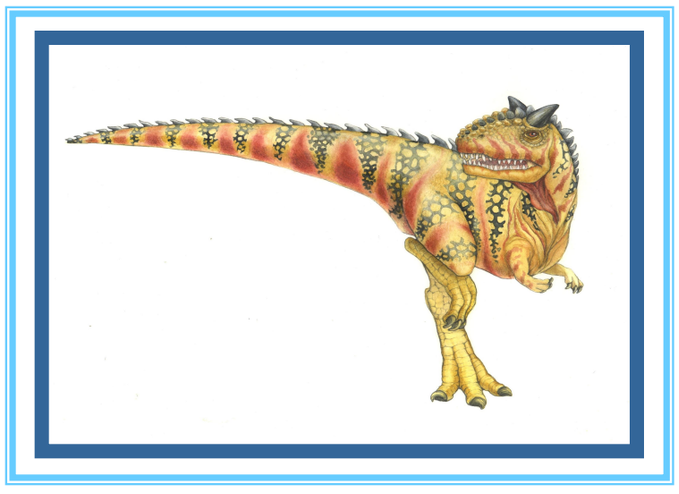
Chapter 8: Main Memory

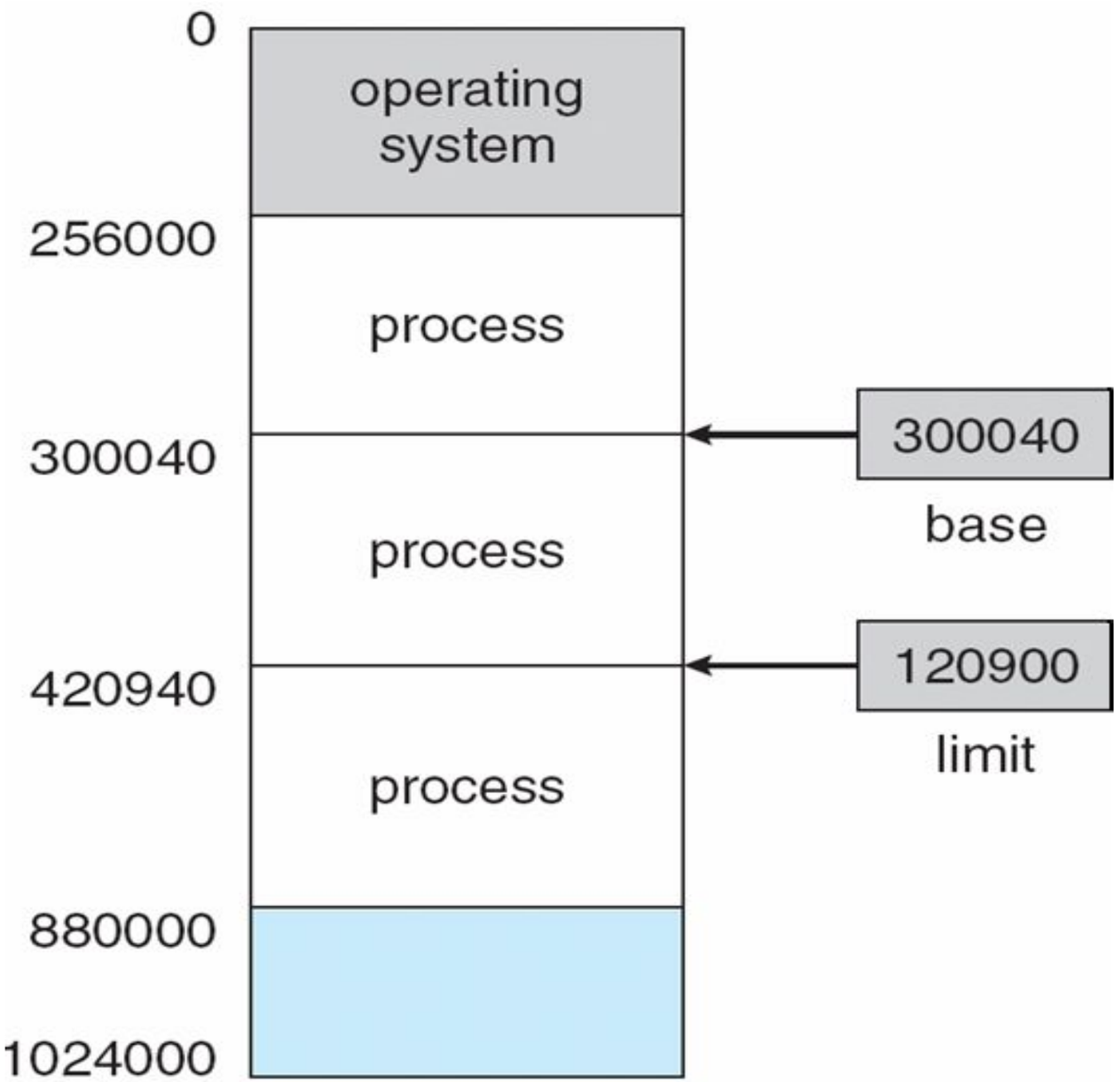


Background

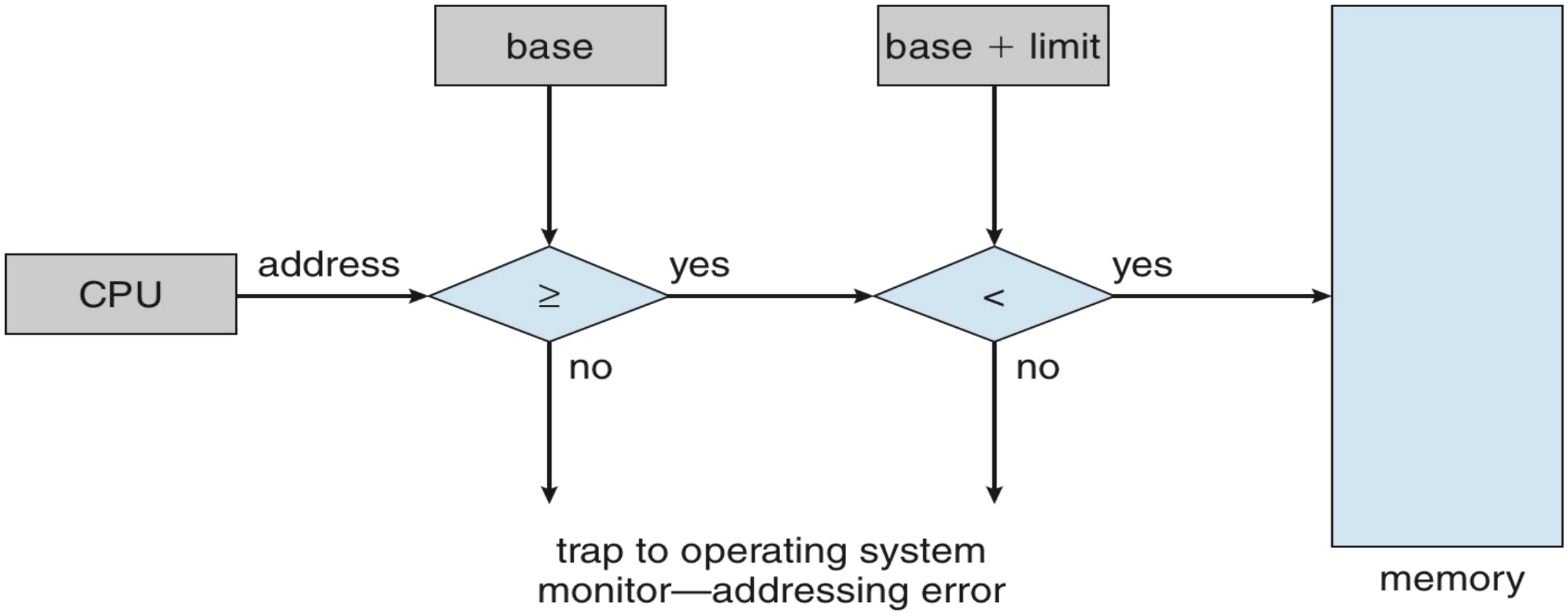
- Program must be brought (from disk) into memory and placed within a process for it to be run
- Main memory and registers are only storage CPU can access directly

Base and Limit Registers

- A pair of **base** and **limit** registers define the logical address space



Hardware Address Protection with Base and Limit Registers



Address Binding

- Addresses represented in different ways at different stages of a program's life
  - Source code addresses usually symbolic
  - Compiled code addresses **bind** to relocatable addresses
    - i.e. "14 bytes from beginning of this module"
  - Linker or loader will bind relocatable addresses to absolute addresses
    - i.e. 74014
- Each binding maps one address space to another

Binding of Instructions and Data to Memory

- Address binding of instructions and data to memory addresses can happen at three different stages
  - **Compile time**: If memory location known a priori, **absolute code** can be generated; must recompile code if starting location changes
  - **Load time**: Must generate **relocatable code** if memory location is not known at compile time
  - **Execution time**: Binding delayed until run time if the process can be moved during its execution from one memory segment to another
    - Need hardware support for address maps (e.g., base and limit registers)

Logical vs. Physical Address Space

- The concept of a logical address space that is bound to a separate **physical address space** is central to proper memory management
  - **Logical address** – generated by the CPU; also referred to as **virtual address**
  - **Physical address** – address seen by the memory unit

- Logical and physical addresses are the same in compile-time and load-time address-binding schemes; logical (virtual) and physical addresses differ in execution-time address-binding scheme
- **Logical address space** is the set of all logical addresses generated by a program
- **Physical address space** is the set of all physical addresses generated by a program
- **Memory management Unit (MMU)** is a hardware device that at run time maps virtual to physical address

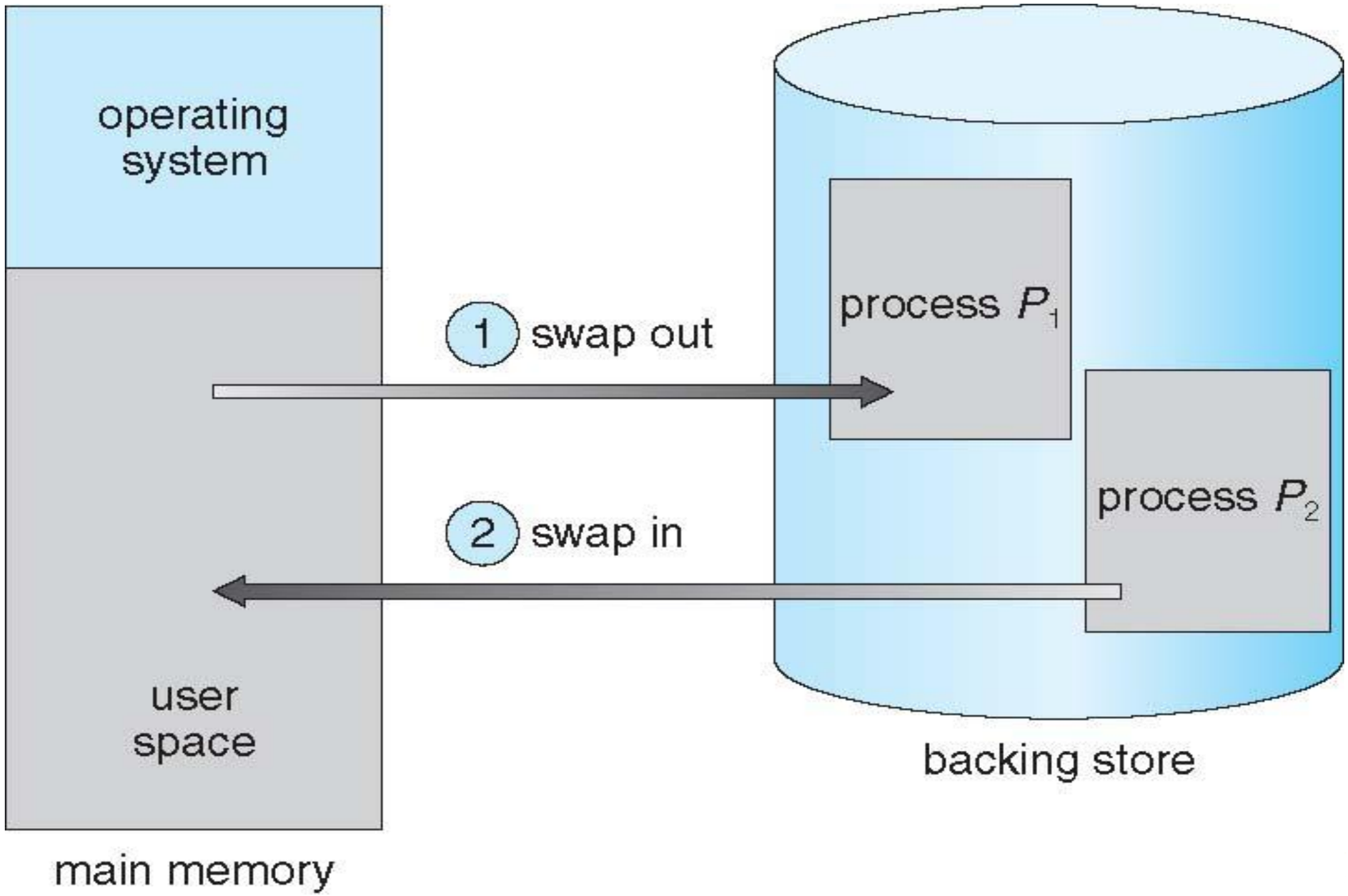
Swapping

- A process can be swapped temporarily out of memory to a backing store, and then brought back into memory for continued execution
  - Total physical memory space of processes can exceed physical memory
- **Backing store** – fast disk large enough to accommodate copies of all memory images for all users; must provide direct access to these memory images

Swapping

- Does the swapped out process need to swap back in to same physical addresses?
- Depends on address binding method
  - Yes, if static or load time binding
  - No if execution time binding

Schematic View of Swapping



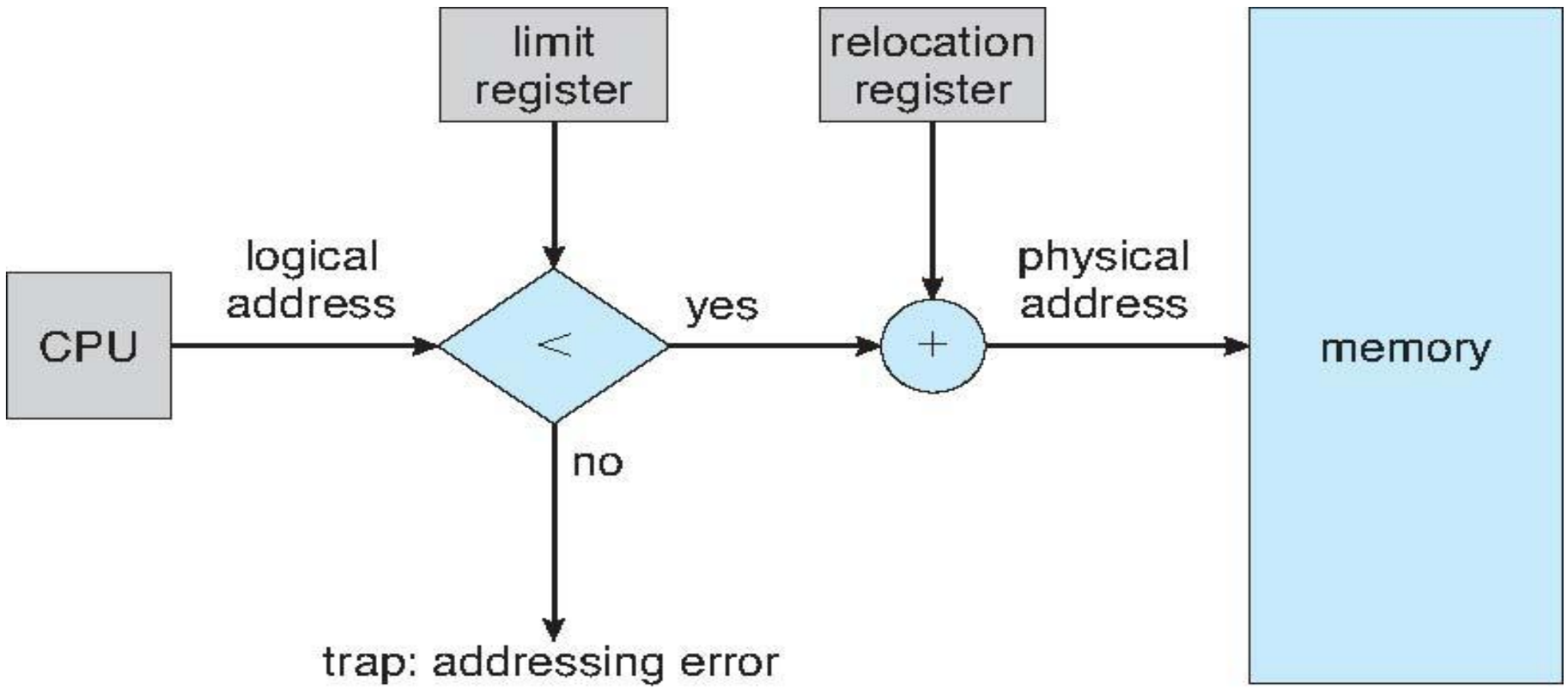
Context Switch Time including Swapping

- If next processes to be put on CPU is not in memory, need to swap out a process and swap in target process
- Context switch time can then be very high
- 100MB process swapping to hard disk with transfer rate of 50MB/sec
  - Plus disk latency of 8 ms
  - Swap out time of 2008 ms
  - Plus swap in of same sized process
  - Total context switch swapping component time of 4016ms (> 4 seconds)

Contiguous Allocation

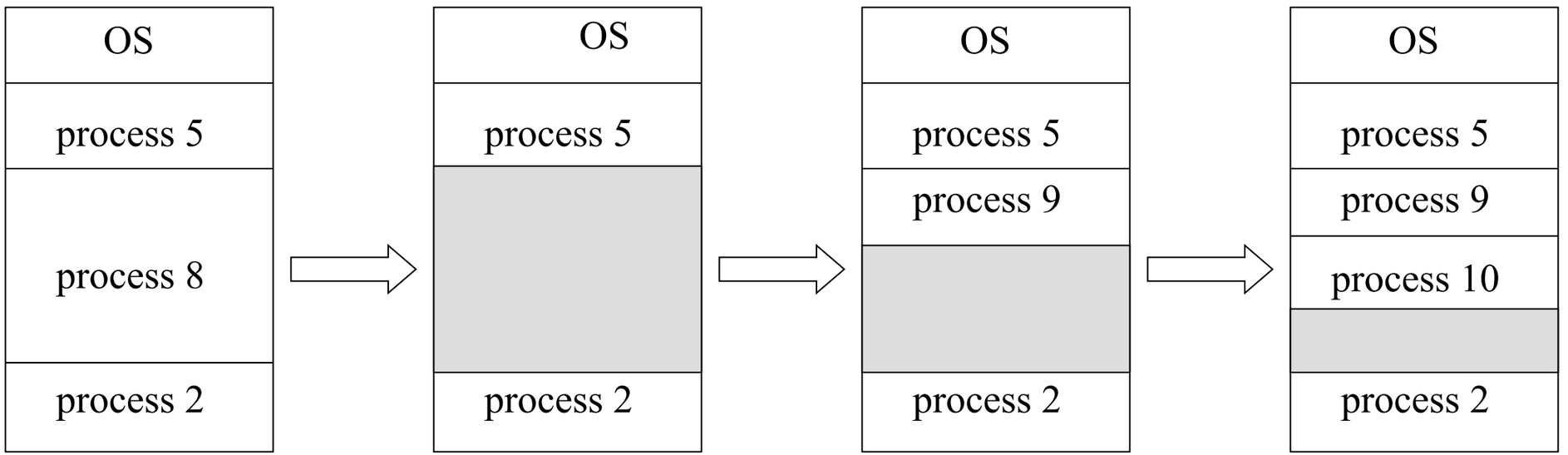
- Main memory usually into two partitions:
  - Resident operating system, usually held in low memory
  - User processes then held in high memory
  - Each process contained in single contiguous section of memory
- **Relocation registers** used to protect user processes from each other, and from changing operating-system code and data
  - **Base register** contains value of smallest physical address
  - **Limit register** contains range of logical addresses – each logical address must be less than the limit register
  - MMU maps logical address *dynamically*

Hardware Support for Relocation and Limit Registers



Contiguous Allocation (Cont.)

- Multiple-partition allocation
  - Degree of multiprogramming limited by number of partitions
  - Hole – block of available memory; holes of various size are scattered throughout memory
  - When a process arrives, it is allocated memory from a hole large enough to accommodate it
  - Process exiting frees its partition, adjacent free partitions combined
  - Operating system maintains information about:
    a) allocated partitions b) free partitions (hole)



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 and best-fit better than worst-fit in terms of speed and storage utilization

Fragmentation

- **External Fragmentation** – total memory space exists to satisfy a request, but it is not contiguous

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

- First fit analysis reveals that given *N* blocks allocated, 0.5 *N* blocks lost to fragmentation
  - 1/3 may be unusable -> **50-percent rule**

Fragmentation (Cont.)

- 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

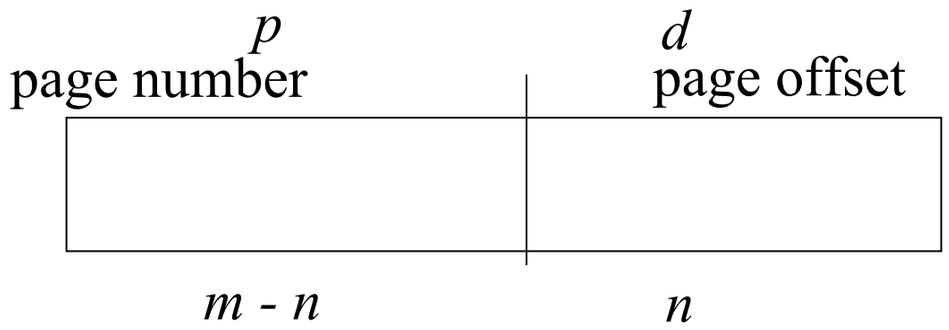
- Use Swapping to move processes out of memory.

Paging

- 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 Mbytes
  - 4KB is typical
- 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
- Backing store likewise split into pages
- Internal fragmentation may be there

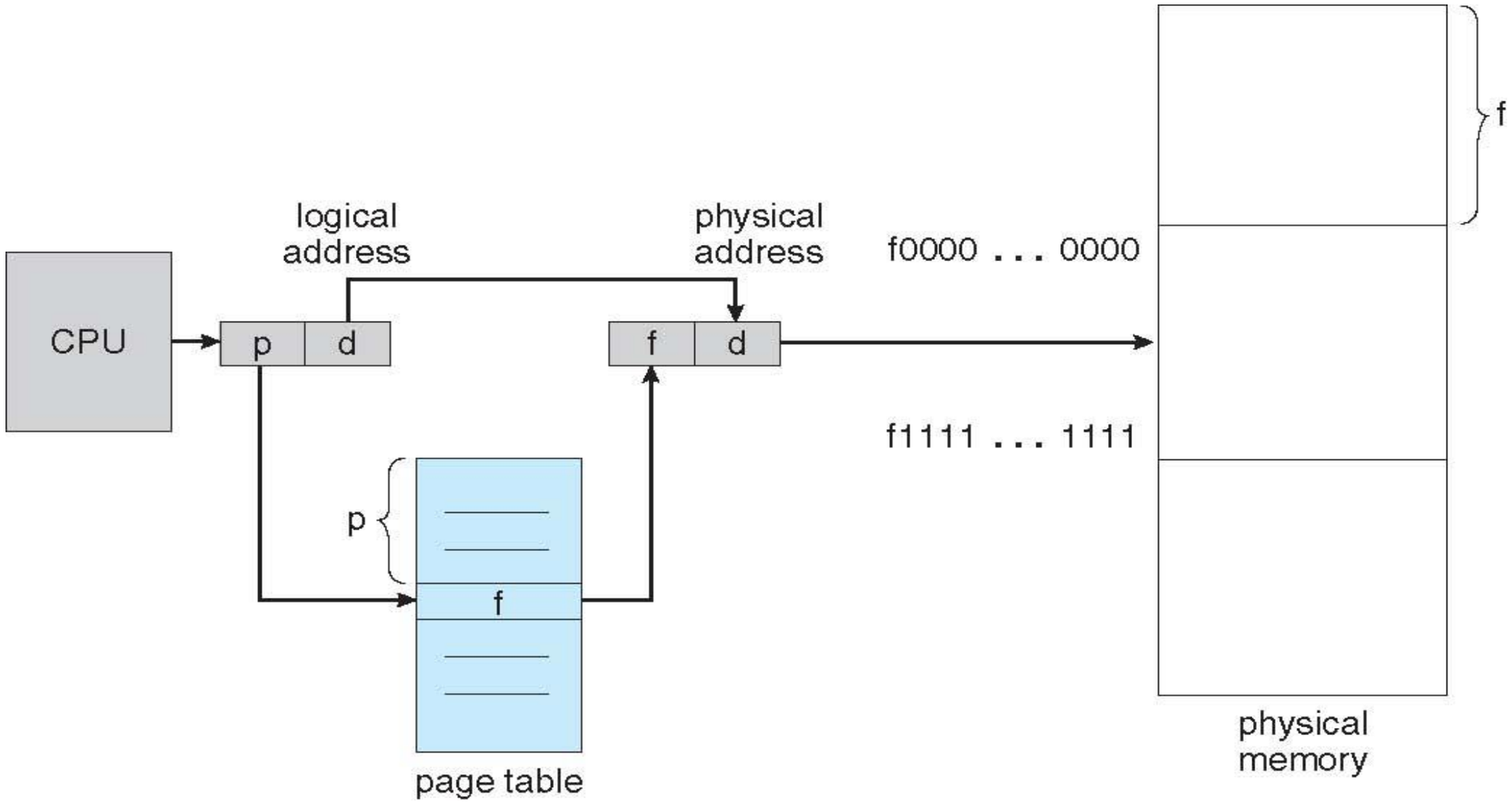
Address Translation Scheme

- 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

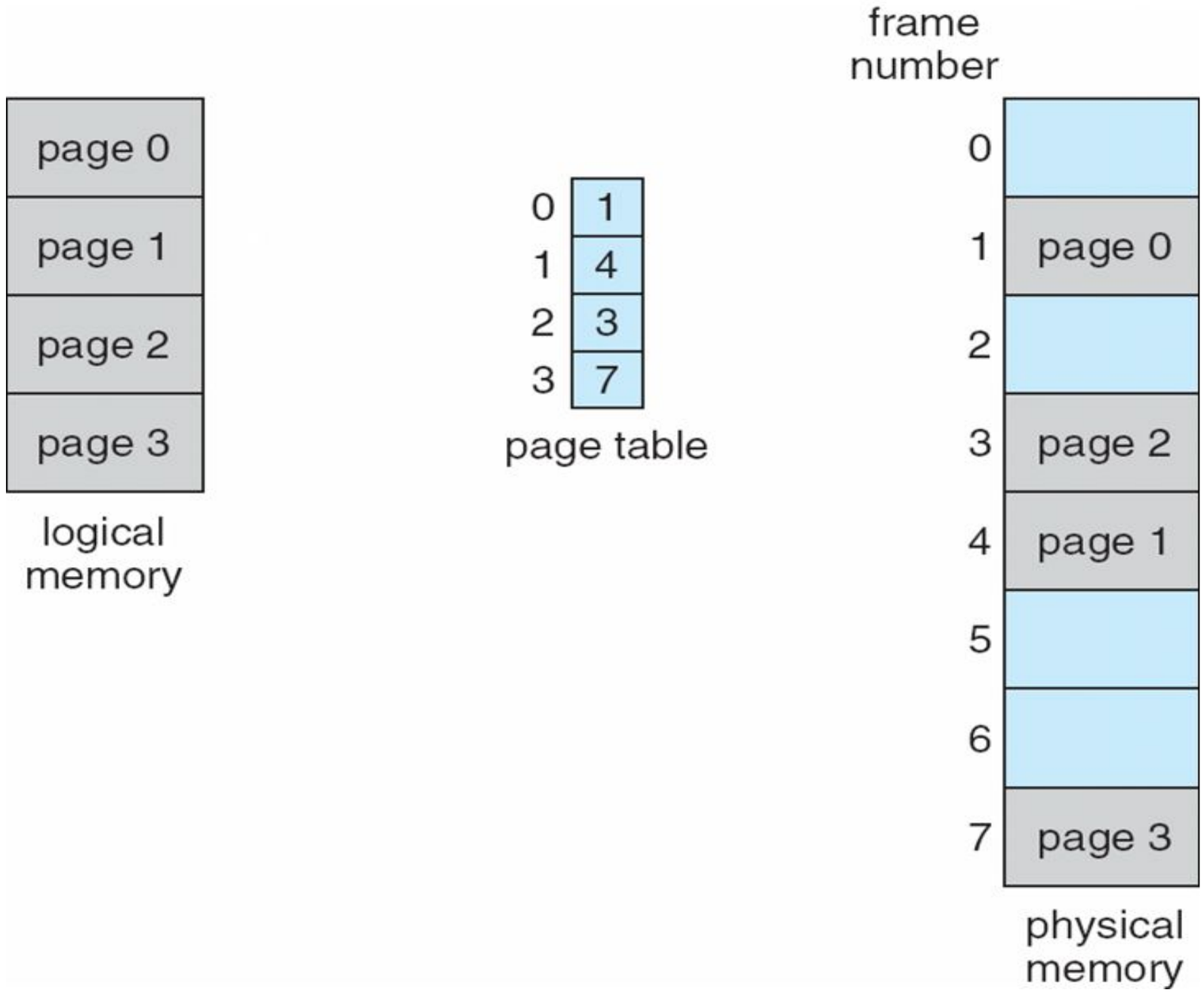


- For given logical address space 2^m and page size 2^n

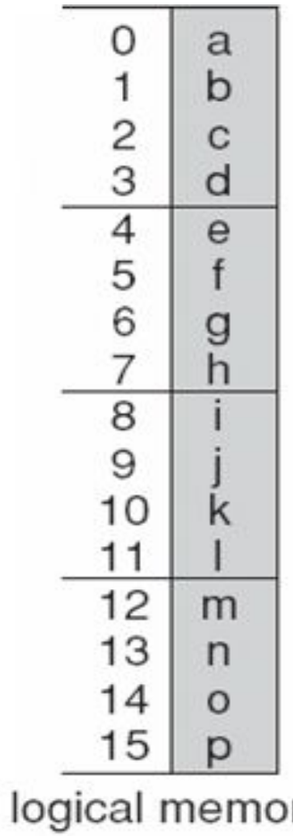
Paging Hardware

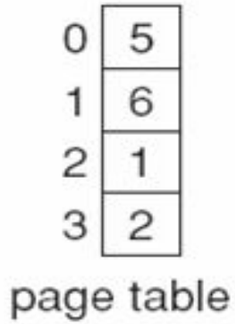


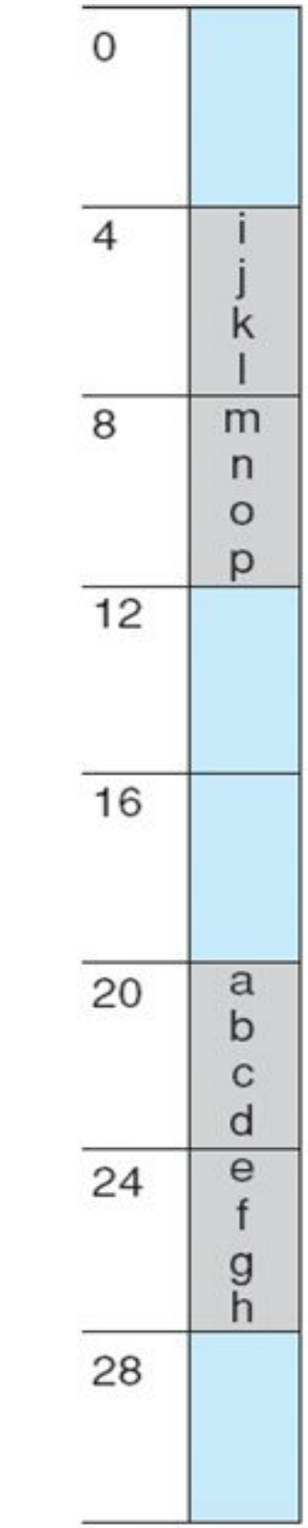
Paging Model of Logical and Physical Memory



n=2 and m=4
32-byte
memory and
4-byte pages







Paging (Cont.)

- Calculating internal fragmentation
  - Page size = 2,048 bytes
  - Process size = 72,766 bytes
  - 35 pages + 1,086 bytes
  - Internal fragmentation of 2,048 - 1,086 = 962 bytes
  - Worst case fragmentation = 1 frame – 1 byte
  - On average fragmentation = 1 / 2 frame size
  - So small frame sizes desirable?
  - But each page table entry takes memory to track

Free Frames


free-frame list
14
13
18
20
15
page 0
page 1
page 2
page 3
new process
13
14
15
16
17
18
19
20
21
(a)
free-frame list
15
page 0
page 1
page 2
page 3
new process
0 14
1 13
2 18
3 20
new-process page table
13 page 1
14 page 0
15
16
17
18 page 2
19
20 page 3
21
(b)

Implementation of Page Table

- Page table is kept in main memory
- **Page-table base register (PTBR)** points to the page table
- **Page-table length register (PTLR)** indicates size of the page table
- In this scheme every data/instruction access requires two memory accesses
  - One for the page table and one for the data / instruction

- The two memory access problem can be solved by the use of a special fast-lookup hardware cache called **associative memory** or **translation look-aside buffers (TLBs)**

- TLBs typically small (64 to 1,024 entries)

- On a TLB miss, value is loaded into the TLB for faster access next time
  - Replacement policies must be considered
  - Some entries can be **wired down** for permanent fast access

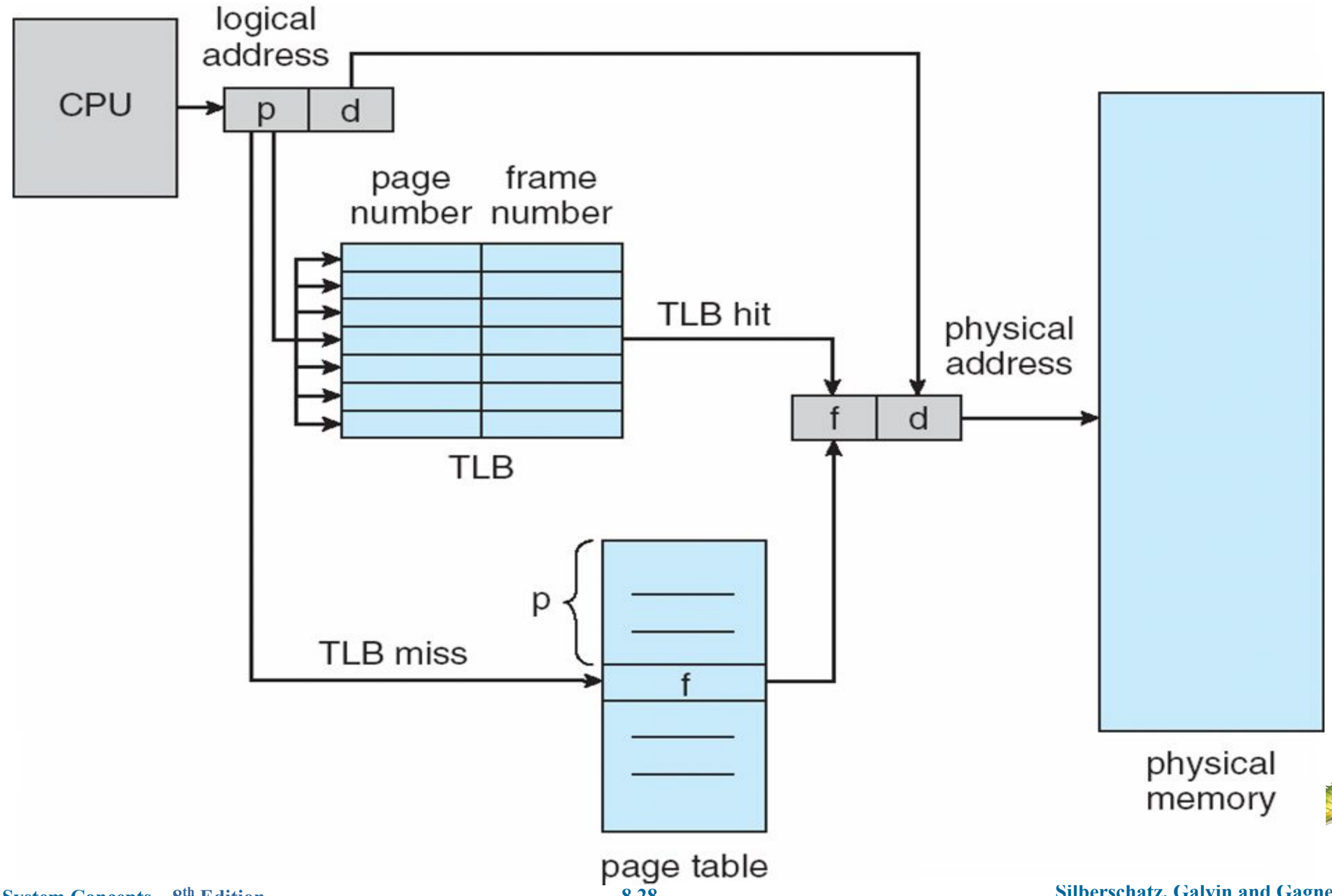
Associative Memory

- Associative memory – parallel search

Page #	Frame #

- Address translation (p, d)
  - If p is in associative register, get frame # out
  - Otherwise get frame # from page table in memory

Paging Hardware With TLB



Effective Access Time

- Associative Lookup = ε time unit
  - Can be < 10% of memory access time
- Hit ratio = α
  - Hit ratio – percentage of times that a page number is found in the associative registers; ratio related to number of associative registers
- Consider α = 80%, ε = 20ns for TLB search, M = memory access TIme

- **Effective Access Time (EAT)**

  $$EAT = (M + \varepsilon)\,\alpha + (2M + \varepsilon)(1 - \alpha)$$

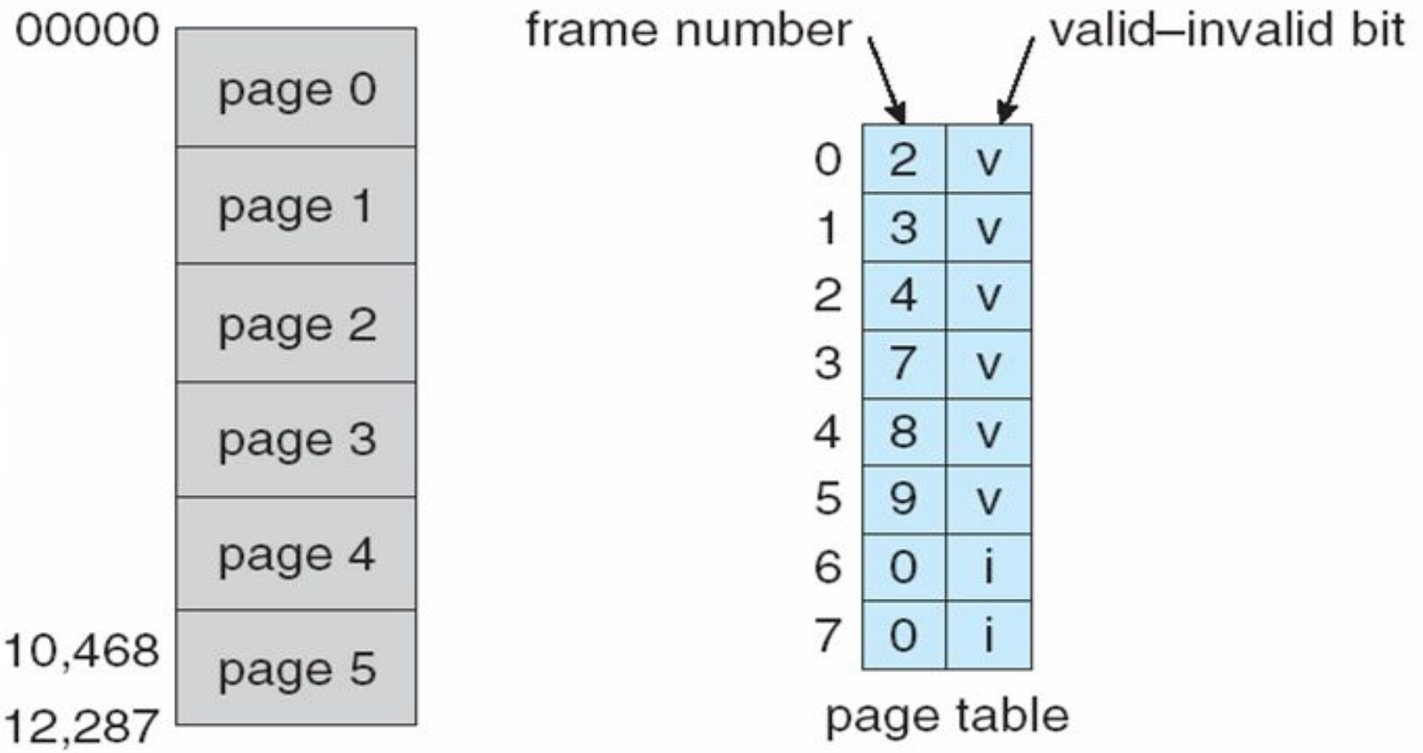
- Consider $\alpha = 80\%$, $\varepsilon = 20$ns for TLB search, 100ns for memory access
  - EAT = (100+20)*.80 + (200+20)*.20 = 140ns

- Consider slower memory but better hit ratio -> $\alpha = 98\%$, $\varepsilon = 20$ns for TLB search, M = 140ns for memory access
  - EAT = 0.98 x 160 + 0.02 x 300 = 162.8ns

Memory Protection

- Memory protection implemented by associating protection bit with each frame to indicate if read-only or read-write access is allowed
  - Can also add more bits to indicate page execute-only, and so on
- **Valid-invalid** bit attached to each entry in the page table:
  - "valid" indicates that the associated page is in the process' logical address space, and is thus a legal page
  - "invalid" indicates that the page is not in the process' logical address space
- Any violations result in a trap to the kernel

Valid (v) or Invalid (i) Bit In A Page Table

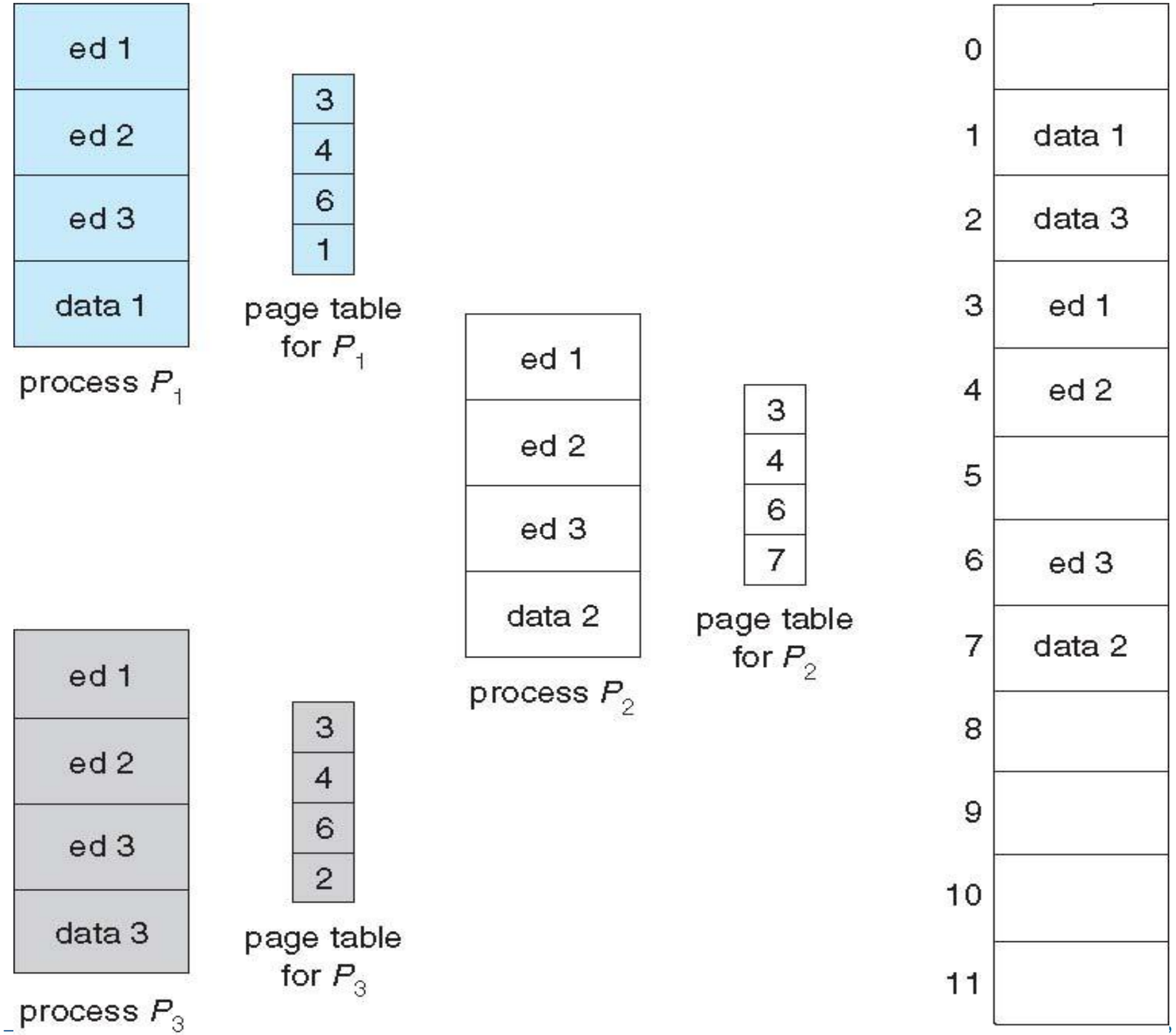


Shared Pages

- **Shared code**
  - One copy of read-only (**reentrant**) code shared among processes (i.e., text editors, compilers, window systems)
  - Similar to multiple threads sharing the same process space
  - Also useful for interprocess communication if sharing of read-write pages is allowed

- **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



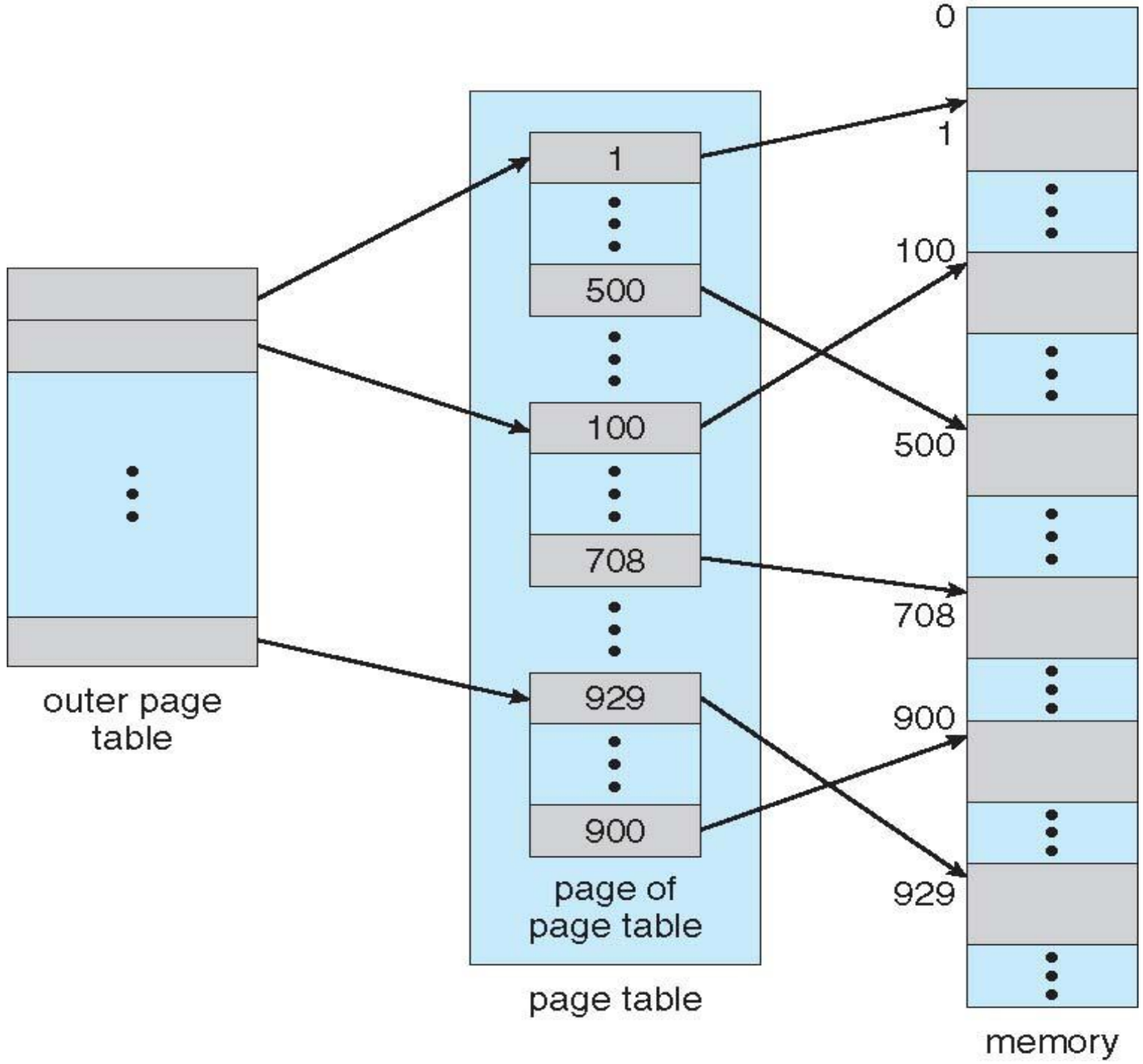
Structure of the Page Table

- Memory structures for paging can get huge using straight-forward methods
  - Consider a 32-bit logical address space as on modern computers
  - Page size of 4 KB (2^{12})
  - Page table would have 1 million entries (2^{32} / 2^{12})
  - If each entry is 4 bytes -> 4 MB of physical address space / memory for page table alone
    - That amount of memory used to cost a lot
    - Don't want to allocate that contiguously in main memory
- Hierarchical Paging
- Hashed Page Tables
- Inverted Page Tables

Hierarchical Page Tables

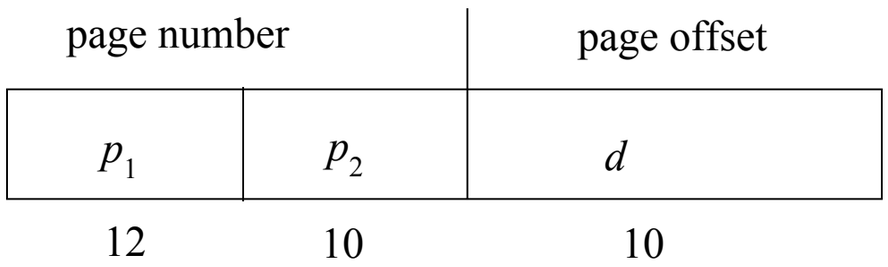
- Break up the logical address space into multiple page tables
- A simple technique is a two-level page table
- We then page the page table

Two-Level Page-Table Scheme



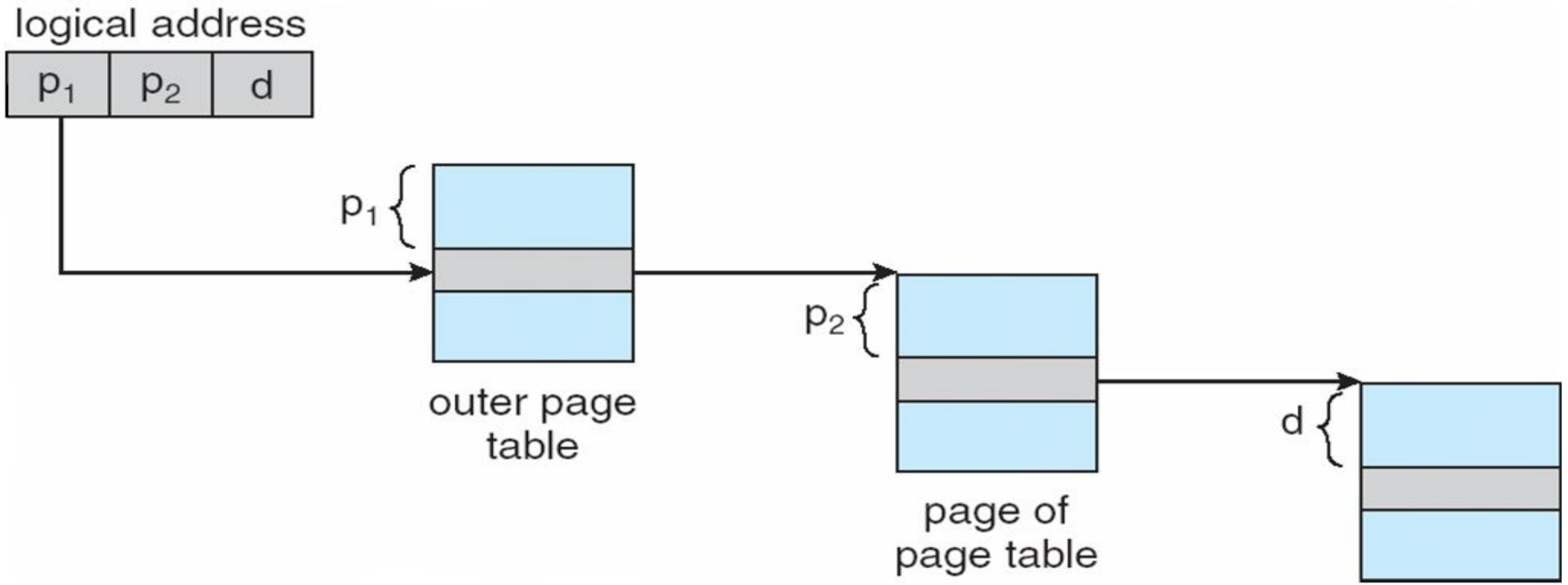
Two-Level Paging Example

- A logical address (on 32-bit machine with 1K page size) is divided into:
  - a page number consisting of 22 bits
  - a page offset consisting of 10 bits
- Since the page table is paged, the page number is further divided into:
  - a 12-bit page number
  - a 10-bit page offset
- Thus, a logical address is as follows:



- where p_1 is an index into the outer page table, and p_2 is the displacement within the page of the inner page table
- Known as **forward-mapped page table**

Address-Translation Scheme



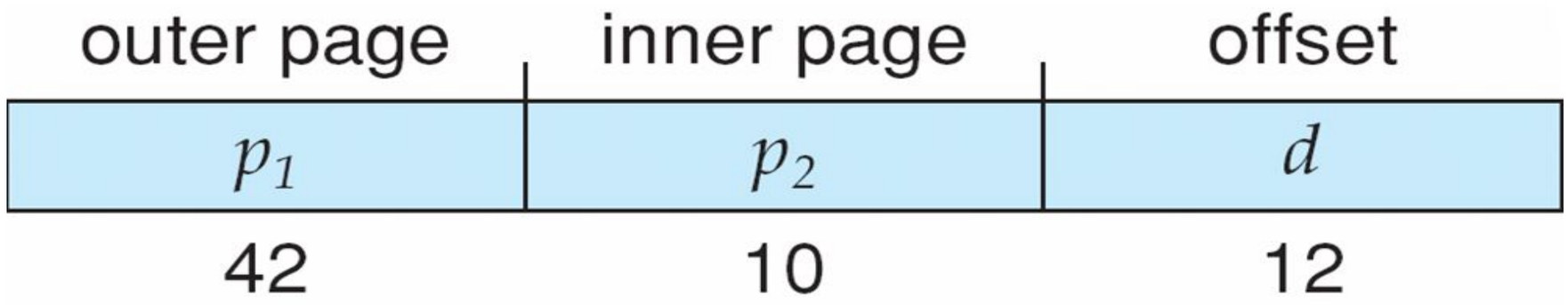
64-bit Logical Address Space

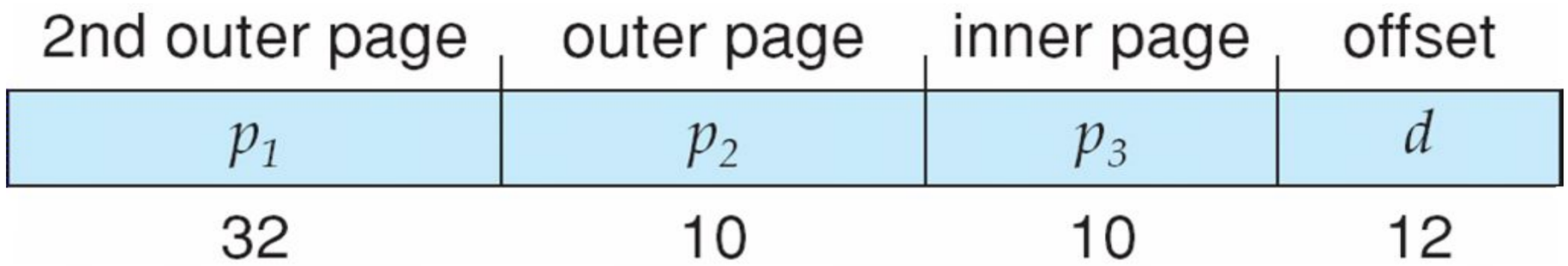
- Even two-level paging scheme not sufficient
- If page size is 4 KB (2^{12})
  - Then page table has 2^{52} entries
  - If two level scheme, inner page tables could be 2^{10} 4-byte entries
  - Address would look like

outer page	inner page	page offset
p_1	p_2	d
42	10	12

  - Outer page table has 2^{42} entries or 2^{44} bytes
  - One solution is to add a 2^{nd} outer page table
  - But in the following example the 2^{nd} outer page table is still 2^{34} bytes in size
    - And possibly 4 memory access to get to one physical memory location

Three-level Paging Scheme

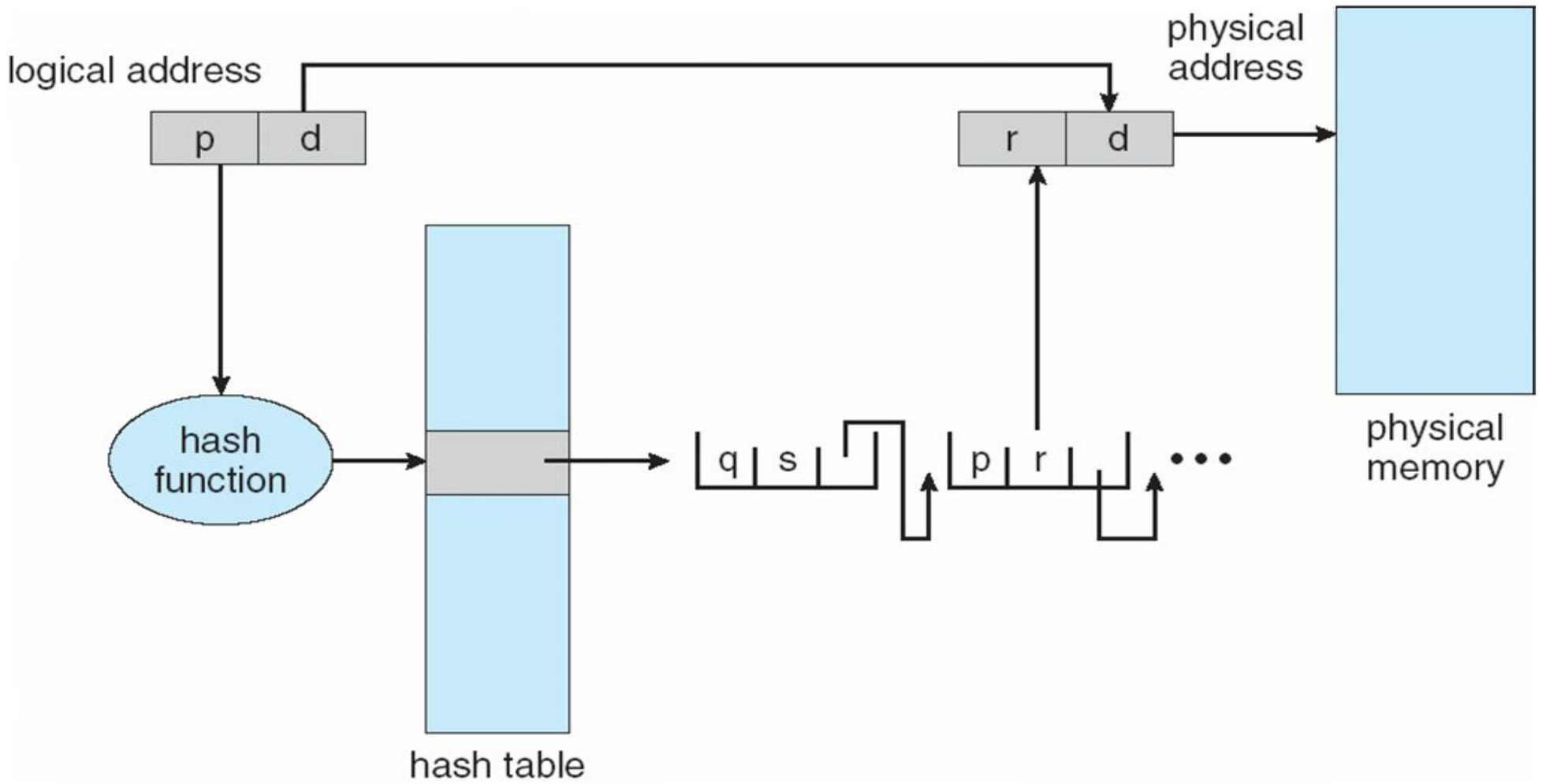




Hashed Page Tables

- Common in address spaces > 32 bits
- The virtual page number is hashed into a page table
  - This page table contains a chain of elements hashing to the same location
- Each element contains (1) the virtual page number (2) the value of the mapped page frame (3) a pointer to the next element
- Virtual page numbers are compared in this chain searching for a match
  - If a match is found, the corresponding physical frame is extracted

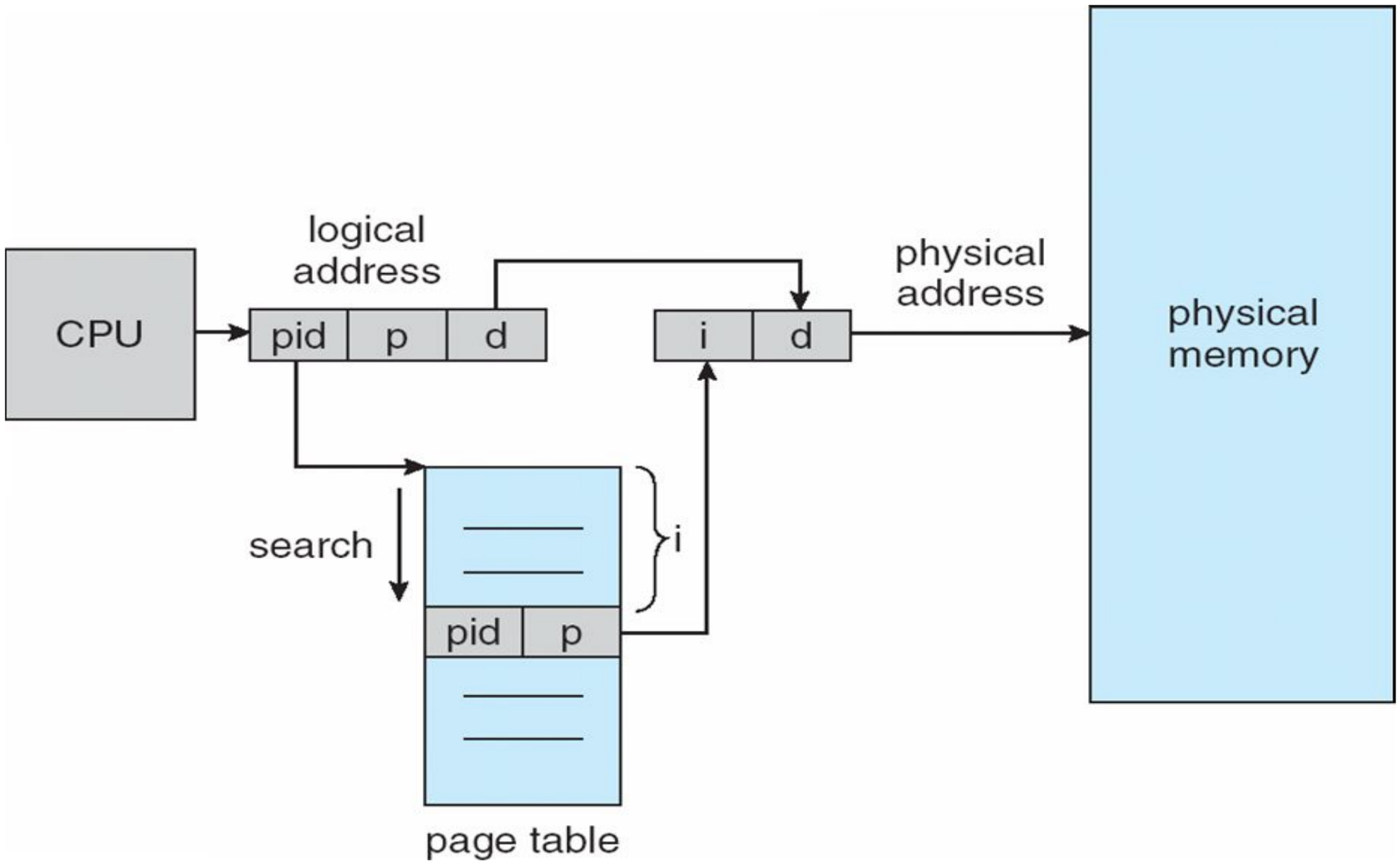
Hashed Page Table



Inverted Page Table

- Rather than each process having a page table and keeping track of all possible logical pages, track all physical pages
- One entry for each real page of memory
- Entry consists of the virtual address of the page stored in that real memory location, with information about the process that owns that page
- Decreases memory needed to store each page table, but increases time needed to search the table when a page reference occurs
- Use hash table to limit the search to one — or at most a few — page-table entries
  - TLB can accelerate access
- But how to implement shared memory?
  - One mapping of a virtual address to the shared physical address

Inverted Page Table Architecture

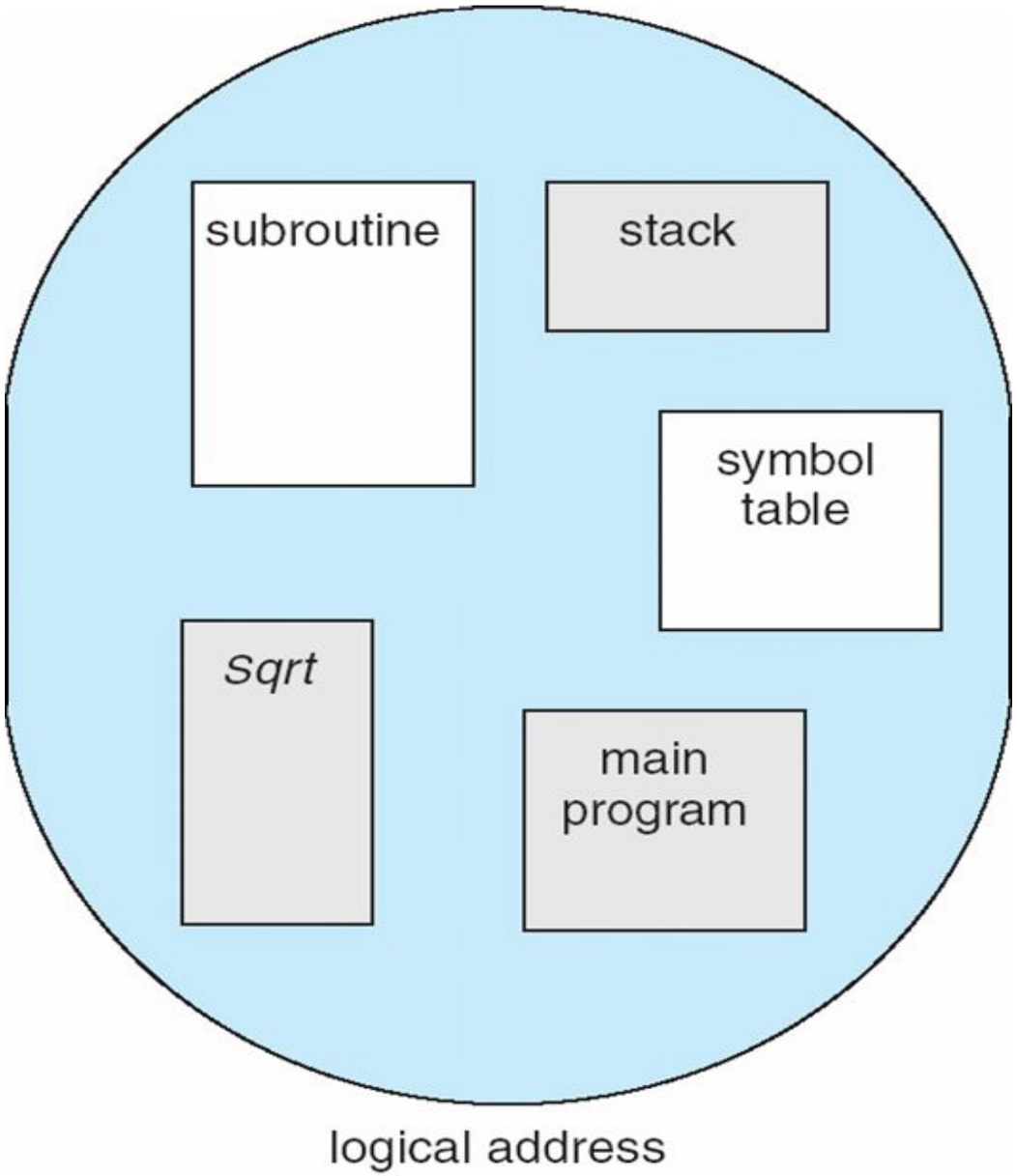


Segmentation

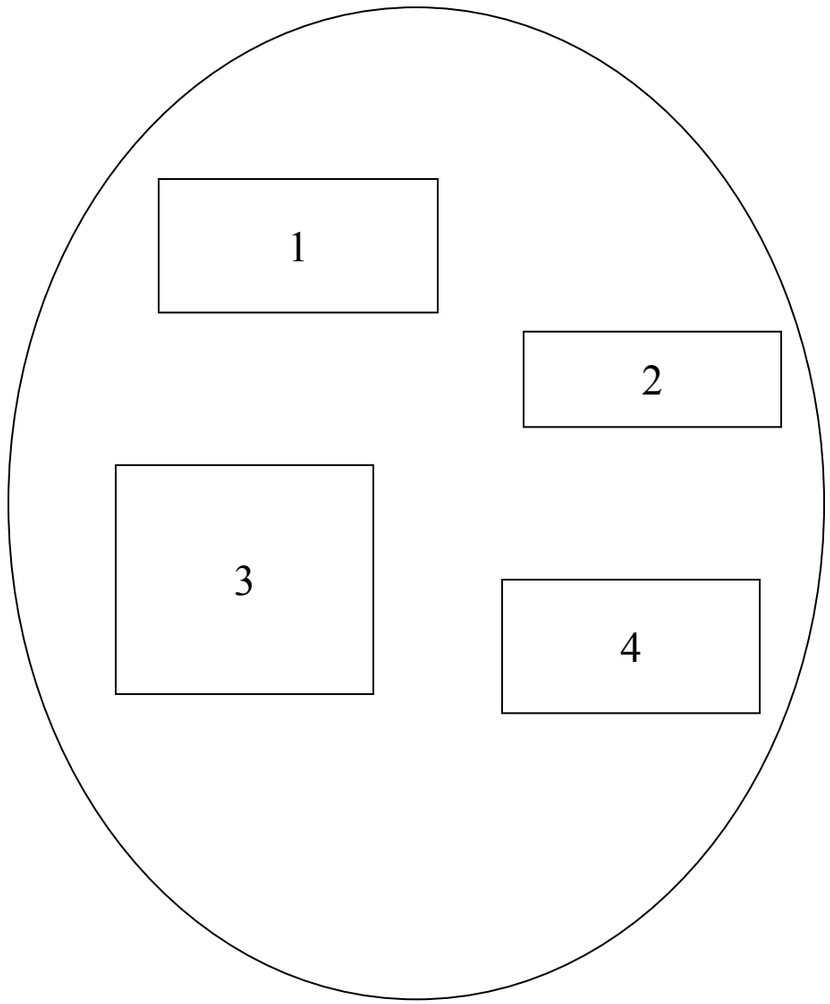
- Memory-management scheme that supports user view of memory
- A program is a collection of segments
  - A segment is a logical unit such as:

    main program
    procedure
    function
    method
    object
    local variables, global variables
    common block
    stack
    symbol table
    arrays

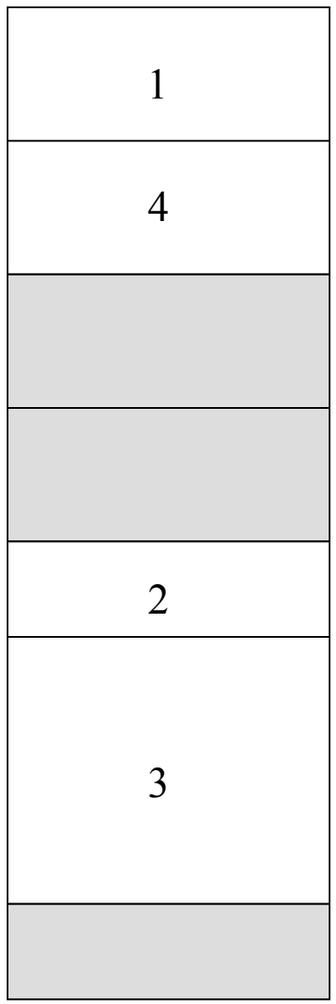
User's View of a Program



Logical View of Segmentation



user space



physical memory space

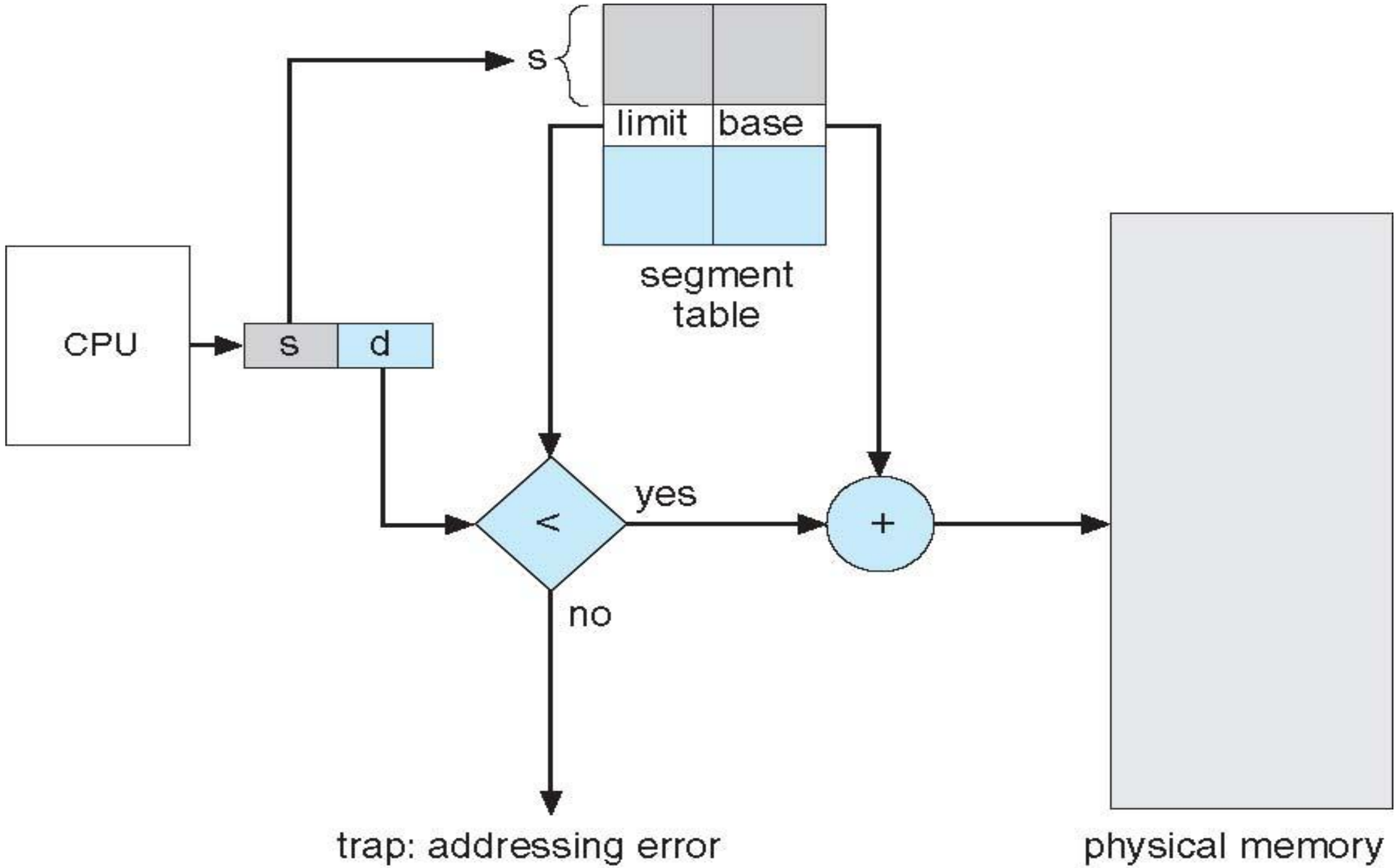
Segmentation Architecture

- 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 number of segments used by a program;
  segment number ***s*** is legal if ***s*** < **STLR**

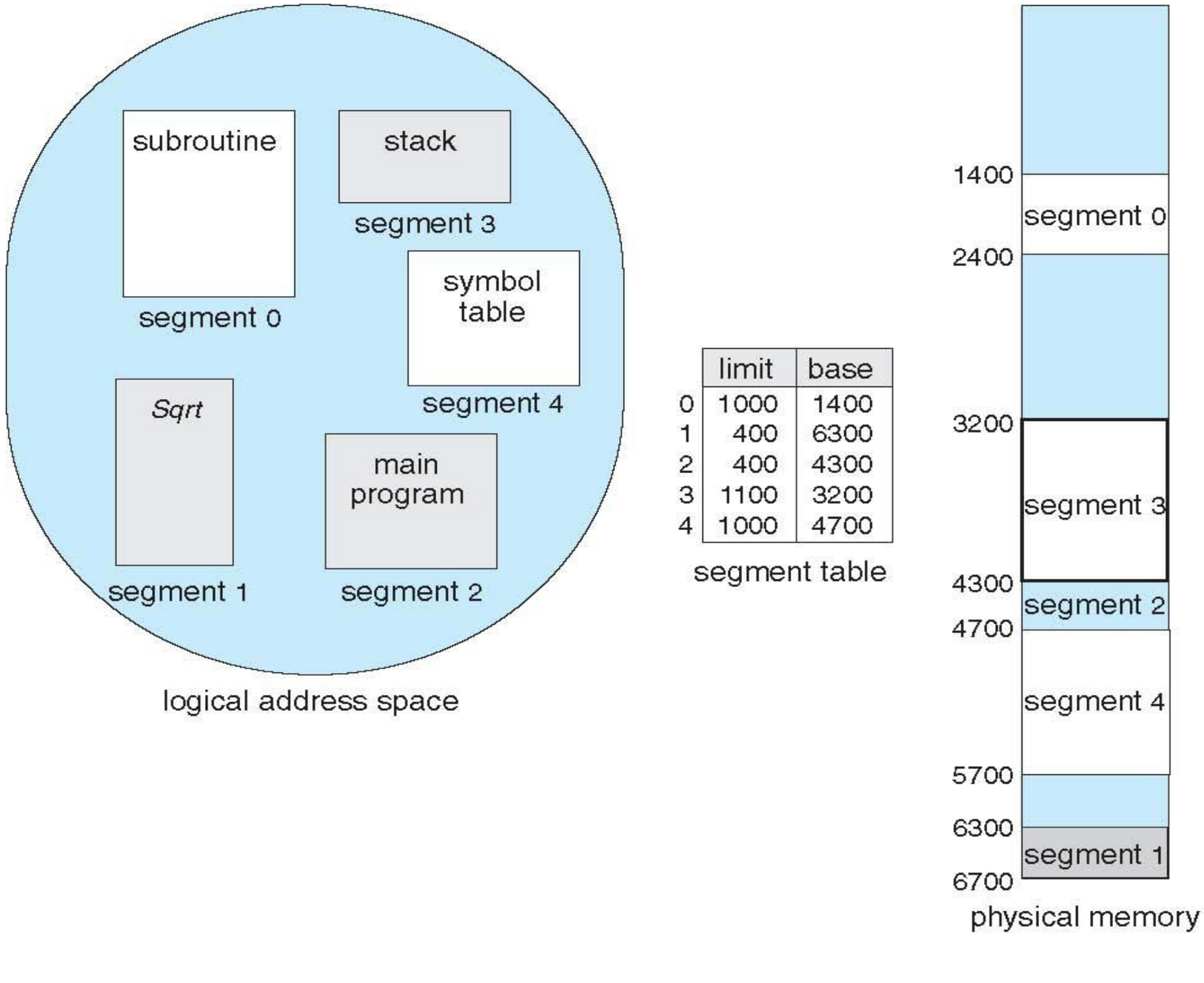
Segmentation Architecture (Cont.)

- Protection
  - With each entry in segment table associate:
    - validation bit = 0 ⇒ illegal segment
    - read/write/execute privileges
- Protection bits associated with segments; code sharing occurs at segment level
- Since segments vary in length, memory allocation is a dynamic storage-allocation problem
- A segmentation example is shown in the following diagram

Segmentation Hardware



Example of Segmentation



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

segment table

End of Chapter 8