ECE 550D
Fundamentals of Computer Systems and Engineering

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Virtual Memory

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Slides are derived from work by
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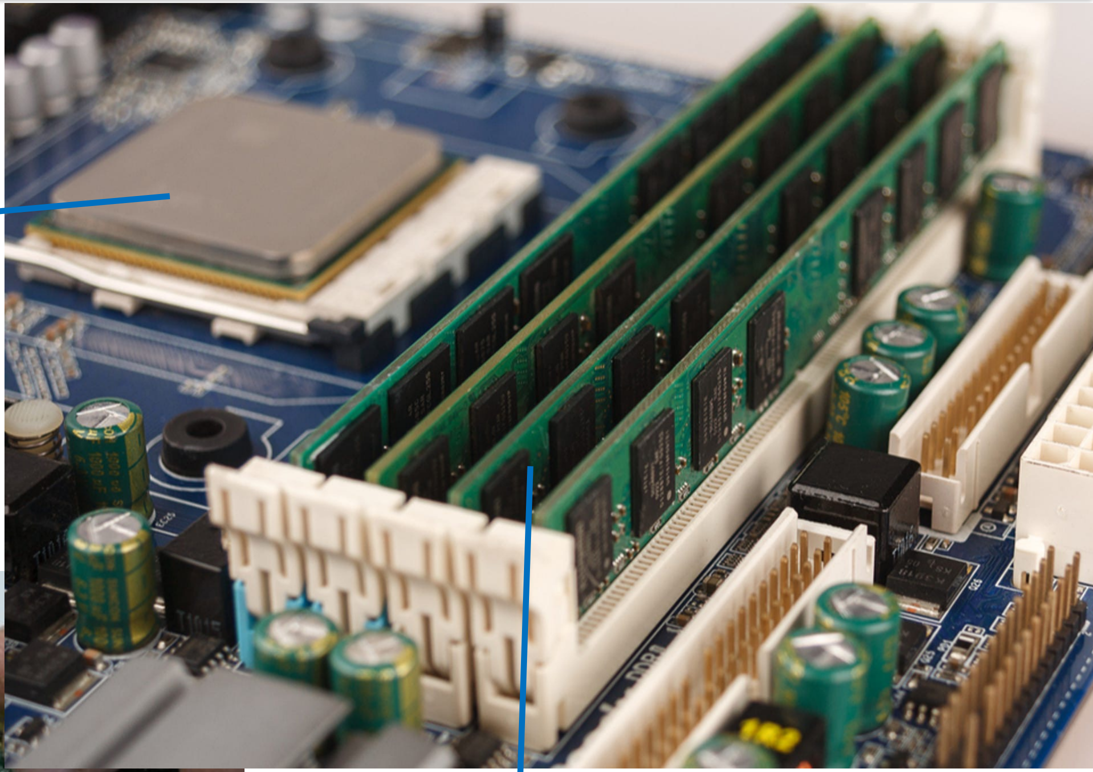
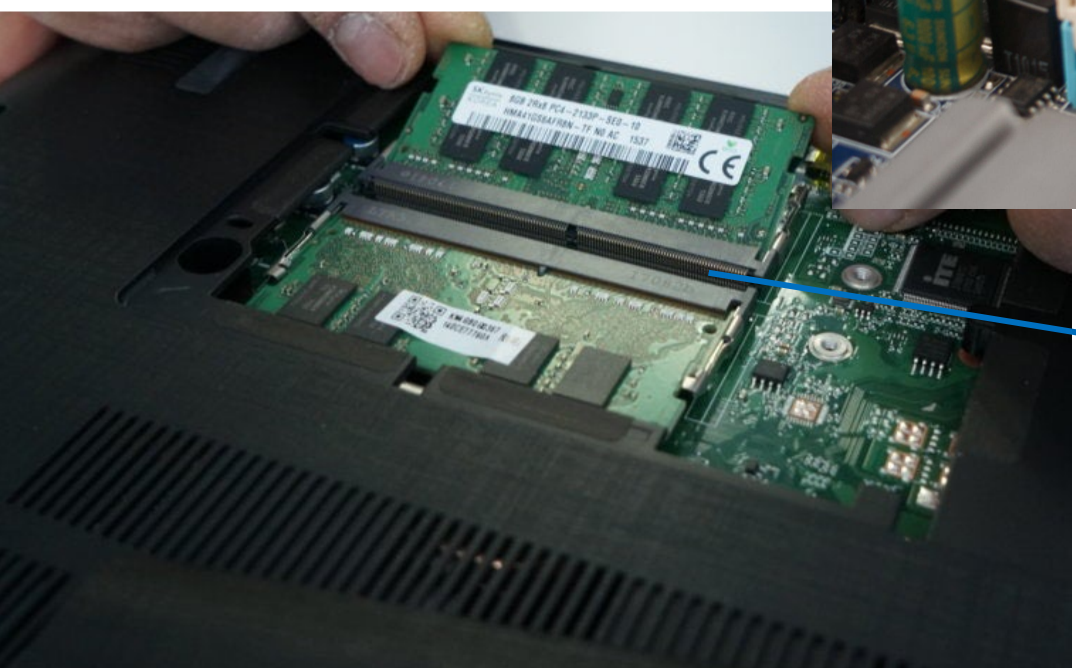
Main Memory (DRAM)





Problems With Our Current Approach to Memory?

- Reasonable (main) memory: 4GB—64GB?
  - In 32-bit systems:
    - Program can address 2^32 bytes = **4GB**/program
  - In 64-bit systems:
    - Program can address 2^64 bytes = **16EB**/program!
- What if we're running many programs, not just 1?
  - Impossible using what we know for now
- → We need an approach called: **virtual memory**
  - Gives every program **the illusion** of having access to the entire address space
  - Hardware and OS (operating system) move things around behind the scenes
- How?
  - Good rule to know: when we have a functionality problem
    → we can usually solve it by adding a level of indirection

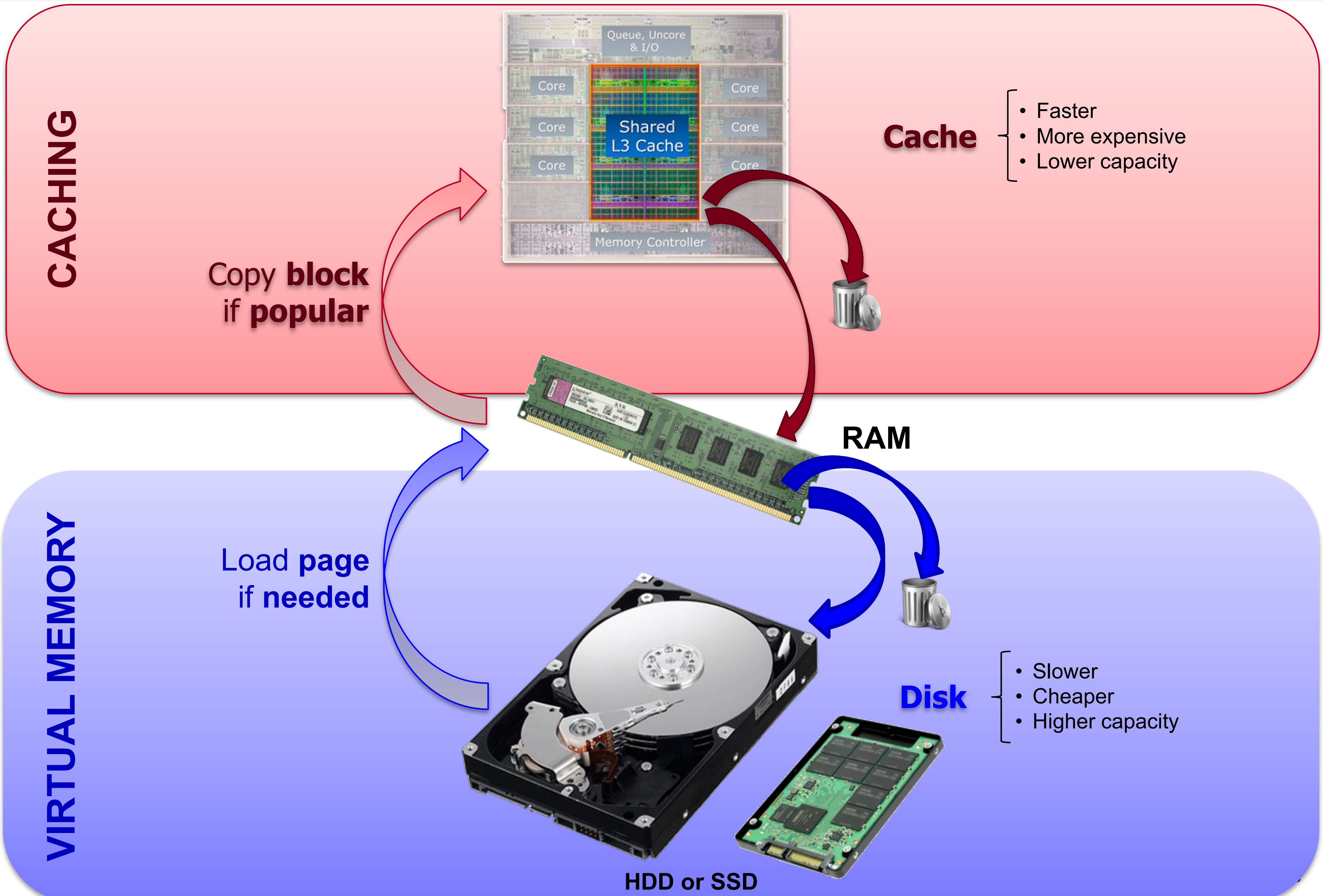
Virtual Memory

- Predates "caches" (by a little)

- Original motivation: **compatibility**
  - Ability to run the same program on machines with different main memory sizes
  - Prior to virtual memory, programmers needed to explicitly account for memory size

- **Virtual memory:**
  - Treats memory like a cache for disks (or other secondary storage)
    - Disks should be able to contain all our data
  - Contents of memory would be a dynamic subset of program's address space
  - Dynamic content management of memory is transparent to program
    - Caching mechanism makes it appear as if memory is 2^N bytes regardless of how much memory there actually is

Caching vs. Virtual Memory

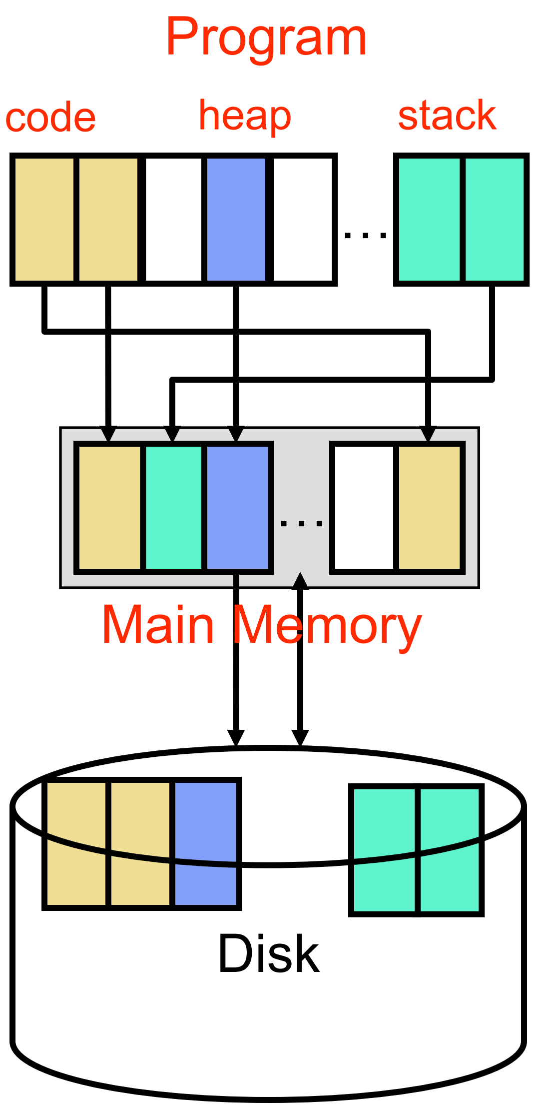


Pages

- What is swapped between disk and memory?
  - A **page** (vs. **block** in caching)
    - Using a process called "demand paging" (or "paging")

- **Page:** A small chunk (~4KB) of memory with its own record in the memory management hardware

How Virtual Memory Solves Our Problem(s)

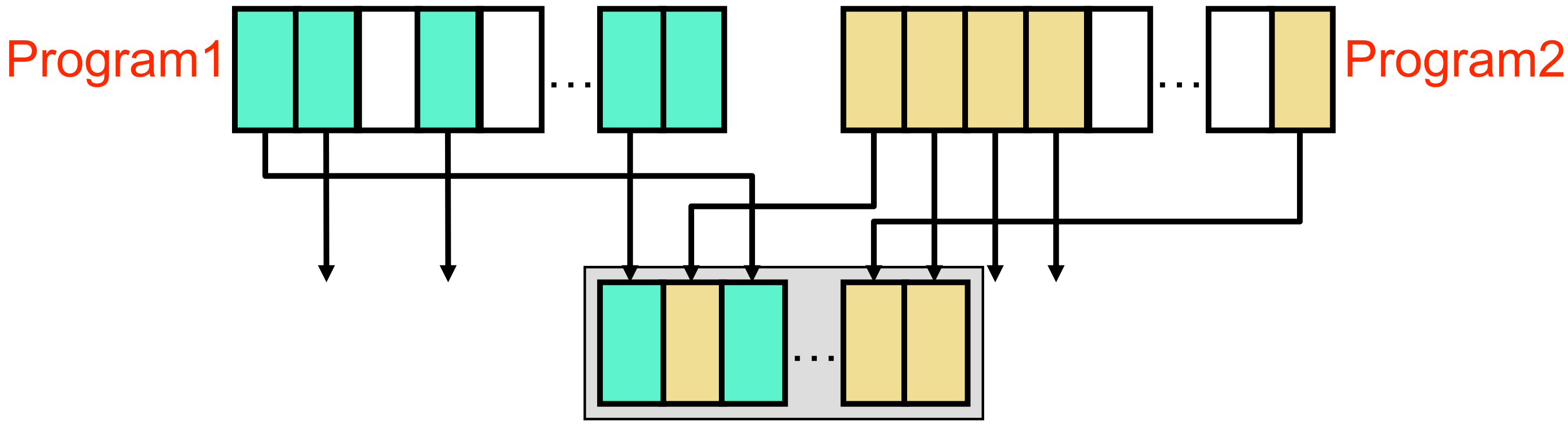


- Programs use **virtual addresses (VA)**
  - 0 to 2^N–1
  - N is the machine/system size (bus width)
    - E.g., Pentium4 is 32-bit, Core i9 is 64-bit
- Memory uses **physical addresses (PA)**
  - 0 to 2^M–1 (M<N, especially if N=64)
  - 2^M is most physical memory machine supports
- VA to PA translation at page granularity
  - → **VP to PP translation**

(Virtual Page to Physical Page)

Other Uses of Virtual Memory

- Virtual memory is quite useful for 1 program, but is also very useful for **multiprogramming** (more than 1 program)
  - Each process thinks it has 2^N bytes of address space
  - Each thinks its stack starts at address 0xFFFFFFFF
  - "System" maps VPs from different processes to different PPs
    - + Prevents processes from reading/writing each other's memory



Even More Uses of Virtual Memory

- Inter-process communication
  - Map VPs in different processes to same PPs

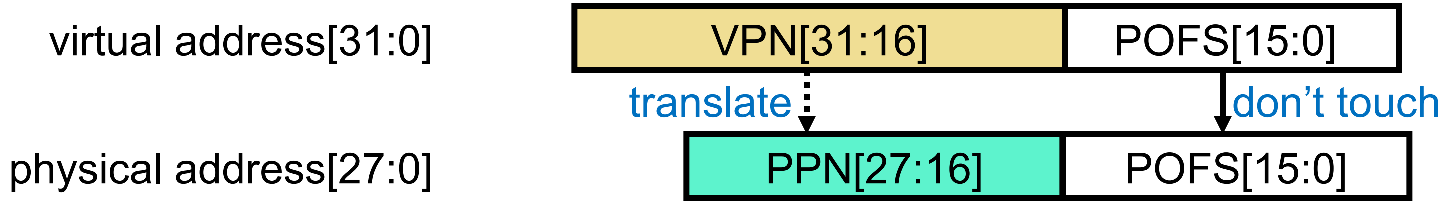
- Direct memory access I/O
  - Think of I/O device as another process
  - Will talk more about I/O in the future

- Protection
  - Piggy-back mechanism to implement page-level protection
  - Map VP to PP … and RWX protection bits
  - Attempt to execute data, or attempt to write insn/read-only data?
    - Exception → OS terminates program

Address Translation (VA→PA or VP→PP)

Address Translation

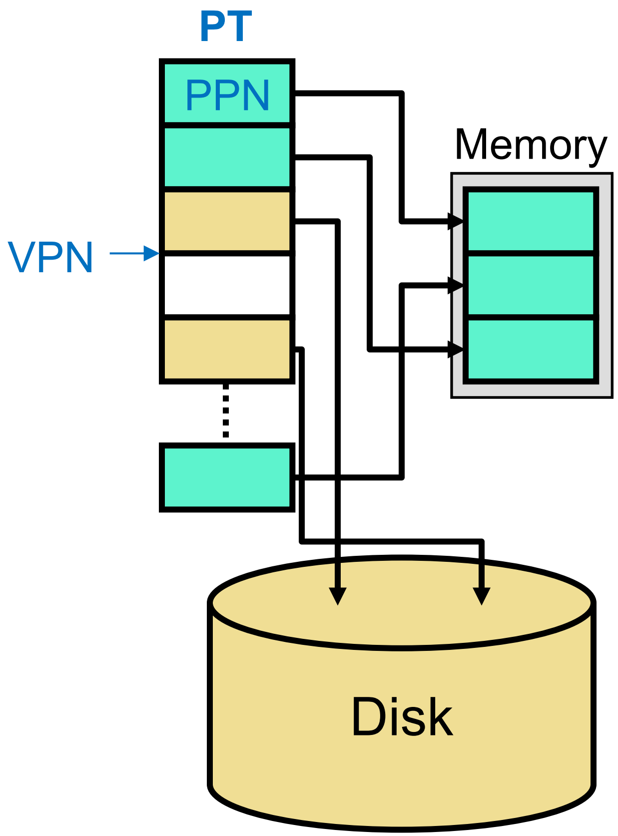
- VA→PA mapping is called **address translation**
  - Split VA into virtual page number (VPN) and page offset (POFS)
  - Translate VPN into physical page number (PPN)
  - POFS is not translated
    - Why? Because it takes us to the desired byte in a page, regardless of where that page is residing
  - VA→PA = [VPN, POFS]→[PPN, POFS]



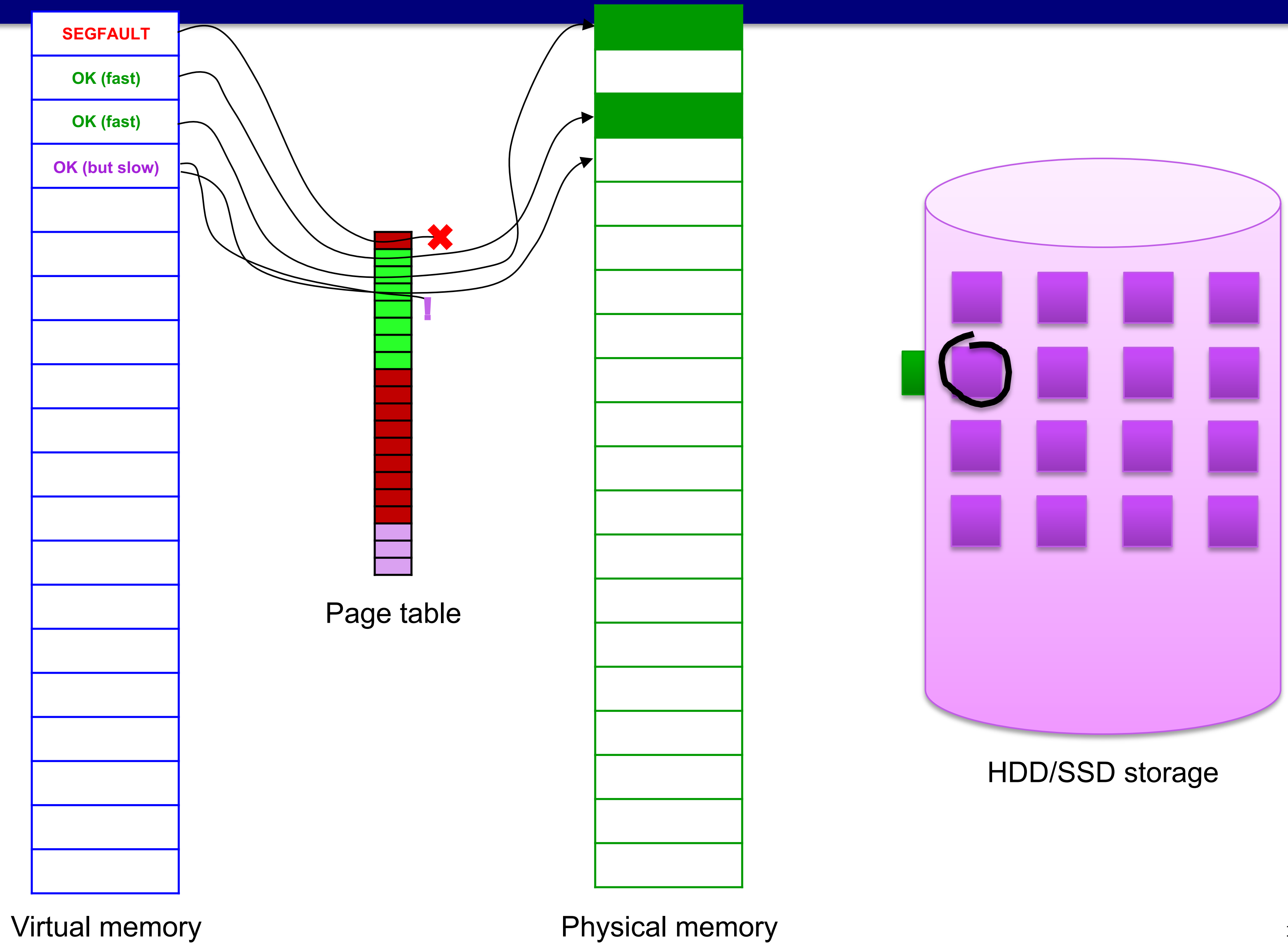
- In the example above:
  - 64KB pages? → 16-bit (= $\log_2 64K = \log_2 2^{16}$) POFS
  - 32-bit machine? → 32-bit VA → 16-bit VPN (= 32b VA – 16b POFS)
  - Maximum 256MB memory? → 28-bit PA → 12-bit PPN (= 28b – 16b)

Mechanics of Address Translation

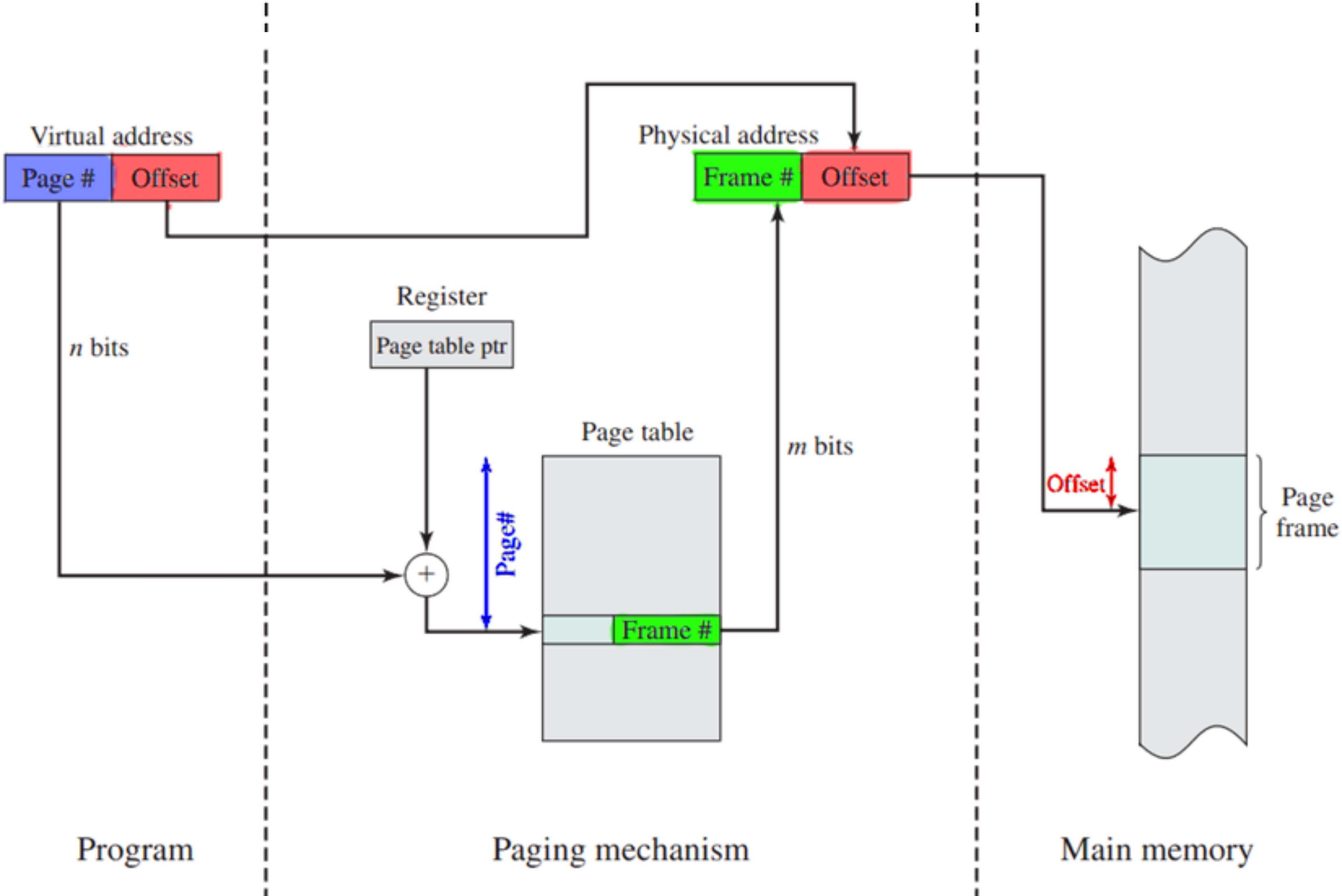
- Each process is allocated a **page table (PT)**
  - PT maps VPs to PPs or to disk addresses
    - VP entries are empty if page is never referenced
  - Translation is called **table lookup**
    - PT here is a lookup table (LUT)



High-Level Operation



Address Translation



Note that PT has to reside in memory

Adapted from Operating System Concepts by Silberschatz, Galvin, and Gagne

Address Translation

Virtual page number | Page offset

Virtual address: $\underbrace{00000000000000000111}_{\text{Virtual page number}}\underbrace{000000000101}_{\text{Page offset}}$

Page table:

Index	Data	Valid?
0	463	0
1	116	1
2	460	1
3	407	1
4	727	0
5	719	1
6	203	0
7	12	1
8	192	1

…

Physical address: $\underbrace{00000000000000001100}_{\text{Physical page number}}\underbrace{000000000101}_{\text{Page offset}}$

Structure of the Page Table

Page Table Size

- How big is a page table on the following machine?
  - 4B page table entries (PTEs)
  - 32-bit machine
  - 4KB pages

- How big would the page table be with 64KB pages?
- How big would it be for a 64-bit machine?