Modern Virtual Memory Systems

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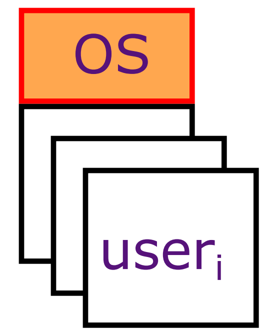
Recap: Modern Virtual Memory Systems

Illusion of a large, private, uniform store

Protection & Privacy

several users, each with their private address space and one or more shared address spaces

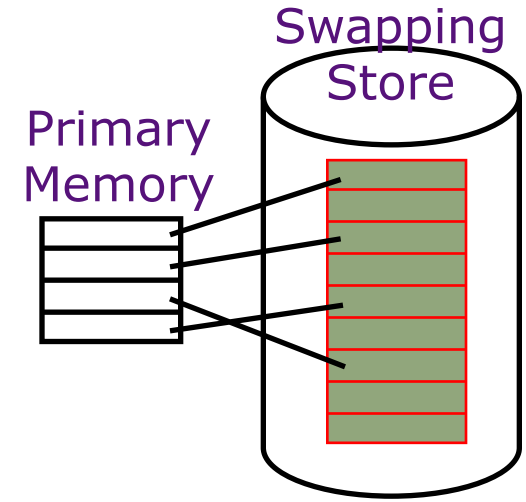
page table ≡ name space



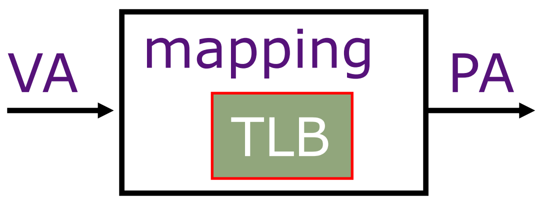
Demand Paging

Provides the ability to run programs larger than the primary memory

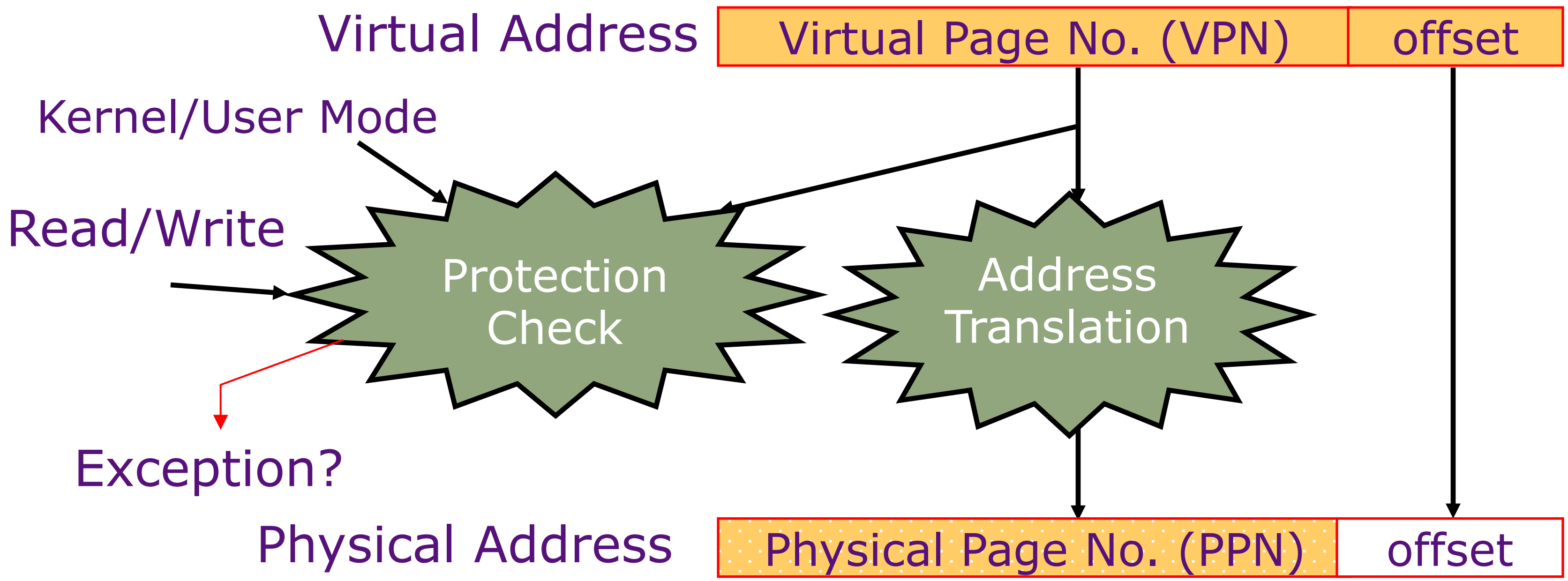
Hides differences in machine configurations



The price is address translation on each memory reference



Address Translation & Protection

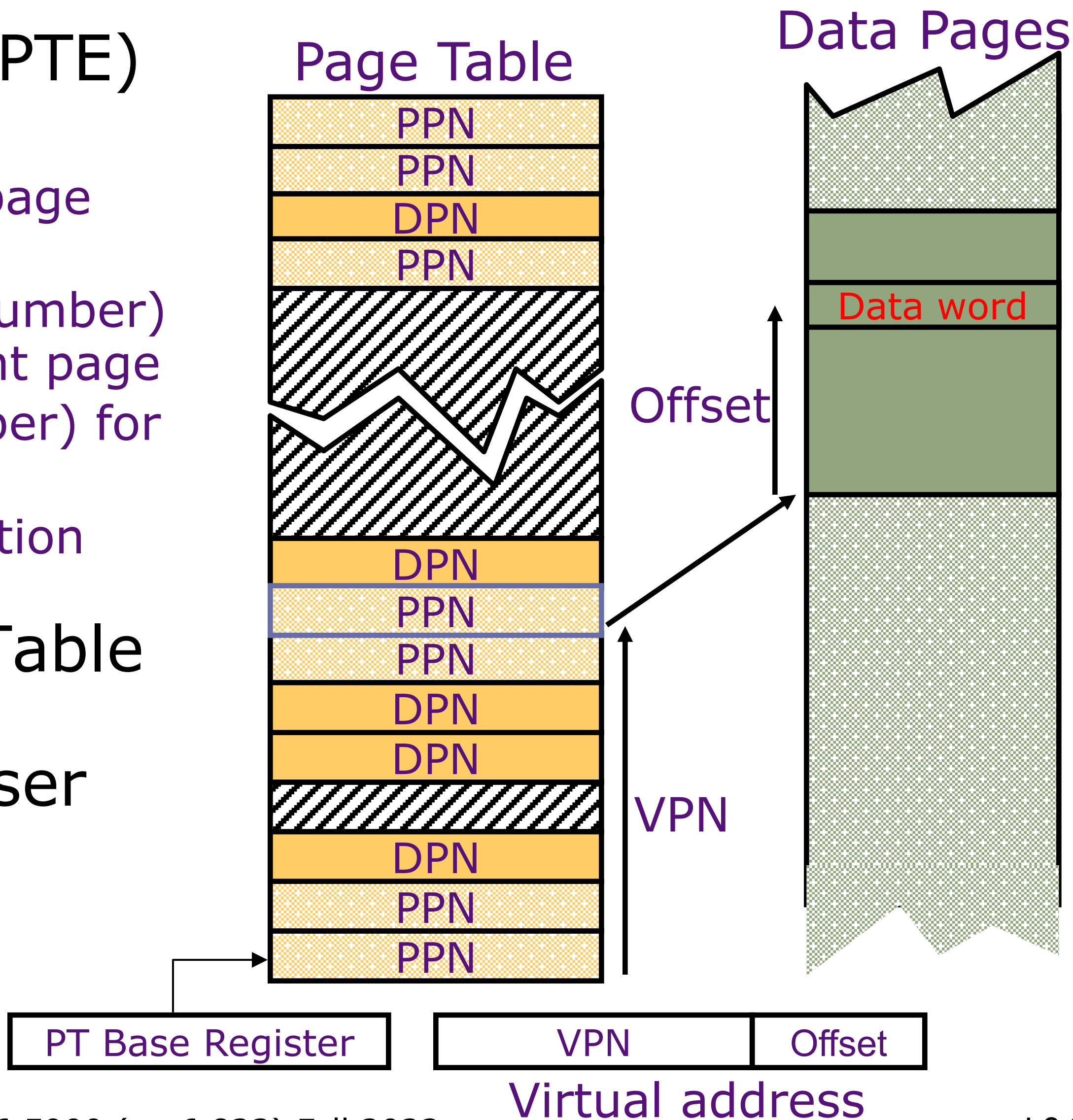


- Every instruction and data access needs address translation and protection checks

A good VM design needs to be fast (~ one cycle) and space-efficient

Recap: Linear Page Table

- Page Table Entry (PTE) contains:
  - A bit to indicate if a page exists
  - PPN (physical page number) for a memory-resident page
  - DPN (disk page number) for a page on the disk
  - Status bits for protection and usage
- OS sets the Page Table Base Register whenever active user process changes



Recap: Size of Linear Page Table

With 32-bit addresses, 4 KB pages & 4-byte PTEs:

$\Rightarrow$ 2^{20} PTEs, i.e, 4 MB page table per user

$\Rightarrow$ 4 GB of swap space needed to back up the full virtual address space

Larger pages?

- Internal fragmentation (Not all memory in a page is used)
- Larger page fault penalty (more time to read from disk)

What about 64-bit virtual address space???

- Even 1MB pages would require 2^{44} 8-byte PTEs (35 TB!)

What is the "saving grace"?

Atlas Revisited

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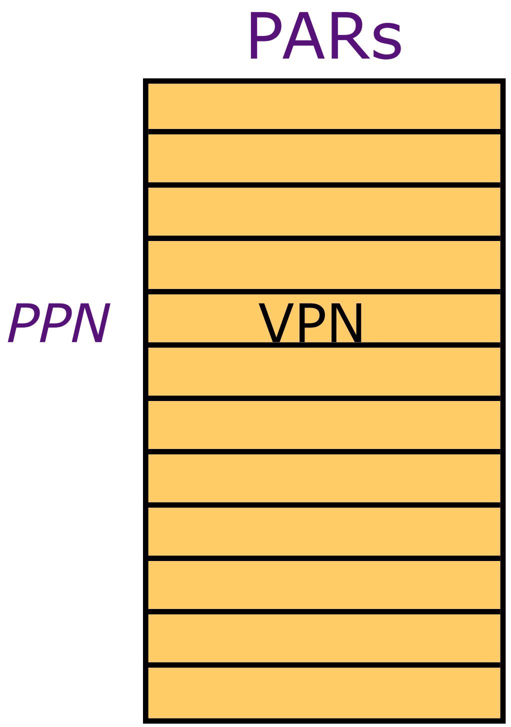
- PAR's contain the VPN's of the pages *resident in primary memory*
- *Advantage:* The size is proportional to the size of the primary memory
- *What is the disadvantage?*



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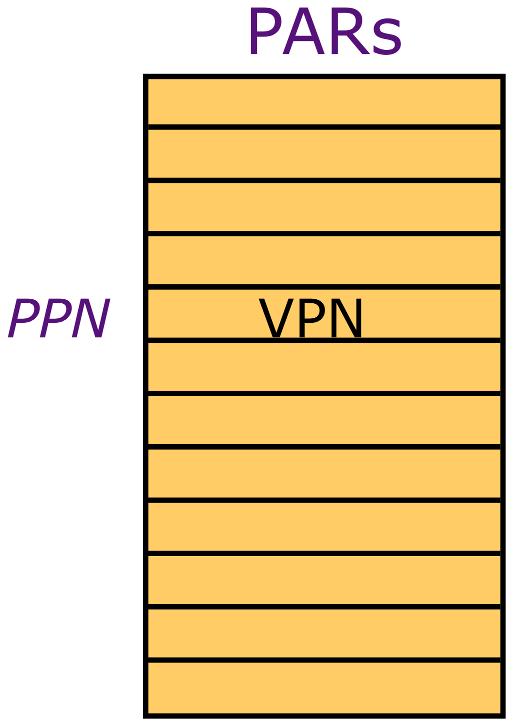
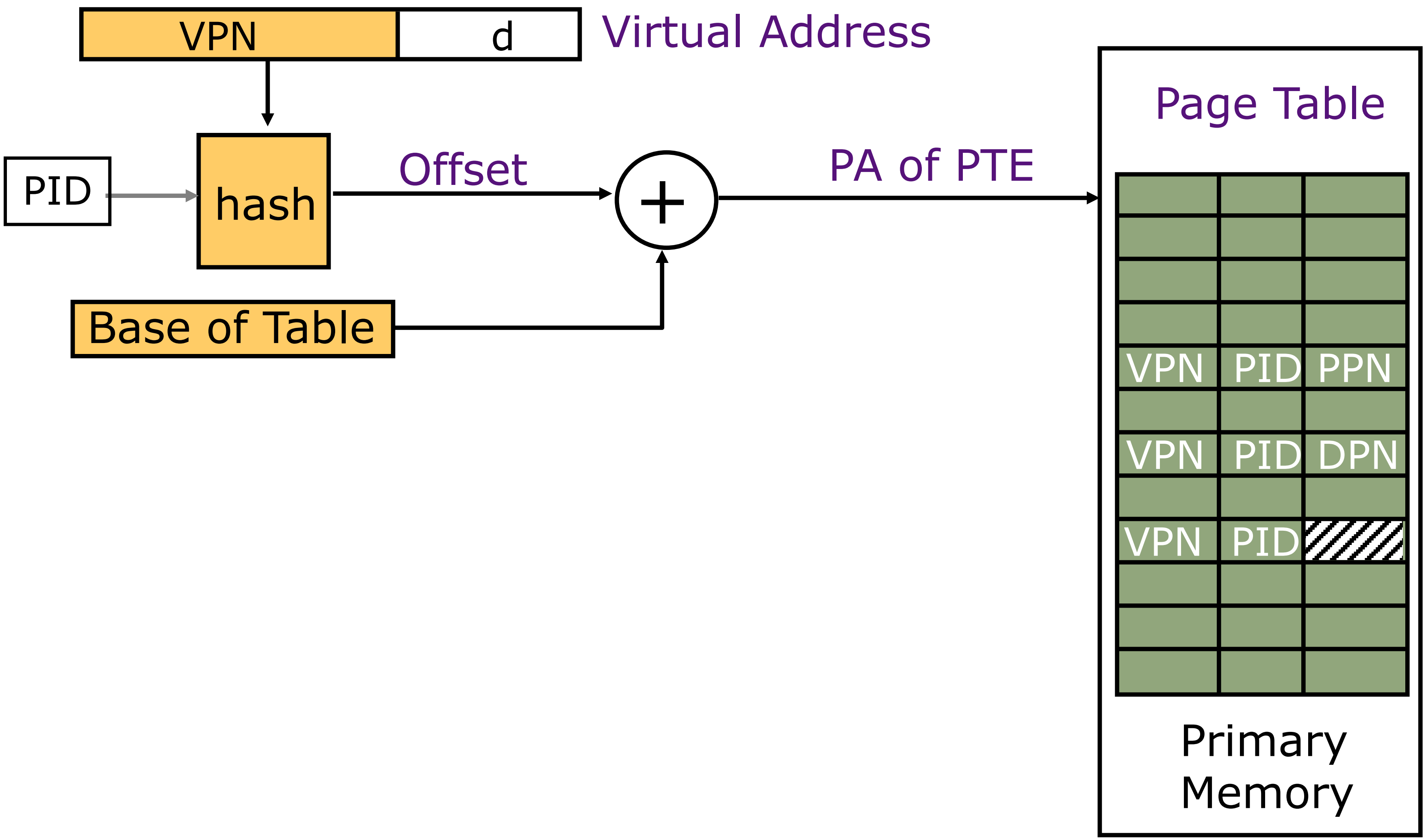


Hashed Page Table:
Approximating Associative Addressing



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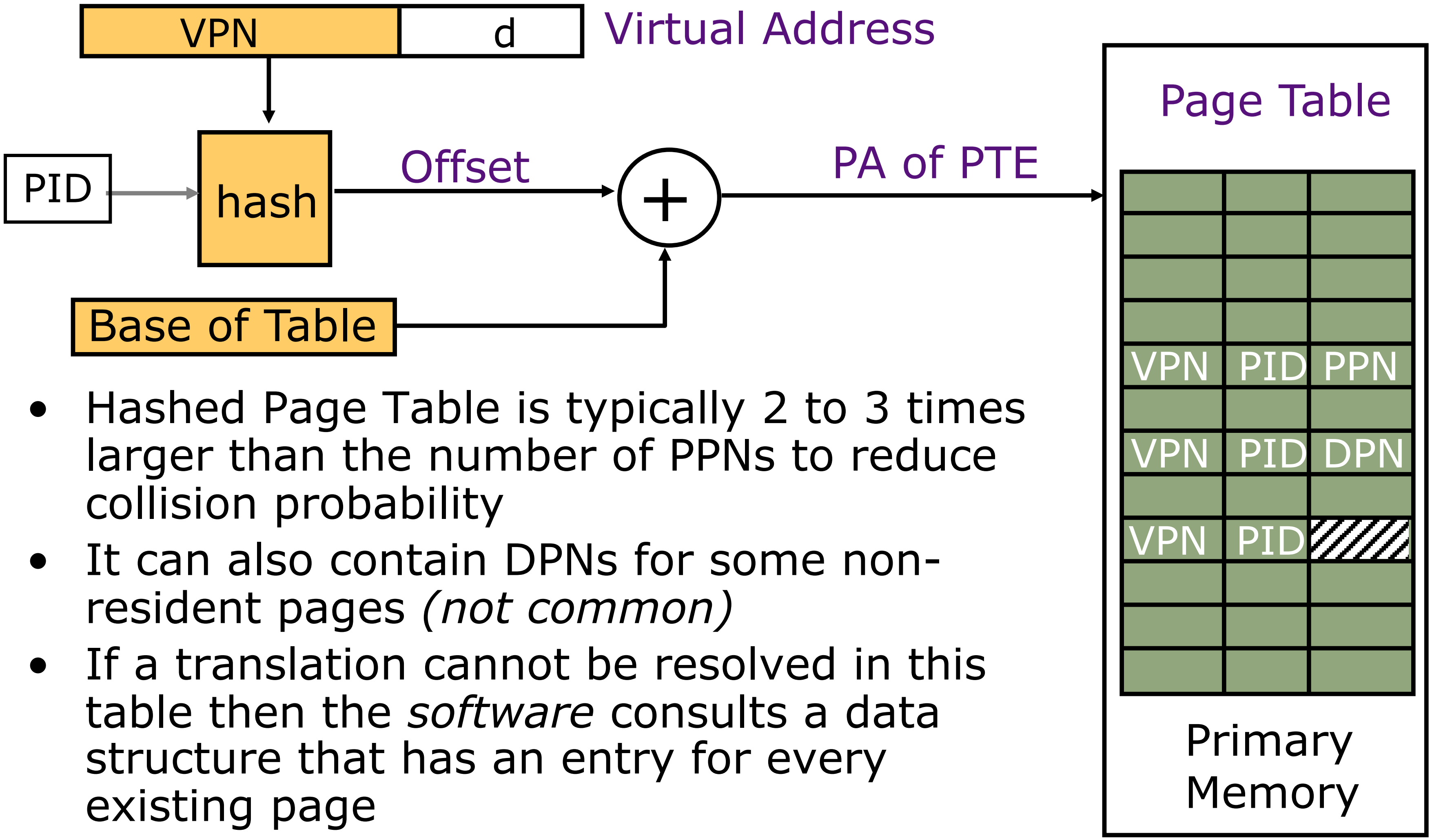
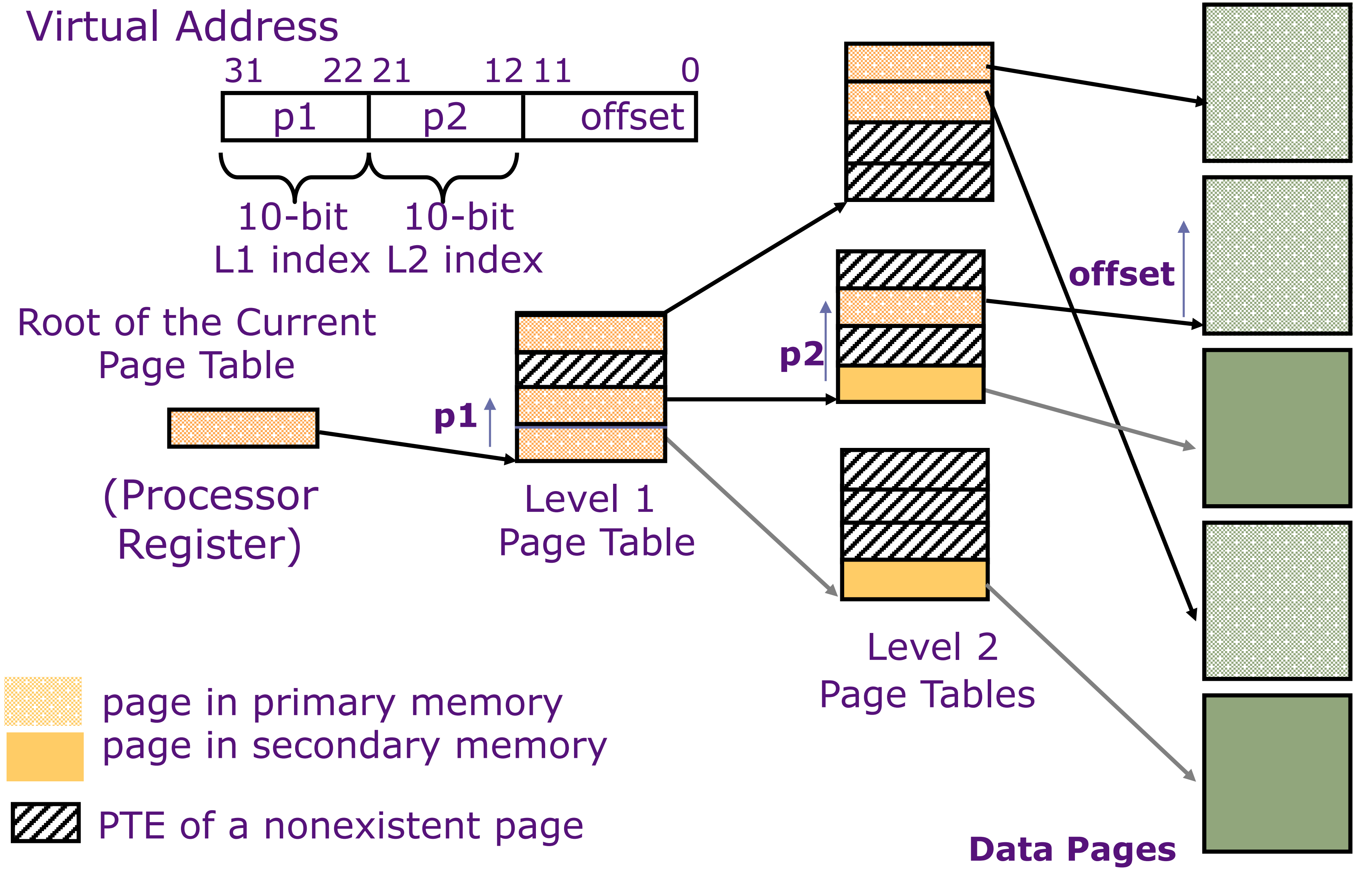


- Hashed Page Table is typically 2 to 3 times larger than the number of PPNs to reduce collision probability
- It can also contain DPNs for some non-resident pages *(not common)*
- If a translation cannot be resolved in this table then the *software* consults a data structure that has an entry for every existing page

Hierarchical Page Table



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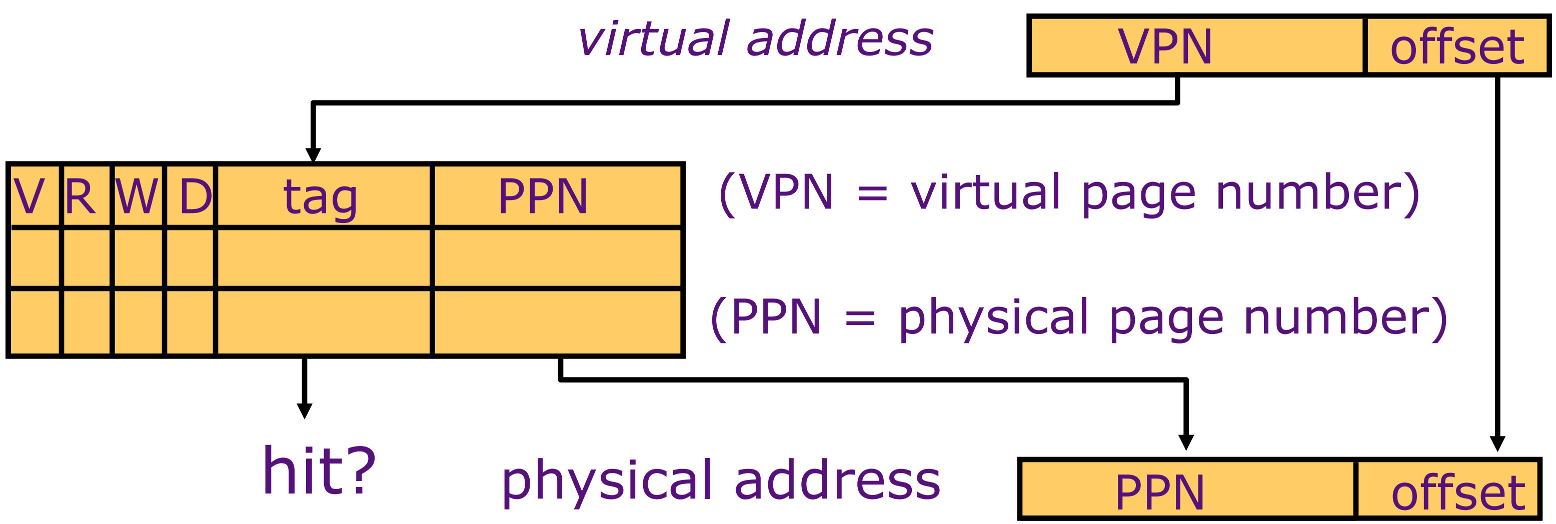

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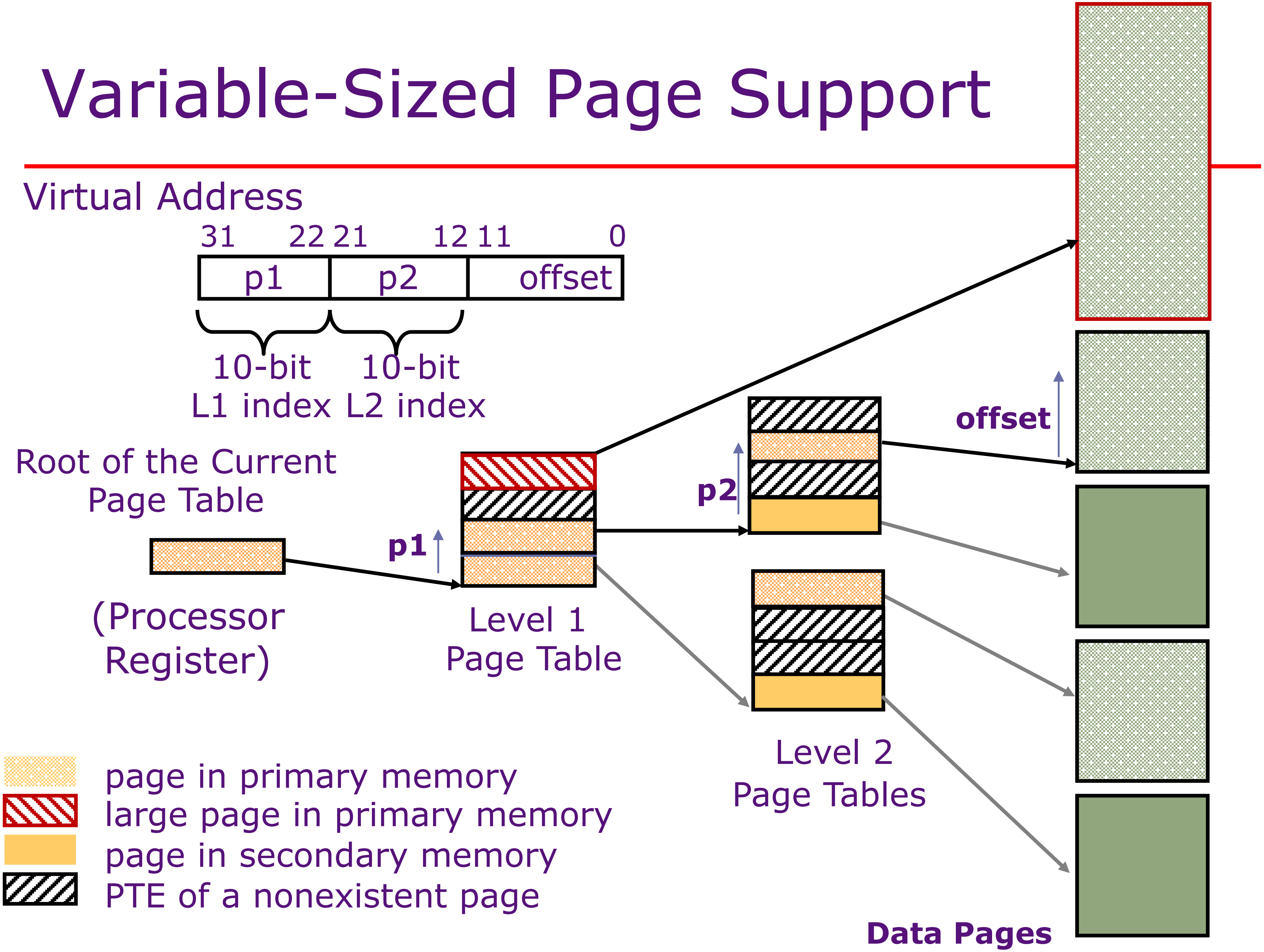
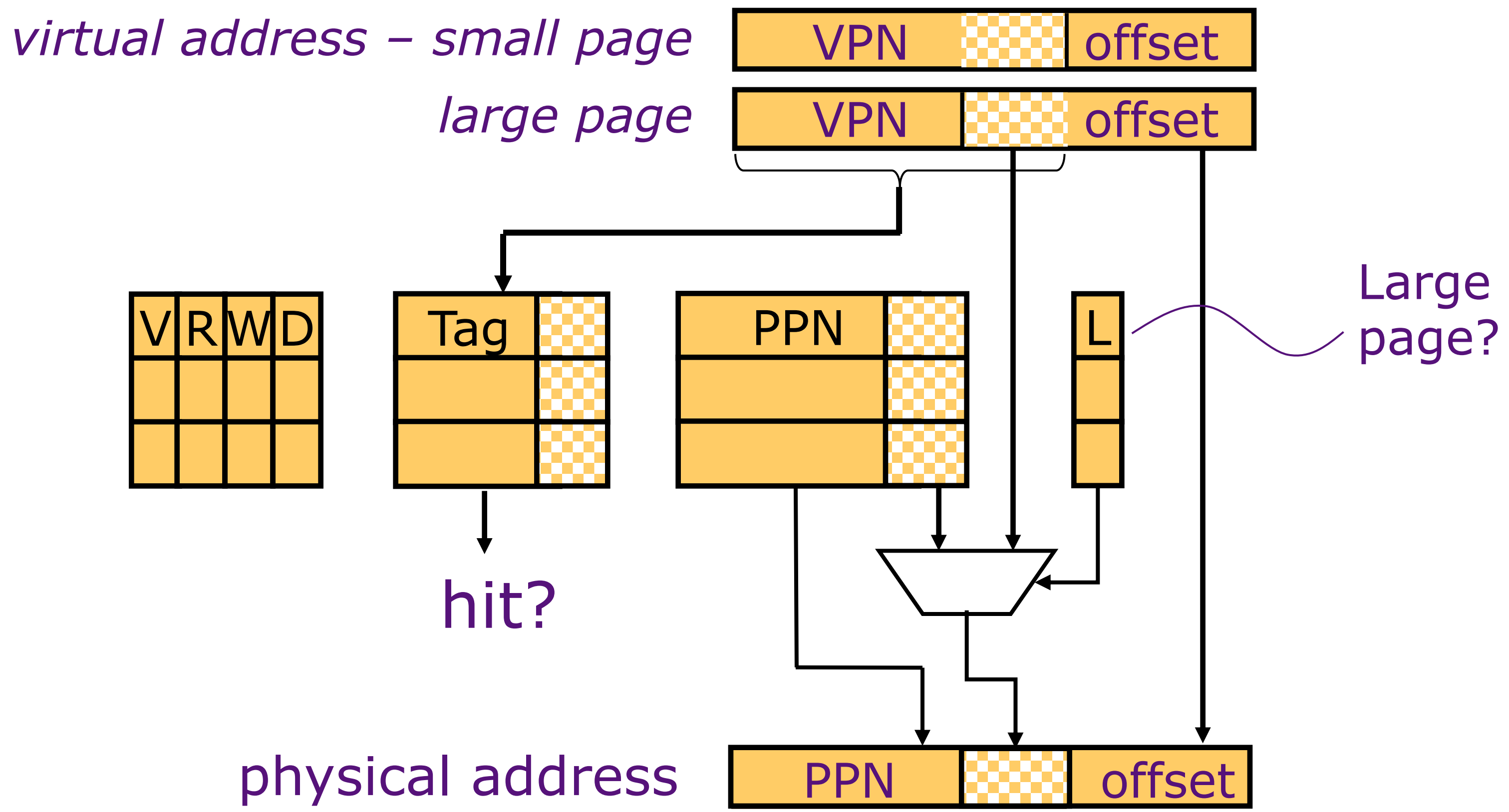
- Ways to increase TLB reach
  - Multi-level TLBs (e.g., Intel Skylake: 64-entry L1 data TLB, 128-entry L1 instruction TLB, 1.5K-entry L2 TLB)
  - Multiple page sizes, e.g., x86 (32-bit): 4MB; x86-64: 2MB, 1GB

Variable-Sized Page Support



Variable-Size Page TLB



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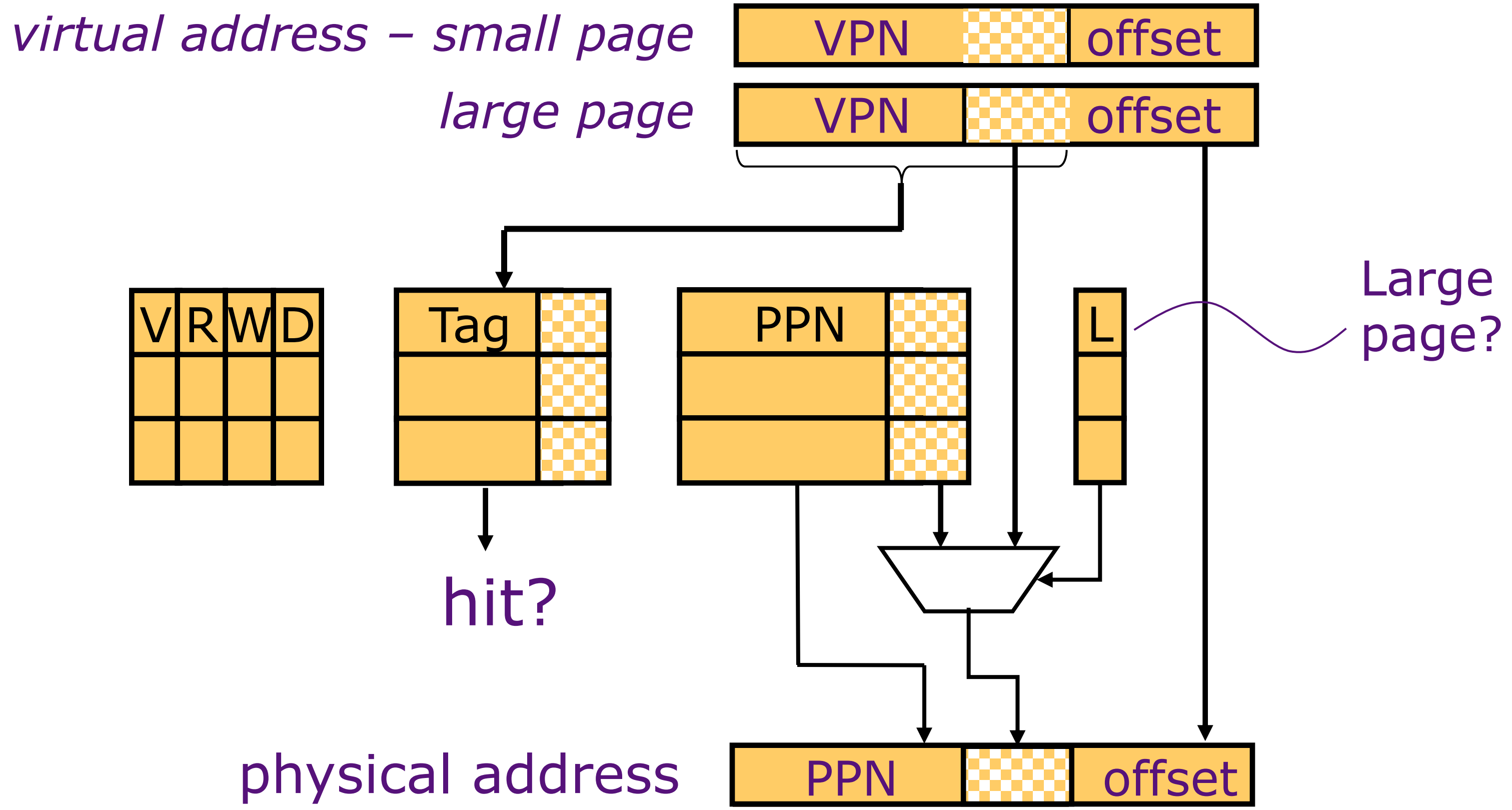

Step 1: Assume 4KB page size, calculate index and probe
Step 2: If miss, assume 2MB page, re-calculate index and probe

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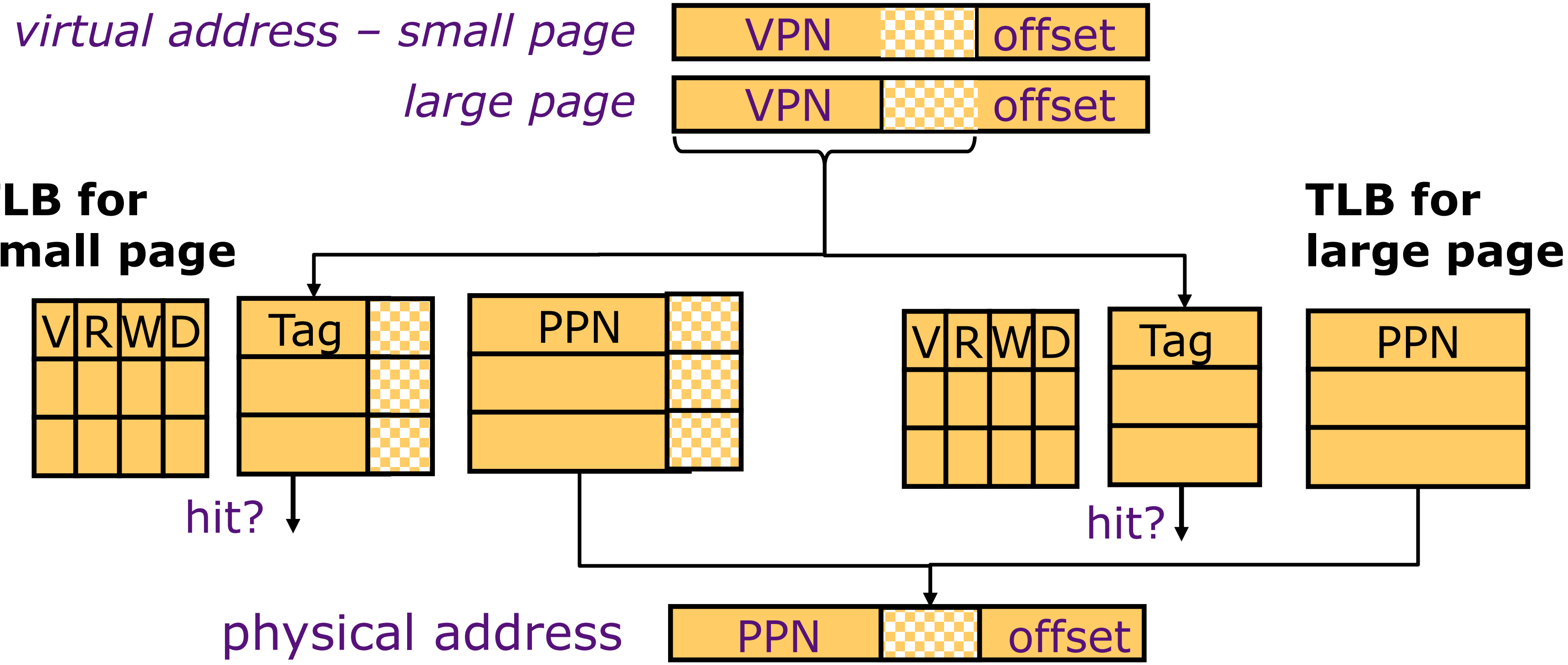

Alternatively, have a separate TLB for each page size (pros/cons?)

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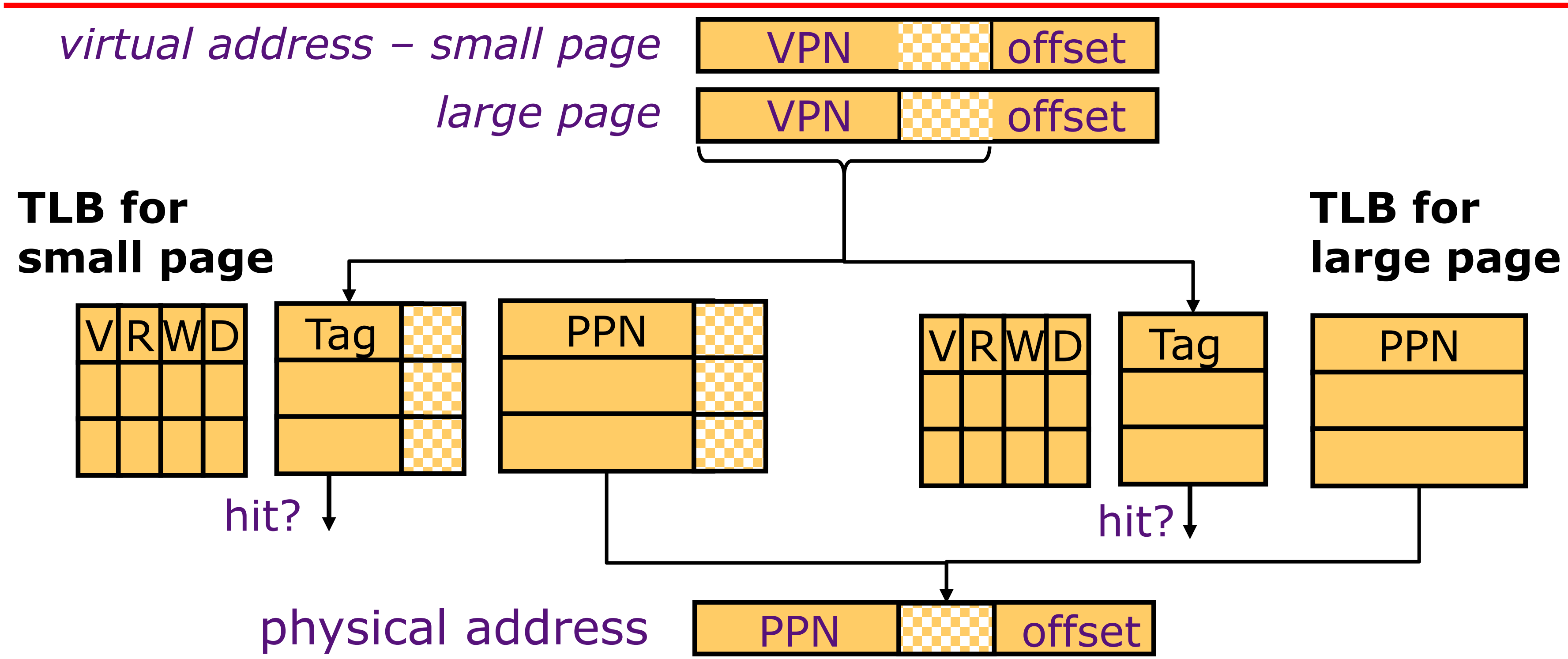

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Example: Intel Skylake

	4KB	**2MB**	**1GB**
L1-D TLB	64	32	4
L1-I TLB	128	8	/
L2 STLB	1536		16

Handling a TLB Miss

Software (MIPS, Alpha)

TLB miss causes an exception and the operating system walks the page tables and reloads TLB. *A privileged "untranslated" addressing mode used for walk*

Hardware (SPARC v8, x86, PowerPC)

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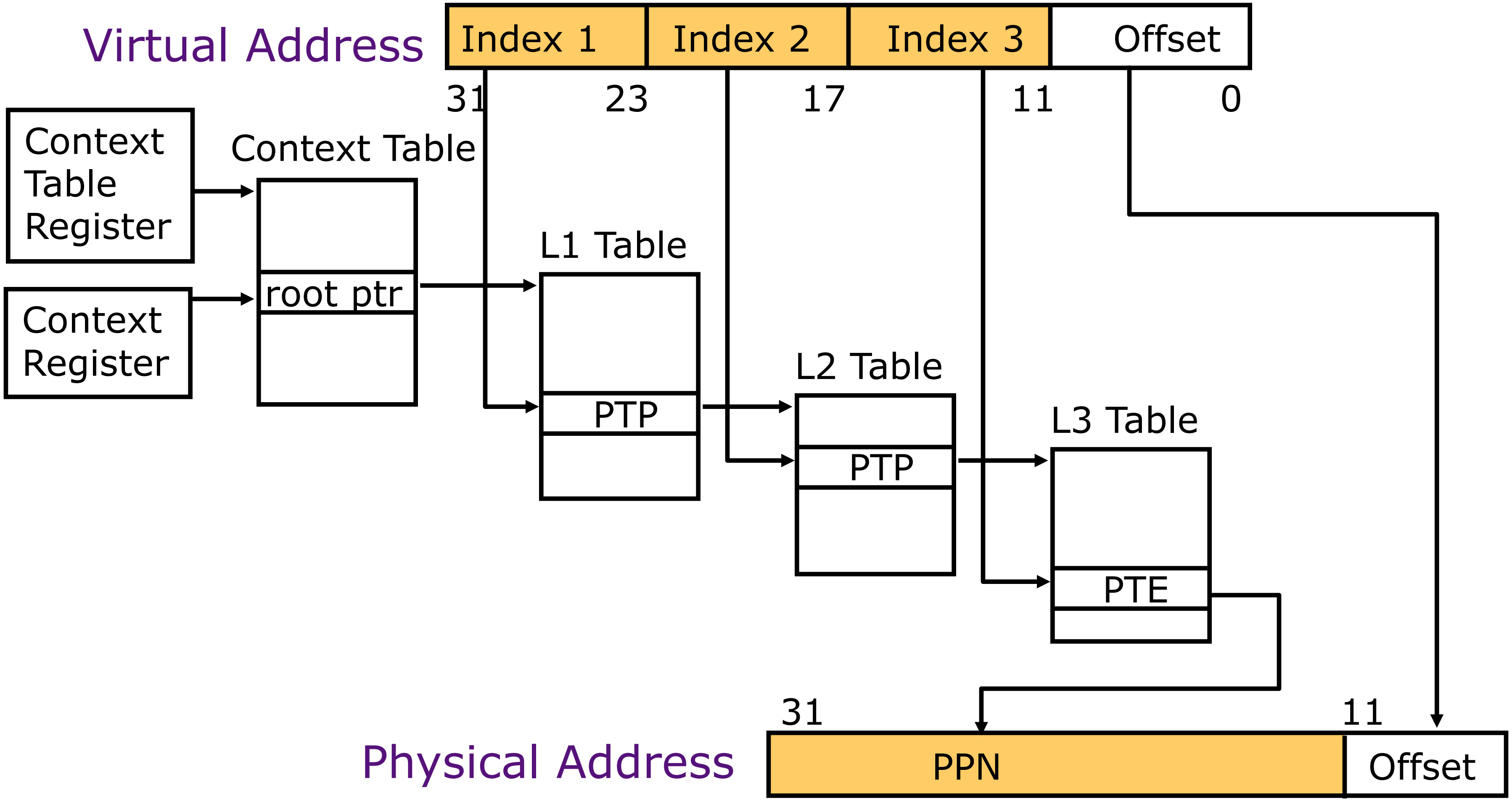
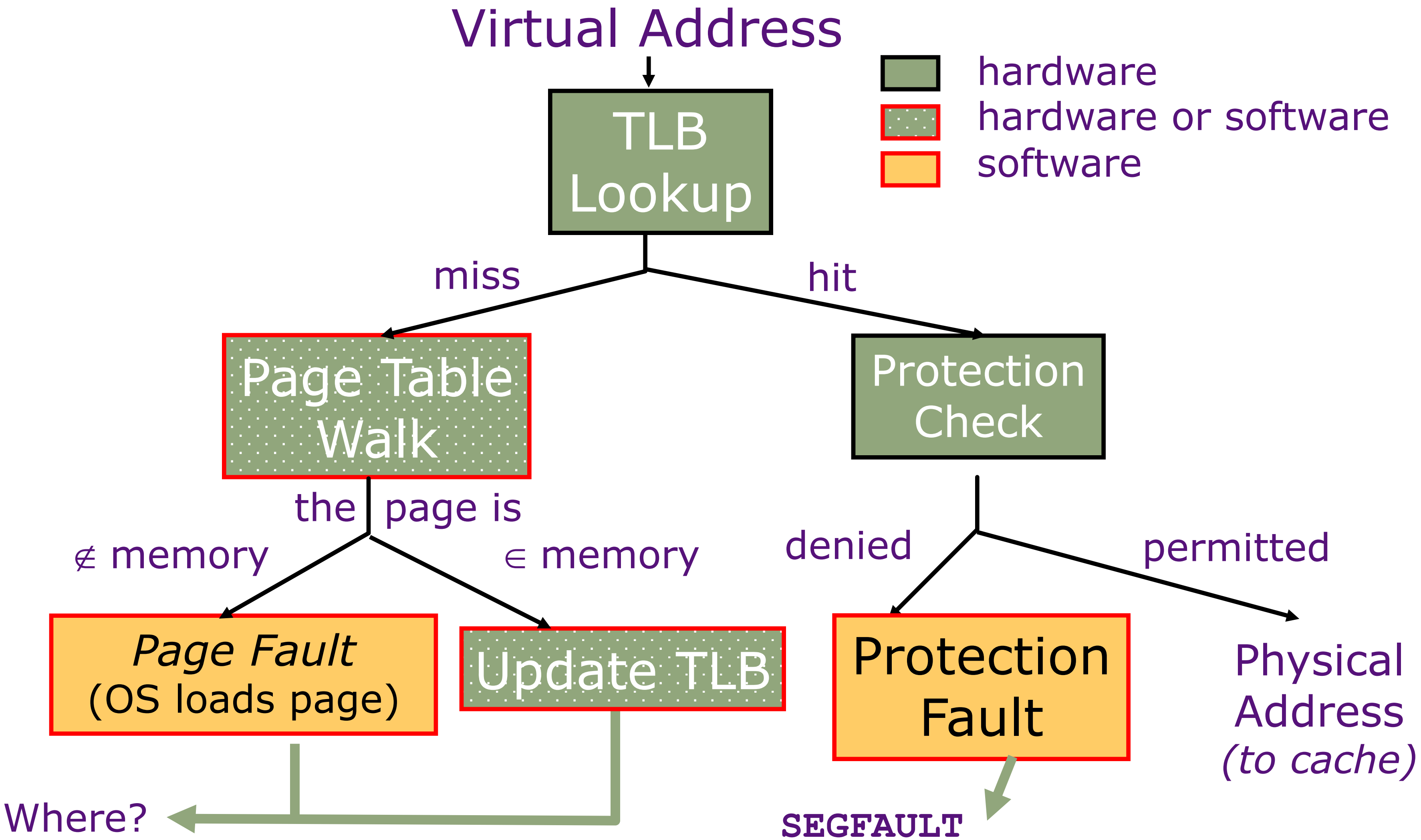
What is the trade-off?

Hierarchical Page Table Walk: SPARC v8



MMU does this table walk in hardware on a TLB miss

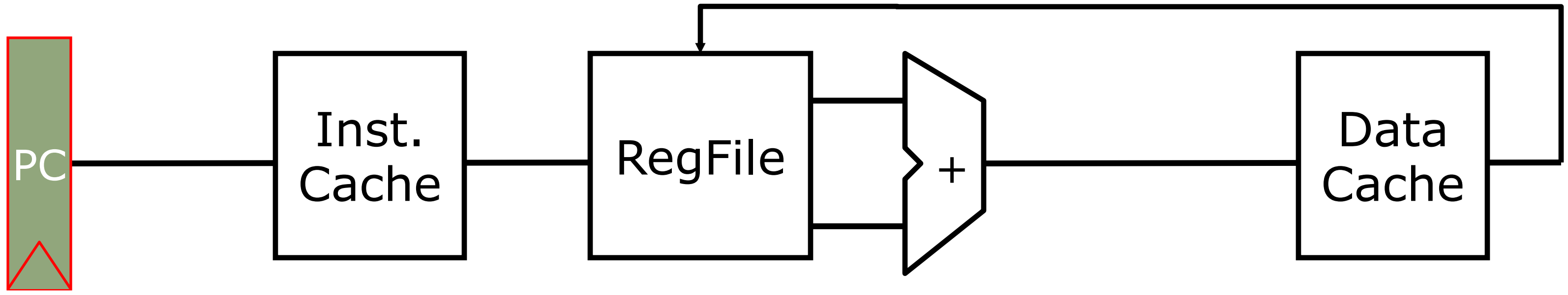
Address Translation: *putting it all together*



Topics

- Speeding up the common case:
  - TLB & Cache organization
- Interrupts
- Modern Usage

Address Translation in CPU



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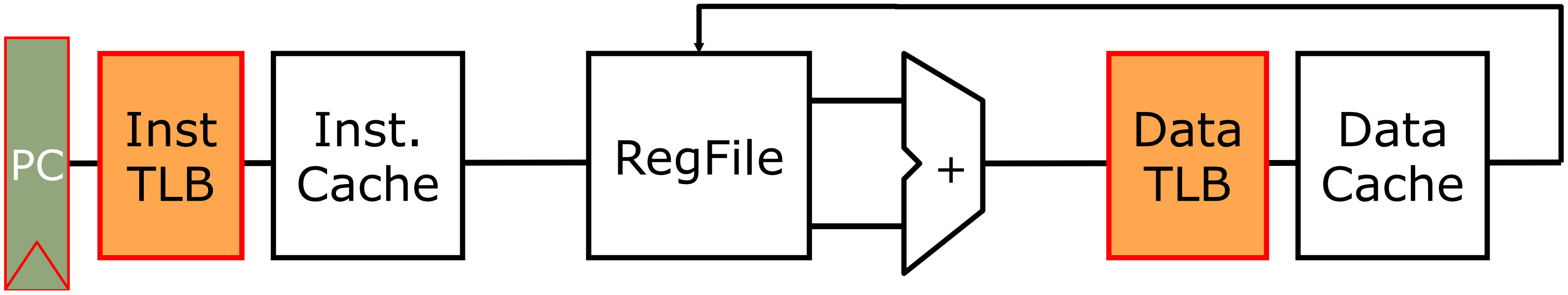

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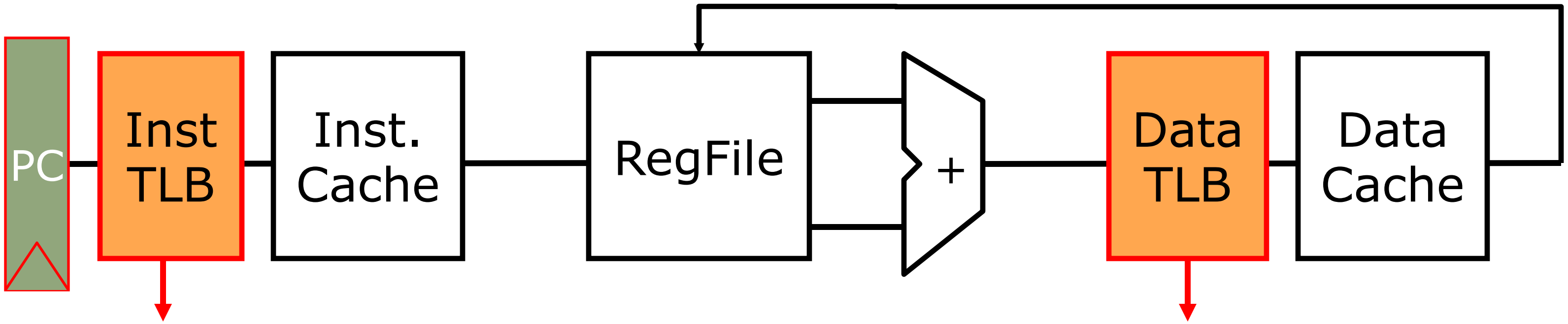

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Protection violation?

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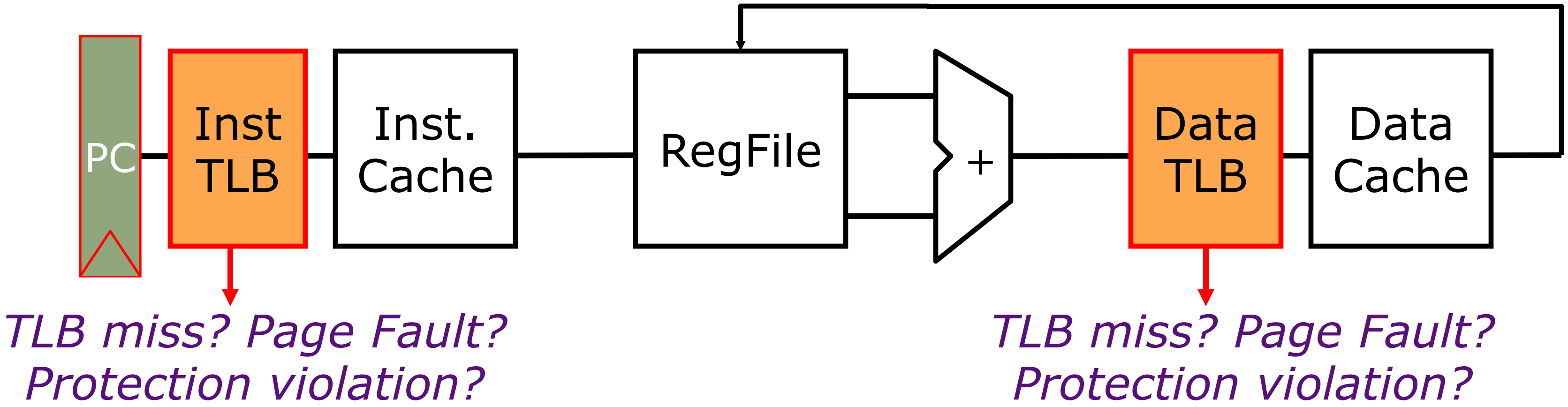

- Software handlers need a *restartable* exception on page fault or protection violation
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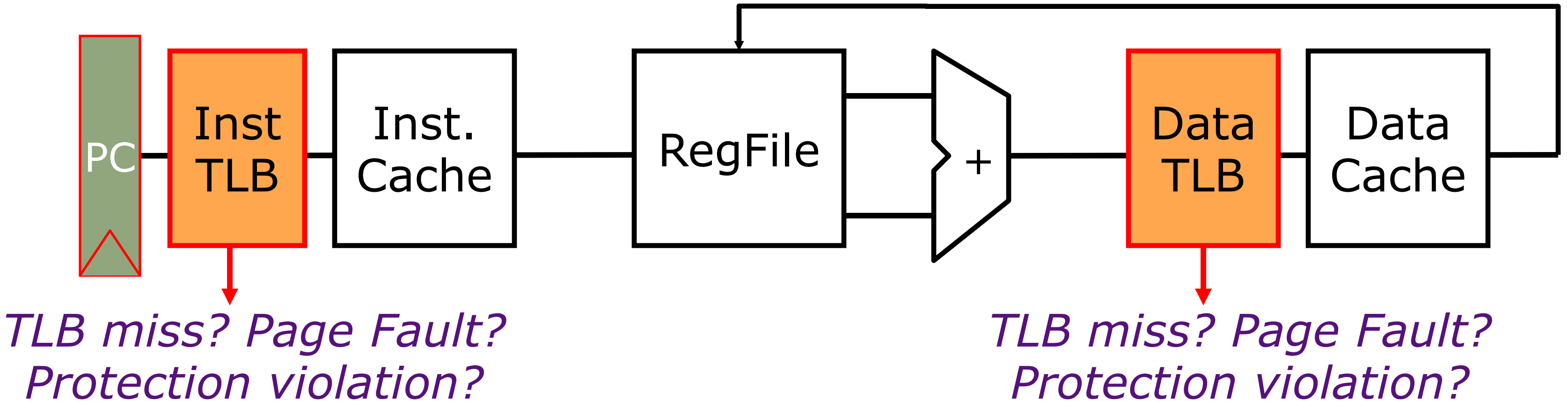

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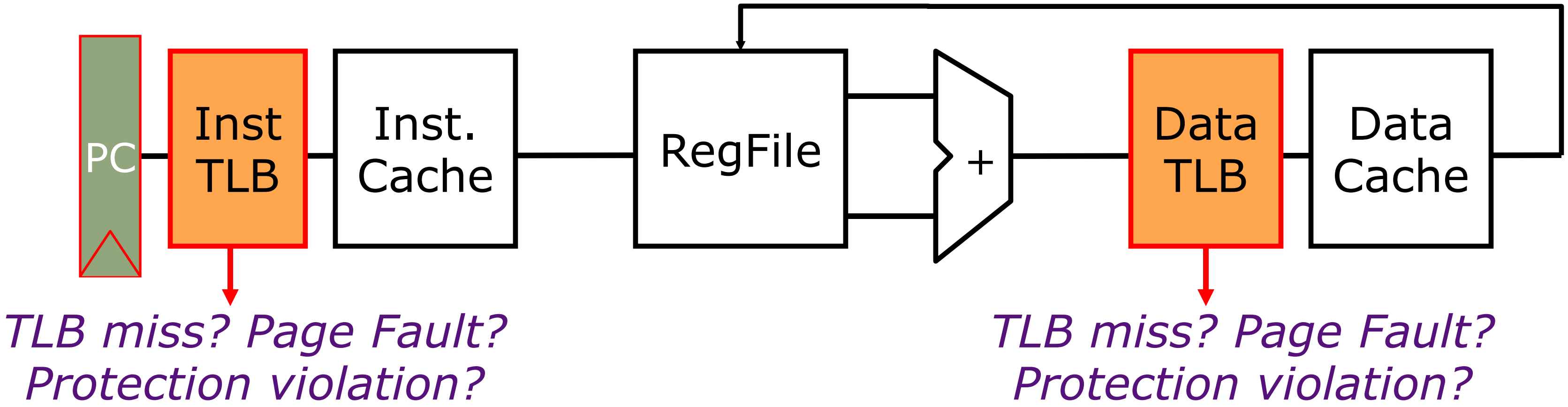

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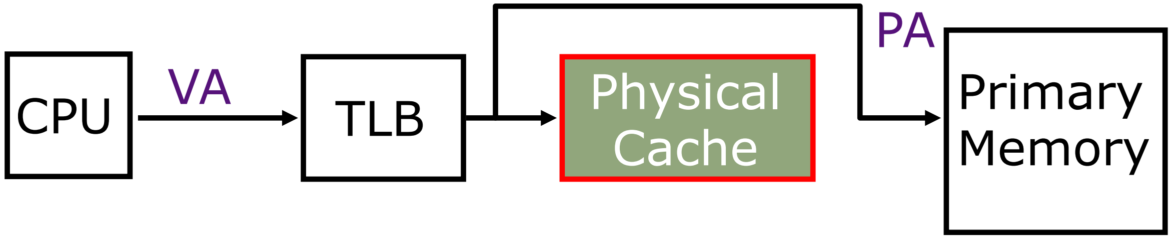
- Need mechanisms to cope with the additional latency of TLB:
  - slow down the clock
  - pipeline the TLB and cache access
  - virtual-address caches
  - parallel TLB/cache access

Virtual-Address Caches



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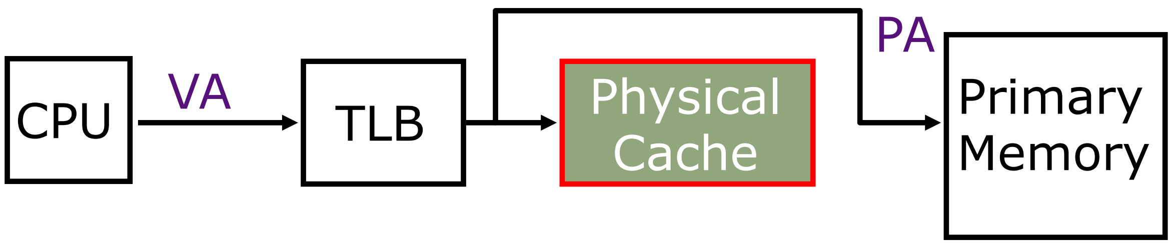

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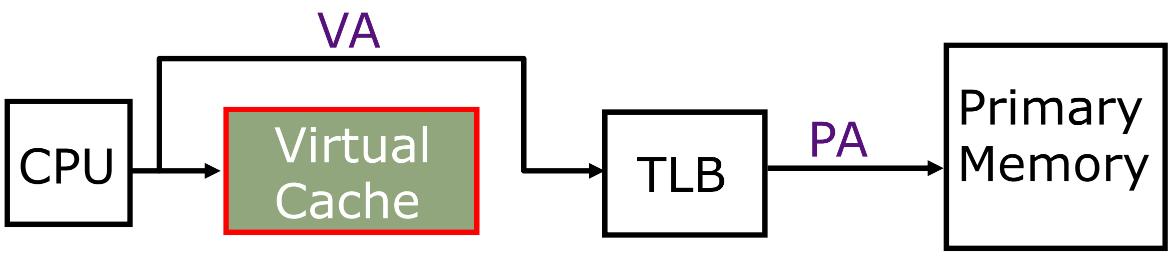

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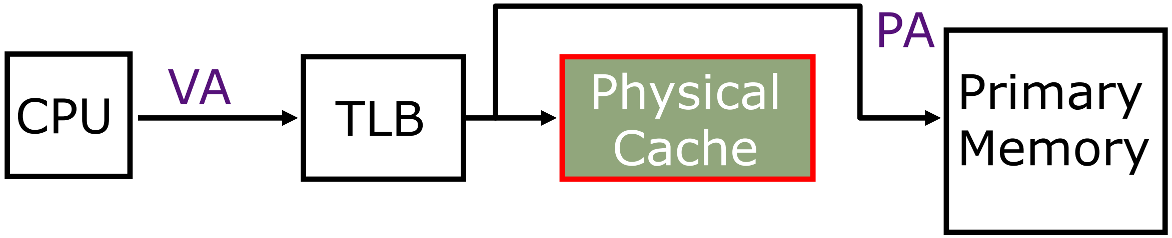

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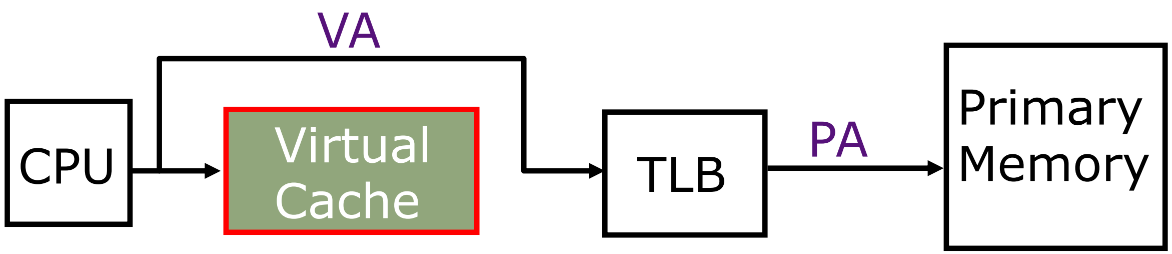

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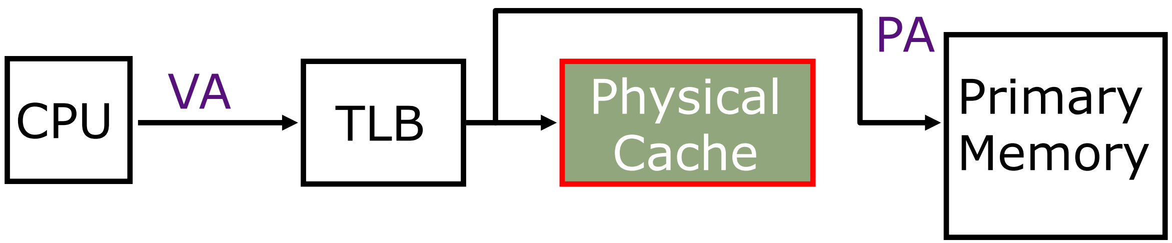

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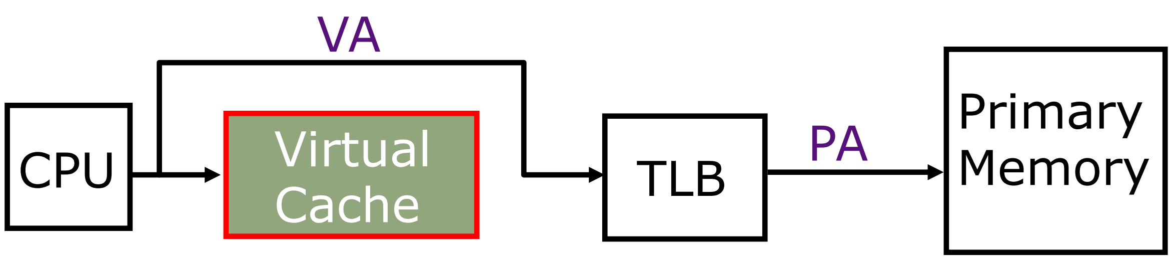

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- one-step process in case of a hit (+)

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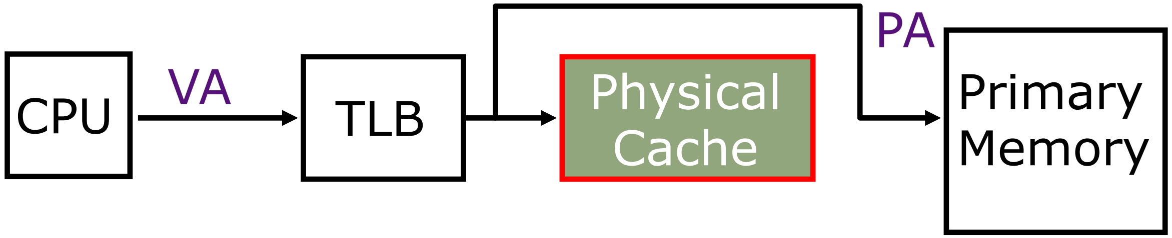

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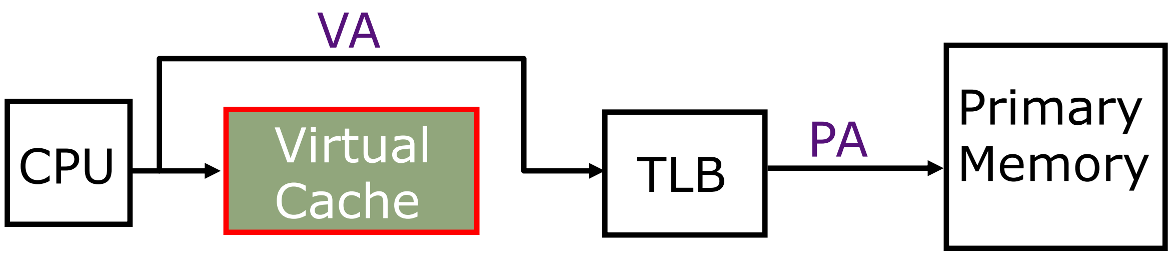

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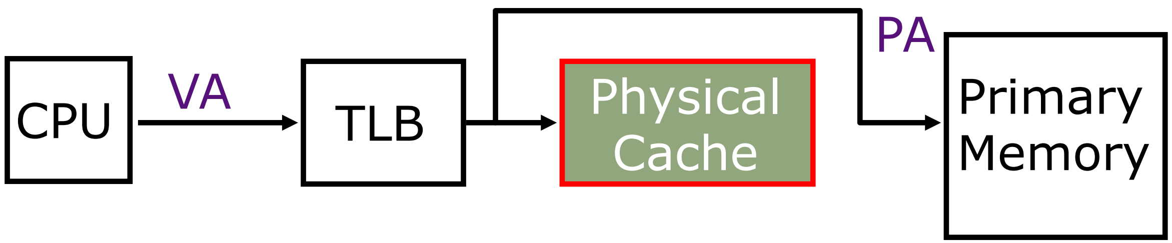

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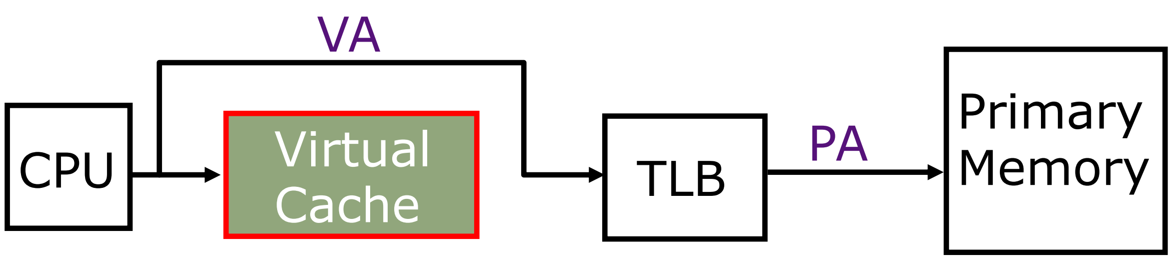

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- one-step process in case of a hit (+)
- cache needs to be flushed on a context switch unless address space identifiers (ASIDs) included in tags (-)
- *aliasing problems* due to the sharing of pages (-)

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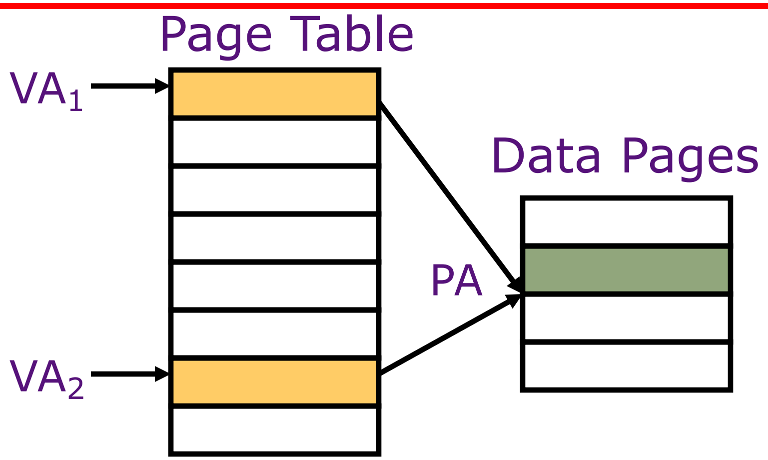

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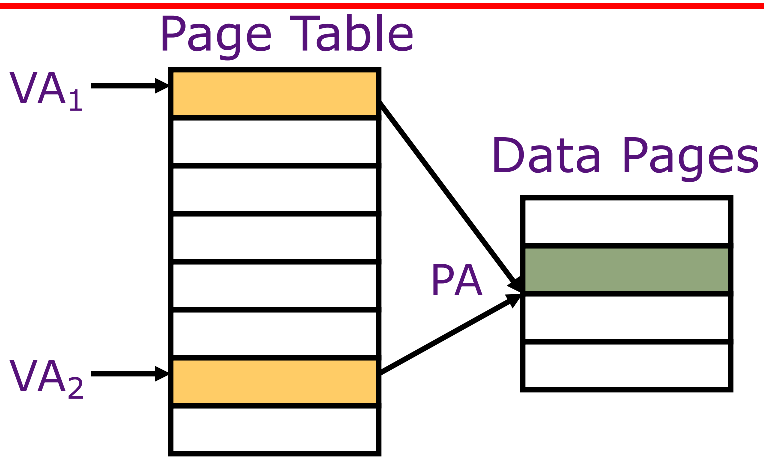

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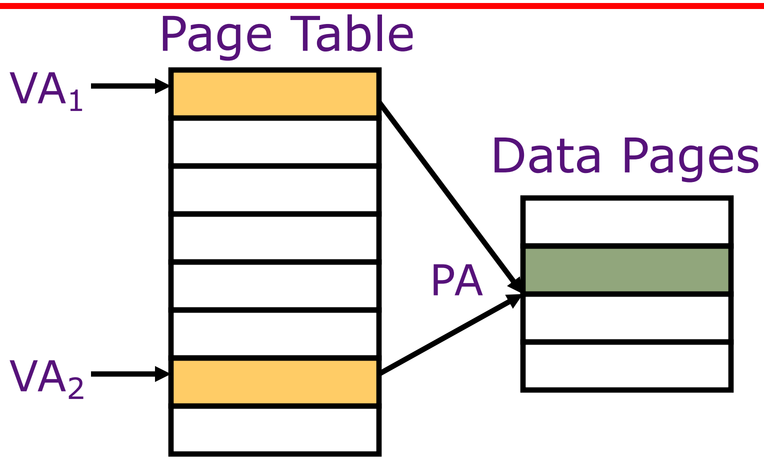

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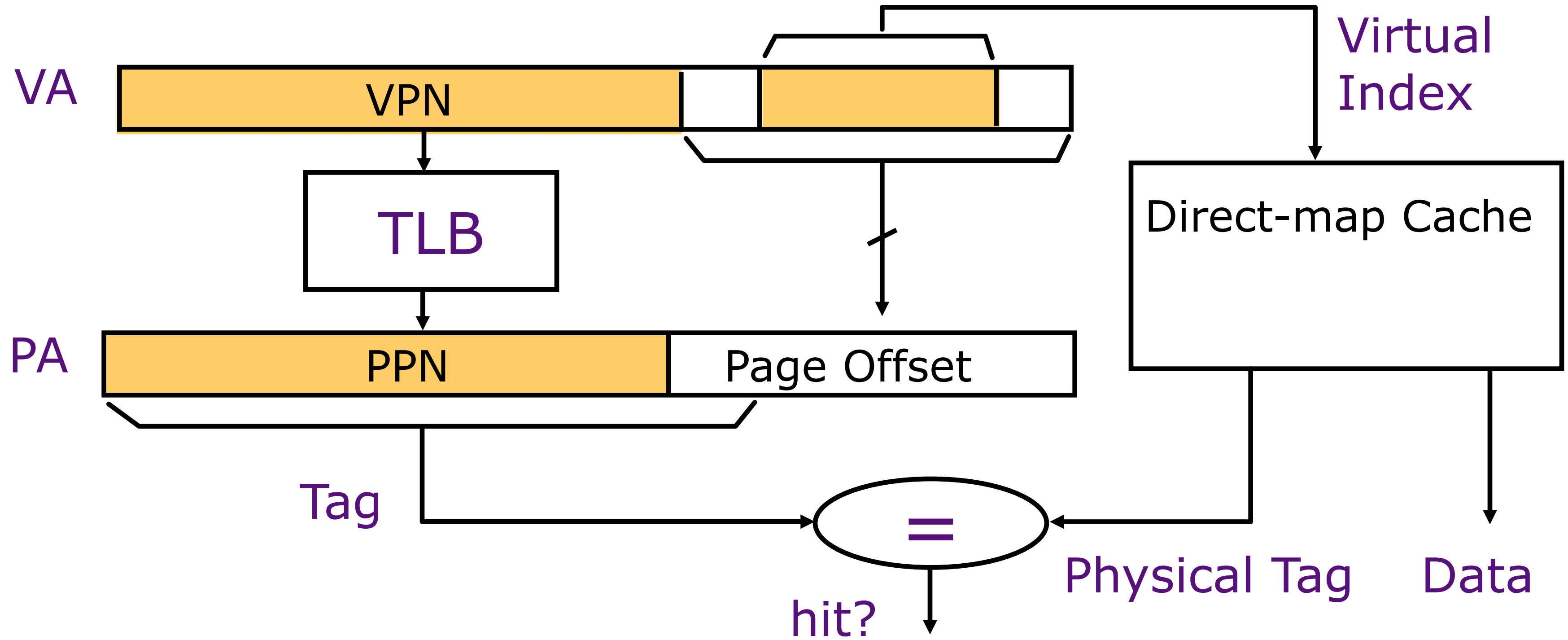
General Solution: *Disallow aliases to coexist in cache*

Software (i.e., OS) solution for direct-mapped cache

- VAs of shared pages must agree in cache index bits; this ensures all VAs accessing same PA will conflict in direct-mapped cache (early SPARCs)

Concurrent Access to TLB & Cache



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Tag comparison is made after both accesses are completed

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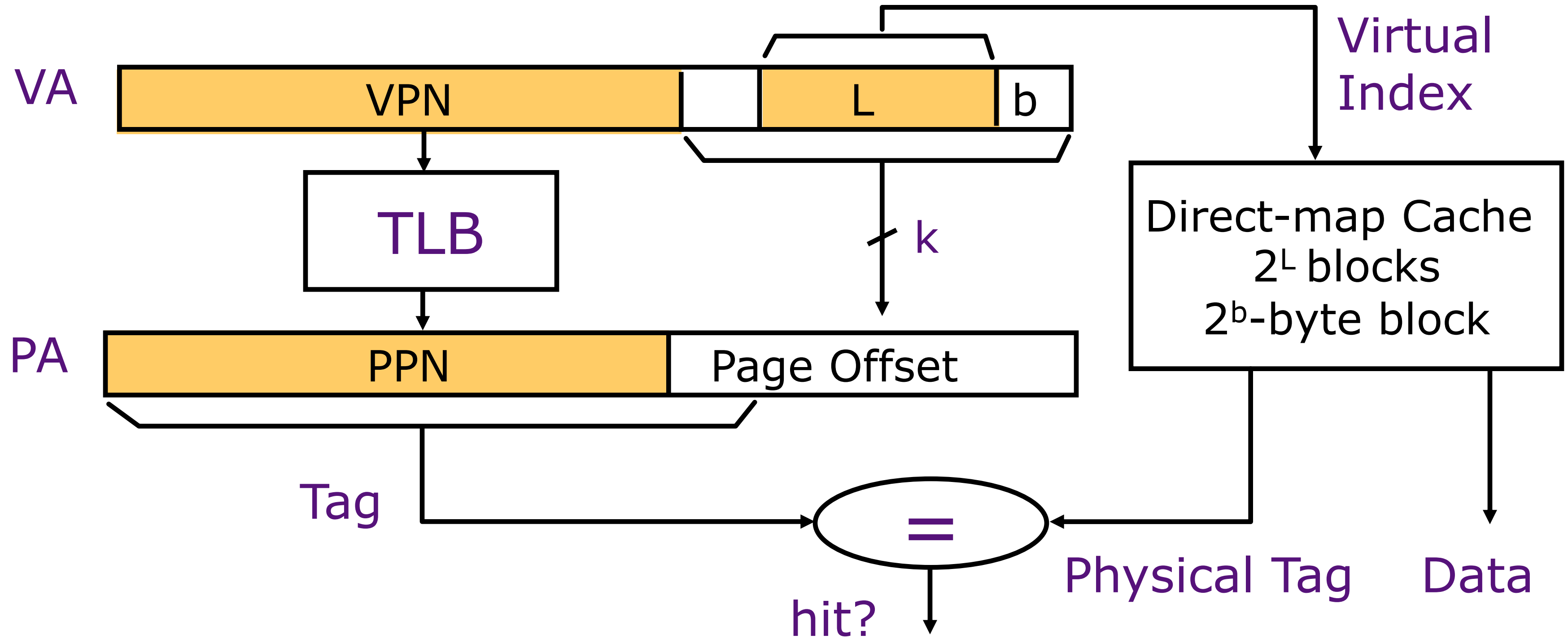

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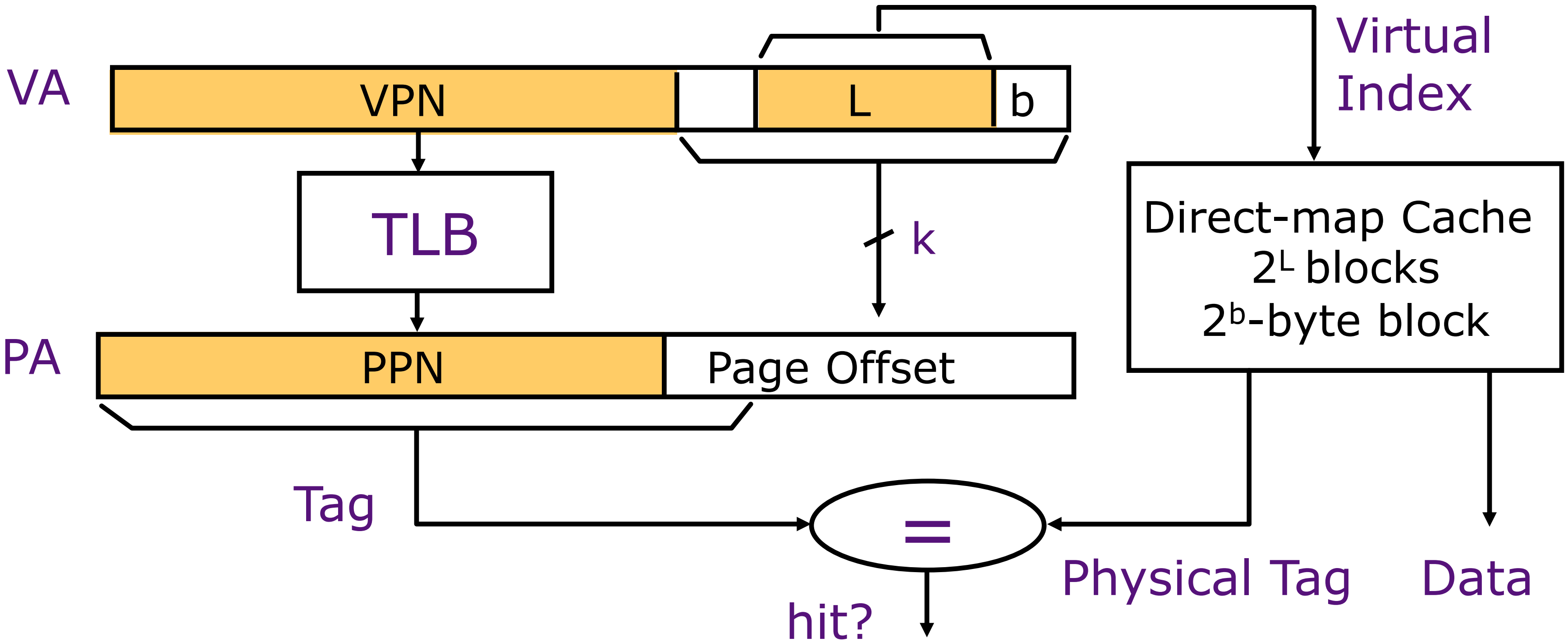

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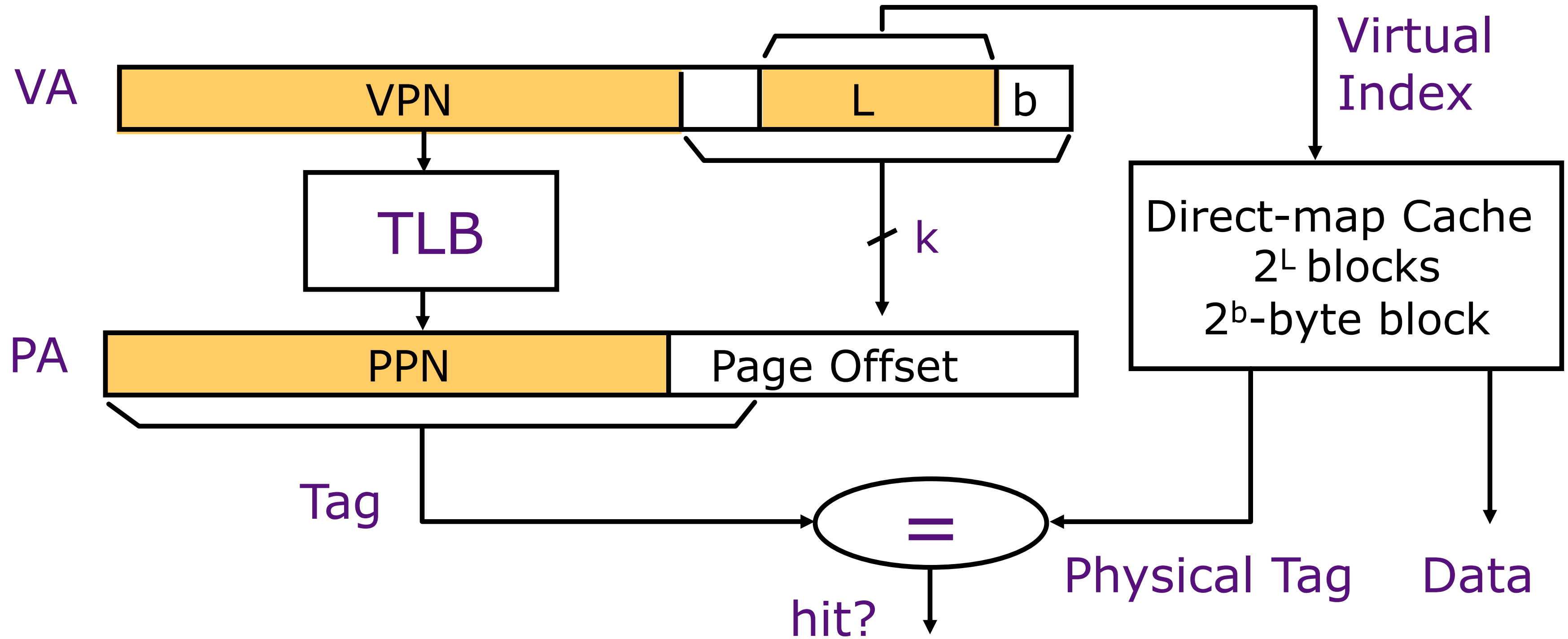

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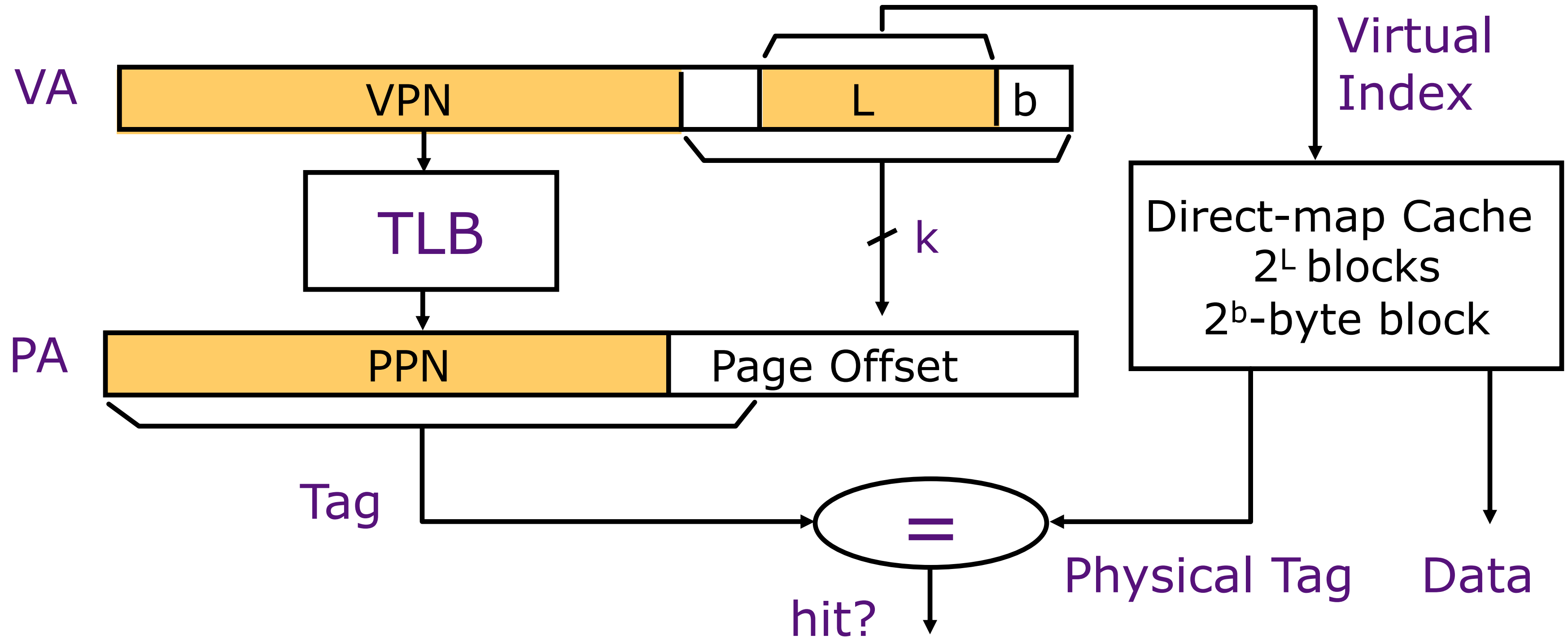

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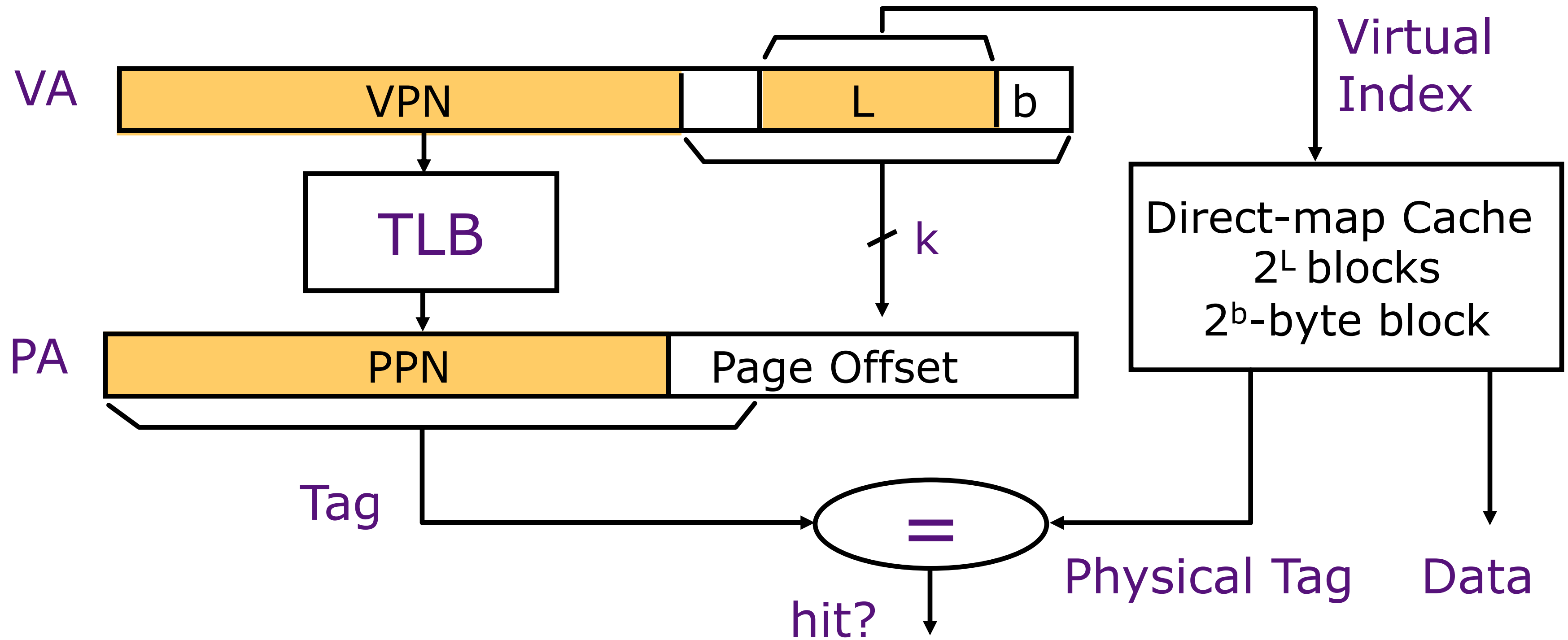

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Concurrent Access to TLB & Large L1

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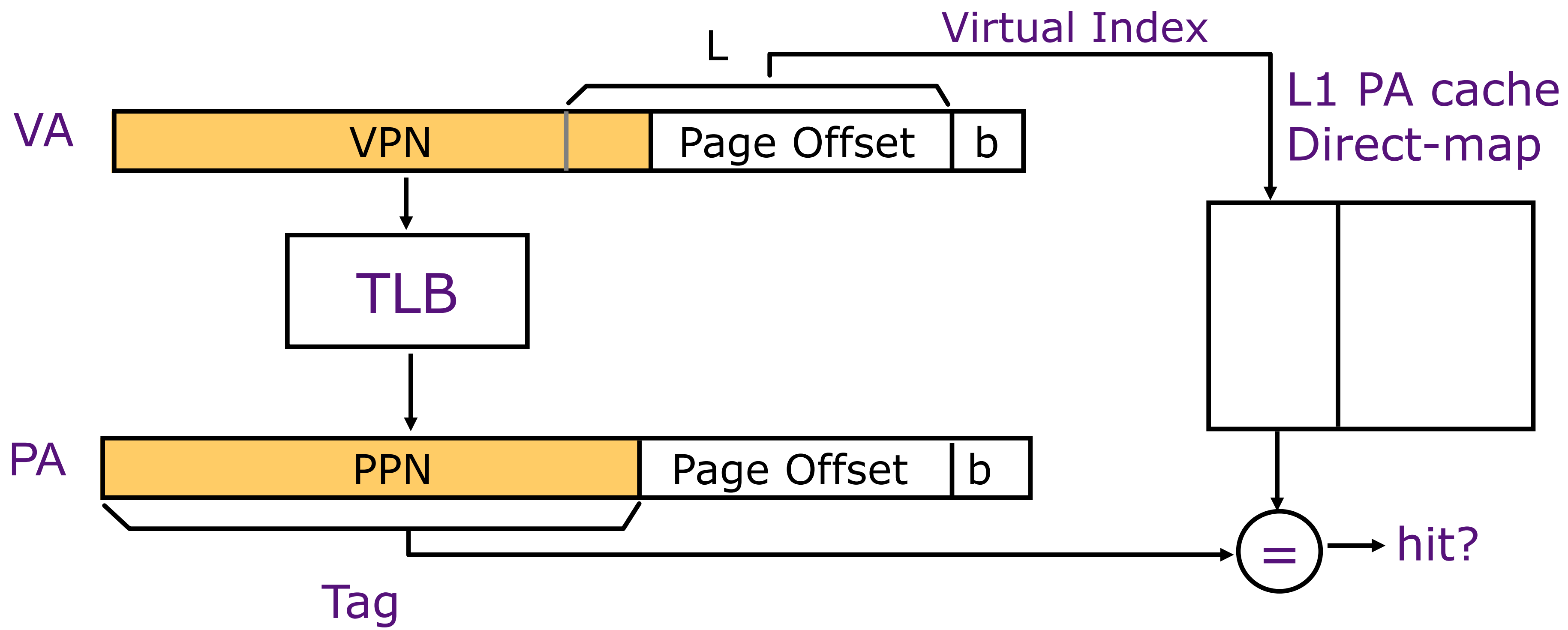

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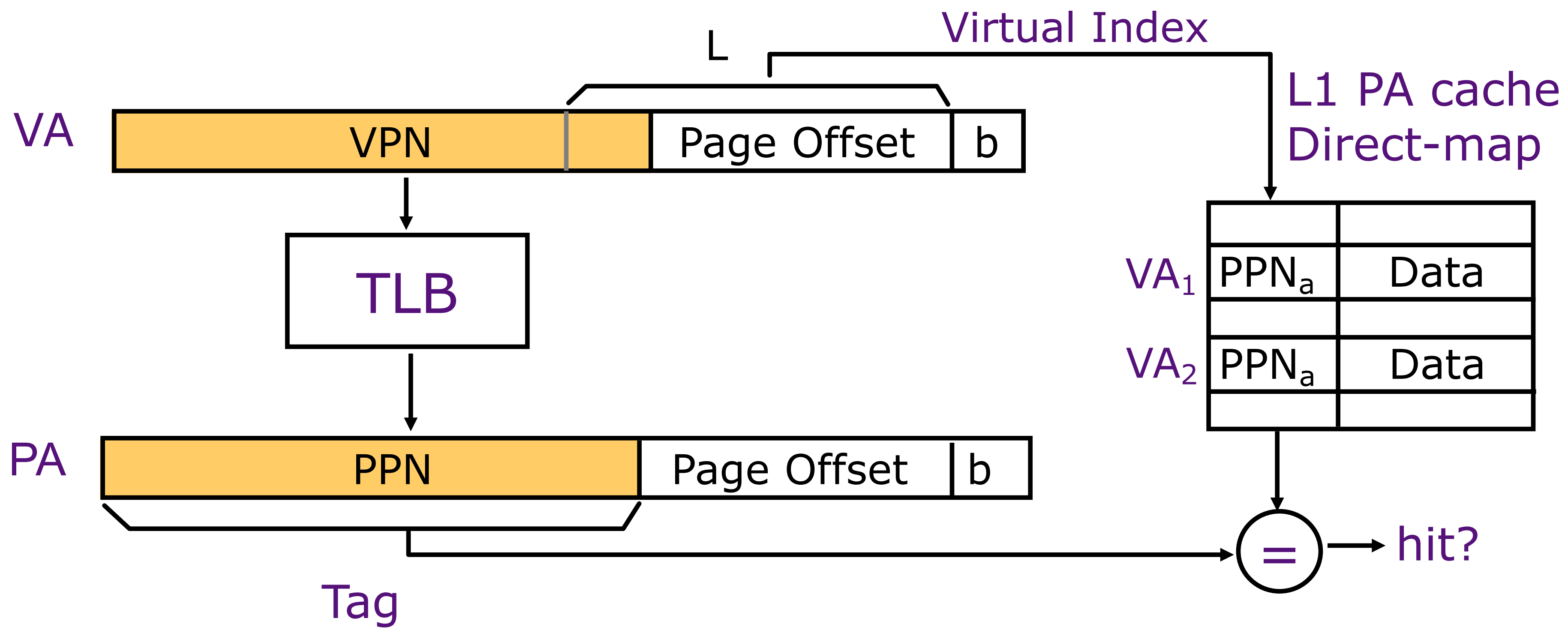

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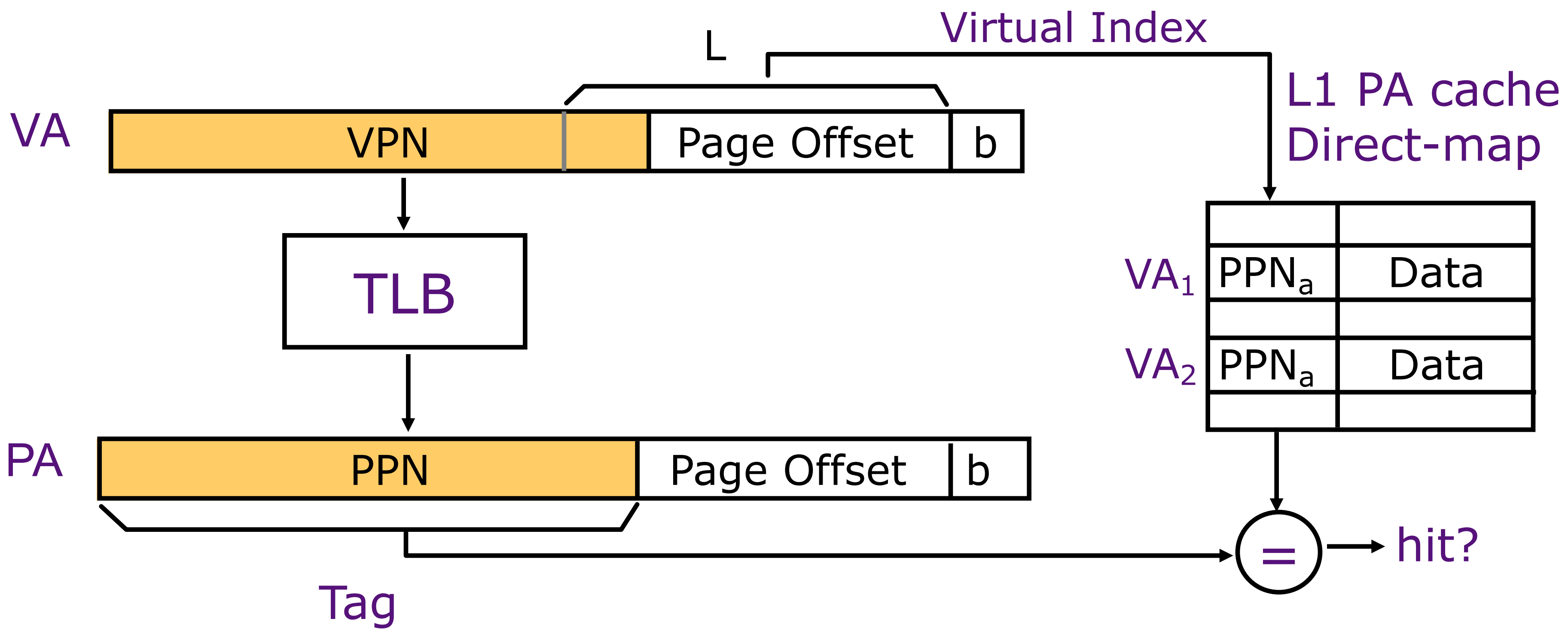

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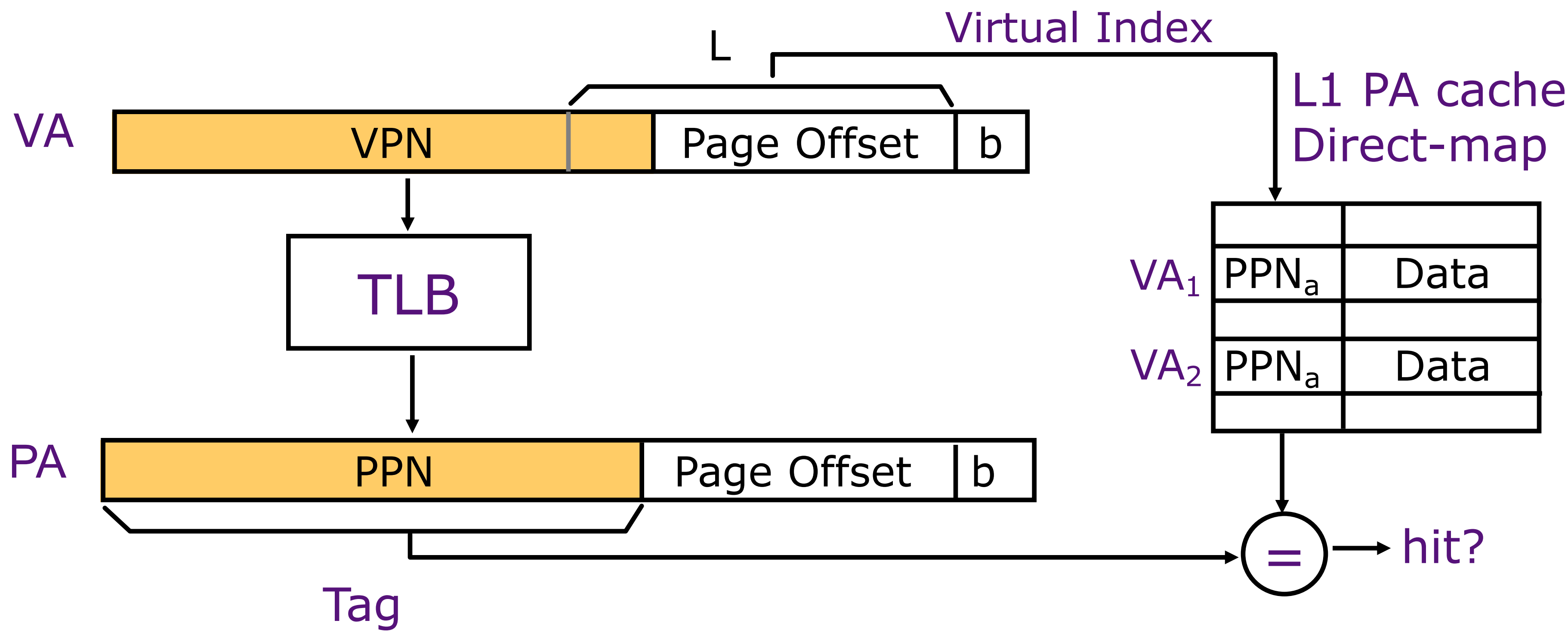
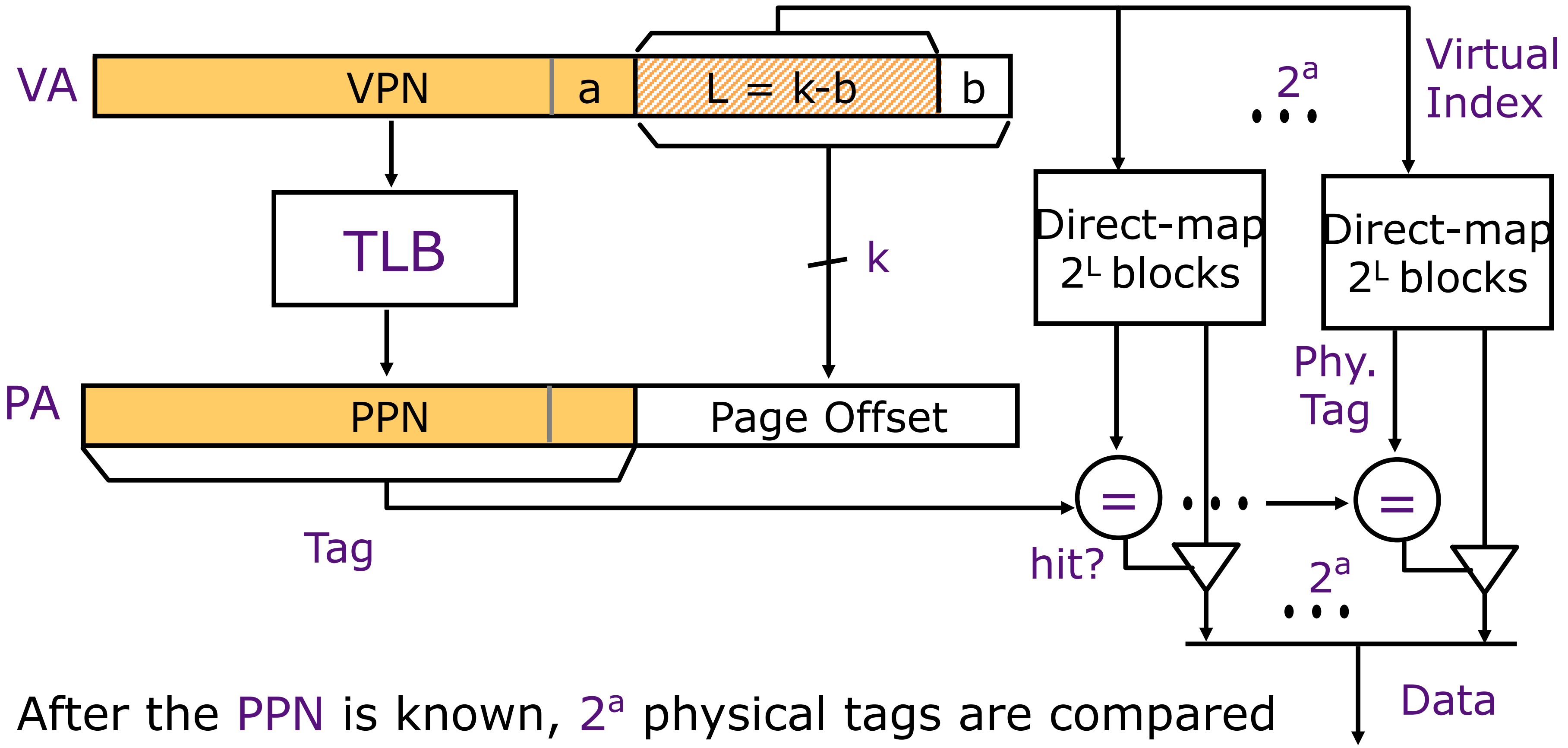


Can VA_1 *and* VA_2 *both map to PA?* Yes

Virtual-Index Physical-Tag Caches:
Associative Organization



After the PPN is known, 2^a physical tags are compared

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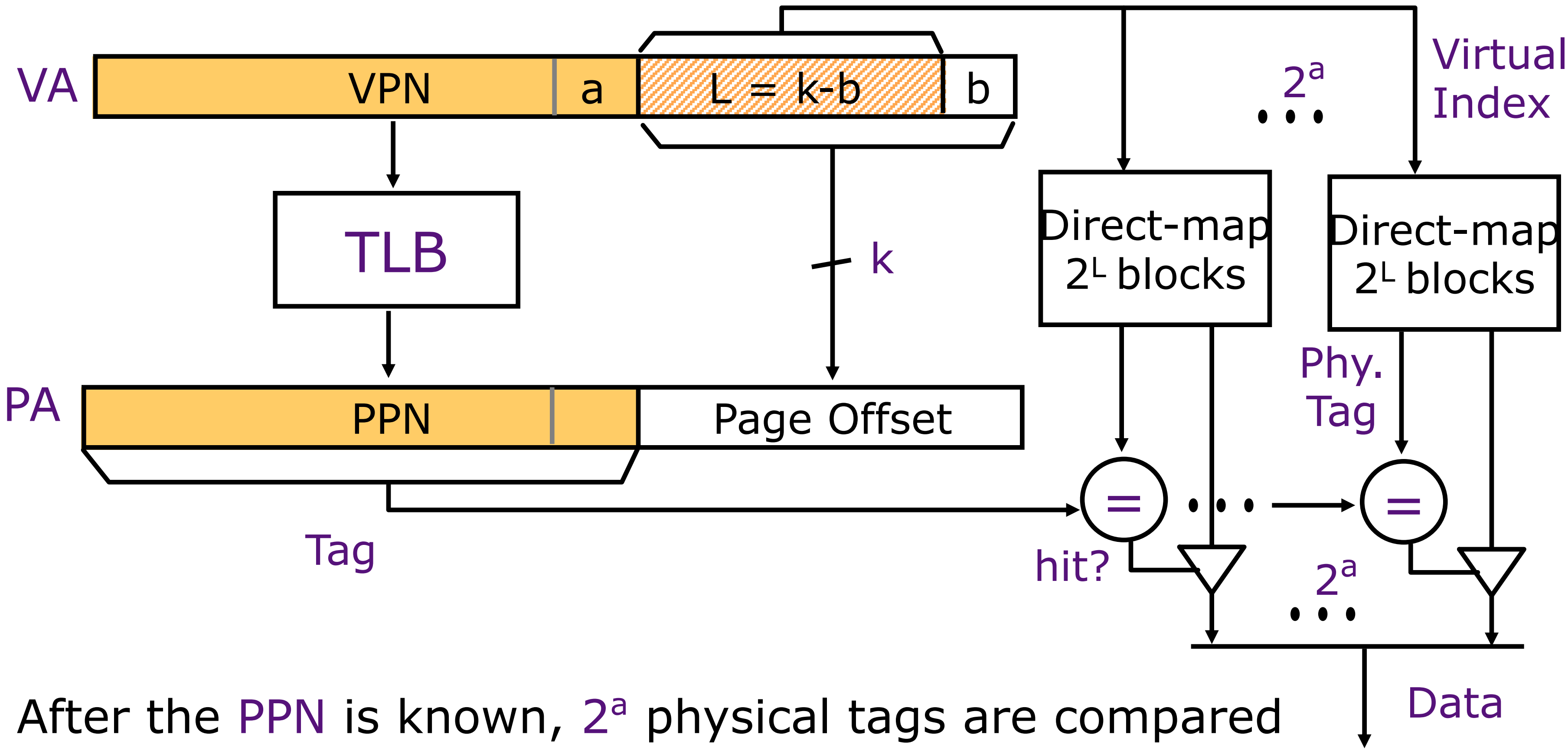

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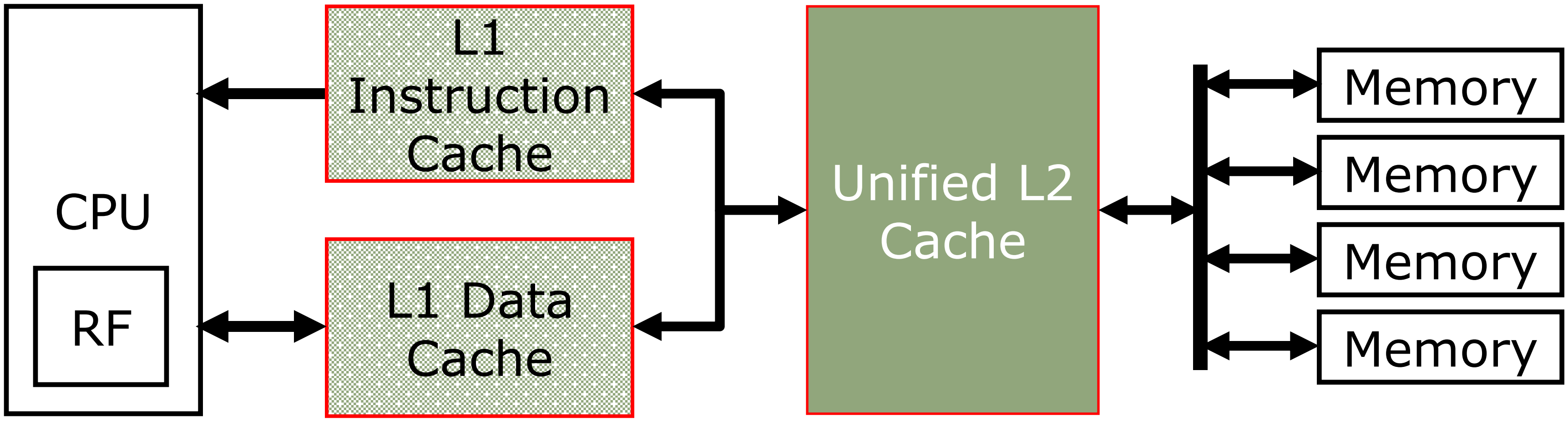
Is this scheme realistic for larger caches?

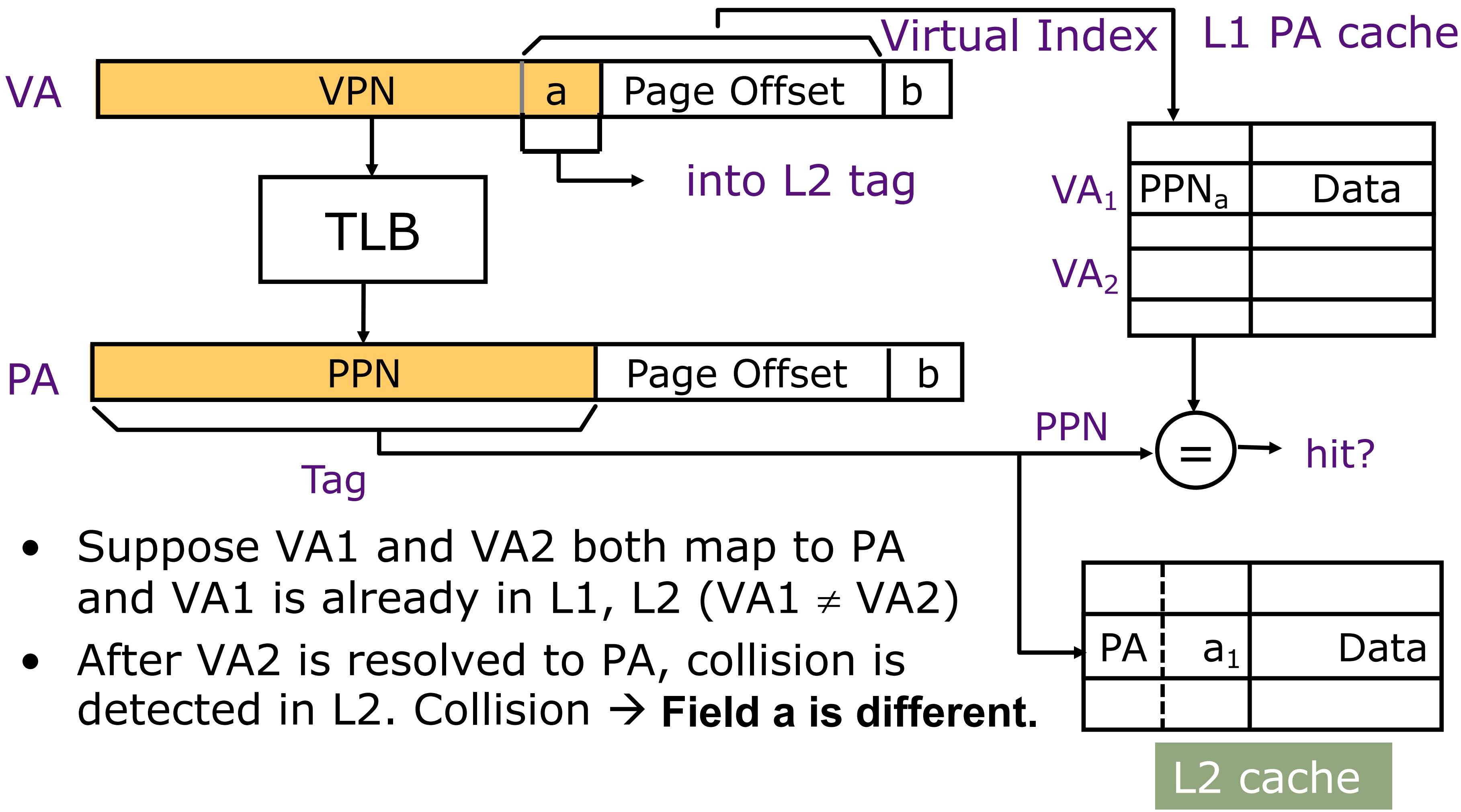
A solution via Second-Level Cache



Usually a common L2 cache backs up both Instruction and Data L1 caches

L2 is "inclusive" of both Instruction and Data caches

Anti-Aliasing Using L2: *MIPS R10000*



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- After VA2 is resolved to PA, collision is detected in L2. Collision → **Field a is different.**

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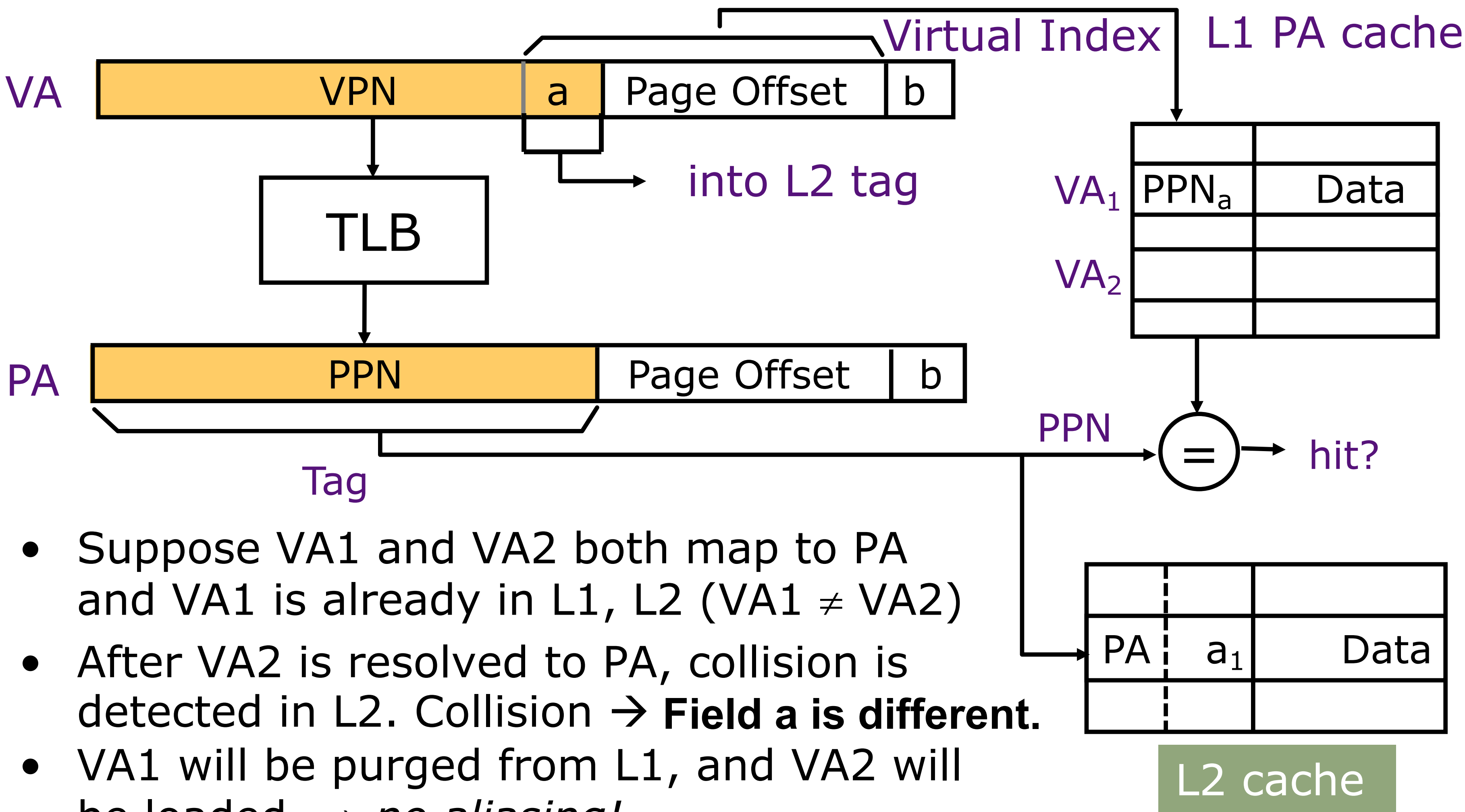

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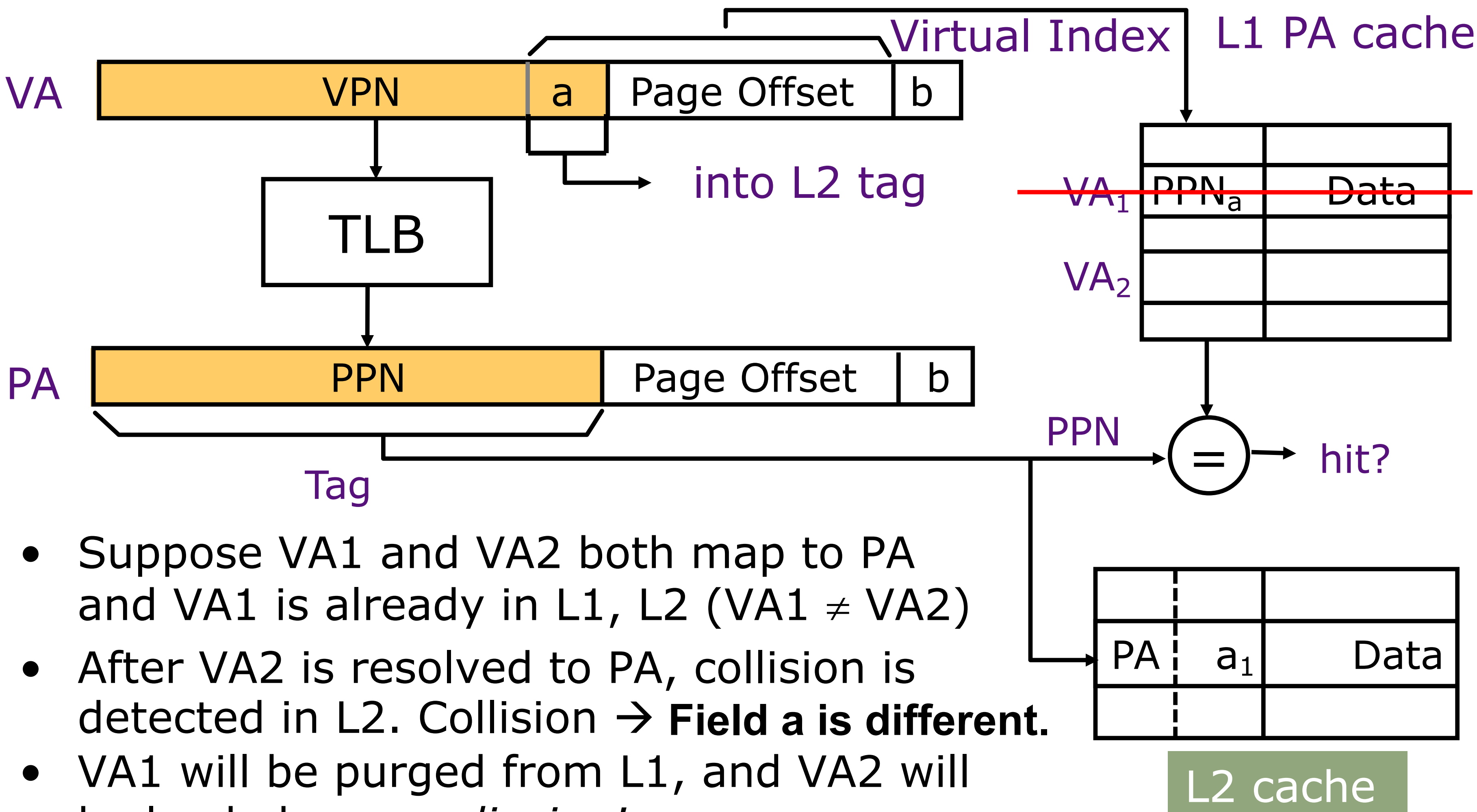

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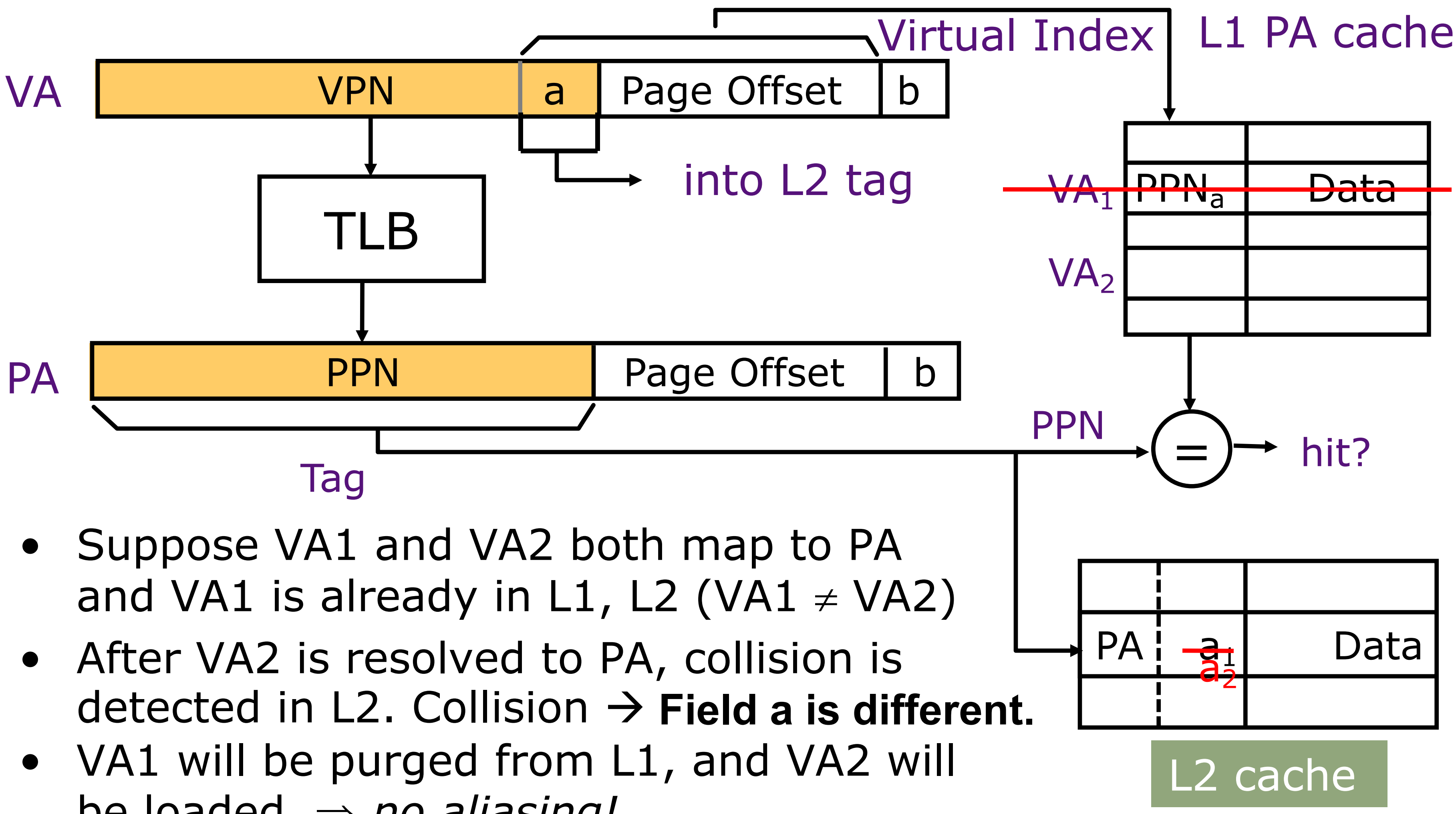

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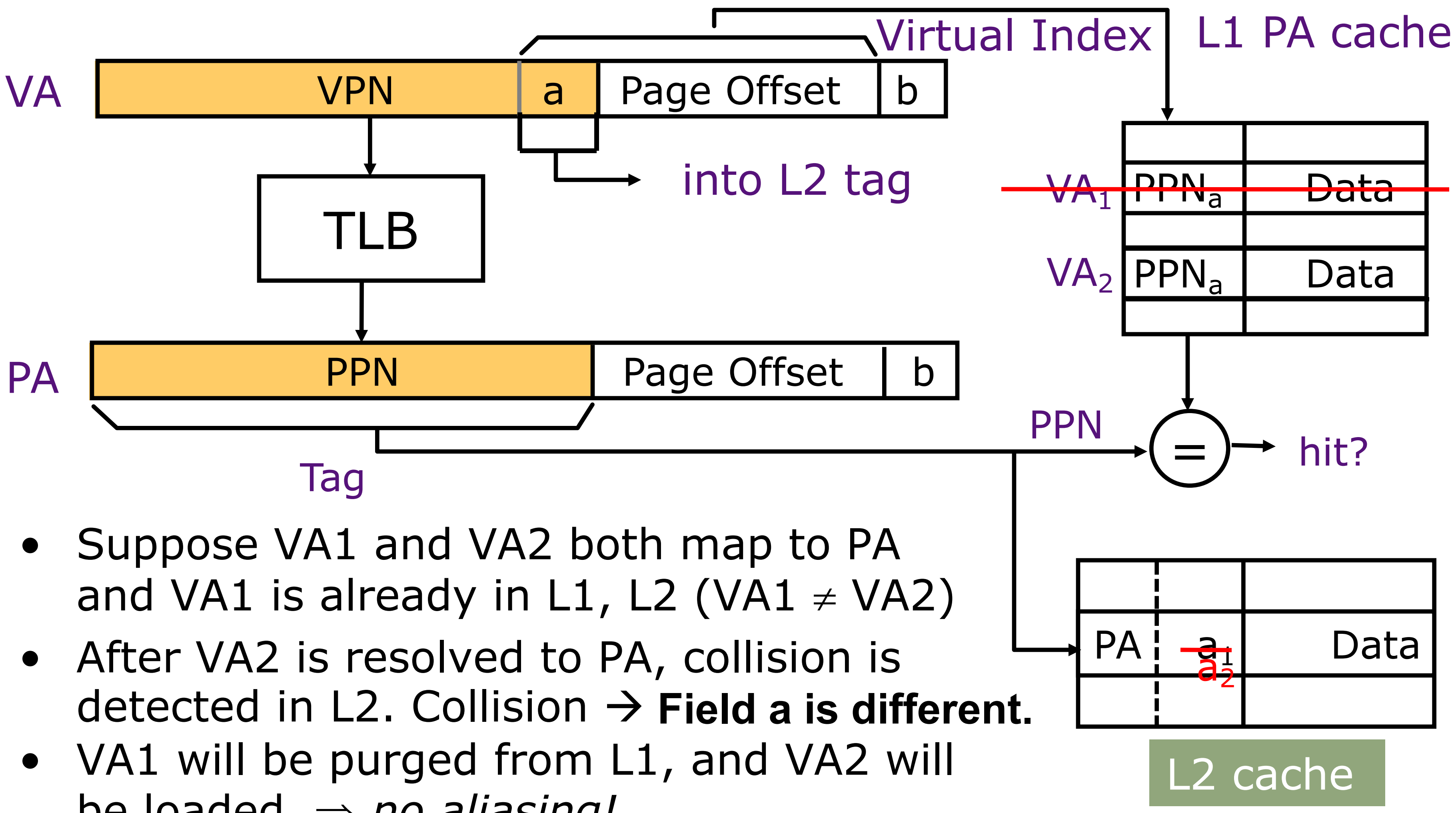

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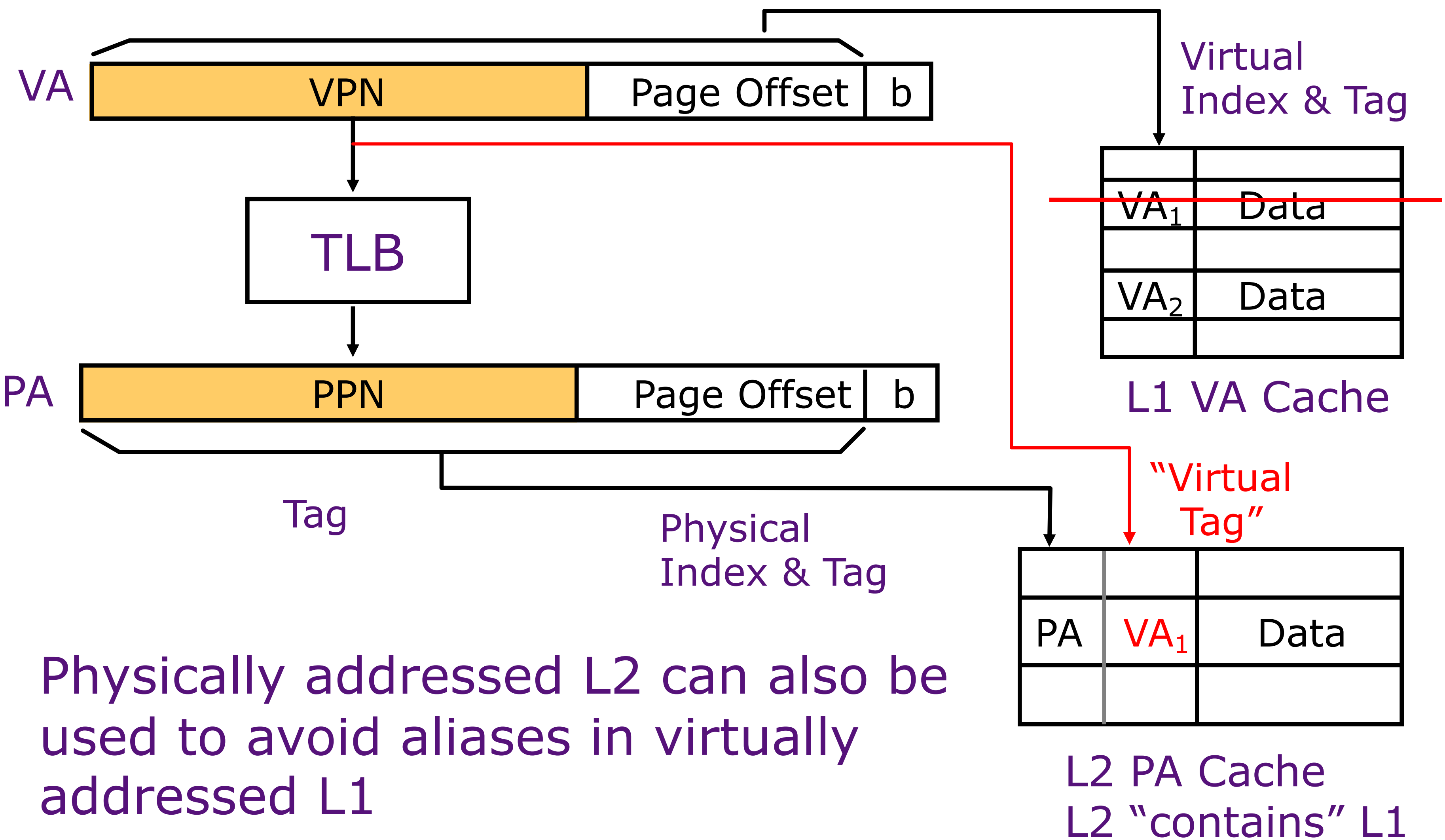
Virtually Addressed L1:
Anti-Aliasing using L2



Physically addressed L2 can also be used to avoid aliases in virtually addressed L1

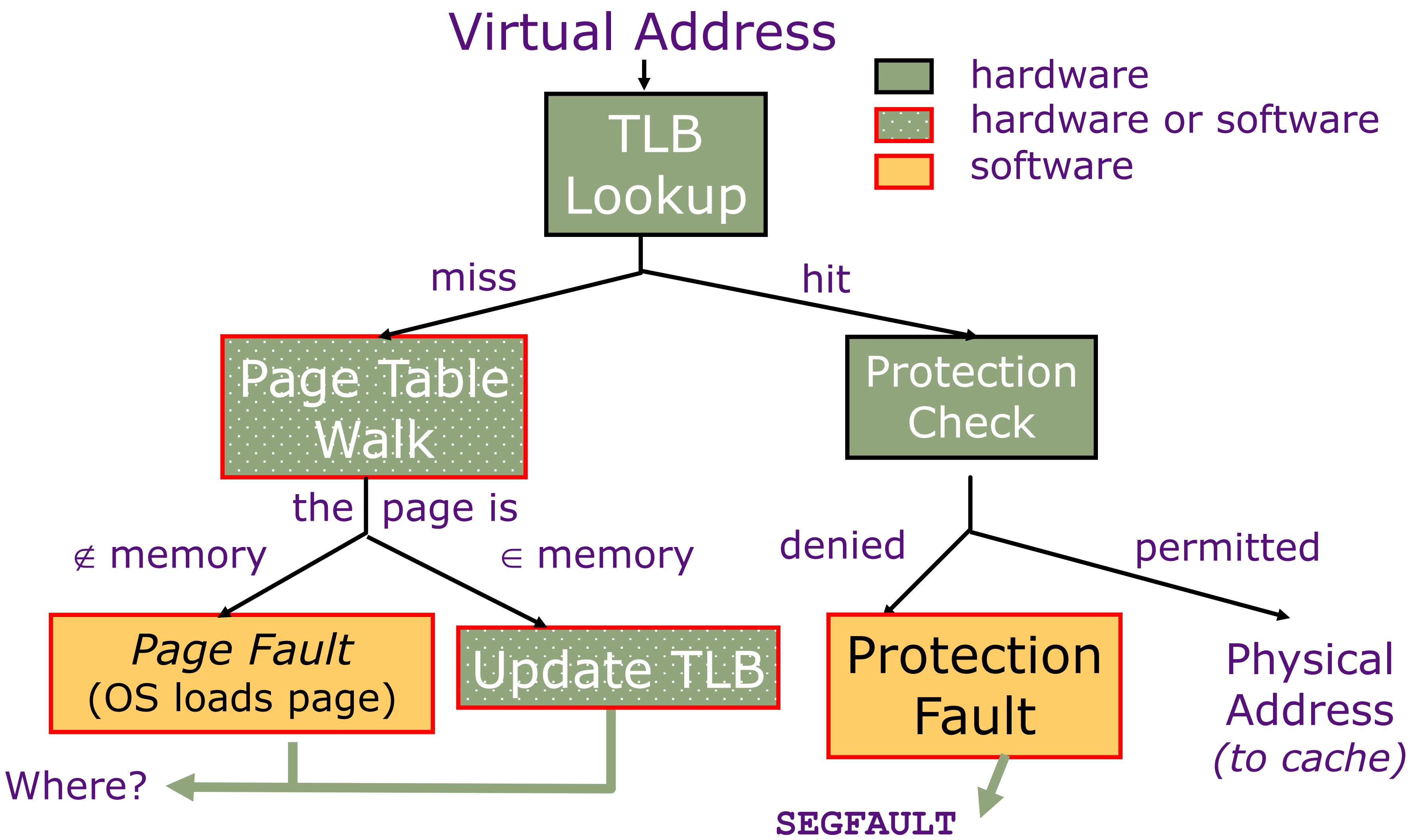
Topics

- Speeding up the common case:
  - TLB & Cache organization

- Interrupts

- Modern Usage

Address Translation: *putting it all together*



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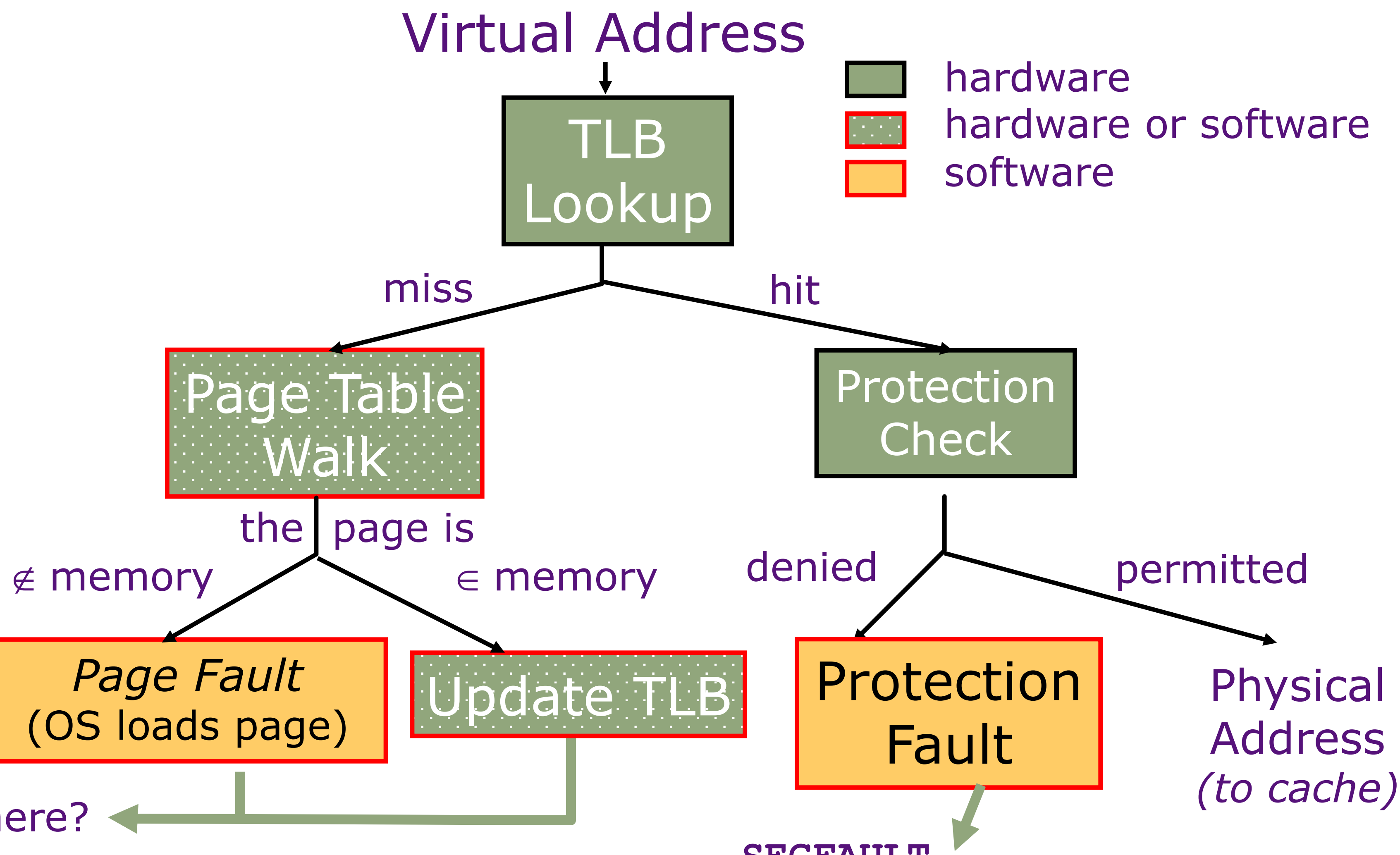
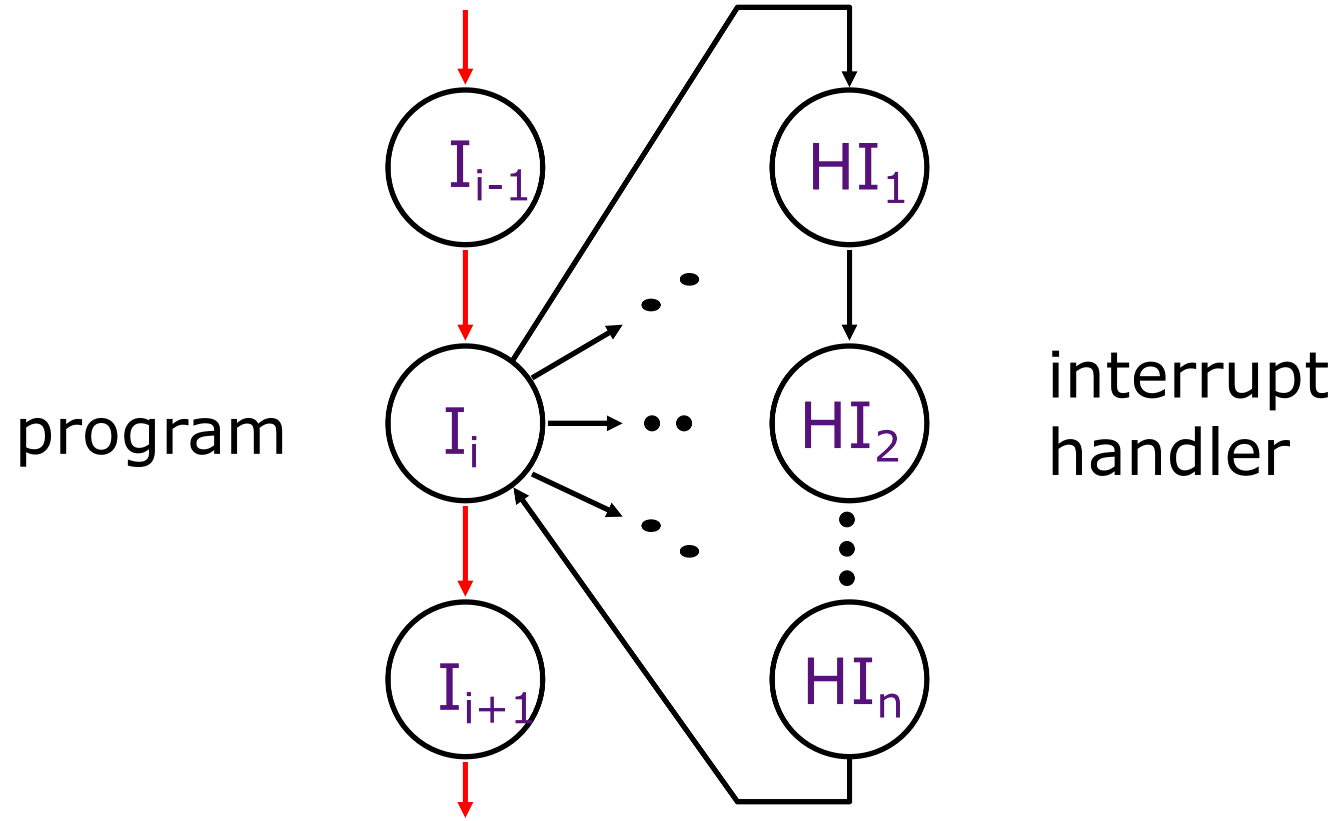


Need a restartable exception

Interrupts:
altering the normal flow of control



An *external or internal event* that needs to be processed by another (system) program. The event is usually unexpected or rare from program's point of view.

Causes of Interrupts

Interrupt: an *event* that requests the attention of the processor

- Asynchronous: an *external event*
  - input/output device service-request
  - timer expiration
  - power disruptions, hardware failure
- Synchronous: an *internal event (a.k.a. exception)*
  - undefined opcode, privileged instruction
  - arithmetic overflow, FPU exception
  - misaligned memory access
  - *virtual memory exceptions:* page faults, TLB misses, protection violations
  - *traps:* system calls, e.g., jumps into kernel

Asynchronous Interrupts

Invoking the interrupt handler

- An I/O device requests attention by asserting one of the *prioritized interrupt request lines*
- When the processor decides to process interrupt
  - It stops the current program at instruction I_i, completing all the instructions up to I_{i-1} (*precise interrupt)*
  - It saves the PC of instruction I_i in a special register (EPC)
  - It disables interrupts and transfers control to a designated interrupt handler running in kernel mode

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Interrupt Handler

- Saves EPC before enabling interrupts to allow nested interrupts $\Rightarrow$
  - need an instruction to move EPC into GPRs
  - need a way to mask further interrupts at least until EPC can be saved
- Needs to read a *status register* that indicates the cause of the interrupt
- Uses a special indirect jump instruction RFE (*return-from-exception*) that
  - enables interrupts
  - restores the processor to the user mode
  - restores hardware status and control state

Synchronous Interrupts

- A synchronous interrupt (exception) is caused by a *particular instruction*
- In general, the instruction cannot be completed and needs to be *restarted* after the exception has been handled
  - With pipelining, requires undoing the effect of one or more partially executed instructions

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  - With pipelining, requires undoing the effect of one or more partially executed instructions
- In case of a trap (system call), the instruction is considered to have been completed
  - A special jump instruction involving a change to privileged kernel mode

Page Fault Handler

- When the referenced page is not in DRAM:
  - The missing page is located (or created)
  - It is brought in from disk, and page table is updated

    Another job may be run on the CPU while the first job waits for the requested page to be read from disk
  - If no free pages are left, a page is swapped out

    Pseudo-LRU replacement policy
- Since it takes a long time to transfer a page (msecs), page faults are handled completely in software by the OS
  - Untranslated addressing mode is essential to allow kernel to access page tables

Topics

- Speeding up the common case:
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Virtual Memory Use Today - 1

- Desktop/server/cellphone processors have full demand-paged virtual memory
  - Portability between machines with different memory sizes
  - Protection between multiple users or multiple tasks
  - Share small physical memory among active tasks
  - Simplifies implementation of some OS features

- Vector supercomputers and GPUs have translation and protection but not demand paging
  (Older Crays: base&bound, Japanese & Cray X1: pages)
  - Don’t waste expensive processor time thrashing to disk (make jobs fit in memory)
  - Mostly run in batch mode (run set of jobs that fits in memory)
  - Difficult to implement restartable vector instructions

Virtual Memory Use Today - 2

- Most embedded processors and DSPs provide physical addressing only
  - Can't afford area/speed/power budget for virtual memory support
  - Often there is no secondary storage to swap to!
  - Programs custom-written for particular memory configuration in product
  - Difficult to implement restartable instructions for exposed architectures

Next lecture: Pipelining!