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22. Virtual Memory: Basics

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EECS 370 – Introduction to Computer Organization – Fall 2020

<https://powcoder.com>

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Add WeChat powcoder

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Announcement

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

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Interactive Cache Simulator Add WeChat powcoder

Instructions ?

Cache ?

Memory (512 B) ?

Set 0

INV INV INV INV

Set 1

INV INV INV INV

Set 2

INV INV INV INV

Cache Configuration ?

Custom # Hits 0 # Misses 0

Block Size (B) 8 # Sets 4 # Blocks/Set 4

Verify Step > >>

Load Instructions

0

1

2

3

4

5

6

7

8

9

10

11

12

13

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

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Go check cache organization in your computer!

For Linux you can use following command:

`$: sudo dmidecode -t cache`

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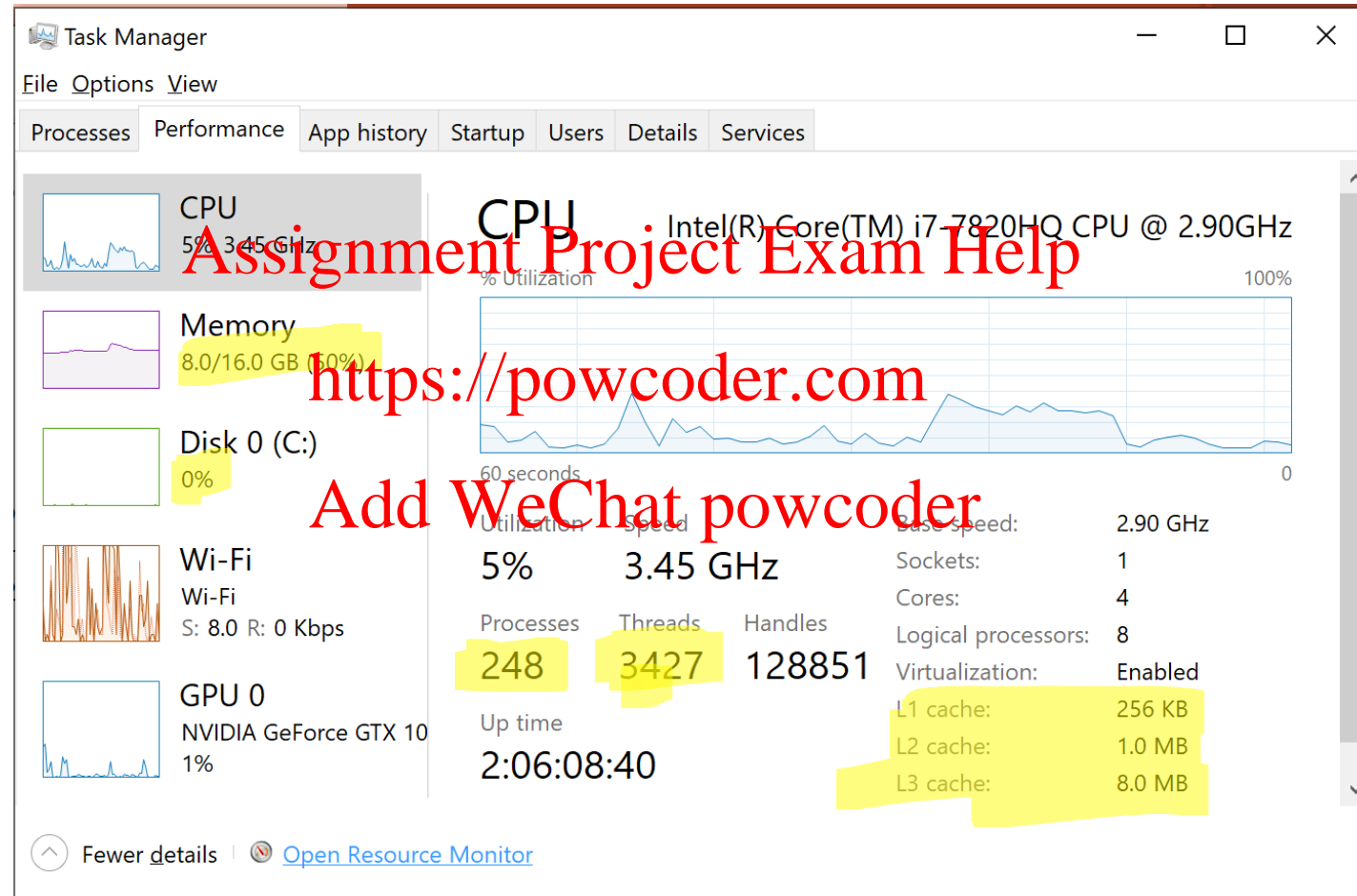
DMI—desktop management interface

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

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3 Levels of Caches on a Modern Computer

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Memory System: Learning objective

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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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<https://powcoder.com>

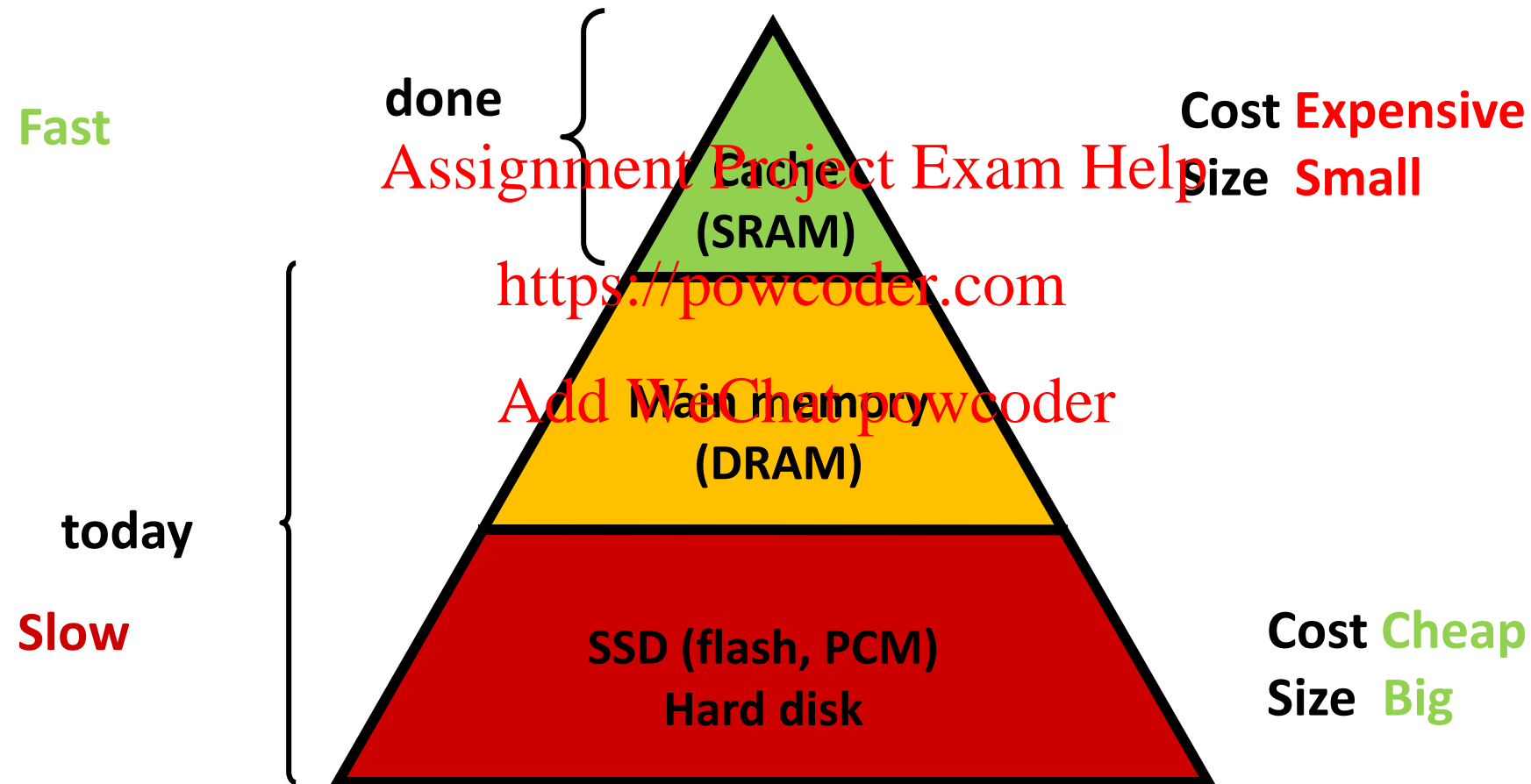
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Problem: No one memory technology is both fast and big to store all of program's data

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

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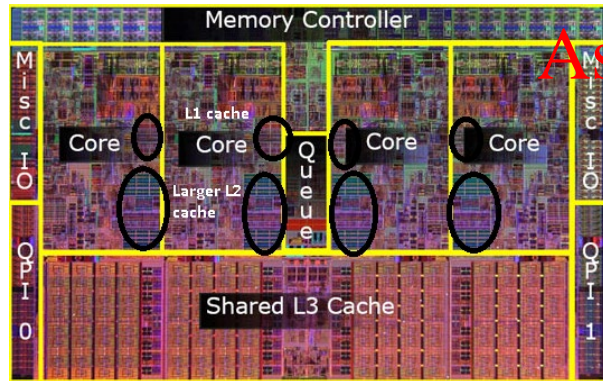
Memory Pyramid



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A modern computing system is composed of several memory devices

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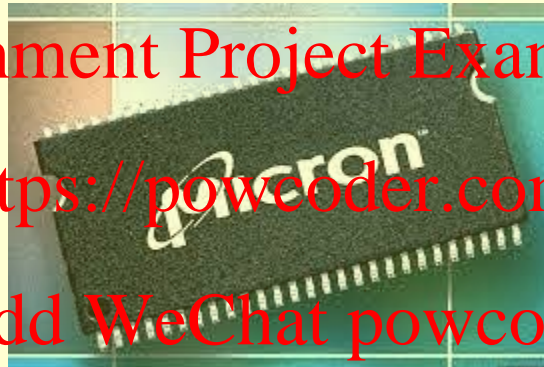


Processor
w/ three levels of
caches

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<https://powcoder.com>

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Main memory
(DRAM)



SSD Flash



Hard disk

Focus today: Virtual Memory

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Virtual Memory
<https://powcoder.com>

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What is Virtual Memory?

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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

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Virtual Memory Roles

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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.

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

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How to be **not limited by DRAM capacity?**

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

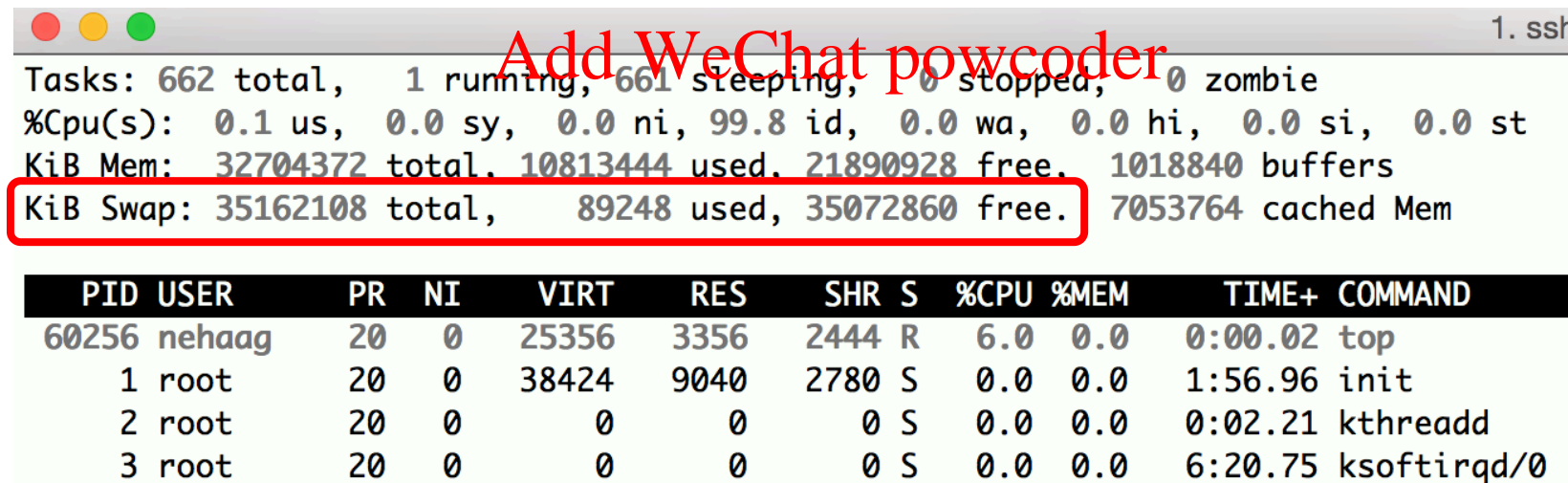
This space in disk is called **swap partition** in Linux-based systems

For fun check swap space in a linux system by:

\$: `top`

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<https://powcoder.com>



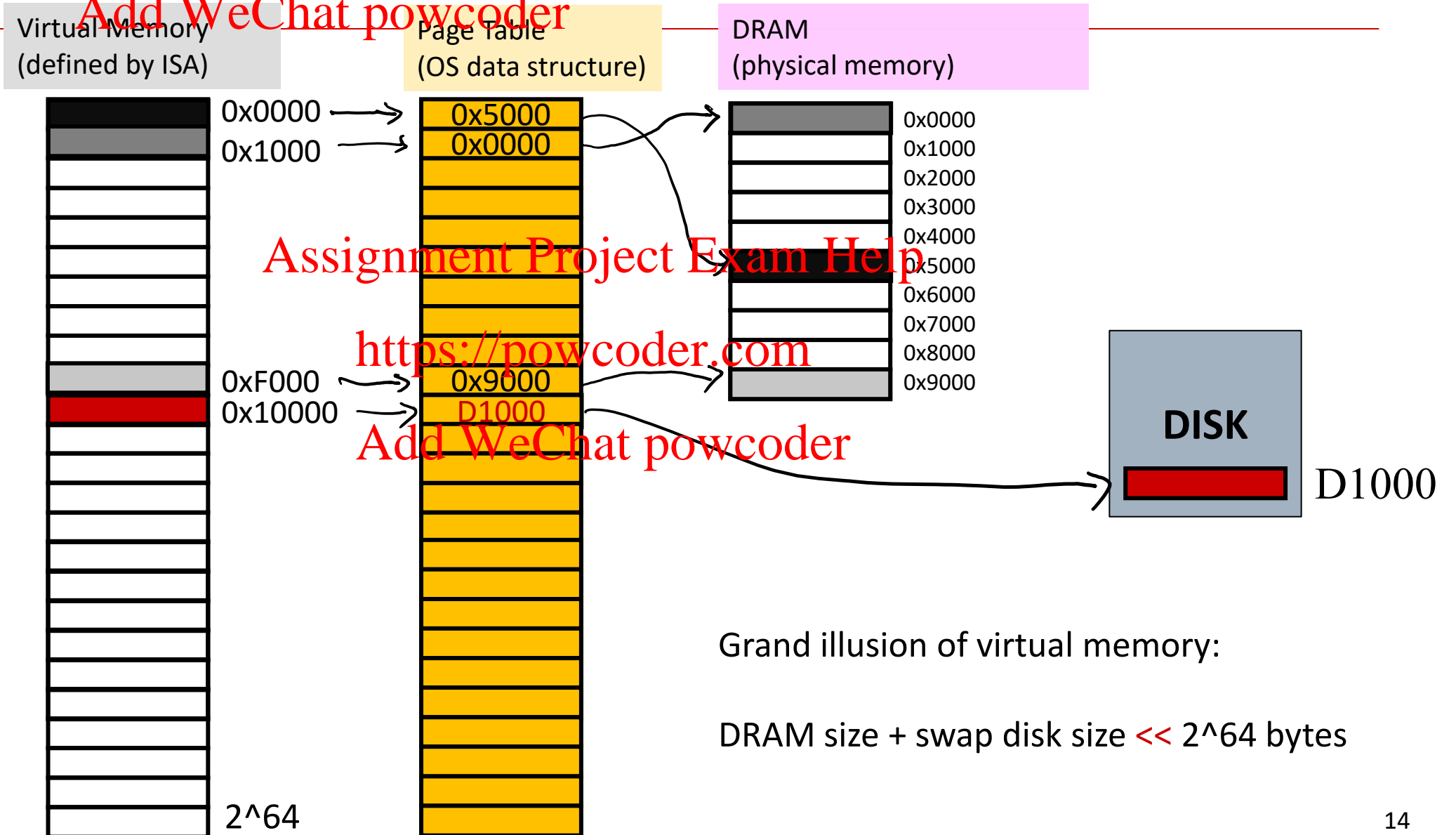
The screenshot shows a terminal window titled "1. ssh". It displays system statistics from the 'top' command. A red box highlights the swap space information: "KiB Swap: 35162108 total, 89248 used, 35072860 free. 7053764 cached Mem". Below the statistics is a table of running processes.

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
60256	nehaag	20	0	25356	3356	2444	R	6.0	0.0	0:00.02	top
1	root	20	0	38424	9040	2780	S	0.0	0.0	1:56.96	init
2	root	20	0	0	0	0	S	0.0	0.0	0:02.21	kthreadd
3	root	20	0	0	0	0	S	0.0	0.0	6:20.75	ksoftirqd/0

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How to be not limited by DRAM capacity?

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

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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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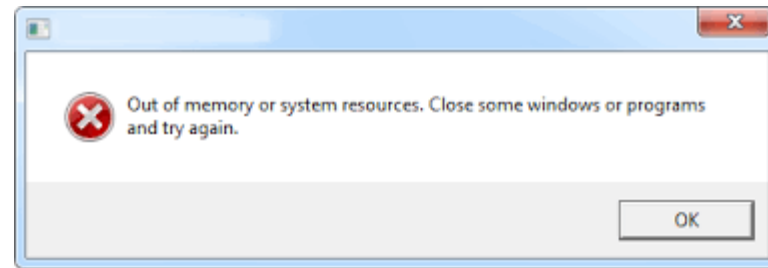
<https://powcoder.com>

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

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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



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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

0x800

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

to a

physical address

Disk ID 803C4

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

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What are Pages?

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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)

Virtual address



63 31 0

Physical address



29 11 0

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

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Data structure used for address translation: Page Table

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Each process has its own page table
maintained by the operating system

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Page table contains address translation
i.e., virtual page number → physical page number

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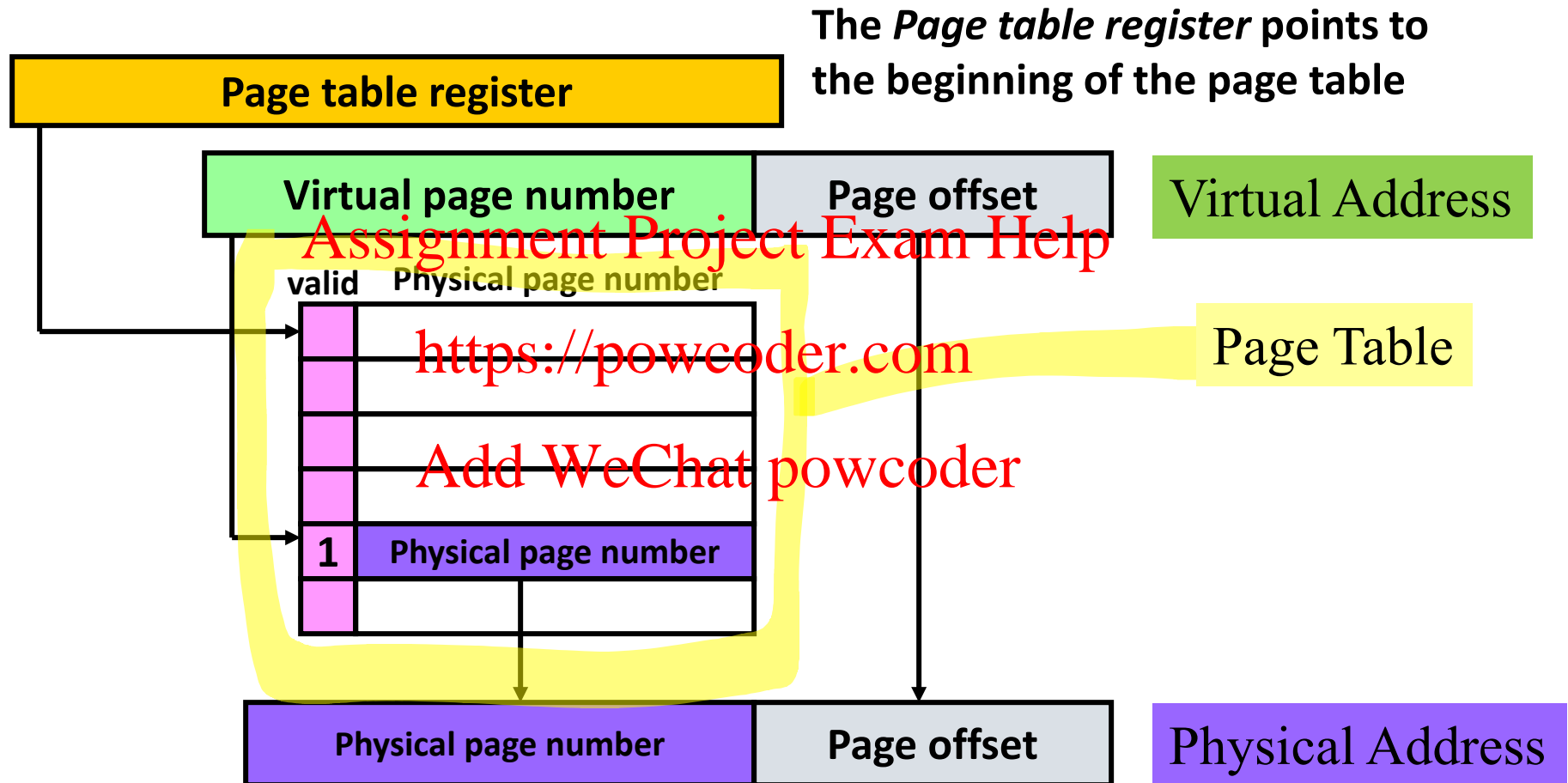
Page tables are stored in memory.

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

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

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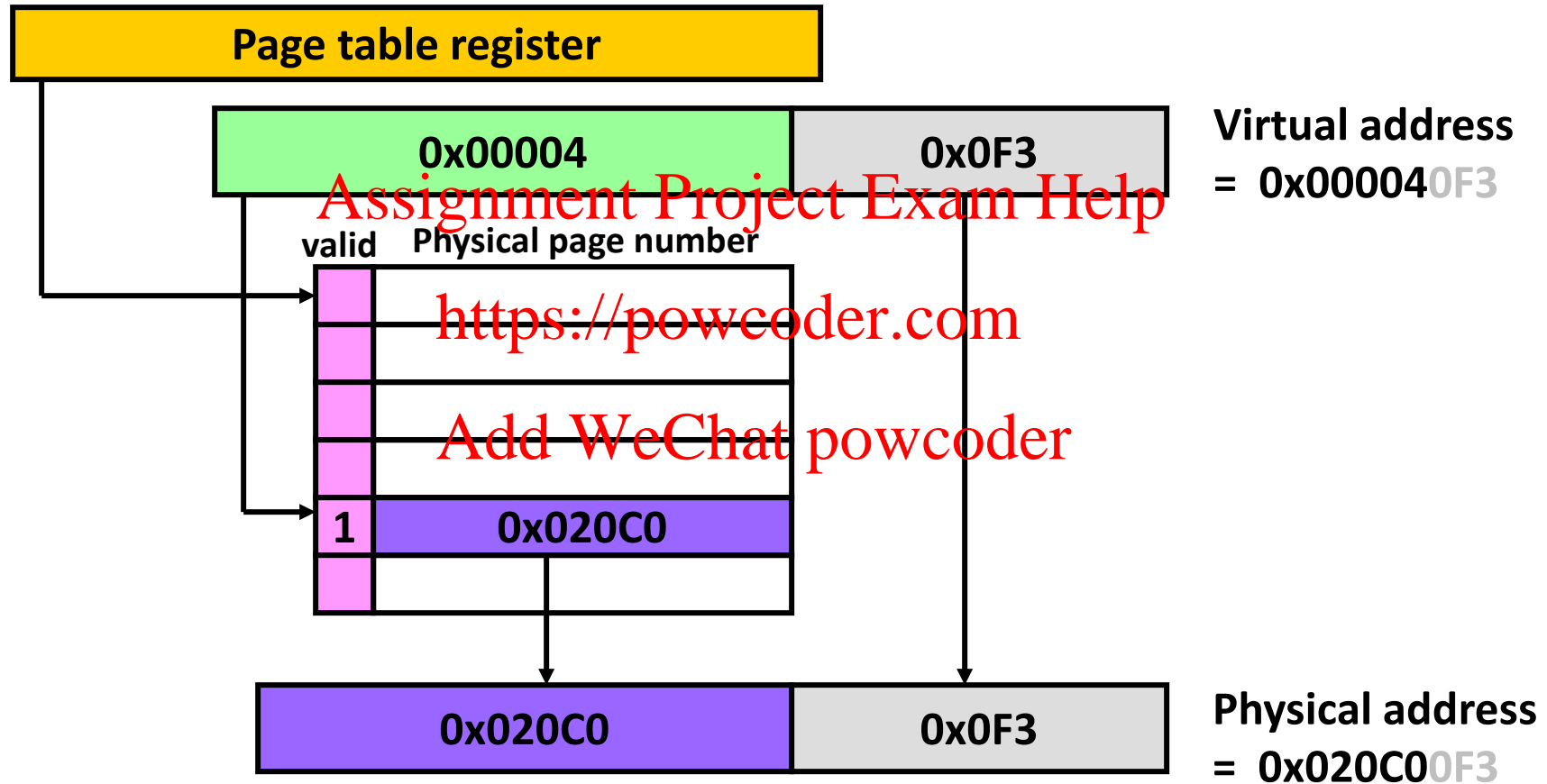
Address translation using Page table



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Address translation: Example

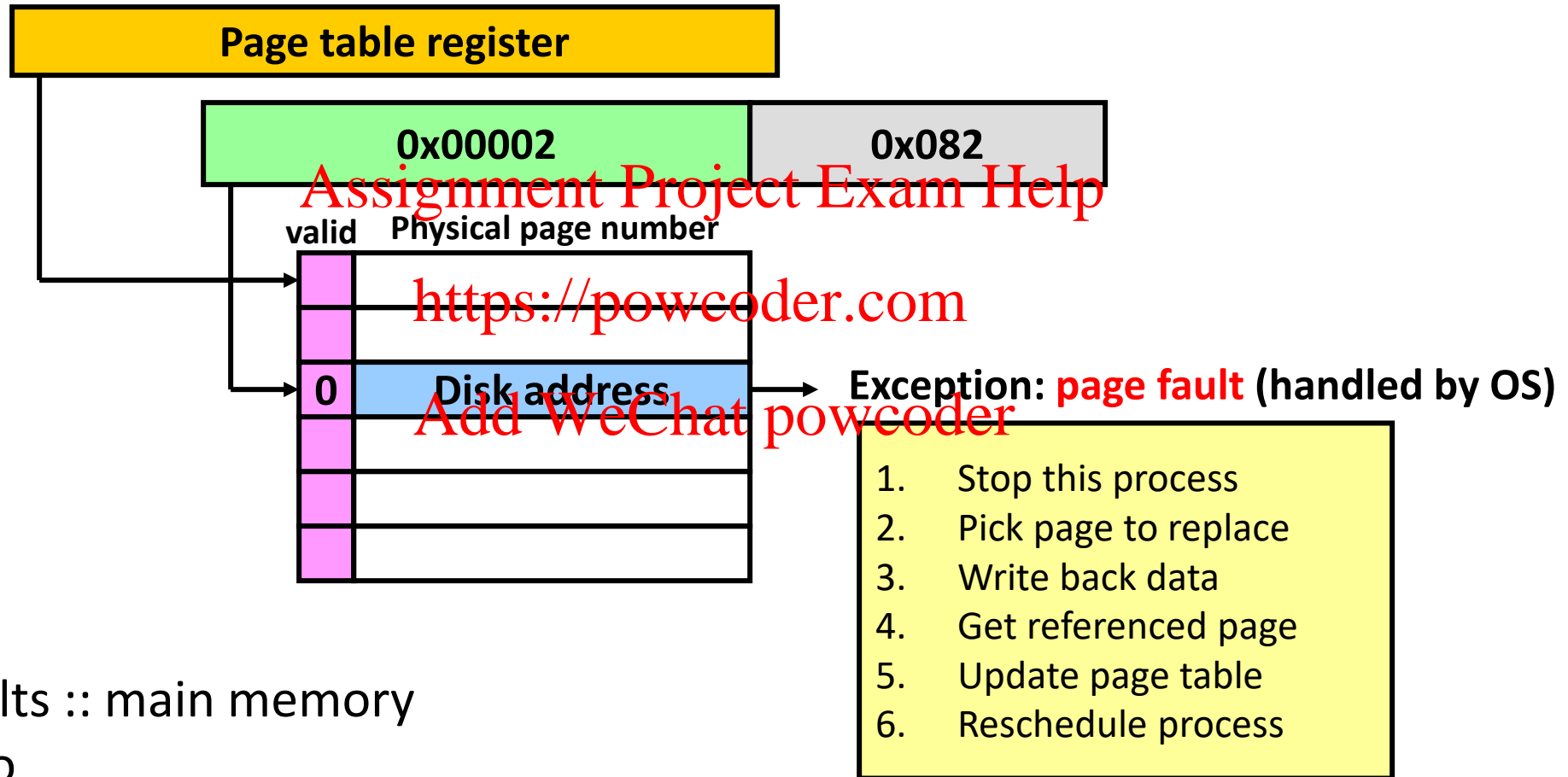
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Page faults

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Page faults :: main memory
similar to

Cache miss :: processor caches

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How do we find it on disk?

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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

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(C: , D: , /home, etc.)

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

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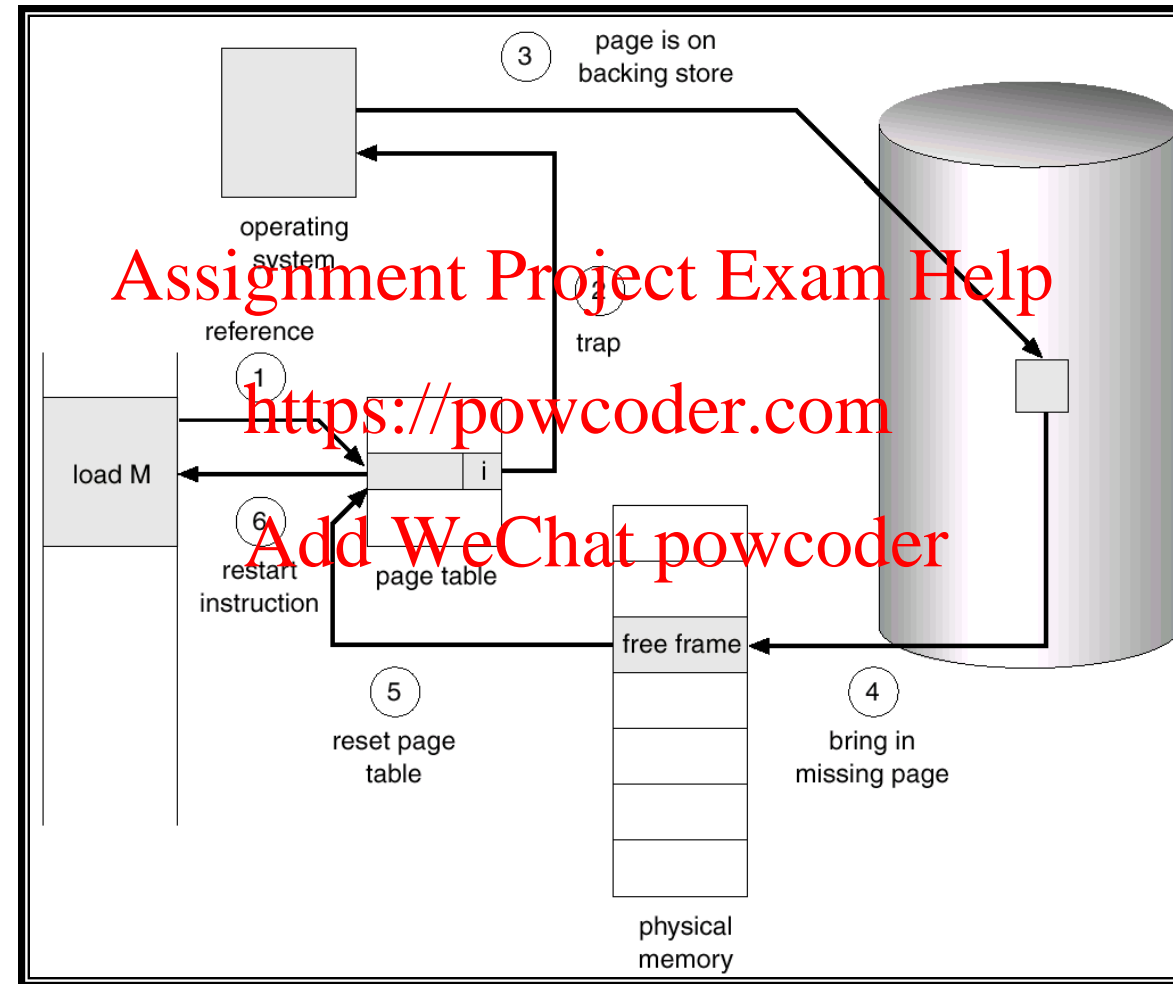
Swap partition on UNIX machines

You then index into the correct page in the swap partition.

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Operating System handles Page faults

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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

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

<https://powcoder.com>

Address translation is needed for every load/store:

- 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)

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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

On a “miss”

Cache:

Go to main memory. Processor fetches data.

Main memory:

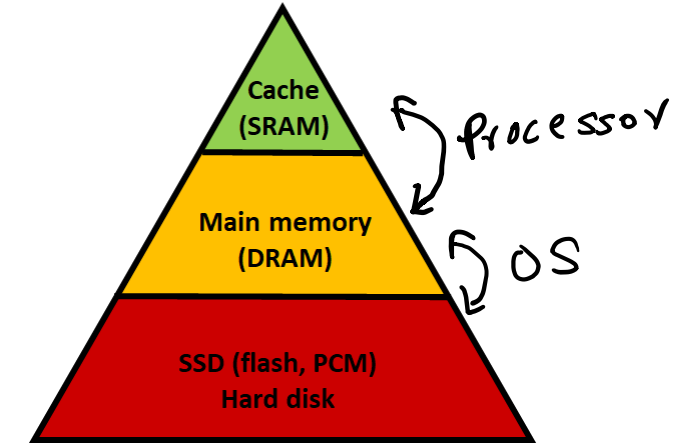
Go to disk. OS **page fault** handler fetches data.

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



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Class Problem

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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:

<https://powcoder.com>

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

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Class Problem

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Assume the following:

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

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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 = $16 \text{ KB} / 4 \text{ KB} = 4$ pages.

virtual pages = $2^{20} / 4 \text{ KB} = 2^8 = 256$ pages. \rightarrow # entries in page table = 256

Page offset size = $\log(4 \text{ KB}) = 12$ bits

Fill in the table on the next slide for each reference

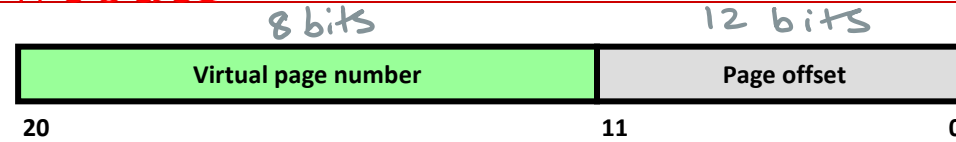
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$$\text{Page offset size} = \log(4 \text{ KB}) = 12 \text{ bits}$$

Class Problem: Illustration – Initial state

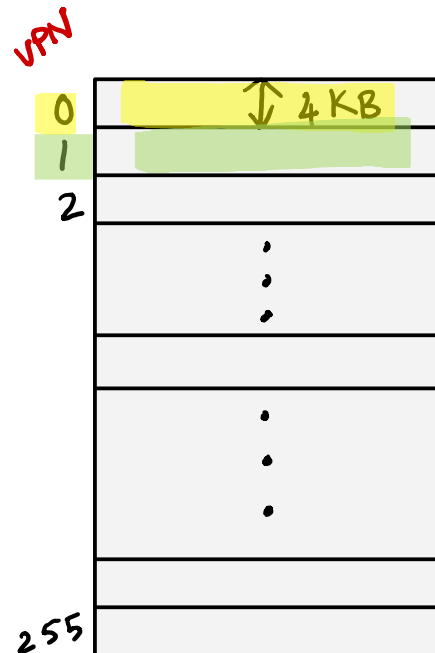
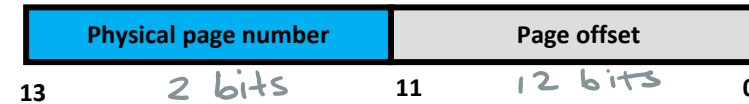
Virtual memory
(2^{20} bytes = 256 pages)

Virtual address



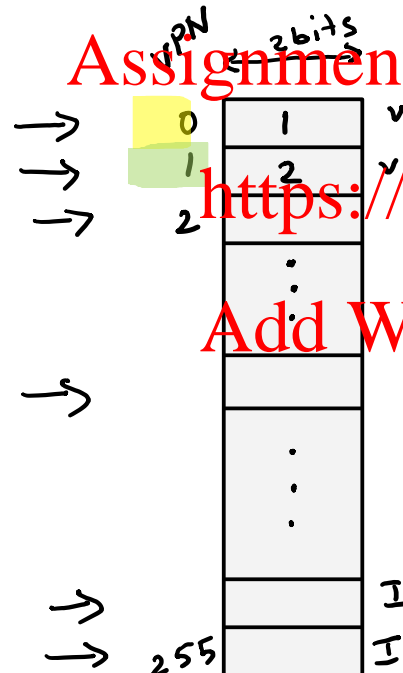
Physical Memory
(16 KB = 4 pages)

Physical address



Virtual memory: 2^{20} bytes

$$2^{20} / 4 \text{ KB} = 256 \text{ pages}$$

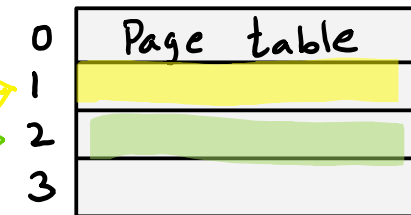


Page Table
(256 entries)

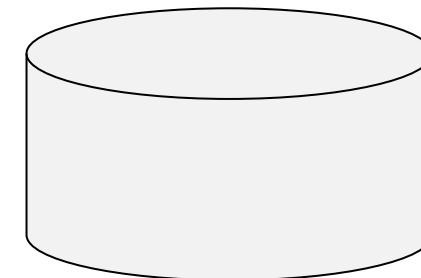
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Physical Memory: 16 KB
(16 KB / 4 KB = 4 pages)



Disk
(swap partition)

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Class Problem (continued)

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Virt addr	Virt page	Page fault?	Phys addr
0x00F0C			
0x01F0C	Assignment Project Exam Help https://powcoder.com Add WeChat powcoder		
0x20F0C			
0x00100			
0x00200			
0x30000			
0x01FFF			
0x00200			

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Class Problem (continued)

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Virt addr	Virt page	Page fault?	Phys addr
0x00F0C	0x0	N	0x1F0C
0x01F0C	Assignment Project Exam Help https://powcoder.com Add WeChat powcoder		
0x20F0C			
0x00100			
0x00200			
0x30000			
0x01FFF			
0x00200			

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Class Problem (continued)

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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)

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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)

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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

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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.

Solution:

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<https://powcoder.com>

Security features

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Isolation

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

Permissions

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

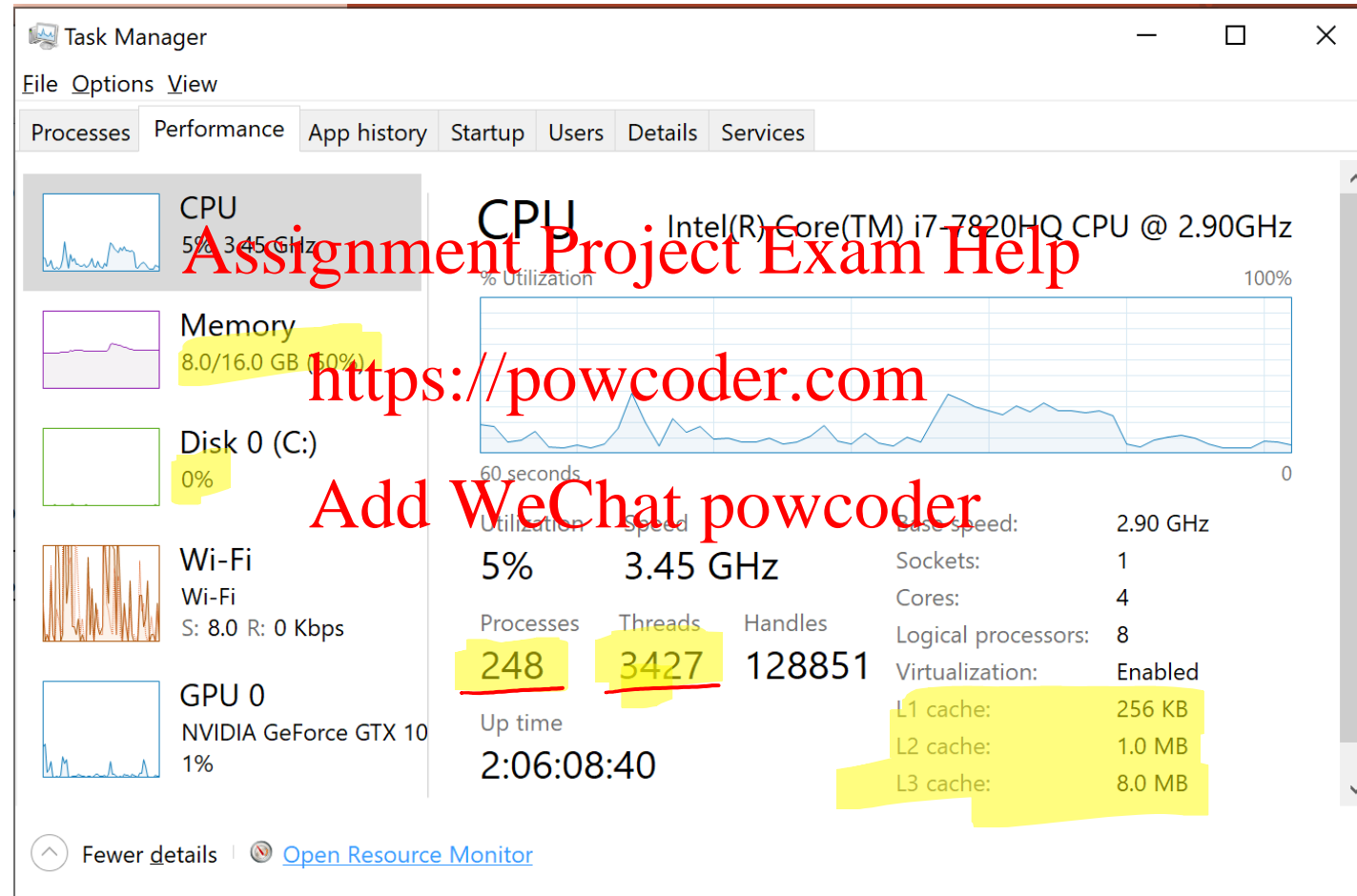
Programs may want to **disable read/write permissions** to some portions of memory

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

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Processes and threads on my computer

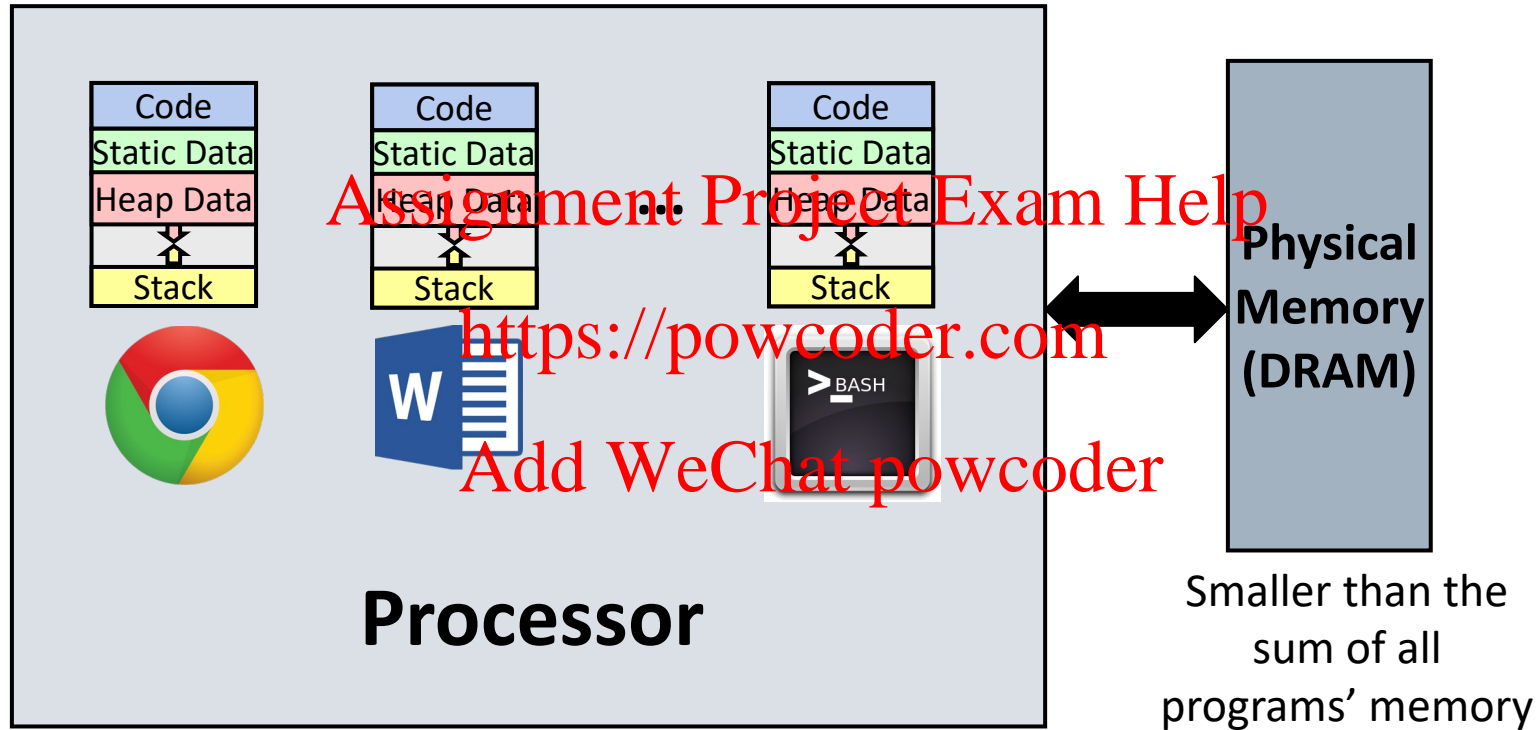
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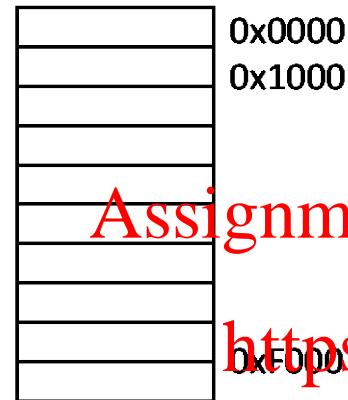
Revisit real system view—multitasking

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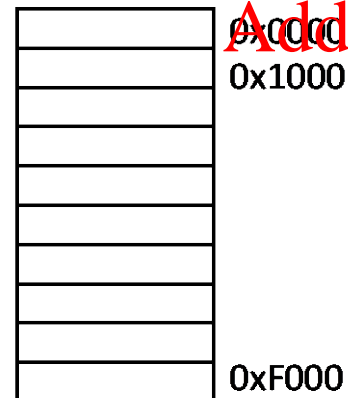
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How to achieve **isolation**?



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<https://powcoder.com>



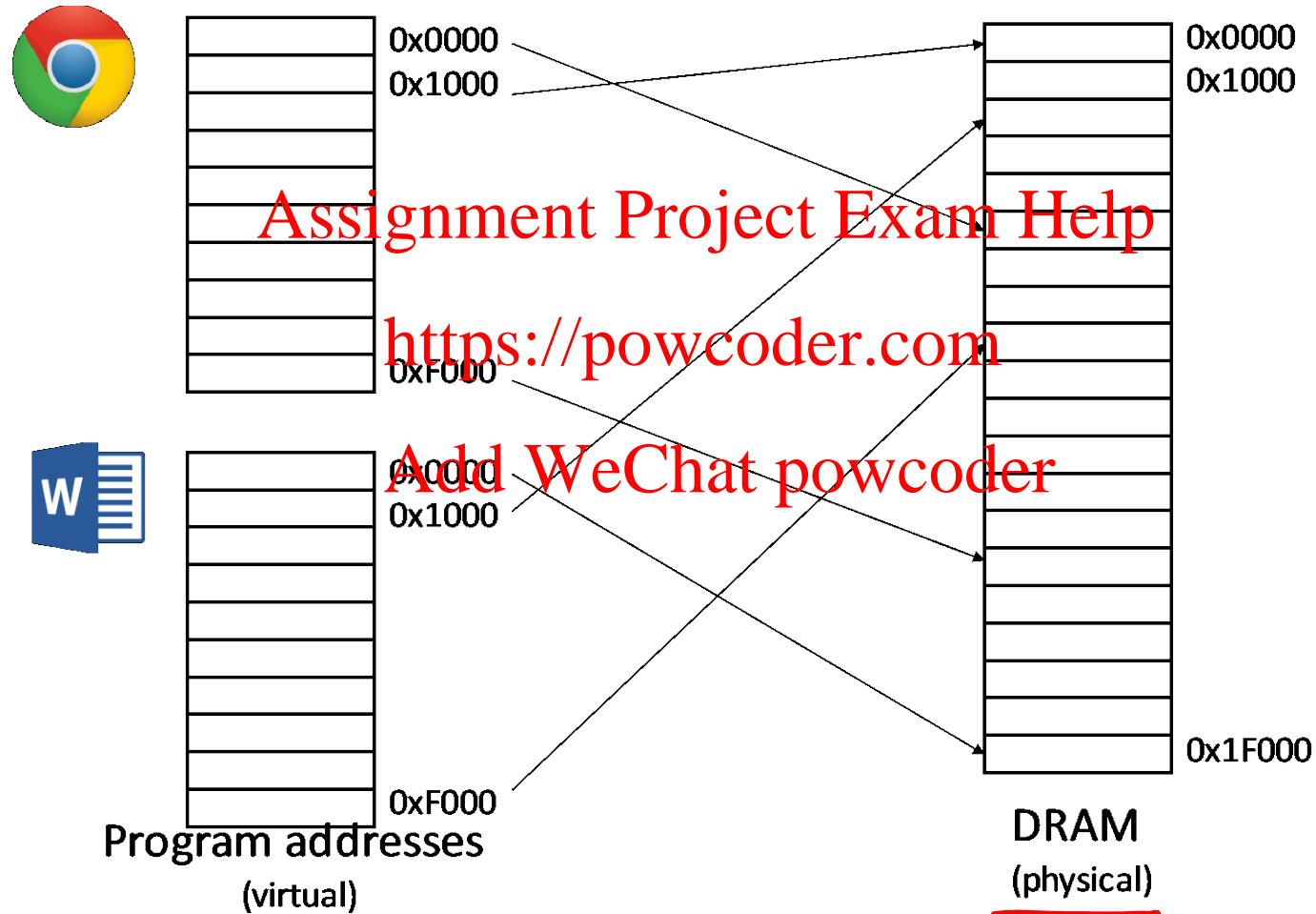
Program addresses
(virtual)

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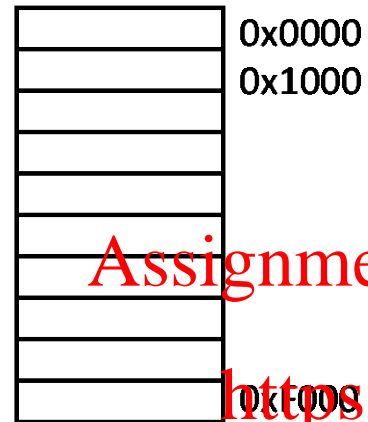
How to achieve **isolation**?

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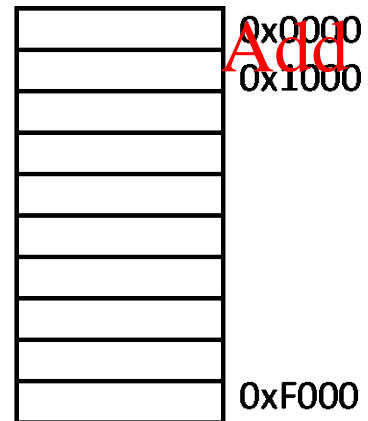


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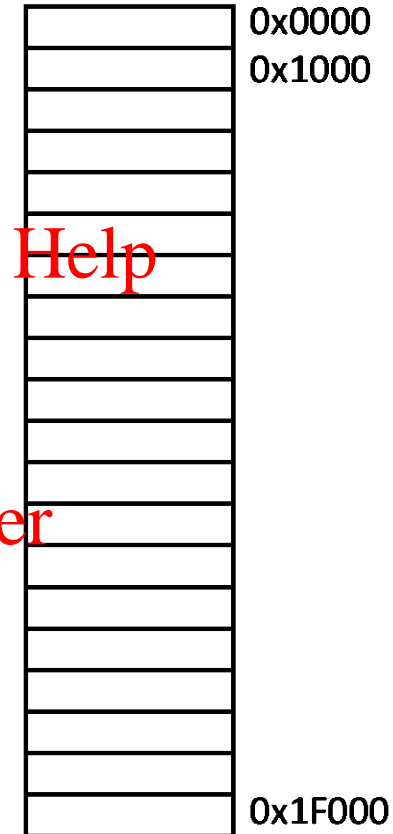
How to achieve isolation?



Page table for Chrome



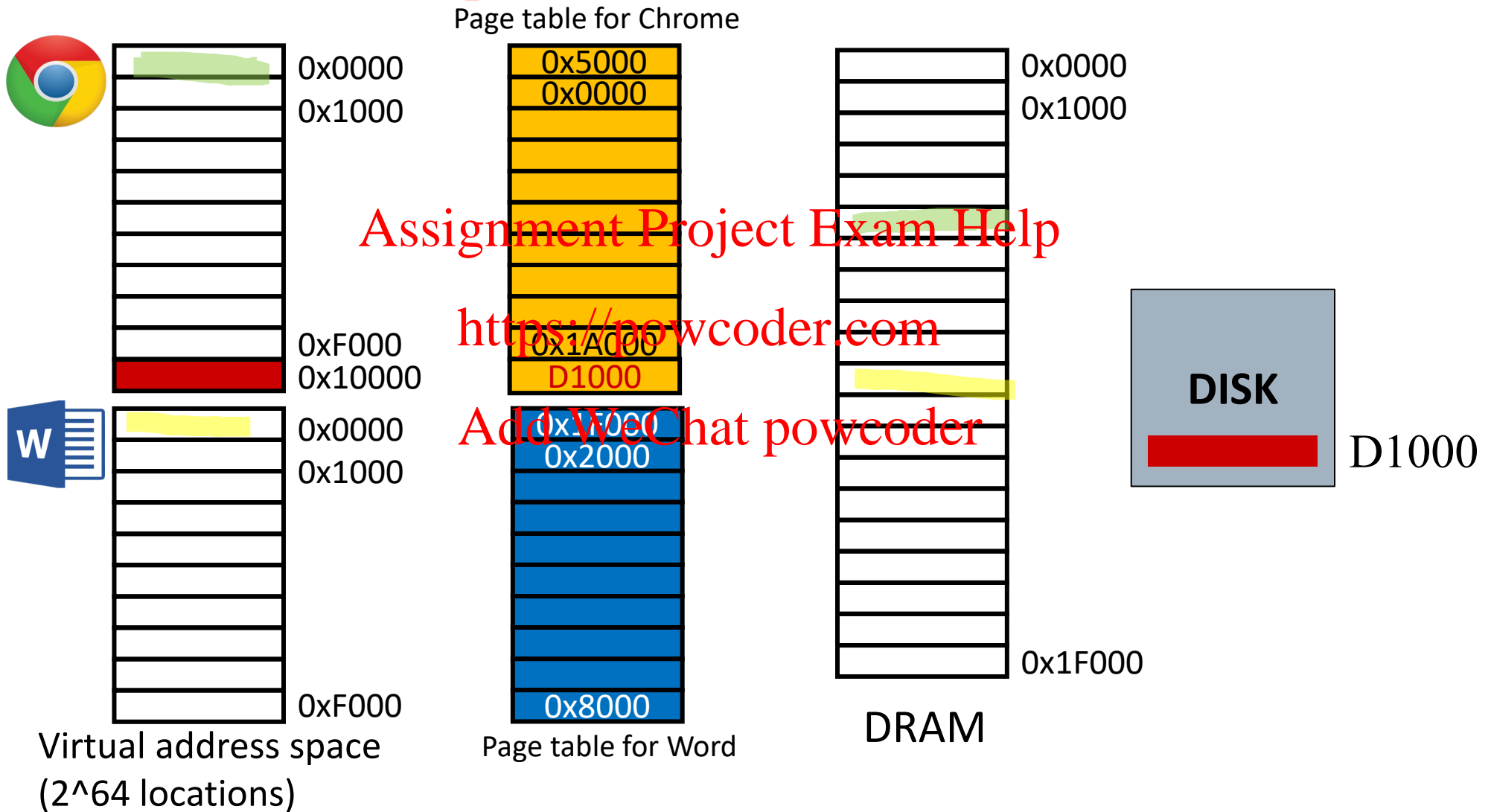
Page table for Word



DRAM
(physical)

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Some pages may be swapped out to disk



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Virtual Memory Roles

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Security features

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

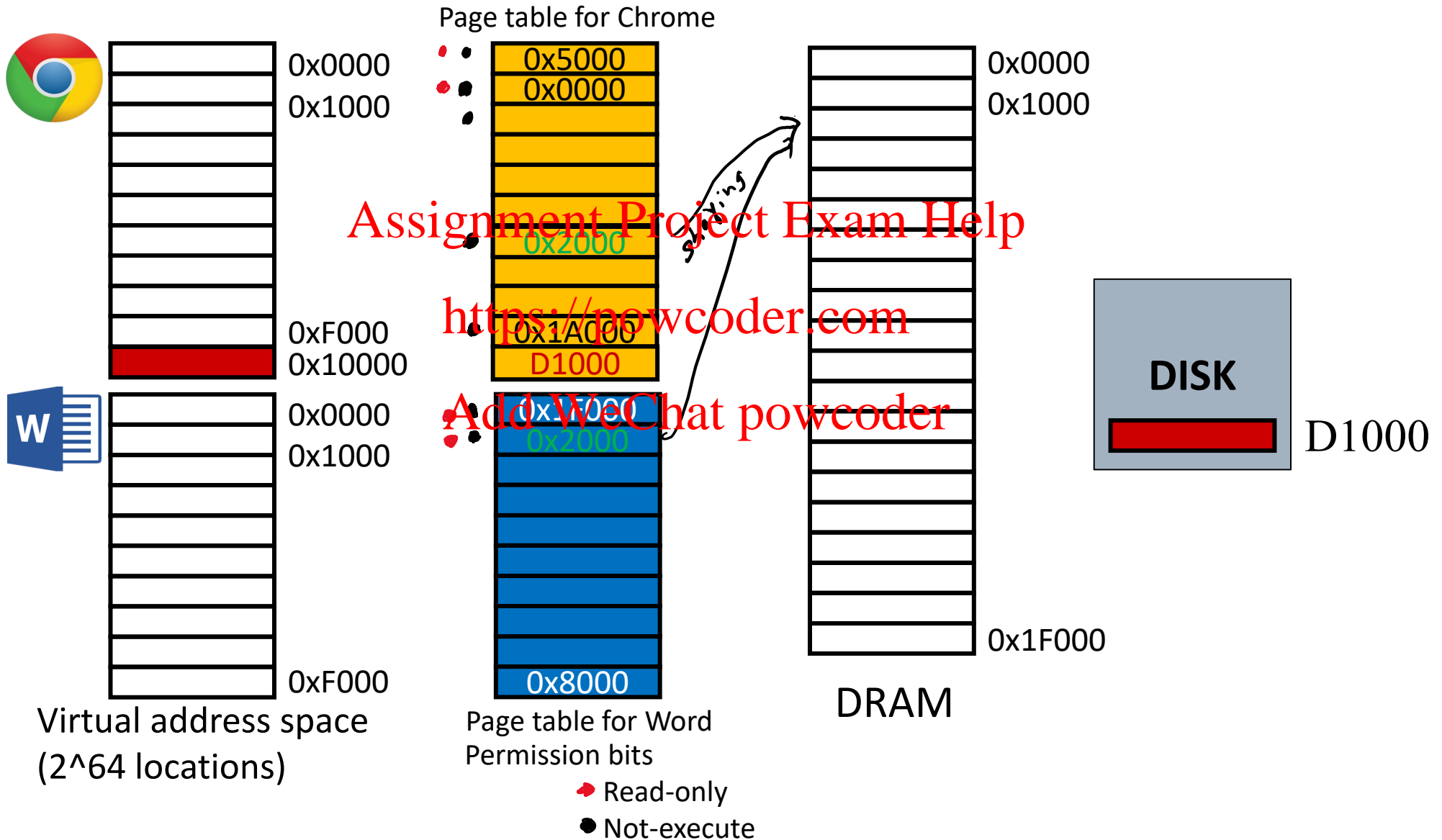
Permissions

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

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



VM integration with processor caches

(to be discussed later)

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VM systems give us two different addresses:
virtual and physical

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Which address should we use to access the data cache?

<https://powcoder.com>

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

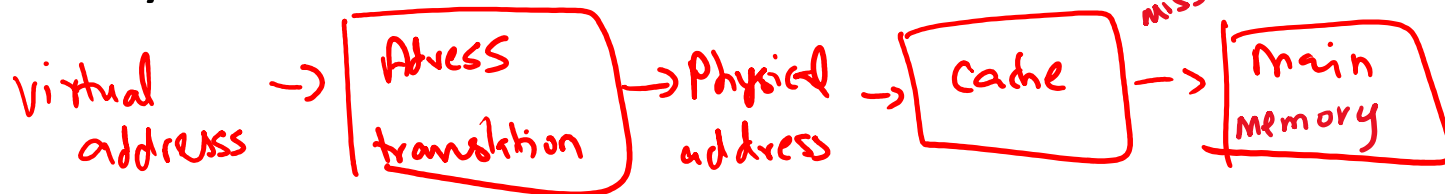
virtual address

miss

Address translation

Physical address

Main memory



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Check
your
computer

System Information		
System Summary		
Hardware Resources	Item	Value
Conflicts/Sharing	OS Name	Microsoft Windows 10 Pro
DMA	Version	10.0.18363 Build 18363
Forced Hardware	Other OS Description	Not Available
I/O	OS Manufacturer	Microsoft Corporation
IRQs	System Name	DESKTOP-██████████
Memory	System Manufacturer	Microsoft Corporation
Components	System Model	Surface Studio 2
Multimedia	System Type	x64-based PC
CD-ROM	System SKU	Surface_Studio_2_1707_Commercial
Sound Device	Processor	Intel(R) Core(TM) i7-7820HQ CPU @ ...
Display	BIOS Version/Date	Microsoft Corporation 532.3238.768, ..
Infrared	SMBIOS Version	3.2
Input	Embedded Controller Version	255.255
Modem	BIOS Mode	UEFI
Network	Base Board Manufacturer	Microsoft Corporation
Ports	BaseBoard Product	Surface Studio 2
Storage	BaseBoard Version	Not Available
Drives	Platform Role	Desktop
Disks	Secure Boot State	On
SCSI	PCR7 Configuration	Elevation Required to View
IDE	Windows Directory	C:\WINDOWS
Printing	System Directory	C:\WINDOWS\system32
Problem Devices	Boot Device	Device Harddisk Volume1
USB	Locale	United States
Software Environment	Hardware Abstraction Layer	Version = "10.0.18362.1171"
	User Name	██████████
	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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?