Modern Virtual Memory Systems

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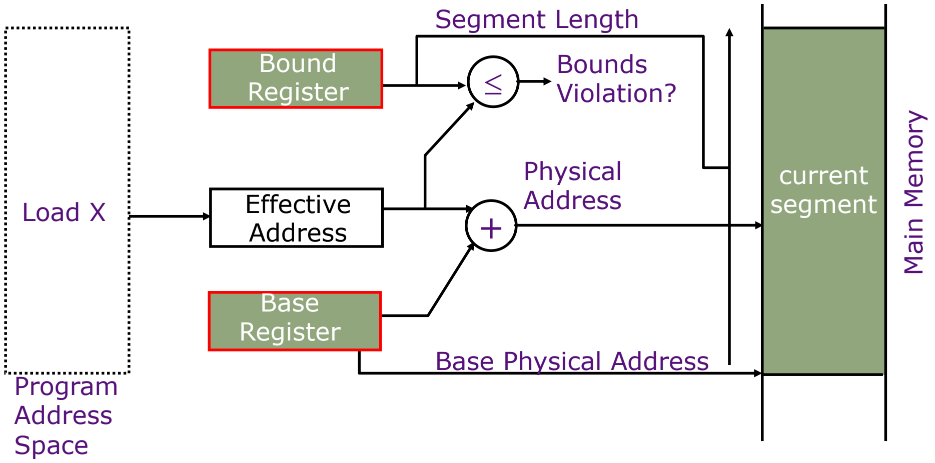
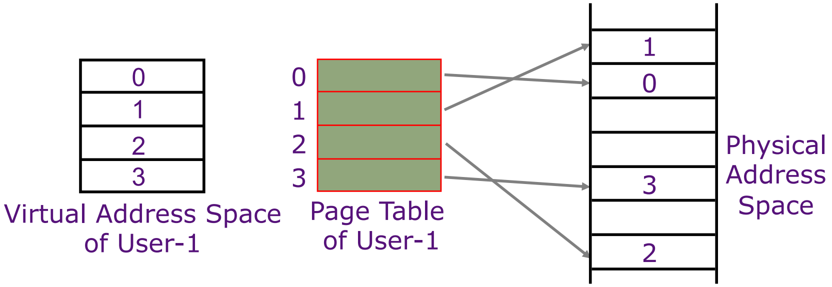
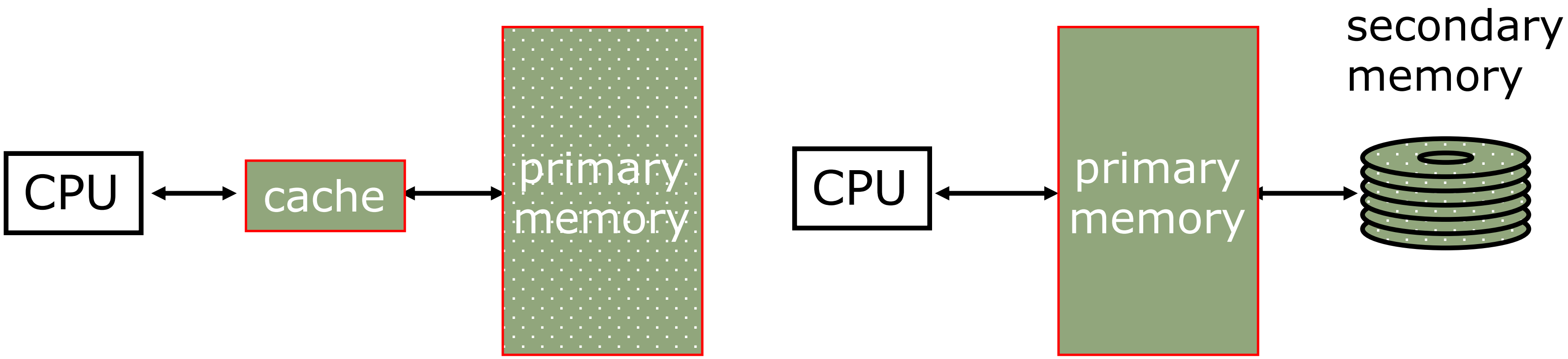
Recap: Evolution of Virtual Memory

- Initial need for multiprogramming
  - Segmentation (Base and bound translation)
- Problem: Fragmentation
  - Paged memory systems
- Problem: Program cannot fit in primary memory
  - Demand paging





Caching vs. Demand Paging



Caching

cache entry
cache block (~32 bytes)
cache miss rate (1% to 20%)
cache hit (~1 cycle)
cache miss (~100 cycles)
a miss is handled
in *hardware*

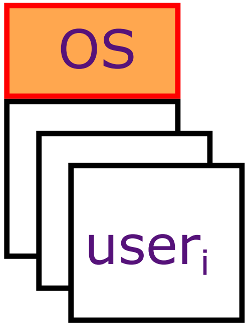
Demand paging

page frame
page (~4K bytes)
page miss rate (<0.001%)
page hit (~100 cycles)
page miss (~5M cycles)
a miss is handled
mostly in *software*

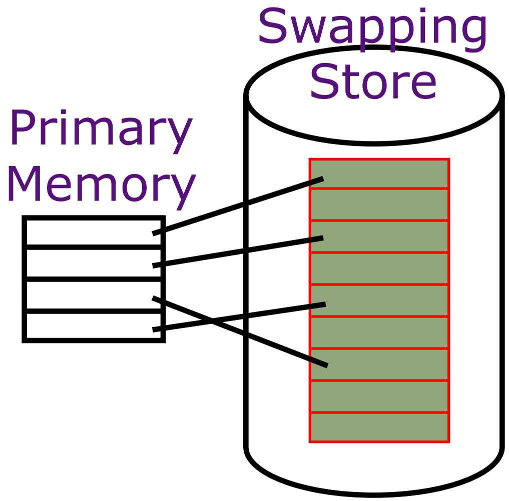
Modern Virtual Memory Systems

Illusion of a large, private, uniform store

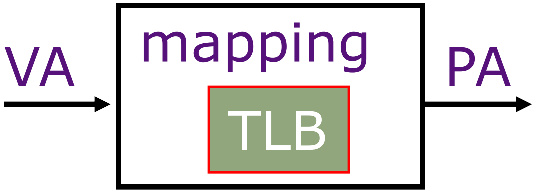
- Protection & Privacy
  - several users, each with their private address space and one or more shared address spaces
  - page table ≡ *memory view* ≡ name space



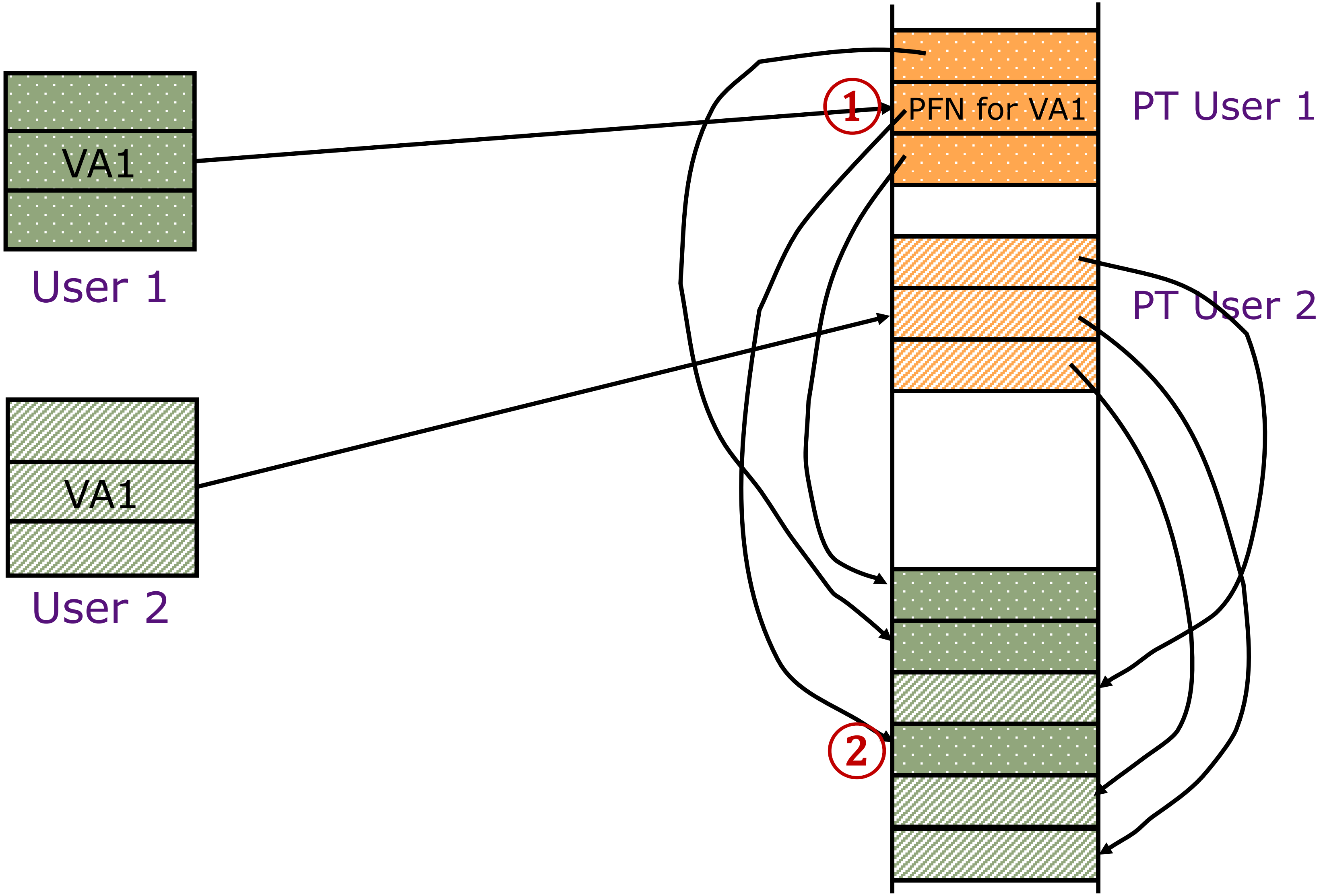
- Demand Paging
  - Provides the ability to run programs larger than the primary memory
  - Hides differences in machine configurations



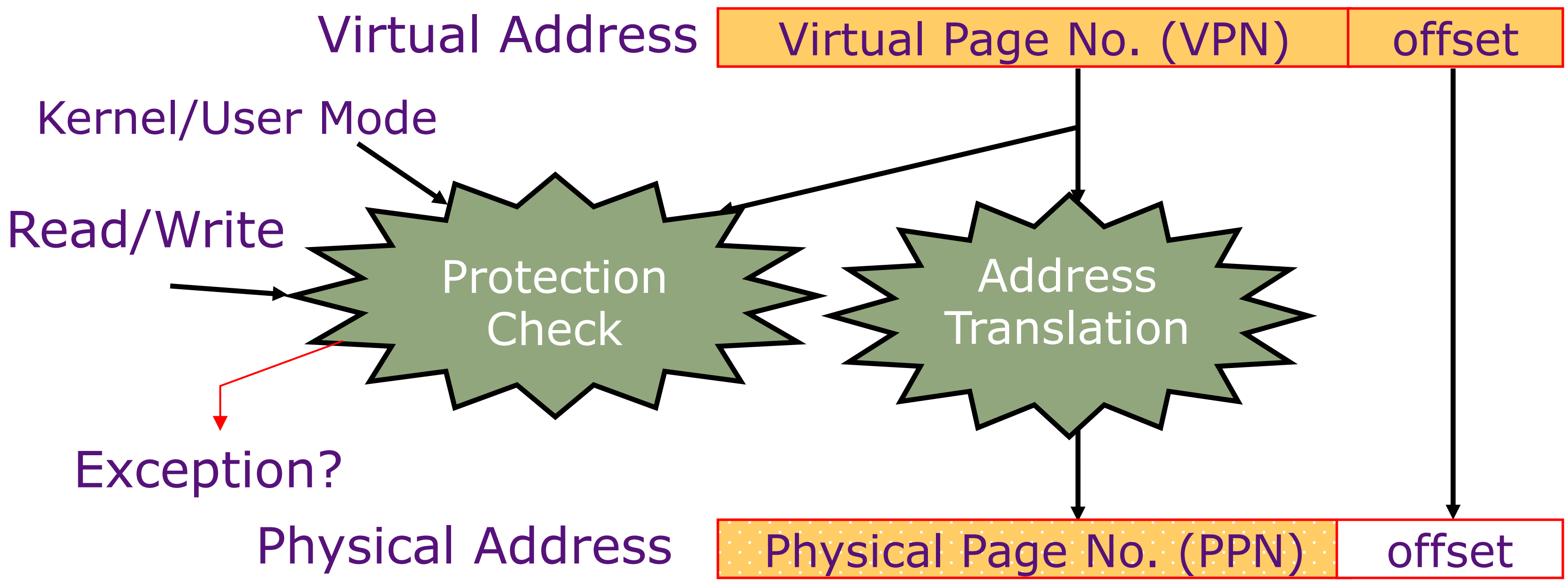
- *The price is address translation on each memory reference*



Reminder: Page Tables are Stored in Physical Memory



Address Translation & Protection

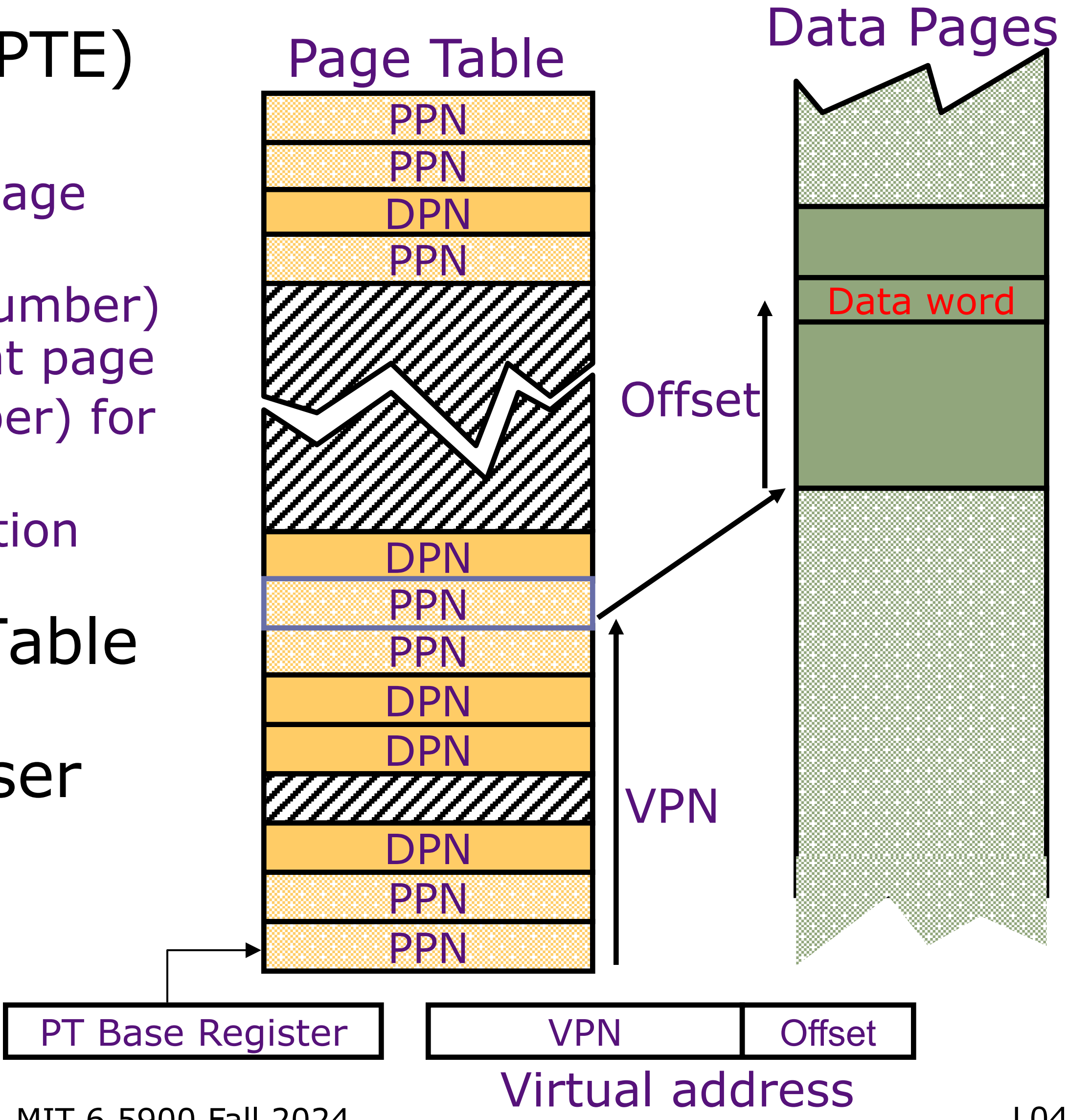


- Every instruction and data access needs address translation and protection checks

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

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



Size of Linear Page Table

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

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

⇒ 4 GB of swap space needed to back up the full virtual address space

Larger pages?

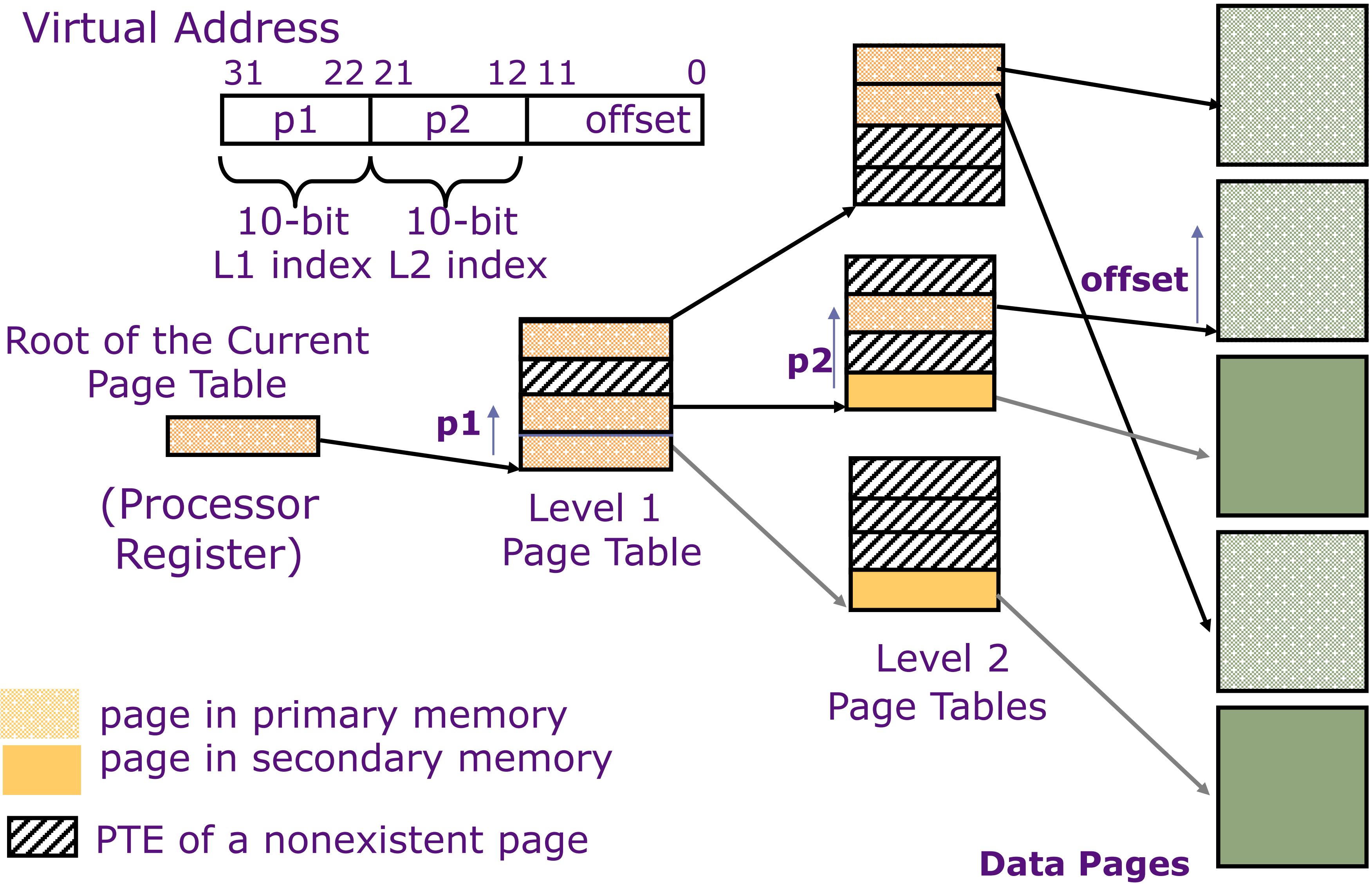
- Internal fragmentation (Not all memory in a page is used)
- Larger page fault penalty (more time to read from disk)

What about 64-bit virtual address space???

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

What is the "saving grace"?

Hierarchical Page Table



Virtual Address

31 22	21 12	11 0
p1	p2	offset

10-bit L1 index

10-bit L2 index

Root of the Current Page Table

(Processor Register)

Level 1 Page Table

Level 2 Page Tables

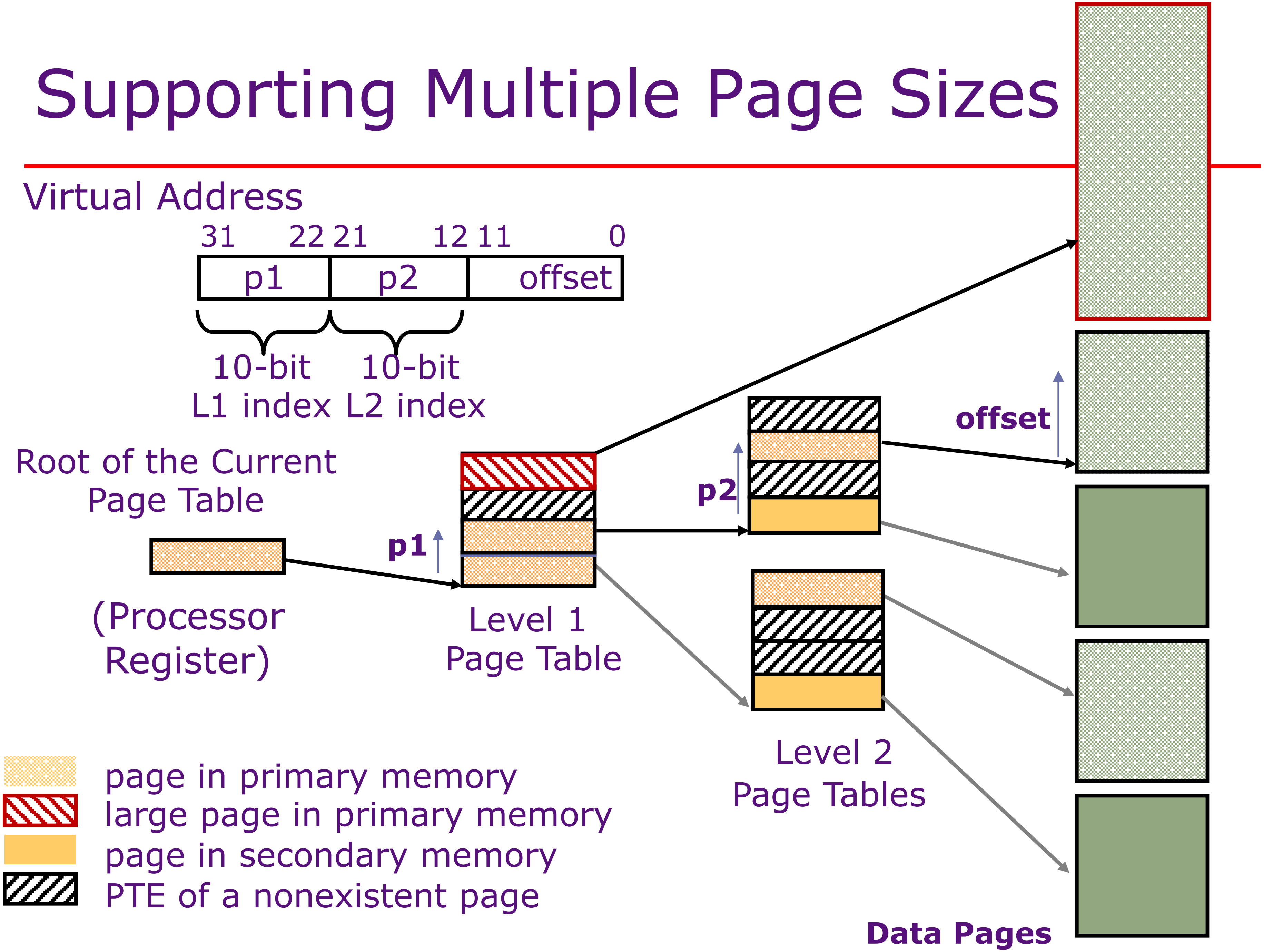
Data Pages

▨ page in primary memory

🟧 page in secondary memory

▨ PTE of a nonexistent page

Supporting Multiple Page Sizes



Virtual Address

Root of the Current Page Table

(Processor Register)

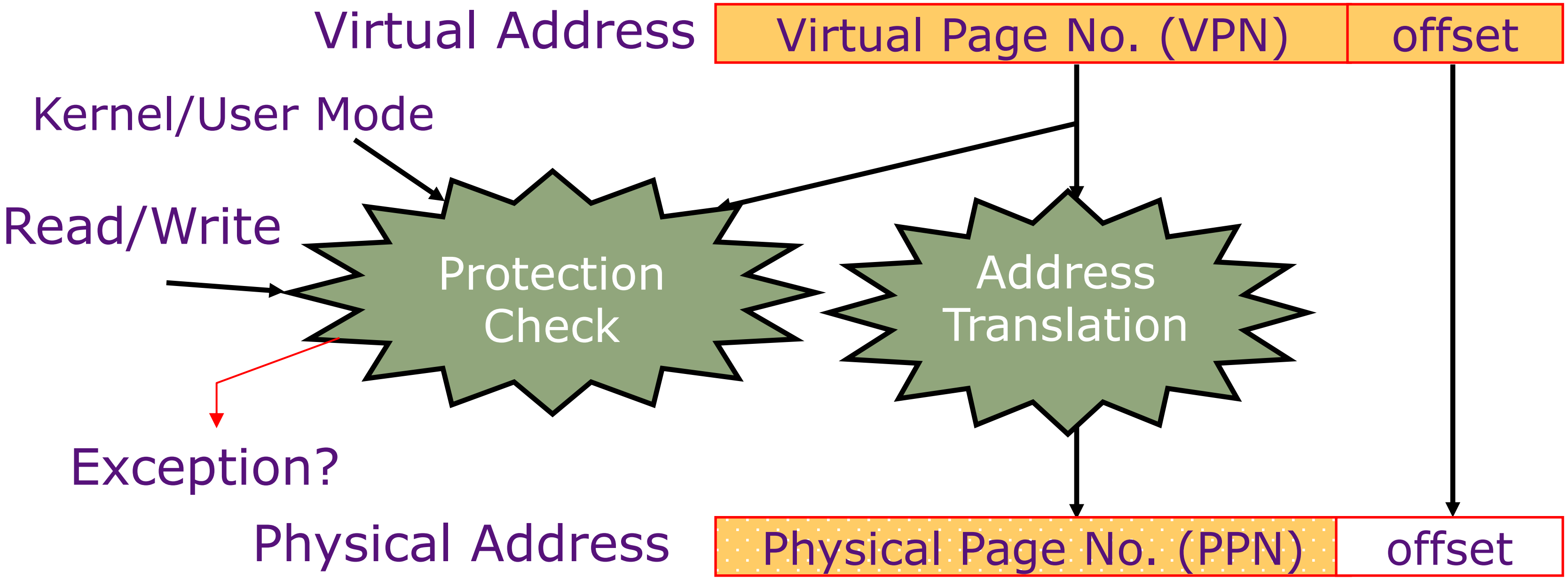
▨ page in primary memory

🟥 large page in primary memory

🟧 page in secondary memory

▨ PTE of a nonexistent page

Address Translation & Protection



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

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

Translation Lookaside Buffers

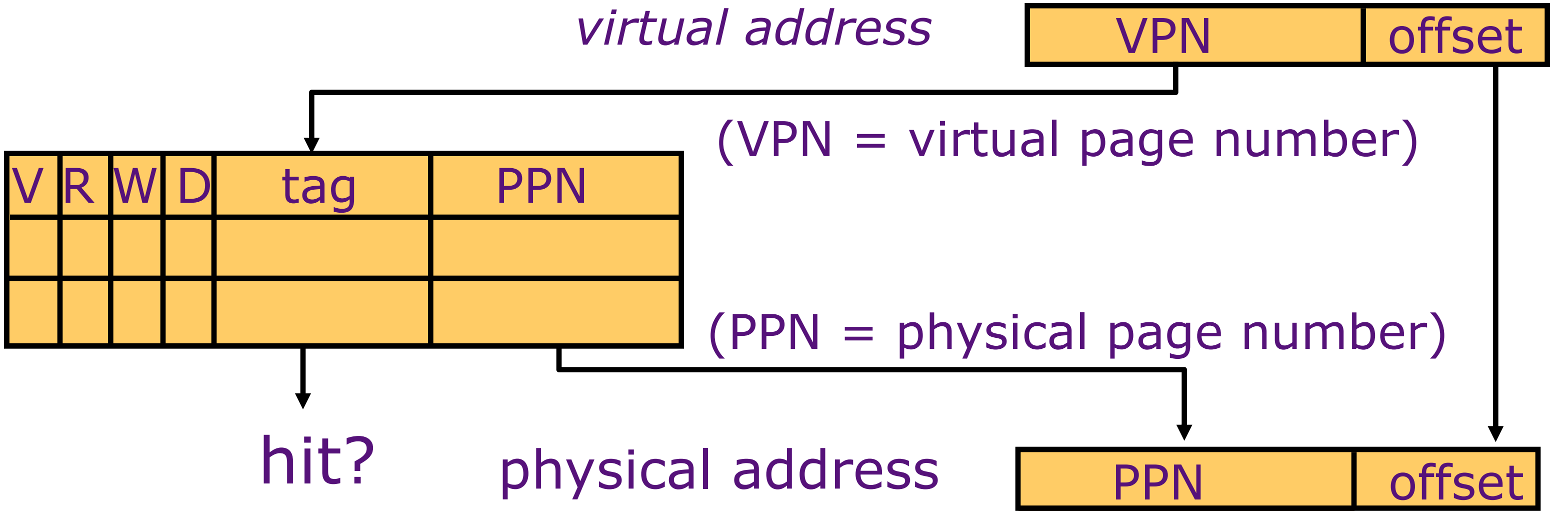
Address translation is very expensive!

In a hierarchical page table, each reference becomes several memory accesses

Solution: *Cache translations in TLB*

TLB hit ⇒ *Single-cycle Translation*

TLB miss ⇒ *Page Table Walk to refill*



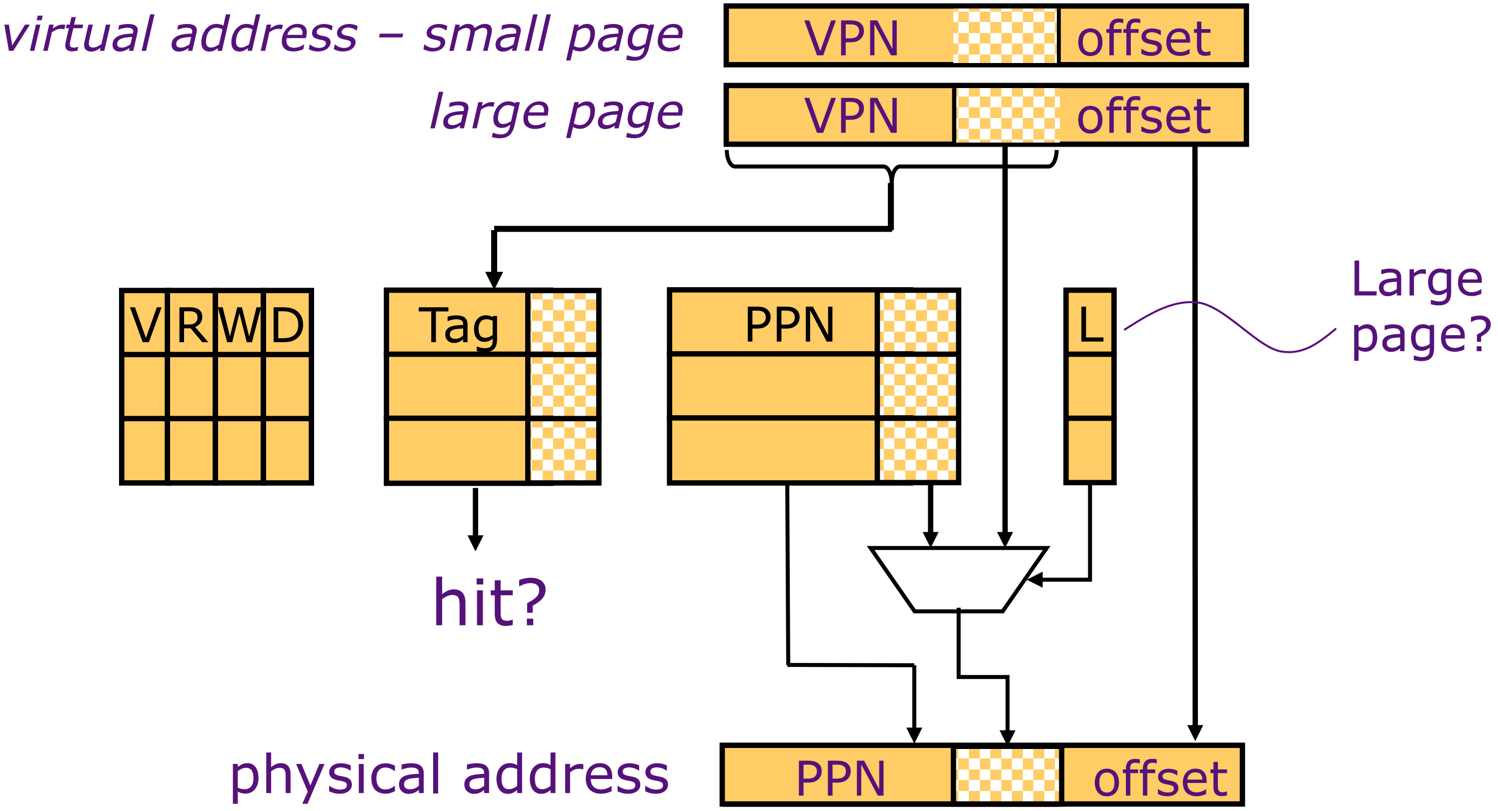
TLB Designs

- Keep process information in TLB?
  - No process id → Must flush on context switch
  - Tag each entry with process id → No flush, but costlier
- Size and Associativity
  - Typically 32-128 entries, usually highly associative
- TLB Reach: Size of largest virtual address space that can be simultaneously mapped by TLB

  Example: 64 TLB entries, 4KB pages, one page per entry

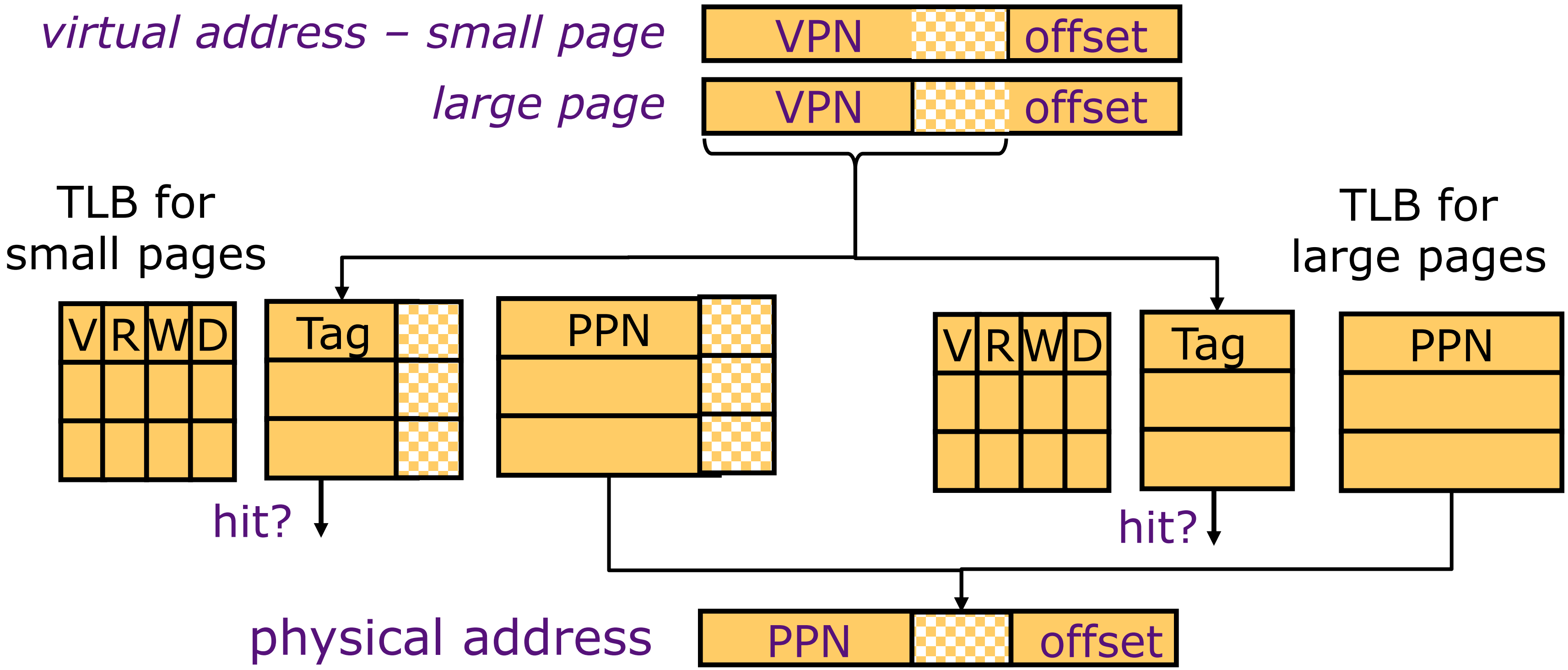
  TLB Reach = *64 entries * 4 KB = 256 KB (if contiguous)* ?
- Ways to increase TLB reach
  - Multi-level TLBs (e.g., Intel Skylake: 64-entry L1 data TLB, 128-entry L1 instruction TLB, 1.5K-entry L2 TLB)
  - Multiple page sizes, e.g., x86-64: 4KB, 2MB, 1GB

TLB Supporting Multiple Page Sizes



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

TLB Supporting Multiple Page Sizes



Alternatively, have a separate TLB for each page size

Pros/cons compared to unified TLB?

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*

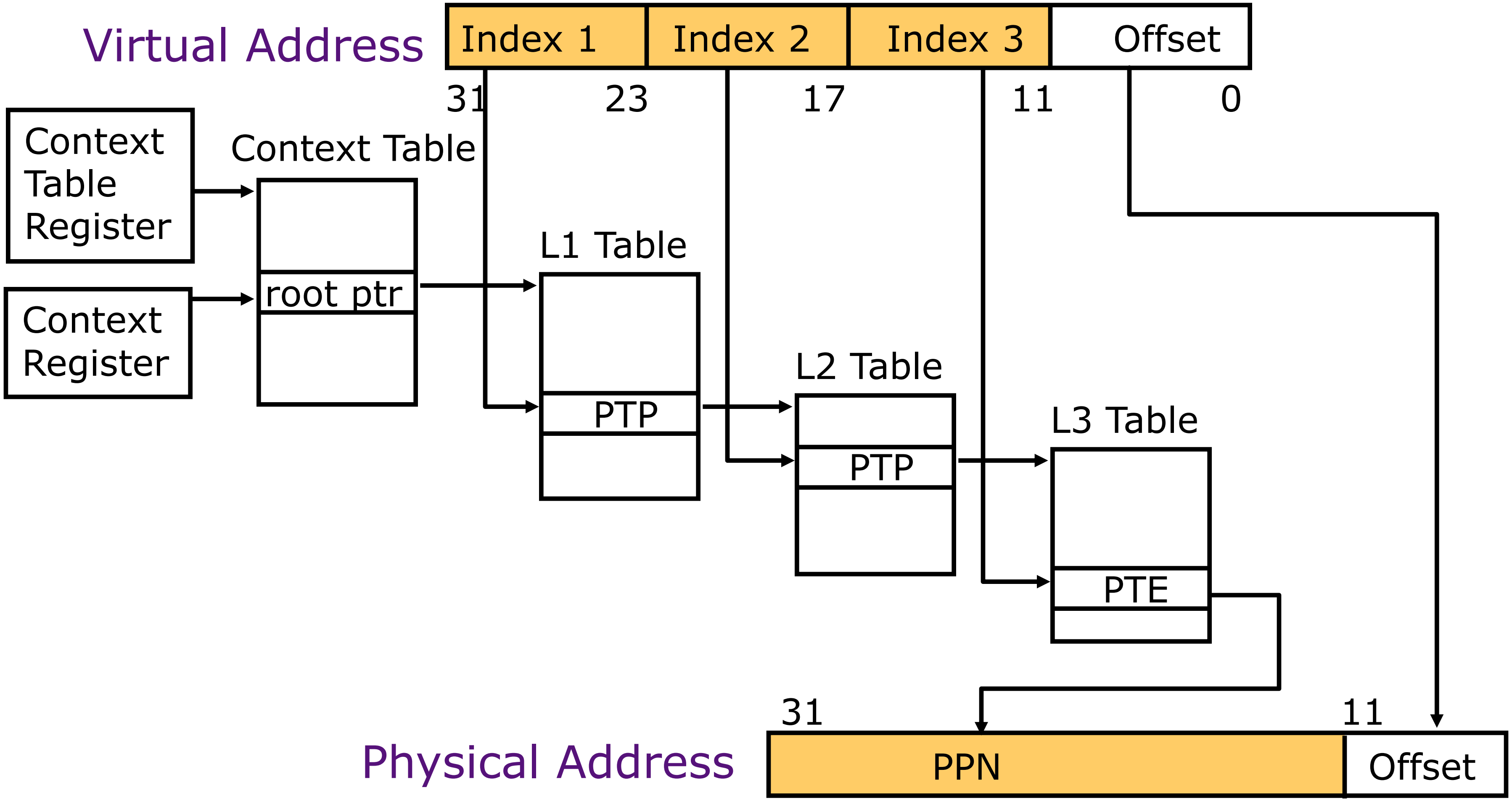
Hardware (SPARC v8, x86, PowerPC)

A memory management unit (MMU) walks the page tables and reloads the TLB

If a missing (data or PT) page is encountered during the TLB reloading, MMU gives up and signals a Page-Fault exception for the original instruction

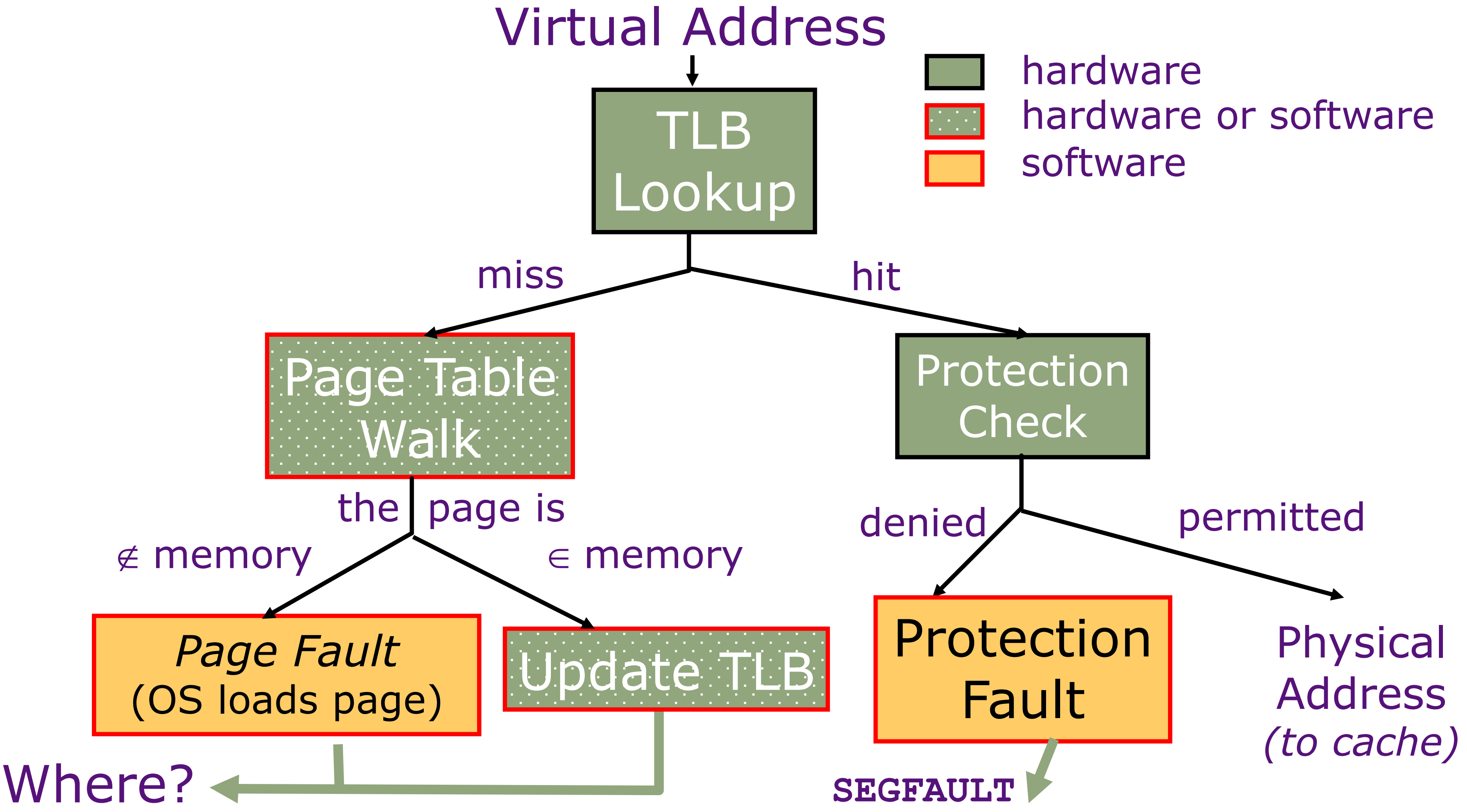
Pros and cons of each?

Hierarchical Page Table Walk: SPARC v8



MMU does this table walk in hardware on a TLB miss

Address Translation: *putting it all together*



Virtual Address

🟩 hardware
▨ hardware or software
🟧 software

TLB Lookup

miss

hit

Page Table Walk

Protection Check

the page is

∉ memory

∈ memory

denied

permitted

Page Fault
(OS loads page)

Update TLB

Protection Fault

Physical Address *(to cache)*

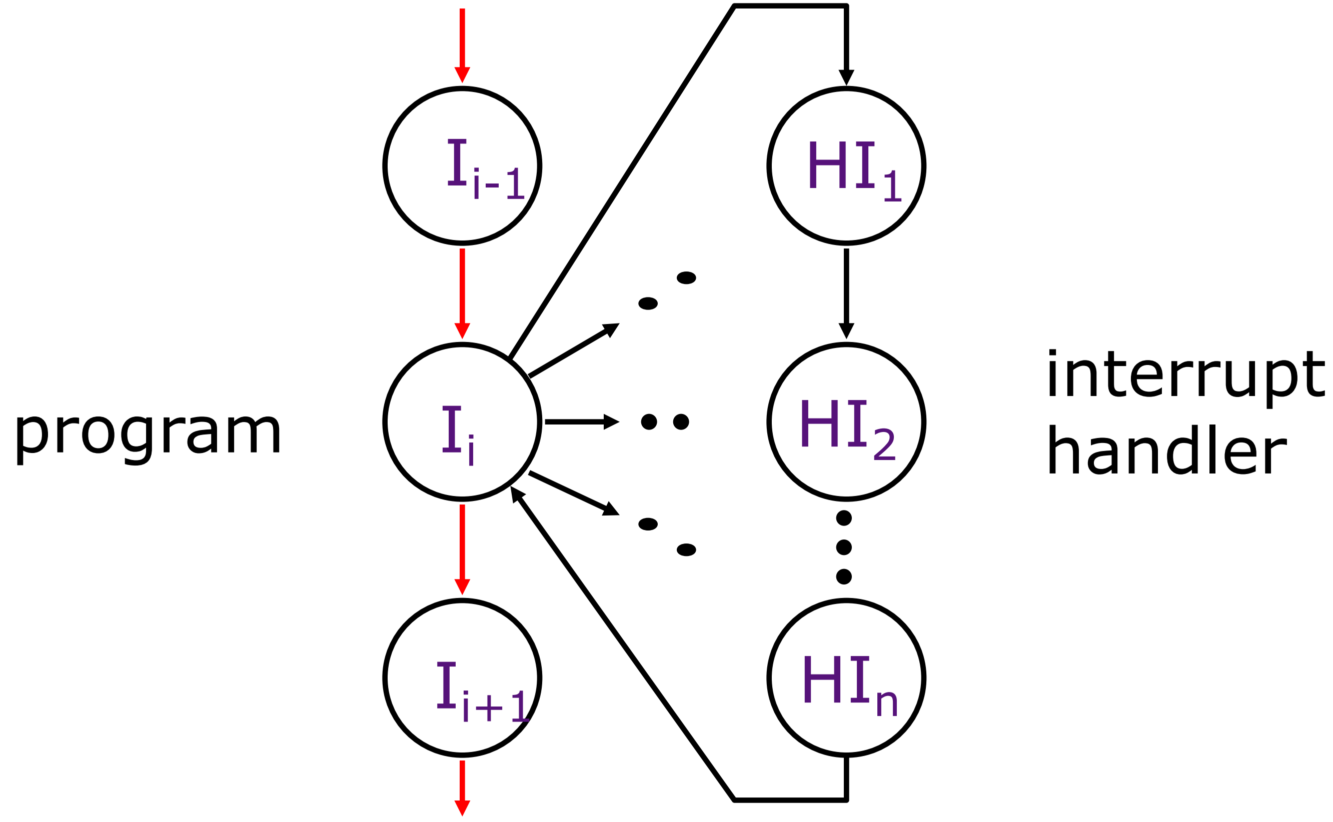
Where?

SEGFAULT

Topics

- Modern VM implementation
  - Page tables: Linear, hierarchical, multiple page sizes
  - TLBs
- Interrupts
- TLB & Cache organization
- Modern usage

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

Interrupt Handler

- Saves EPC before enabling interrupts to allow nested interrupts ⇒
  - 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 `mret` (*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
- 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

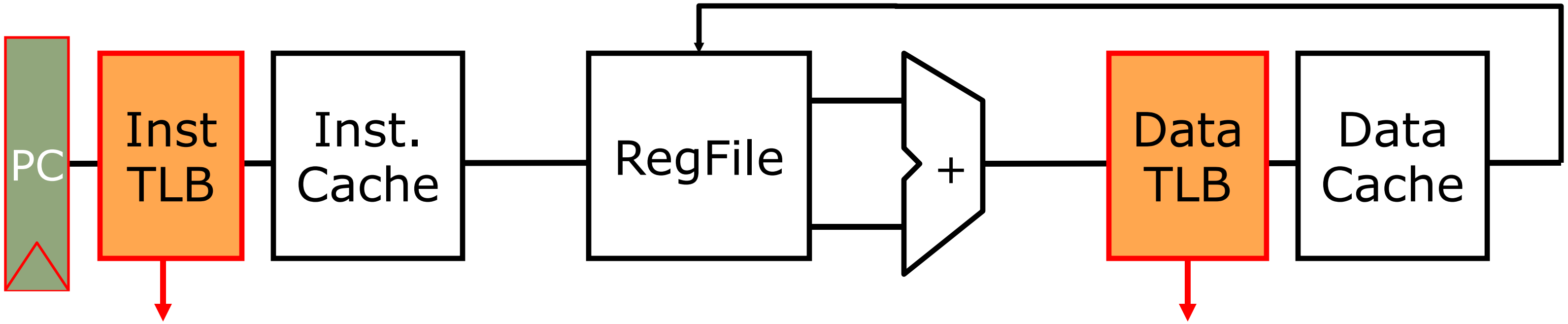
    Another job may be run on the CPU while the first job waits for the requested page to be read from disk
  - If no free pages are left, a page is swapped out

    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

- Modern VM implementation
- Interrupts
- TLB & Cache organization
- Modern usage

Address Translation in CPU

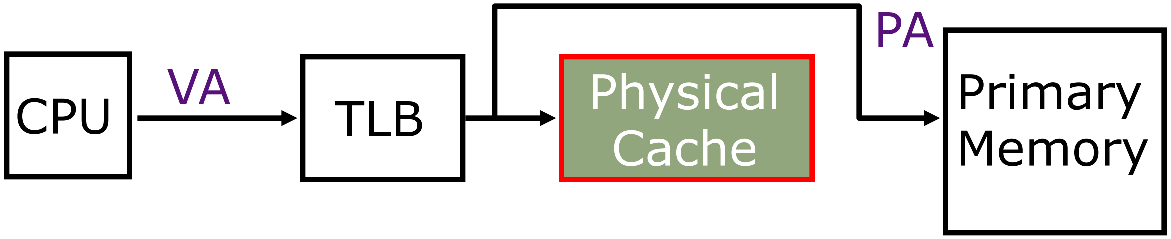


TLB miss? Page Fault?
Protection violation?

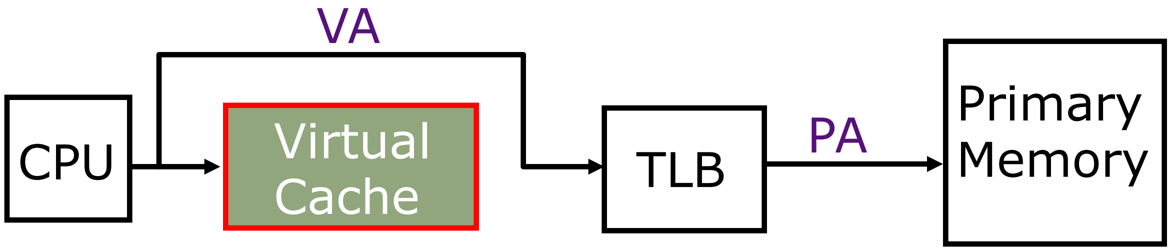
TLB miss? Page Fault?
Protection violation?

- Software handlers need a *restartable* exception on page fault or protection violation
- Handling a TLB miss needs a *hardware* or *software* mechanism to refill TLB
- 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

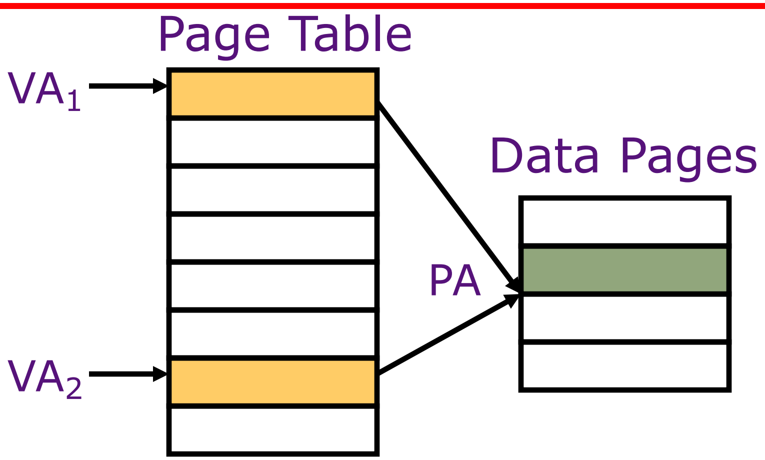


Alternative: place the cache before the TLB



- 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 (-)

Aliasing in Virtual-Address Caches



Two virtual pages share one physical page

Tag	Data
VA_1	1st Copy of Data at PA
VA_2	2nd Copy of Data at PA

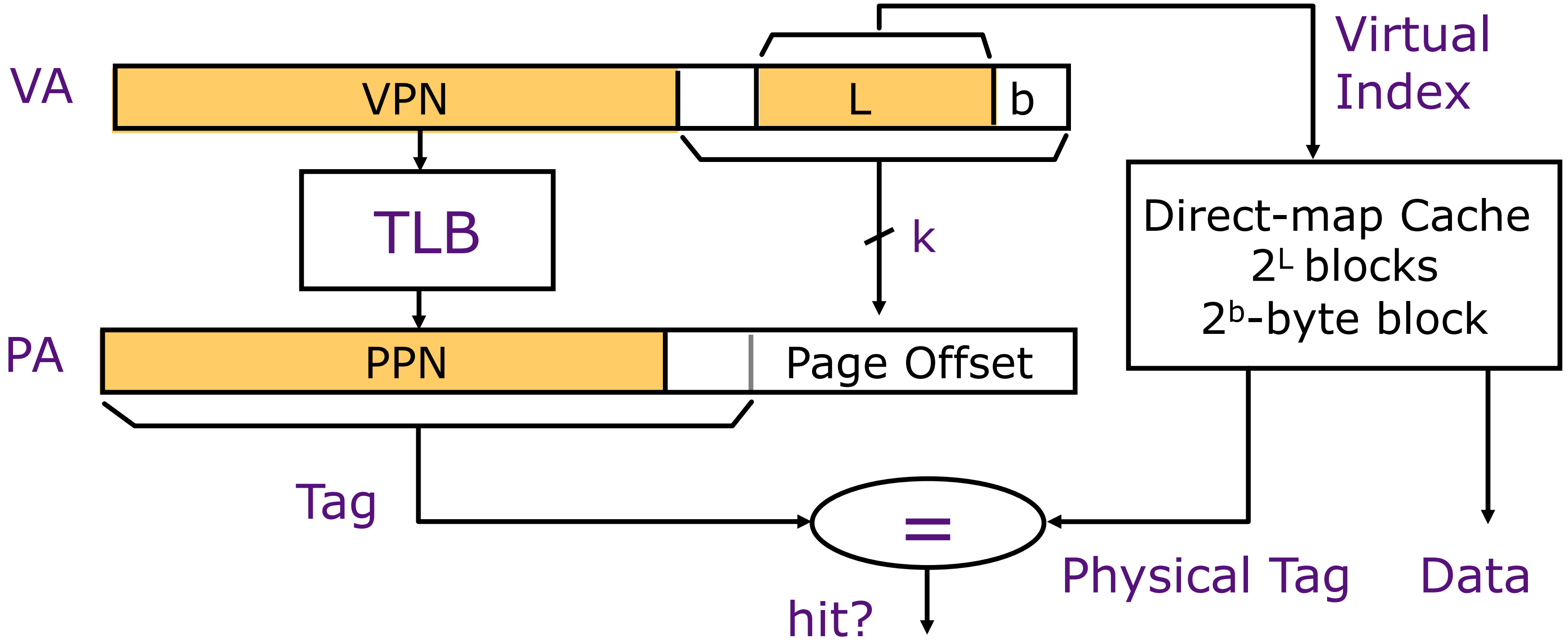
Virtual cache can have two copies of same physical data. Writes to one copy not visible to reads of other!

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



Index L is available without consulting the TLB

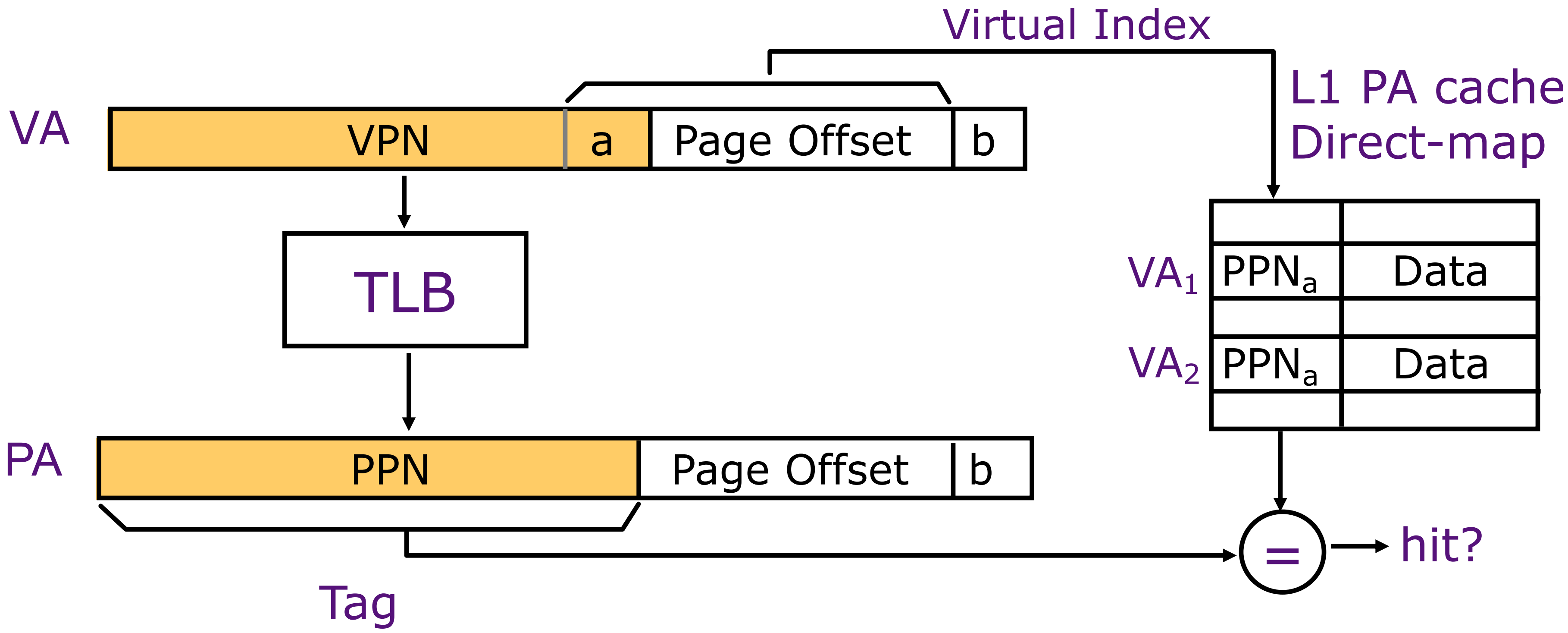
⇒ *cache and TLB accesses can begin simultaneously*

Tag comparison is made after both accesses are completed

When does this work? $L + b < k$ ✓ $L + b = k$ ✓ $L + b > k$ ✗

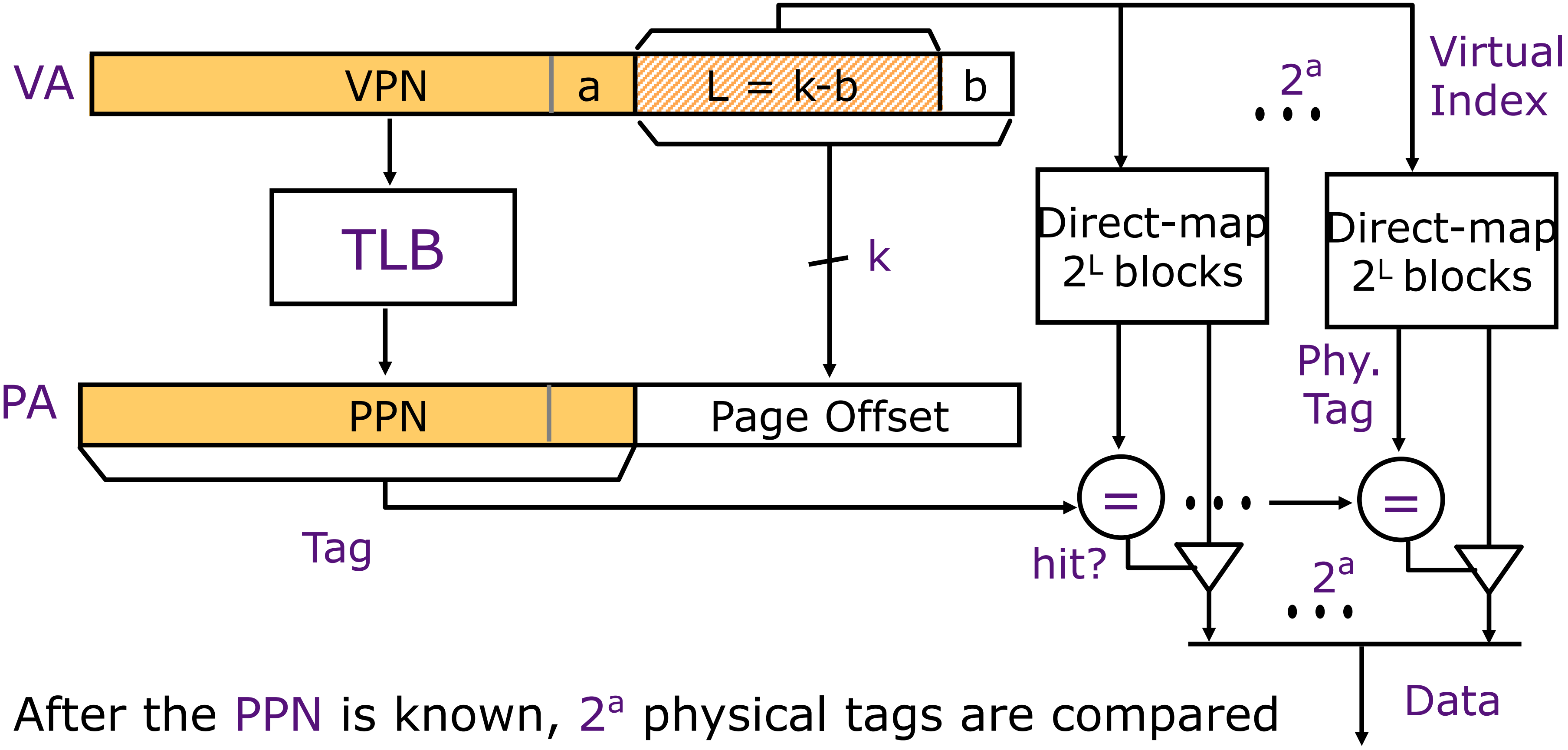
Concurrent Access to TLB & Large L1

The problem with L1 > Page size



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

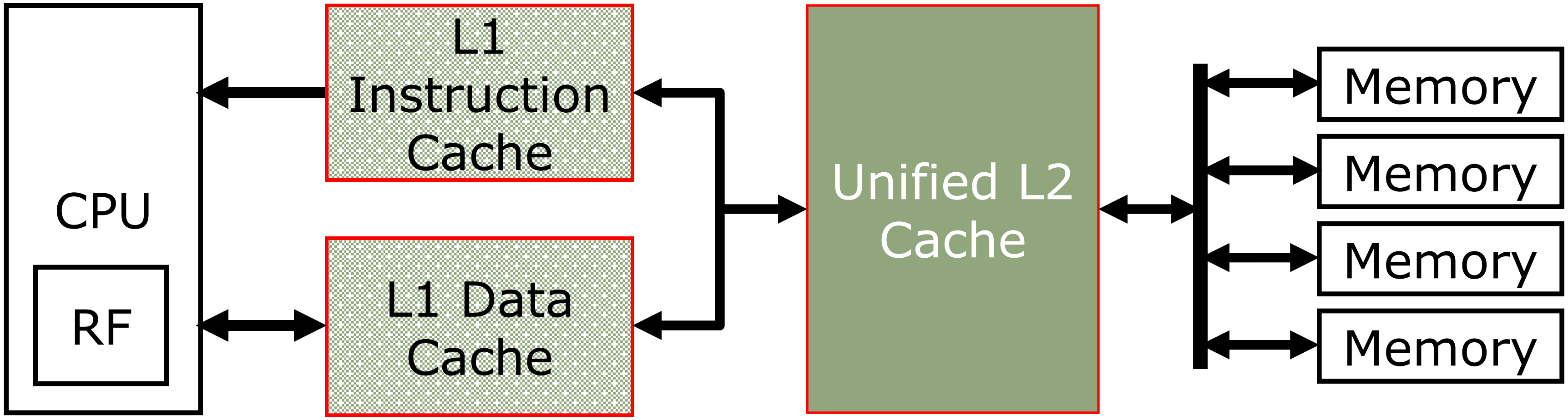
Virtual-Index Physical-Tag Caches:
Associative Organization



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

Is this scheme realistic?

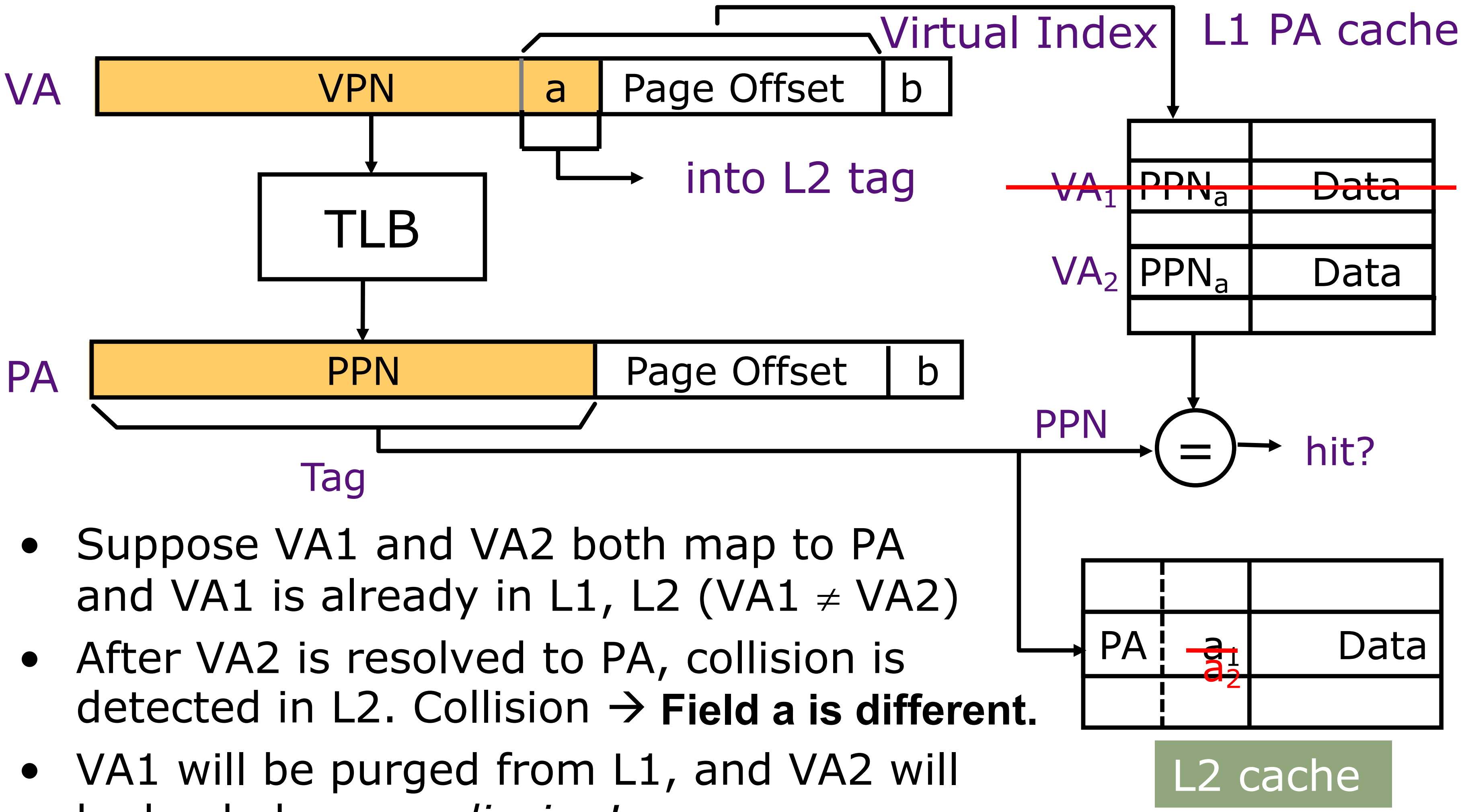
A solution via Second-Level Cache



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

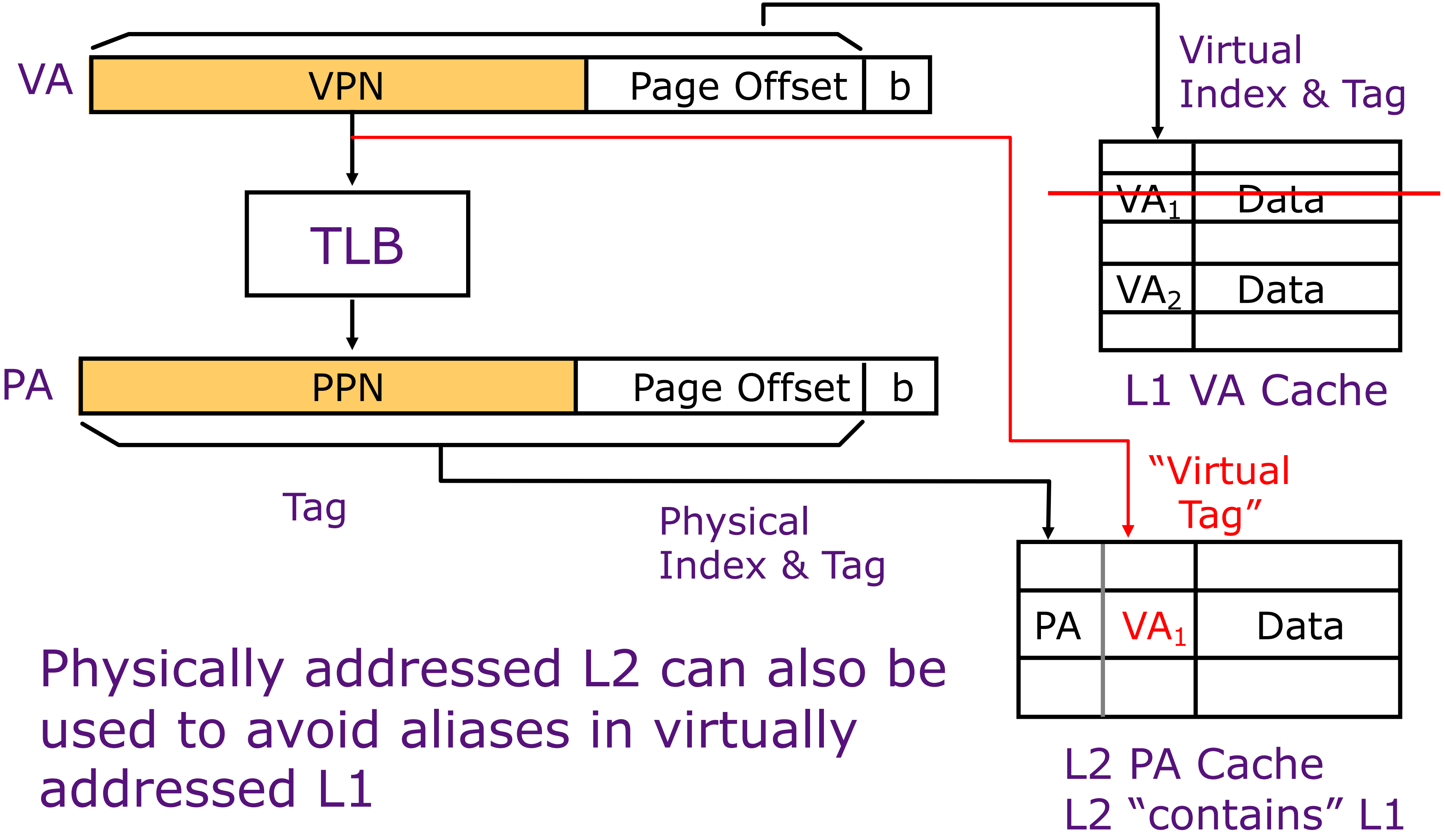
L2 is “inclusive” of both Instruction and Data caches

Anti-Aliasing Using L2: *MIPS R10000*



- Suppose VA1 and VA2 both map to PA and VA1 is already in L1, L2 (VA1 ≠ VA2)
- After VA2 is resolved to PA, collision is detected in L2. Collision → **Field a is different.**
- VA1 will be purged from L1, and VA2 will be loaded ⇒ *no aliasing!*

Virtually Addressed L1:
Anti-Aliasing using L2



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

Topics

- Modern VM implementation
- Interrupts
- TLB & Cache organization
- Modern usage

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!