15-213

“The course that gives CMU its Zip!”

Virtual Memory
Oct. 29, 2002

Topics

- Motivations for VM
- Address translation
- Accelerating translation with TLBs

Motivations for Virtual Memory

Use Physical DRAM as a Cache for the Disk

- Address space of a process can exceed physical memory size
- Sum of address spaces of multiple processes can exceed physical memory

Simplify Memory Management

- Multiple processes resident in main memory.
  - Each process with its own address space
- Only “active” code and data is actually in memory
  - Allocate more memory to process as needed.

Provide Protection

- One process can’t interfere with another.
  - because they operate in different address spaces.
- User process cannot access privileged information
  - different sections of address spaces have different permissions.

Motivation #1: DRAM a "Cache" for Disk

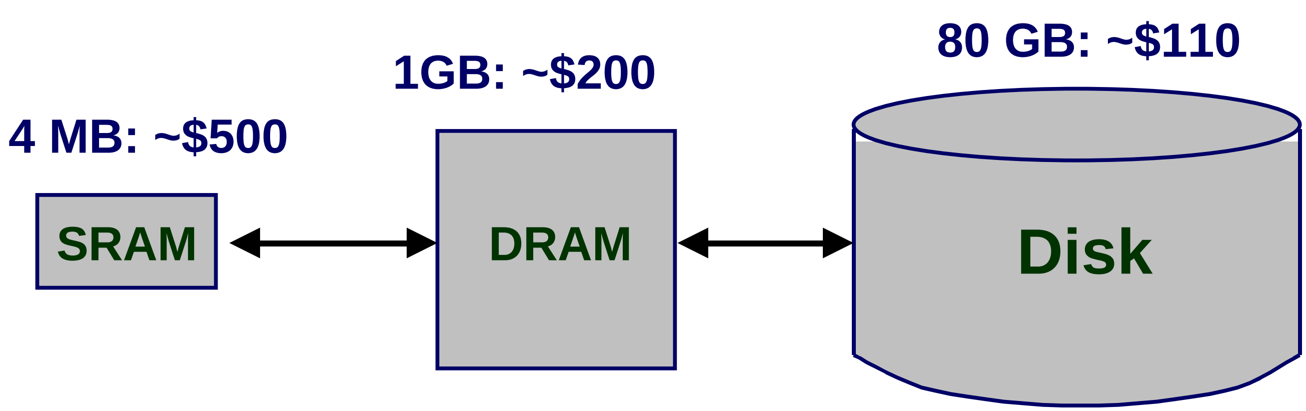
Full address space is quite large:

- 32-bit addresses: ~4,000,000,000 (4 billion) bytes
- 64-bit addresses: ~16,000,000,000,000,000,000 (16 quintillion) bytes

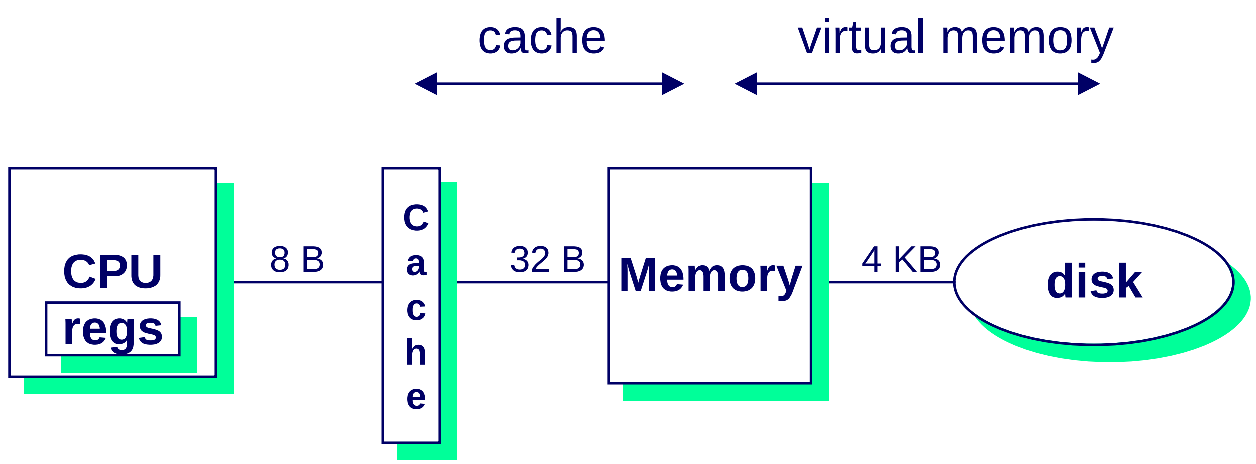
Disk storage is ~300X cheaper than DRAM storage

- 80 GB of DRAM: ~ $33,000
- 80 GB of disk: ~ $110

To access large amounts of data in a cost-effective manner, the bulk of the data must be stored on disk



Levels in Memory Hierarchy



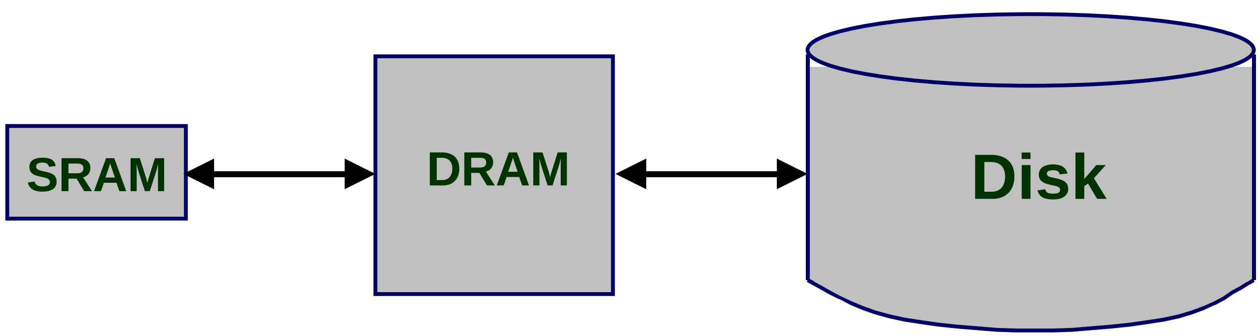
	Register	Cache	Memory	Disk Memory
size:	32 B	32 KB-4MB	1024 MB	100 GB
speed:	1 ns	2 ns	30 ns	8 ms
$/Mbyte:		$125/MB	$0.20/MB	$0.001/MB
line size:	8 B	32 B	4 KB	

larger, slower, cheaper

DRAM vs. SRAM as a "Cache"

DRAM vs. disk is more extreme than SRAM vs. DRAM

- **Access latencies:**
  - **DRAM ~10X slower than SRAM**
  - **Disk ~**100,000X **slower than DRAM**
- **Importance of exploiting spatial locality:**
  - **First byte is ~**100,000X **slower than successive bytes on disk**
    - » **vs. ~4X improvement for page-mode vs. regular accesses to DRAM**
- **Bottom line:**
  - **Design decisions made for DRAM caches driven by enormous cost of misses**



Impact of Properties on Design

If DRAM was to be organized similar to an SRAM cache, how would we set the following design parameters?

- **Line size?**
  - **Large, since disk better at transferring large blocks**
- **Associativity?**
  - **High, to mimimize miss rate**
- **Write through or write back?**
  - **Write back, since can't afford to perform small writes to disk**

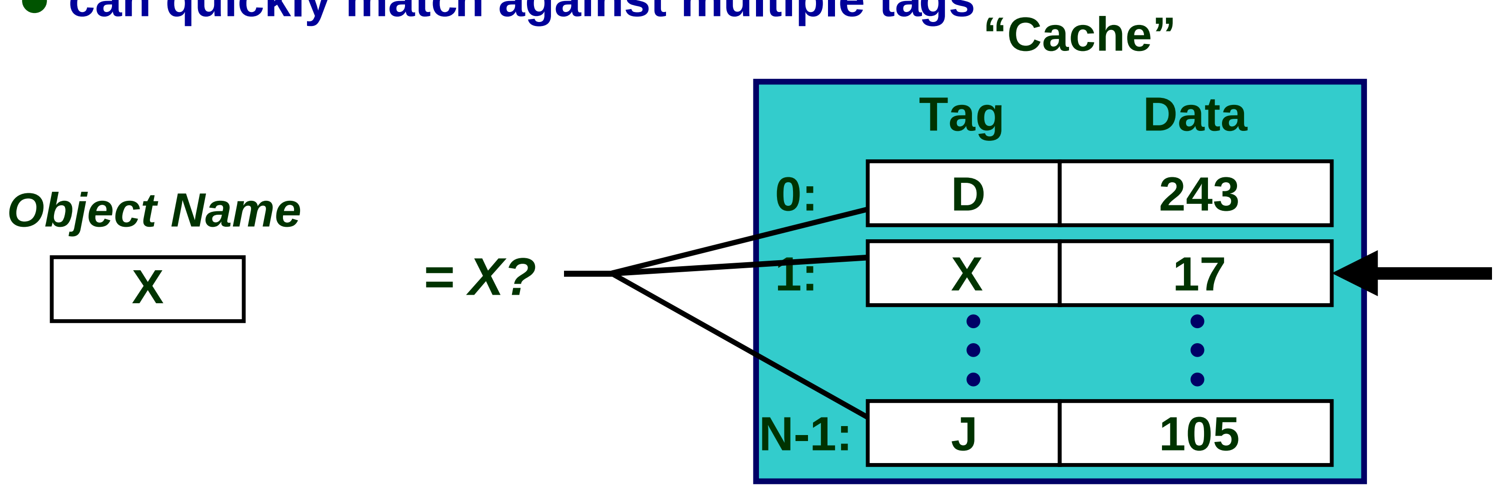
What would the impact of these choices be on:

- **miss rate**
  - **Extremely low. << 1%**
- **hit time**
  - **Must match cache/DRAM performance**
- **miss latency**
  - **Very high. ~20ms**
- **tag storage overhead**
  - **Low, relative to block size**

Locating an Object in a "Cache"

SRAM Cache

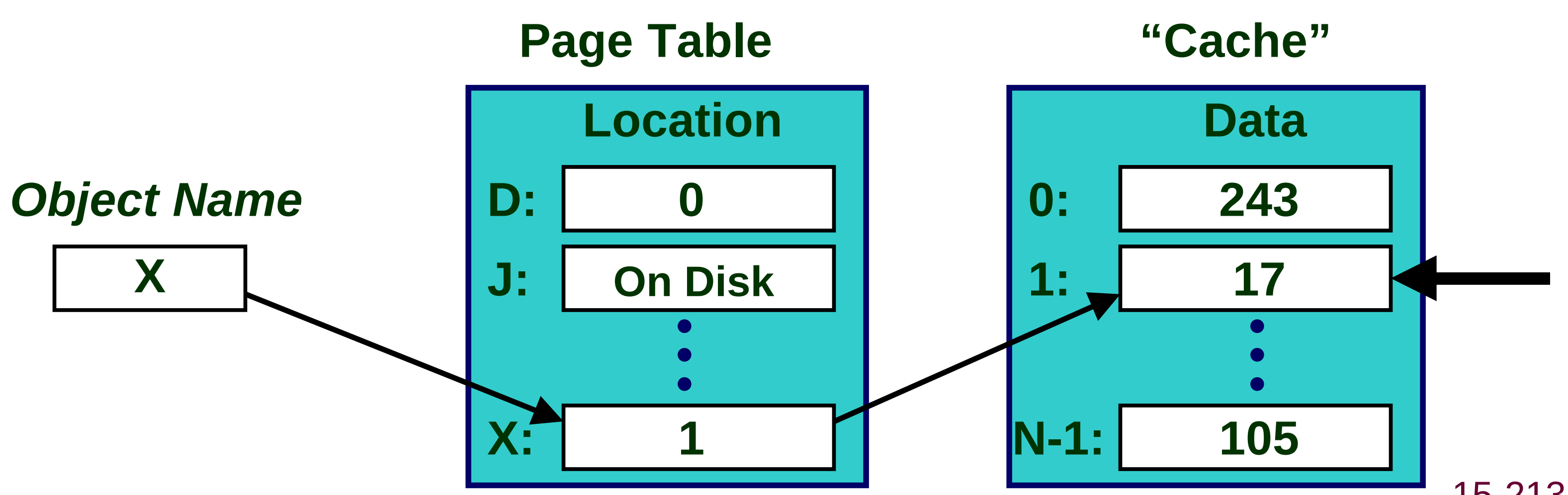
- Tag stored with cache line
- Maps from cache block to memory blocks
  - From cached to uncached form
  - Save a few bits by only storing tag
- No tag for block not in cache
- Hardware retrieves information
  - can quickly match against multiple tags



Locating an Object in “Cache” (cont.)

DRAM Cache

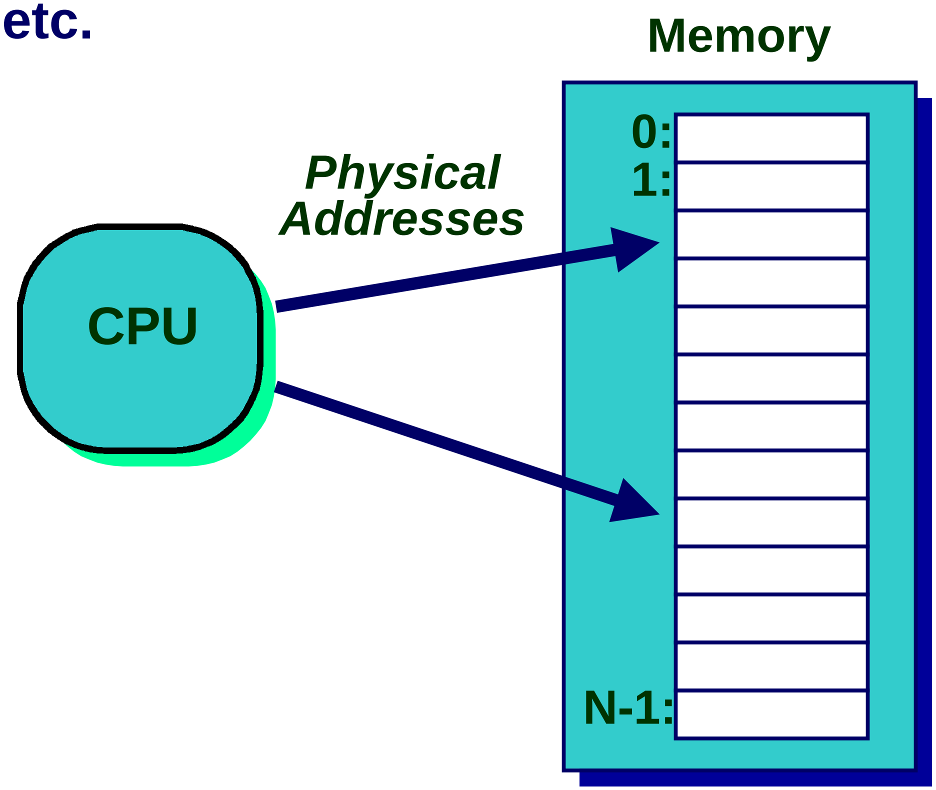
- Each allocated page of virtual memory has entry in *page table*
- Mapping from virtual pages to physical pages
  - From uncached form to cached form
- Page table entry even if page not in memory
  - Specifies disk address
  - Only way to indicate where to find page
- OS retrieves information



A System with Physical Memory Only

Examples:

- most Cray machines, early PCs, nearly all embedded systems, etc.

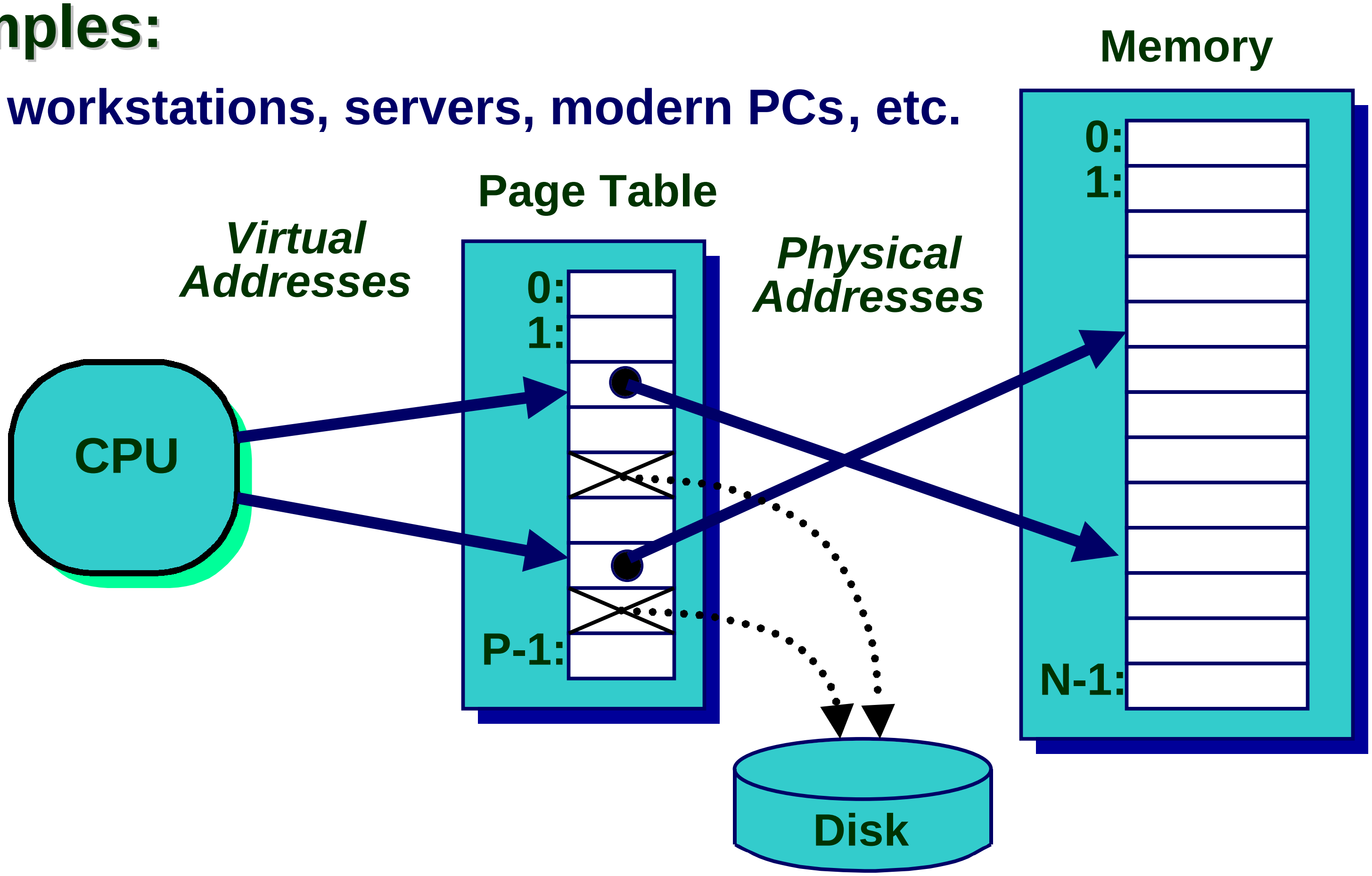


- Addresses generated by the CPU correspond directly to bytes in physical memory

A System with Virtual Memory

Examples:

- workstations, servers, modern PCs, etc.



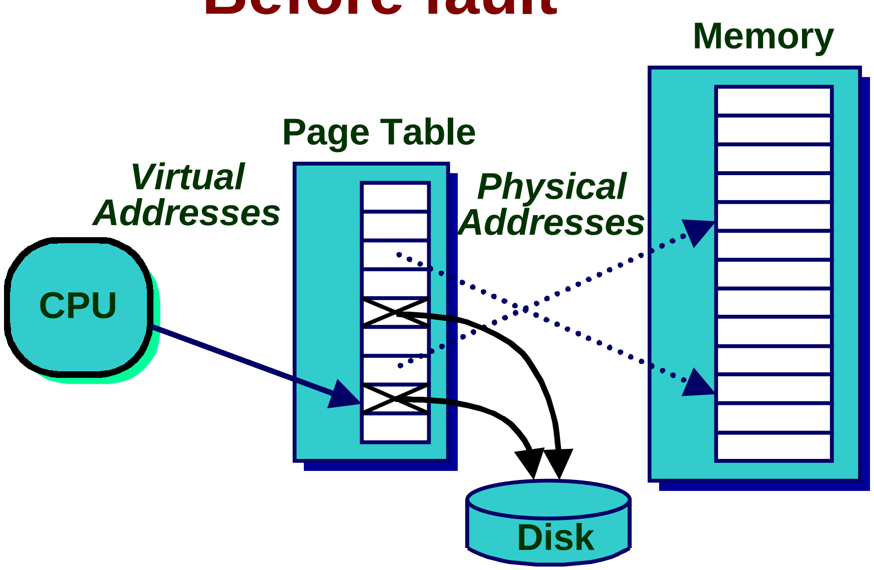
- Address Translation: Hardware converts virtual addresses to physical addresses via OS-managed lookup table (page table)

Page Faults (like "Cache Misses")

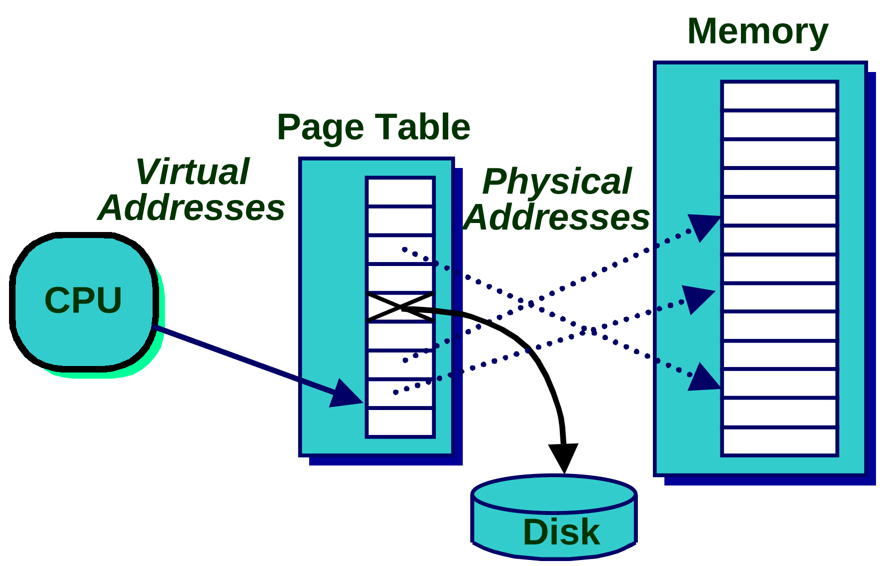
What if an object is on disk rather than in memory?

- Page table entry indicates virtual address not in memory
- OS exception handler invoked to move data from disk into memory
  - current process suspends, others can resume
  - OS has full control over placement, etc.

Before fault



After fault



Servicing a Page Fault

Processor Signals Controller

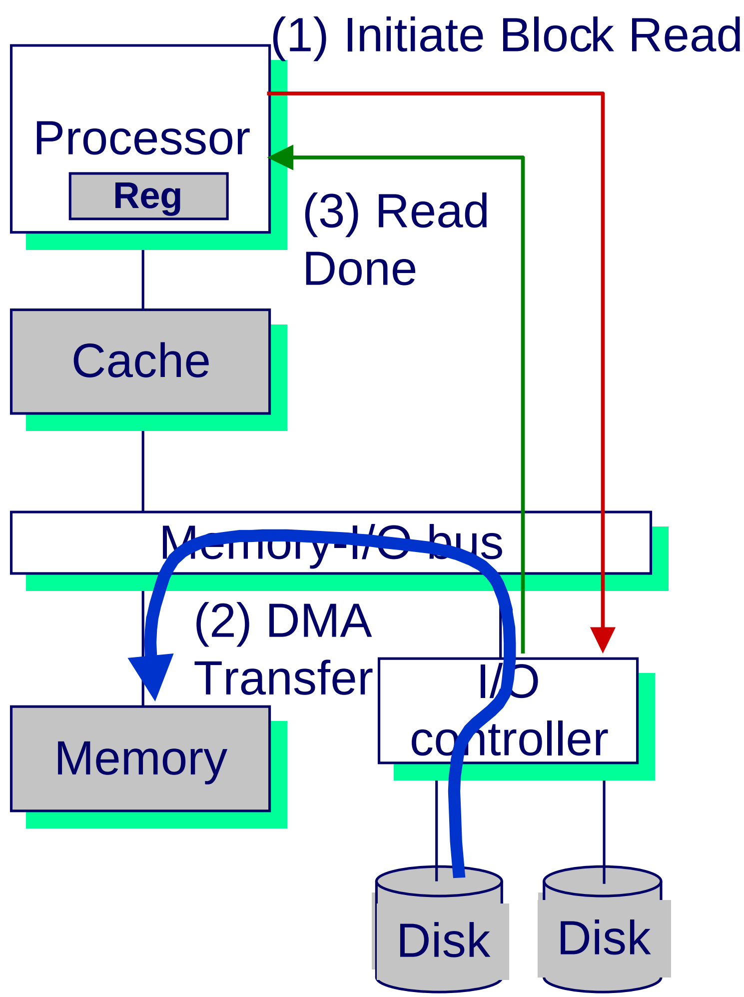
- **Read block of length P starting at disk address X and store starting at memory address Y**

Read Occurs

- **Direct Memory Access (DMA)**
- **Under control of I/O controller**

I / O Controller Signals Completion

- **Interrupt processor**
- **OS resumes suspended process**



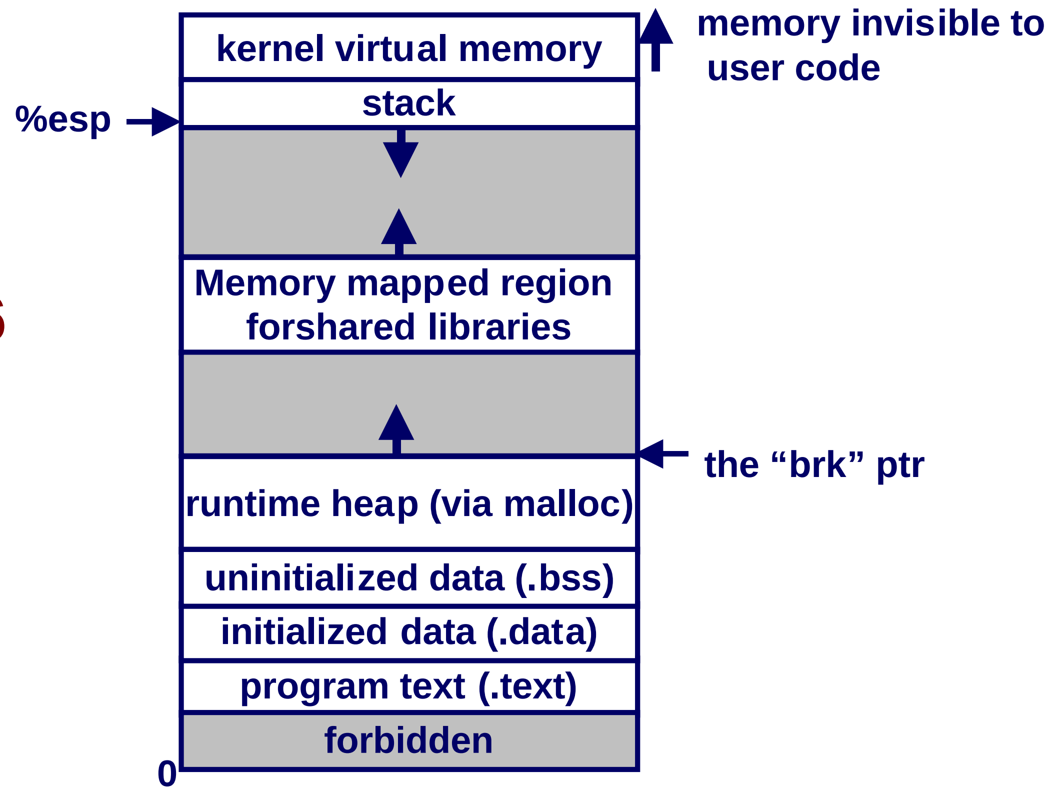
Motivation #2: Memory Management

Multiple processes can reside in physical memory.

How do we resolve address conflicts?

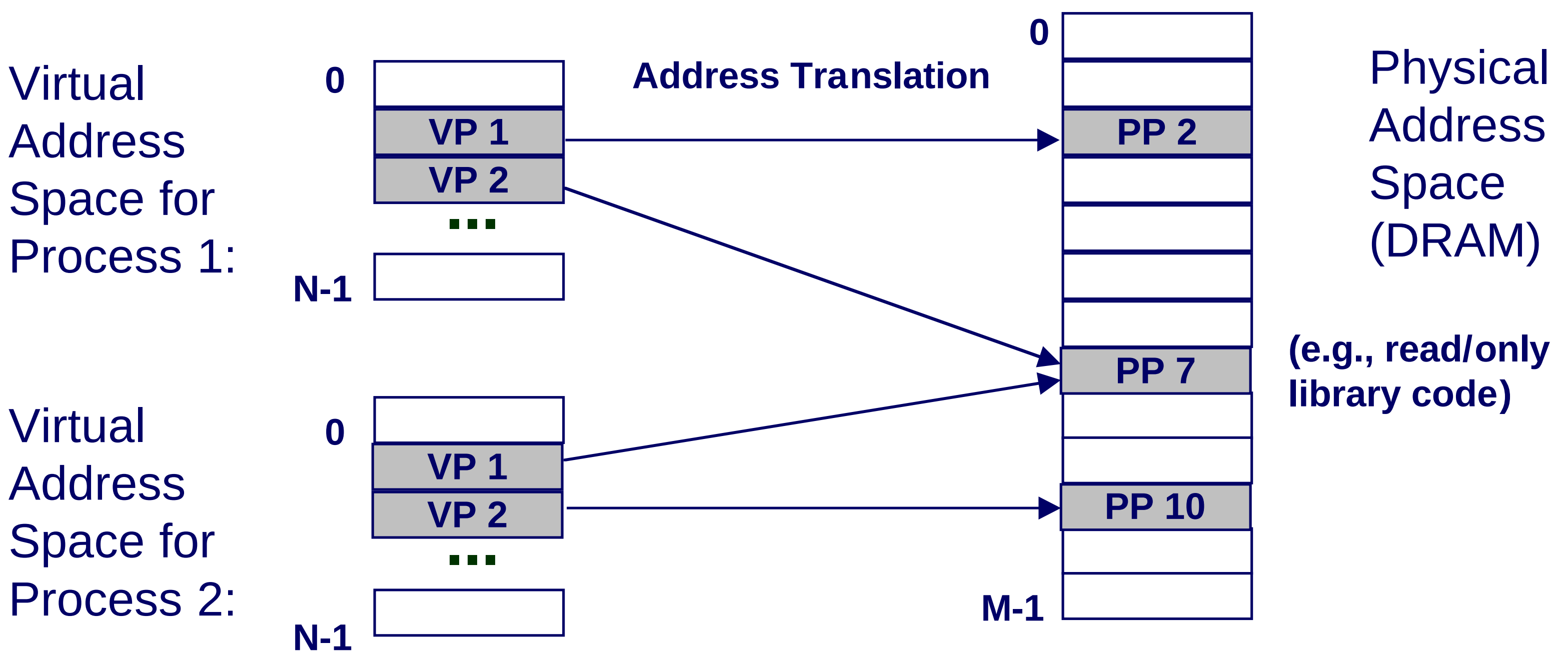
- what if two processes access something at the same address?

Linux/x86 process memory image



Solution: Separate Virt. Addr. Spaces

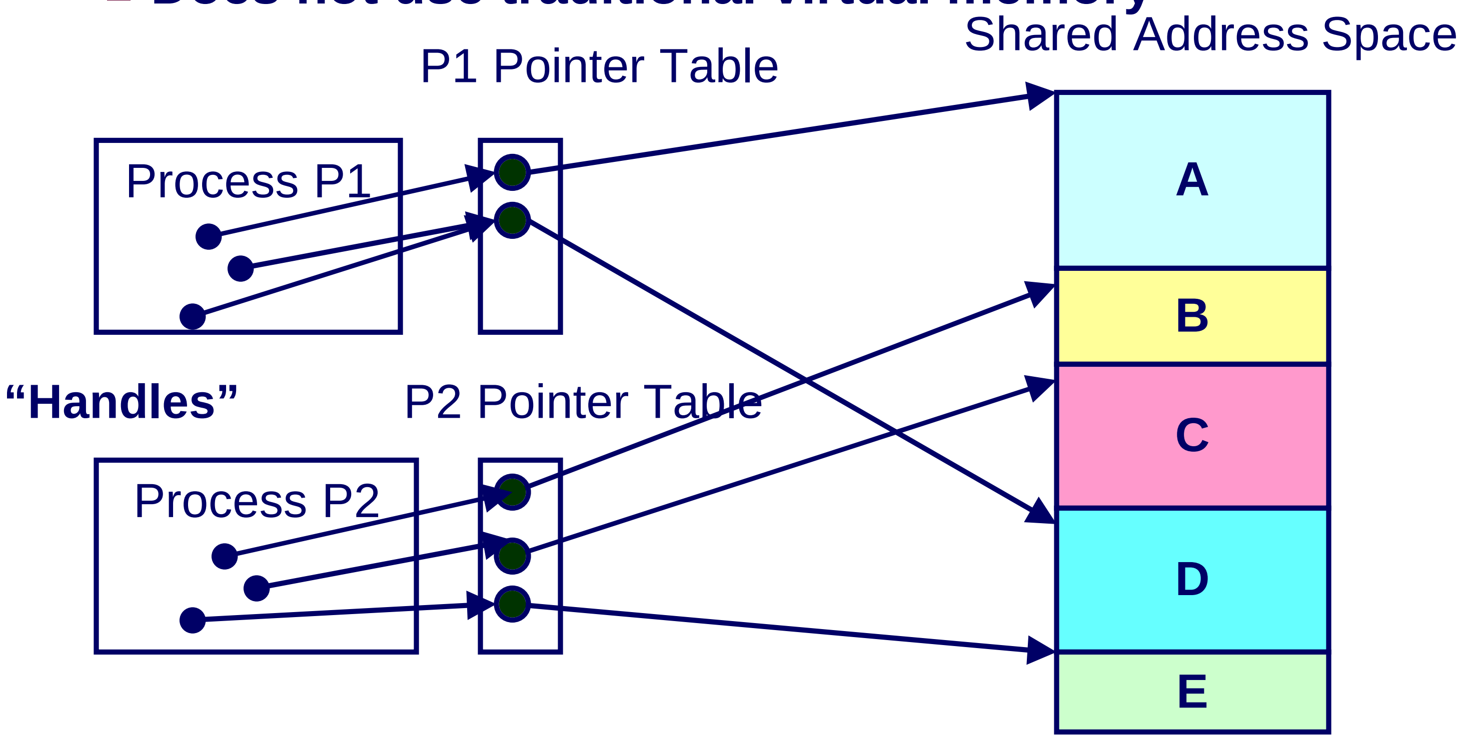
- Virtual and physical address spaces divided into equal-sized blocks
  - blocks are called “pages” (both virtual and physical)
- Each process has its own virtual address space
  - operating system controls how virtual pages as assigned to physical memory



Contrast: Macintosh Memory Model

MAC OS 1–9

- **Does not use traditional virtual memory**



All program objects accessed through “handles”

- **Indirect reference through pointer table**
- **Objects stored in shared global address space**

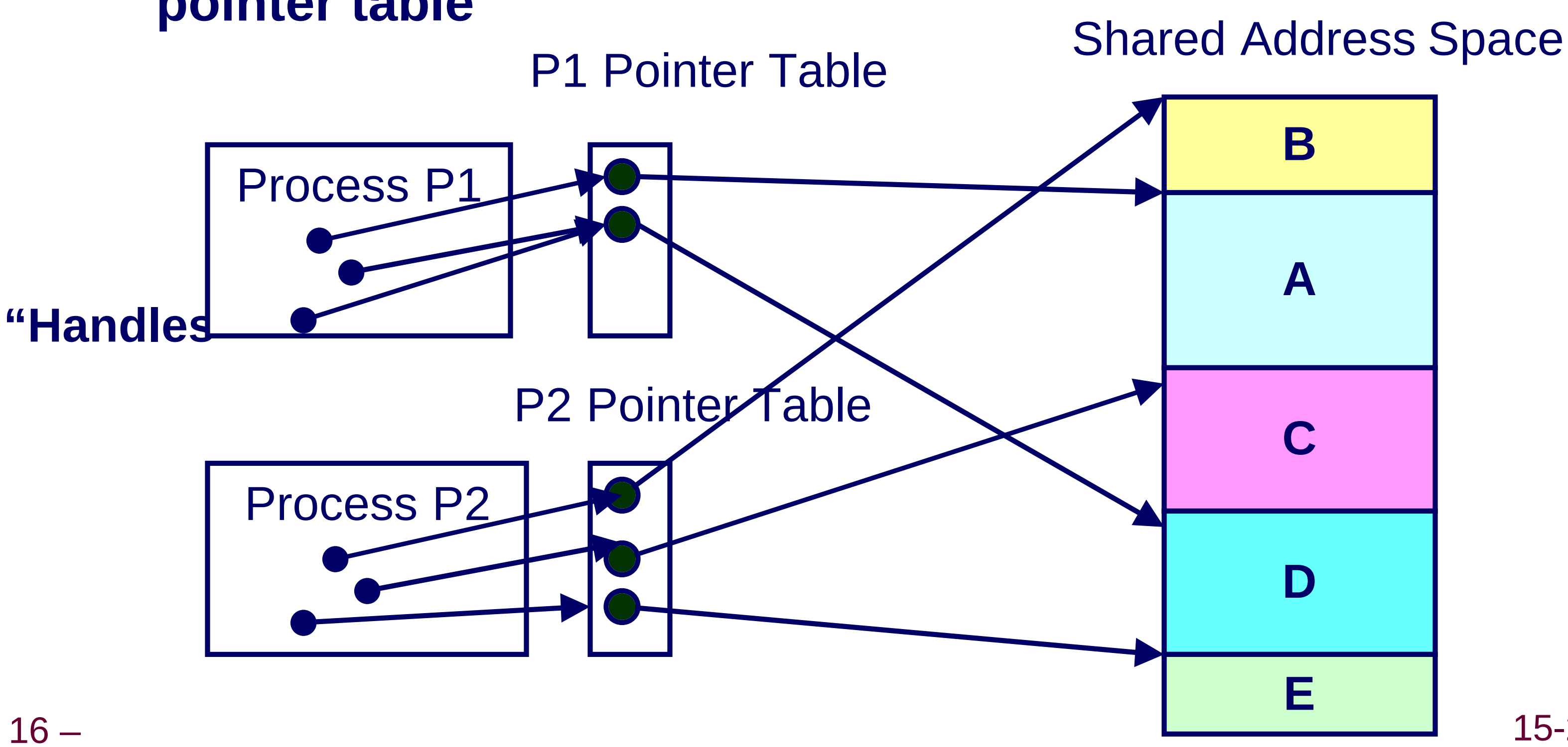
Macintosh Memory Management

Allocation / Deallocation

- Similar to free-list management of malloc/free

Compaction

- Can move any object and just update the (unique) pointer in pointer table



Mac vs. VM-Based Memory Mgmt

Allocating, deallocating, and moving memory:

- can be accomplished by both techniques

Block sizes:

- Mac: variable-sized
  - may be very small or very large
- VM: fixed-size
  - size is equal to *one page* (4KB on x86 Linux systems)

Allocating contiguous chunks of memory:

- Mac: contiguous allocation is *required*
- VM: can map contiguous range of virtual addresses to disjoint ranges of physical addresses

Protection

- Mac: “wild write” by one process can corrupt another’s data

MAC OS X

"Modern" Operating System

- **Virtual memory with protection**
- ***Preemptive multitasking***
  - **Other versions of MAC OS require processes to voluntarily relinquish control**

Based on MACH OS

- **Developed at CMU in late 1980's**

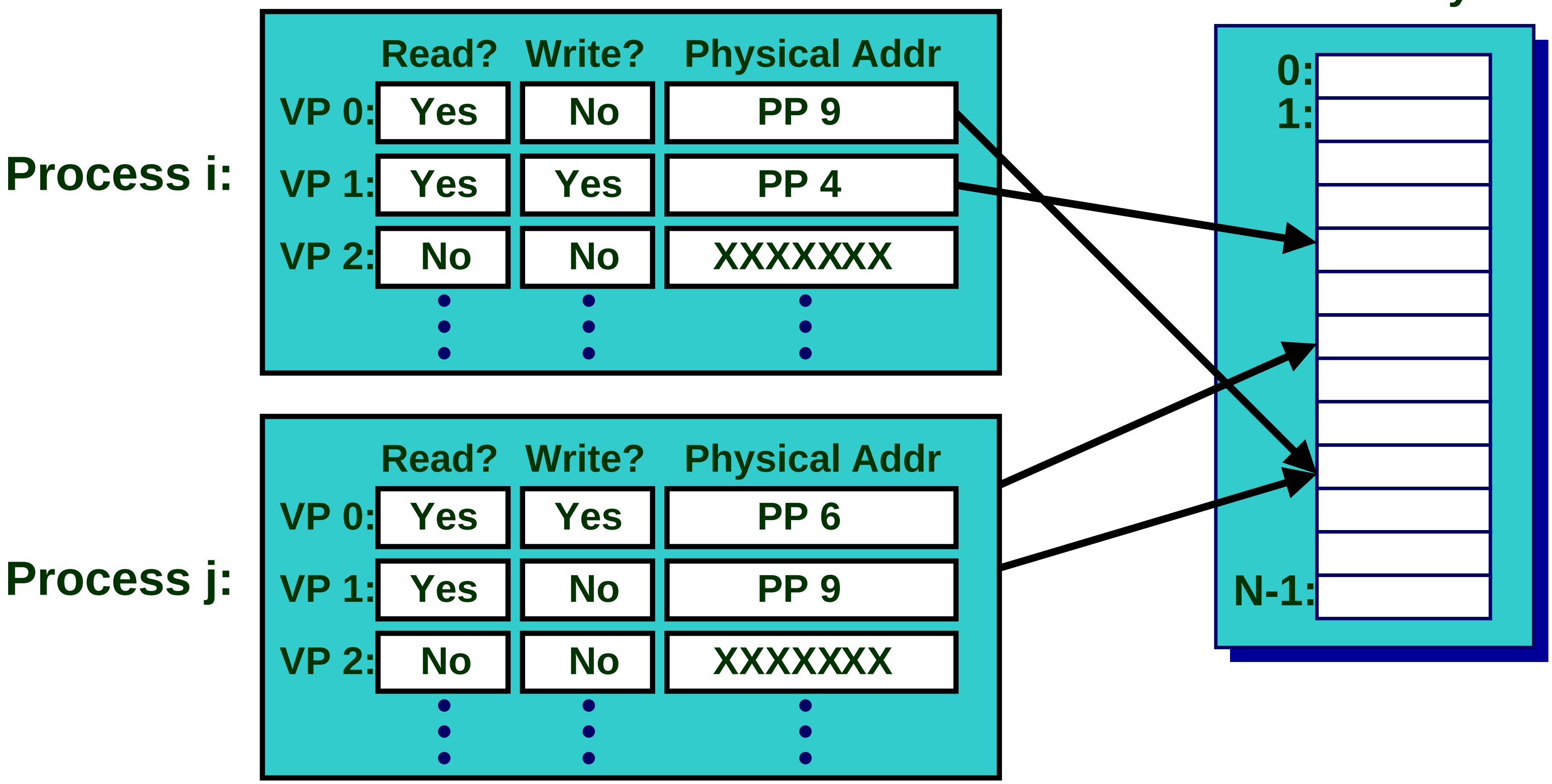
Motivation #3: Protection

Page table entry contains access rights information

- hardware enforces this protection (trap into OS if violation occurs)

Page Tables

Memory



VM Address Translation

Virtual Address Space

- $V = \{0, 1, \ldots, N-1\}$

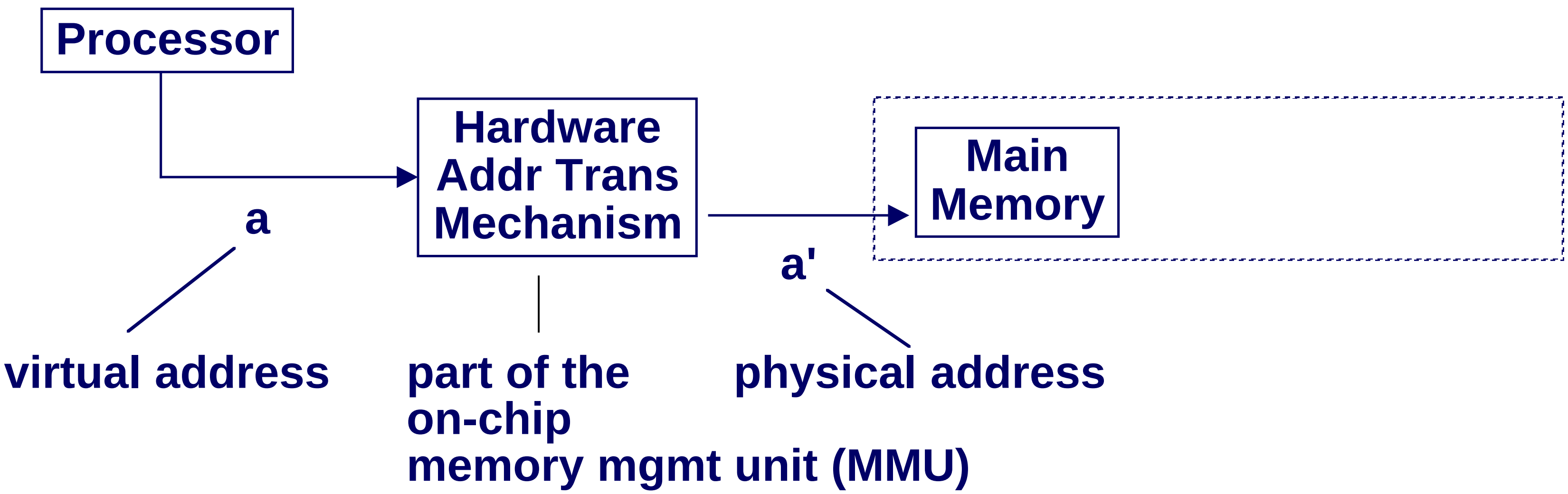
Physical Address Space

- $P = \{0, 1, \ldots, M-1\}$
- $M < N$

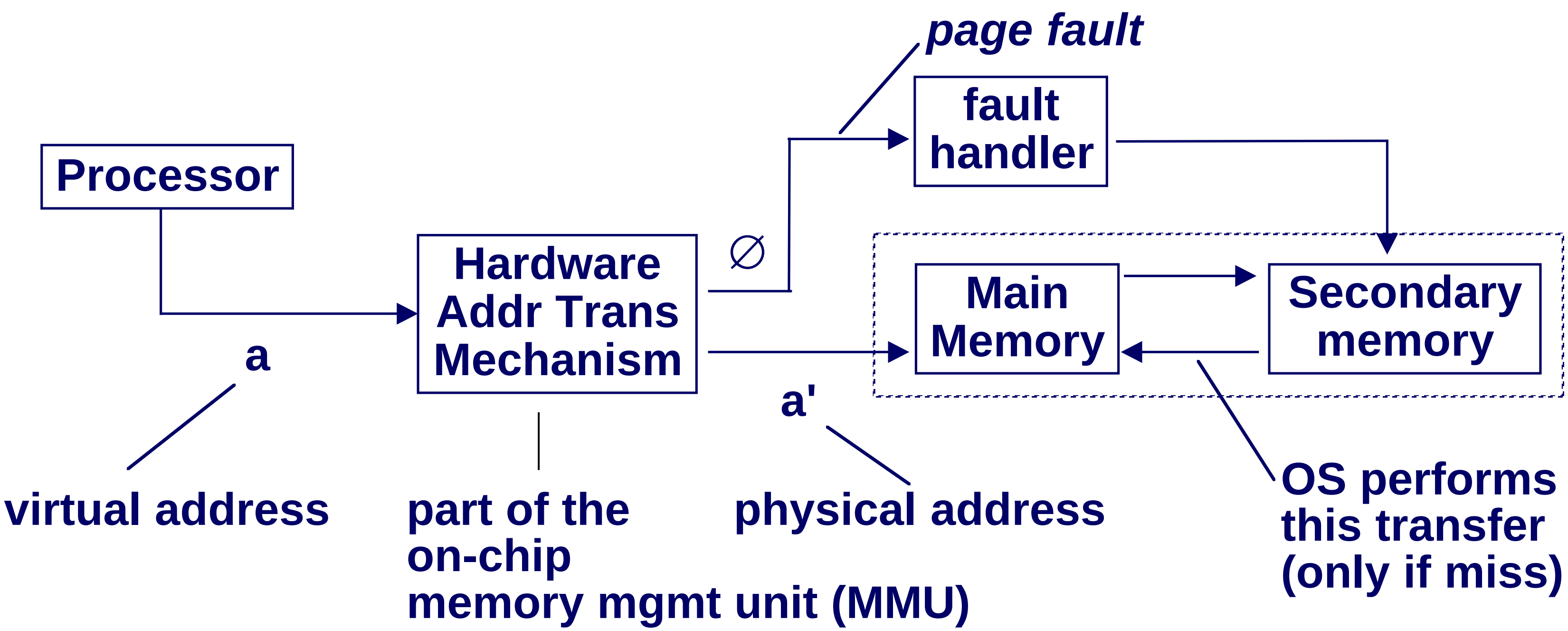
Address Translation

- MAP: $V \rightarrow P \cup \{\varnothing\}$
- For virtual address a:
  - MAP(a) = a' if data at virtual address a at physical address a' in P
  - MAP(a) = $\varnothing$ if data at virtual address a not in physical memory
    - » Either invalid or stored on disk

VM Address Translation: Hit



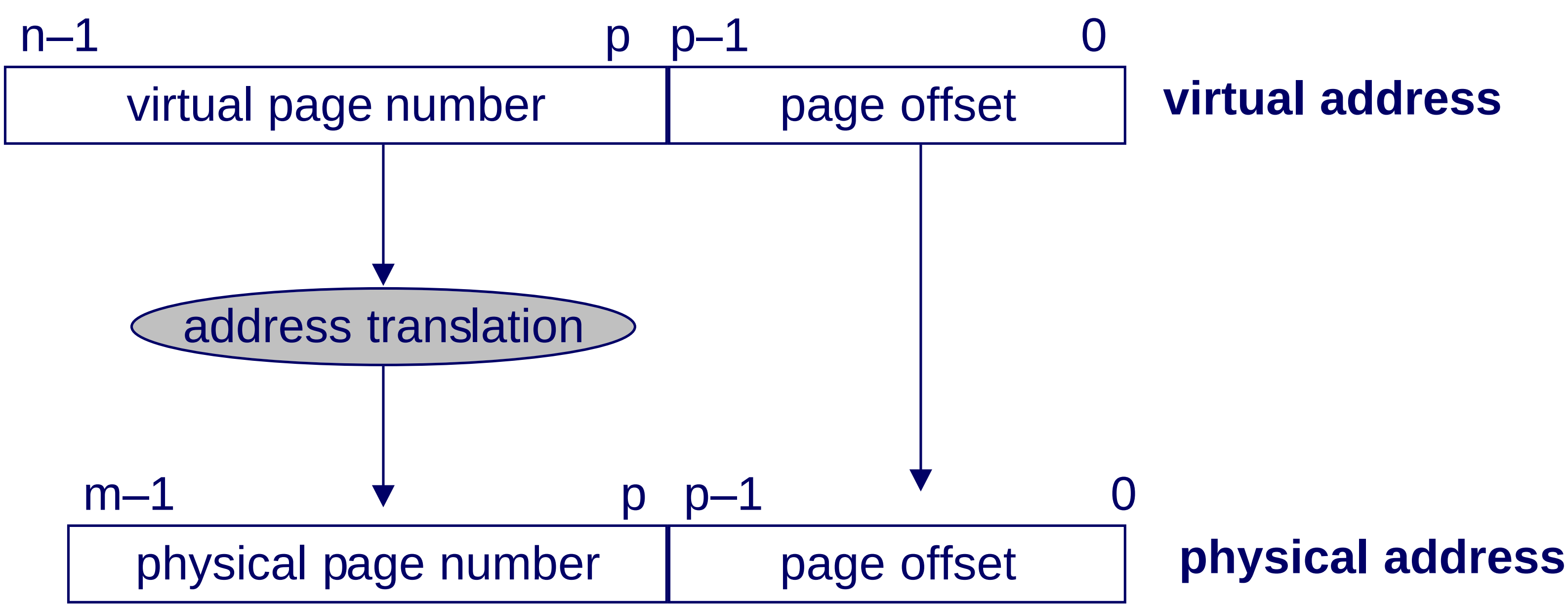
VM Address Translation: Miss



VM Address Translation

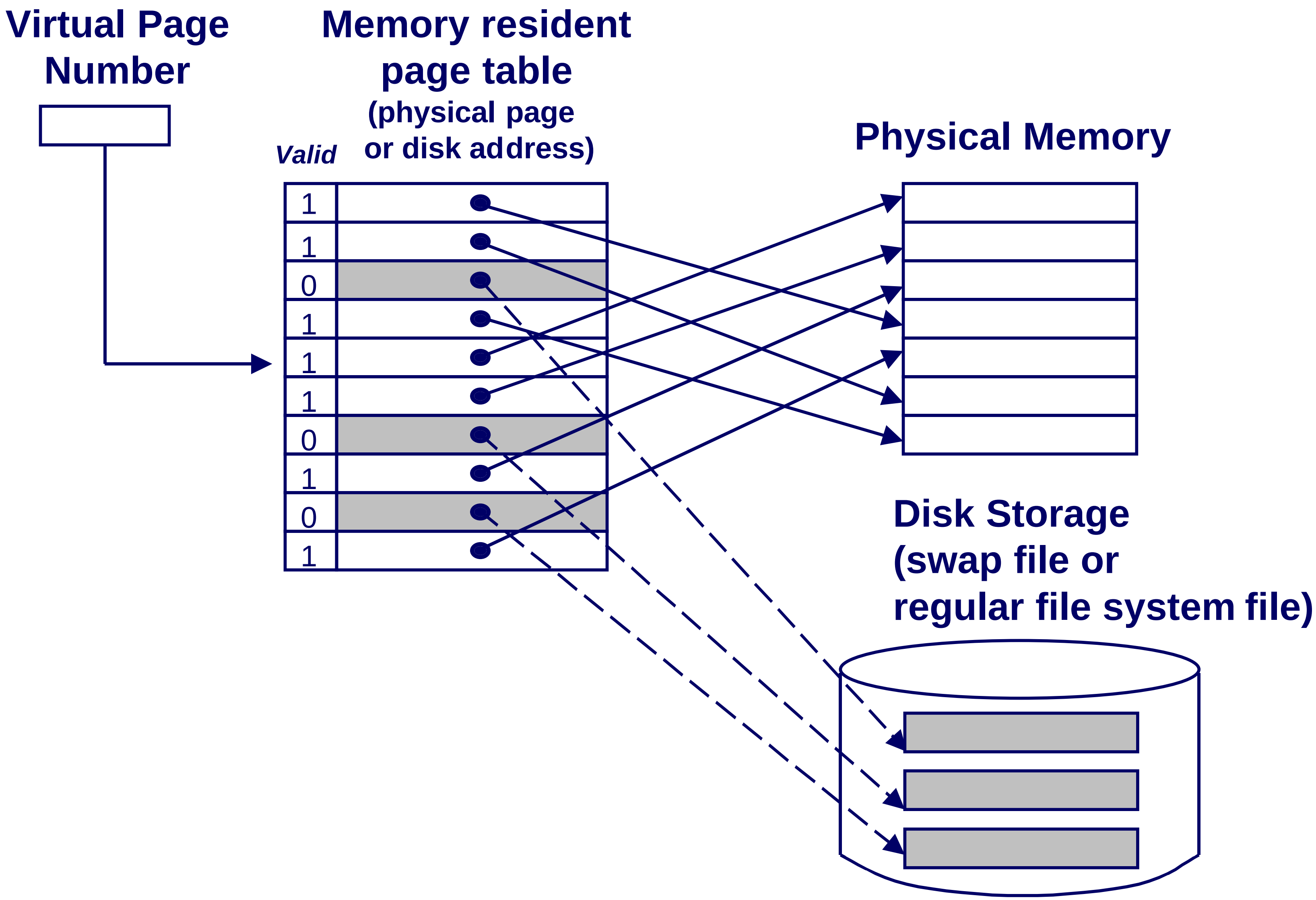
Parameters

- $P = 2^p$ = page size (bytes).
- $N = 2^n$ = Virtual address limit
- $M = 2^m$ = Physical address limit



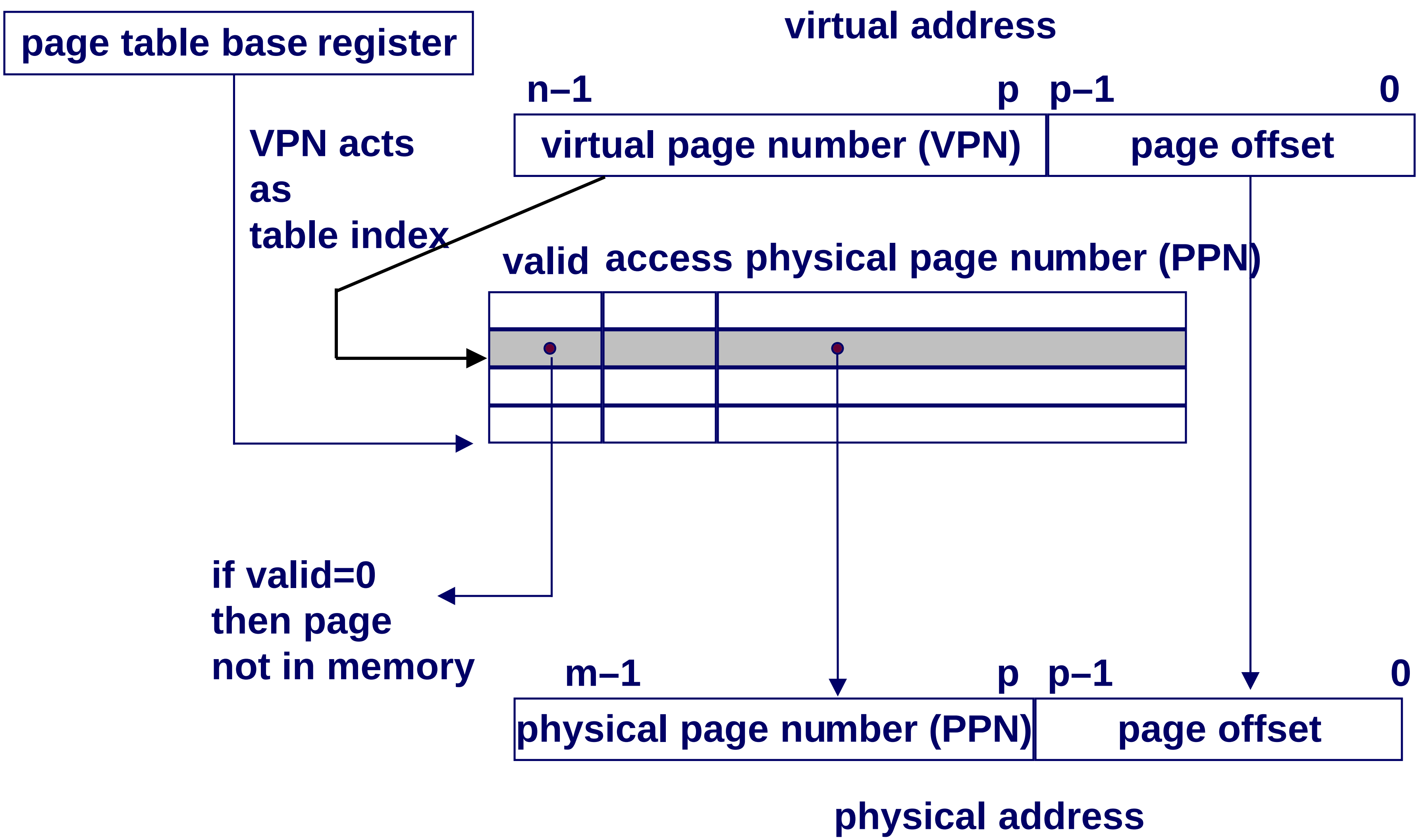
Page offset bits don't change as a result of translation

Page Tables



Virtual Page Number
Memory resident page table
(physical page or disk address)
Valid
1
1
0
1
1
1
0
1
0
1
Physical Memory
Disk Storage
(swap file or regular file system file)

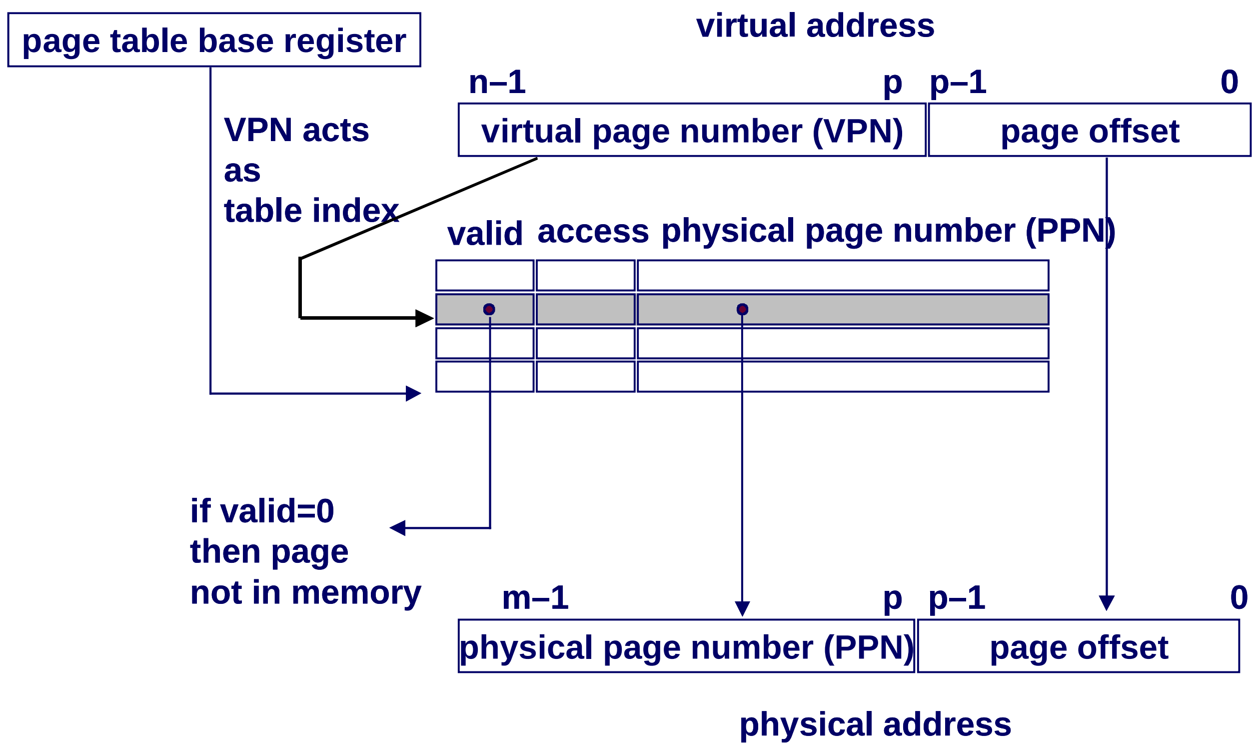
Address Translation via Page Table



Page Table Operation

Translation

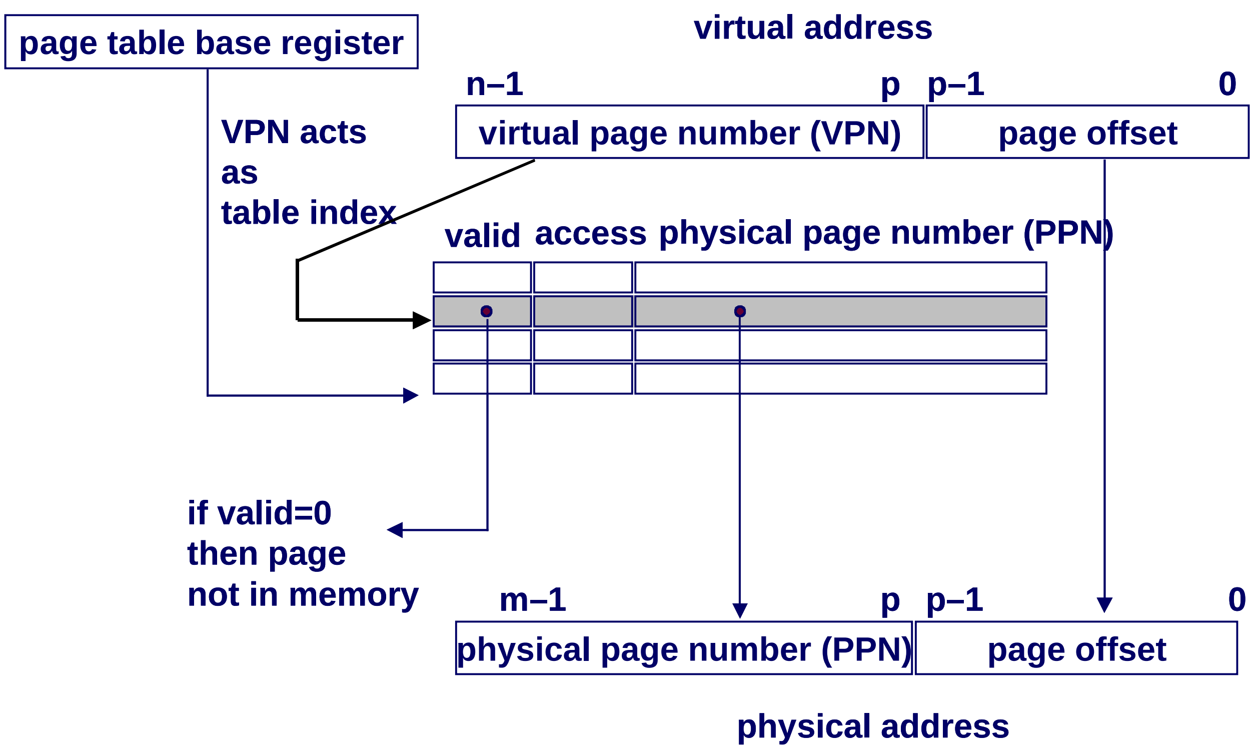
- Separate (set of) page table(s) per process
- VPN forms index into page table (points to a page table entry)



Page Table Operation

Computing Physical Address

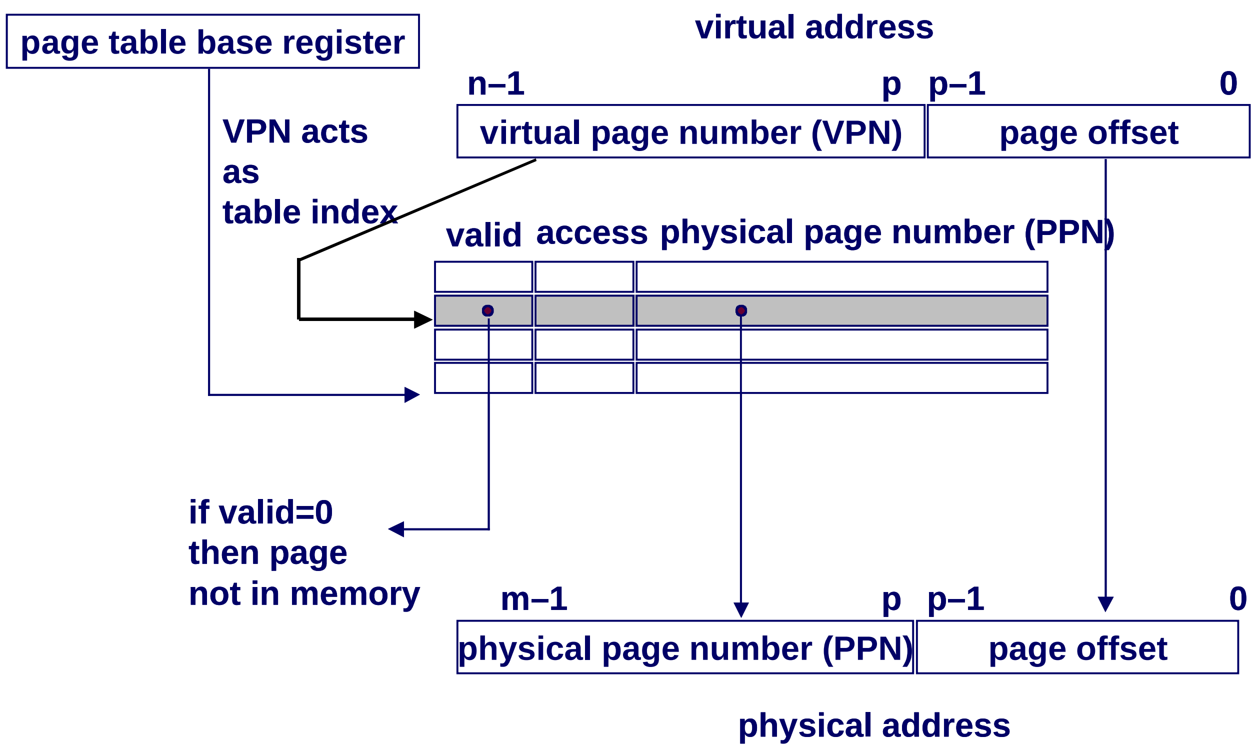
- Page Table Entry (PTE) provides information about page
  - if (valid bit = 1) then the page is in memory.
    - » Use physical page number (PPN) to construct address
  - if (valid bit = 0) then the page is on disk
    - » Page fault



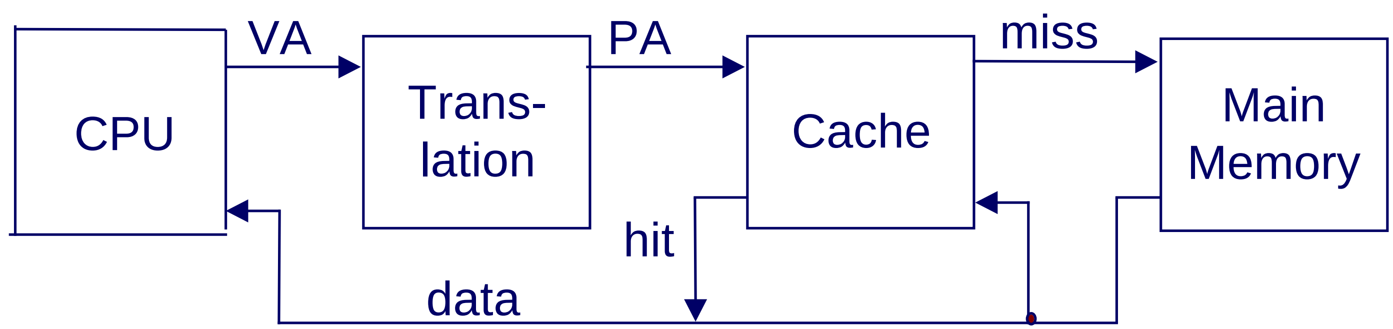
Page Table Operation

Checking Protection

- Access rights field indicate allowable access
  - e.g., read-only, read-write, execute-only
  - typically support multiple protection modes (e.g., kernel vs. user)
- Protection violation fault if user doesn't have necessary permission



Integrating VM and Cache



Most Caches “Physically Addressed”

- Accessed by physical addresses
- Allows multiple processes to have blocks in cache at same time
- Allows multiple processes to share pages
- Cache doesn’t need to be concerned with protection issues
  - Access rights checked as part of address translation

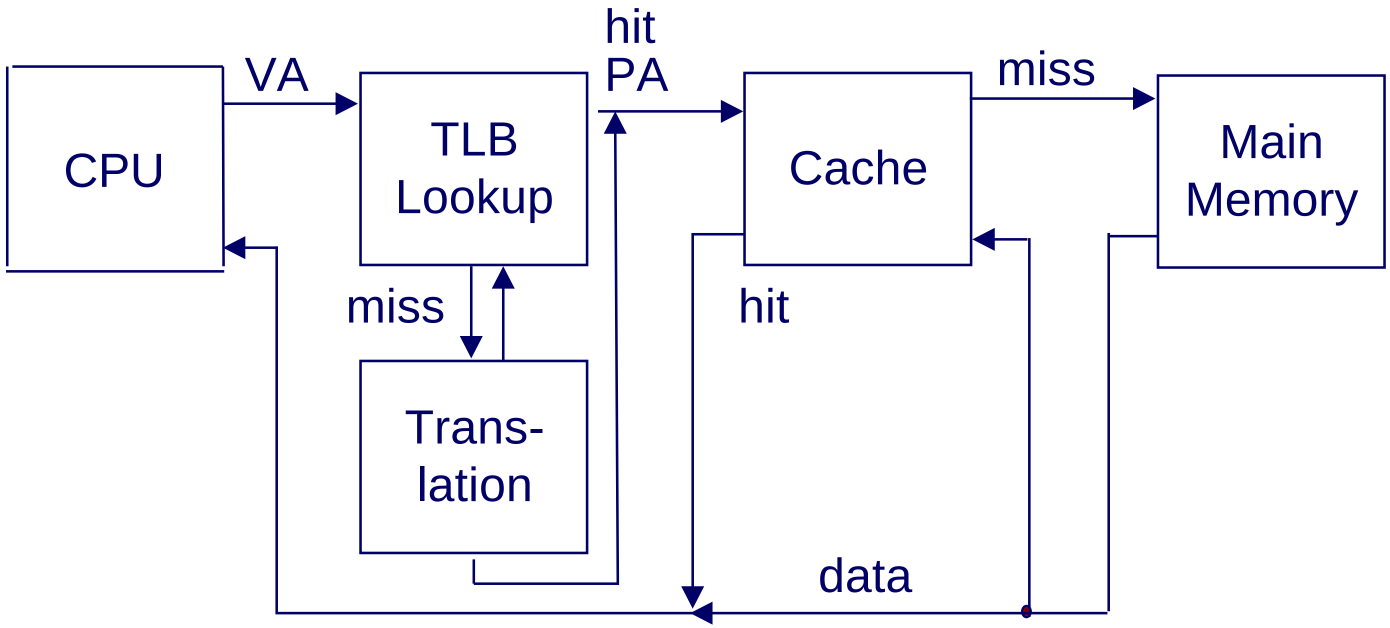
Perform Address Translation Before Cache Lookup

- But this could involve a memory access itself (of the PTE)
- Of course, page table entries can also become cached

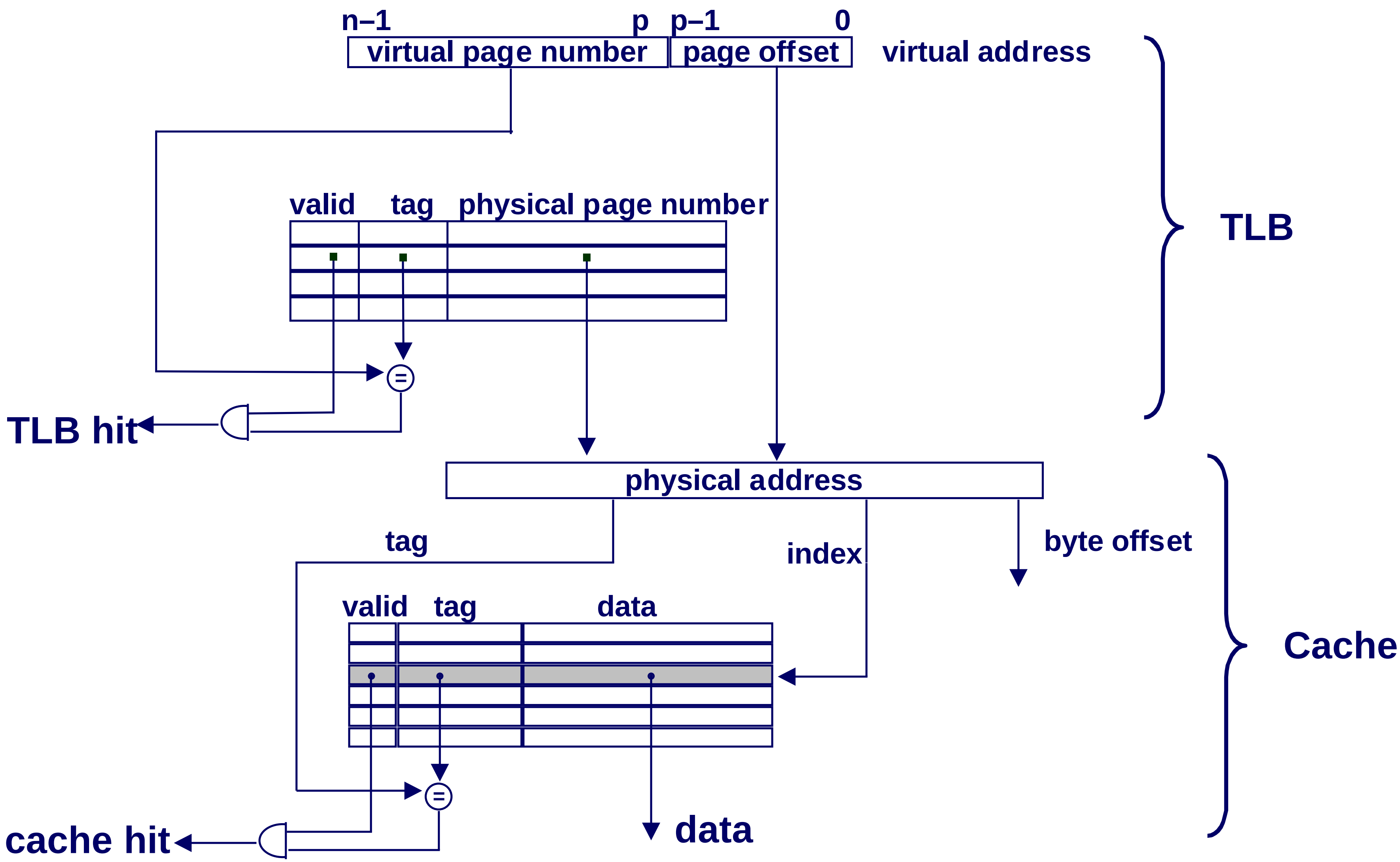
Speeding up Translation with a TLB

"Translation Lookaside Buffer" (TLB)

- **Small hardware cache in MMU**
- **Maps virtual page numbers to physical page numbers**
- **Contains complete page table entries for small number of pages**



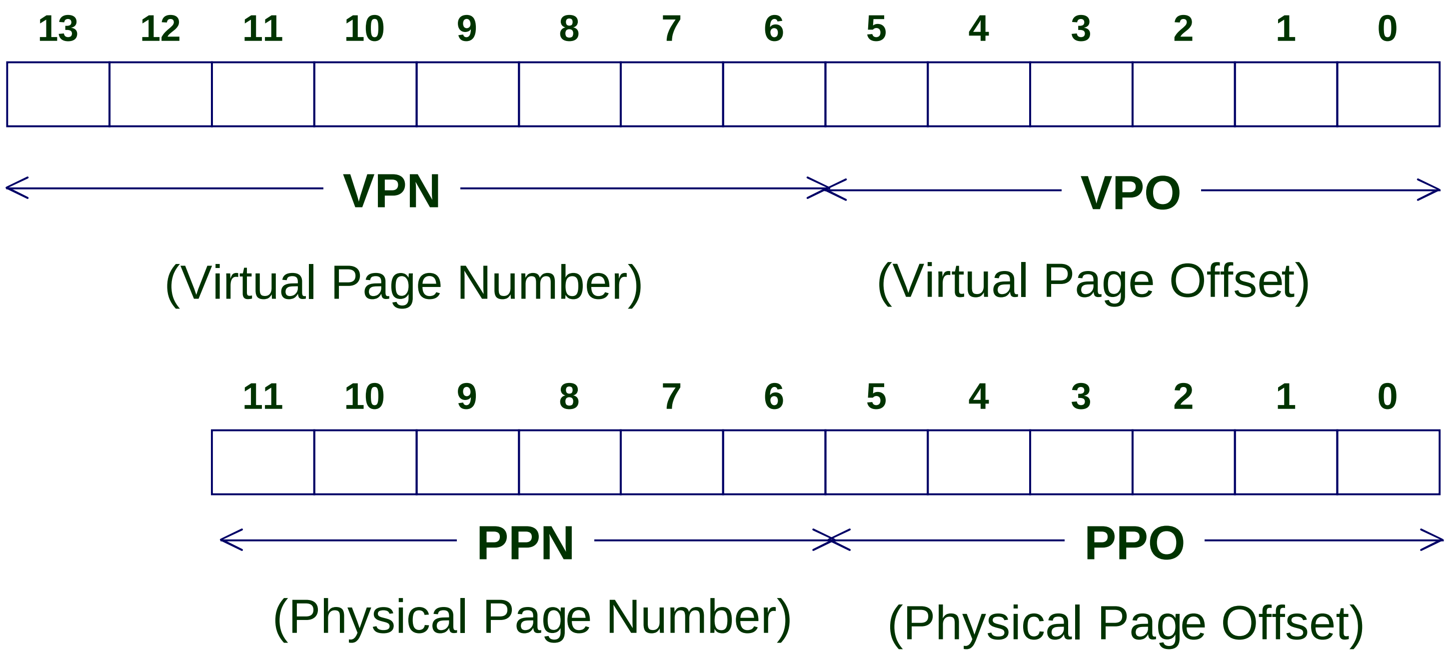
Address Translation with a TLB



Simple Memory System Example

Addressing

- 14-bit virtual addresses
- 12-bit physical address
- Page size = 64 bytes



Simple Memory System Page Table

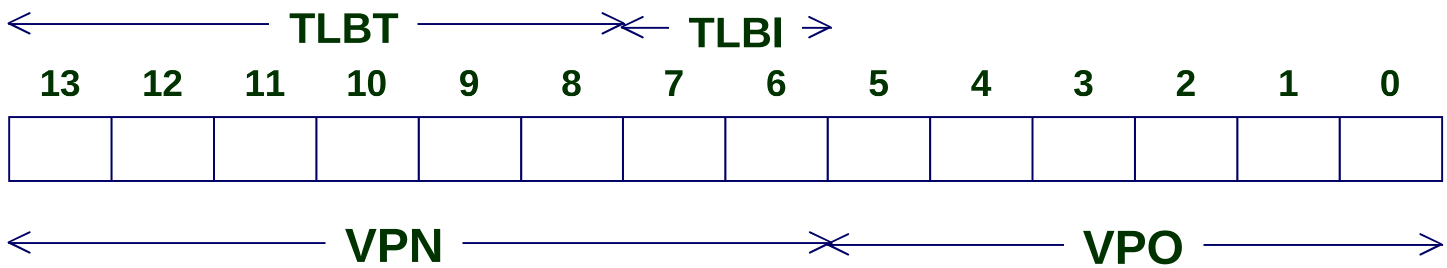
- Only show first 16 entries

VPN	PPN	Valid	VPN	PPN	Valid
00	28	1	08	13	1
01	–	0	09	17	1
02	33	1	0A	09	1
03	02	1	0B	–	0
04	–	0	0C	–	0
05	16	1	0D	2D	1
06	–	0	0E	11	1
07	–	0	0F	0D	1

Simple Memory System TLB

TLB

- 16 entries
- 4-way associative



Set	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid
0	03	–	0	09	0D	1	00	–	0	07	02	1
1	03	2D	1	02	–	0	04	–	0	0A	–	0
2	02	–	0	08	–	0	06	–	0	03	–	0
3	07	–	0	03	0D	1	0A	34	1	02	–	0

Simple Memory System Cache

Cache

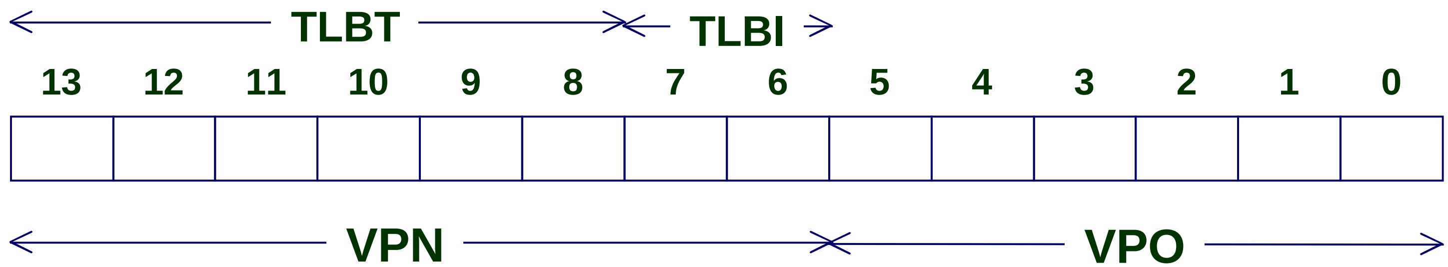
- 16 lines
- 4-byte line size
- Direct mapped

CT						CI				CO	
11	10	9	8	7	6	5	4	3	2	1	0
PPN						PPO					

Idx	Tag	Valid	B0	B1	B2	B3	Idx	Tag	Valid	B0	B1	B2	B3
0	19	1	99	11	23	11	8	24	1	3A	00	51	89
1	15	0	–	–	–	–	9	2D	0	–	–	–	–
2	1B	1	00	02	04	08	A	2D	1	93	15	DA	3B
3	36	0	–	–	–	–	B	0B	0	–	–	–	–
4	32	1	43	6D	8F	09	C	12	0	–	–	–	–
5	0D	1	36	72	F0	1D	D	16	1	04	96	34	15
6	31	0	–	–	–	–	E	13	1	83	77	1B	D3
7	16	1	11	C2	DF	03	F	14	0	–	–	–	–

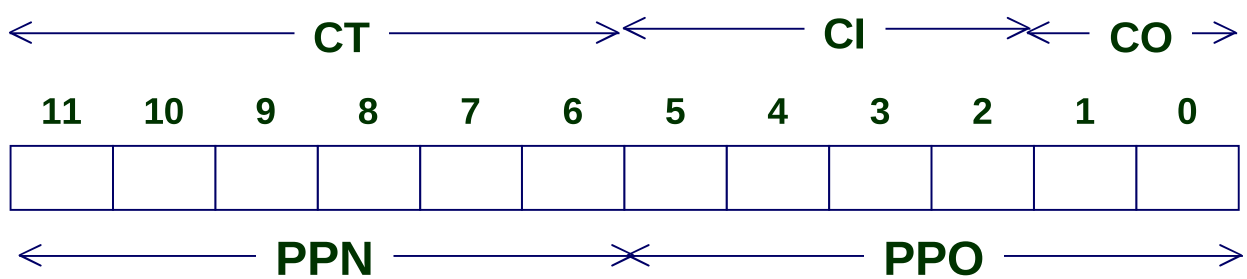
Address Translation Example #1

Virtual Address `0x03D4`



VPN ___ TLBI ___ TLBT ____ TLB Hit? __ Page Fault? __ PPN: ____

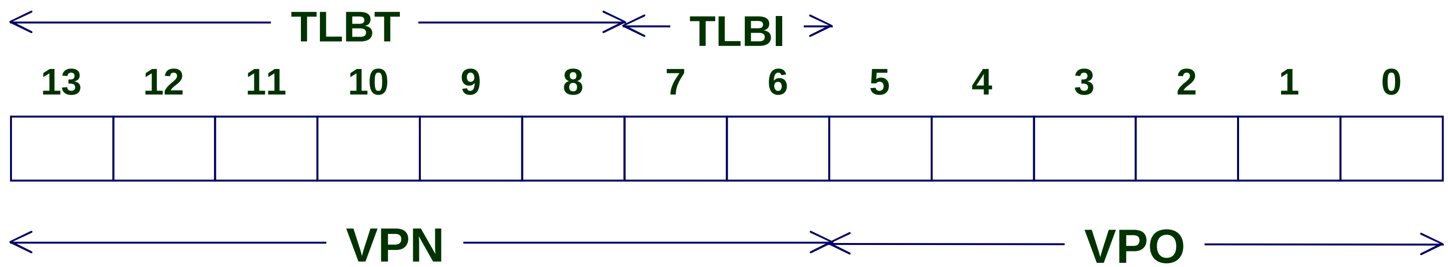
Physical Address



Offset ___ CI___ CT ____ Hit? __ Byte: ____

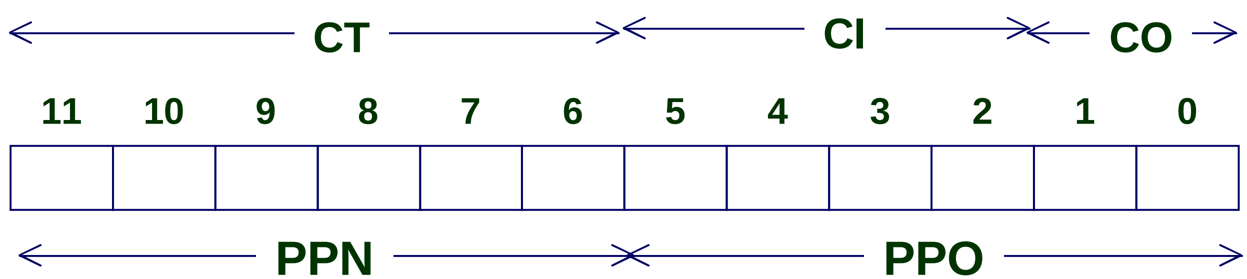
Address Translation Example #2

Virtual Address `0x0B8F`



VPN ___ TLBI ___ TLBT ____ TLB Hit? __ Page Fault? __ PPN: ____

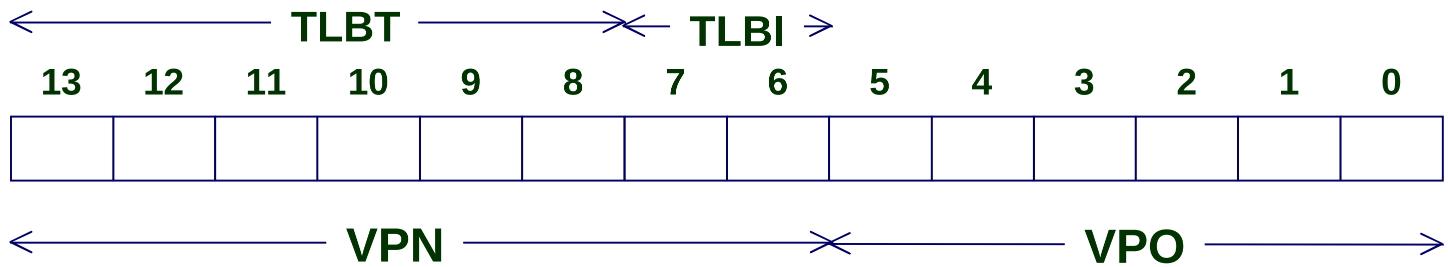
Physical Address



Offset ___ CI___ CT ____ Hit? __ Byte: ____

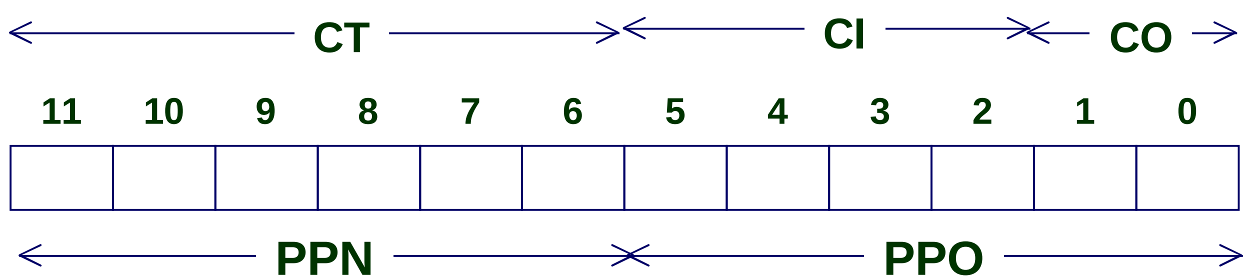
Address Translation Example #3

Virtual Address 0x0040



VPN ___ TLBI ___ TLBT ____ TLB Hit? __ Page Fault? __ PPN: ____

Physical Address



Offset ___ CI___ CT ____ Hit? __ Byte: ____

Multi-Level Page Tables

Given:

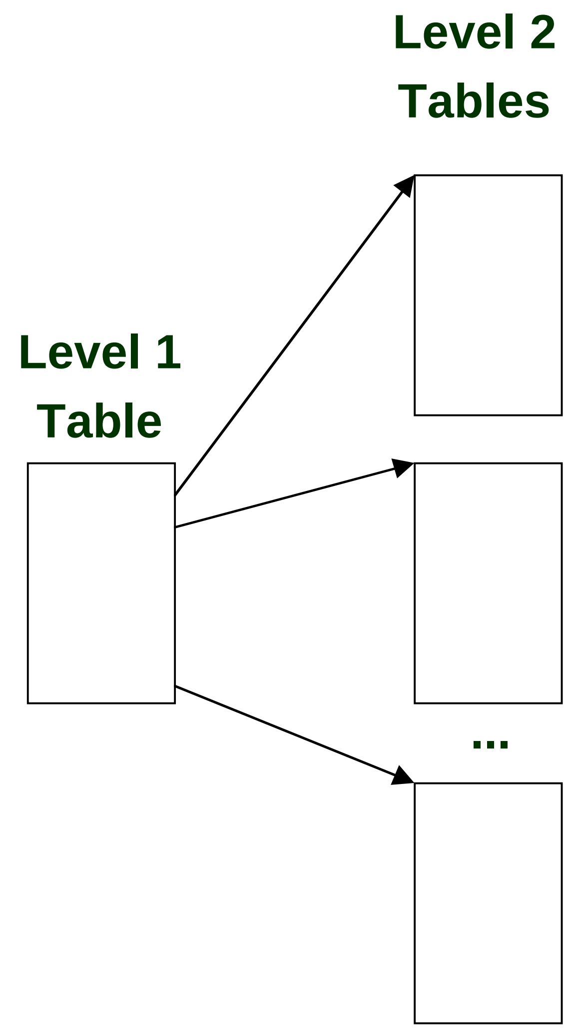
- 4KB (2^{12}) page size
- 32-bit address space
- 4-byte PTE

Problem:

- Would need a 4 MB page table!
  - 2^{20} *4 bytes

Common solution

- multi-level page tables
- e.g., 2-level table (P6)
  - Level 1 table: 1024 entries, each of which points to a Level 2 page table.
  - Level 2 table: 1024 entries, each of which points to a page



Main Themes

Programmer's View

- Large "flat" address space
  - Can allocate large blocks of contiguous addresses
- Processor "owns" machine
  - Has private address space
  - Unaffected by behavior of other processes

System View

- User virtual address space created by mapping to set of pages
  - Need not be contiguous
  - Allocated dynamically
  - Enforce protection during address translation
- OS manages many processes simultaneously
  - Continually switching among processes
  - Especially when one must wait for resource
    - » E.g., disk I/O to handle page fault