CHAPTER 9 - MAIN MEMORY

OBJECTIVES

- Logical and physical adresses and how memory management unit translates
- Detailed description of various ways of organizing memory hardware
- Algorithms for contiguous memory allocation
- Memory-management techniques, including paging with translation look-aside buffer
- Discuss fragmentation (internal and external)

BACKGROUND

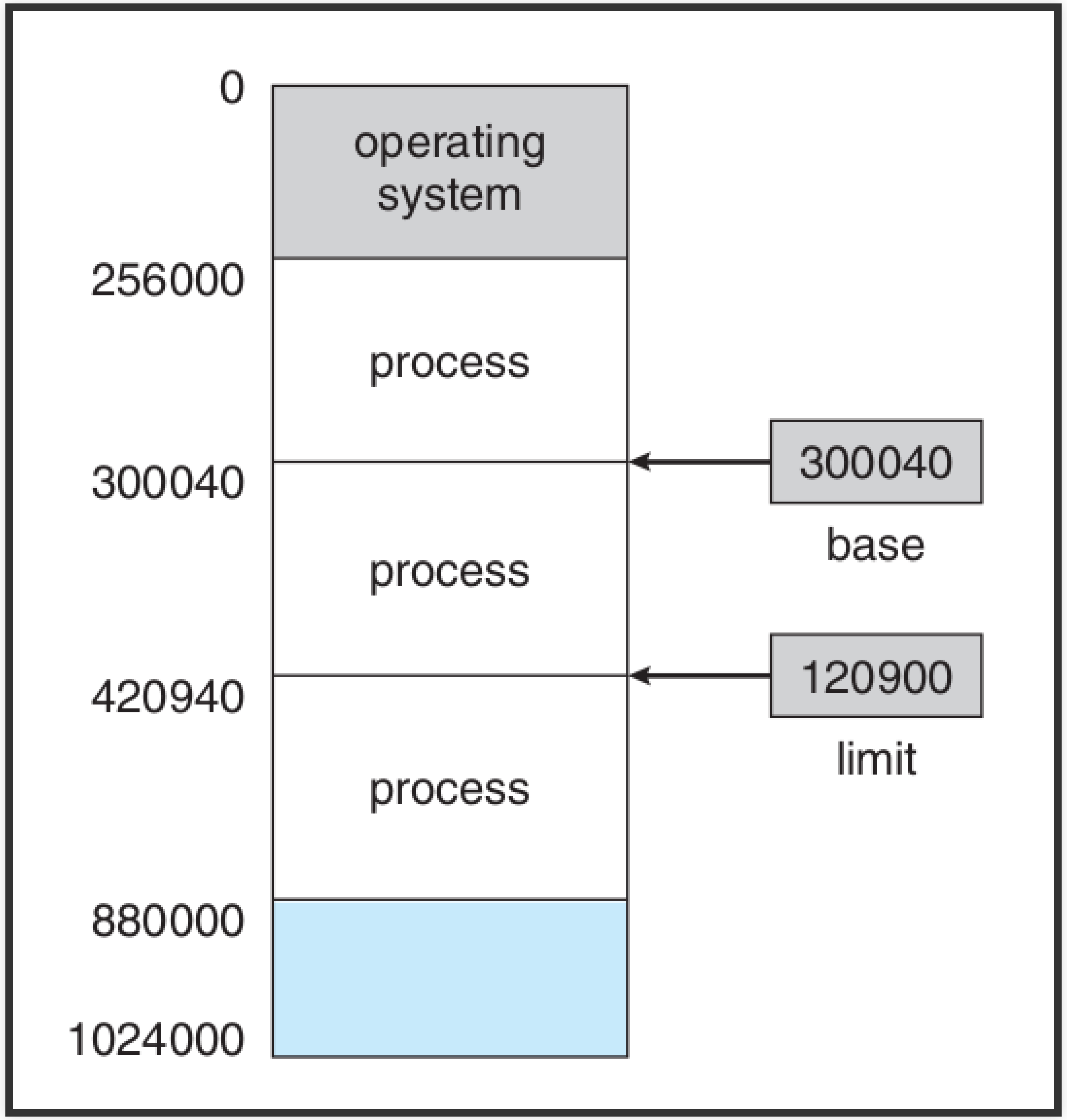
BACKGROUND

- 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
- Memory unit only sees a stream of addresses + read requests, or address + data and write requests

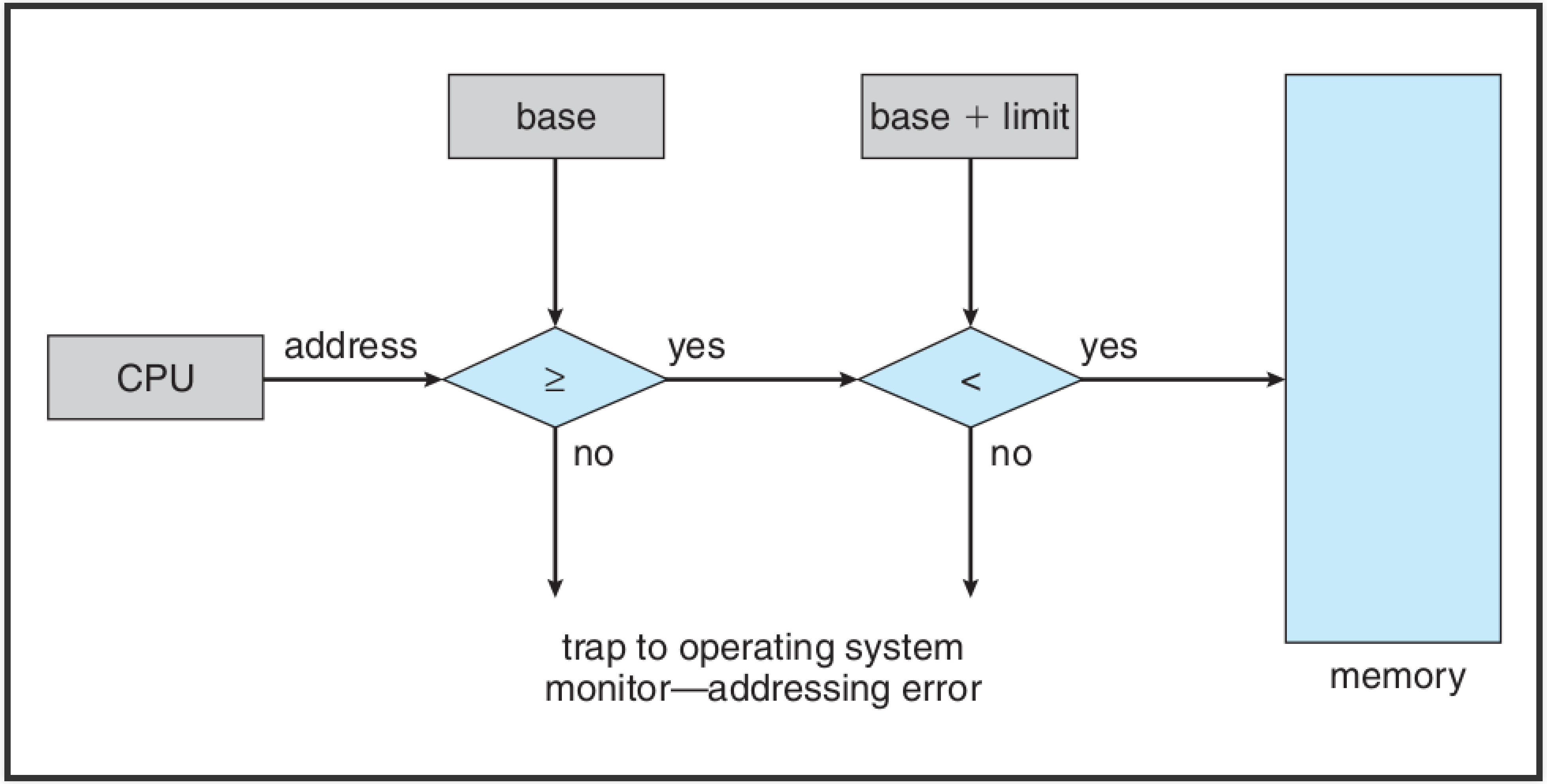
BACKGROUND

- Register access in one CPU clock (or less)
- Main memory can take many cycles, causing a stall
- Cache sits between main memory and CPU registers
- Protection of memory required to ensure correct operation

BASE AND LIMIT REGISTERS



HARDWARE ADDRESS PROTECTION WITH BASE AND LIMIT REGISTERS



ADDRESS BINDING

- Programs on disk, ready to be brought into memory to execute form an input queue
    - Without support, must be loaded into address 0000
- Inconvenient to have first user process physical address always at 0000
    - How can it not be?

ADDRESS BINDING

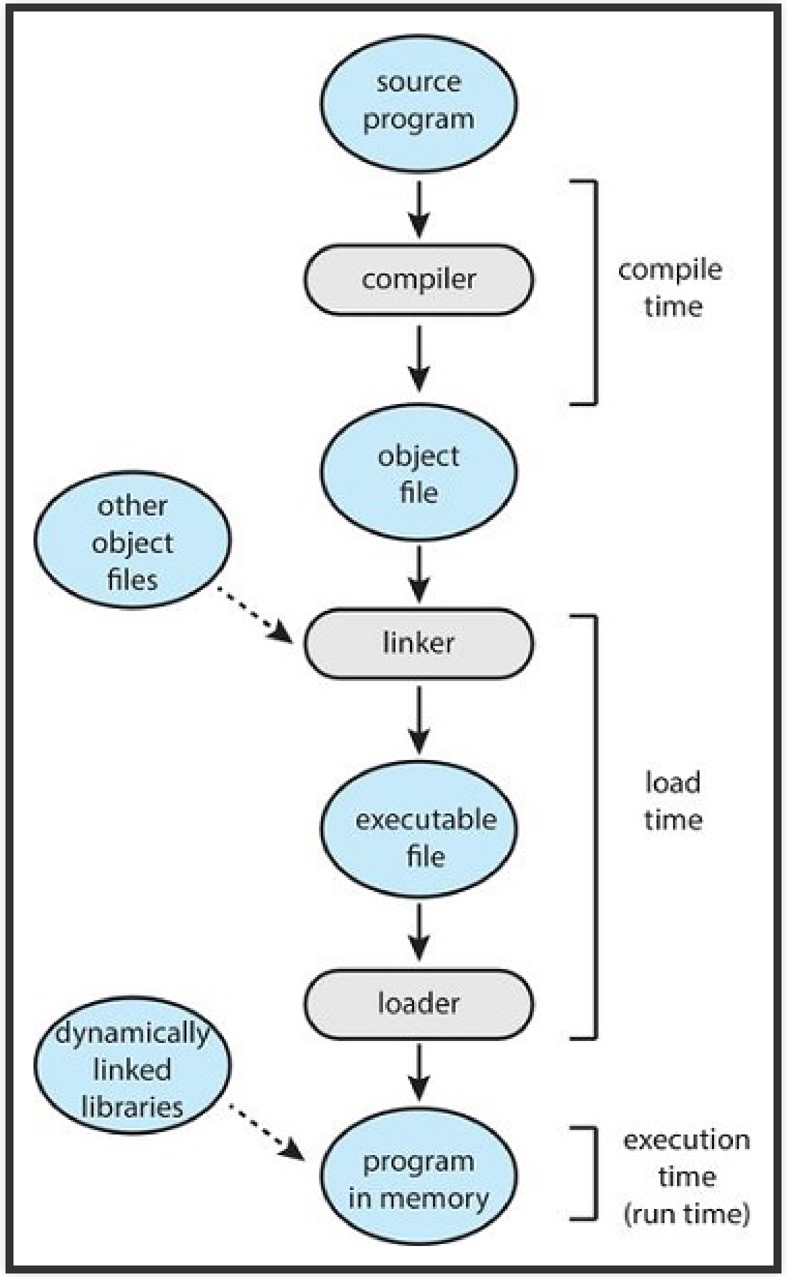
- Further, addresses represented in different ways at different stages of a program’s life
    - Source code addresses usually symbolic
    - Compiled code addresses bind to relocatable addresses → i.e. "14 bytes from beginning of this module"
    - Linker or loader will bind relocatable addresses to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

ADDRESS BINDING

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

MULTISTEP PROCESSING



LOGICAL VS. PHYSICAL ADDRESS SPACE

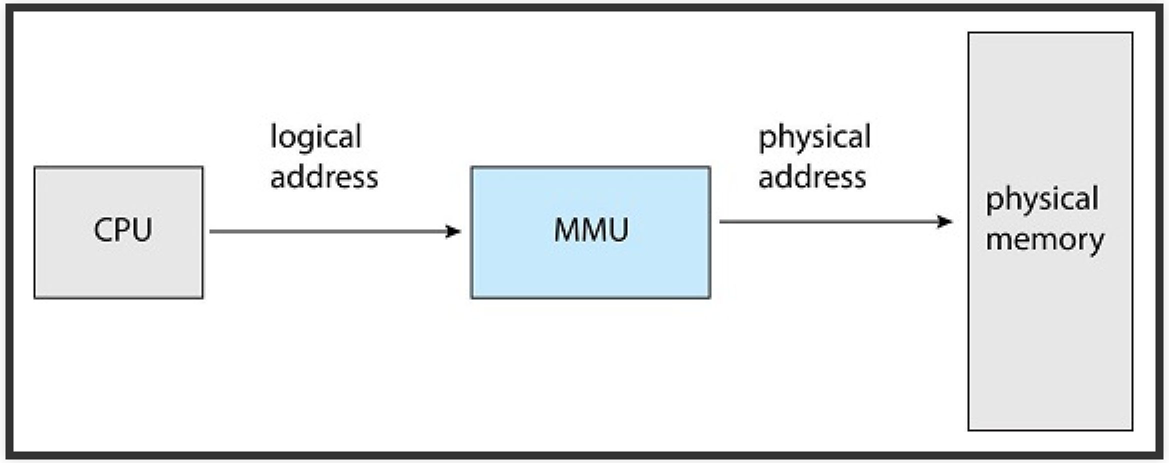
The concept of a logical address space that is bound to a separate physical address space is central to proper memory management

- **Logical address** – generated by the CPU; also referred to as **virtual address**
- **Physical address** – address seen by the memory unit

MEMORY-MANAGEMENT UNIT (MMU)

- Hardware device that at run time maps virtual to physical address
- Many methods possible, covered in the rest of this chapter
- To start, consider simple scheme where the value in the relocation register is added to every address generated by a user process at the time it is sent to memory

MEMORY-MANAGEMENT UNIT (MMU)



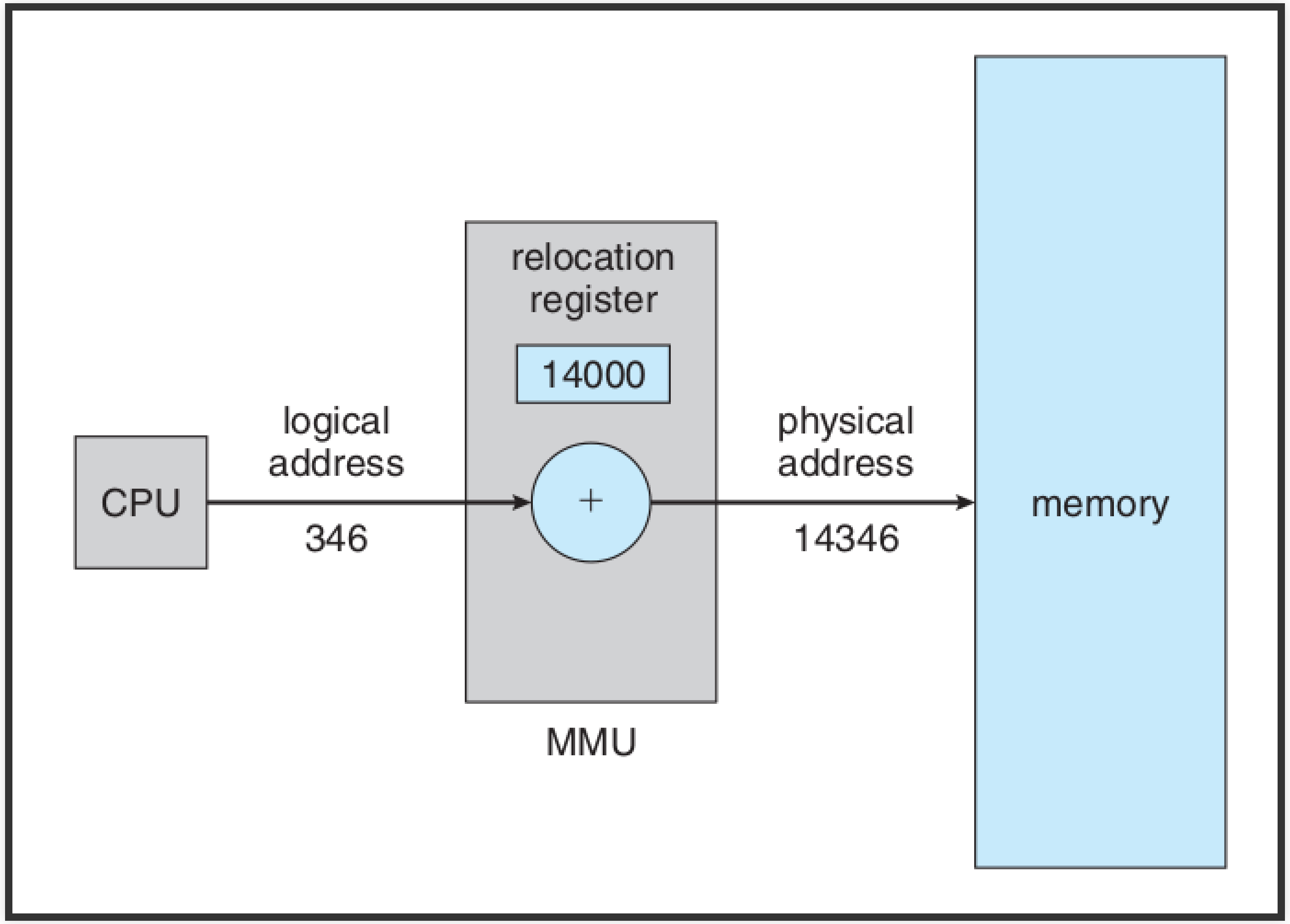
LOGICAL VS. PHYSICAL ADDRESS SPACE

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

DYNAMIC RELOCATION USING A RELOCATION REGISTER



MEMORY-MANAGEMENT UNIT (MMU)

- Base register now called relocation register
  - MS-DOS on Intel 80x86 used 4 relocation registers
- The user program deals with logical addresses; it never sees the real physical addresses
  - Execution-time binding occurs when reference is made to location in memory
  - Logical address bound to physical addresses

DYNAMIC LOADING

- Routine is not loaded until it is called
- Better memory-space utilization; unused routine is never loaded
- All routines kept on disk in relocatable load format
- Useful when large amounts of code are needed to handle infrequently occurring cases
- No special support from the operating system is required
    - Implemented through program design
    - OS can help by providing libraries to implement dynamic loading

DYNAMIC LINKING

- **Static linking** – system libraries and program code combined by the loader into the binary program image
- **Dynamic linking** –linking postponed until execution time
- Small piece of code, **stub**, used to locate the appropriate memory-resident library routine
- Stub replaces itself with the address of the routine, and executes the routine

DYNAMIC LINKING

- Operating system checks if routine is in processes’ memory address
    - If not in address space, add to address space
- Dynamic linking is particularly useful for libraries
- System also known as shared libraries
- Consider applicability to patching system libraries
    - Versioning may be needed

CONTIGUOUS MEMORY ALLOCATION

CONTIGUOUS MEMORY ALLOCATION

Main memory must support both OS and user processes

Limited resource, must allocate efficiently

Contiguous allocation is one early method

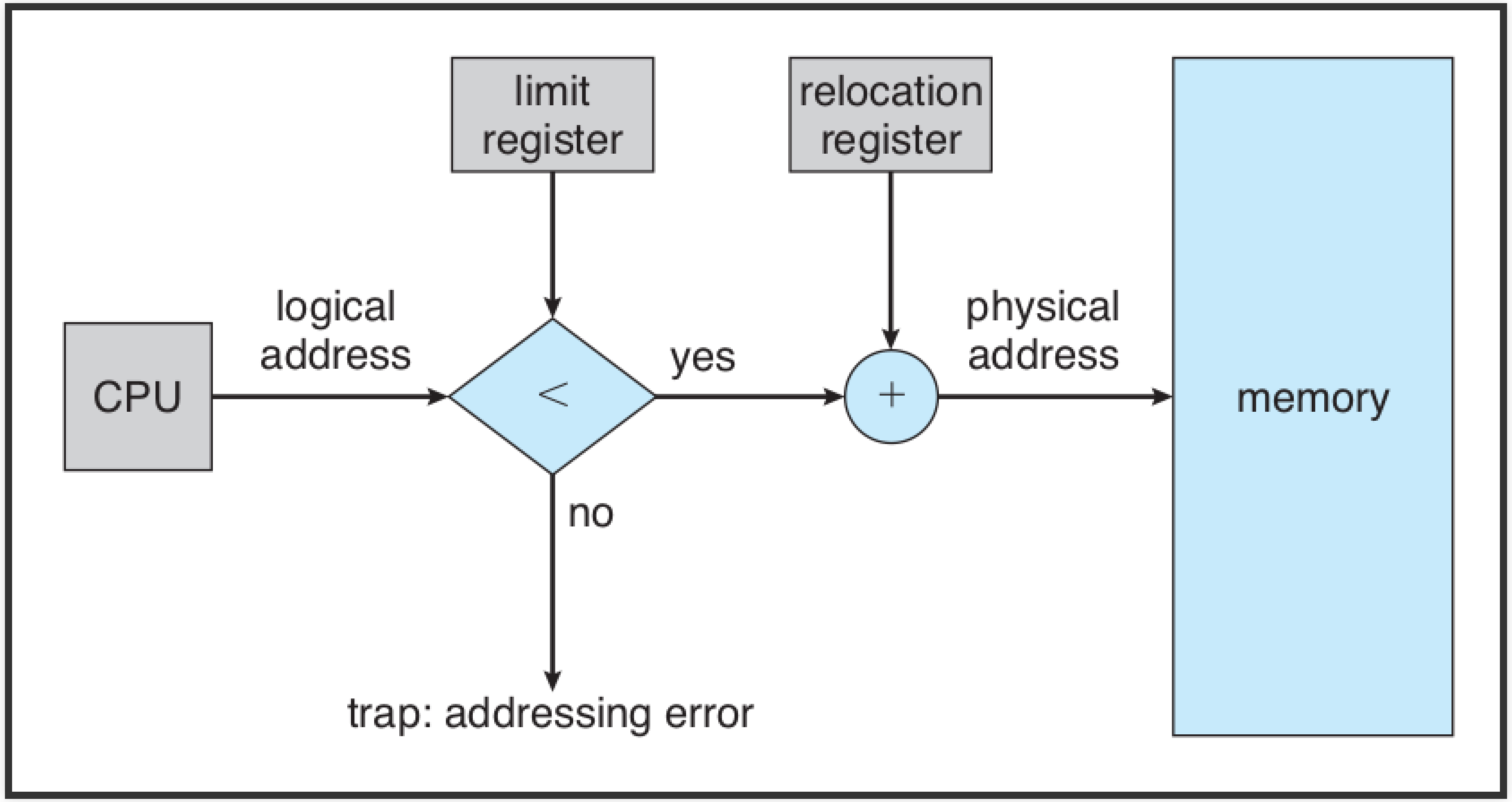
CONTIGUOUS MEMORY ALLOCATION

- Main memory usually into two partitions:
  - Resident operating system, usually held in low memory with interrupt vector
  - User processes then held in high memory
  - Each process contained in single contiguous section of memory

CONTIGUOUS MEMORY ALLOCATION

- 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
  - Can then allow actions such as kernel code being transient and kernel changing size

HARDWARE SUPPORT FOR RELOCATION AND LIMIT REGISTERS



MULTIPLE-PARTITION ALLOCATION

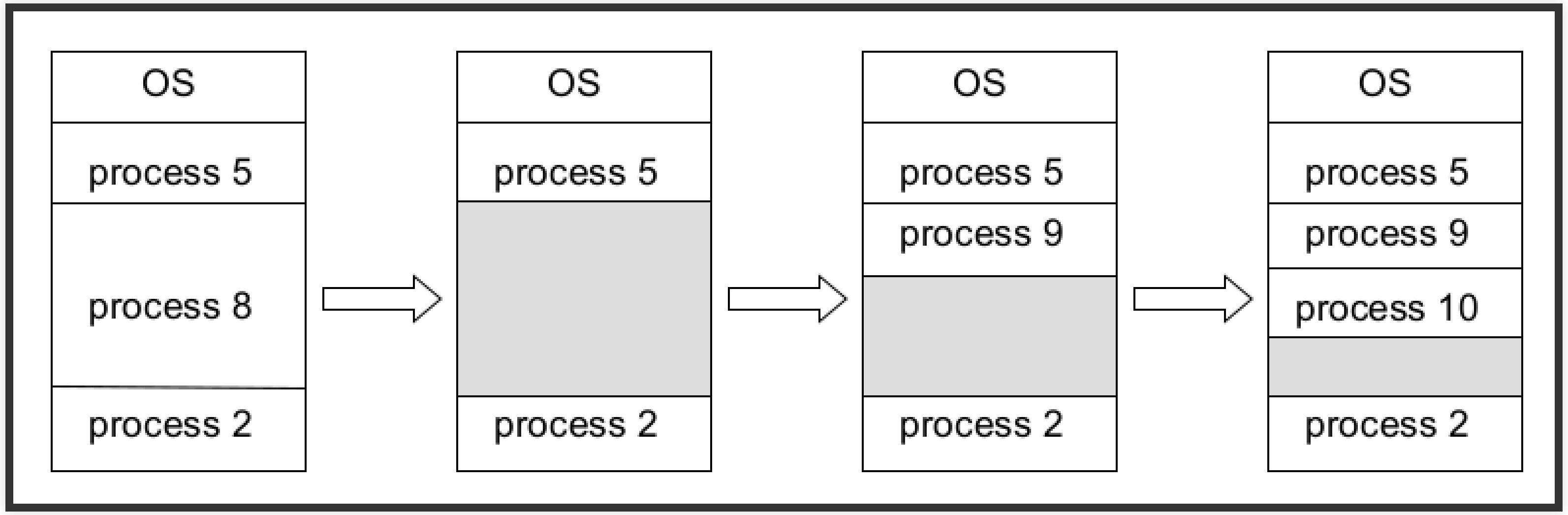
- Degree of multiprogramming limited by number of partitions
- Variable-partition sizes for efficiency (sized to a given process' needs)
- Hole – block of available memory; holes of various size are scattered throughout memory

MULTIPLE-PARTITION ALLOCATION

- 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:

  1. allocated partitions
  2. free partitions (hole)

MULTIPLE-PARTITION ALLOCATION



DYNAMIC STORAGE-ALLOCATION PROBLEM

❓ How to satisfy a request of size n from a list of free holes?

DYNAMIC STORAGE-ALLOCATION

- **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

- 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
  - I/O problem
    - Latch job in memory while it is involved in I/O
    - Do I/O only into OS buffers
- Now consider that backing store has same fragmentation problems

PAGING

PAGING

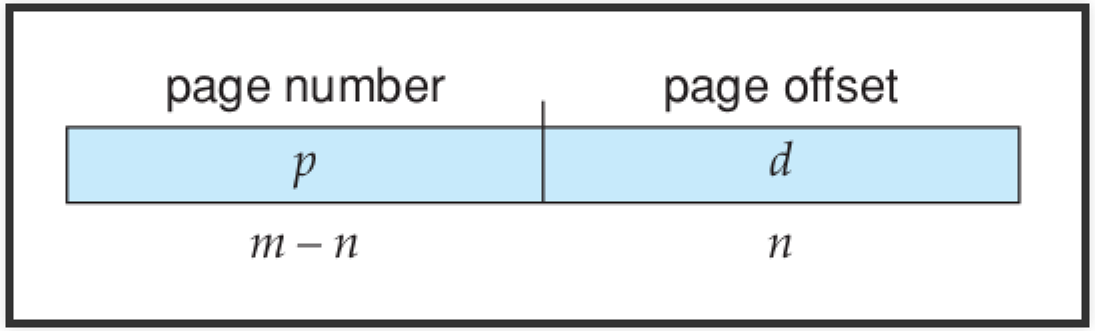
- Physical address space of a process can be noncontiguous; process is allocated physical memory whenever the latter is available
  - Avoids external fragmentation
  - Avoids problem of varying sized memory chunks
- Divide physical memory into fixed-sized blocks called frames
  - Size is power of 2, between 512 bytes and 16 Mbytes

PAGING

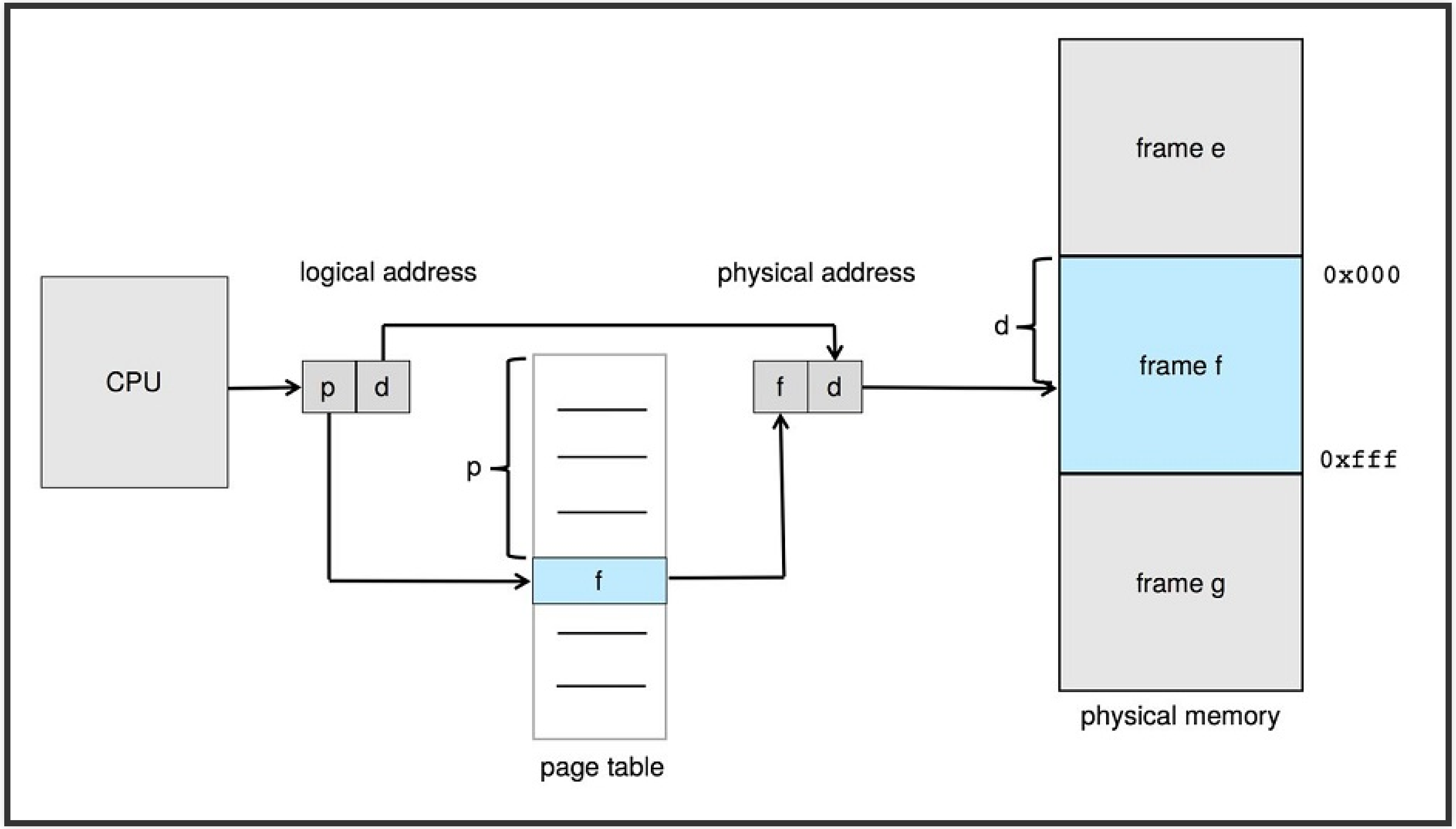
- Divide logical memory into blocks of same size called pages
- Keep track of all free frames
- To run a program of size N pages, need to find N free frames and load program
- Set up a page table to translate logical to physical addresses
- Backing store likewise split into pages
- Still have Internal fragmentation

ADDRESS TRANSLATION SCHEME

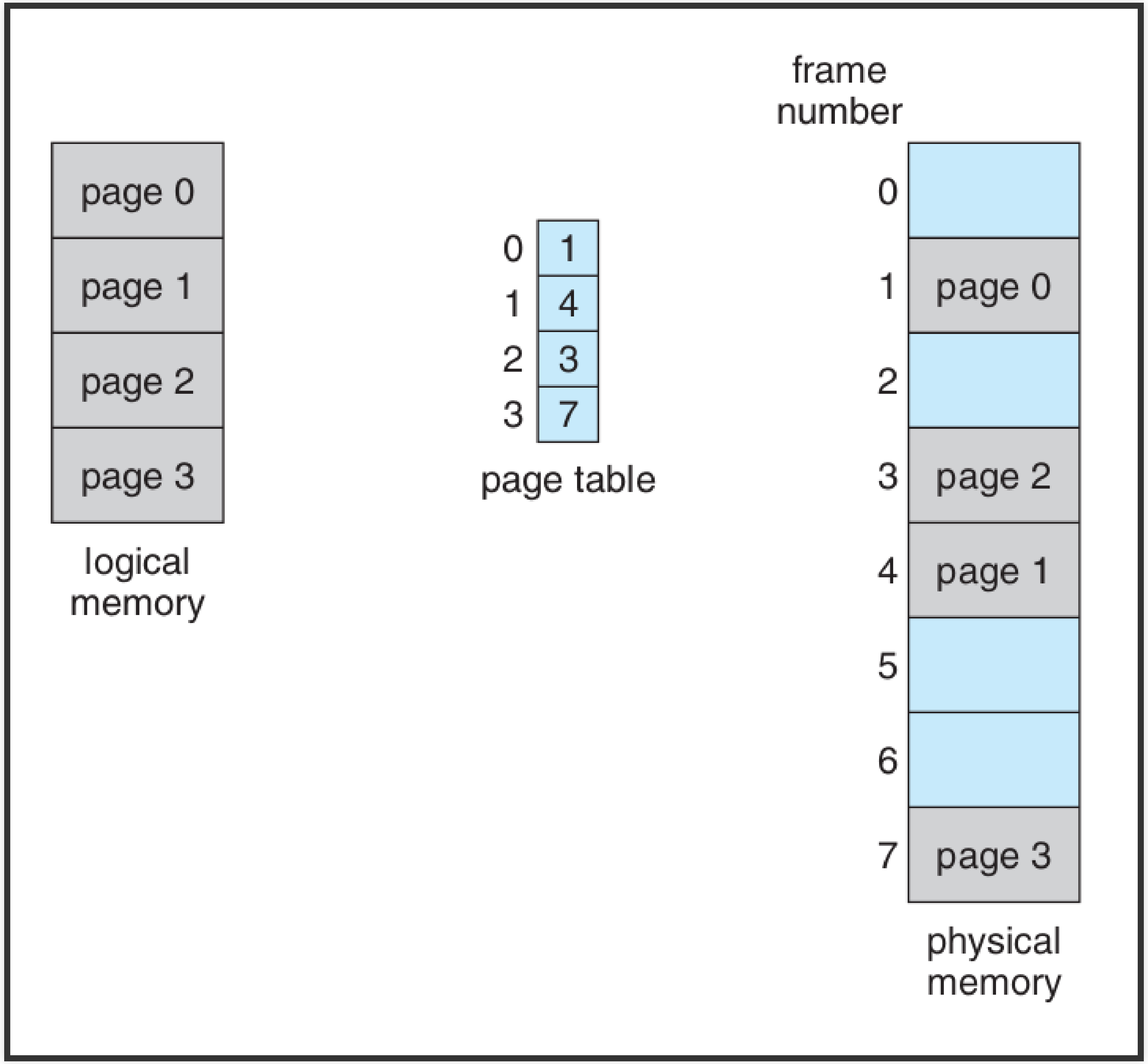
- Address generated by CPU is divided into:
  - Page number (p) – used as an index into a page table which contains base address of each page in physical memory
  - Page offset (d) – combined with base address to define the physical memory address that is sent to the memory unit



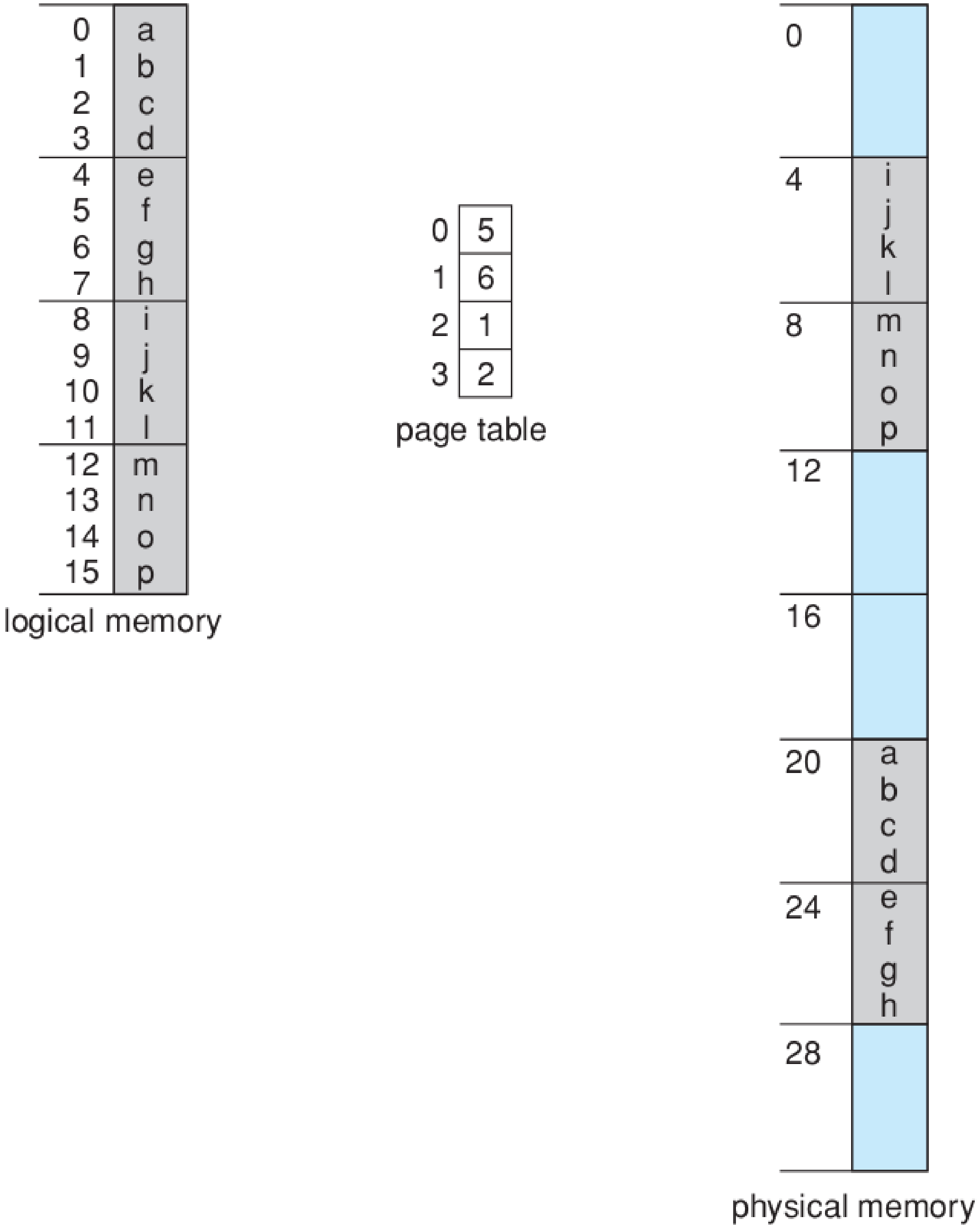
PAGING HARDWARE



PAGING MODEL


frame number
page 0
page 1
page 2
page 3
logical memory
0 1
1 4
2 3
3 7
page table
0
1 page 0
2
3 page 2
4 page 1
5
6
7 page 3
physical memory

PAGING EXAMPLE


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

PAGING

Calculating internal fragmentation

- Page size = 2,048 bytes
- Process size = 72,766 bytes
- 35 pages + 1,086 bytes

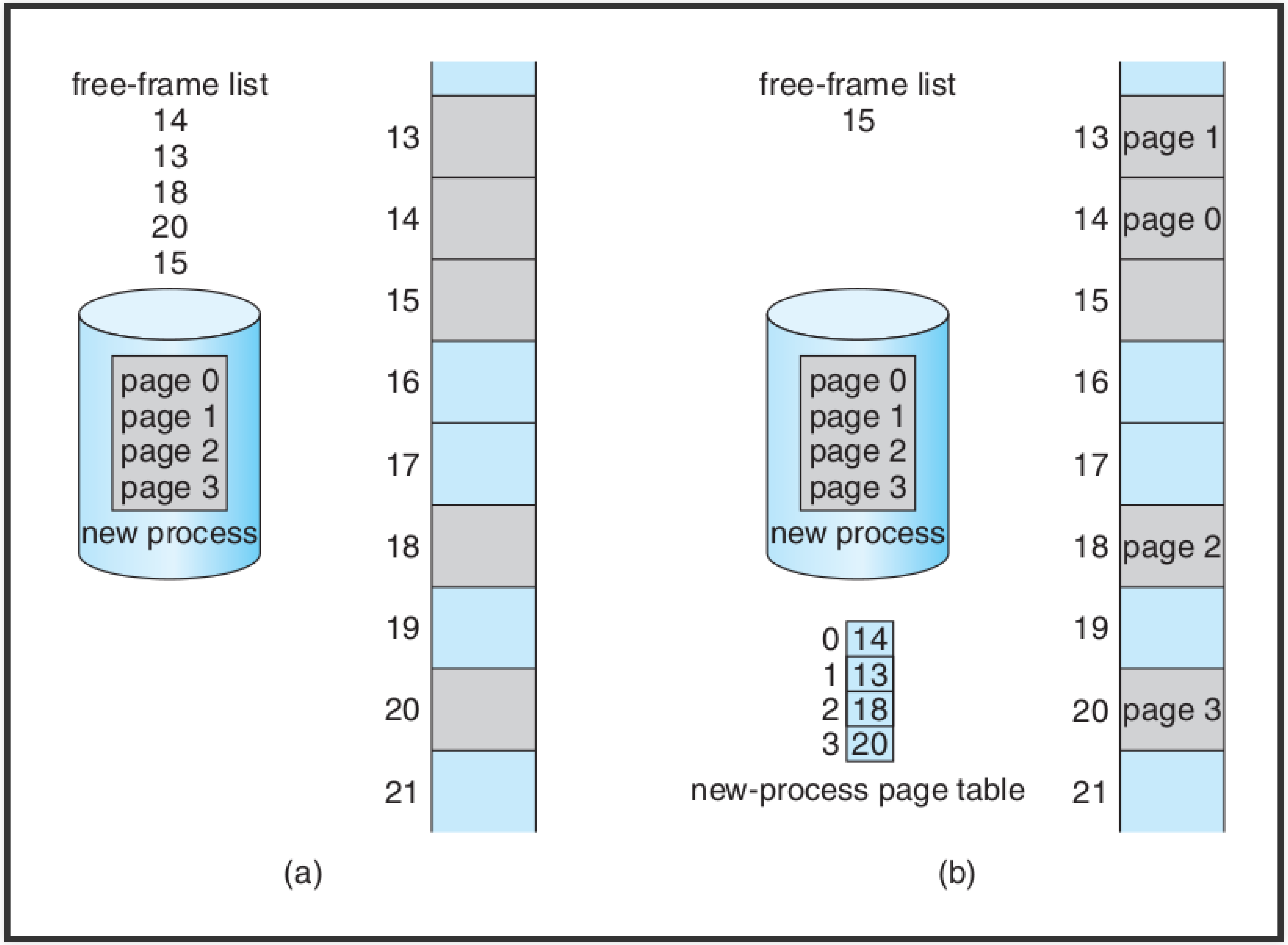
PAGING

- 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
- Page sizes growing over time

PAGING

- Solaris supports two page sizes – 8 KB and 4 MB
- Process view and physical memory now very different
- By implementation process can only access its own memory

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 (HARDWARE SUPPORT)

- 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

IMPLEMENTATION OF PAGE TABLE

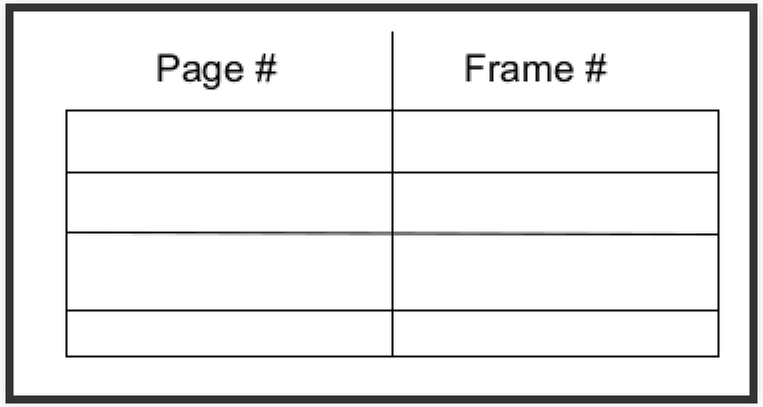
- The two memory access problem can be solved by the use of a special fast-lookup hardware cache called associative memory or **translation look-aside buffers** (TLBs)
- Some TLBs store address-space identifiers (ASIDs) in each TLB entry – uniquely identifies each process to provide address-space protection for that process
    - Otherwise need to flush at every context switch

IMPLEMENTATION OF PAGE TABLE

- 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

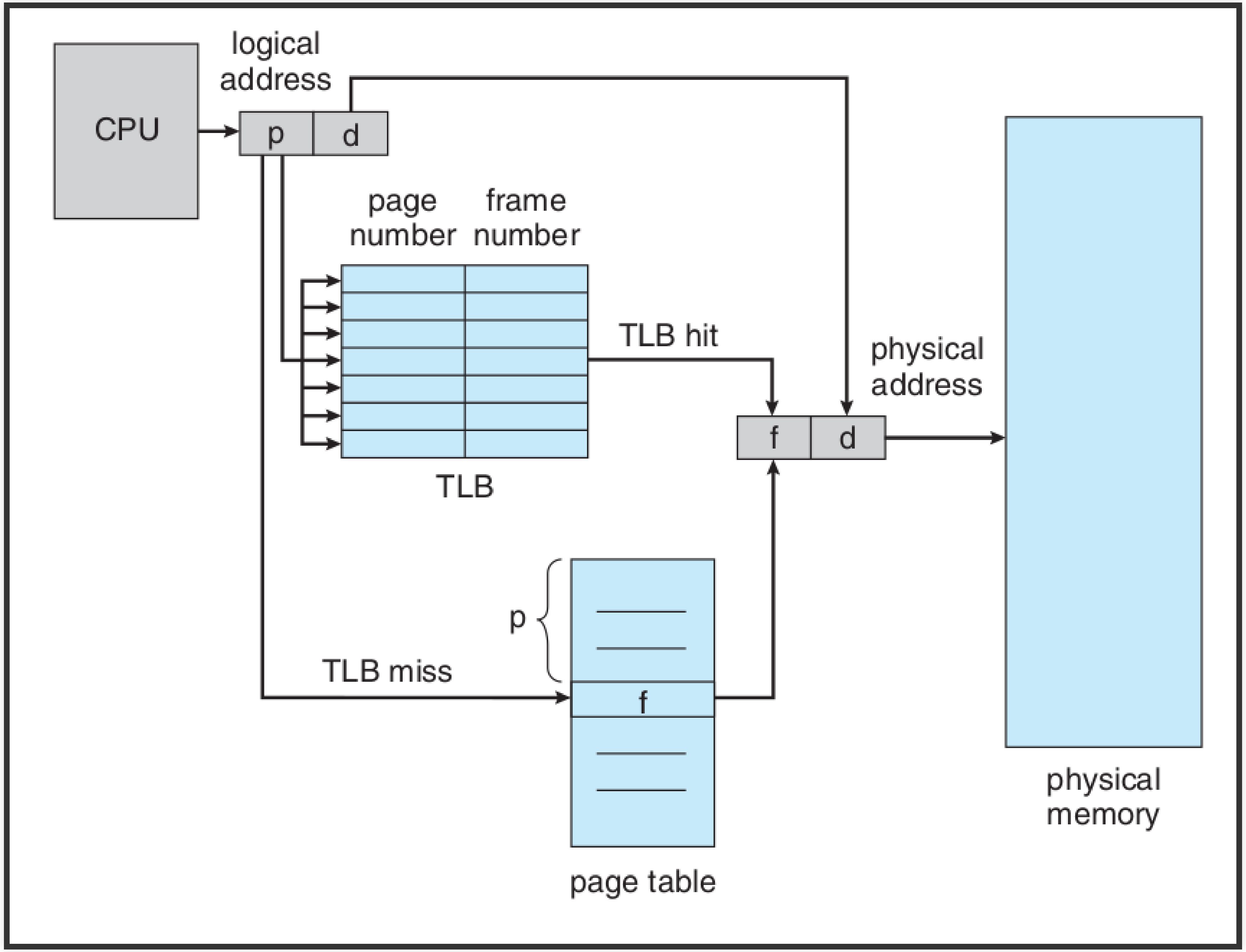
Associative memory – parallel search



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
- Effective Access Time (EAT) → Weight the case by probability

EFFECTIVE ACCESS TIME

- Consider α = 80%, ε = 20ns for TLB search, 100ns for memory access
  - EAT = 0.80 x 100 + 0.20 x 200 = 120ns
- Consider more realistic hit ratio → α = 99%, ε = 20ns for TLB search, 100ns for memory access
  - EAT = 0.99 x 100 + 0.01 x 200 = 101ns

MEMORY PROTECTION

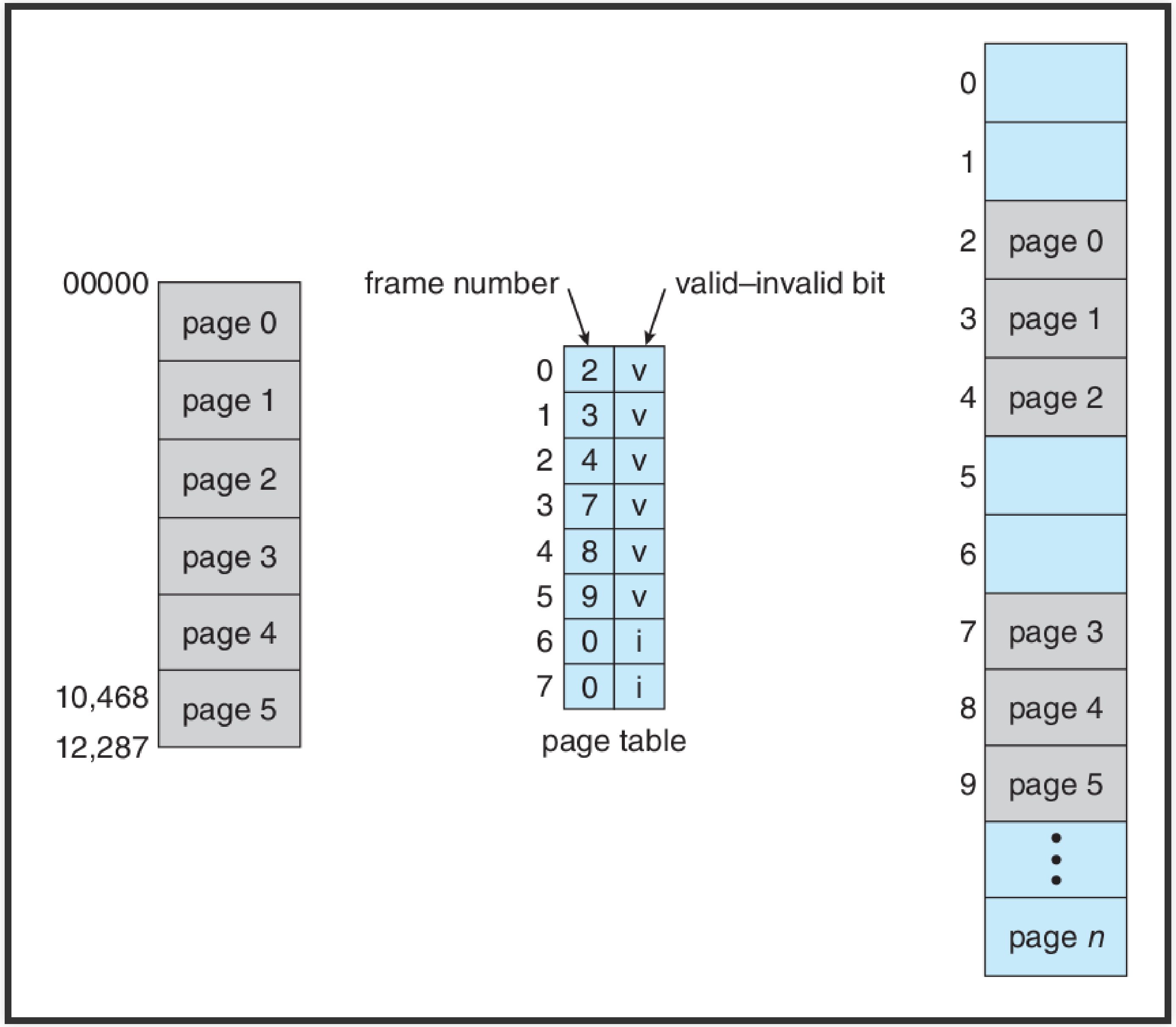
- Memory protection implemented by associating protection bit with each frame to indicate if read-only or read-write access is allowed
    - Can also add more bits to indicate page execute-only, and so on

MEMORY PROTECTION

- 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 PAGES

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



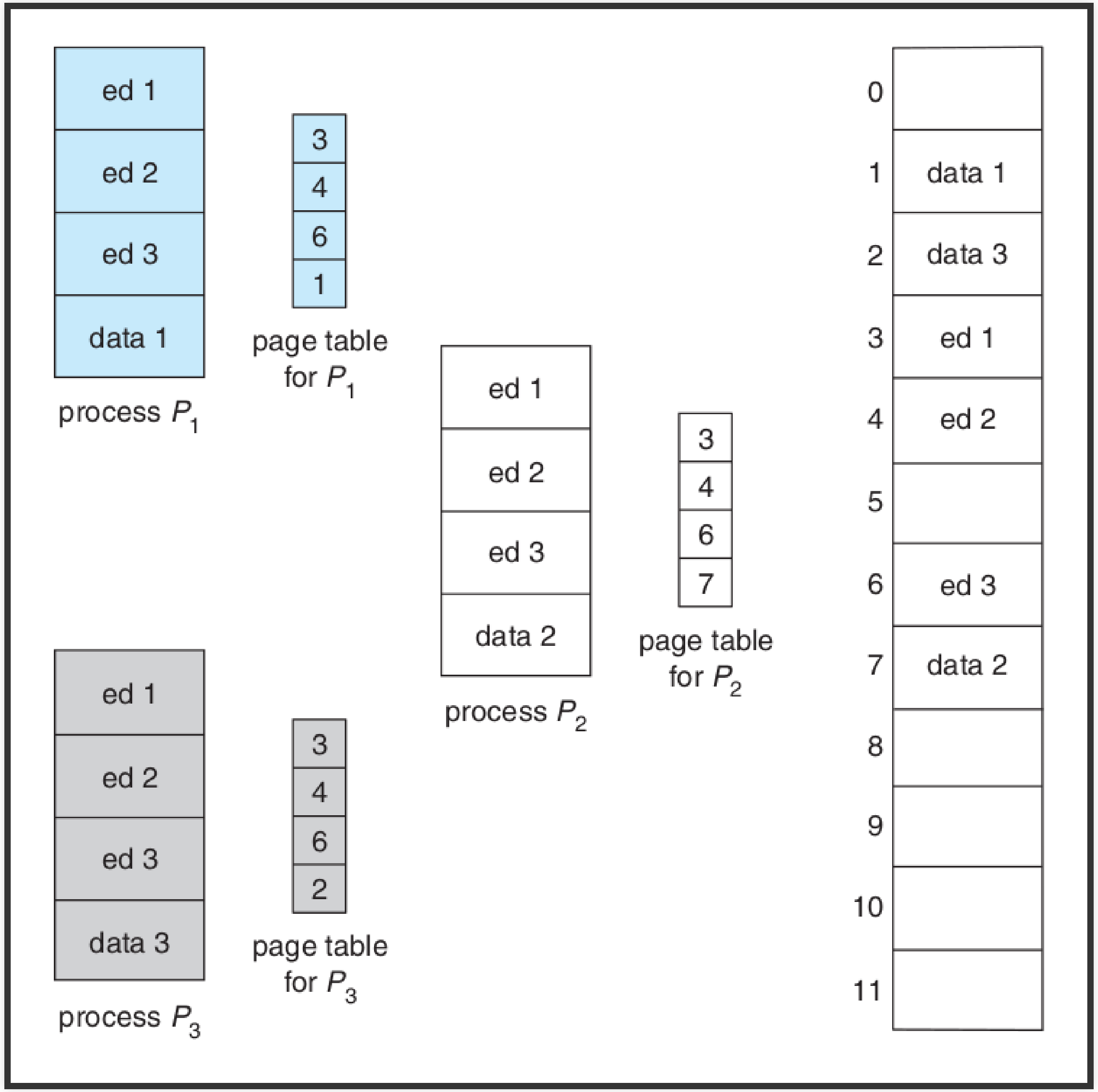
SHARED PAGES

- 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

SHARED PAGES

- 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


ed 1
ed 2
ed 3
data 1
3
4
6
1
page table for P_1
process P_1
ed 1
ed 2
ed 3
data 2
3
4
6
7
page table for P_2
process P_2
ed 1
ed 2
ed 3
data 3
3
4
6
2
page table for P_3
process P_3
0
1 data 1
2 data 3
3 ed 1
4 ed 2
5
6 ed 3
7 data 2
8
9
10
11

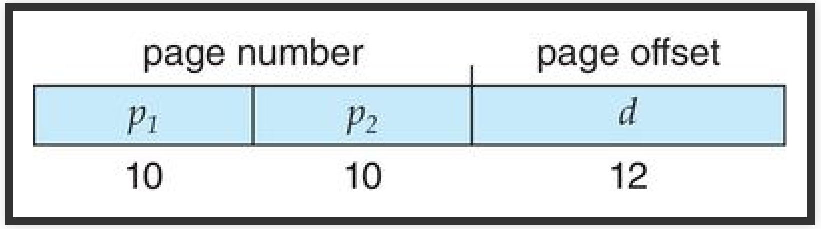
STRUCTURE OF THE PAGE TABLE

STRUCTURE OF THE PAGE TABLE

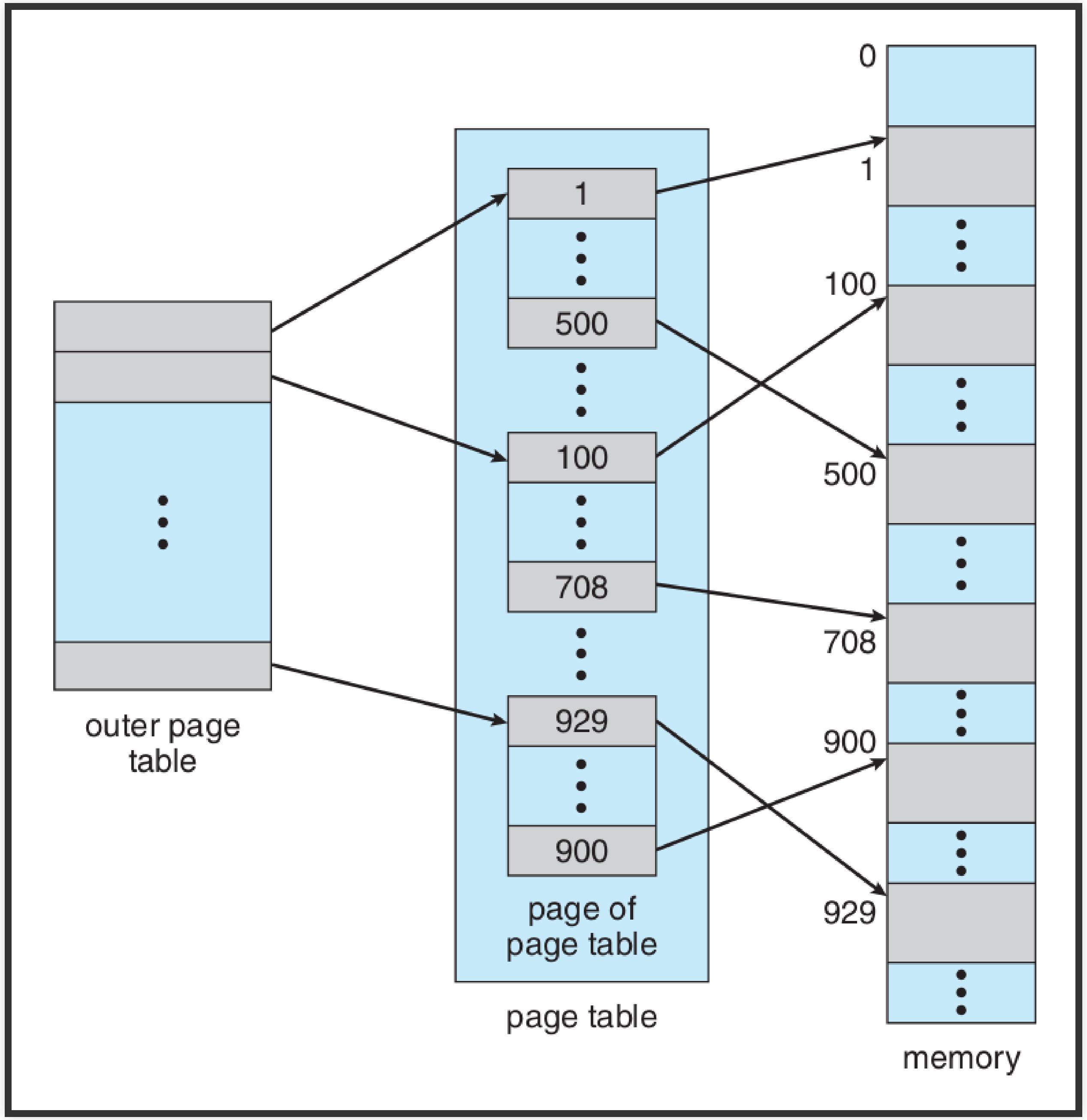
- Memory structures for paging can get huge using straight-forward methods
  - Consider a 32-bit logical address space
  - Page size of 4 KB (2^{12}) → Page table would have 1 million entries ($2^{32}/2^{12}$)
  - If each entry is 4 bytes → 4 MB of physical address space / memory for page table alone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

HIERARCHICAL 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

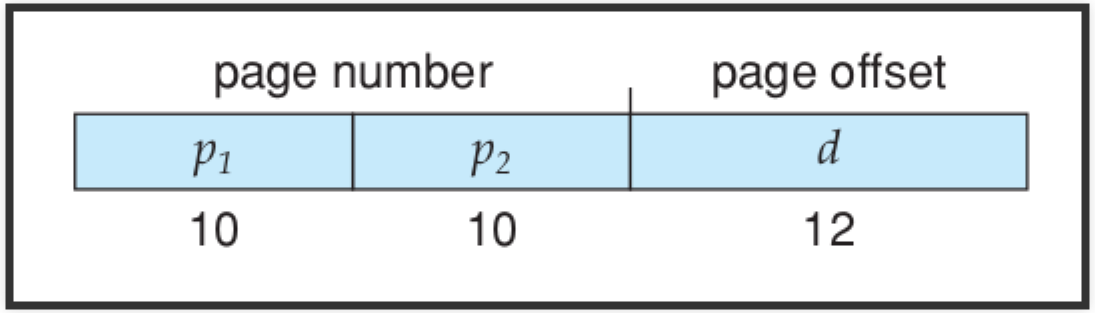


TWO-LEVEL PAGING EXAMPLE

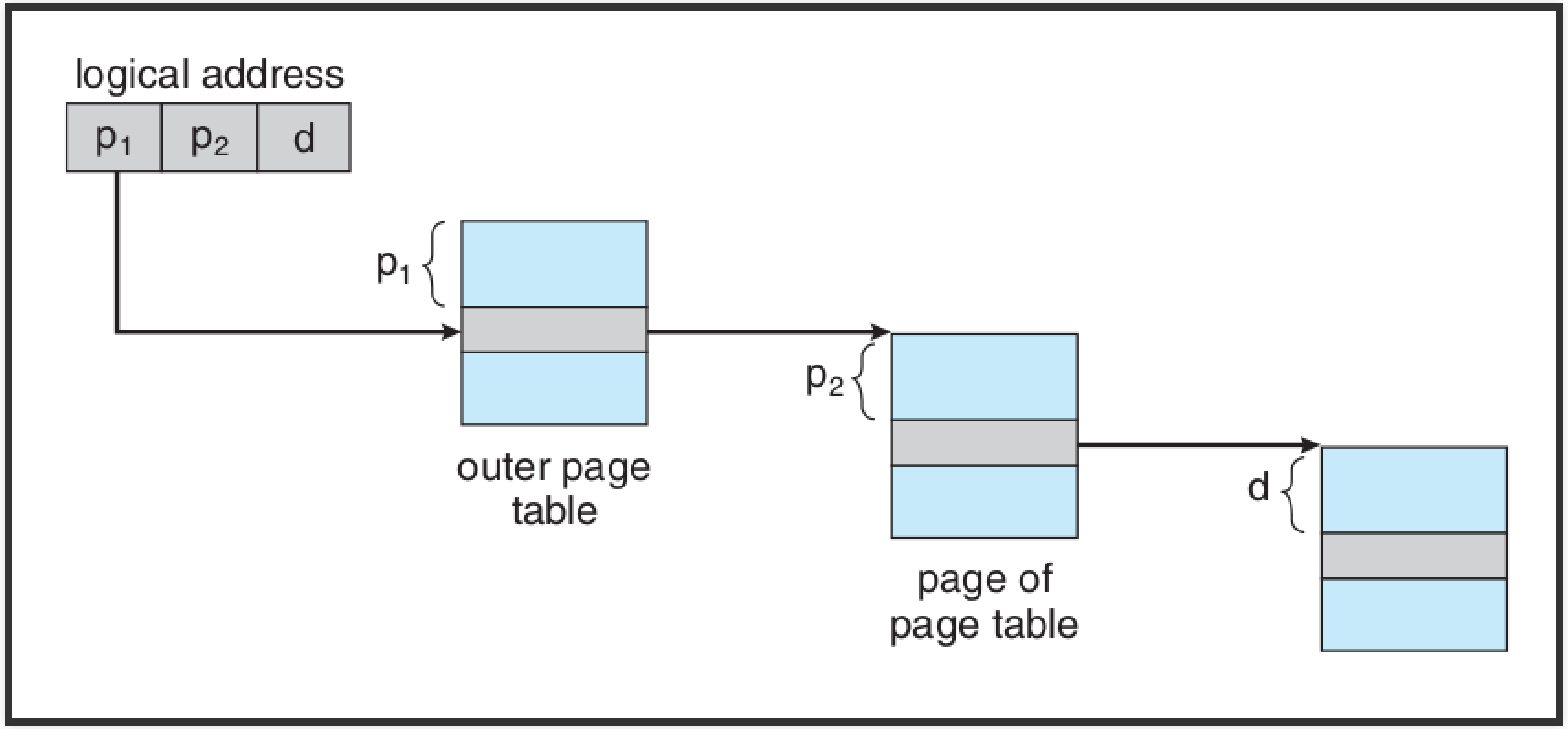
- A logical address (on 32-bit machine with 1K page size) is divided into:
  - a page number consisting of 20 bits
  - a page offset consisting of 12 bits
- Since the page table is paged, the page number is further divided into:
  - a 12-bit page number
  - a 10-bit page offset

TWO-LEVEL PAGING EXAMPLE

Thus, a logical address is as follows:



ADDRESS-TRANSLATION SCHEME

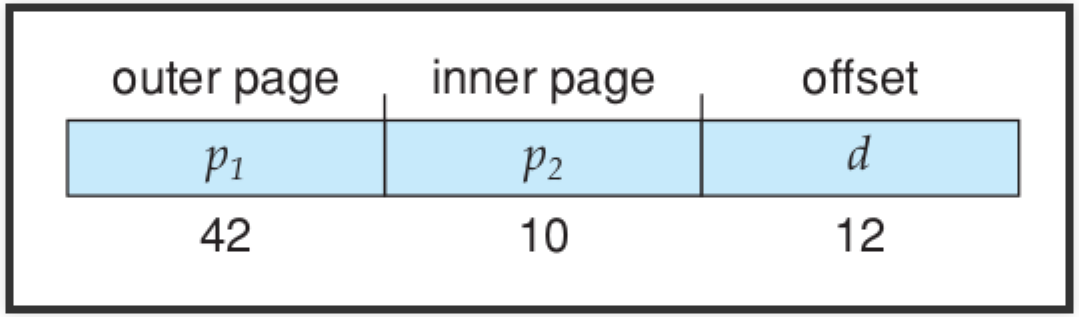


LOGICAL ADDRESS SPACE (64-BIT)

- 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

LOGICAL ADDRESS SPACE (64-BIT)

- Address would look like



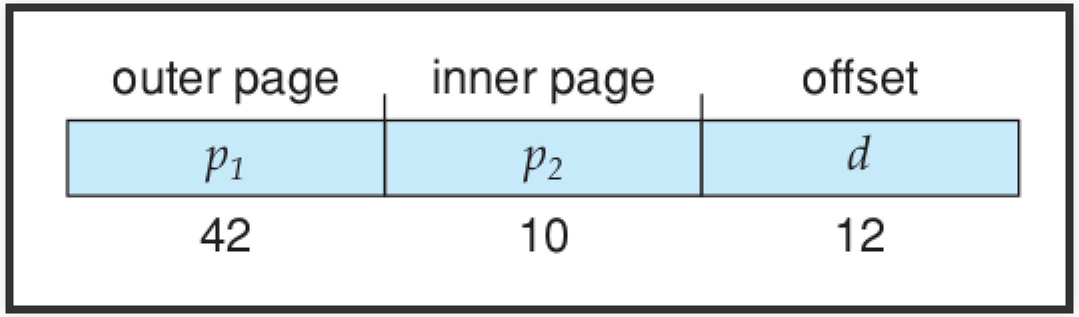
- Outer page table has 2^{42} entries or 2^{44} bytes
- One solution is to add a 2nd outer page table

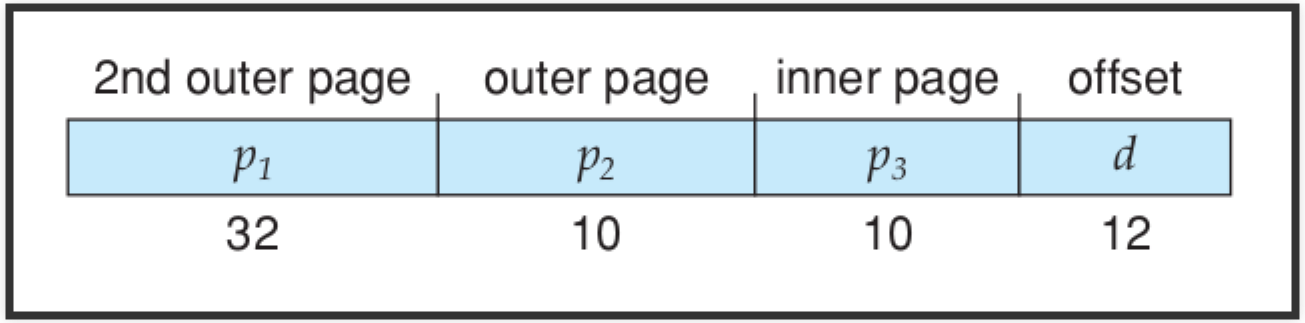
LOGICAL ADDRESS SPACE (64-BIT)

But in the following example the 2nd outer page table is still 2^{34} bytes in size

⚠ Possibly 4 memory access to get to one physical memory location

THREE-LEVEL PAGING SCHEME



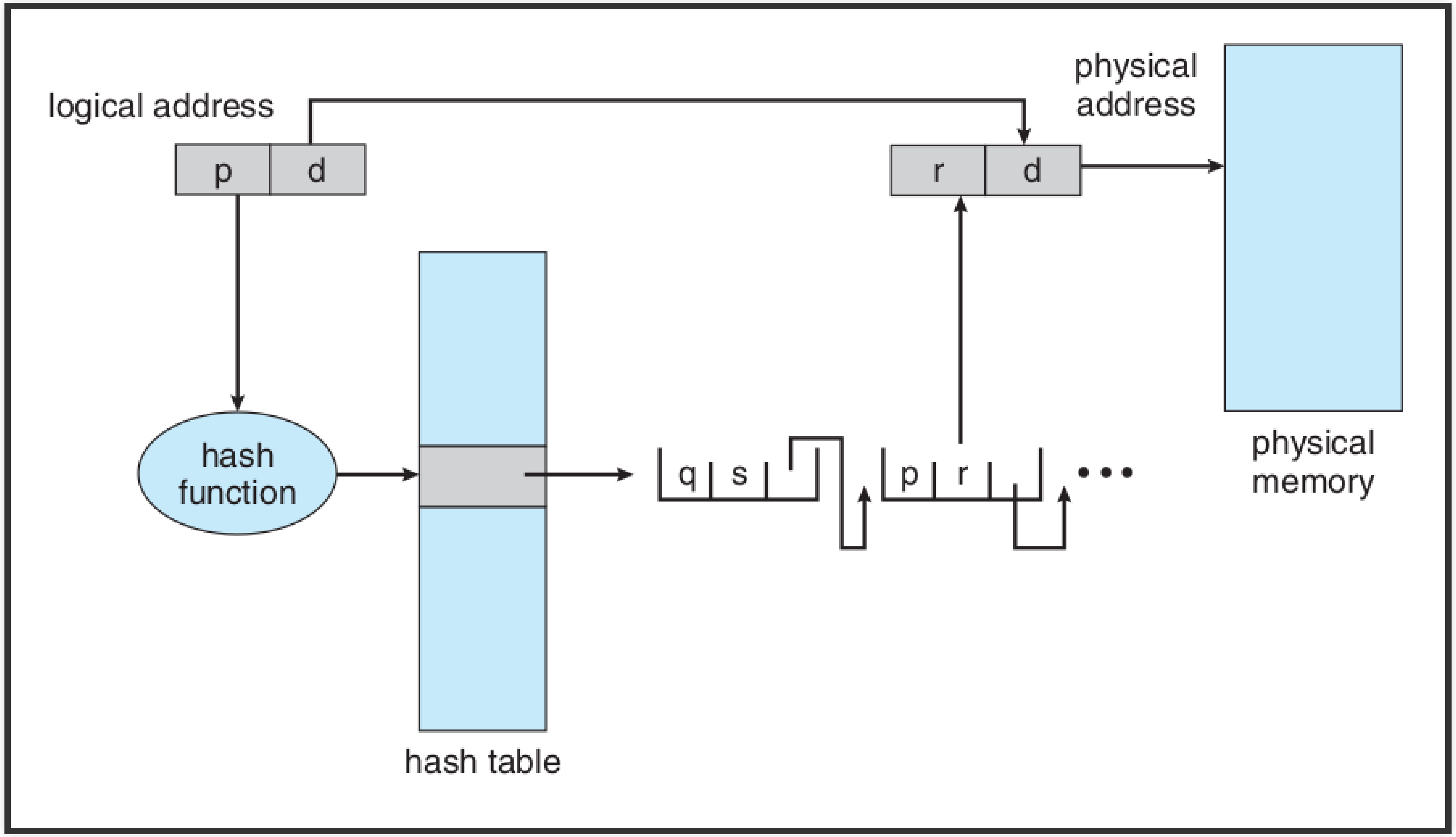


HASHED PAGE TABLES

- 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

HASHED PAGE TABLE



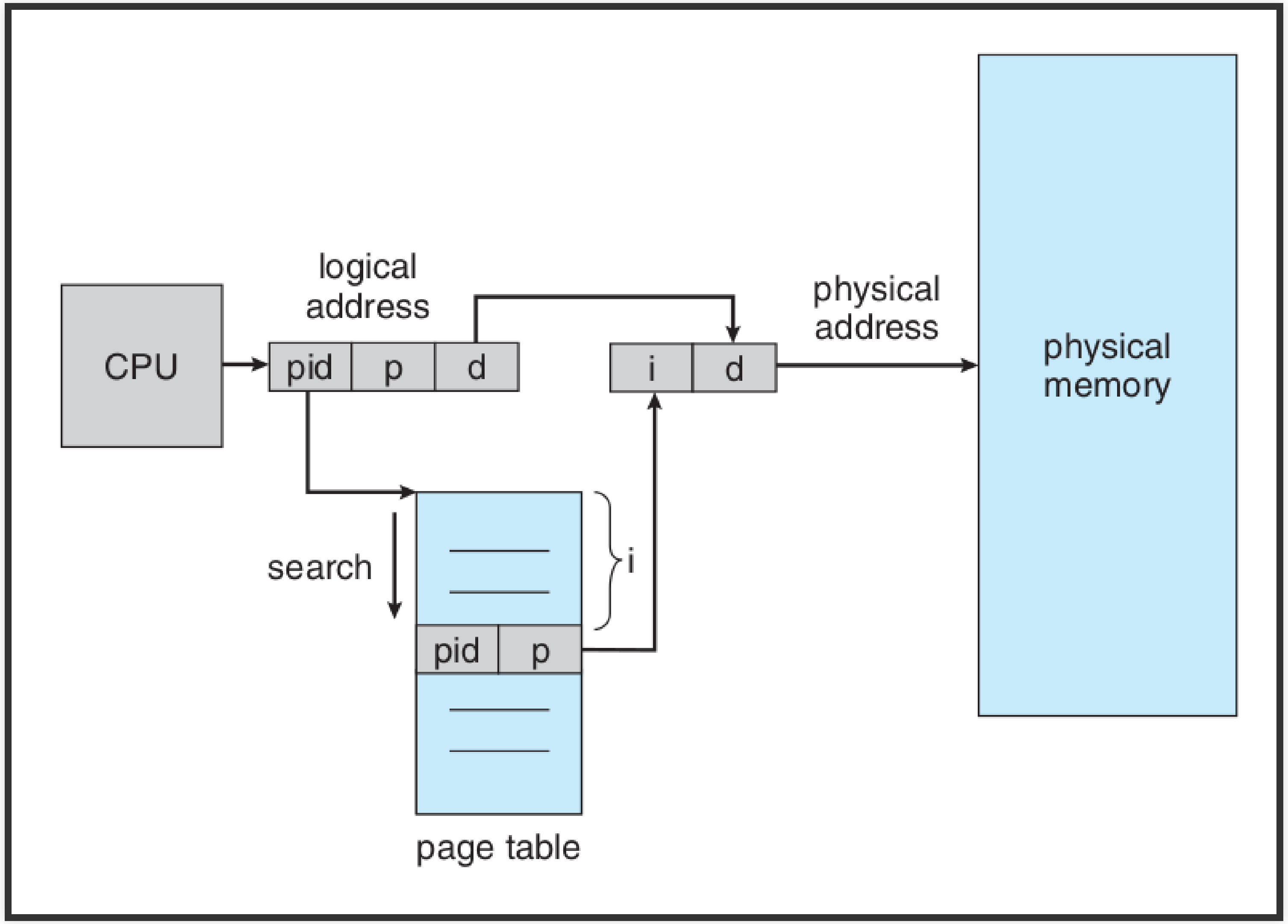
HASHED PAGE TABLES

- Virtual page numbers are compared in this chain searching for a match
    - If a match is found, the corresponding physical frame is extracted
- Variation for 64-bit addresses is clustered page tables
    - Similar to hashed but each entry refers to several pages (such as 16) rather than 1
    - Especially useful for sparse address spaces (where memory references are non-contiguous and scattered)

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

INVERTED PAGE TABLE ARCHITECTURE



INVERTED PAGE TABLE

- 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

ORACLE SPARC SOLARIS

- Consider modern, 64-bit operating system example with tightly integrated HW
  - Goals are efficiency, low overhead
- Based on hashing, but more complex

ORACLE SPARC SOLARIS

- Two hash tables
    - One kernel and one for all user processes
    - Each maps memory addresses from virtual to physical memory
    - Each entry represents a contiguous area of mapped virtual memory,
        - More efficient than having a separate hash-table entry for each page
    - Each entry has base address and span (indicating the number of pages the entry represents)

ORACLE SPARC SOLARIS

- TLB holds translation table entries (TTEs) for fast hardware lookups
  - A cache of TTEs reside in a translation storage buffer (TSB)
    - Includes an entry per recently accessed page

ORACLE SPARC SOLARIS

- Virtual address reference causes TLB search
    - If miss, hardware walks the in-memory TSB looking for the TTE corresponding to the address
        - If match found, the CPU copies the TSB entry into the TLB and translation completes
        - If no match found, kernel interrupted to search the hash table

ORACLE SPARC SOLARIS

The kernel then creates a TTE from the appropriate hash table and stores it in the TSB,

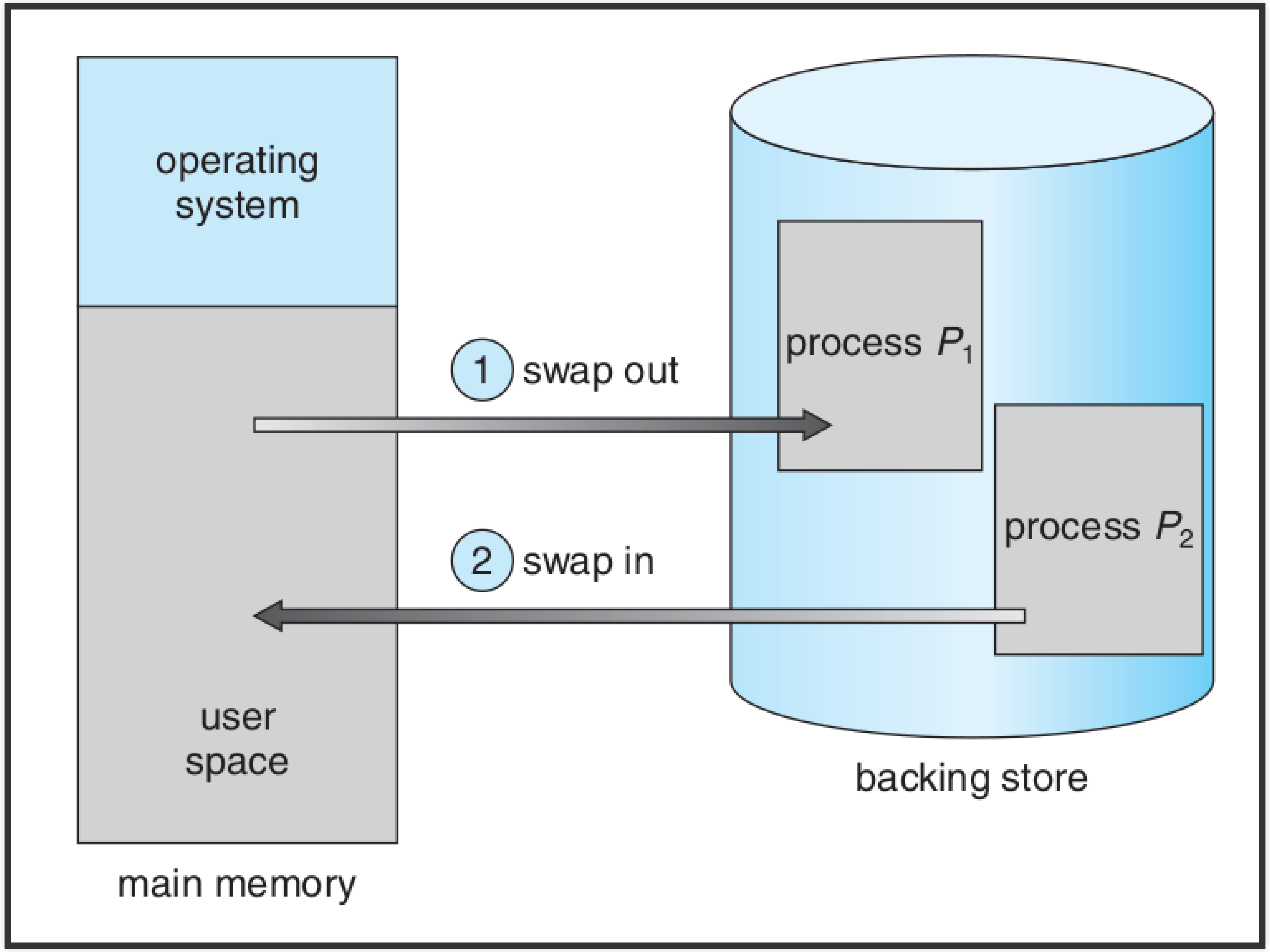
Interrupt handler returns control to the MMU, which completes the address translation.

SWAPPING

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*
        - ⇒ increasing the degree of multiprogramming in a system

SCHEMATIC VIEW OF SWAPPING



SWAPPING

- **Backing store** – fast disk large enough to accommodate copies of all memory images for all users; must provide direct access to these memory images
- **Roll out, roll in** – swapping variant used for priority-based scheduling algorithms; lower-priority process is swapped out so higher-priority process can be loaded and executed

SWAPPING

- Major part of swap time is transfer time; total transfer time is directly proportional to the amount of memory swapped
- System maintains a ready queue of ready-to-run processes which have memory images on disk
- Does the swapped out process need to swap back in to same physical addresses?
  - Depends on address binding method
  - Plus consider pending I/O to/from process memory space

SWAPPING

- Modified versions of swapping are found on many systems (i.e., UNIX, Linux, and Windows)
  - Swapping normally disabled
  - Started if more than threshold amount of memory allocated
  - Disabled again once memory demand reduced below threshold

CONTEXT SWITCH TIME INCL 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

CONTEXT SWITCH TIME INCL SWAPPING

100MB process swapping to hard disk with transfer rate of 50MB/sec

- Swap out time of 2000 ms
- Plus swap in of same sized process
- Total context switch swapping component time of 4000ms (4 seconds)

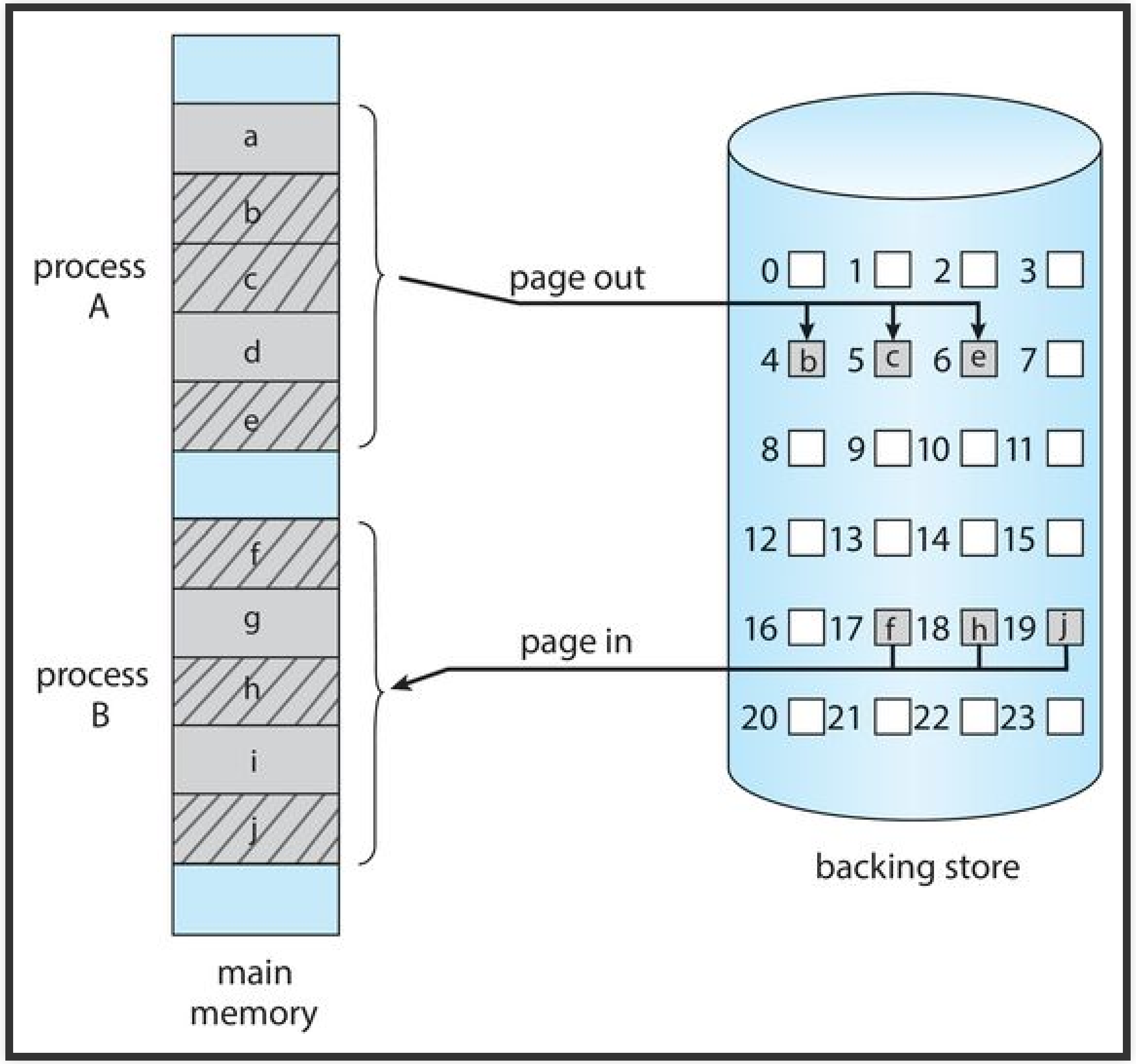
CONTEXT SWITCH INCL SWAPPING

- Can reduce if reduce size of memory swapped – by knowing how much memory really being used
  - System calls to inform OS of memory use via `request_memory()` and `release_memory()`
- Other constraints as well on swapping
  - Pending I/O – can’t swap out as I/O would occur to wrong process
  - Or always transfer I/O to kernel space, then to I/O device
    - Known as double buffering, adds overhead

CONTEXT SWITCH INCL SWAPPING

- Standard swapping not used in modern operating systems
    - But modified version common
        - Swap only when free memory extremely low

SWAPPING WITH PAGING



SWAPPING ON MOBILE SYSTEMS

Not typically supported

- Flash memory based
    - Small amount of space
    - Limited number of write cycles
    - Poor throughput between flash memory and CPU on mobile platform

SWAPPING ON MOBILE SYSTEMS

Instead use other methods to free memory if low

- iOS asks apps to voluntarily relinquish allocated memory
    - Read-only data thrown out and reloaded from flash if needed
    - Failure to free can result in termination
- Android terminates apps if low free memory, but first writes application state to flash for fast restart
- Both OSes support paging as discussed later

EXAMPLE: INTEL 32 AND 64-BIT ARCHITECTURES

EXAMPLE: INTEL 32 AND 64-BIT

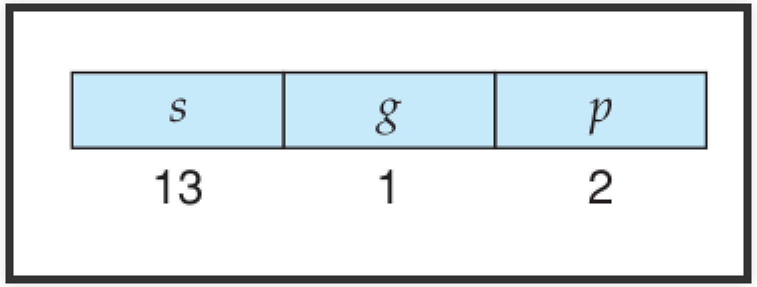
- Dominant industry chips (exept on mobile → ARM successful)
- Pentium CPUs are 32-bit and called IA-32 architecture
- Current Intel CPUs are 64-bit and called IA-64 architecture
- Many variations in the chips, cover the main ideas here

EXAMPLE: INTEL 32 AND 64-BIT

- Supports both segmentation and segmentation with paging
    - Each segment can be 4 GB
    - Up to 16 K segments per process
    - Divided into two partitions
        - First partition of up to 8 K segments are private to process (kept in local descriptor table (LDT))
        - Second partition of up to 8K segments shared among all processes (kept in global descriptor table (GDT))

EXAMPLE: INTEL 32 AND 64-BIT

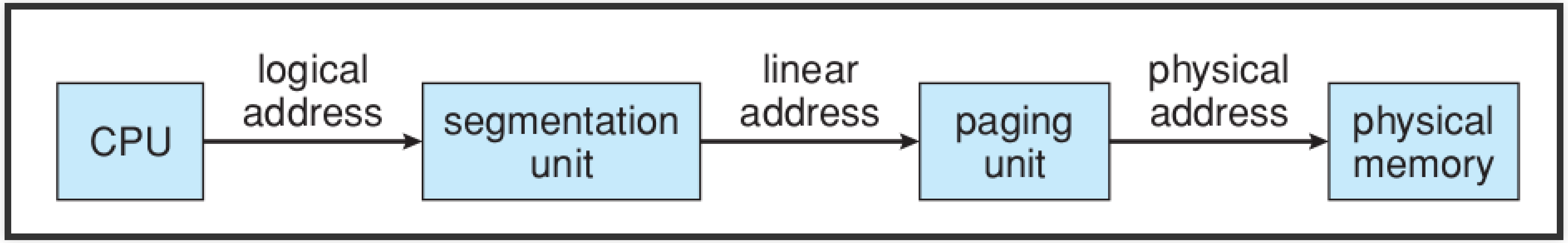
- CPU generates logical address
  - Selector given to segmentation unit
  - Which produces linear addresses



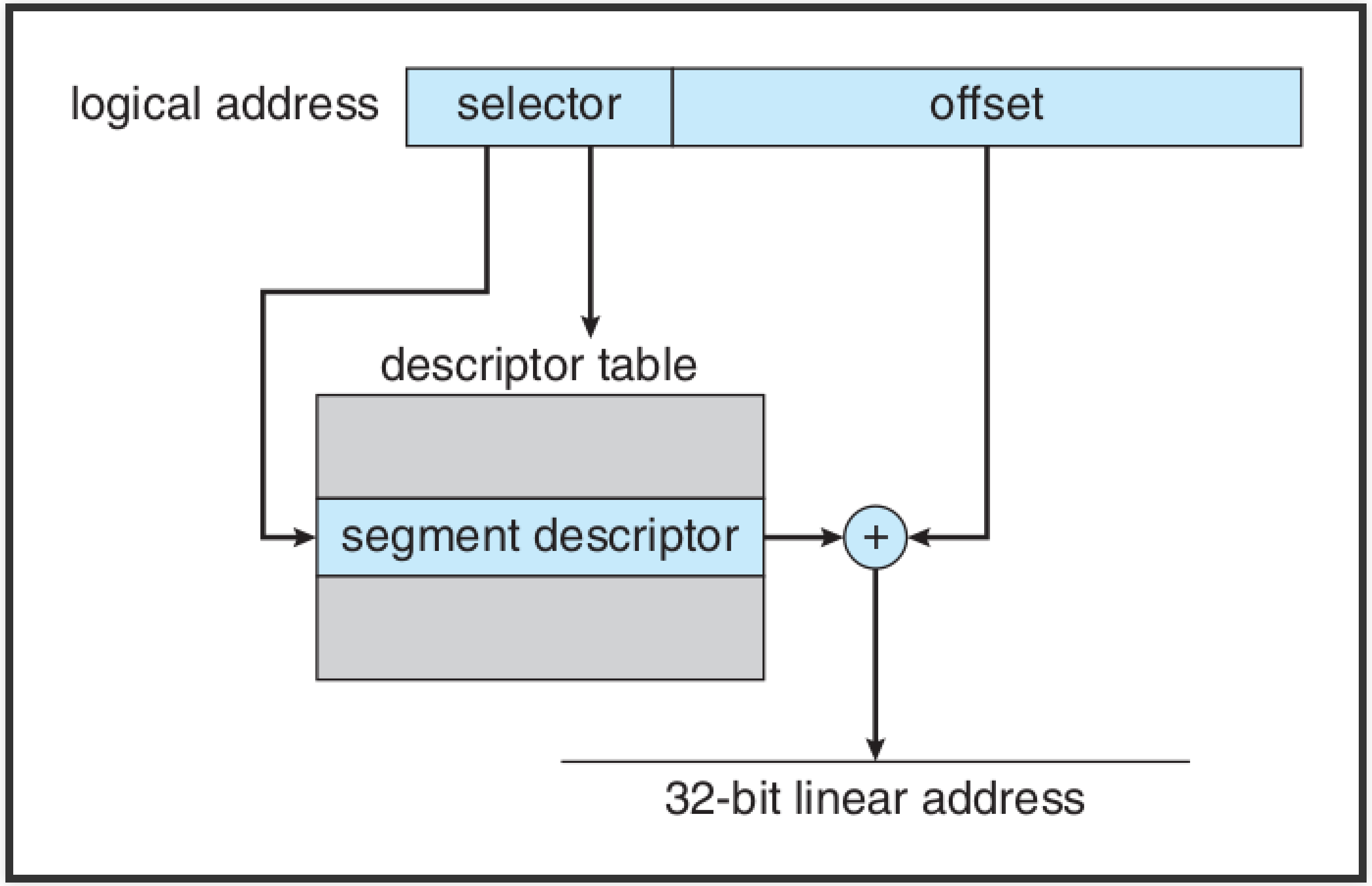
EXAMPLE: INTEL 32 AND 64-BIT

- Linear address given to paging unit
    - Which generates physical address in main memory
    - Paging units form equivalent of MMU
    - Pages sizes can be 4 KB or 4 MB

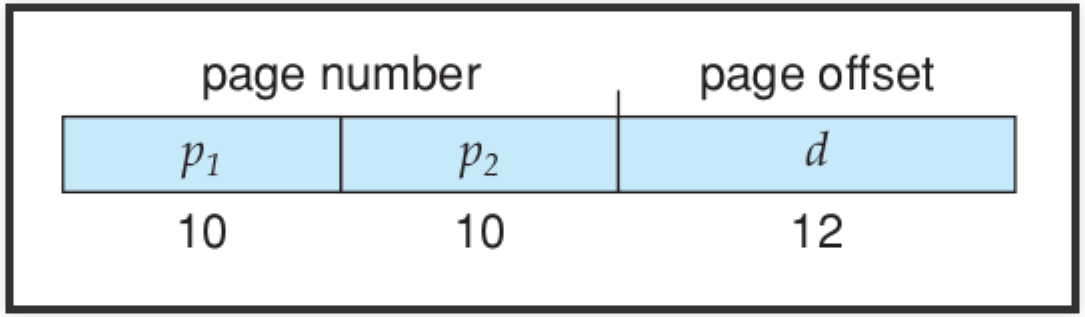
LOGICAL TO PHYSICAL ADDRESS TRANSLATION IN IA-32



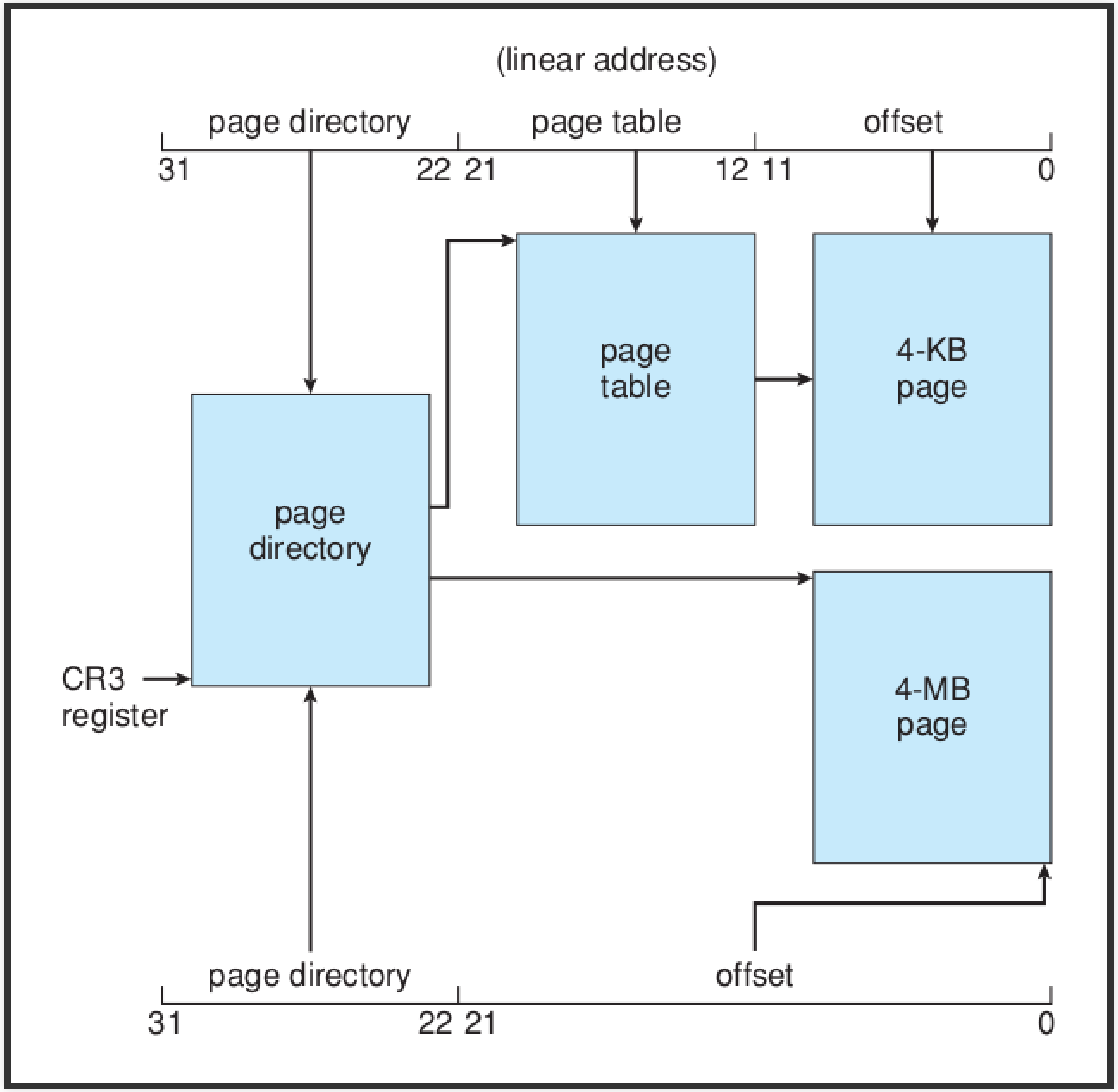
INTEL IA-32 SEGMENTATION



INTEL IA-32 PAGING ARCHITECTURE



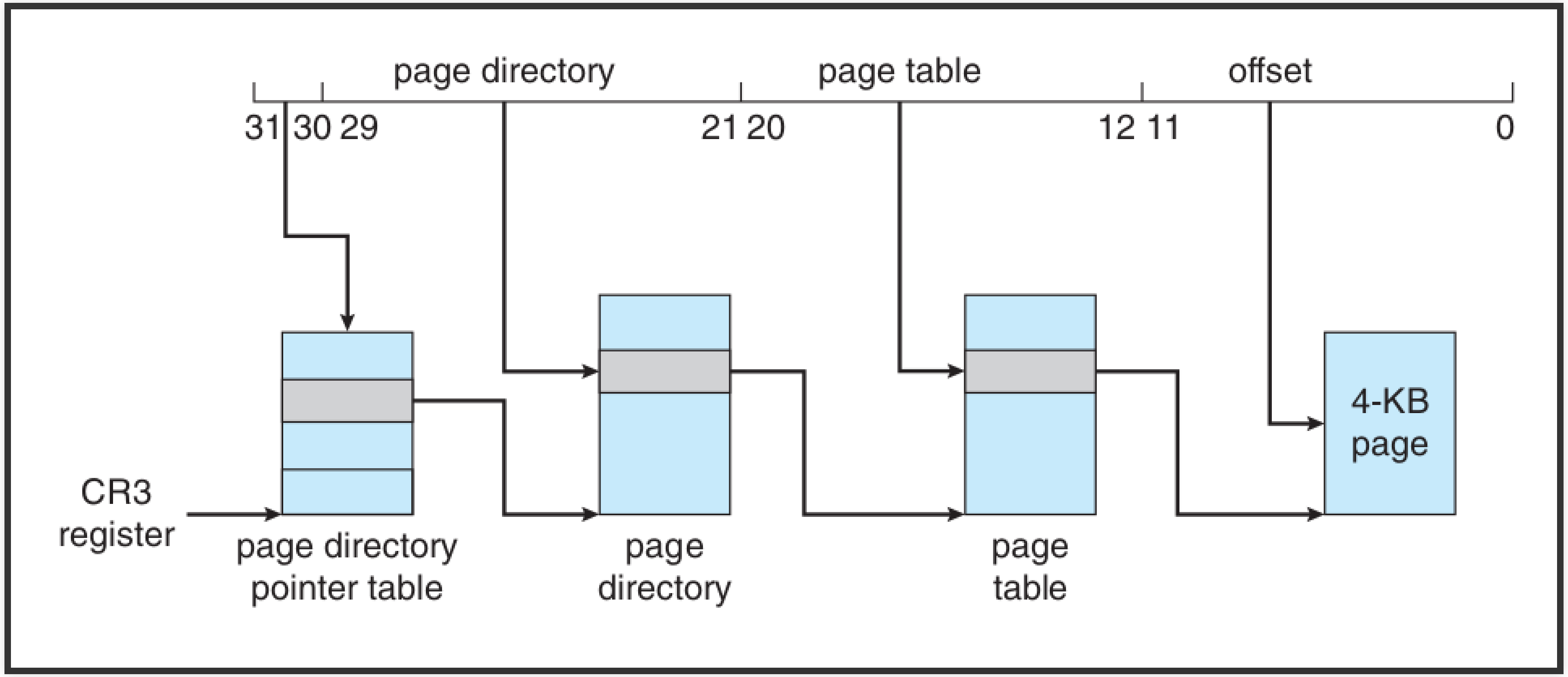
INTEL IA-32 PAGING ARCHITECTURE



IA-32 PAGE ADDRESS EXTENSIONS

- 32-bit address limits led Intel to create page address extension (PAE), allowing 32-bit apps access to more than 4GB of memory space
  - Paging went to a 3-level scheme
  - Top two bits refer to a page directory pointer table
  - Page-directory and page-table entries moved to 64-bits in size
  - Net effect is increasing address space to 36 bits – 64GB of physical memory

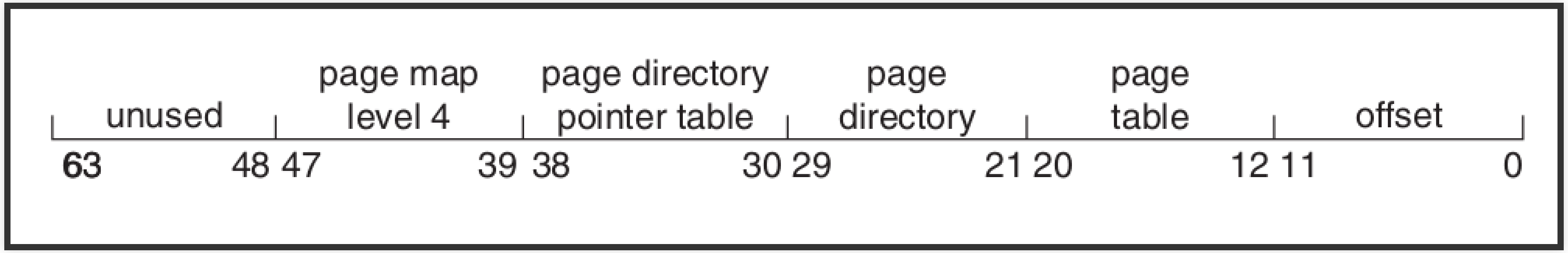
IA-32 PAGE ADDRESS EXTENSIONS



INTEL X86-64

- Current generation Intel x86 architecture
- 64 bits is ginormous (> 16 exabytes)
- In practice only implement 48 bit addressing
- Page sizes of 4 KB, 2 MB, 1 GB
- Four levels of paging hierarchy
    - Can also use PAE so virtual addresses are 48 bits and physical addresses are 52 bits

INTEL X86-64


unused
page map level 4
page directory pointer table
page directory
page table
offset
63
48 47
39 38
30 29
21 20
12 11
0

EXAMPLE: ARMV8 ARCHITECTURE

ARMV8 ARCHITECTURE

- Dominant mobile platform chip
  - Apple iOS
  - Google Android devices
- Modern, energy efficient, 64-bit CPU
- 3 different translation granules: 4 KB, 16 KB, and 64 KB.
  - Each with different page sizes, as well as larger sections of contiguous memory, known as regions.
- Also architechture for many embedded systems

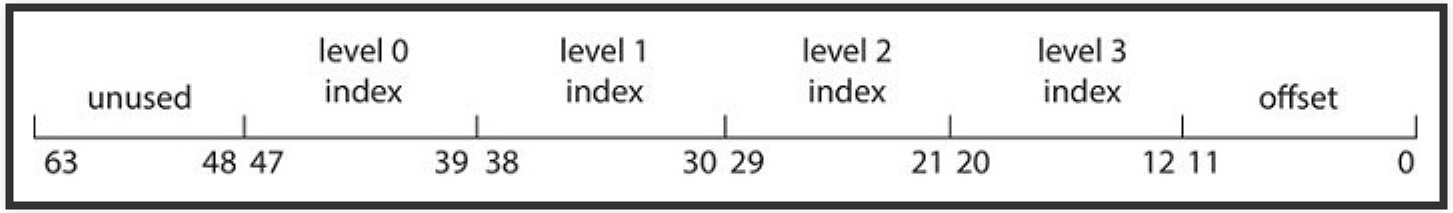
ARMV8 ARCHITECTURE

Translation Granule Size	Page Size	Region Size
4 KB	4 KB	2 MB, 1 GB
16 KB	16 KB	32 MB
64 KB	64 KB	512 MB

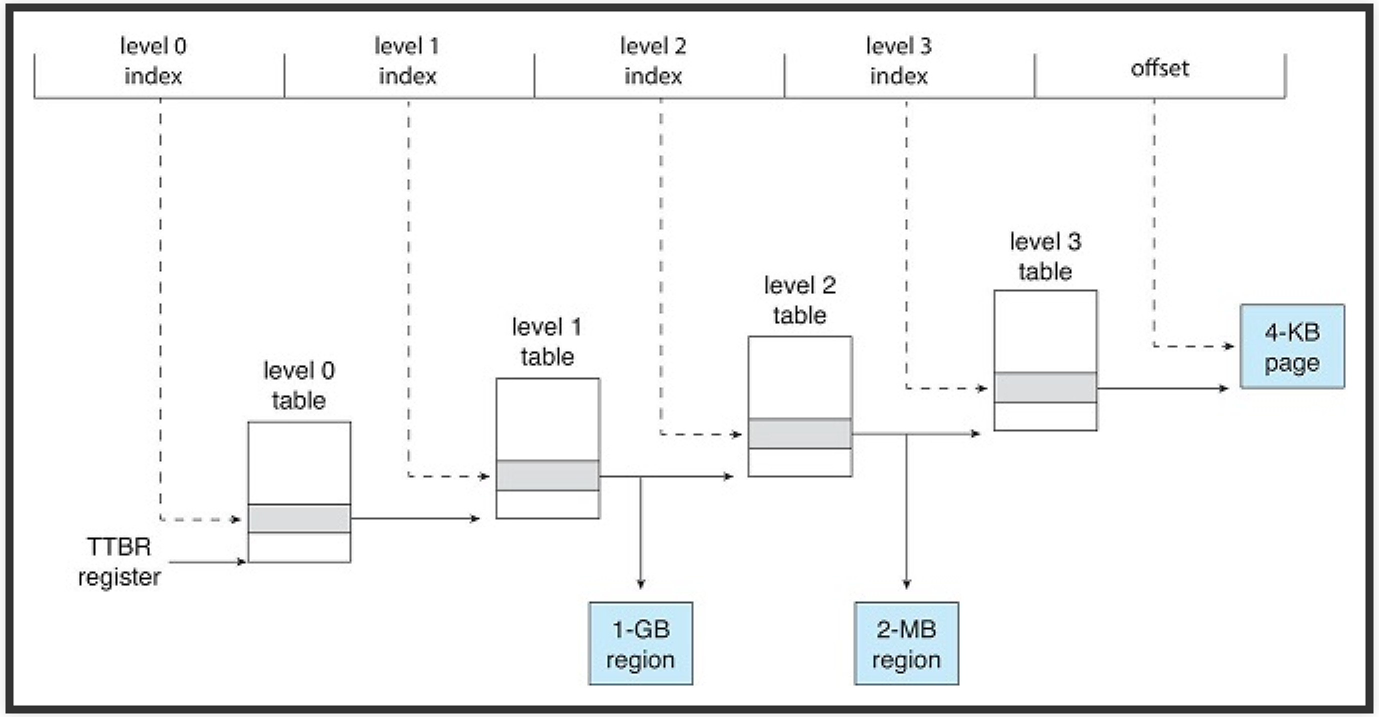
ARMV8 ARCHITECTURE

- 4-KB and 16-KB granules ⇒ up to four levels of paging
- 64-KB granules ⇒ up to three levels of paging

Address structure 4KB Granule



ARMV8 ARCHITECTURE



QUESTIONS

BONUS

💡 Exam question number 6: **Main Memory**