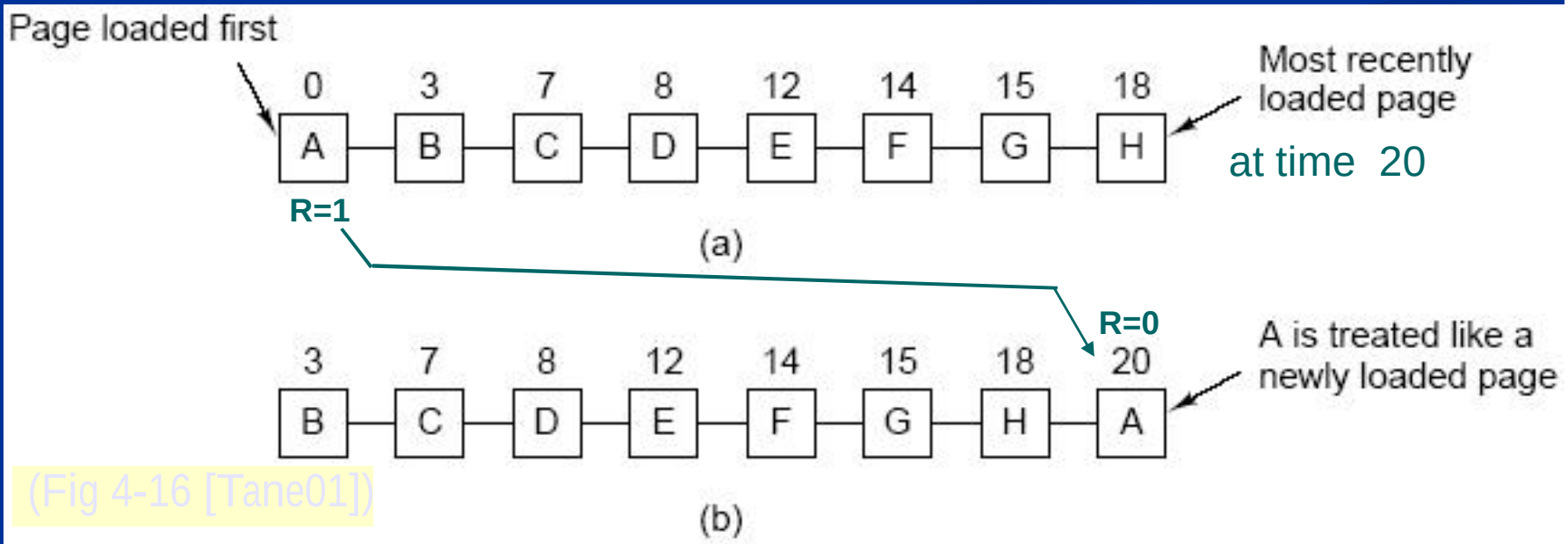
- Recently used pages assumed to be used again soon
- Evict page that has been unused for longest time
  - How to find?
- Heavy bookkeeping
  - Update each reference time to the pages
  - Maintain pages in the referenced order (linked list)
- Infeasible if followed strict

# FIFO (First-In First-Out) Page Replacement Algorithm

- Replace the page that has been in the memory longest time
- Page at beginning of list replaced
- Maintain a linked list of all pages
  - In order they came into memory
  - Alternatively: store the load time on each page
- Disadvantage
  - Page in memory the longest may be often used and should not be evicted

# Second Chance

- Pages sorted in FIFO order
- Use reference bit R and modified bit M
- If the page to be evicted has been recently used (R=1) give it second chance; move to end of queue and set R=0
  - Will be evicted, if all other pages are also given second chance

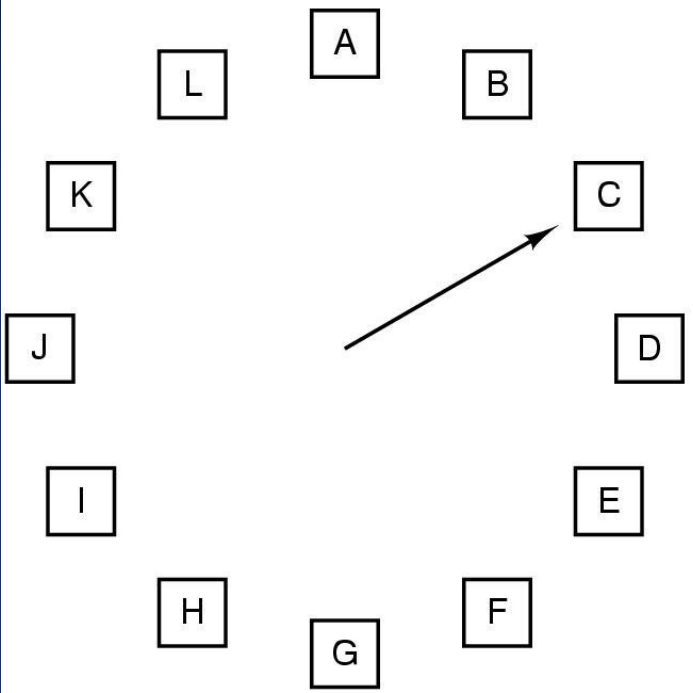



(Fig 4-16 [Tane01])

# Not Recently Used Page Replacement Algorithm

- Each page has Reference bit, Modified bit
  - bits are set when page is referenced, modified
  - R cleared periodically, M cleared at disk writes
- 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

# The Clock Page Replacement Alg.




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

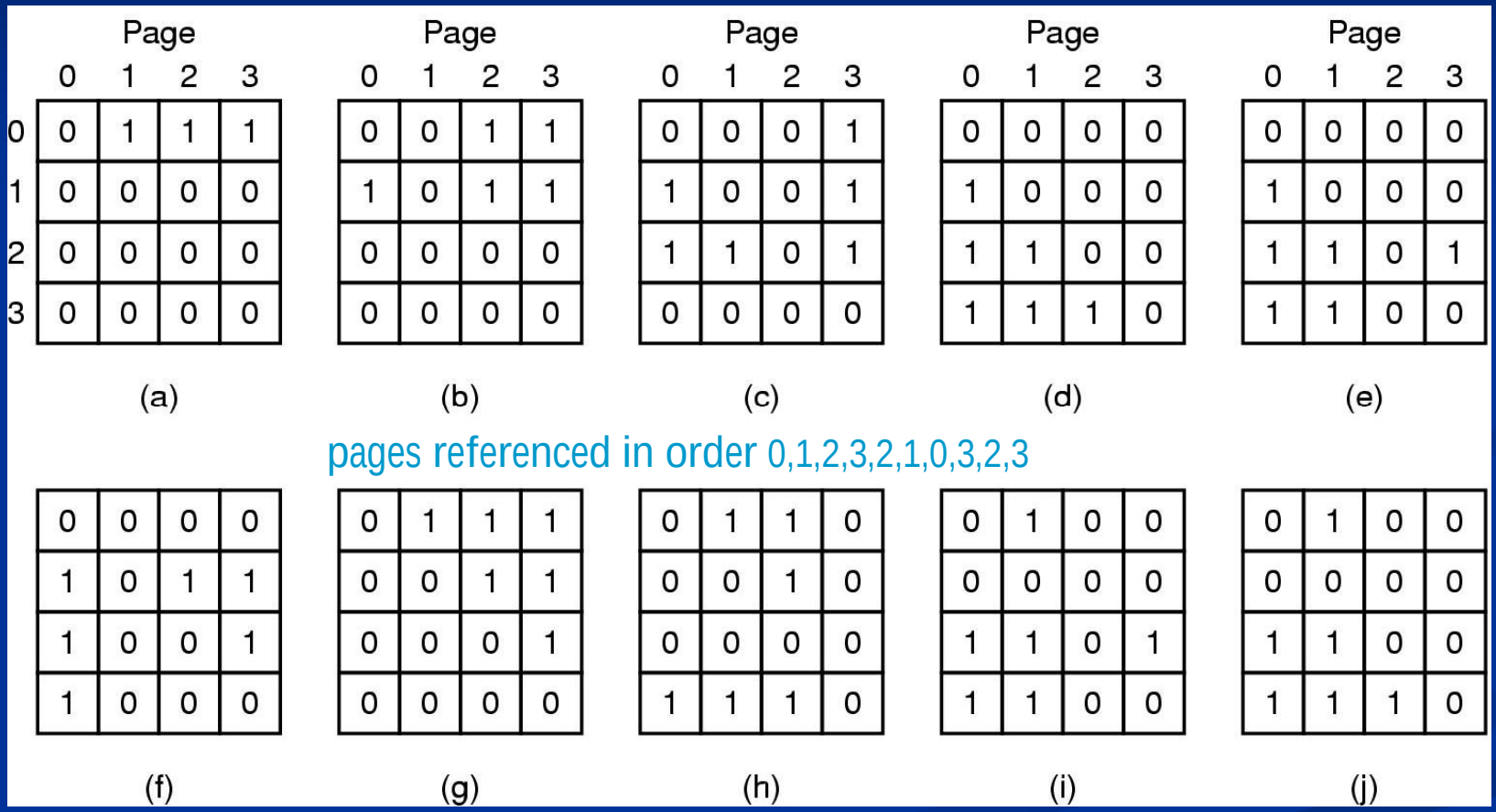
R = 1: Clear R and advance hand

- Go trough all pages in circular fashion
- Try to locate unused page with the NRU classification, used page gets second chance

# Least Recently Used (LRU)

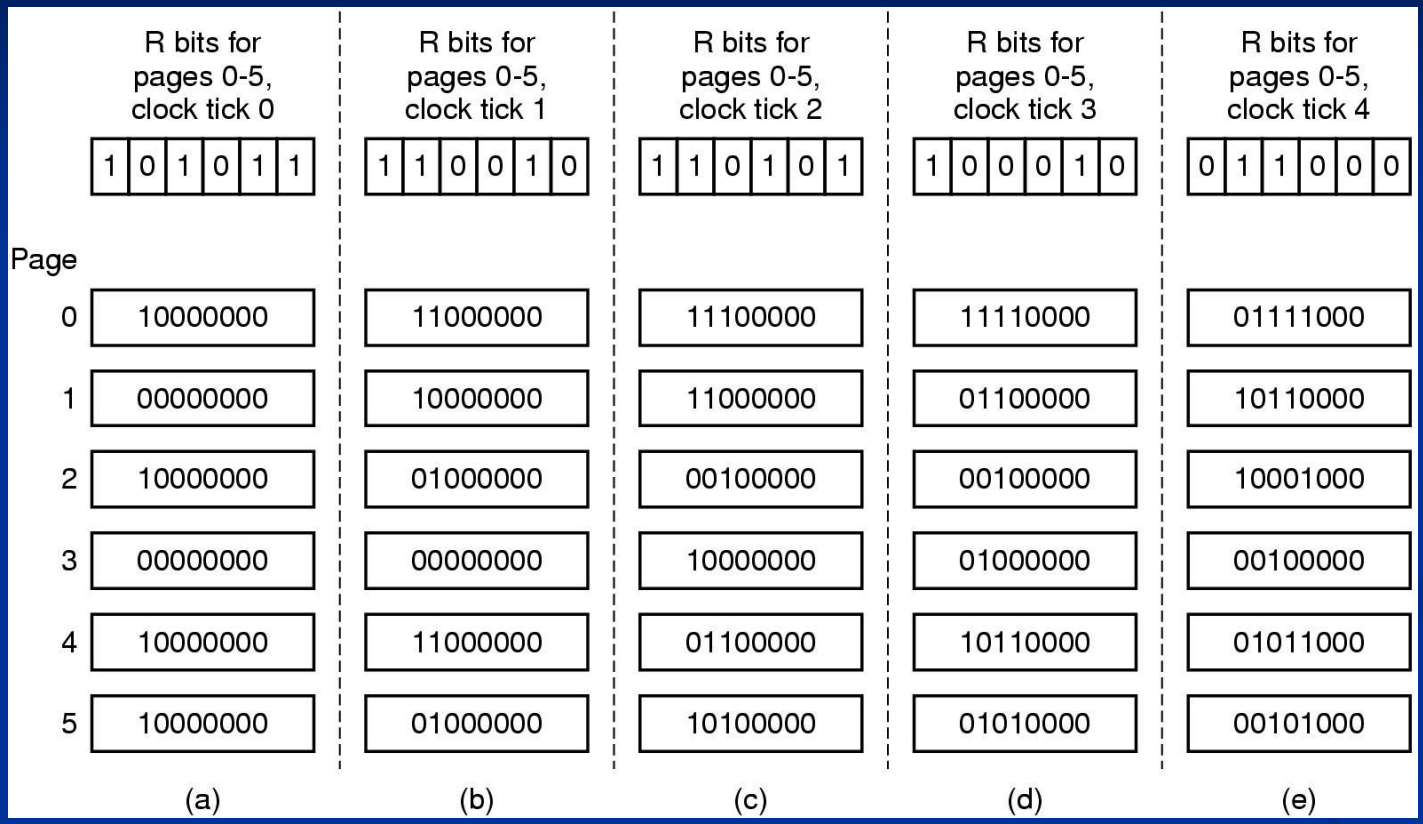
- Strict alternatives:
  - Keep a linked list of pages in reference order, update this list on every memory reference !!
  - Keep counter in each page table entry
    - Use special hardware to increment the counter
    - choose page with lowest value counter
    - periodically zero the counter
- Simulating algorithms: NFU, Aging
  - NFU – Not Frequently used
  - Aging
    - In the adding: shift counter right, add R bit to leftmost
    - Forgets the history

# LRU hardware using matrix




- On reference: set row all 1s and column all 0s
- At any time the row with lowest binary value is LFU page

# Aging algorithm simulates LRU



| 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 |
| | (a) | (b) | (c) | (d) | (e) |

- On each clock time process the counters:
- Shift right one bit
- Set left-most bit to one on pages referenced after previous tick

# Working set model

# Resident Set vs. Working Set

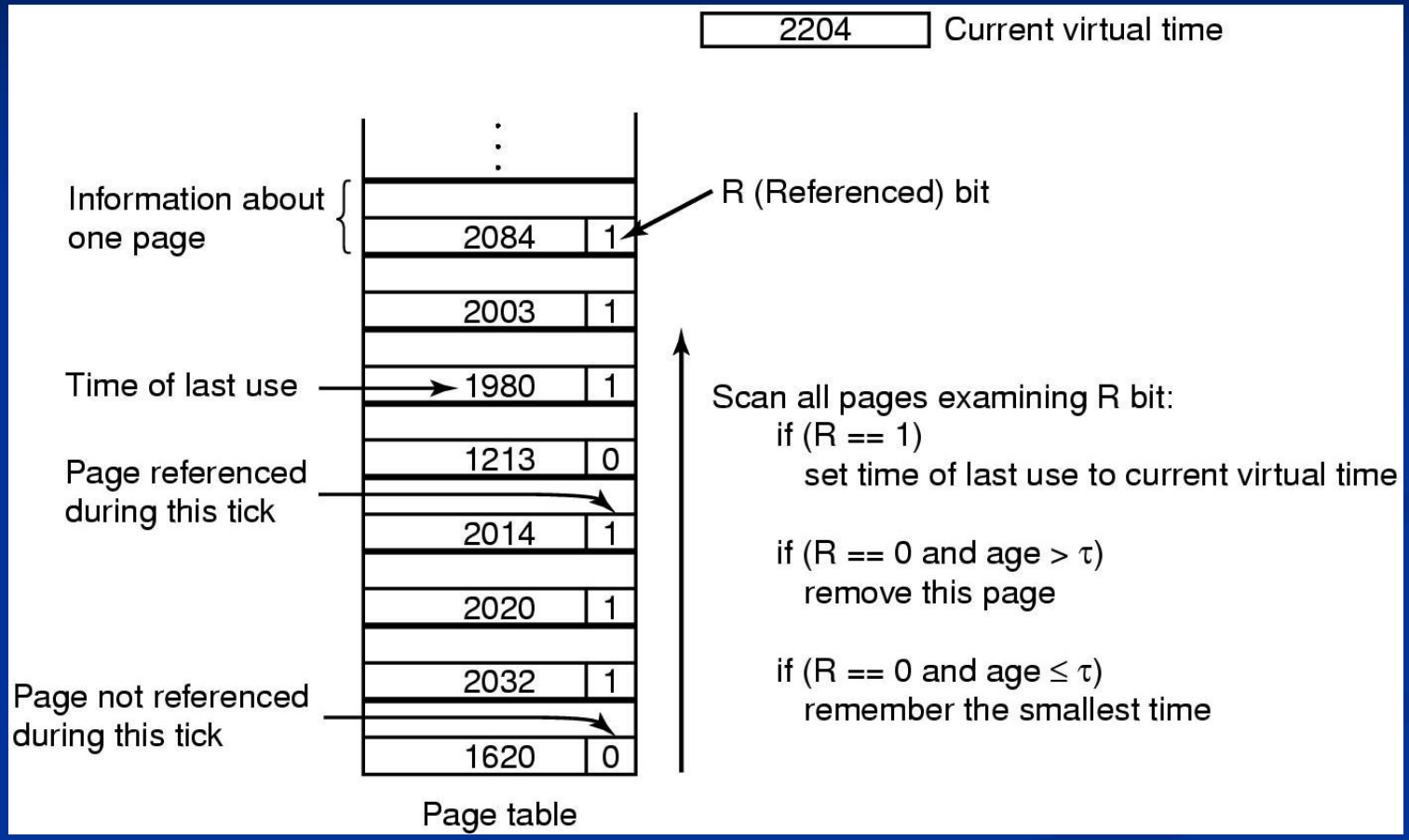
- Working set = Set of pages the process is currently using
  - *w(k,t)* is the size of the working set at time, *t*
- Resident set = Page frames currently allocated for process
- Number of allocated page frames *(sivukehysten lkm)*
  - Too small
    - more processes in the memory, more page faults
      - Too many? Trashing? *(ruuhkautuminen)*
  - Too large
    - occupy space that beneficial for other processes
    - CPU utilisation *(käyttöaste)* too low
    - ”wasted space”

# Working Set Strategy

- Pages used by the most recent k memory references (window size)
- Common approximation
  - Pages used during the recent t msec of current virtual time, time that the process has been actually executing
- Pages not in the working set, can be evicted
- For page replacement:
  - Hardware set the R and M bits
  - Each page entry has ’time of last use’

$$W(t, \Delta)$$

# The Working Set Algorithm

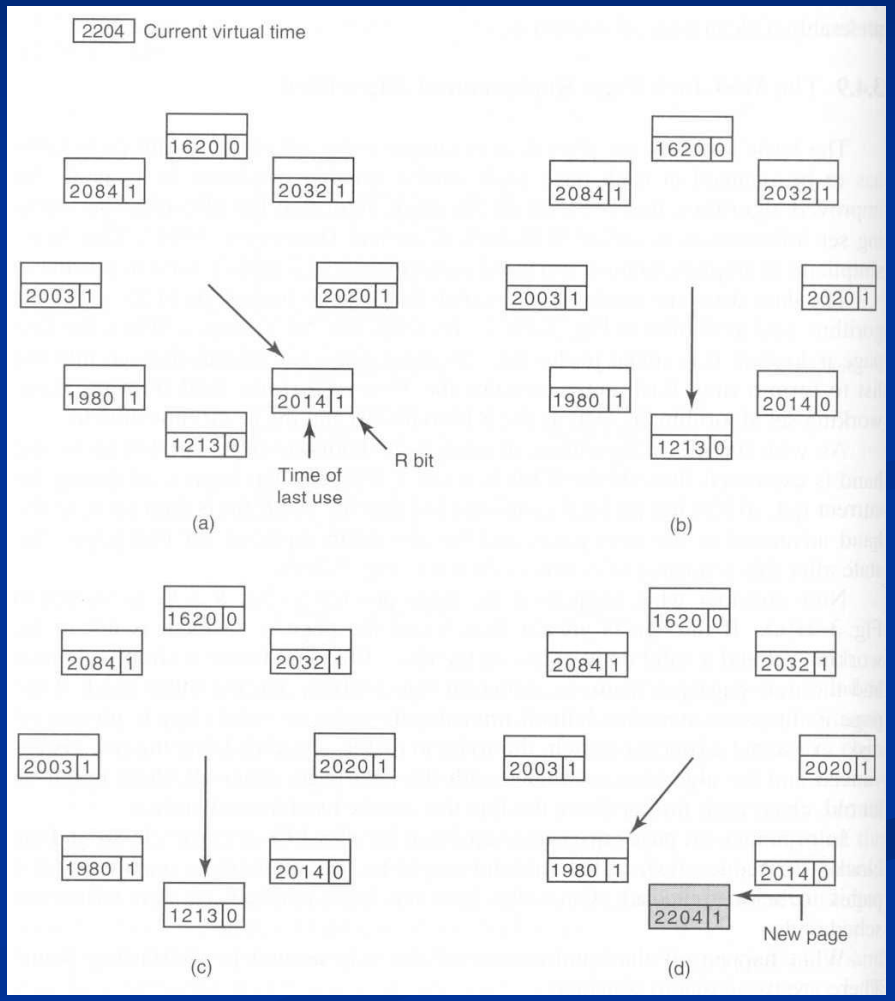



In case all pages in working set,

evicts the oldest unreferenced and/or unmodified page

# The WSClock Page Replacement Algorithm

- As clock, but only residence set
- Evict unmodified page not in working set and
- Schedule for disk write modified page not in WS
- If no candidate page found during one round, wait for writes or evict any clean (=unmodified) WS page

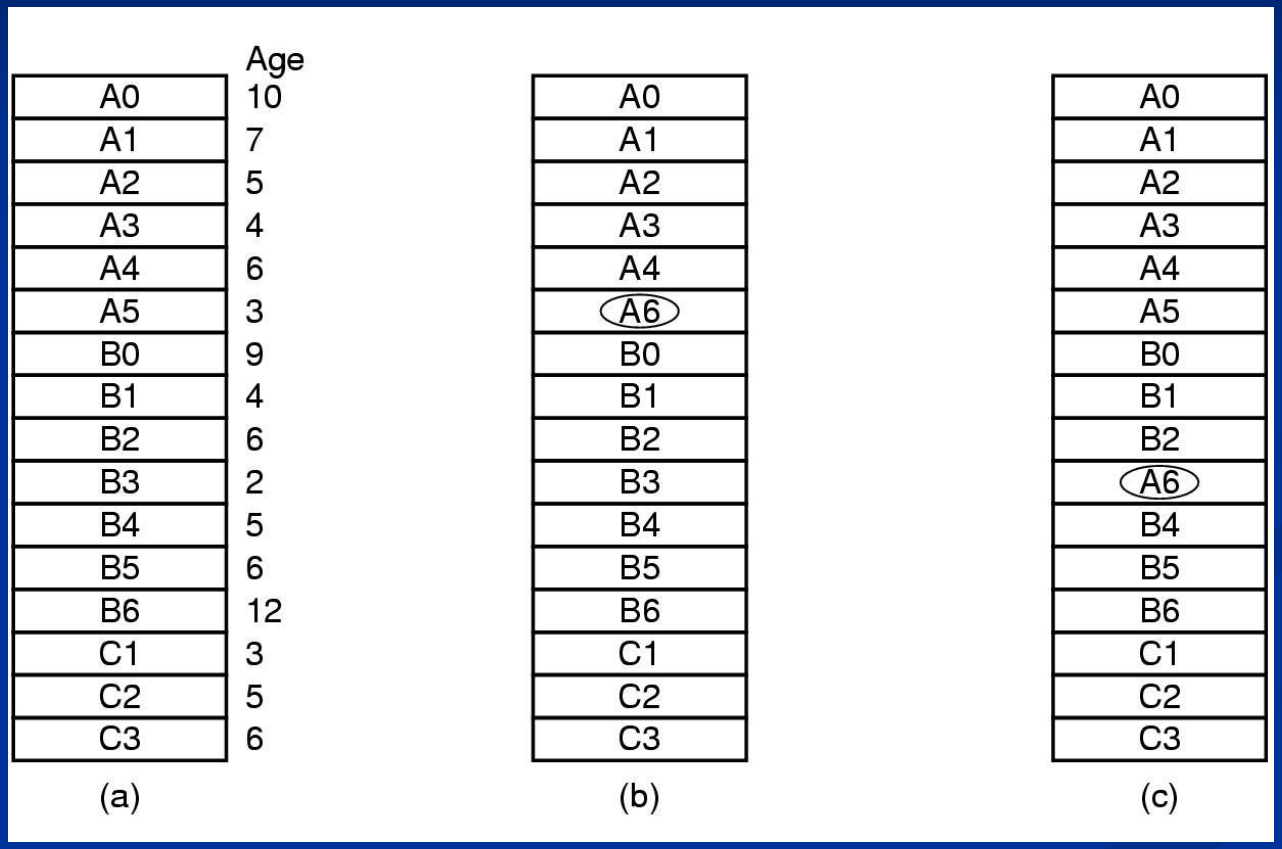


# Review of Page Replacement Algorithms

| 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 |

# Design Issues

# Design Issues for Paging Systems:
## Local versus Global Allocation Policies



| | Age |
|---|---|
| A0 | 10 |
| A1 | 7 |
| A2 | 5 |
| A3 | 4 |
| A4 | 6 |
| A5 | 3 |
| B0 | 9 |
| B1 | 4 |
| B2 | 6 |
| B3 | 2 |
| B4 | 5 |
| B5 | 6 |
| B6 | 12 |
| C1 | 3 |
| C2 | 5 |
| C3 | 6 |

(a)

| |
|---|
| A0 |
| A1 |
| A2 |
| A3 |
| A4 |
| A6 |
| B0 |
| B1 |
| B2 |
| B3 |
| B4 |
| B5 |
| B6 |
| C1 |
| C2 |
| C3 |

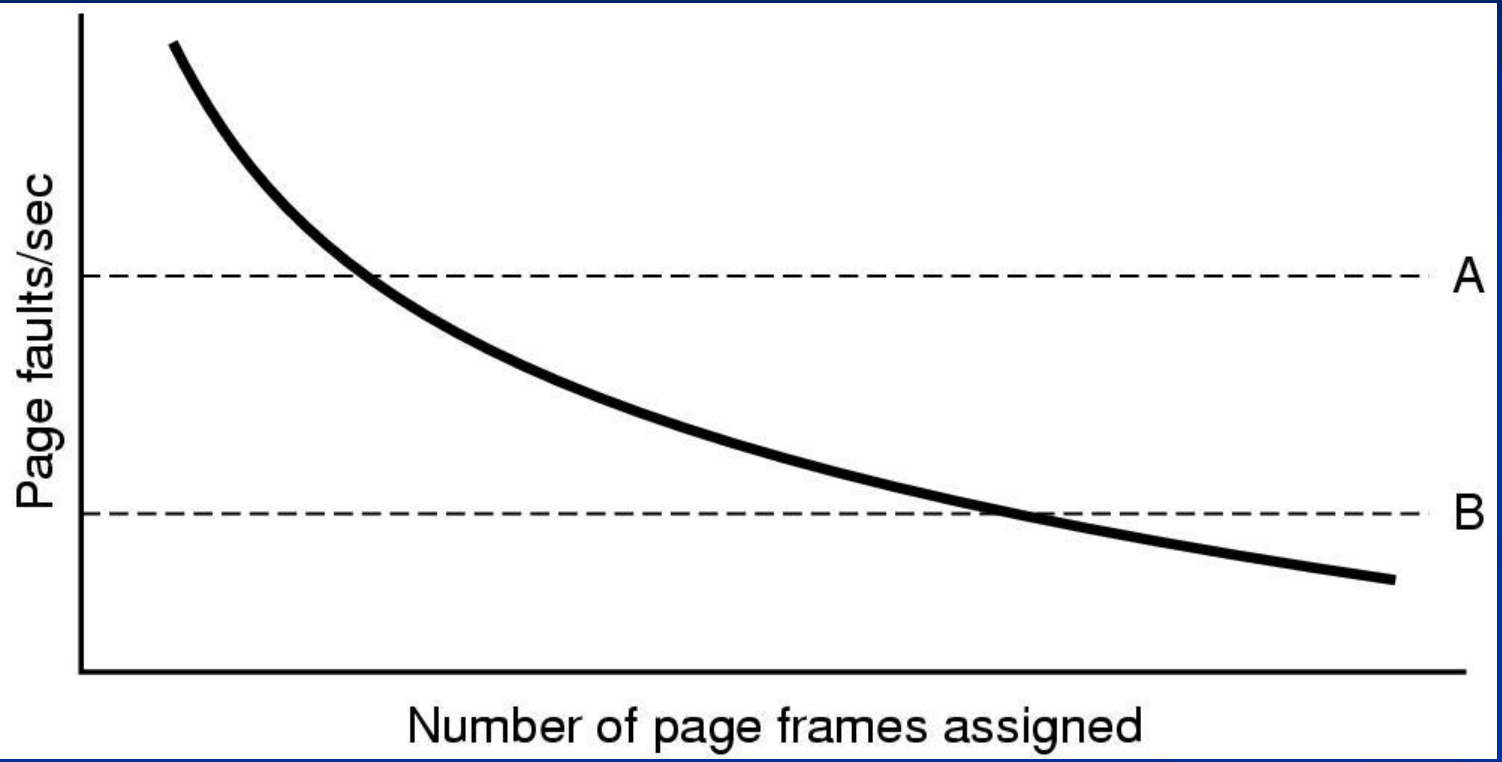
(b)

| |
|---|
| A0 |
| A1 |
| A2 |
| A3 |
| A4 |
| A5 |
| B0 |
| B1 |
| B2 |
| A6 |
| B4 |
| B5 |
| B6 |
| C1 |
| C2 |
| C3 |

(c)

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

# Page Fault Rate




- Page fault rate as a function of the number of page frames assigned
- Page Fault Frequency algorithm (PFF):
  - Keep page fault rate between A and B for each process
  - Increase residence set size at A and reduce at B

# Allocation and replacement

| | Local Replacement | Global Replacement |
|---|---|---|
| **Fixed Allocation** | •Number of frames allocated to process is fixed.<br>•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.<br>•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]

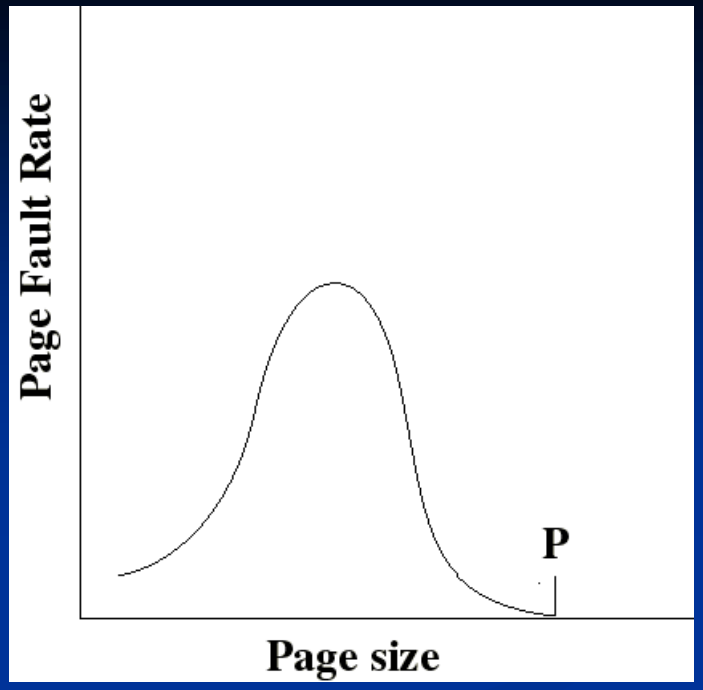
# Load Control

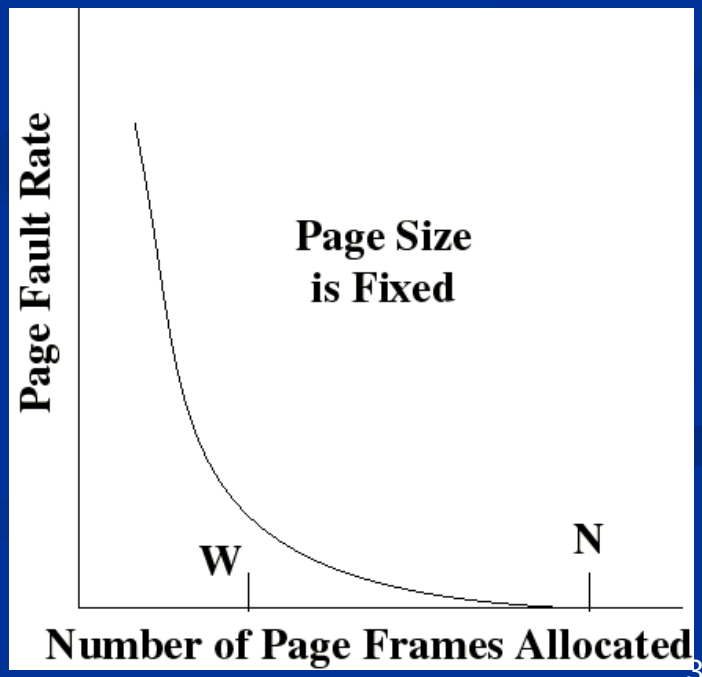
- Despite good designs, system may still thrash
- When Page Fault Frequency (PFF) algorithm indicates
  - some processes need more memory
  - but no processes need less
- Solution :
  Reduce number of processes competing for memory
  - swap one or more to disk, divide up pages they held
  - reconsider degree of multiprogramming

# 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

- Too small working set size -> larger page fault rate
- Large working set size -> nearly all pages in the memory



# 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]

## Table 8.2 Example Page Sizes

| Computer | Page Size |
|---|---|
| Atlas | 512 48-bit words |
| Honeywell-Multics | 1024 36-bit word |
| IBM 370/XA and 370/ESA | 4 Kbytes |
| VAX family | 512 bytes |
| IBM AS/400 | 512 bytes |
| DEC Alpha | 8 Kbytes |
| MIPS | 4 kbyes to 16 Mbytes |
| UltraSPARC | 8 Kbytes to 4 Mbytes |
| Pentium | 4 Kbytes or 4 Mbytes |
| PowerPc | 4 Kbytes |
| Itanium | 4 Kbytes to 256 Mbytes |

# Page Size

- Overhead due to page table and internal fragmentation

- Where

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

page table space

internal fragmentation

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

Optimized when

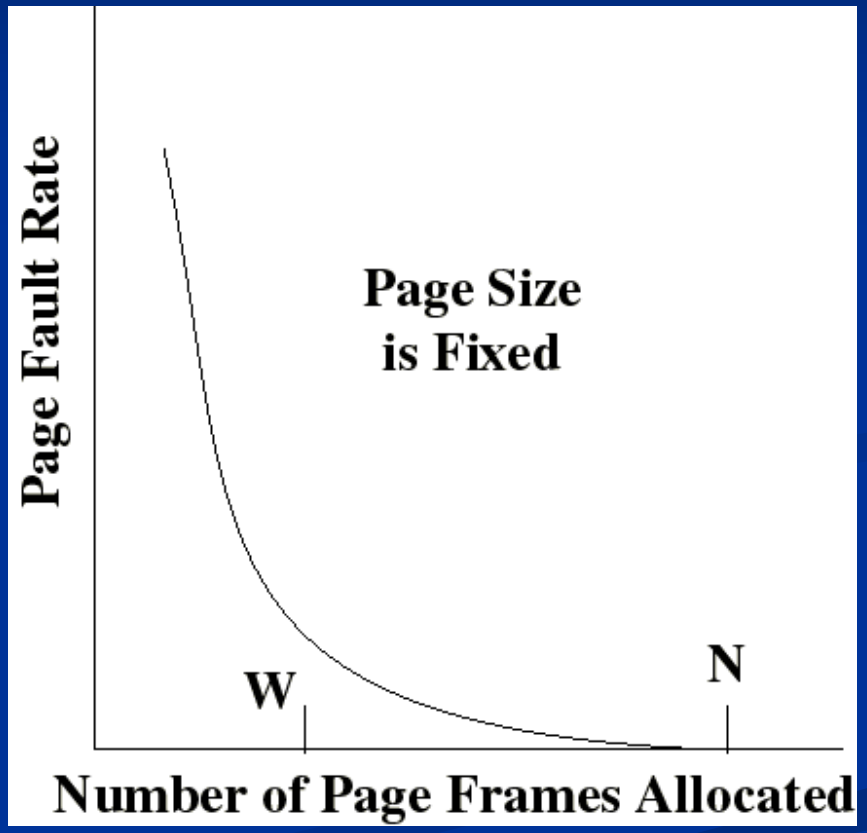
$$p = \sqrt{2se}$$

s = 1 MB e = 8B → $p_{opt}$ = 4 KB

s = 100 MB e = 8B → $p_{opt}$ = 40 KB

# 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




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

# Cleaning Policy

- Need for a background process, paging daemon
  - periodically inspects state of memory
- When too few frames are free
  - selects pages to evict using a replacement algorithm
- It can use same circular list (clock)
  - as regular page replacement algorithm but with different pointer

# When to clean the page? (write to disk)

- Only when changed
- Demand cleaning *(tarvetalletus)*
  - Write to disk only when the page frame is needed
  - Long delay in freeing, crash?
- Precleaning *(ennaltatalletus)*
  - Write to disk periodically in bigger groups
- Cleaning the freed page frame
  - Zeroing might be wasted work
  - What if the page is needed soon again?
    - unmodified free page might be reused
- What if the disk utilization is low (no work on disk)?

# Page buffering

- Maintain certain number of free page frames
- ~ page frame cache (of freed pages frames)
  - Fast recovery from page frame buffer, if the page on freed frame is referenced
- Page marked to be cleaned
  - Add to free page frame list, if not modified
  - Add to write-to-disk list, if modified
- Page still on the same allocated page frame
  - Remove the reference from page table
- Allocate page frames from the free frames list using FIFO order