22. Virtual Memory: Basics

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EECS 370 – Introduction to Computer Organization – Fall 2020

https://powcoder.com

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University of Michigan in Ann Arbor, USA

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Announcement

Project 3 due date extended to Tuesday November 17 11:59PM EST

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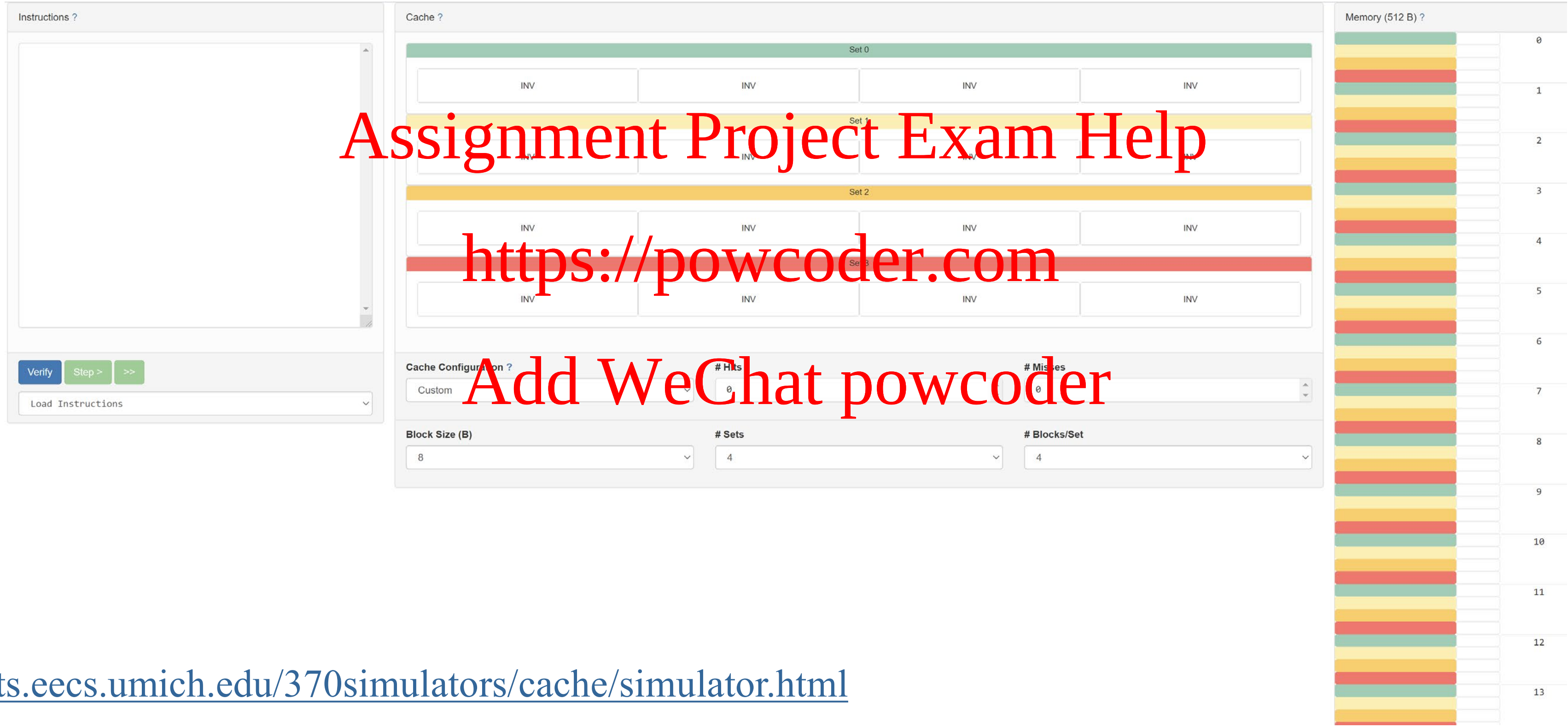
Interactive Cache Simulator



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http://vhosts.eecs.umich.edu/370simulators/cache/simulator.html

Go check cache organization in your computer!

For Linux you can use following command:

`$:sudo dmidecode -t cache`

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DMI—desktop management interface

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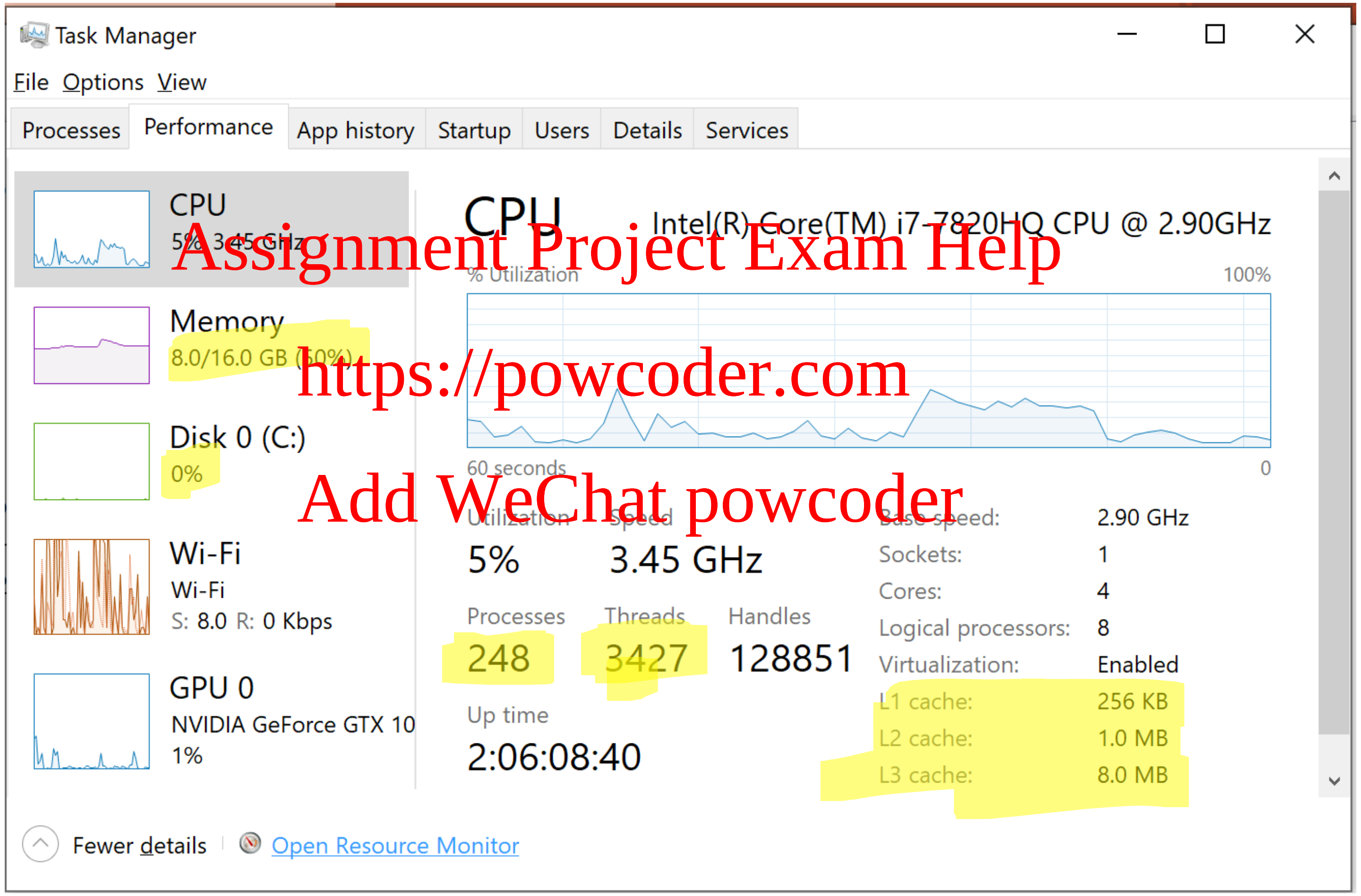
(you may need to install **`dmidecode`** on your machine)

3 Levels of Caches on a Modern Computer



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Memory System: Learning objective

LC2k program	can access	2^{18} bytes of memory
MIPS program	can access	2^{32} bytes of memory
ARM64 or x86-64 program	can access	2^{64} bytes of memory (18 billion billion bytes!)

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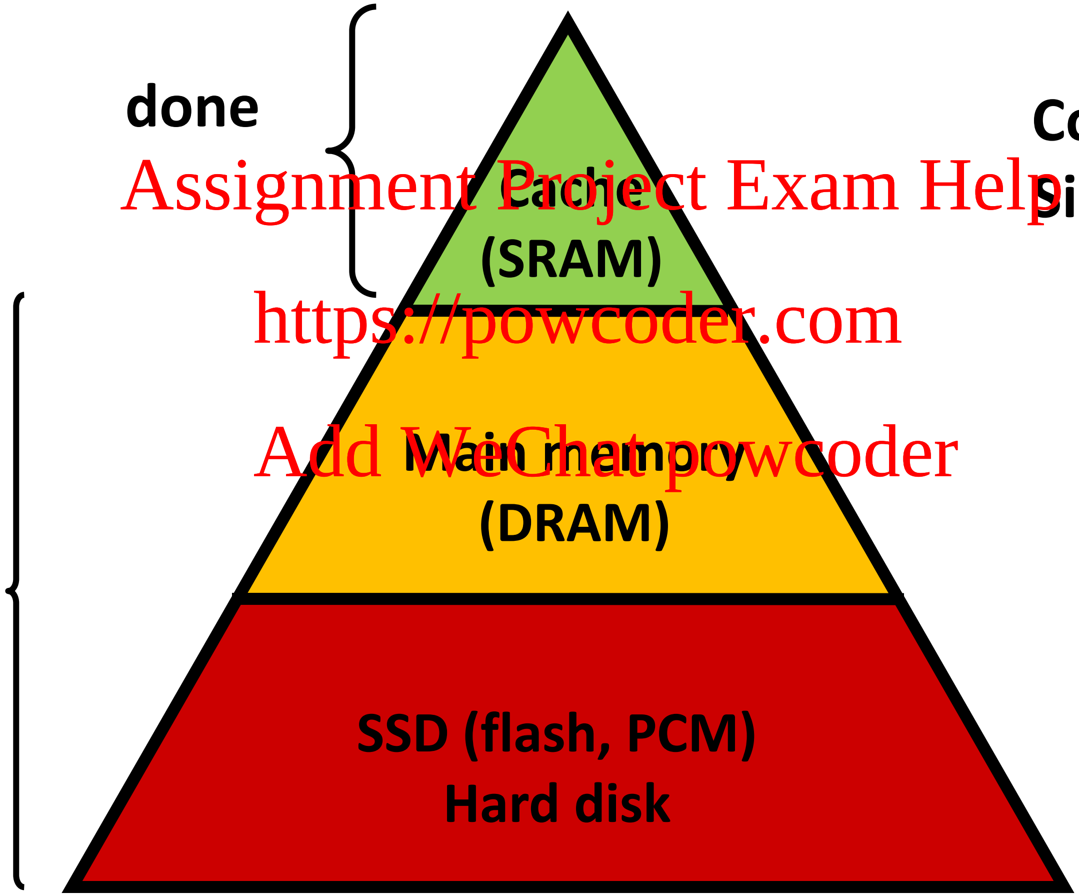
Problem: No one memory technology is both fast and big to store all of program's data

Goal: Design a fast, big, and cheap memory system to store a program's data.

Memory Pyramid

Fast

done



today

Slow

Cost **Expensive**
Size **Small**

Cost **Cheap**
Size **Big**

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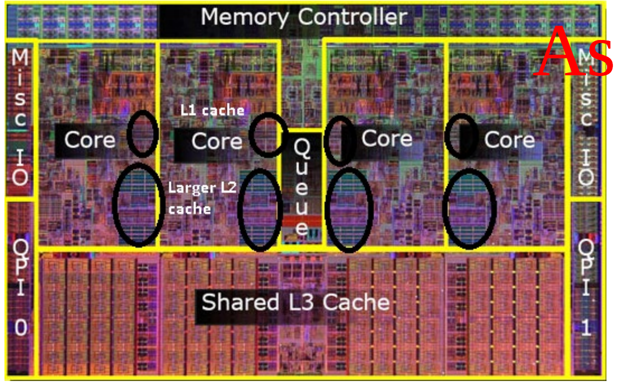
A modern computing system is composed of several memory devices



Processor
w/ three levels of
caches

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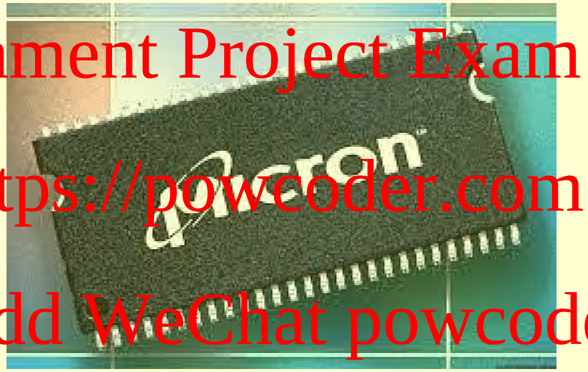

Main memory
(DRAM)

SSD Flash

Hard disk

Focus today: Virtual Memory

Virtual Memory

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What is Virtual Memory?

An operating system (OS) functionality that enables multiple concurrently running programs to share physical memory and swap disk space.

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Hardware (TLB – a special cache) helps OS efficiently implement this functionality

Virtual Memory Roles

Capacity: Main memory is not enough

Problem:

Modern systems can afford ~128 GBs DRAM space = 2^37 bytes. Programs written in 64-bit ISA need 2^64 bytes!

Need to run many programs simultaneously on the same machine. Each program may require GBs of memory.

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Solution:

Provide an illusion of storage large enough for 2^64 bytes of data for all concurrently running programs

Manage main memory like an exclusive fully-associative cache. Spills to disk.

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Security features

Isolation

Unrelated programs must not have access to each other's data

Permissions

Programs may want to share data and code (e.g., library)

Programs may want to disable read/write permissions to some portions of memory

e.g., mark instructions are read-only, no read/write permission for unallocated heap

How to be not limited by DRAM capacity?

Use disk as “extra” space in case main memory capacity is exhausted

- This space in disk is called swap partition in Linux-based systems
- For fun check swap space in a linux system by:

$: top

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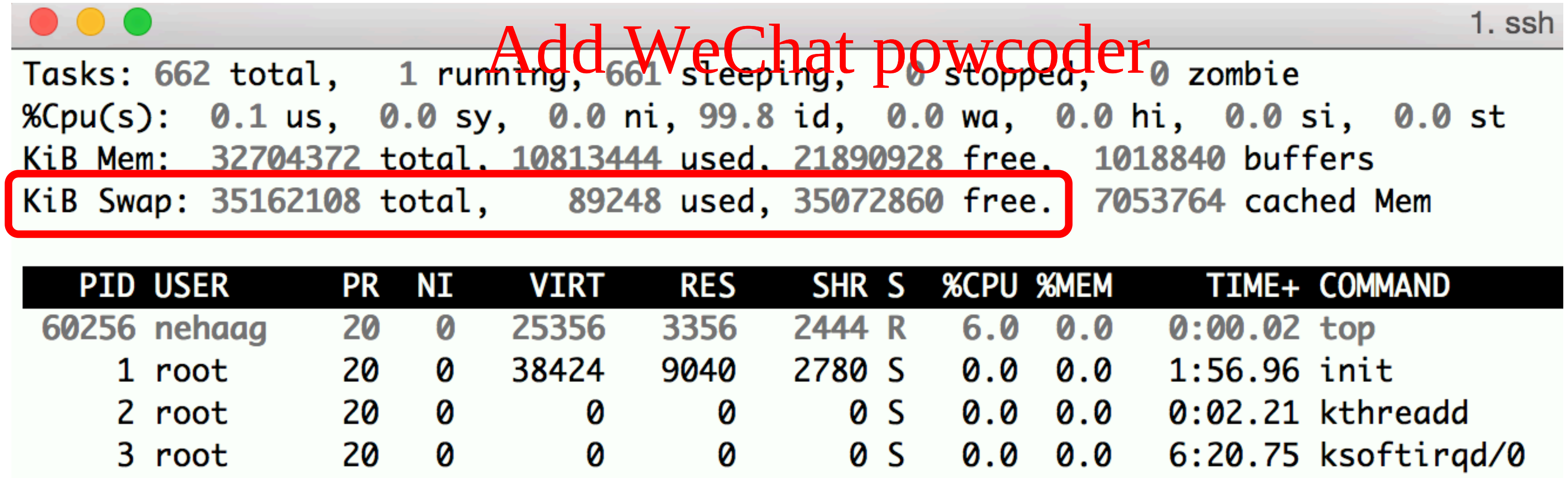
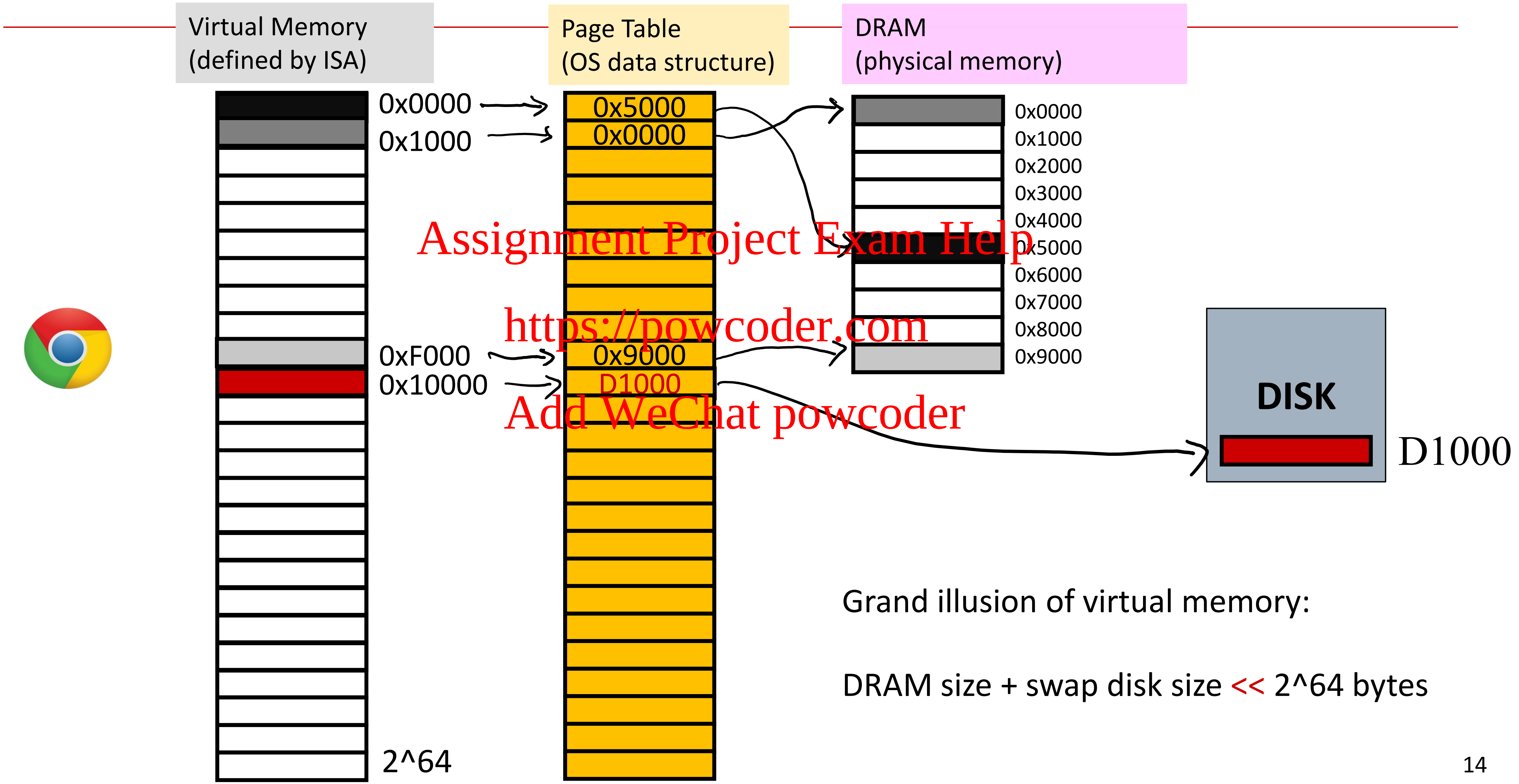


How to be not limited by DRAM capacity?



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Grand illusion of virtual memory:

DRAM size + swap disk size << 2^64 bytes

No memory is enough for a 64-bit ISA (ARM64) program

Hard disk cost for storing all addresses accessible to a ARM64 program

$760 million for 2^64 bytes

Don’t provision 2^{64} bytes of storage (even a hard disk is too expensive!)

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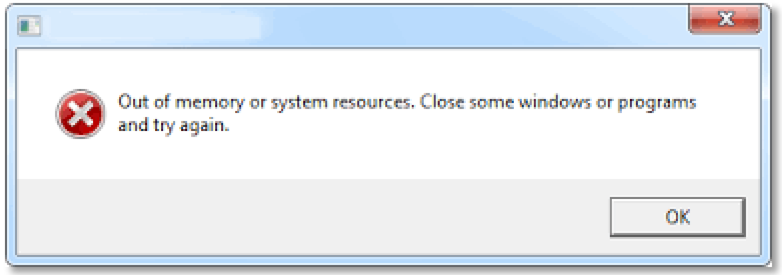
Fake it. Use “virtual memory” to provide an illusion that ISA’s entire address space is available.

A few TB is enough for most desktop machines today, or a smartphone in a few years

Computer “crashes” if your program exceeds machine’s available swap space on disk



Central to Virtual memory: Address translation

Address produced by executing a load or store is a “virtual address”

In 64-bit ISA, it is a 64-bit address, capable of addressing 2^64 bytes

Virtual memory is a hardware and software co-designed system that dynamically translates a load/store’s

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virtual address

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0x800

(which the programmer (load/store) sees as an array of bytes)

to a

Disk ID 803C4

physical address

(which the hardware uses to either index DRAM or identify where the storage resides on disk)

What are Pages?

Divide memory in chunks of **Pages** (e.g., 4KB for x86)

- Size of physical page = size of virtual page
- A virtual address consists of
  - A virtual page number
  - A page offset field (low order bits of the address)

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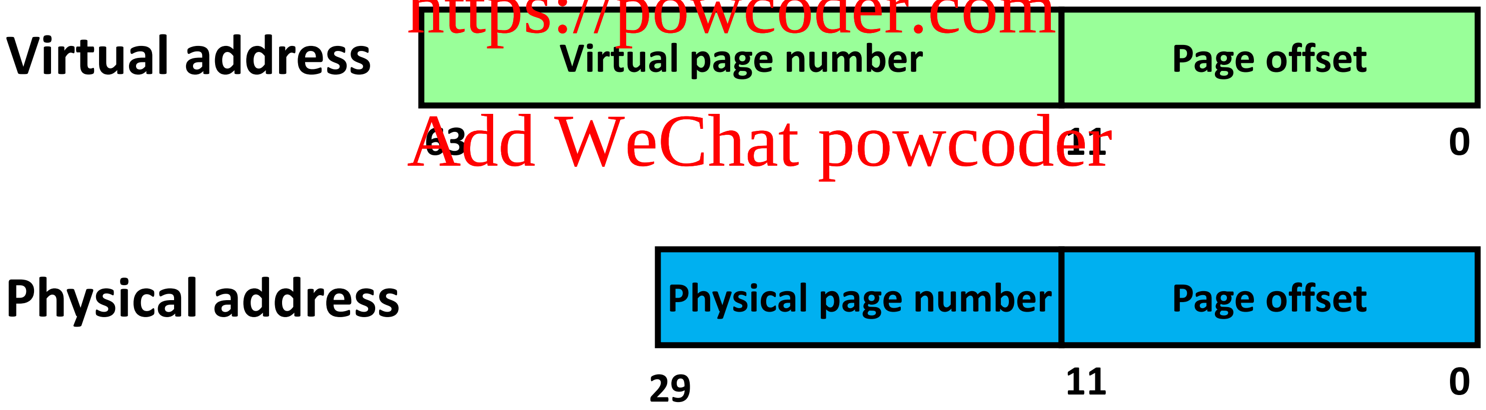

Virtual Page accesses that are not found in physical memory (DRAM) are called **Page Faults**

Data structure used for address translation: Page Table

Each process has its own page table

maintained by the operating system

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Page table contains address translation

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i.e., virtual page number ➔ physical page number

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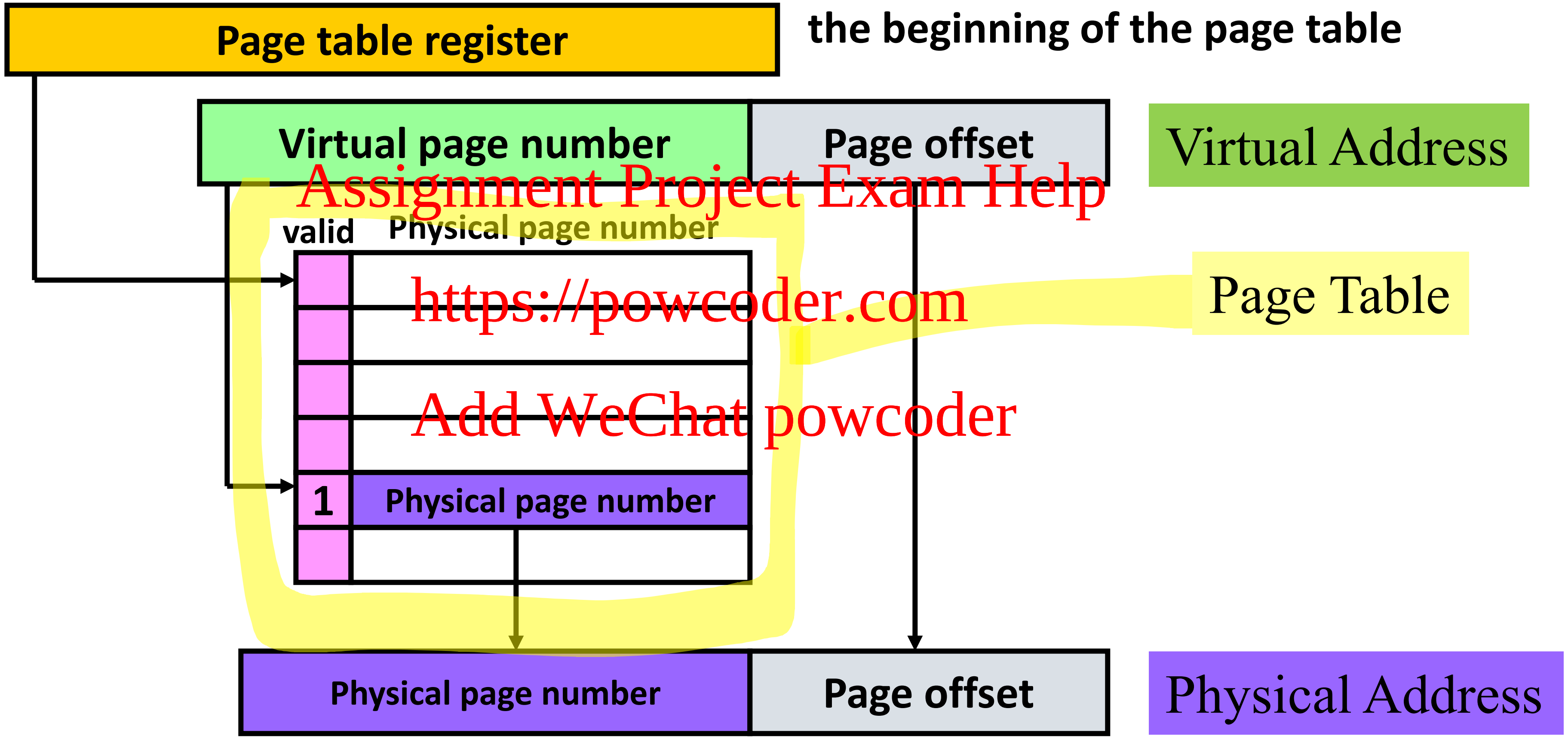
Page tables are stored in memory.

OS knows the physical address of a program's page table.

No address translation is required by the OS for accessing the page tables

Address translation using Page table

The *Page table register* points to the beginning of the page table



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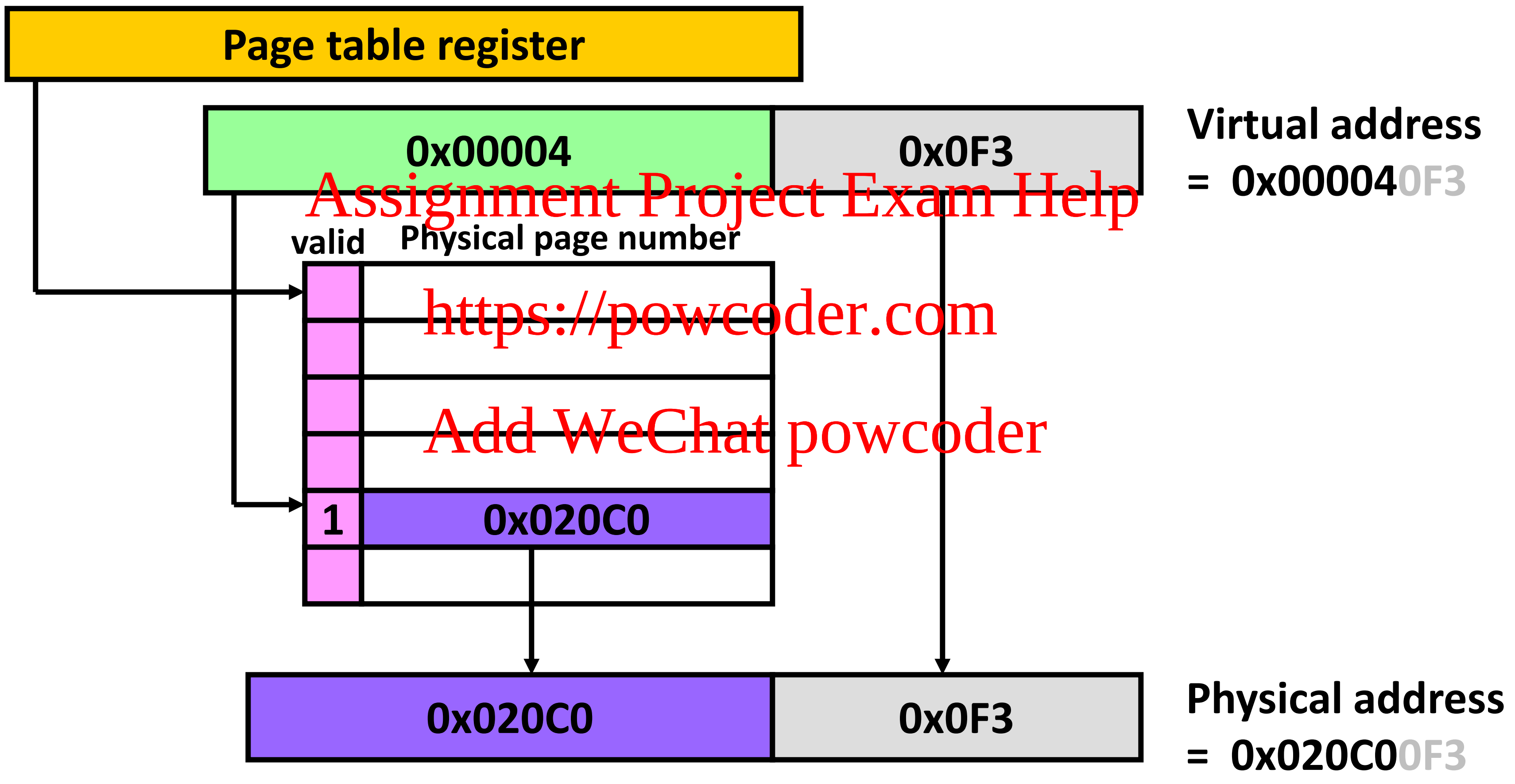
Address translation: Example



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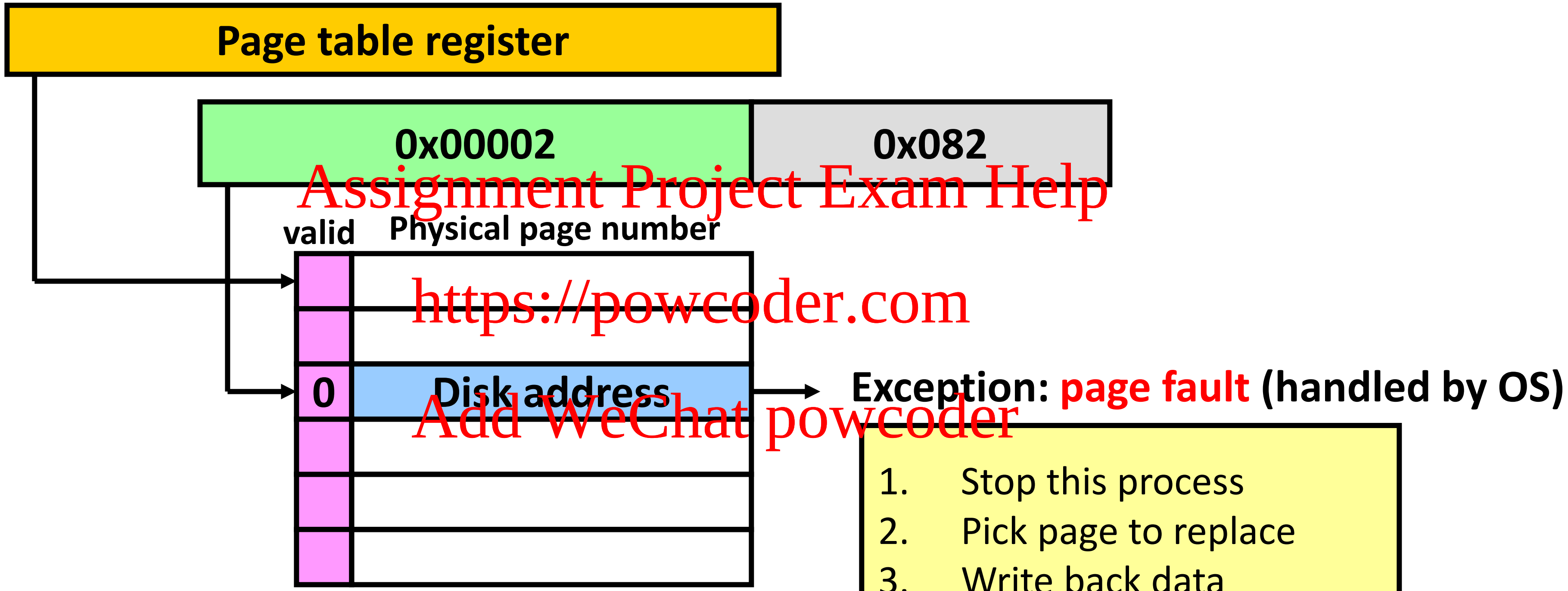
Page faults



1. Stop this process
2. Pick page to replace
3. Write back data
4. Get referenced page
5. Update page table
6. Reschedule process

Page faults :: main memory
similar to
Cache miss :: processor caches

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How do we find it on disk?

That is not a hardware problem! Go take EECS 482! ☺

This is the operating system's job. Most operating systems partition the disk into logical devices
(C: , D: , /home, etc.)

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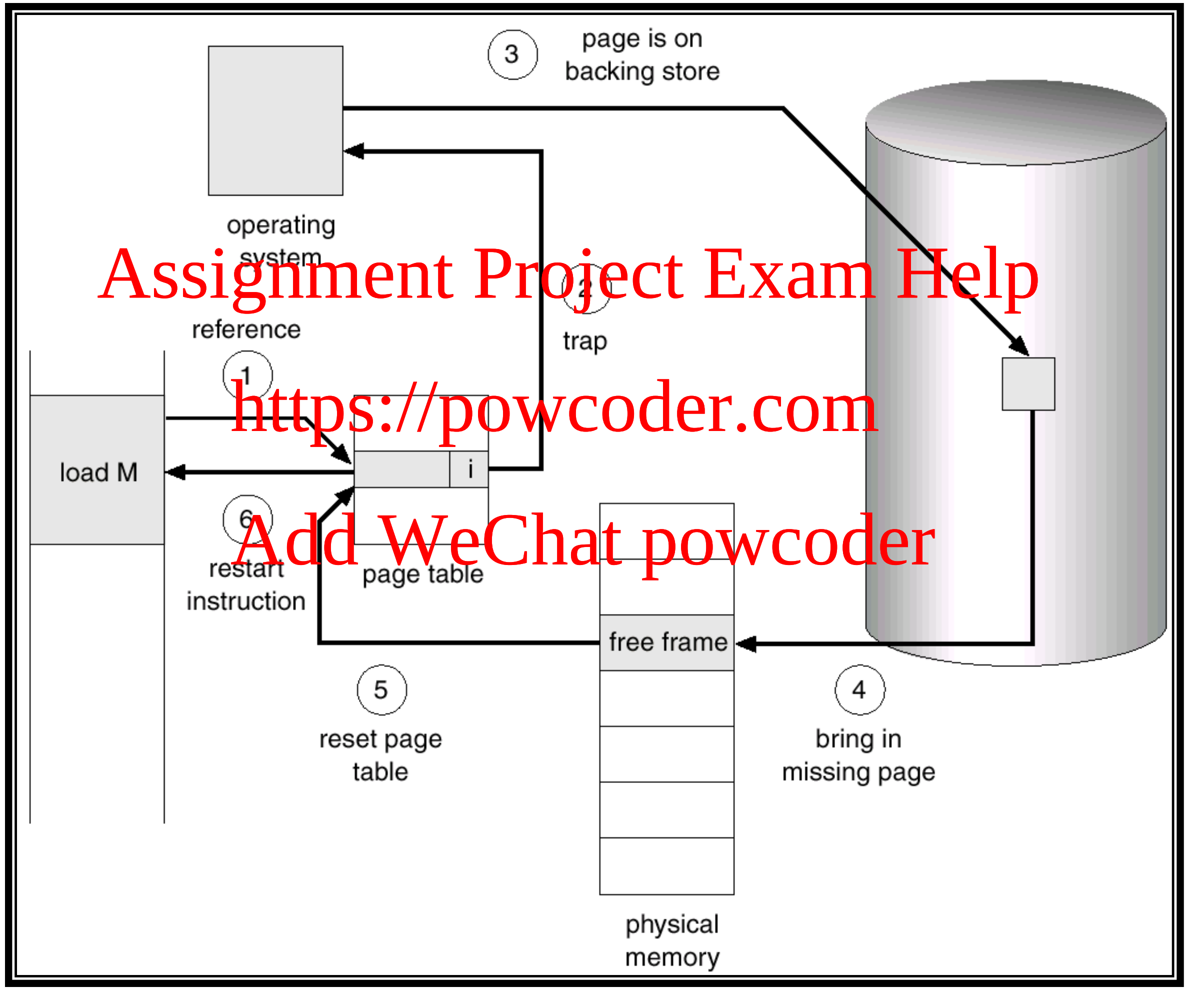
They also have a hidden partition to support the disk portion of virtual memory

- Swap partition on UNIX machines
- You then index into the correct page in the swap partition.

Operating System handles Page faults



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Slide credit: Operating System Concepts
Silberschatz, Galvin and Gagne

Who implements Virtual Memory (VM)?

When OS creates a process, it allocates a page table to it.

OS (page fault handler) makes changes to a page table

Includes page replacement

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Moves data from main memory to and fro swap space on disk

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Address translation is needed for every load/store:

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Reading from the page table every load/store would be expensive

Processor provides special support (TLB) to speed this up

VM is a good example for hardware-software co-design

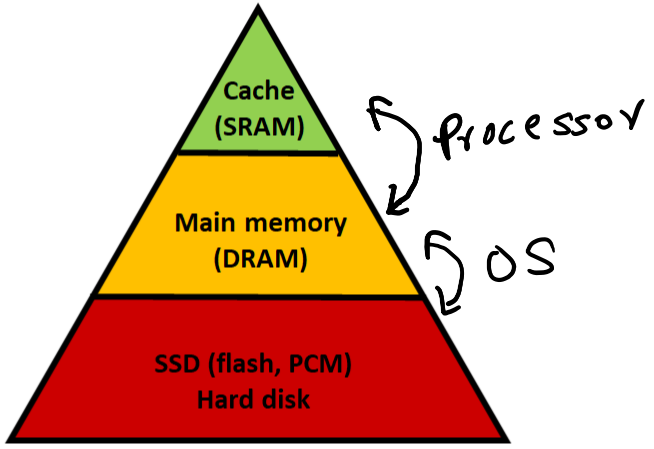
*(do not confuse VM for “Virtual Machine”, which is another concept entirely)

Main memory Vs Cache : Similarities and Differences

Data granularity:

Cache: “cache block”

Main memory: “page”



Who decides where to store and what to replace?

Cache: Processor

Main memory: Operating system

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On a “miss”

Cache: Go to main memory. Processor fetches data.

Main memory: Go to disk. OS page fault handler fetches data.

OS treats main memory like an exclusive fully-associative “cache”

Instead of searching by comparing tags, OS uses page table to find a page’s storage location

Exclusive: Data is either in main memory or in disk, not both

Processor’s last-level caches are inclusive set-associative

Class Problem

Assume the following:

20-bit byte-addressable ISA (virtual address space)

Physical memory size	:	16 KB
Page size	:	4 KB

LRU replacement policy for main memory

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Assume the following initial page-table state:

Page table	is in	physical page 0. Can never be evicted (pinned)
Virtual page 0	is in	physical page 1.
Virtual page 1	is in	physical page 2.

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Other physical pages are invalid.

Answer the following:

\# physical pages = ______________________________

\# virtual pages = __________________________________

Page offset size = __________________________________

Fill in the table on the next slide for each reference

Class Problem

Assume the following:

- 20-bit byte-addressable ISA (virtual address space)
- Physical memory size : 16 KB
- Page size : 4 KB
- LRU replacement policy for main memory

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Assume the following initial page-table state:

Page table	is in	physical page 0. Can never be evicted (pinned)
Virtual page 0	is in	physical page 1.
Virtual page 1	is in	physical page 2.

Other physical pages are invalid.

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Answer the following:

- # physical pages = 16 KB / 4 KB = 4 pages.
- # virtual pages = 2^20 / 4 KB = 2^8 = 256 pages. ➔ # entries in page table = 256
- Page offset size = log(4 KB) = 12 bits
- Fill in the table on the next slide for each reference

Page offset size = log(4 KB) = 12 bits

Class Problem: Illustration – Initial state

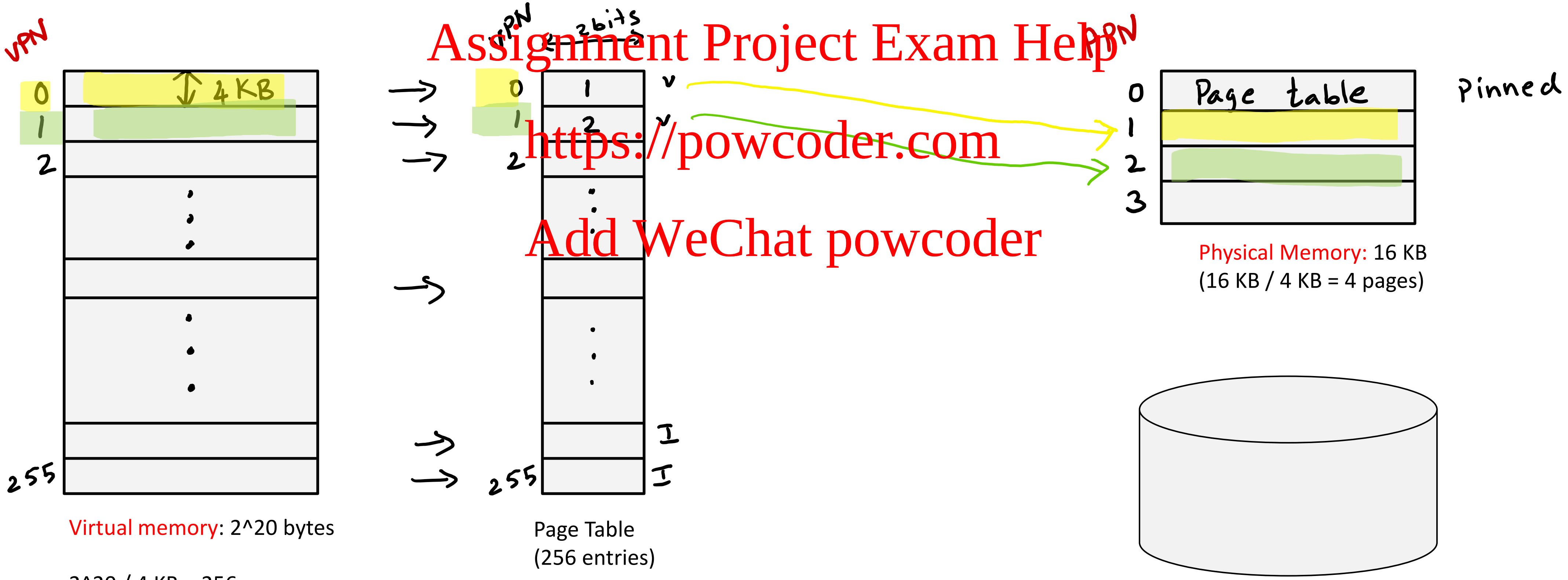
Page size = 4 KB

Virtual memory
(2^20 bytes = 256 pages)

Physical Memory
(16 KB = 4 pages)

Virtual address: Virtual page number (8 bits, bits 20–11) | Page offset (12 bits, bits 11–0)

Physical address: Physical page number (2 bits, bits 13–11) | Page offset (12 bits, bits 11–0)



Virtual memory: 2^20 bytes

2^20 / 4 KB = 256 pages

Page Table
(256 entries)

Physical Memory: 16 KB
(16 KB / 4 KB = 4 pages)

Disk
(swap partition)

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Class Problem (continued)

Virt addr	Virt page	Page fault?	Phys addr
0x00F0C			
0x01F0C			
0x20F0C			
0x00100			
0x00200			
0x30000			
0x01FFF			
0x00200			

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Class Problem (continued)

Virt addr	Virt page	Page fault?	Phys addr
0x00F0C	0x0	N	0x1F0C
0x01F0C			
0x20F0C			
0x00100			
0x00200			
0x30000			
0x01FFF			
0x00200			

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Class Problem (continued)

Virt addr	Virt page	Page fault?	Phys addr
0x00F0C	0x0	N	0x1F0C
0x01F0C	0x1	N	0x2F0C
0x20F0C			
0x00100			
0x00200			
0x30000			
0x01FFF			
0x00200			

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Class Problem (continued)

Virt addr	Virt page	Page fault?	Phys addr
0x00F0C	0x0	N	0x1F0C
0x01F0C	0x1	N	0x2F0C
0x20F0C	0x20	Y (into 3)	0x3F0C
0x00100			
0x00200			
0x30000			
0x01FFF			
0x00200			

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Class Problem (continued)

Virt addr	Virt page	Page fault?	Phys addr
0x00F0C	0x00	N	0x1F0C
0x01F0C	0x01	N	0x2F0C
0x20F0C	0x20	Y (into 3)	0x3F0C
0x00100	0x00	N	0x1100
0x00200	0x00	N	0x1200
0x30000	0x30	Y (into 2)	0x2000
0x01FFF	0x01	Y (into 3)	0x3FFF
0x00200	0x00	N	0x1200

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Virtual Memory Roles

Capacity: Main memory is not enough

Problem:

Modern systems can afford ~128 GBs DRAM space = 2^37 bytes. Programs written in 64-bit ISA need 2^64 bytes!

Need to run many programs simultaneously on the same machine. Each program may require GBs of memory.

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Solution:

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Manage main memory like an exclusive fully-associative cache. Spills to disk.

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Security features

Isolation

Unrelated programs must not have access to each other’s data

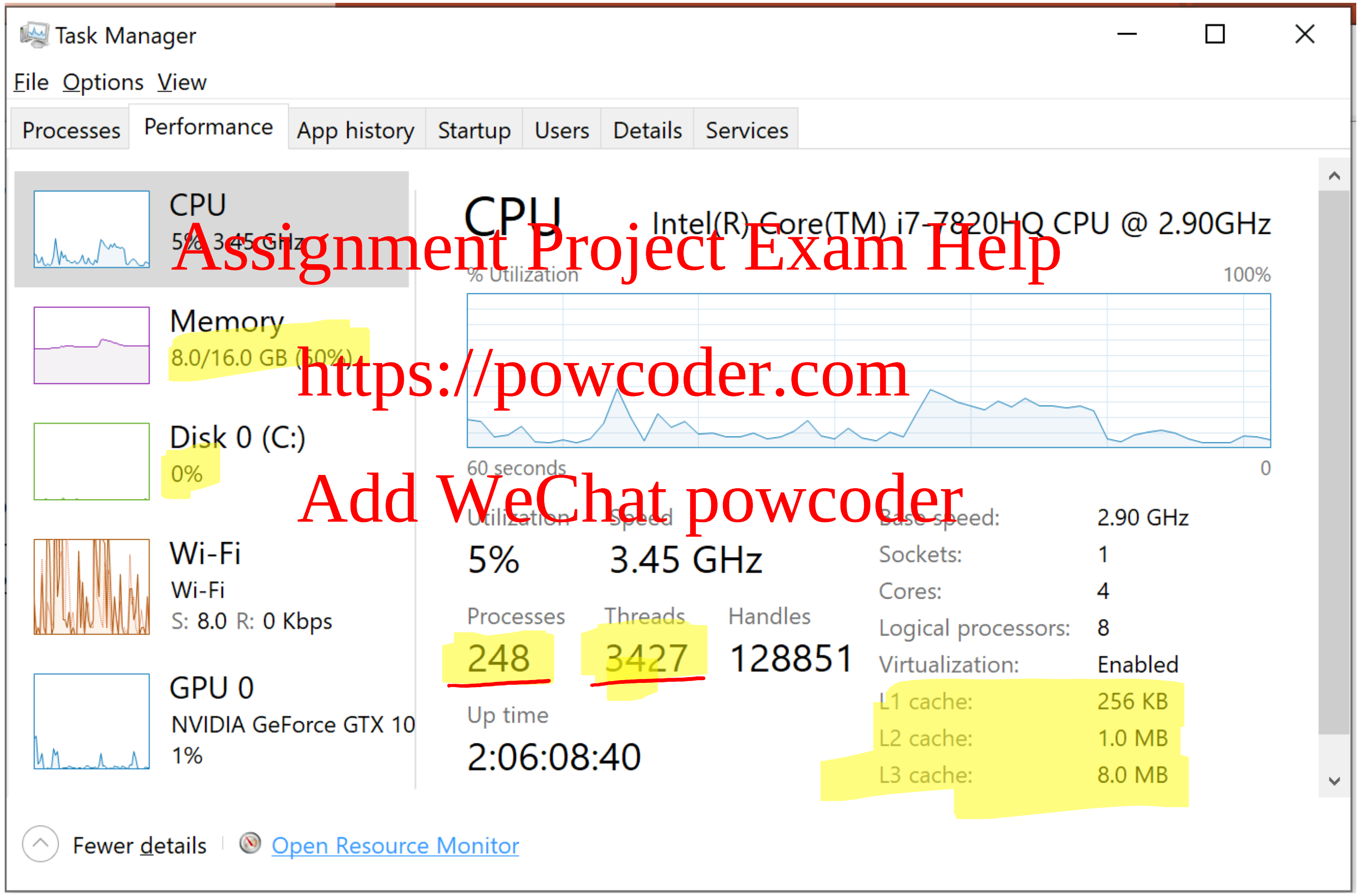
Permissions

Programs may want to share data and code (e.g., library)

Programs may want to disable read/write permissions to some portions of memory

e.g., mark instructions are read-only, no read/write permission for unallocated heap

Processes and threads on my computer



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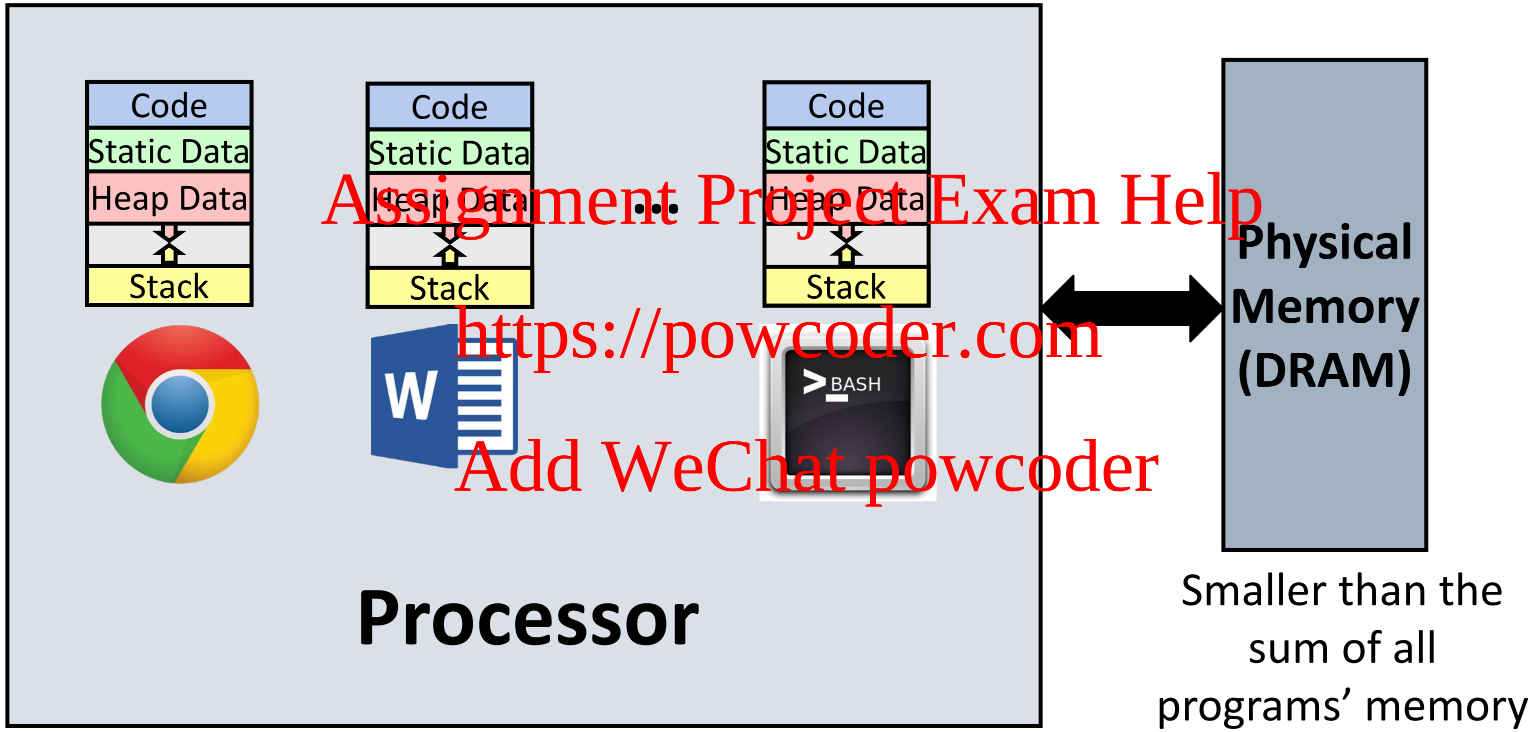
Revisit real system view—multitasking



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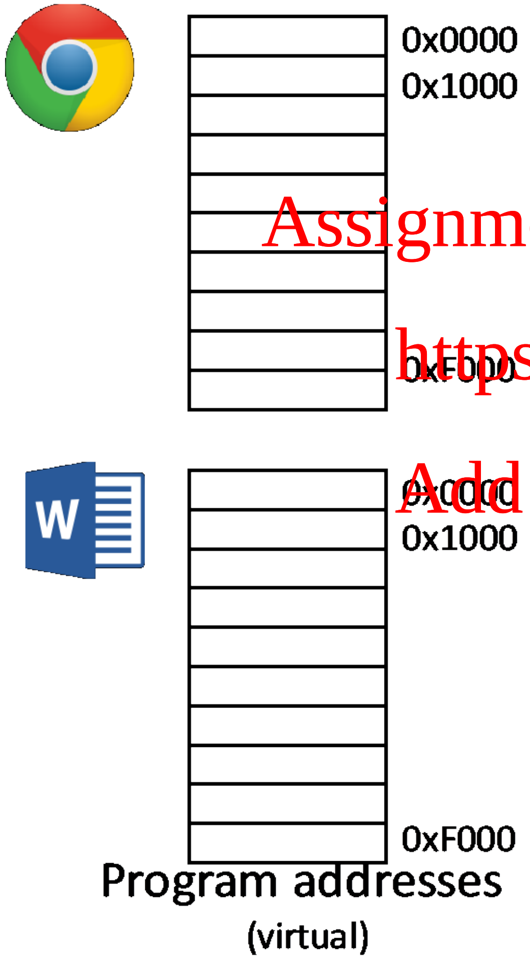
How to achieve isolation?



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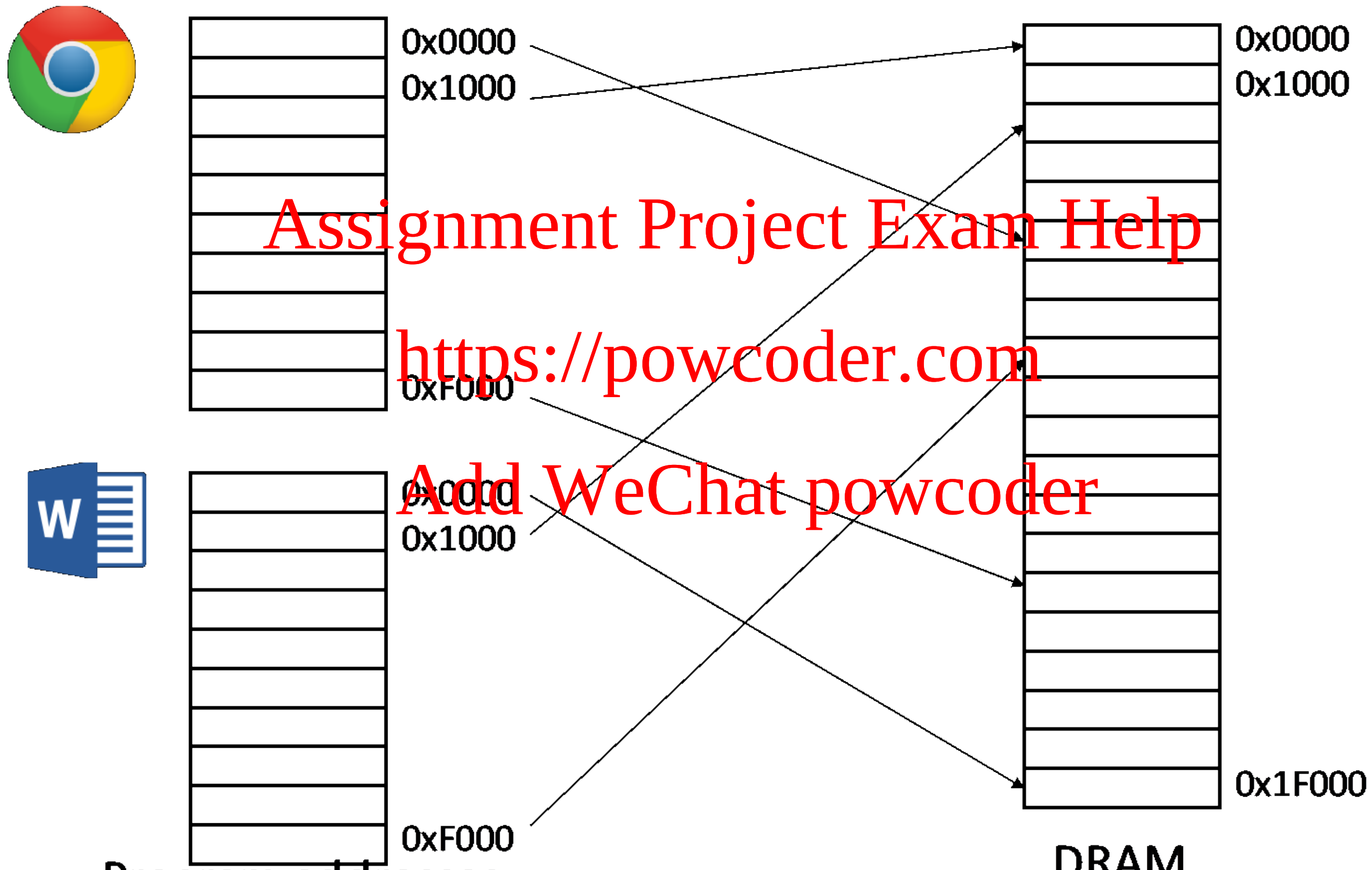
How to achieve isolation?



Program addresses
(virtual)

DRAM
(physical)

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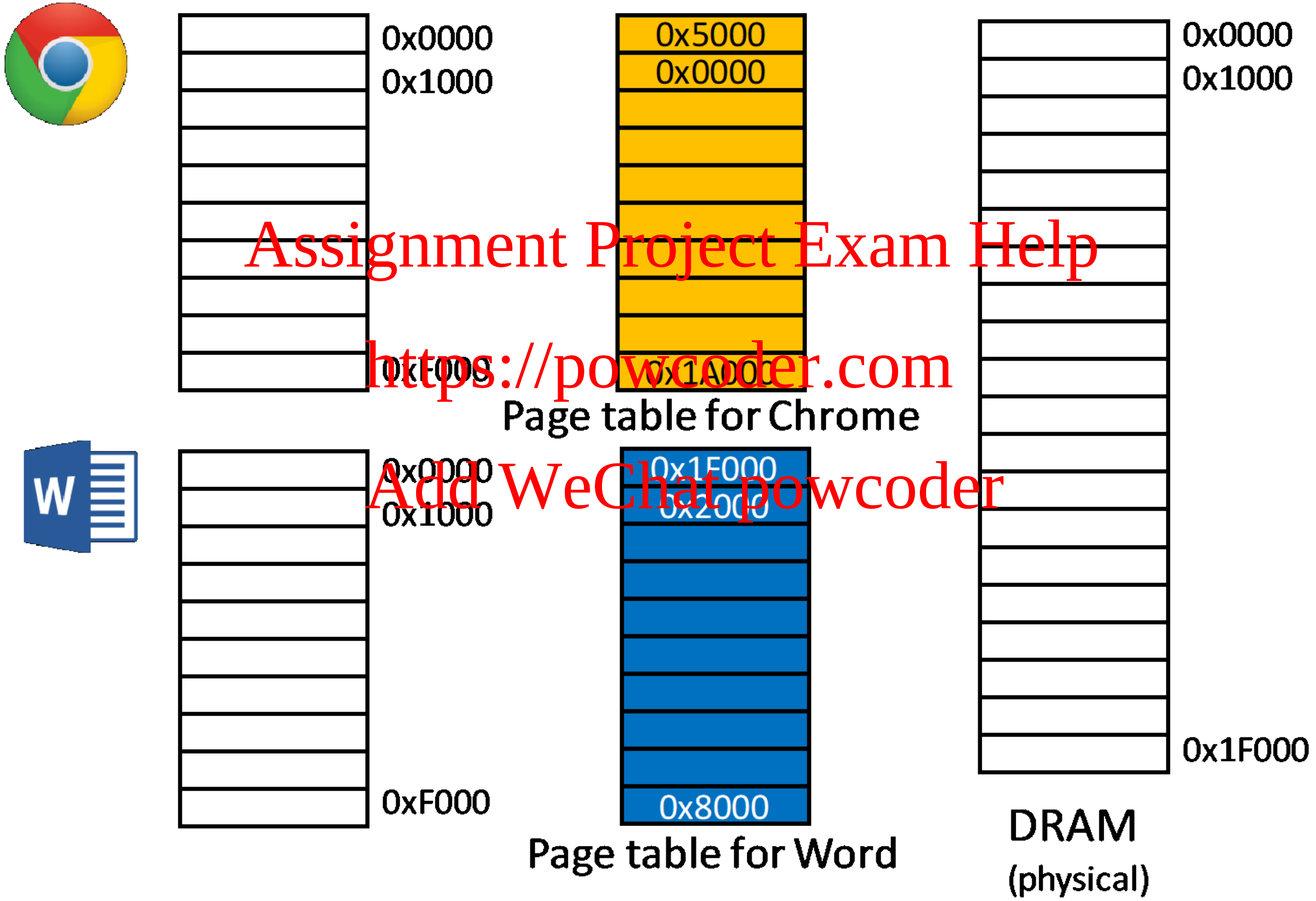
How to achieve isolation?



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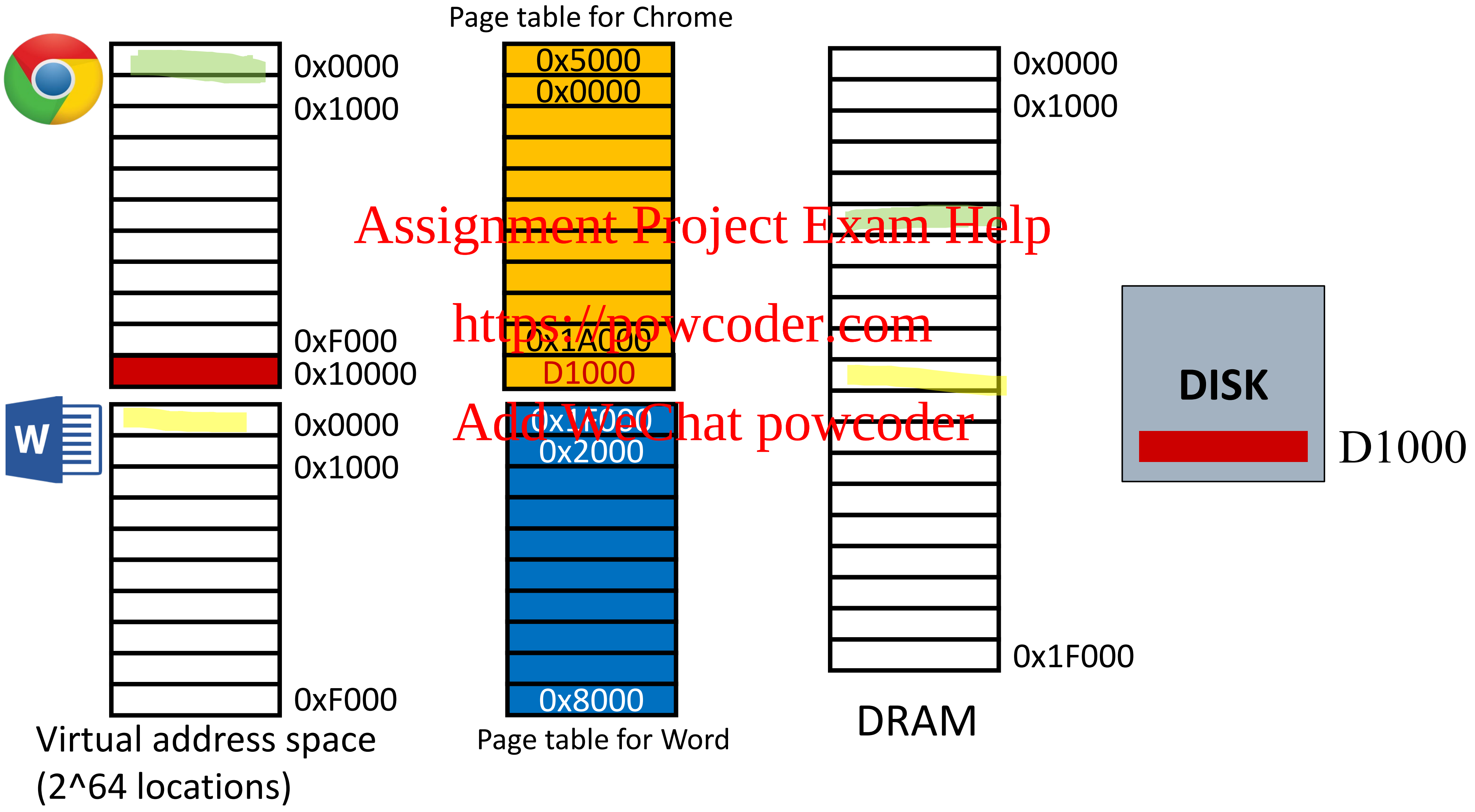
Some pages may be swapped out to disk



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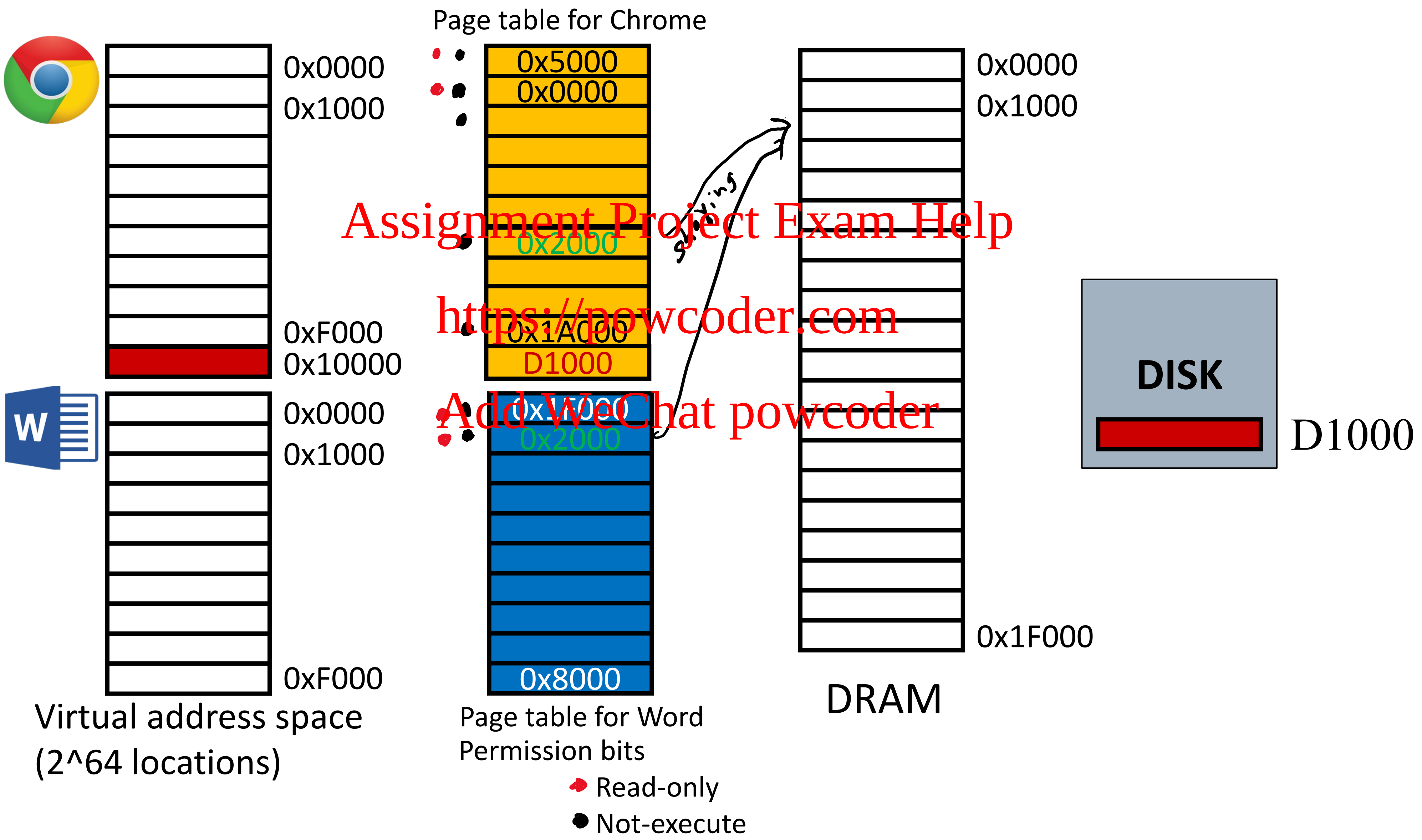
Programs may want to disable read/write permissions to some portions of memory

e.g., mark instructions are read-only, no read/write permission for unallocated heap

Some pages can be shared between programs; Permissions per page: invalid, read-only, not-execute, etc.



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VM integration with processor caches (to be discussed later)

VM systems give us two different addresses:

virtual and physical

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Which address should we use to access the data cache?

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- Virtual address (before VM translation).
  - Faster access.
  - More complex.
- Physical address (after VM translations).
  - Delayed access.

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virtual address → $\boxed{\text{cache}}$ $\xrightarrow{\text{miss}}$ $\boxed{\text{Address translation}}$ → Physical address → $\boxed{\text{Main memory}}$

virtual address → $\boxed{\text{Adress translation}}$ → Physical address → $\boxed{\text{Cache}}$ $\xrightarrow{\text{miss}}$ $\boxed{\text{main memory}}$

Check your computer

System Information

File Edit View Help

- System Summary
  - Hardware Resources
    - Conflicts/Sharing
    - DMA
    - Forced Hardware
    - I/O
    - IRQs
    - Memory
  - Components
    - Multimedia
    - CD-ROM
    - Sound Device
    - Display
    - Infrared
    - Input
    - Modem
    - Network
    - Ports
    - Storage
      - Drives
      - Disks
      - SCSI
      - IDE
    - Printing
    - Problem Devices
    - USB
  - Software Environment

Item	Value
OS Name	Microsoft Windows 10 Pro
Version	10.0.18363 Build 18363
Other OS Description	Not Available
OS Manufacturer	Microsoft Corporation
System Name	DESKTOP[redacted]
System Manufacturer	Microsoft Corporation
System Model	Surface Studio 2
System Type	x64-based PC
System SKU	Surface_Studio_2_1707_Commercial
Processor	Intel(R) Core(TM) i7-7820HQ CPU @ ...
BIOS Version/Date	Microsoft Corporation 532.3238.768, ..
SMBIOS Version	3.2
Embedded Controller Version	255.255
BIOS Mode	UEFI
BaseBoard Manufacturer	Microsoft Corporation
BaseBoard Product	Surface Studio 2
BaseBoard Version	Not Available
Platform Role	Desktop
Secure Boot State	On
PCR7 Configuration	Elevation Required to View
Windows Directory	C:\WINDOWS
System Directory	C:\WINDOWS\system32
Boot Device	\Device\HarddiskVolume1
Locale	United States
Hardware Abstraction Layer	Version = "10.0.18362.1171"
User Name	[redacted]
Time Zone	Eastern Standard Time
Installed Physical Memory (RAM)	16.0 GB
Total Physical Memory	16.0 GB
Available Physical Memory	6.73 GB
Total Virtual Memory	29.5 GB
Available Virtual Memory	5.74 GB
Page File Space	13.5 GB
Page File	C:\pagefile.sys
Kernel DMA Protection	Off
Virtualization-based security	Not enabled
Device Encryption Support	Elevation Required to View
Hyper-V - VM Monitor Mode Extensi...	Yes
Hyper-V - Second Level Address Tran...	Yes
Hyper-V - Virtualization Enabled in F...	Yes
Hyper-V - Data Execution Protection	Yes

?

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