

Virtual Memory and Address Translation

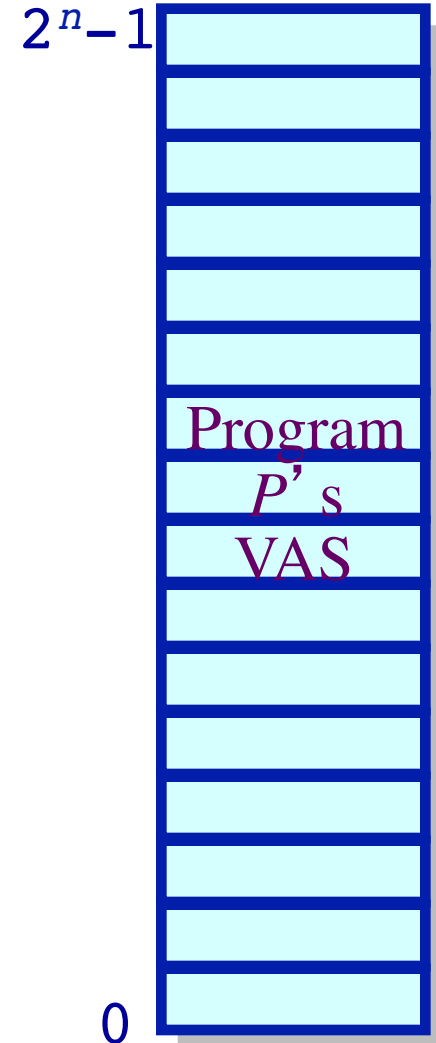
Review

- ◆ Program addresses are virtual addresses.
 - Relative offset of program regions can not change during program execution. E.g., heap can not move further from code.
 - Virtual addresses == physical address inconvenient.
 - ❖ Program location is compiled into the program.
- ◆ A single offset register allows the OS to place a process' virtual address space anywhere in physical memory.
 - Virtual address space must be smaller than physical.
 - Program is swapped out of old location and swapped into new.
- ◆ Segmentation creates external fragmentation and requires large regions of contiguous physical memory.
 - We look to fixed sized units, memory pages, to solve the problem.

Virtual Memory

Concept

- ◆ **Key problem:** How can one support programs that require more memory than is physically available?
 - How can we support programs that do not use all of their memory at once?
- ◆ Hide physical size of memory from users
 - Memory is a “large” *virtual address space* of 2^n bytes
 - Only portions of VAS are in physical memory at any one time (increase memory utilization).
- ◆ Issues
 - Placement strategies
 - ❖ Where to place programs in physical memory
 - Replacement strategies
 - ❖ What to do when there exist more processes than can fit in memory
 - Load control strategies
 - ❖ Determining how many processes can be in memory at one time



Realizing Virtual Memory

Paging

- ◆ Physical memory partitioned into equal sized $(f_{MAX}-1, o_{MAX}-1)$ *page frames*
 - Page frames avoid external fragmentation.

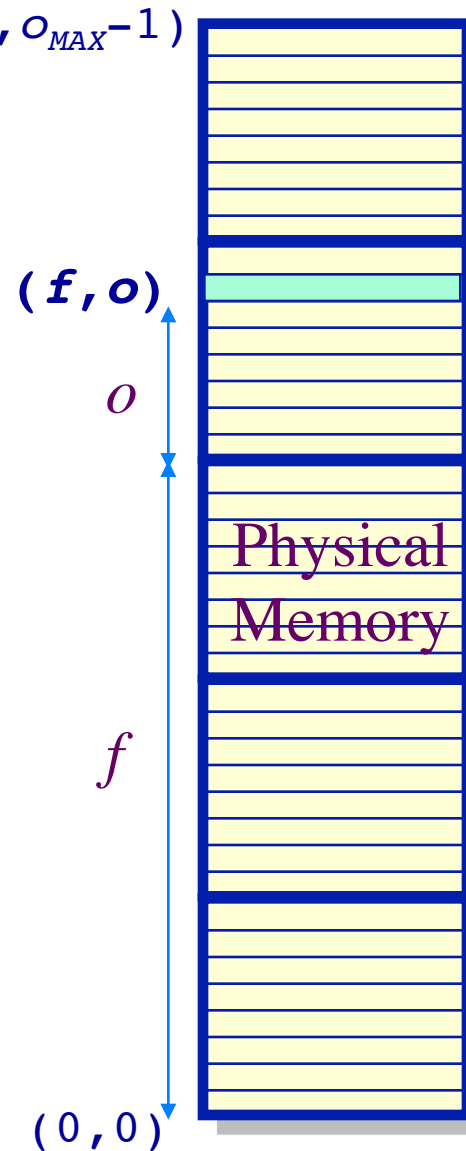
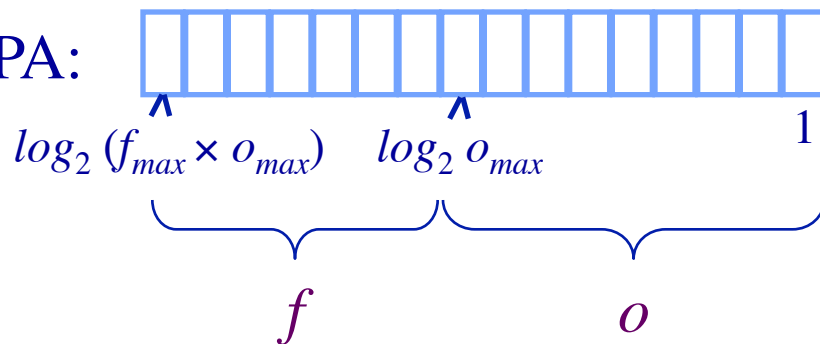
A memory address is a pair (f, o)

f — frame number (f_{max} frames)

o — frame offset (o_{max} bytes/frames)

Physical address = $o_{max} \times f + o$

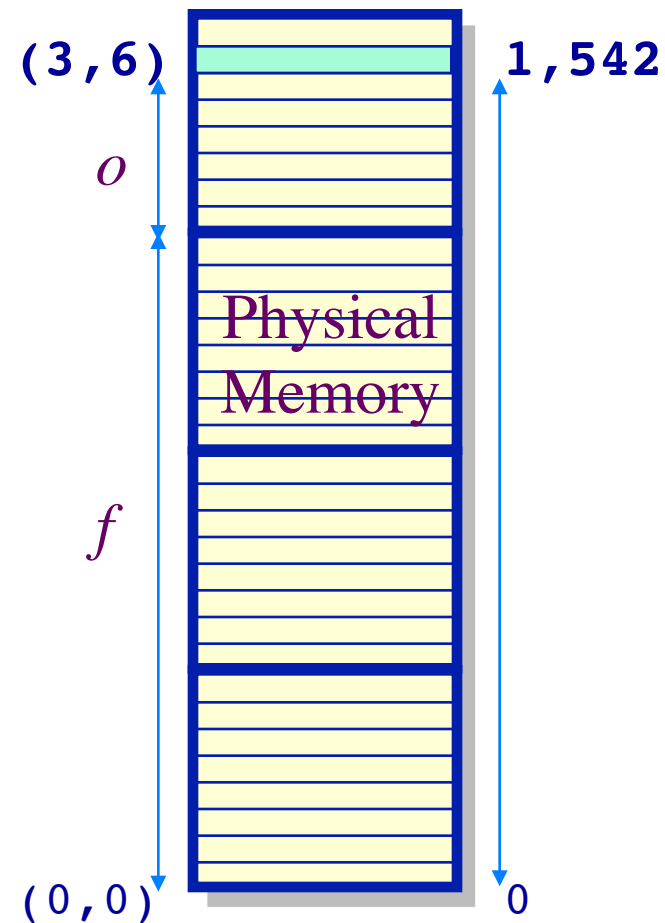
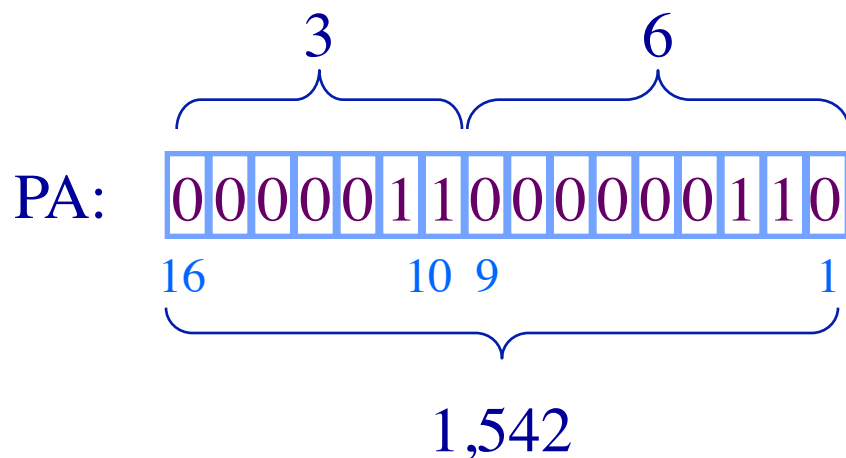
PA:



Physical Address Specifications

Frame/Offset pair v. An absolute index

- ◆ Example: A 16-bit address space with ($o_{max} =$) 512 byte page frames
 - Addressing location (3, 6) = 1,542



Questions

- ◆ The offset is the same in a virtual address and a physical address.
 - A. True
 - B. False
- ◆ If your level 1 data cache is equal to or smaller than $2^{\text{number of page offset}}$ bits then address translation is not necessary for indexing the data cache.
 - A. True
 - B. False

Realizing Virtual Memory

Paging

- ◆ A process' s virtual address space is partitioned into equal sized *pages*

➤ $|page| = |page\ frame|$

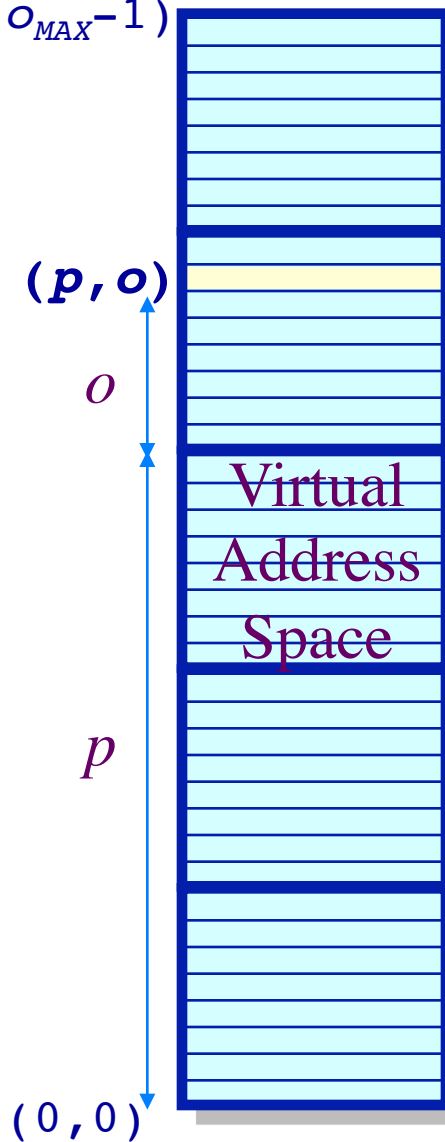
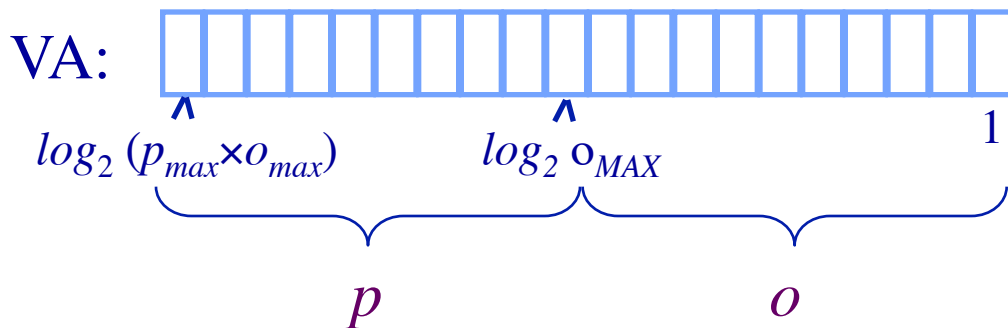
A virtual address is a pair (p, o)

p — page number (p_{max} pages)

o — page offset (o_{max} bytes/pages)

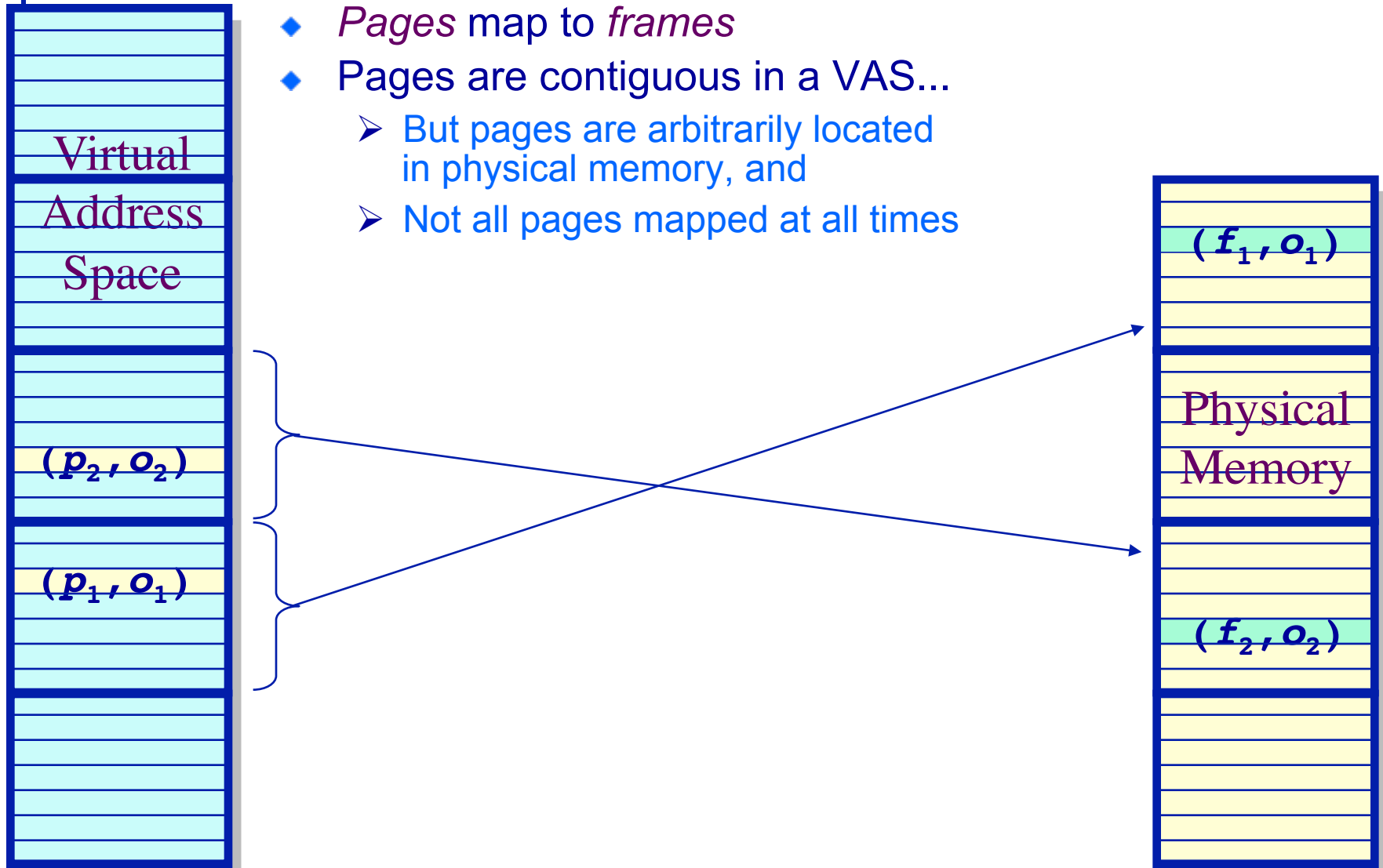
$$\text{Virtual address} = o_{max} \times p + o$$

$$2^n - 1 = (p_{MAX} - 1, o_{MAX} - 1)$$



Paging

Mapping virtual addresses to physical addresses



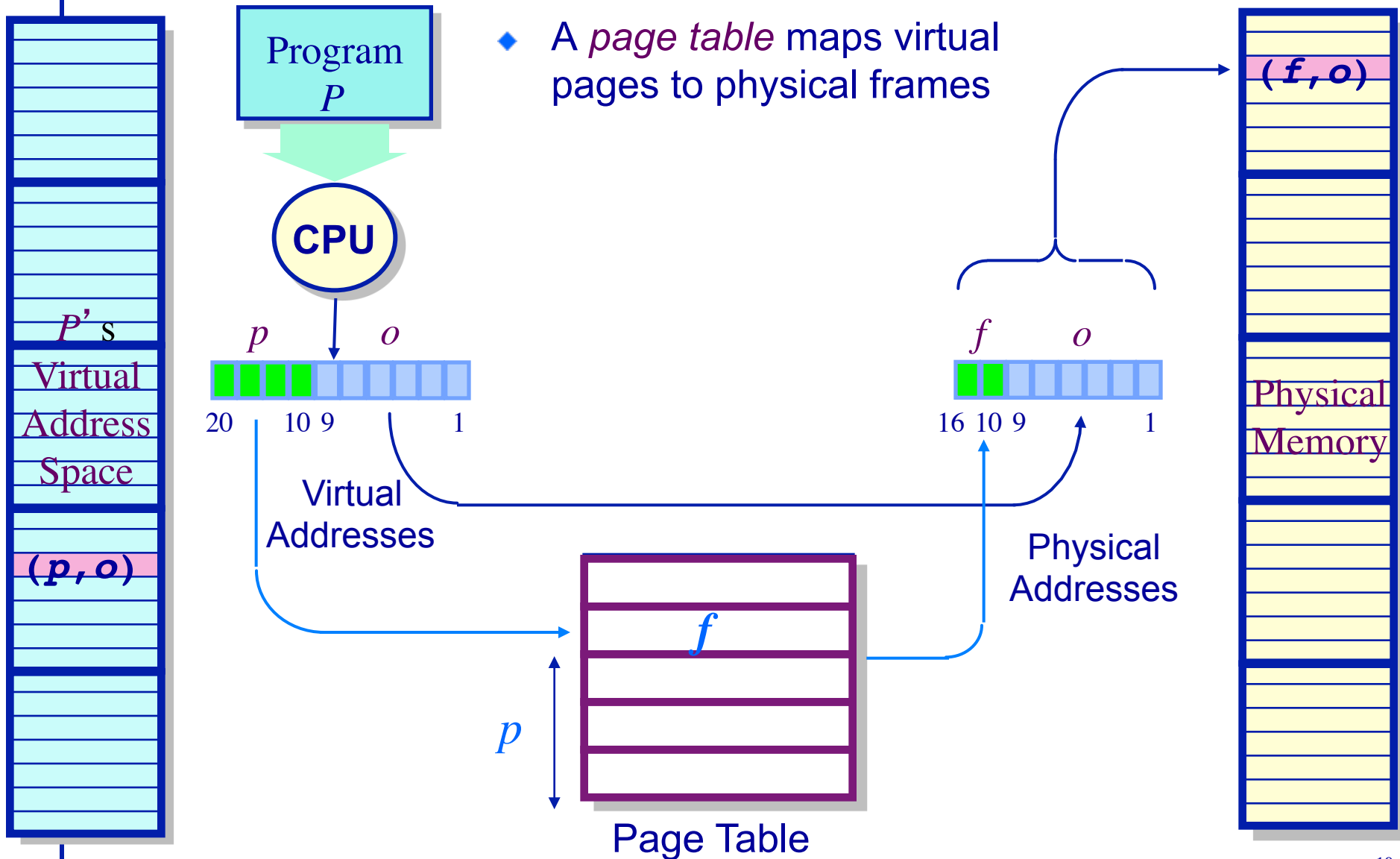
Frames and pages

- ◆ Only mapping virtual pages that are in use does what?
 - A. Increases memory utilization.
 - B. Increases performance for user applications.
 - C. Allows an OS to run more programs concurrently.
 - D. Gives the OS freedom to move virtual pages in the virtual address space.

- ◆ Address translation and changing address mappings are
 - A. Frequent and frequent
 - B. Frequent and infrequent
 - C. Infrequent and frequent
 - D. Infrequent and infrequent

Paging

Virtual address translation

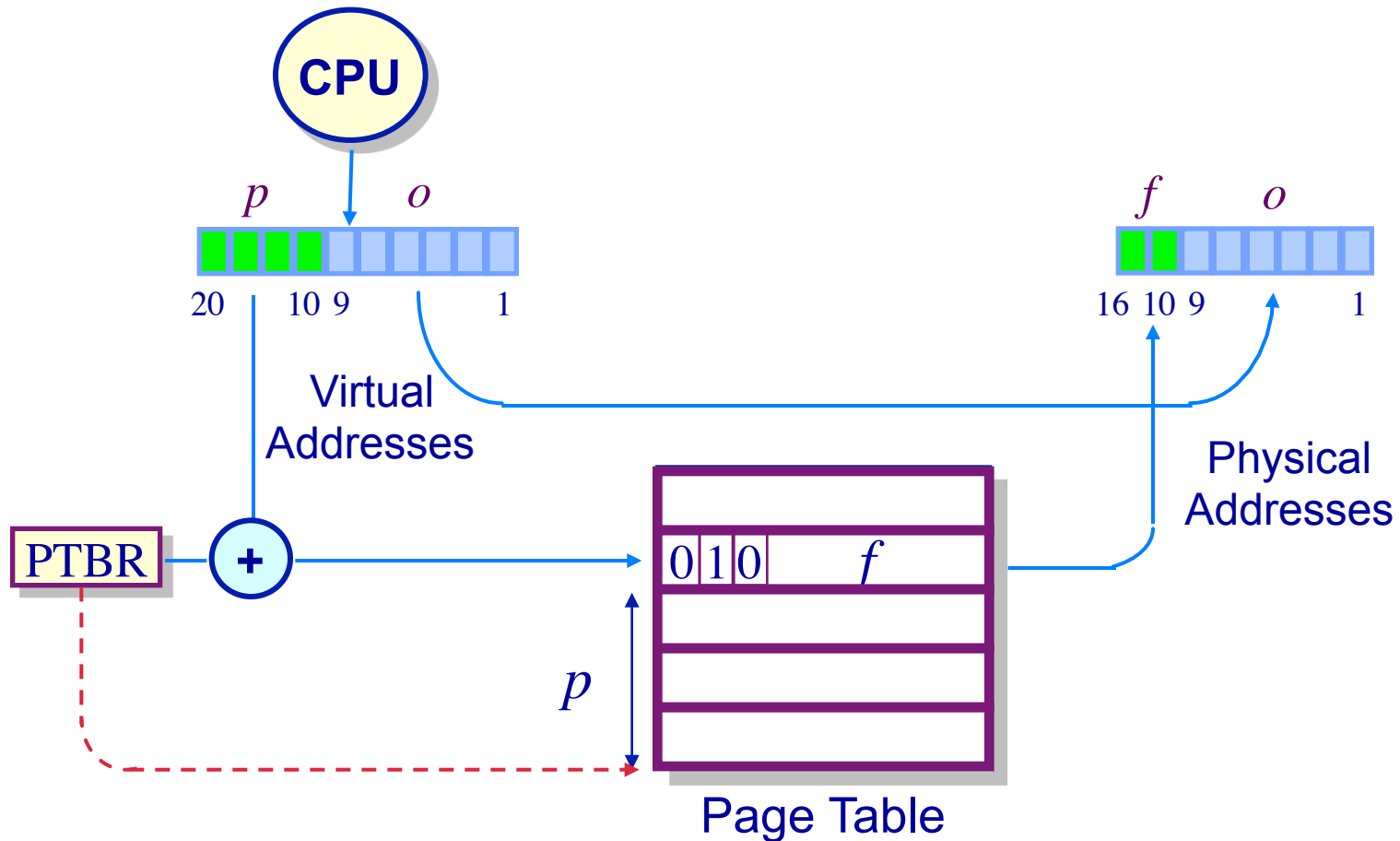


Virtual Address Translation Details

Page table structure

1 table per process
Part of process's state

- ◆ Contents:
 - Flags — dirty bit, resident bit, clock/reference bit
 - Frame number

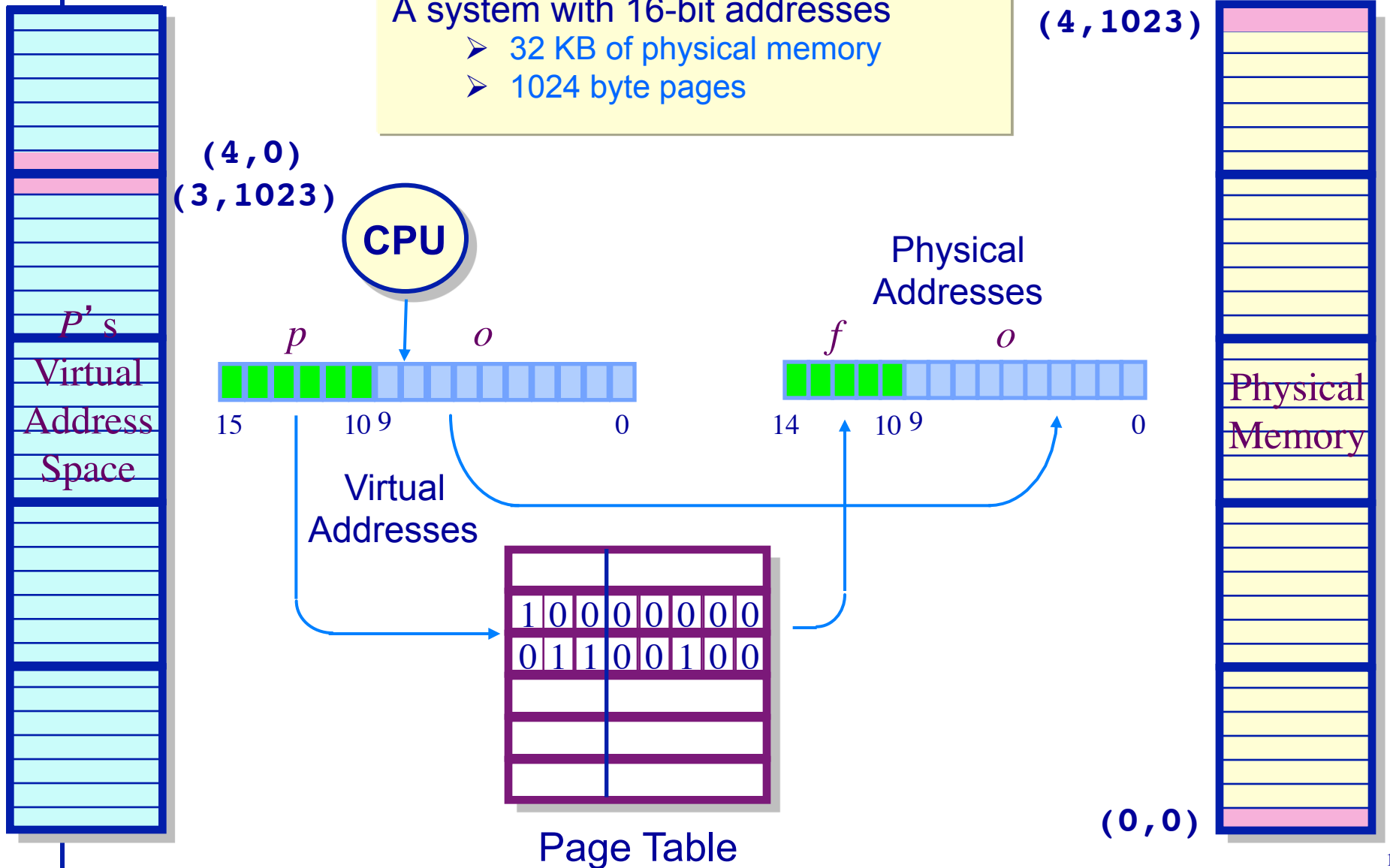


Virtual Address Translation Details

Example

A system with 16-bit addresses

- 32 KB of physical memory
- 1024 byte pages



Virtual Address Translation

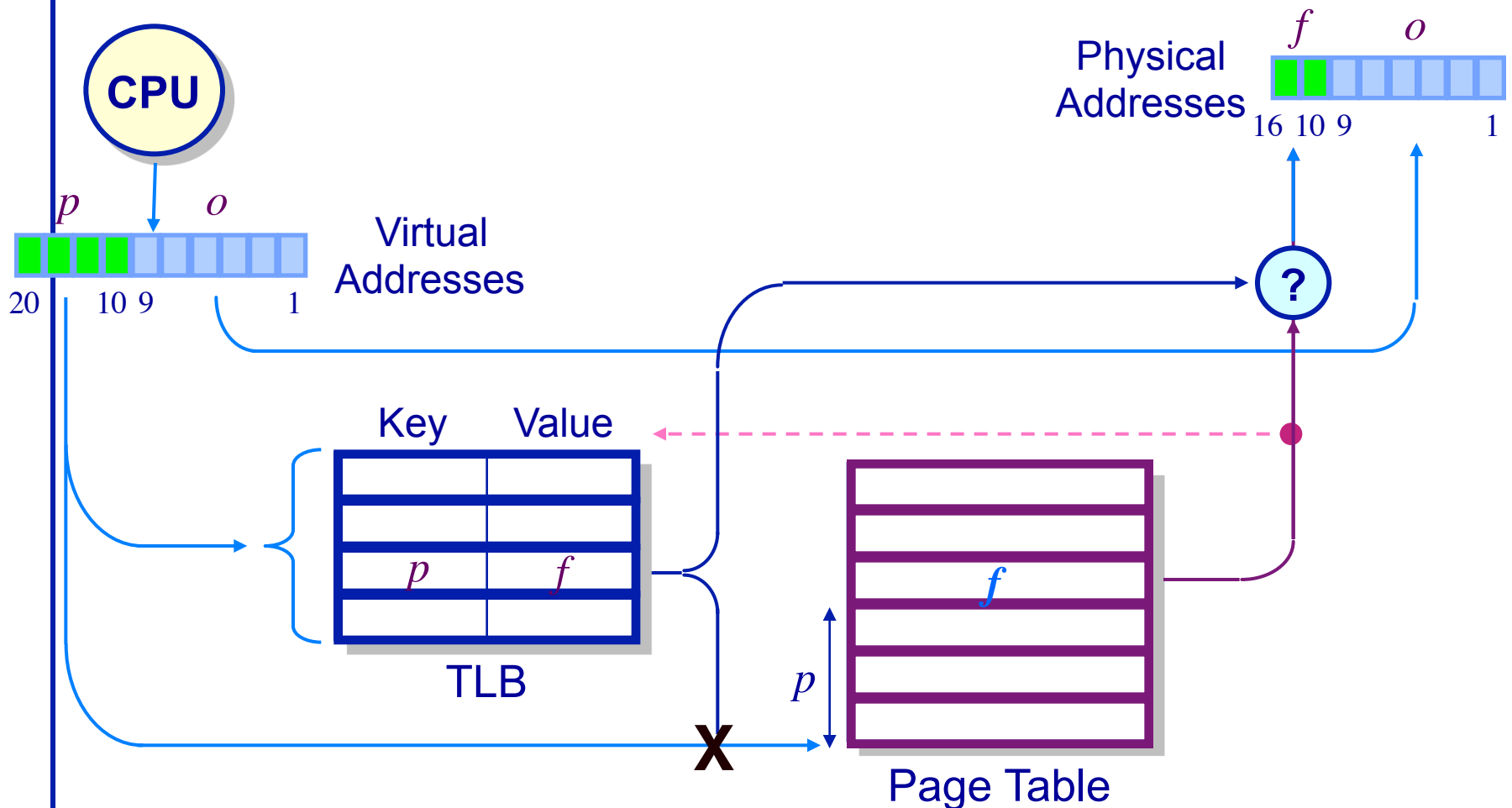
Performance Issues

- ◆ Problem — VM reference requires 2 memory references!
 - One access to get the page table entry
 - One access to get the data
- ◆ Page table can be very large; a part of the page table can be on disk.
 - For a machine with 64-bit addresses and 1024 byte pages, what is the size of a page table?
- ◆ What to do?
 - Most computing problems are solved by some form of...
 - ❖ Caching
 - ❖ Indirection

Virtual Address Translation

Using TLBs to Speedup Address Translation

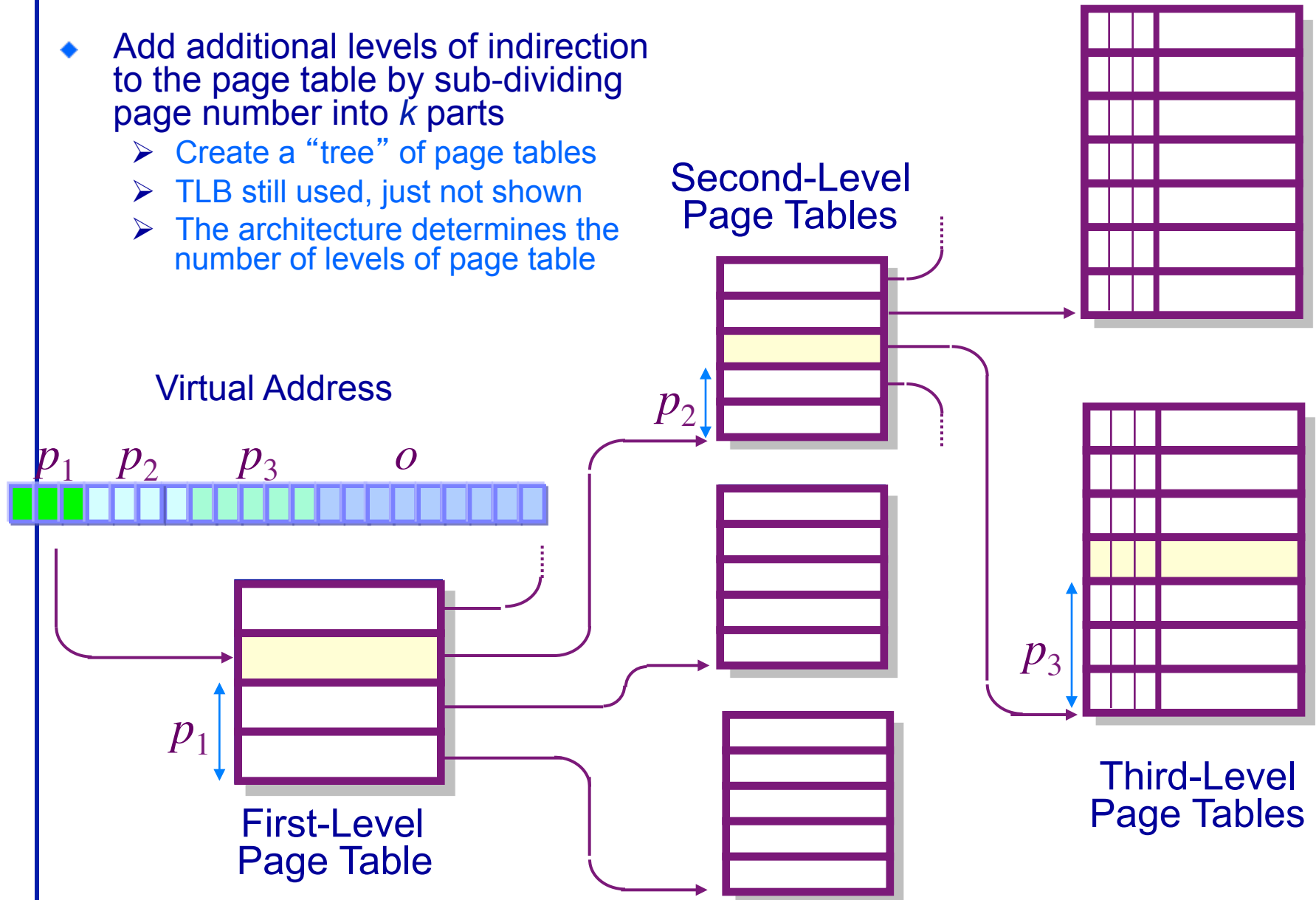
- ◆ Cache recently accessed page-to-frame translations in a TLB
 - For TLB hit, physical page number obtained in 1 cycle
 - For TLB miss, translation is updated in TLB
 - Has high hit ratio (why?)



Dealing With Large Page Tables

Multi-level paging

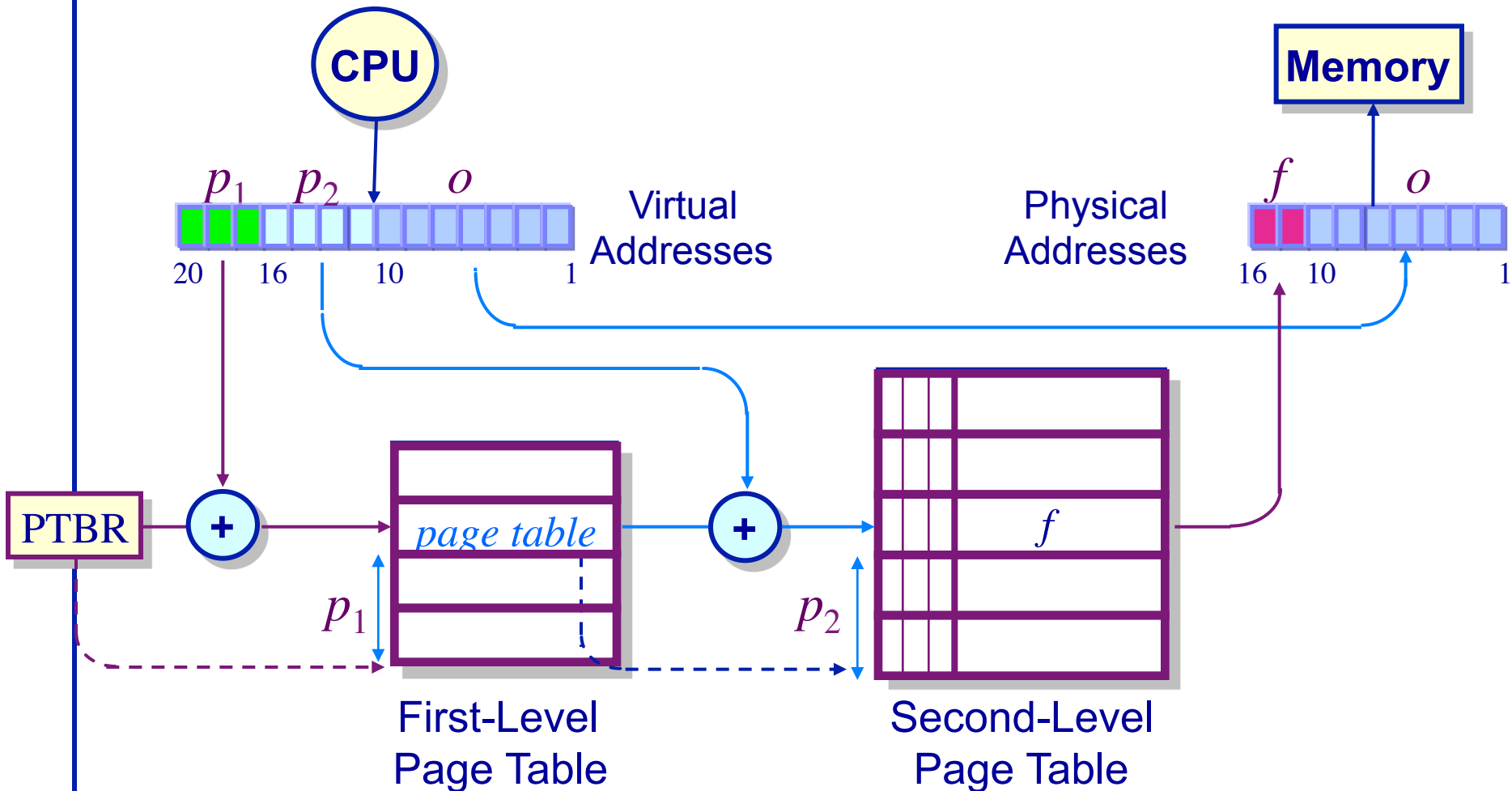
- ◆ Add additional levels of indirection to the page table by sub-dividing page number into k parts
 - Create a “tree” of page tables
 - TLB still used, just not shown
 - The architecture determines the number of levels of page table



Dealing With Large Page Tables

Multi-level paging

- ◆ Example: Two-level paging



The Problem of Large Address Spaces

- ◆ With large address spaces (64-bits) forward mapped page tables become cumbersome.
 - E.g. 5 levels of tables.
- ◆ Instead of making tables proportional to size of virtual address space, make them proportional to the size of physical address space.
 - Virtual address space is growing faster than physical.
- ◆ Use one entry for each physical page with a hash table
 - Translation table occupies a very small fraction of physical memory
 - Size of translation table is independent of VM size
- ◆ Page table has 1 entry per virtual page
- ◆ Hashed/Inverted page table has 1 entry per physical frame

Virtual Address Translation

Using Page Registers (aka Hashed/Inverted Page Tables)

- ◆ Each frame is associated with a register containing
 - Residence bit: whether or not the frame is occupied
 - Occupier: page number of the page occupying frame
 - Protection bits

- ◆ Page registers: an example
 - Physical memory size: 16 MB
 - Page size: 4096 bytes
 - Number of frames: 4096
 - Space used for page registers (assuming 8 bytes/register): 32 Kbytes
 - Percentage overhead introduced by page registers: 0.2%
 - Size of virtual memory: irrelevant

Page Registers

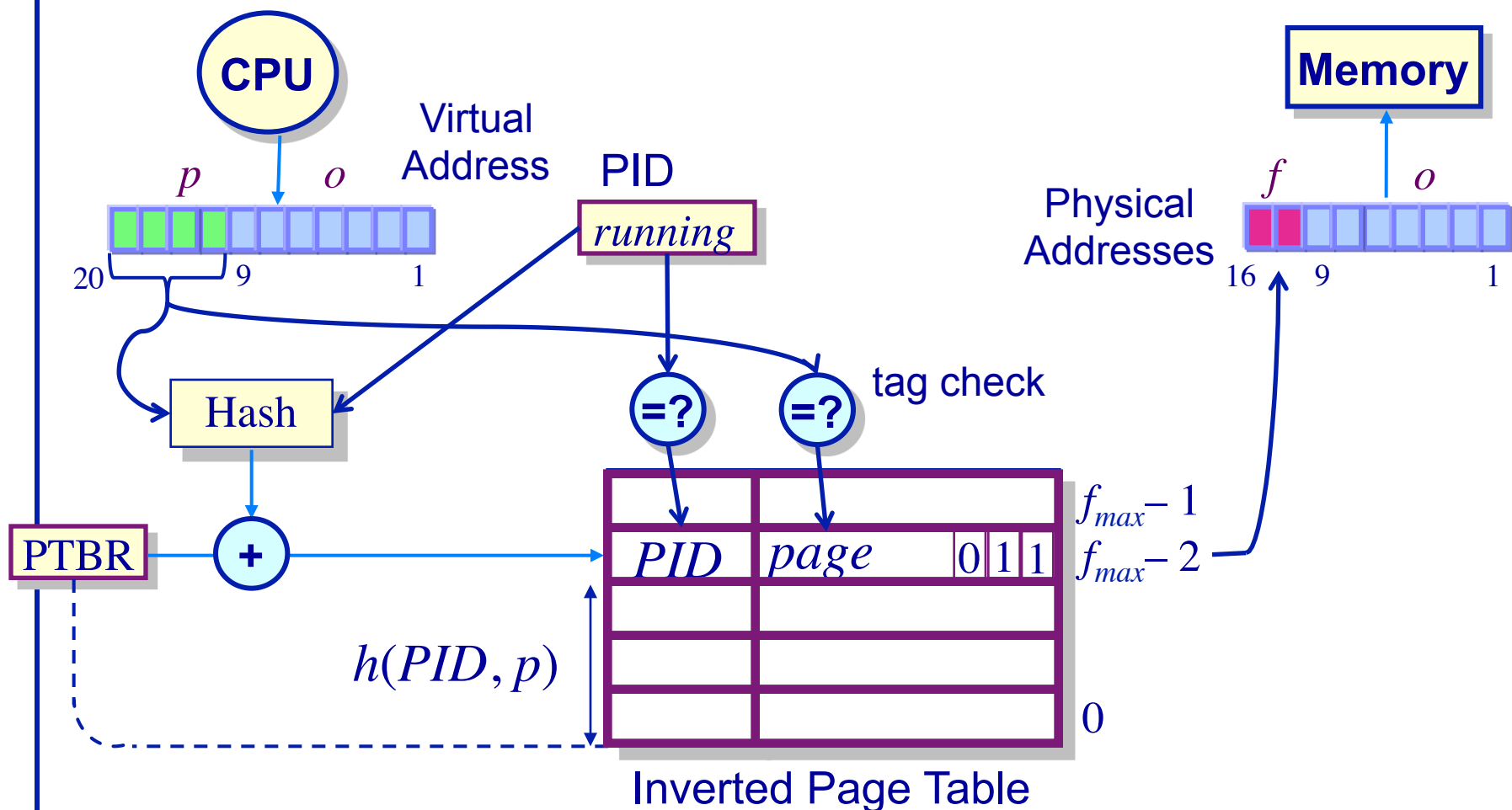
How does a virtual address become a physical address?

- ◆ CPU generates virtual addresses, where is the physical page?
 - Hash the virtual address
 - Must deal with conflicts
- ◆ TLB caches recent translations, so page lookup can take several steps
 - Hash the address
 - Check the tag of the entry
 - Possibly rehash/traverse list of conflicting entries
- ◆ TLB is limited in size
 - Difficult to make large and accessible in a single cycle.
 - They consume a lot of power (27% of on-chip for StrongARM)

Indexing Hashed Page Tables

Using Hash Tables

- ◆ Hash page numbers to find corresponding frame number
 - Page frame number is not explicitly stored (1 frame per entry)
 - Protection, dirty, used, resident bits also in entry



Searching Hashed Page Tables

Using Hash Tables

- ◆ Page registers are placed in an array
- ◆ Page i is placed in slot $f(i)$ where f is an agreed-upon hash function
- ◆ To lookup page i , perform the following:
 - Compute $f(i)$ and use it as an index into the table of page registers
 - Extract the corresponding page register
 - Check if the register tag contains i , if so, we have a hit
 - Otherwise, we have a miss

Searching Hashed Page Tables

Using Hash Tables (Cont' d.)

- ◆ Minor complication
 - Since the number of pages is usually larger than the number of slots in a hash table, two or more items *may* hash to the same location
- ◆ Two different entries that map to same location are said to collide
- ◆ Many standard techniques for dealing with collisions
 - Use a linked list of items that hash to a particular table entry
 - Rehash index until the key is found or an empty table entry is reached (open hashing)

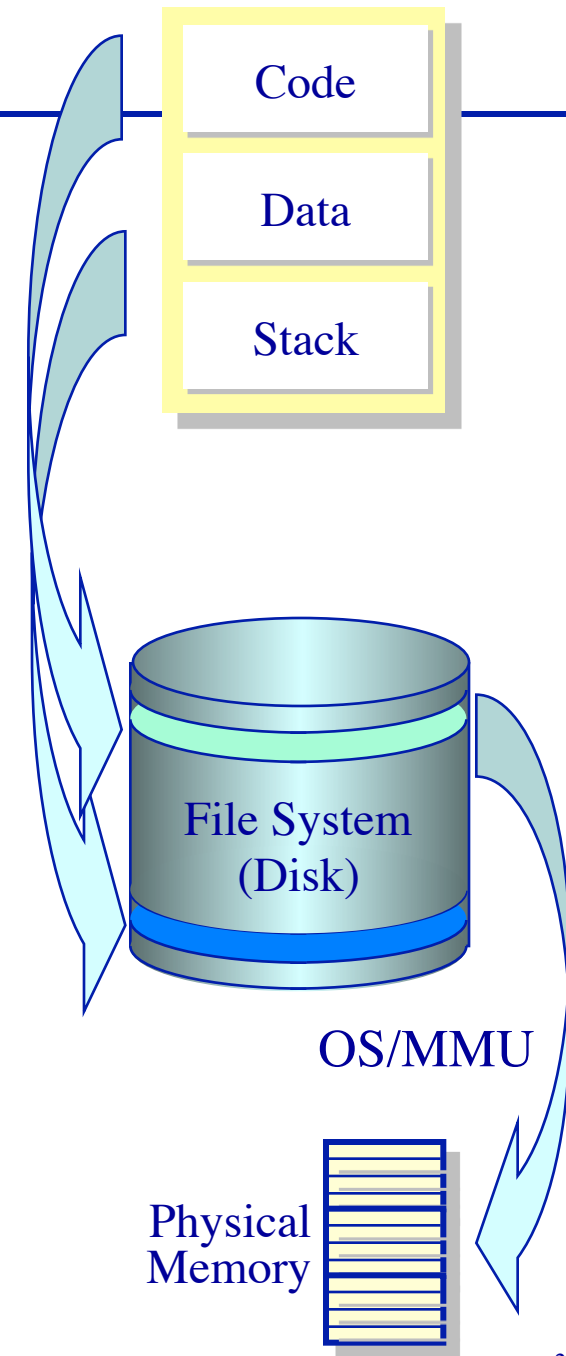
Questions

- ◆ Why use hashed/inverted page tables?
 - A. Forward mapped page tables are too slow.
 - B. Forward mapped page tables don't scale to larger virtual address spaces.
 - C. Inverted pages tables have a simpler lookup algorithm, so the hardware that implements them is simpler.
 - D. Inverted page tables allow a virtual page to be anywhere in physical memory.

Virtual Memory (Paging)

The bigger picture

- ◆ A process' s VAS is its context
 - Contains its code, data, and stack
- ◆ Code pages are stored in a user' s file on disk
 - Some are currently residing in memory; most are not
- ◆ Data and stack pages are also stored in a file
 - Although this file is typically not visible to users
 - File only exists while a program is executing
- ◆ OS determines which portions of a process' s VAS are mapped in memory at any one time



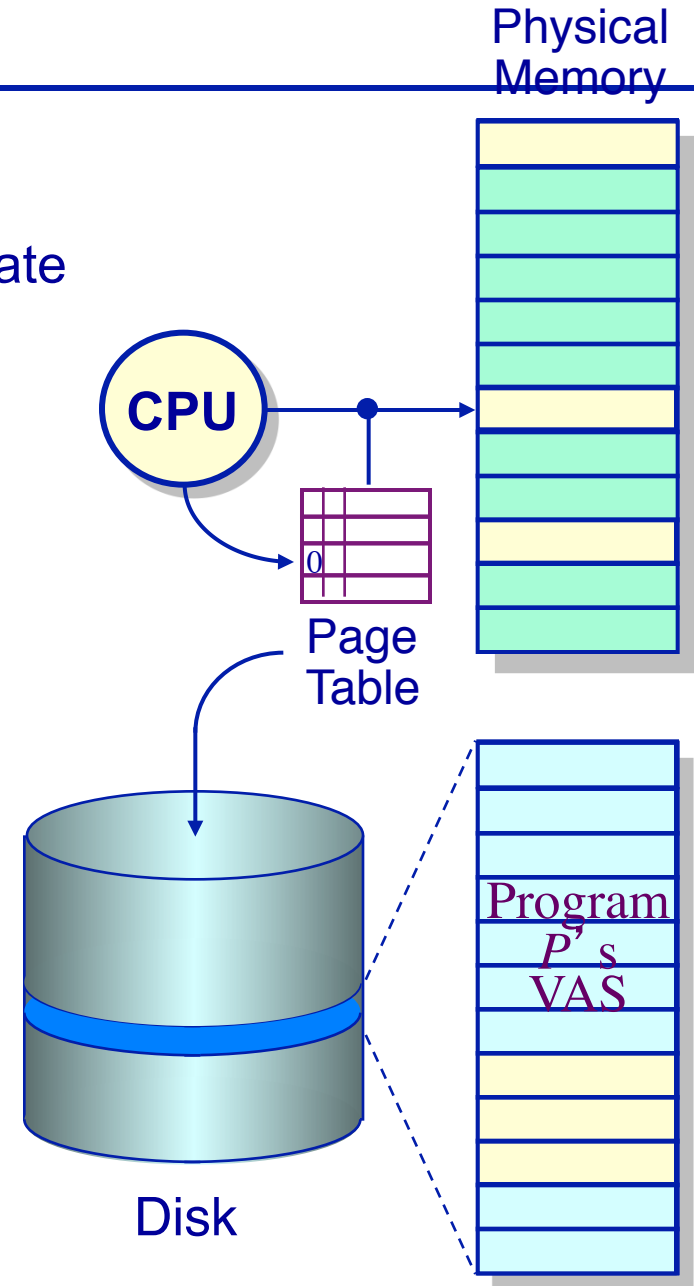
Virtual Memory

Page fault handling

- ◆ References to non-mapped pages generate a *page fault*

Page fault handling steps:

- Processor runs the interrupt handler
- OS blocks the running process
- OS starts read of the unmapped page
- OS resumes/initiates some other process
- Read of page completes
- OS maps the missing page into memory
- OS restart the faulting process



Virtual Memory Performance

Page fault handling analysis

- ◆ To understand the overhead of paging, compute the *effective memory access time (EAT)*
 - $EAT = \text{memory access time} \times \text{probability of a page hit} + \text{page fault service time} \times \text{probability of a page fault}$
- ◆ Example:
 - Memory access time: 60 ns
 - Disk access time: 25 ms
 - Let p = the probability of a page fault
 - $EAT = 60(1-p) + 25,000,000p$
- ◆ To realize an *EAT* within 5% of minimum, what is the largest value of p we can tolerate?

Virtual Memory

Summary

- ◆ Physical and virtual memory partitioned into equal size units
- ◆ Size of VAS unrelated to size of physical memory
- ◆ Virtual *pages* are mapped to physical *frames*
- ◆ Simple placement strategy
- ◆ There is no external fragmentation
- ◆ Key to good performance is minimizing page faults

Segmentation vs. Paging

- ◆ Segmentation has what advantages over paging?
 - A. Fine-grained protection.
 - B. Easier to manage transfer of segments to/from the disk.
 - C. Requires less hardware support
 - D. No external fragmentation
- ◆ Paging has what advantages over segmentation?
 - A. Fine-grained protection.
 - B. Easier to manage transfer of pages to/from the disk.
 - C. Requires less hardware support.
 - D. No external fragmentation.