
Virtual Memory II

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Address Space



- Virtual memory size: $N = 2^n$ bytes
- Physical memory size: $M = 2^m$ bytes
- Page (block of memory): $P = 2^p$ bytes
- A virtual address can be encoded in n bits

Address Translation



- Task: mapping virtual address to physical address
 - virtual address (VA): used by machine code instructions
 - physical address (PA): location in RAM

- Formally

$$\text{MAP: } VA \rightarrow PA \cup \emptyset$$

where:

$$\begin{aligned} \text{MAP}(A) &= PA \text{ if in RAM} \\ &= \emptyset \text{ otherwise} \end{aligned}$$

- Note: this happens very frequently in machine code
- We will do this in hardware: Memory Management Unit (MMU)

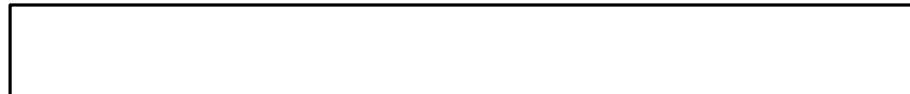
Basic Architecture



Virtual address



Physical address



Basic Architecture



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Virtual address

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page table
base register



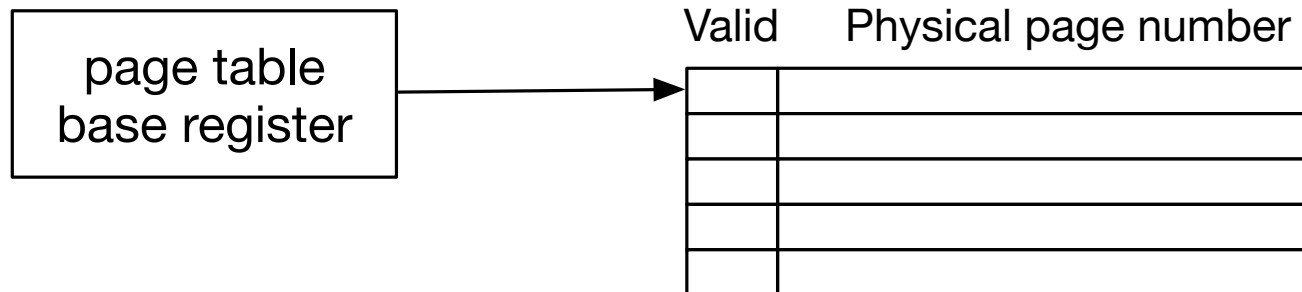
Valid Physical page number

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Physical address

Virtual address

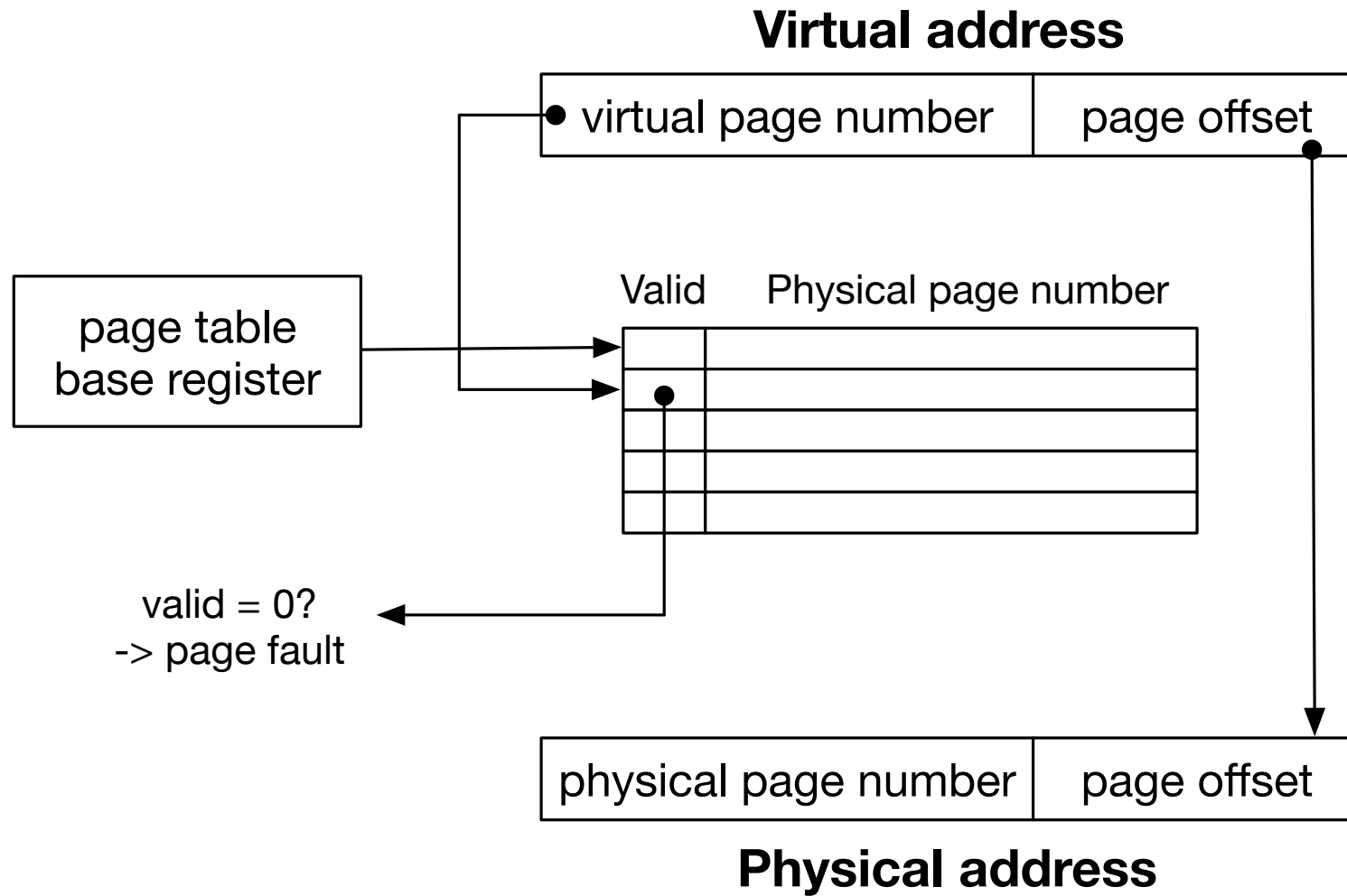
virtual page number	page offset
---------------------	-------------



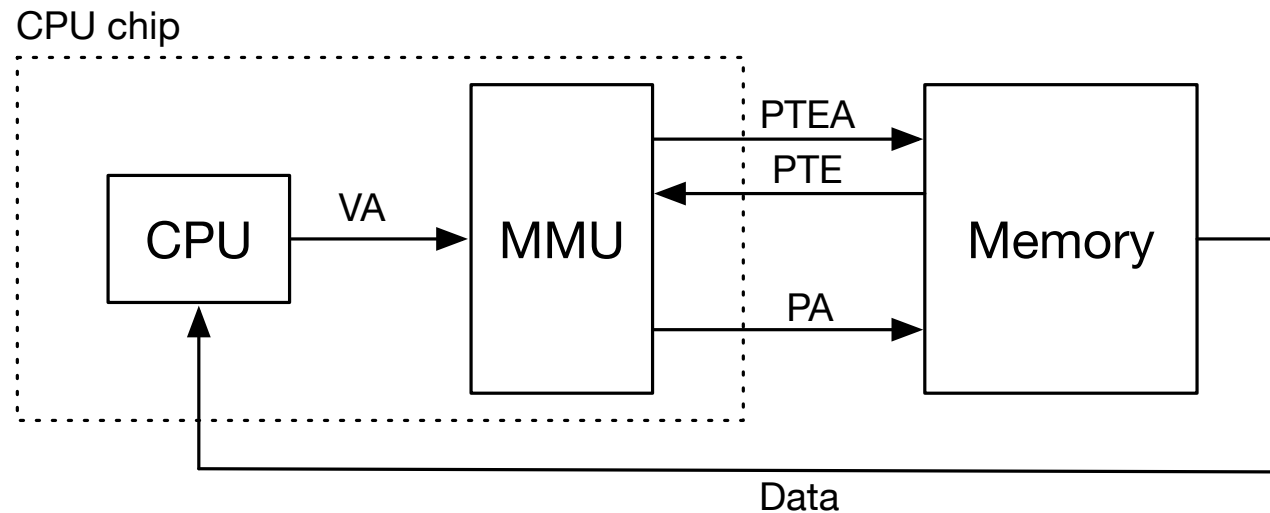
physical page number	page offset
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Physical address

Basic Architecture

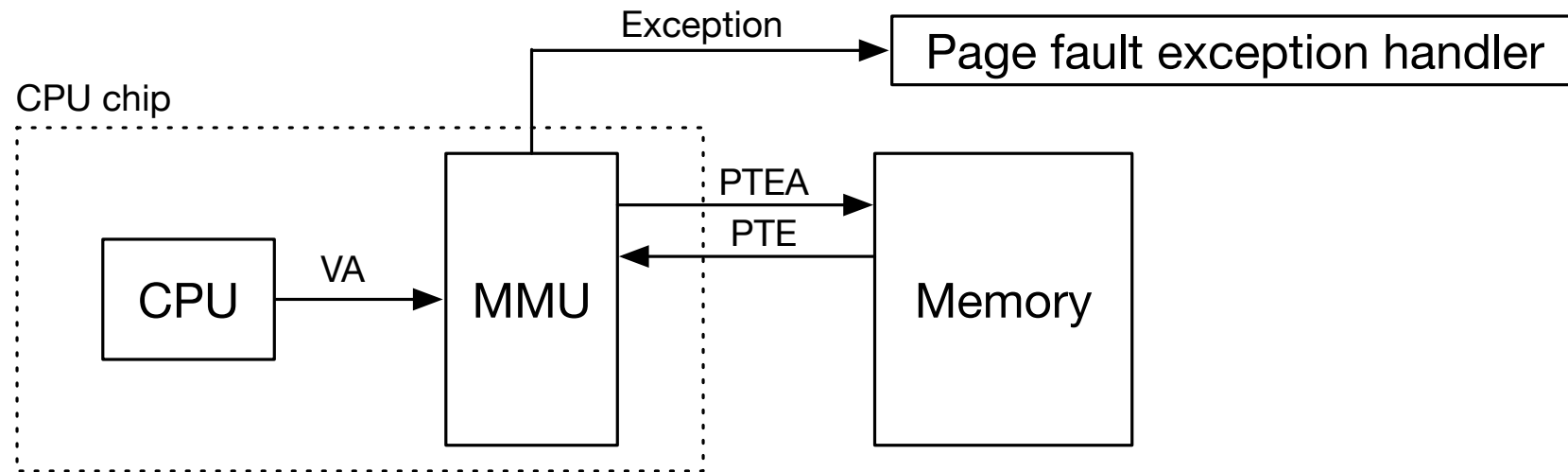


Page Hit



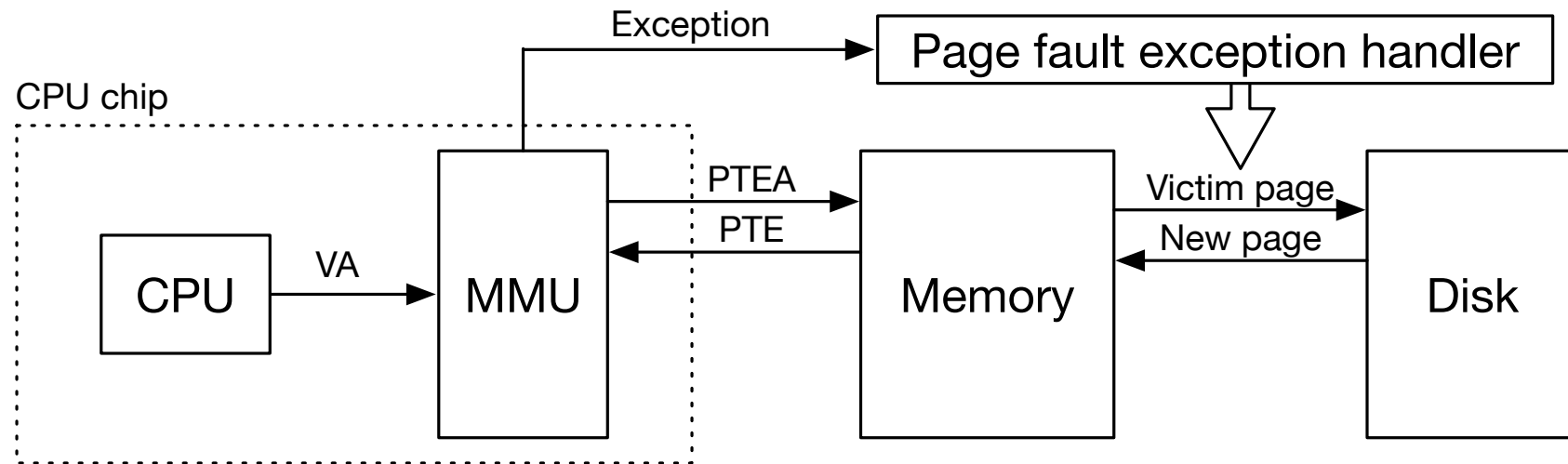
- VA: CPU requests data at virtual address
- PTEA: look up page table entry in page table
- PTE: returns page table entry
- PA: get physical address from entry, look up in memory
- Data: returns data from memory to CPU

Page Fault



- VA: CPU requests data at virtual address
- PTEA: look up page table entry in page table
- PTE: returns page table entry
- Exception: page not in physical memory

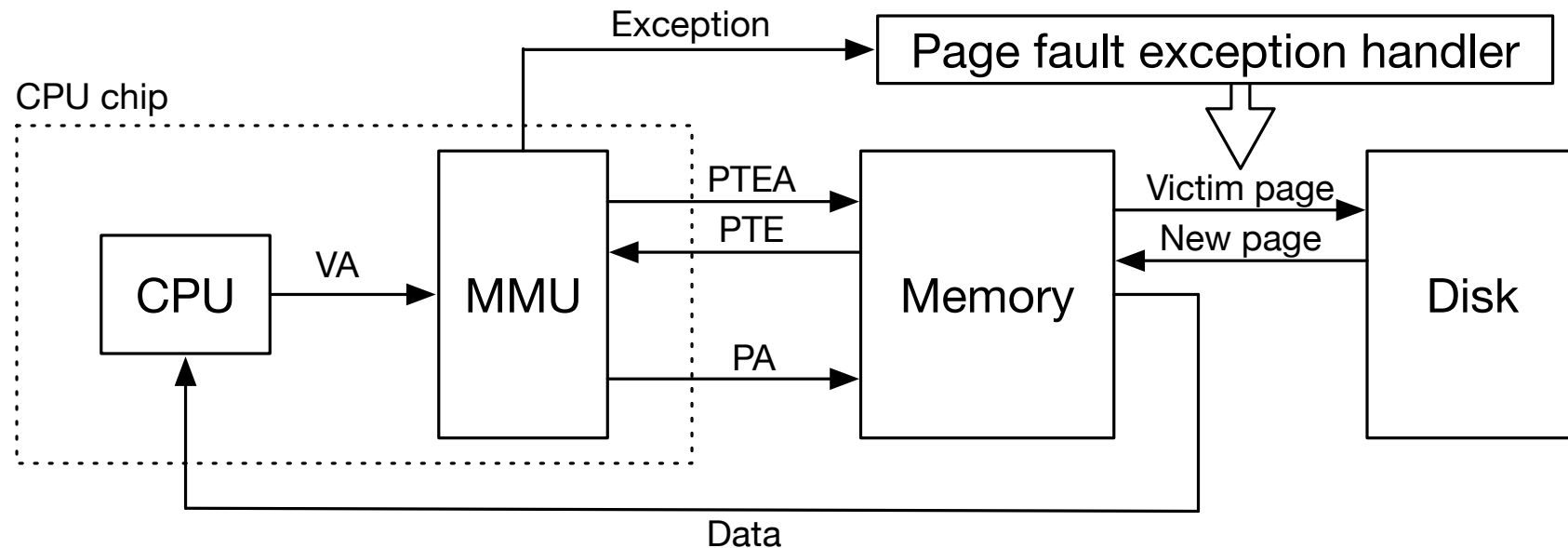
Page Fault



- VA: CPU requests data at virtual address
- PTEA: look up page table entry in page table
- PTE: returns page table entry
- Exception: page not in physical memory
- Page fault exception handler
 - victim page to disk
 - new page to memory
 - update page table entries

Page Fault

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- VA: CPU requests data at virtual address
- PTEA: look up page table entry in page table
- PTE: returns page table entry
- Exception: page not in physical memory
- Page fault exception handler
 - victim page to disk
 - new page to memory
 - update page table entries
- Re-do memory request

Page Miss Exception

- Complex task
 - identify which page to remove from RAM (victim page)
 - load page from disk to RAM
 - update page table entry
 - trigger do-over of instruction that caused exception
- Note
 - loading into RAM very slow
 - added complexity of handling in software no big deal



- On-CPU cache
- Slow look-up time
- Huge address space
- Putting it all together

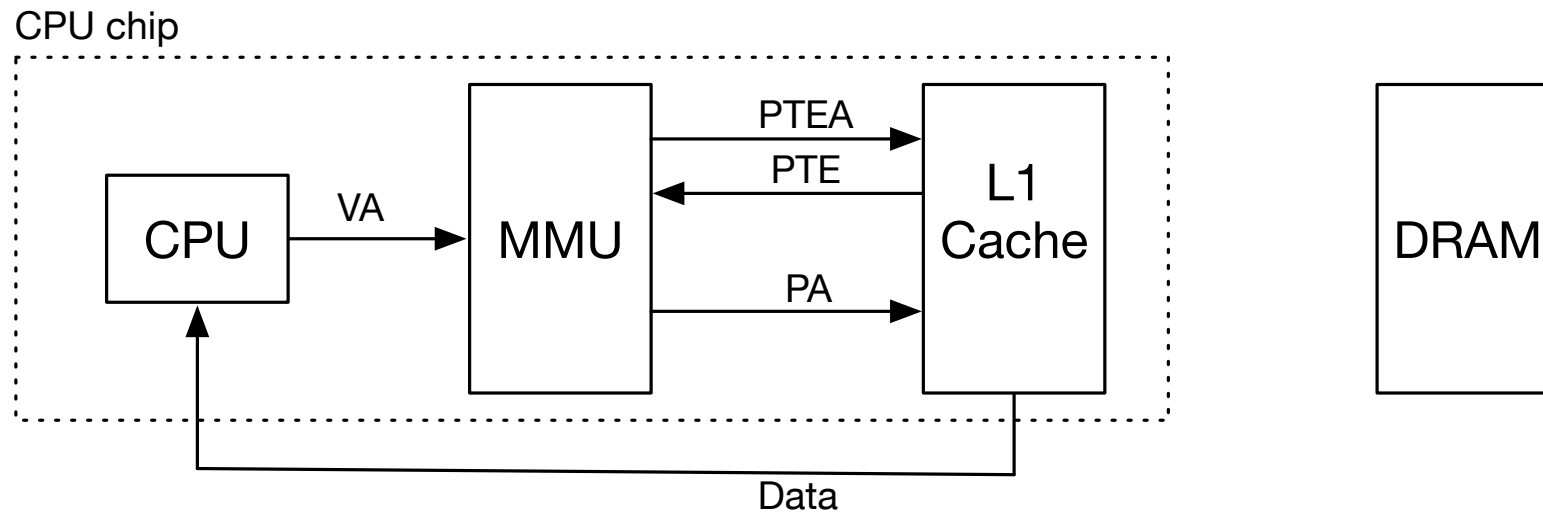
- On-CPU cache
 - integrate cache and virtual memory
- Slow look-up time
- Huge address space
- Putting it all together



- Note
 - we claim that using on-disk memory is too slow
 - having data in RAM only practical solution
- Recall
 - we previously claimed that using RAM is too slow
 - having data in cache only practical solution
- Both true, so we need to combine

Integrating Caches and Virtual Memory

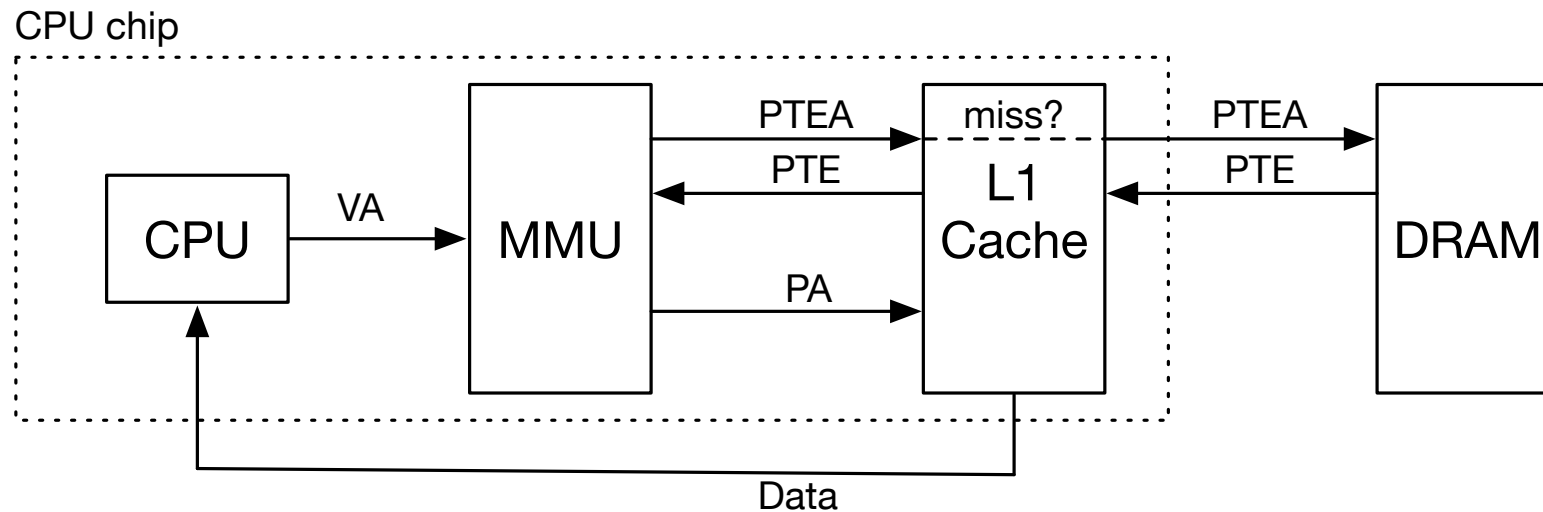
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- MMU resolves virtual address to physical address
- Physical address is checked against cache

Integrating Caches and Virtual Memory

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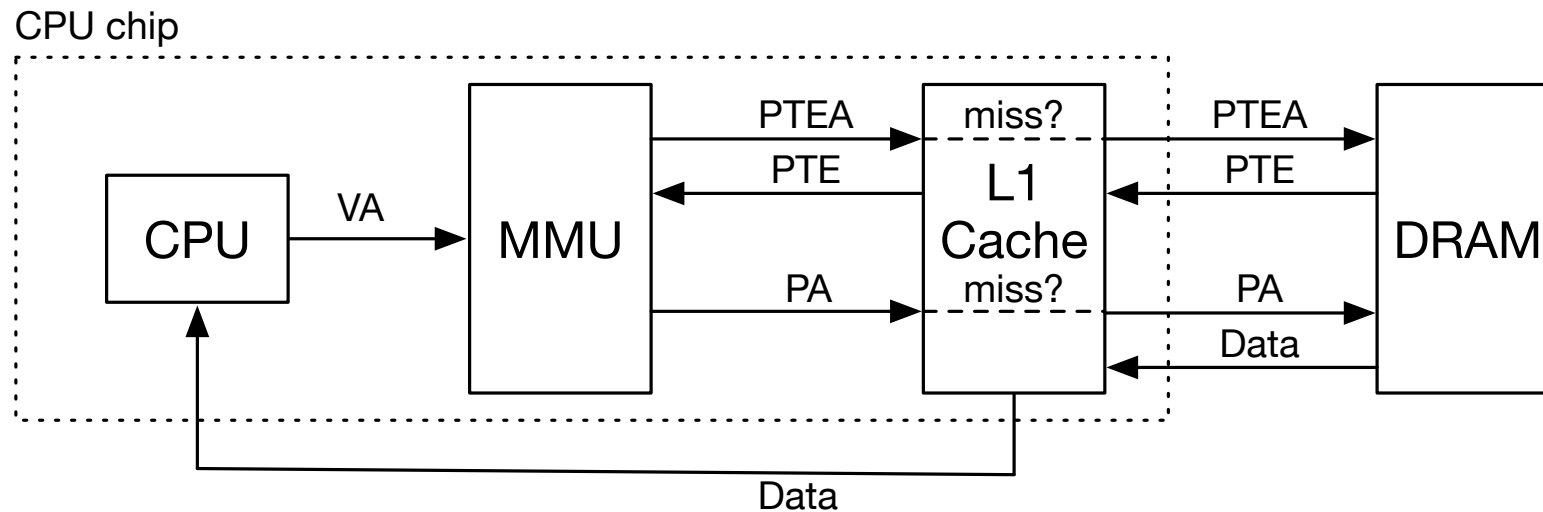


- Cache miss in page table retrieval?

⇒ Get page table from memory

Integrating Caches and Virtual Memory

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- Cache miss in data retrieval?

⇒ Get data from memory

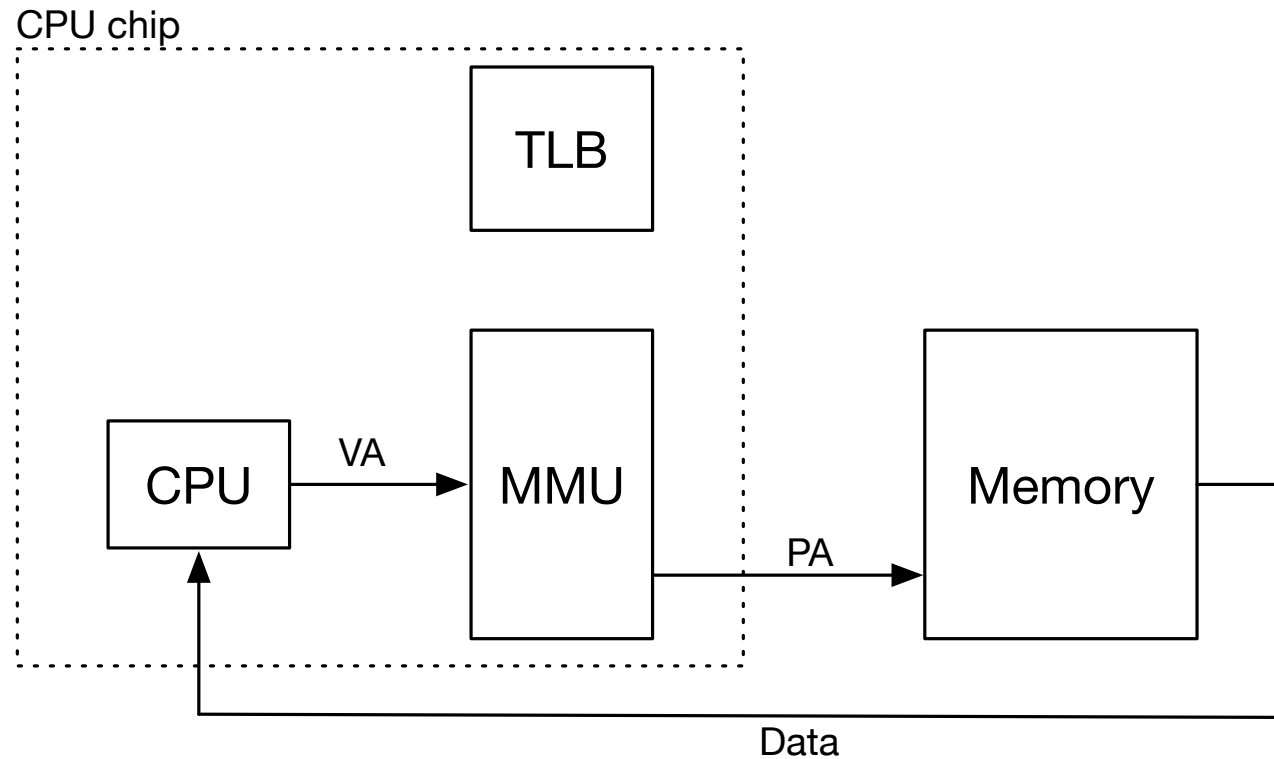
- On-CPU cache
 - integrate cache and virtual memory
- Slow look-up time
 - use translation lookahead buffer (TLB)
- Huge address space
- Putting it all together

Look-Ups

- Every memory-related instruction must pass through MMU (virtual memory look-up)
- Very frequent, this has to be very fast
- Locality to the rescue
 - subsequent look-ups in same area of memory
 - look-up for a page can be cached

Translation Lookup Buffer

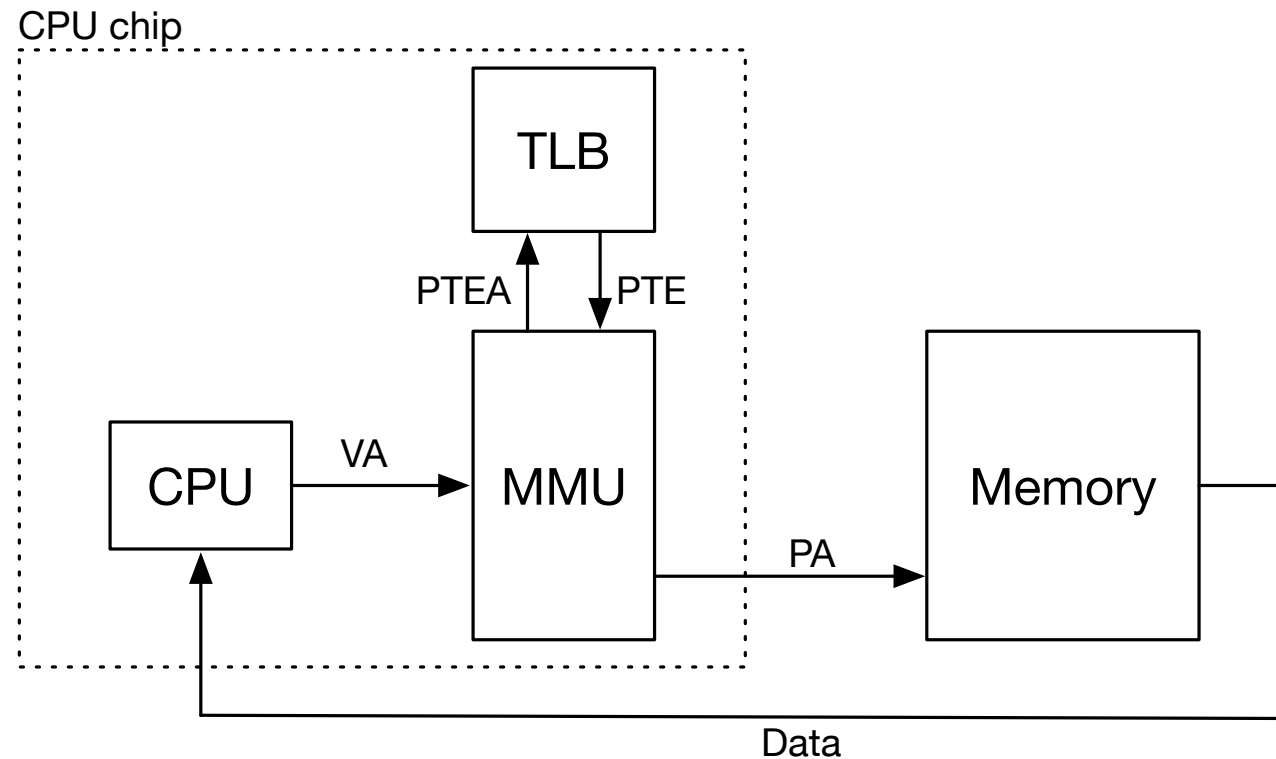
- Same structure as cache
- Break up address into 3 parts
 - lowest bits: offset in page
 - middle bits: index (location) in cache
 - highest bits: tag in cache
- Associative cache: more than one entry per index



- Translation lookup buffer (TLB) on CPU chip

Translation Lookup Buffer (TLB) Hit

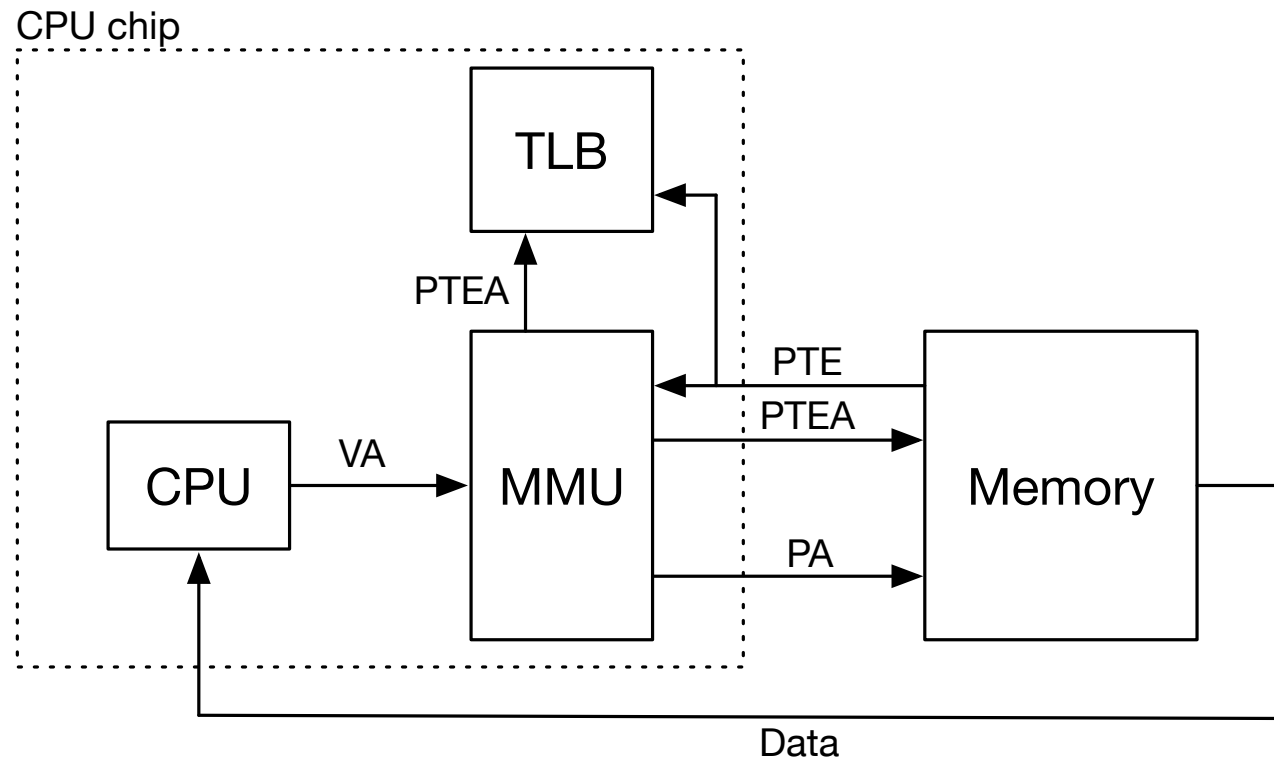
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- Look up page table entry in TLB

Translation Lookup Buffer (TLB) Miss

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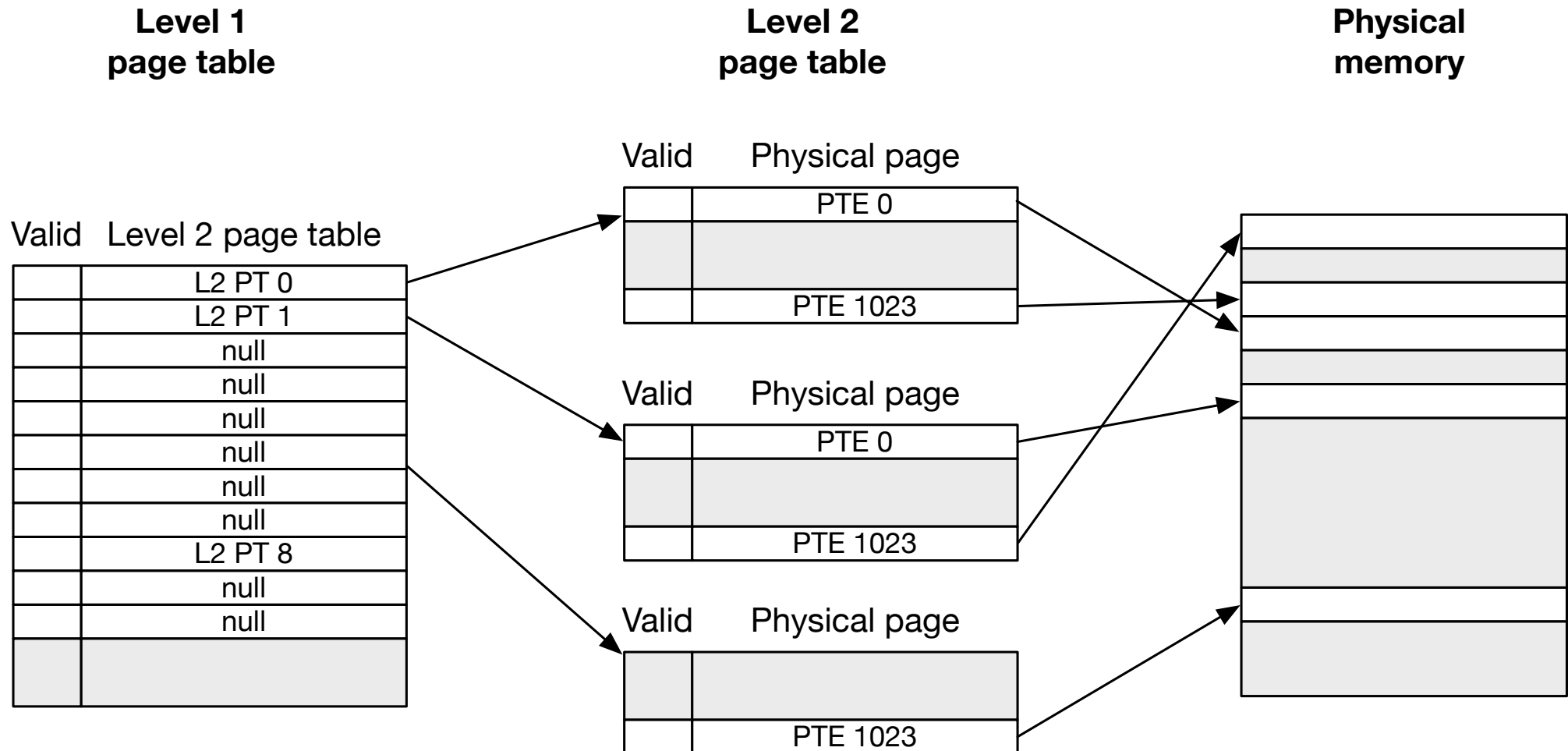
- Page table entry not in TLB
- Retrieve page table entry from RAM

- On-CPU cache
 - integrate cache and virtual memory
- Slow look-up time
 - use translation lookahead buffer (TLB)
- **Huge address space**
 - **multi-level page table**
- Putting it all together

Page Table Size

- Example
 - 32 bit address space: 4GB
 - Page size: 4KB
 - Size of page table entry: 4 bytes
 - Number of pages: 1M
 - Size of page table: 4MB
- Recall: one page table per process
- Very wasteful: most of the address space is not used

2-Level Page Table



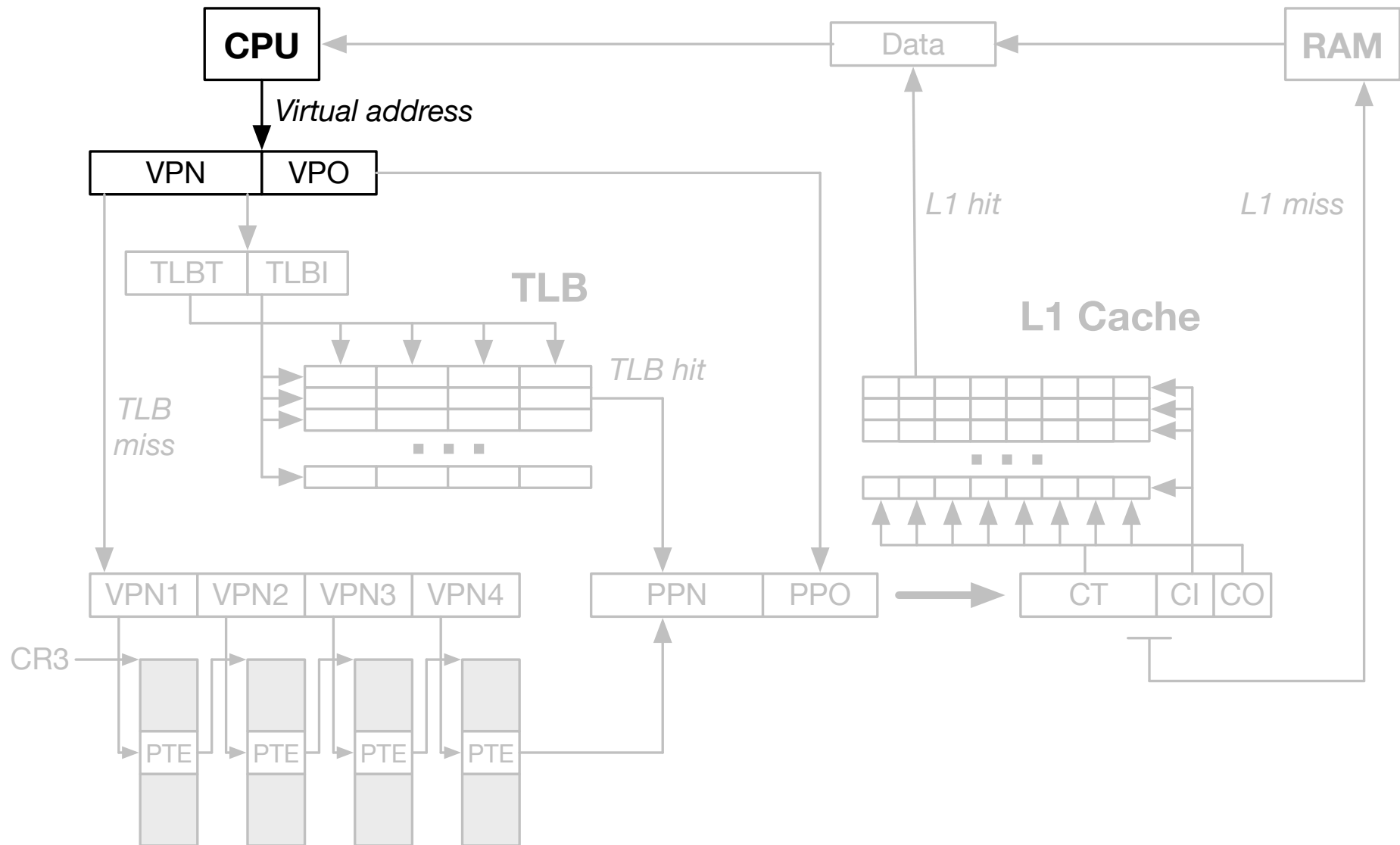
Multi-Level Page Table

- Our example: 1M entries
- 2-level page table
 - each level 1K entry ($1K^2=1M$)
- 4-level page table
 - each level 32 entry ($32^4=1M$)

- On-CPU cache
 - integrate cache and virtual memory
- Slow look-up time
 - use translation lookahead buffer (TLB)
- Huge address space
 - multi-level page table
- **Putting it all together**

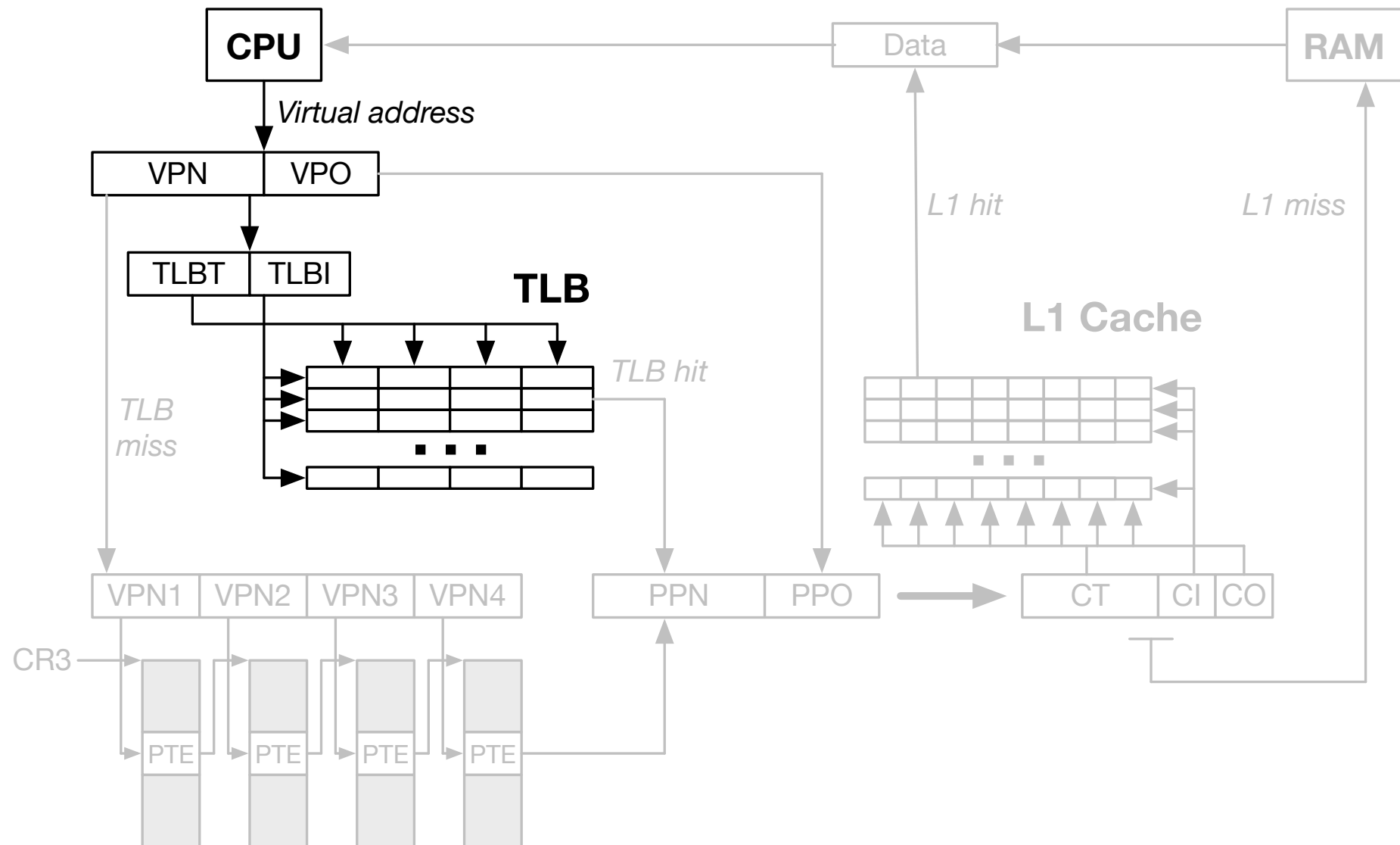
Virtual Address

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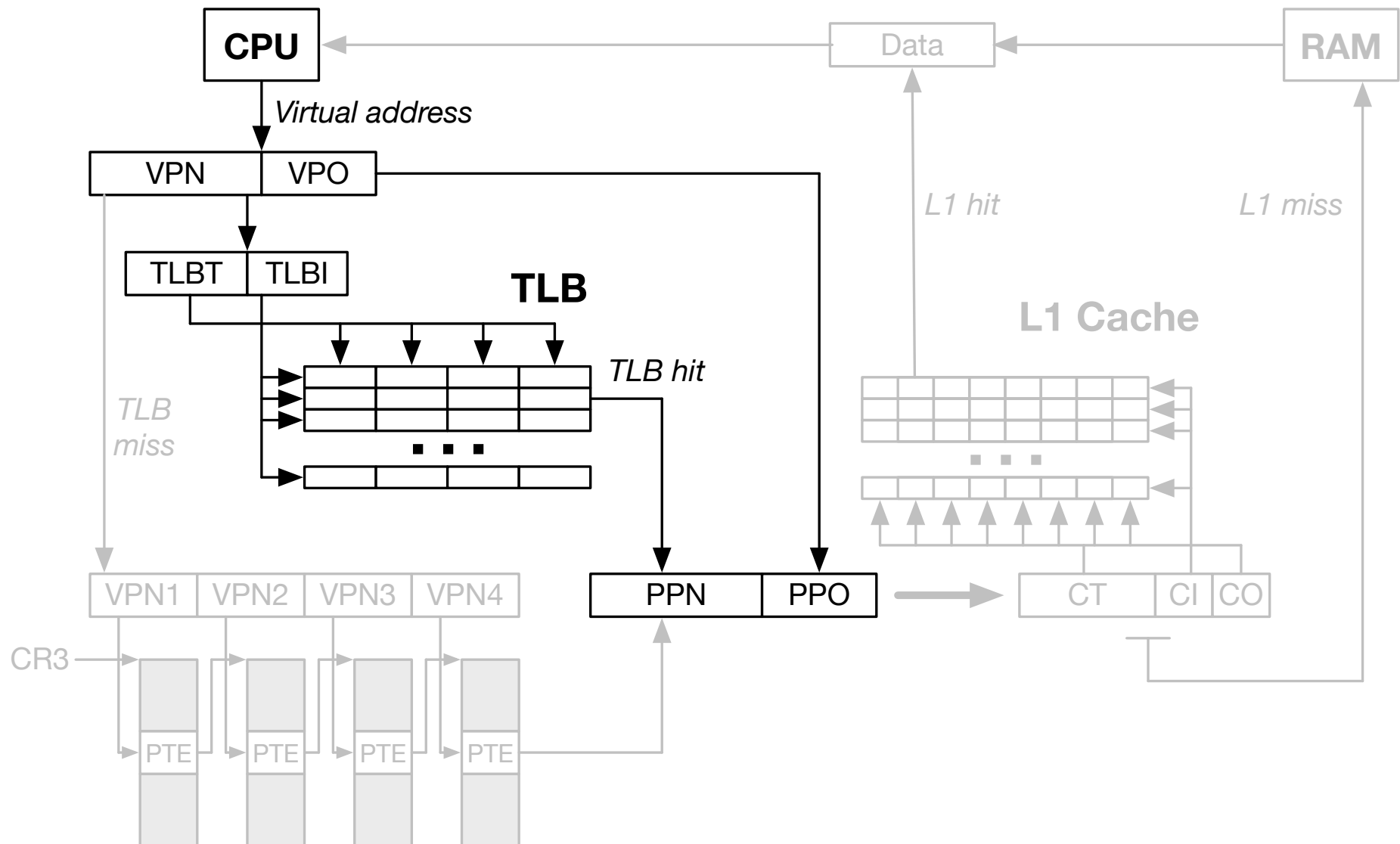
Translation Lookup Buffer

30

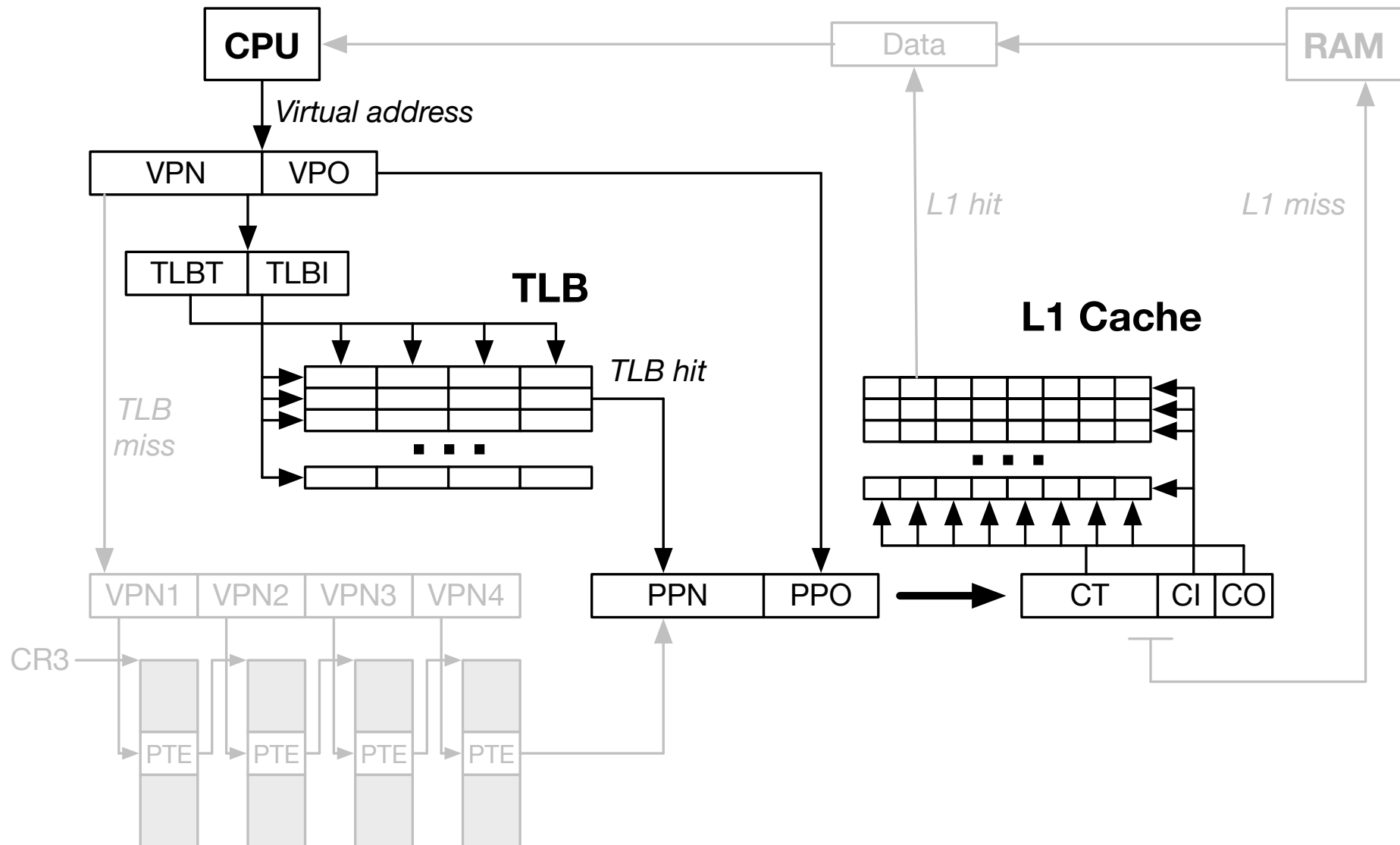


Compose Address

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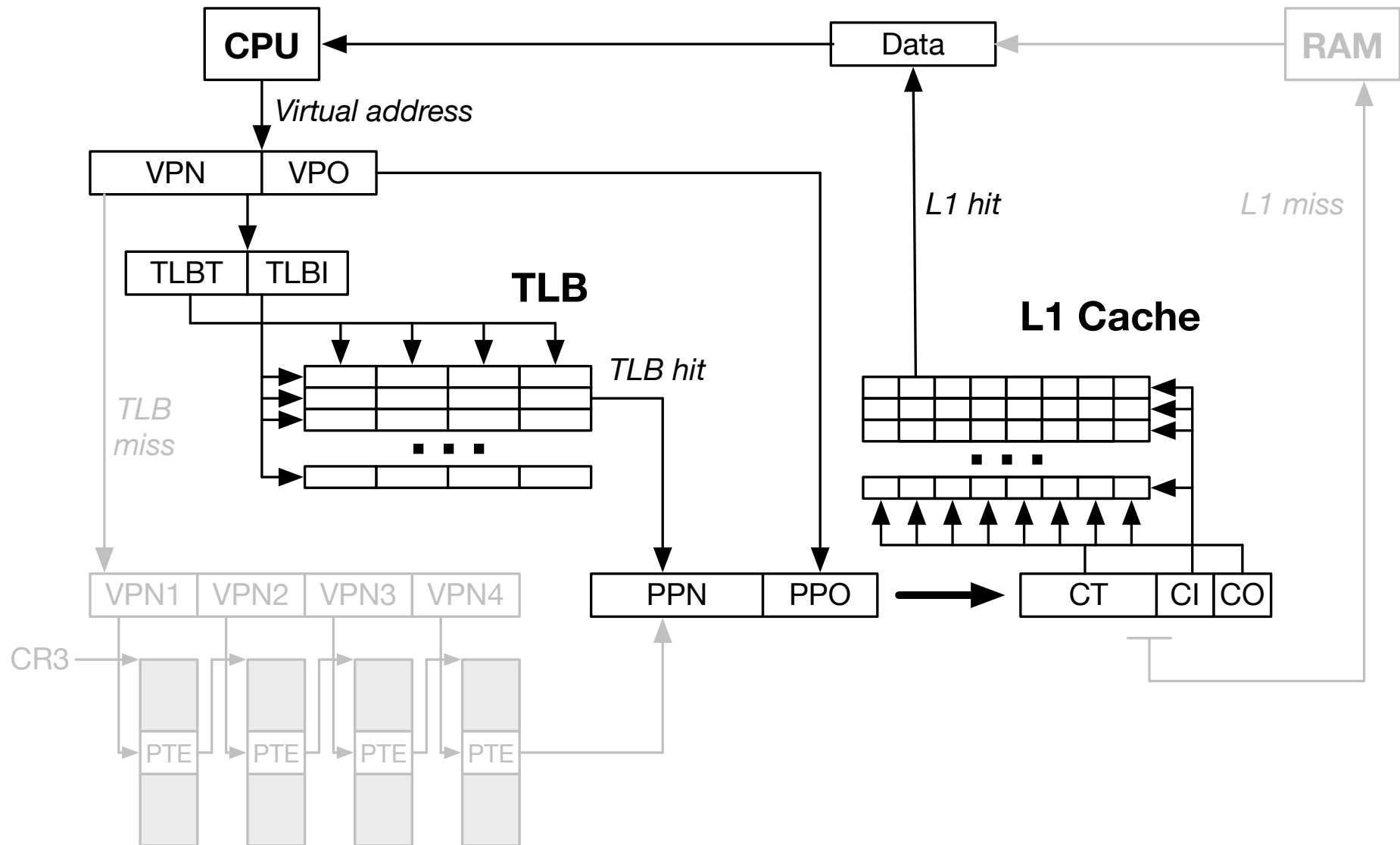


L1 Cache Lookup



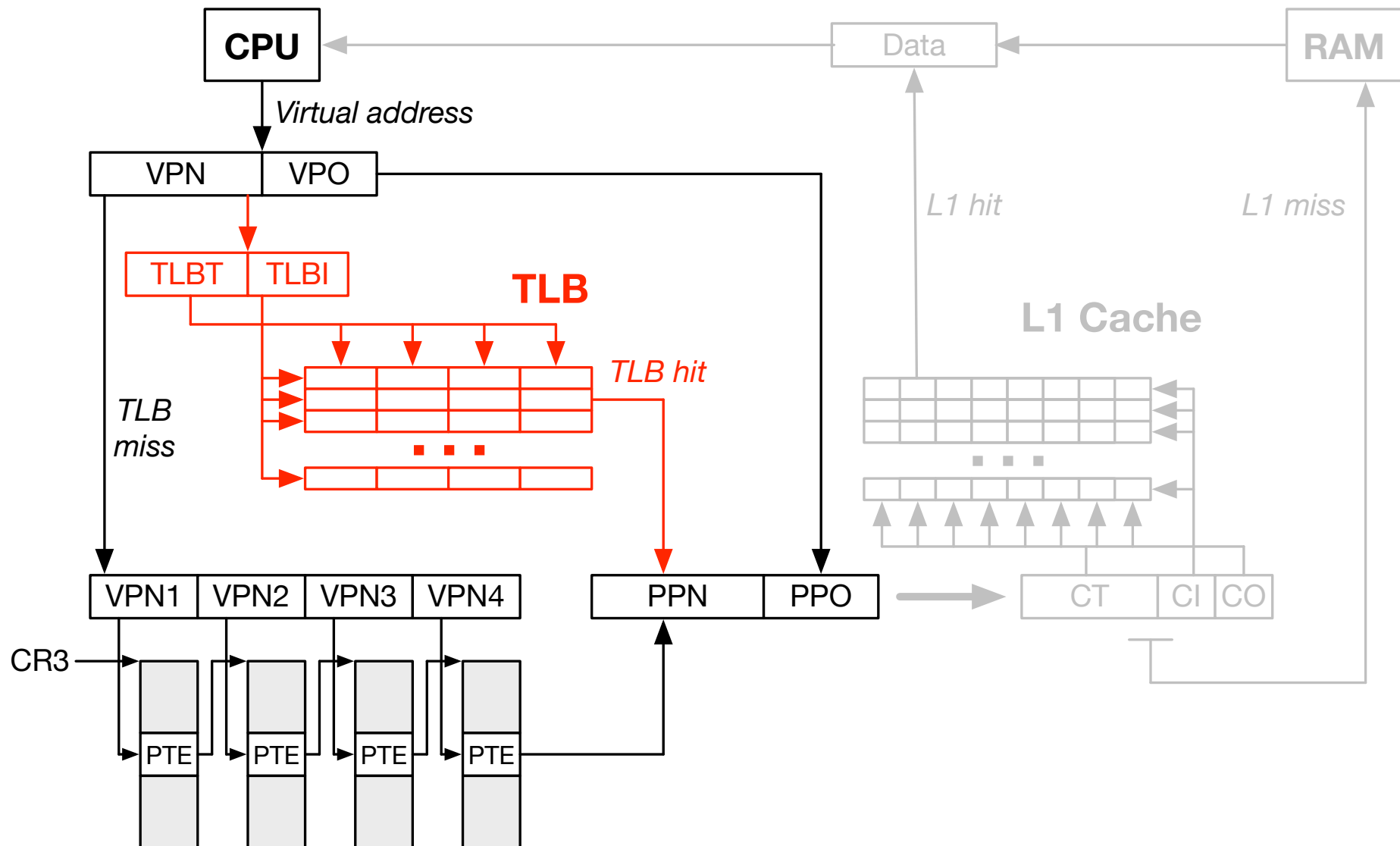
Return Data From L1 Cache

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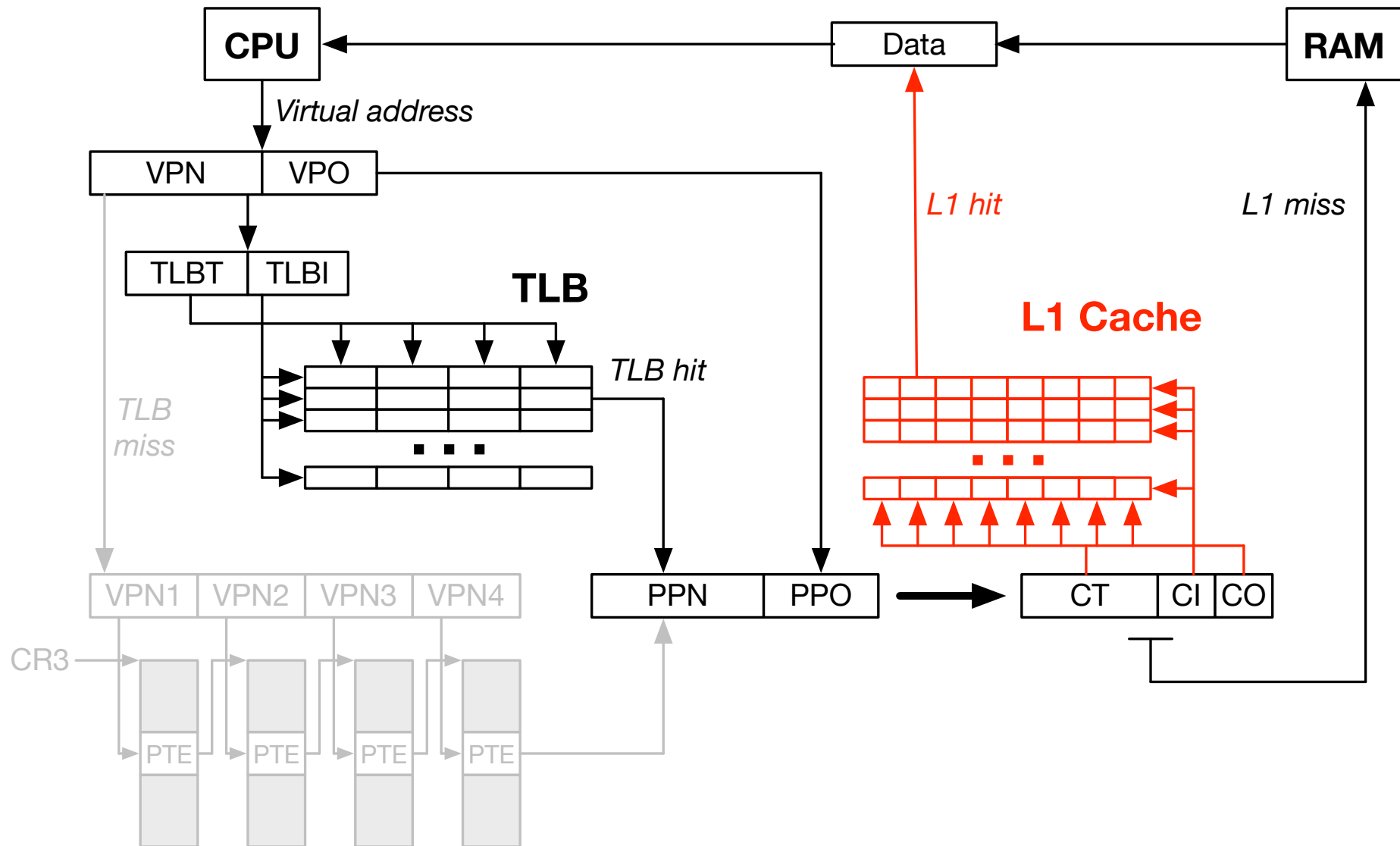


Translation Lookup Buffer Miss

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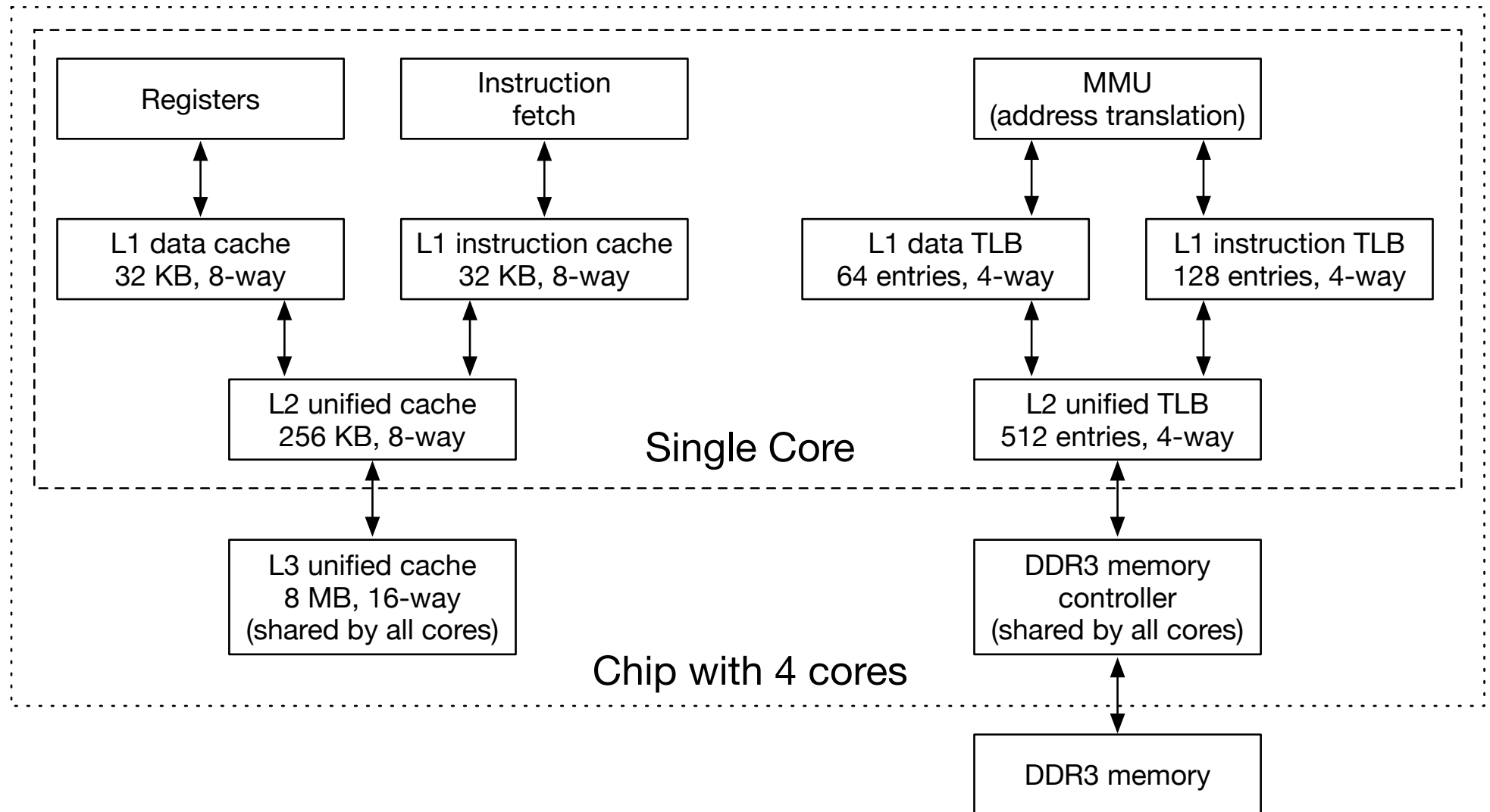
L1 Cache Miss





core i7

Chip Layout



- Virtual memory: 48 bit ($\rightarrow 2^{48} = 256\text{TB}$ address space)
- Physical memory: 52 bit ($\rightarrow 2^{52} = 4\text{PB}$ address space)
- Page size: 12 bit ($\rightarrow 2^{12} = 4\text{KB}$)
 $\Rightarrow 2^{36} = 64\text{G}$ entries, split in 4 levels (512 entries each)
- Translation lookup buffer (TLB): 4-way associative, 16 entries
- L1 cache: 8-way associative, 64 sets, 64 byte blocks (32 KB)
- L2 cache: 8-way associative, 512 sets, 64 byte blocks (256 KB)
- L3 cache: 16-way associative, 8K sets, 64 byte blocks (8 MB)



linux

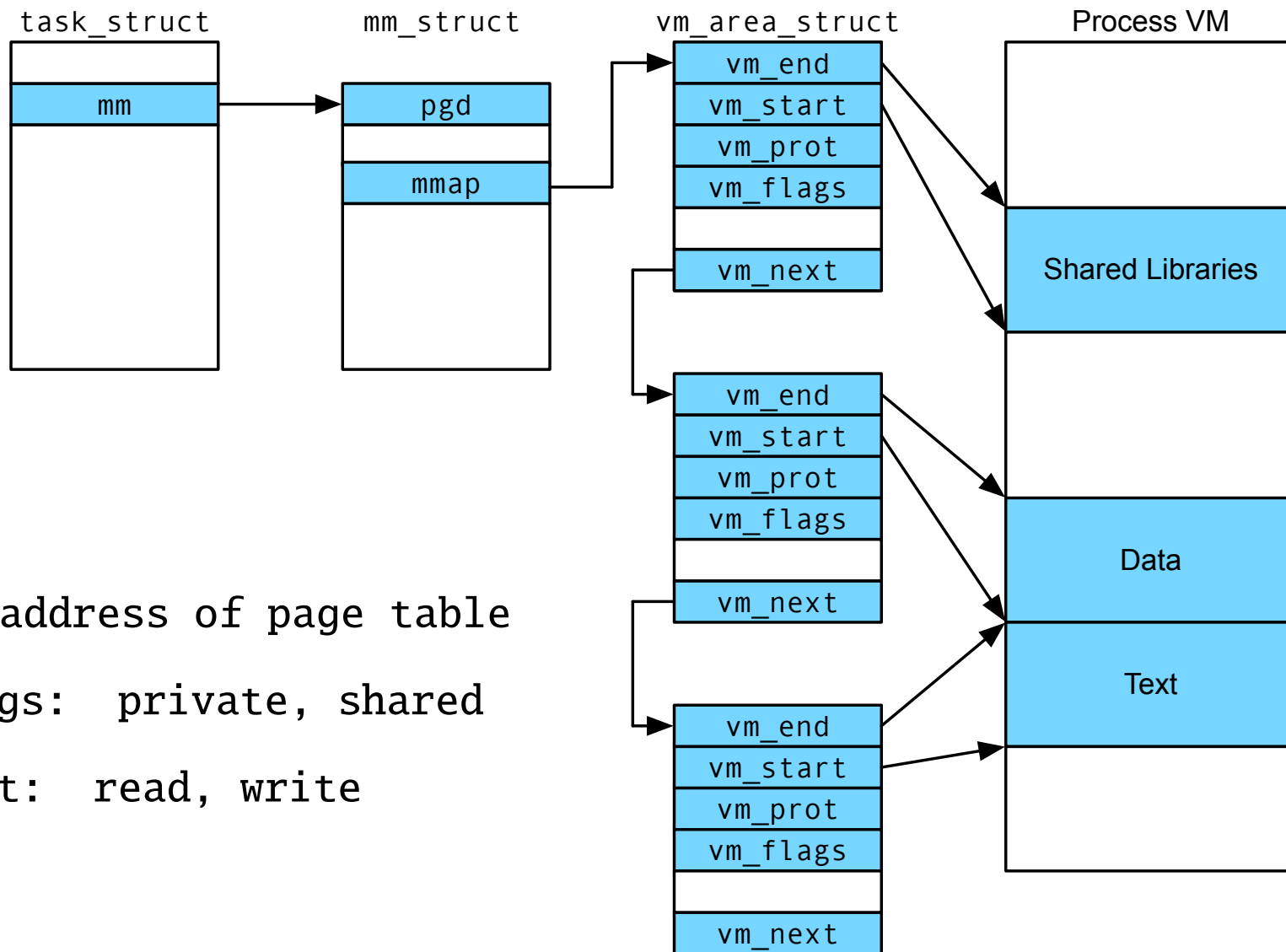
Big Picture

- Close co-operation between hardware and software
- Each process has its own virtual address space, page table
- Translation look-up buffer
when switching processes → flush
- Page table
when switching processes → update pointer to top-level page table
- Page tables are always in physical memory
→ pointers to page table do not require translation

Handling Page Faults

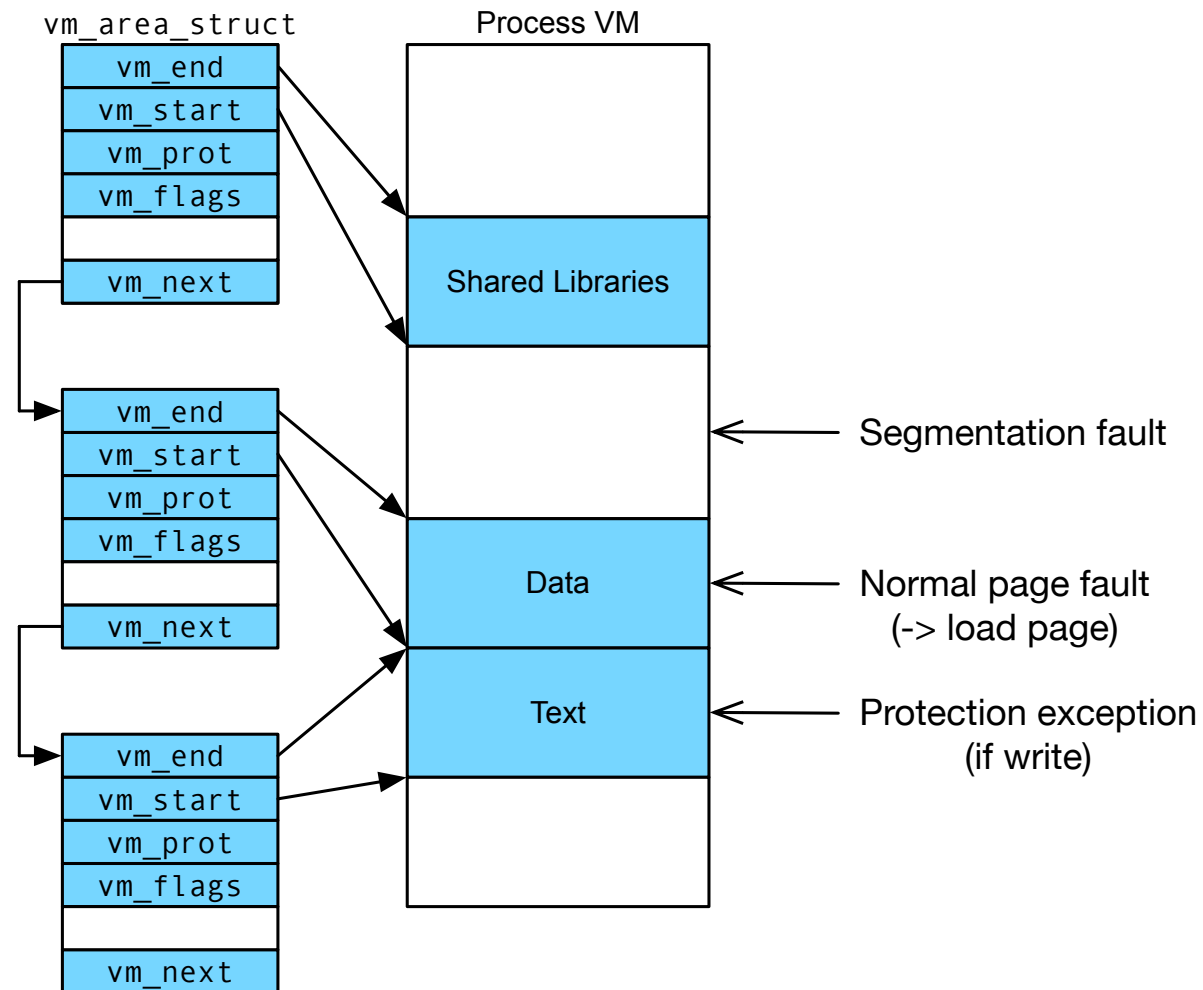
- Page faults trigger an exception (hardware)
- Exception is handled by software (Linux kernel)
- Kernel must determine what to do

Linux Virtual Memory Areas



- `pgd`: address of page table
- `vm_flags`: private, shared
- `vm_prot`: read, write

Handling Page Faults



Kernel walks through `vm_area_struct` list to resolve page fault

memory mapping

Objects on Disk

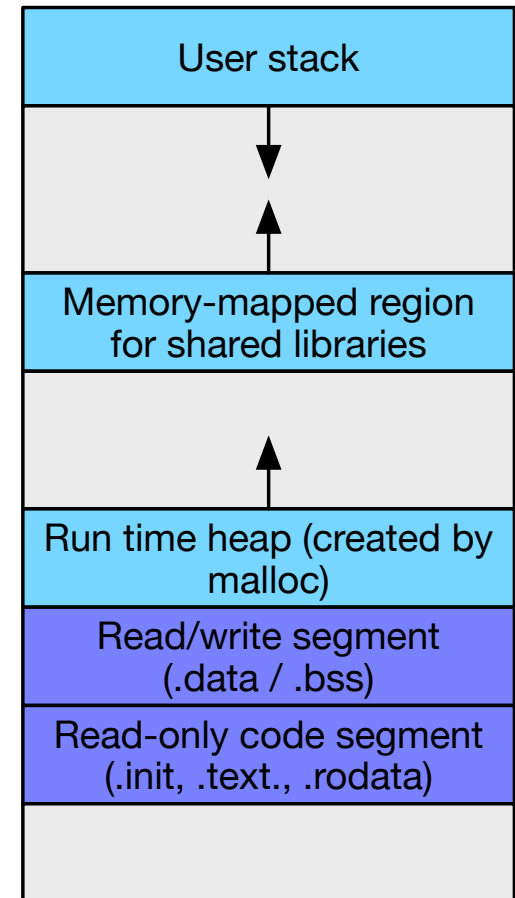
- Area of virtual memory = file on disk
- Regular file in file system
 - file divided up into pages
 - demand loading: just mapped to addresses, not actually loaded
 - could be code, shared library, data file
- Anonymous file
 - typically allocated memory
 - when used for the first time: set all values to zero
 - never really on disk, except when swapped out

Shared Object

- A shared object is a file on disk
- Private object
 - only its process can read/write
 - changes not visible to other processes
- Shared object
 - multiple processes can read/write
 - changes visible to other processes

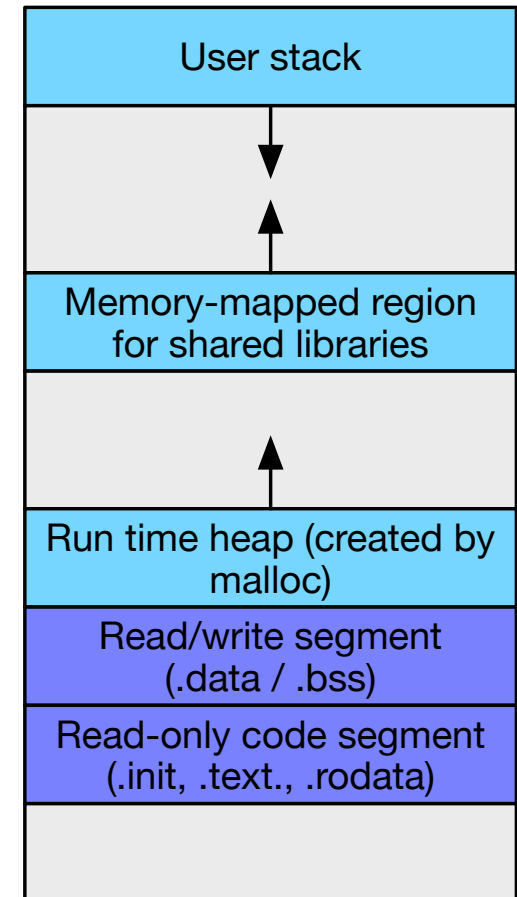
fork()

- Creates a new child process
- Copies all
 - virtual memory area structures
 - memory mapping structures
 - page tables
- New process has identical access to existing memory



execve()

- Creates a new process
- Deletes all user areas
- Map private areas (.data, .code, .bss)
- Map shared libraries
- Set program counter



User-Level Memory Mapping

- Process can create virtual memory areas with mmap (may be loaded from file)
- Protection options (handled by kernel / hardware)
 - executable code
 - read
 - write
 - inaccessible
- Mapping options
 - anonymous: data object initially zeroed out
 - private
 - shared

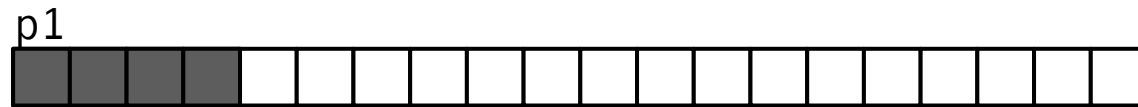


dynamic memory allocation

- `malloc()`
 - allocate specified amount of data
 - return pointer to (virtual) address
 - memory is allocated on heap
- `free()`
 - frees memory allocated at pointer location
 - may be between other allocated memory
- Need to track of list of allocated memory

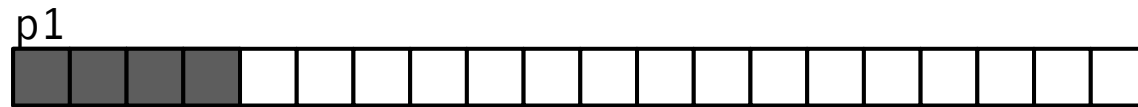
Example

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```
p1 = malloc(4*sizeof(int))
```

Example

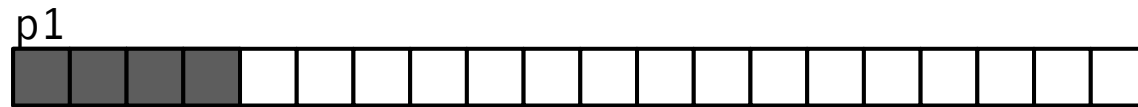


```
p1 = malloc(4*sizeof(int))
```



```
p2 = malloc(5*sizeof(int))
```

Example



```
p1 = malloc(4*sizeof(int))
```

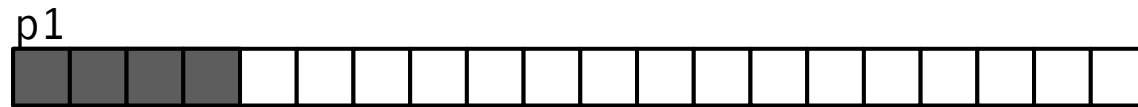


```
p2 = malloc(5*sizeof(int))
```



```
p3 = malloc(6*sizeof(int))
```

Example



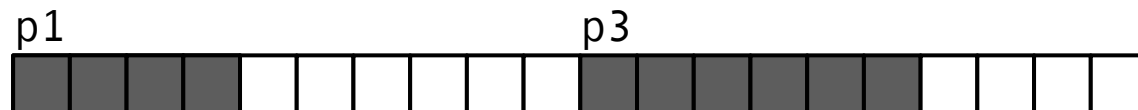
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p1 = malloc(4*sizeof(int))
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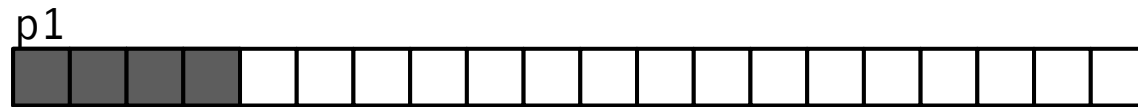


```
p3 = malloc(6*sizeof(int))
```



```
free(p2)
```

Example



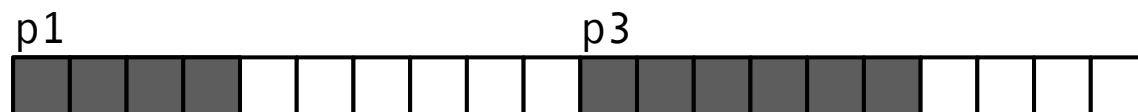
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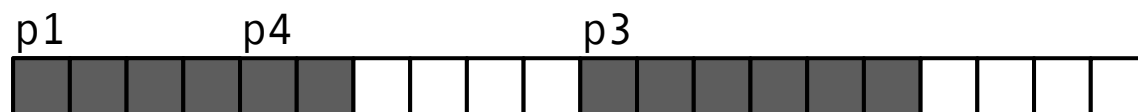
```
p2 = malloc(5*sizeof(int))
```



```
p3 = malloc(6*sizeof(int))
```



```
free(p2)
```



```
p4 = malloc(2*sizeof(int))
```

- Memory fragmentation
 - internal: frequent `malloc()` and `free()` creates fragmented memory use
 - external: new `malloc()` exceeds heap space → is split
- Free list
 - need to maintain a list of free memory areas
 - implicit: space between allocated memory
 - explicit: maintain a separate list