Digital Design & Computer Arch.

Lecture 23b: Virtual Memory

Prof. Onur Mutlu

ETH Zürich

Spring 2020

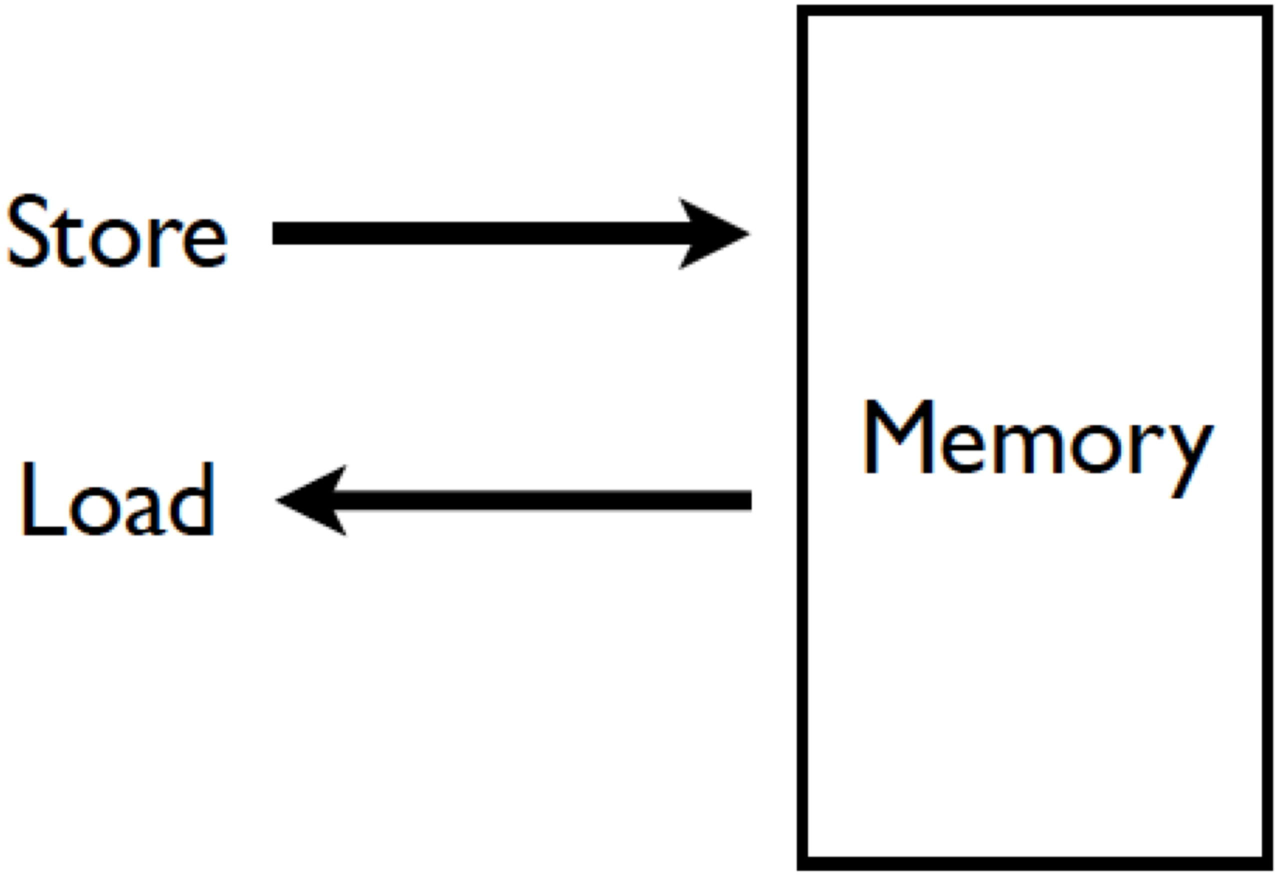
22 May 2020

Readings

- Virtual Memory

- Required
  - H&H Chapter 8.4

Memory (Programmer's View)



Ideal Memory

- Zero access time (latency)
- Infinite capacity
- Zero cost
- Infinite bandwidth (to support multiple accesses in parallel)

Abstraction: Virtual vs. Physical Memory

- Programmer sees virtual memory
  - Can assume the memory is "infinite"
- Reality: Physical memory size is much smaller than what the programmer assumes
- The system (system software + hardware, cooperatively) maps virtual memory addresses to physical memory
  - The system automatically manages the physical memory space transparently to the programmer

+ Programmer does not need to know the physical size of memory nor manage it → A small physical memory can appear as a huge one to the programmer → Life is easier for the programmer

-- More complex system software and architecture

A classic example of the programmer/(micro)architect tradeoff

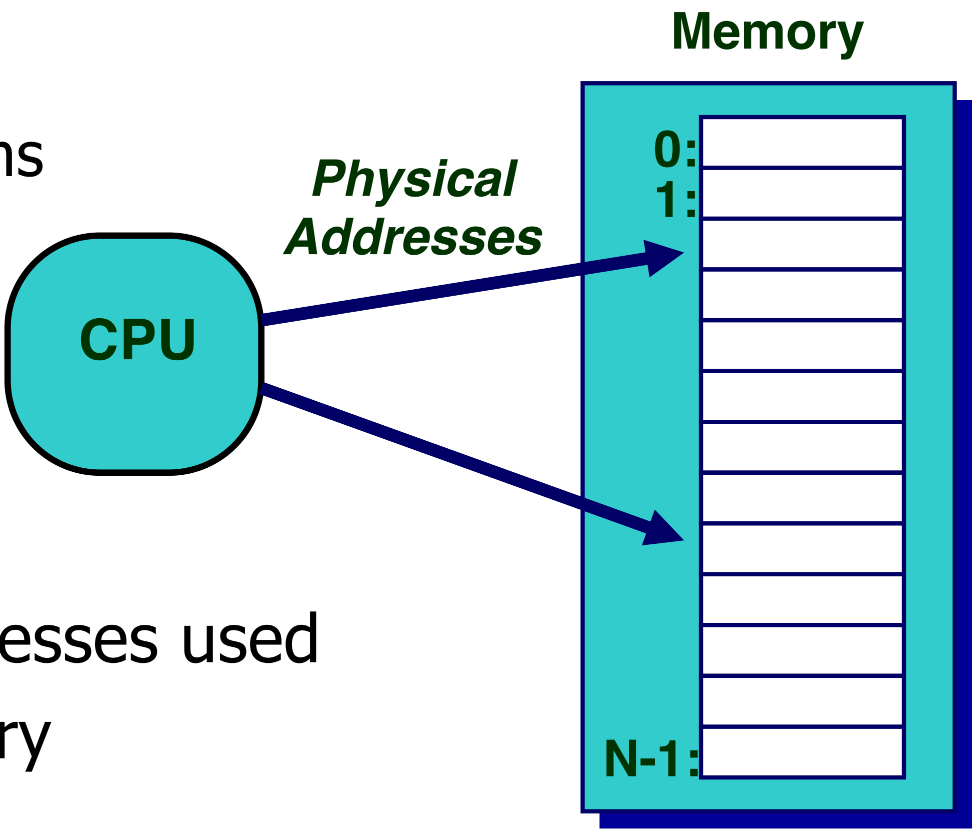
Benefits of Automatic Management of Memory

- Programmer does not deal with physical addresses
- Each process has its own mapping from virtual→physical addresses

- Enables
  - Code and data to be located anywhere in physical memory (relocation)
  - Isolation/separation of code and data of different processes in physical memory (protection and isolation)
  - Code and data sharing between multiple processes (sharing)

A System with Physical Memory Only

- Examples:
  - most Cray machines
  - early PCs
  - many embedded systems



CPU's load or store addresses used directly to access memory

The Problem

- Physical memory is of limited size (cost)
  - What if you need more?
  - Should the programmer be concerned about the size of code/data blocks fitting physical memory?
  - Should the programmer manage data movement from disk to physical memory?
  - Should the programmer ensure two processes (different programs) do not use the same physical memory?
- Also, ISA can have an address space greater than the physical memory size
  - E.g., a 64-bit address space with byte addressability
  - What if you do not have enough physical memory?

Difficulties of Direct Physical Addressing

- Programmer needs to manage physical memory space
  - Inconvenient & hard
  - Harder when you have multiple processes

- Difficult to support code and data relocation
  - Addresses are directly specified in the program

- Difficult to support multiple processes
  - Protection and isolation between multiple processes
  - Sharing of physical memory space

- Difficult to support data/code sharing across processes

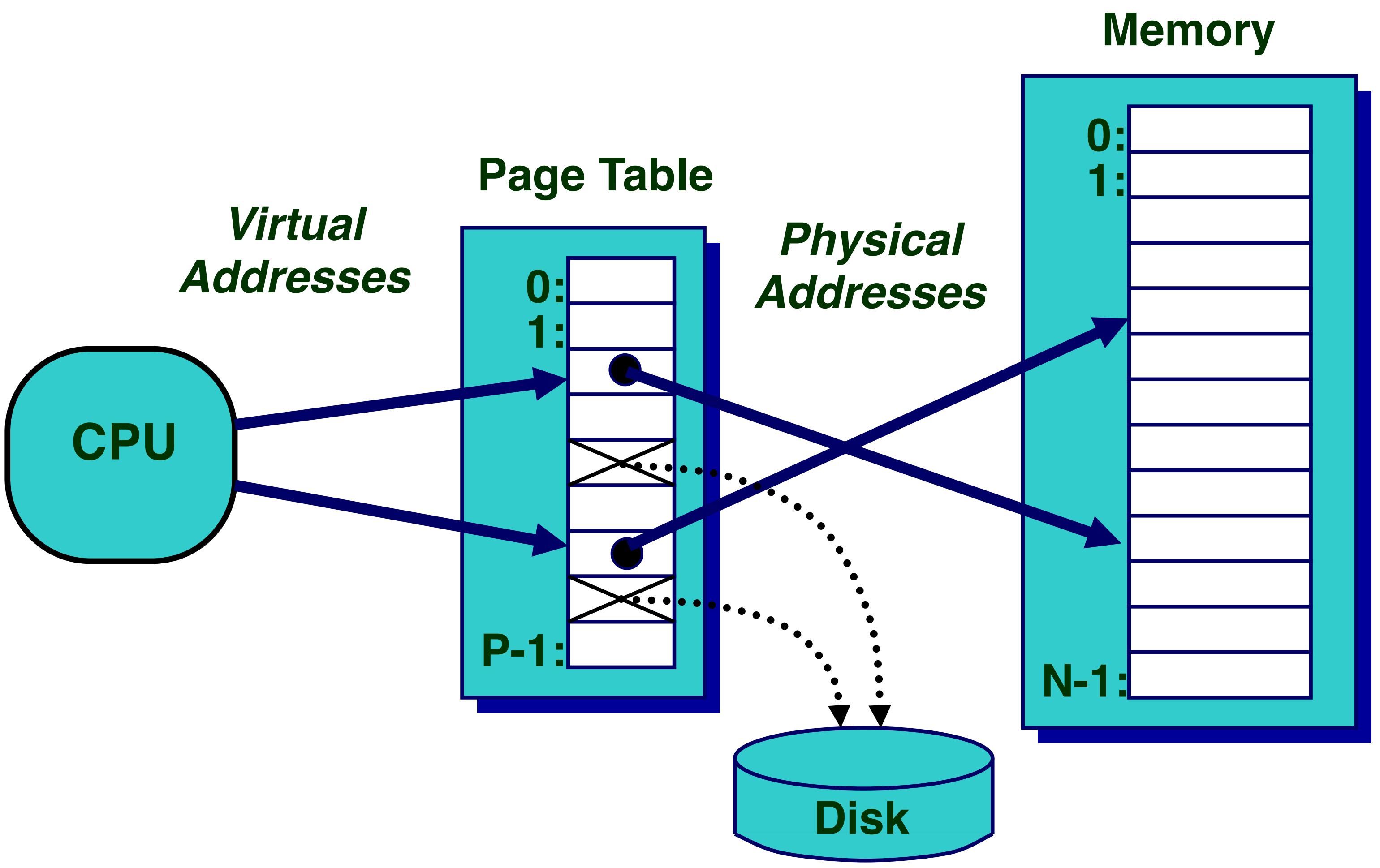
Virtual Memory

- Idea: Give the programmer the illusion of a large address space while having a small physical memory
  - So that the programmer does not worry about managing physical memory
- Programmer can assume he/she has “infinite” amount of physical memory
- Hardware and software cooperatively and automatically manage the physical memory space to provide the illusion
  - Illusion is maintained for each independent process

Basic Mechanism

- Indirection (in addressing)
- Address generated by each instruction in a program is a "virtual address"
  - i.e., it is not the physical address used to address main memory
  - called "linear address" in x86
- An "address translation" mechanism maps this address to a "physical address"
  - called "real address" in x86
  - Address translation mechanism can be implemented in hardware and software together

A System with Virtual Memory (Page based)



- Address Translation: The hardware converts virtual addresses into physical addresses via an OS-managed lookup table (page table)

Virtual Pages, Physical Frames

- Virtual address space divided into pages
- Physical address space divided into frames

- A virtual page is mapped to
  - A physical frame, if the page is in physical memory
  - A location in disk, otherwise

- If an accessed virtual page is not in memory, but on disk
  - Virtual memory system brings the page into a physical frame and adjusts the mapping → this is called demand paging

- Page table is the table that stores the mapping of virtual pages to physical frames

Physical Memory as a Cache

- In other words…

- Physical memory is a cache for pages stored on disk
  - In fact, it is a fully associative cache in modern systems (a virtual page can potentially be mapped to any physical frame)

- Similar caching issues exist as we have covered earlier:
  - Placement: where and how to place/find a page in cache?
  - Replacement: what page to remove to make room in cache?
  - Granularity of management: large, small, uniform pages?
  - Write policy: what do we do about writes? Write back?

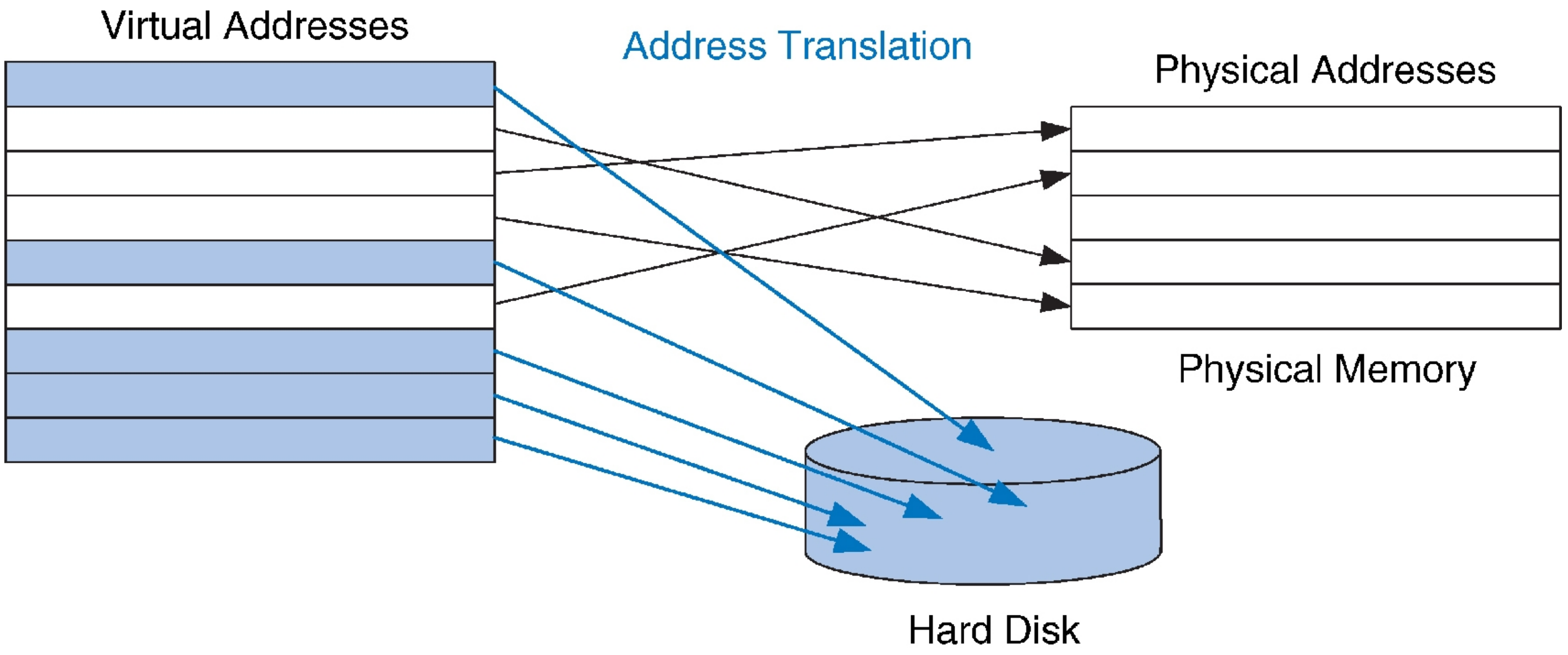
Cache/Virtual Memory Analogues

Cache	Virtual Memory
Block	Page
Block Size	Page Size
Block Offset	Page Offset
Miss	Page Fault
Tag	Virtual Page Number

Virtual Memory Definitions

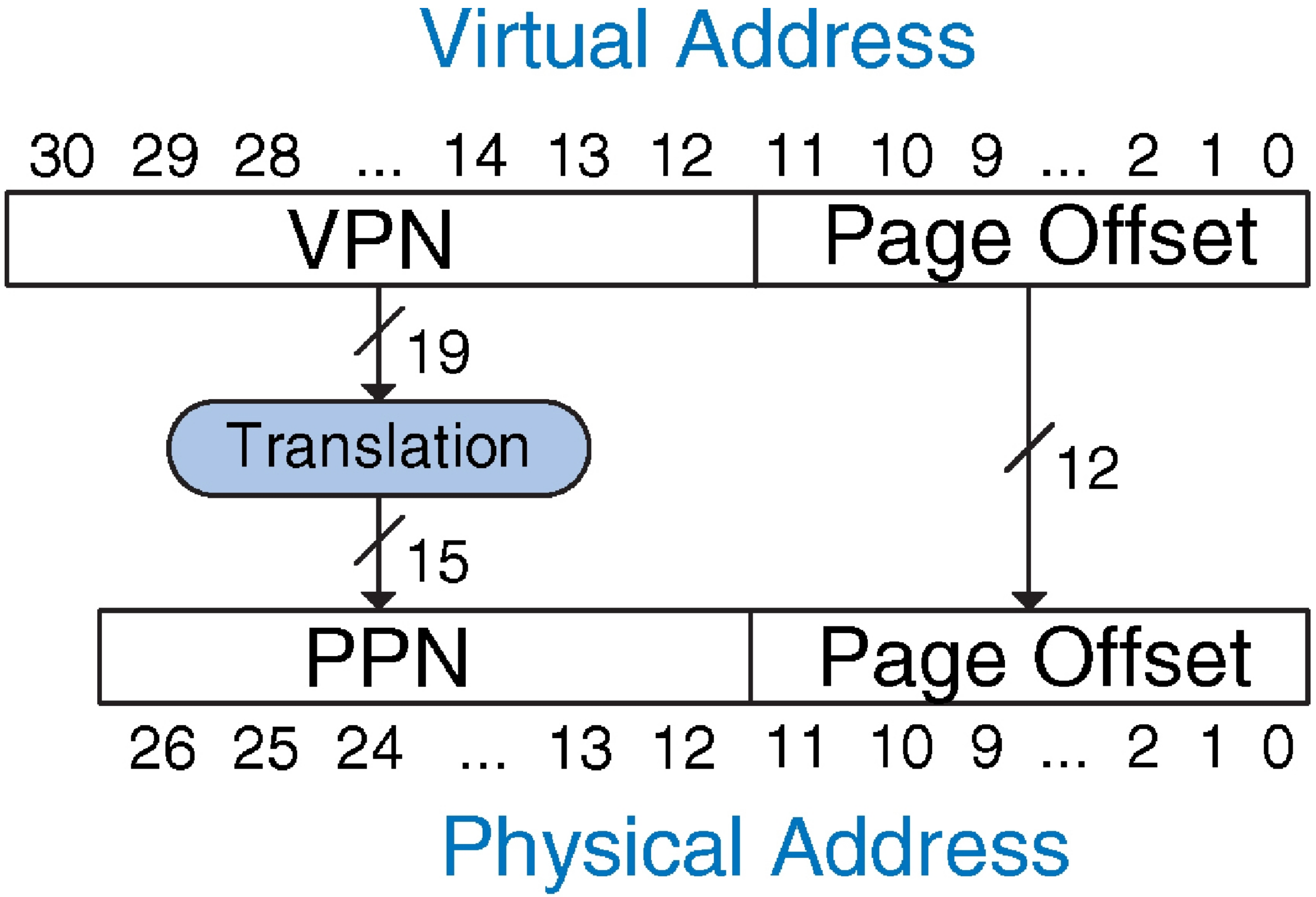
- Page size: amount of memory transferred from hard disk to DRAM at once
- Address translation: determining the physical address from the virtual address
- Page table: lookup table used to translate virtual addresses to physical addresses (and find where the associated data is)

Virtual and Physical Addresses



- Most accesses hit in physical memory
- But programs see the large capacity of virtual memory

Address Translation



Virtual Memory Example

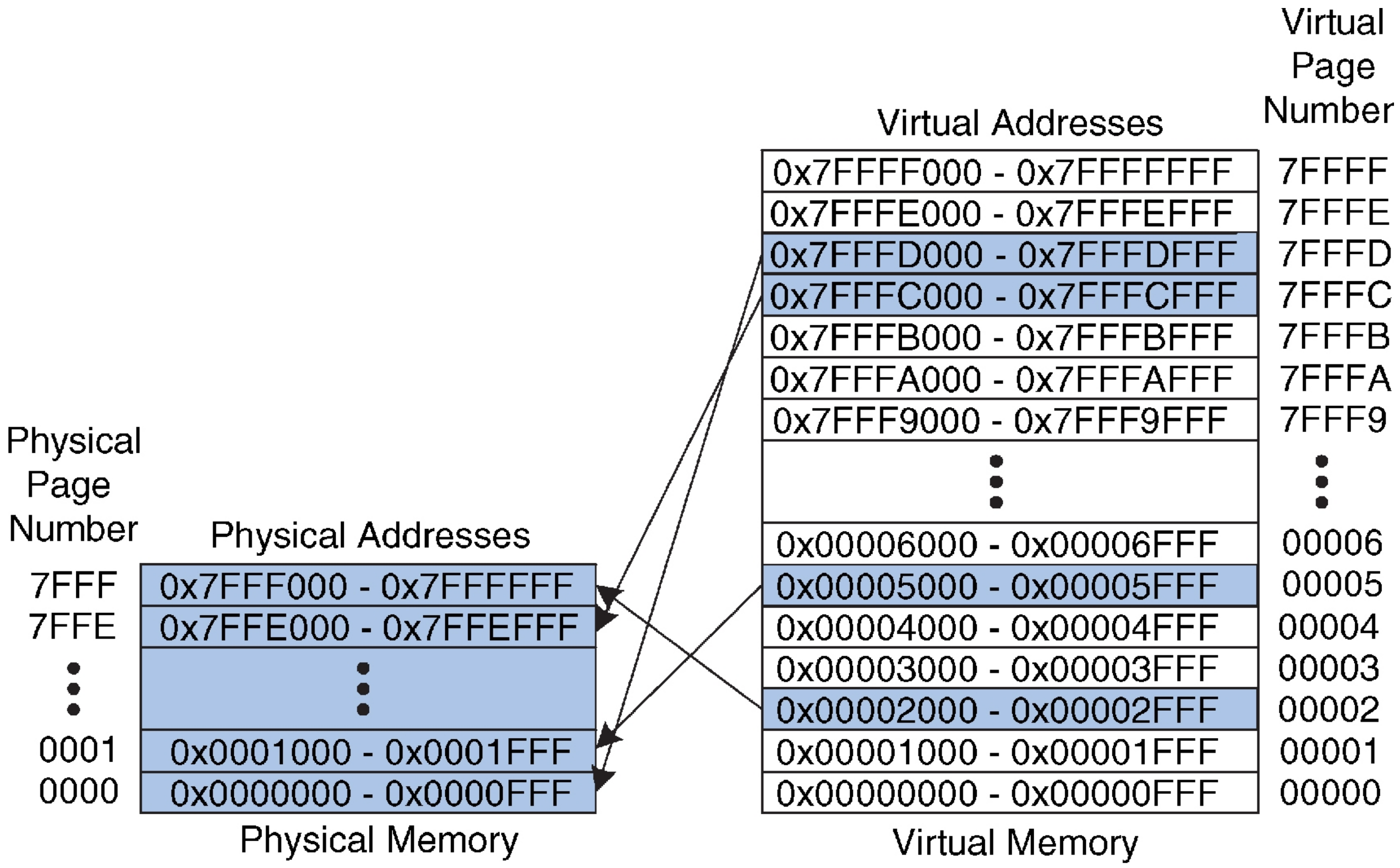
- System:
  - Virtual memory size: 2 GB = 2^{31} bytes
  - Physical memory size: 128 MB = 2^{27} bytes
  - Page size: 4 KB = 2^{12} bytes

Virtual Memory Example

- System:
  - Virtual memory size: 2 GB = 2^{31} bytes
  - Physical memory size: 128 MB = 2^{27} bytes
  - Page size: 4 KB = 2^{12} bytes

- Organization:
  - Virtual address: **31** bits
  - Physical address: **27** bits
  - Page offset: **12** bits
  - # Virtual pages = $2^{31}/2^{12}$ = $\mathbf{2^{19}}$ (VPN = 19 bits)
  - # Physical pages = $2^{27}/2^{12}$ = $\mathbf{2^{15}}$ (PPN = 15 bits)

Virtual Memory Example


Virtual Addresses
Virtual Page Number
0x7FFFF000 - 0x7FFFFFFF 7FFFF
0x7FFFE000 - 0x7FFFEFFF 7FFFE
0x7FFFD000 - 0x7FFFDFFF 7FFFD
0x7FFFC000 - 0x7FFFCFFF 7FFFC
0x7FFFB000 - 0x7FFFBFFF 7FFFB
0x7FFFA000 - 0x7FFFAFFF 7FFFA
0x7FFF9000 - 0x7FFF9FFF 7FFF9
0x00006000 - 0x00006FFF 00006
0x00005000 - 0x00005FFF 00005
0x00004000 - 0x00004FFF 00004
0x00003000 - 0x00003FFF 00003
0x00002000 - 0x00002FFF 00002
0x00001000 - 0x00001FFF 00001
0x00000000 - 0x00000FFF 00000
Virtual Memory
Physical Page Number
Physical Addresses
7FFF 0x7FFF000 - 0x7FFFFFF
7FFE 0x7FFE000 - 0x7FFEFFF
0001 0x0001000 - 0x0001FFF
0000 0x0000000 - 0x0000FFF
Physical Memory

Digital Design & Computer Arch.

Lecture 23b: Virtual Memory

Prof. Onur Mutlu

ETH Zürich

Spring 2020

22 May 2020

We did not cover the following slides in lecture. These are for your benefit.

How Do We Translate Addresses?

- **Page table**
  - Has entry for each virtual page

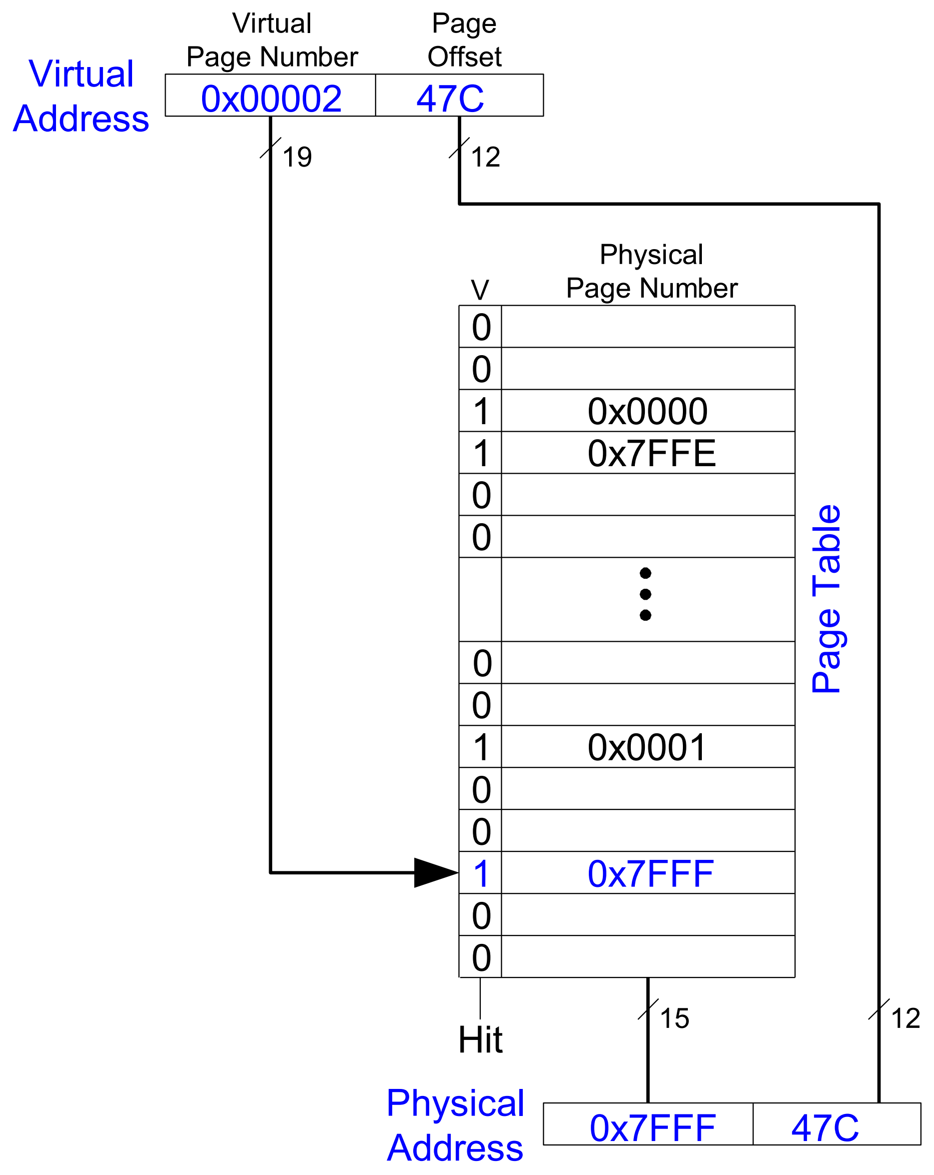
- Each page table entry has:

  - Valid bit: whether the virtual page is located in physical memory (if not, it must be fetched from the hard disk)

  - Physical page number: where the virtual page is located in physical memory

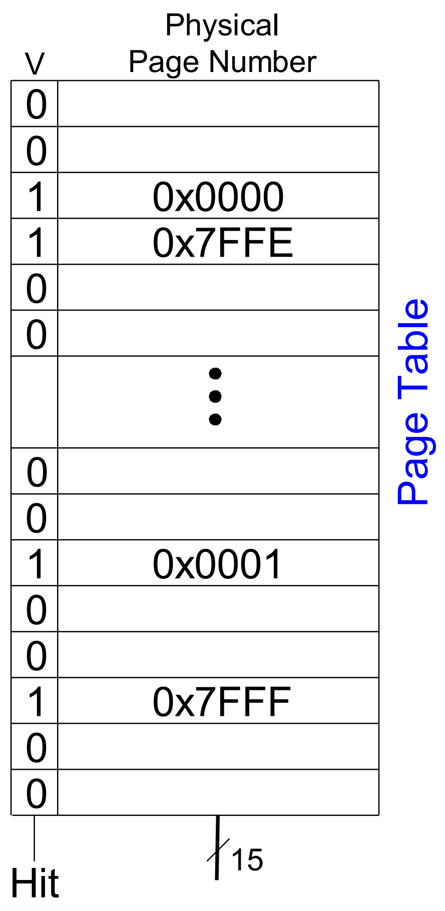
  - (Replacement policy, dirty bits)

Page Table Example



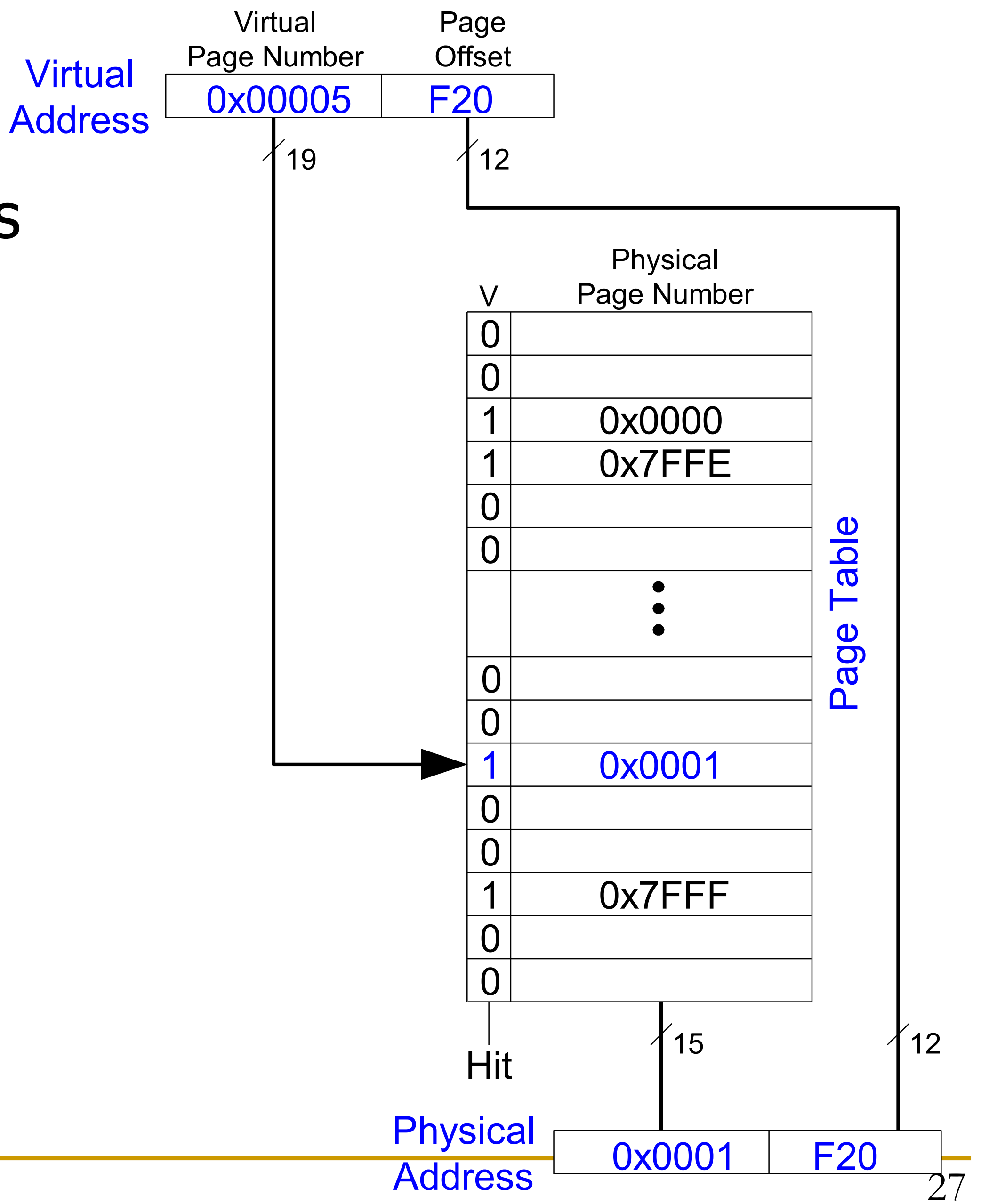
Page Table Example 1

- What is the physical address of virtual address 0x5F20?



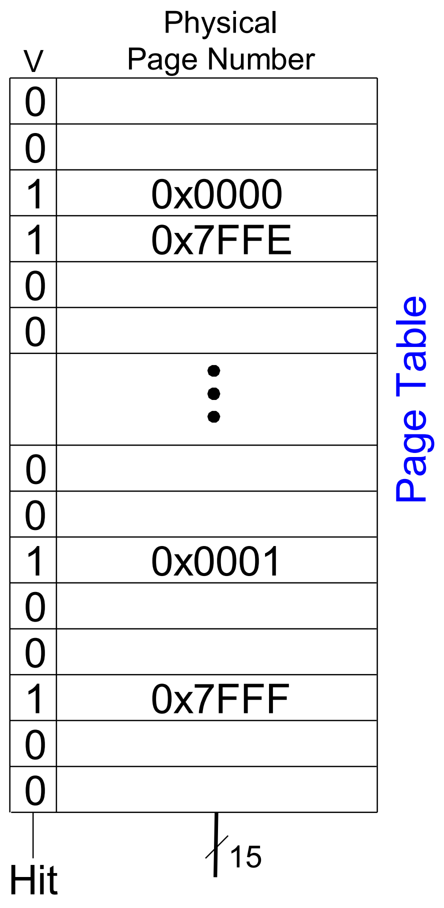
Page Table Example 1

- What is the physical address of virtual address 0x5F20?
  - VPN = 5
  - Entry 5 in page table indicates VPN 5 is in physical page 1
  - Physical address is 0x1F20



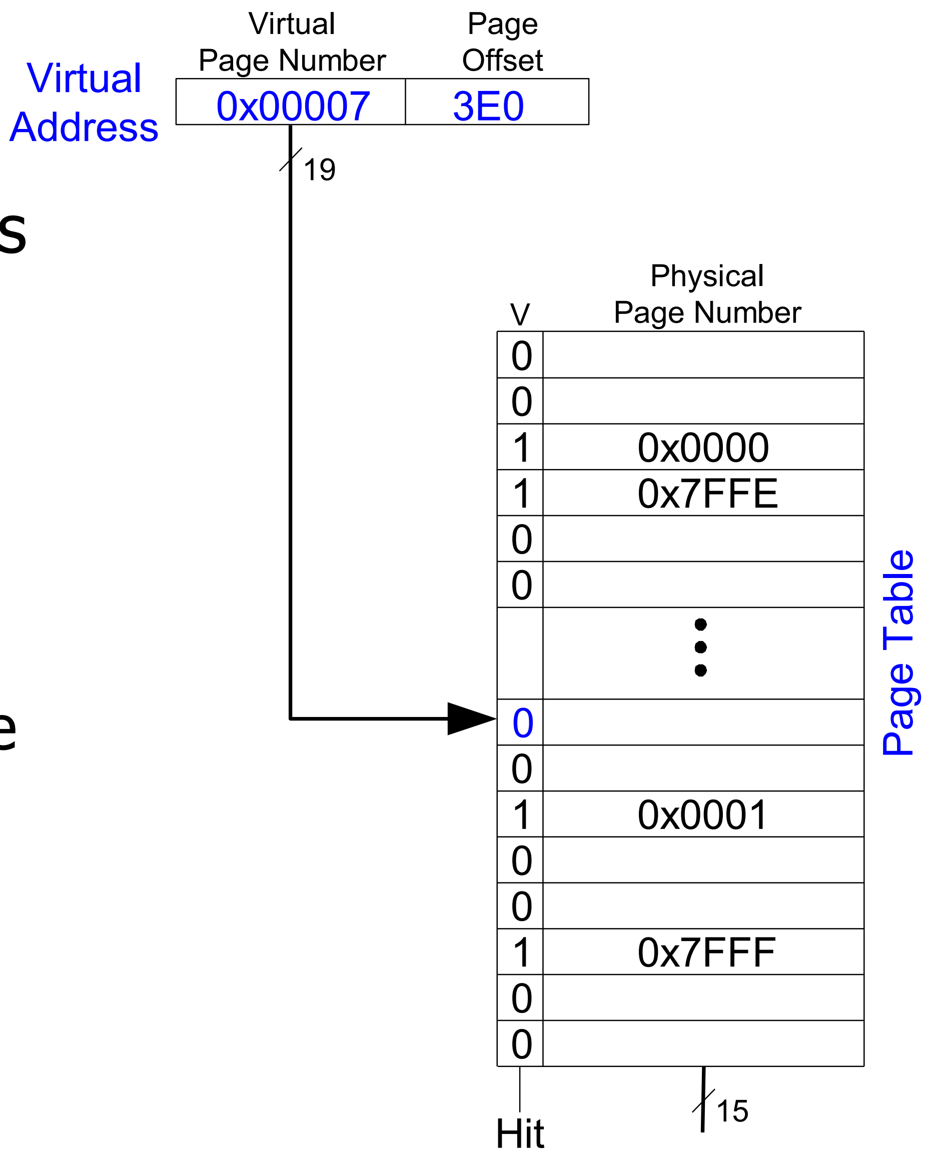
Page Table Example 2

- What is the physical address of virtual address 0x73E0?

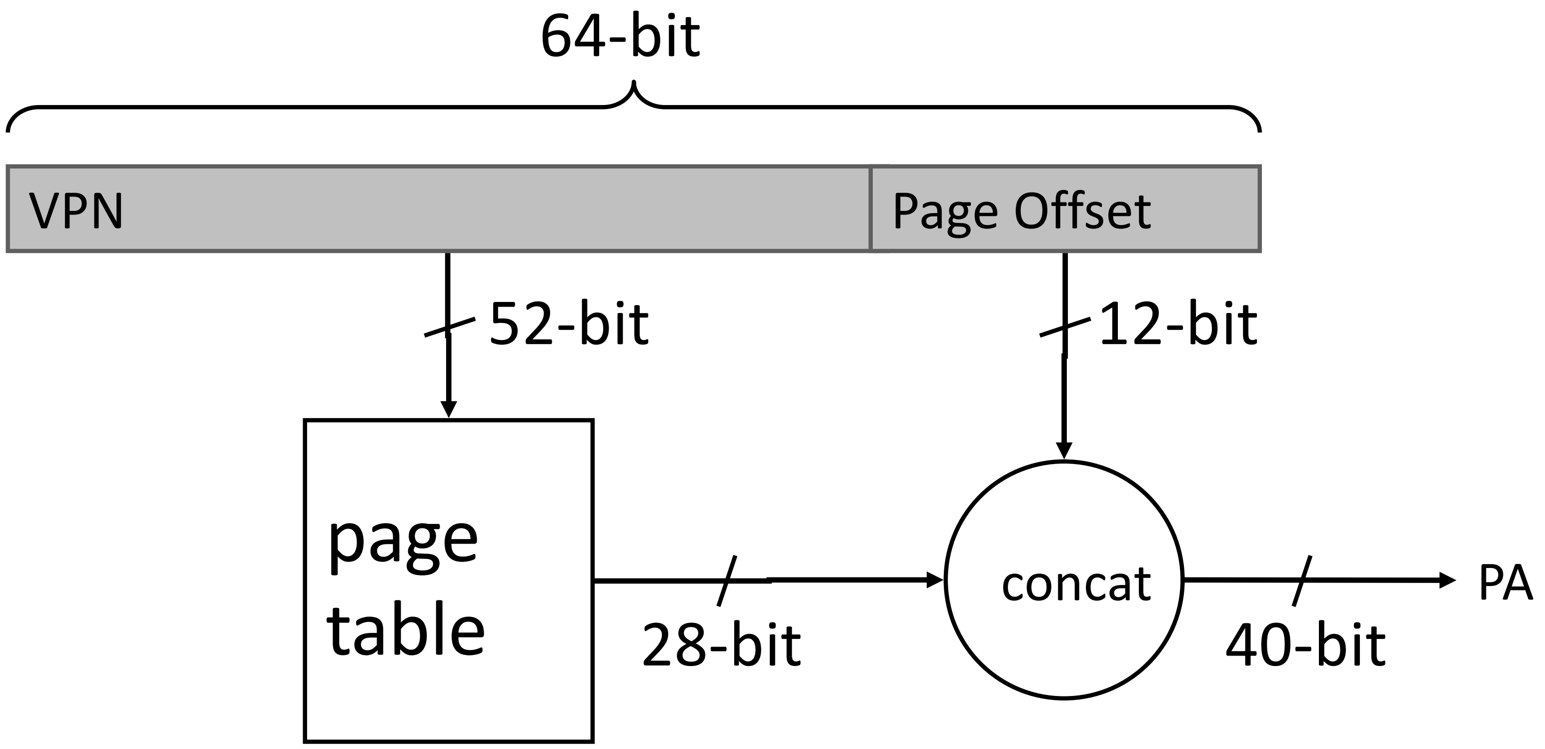


Page Table Example 2

- What is the physical address of virtual address 0x73E0?
  - VPN = 7
  - Entry 7 in page table is invalid, so the page is not in physical memory
  - The virtual page must be swapped into physical memory from disk



Issue: Page Table Size



- Suppose 64-bit VA and 40-bit PA, how large is the page table?
    - **2^{52} entries x ~4 bytes ≈ 2^{54} bytes**

      and that is for just one process!

      and the process may not be using the entire VM space!

Page Table Challenges

- Page table is large
  - at least part of it needs to be located in physical memory

- Each load/store requires at least two memory accesses:

  1. one for address translation (page table read)
  2. one to access data with the physical address (after translation)

- Two memory accesses to service a load/store greatly degrades load/store execution time
  - Unless we are clever…

Translation Lookaside Buffer (TLB)

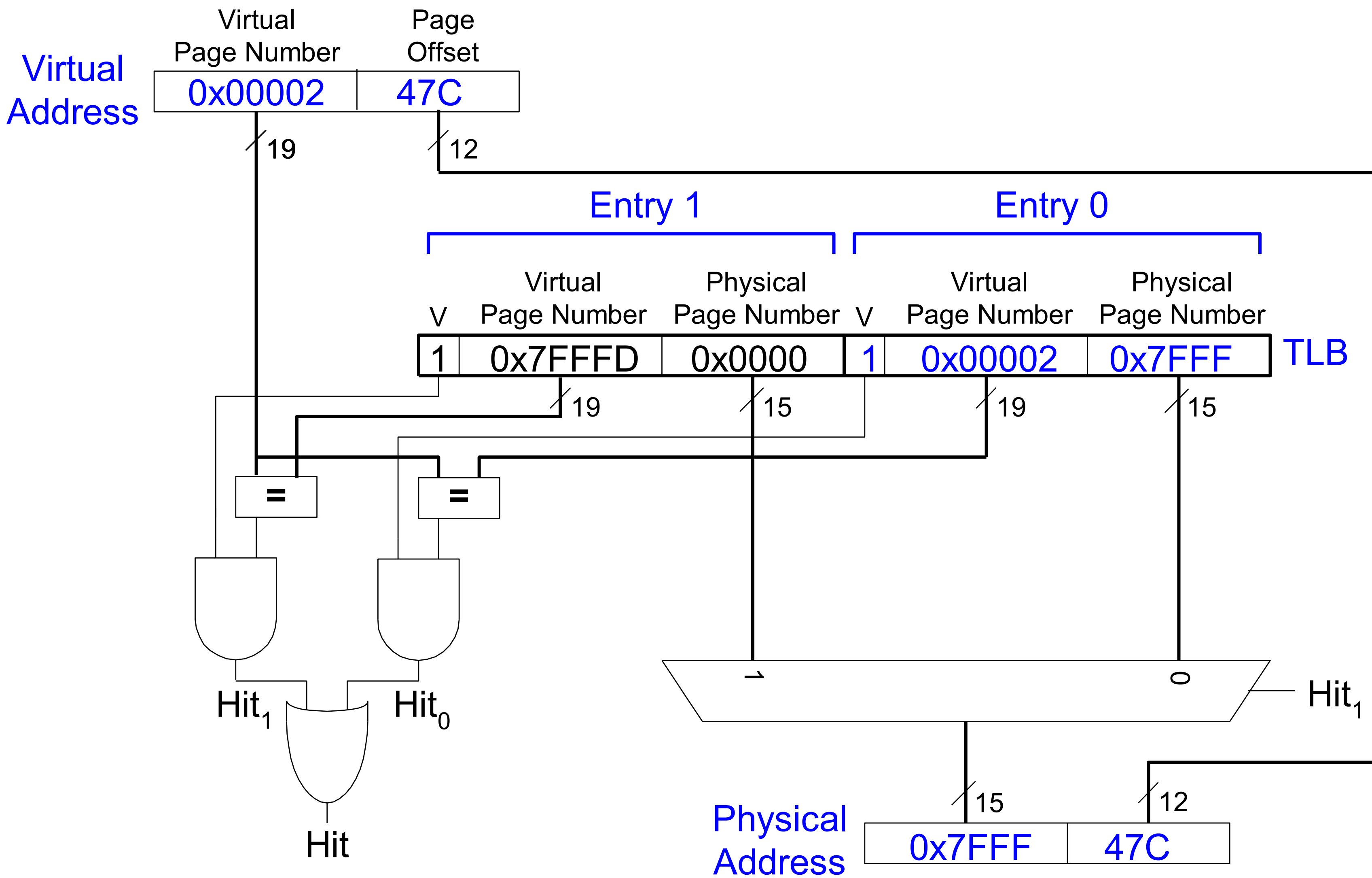
- Idea: Cache the page table entries (PTEs) in a hardware structure in the processor
- Translation lookaside buffer (TLB)
    - Small cache of most recently used translations (PTEs)
    - Reduces number of memory accesses required for *most* loads/stores to only one

Translation Lookaside Buffer (TLB)

- Page table accesses have a lot of temporal locality
  - Data accesses have temporal and spatial locality
  - Large page size (say 4KB, 8KB, or even 1-2GB), so consecutive loads/stores likely to access same page

- TLB
  - Small: accessed in < 1 cycle
  - Typically 16 - 512 entries
  - High associativity
  - > 95-99 % hit rates typical (depends on workload)
  - Reduces # of memory accesses for most loads and stores to only 1

Example Two-Entry TLB

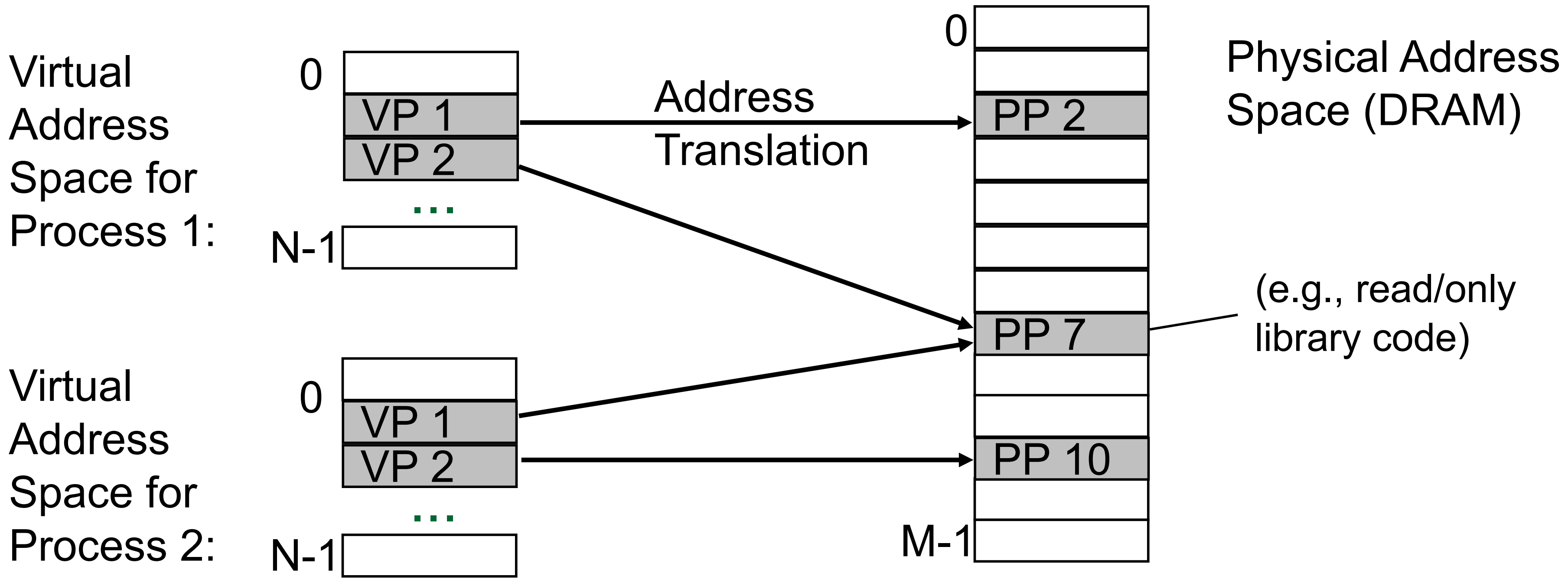


Memory Protection

- Multiple programs (*processes*) run at once
  - Each process has its own page table
  - Each process can use entire virtual address space without worrying about where other programs are
- A process can only access physical pages mapped in its page table – cannot overwrite memory of another process
  - Provides protection and isolation between processes
  - Enables access control mechanisms per page

Page Table is Per Process

- Each process has its own virtual address space
  - Full address space for each program
  - Simplifies memory allocation, sharing, linking and loading.



Virtual Address Space for Process 1:
0
VP 1
VP 2
...
N-1
Address Translation
0
PP 2
PP 7
PP 10
M-1
Physical Address Space (DRAM)
(e.g., read/only library code)
Virtual Address Space for Process 2:
0
VP 1
VP 2
...
N-1

Virtual Memory Summary

- Virtual memory gives the illusion of "infinite" capacity
- A subset of virtual pages are located in physical memory
- A page table maps virtual pages to physical pages – this is called address translation
- A TLB speeds up address translation
- Using different page tables for different programs provides memory protection

Digital Design & Computer Arch.

Lecture 23b: Virtual Memory

Prof. Onur Mutlu

ETH Zürich

Spring 2020

22 May 2020

Supporting Virtual Memory

- Virtual memory requires both HW+SW support
  - Page Table is in memory
  - Can be cached in special hardware structures called Translation Lookaside Buffers (TLBs)

- The hardware component is called the MMU (memory management unit)
  - Includes Page Table Base Register(s), TLBs, page walkers

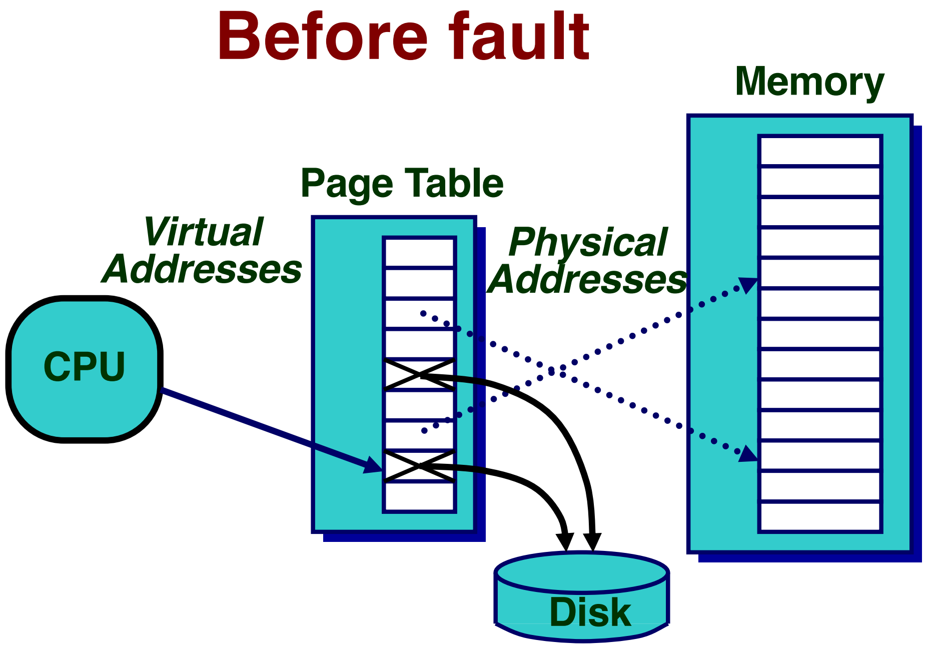
- It is the job of the software to leverage the MMU to
  - Populate page tables, decide what to replace in physical memory
  - Change the Page Table Register on context switch (to use the running thread's page table)
  - Handle page faults and ensure correct mapping

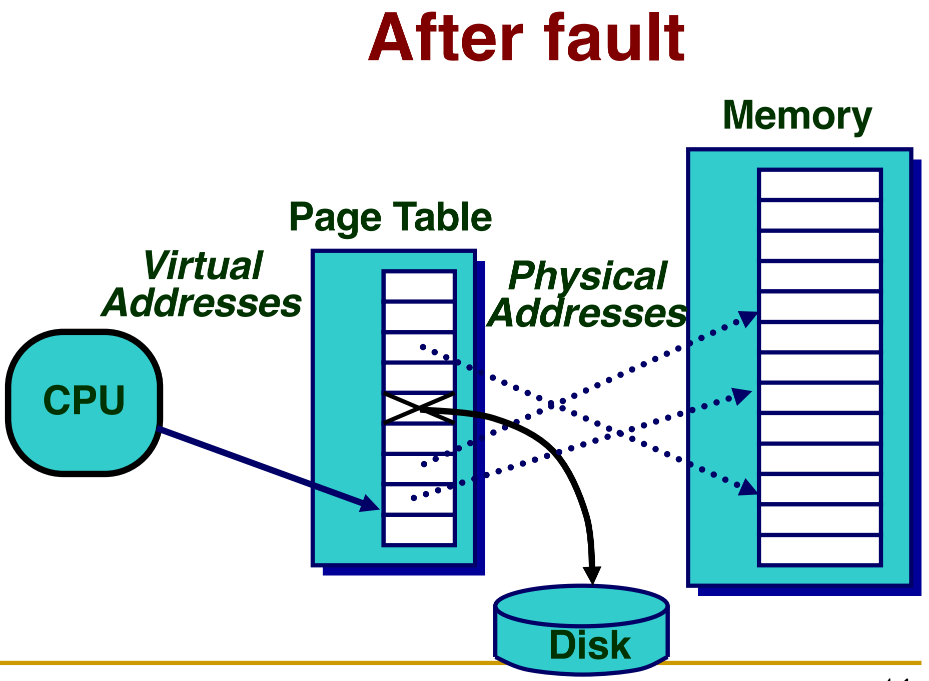
Some System Software Jobs for VM

- Keeping track of which physical frames are free
- Allocating free physical frames to virtual pages
- Page replacement policy
  - When no physical frame is free, what should be swapped out?
- Sharing pages between processes
- Copy-on-write optimization
- Page-flip optimization

Page Fault ("A Miss in Physical Memory")

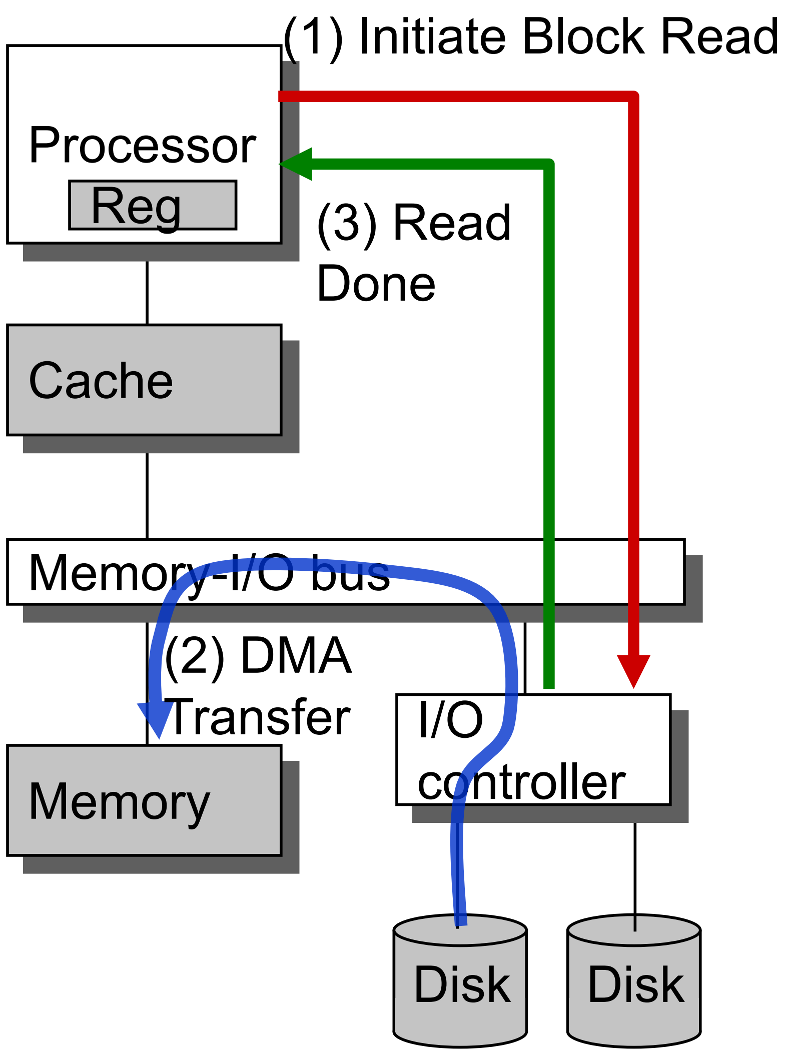
- If a page is not in physical memory but disk
  - Page table entry indicates virtual page not in memory
  - Access to such a page triggers a page fault exception
  - OS trap handler invoked to move data from disk into memory
    - Other processes can continue executing
    - OS has full control over placement





Servicing a Page Fault

- (1) Processor signals controller
  - Read block of length P starting at disk address X and store starting at memory address Y
- (2) Read occurs
  - Direct Memory Access (DMA)
  - Under control of I/O controller
- (3) Controller signals completion
  - Interrupt processor
  - OS resumes suspended process



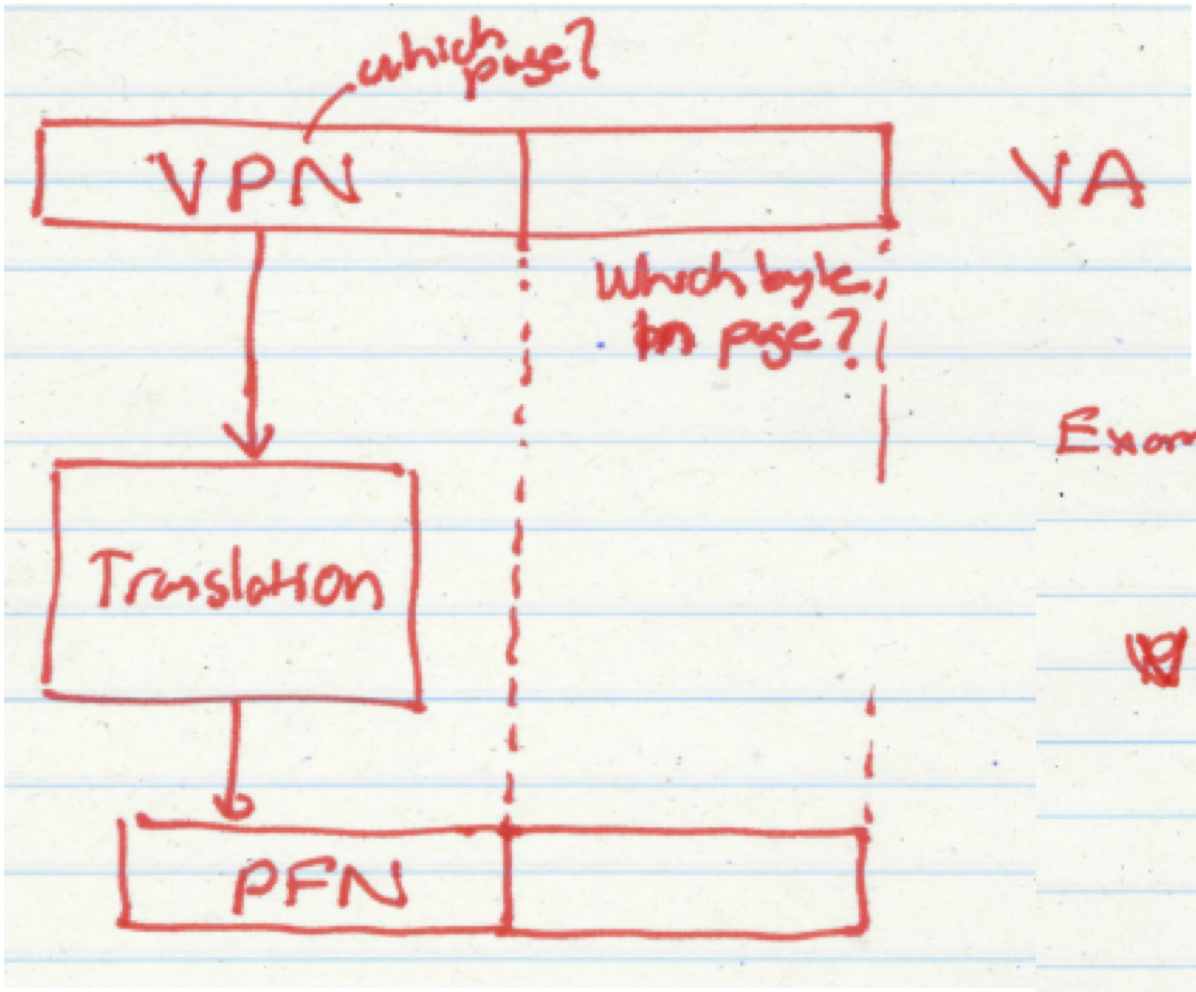
Address Translation

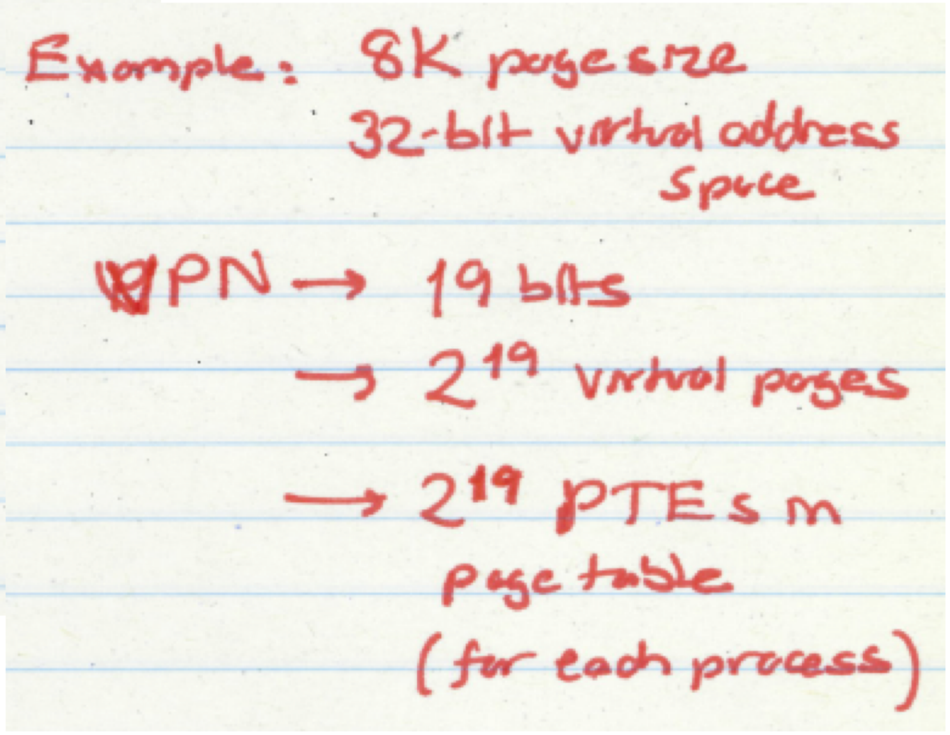
- How to obtain the physical address from a virtual address?

- Page size specified by the ISA
  - VAX: 512 bytes
  - Today: 4KB, 8KB, 2GB, … (small and large pages mixed together)
  - Trade-offs? (remember cache lectures)

- Page Table contains an entry for each virtual page
  - Called Page Table Entry (PTE)
  - What is in a PTE?

Address Translation (II)



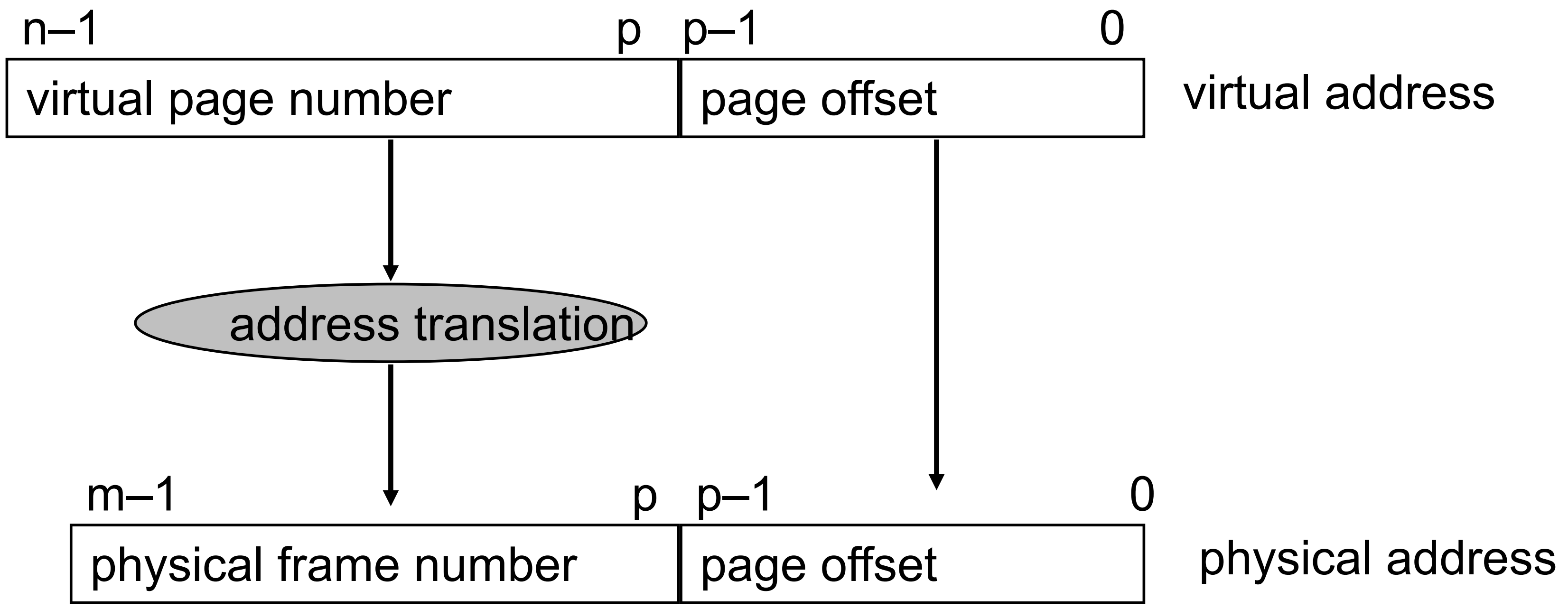


Example: 8K page size
32-bit virtual address space

VPN → 19 bits
→ 2^{19} virtual pages
→ 2^{19} PTEs in page table
(for each process)

Address Translation (III)

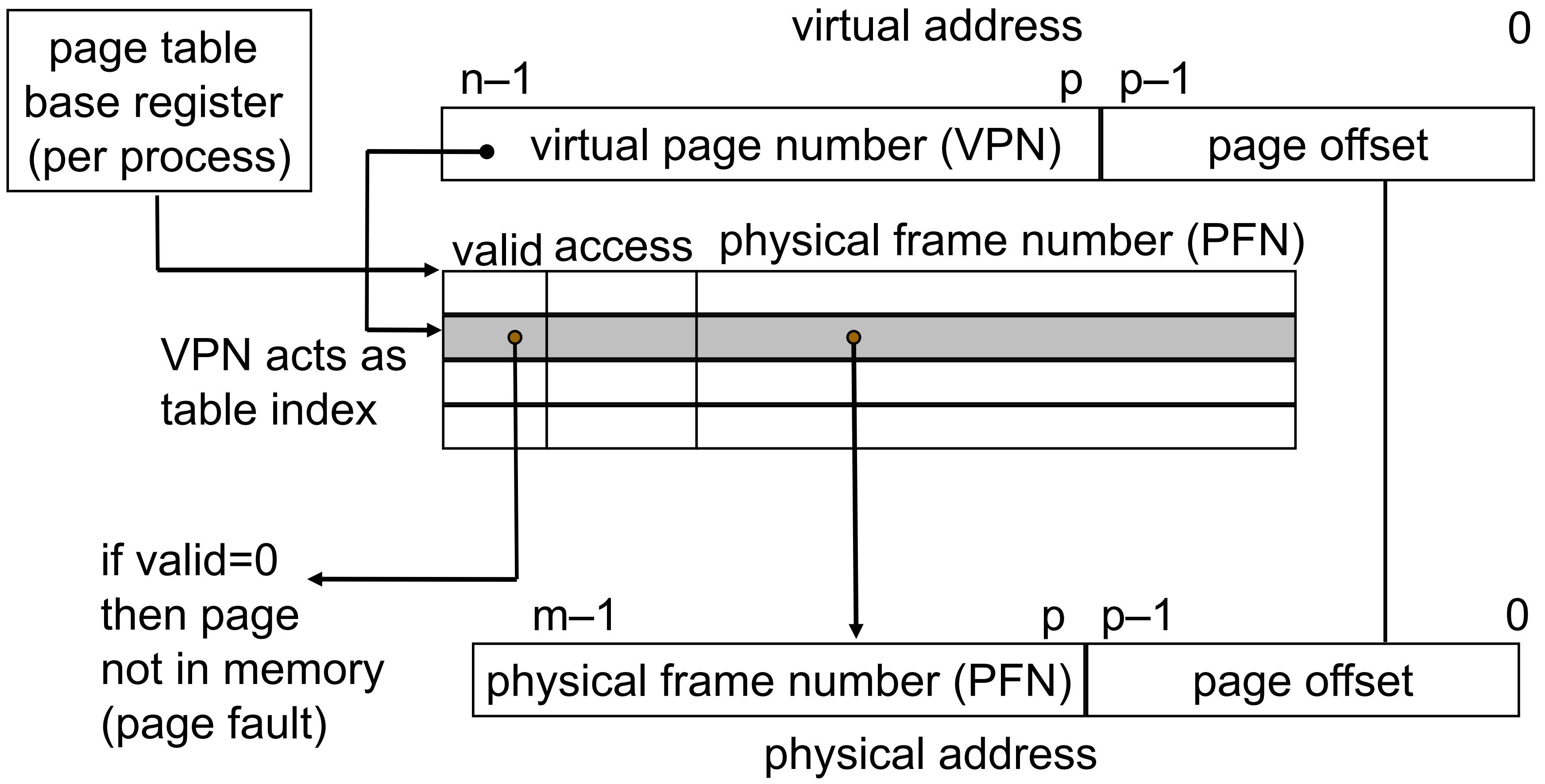
- Parameters
  - $P = 2^p$ = page size (bytes).
  - $N = 2^n$ = Virtual-address limit
  - $M = 2^m$ = Physical-address limit



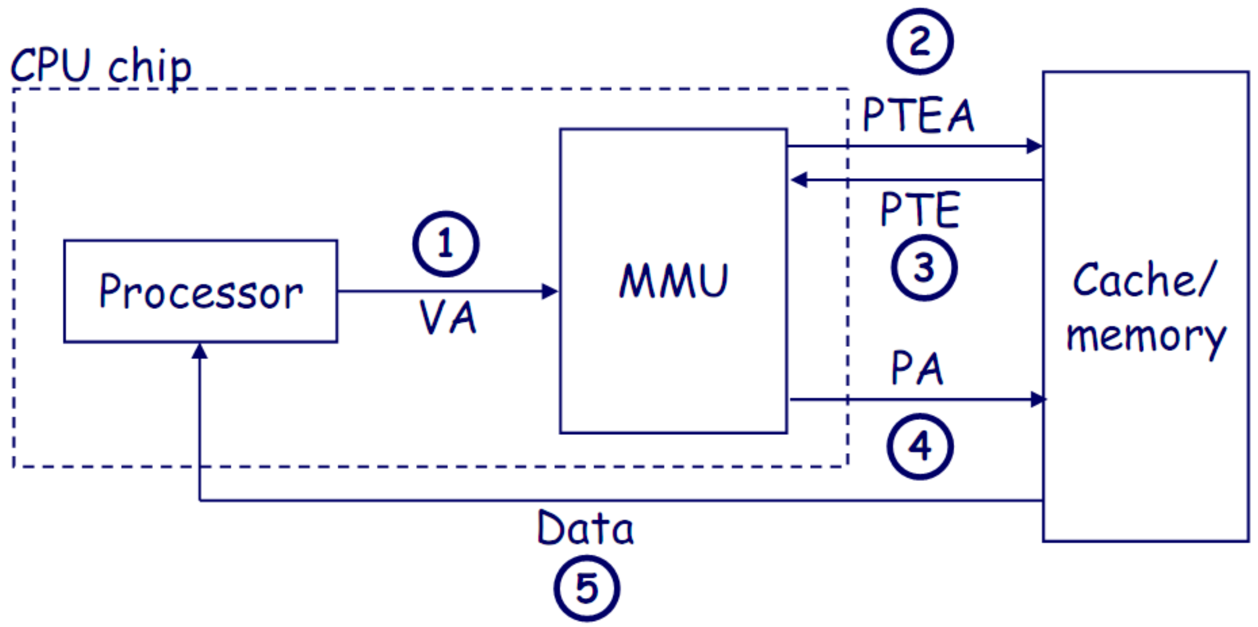
Page offset bits don't change as a result of translation

Address Translation (IV)

- Separate (set of) page table(s) per process
- VPN forms index into page table (points to a page table entry)
- Page Table Entry (PTE) provides information about page


page table base register (per process)
virtual address
n–1
p
p–1
0
virtual page number (VPN)
page offset
valid
access
physical frame number (PFN)
VPN acts as table index
if valid=0 then page not in memory (page fault)
m–1
p
p–1
0
physical frame number (PFN)
page offset
physical address

Address Translation: Page Hit



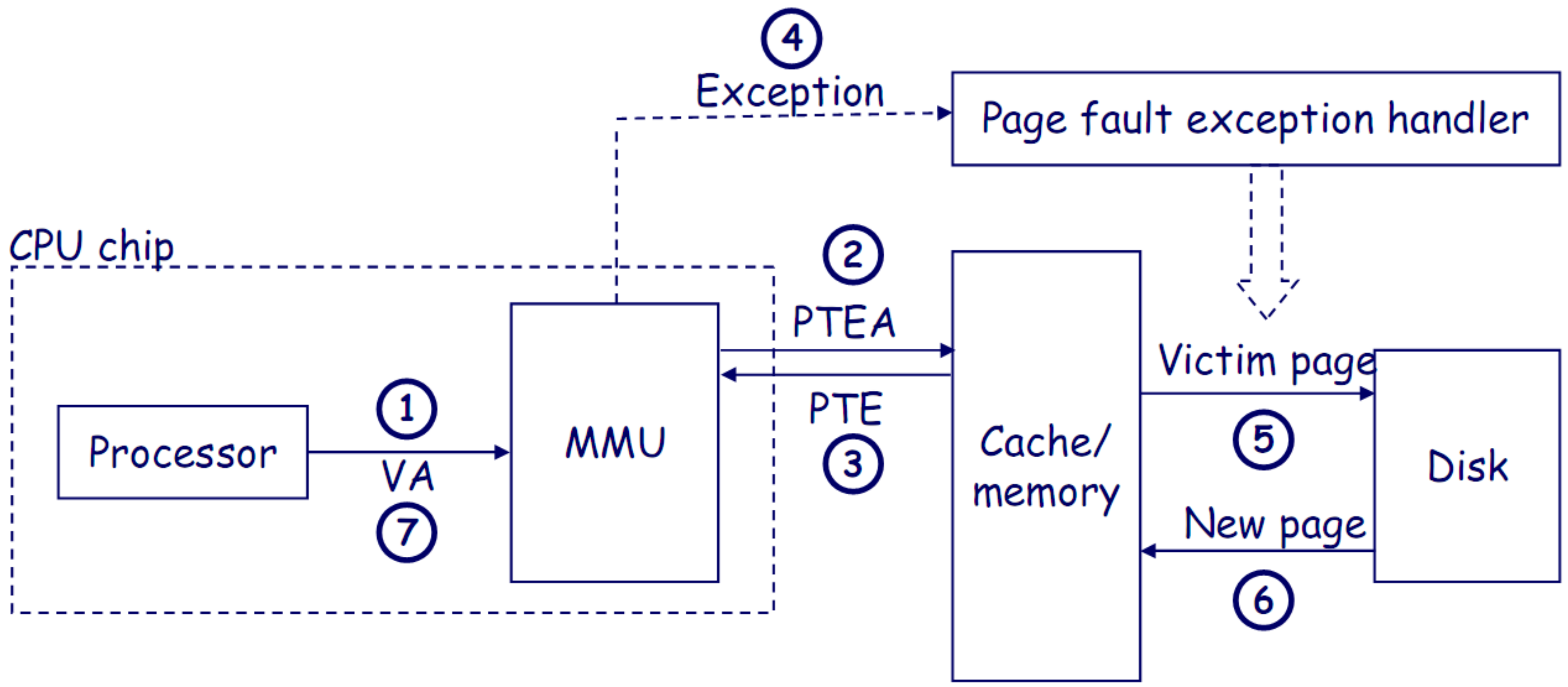
1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

4) MMU sends physical address to L1 cache

5) L1 cache sends data word to processor

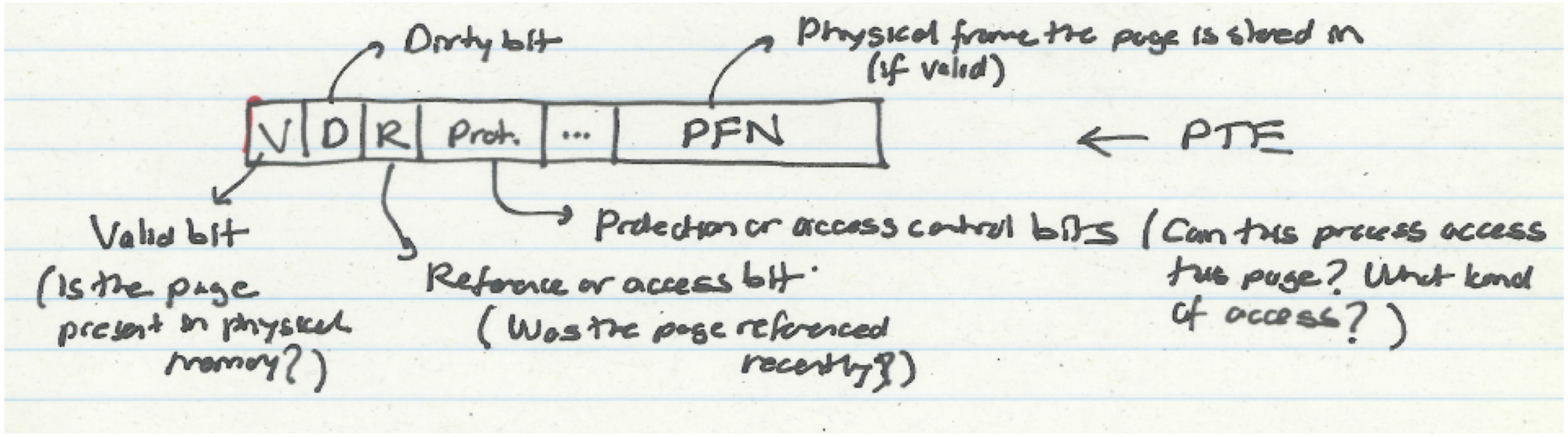
Address Translation: Page Fault



1) Processor sends virtual address to MMU
2-3) MMU fetches PTE from page table in memory
4) Valid bit is zero, so MMU triggers page fault exception
5) Handler identifies victim, and if dirty pages it out to disk
6) Handler pages in new page and updates PTE in memory
7) Handler returns to original process, restarting faulting instruction.

What Is in a Page Table Entry (PTE)?

- Page table is the "tag store" for the physical memory data store
  - A mapping table between virtual memory and physical memory
- PTE is the "tag store entry" for a virtual page in memory
  - Need a valid bit → to indicate validity/presence in physical memory
  - Need tag bits (PFN) → to support translation
  - Need bits to support replacement
  - Need a dirty bit to support "write back caching"
  - Need protection bits to enable access control and protection


Dirty bit
Physical frame the page is stored in (if valid)
V
D
R
Prot.
...
PFN
← PTE
Valid bit (Is the page present in physical memory?)
Reference or access bit: (Was the page referenced recently?)
Protection or access control bits (Can this process access this page? What kind of access?)

Cache versus Page Replacement

- Physical memory (DRAM) is a cache for disk
  - Usually managed by system software via the virtual memory subsystem

- Page replacement is similar to cache replacement
- Page table is the "tag store" for physical memory data store

- What is the difference?
  - Required speed of access to cache vs. physical memory
  - Number of blocks in a cache vs. physical memory
  - "Tolerable" amount of time to find a replacement candidate (disk versus memory access latency)
  - Role of hardware versus software

Page Replacement Algorithms

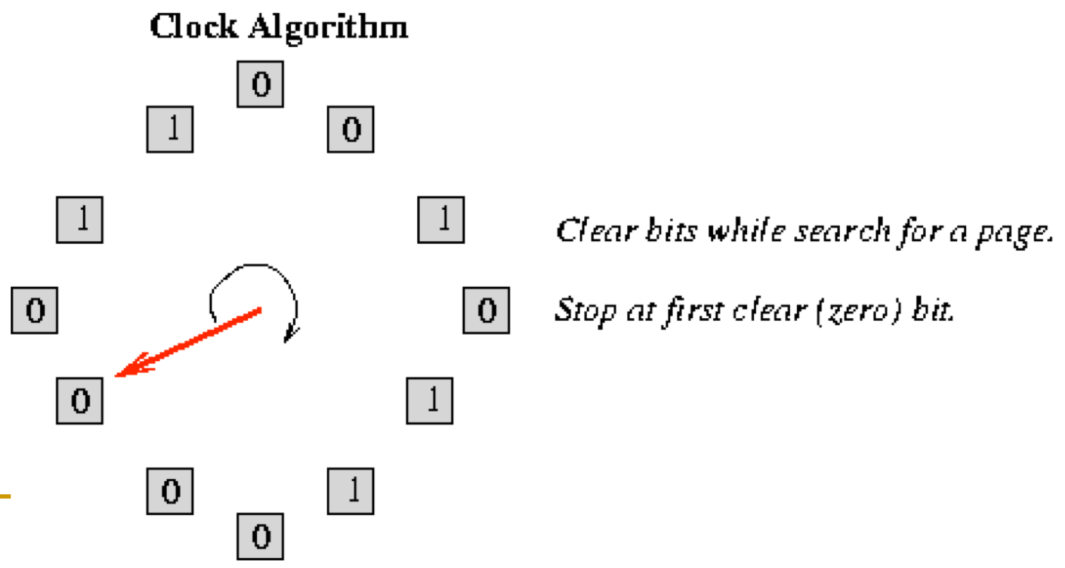
- If physical memory is full (i.e., list of free physical pages is empty), which physical frame to replace on a page fault?

- Is True LRU feasible?
  - 4GB memory, 4KB pages, how many possibilities of ordering?

- Modern systems use approximations of LRU
  - E.g., the CLOCK algorithm
- And, more sophisticated algorithms to take into account "frequency" of use
  - E.g., the ARC algorithm
  - Megiddo and Modha, "ARC: A Self-Tuning, Low Overhead Replacement Cache," FAST 2003.

CLOCK Page Replacement Algorithm

- Keep a circular list of physical frames in memory
- Keep a pointer (hand) to the last-examined frame in the list
- When a page is accessed, set the R bit in the PTE
- When a frame needs to be replaced, replace the first frame that has the reference (R) bit not set, traversing the circular list starting from the pointer (hand) clockwise
  - During traversal, clear the R bits of examined frames
  - Set the hand pointer to the next frame in the list


Clock Algorithm
0
1
0
1
1
0
0
0
1
0
1
0
Clear bits while search for a page.
Stop at first clear (zero) bit.