CSCI-GA.2250-001

Operating Systems

Lecture 6: Memory Management II

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What is the problem?

- Not enough memory
  - Have enough memory is not possible with current technology
    - How do you determine "enough"?
- Processor does not execute anything that is not in the memory.

But We Can See That …

- All memory references are logical addresses that are dynamically translated into physical addresses at run time
- A process may be broken up into a number of pieces that don't need to be contiguously located in main memory during execution.

So:

It is not necessary that all of the pieces of a process be in main memory during execution.

Scientific Definition of Virtual Memory

Mapping from logical (virtual) address space to physical address space

The Story

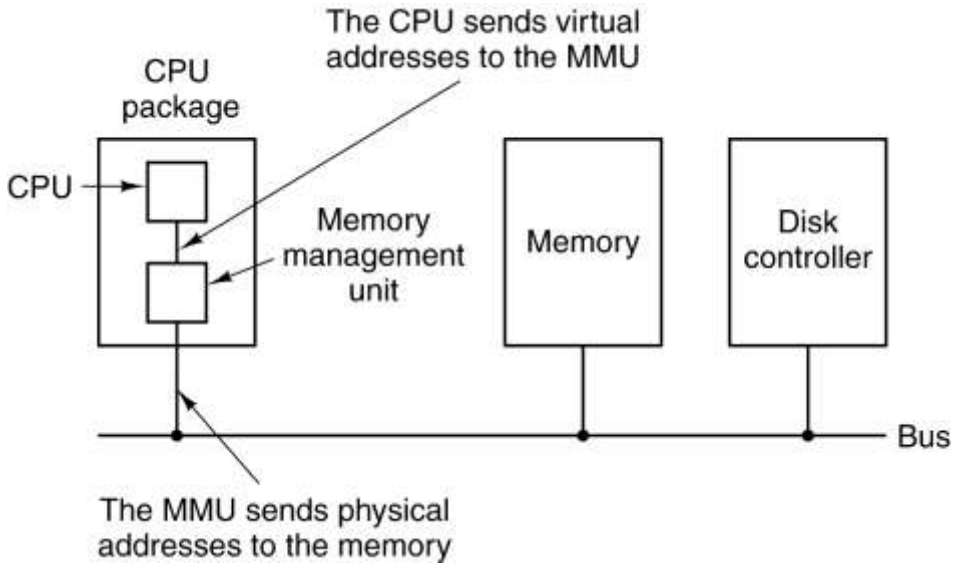
1. Operating system brings into main memory a few pieces of the program.
2. An interrupt is generated when an address is needed that is not in main memory.
3. Operating system places the process in a blocking state.
4. Operating system issues a disk I/O Read request.
5. Another process is dispatched to run while the disk I/O takes place.
6. An interrupt is issued when disk I/O is complete, which causes the operating system to place the affected process in the Ready state
7. Piece of process that contains the logical address is brought into main memory.

The Story

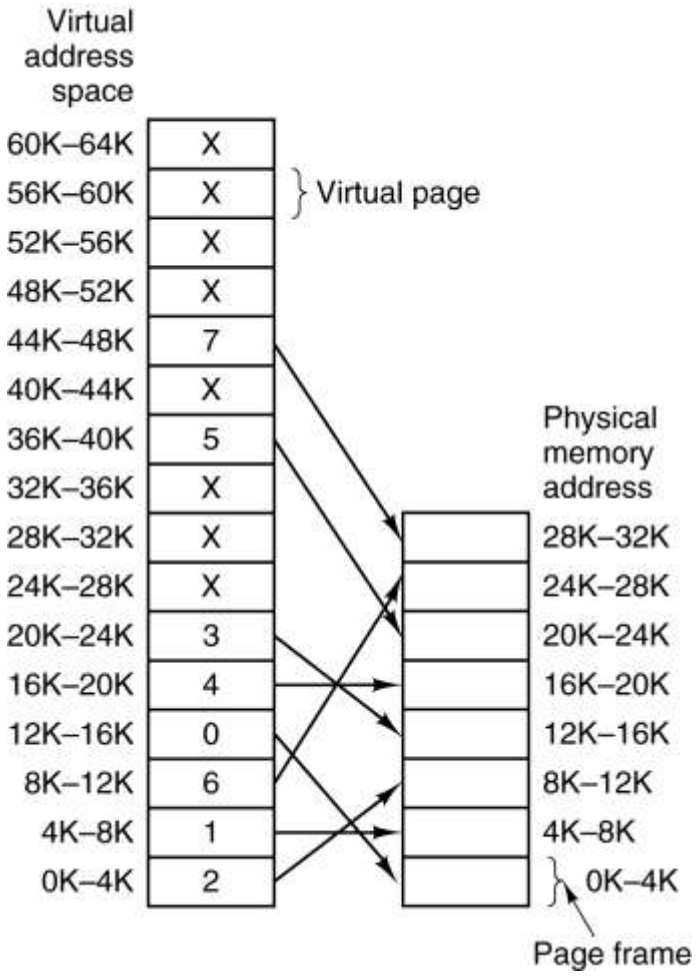
1. Operating system brings into main memory a few pieces of the program. What do you mean by "pieces"?
2. An interrupt is generated when an address is needed that is not in main memory. How do you know it isn't in memory?
3. Operating system places the process in a blocking state.
4. Operating system issues a disk I/O Read request. Why?
5. Another process is dispatched to run while the disk I/O takes place.
6. An interrupt is issued when disk I/O is complete, which causes the operating system to place the affected process in the Ready state
7. Piece of process that contains the logical address is brought into main memory. What if memory is full?

Virtual Memory

- Each program has its own address space
- This address space is divided into pages
- Pages are mapped into physical memory

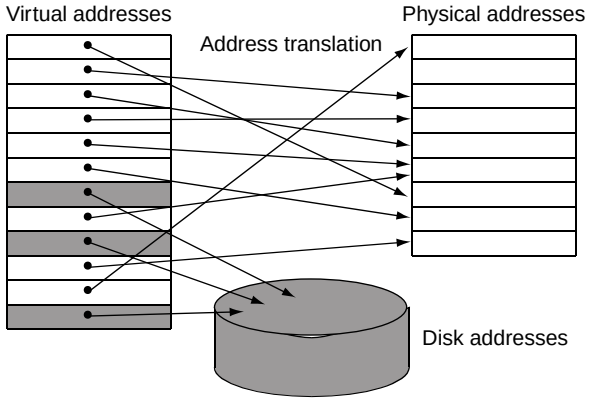


Virtual Memory

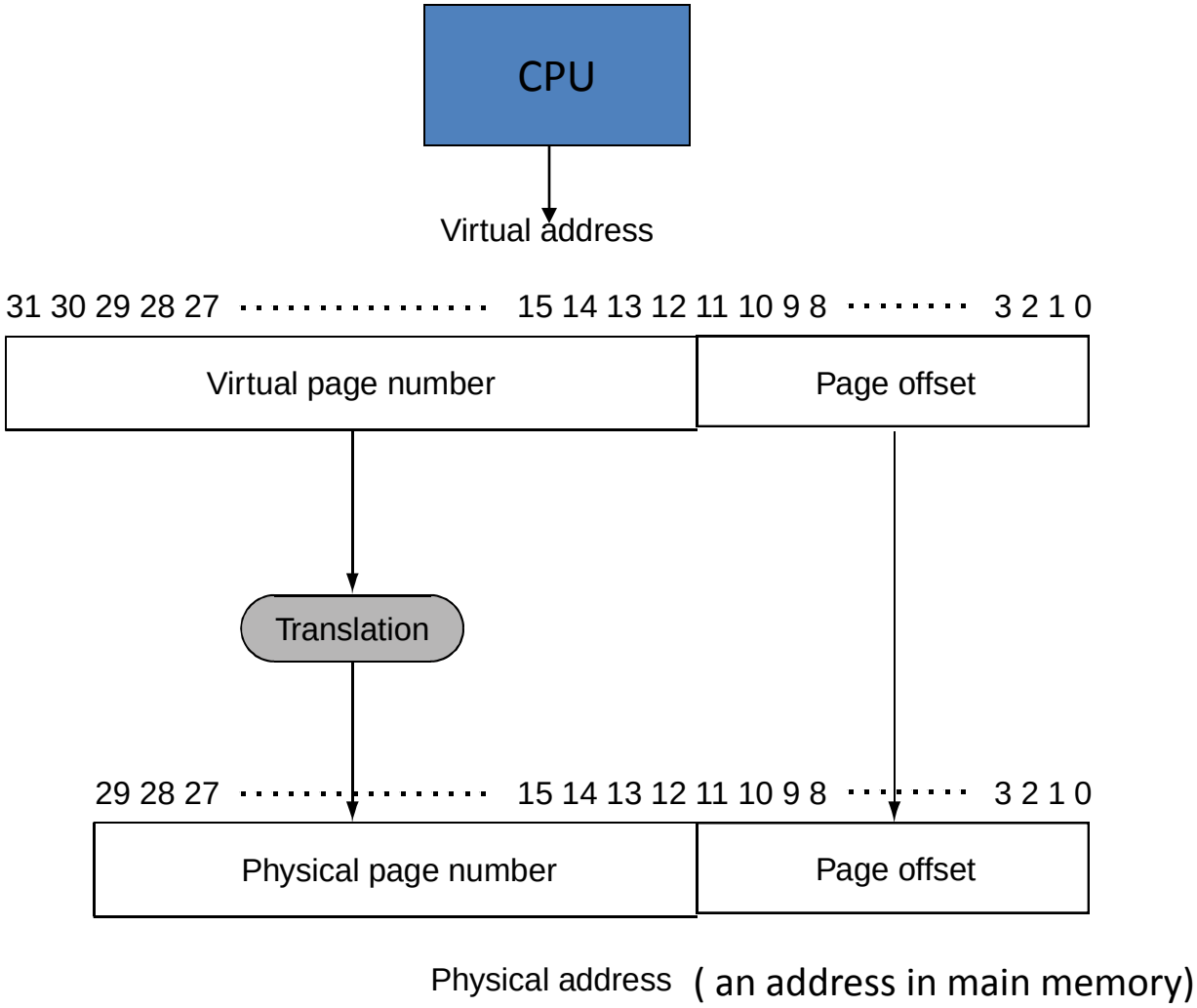


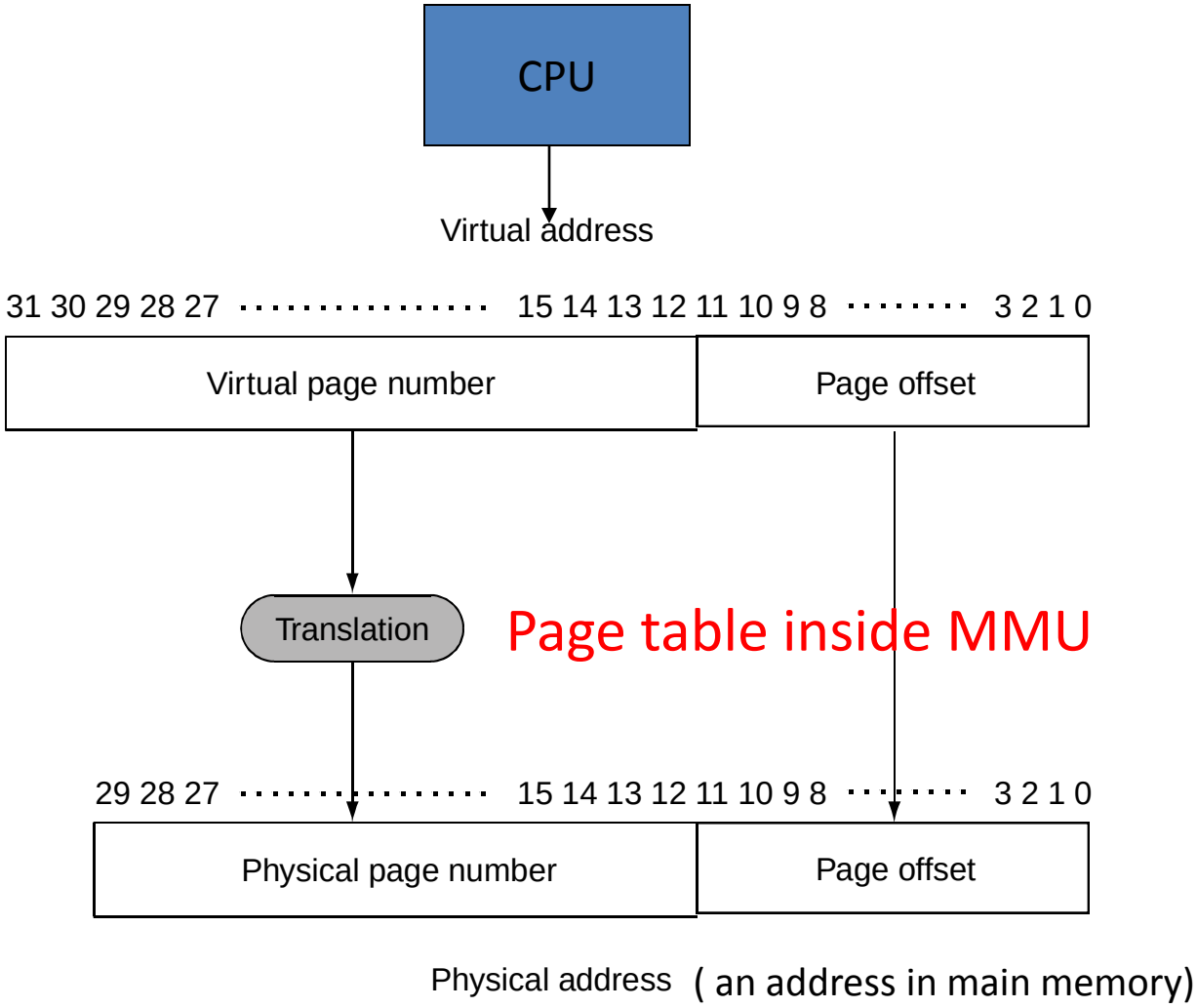
Virtual Memory

- Main memory can act as a cache for the secondary storage (disk)



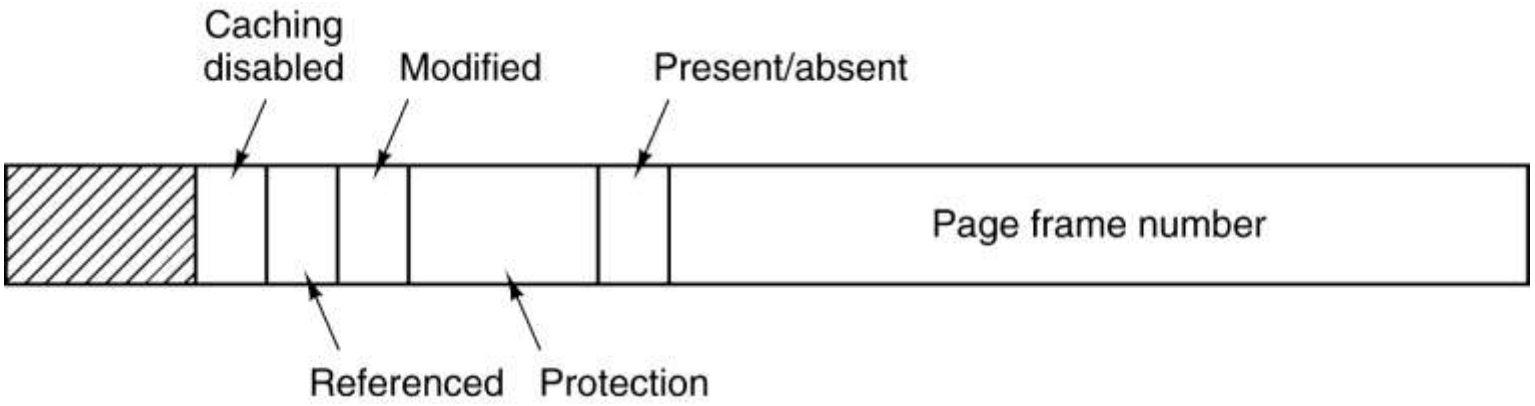
- Advantages:
  - illusion of having more physical memory
  - program relocation
  - protection


CPU
Virtual address
31 30 29 28 27 ..... 15 14 13 12 11 10 9 8 ..... 3 2 1 0
Virtual page number
Page offset
Translation
29 28 27 ..... 15 14 13 12 11 10 9 8 ..... 3 2 1 0
Physical page number
Page offset
Physical address (an address in main memory)



MMU = Memory Management Unit

Structure of a Page Table Entry



Speeding Up Paging

- Challenges:
  - Mapping virtual to physical address must be fast
  - If address space is large, page table will be large

Speeding Up Paging

- Challenges:
  - Mapping virtual to physical address must be fast → Translation Lookaside Bufferc(TLB)
  - If address space is large, page table will be large →
    - Multi-level page table
    - Inverted page table

TLB

- **Observation**: most programs tend to make a large number of references to a small number of pages -> only fraction of the page table is heavily used
- TLB
  - Hardware device inside the MMU
  - Maps virtual to physical address without going to the page table

TLB

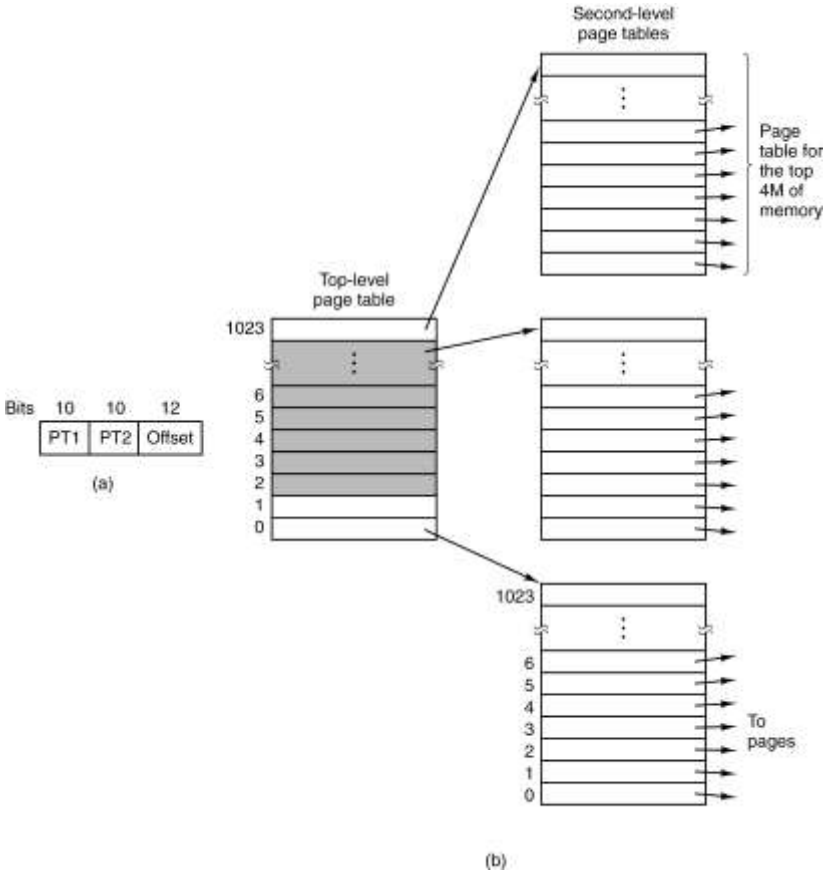
- In case of TLB miss -> MMU accesses page table
- TLB misses occur more frequently than page faults
- Optimizations
  - Software TLB management
    - Simpler MMU

TLB

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

Multi-Level Page Table

- To reduce storage overhead in case of large memories

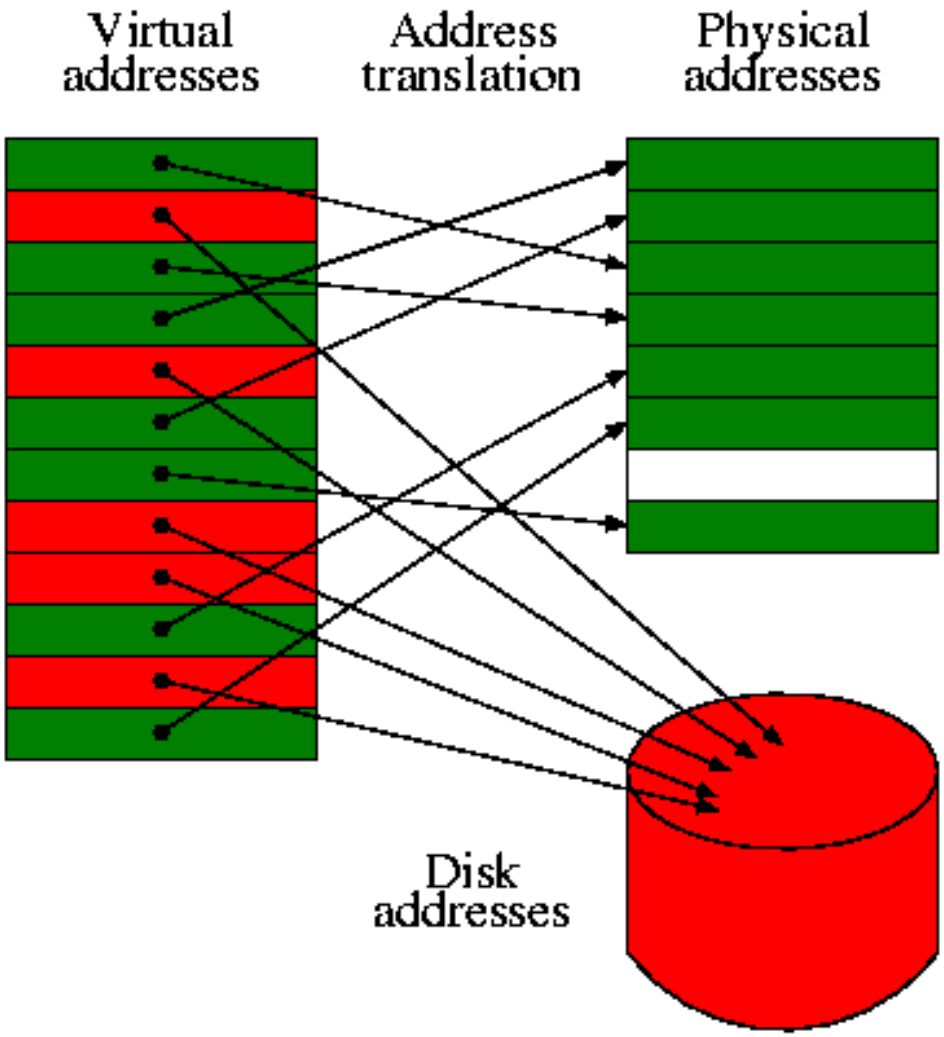


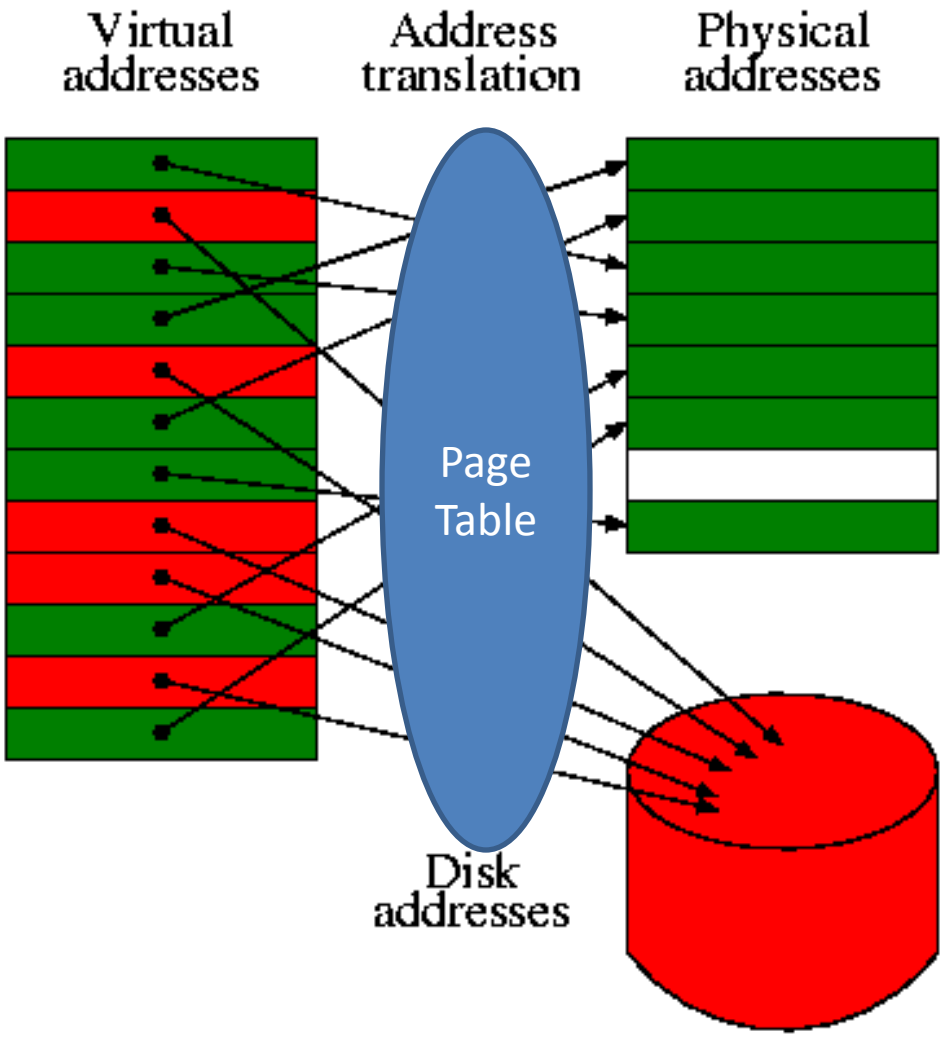
Inverted Page Table

- One entry per page frame

+ Save vast amount of storage

- virtual-to-physical translation much harder


Virtual addresses
Address translation
Physical addresses
Disk addresses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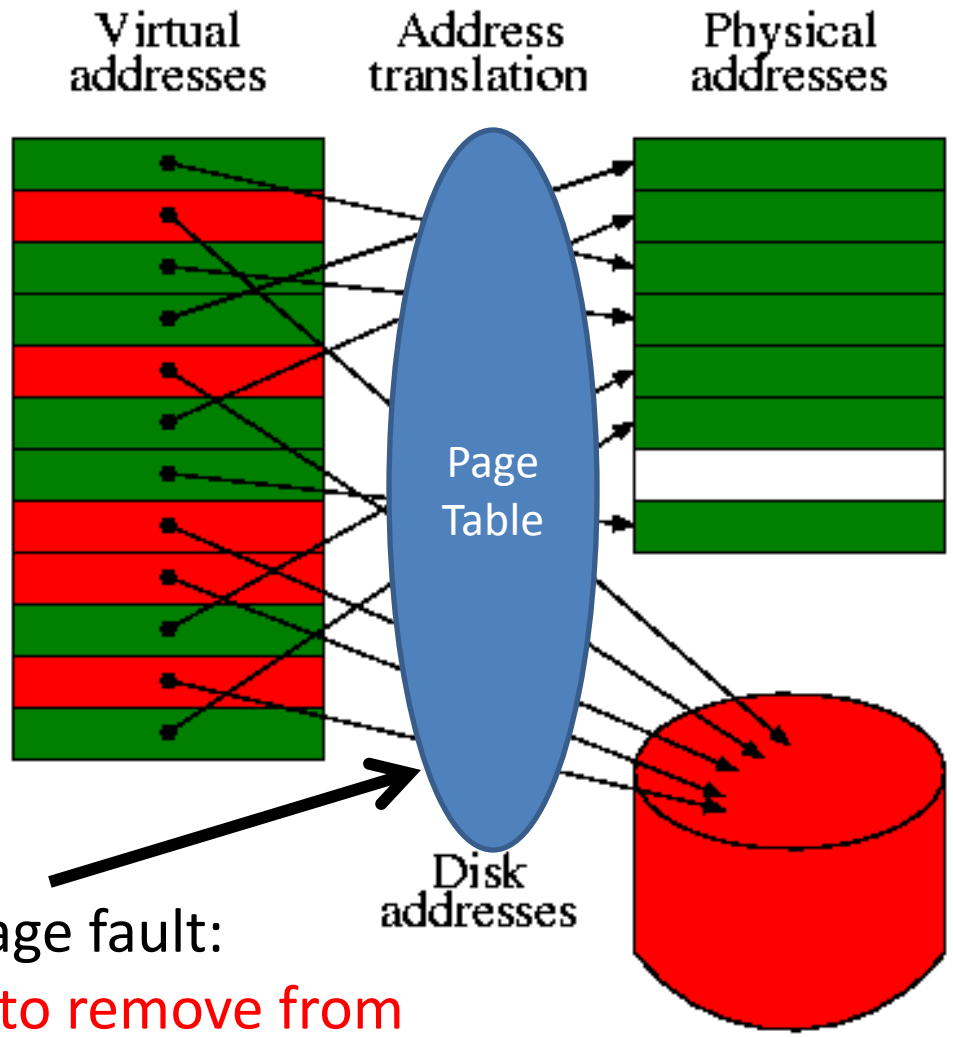
Address translation
Physical addresses
Page Table
Disk addresses



In case of page fault:

which page to remove from Memory?

Replacement Policies

- Used in many contexts when storage is not enough
  - caches
  - web servers
  - pages
- Things to take into account when designing a replacement policy
  - measure of success
  - cost

Optimal Page Replacement Algorithm

- Each page labeled with the number of instructions that will be executed before this page is referenced
- Page with the highest label should be removed
- Impossible to implement

The Not Recently Used Replacement Algorithm

- Two status bits with each page
  - R: Set whenever the page is referenced (used)
  - M: Set when the page is written
- R and M bits are available in most computers implementing virtual memory
- Those bits are updated with each memory reference
  - Must be updated by hardware
  - Reset only by the OS
- Periodically (e.g. on each clock interrupt) the R bit is cleared
  - To distinguish pages that have been referenced recently

The Not Recently Used Replacement Algorithm

	R	M
Class 0:	0	0
Class 1:	0	1
Class 2:	1	0
Class 3:	1	1

NRU algorithm removes a page at random from the lowest numbered unempty class

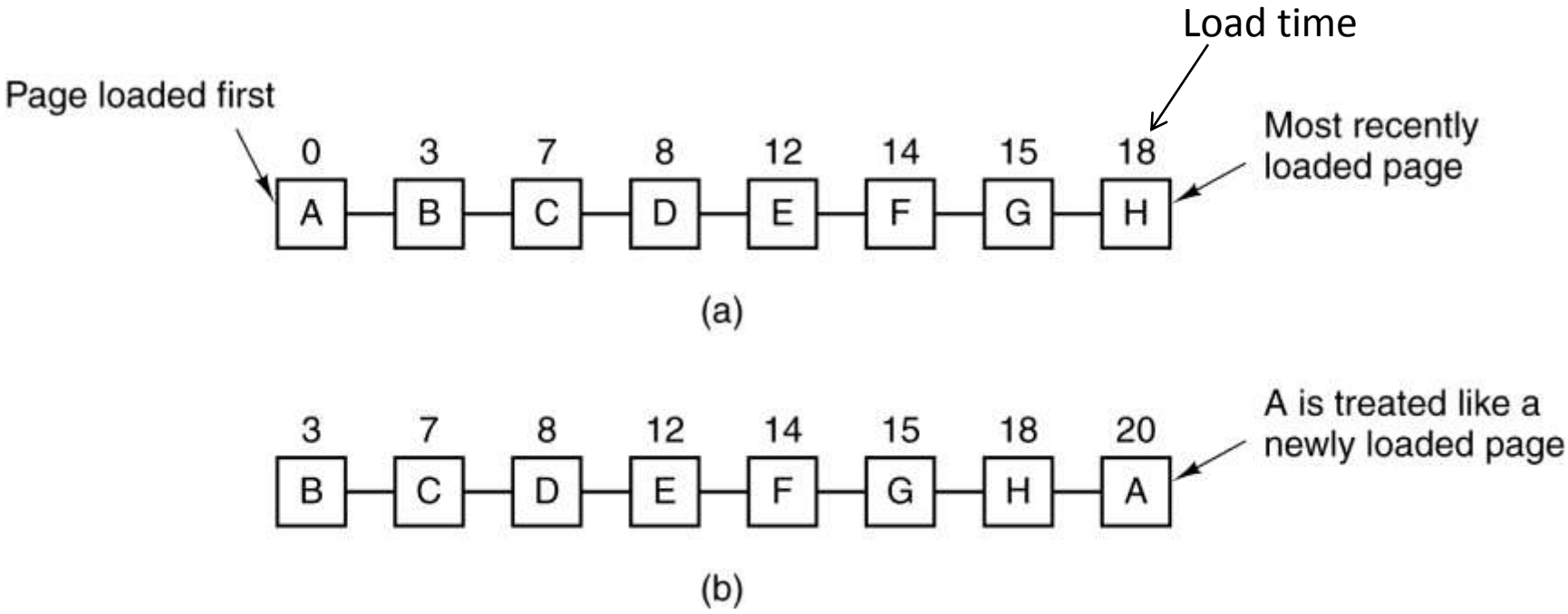
The FIFO Replacement Algorithm

- OS maintains a list of the pages currently in memory
- The most recent arrival at the tail
- On a page fault, the page at the head is removed

The Second-Chance Page Replacement Algorithm

- Modification to FIFO
- Inspect the R bit of the oldest page
  - If R=0 page is old and unused -> replace
  - If R=1 then
    - bit is cleared
    - page is put at the end of the list
    - the search continues
- If all pages have R=1, the algorithm degenerates to FIFO

The Second-Chance Page Replacement Algorithm

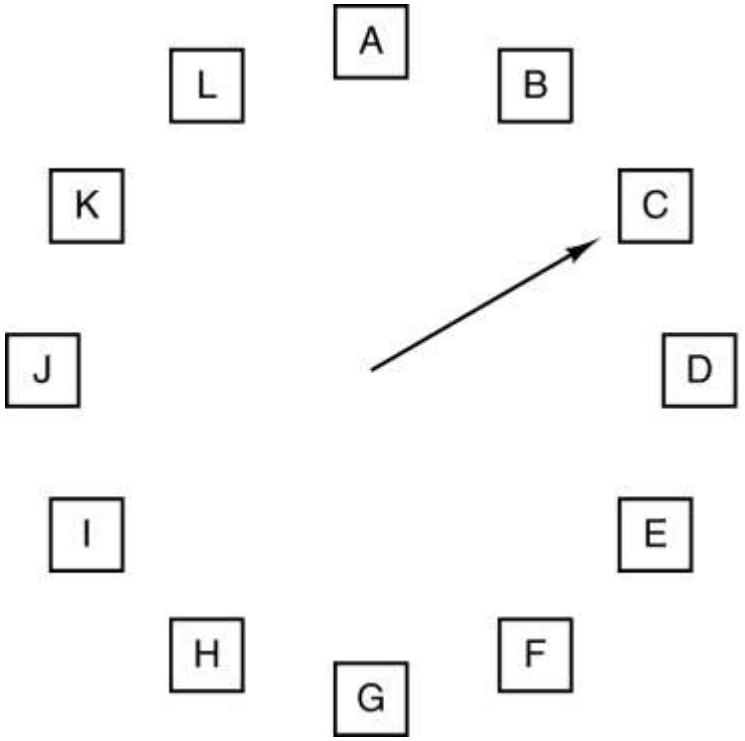


Moving pages around on the lists is inefficient

The Clock Page Replacement Policy

- Keep page frames on a circular list in the form of a clock
- The hand points to the oldest page
- When page fault occurs
  - The page pointed to by the hand is inspected
  - If R=0
    - page evicted
    - new page inserted into its place
    - hand is advanced
  - If R = 1
    - R is set to 0
    - hand is advanced

The Clock Page Replacement Policy



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

The Least Recently Used (LRU) Page Replacement Algorithm

- Good approximation to optimal
- When page fault occurs, replace the page that has been unused for the longest time
- Realizable but not cheap

LRU
Hardware Implementation 1

- 64-bit counter increment after each instruction
- Each page table entry has a field large enough to include the value of the counter
- After each memory reference, the value of the counter is stored in the corresponding page entry.
- At page fault, the page with lowest value is discarded

LRU
Hardware Implementation 1

- 64-bit counter increment after each instruction
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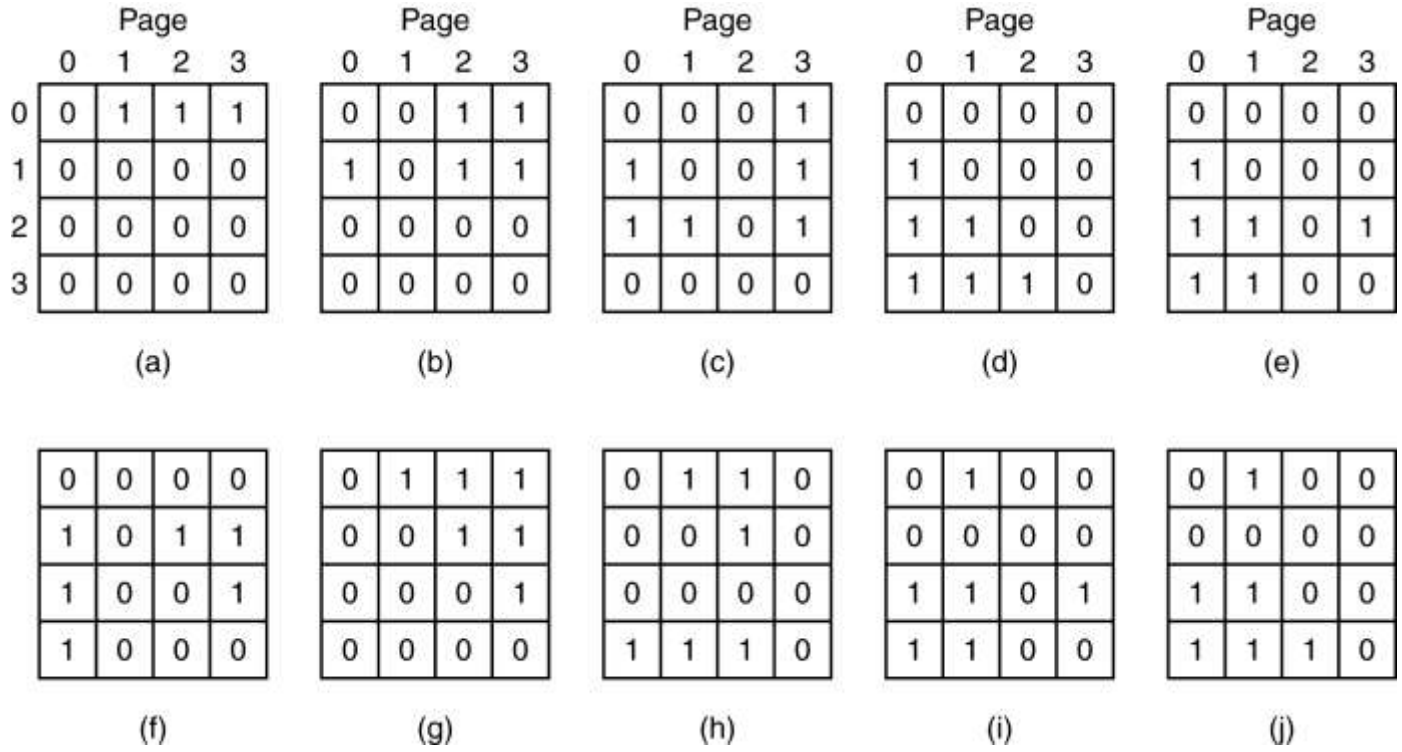
LRU: Hardware Implementation 2

- Machine with n page frames
- Hardware maintains a matrix of nxn bits
- Matrix initialized to all 0s
- Whenever page frame k is referenced
  - Set all bits of row k to 1
  - Set all bits of column k to 0
- The row with lowest value is the LRU

LRU: Hardware Implementation 2



Pages referenced: 0 1 2 3 2 1 0 3 2 3

LRU Implementation

- Slow
- Few machines have required hardware

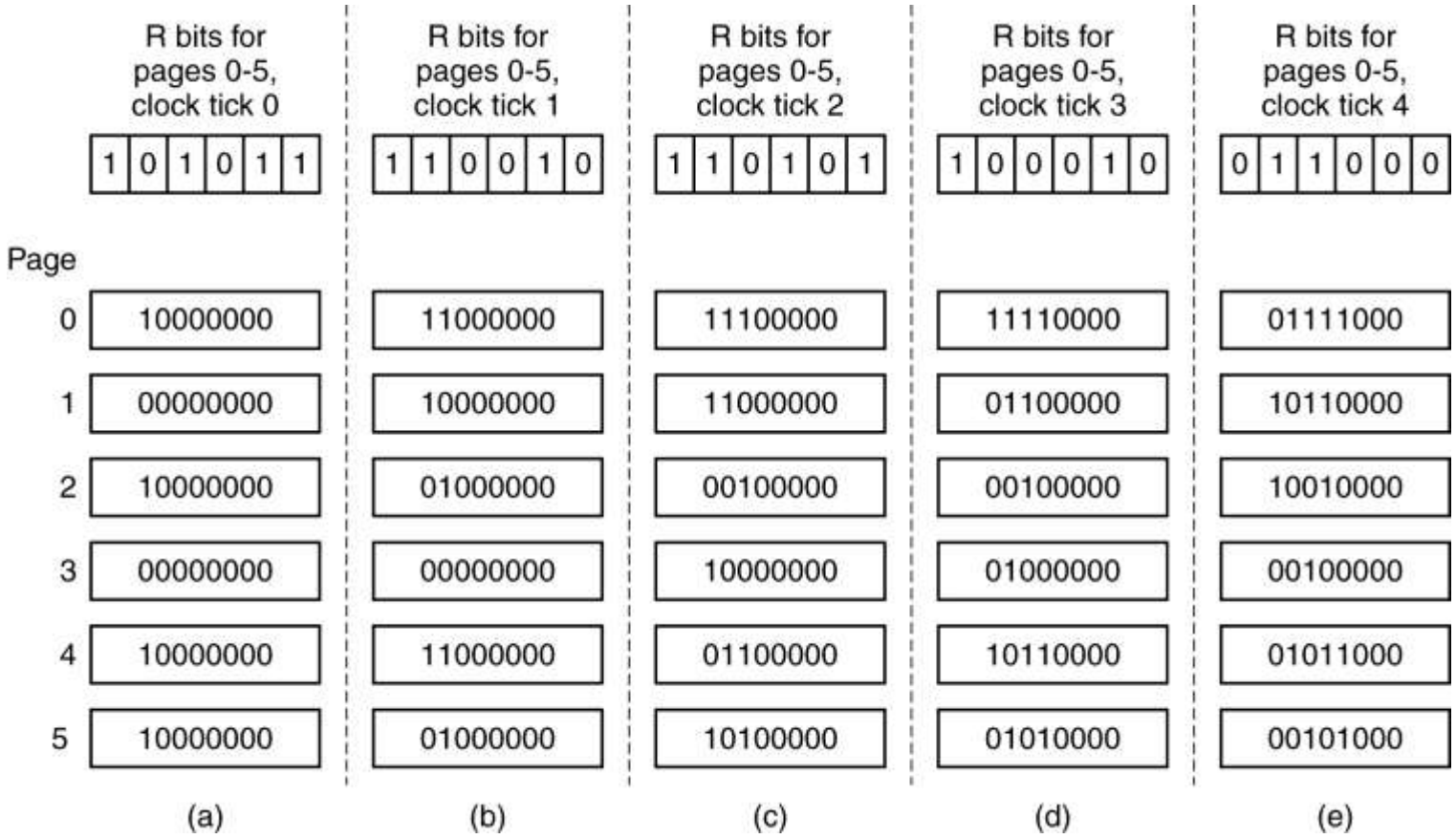
Simulating LRU in Software

- Not Frequently Used (NFU) algorithm
- Software counter associated with each page, initially zero
- At each clock interrupt, the OS scans all pages and add the R bit to the counter
- At page fault: the page with lowest counter is replaced

Enhancing NRU

- NRU never forgets anything -> high inertia
- Modifications:
  - shift counter right 1 bit before adding R
  - R is added to the leftmost
- This modified algorithm is called aging
- The page whose counter is lowest is replaced at page fault

Aging Algorithm



The Working Set Model

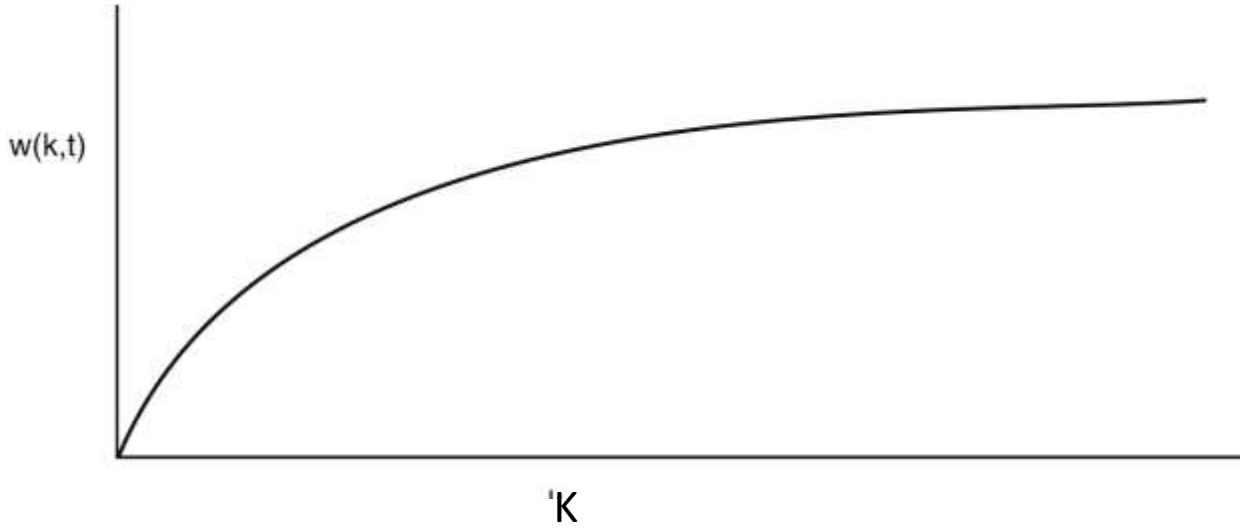
- Working set: the set of pages that a process is currently using
- Thrashing: a program causing page faults every few instructions

An important question:

In multiprogramming systems, processes are sometimes swapped to disk (i.e. all their pages are removed from memory). When they are brought back, which pages to bring?

The Working Set Model

- Try to keep track of each process' working set and make sure it is in memory before letting the process run.

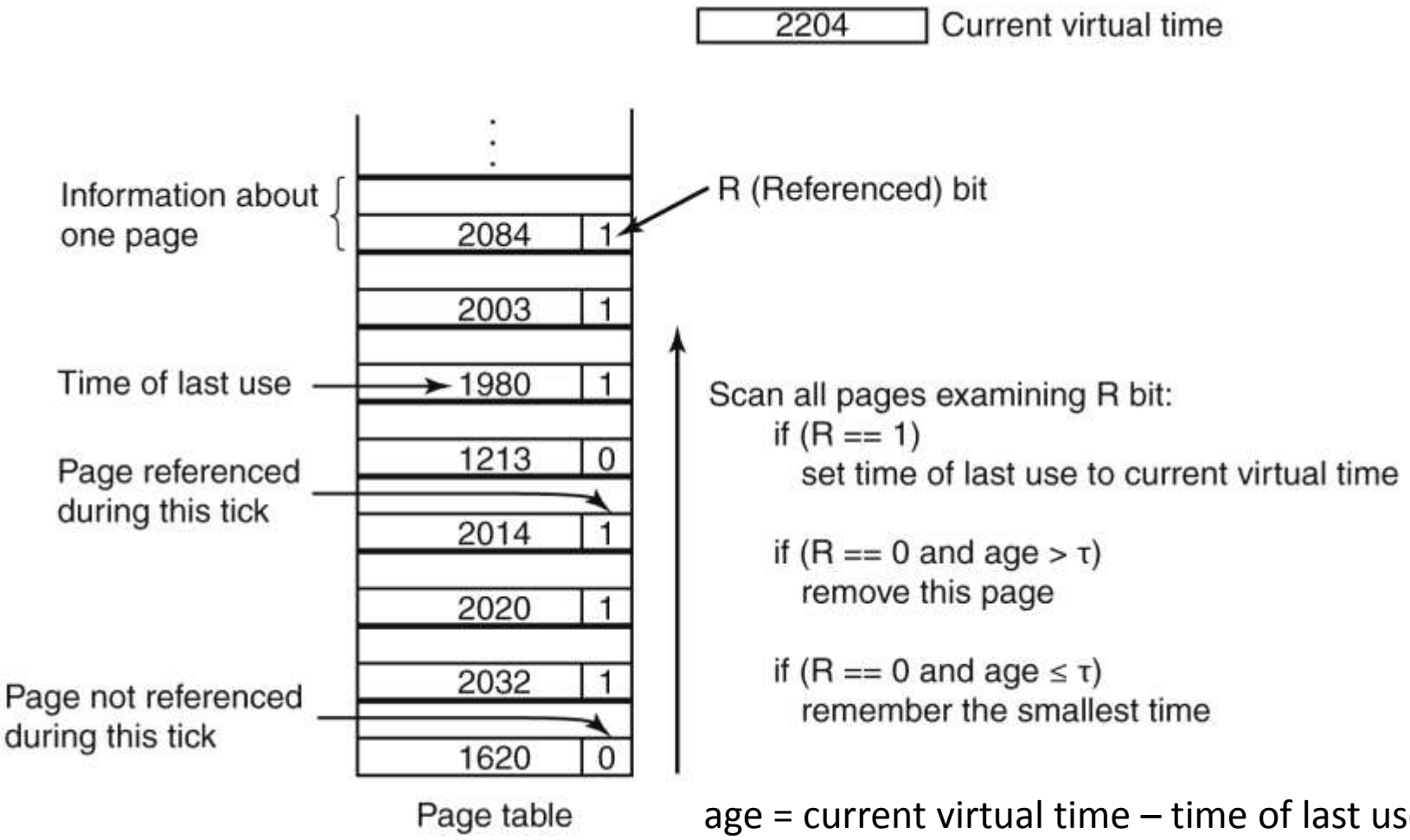


w(k,t): the set of pages accessed in the last k references at instant t

The Working Set Model

- OS must keep track of which pages are in the working set
- Replacement algorithm: evict pages not in the working set
- Possible implementation (but expensive):
  - working set = set of pages accessed in the last k memory references
- Approximations
  - working set = pages used in the last 100 msec

Working Set Page Replacement Algorithm

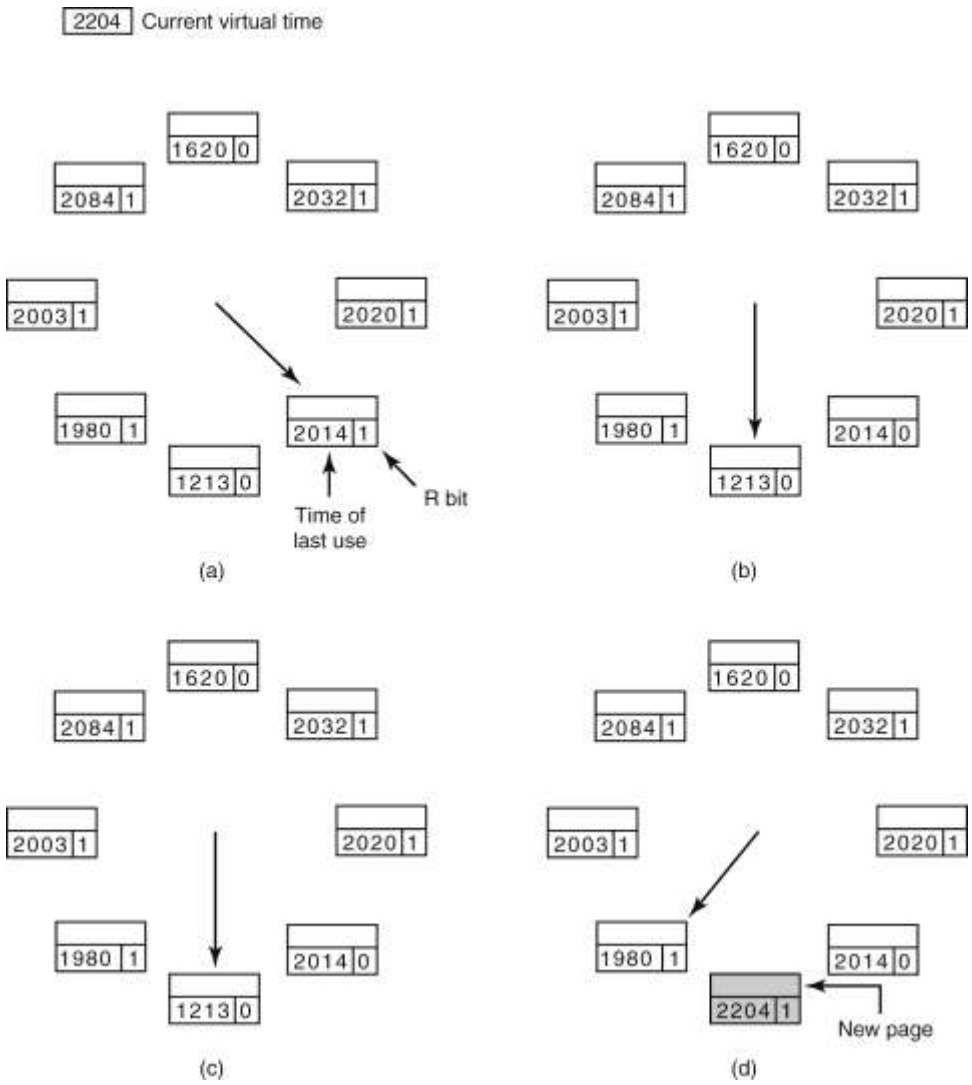


age = current virtual time – time of last use

The WSClock Page Replacement Algorithm

- Based on the clock algorithm and uses working set
- data structure: circular list of page frames
- Each entry contains: time of last use, R bit, and M bit
- At page fault: page pointed by hand is examined
  - If R = 1, the hand advances to next page and R is reset
  - If R = 0
    - If age > threshold and page is clean -> it is reclaimed
    - If page is dirty -> write to disk is scheduled and hand advances

The WSClock Page Replacement Algorithm



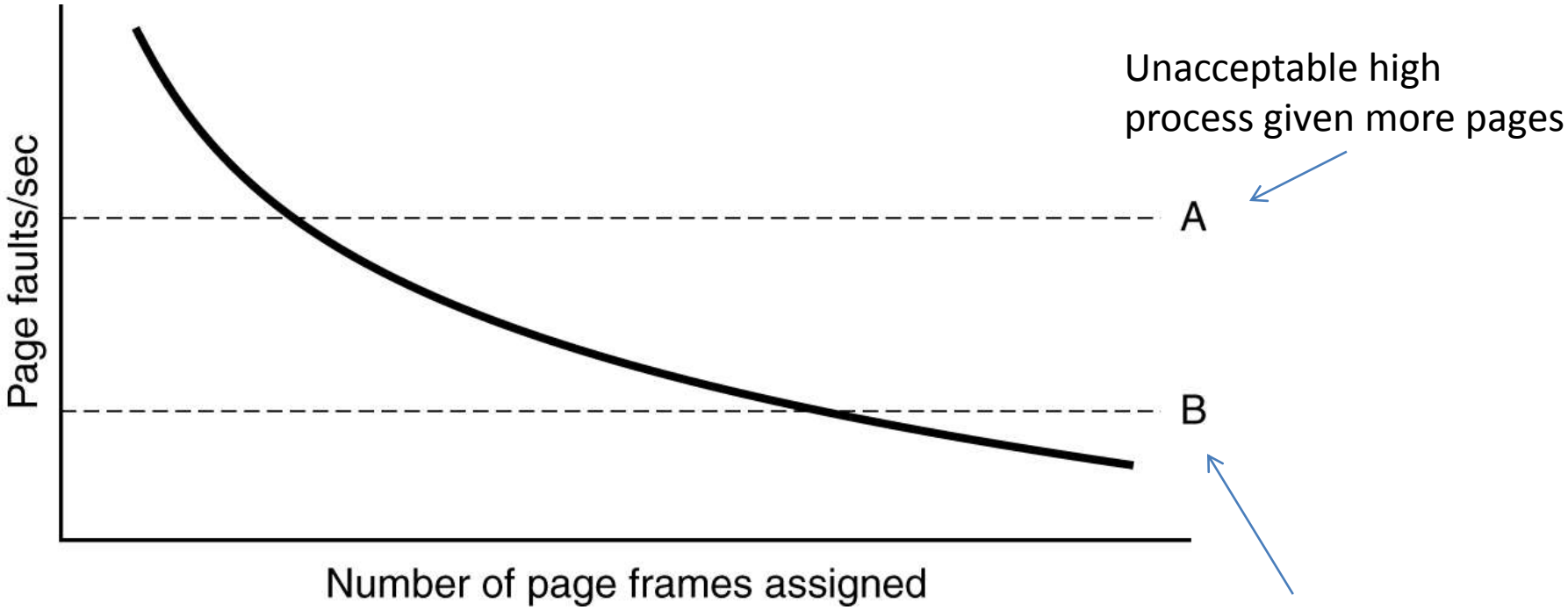
Design Issues for Paging: Local vs Global Allocation

- How memory should be allocated among the competing runnable processes?
- Local algorithms: allocating every process a fixed fraction of the memory
- Global algorithms: dynamically allocate page frames
- Global algorithms work better
  - If local algorithm used and working set grows → thrashing will result
  - If working set shrinks → local algorithms waste memory

Global Allocation

- Method 1: Periodically determine the number of running processes and allocate each process an equal share
- Method 2 (better): Pages allocated in proportion to each process total size
- Page Fault Frequency (PFF) algorithm: tells when to increase/decrease page allocation but says nothing about which page to replace.

Global Allocation: PFF



Design Issues: Load Control

- What if PFF indicates that some processes need more memory but none need less?
- Swap some processes to disk and free up all the pages they are holding.
- Which process(es) to swap?
  - Strive to make CPU busy (I/O bound vs CPU bound processes)
  - Process size

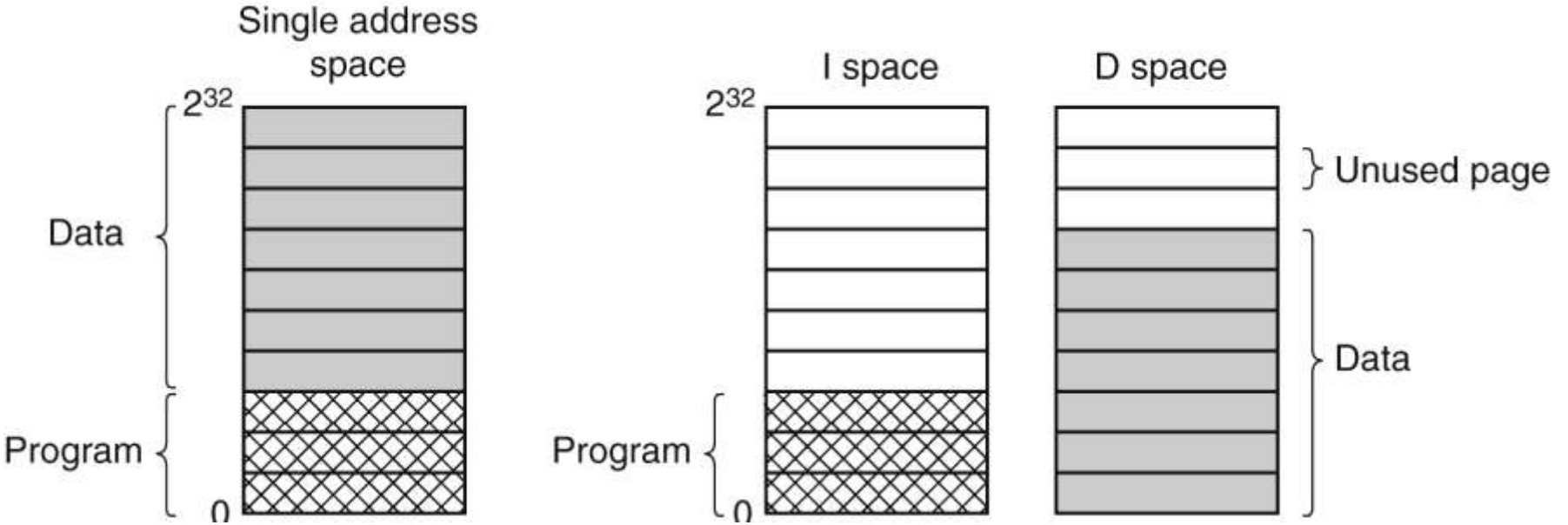
Design Issues: Page Size

- Large page size → internal fragmentation
- Small page size →
  - larger page table
  - More overhead transferring from disk

Design Issues: Page Size

- Assume:
  - s = process size
  - p = page size
  - e = size of each page table entry
- So:
  - number of pages needed = s/p
  - occupying: se/p bytes of page table space
  - wasted memory due to fragmentation: p/2
  - overhead = se/p + p/2
- We want to minimize the overhead:
  - Take derivative of overhead and equate to 0:
  - $-se/p^2 + \frac{1}{2} = 0 \rightarrow p = \sqrt{2se}$

Design Issues:
Separate Instruction and Data Spaces



- The linker must know about it
- Paging can be used in each separately

Design Issues: Shared Pages

- To save space, when same program is running by several users for example
- If separate I and D spaces: process table has pointers to Instruction page table and Data page table
- In case of common I and D spaces:
  - Special data structure is needed to keep track of shared pages
  - Copy on write for data pages

Design Issues: Shared Libraries

- Dynamically linked
- Loaded when program is loaded or when functions in them are called for the first time
- Compilers must not produce instructions using absolute addresses in libraries → position-independent code

Design Issues: Cleaning Policy

- Paging daemon
- Sleeps most of the time
- Awakened periodically to inspect state of the memory
- If too few pages are free -> daemon begins selecting pages to evict

Segmentation

- Different address space
- Segments
  - of variable size
  - programmer is aware of segments
- Paging makes life simpler for operating system and CPU designers, and therefore is much more common than segmentation.
- Segments can be used together with paging (i.e. the segment is paged).

Conclusions

- Virtual memory is very widely used
- Many design issues for paging systems:
  - Page replacement algorithm
    - The two best ones: aging and WSClock
  - Page size
  - Local vs Global Allocation
    - Global algorithms work better
  - Load control
  - Dealing with shared pages