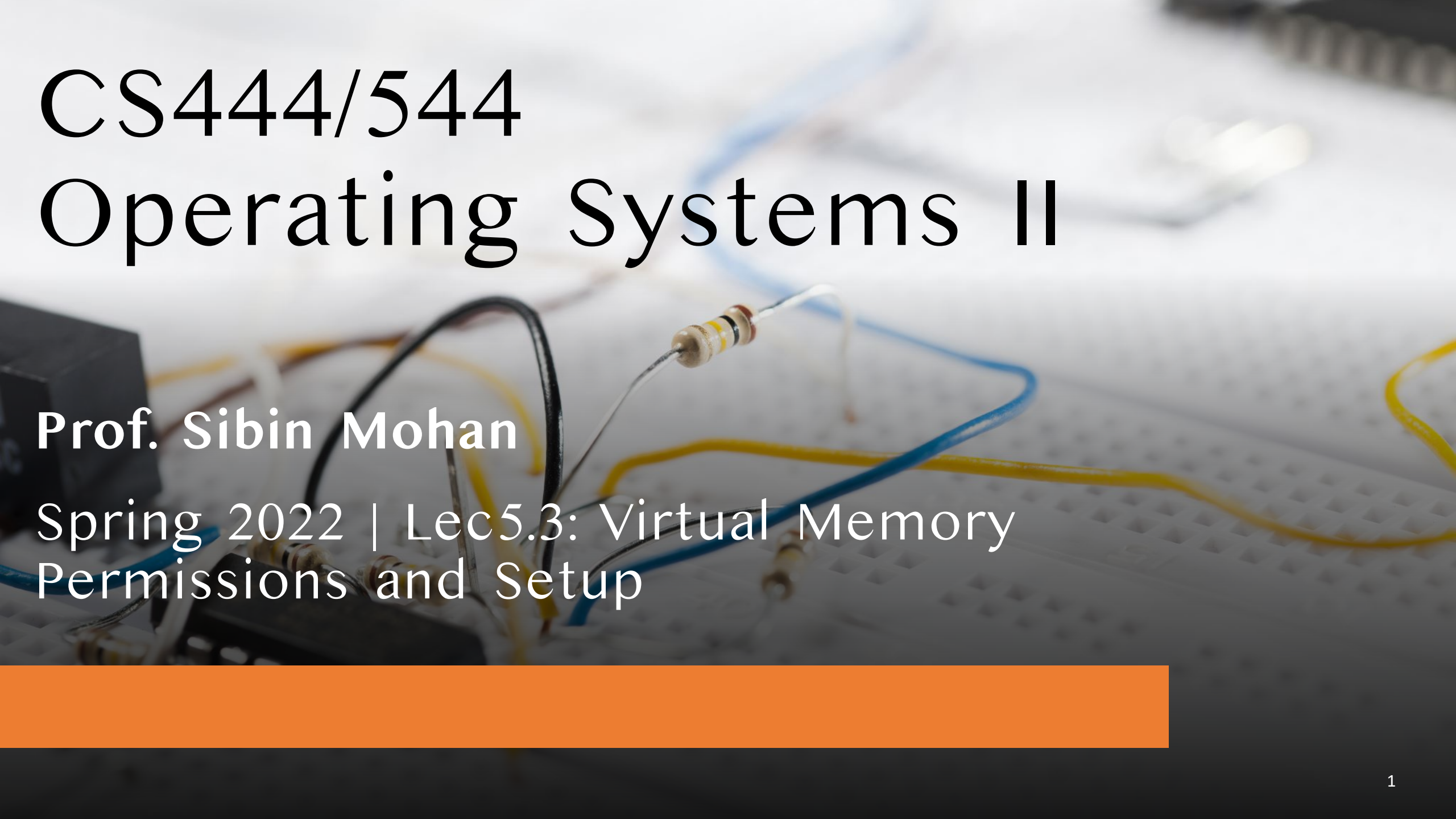
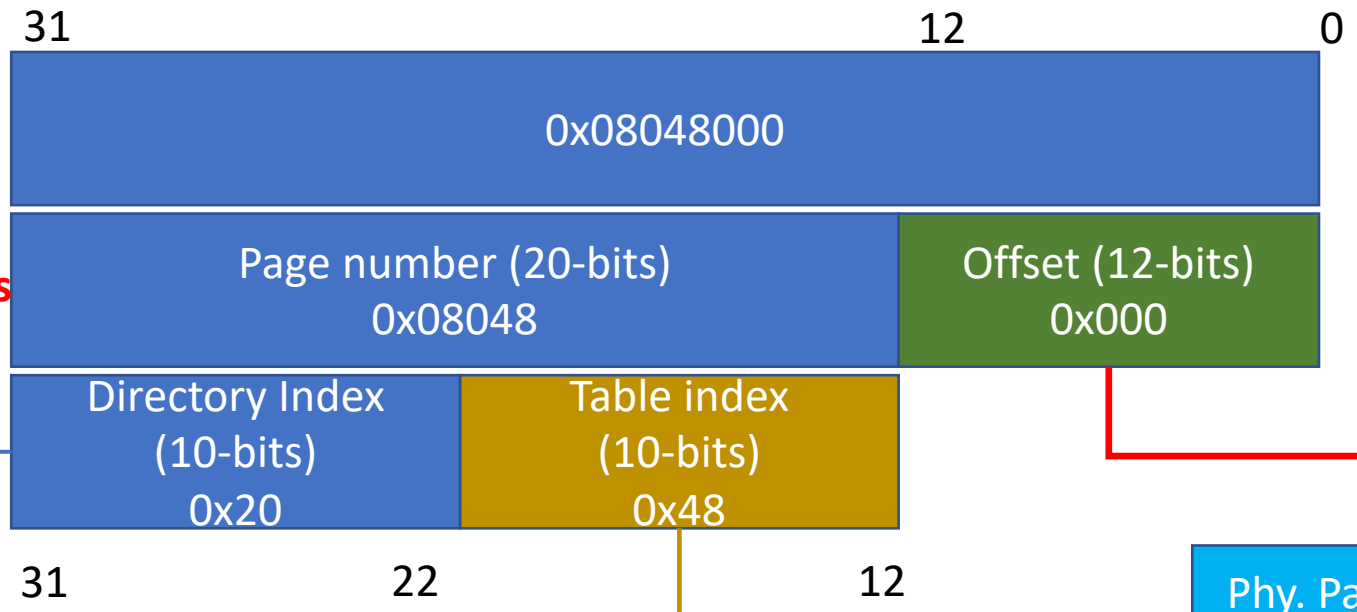


# CS444/544 Operating Systems II

**Prof. Sibin Mohan**

Spring 2022 | Lec5.3: Virtual Memory Permissions and Setup

# Recap – Page Table & Addr Translation




**Mem access #1**

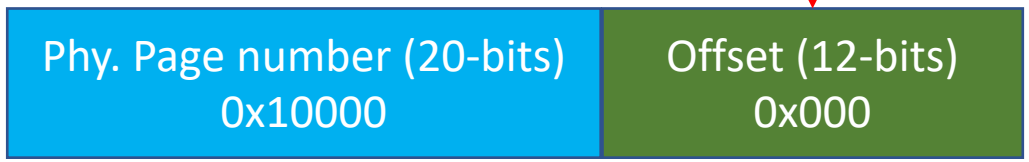
**CR3[0x20]**

| Virtual | Physical |
|---|---|
| 0x8048000 | 0x10000 |
| 0x8049000 | 0x11000 |
| 0x804a000 | 0x50000 |

| | Page Directory Entry |
|---|---|
| 0 | Addr PT |
| .. | Addr PT |
| 0x20 | Addr PT |
| 0x3ff | Addr PT |

**PDE[0x48]**
**Mem access #2**

| | Page Table Entry |
|---|---|
| 0 | Addr PT |
| 0x48 | 0x10000 |
| 0x49 | 0x11000 |
| 0x4a | 0x50000 |




**Mem access #3 (required)**

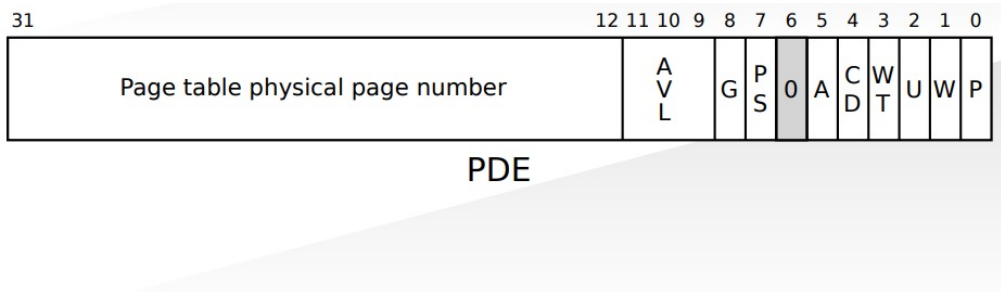
# More About Virtual Memory

- Page Permissions
- Virtual Memory Layout
- How JOS Manages Physical Memory?

# Page Directory / Table Entry (PDE/PTE)

- Top 20 bits: physical page number
  - Physical page number of a page table (PDE)
  - Physical page number of the requested virtual address (PTE)

- Lower 12 bits: some flags
  - Permission
  - Etc.

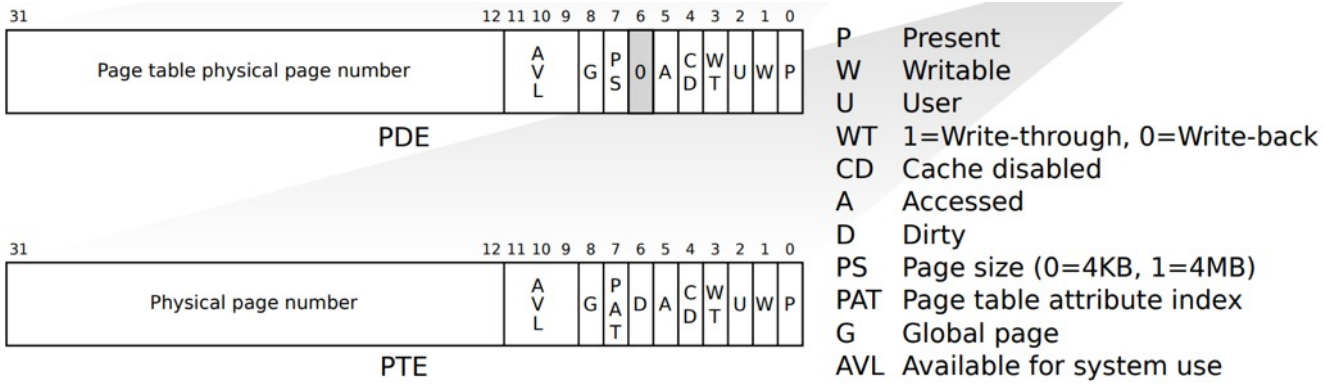



| | |
|---|---|
| P | Present |
| W | Writable |
| U | User |
| WT | 1=Write-through, 0=Write-back |
| CD | Cache disabled |
| A | Accessed |
| D | Dirty |
| PS | Page size (0=4KB, 1=4MB) |
| PAT | Page table attribute index |
| G | Global page |
| AVL | Available for system use |

# Permission Flags

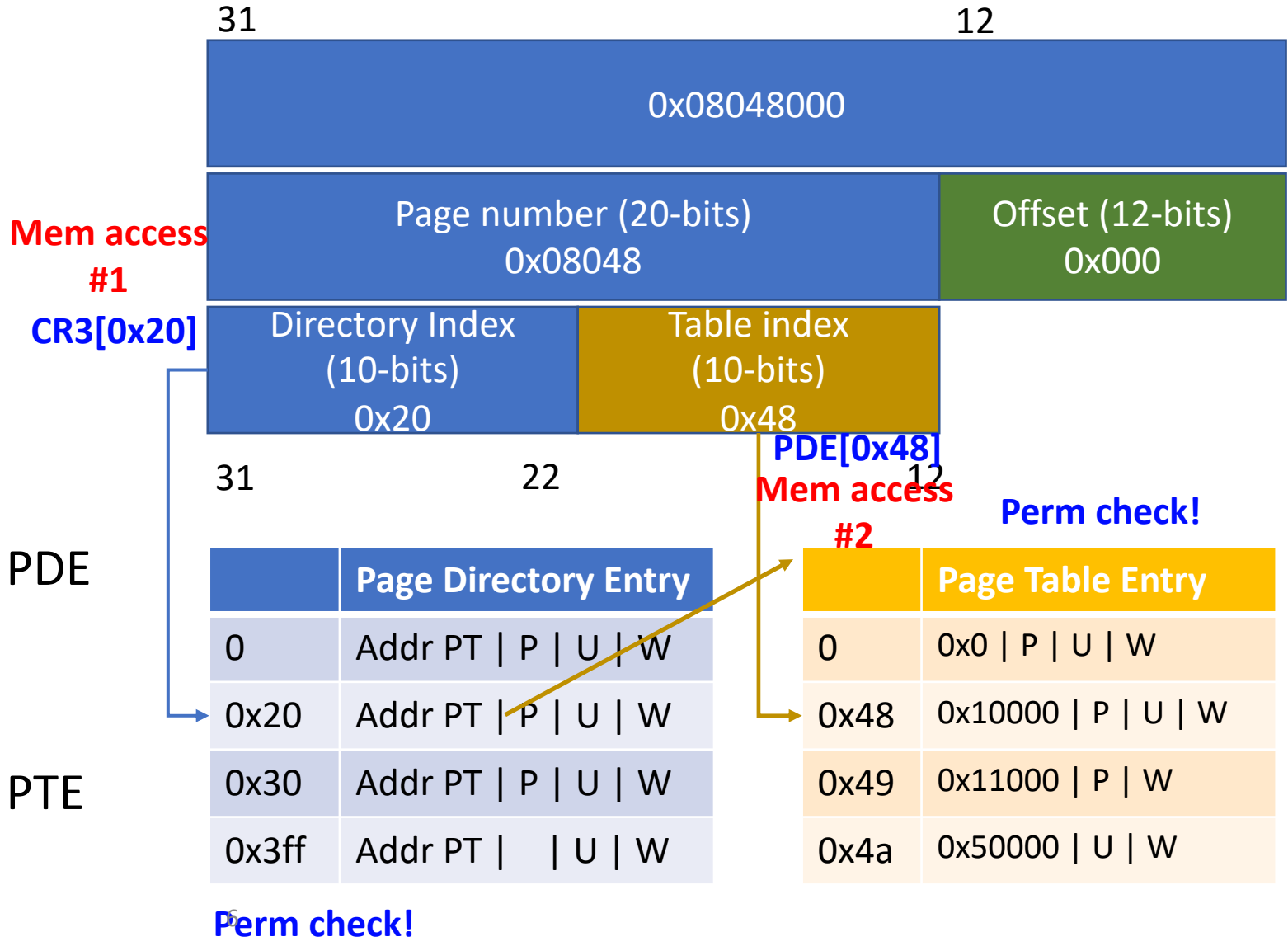
- PTE_P (PRESENT)
  - 0: invalid entry
  - 1: valid entry
- PTE_W (WRITABLE)
  - 0: read only
  - 1: writable
- PTE_U (USER)
  - 0: kernel (only ring 0 can access)
  - 1: user (accessible by ring 3)

| | Page Table Entry | |
|---|---|---|
| 0 | Addr PT | |
| 0x48 | 0x10000 << 12 \| PTE_U \| PTE_W | Invalid |
| 0x49 | 0x11000 << 12 \| PTE_P \| PTE_W | Kernel, writable |
| 0x4a | 0x50000 << 12 \| PTE_P \| PTE_U | User, read-only |



# When CPU Checks Permission Bits?

- In address translation
- 1. Virtual address
- 2. PDE = CR3[PDX]
  - Checks permission bits in PDE
- 3. PTE = PDE[PTX]
  - Checks permission bits in PTE



# CPU checks PDE permission first and then PTE permission next…

- A virtual memory address is inaccessible if PDE disallows the access
- A virtual memory address is inaccessible if PTE disallows the access
- Both PDE and PTE should allow the access…

# PDE/PTE Permission Examples 0

- Virtual address 0x01020304
- PDE: PTE_P | PTE_W | PTE_U
- PTE: PTE_P | PTE_W | PTE_U
- Valid, accessible by ring 3, and writable

- PTE_P (PRESENT)
  - 0: invalid entry
  - 1: valid entry
- PTE_W (WRITABLE)
  - 0: read only
  - 1: writable
- PTE_U (USER)
  - 0: kernel (only ring 0 can access)
  - 1: user (accessible by ring 3)

# PDE/PTE Permission Examples 1

- Virtual address 0x01020304
- PDE: PTE_P | PTE_W | PTE_U
- PTE: PTE_P | PTE_U
- Valid, accessible by ring 3, but not writable

- PTE_P (PRESENT)
  - 0: invalid entry
  - 1: valid entry
- PTE_W (WRITABLE)
  - 0: read only
  - 1: writable
- PTE_U (USER)
  - 0: kernel (only ring 0 can access)
  - 1: user (accessible by ring 3)

# PDE/PTE Permission Examples 2

- Virtual address 0x01020304
- PDE: PTE_P | PTE_U
- PTE: PTE_P | PTE_W | PTE_U
- Valid, accessible by ring 3, but not writable

- PTE_P (PRESENT)
  - 0: invalid entry
  - 1: valid entry
- PTE_W (WRITABLE)
  - 0: read only
  - 1: writable
- PTE_U (USER)
  - 0: kernel (only ring 0 can access)
  - 1: user (accessible by ring 3)

# PDE/PTE Permission Examples 3

- Virtual address 0x01020304
- PDE: PTE_P | PTE_W | PTE_U
- PTE: PTE_P
- valid, inaccessible by ring3, not writable

- PTE_P (PRESENT)
  - 0: invalid entry
  - 1: valid entry
- PTE_W (WRITABLE)
  - 0: read only
  - 1: writable
- PTE_U (USER)
  - 0: kernel (only ring 0 can access)
  - 1: user (accessible by ring 3)

# PDE/PTE Permission Examples 4

- Virtual address 0x01020304
- PDE: PTE_P | PTE_W
- PTE: PTE_P | PTE_U
- valid, inaccessible by ring3, not writable

- PTE_P (PRESENT)
  - 0: invalid entry
  - 1: valid entry
- PTE_W (WRITABLE)
  - 0: read only
  - 1: writable
- PTE_U (USER)
  - 0: kernel (only ring 0 can access)
  - 1: user (accessible by ring 3)

# PDE/PTE Permission Examples 5

- Virtual address 0x01020304
- PDE: PTE_P | PTE_U
- PTE: PTE_U
- invalid

- PTE_P (PRESENT)
  - 0: invalid entry
  - 1: valid entry
- PTE_W (WRITABLE)
  - 0: read only
  - 1: writable
- PTE_U (USER)
  - 0: kernel (only ring 0 can access)
  - 1: user (accessible by ring 3)

# PDE/PTE Permission Examples 6

- Virtual address 0x01020304
- PDE: PTE_U
- PTE: PTE_P | PTE_U
- invalid

- PTE_P (PRESENT)
  - 0: invalid entry
  - 1: valid entry
- PTE_W (WRITABLE)
  - 0: read only
  - 1: writable
- PTE_U (USER)
  - 0: kernel (only ring 0 can access)
  - 1: user (accessible by ring 3)

# Can you setup a page permission as…

- Kernel: R, User: --
  - PTE_P
- Kernel: R, User: R
  - PTE_P | PTE_U
- Kernel: RW, User: RW
  - PTE_P | PTE_U | PTE_W

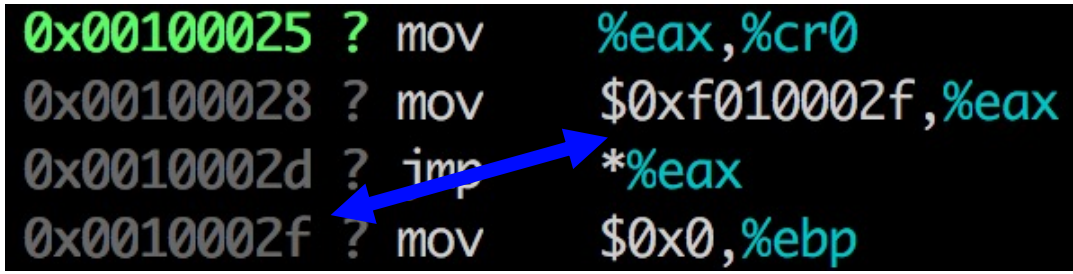
# You can't setup a page permission as…

- Kernel: RW, User: R
  - PTE_P | PTE_W | PTE_U -> User RW…
  - PTE_P | PTE _W  -> User --
- Kernel: R, User: RW
  - PTE_P | PTE_U | PTE_W -> Kernel RW…
  - PTE_P | PTE_U  -> User R…
- Kernel: --, User: RW
  - PTE_P | PTE_U | PTE_W -> Kernel RW…

# You can enable such a conflicting permission setup by having N-to-1 mapping

- Virtual to physical address mapping is in N-to-1 relation
  - N number of virtual addresses could be mapped to 1 physical address

- E.g., for a physical address 0x100000
  - JOS maps VA 0x100000 to PA 0x100000
  - JOS maps VA 0xf0100000 to PA 0x100000




- Why?
  - EIP before enabling paging: 0x100025
  - EIP after enabling paging: 0x100028
  - Then jumps to 0xf010002f

# Sharing a Physical Page

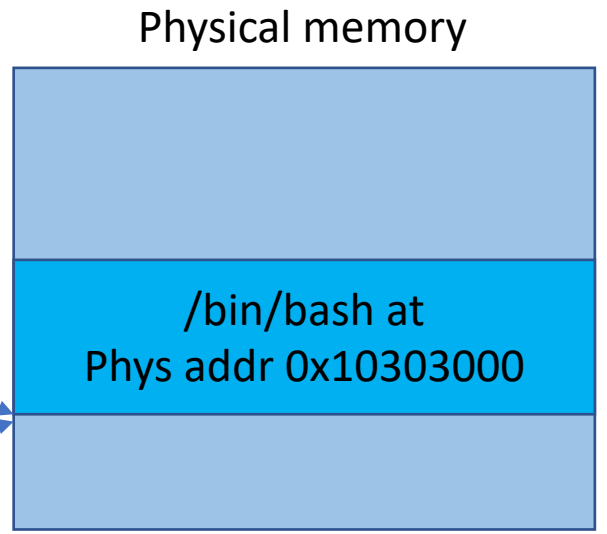
- Example: Loading of the same program

Process 0, runs /bin/bash,
loads at virt addr 0x35555000

| | Page Table Entry |
|---|---|
| 0 | … |
| 0x155 | 0x10303 \| FLAG |

Process 1, runs /bin/bash,
loads at virt addr 0x43132000

| | Page Table Entry |
|---|---|
| 0 | … |
| 0x132 | 0x10303 \| FLAG |




2 or more mappings to 0x10303000 is possible!

# You can't setup a page permission as…

- Kernel: RW, User: R
  - VA 0x00001000 -> PA 0x50000, PTE_P | PTE_U (User R)
  - VA 0xf0050000 -> PA 0x50000, PTE_P | PTE_W (Kernel RW)
- Kernel: R, User: RW
  - VA 0x00002000 -> PA 0x60000, PTE_P | PTE_U | PTE_W (User RW)
  - VA 0xf0060000 -> PA 0x60000, PTE_P (Kernel R)

- Kernel: --, User: RW
  - VA 0x00003000 -> PA 0x70000, PTE_P | PTE_U | PTE_ W
  - VA 0xf0070000 -> PA 0x70000, 0 for flag…

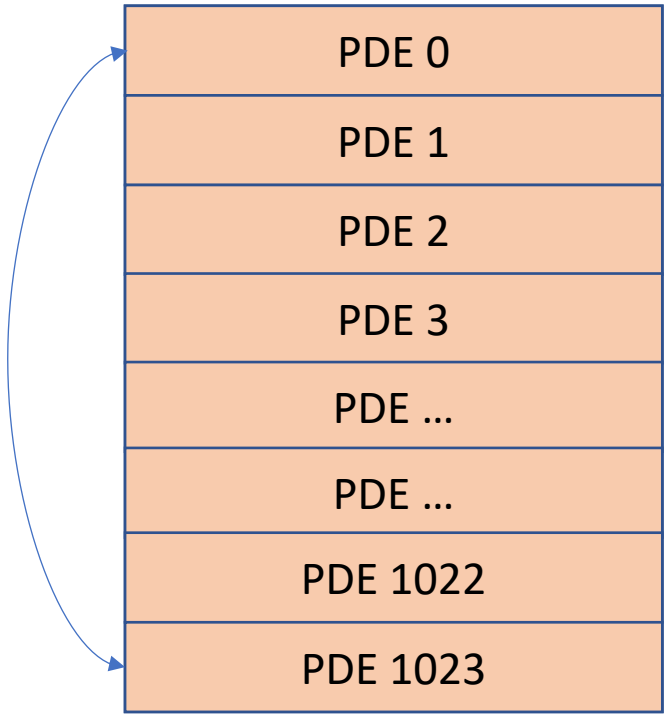
# PDE/PTE Permissions CAVEAT

- A virtual address access is allowed if both **PDE** and **PTE** entries allows the access…
- General practice: put **a more permissive** permission bits in **PDE**, and **be strict** on setting permission bits in **PTE**
- For a conflicting permission setup for Kernel/User, add **an additional virtual address mapping** can enable such a setup

# How To Create a Page Directory?

- For a 32-bit Intel processor, we use only 1 page for a Page Directory

**One page, 4KB**




**4096** / **4** = 1024 entries

1024 == $2^{10}$

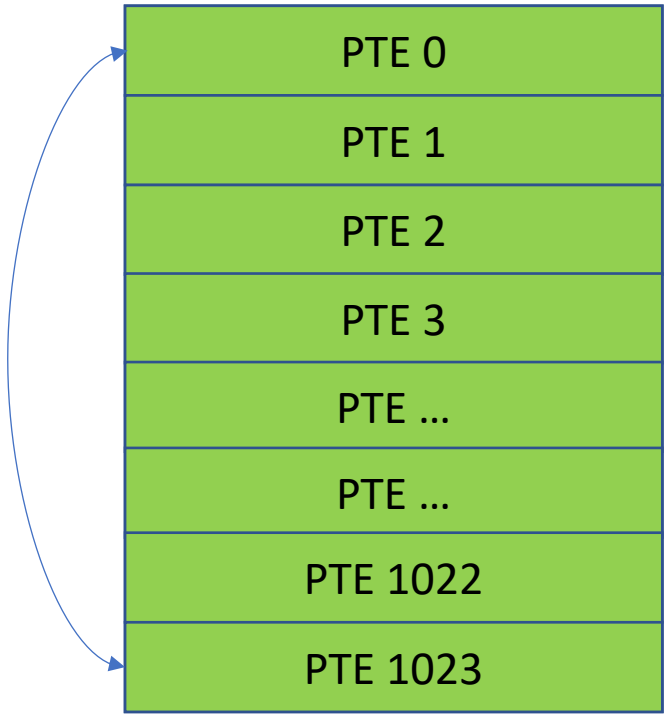
10-bit index for PD

**Each entry is 4-byte (32 bits)**

# How To Create a Page Table?

- For a 32-bit Intel processor, we use only 1 page for a Page Table

**One page, 4KB**




**4096** / **4** = 1024 entries

1024 == $2^{10}$

10-bit index for PT

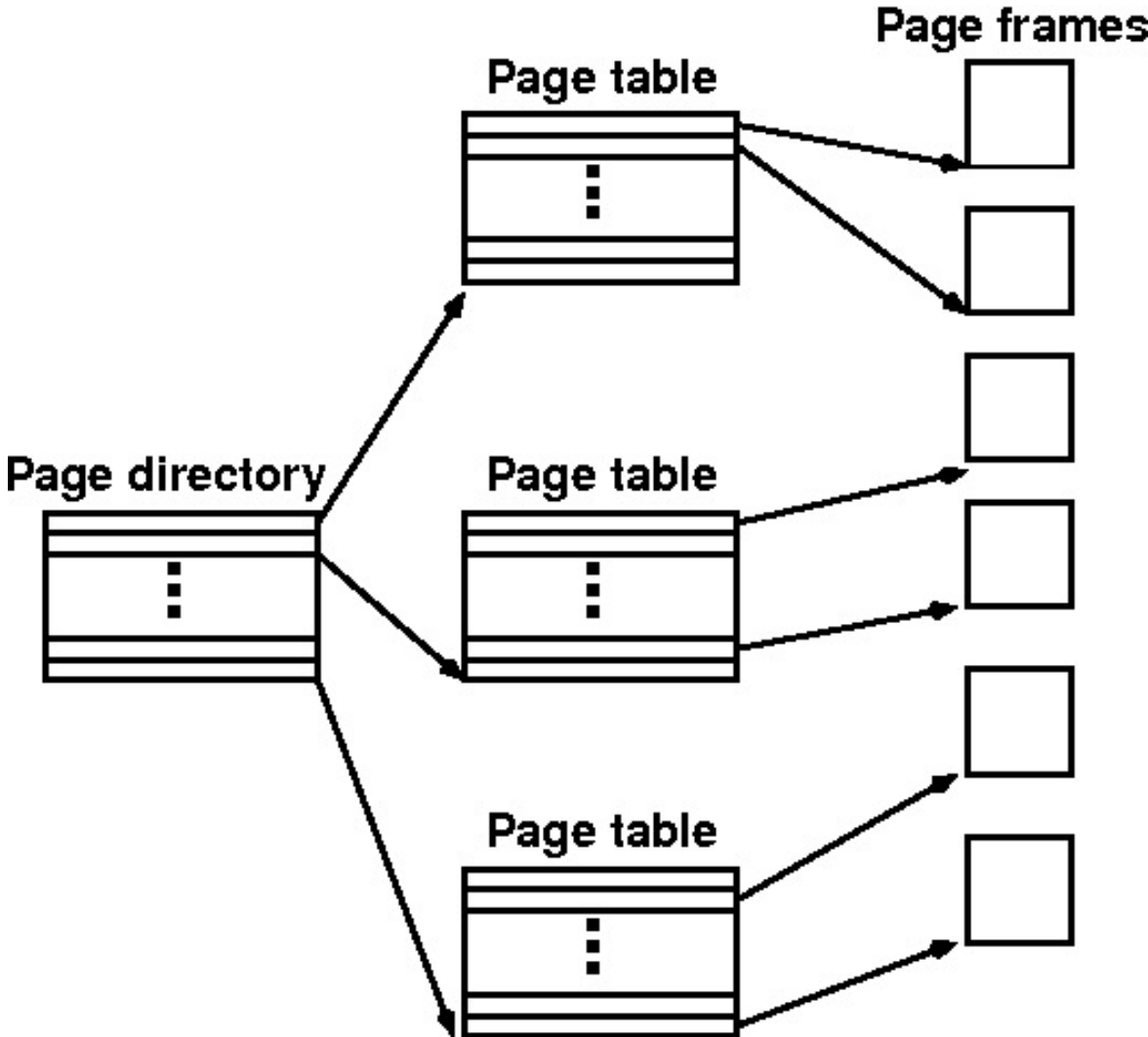
**Each entry is 4-byte (32 bits)**

# Intel 32-bit Processor uses a 2-level page table

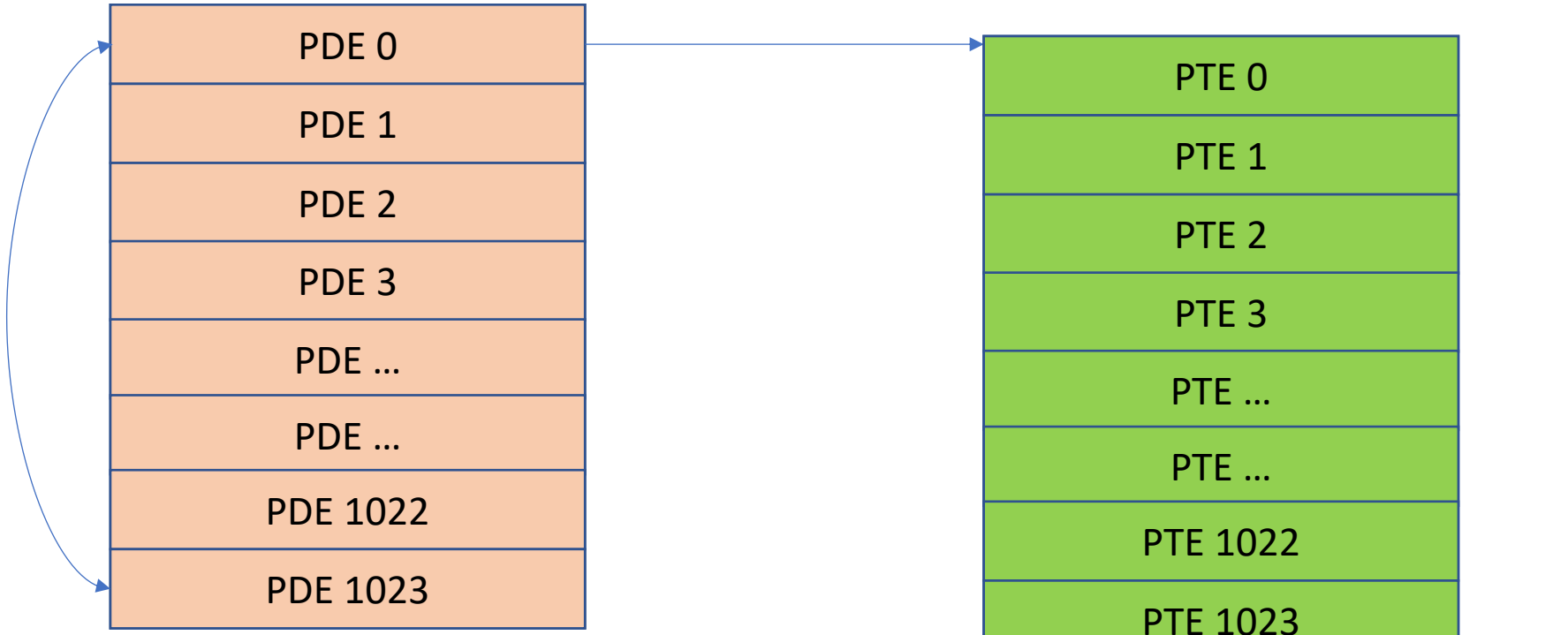
- Virtual address

- Page directory (level 1)
- Page table (level 2)

- Physical page!



# What will be the size of full PD/PT?




**One page, 4KB**

**Each entry is 4-byte (32 bits)**

**4KB for page directory**

**4KB per each Page Table…**

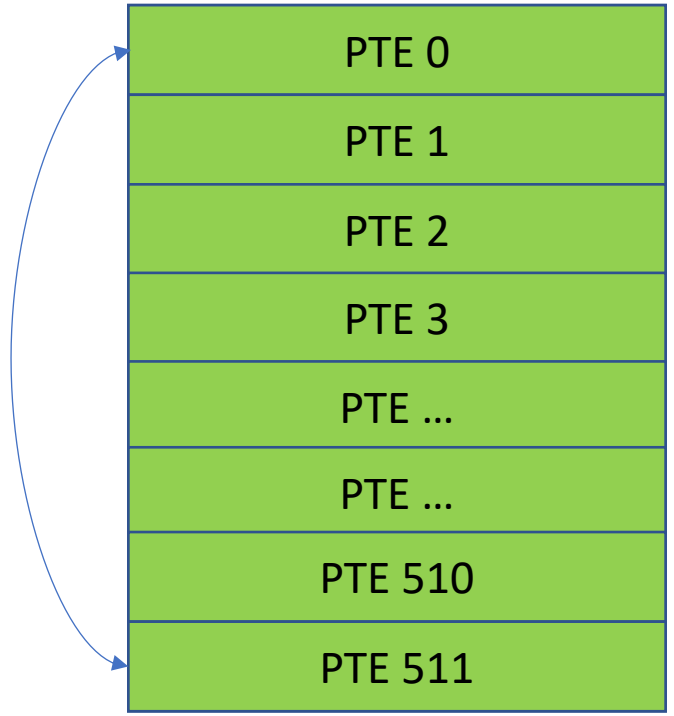
# Size of Page Table

- 4 KB for a Page Directory (only one per each process)
- 1024 Page Tables available
  - 4 KB for a Page Table
- 4 KB (PD) + 1024 * 4 KB (PT)
  - 4 KB + 4MB
  - ~ 4MB, 4,198,400 bytes…

# What about amd64 (x86_64)?

- Pointer size in 64 bit computer: 8 bytes
  - Pointer size in 32 bit computer was 4 bytes
- "Basic" Page size in 64-bit computer: 4KB
  - Basic page size in 32-bit computer was the same 4KB
- How many entries available in PD/PT?
  - 512 entries. Half of 32 bit

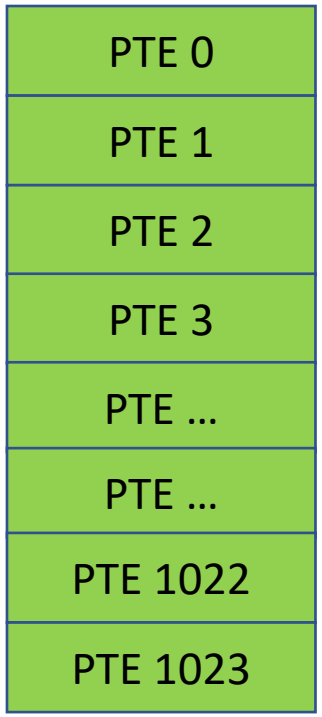
**One page, 4KB**

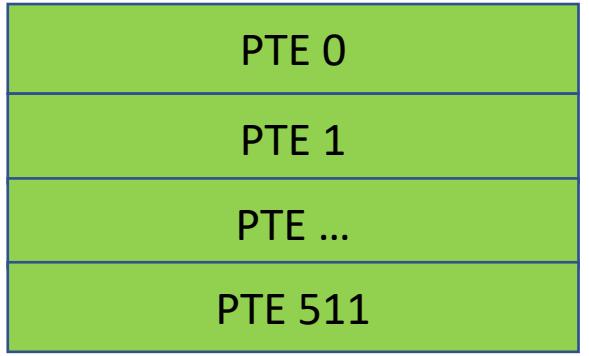



**Each entry is 8-byte (64 bits)**

# We do not use the entire 64-bit memory space

- 32-bit memory space
  - 2^32 == total 4GB
  - We ignore lower 12 bits = 2^20 total pages
  - 20bits required to index all pages
  - 10 bit PDE, 10 bit PTE -> 2 level page table
- 64-bit memory space
  - 2^64 == 16 EB == 16,384 PB == 16,777,216 TB
  - We ignore lower 12 bits = 2^52 total pages
  - Requires 52 bit, each table can index 9 bits
  - We need 6 level page table…



# 48-bit address space

- Initial amd64 processors use only 48-bit virtual address space
  - 2^48 = 256 TB
- Each level of table tree can process 9 bits (512 entries in table)
- We ignore lower 12 bits
  - 48 – 12 = 36 (total 2^36 pages)
  - 36 / 9 = 4  (each table can process 9 bits of address space)
- We use 4-level page table

# Two-level Page Table (32-bit)

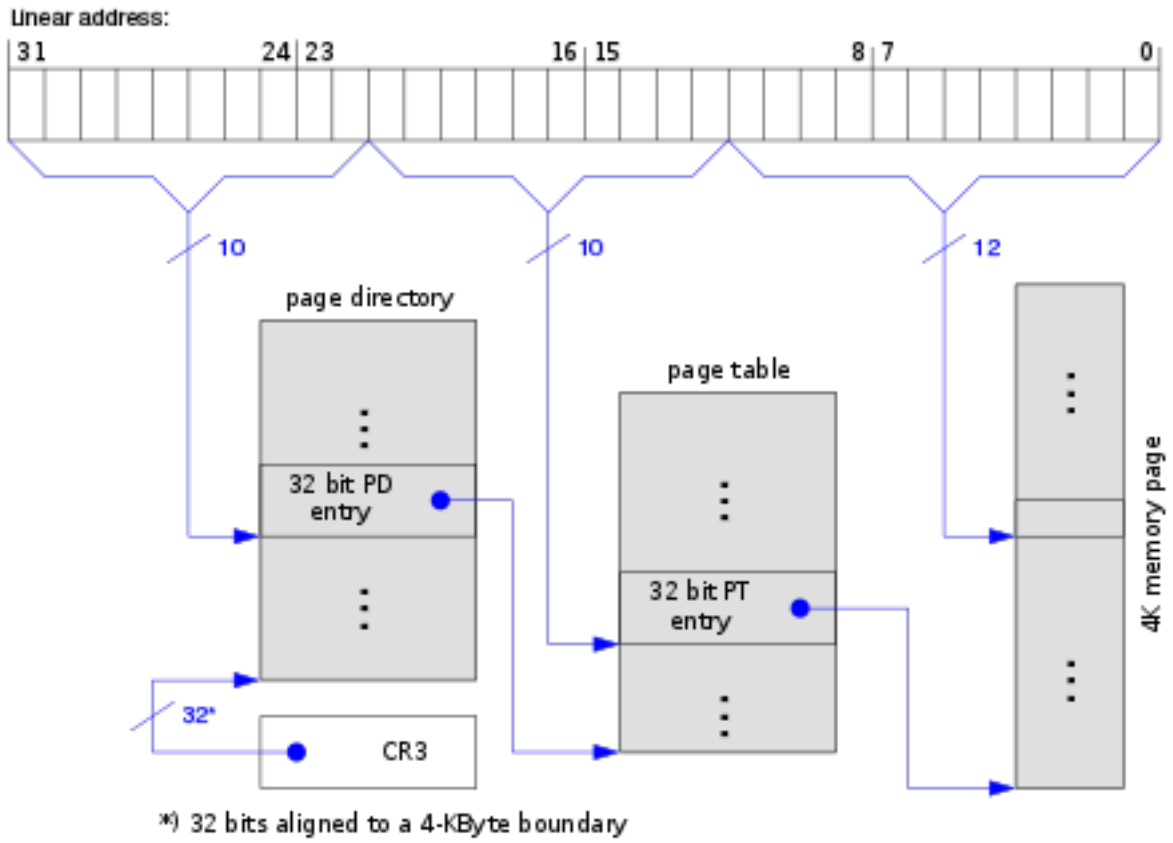
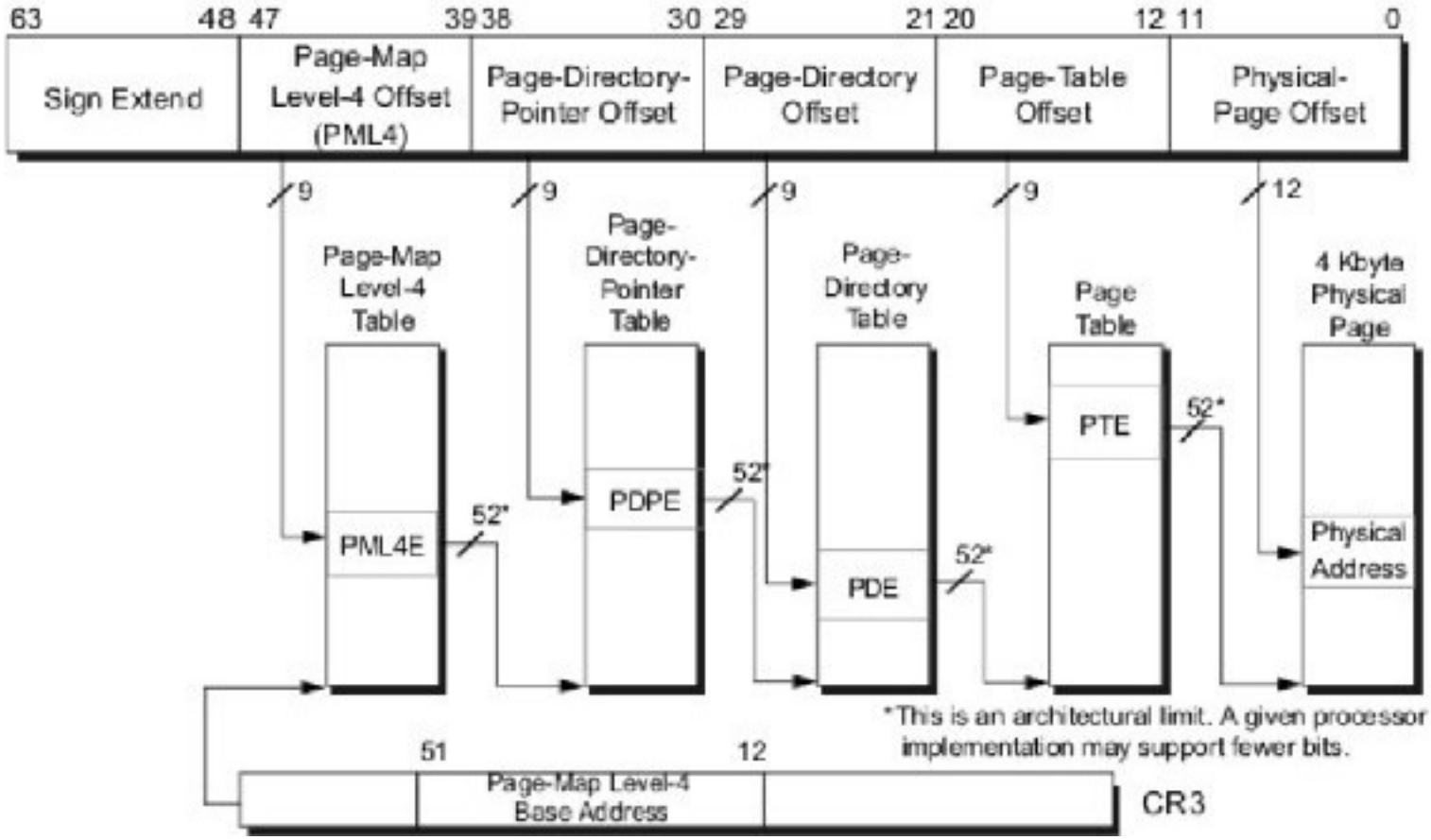



Image from: https://en.wikipedia.org/wiki/Page_table

# Four-level Page Table (64-bit)



# What's more?

- 256 TB might not enough for big data processing
  - E.g., analyzing online social network of users in Facebook
    - More than 1 billion users, more than 1 trillion edges among users
    - 1 byte per edge = 1TB

- 4 levels, 48 bit
- 5 levels? Yes we can, 48 + 9 = 57 bits = 128PB
- 6 levels? Maybe, but 57 + 9 = 68 bits, out of 64 bits…

# Virtual Machines

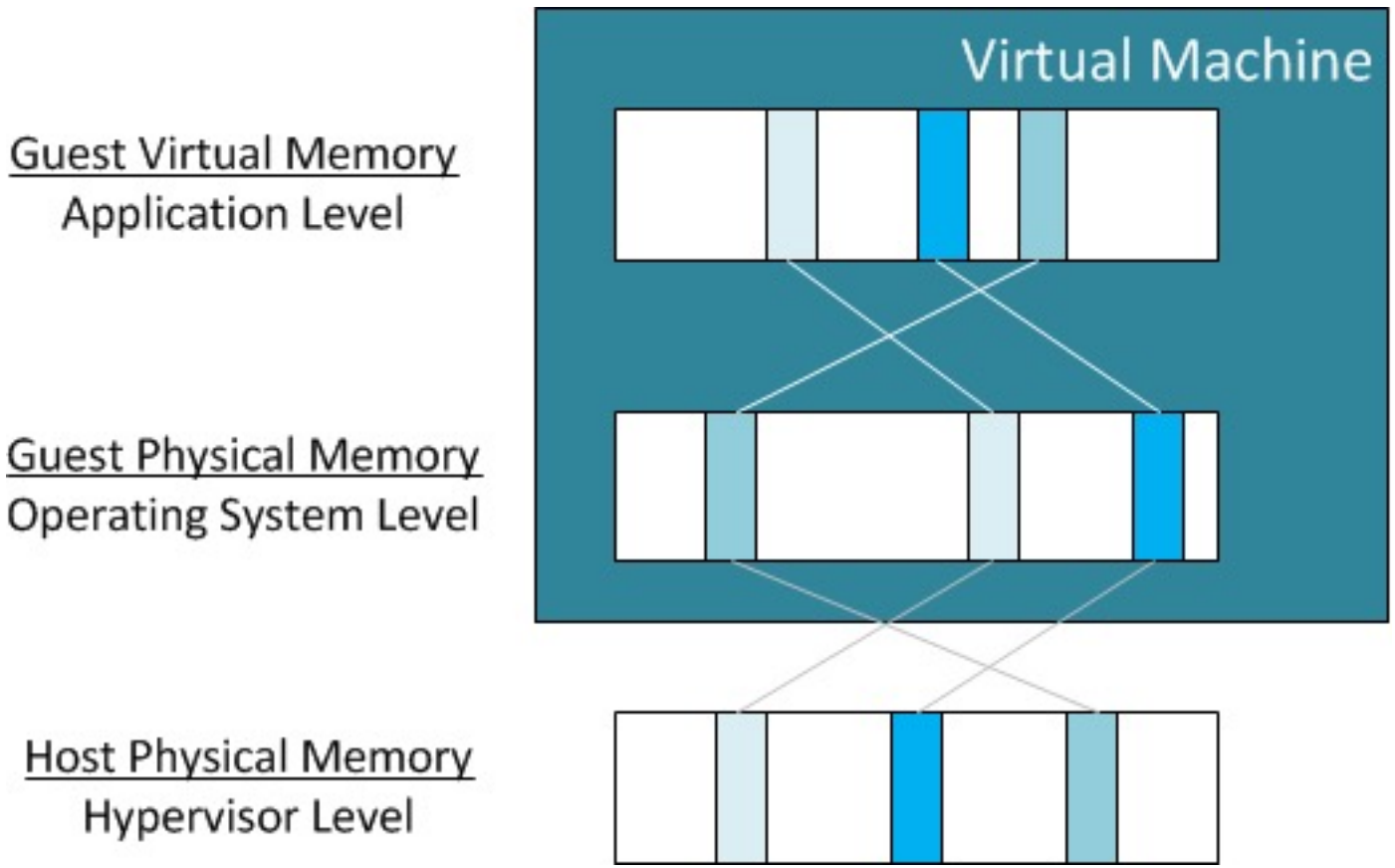
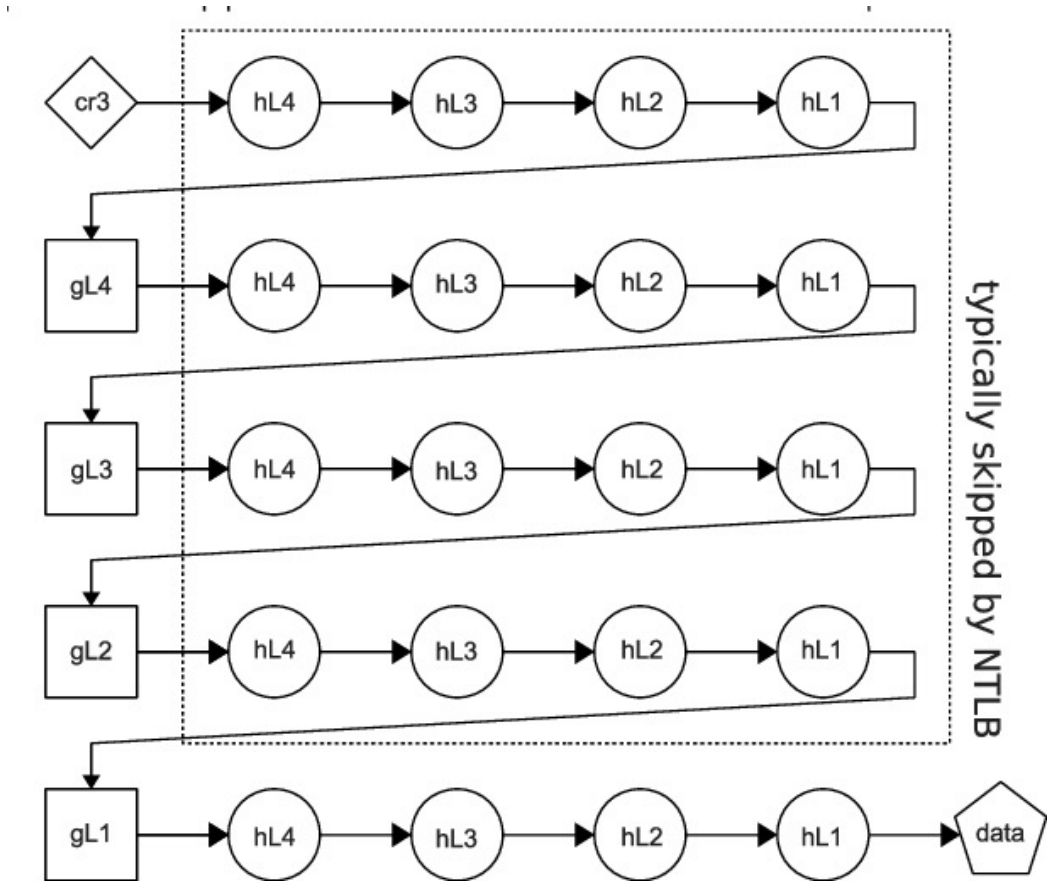





Image from: https://www.simongreaves.co.uk/vmware-virtual-machine-memory-guide/

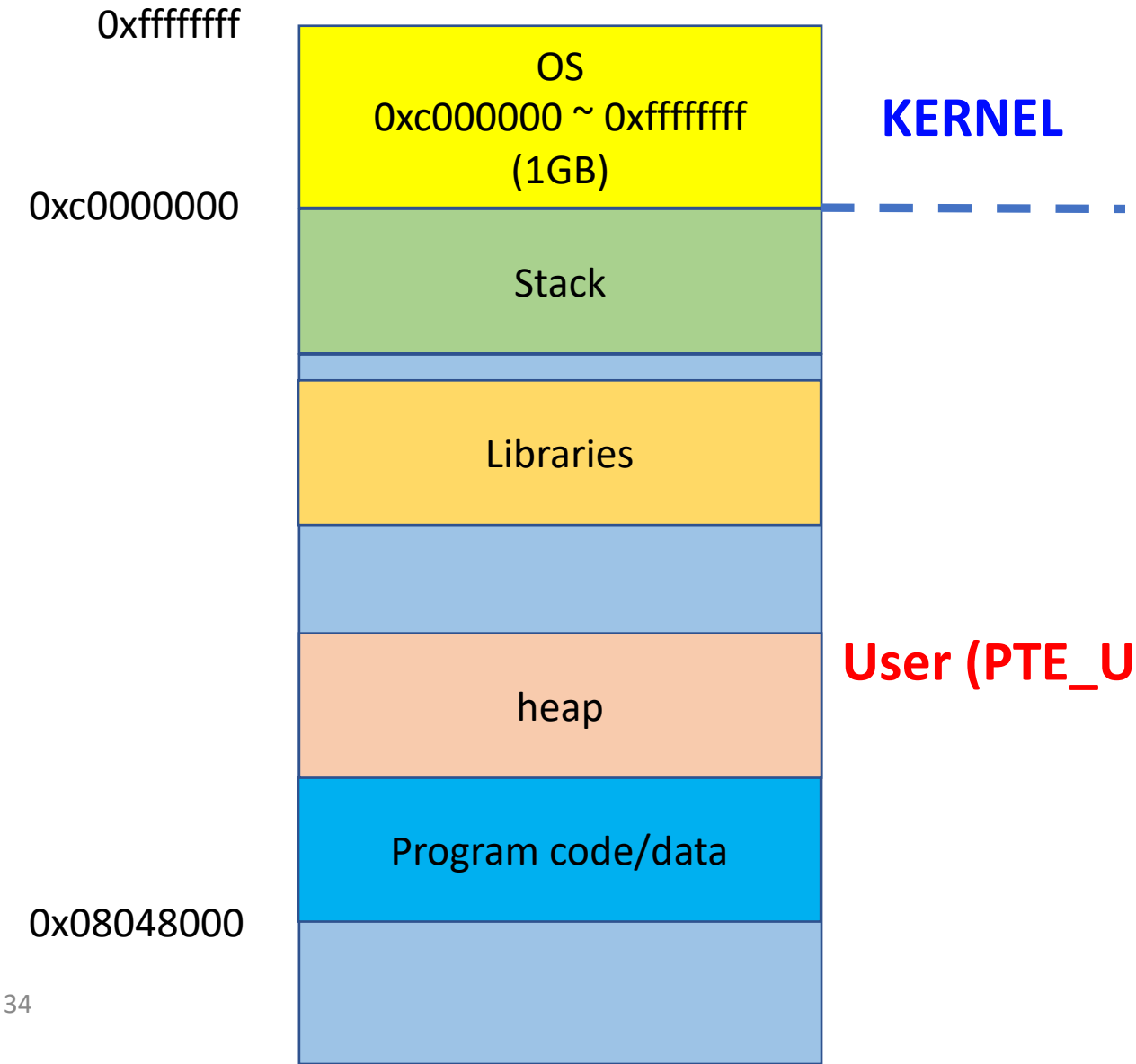
# Nested Page Table (NPT, EPT)

- A case of 48-bit 4-level page table
- Suppose you run Windows
  - Install VMWARE
  - Install a Linux VM
- Host: Windows
- Guest: Linux
- Physical address of Linux
  - This is just a virtual address of Windows



# Virtual Memory Layout

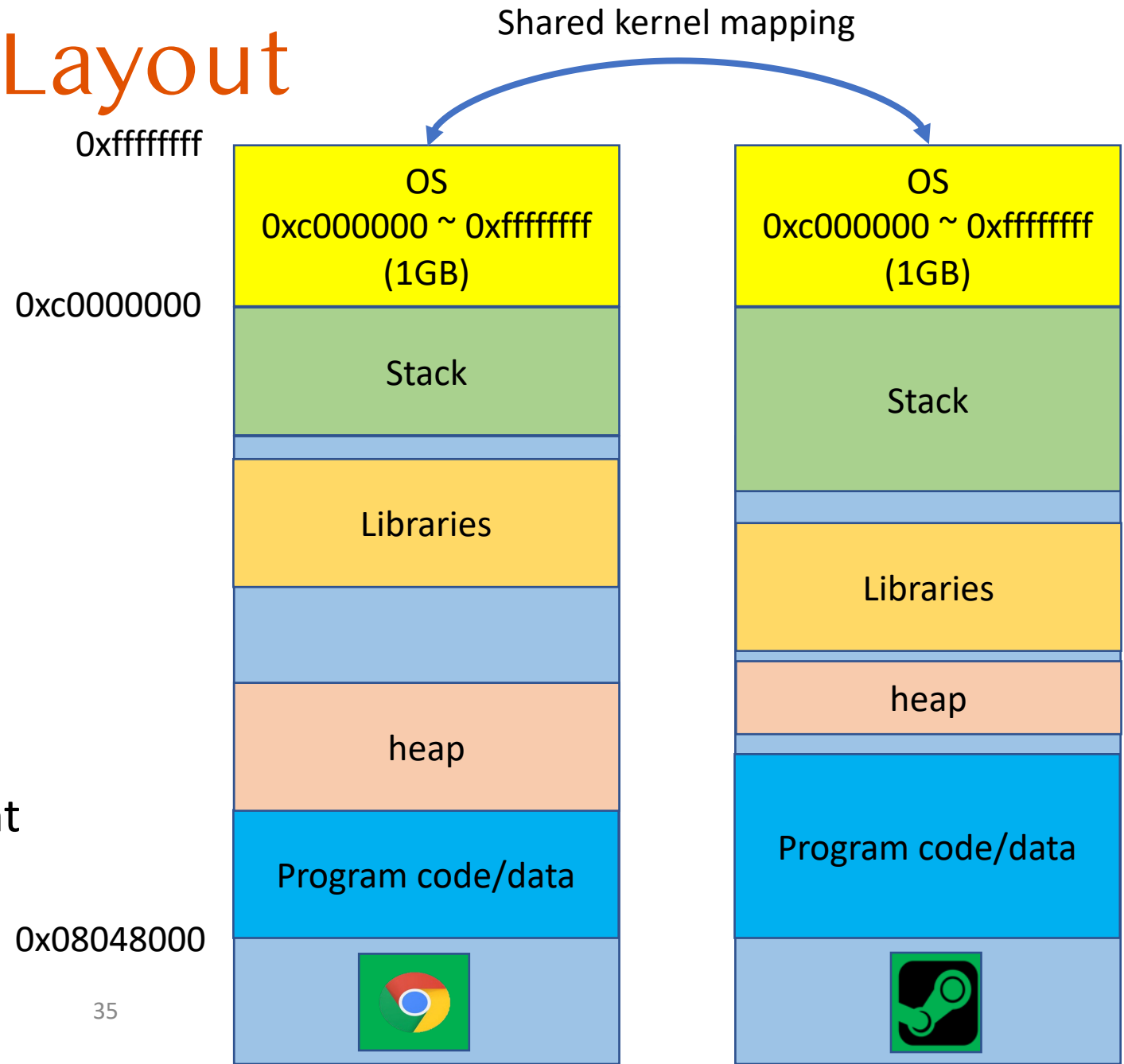
- OS allocates a separate virtual memory space to each process
- Transparency
  - Do not have to worry about a system's memory usage status
- Isolation
  - Others can't access my virtual memory space



# Virtual Memory Layout

- Each process will have almost the same mapping for the kernel but having a different mapping for userspace

- Why?
  - Kernel is shared among processes
  - Each process could run different apps



# Example: Linux on 32-bit Intel

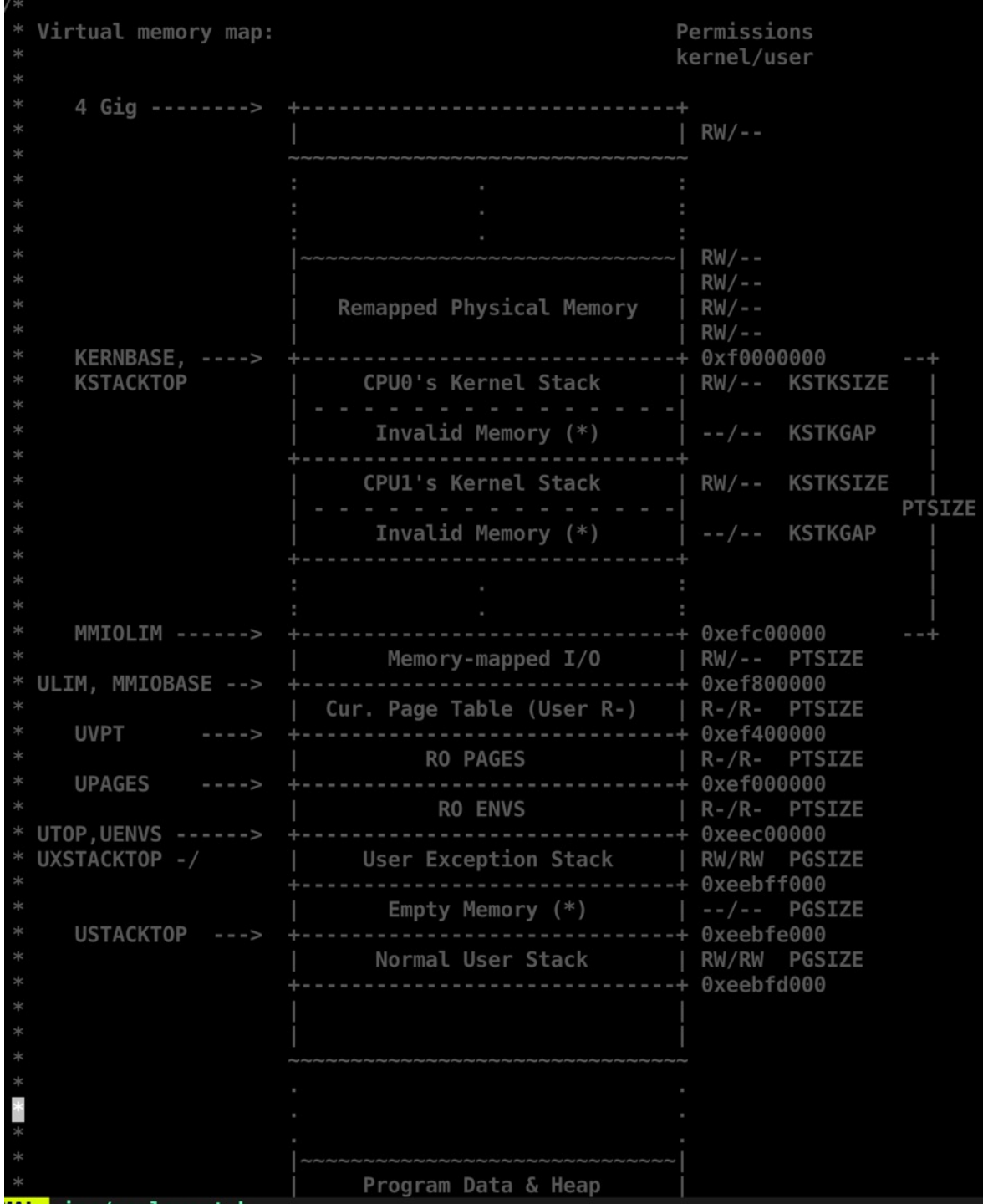
```
blue9057@blue9057-vm-ctf3 ~ $ cat /proc/self/maps
08048000-08054000 r-xp 00000000 08:01 1835032    /bin/cat
08054000-08055000 r--p 0000b000 08:01 1835032    /bin/cat
08055000-08056000 rw-p 0000c000 08:01 1835032    /bin/cat
08910000-08931000 rw-p 00000000 00:00 0          [heap]
b7b55000-b7b77000 rw-p 00000000 00:00 0
b7b77000-b7d77000 r--p 00000000 08:01 3278358    /usr/lib/locale/locale-archive
b7d77000-b7d78000 rw-p 00000000 00:00 0
b7d78000-b7f28000 r-xp 00000000 08:01 2114585    /lib/i386-linux-gnu/libc-2.23.so
b7f28000-b7f2a000 r--p 001af000 08:01 2114585    /lib/i386-linux-gnu/libc-2.23.so
b7f2a000-b7f2b000 rw-p 001b1000 08:01 2114585    /lib/i386-linux-gnu/libc-2.23.so
b7f2b000-b7f2e000 rw-p 00000000 00:00 0
b7f44000-b7f45000 r--p 002d4000 08:01 3278358    /usr/lib/locale/locale-archive
b7f45000-b7f46000 rw-p 00000000 00:00 0
b7f46000-b7f49000 r--p 00000000 00:00 0          [vvar]
b7f49000-b7f4b000 r-xp 00000000 00:00 0          [vdso]
b7f4b000-b7f6e000 r-xp 00000000 08:01 2114571    /lib/i386-linux-gnu/ld-2.23.so
b7f6e000-b7f6f000 r--p 00022000 08:01 2114571    /lib/i386-linux-gnu/ld-2.23.so
b7f6f000-b7f70000 rw-p 00023000 08:01 2114571    /lib/i386-linux-gnu/ld-2.23.so
bf9a9000-bf9ca000 rw-p 00000000 00:00 0          [stack]
```

# Example: Linux on 32-bit Intel

```
blue9057@blue9057-vm-ctf3 ~ $ cat /proc/self/maps
08048000-08054000 r-xp 00000000 08:01 1835032    /bin/cat
08054000-08055000 08048000-08051000 r-xp 00000000 08:01 1835015    /bin/more
08055000-08056000 08051000-08052000 r--p 00008000 08:01 1835015    /bin/more
08910000-08931000 08052000-08053000 rw-p 00009000 08:01 1835015    /bin/more
b7b55000-b7b77000 08bb6000-08bd7000 rw-p 00000000 00:00 0          [heap]
b7b77000-b7d77000 b7b85000-b7d85000 r--p 00000000 08:01 3278358    /usr/lib/locale/locale-archive
b7d77000-b7d78000 b7d85000-b7d86000 rw-p 00000000 00:00 0
b7d78000-b7f28000 b7d86000-b7f36000 r-xp 00000000 08:01 2114585    /lib/i386-linux-gnu/libc-2.23.so
b7f28000-b7f2a000 b7f36000-b7f38000 r--p 001af000 08:01 2114585    /lib/i386-linux-gnu/libc-2.23.so
b7f2a000-b7f2b000 b7f38000-b7f39000 rw-p 001b1000 08:01 2114585    /lib/i386-linux-gnu/libc-2.23.so
b7f2b000-b7f2e000 b7f39000-b7f3c000 rw-p 00000000 00:00 0
b7f44000-b7f45000 b7f3c000-b7f5c000 r-xp 00000000 08:01 2098856    /lib/i386-linux-gnu/libtinfo.so.
b7f45000-b7f46000 b7f5c000-b7f5e000 r--p 0001f000 08:01 2098856    /lib/i386-linux-gnu/libtinfo.so.
b7f46000-b7f49000 b7f5e000-b7f5f000 rw-p 00021000 08:01 2098856    /lib/i386-linux-gnu/libtinfo.so.
b7f49000-b7f4b000 b7f75000-b7f76000 r--p 002d4000 08:01 3278358    /usr/lib/locale/locale-archive
b7f4b000-b7f6e000 b7f76000-b7f77000 rw-p 00000000 00:00 0
b7f6e000-b7f6f000 b7f77000-b7f7a000 r--p 00000000 00:00 0          [vvar]
b7f6f000-b7f70000 b7f7a000-b7f7c000 r-xp 00000000 00:00 0          [vdso]
bf9a9000-bf9ca000 b7f7c000-b7f9f000 r-xp 00000000 08:01 2114571    /lib/i386-linux-gnu/ld-2.23.so
                  b7f9f000-b7fa0000 r--p 00022000 08:01 2114571    /lib/i386-linux-gnu/ld-2.23.so
                  b7fa0000-b7fa1000 rw-p 00023000 08:01 2114571    /lib/i386-linux-gnu/ld-2.23.so
                  bfa73000-bfa94000 rw-p 00000000 00:00 0          [stack]
```

# Memlayout.h

- In Lab2, after bootstrapping virtual memory system, you need to create the following memory layout for kernel
- This layout will be shared across all user processes you will develop in Lab3



# Summary

- Page Directory Entry / Page Table Entry
  - Permission bits (P, W, U)
  - Permission: {bits in PDE} ⋂ {bits in PTE}
- Virtual memory is N-to-1 mapping
  - Sharing physical page
  - Allowing conflicting permission assignment
    - Kernel RW  and User R
- Virtual Memory Layout
  - Shares kernel space (typically at the top of virtual memory space)
  - Can use user space arbitrarily (full transparency and isolation)