TI III: Operating Systems & Computer Networks
Memory

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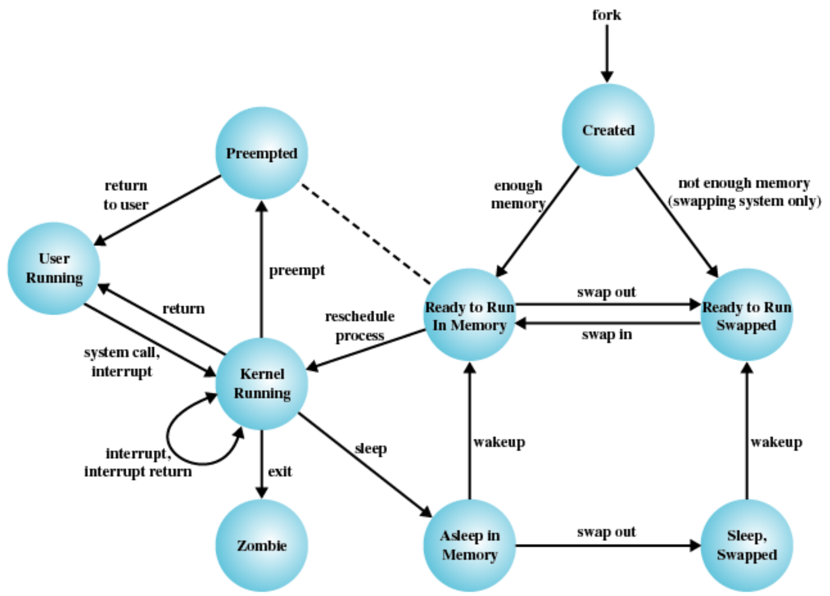


Content

Motivation

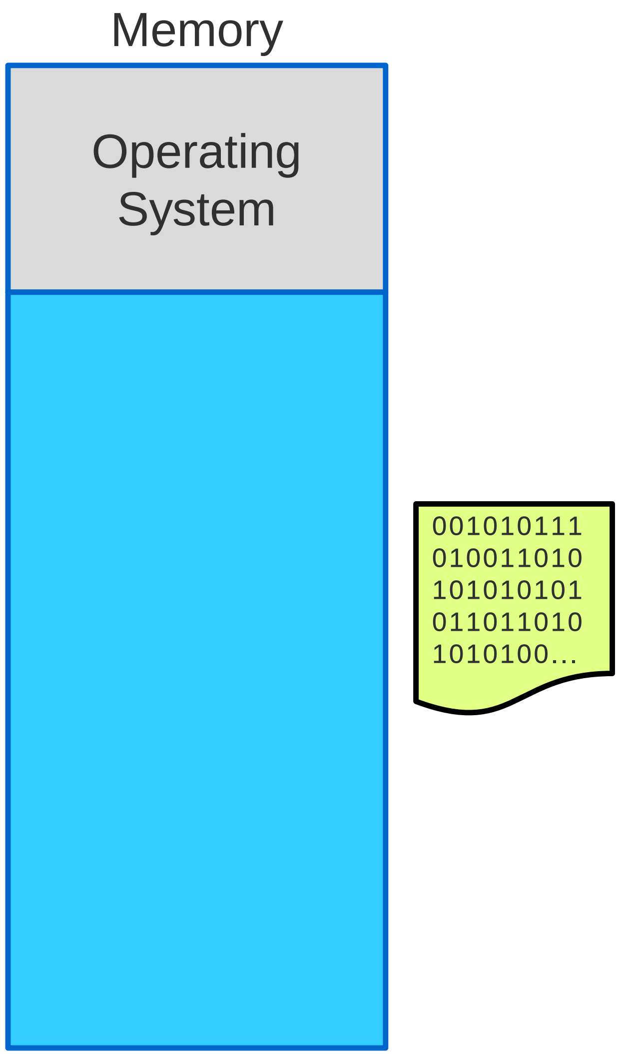
To which location in memory should the process image be loaded?

What happens to all the addresses contained in the process image?

How does the OS know that no other process is using that memory?

How can the OS prevent a process from accessing memory that it doesn’t “own”?

What’s the best method to efficiently manage memory requests?



Motivation

See course Computer Architecture!

- Here many pointers to this course
- Lecture does not cover all slides

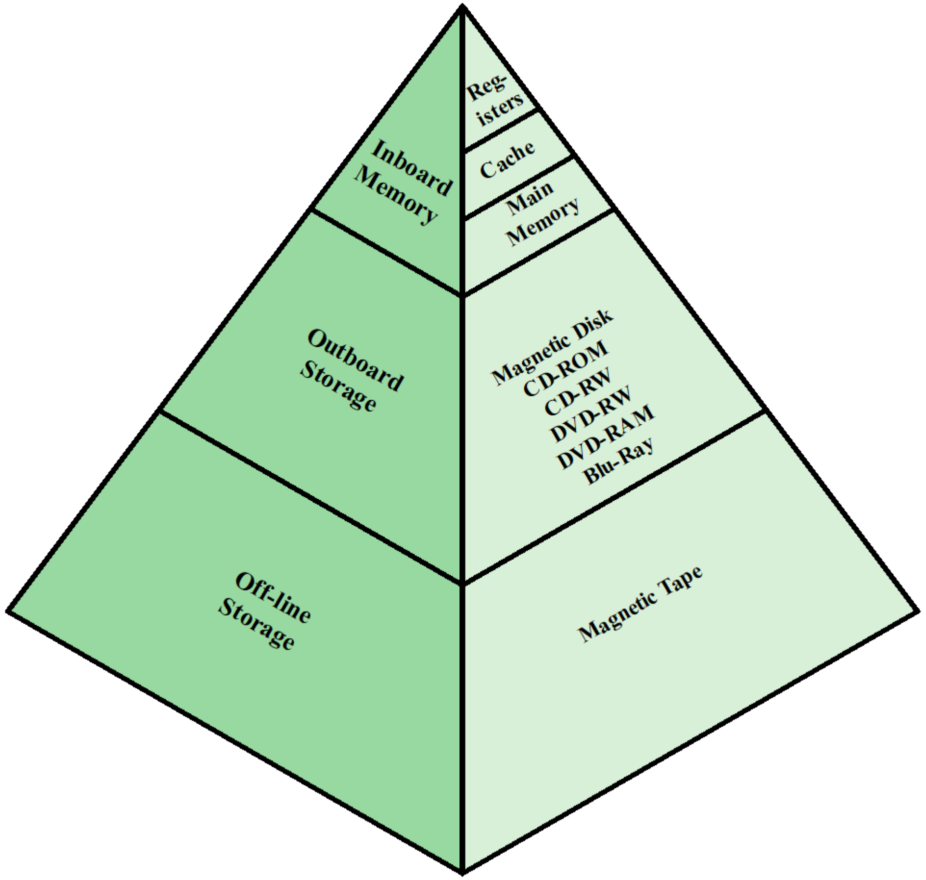


Figure 1.14 The Memory Hierarchy

Memory Management

Closely related to processes

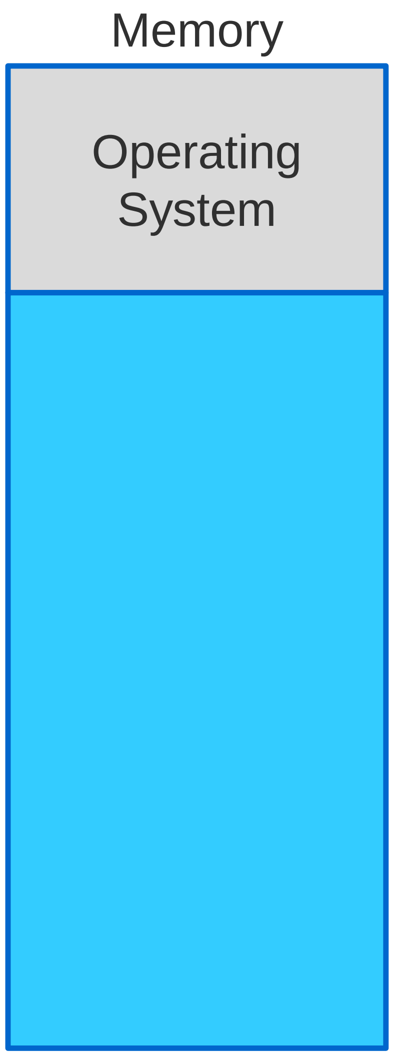
- Memory management isolates processes from each other

Goals

- Subdividing memory to accommodate multiple processes
- Memory needs to be allocated to ensure a reasonable supply of ready processes to consume available processor time

Requirements

- Relocation: Location in (physical) memory unknown or may change
- Protection: Disallow access to memory of other processes
- Sharing: Data for communication (IPC), program copy for memory reduction



Addressing

Physical Address

- The absolute address or actual location in main memory
- Used by the kernel (to implement logical addresses)

Relative Address

- Address expressed as a location relative to some known point
- Also commonly found in application programming (arrays)

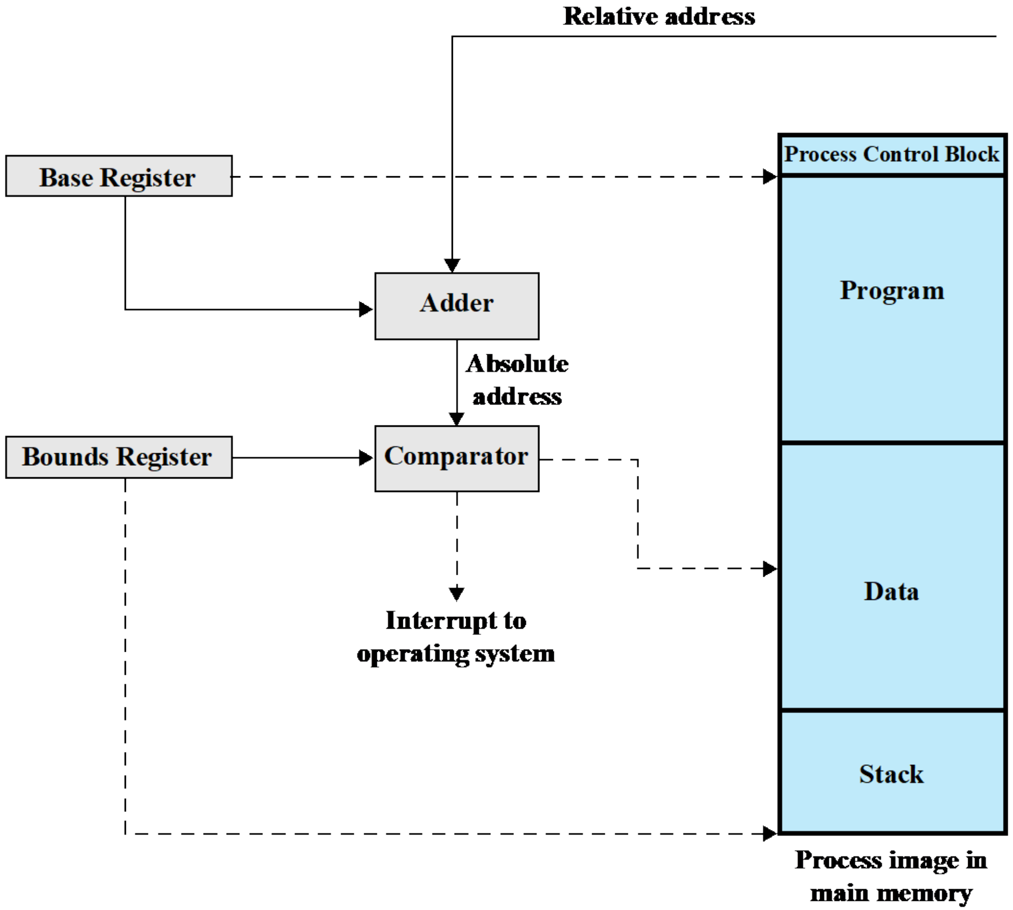
Logical/Virtual Address

- Reference to memory location independent of current assignment of data to memory
- Translation must be made to physical address
- Requires hardware support

Address space

- Range of addresses that are (within the address space) unambiguously addressable

Addressing



Relative address
Base Register
Process Control Block
Program
Adder
Absolute
address
Bounds Register
Comparator
Data
Interrupt to
operating system
Stack
Process image in
main memory

Memory Access

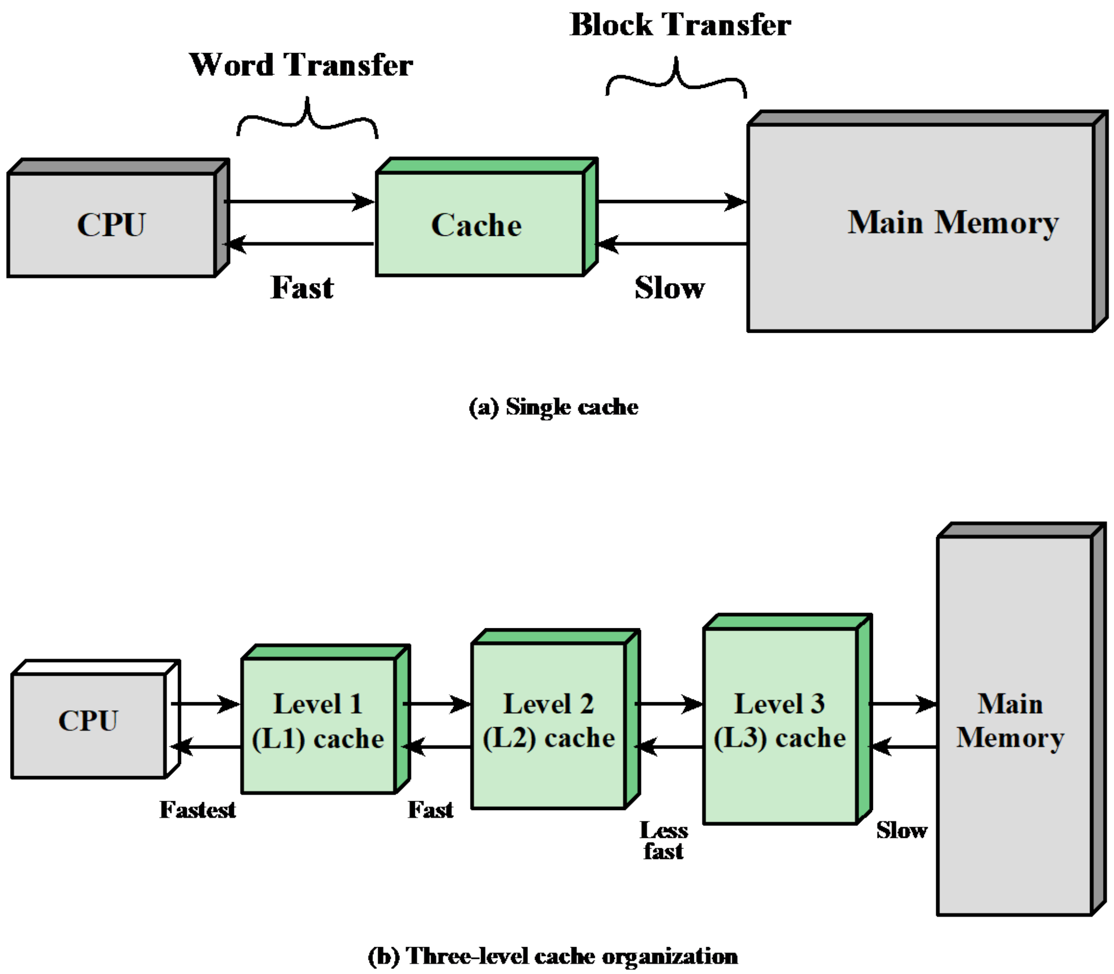


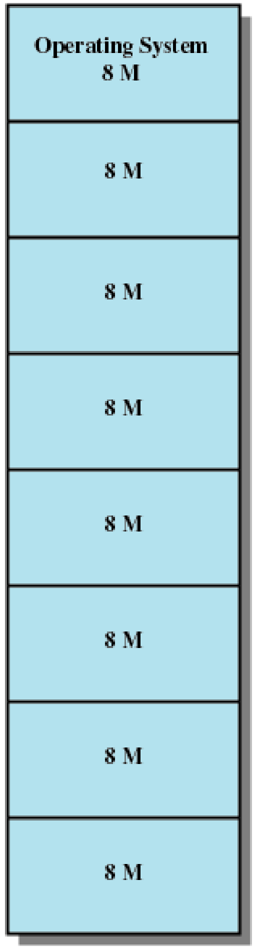
Figure 1.16 Cache and Main Memory

Questions & Tasks

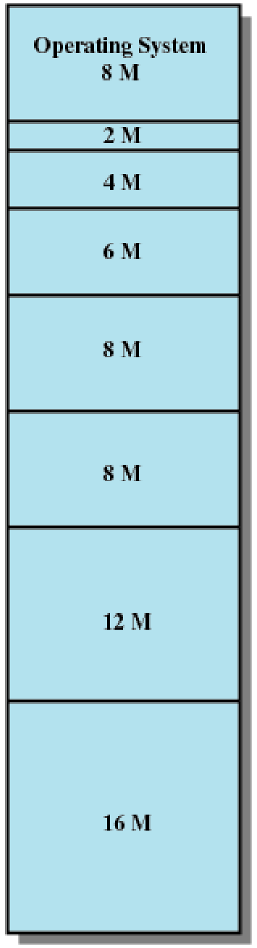
- Can you imagine a computer system without memory management?
- What are pros and cons of having many/few processes in memory?
- Repeat relevant sections of Computer Architecture if you have to refresh your knowledge about caches, memory access, memory hierarchy etc.

FIXED AND DYNAMIC PARTITIONING

Fixed Partitioning



(a) Equal-size partitions



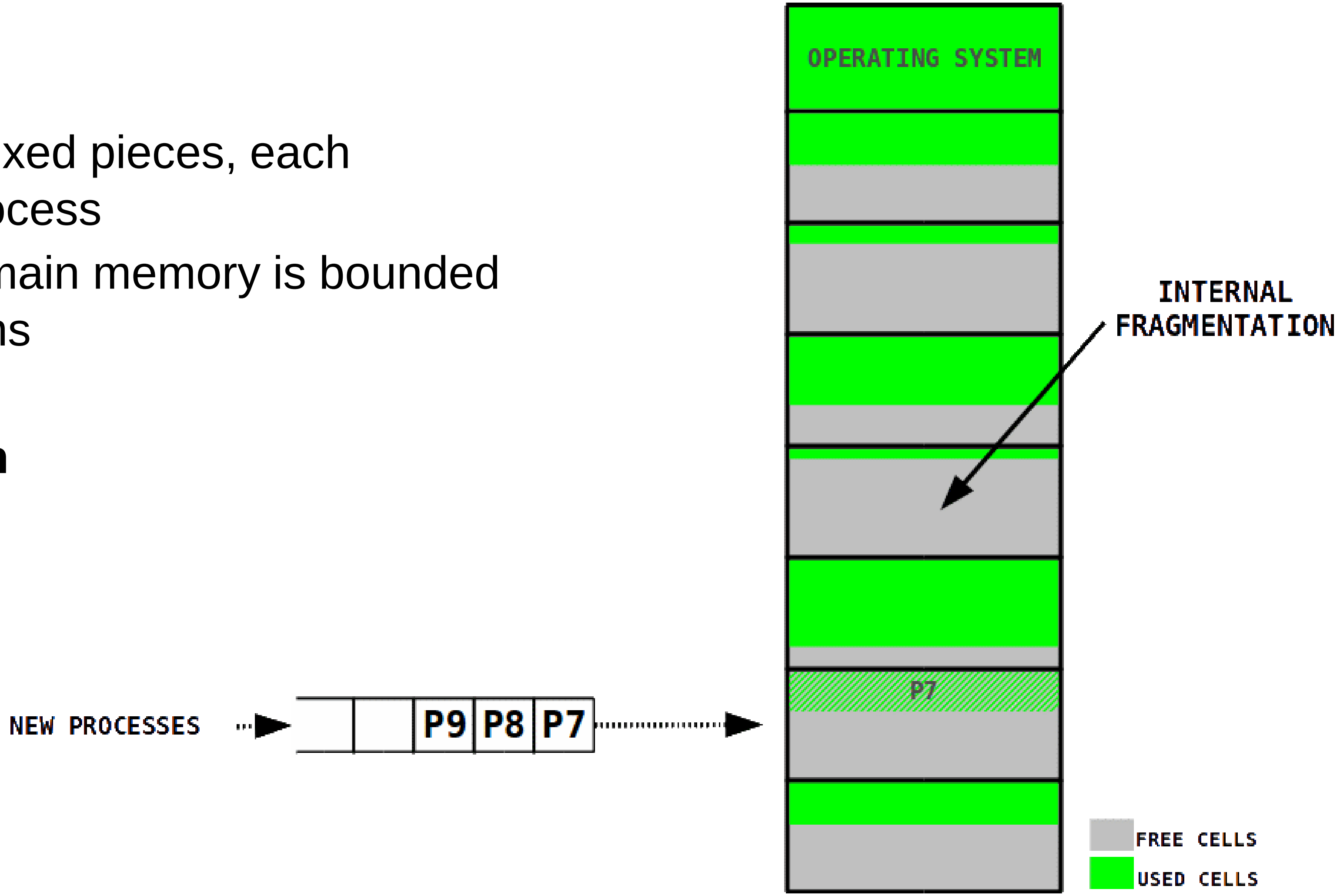
(b) Unequal-size partitions

Fixed Partitions

Memory partitioned into fixed pieces, each partition can hold one process

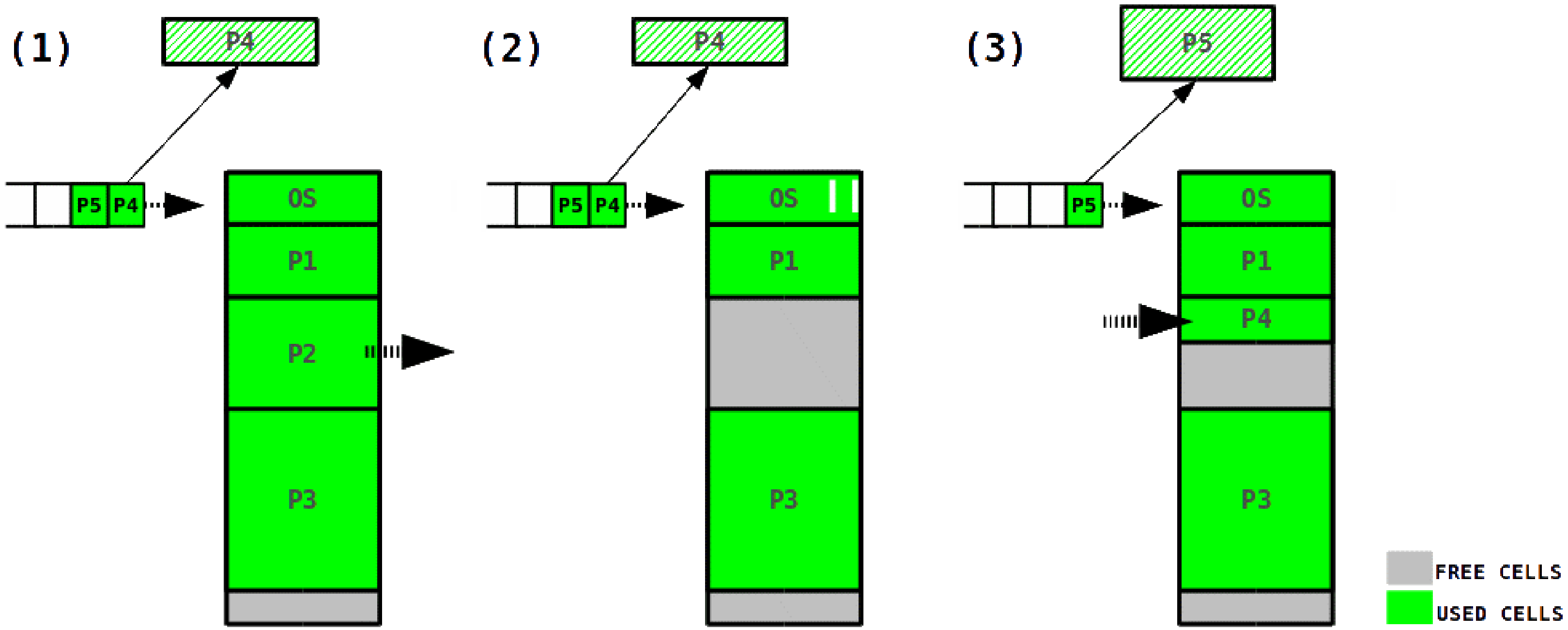
Amount of processes in main memory is bounded by the number of partitions

➢**Internal fragmentation**



Dynamic Partitions

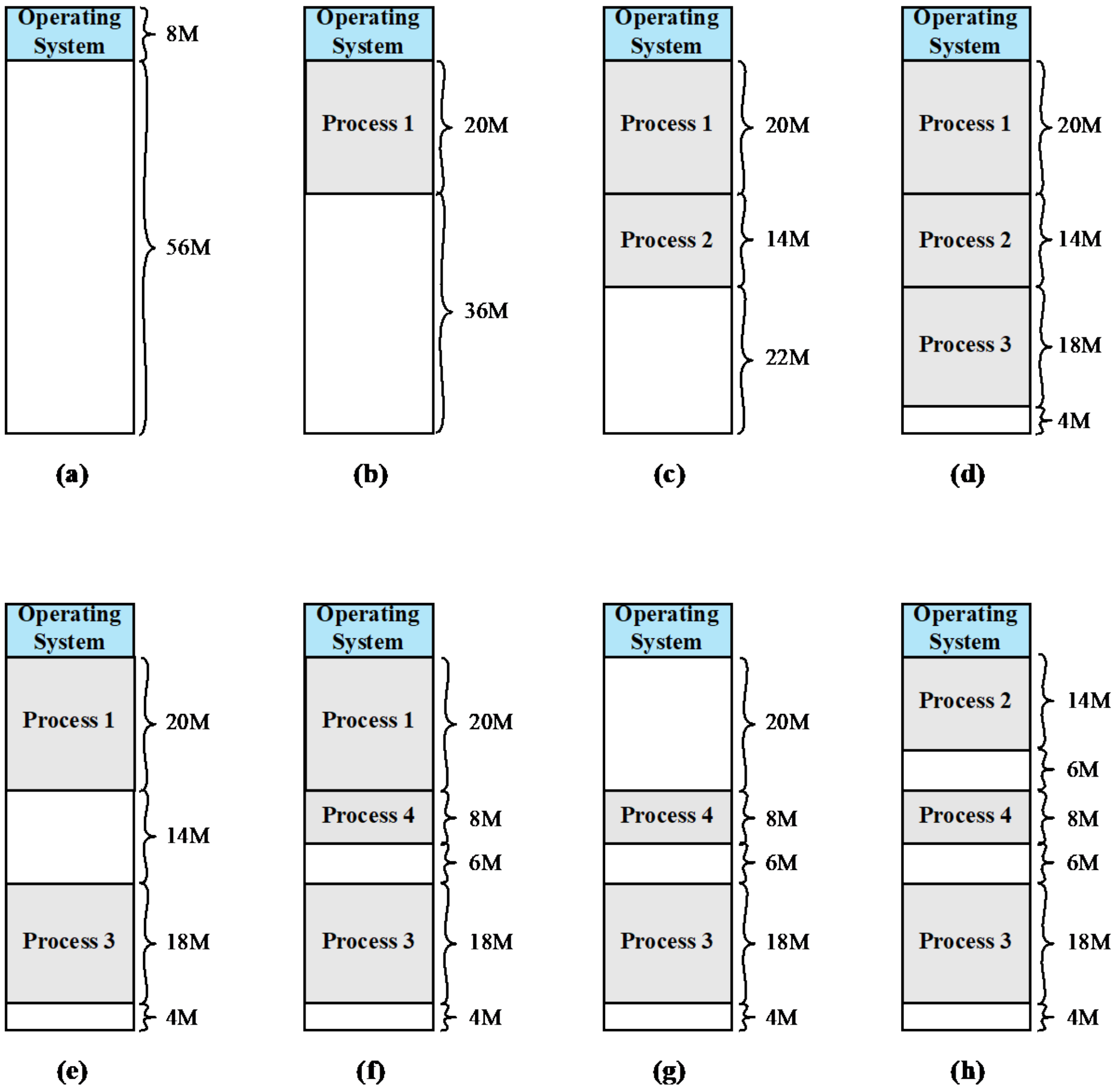
Memory is divided into variable sized partitions on demand



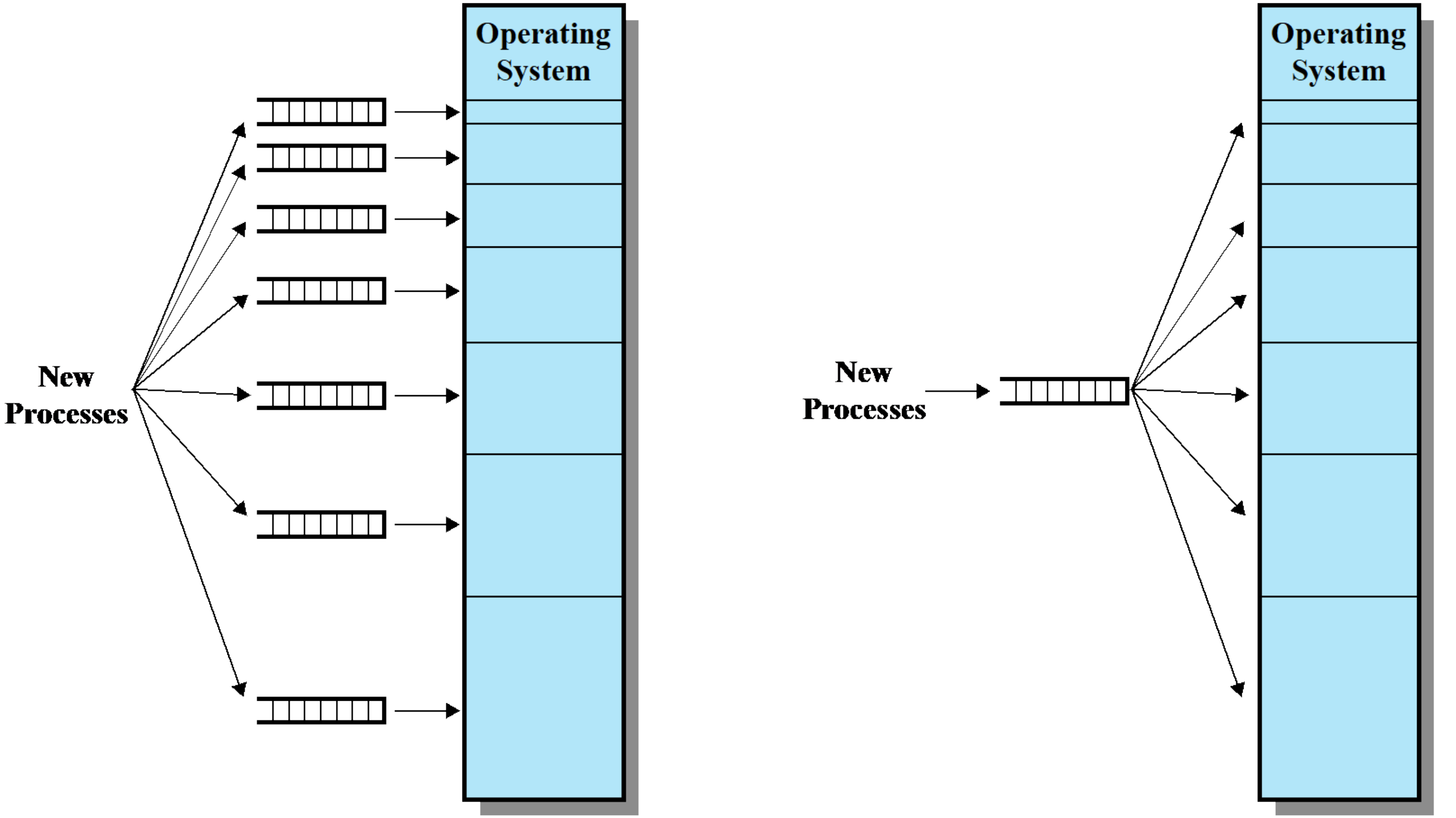
Although there is enough space left for P5 it can not be allocated to the process because it is not continuous

➢**External fragmentation**

Dynamic Partitioning



Implementation



(a) One process queue per partition

(b) Single queue

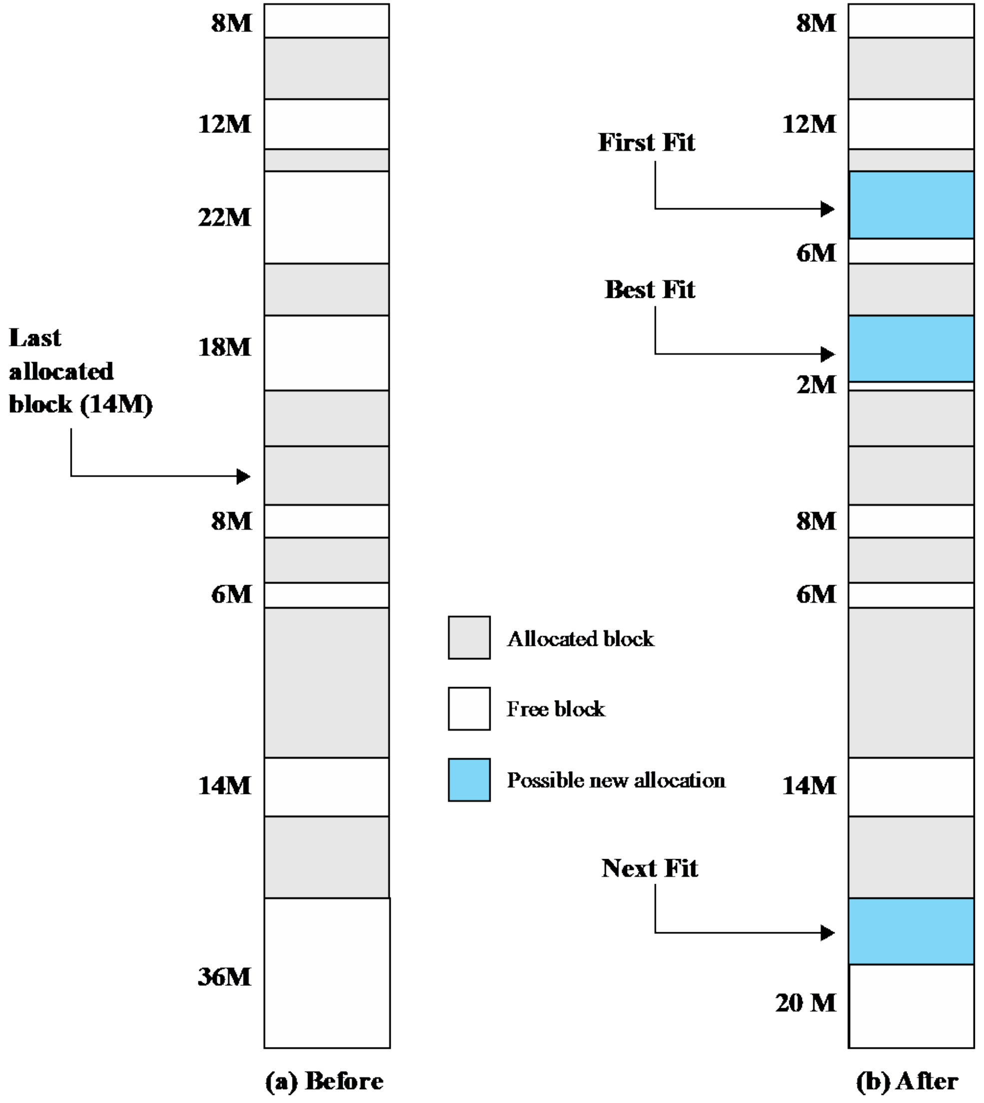
Dynamic Placement Algorithms

First-fit algorithm:

- Scans memory from the beginning
  - ➢Chooses first available block that is large enough

Next-fit algorithm:

- Scans memory from the location of the last placement
  - ➢Tends to allocate block of memory at end of memory (where largest block is commonly found)



Buddy System

Combines advantages of fixed and dynamic allocation

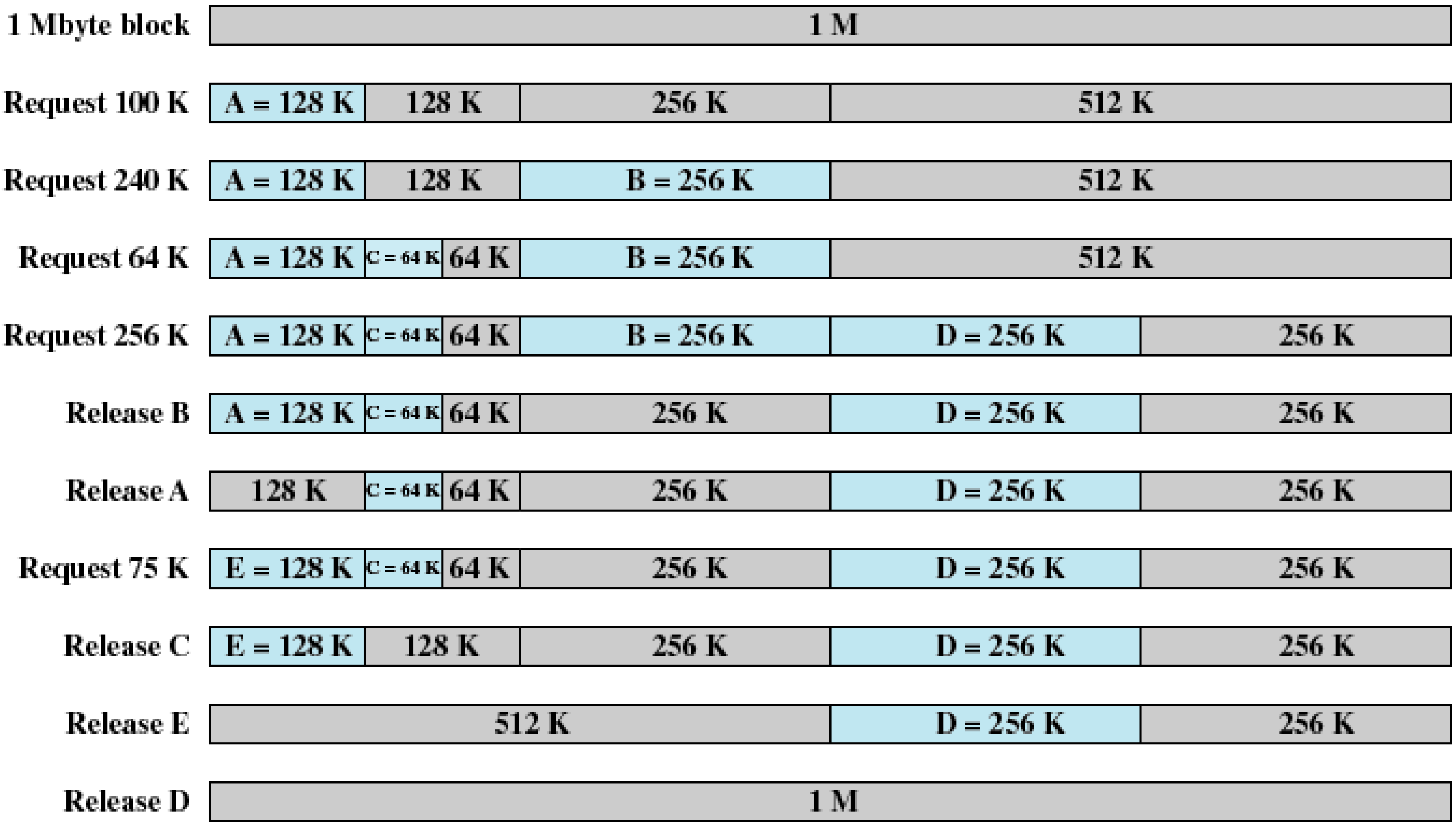
Entire available space is treated as single block of size 2^U bytes
- U := number of bits in address

If memory of size s is requested ($2^{U-1} < s <= 2^U$), entire block is allocated
- Otherwise block is split into two equal buddies
- Process continues until smallest block greater than or equal to s is generated

➢ Free blocks can easily be merged into bigger blocks

➢ Compactification eased by regularly sized blocks

Buddy System: Example



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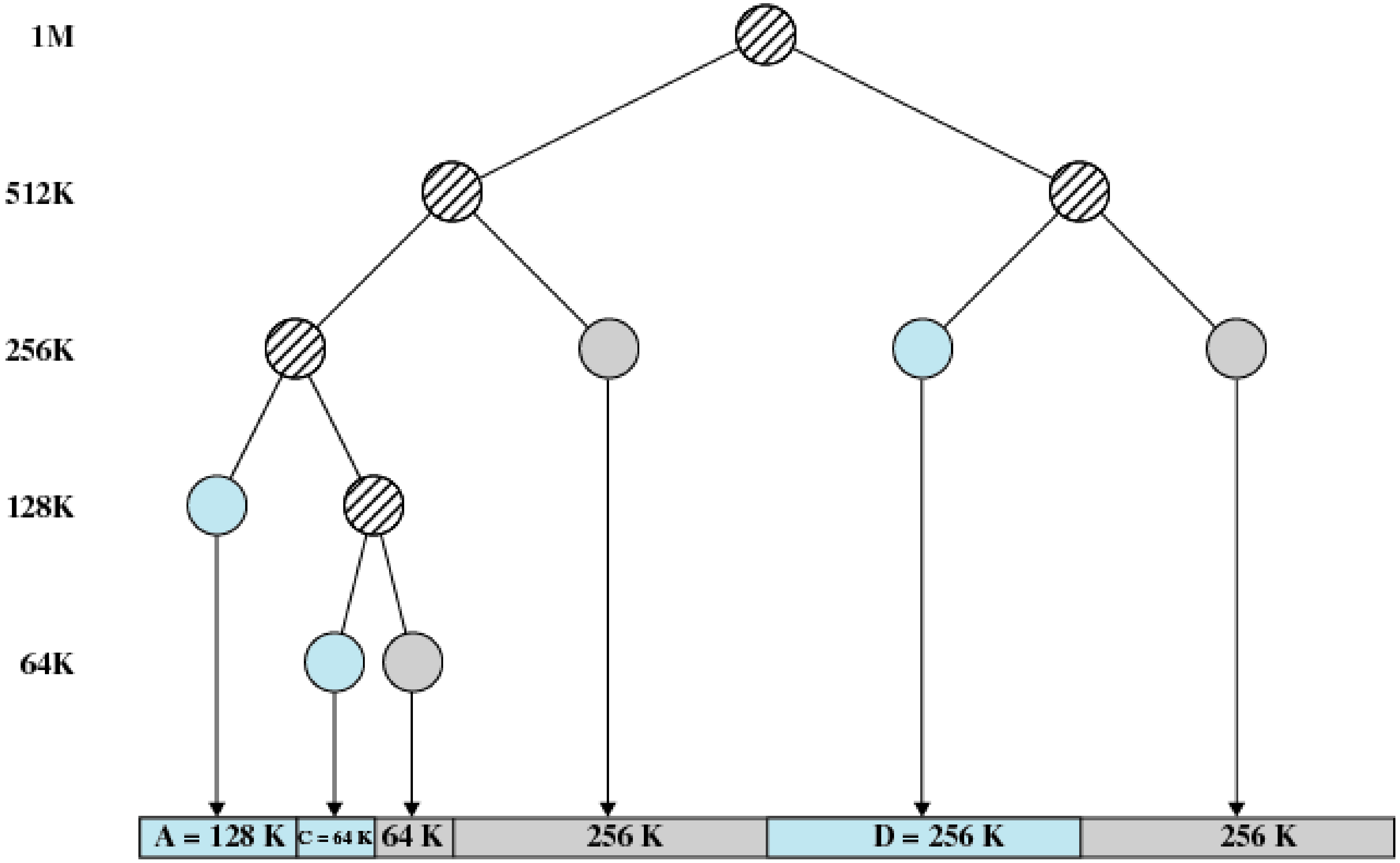
Buddy System: Example



Fragmentation of main memory

Fragmentation: free cells in main memory are unusable because of the allocation scheme

- memory space is wasted

Internal fragmentation: the free memory cells are within the area allocated to a process

- occurs using fixed partitions

External fragmentation: the free memory cells are not in the area allocated to any process

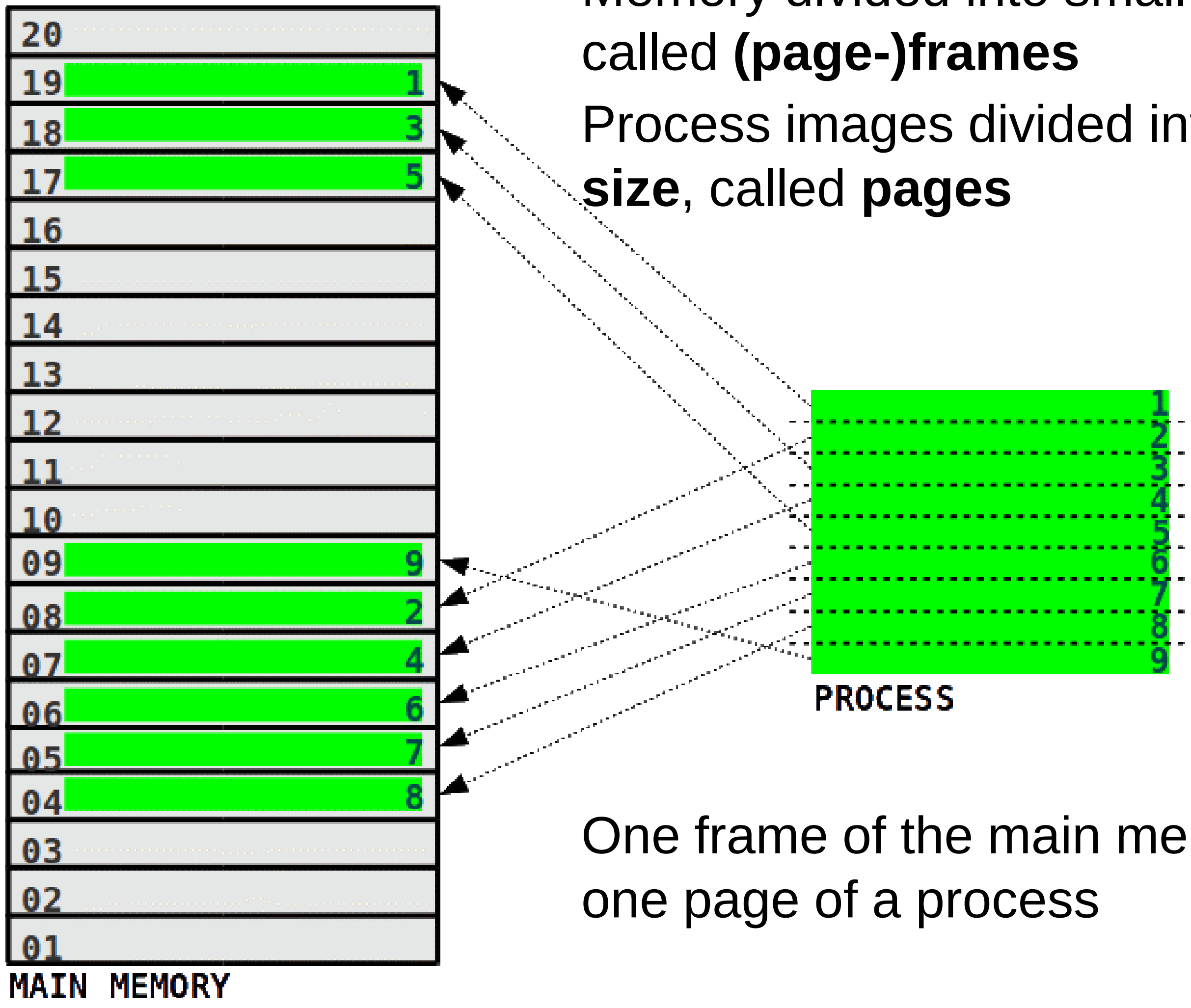
- occurs using dynamic partitions

Questions & Tasks

- What are the advantages and disadvantages of fixed and dynamic partitions, respectively?
- What happens if there is not enough memory available for placing a new block of memory?
- How does the size of partitions influence internal and external fragmentation, respectively?
- And how does this influence the management overhead?

PAGING

Paging

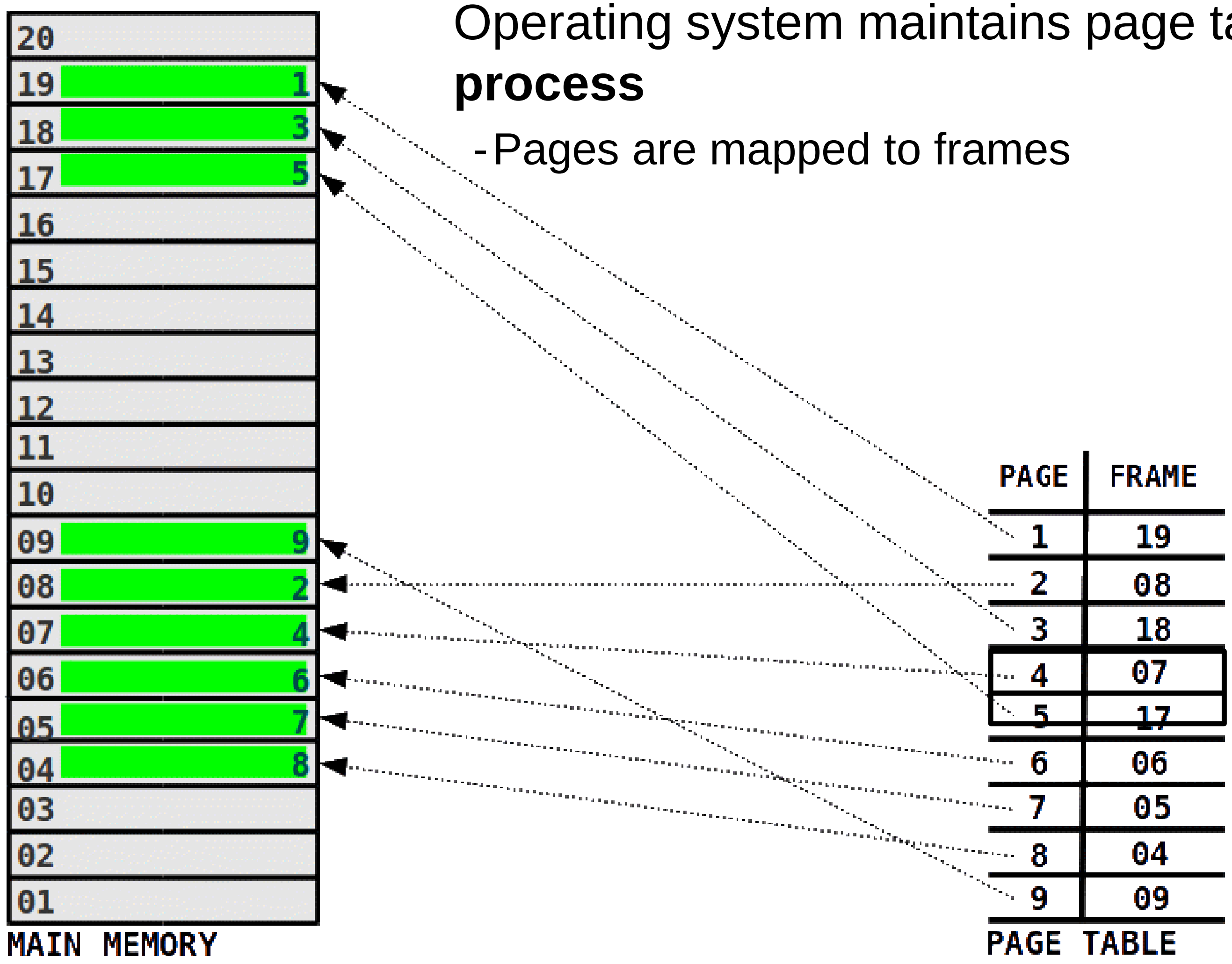


Memory divided into small fixed-sized pieces, called **(page-)frames**

Process images divided into pieces **of the same size**, called **pages**

One frame of the main memory is allocated to one page of a process

Page Table



Operating system maintains page table **for each process**

- Pages are mapped to frames

Size of Frames/Pages

Paging creates no external fragmentation

- Since size of frames/pages is fixed

Internal fragmentation depends on frame size

- The smaller the frames the lower the internal fragmentation
- BUT: the smaller the frames the bigger the page tables

Assignment of Pages to Frames

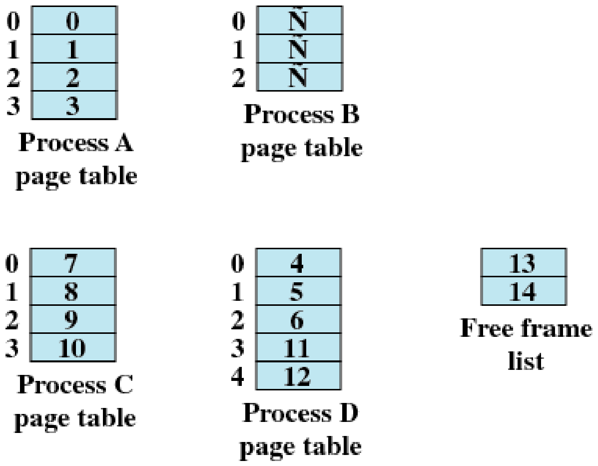
Example:

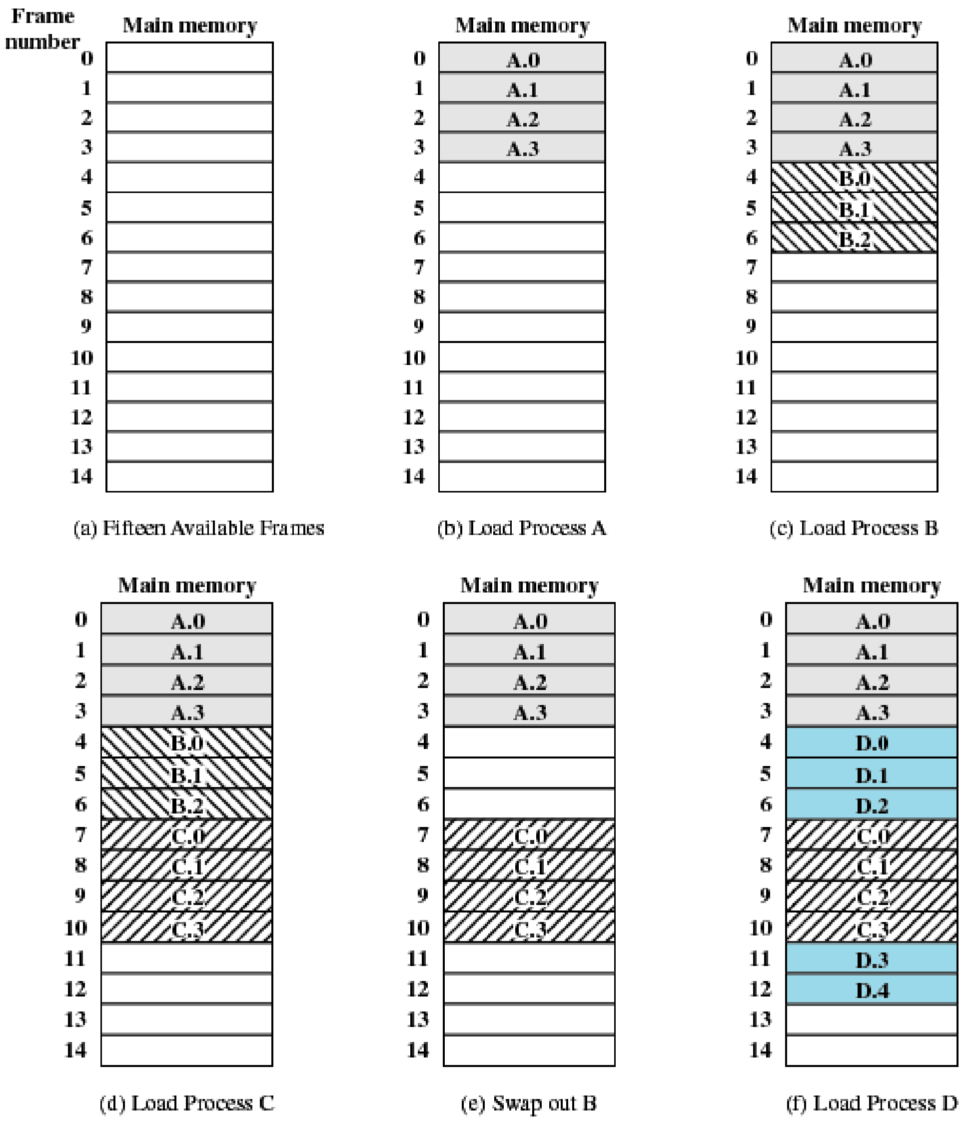
(a) – (d) Load processes A, B, and C

(e) Swap out process B

(f) Load process D

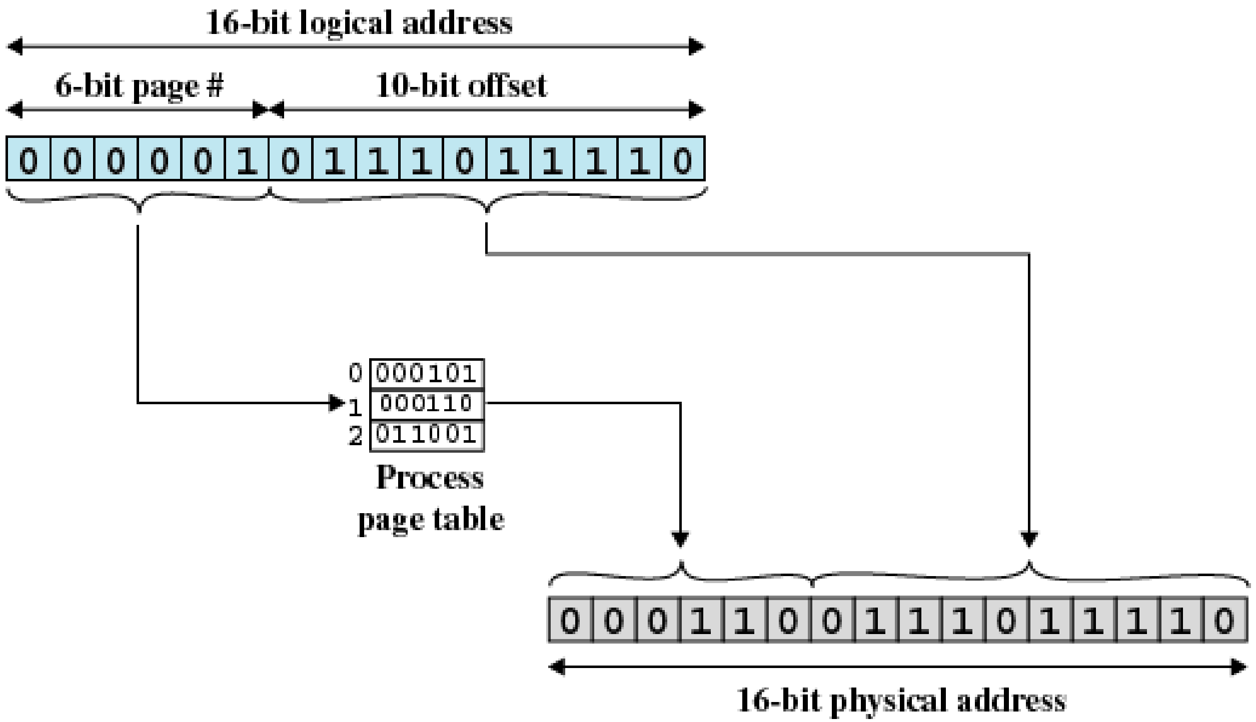
Page Tables



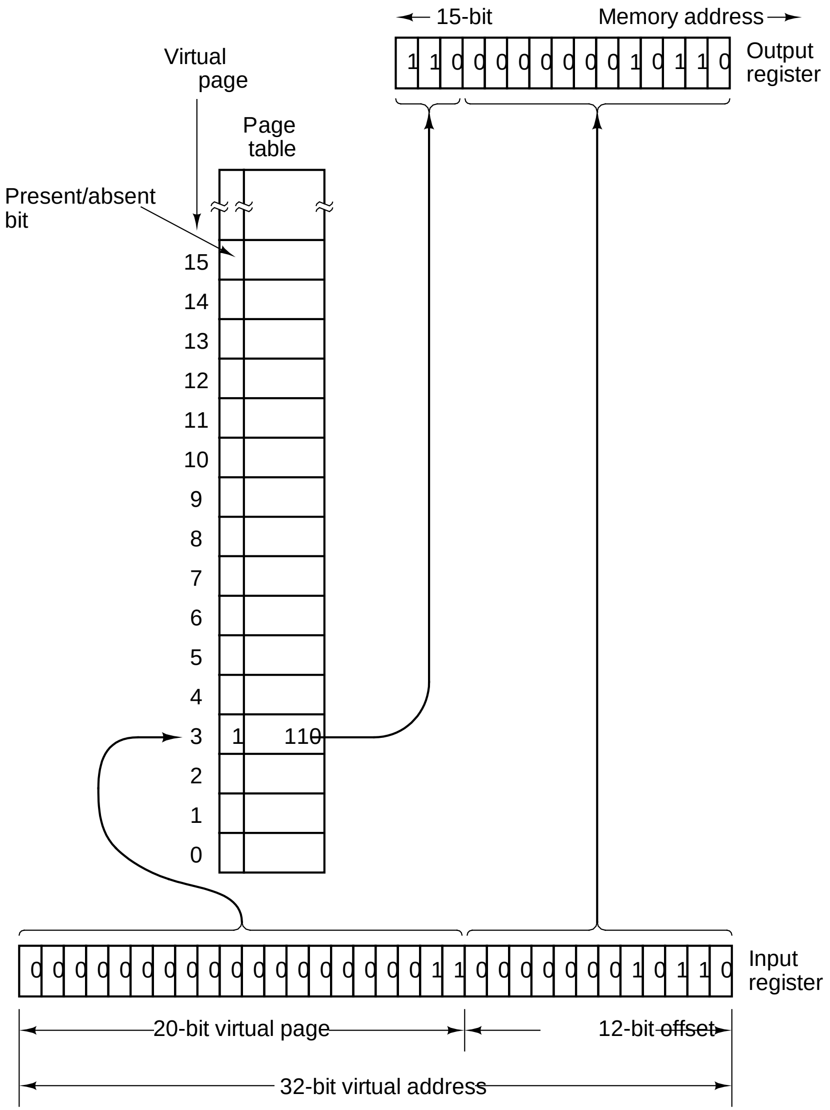


Addresses

Memory address consists of a page number and offset within the page



Translation of virtual to real addresses



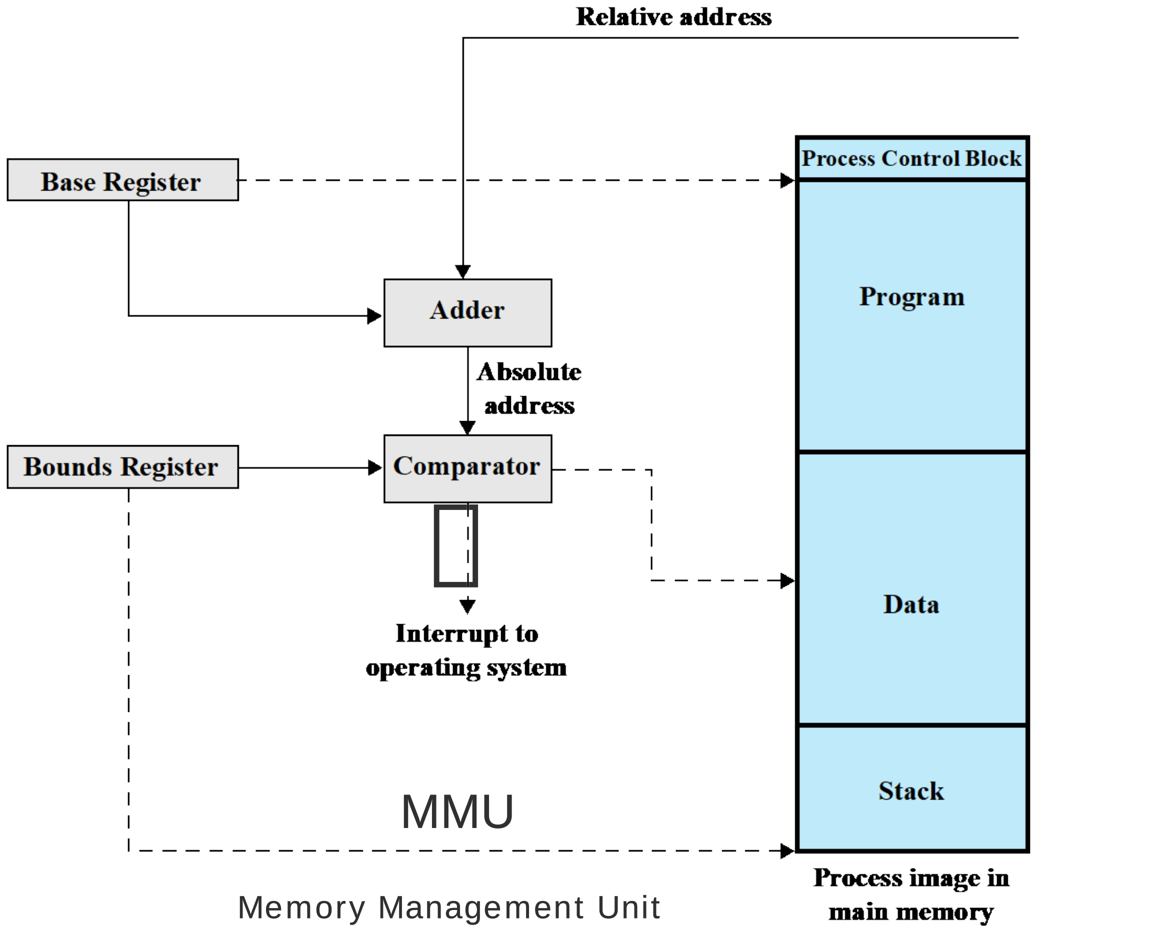
Hardware Support (MMU)

Base register (starting address for the process)

Bounds register (ending location of the process)

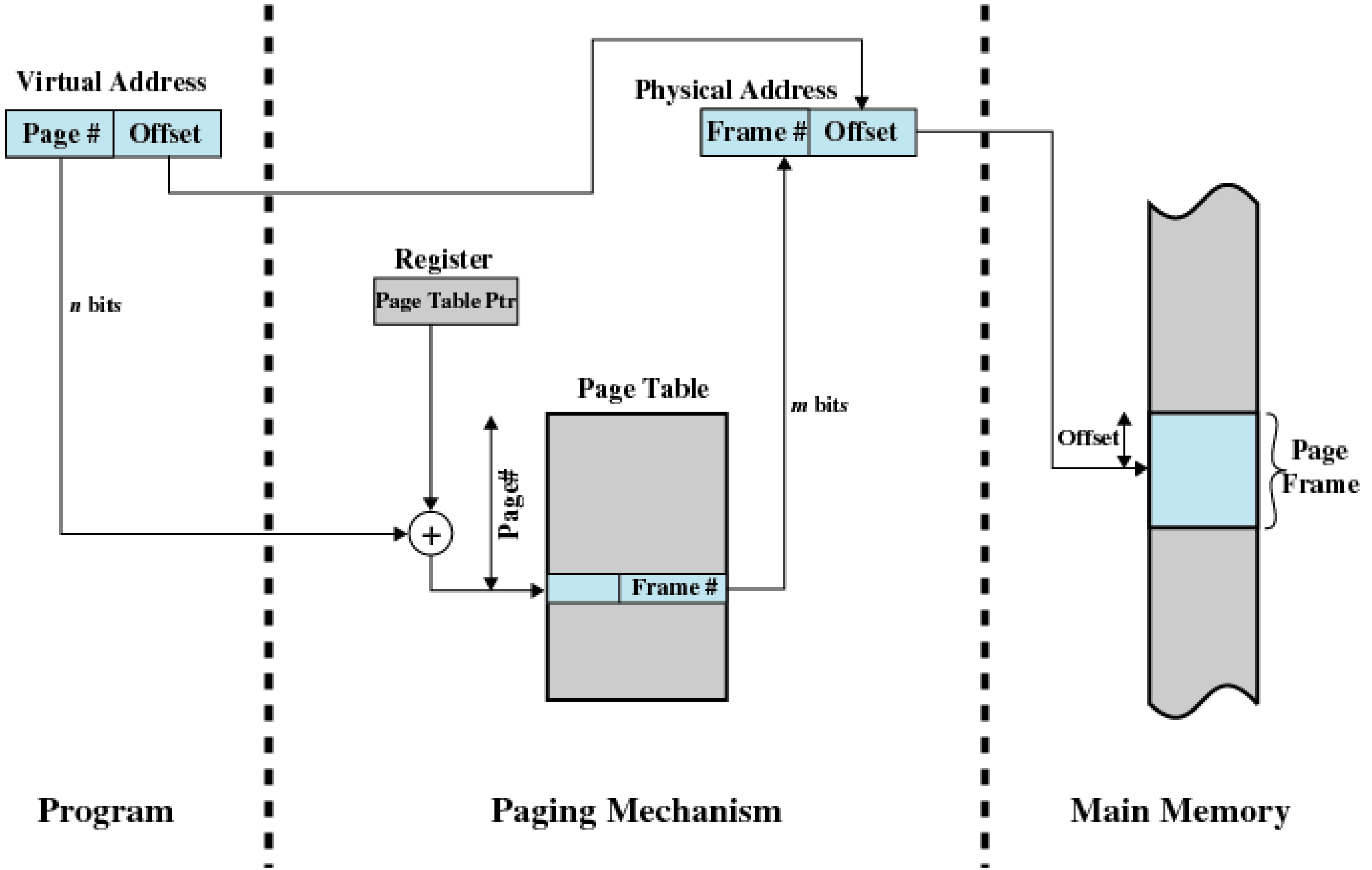
Registers are set when process is loaded

Bounds register is used for security purpose



Memory Management Unit

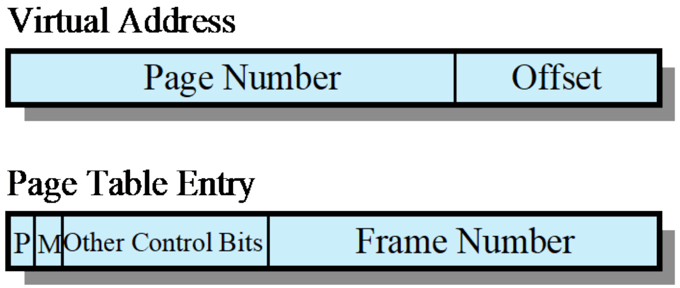
Paging Address Translation



Support Needed for Virtual Memory

Hardware Support

- Present bit: Page/segment is available in main memory
- Modified bit: Content of page/segment has been modified
- Implementation:
  - Paging:



(a) Paging only

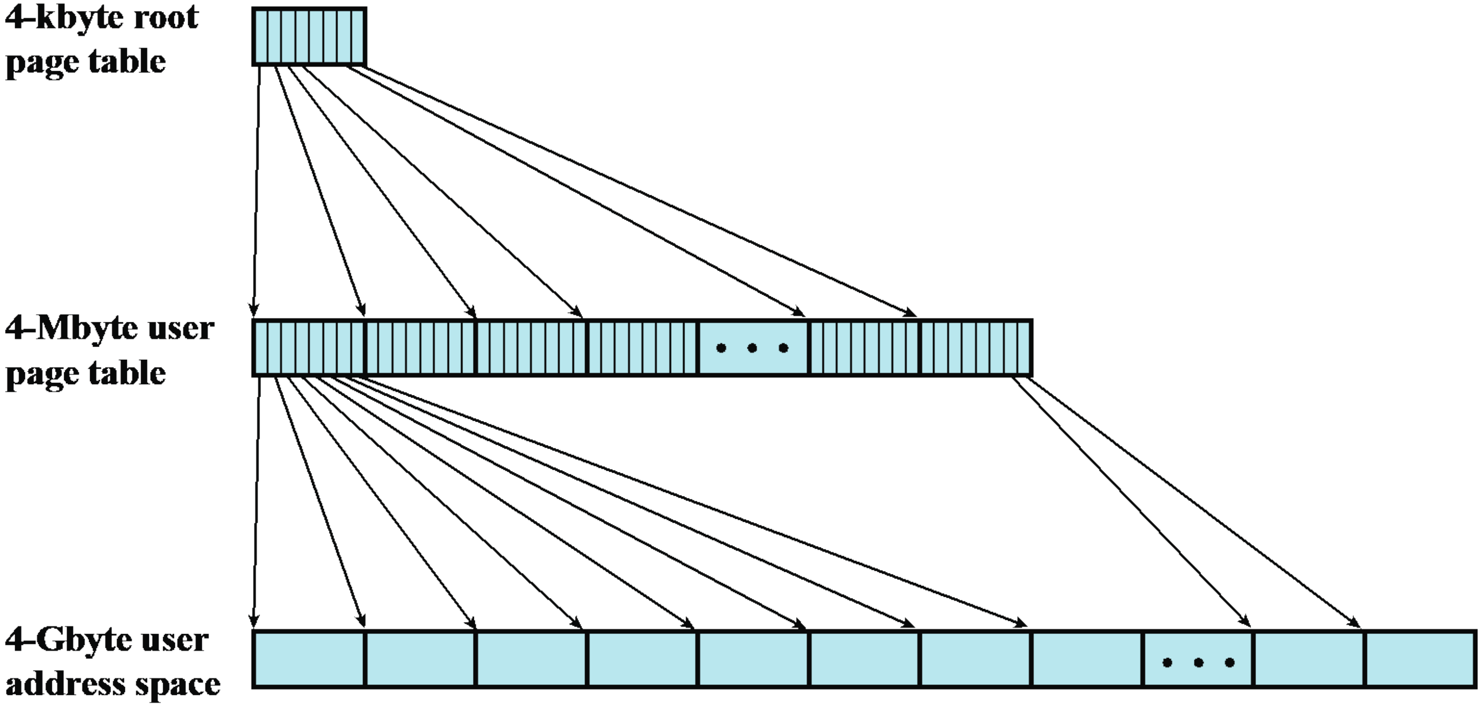
Other control bits:

- Write enabled
- Executable
- Shared between processes
- …

OS must be able to manage moving pages between primary and secondary memory

Hierarchical Page Table

Page table itself may grow to considerable size



Swap parts of page table to secondary storage

- Problem: One virtual memory reference may cause two physical memory accesses (one to fetch page table, one to fetch data)
- Performance penalty due to disk I/O delays

Translation Lookaside Buffer

Problem: How to know which pages are loaded and up to date?

- Translation Lookaside Buffer (TLB)
- Built into CPU
- Caches most recently used page table entries

Translation Lookaside Buffer

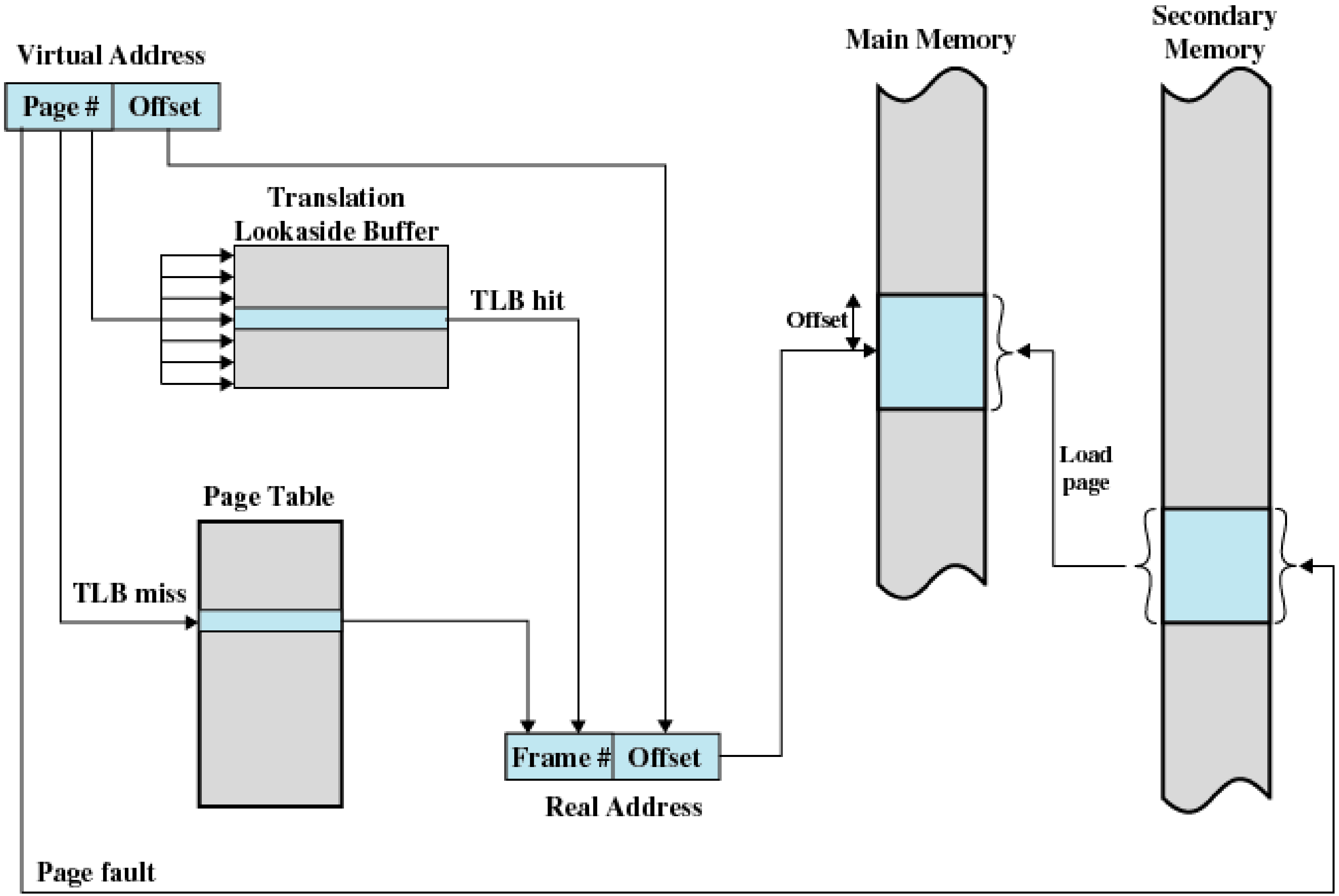
Basic steps:

1. Given a virtual address, processor examines TLB
   - If page table entry is present (TLB hit)
     - ➢ Retrieve frame number and form physical address
   - If page table entry is not found in TLB (TLB miss)
     - ➢ Fall back to process page table in main memory
       - For hierarchical page tables, possibly start recursion

2. OS checks if page is present in main memory
   - If not, issue page fault and fetch page from disk

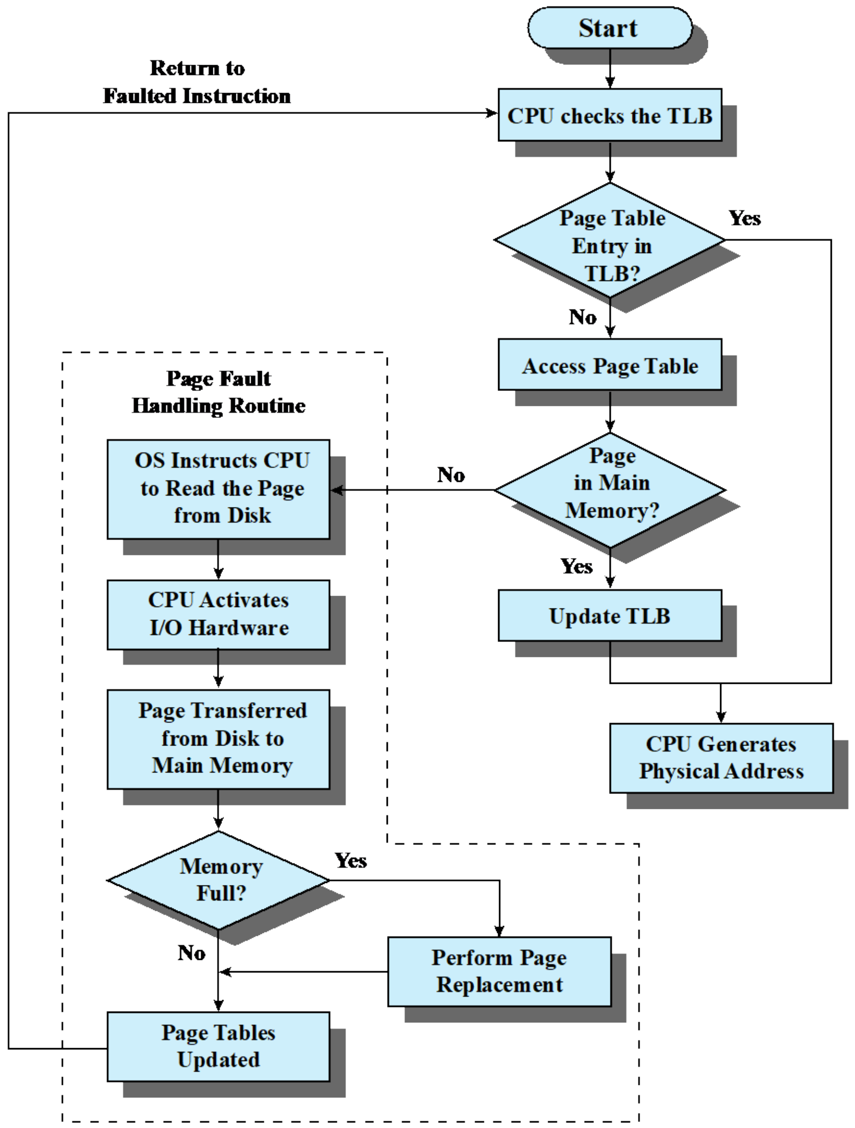
3. Update TLB to include new page entry

Translation Lookaside Buffer

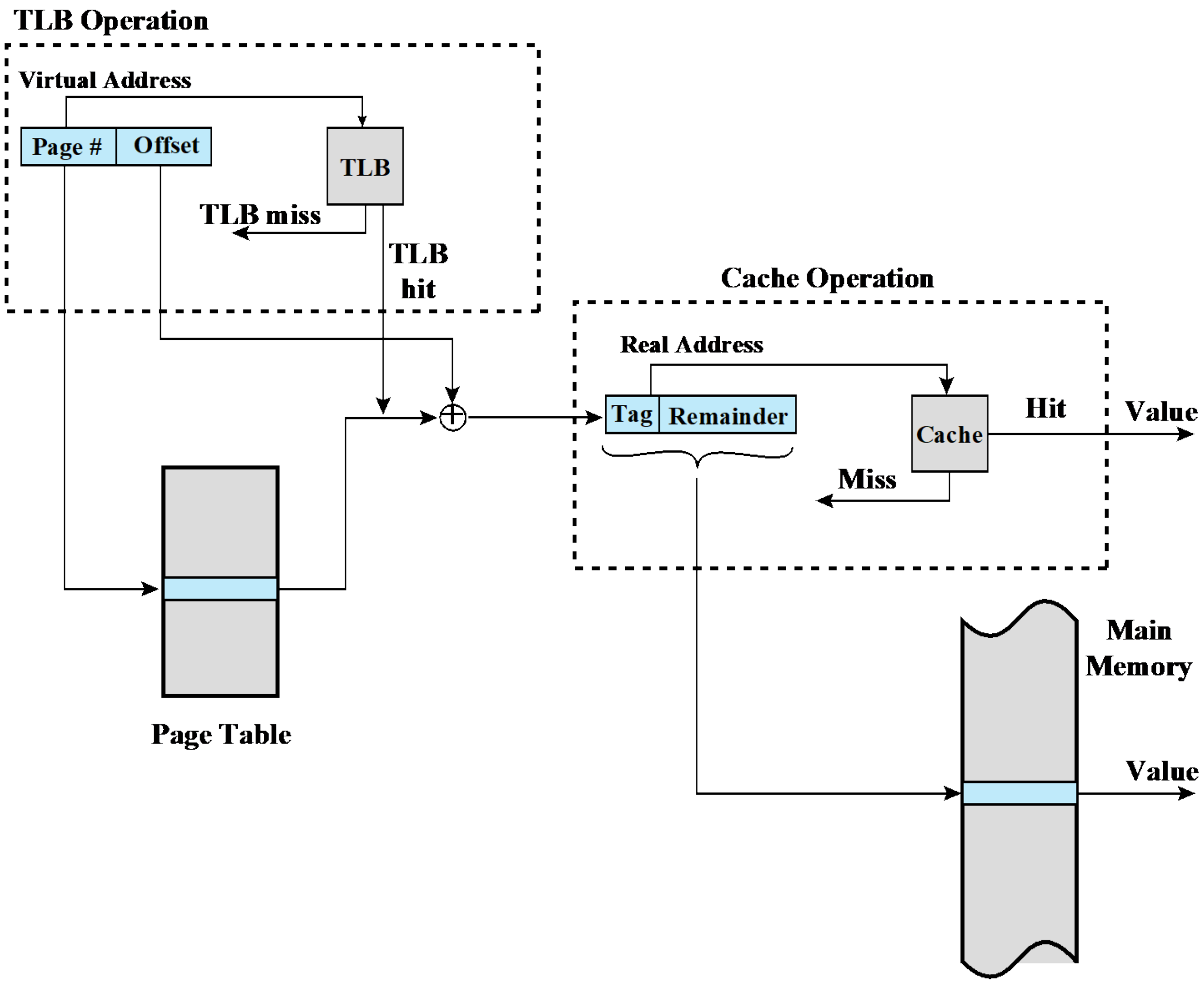


Translation Lookaside Buffer

Operation of Paging and Translation Lookaside Buffer



Translation Lookaside Buffer



Questions & Tasks

- Does it “hurt” (in terms of performance) if a process is distributed over several non-continuous pages?
  - i.e. is memory defragmentation necessary? Explain difference to hard disk!
- Who calls the operating system if a page is not present in main memory? What happens to the process?
- Who “informs” the process if the needed page is available?
- How can the operating system speed-up the page table look-ups?
- What is the role of an MMU?

Paging

PAGE SIZE

Page Size

Smaller page size …

- less amount of internal fragmentation
- more pages required per process
- large number of pages will be found in main memory

More pages per process means larger page tables

- large portion of page tables in virtual memory
- secondary memory is designed to efficiently transfer large blocks of data so a large page size is better

With time pages in memory will contain portions of the process near recent references

- Page faults low

Increased page size causes pages to contain locations further from any recent reference

- Page faults rise

Page Size

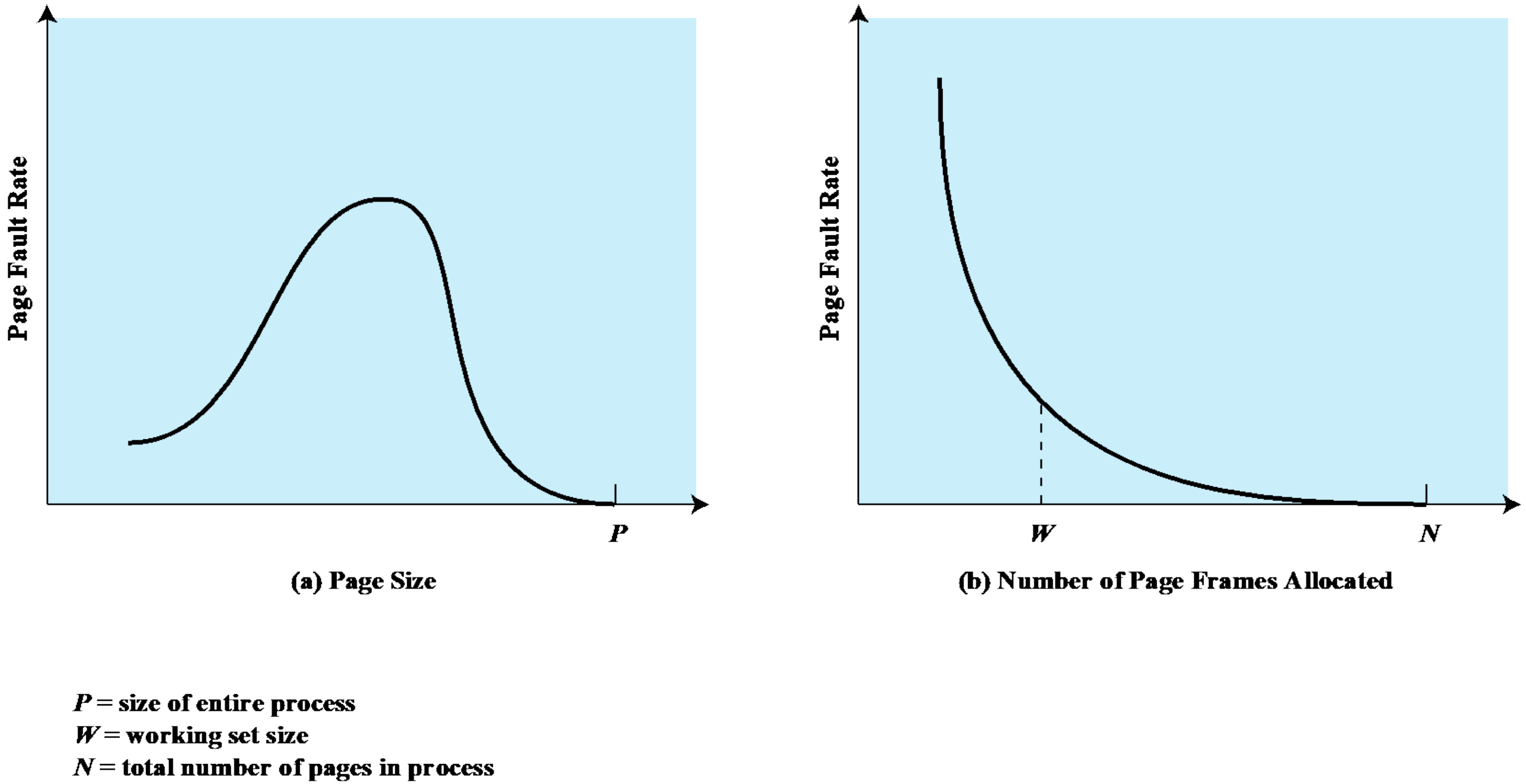


Figure 8.11 Typical Paging Behavior of a Program

Example Page Sizes

Architecture	Smallest page size	Larger page sizes
x86 (classical 32 bit)	4 kbyte	2 Mbyte, 4 Mbyte
x86-64 (64 bit)	4 kbyte	2 Mbyte, 1 Gbyte
IA-64 (Itanium, VLIW)	4 kbyte	8 / 64 / 256 kbyte, 1 / 4 / 16 / 256 Mbyte
SPARC v8	4 kbyte	256 kbyte, 16 Mbyte
UltraSPARC	8 kbyte	64 / 512 kbyte, 4 / 32 / 256 Mbyte, 2 / 16 Gbyte
ARMv7	4 kbyte	64 kbyte, 1 / 16 Mbyte
Power	4 kbyte	64 kbyte, 16 Mbyte, 1 Gbyte

Paging

PAGE REPLACEMENT

Problem: Thrashing

VM Thrashing

Page/segment of process is swapped out *just before* its needed

- Happens under memory pressure, i.e., too many resource-hungry processes running on too little main memory

Processor spends most of its time swapping pages/segments rather than executing user instructions

- ➢ Computer stalls with heavy disk I/O

➢ Solution: “Good” page replacement policies

- Principle of Locality:
    - Program and data references within a process tend to cluster
    - Possible to make intelligent guesses about which pieces will be needed in the future

Algorithms / Policies

Fetch Policy

Which page should be swapped in? When?

Alternatives

- Demand paging:
  - only brings pages into main memory when reference is made to address on page
- Prepaging:
  - brings in more pages than needed
  - anticipates future requests

Replacement Policy

Which page should be swapped out / replaced?

Approaches

- Remove page that is least likely to be referenced in near future
- Most policies predict future behavior on basis of past behavior, e.g.
  - First-In, First Out (FIFO)
  - Not Recently Used (NRU)
  - Least Recently Used (LRU)
  - ...

Some Basic Replacement Algorithms

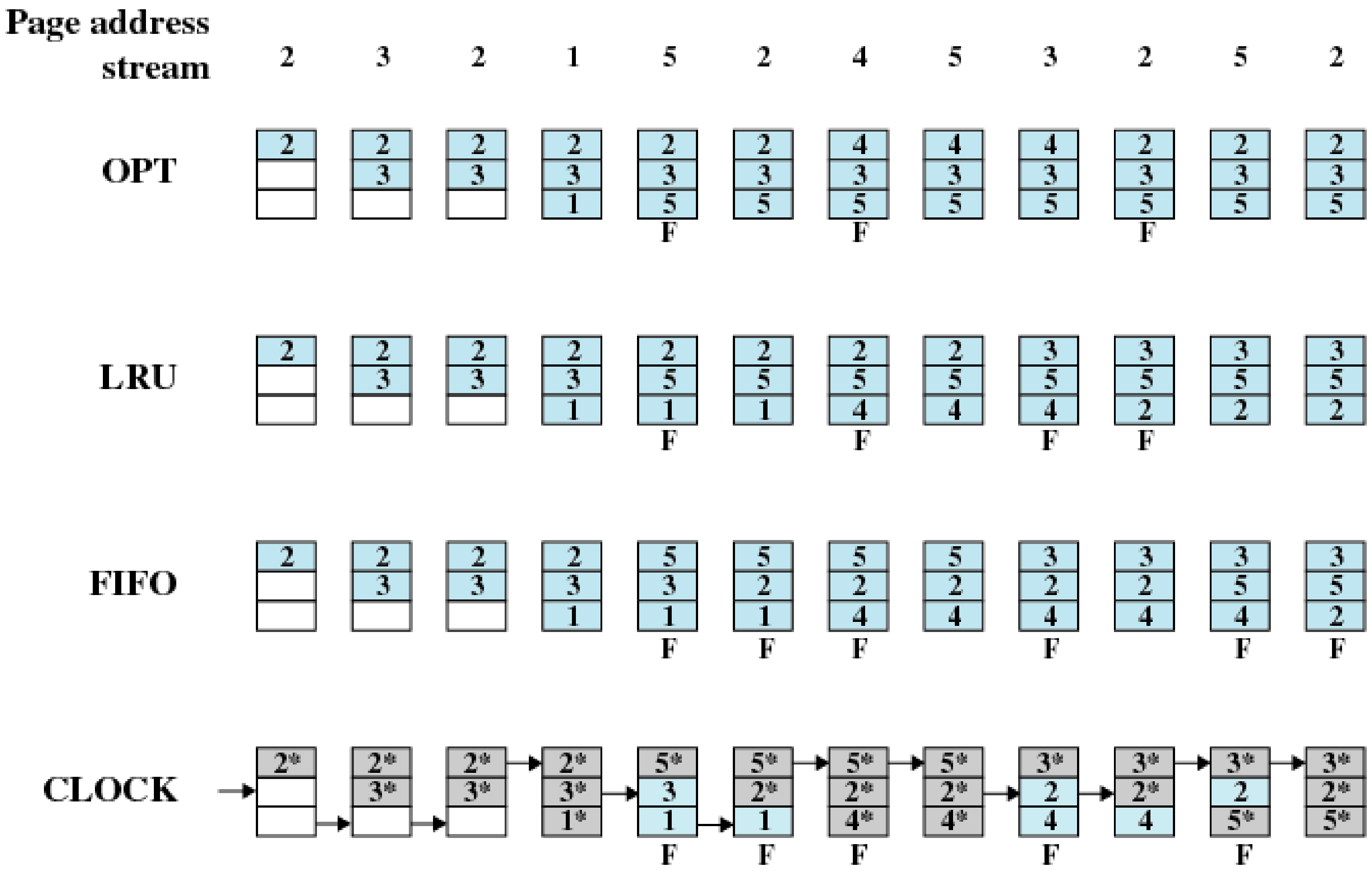
Optimal policy (for reference *only*)
- Selects page for which time to next reference is longest
- ➢ *Impossible* to have perfect knowledge of future events

Least Recently Used (LRU)
- Replaces page that has not been referenced for longest time
- By principle of locality, least likely to be referenced in near future

First-in, First-out (FIFO)
- Treats page frames allocated to a process as circular buffer
- Pages are removed in round-robin style
- Page that has been in memory the longest is replaced (but may be needed soon)

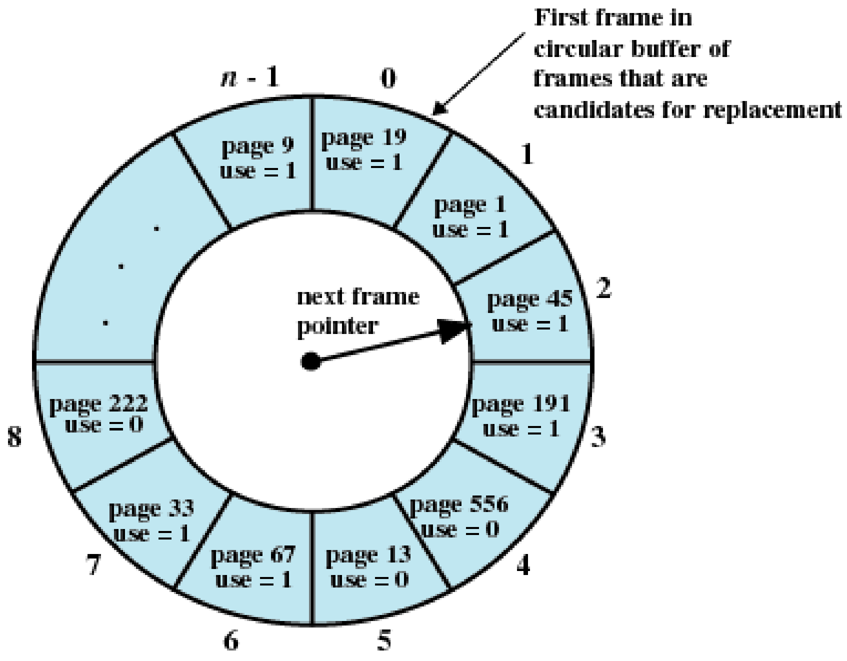
Clock Policy
- When a page is first loaded in memory, *use bit* is set to 1
- When page is referenced, use bit is set to 1
- During search for replacement, each use bit is changed to 0
- When replacing pages, first frame with use bit set to 0 is replaced

Page Replacement Example

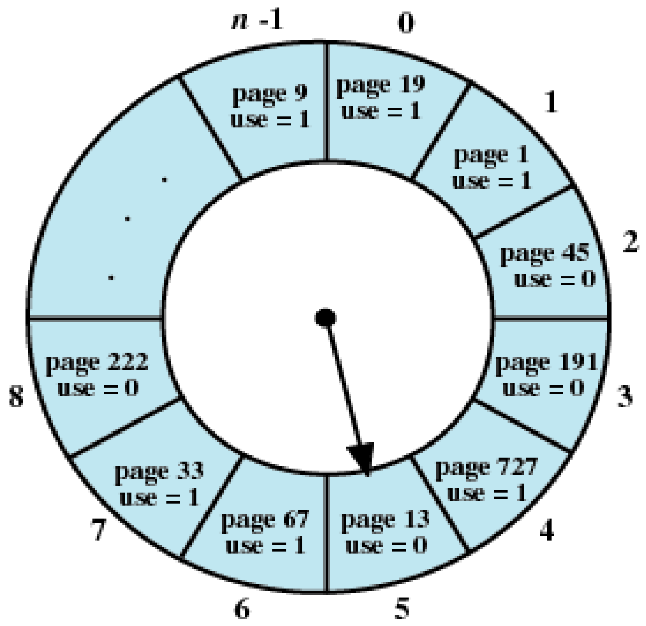


F = page fault occurring after the frame allocation is initially filled

Page Replacement Example

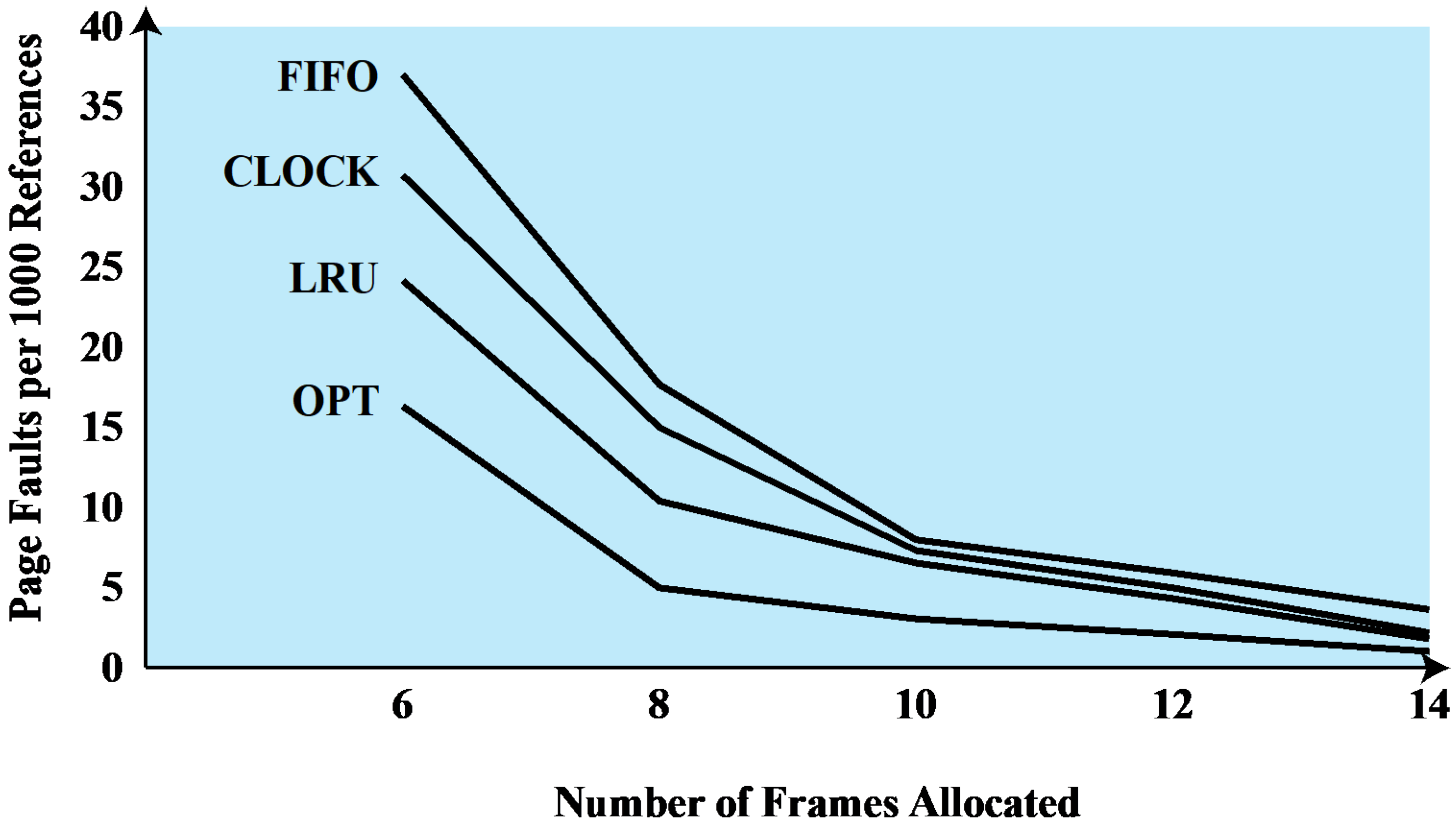


(a) State of buffer just prior to a page replacement



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

Comparison of Placement Algorithms



Paging

RESIDENT SIZE

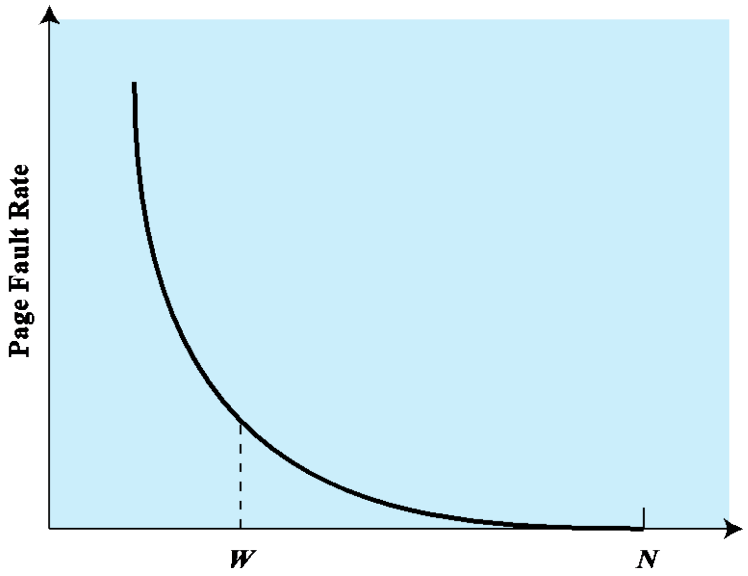
Resident Set Size

Fixed-allocation

- Gives a process a fixed number of pages
- When a page fault occurs, one of the pages of that process must be replaced

Variable-allocation

- Number of pages varies over the lifetime of the process



(b) Number of Page Frames Allocated

Resident Set Size

Decide ahead of time the amount of allocation to give a process

- If allocation is too small, there will be a high page fault rate
- If allocation is too large there will be too few programs in main memory

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Resident Set Size

Working Set of a process: set of pages of the process that have been referenced in the last *t* time units

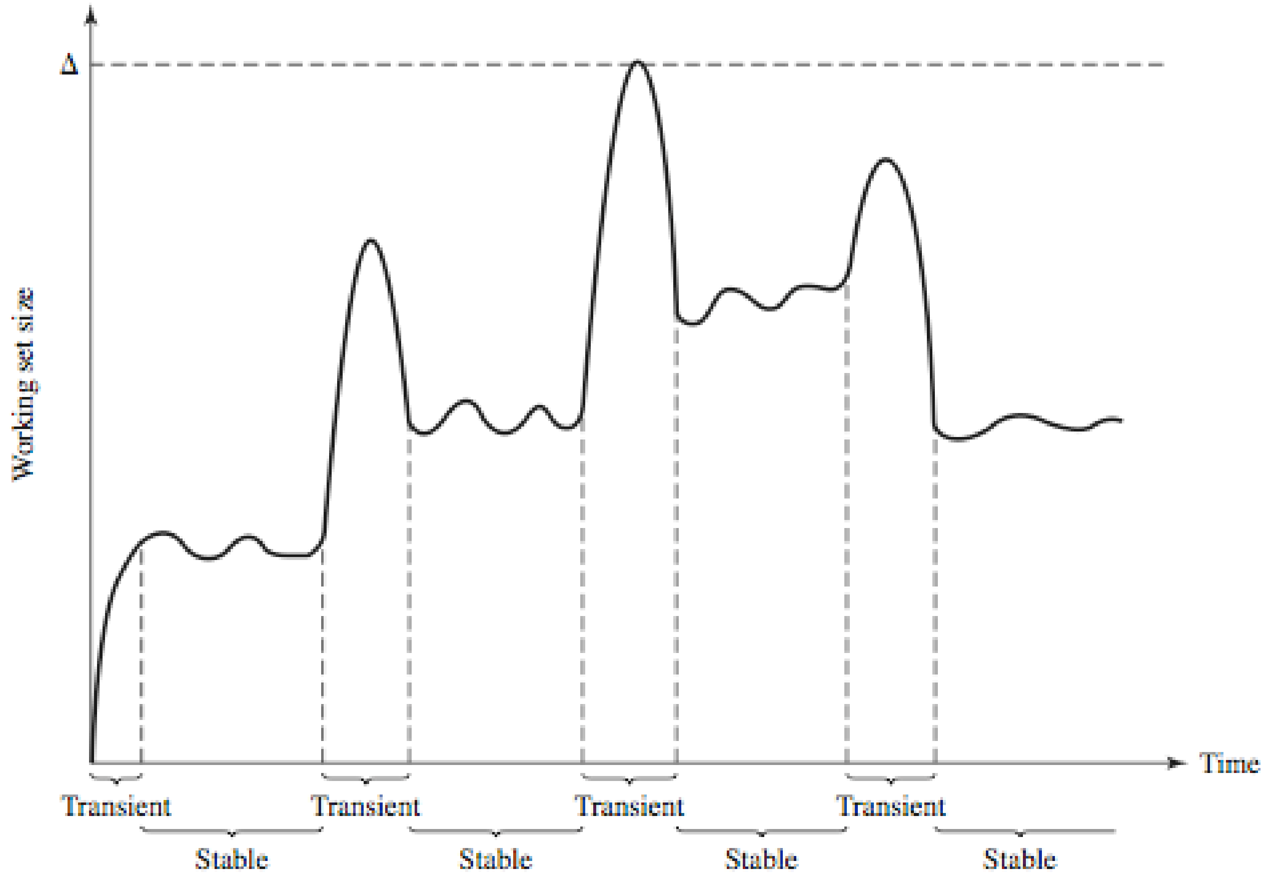


Figure 8.20 **Typical Graph of Working Set Size [MAEK87]**

Working Set

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

Figure 8.19 Working Set of Process as Defined by Window Size

Load Control

Determines the number of processes that will be resident in main memory

Too few processes, many occasions when all processes will be blocked and much time will be spent in swapping

Too many processes will lead to thrashing

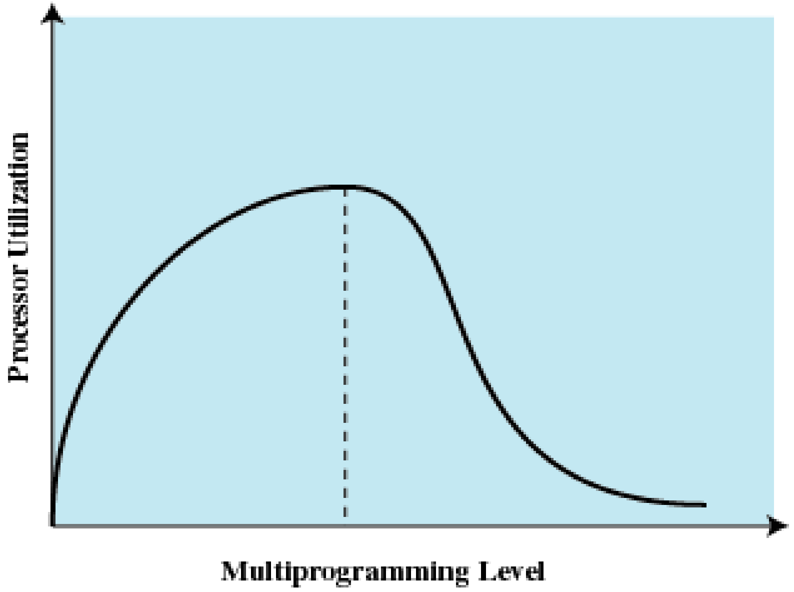


Figure 8.21 Multiprogramming Effects

Segmentation

All segments of all programs do not have to be of the same length

There is a maximum segment length

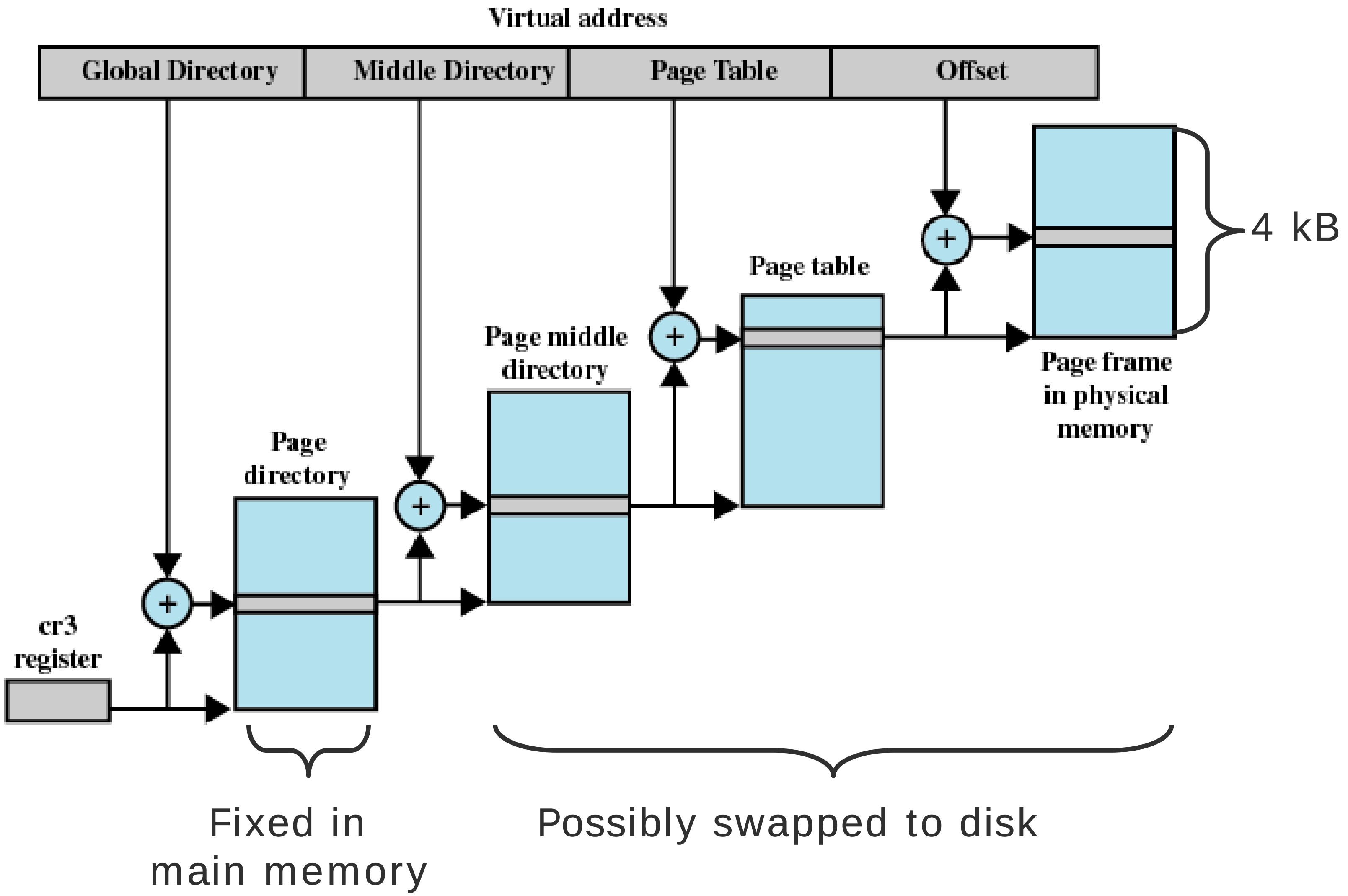
Addressing consist of two parts - a segment number and an offset

Since segments are not equal, segmentation is similar to dynamic partitioning

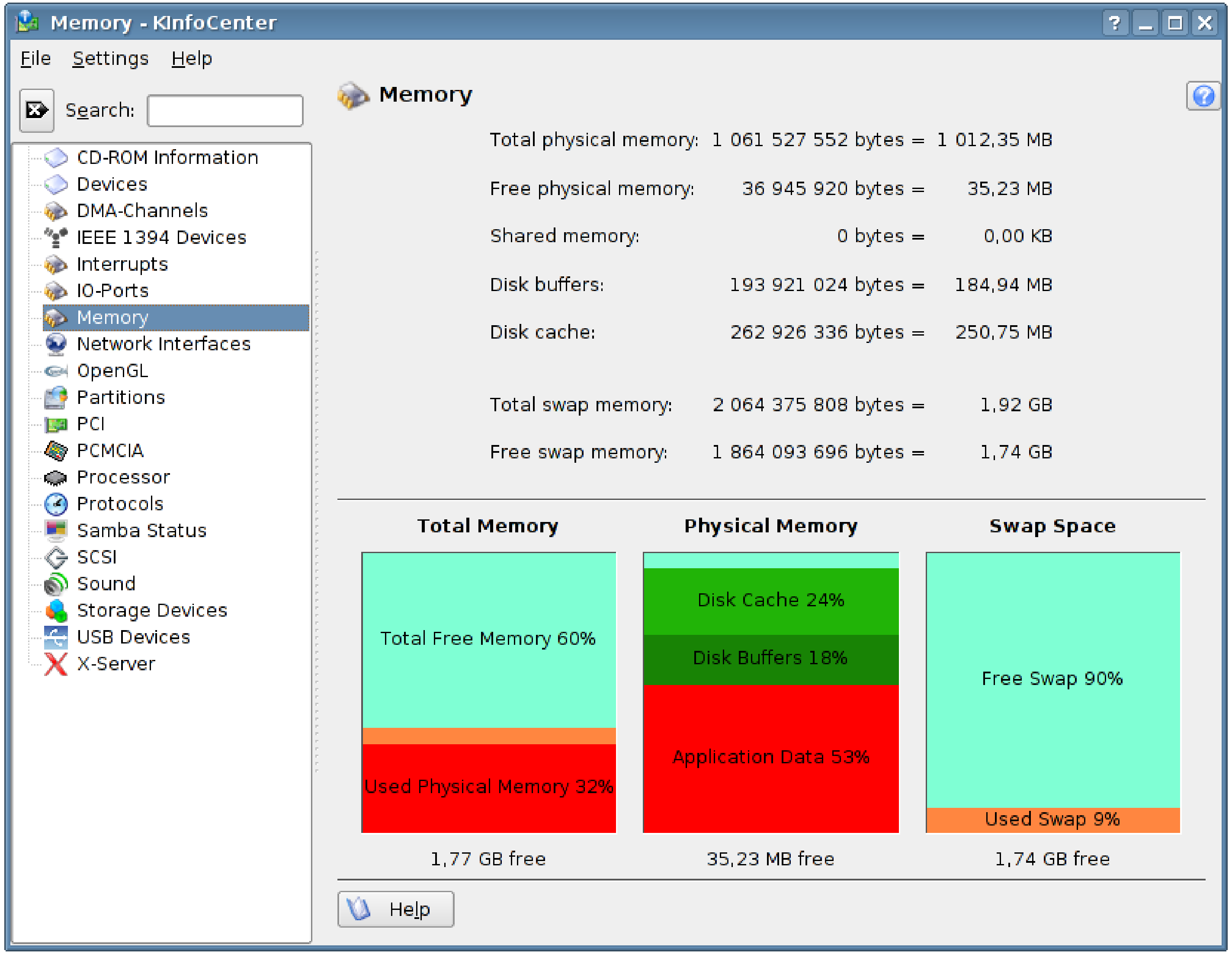
Questions & Tasks

- Where else do you know the “Principle of Locality” from? Which elements of a computer do also benefit from this principle?
- How do you as a user recognize VM thrashing?
- Can the OS swap out all pages?
- Is the replacement algorithm relevant for larger number of allocated frames in memory processes? Why?

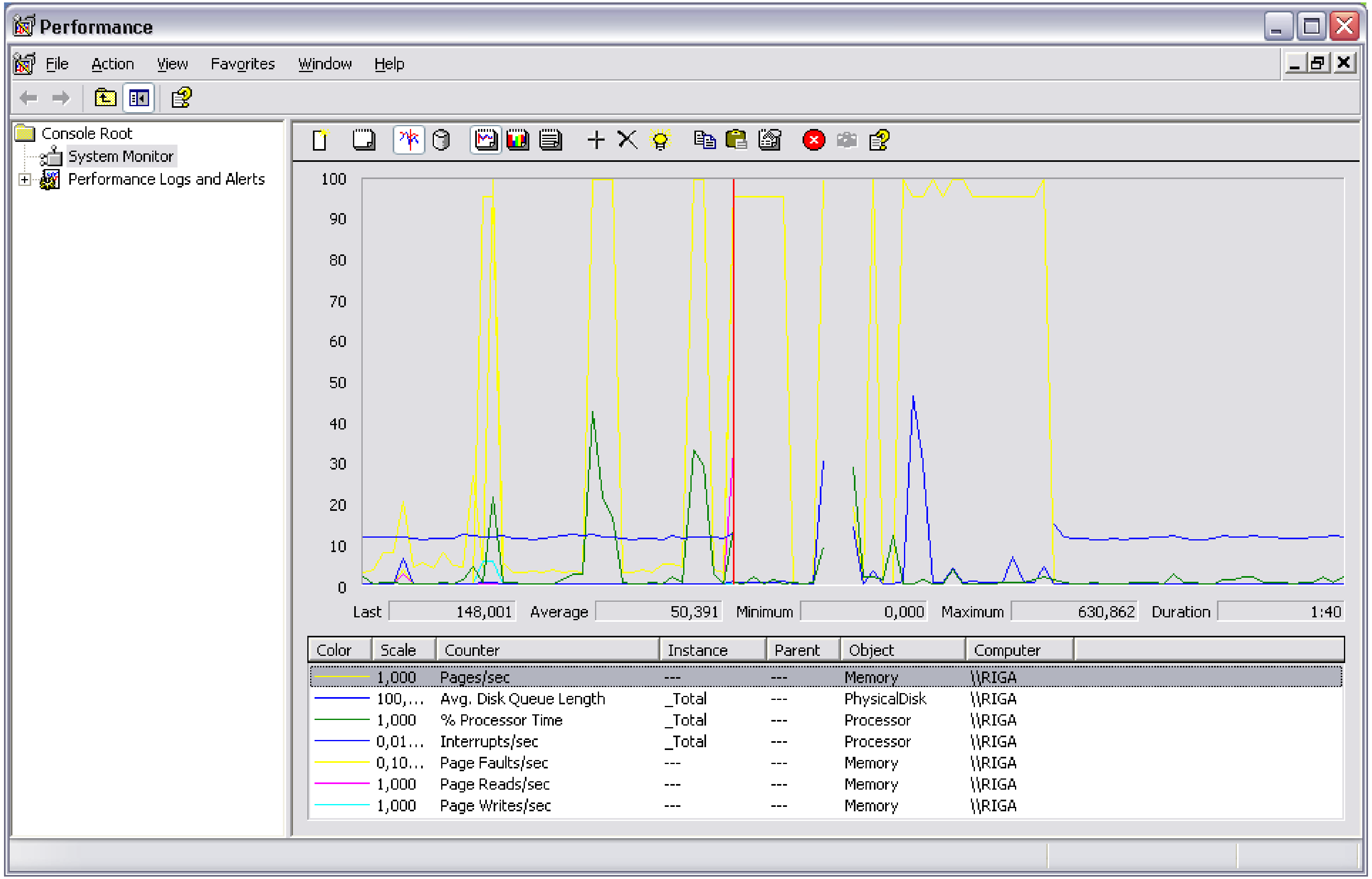
Example: Linux VM Implementation



Example: Linux Memory Utilization



Example: Windows Paging (perfmon)



Related System Calls (Linux)

`int brk(void *end_data_segment)`

- Sets end of data segment of process to **`end_data_segment`**

`void *sbrk(intptr_t increment)`

- Increments the program's data space by **`increment`** bytes

`void *mmap(void *start, size_t length, int prot, int flags, int fd, off_t offset)`

- Maps **`length`** bytes of file descriptor **`fd`** to address **`start`**
- With flag **`MAP_ANONYMOUS`** no actual file is needed

`int munmap(void *start, size_t length)`

- Deletes mapping to specified address

Related Library Wrappers

`void *malloc(size_t size)`

- Allocates **`size`** bytes and returns pointer
- Returns NULL if no memory is available

`void free(void *ptr)`

- Frees memory pointed to by **`ptr`**

`void *calloc(size_t nmemb, size_t size)`

- Allocates and zeroes memory for **`nmemb`** elements of size **`size`** bytes

`void *realloc(void *ptr, size_t size)`

- Changes size of previously allocated memory at **`ptr`** to **`size`** bytes

Content

1. Introduction and Motivation
2. Subsystems, Interrupts and System Calls
3. Processes
4. **Memory**
5. Scheduling
6. I/O and File System
7. Booting, Services, and Security