

# Operating Systems Concepts

Main Memory: Address Translation



CS 4375, Fall 2025

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# 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

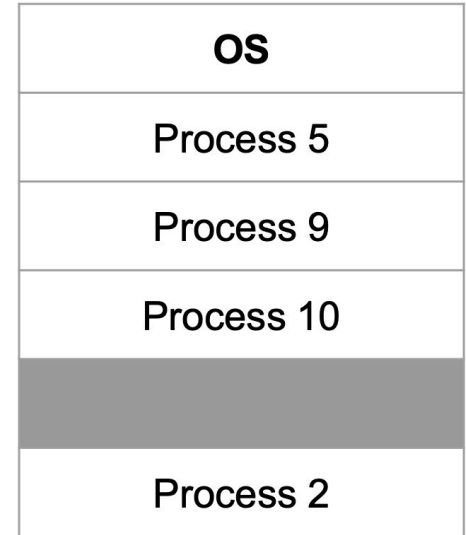
# Memory Management

- 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

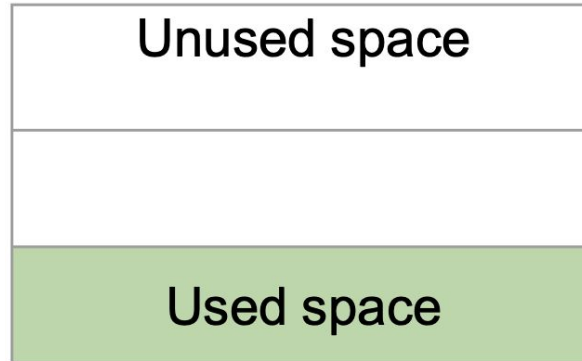
- Fixed-partition allocation
  - Divide memory into fixed-size partitions
  - Each partition contains exactly one process
  - The degree of multiprogramming is bound by the number of partitions
  - When a process terminates, the partition becomes available for other processes
- May lead to **Internal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

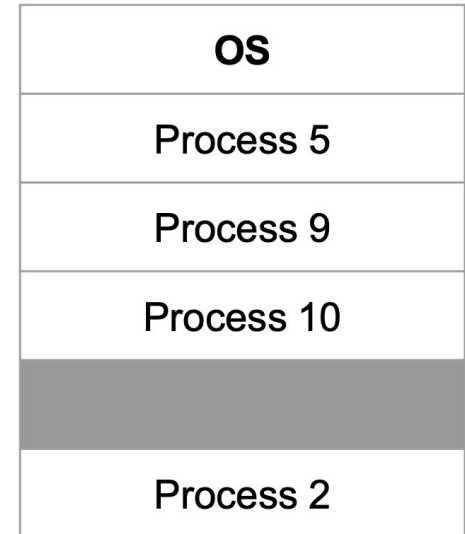
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## Allocated Memory



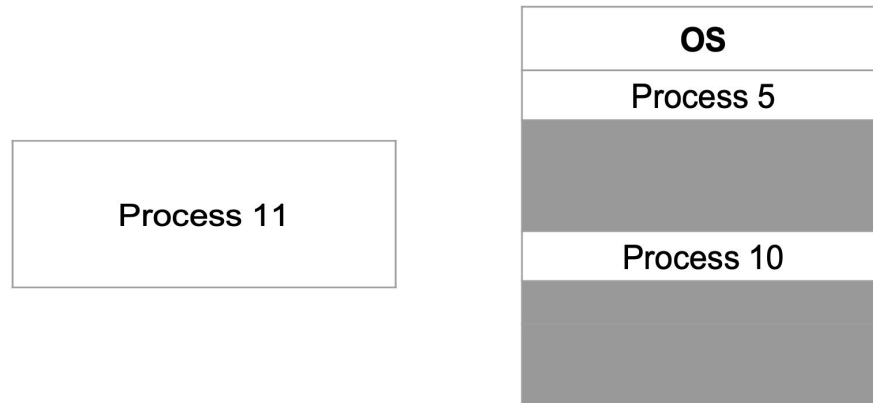
# Memory Allocation

- 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?

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- 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

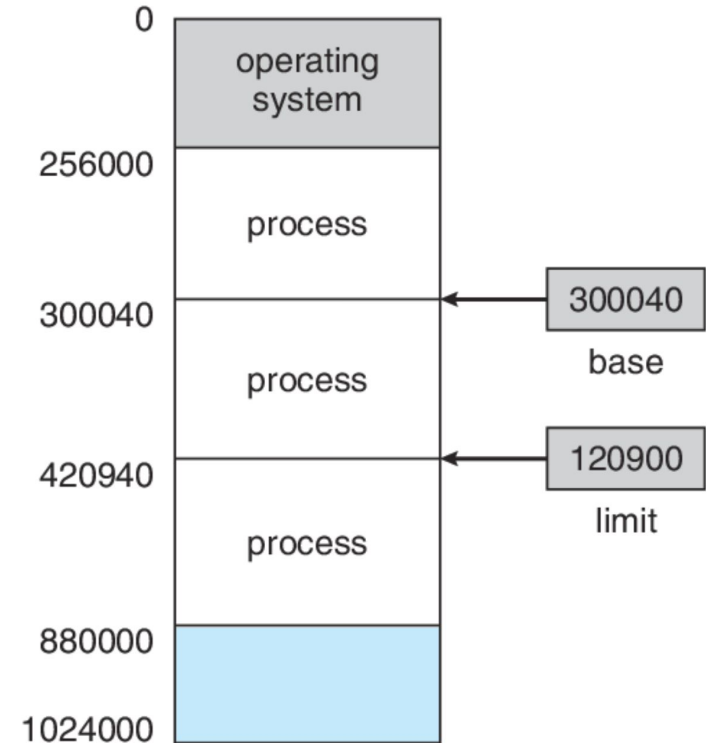
Available partitions after **worst fit**: [100, 83, 200, 300, 276] KB [426 KB!!]

# 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

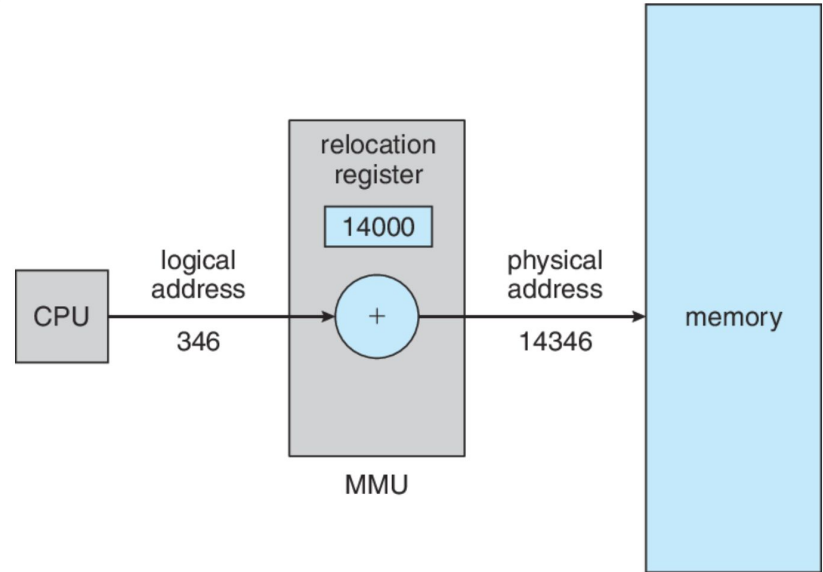
# Logical Address Space

- 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



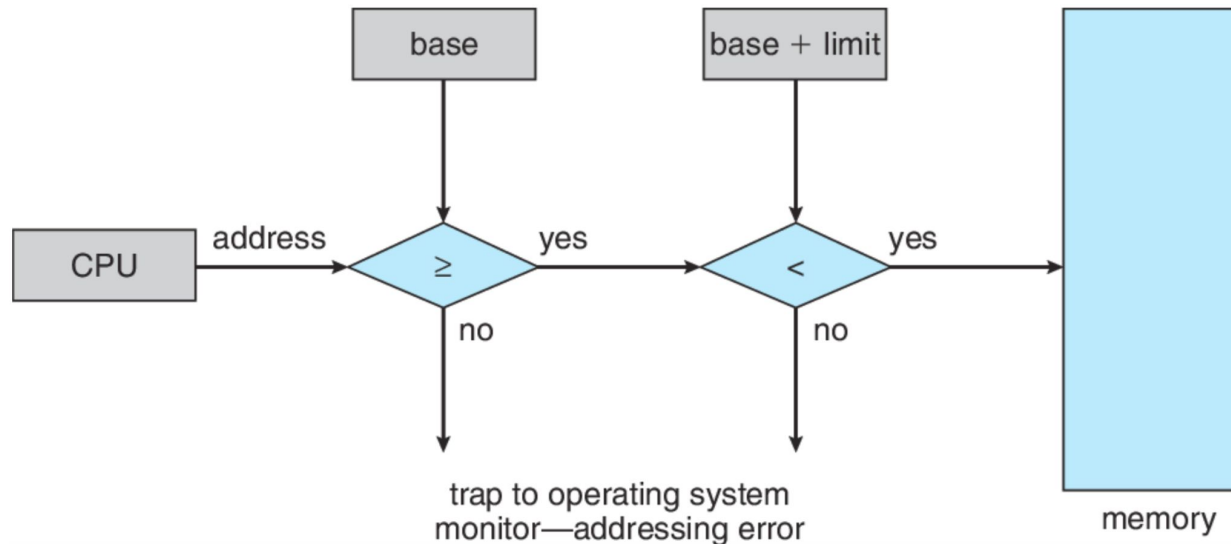
# Memory-Management Unit (MMU)

- 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

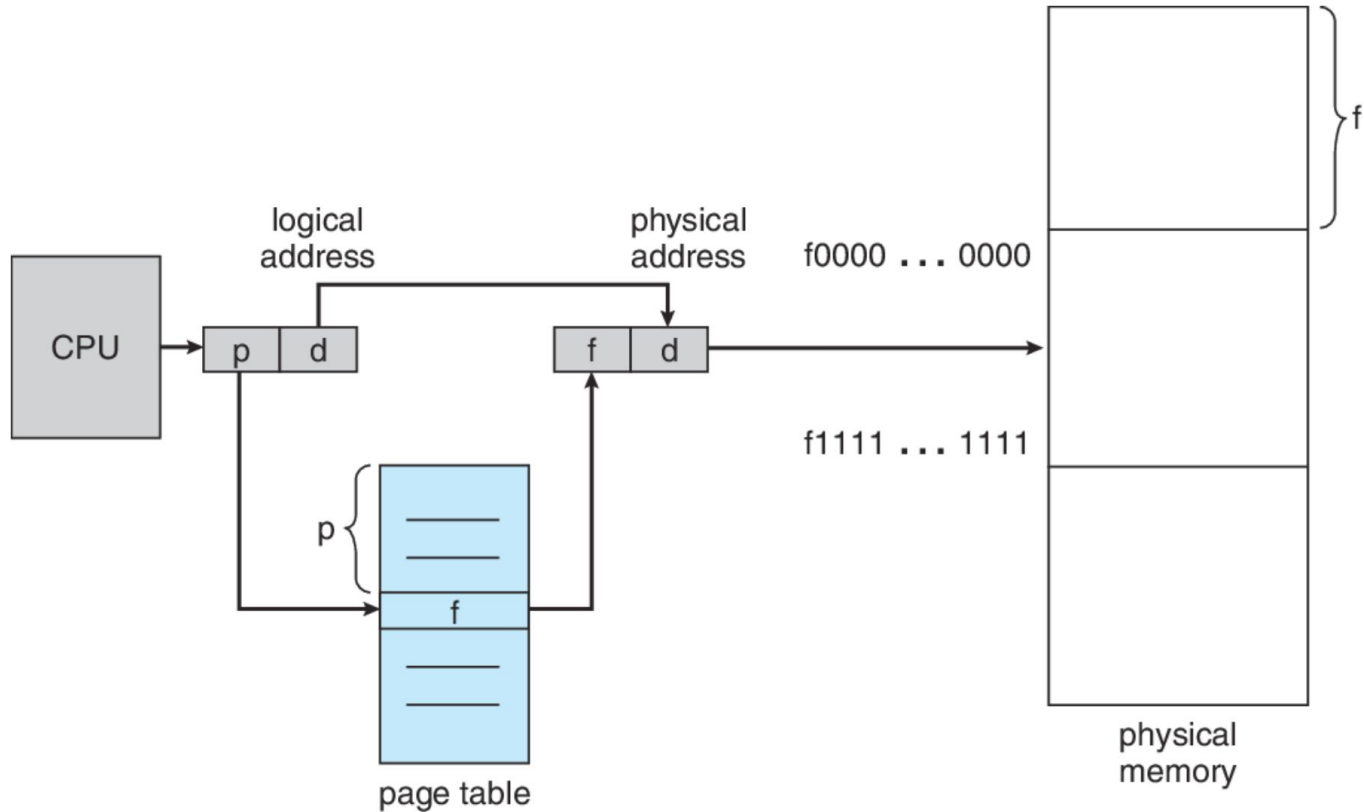
- Physical address space of a process can be noncontiguous
- Divide physical memory into **fixed-sized blocks** called **frames** (size is power of 2, between 512 bytes and 16 megabytes)
- Divide logical memory into blocks of same size called **pages**
- Keep track of all free frames
- To run a program 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**



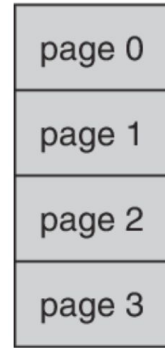
# Paging Address Translation Scheme

- 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

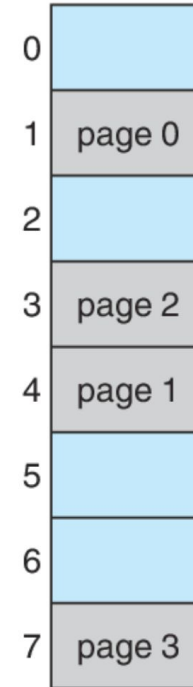


logical  
memory

0	1
1	4
2	3
3	7

page table

frame  
number



physical  
memory

# Paging Example

0	a
1	b
2	c
3	d
4	e
5	f
6	g
7	h
8	i
9	j
10	k
11	l
12	m
13	n
14	o
15	p

logical memory

0	5
1	6
2	1
3	2

page table

0	
4	
8	
12	
16	
20	
24	
28	

physical memory

# Paging Example

0	a
1	b
2	c
3	d
4	e
5	f
6	g
7	h
8	i
9	j
10	k
11	l
12	m
13	n
14	o
15	p

logical memory

0	5
1	6
2	1
3	2

page table

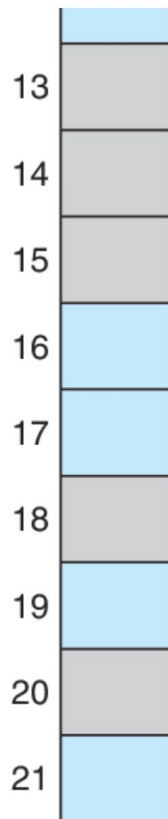
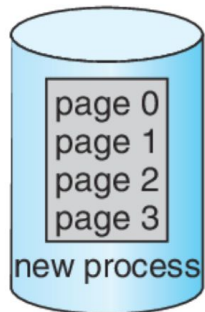
0	
4	i j k l
8	m n o p
12	
16	
20	a b c d
24	e f g h
28	

physical memory

# Free Frames

free-frame list

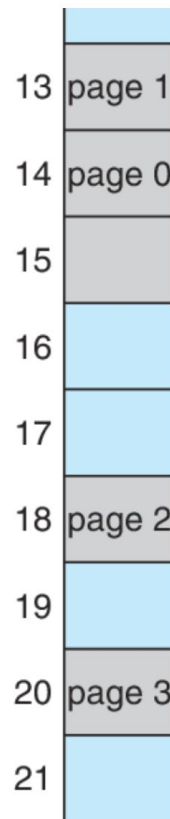
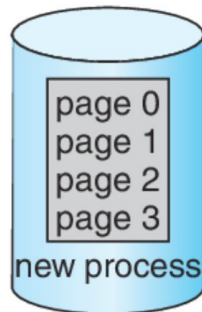
14  
13  
18  
20  
15



(a)

free-frame list

15



(b)

0	14
1	13
2	18
3	20

new-process page table

# Shared Pages

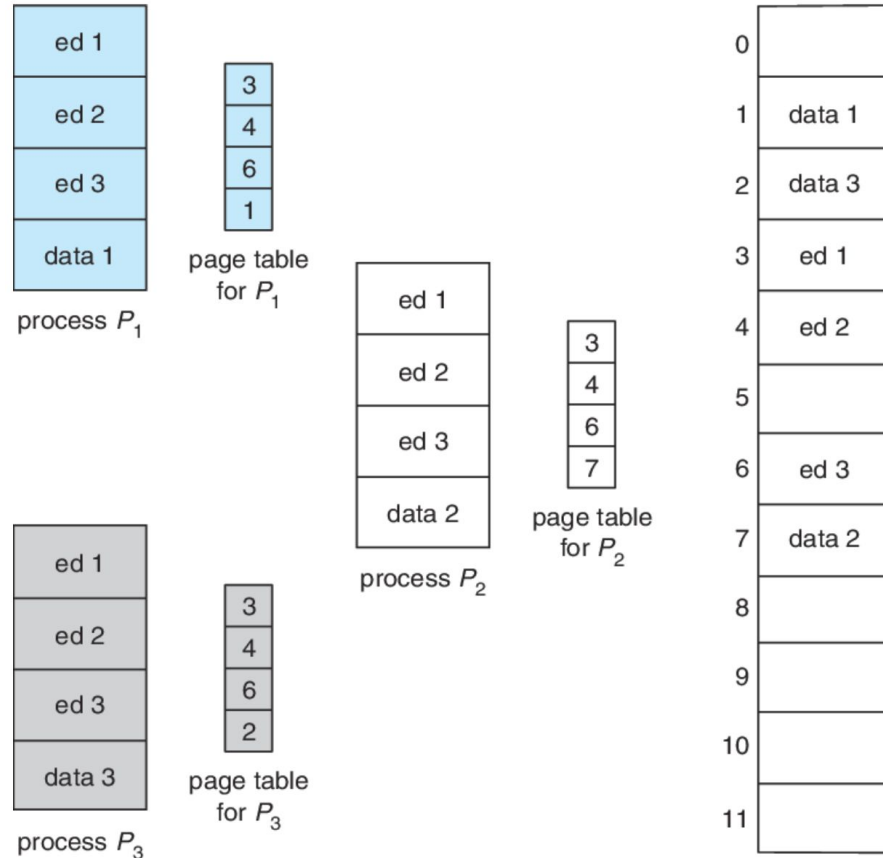
- **Shared code**

- 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**

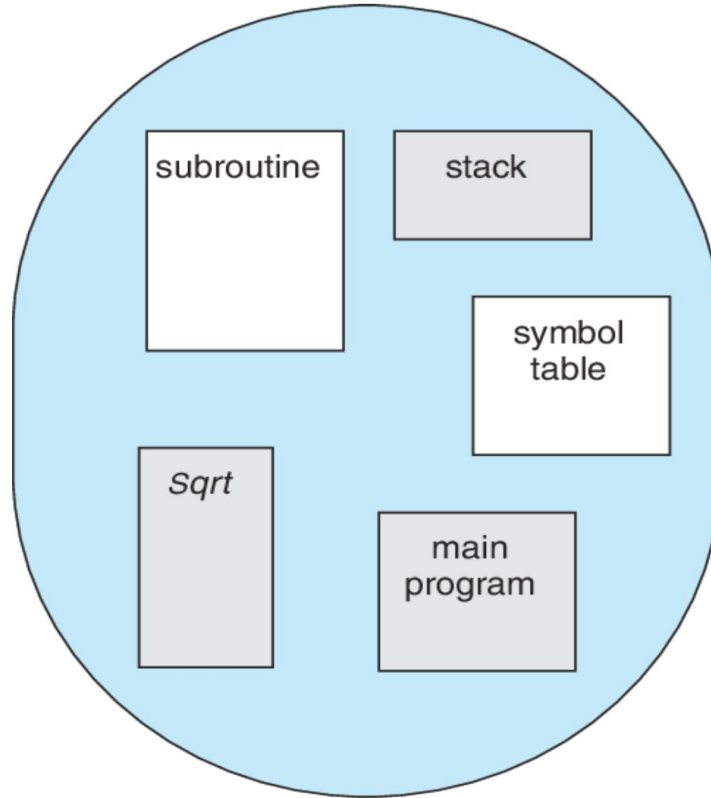
- Each process keeps a separate copy of the code and data
- The pages for the private code and data can appear anywhere in the logical address space

# Shared Pages Example





# User's View of a Program

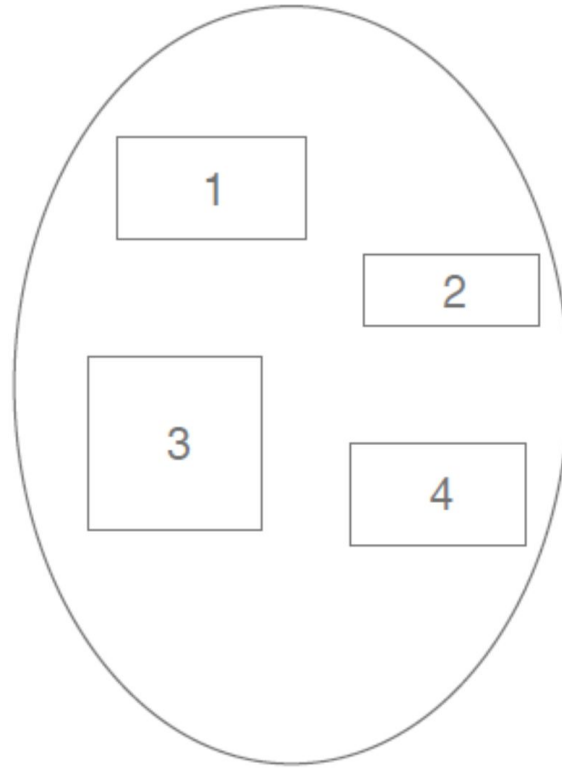


logical address

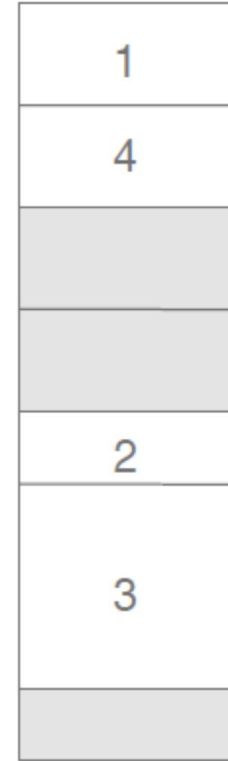
# Segmentation

- 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



user space

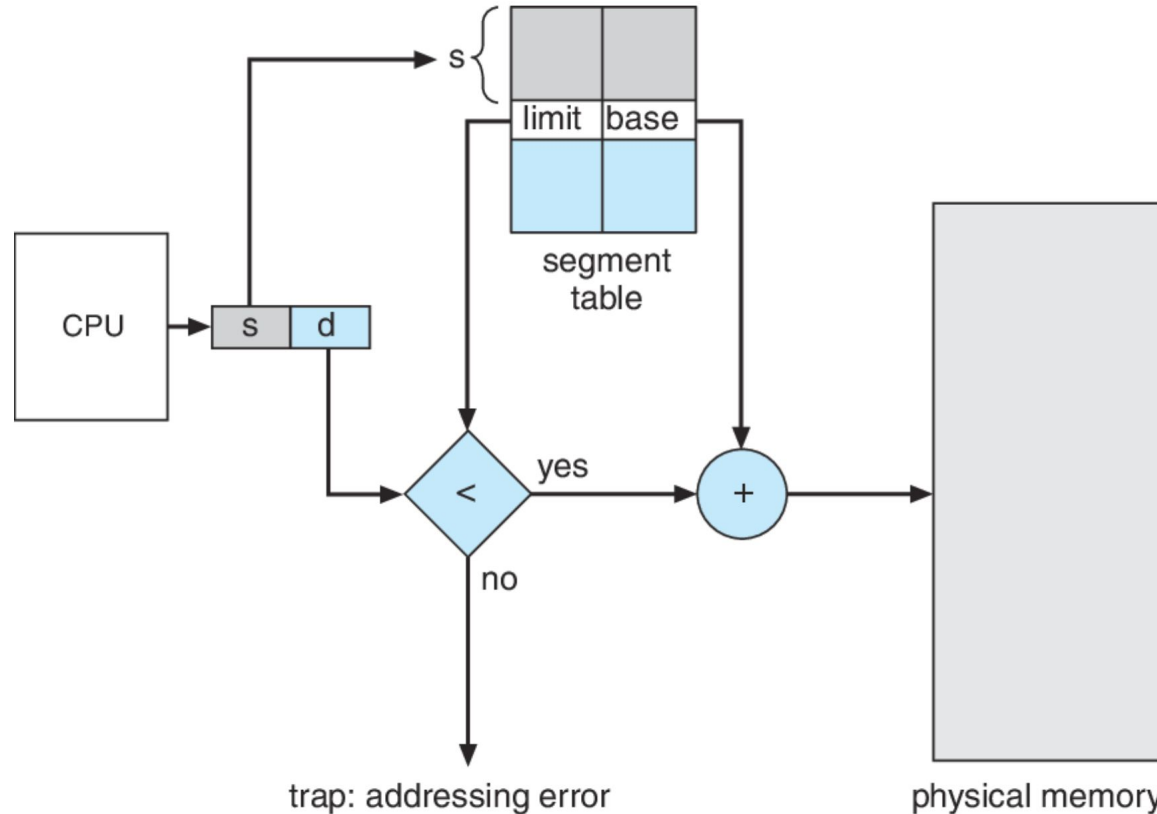


physical memory space

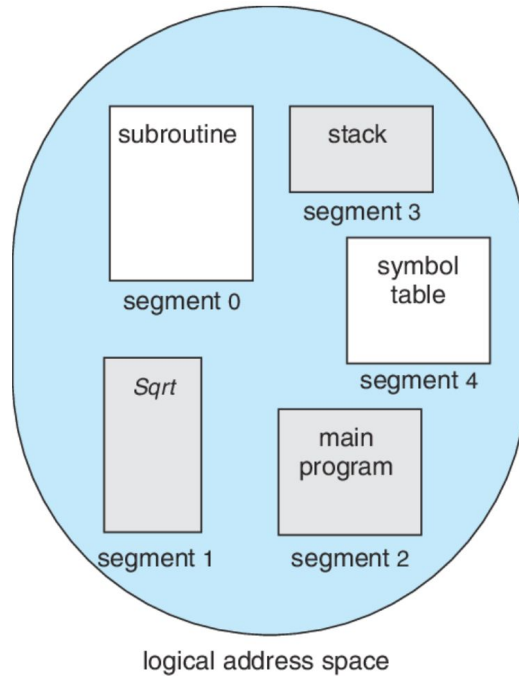
# Segmentation: Architecture

- Logical address consists of a two tuple:
  - $\langle \text{segment-number}, \text{offset} \rangle$
- **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  $d(\text{offset}) < \text{STLR}$

# Segmentation: Address Translation Architecture

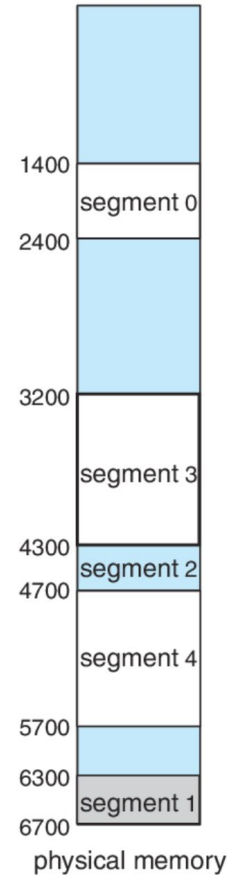


# Segmentation: Example



	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:

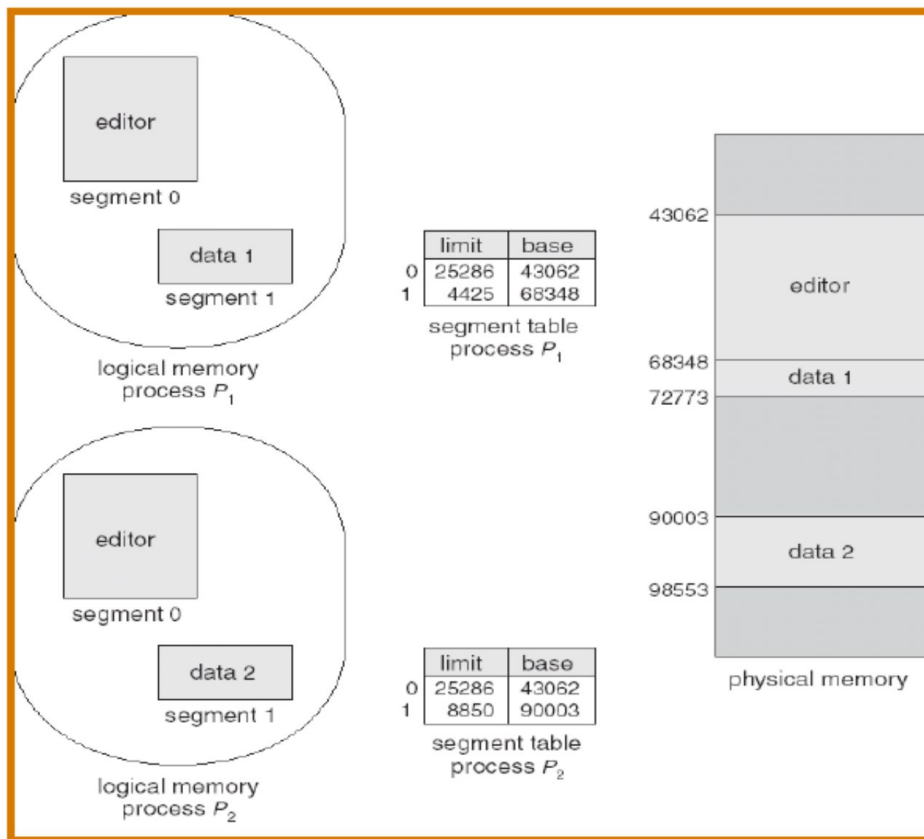
Segment	Base	Length
0	219	600
1	2300	14
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3	1327	580
4	1952	96

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

<b>Paging</b>	<b>Segmentation</b>
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 2: Could be in class or take home
  - xv6 scheduling: **IMPORTANT FOR HOMEWORK 3**
- Homework 2
  - Due on Today October 6th, 11.59 PM