



Virtual Memory: Paging

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Portions courtesy Emmett Witchel and Kevin Jeffay



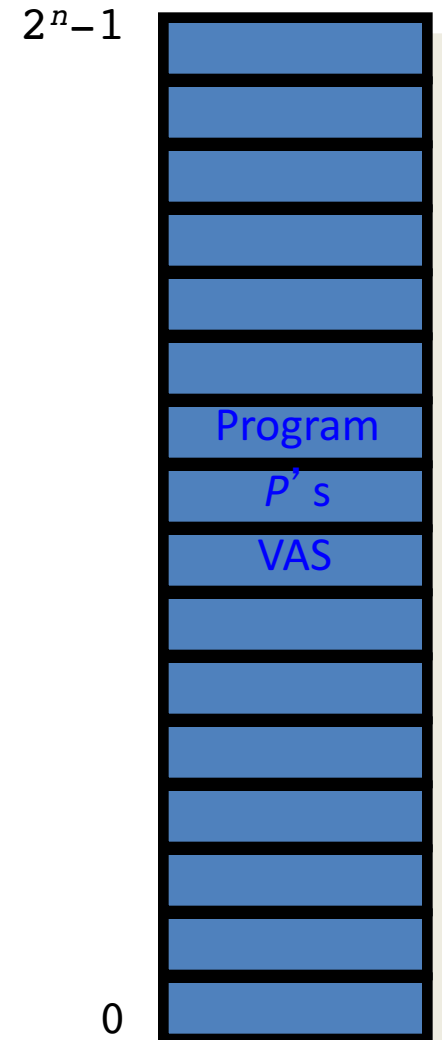
Review

- 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 address == physical address) is inconvenient.
 - Program location is compiled into the program.
- Segmentation:
 - Simple: two registers (base, offset) sufficient
 - Limited: Virtual address space must be \leq physical
 - Push complexity to space management:
 - Must allocate physically contiguous region for segments
 - Must deal with external fragmentation
 - Swapping only at segment granularity
- Key idea for today: Fixed size units (pages) for translation
 - More complex mapping structure
 - Less complex space management



Virtual Memory

- **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

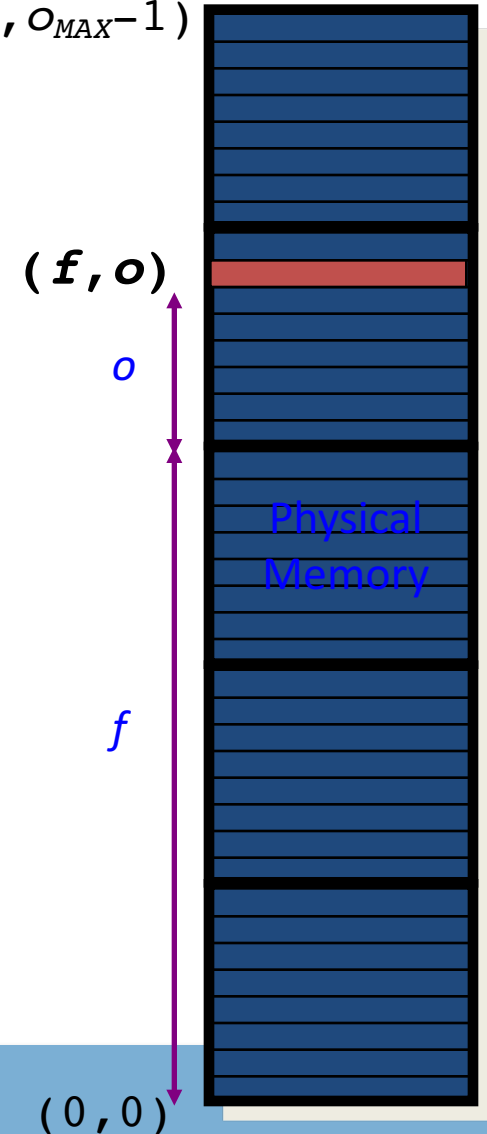




Solution: Paging

$(f_{MAX}-1, o_{MAX}-1)$

- Physical memory partitioned into equal sized *page frames*
 - Example page size: 4KB
- Memory only allocated in page frame sized increments
 - No external fragmentation
 - Can have internal fragmentation (rounding up smaller allocations to 1 page)
- Can map any page-aligned virtual address to a physical page frame



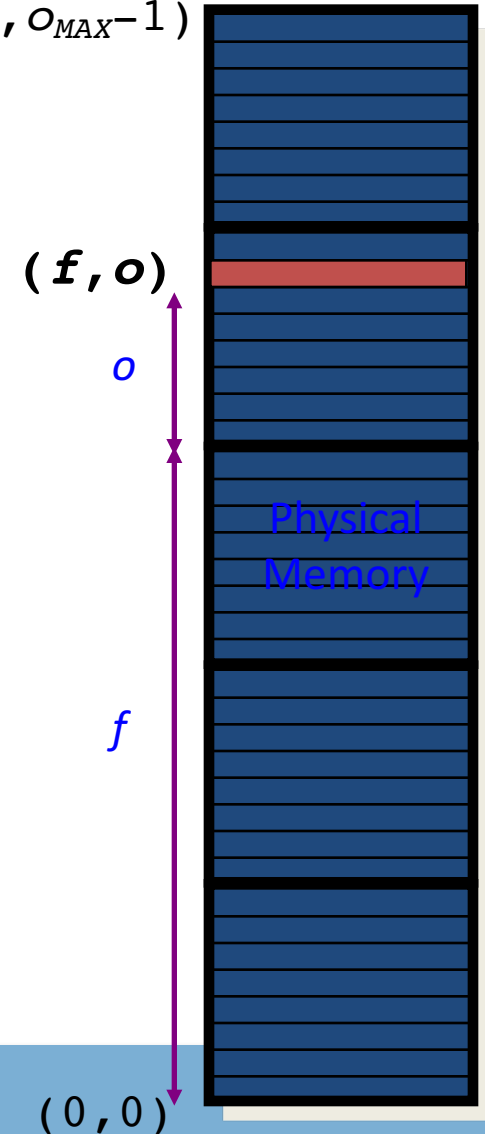


Page Mapping

$(f_{MAX}-1, o_{MAX}-1)$

Abstraction: 1:1 mapping of page-aligned virtual addresses to physical frames

- Imagine a ***big ole' table (BOT)***:
 - The size of memory / the size of a page frame
- Address translation is a 2-step process
 1. Map virtual page onto physical frame (using BOT)
 2. Add offset within the page





Physical Address Decomposition

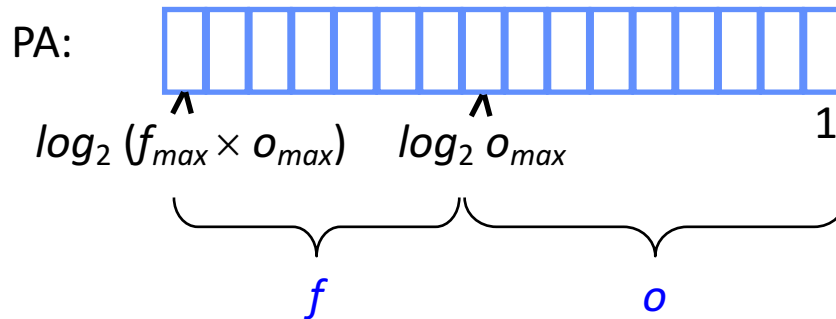
$(f_{MAX}-1, o_{MAX}-1)$

A physical address can be split into a pair (f, o)

f — frame number (f_{max} frames)

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

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



(f, o)

o

f

Physical
Memory

As long as a frame size is a power of 2, easy to split address using bitwise shift operations

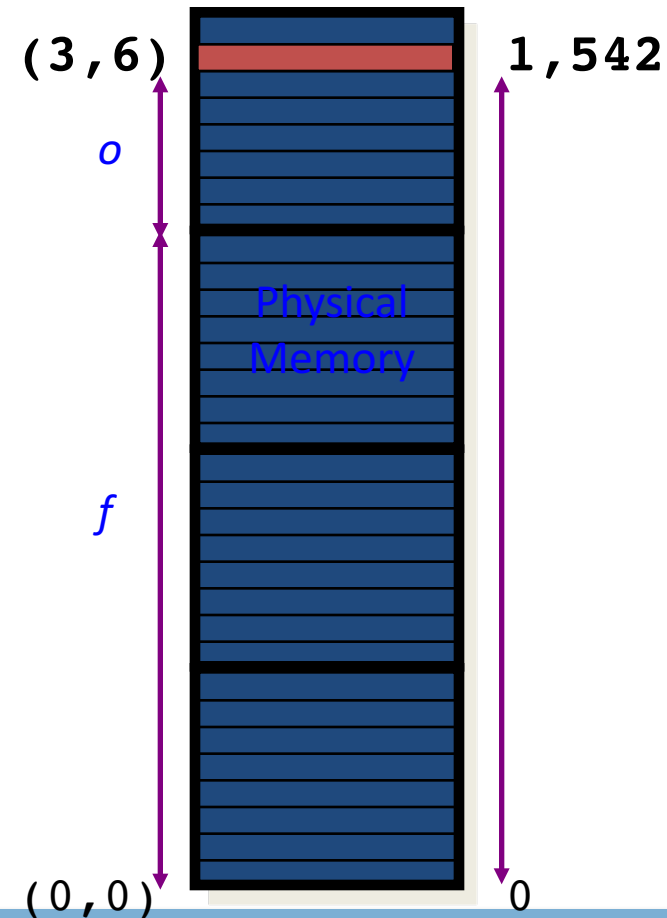
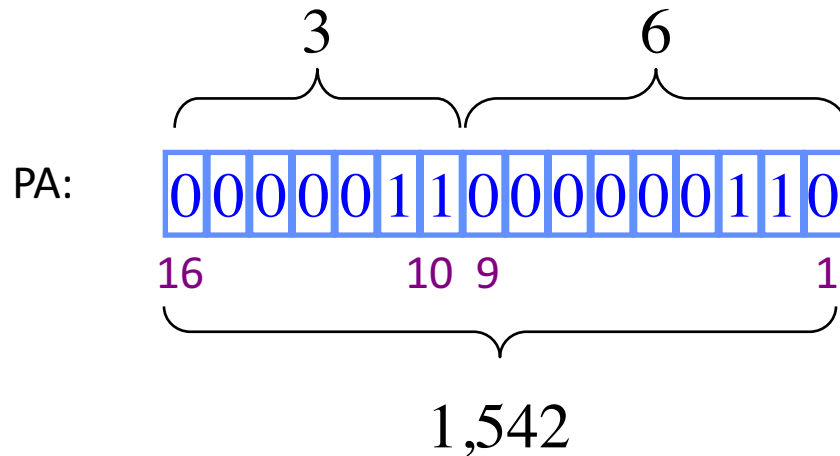
- Prepare for lots of power-of-2 arithmetic...

$(0, 0)$



Physical Addressing Example

- Suppose a 16-bit address space with ($o_{max} =$) 512 byte page frames
 - Reminder: $512 == 2^9$
 - Address 1,542 can be translated to:
 - Frame: $1,542 / 512 == 1,542 \gg 9 = 3$
 - Offset: $1,542 \% 512 == 1,542 \& (512-1) == 6$
 - More simply: (3,6)

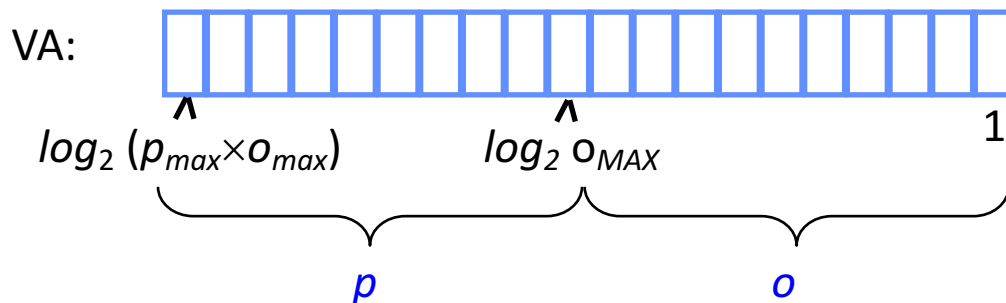




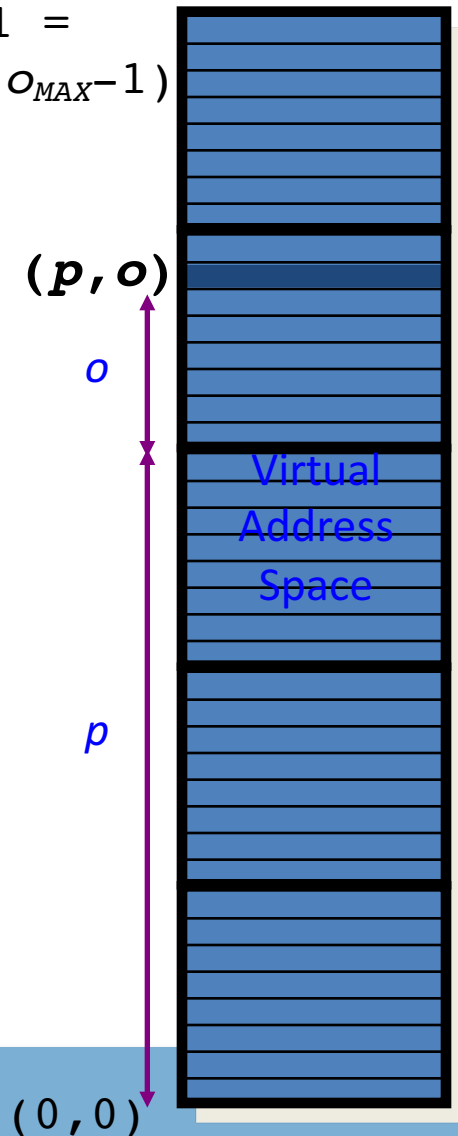
Virtual Page Addresses

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



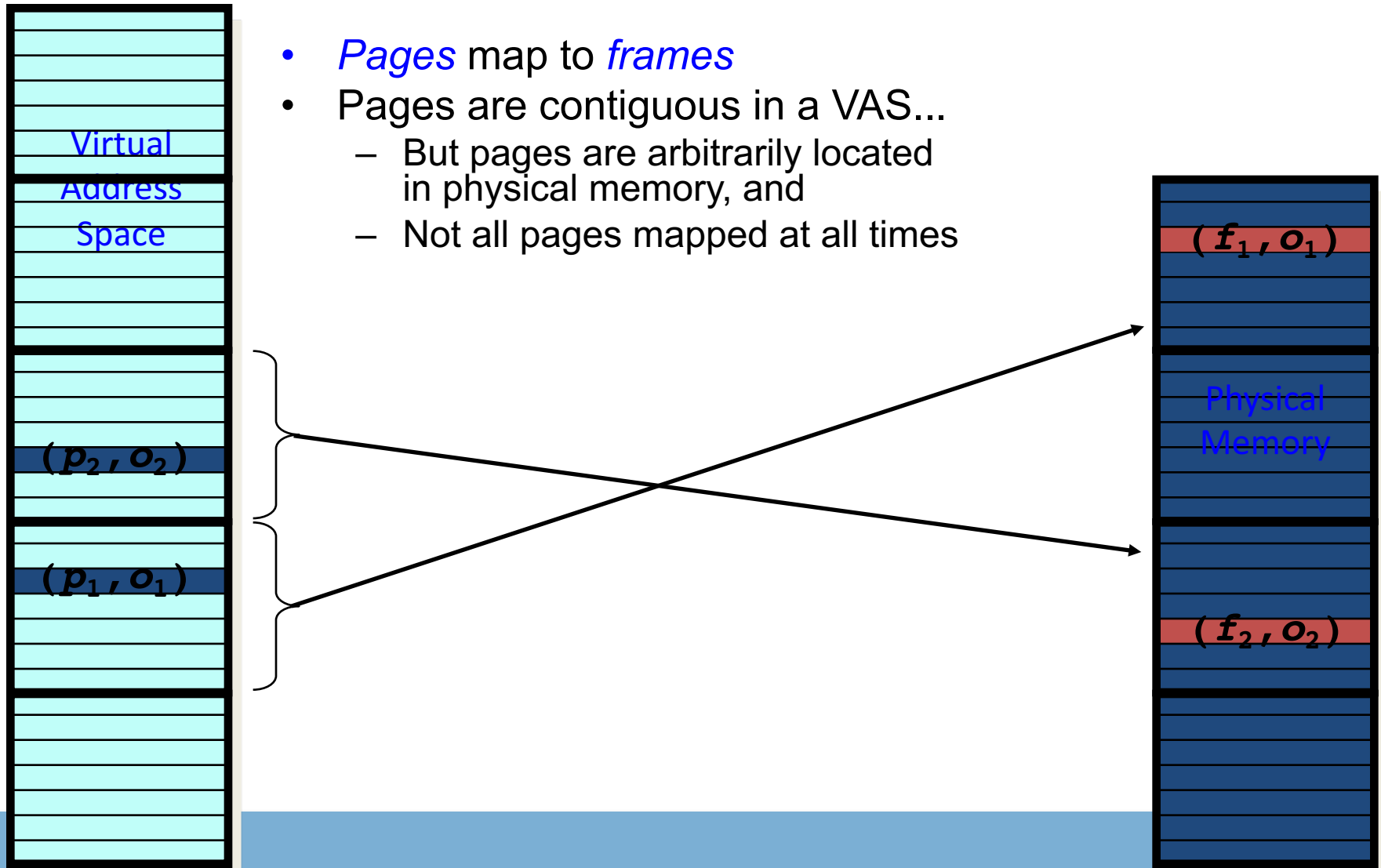
$$2^n - 1 = (p_{MAX} - 1, o_{MAX} - 1)$$





Page mapping

- *Pages* map to *frames*
- Pages are contiguous in a VAS...
 - But pages are arbitrarily located in physical memory, and
 - Not all pages mapped at all times



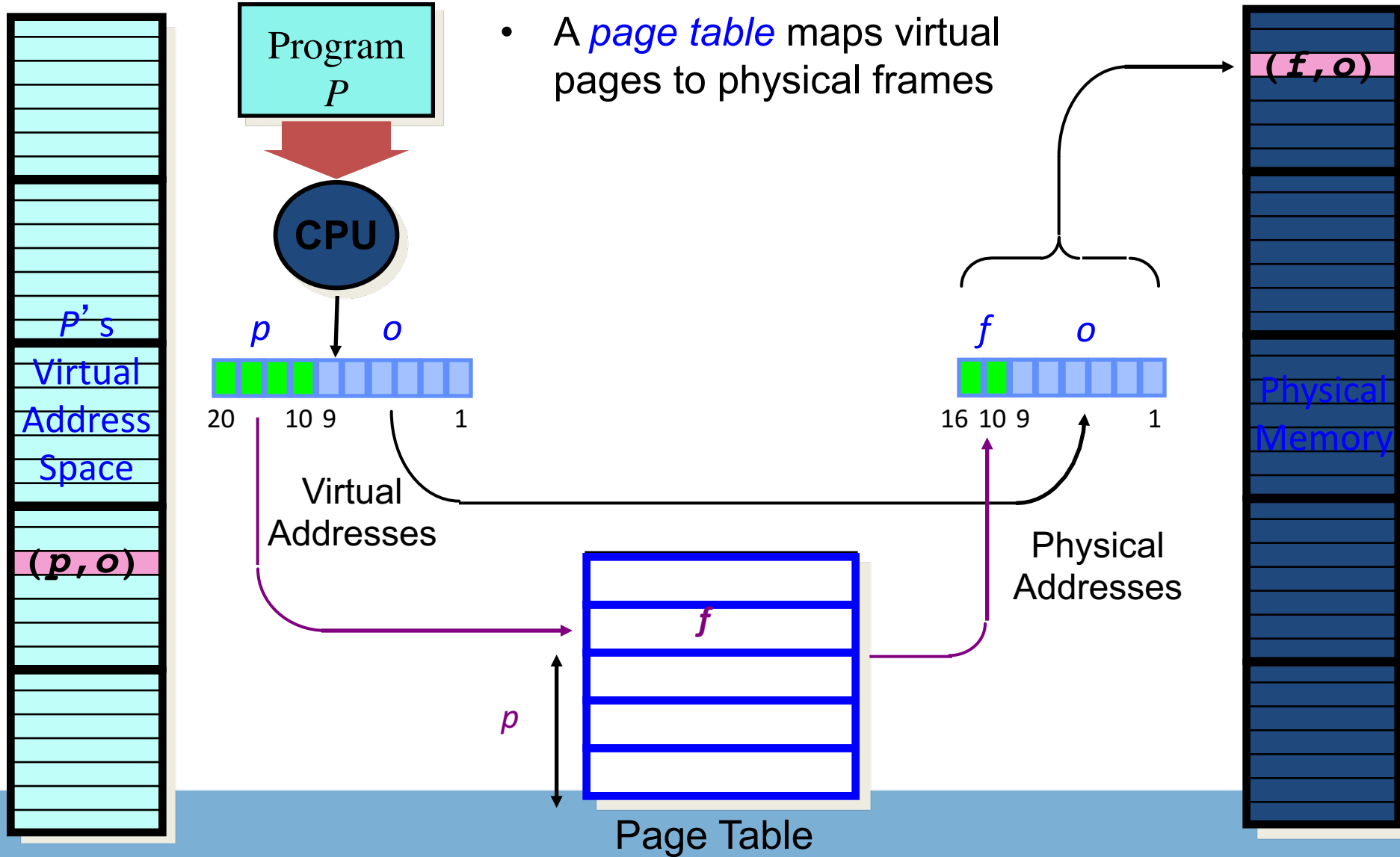


Questions

- The offset is the same in a virtual address and a physical address.
 - A. True
 - B. False



Page Tables (aka Big Ole' Table)



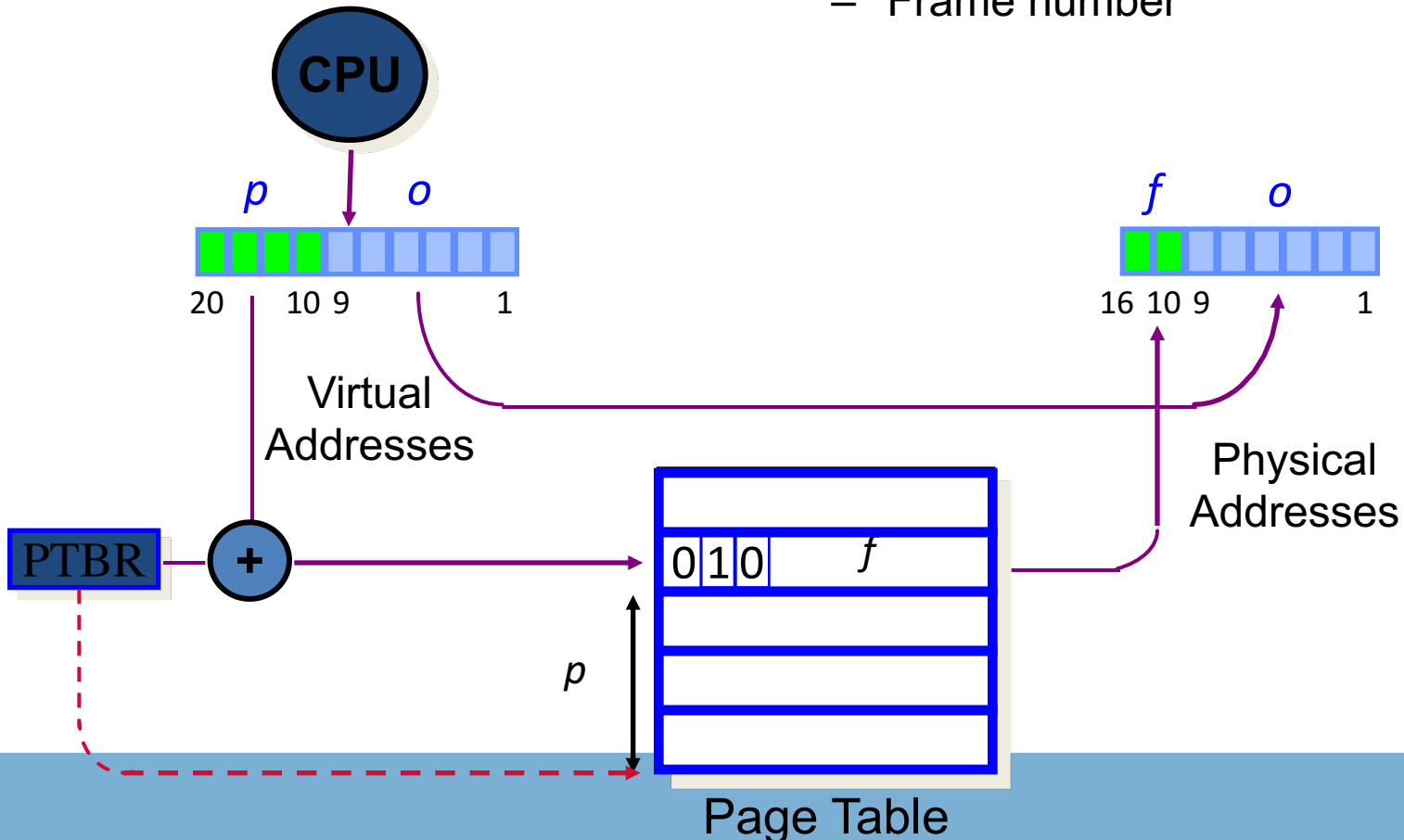


Page Table Details

1 table per process

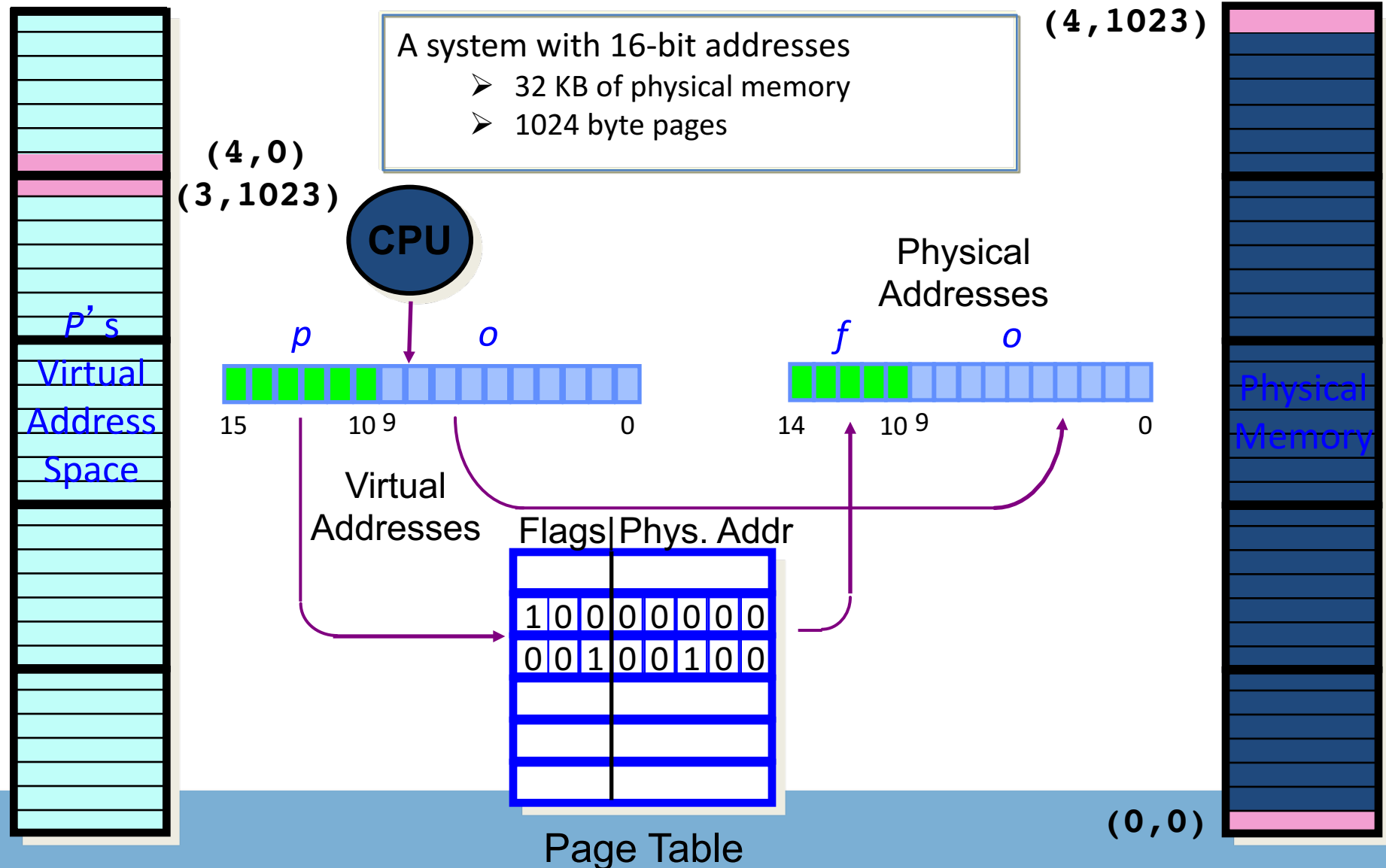
Part of process metadata/state

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





Example





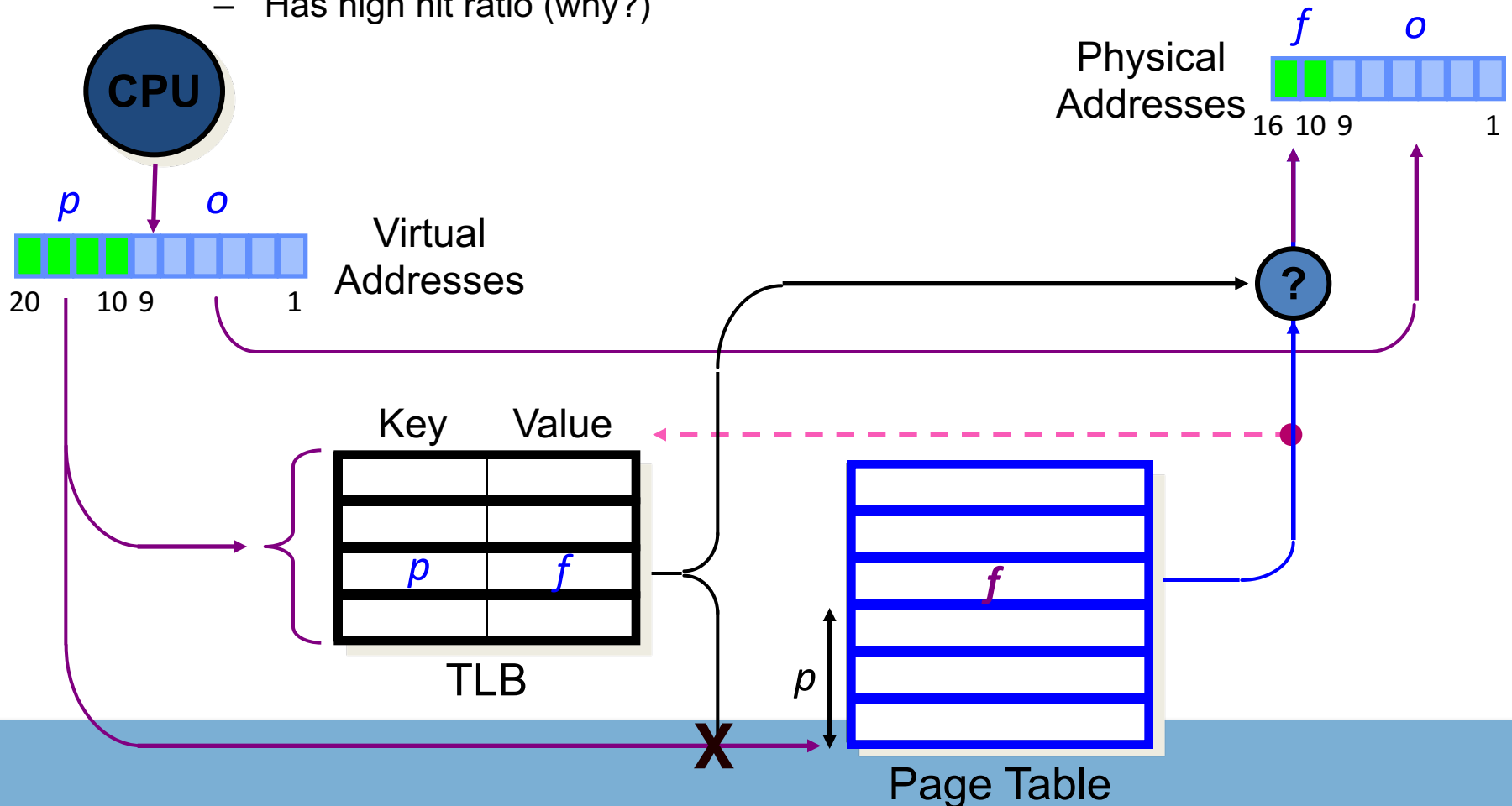
Performance Issues with Paging

- 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



Using a TLB to Cache Translations

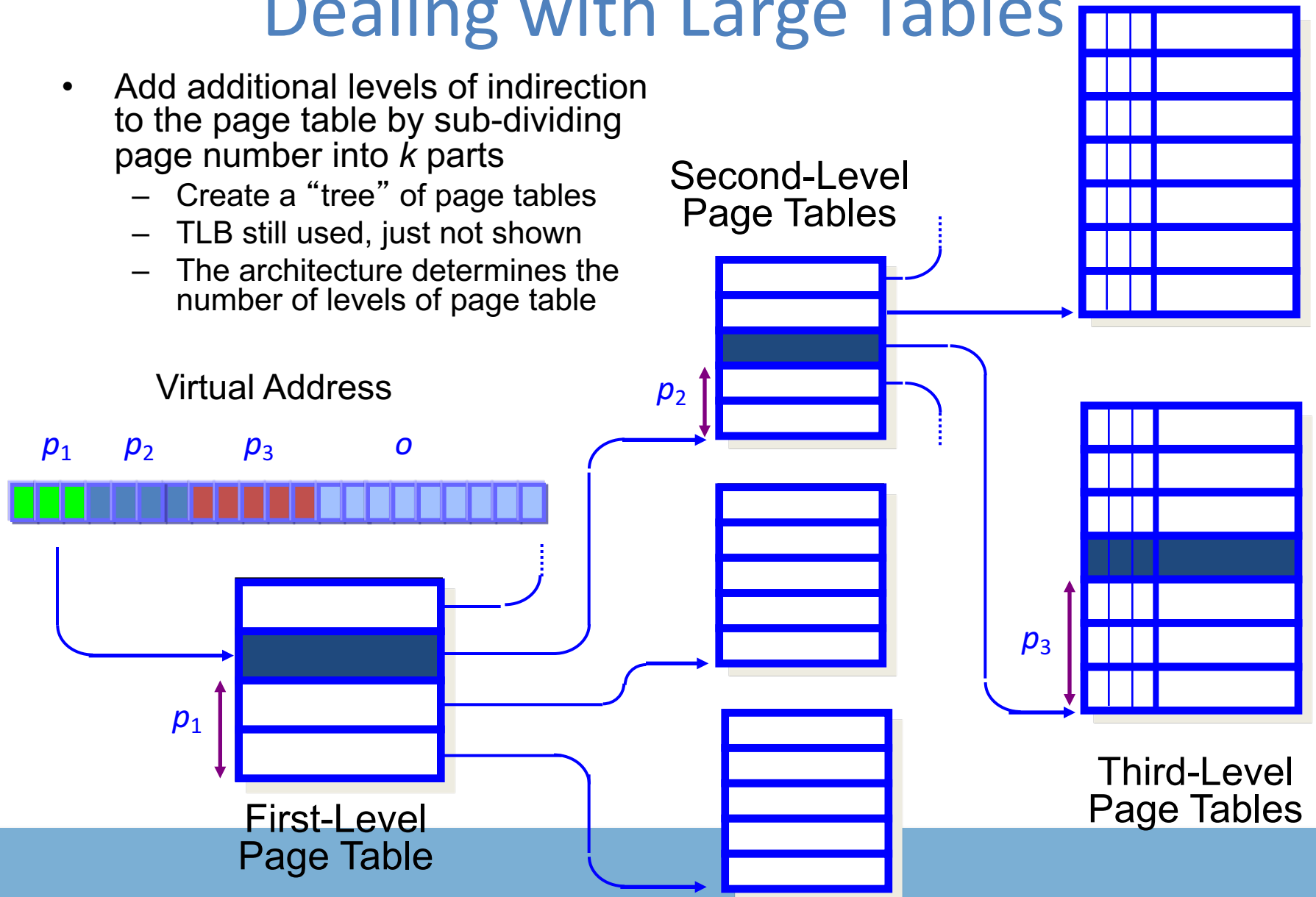
- Cache recently accessed page-to-frame translations in a TLB
 - For TLB hit, physical page number obtained in 1 cycle
 - For TLB miss, translation is updated in TLB
 - Has high hit ratio (why?)





Dealing with Large Tables

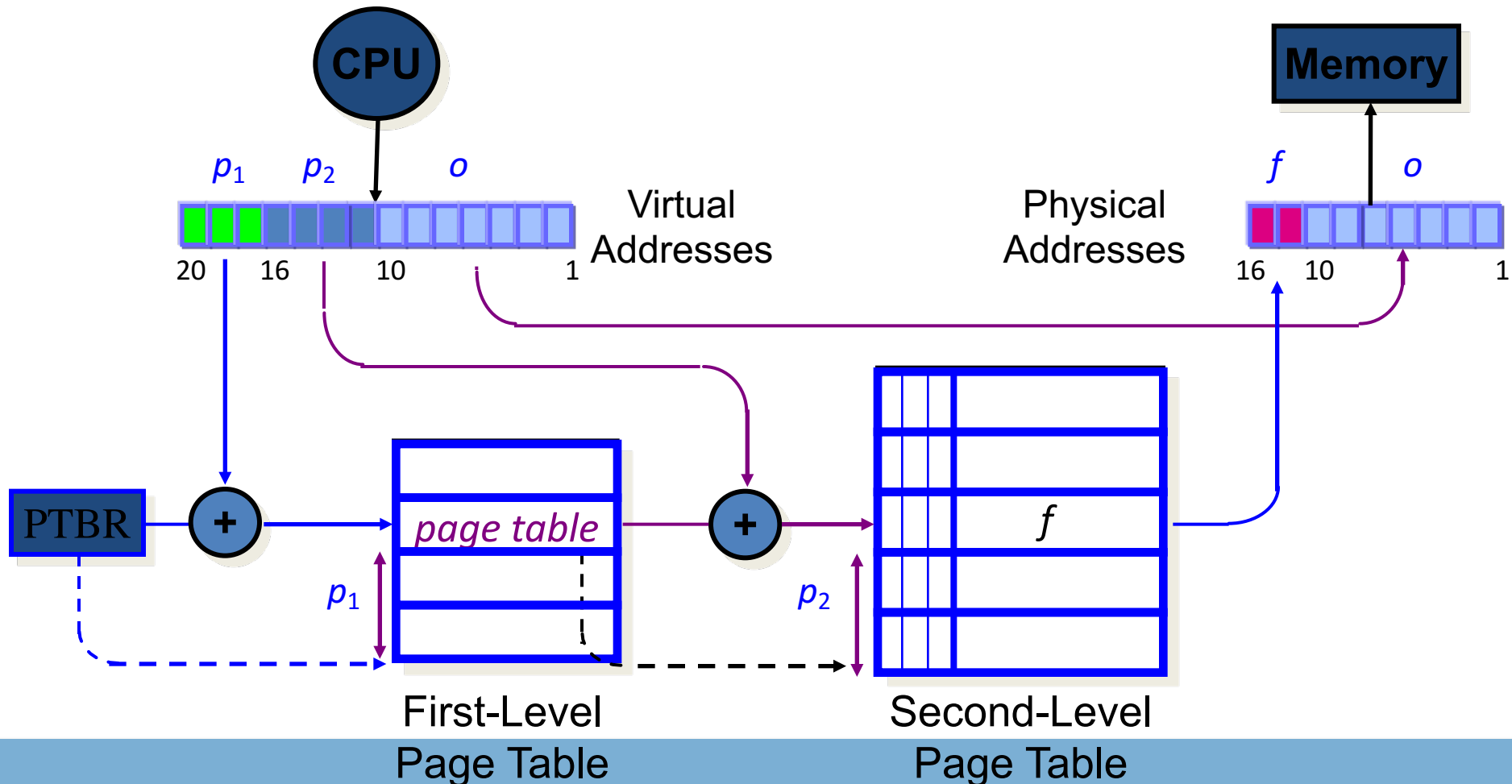
- Add additional levels of indirection to the page table by sub-dividing page number into k parts
 - Create a “tree” of page tables
 - TLB still used, just not shown
 - The architecture determines the number of levels of page table





Dealing with Large Tables

- Example: Two-level paging





Large Virtual 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



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



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



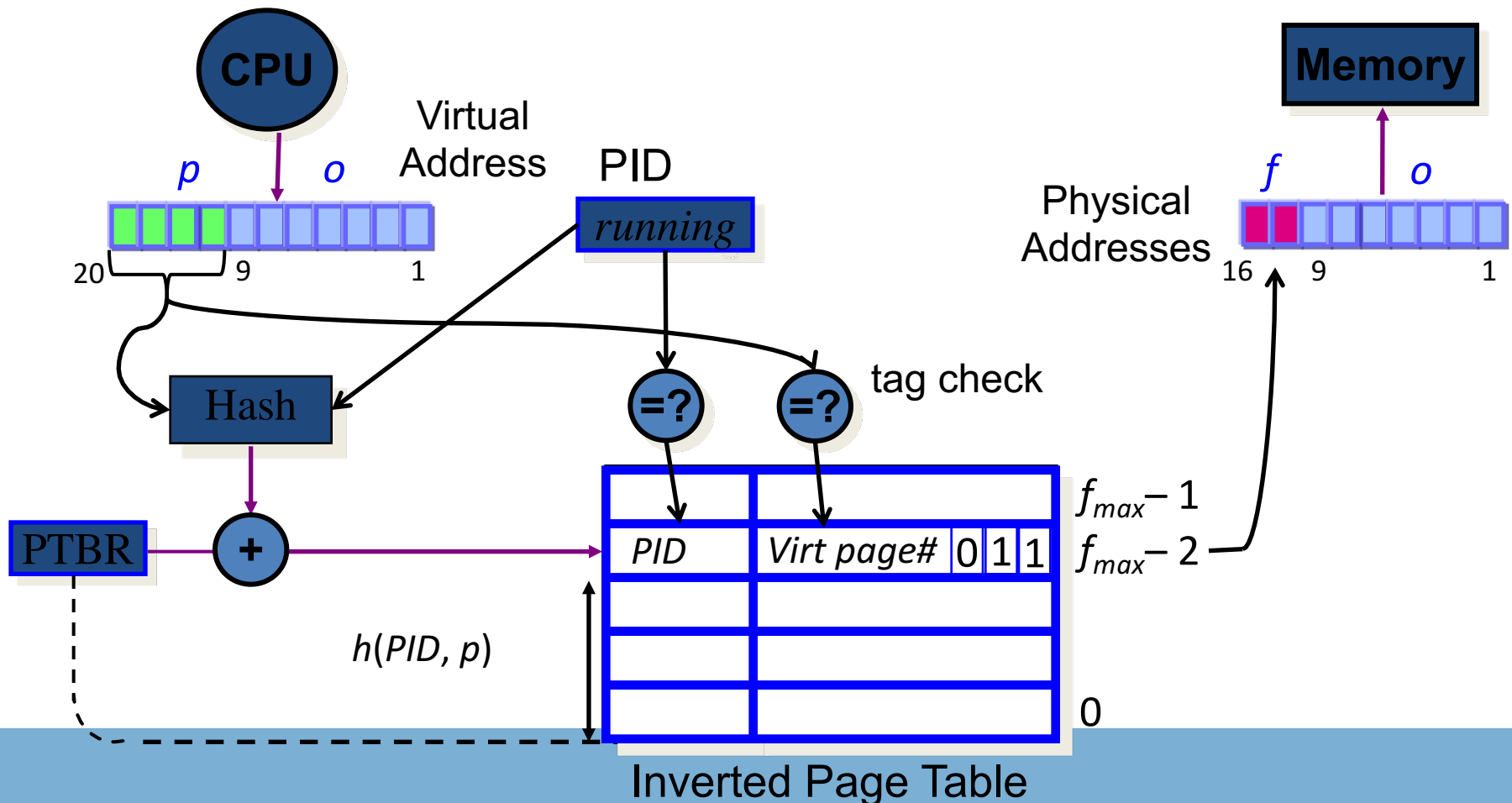
Inverted Page Table Lookup

- 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)



Inverted Page Table Lookup

- 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 Inverted Page 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 Inverted Page Tables

- 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)



Observation

- One cool feature of inverted page tables is that you only need one for the entire OS
 - Recall: each entry stores PID and virtual address
 - Multiple processes can share one inverted table
- Forward mapped tables have one table per process



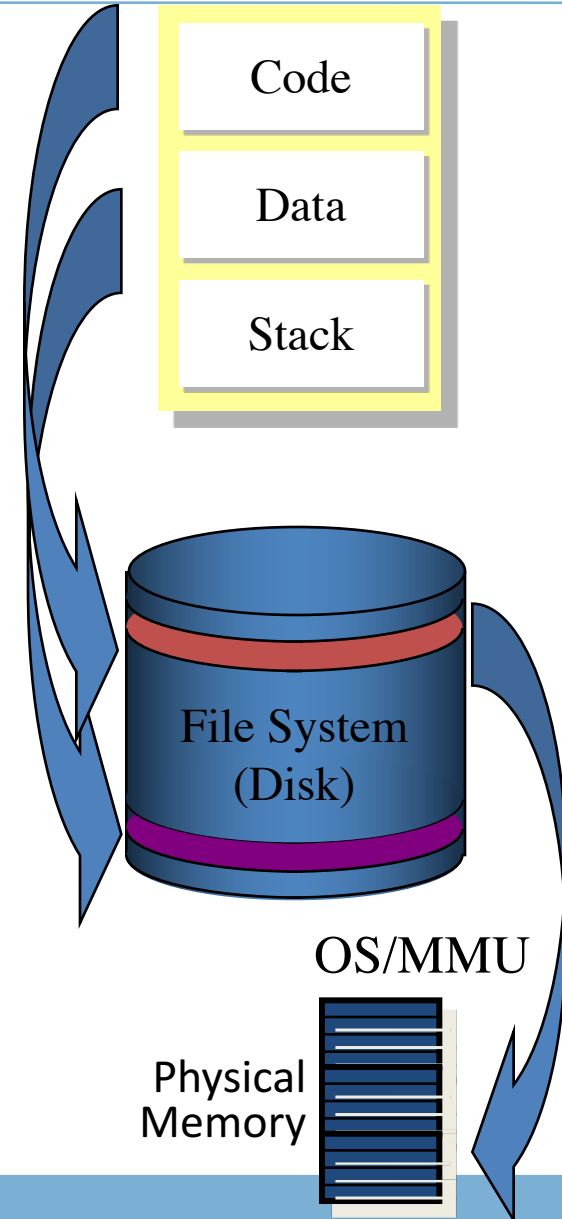
Questions

- 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.



Swapping

- 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



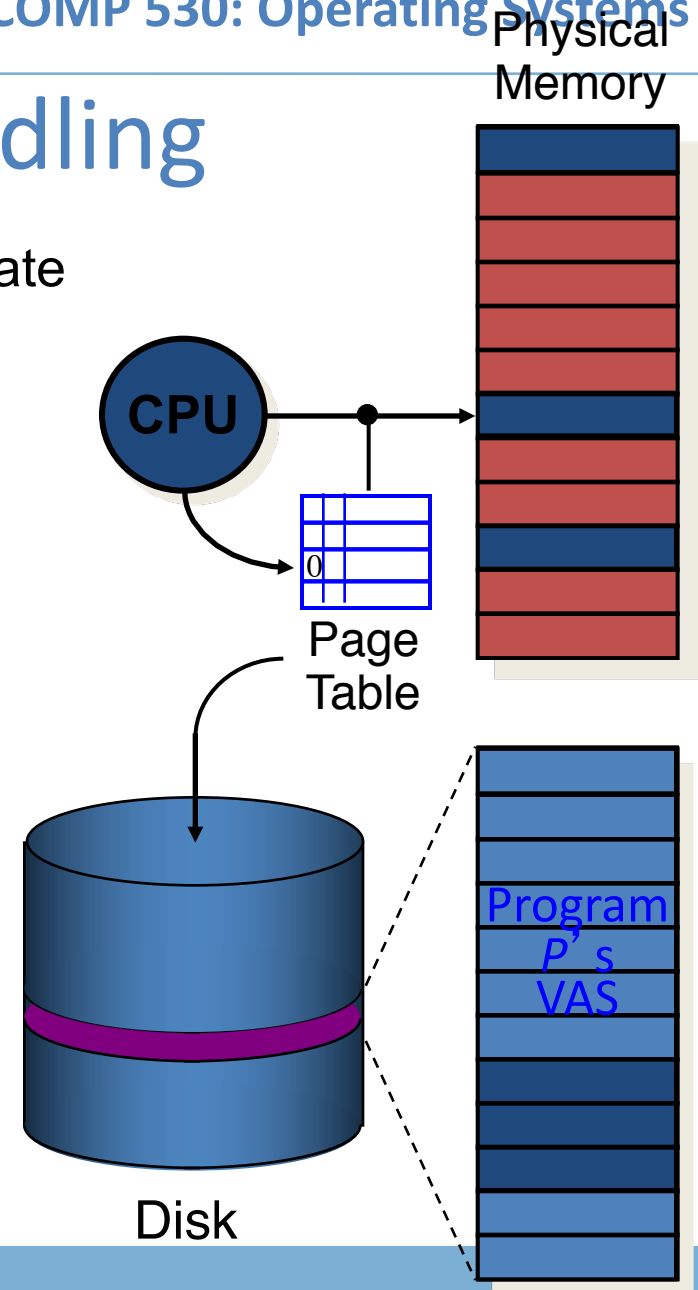


Page Fault Handling

- References to non-mapped pages generate a *page fault*
 - Remember Interrupts?*

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





Performance 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?



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.



Meta-Commentary

- Paging is really efficient when memory is relatively scarce
 - But comes with higher latency, higher management costs in hardware and software
- But DRAM is getting more abundant!
 - Push for larger page granularity (fewer levels of page tables)
 - Or just go back to segmentation??
 - If everything fits into memory with space to spare, why not?



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