Operating Systems Concepts

Main Memory: Address Translation

CS 4375, Fall 2025
Instructor: MD Armanuzzaman (***Arman***)
marmanuzzaman@utep.edu
October 6, 2025

Summary

- Address Space
- Virtual memory
- Linux Memory APIs
  - malloc(), free()
- Example Code

Agenda

- Main Memory:
  - Fixed and Dynamic Memory Allocation
  - External and Internal Fragmentation
  - Address Binding
  - Hardware Address Protection
  - Paging
  - Segmentation

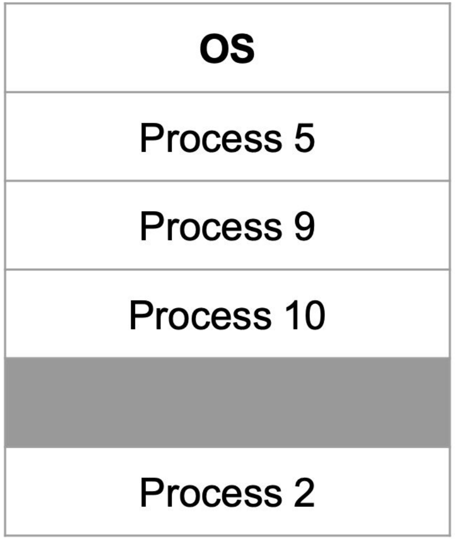
Memory Management

- Memory needs to be subdivided to accommodate multiple processes
- Memory management is an optimization task under constraints
- Movement between levels of storage hierarchy:

Level	1	2	3	4	5
Name	registers	cache	main memory	solid state disk	magnetic disk
Typical size	< 1 KB	< 16MB	< 64GB	< 1 TB	< 10 TB
Implementation technology	custom memory with multiple ports CMOS	on-chip or off-chip CMOS SRAM	CMOS SRAM	flash memory	magnetic disk
Access time (ns)	0.25 - 0.5	0.5 - 25	80 - 250	25,000 - 50,000	5,000,000
Bandwidth (MB/sec)	20,000 - 100,000	5,000 - 10,000	1,000 - 5,000	500	20 - 150
Managed by	compiler	hardware	operating system	operating system	operating system
Backed by	cache	main memory	disk	disk	disk or tape

Memory Allocation

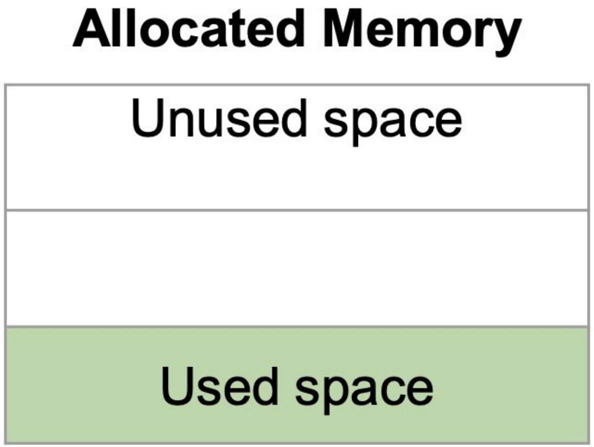
- Fixed-partition allocation
  - Divide memory into fixed-size partitions
  - Each partition contains exactly one process
  - The degree of multiprogramming is bound by the number of partitions
  - When a process terminates, the partition becomes available for other processes



- May lead to Internal Fragmentation– allocated memory may be slightly larger than **requested** memory; this size difference is memory **internal** to a partition, but not being **used**

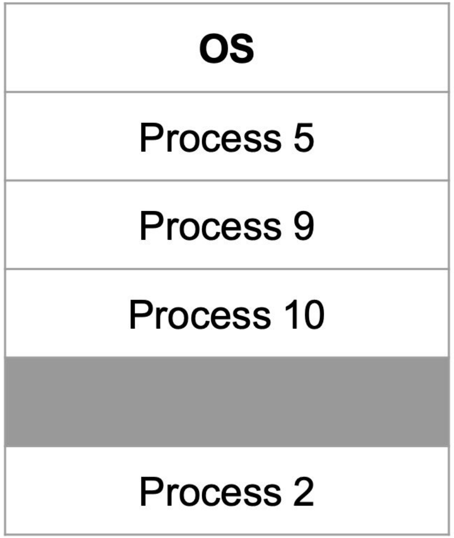
Memory Allocation

- May lead to Internal Fragmentation– allocated memory may be slightly larger than **requested** memory; this size difference is memory **internal** to a partition, but not being **used**



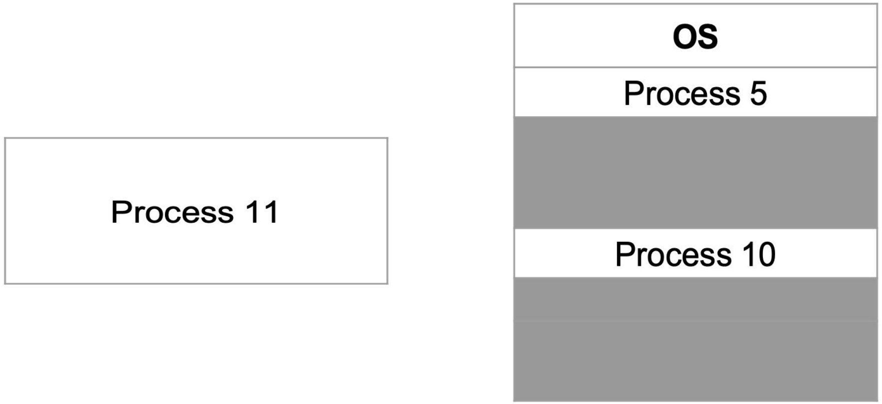
Memory Allocation

- Variable-partition Scheme (Dynamic)
  - When a process arrives, search for a hole large enough for this process
  - **Hole** – block of available memory; holes of various size are scattered throughout memory
  - Allocate only as much memory as needed
  - Operating system maintains information about:
    - allocated partitions
    - free partitions (hole)



Memory Allocation

- Can lead to External Fragmentation– total memory space exists to satisfy a request, but it is not contiguous (in average ~50% lost)



- Reduce external fragmentation by compaction
  - Shuffle memory contents to place all free memory together in one large block
  - Compaction is possible only if relocation is dynamic, and is done at execution time

Dynamic Storage-Allocation Problem

- How to satisfy a request of size n from a list of free holes?
    - **First-fit:** Allocate the first hole that is big enough
    - **Best-fit:** Allocate the smallest hole that is big enough; must search entire list, unless ordered by size. Produces the smallest leftover hole
    - **Worst-fit:** Allocate the largest hole; must also search entire list. Produces the largest leftover hole

- First-fit is faster
- Best-fit is better in terms of storage utilization
- Worst-fit may lead to less fragmentation

Dynamic Storage-Allocation Example

- Given five memory partitions of 100 KB, 500 KB, 200 KB, 300 KB, and 600 KB (in order), how would each of the first-fit, best-fit, and worst-fit algorithms place processes of 212 KB, 417 KB, 112 KB, and 426 KB (in order)?
- Which algorithm makes the most-efficient use of memory?

Dynamic Storage-Allocation Example

- Given five memory partitions of 100 KB, 500 KB, 200 KB, 300 KB, and 600 KB (in order), how would each of the first-fit, best-fit, and worst-fit algorithms place processes of 212 KB, 417 KB, 112 KB, and 426 KB (in order)?
- Which algorithm makes the most-efficient use of memory?

Available partitions after first fit: [100, 176, 200, 300, 183] KB [426 KB!!]

Available partitions after best fit: [100, 83, 88, 88, 174] KB

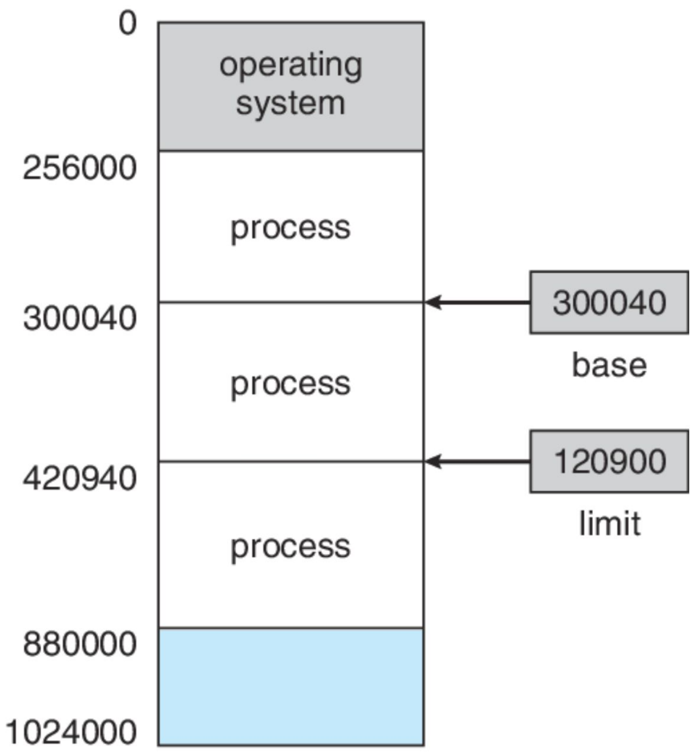
Available partitions after worst fit: [100, 83, 200, 300, 276] KB [426 KB!!]

Address Binding

- Addresses in a source program are generally symbolic
  - e.g. int count;
- A compiler binds these symbolic addresses to relocatable addresses
  - e.g. 100 bytes from the beginning of this module
- The linkage editor or loader will in turn bind the relocatable addresses to absolute addresses
  - e.g. 74014
- Each binding is mapping from one address space to another

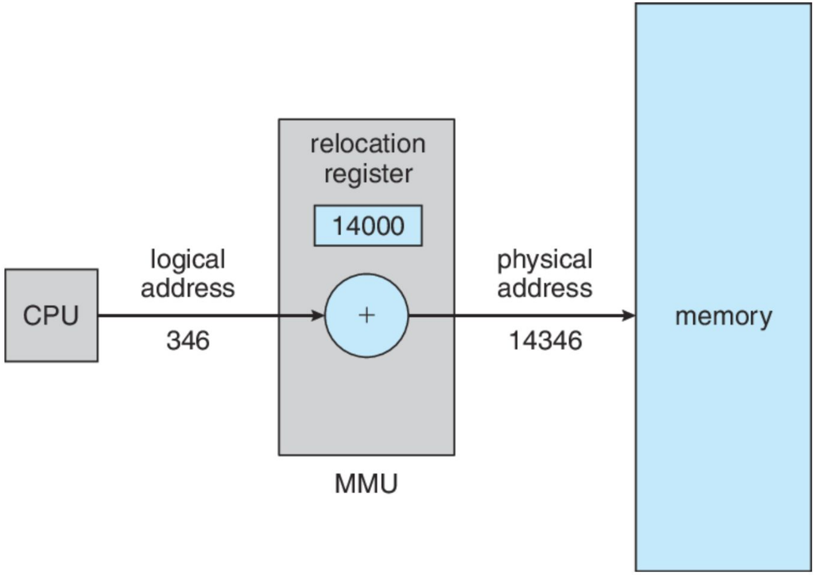
Logical Address Space

- Each process has a separate memory space
- Two registers provide address protection between processes:
  - Base register: smallest legal address space
  - Limit register: size of the legal range



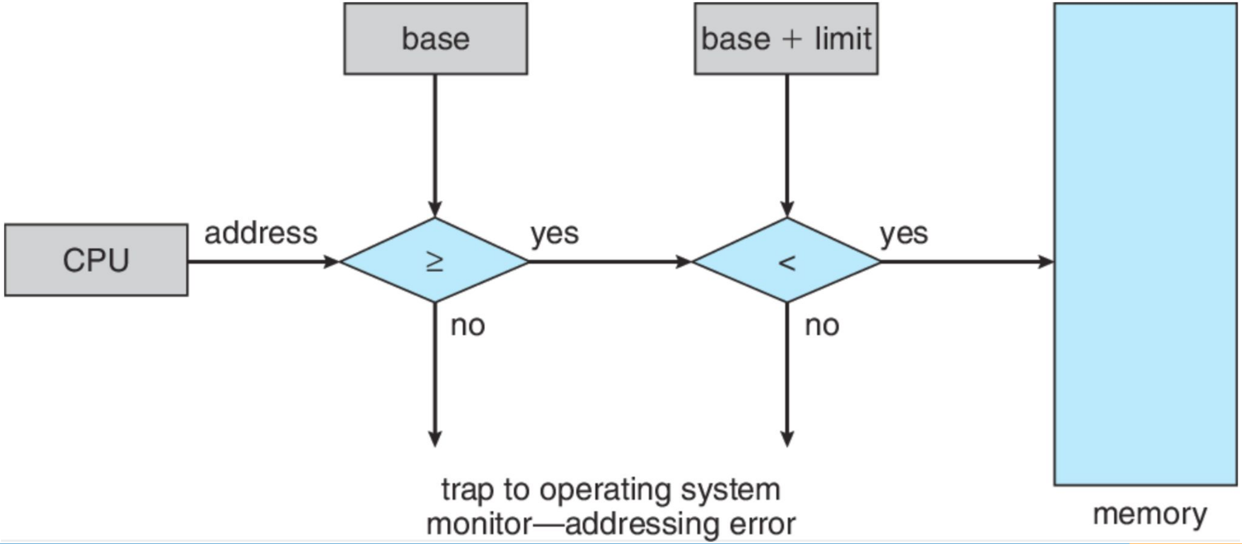
Memory-Management Unit (MMU)

- Hardware device that maps logical to physical address
- In MMU scheme, the value in the relocation register (base register) is added to every address generated by a user process at the time it is sent to memory
- The user program deals with logical addresses; it never sees the real physical addresses



Hardware Address Protection

- CPU hardware compares every address generated in user mode with the registers
- Any attempt to access other processes' memory will be trapped and cause a fatal error



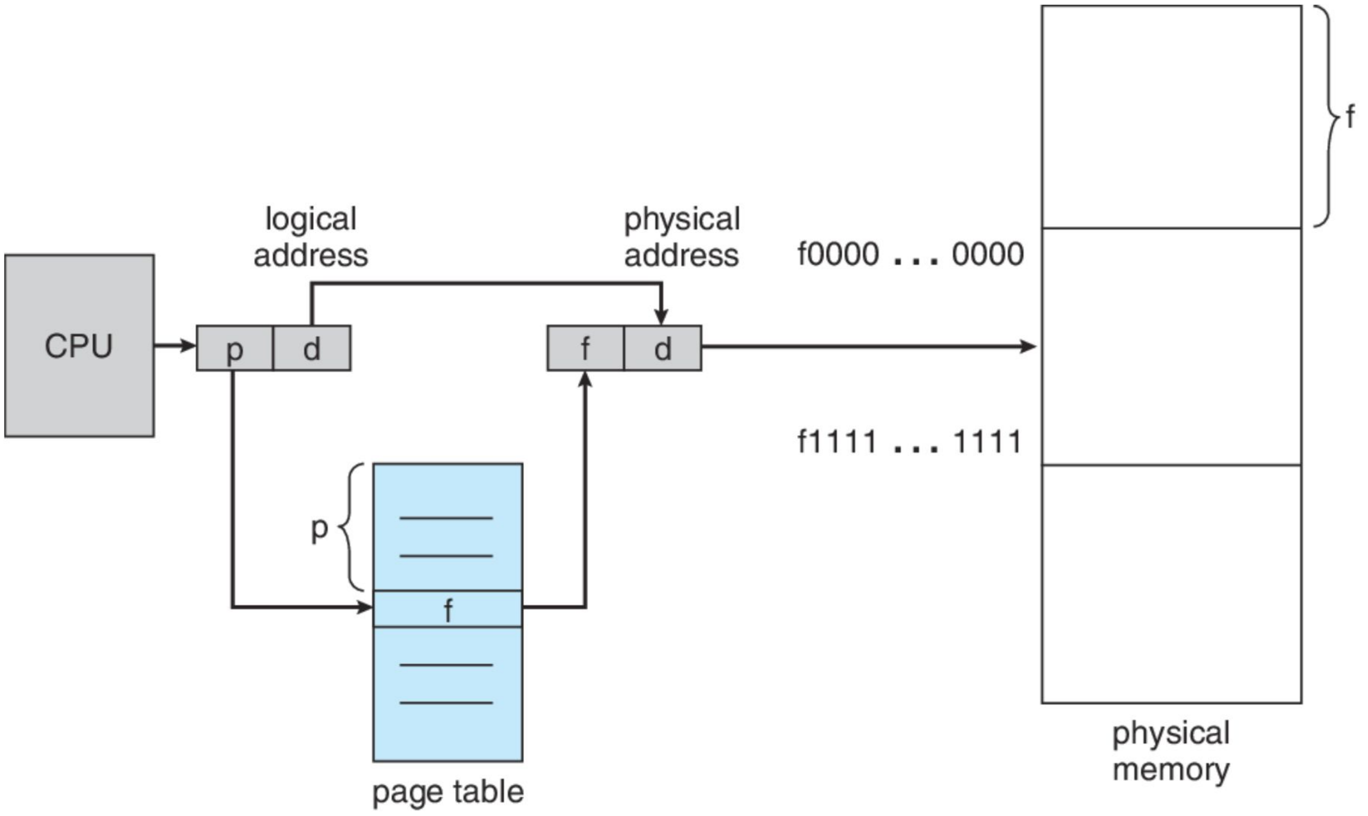
Paging - noncontiguous

- Physical address space of a process can be noncontiguous
- Divide physical memory into **fixed-sized blocks** called frames (size is power of 2, between 512 bytes and 16 megabytes)
- Divide logical memory into blocks of same size called pages
- Keep track of all free frames
- To run a program of size *n* pages, need to find *n* free frames and load program
- Set up a page table to translate logical to physical addresses
- Internal fragmentation

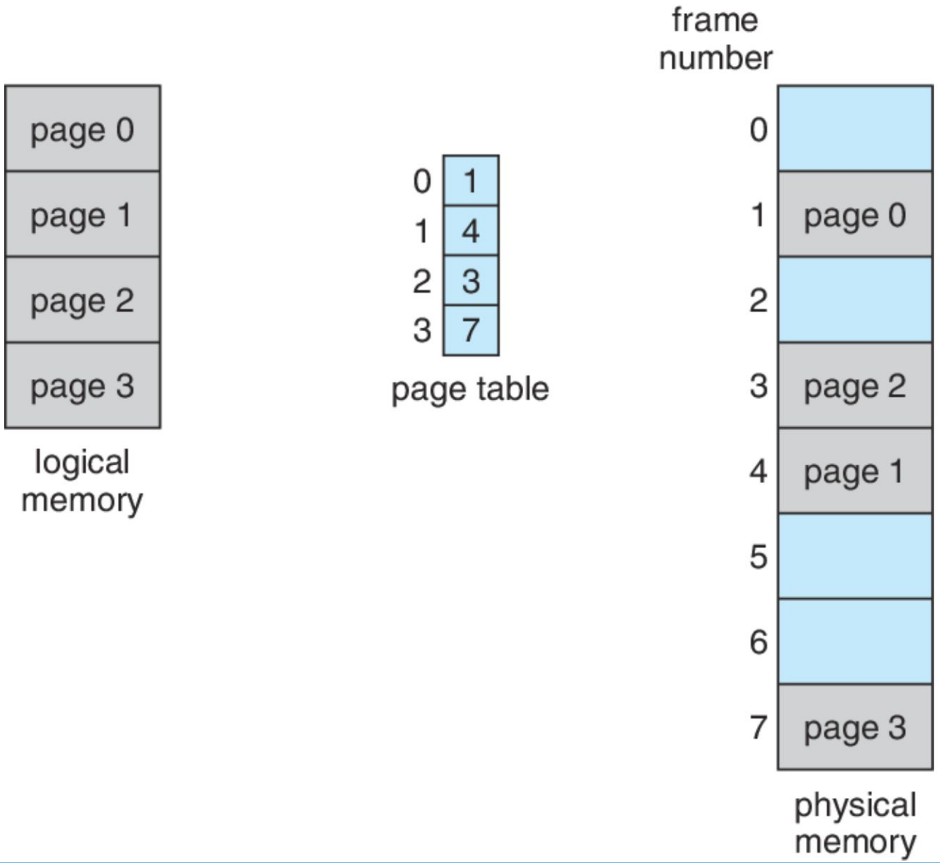
Paging Address Translation Scheme

- Address generated by CPU is divided into:
  - **Page number (p)**– used as an index into a page table which contains base address of each page in physical memory
  - **Page offset (d)**– combined with base address to define the physical memory address that is sent to the memory unit

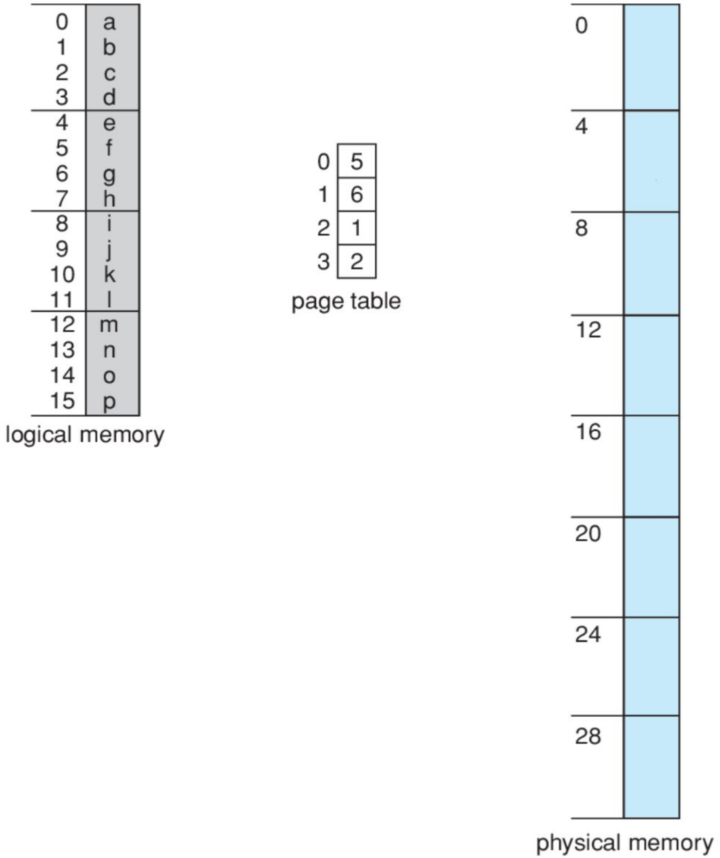
Address Translation Architecture



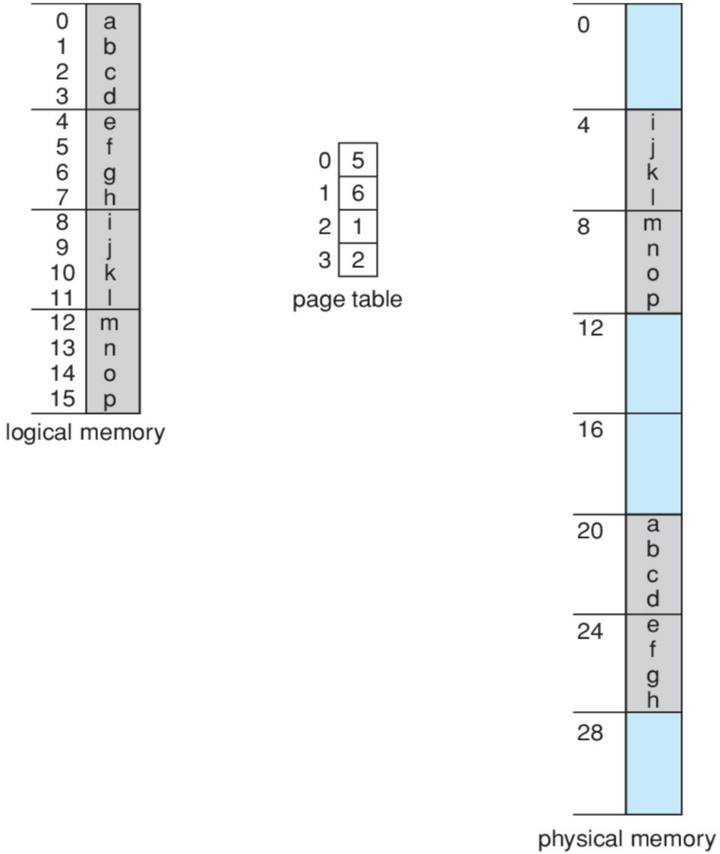
Paging Example



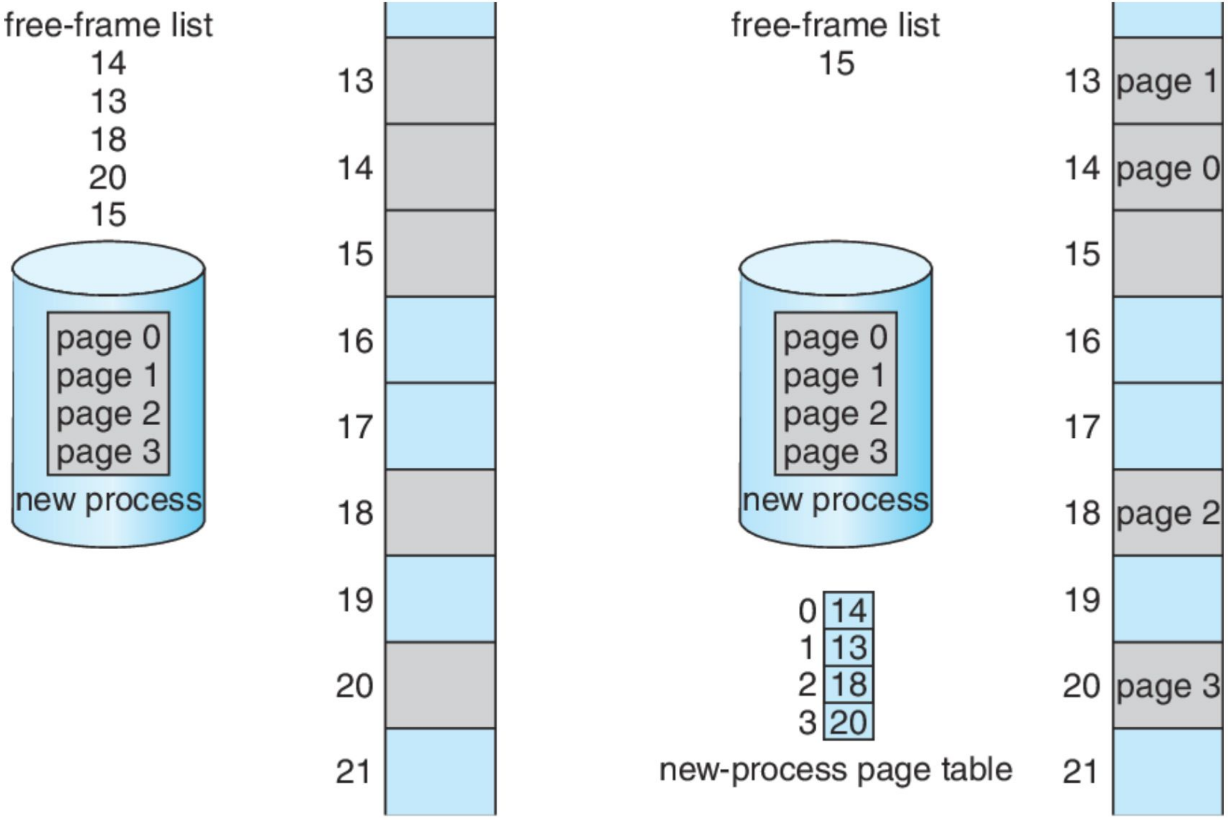
Paging Example



Paging Example



Free Frames

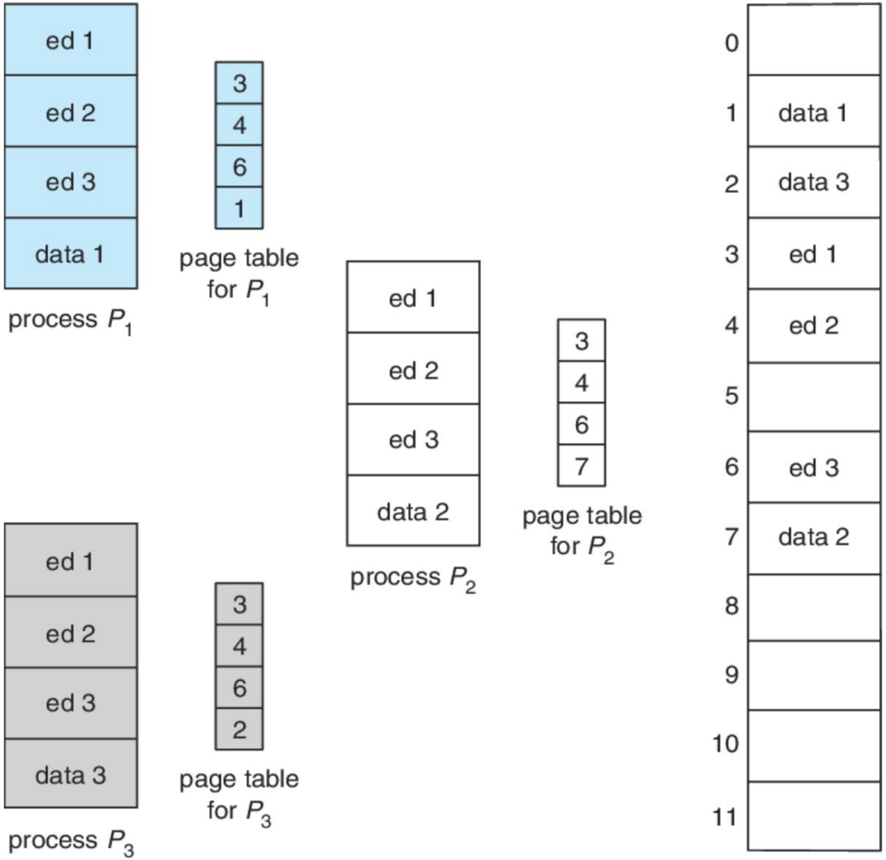


(a) (b)

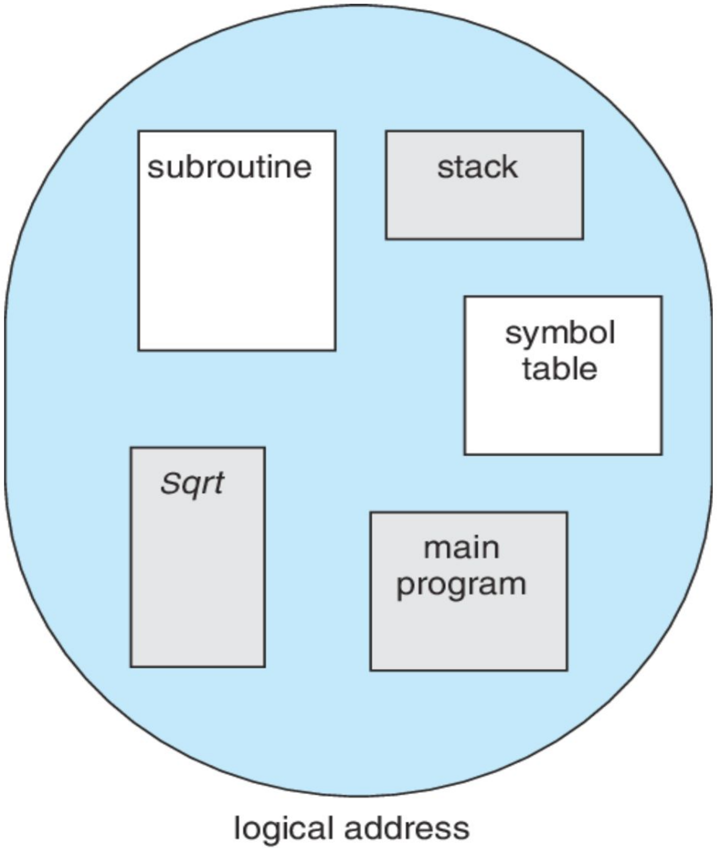
Shared Pages

- **Shared code**
  - One copy of read-only (reentrant) code shared among processes (i.e., text editors, compilers, window systems)
  - Shared code must appear in same location in the logical address space of all processes
- **Private code and data**
  - Each process keeps a separate copy of the code and data
  - The pages for the private code and data can appear anywhere in the logical address space

Shared Pages Example



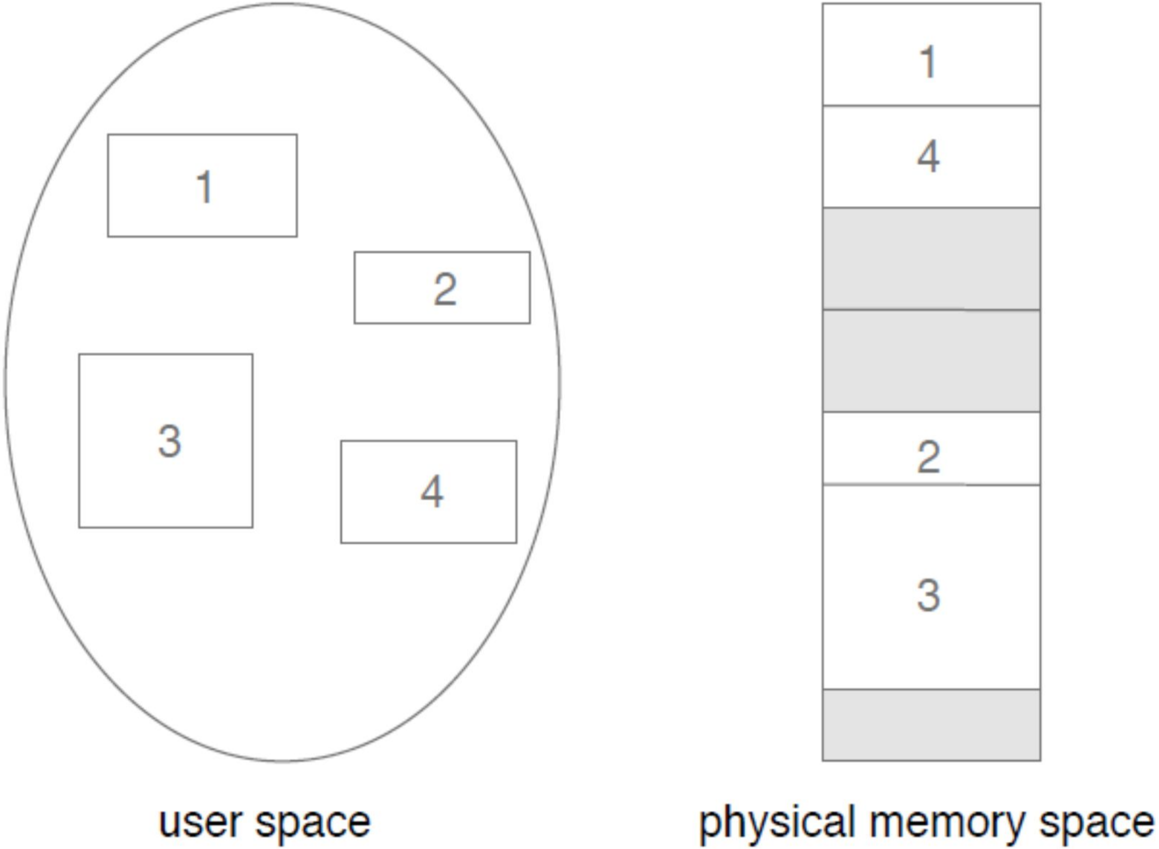
User's View of a Program



Segmentation

- Memory-management scheme that supports user view of memory
- A program is a collection of **variable sized** segments. A segment is a logical unit such as:
  - main program,
  - procedure,
  - function,
  - method,
  - object,
  - local variables, global variables,
  - common block,
  - symbol table, arrays

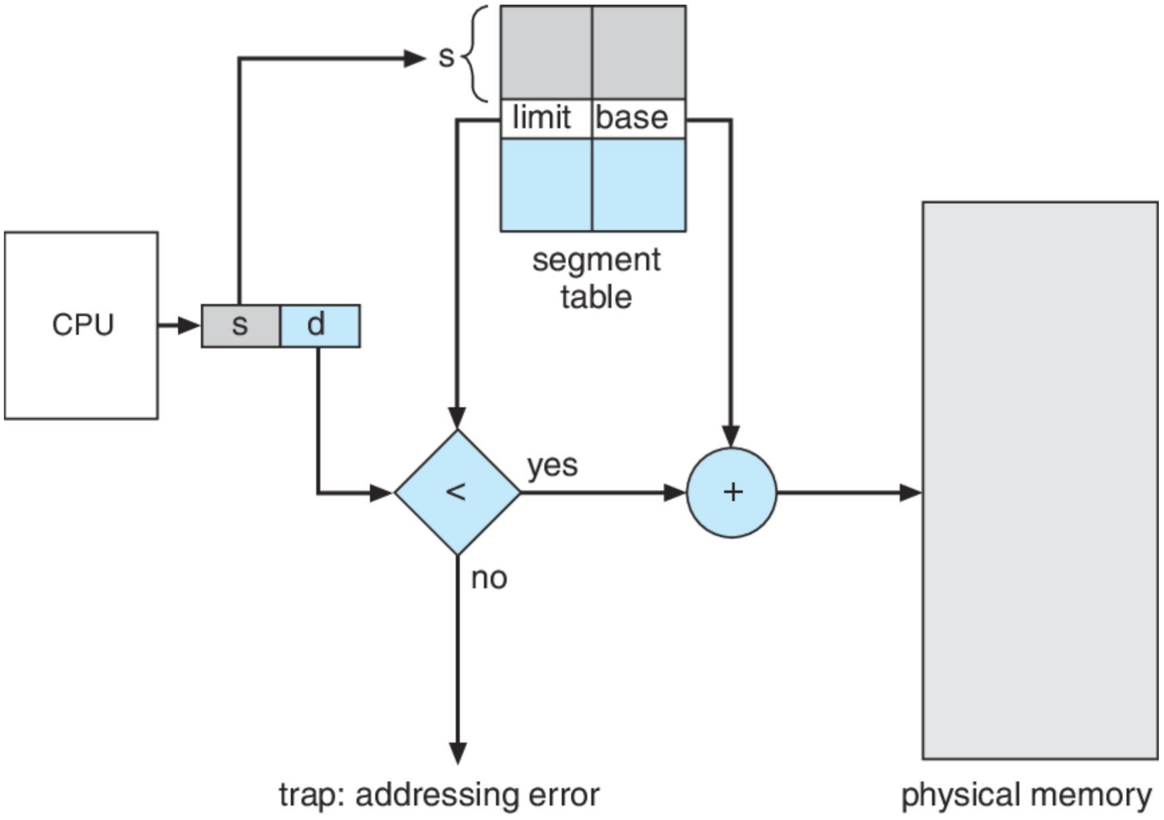
Segmentation: Logical View



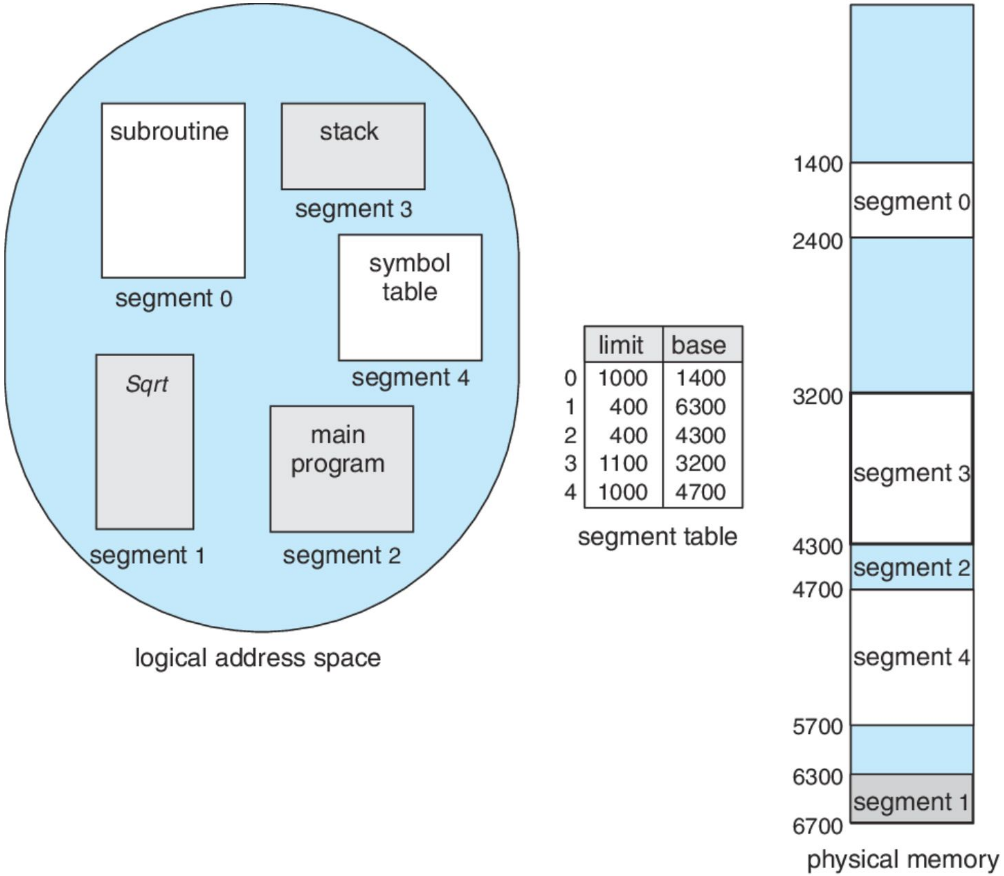
Segmentation: Architecture

- Logical address consists of a two tuple:
  - <segment-number, offset>
- Segment table– maps two-dimensional physical addresses; each table entry has:
  - base – contains the starting physical address where the segments reside in memory
  - limit – specifies the length of the segment
- Segment-table base register (STBR) points to the segment table's location in memory
- Segment-table length register (STLR) indicates the length (limit) of the segment
- Segment addressing is **d (offset) < STLR**

Segmentation: Address Translation Architecture



Segmentation: Example



	limit	base
0	1000	1400
1	400	6300
2	400	4300
3	1100	3200
4	1000	4700

segment table

Exercise

- Consider the following segment table:

Segment	Base	Length
0	219	600
1	2300	14
2	90	100
3	1327	580
4	1952	96

1) What are the physical addresses for the following logical addresses?

   a) 1, 100

   b) 2, 0

   c) 3, 580

Exercise

- Consider the following segment table:

Segment	Base	Length
0	219	600
1	2300	14
2	90	100
3	1327	580
4	1952	96

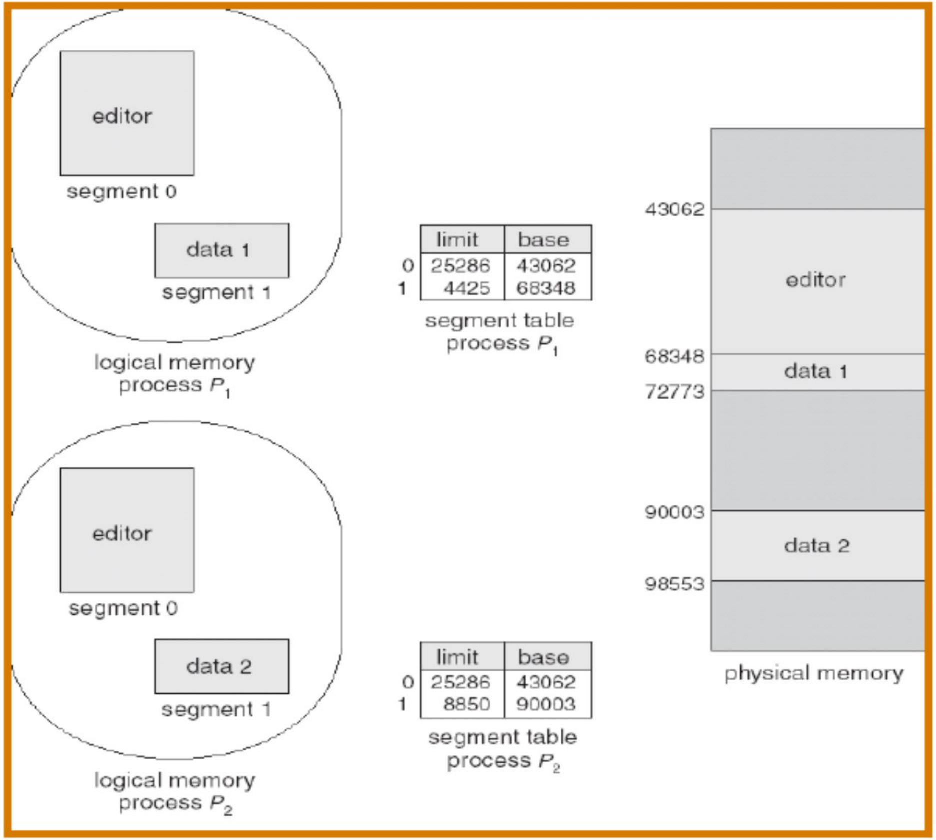
1) What are the physical addresses for the following logical addresses?

   a) 1, 100 — illegal reference, not within segment limits [0..13]

   b) 2, 0 — physical address = 90 + 0 = 90

   c) 3, 580 — illegal reference, not within segment limits [0..579]

Sharing of Segments



Paging vs Segmentation

Paging	**Segmentation**
Fixed-size division	Variable-size division
Managed by OS	Managed by compiler
Fragmentation: Internal	Fragmentation: External
Speed: Faster	Speed: Slower
Unit size by hardware	Unit size by user/programmer
Invisible to the user	Visible to the user

Modern OSes implement a hybrid approach called "**segmentation with paging**"

Acknowledgements

- “Operating Systems Concepts” book and supplementary material by A. Silberschatz, P. Galvin and G. Gagne
- “Operating Systems: Internals and Design Principles” book and supplementary material by W. Stallings
- “Modern Operating Systems” book and supplementary material by A. Tanenbaum
- R. Doursat and M. Yuksel from University of Nevada, Reno
- Farshad Ghanei from Illinois Tech
- T. Kosar and K. Dantu from University at Buffalo

Announcement

- Next class
  - Quiz 3: Could be in class or take home
  - xv6 scheduling: IMPORTANT FOR HOMEWORK 3
- Homework 2
  - Due on Today October 6th, 11.59 PM