Introduction to Operating Systems and Processes

HPPS

David Marchant

Based on slides by:

Randal E. Bryant and David R. O'Hallaron with modifications by Troels Henriksen

A quick note about me

- PhD student from Scotland
- Jeg taler ikke dansk :(
- ‘David’ on the Discord
- Office: HCØ, Building B, room 772-01-0-S06

Why study operating systems?

- **They are where the magic happens**
- **For inspiration**
  - One of the most potent *engineering abstractions* in computing
  - Each program thinks it has an entire machine to itself
  - Controlled communication between programs.
  - Abstracts over hardware differences
- **Practical skills**
  - Performance characteristics of the abstraction
  - What is fundamentally possible?

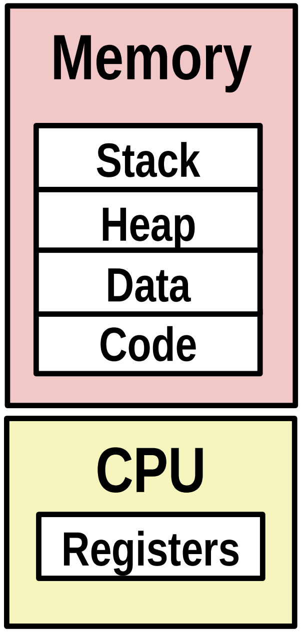
Unix

- **What is Unix?**
  - Unix is an operating system developed in the 1970s by Ken Thompson and Dennis Ritchie
  - Most modern operating systems heavily influenced by Unix (even Windows)
  - Many operating systems are *direct descendants:* Linux, iOS, macOS, the *BSDs, etc
- **Why Unix?**
  - Unix is *simple* and *representative* of modern systems
  - We will use Unix designs for all examples

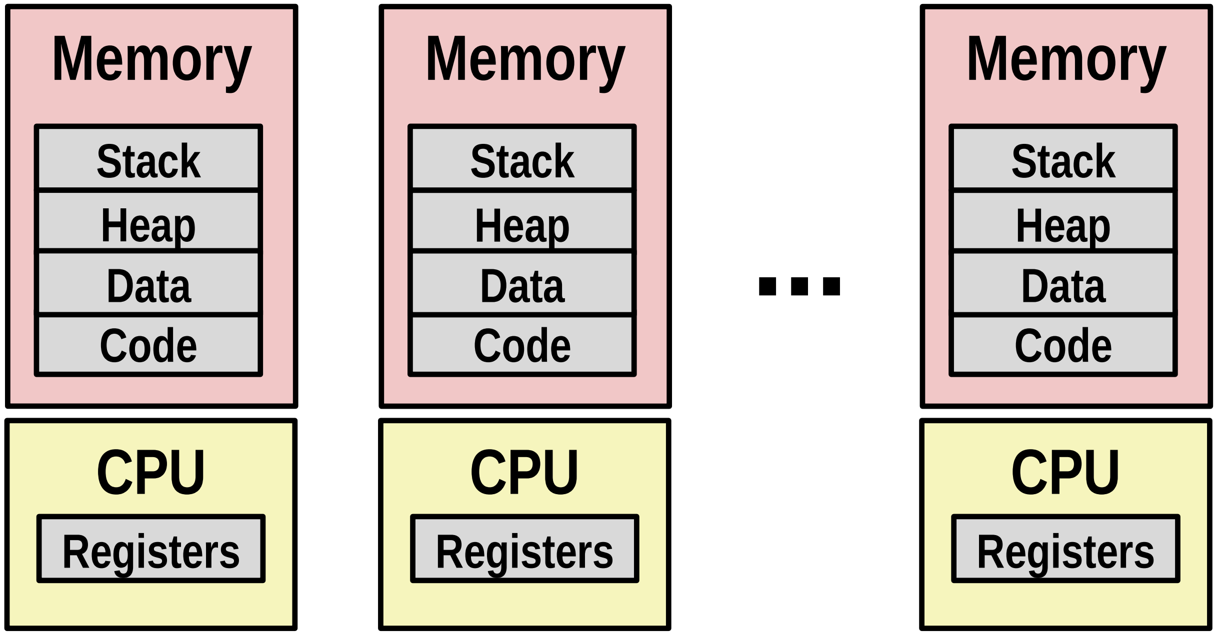
Processes

- **Definition: A *process* is an instance of a running program.**
  - One of the most profound ideas in computer science
  - Not the same as “program” or “processor”

- **Process provides each program with two key abstractions:**
  - ***Logical control flow***
    - Each program seems to have exclusive use of the CPU
    - Provided by kernel mechanism called *context switching*
  - ***Private address space***
    - Each program seems to have exclusive use of main memory.
    - Provided by kernel mechanism called *virtual memory*



Multiprocessing: The Illusion



- **Computer runs many processes simultaneously**
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

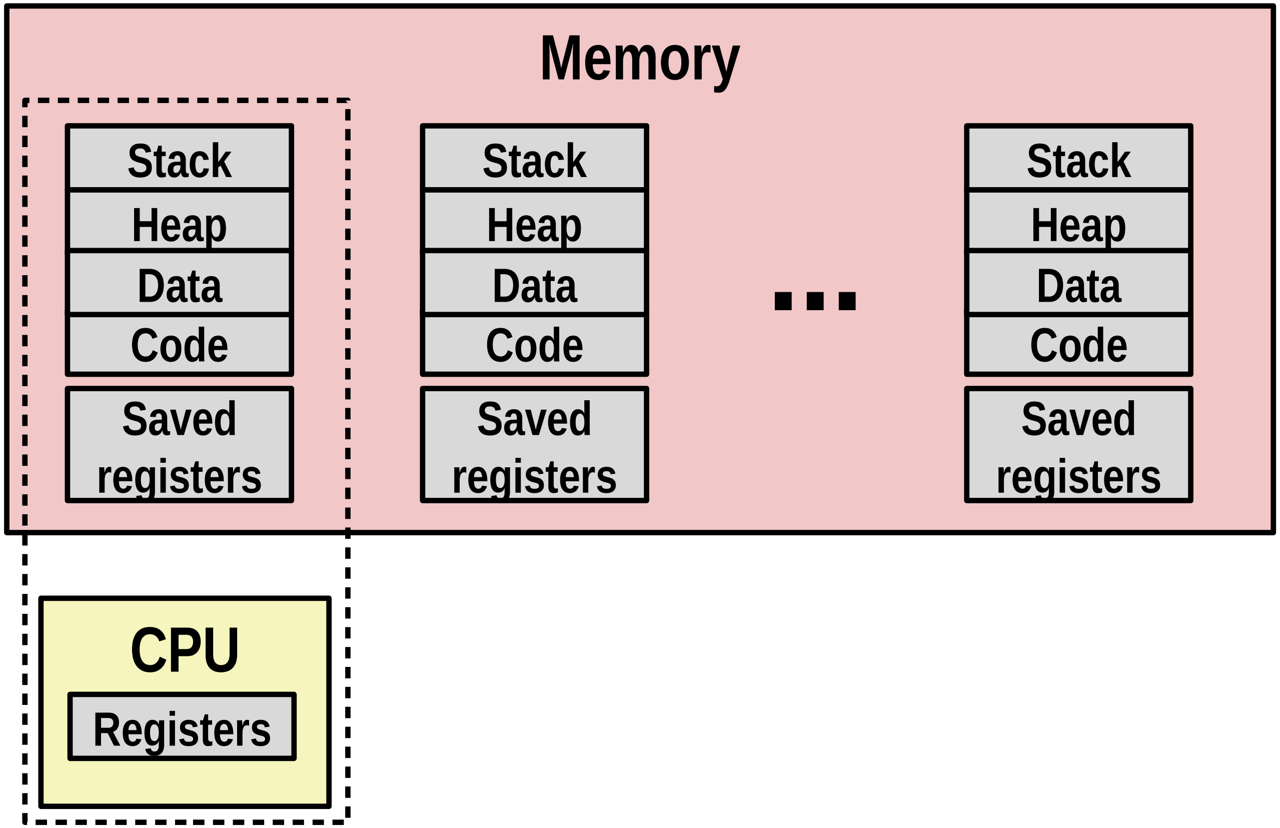
Multiprocessing Example

```
xterm
Processes: 123 total, 5 running, 9 stuck, 109 sleeping, 611 threads          11:47:07
Load Avg: 1.03, 1.13, 1.14  CPU usage: 3.27% user, 5.15% sys, 91.56% idle
SharedLibs: 576K resident, 0B data, 0B linkedit.
MemRegions: 27958 total, 1127M resident, 35M private, 494M shared.
PhysMem: 1039M wired, 1974M active, 1062M inactive, 4076M used, 18M free.
VM: 280G vsize, 1091M framework vsize, 23075213(1) pageins, 5843367(0) pageouts.
Networks: packets: 41046228/11G in, 66083096/77G out.
Disks: 17874391/349G read, 12847373/594G written.

PID    COMMAND      %CPU TIME     #TH   #WQ  #PORT #MREG RPRVT  RSHRD  RSIZE  VPRVT  VSIZE
99217- Microsoft Of 0.0  02:28.34 4     1    202   418   21M    24M    21M    66M    763M
99051  usbmuxd      0.0  00:04.10 3     1    47    66    436K   216K   480K   60M    2422M
99006  iTunesHelper 0.0  00:01.23 2     1    55    78    728K   3124K  1124K  43M    2429M
84286  bash         0.0  00:00.11 1     0    20    24    224K   732K   484K   17M    2378M
84285  xterm        0.0  00:00.83 1     0    32    73    656K   872K   692K   9728K  2382M
55939- Microsoft Ex 0.3  21:58.97 10    3    360   954   16M    65M    46M    114M   1057M
54751  sleep        0.0  00:00.00 1     0    17    20    92K    212K   360K   9632K  2370M
54739  launchdadd   0.0  00:00.00 2     1    33    50    488K   220K   1736K  48M    2409M
54737  top          6.5  00:02.53 1/1   0    30    29    1416K  216K   2124K  17M    2378M
54719  automountd   0.0  00:00.02 7     1    53    64    860K   216K   2184K  53M    2413M
54701  ocspd        0.0  00:00.05 4     1    61    54    1268K  2644K  3132K  50M    2426M
54661  Grab         0.6  00:02.75 6     3    222+  389+  15M+   26M+   40M+   75M+   2556M+
54659  cookied      0.0  00:00.15 2     1    40    61    3316K  224K   4088K  42M    2411M
53818  mdworker     0.0  00:01.67 4     1    52    91    7628K  7412K  16M    48M    2438M
50878  mdworker     0.0  00:11.17 3     [illegible] 53 91 2464K 6148K 9976K  44M    2434M
[illegible]                                0    [illegible] 73 [illegible] 532K 9700K 2382M
50078  emacs        0.0  00:06.70 1     0    20    35    52K    216K   88K    18M    2392M
```

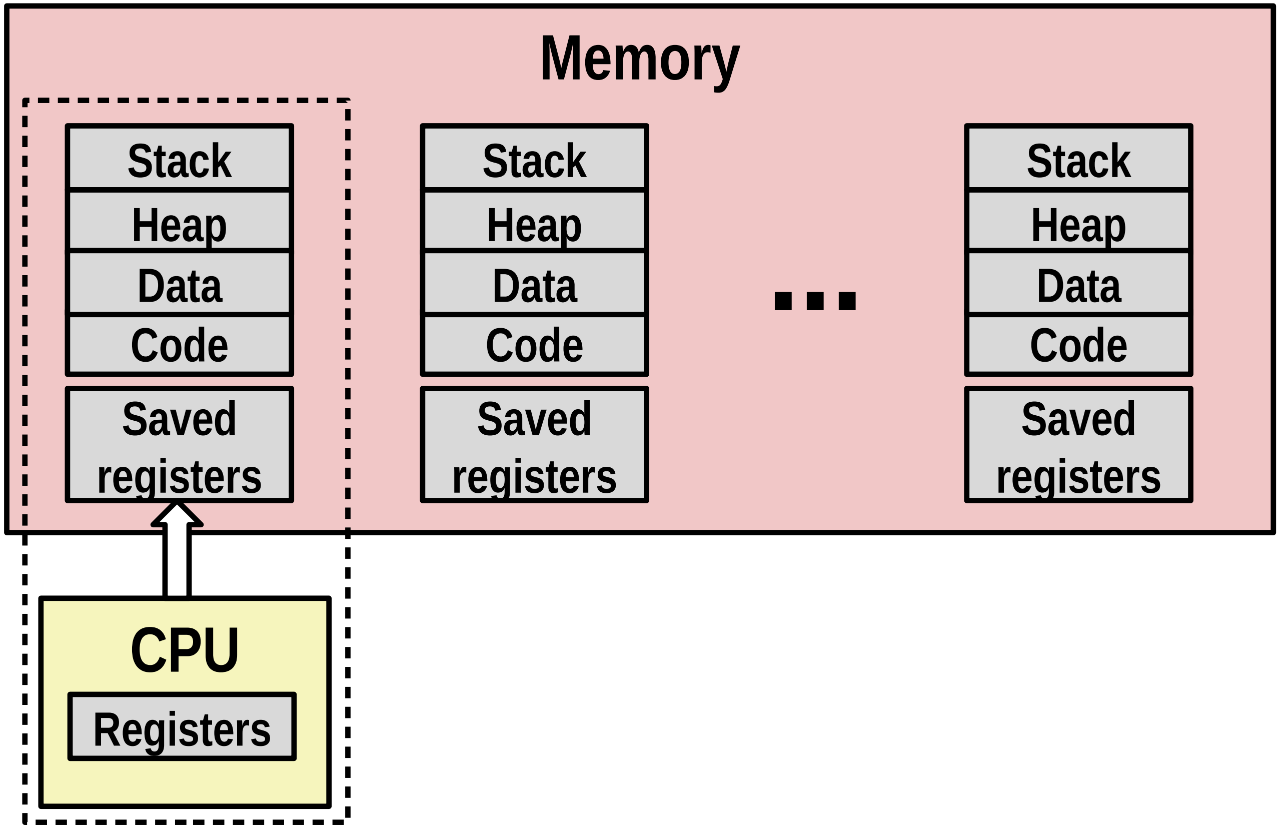
- **Running program "top" on Mac**
  - System has 123 processes, 5 of which are active
  - Identified by Process ID (PID)

Multiprocessing: The (Traditional) Reality



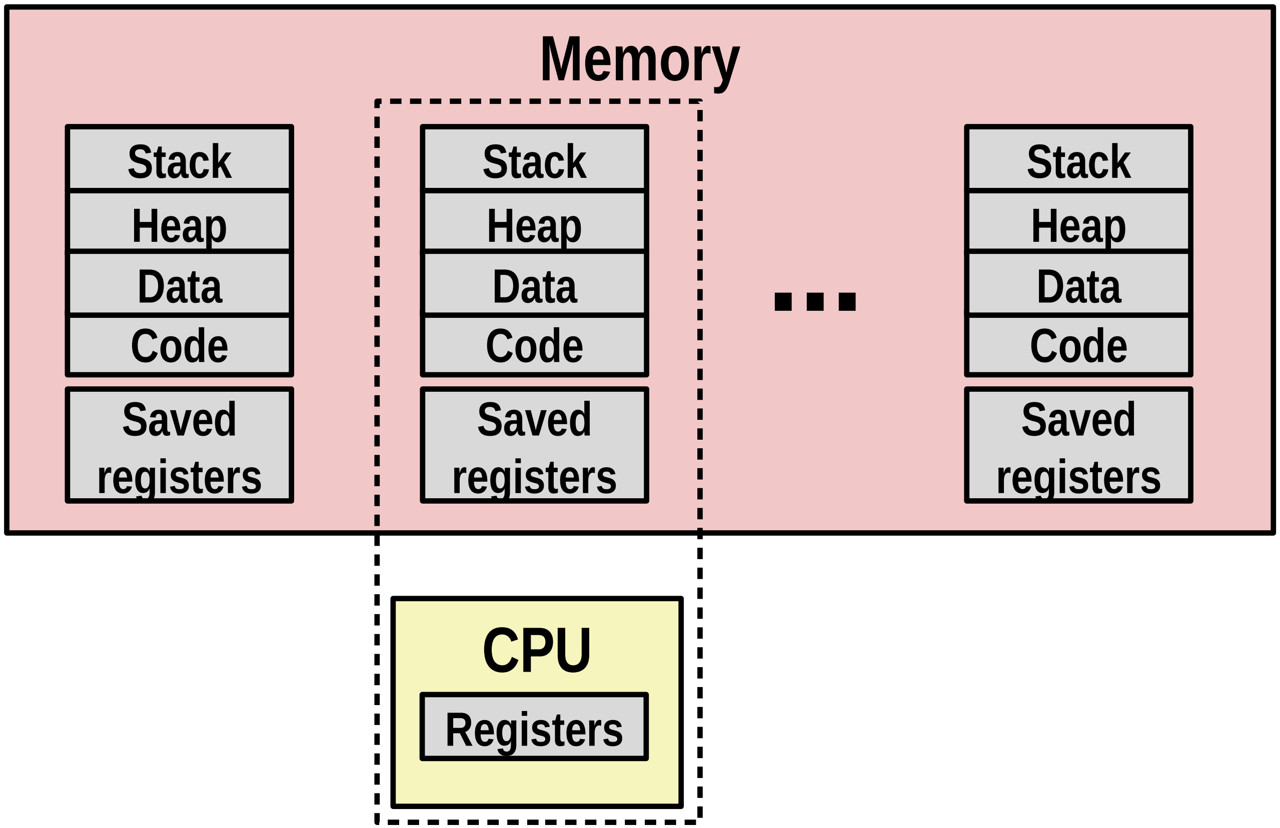
- **Single processor executes multiple processes concurrently**
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system (later in course)
  - Register values for non-executing (suspended) processes saved in memory

Multiprocessing: The (Traditional) Reality



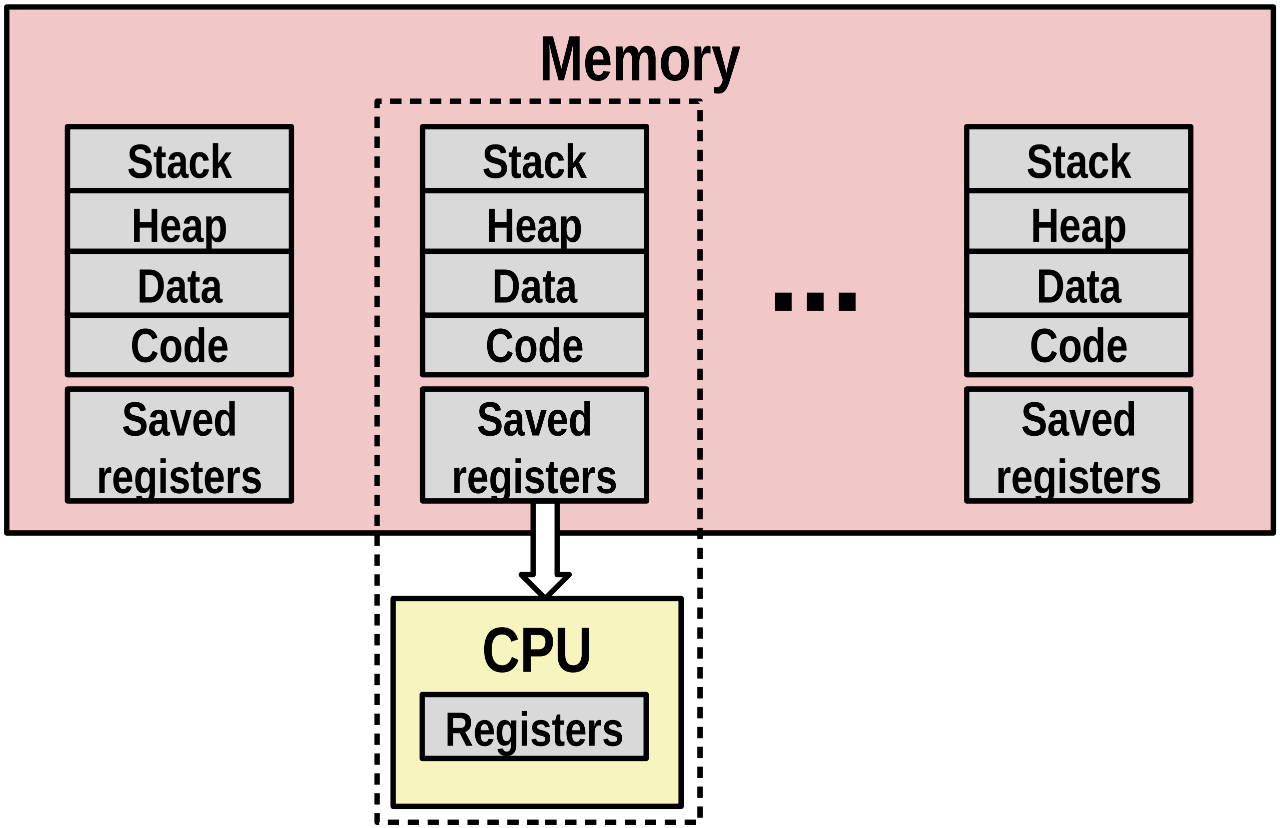
- **Save current registers in memory**

Multiprocessing: The (Traditional) Reality



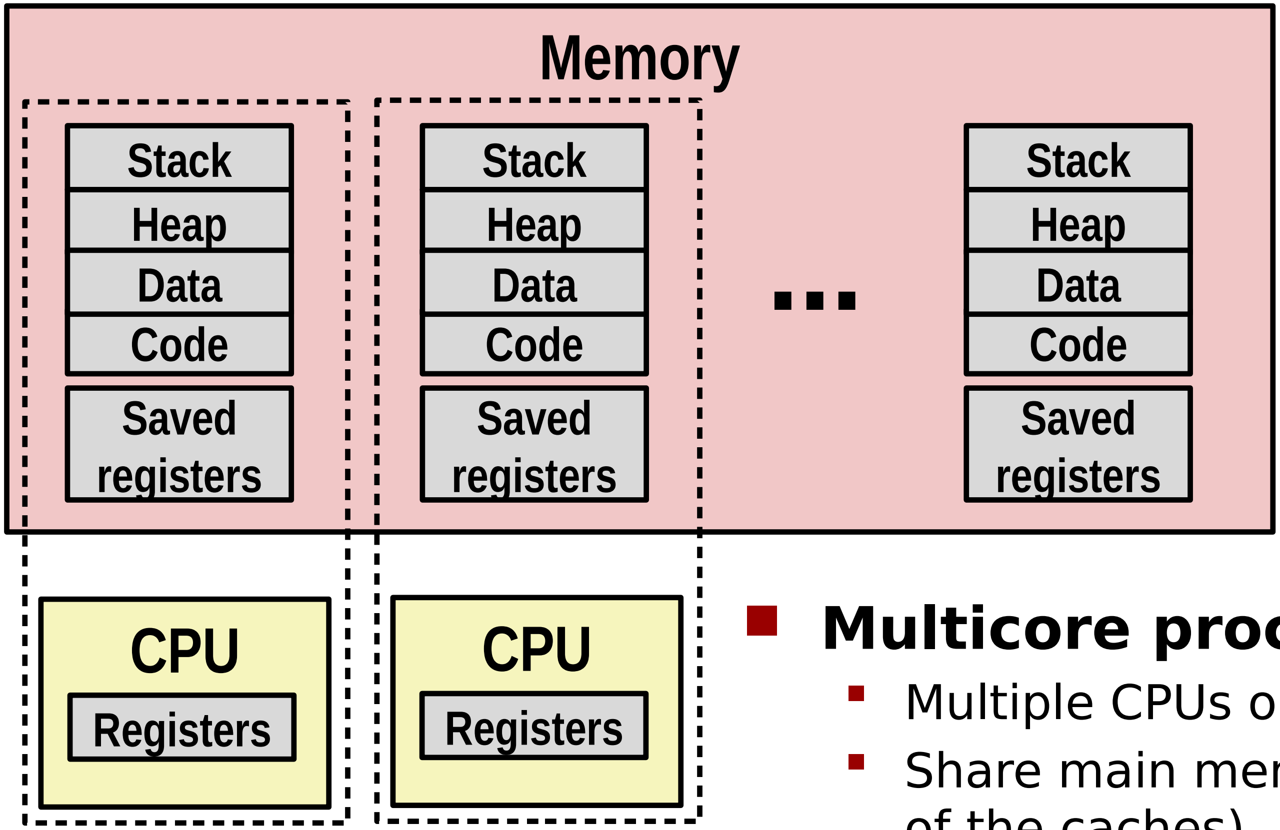
- Schedule next process for execution

Multiprocessing: The (Traditional) Reality



- Load saved registers and switch address space (context switch)

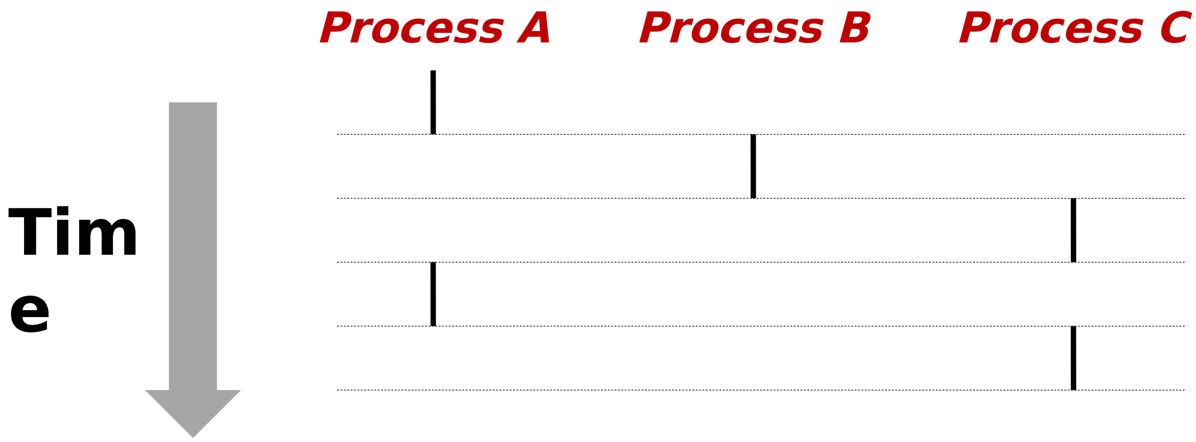
Multiprocessing: The (Modern) Reality



- **Multicore processors**
  - Multiple CPUs on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Scheduling of processors onto cores done by kernel

Concurrent Processes

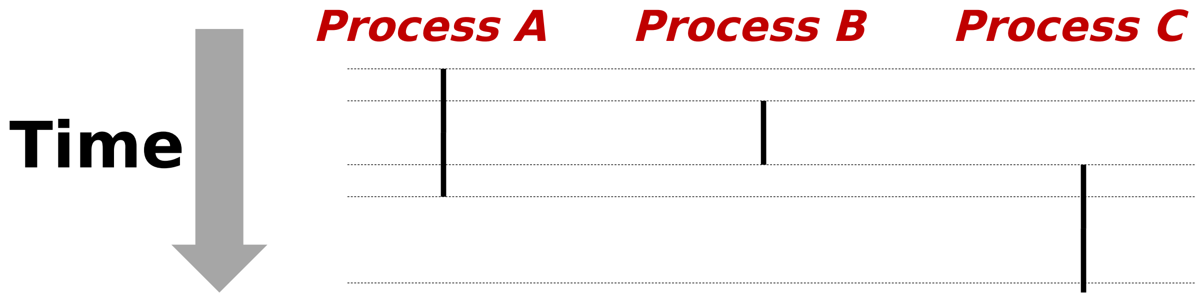
- **Each process is a logical control flow.**
- **Two processes *run* *concurrently* (*are concurrent)* if their flows overlap in time**
- **Otherwise, they are *sequential***
- **Examples (running on single core):**
  - Concurrent: A & B, A & C
  - Sequential: B & C



User View of Concurrent Processes

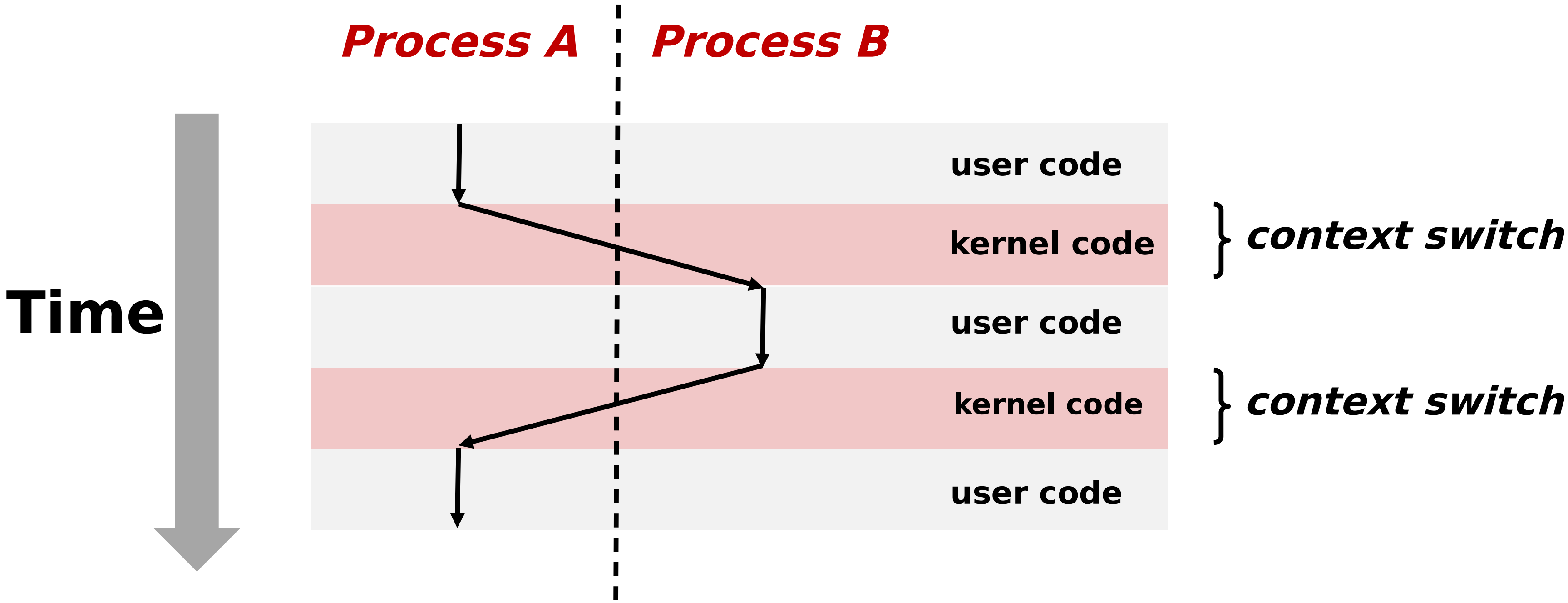
- Control flows for concurrent processes are physically disjoint in time

- However, we can think of concurrent processes as running in parallel with each other



Context Switching

- **Processes are managed by a shared chunk of memory-resident OS code called the *kernel***
  - Important: the kernel is not a separate process, but rather runs as part of some existing process.
- **Control flow passes from one process to another via a *context switch***



System Calls

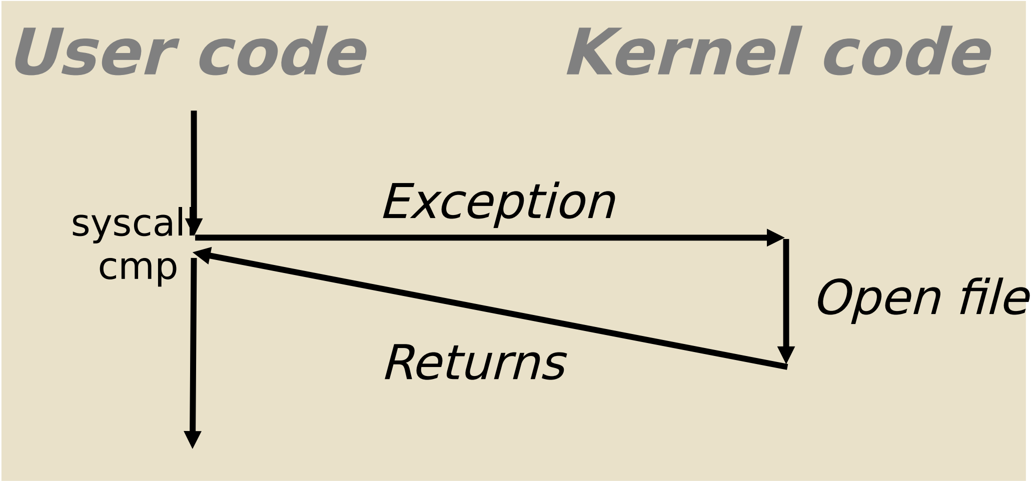
- **Systems calls ask the operating system to perform a task on behalf of the process.**
- **Each x86-64 system call has a unique ID number**
- **Examples:**

Number	*Name*	*Description*
0	`read`	Read file
1	`write`	Write file
2	`open`	Open file
3	`close`	Close file
4	`stat`	Get info about file
57	`fork`	Create process
59	`execve`	Execute a program
60	`_exit`	Terminate process
62	`kill`	Send signal to process

System Call Example: Opening File

- User calls: **`open(filename, options)`**
- Calls **`__open`** function, which invokes system call instruction **`syscall`**

```
00000000000e5d70 <__open>:
...
e5d79:   b8 02 00 00 00      mov  $0x2,%eax   # open is syscall #2
e5d7e:   0f 05               syscall          # Return value in %rax
e5d80:   48 3d 01 f0 ff ff   cmp  $0xfffffffffffff001,%rax
...
e5dfa:   c3                  retq
```

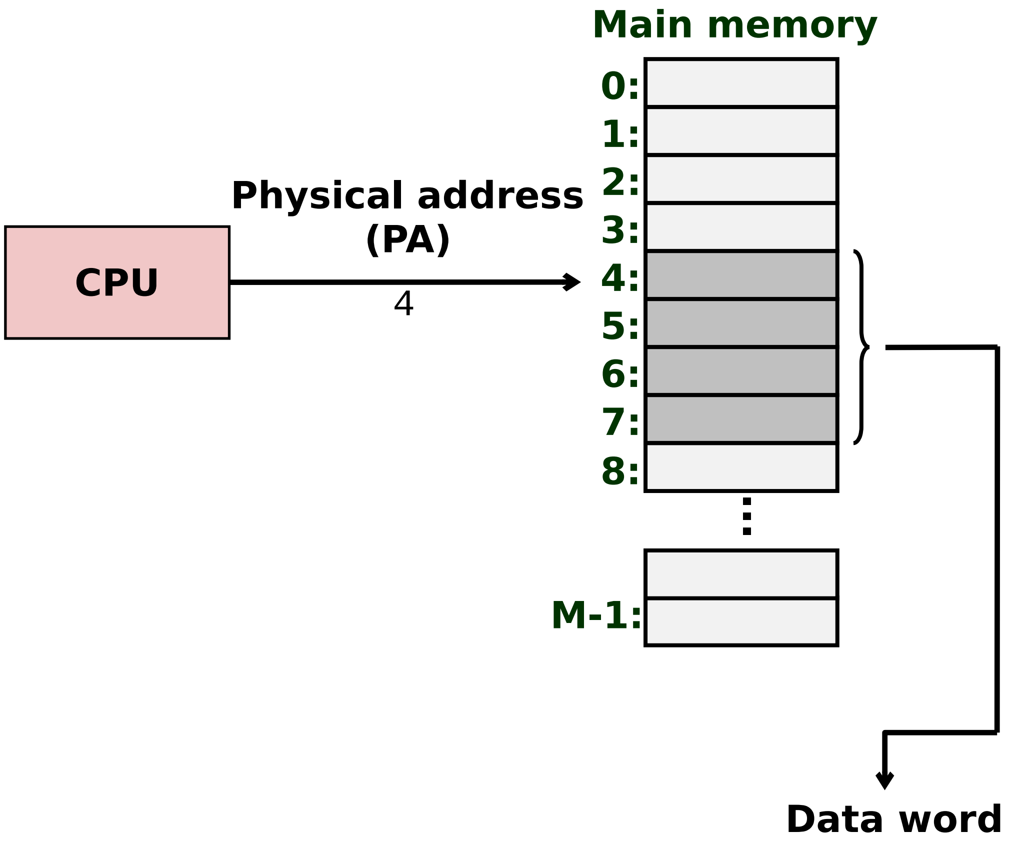


- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Summary

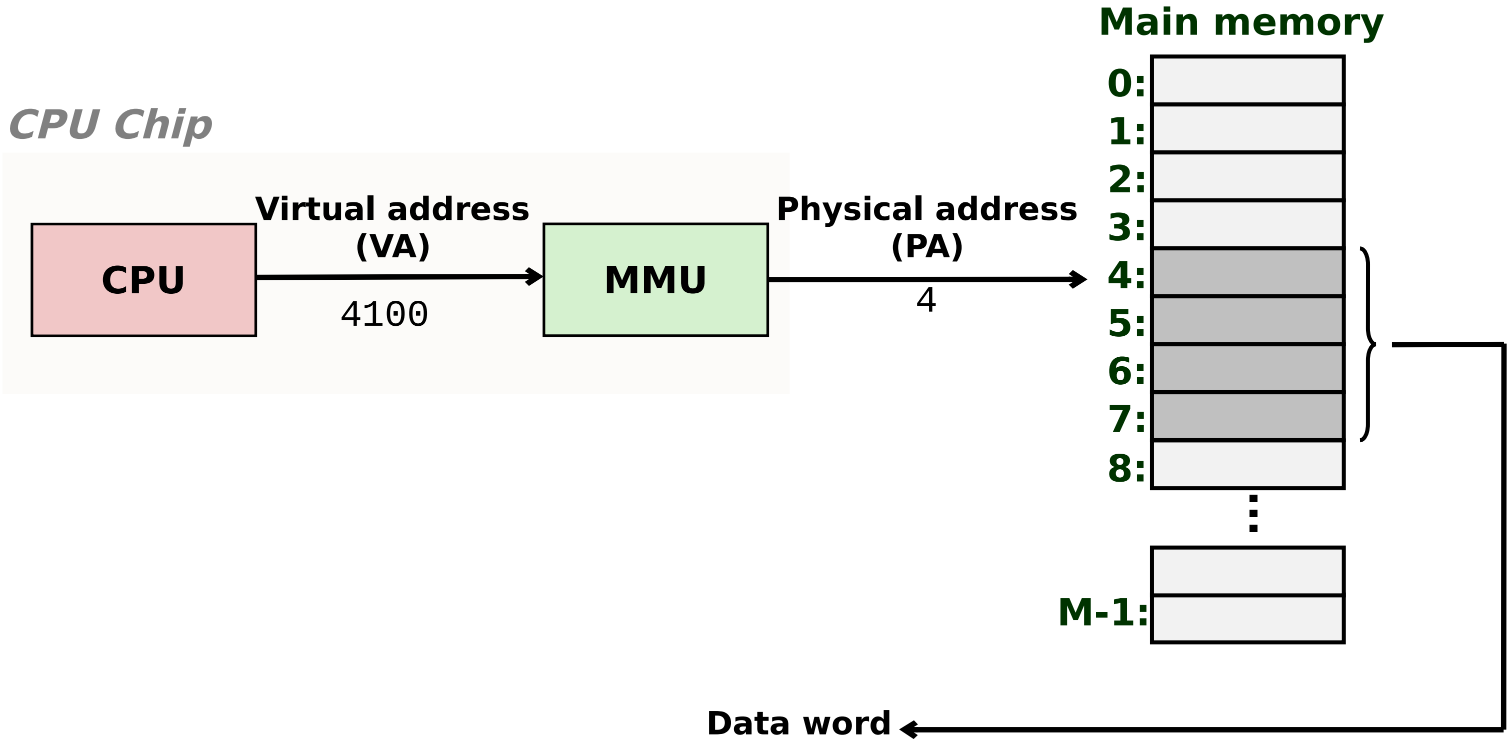
- **Processes**
  - At any given time, system has multiple active processes
  - Only one can execute at a time on a single core, though
  - Each process appears to have total control of processor + private memory space

A System Using Physical Addressing



- Used in "simple" systems like embedded microcontrollers in devices like cars, elevators, and digital picture frames

A System Using Virtual Addressing



- Used in all modern servers, laptops, and smart phones
- One of the great ideas in computer science

Address Spaces

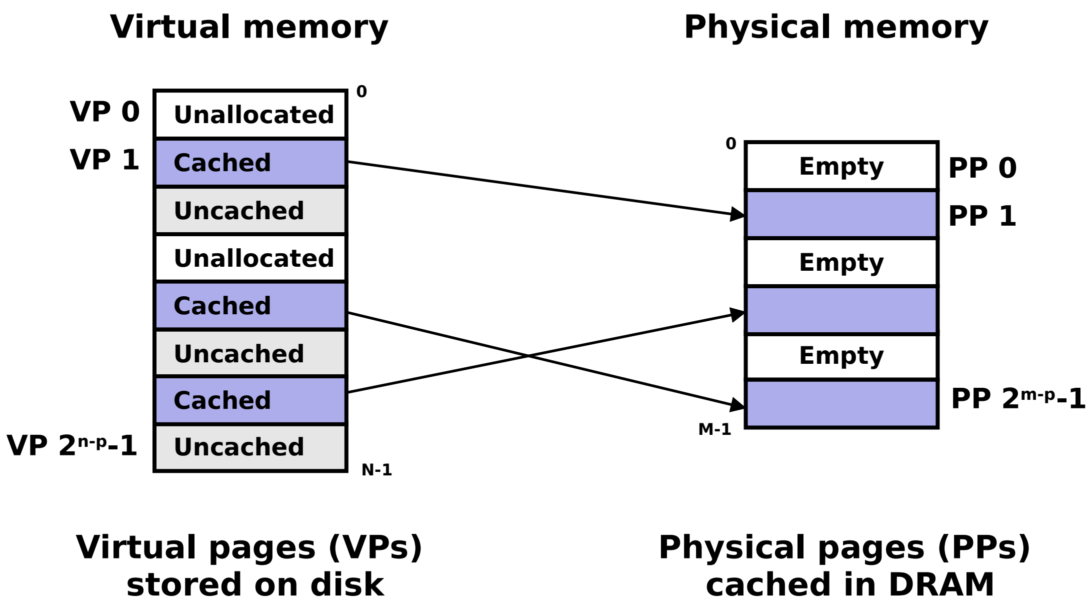
- **Linear address space:** Ordered set of contiguous non-negative integer addresses:
  $\{0, 1, 2, 3 \ldots \}$
- **Virtual address space:** Set of $N = 2^n$ virtual addresses
  $\{0, 1, 2, 3, \ldots, N-1\}$
- **Physical address space:** Set of $M = 2^m$ physical addresses
  $\{0, 1, 2, 3, \ldots, M-1\}$

Why Virtual Memory (VM)?

- **Uses main memory efficiently**
  - Use DRAM as a cache for parts of a virtual address space
- **Simplifies memory management**
  - Each process gets the same uniform linear address space
- **Isolates address spaces**
  - One process can’t interfere with another’s memory
  - User program cannot access privileged kernel information and code

VM as a Tool for Caching

- **Conceptually, *virtual memory* is an array of N contiguous bytes stored on disk (*from a caching perspective!)***
- **The contents of the array on disk are cached in *physical memory* (*DRAM cache*)**
  - These cache blocks are called *pages* (size is $P = 2^p$ bytes)



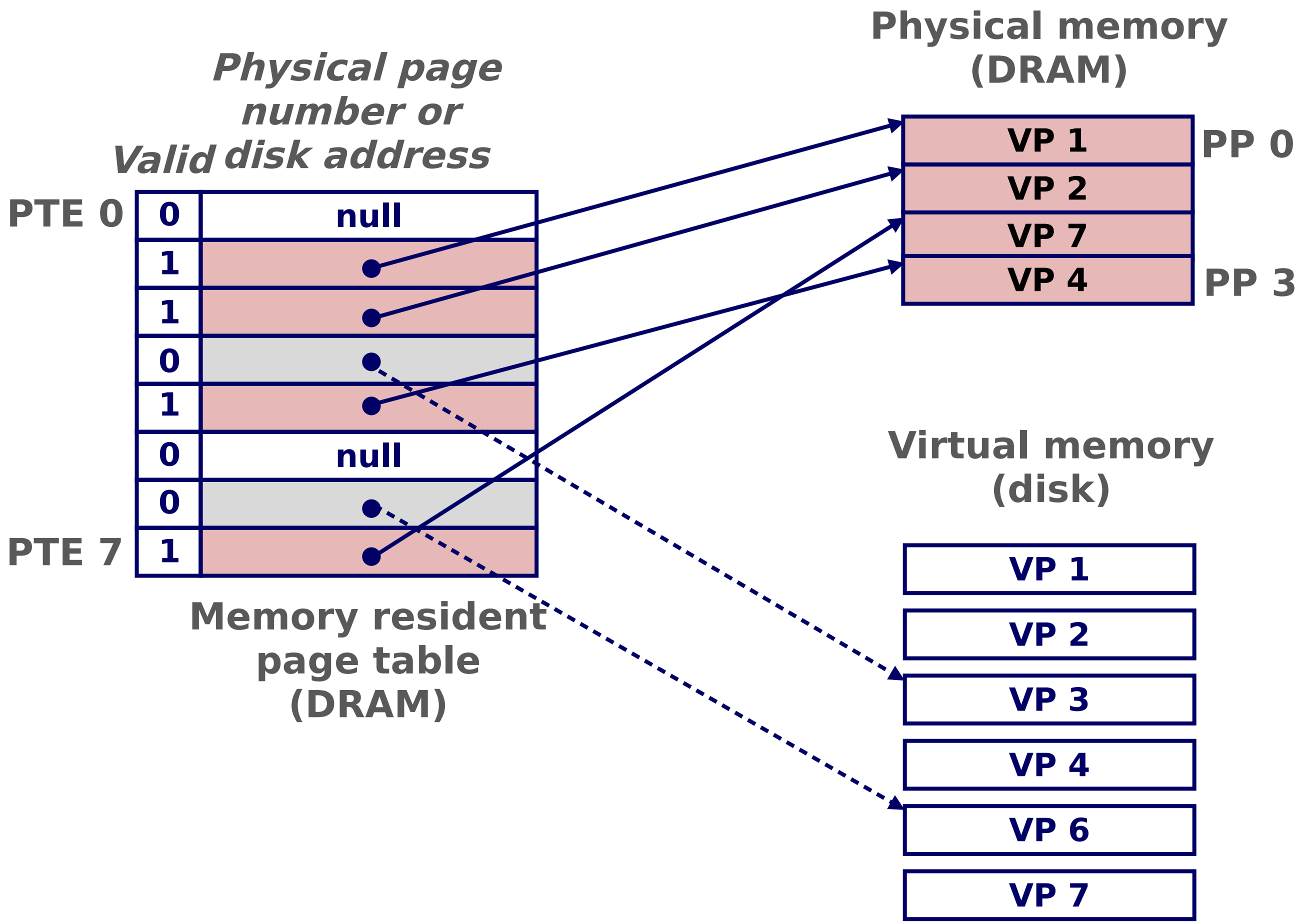
DRAM Cache Organization

- **DRAM cache organization driven by the enormous miss penalty**
  - DRAM is about ***10x*** slower than SRAM (CPU cache)
  - Disk is about ***10,000x*** slower than DRAM

- **Consequences**
  - Large page (block) size: typically 4 KB, sometimes 4 MB
  - Fully associative
    - Any VP can be placed in any PP
    - Requires a “large” mapping function – different from cache memories
  - Highly sophisticated, expensive replacement algorithms
    - Too complicated and open-ended to be implemented in hardware
  - Write-back rather than write-through

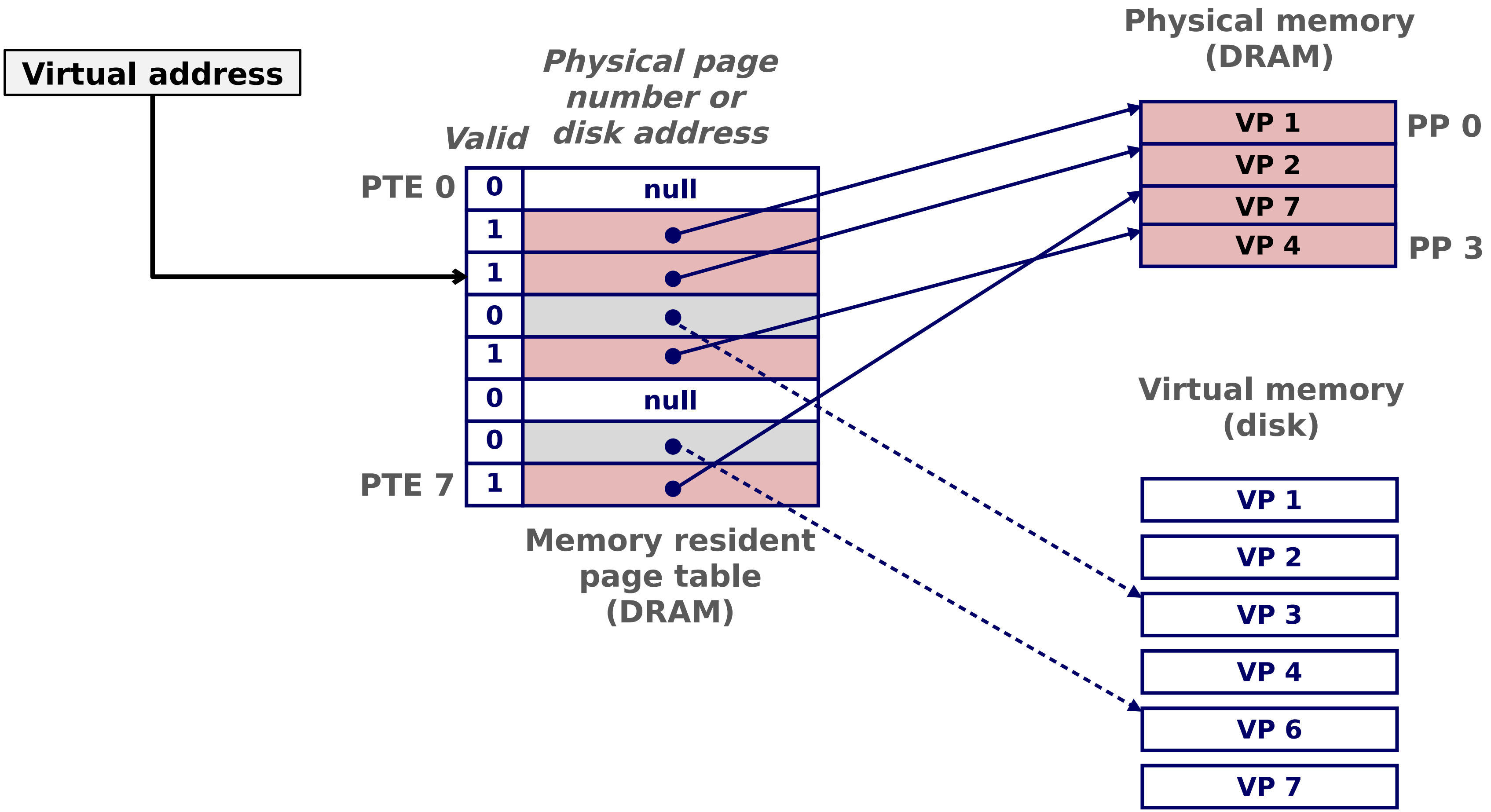
Enabling Data Structure: Page Table

- **A *page table* is an array of page table entries (PTEs) that maps virtual pages to physical pages.**
  - Per-process kernel data structure in DRAM



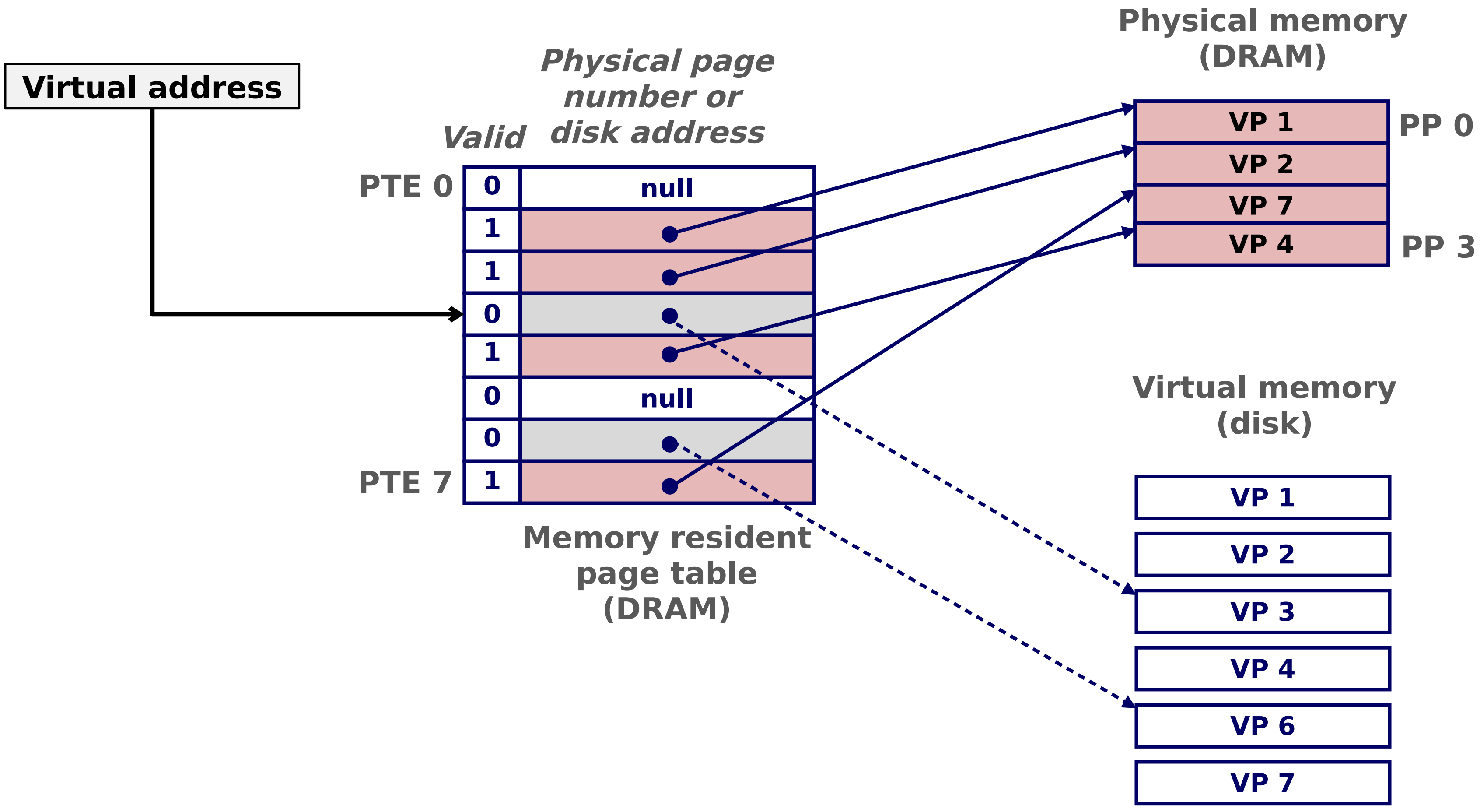
Page Hit

- ***Page hit:*** **reference to VM word that is in physical memory (DRAM cache hit)**



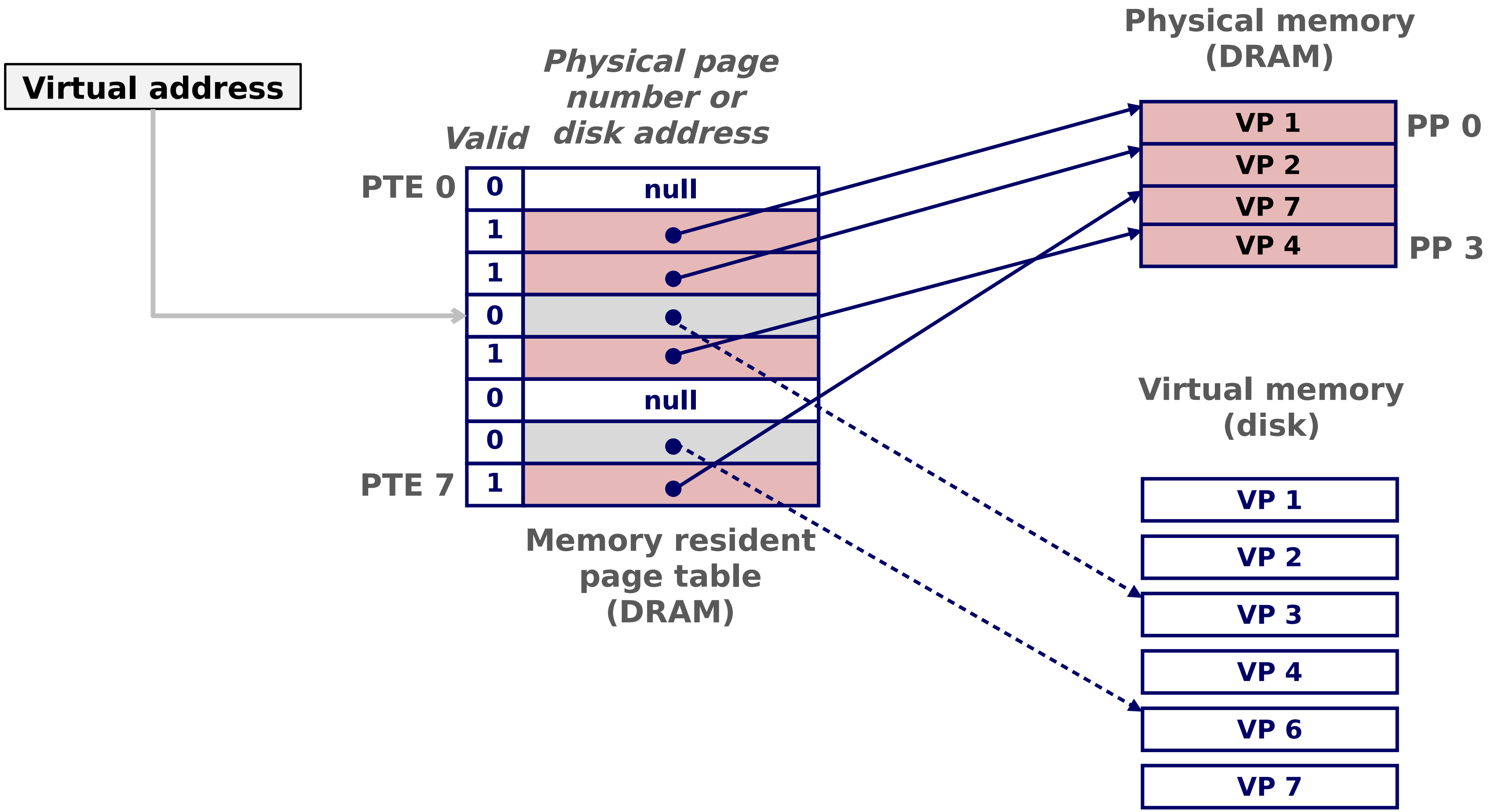
Page Fault

- ***Page fault:*** **reference to VM word that is not in physical memory (DRAM cache miss)**



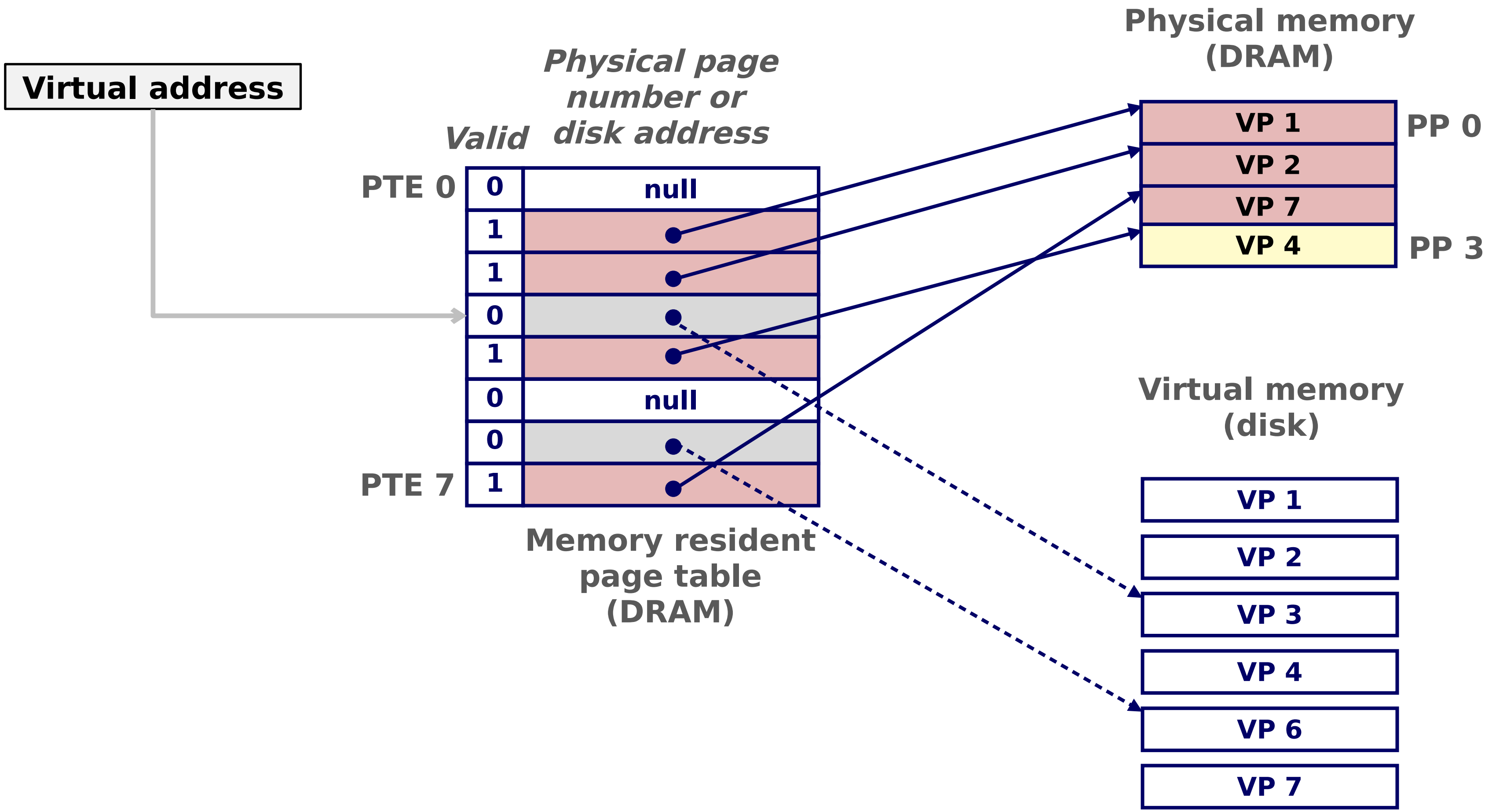
Handling Page Fault

- Page miss causes page fault (an exception)



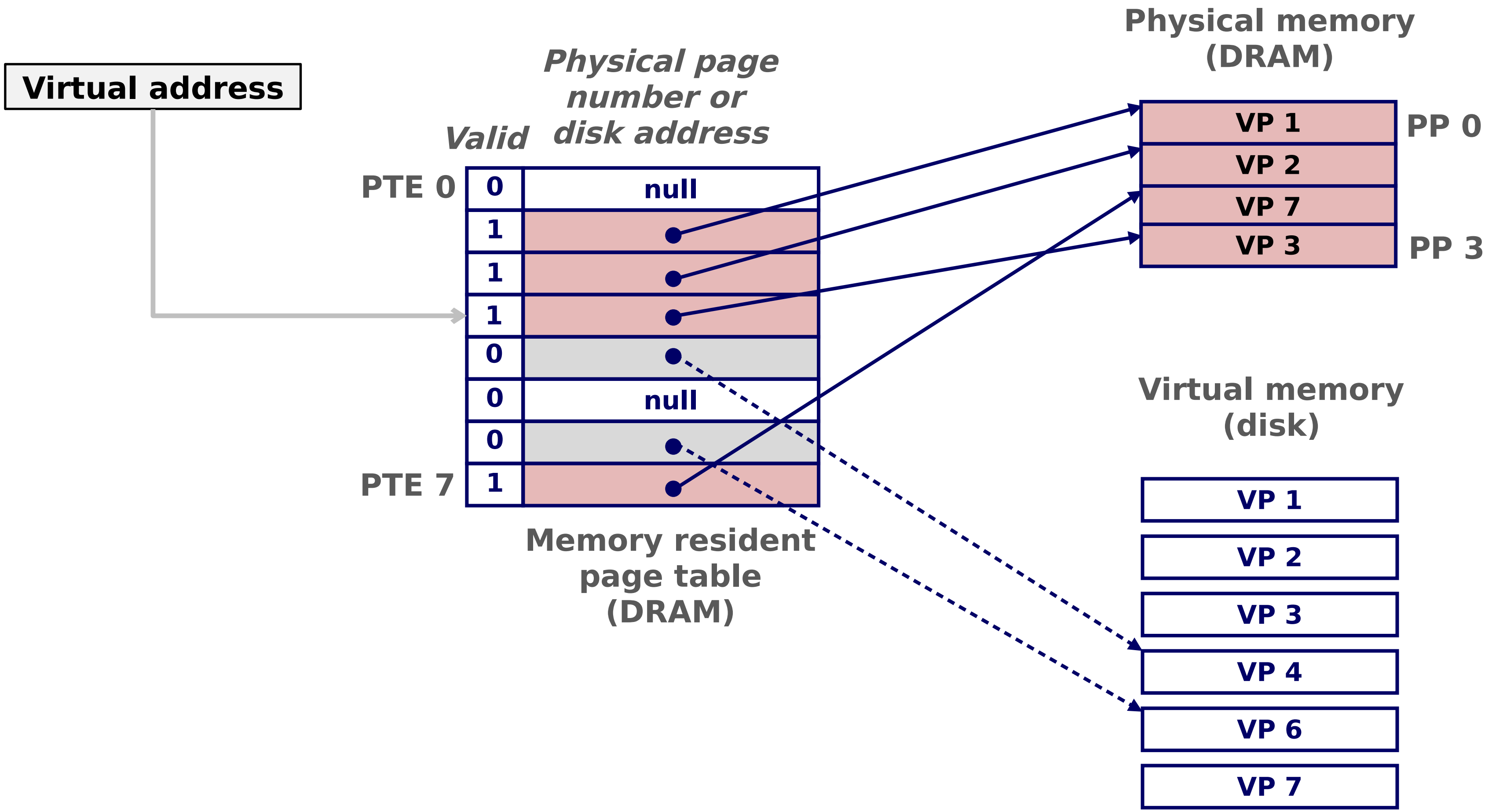
Handling Page Fault

- Page miss causes page fault (an exception)
- Page fault handler selects a victim to be evicted (here VP 4)



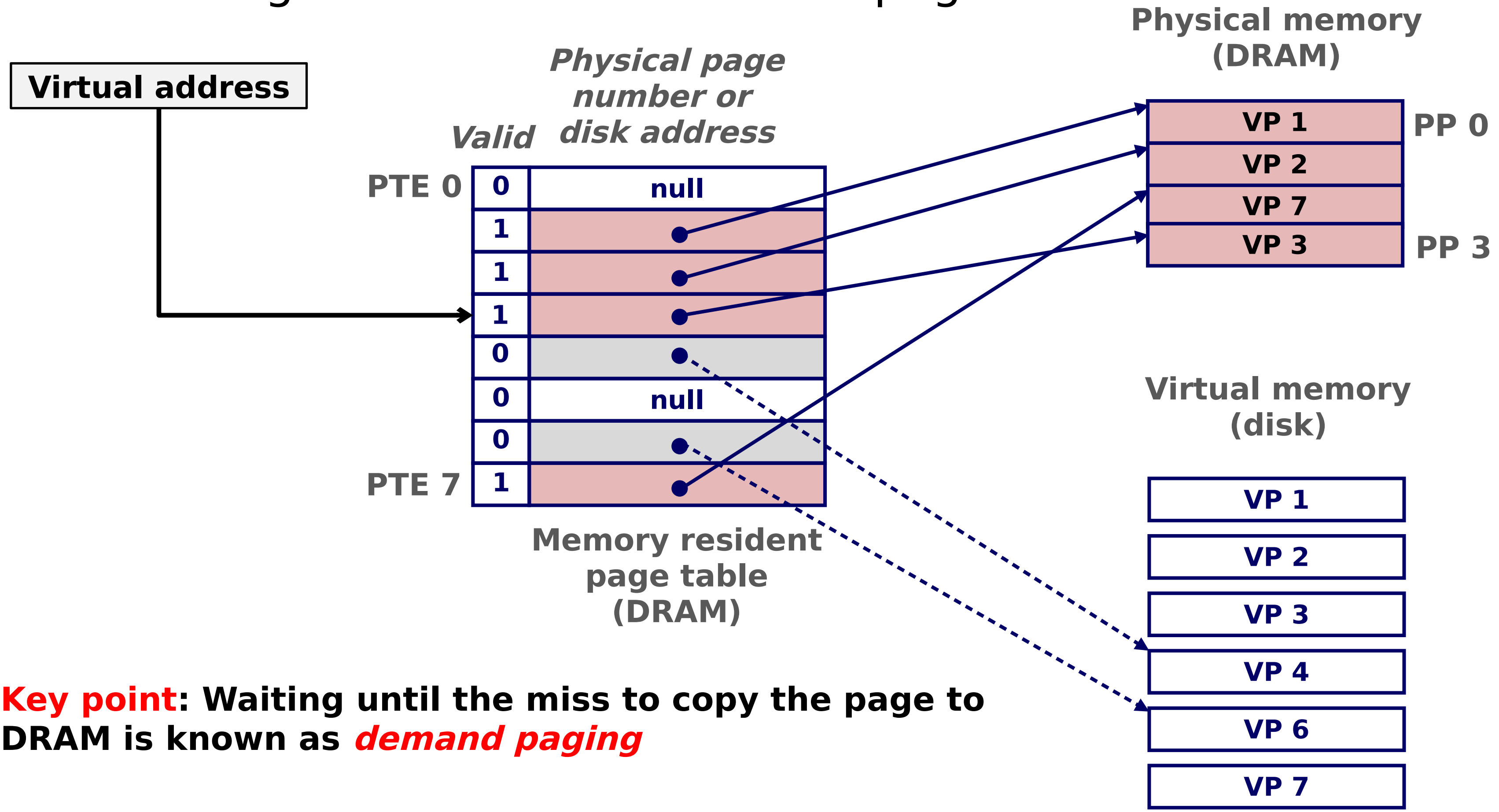
Handling Page Fault

- Page miss causes page fault (an exception)
- Page fault handler selects a victim to be evicted (here VP 4)



Handling Page Fault

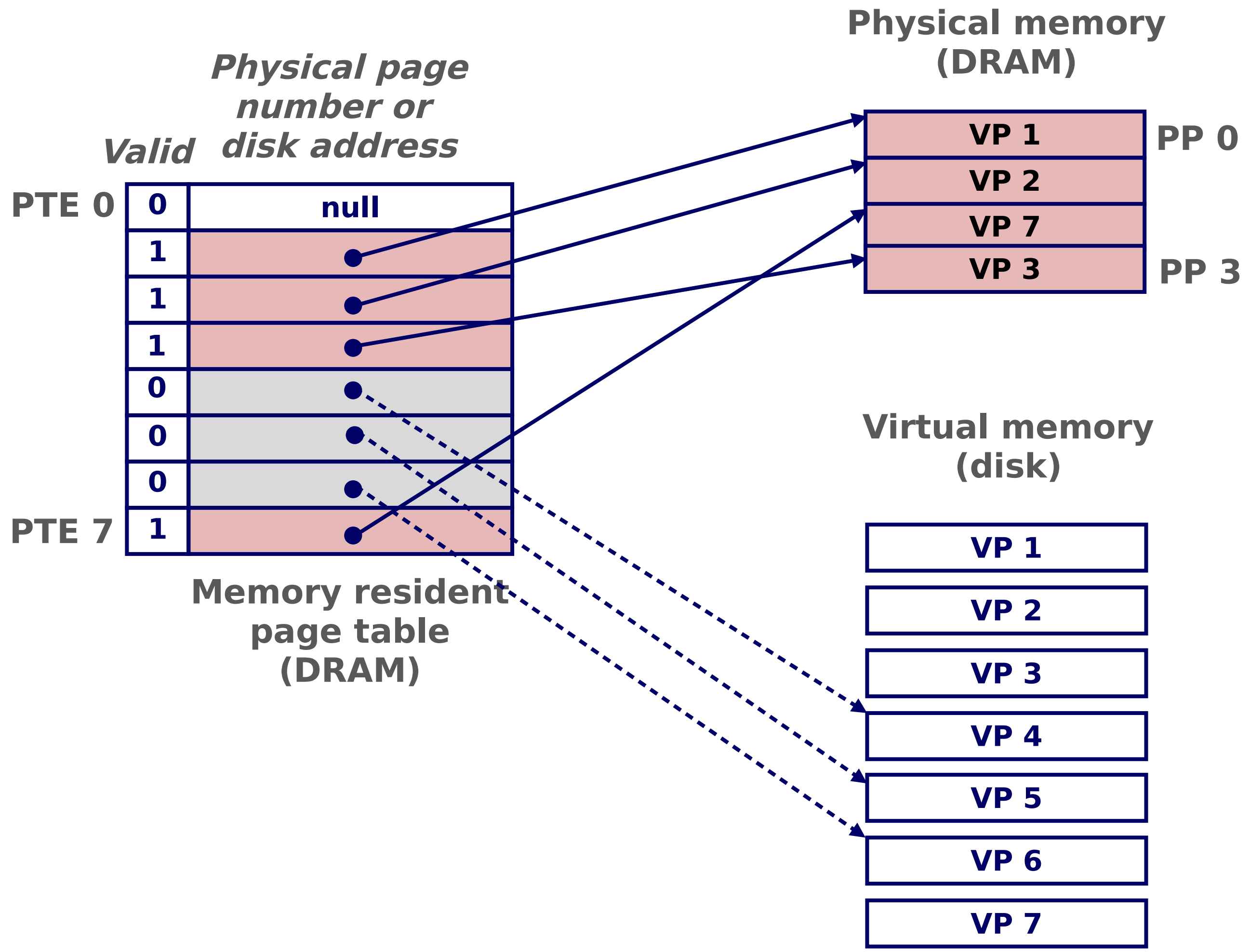
- Page miss causes page fault (an exception)
- Page fault handler selects a victim to be evicted (here VP 4)
- Offending instruction is restarted: page hit!



Key point: Waiting until the miss to copy the page to DRAM is known as *demand paging*

Allocating Pages

- Allocating a new page (VP 5) of virtual memory.



Locality to the Rescue Again!

- **Virtual memory seems terribly inefficient, but it works because of locality.**

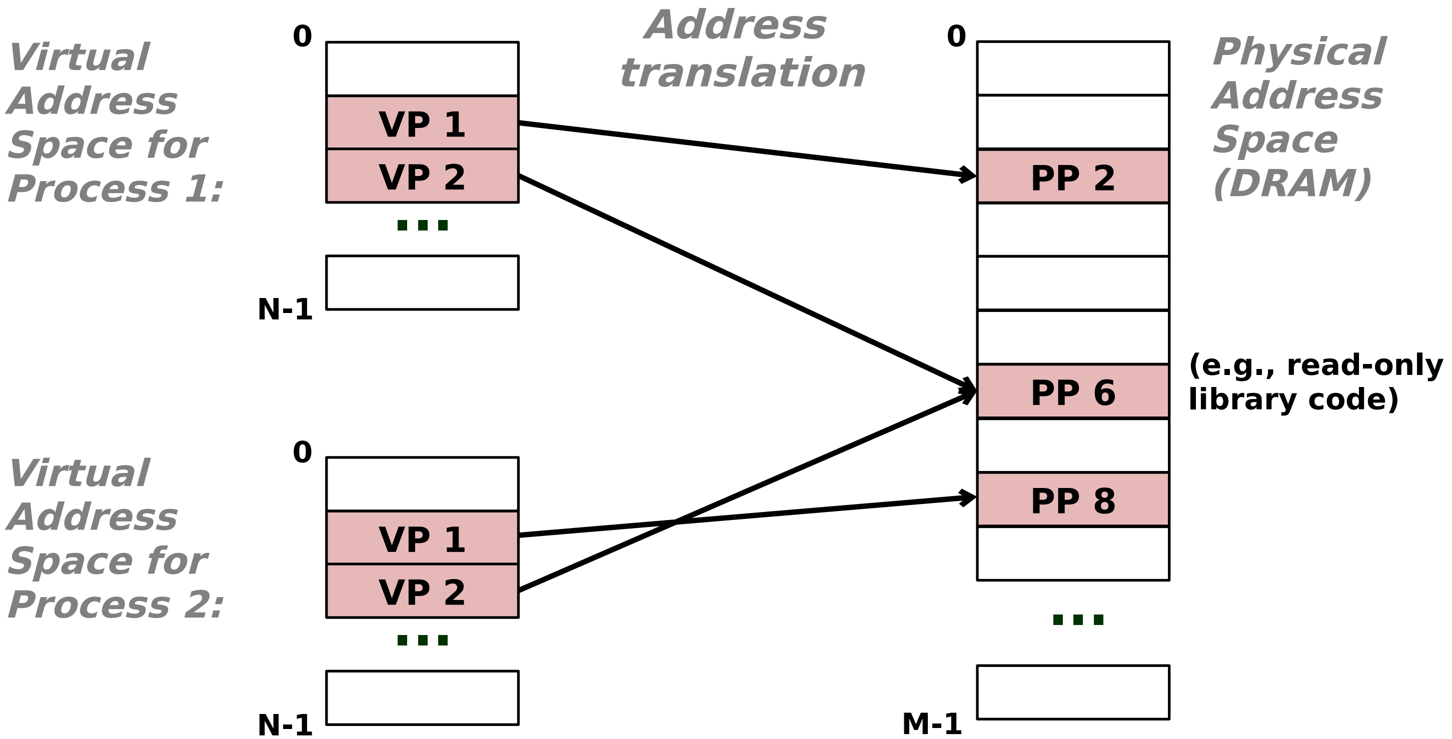
- **At any point in time, programs tend to access a set of active virtual pages called the *working set***
  - Programs with better temporal locality will have smaller working sets

- **If (working set size < main memory size)**
  - Good performance for one process after compulsory misses

- **If (SUM(working set sizes) > main memory size)**
  - *Thrashing:* Performance meltdown where pages are swapped (copied) in and out continuously

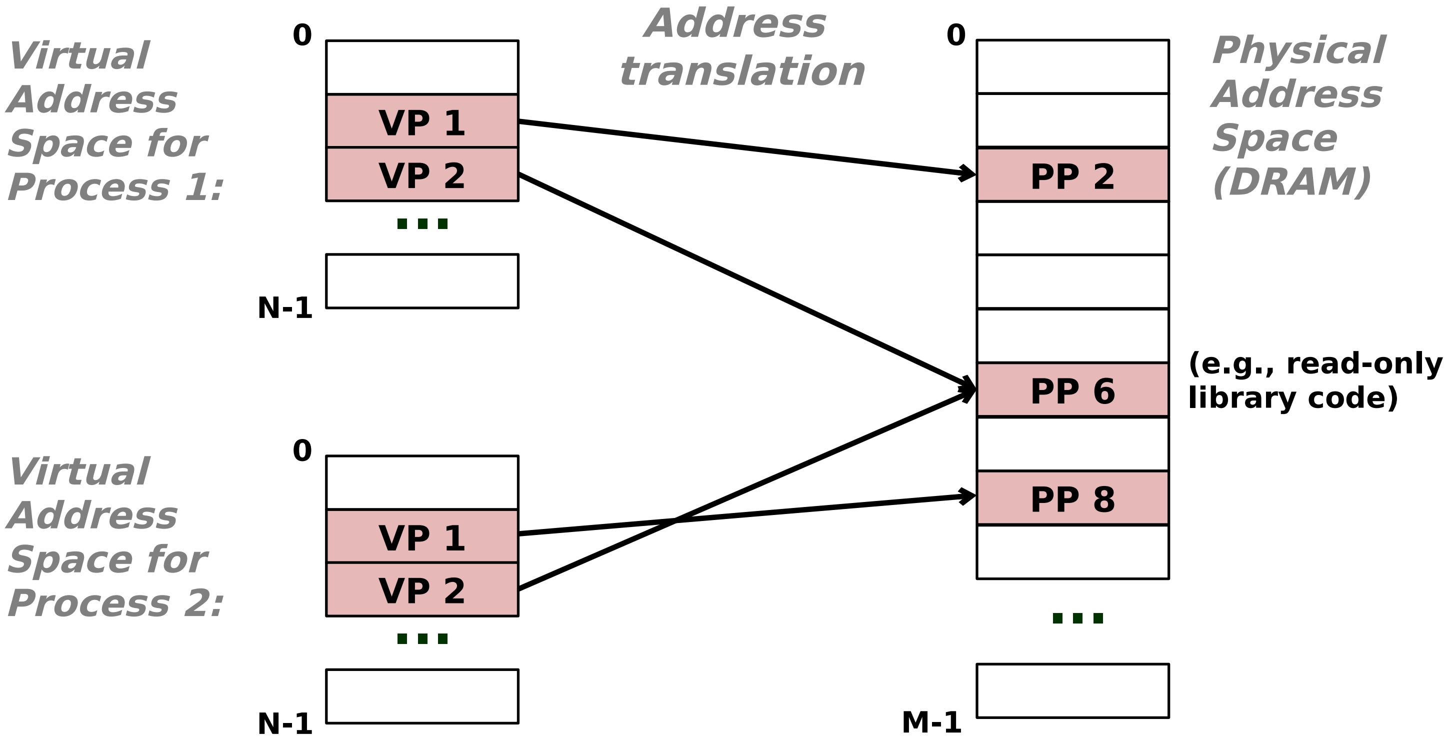
VM as a Tool for Memory Management

- **Key idea: each process has its own virtual address space**
  - It can view memory as a simple linear array
  - Mapping function scatters addresses through physical memory
    - Well-chosen mappings can improve locality



VM as a Tool for Memory Management

- **Simplifying memory allocation**
  - Each virtual page can be mapped to any physical page
  - A virtual page can be stored in different physical pages at different times
- **Sharing code and data among processes**
  - Map virtual pages to the same physical page (here: PP 6)



VM as a Tool for Memory Protection

- Extend PTEs with permission bits
- MMU checks these bits on each access

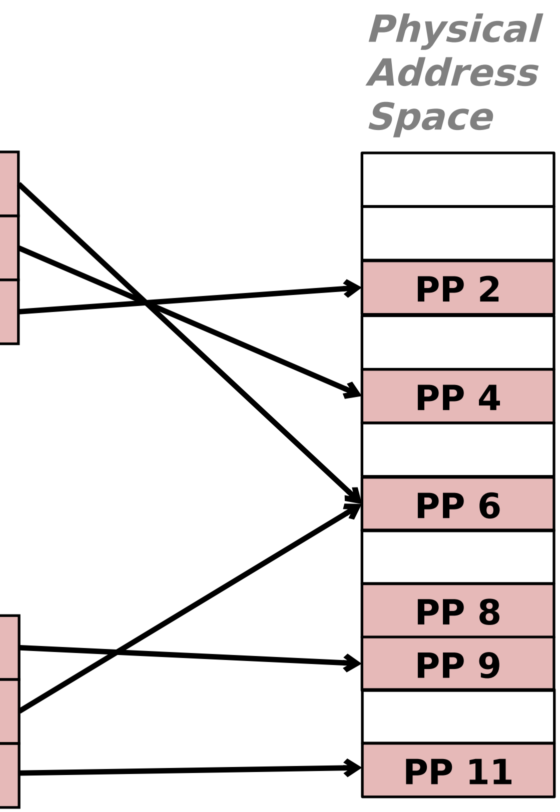
Process i:

	SUP	READ	WRITE	EXEC	Address
VP 0:	No	Yes	No	No	PP 6
VP 1:	No	Yes	Yes	Yes	PP 4
VP 2:	Yes	Yes	Yes	No	PP 2

⋮

Process j:

	SUP	READ	WRITE	EXEC	Address
VP 0:	No	Yes	No	Yes	PP 9
VP 1:	No	Yes	Yes	No	PP 6
VP 2:	No	Yes	Yes	Yes	PP 11



VM Address Translation

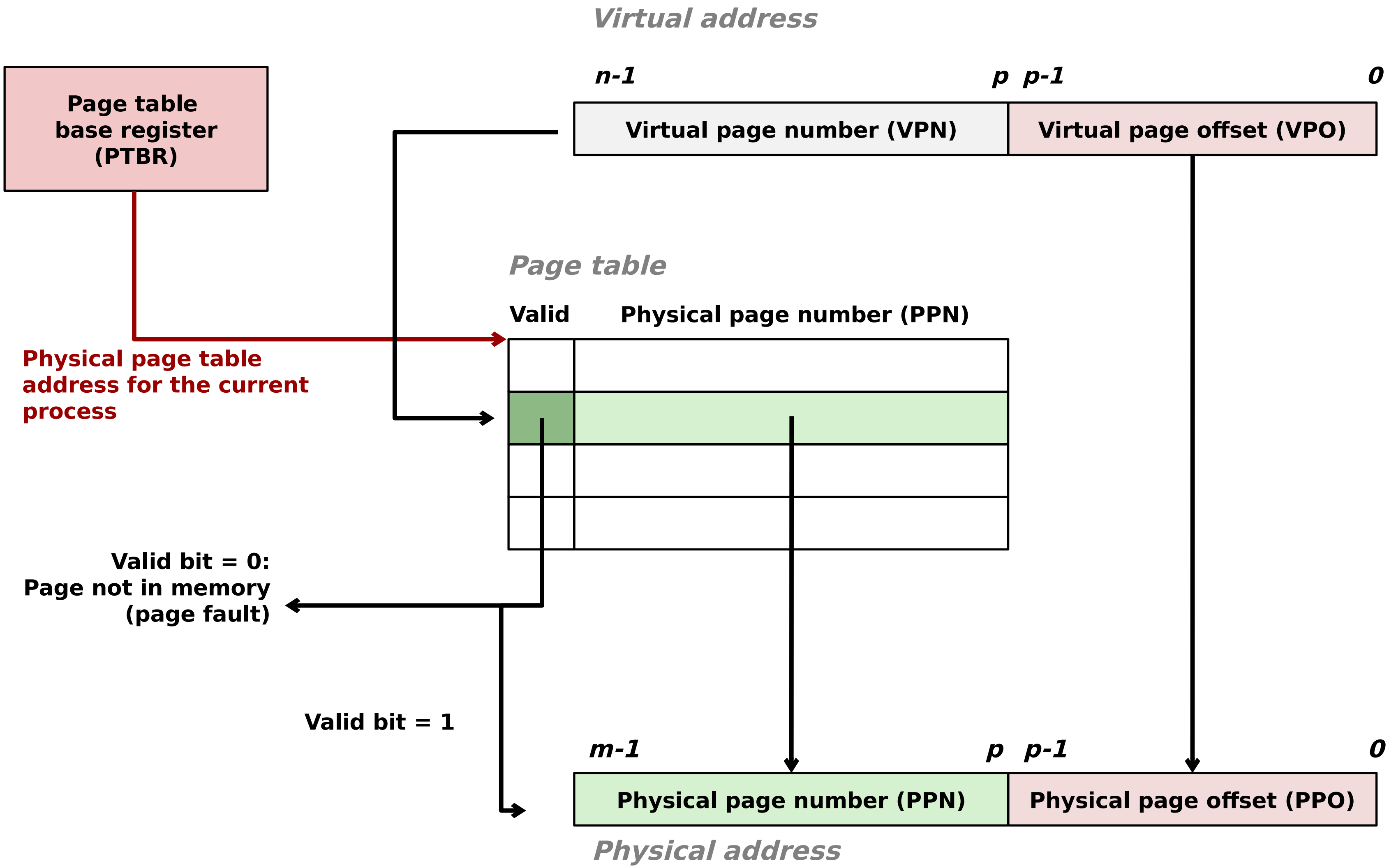
- **Virtual Address Space**
  - *V = {0, 1, …, N–1}*
- **Physical Address Space**
  - *P = {0, 1, …, M–1}*
- **Address Translation**

  MAP: V → P U {¬}
  - For virtual address ***a***:
    - ***MAP(a) = a′*** if data at virtual address ***a*** is at physical address ***a'*** in ***P***
    - ***MAP(a) = ¬*** if data at virtual address ***a*** is not in physical memory
      - Either invalid or stored on disk

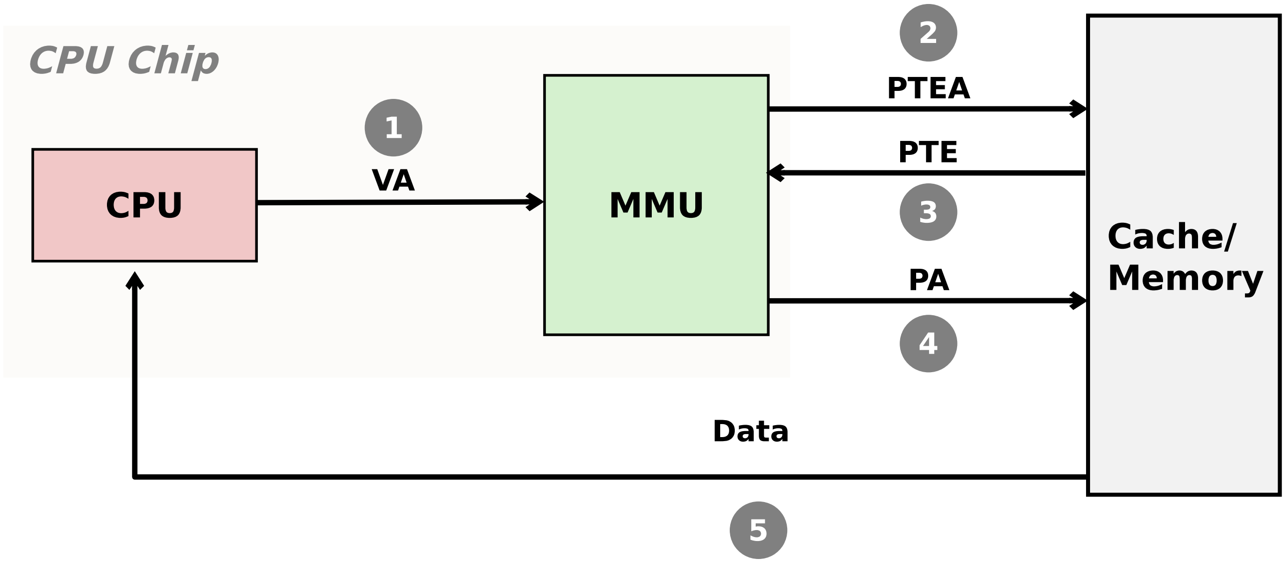
Summary of Address Translation Symbols

- **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 the virtual address (VA)**
  - **TLBI**: TLB index
  - **TLBT**: TLB tag
  - **VPO**: Virtual page offset
  - **VPN**: Virtual page number
- **Components of the physical address (PA)**
  - **PPO**: Physical page offset (same as VPO)
  - **PPN:** Physical page number

Address Translation With a Page Table



Address Translation: Page Hit



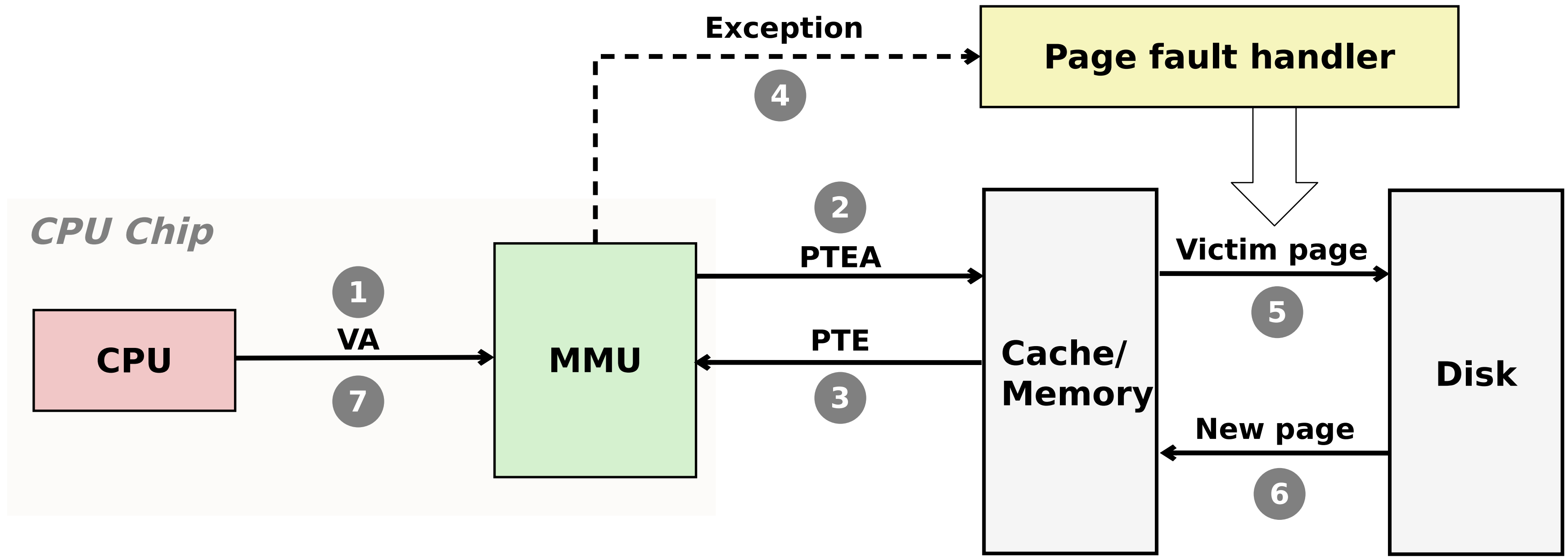
1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

4) MMU sends physical address to cache/memory

5) Cache/memory sends data word to processor

Address Translation: Page Fault



1) Processor sends virtual address to MMU

2-3) MMU fetches PTE from page table in memory

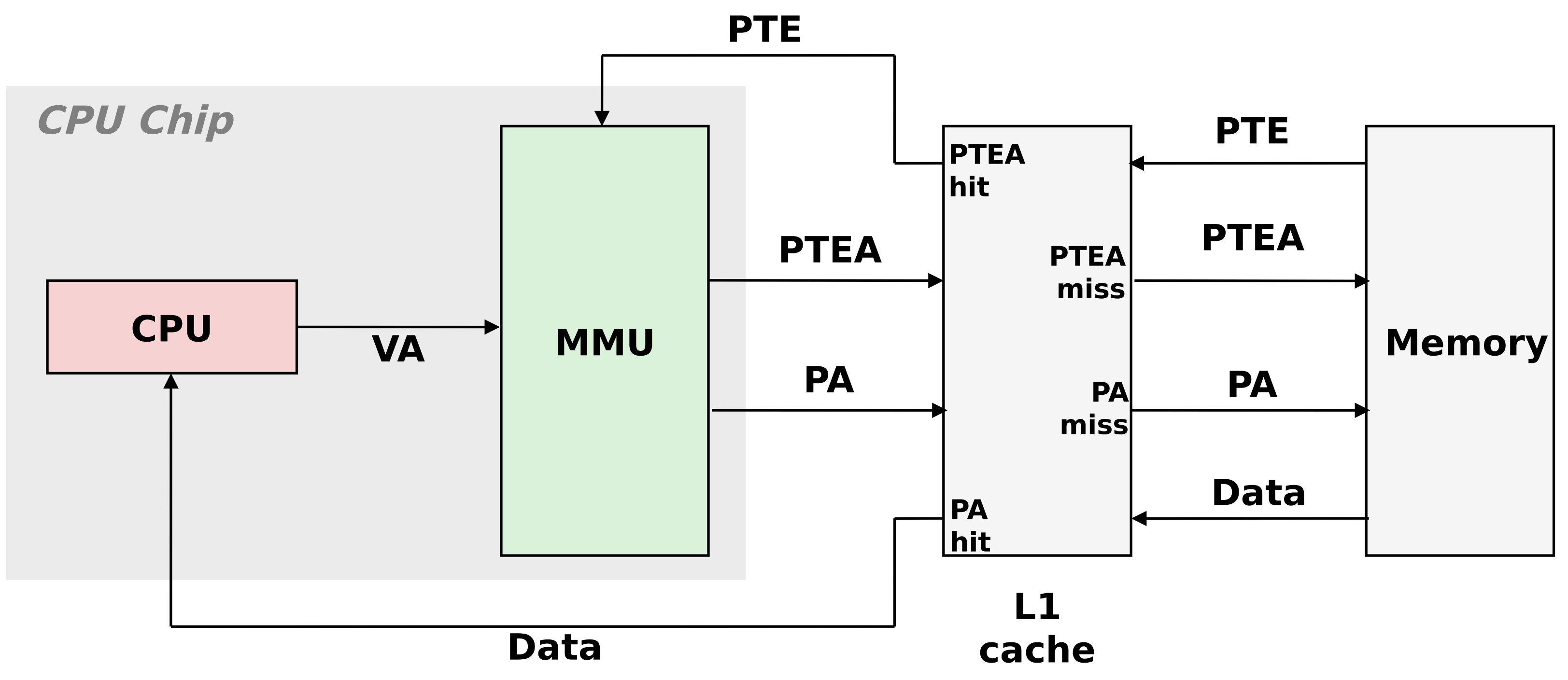
4) Valid bit is zero, so MMU triggers page fault exception

5) Handler identifies victim (and, if dirty, pages it out to disk)

6) Handler pages in new page and updates PTE in memory

7) Handler returns to original process, restarting faulting instruction

Integrating VM and Cache



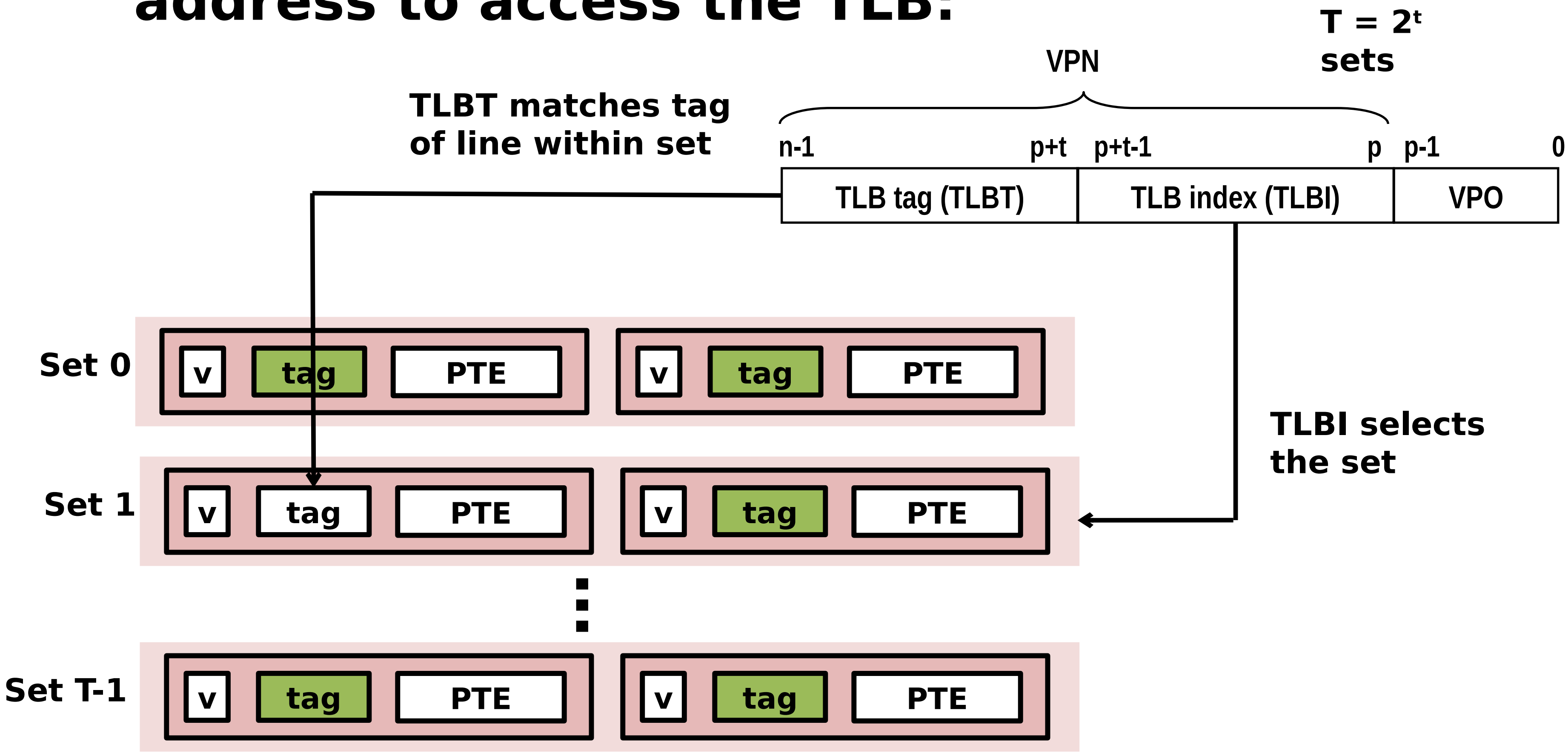
VA: virtual address, PA: physical address, PTE: page table entry, PTEA

Speeding up Translation with a TLB

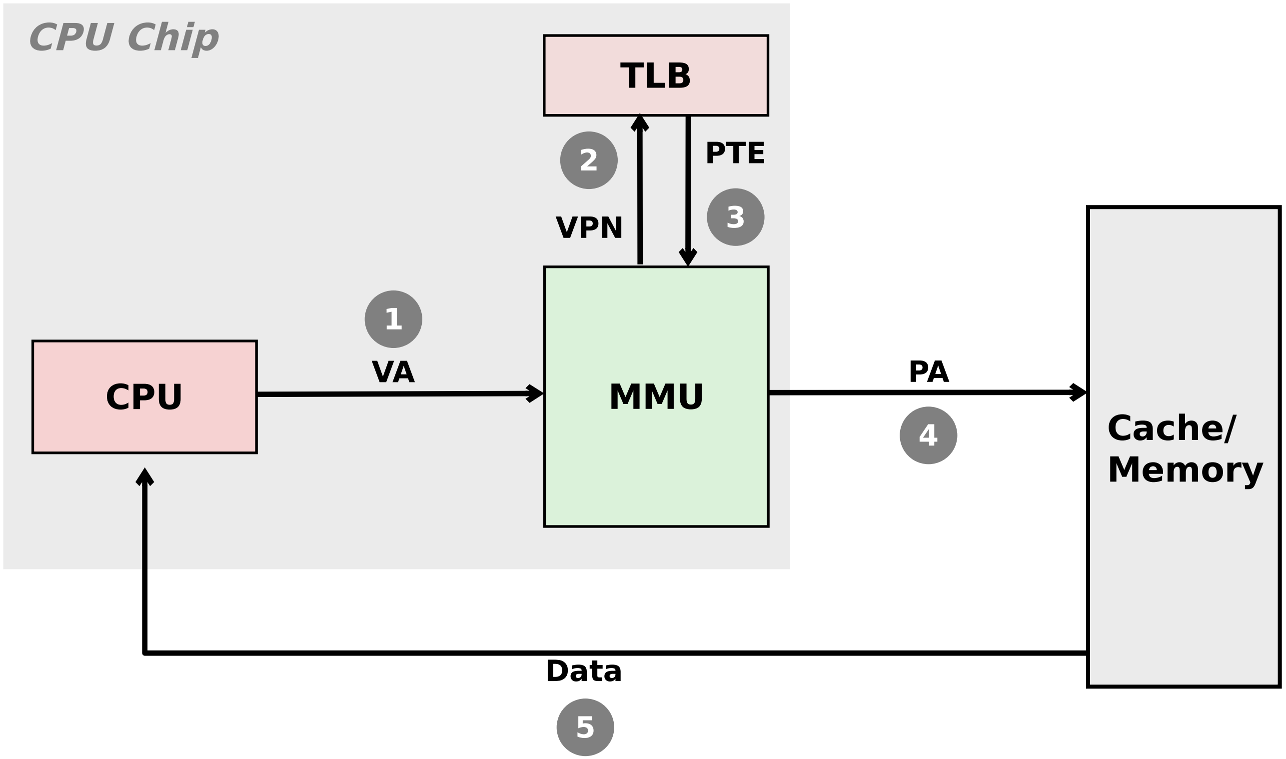
- **Page table entries (PTEs) are cached in L1 like any other memory word**
  - PTEs may be evicted by other data references
  - PTE hit still requires a small L1 delay
- **Solution: *Translation Lookaside Buffer* (TLB)**
  - Small set-associative hardware cache in MMU
  - Maps virtual page numbers to physical page numbers
  - Contains complete page table entries for small number of pages

Accessing the TLB

- MMU uses the VPN portion of the virtual address to access the TLB:

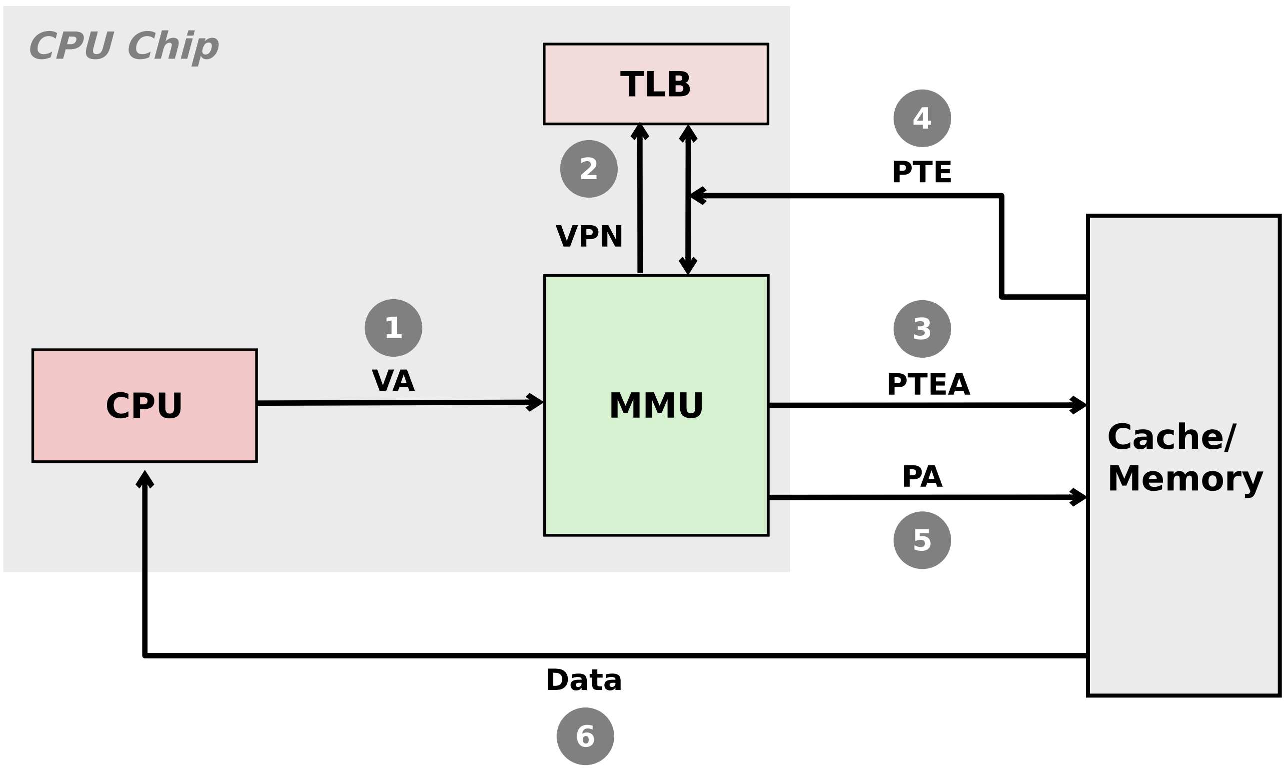


TLB Hit



A TLB hit eliminates a memory access

TLB Miss

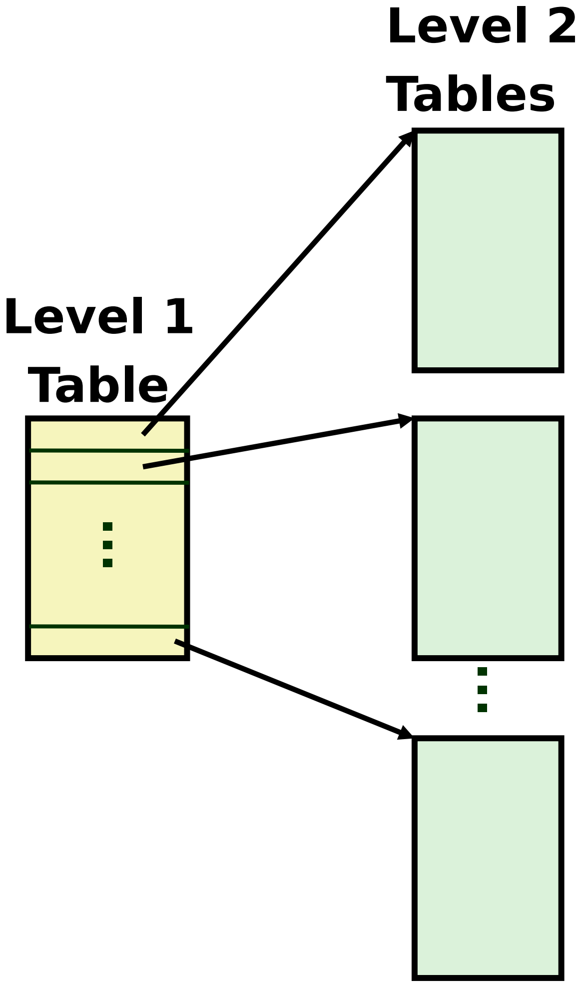


A TLB miss incurs an additional memory access (the PTE)

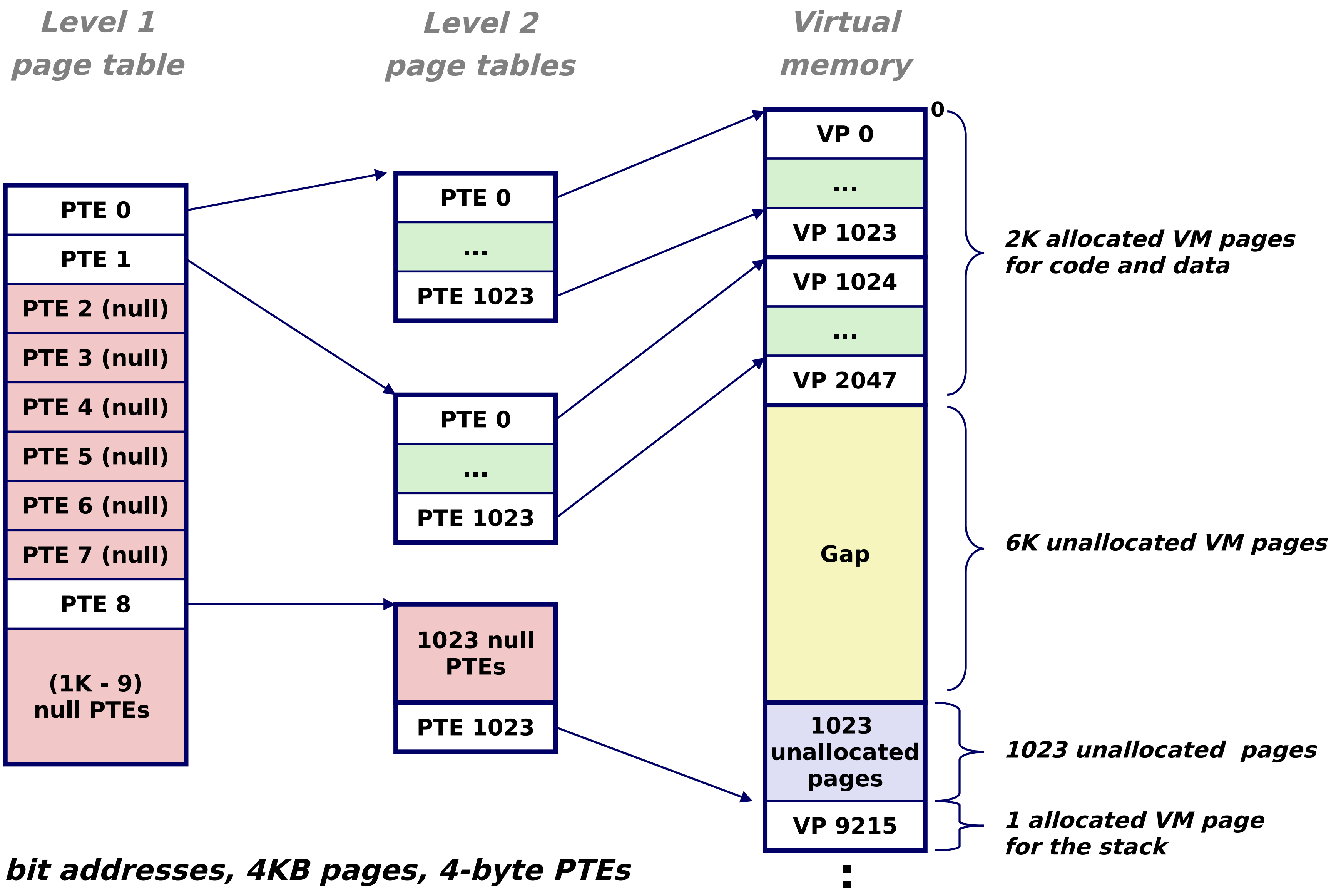
Fortunately, TLB misses are rare. Why?

Multi-Level Page Tables

- **Suppose:**
  - 4KB (2^{12}) page size, 48-bit address space, 8-byte PTE
- **Problem:**
  - Would need a 512 GB page table!
    - $2^{48} * 2^{-12} * 2^{3} = 2^{39}$ bytes
- **Common solution: Multi-level page table**
- **Example: 2-level page table**
  - Level 1 table: each PTE points to a page table (always memory resident)
  - Level 2 table: each PTE points to a page (paged in and out like any other data)

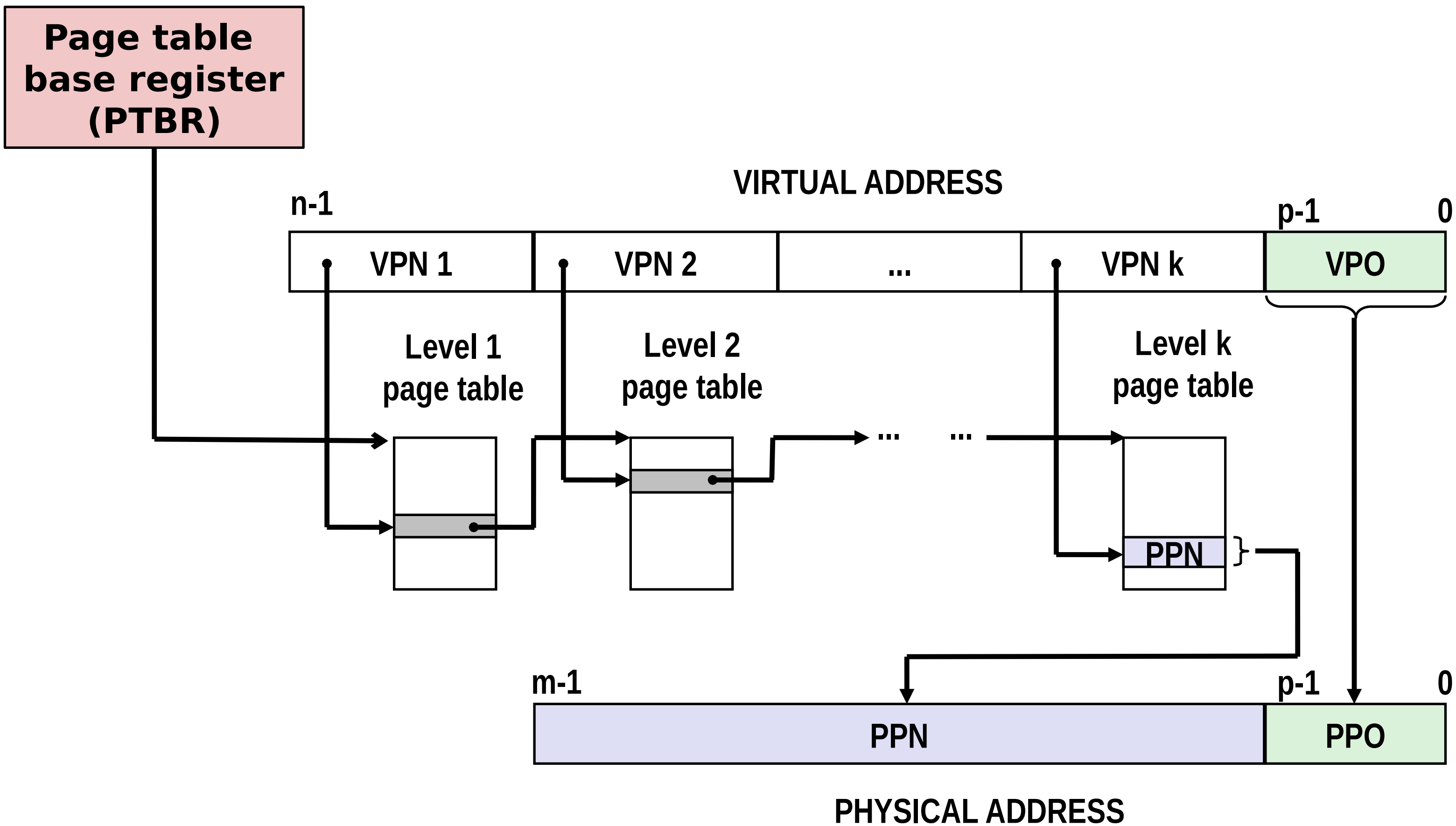


A Two-Level Page Table Hierarchy



32 bit addresses, 4KB pages, 4-byte PTEs

Translating with a k-level Page Table



Summary

- **Programmer's view of virtual memory**
  - Each process has its own private linear address space
  - Cannot be corrupted by other processes

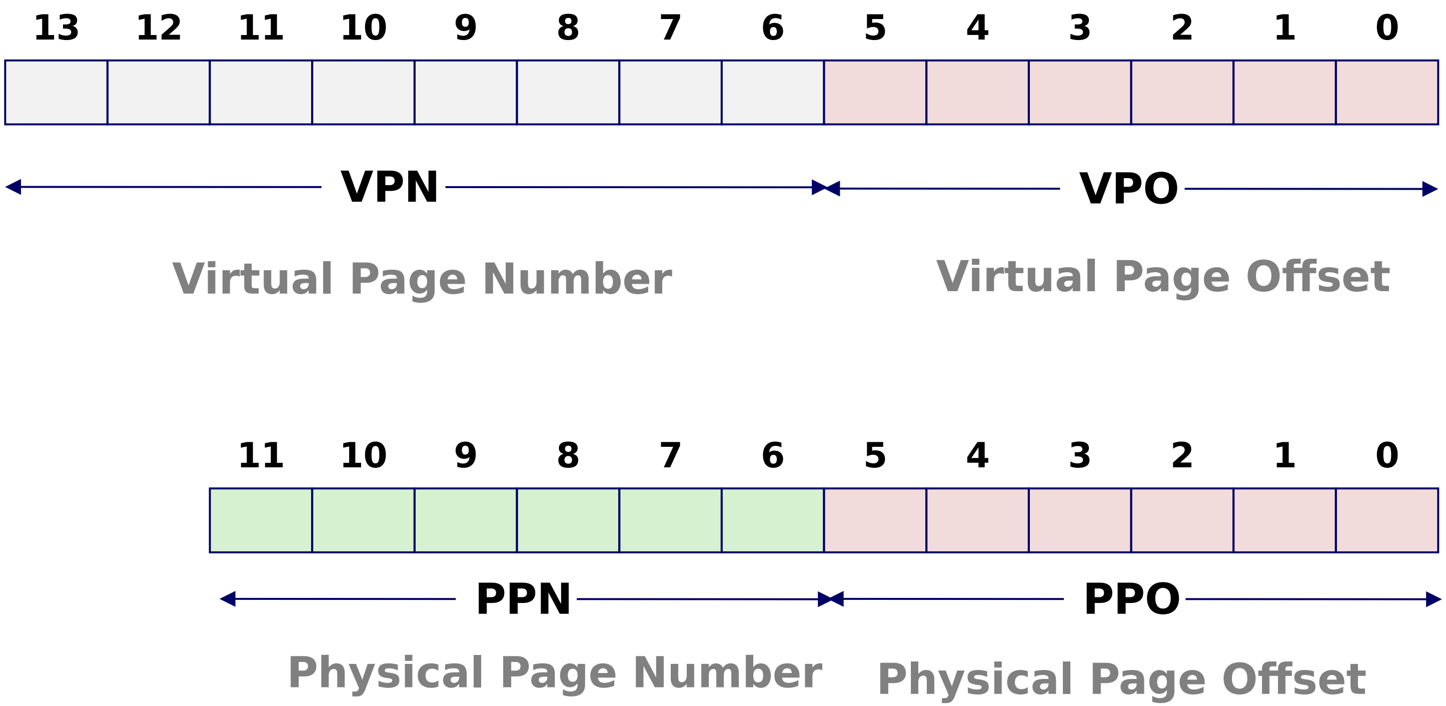
- **System view of virtual memory**
  - Uses memory efficiently by caching virtual memory pages
    - Efficient only because of locality
  - Simplifies memory management and programming
  - Simplifies protection by providing a convenient interpositioning point to check permissions

Review of 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 the virtual address (VA)**
  - **TLBI**: TLB index
  - **TLBT**: TLB tag
  - **VPO**: Virtual page offset
  - **VPN**: Virtual page number
- **Components of the physical address (PA)**
  - **PPO**: Physical page offset (same as VPO)
  - **PPN:** Physical page number
  - **CO**: Byte offset within cache line
  - **CI:** Cache index
  - **CT**: Cache tag

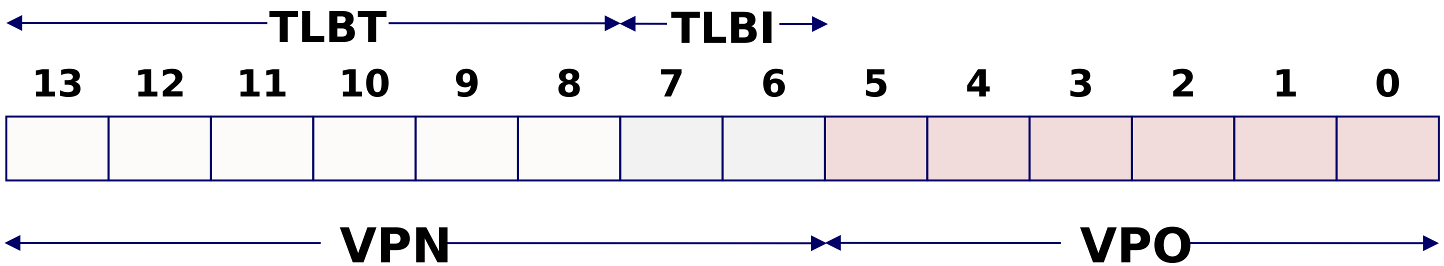
Simple Memory System Example

- **Addressing**
  - 14-bit virtual addresses
  - 12-bit physical address
  - Page size = 64 bytes



1. Simple Memory System TLB

- 16 entries
- 4-way associative



Set	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid
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

2. Simple Memory System Page Table

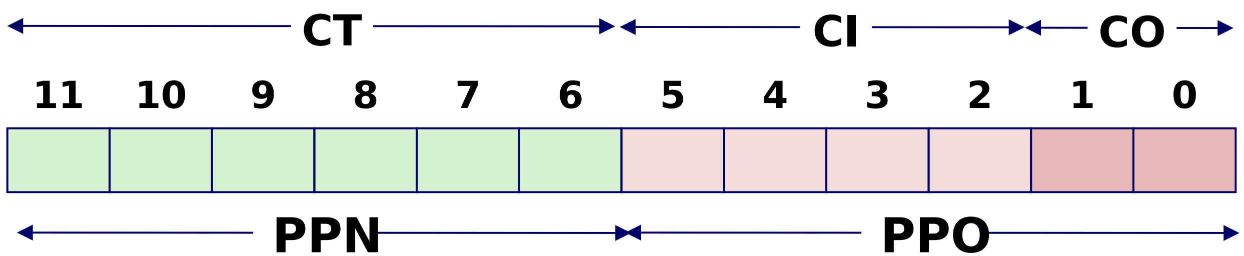
Only show first 16 entries (out of 256)

VPN	PPN	Valid
00	28	1
01	–	0
02	33	1
03	02	1
04	–	0
05	16	1
06	–	0
07	–	0

VPN	PPN	Valid
08	13	1
09	17	1
0A	09	1
0B	–	0
0C	–	0
0D	2D	1
0E	11	1
0F	0D	1

3. Simple Memory System Cache

- 16 lines, 4-byte block size
- Physically addressed
- Direct mapped

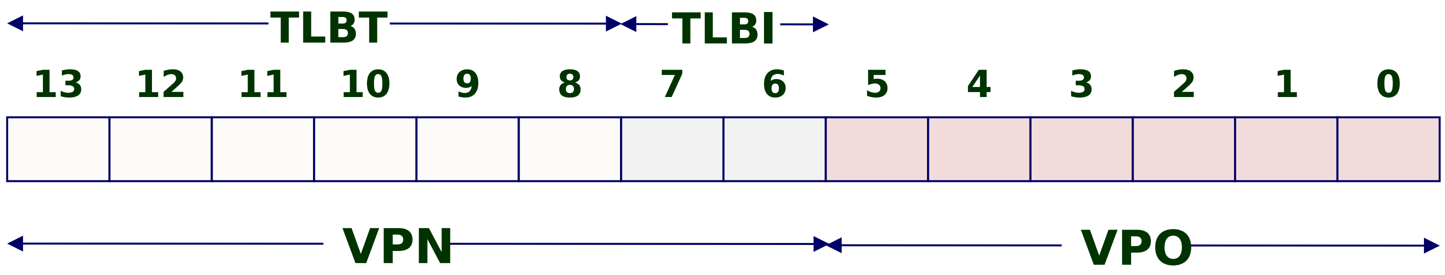


Idx	Tag	Valid	B0	B1	B2	B3
0	19	1	99	11	23	11
1	15	0	–	–	–	–
2	1B	1	00	02	04	08
3	36	0	–	–	–	–
4	32	1	43	6D	8F	09
5	0D	1	36	72	F0	1D
6	31	0	–	–	–	–
7	16	1	11	C2	DF	03

Idx	Tag	Valid	B0	B1	B2	B3
8	24	1	3A	00	51	89
9	2D	0	–	–	–	–
A	2D	1	93	15	DA	3B
B	0B	0	–	–	–	–
C	12	0	–	–	–	–
D	16	1	04	96	34	15
E	13	1	83	77	1B	D3
F	14	0	–	–	–	–

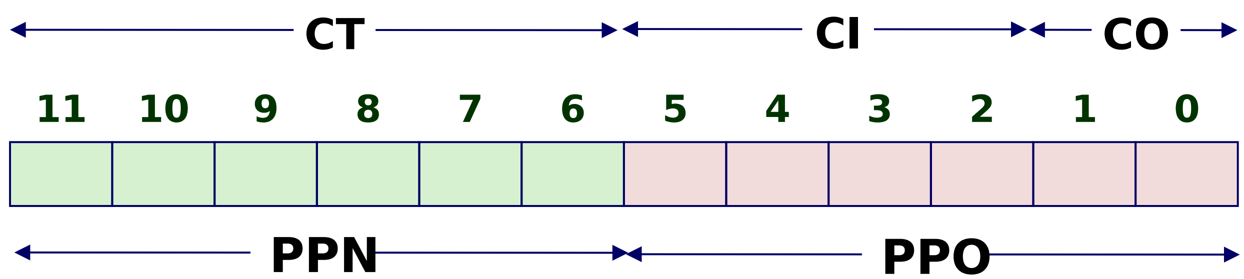
Address Translation Example #1

Virtual Address: `0x03D4`



VPN ___ TLBI ___ TLBT ____ TLB Hit? __ Page Fault? __ PPN: ____

Physical Address

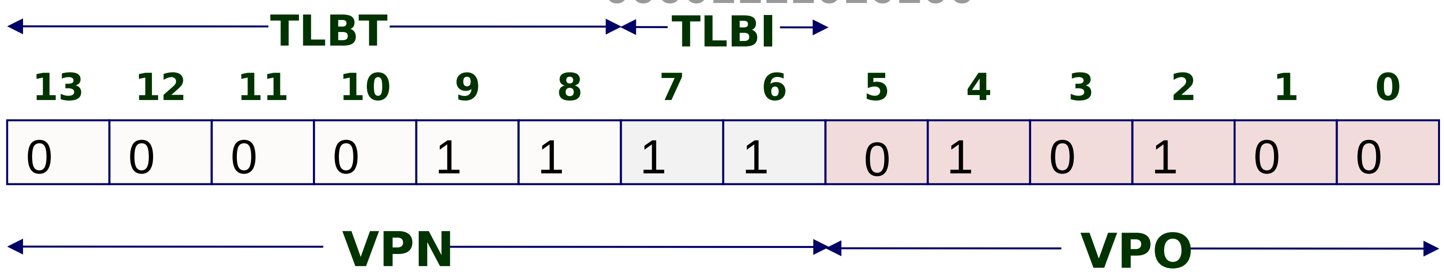


CO ___ CI___ CT ____ Hit? __ Byte: ____

Address Translation Example #1

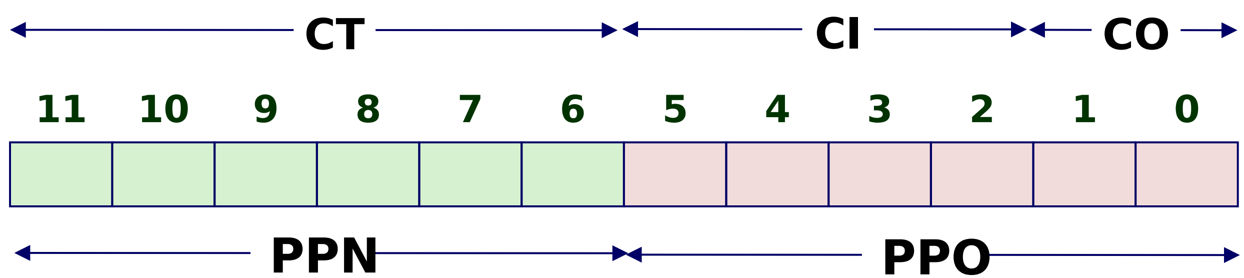
Virtual Address: `0x03D4`

00001111010100



VPN= 0x0f TLBI= 0x03 TLBT=0x03 TLB Hit? __ Page Fault? __ PPN: ____

Physical Address



CO ___ CI___ CT ____ Hit? __ Byte: ____

Address Translation Example #1

Virtual Address: `0x03D4`

00001111010100

TLBT | TLBI

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	1	1	0	1	0	1	0	0

VPN | VPO

VPN= 0x0f TLBI= 0x03 TLBT=0x03 TLB Hit= Yes Page Fault= No PPN: 0x0D

Physical Address

CT | CI | CO

11	10	9	8	7	6	5	4	3	2	1	0

PPN | PPO

CO ___ CI___ CT ____ Hit? __ Byte: ____

Address Translation Example #1

Virtual Address: `0x03D4` =

00001111010100

TLBT | TLBI

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	1	1	0	1	0	1	0	0

VPN | VPO

VPN= 0x0f TLBI= 0x03 TLBT=0x03 TLB Hit= Yes Page Fault= No
PPN: 0x0D

0x0D = 001101

Physical Address

CT | CI | CO

11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	0	1	0	1	0	1	0	0

PPN | PPO

CO= 0x0 CI=0x05 CT=0x0D Hit?__ Byte: ____

Address Translation Example #1

Virtual Address: `0x03D4`

00001111010100

TLBT | TLBI

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	1	1	0	1	0	1	0	0

VPN | VPO

VPN= 0x0f TLBI= 0x03 TLBT=0x03 TLB Hit= Yes Page Fault= No

PPN: 0x0D

0x0D = 001101

Physical Address

CT | CI | CO

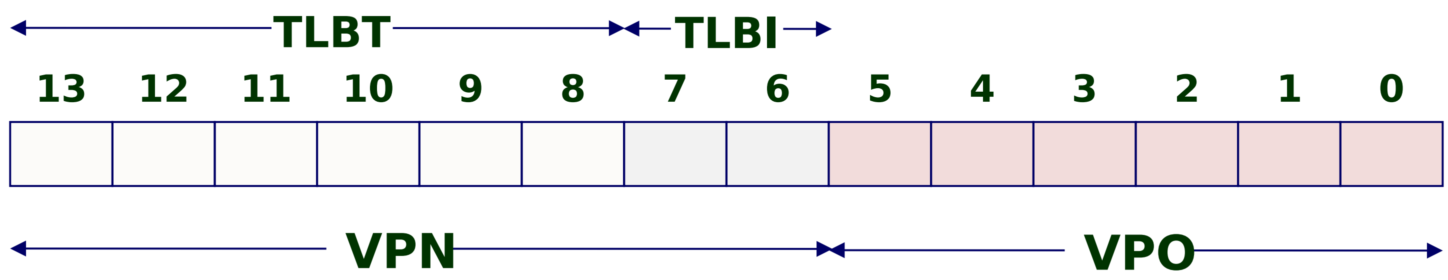
11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	0	1	0	1	0	1	0	0

PPN | PPO

CO= 0x0 CI=0x05 CT=0x0D Hit= Yes Byte: 0x36

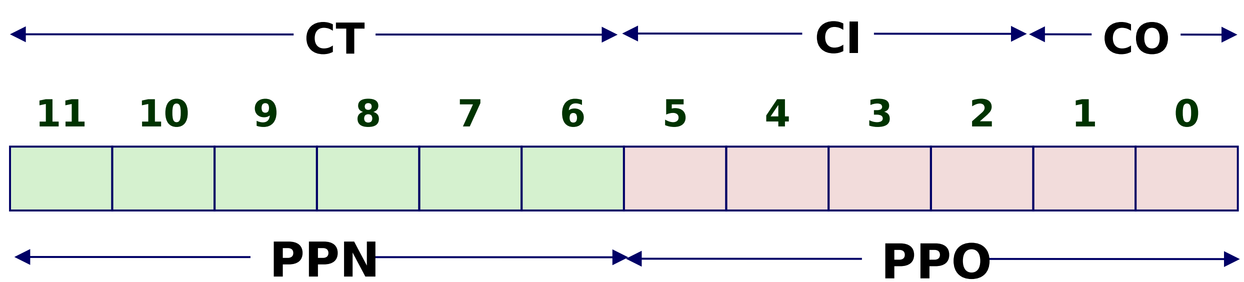
Address Translation Example #2

Virtual Address: `0x0020`



VPN ___ TLBI ___ TLBT ____ TLB Hit? __ Page Fault? __ PPN: ____

Physical Address



CO___ CI___ CT ____ Hit? __ Byte: ____