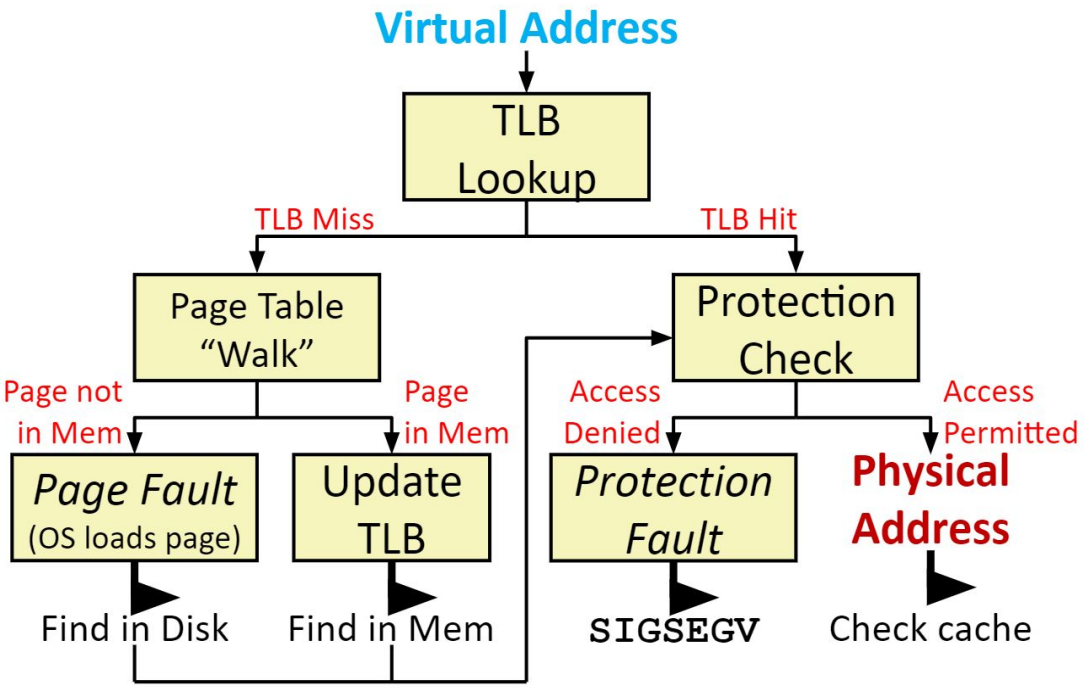
# CS 449 – Virtual Memory

## Address Translation




## Address Translation Symbols

Basic Parameters:

| | |
|---|---|
| $N = 2^n$ | Number of addresses in virtual address space |
| $M = 2^m$ | Number of addresses in physical address space |
| $P = 2^p$ | Page size (bytes) |

Components of Virtual Address (VA):

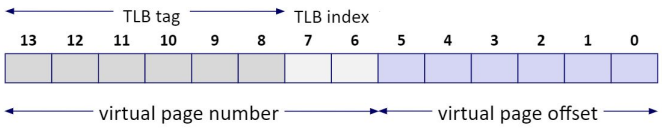
| | |
|---|---|
| **VPO** | Virtual Page Offset |
| **VPN** | Virtual Page Number |
| **TLBI** | TLB Index |
| **TLBT** | TLB Tag |

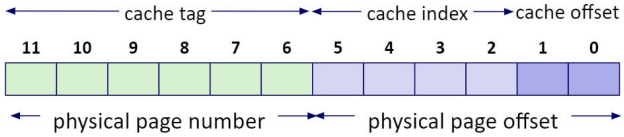
Components of Physical Address (PA):

| | |
|---|---|
| **PPO** | Physical Page Offset (Same as VPO) |
| **PPN** | Physical Page Number |

## A Small Example

Suppose we have a simple memory system with **14-bit** virtual addresses, **12-bit** physical addresses, and a page size of **64 bytes**. The TLB has **16 entries** in total and is **4-way** set associative. The cache is direct-mapped with **16 sets** and a block size of **4 bytes**.




Current State of Memory System:

**TLB:**

| Set | Tag | PPN | V | Tag | PPN | V | Tag | PPN | V | Tag | PPN | V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 03 | – | 0 | 09 | 0D | 1 | 00 | – | 0 | 07 | 02 | 1 |
| 1 | 03 | 2D | 1 | 02 | – | 0 | 04 | – | 0 | 0A | – | 0 |
| 2 | 02 | – | 0 | 08 | – | 0 | 06 | – | 0 | 03 | – | 0 |
| 3 | 07 | – | 0 | 03 | 0D | 1 | 0A | 34 | 1 | 02 | – | 0 |

**Page table (partial):**

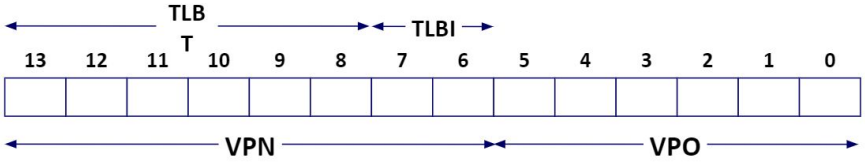
| VPN | PPN | V | VPN | PPN | V |
|---|---|---|---|---|---|
| 0 | 28 | 1 | 8 | 13 | 1 |
| 1 | – | 0 | 9 | 17 | 1 |
| 2 | 33 | 1 | A | 09 | 1 |
| 3 | 02 | 1 | B | – | 0 |
| 4 | – | 0 | C | – | 0 |
| 5 | 16 | 1 | D | 2D | 1 |
| 6 | – | 0 | E | – | 0 |
| 7 | – | 0 | F | 0D | 1 |

**Cache:**

| Index | Tag | V | B0 | B1 | B2 | B3 | Index | Tag | V | B0 | B1 | B2 | B3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 19 | 1 | 99 | 11 | 23 | 11 | 8 | 24 | 1 | 3A | 00 | 51 | 89 |
| 1 | 15 | 0 | – | – | – | – | 9 | 2D | 0 | – | – | – | – |
| 2 | 1B | 1 | 00 | 02 | 04 | 08 | A | 2D | 1 | 93 | 15 | DA | 3B |
| 3 | 36 | 0 | – | – | – | – | B | 0B | 0 | – | – | – | – |
| 4 | 32 | 1 | 43 | 6D | 8F | 09 | C | 12 | 0 | – | – | – | – |
| 5 | 0D | 1 | 36 | 72 | F0 | 1D | D | 16 | 1 | 04 | 96 | 34 | 15 |
| 6 | 31 | 0 | – | – | – | – | E | 13 | 1 | 83 | 77 | 1B | D3 |
| 7 | 16 | 1 | 11 | C2 | DF | 03 | F | 14 | 0 | – | – | – | – |

## Memory Requests

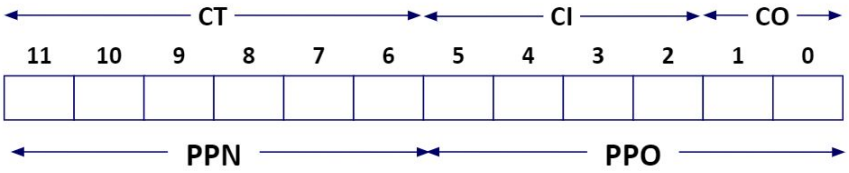
1. **Virtual Address: 0x0ACA**




VPN ____ TLBT ____ TLBI ____

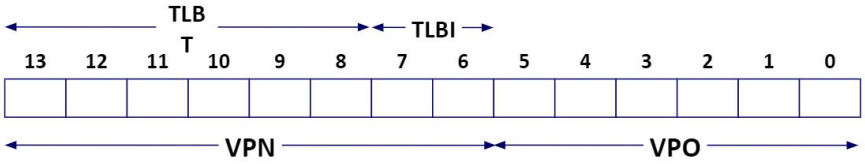
TLB Hit? ____ Page Fault? ____ PPN ____

**Physical Address:**




CT ____ CI ____ CO ____ Cache Hit? ____ Data (byte) ____

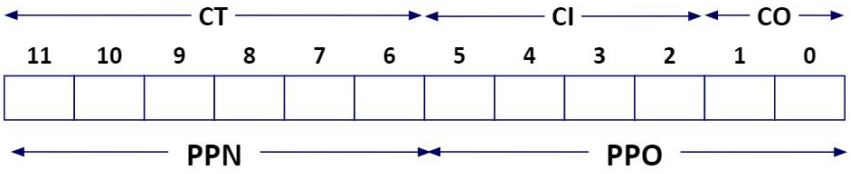
2. **Virtual Address: 0x015D**




VPN ____ TLBT ____ TLBI ____

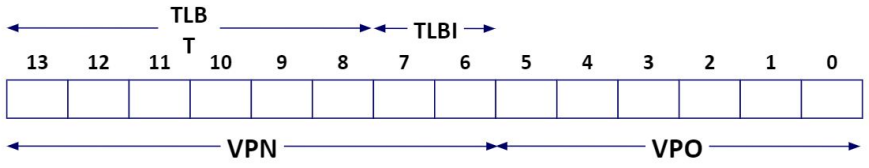
TLB Hit? ____ Page Fault? ____ PPN ____

**Physical Address:**




CT ____ CI ____CO ____ Cache Hit? ____ Data (byte) ____

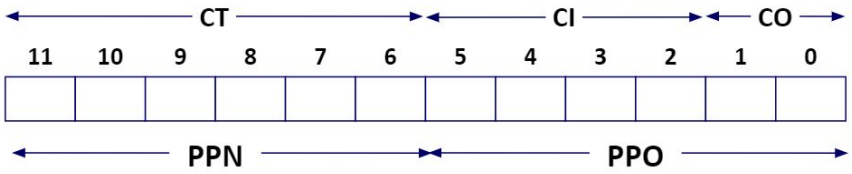
3. **Virtual Address: 0x0273**




VPN _____ TLBT _____ TLBI ____

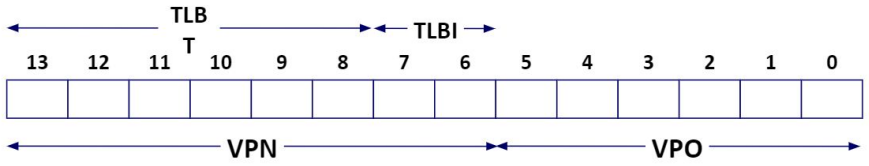
TLB Hit? _____ Page Fault? _____ PPN _____

**Physical Address:**




CT _____ CI _____CO _____ Cache Hit? _____ Data (byte) _____

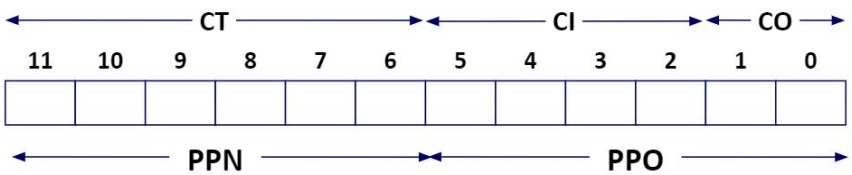
4. **Virtual Address: 0x036B**




VPN _____ TLBT _____ TLBI____

TLB Hit? _____ Page Fault? _____ PPN _____

**Physical Address:**




CT _____ CI _____CO _____ Cache Hit? _____ Data (byte) _____

## Virtual Memory Table

| VA width (n) | PA width (m) | Page size (P) | VPN width | PPN width | Bits in PTE (assume V, D, R, W, X) |
|---|---|---|---|---|---|
| 32 | 32 | 16 KiB | | | |
| 32 | 26 | | | 13 | |
| | 32 | | 21 | | 22 |
| | | 32 KiB | 25 | | 26 |
| 64 | | | 48 | | 29 |