18-447 Lecture 18:
Page Tables and TLBs

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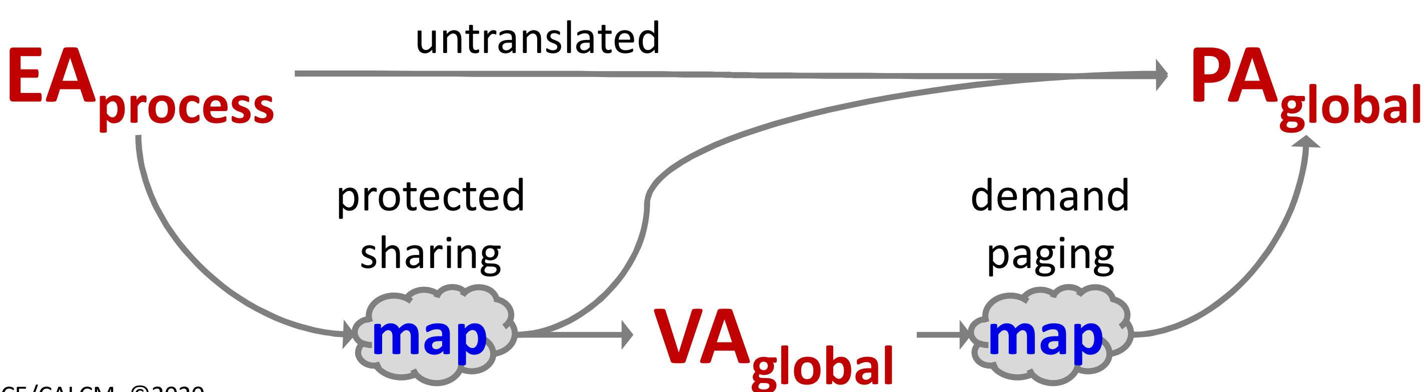
Housekeeping

- Your goal today
  - see the reality of page tables
  - delve into the many nuts and bolts of VM supports
- Notices
  - Lab 3, due this week
  - HW 4, due Friday 4/3
  - Midterm 2, online during class time, Mon, 4/6;
    4-min dress rehearsal, Mon, 3/30
- **Required readings for L19**
  - "Virtual Memory in . . ." [Jacob&Mudge] (Canvas)
  - Meltdown→Mechanism (Wikipedia)

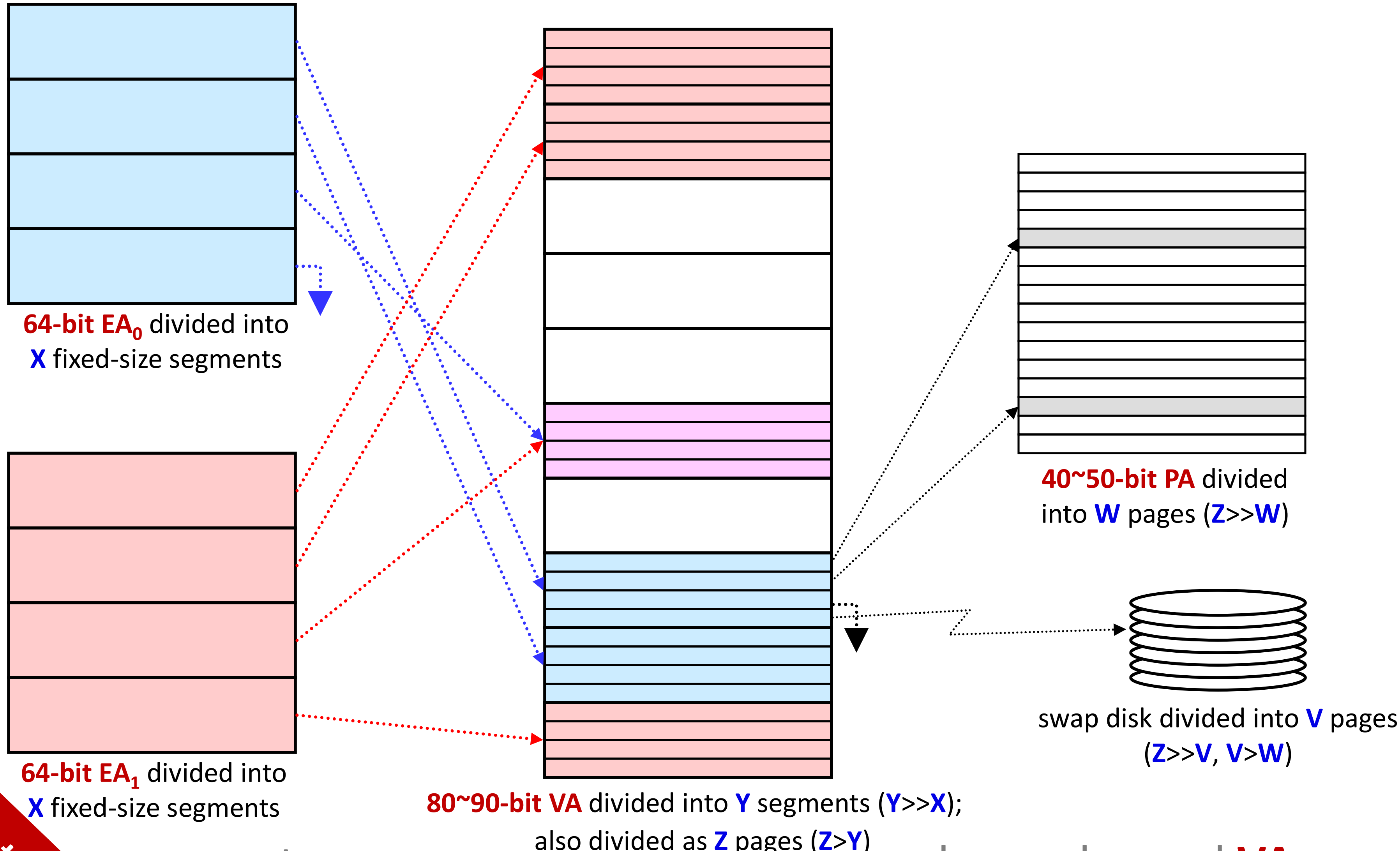
Don’t use “VM” to mean everything

- Effective Address (**EA**): emitted by user instructions in a per-process space (protection)
- Physical Address (**PA**): corresponds to actual storage locations on DRAM or on swap disk
- Virtual Address (**VA**): refers to locations in a system-wide, large, linear address space; not all locations in **VA** space have physical backing (demand paging)



last time

EA, VA and PA (IBM Power view)



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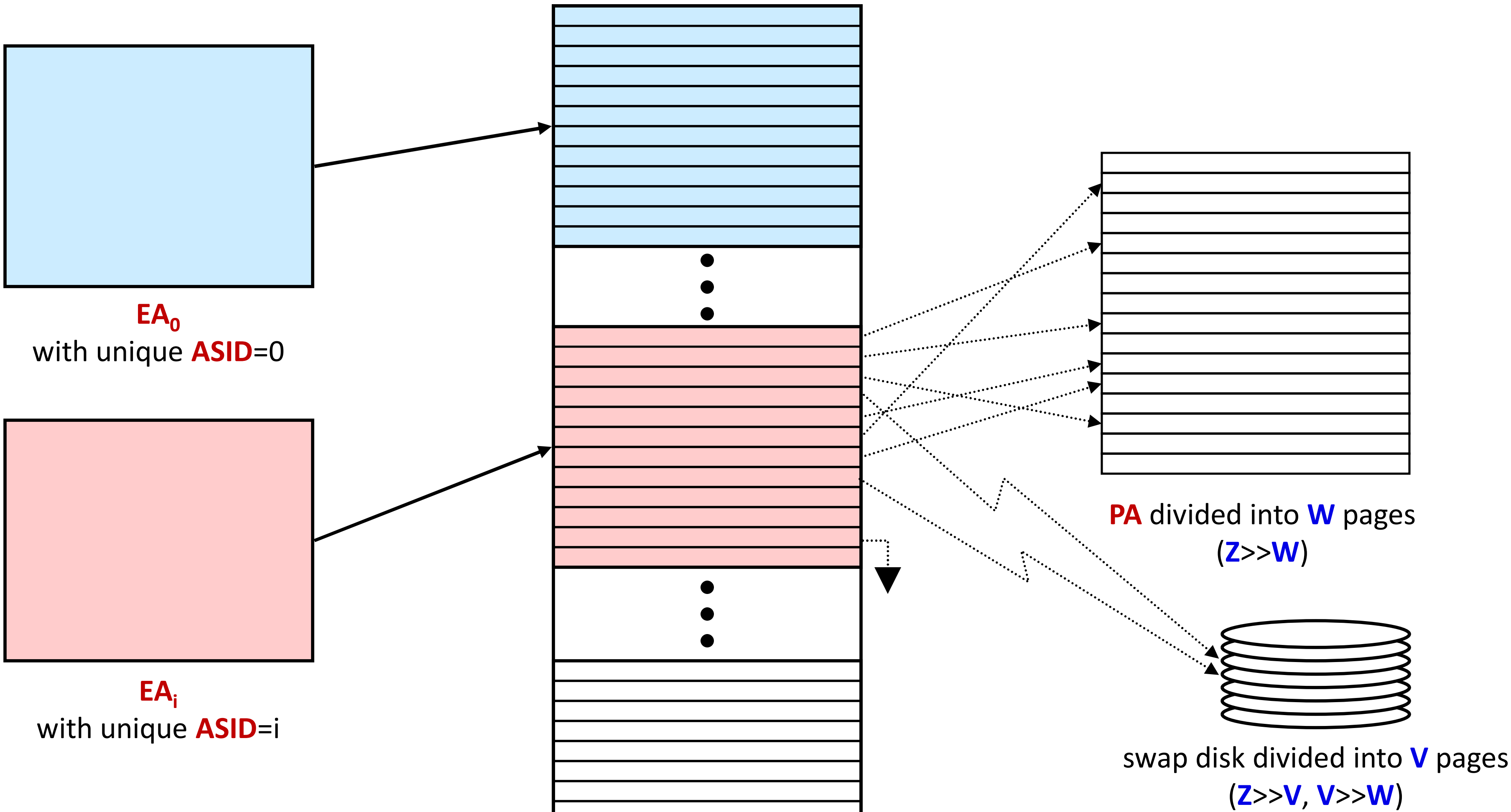
egmented **EA**:
priv ontiguous + sharing

demand paged **VA**:
size of swap, speed of DRAM

EA, VA and PA (almost everyone else)



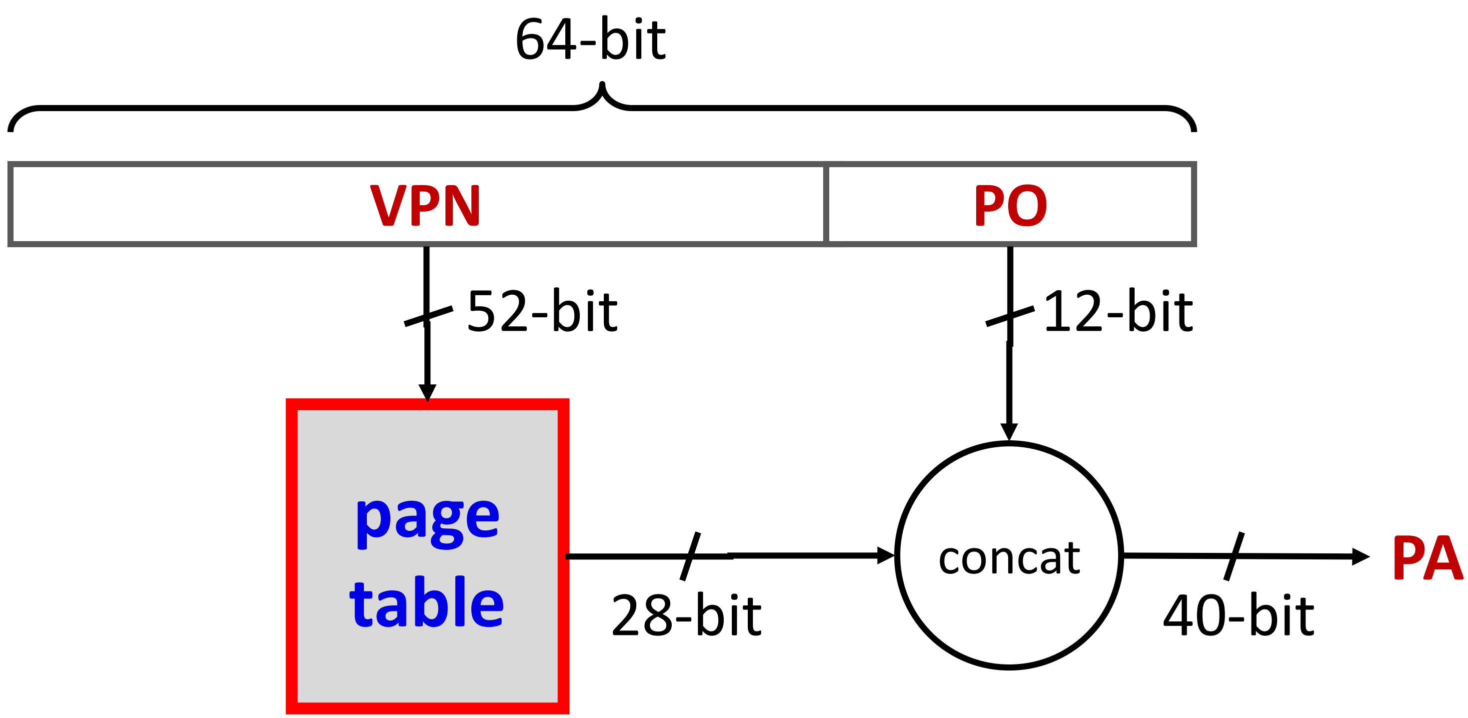
VA divided into N "address spaces"
indexed by ASID;
also divided as Z pages (Z>>N)

last time

to blur **EA** and **VA**

how do processes
share pages?

Just one more thing: How large is the page table?



- A page table holds mapping from **VPN** to **PPN**
- Suppose 64-bit **VA** and 40-bit **PA**, how large is the page table? 2^{52} entries x ~4 bytes ≈ 16×10^{15} Bytes

And that is for just one process!!?

last time

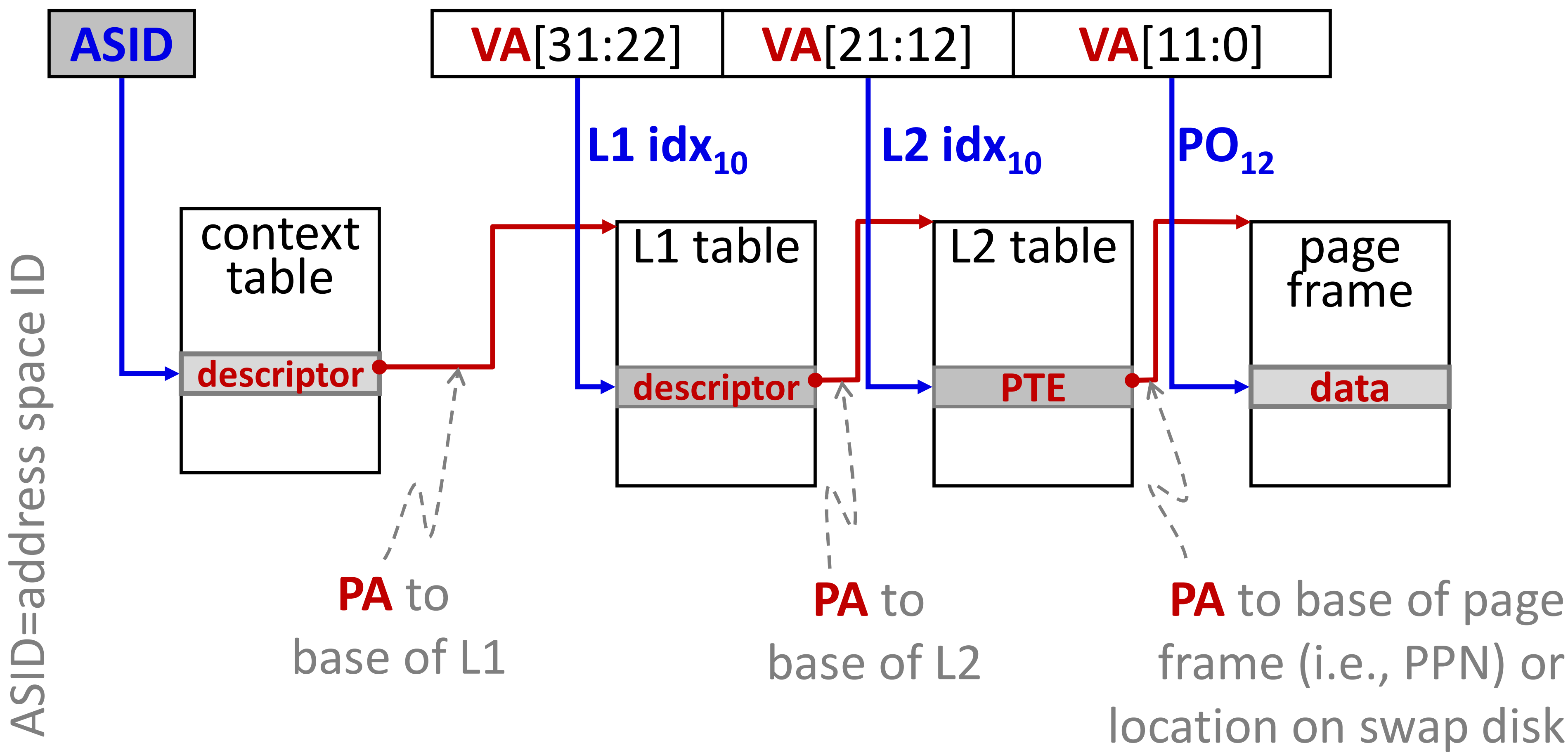
How large should it be?

- Don’t need to track entire **VA** space
  - total allocated **VA** *space* is 2^{64} bytes x # processes, but most of which not backed by *storage*
  - can’t use more memory locations than physically exist (DRAM and swap disk)
- A clever page table should scale linearly with physical *storage* size and not **VA** *space* size
- Table cannot be too convoluted
  - a page table must be “walkable” by HW
  - a page table is accessed not infrequently

Two dominant schemes in use today:
hierarchical page table and *hashed page table*

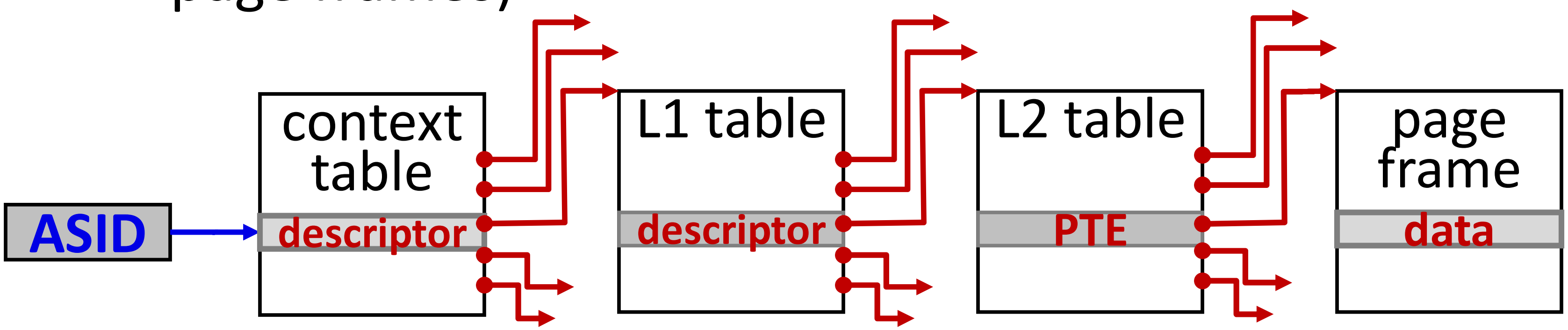
Hierarchical Page Table

- Hierarchical page table is a "tree" data structure in DRAM (and is cacheable)



Hierarchical page table is a tree

- For example on previous page
  - L1 table could have 1024 decedents (L2 tables)
  - each L2 table could have 1024 decedents (physical page frames)



- More levels can be used for larger **VA** space
- If 4-byte descriptors and PTEs, each table is 4KByte (size of page frames) such that the tables can be demand paged between DRAM and disk

Hierarchical page table is a sparse tree

- Most virtual pages are not allocated; corresponding L2 entries point to null
- If a L2 table comprises entirely null pointers (no live decedents), itself does not need to exist; point corresponding L1 entry to null
- When more than 2 levels, an entire unused sub-tree is avoided
- Consider typical size ratio of **VA** to **PA**, the tree should be quite sparse for even the largest programs

How sparse?

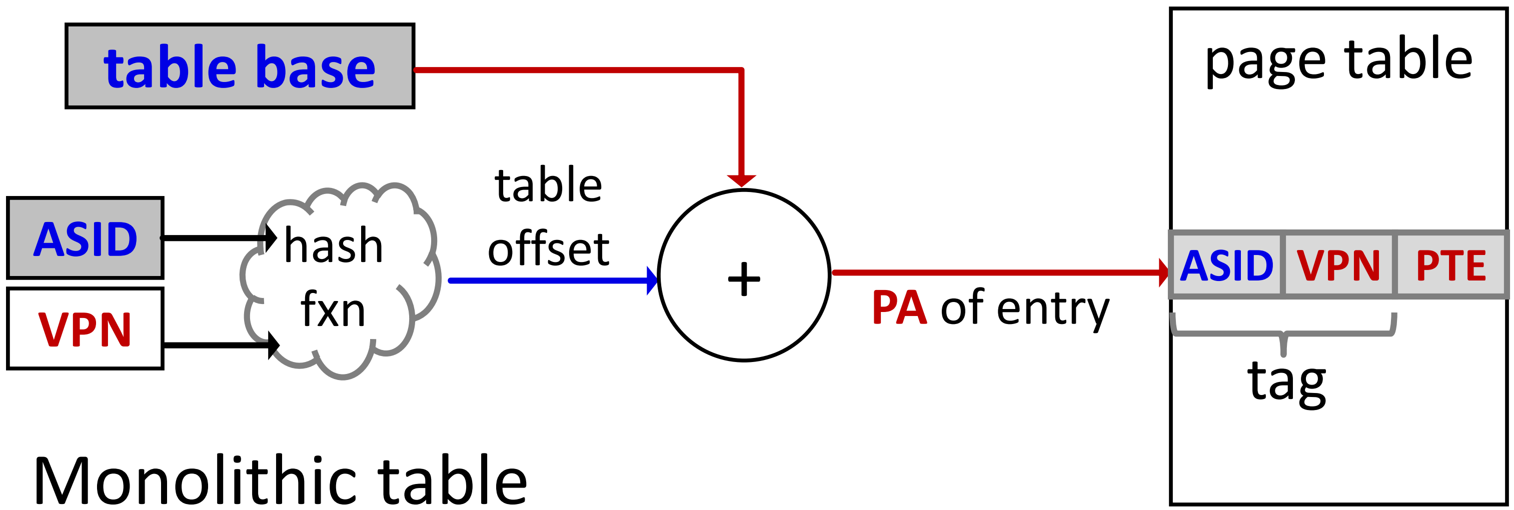
Assume 32-bit VA with 4 MByte in use

- Best Case: one contiguous 4-MByte **VA** region aligned on 4 MByte boundaries
  - 1024 physical page frames used
  - needs 1 L2 table + 1 L1 table=2 x 4KBytes

    overhead ≈ sizeof(PTE) per data page used, or 0.1%
- Worst Case: 1024 x 4-KByte **VA** regions; each is 4-MByte aligned
  - 1024 physical page frames used
  - needs 1K L2 tables (only 1 entry per L2 table used),

    overhead ≈ sizeof(L2 table) per data page, or 100%
- Locality says we should be closer to the best case

Hashed Page Table



- Monolithic table
  - indexed by hashing **VPN** and **ASID**,
  - e.g., index=(**VPN**⊕**ASID**)%table_size
- Entry "tagged" by **ASID** and **VPN** to detect collision
- Hashed table fast to access but not complete
  - lookup can fail even though page is valid
  - on a miss, consult a secondary complete table

How large is the hashed page table?

- Table size is an engineering choice, balancing storage overhead and hash collision
  - at least 1 entry per physical page

    e.g., 1GB DRAM $\Rightarrow$ 256K frames $\Rightarrow$ 256K PTEs
  - typically some factor more to reduce collisions
- Original "inverted" page table
  - allocate 1 entry per physical page frame
  - use hashed index as **PPN** (a bit like direct-map . . .)
  - table entry contains only **VPN** tag

    Viewed out of context, the table seems indexed by **PPN** and returns **VPN**, hence the misnomer

Translation Look-Aside Buffer (TLB)

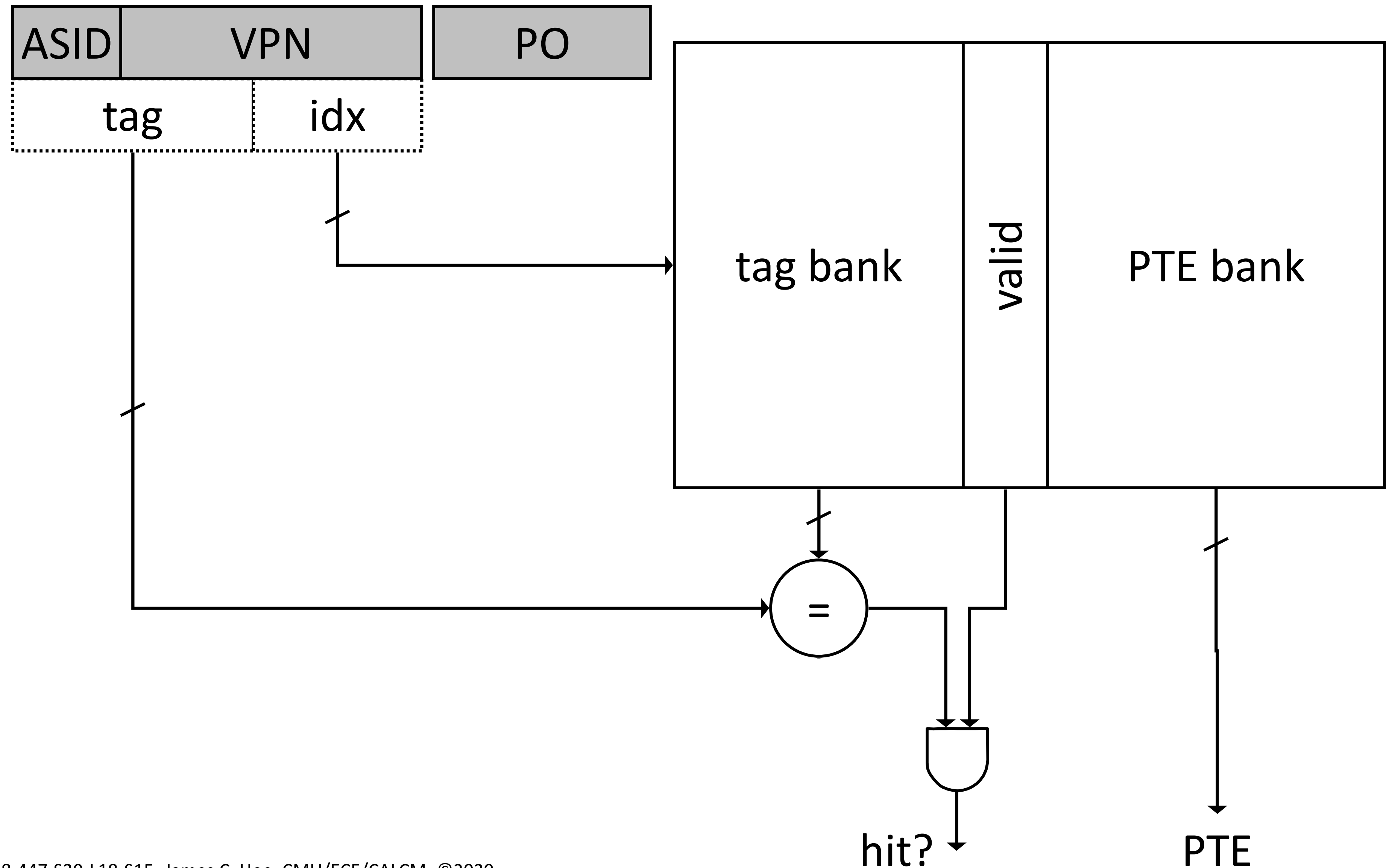
- Every user memory access requires a translation
  - table walk requires its own memory accesses
  - can't possibly be walking the table on every access
- Keep a "cache" of recently used translations
- Similar "tagged" lookup structure as cache and BTB
  - same design considerations: A/B/C, replacement policy, split vs. unified, L1/L2, etc.
  - TLB entry:

    tag: address tag (from **VA**), **ASID**

    PTE: **PPN** & **protections**

    misc: valid, dirty, etc.

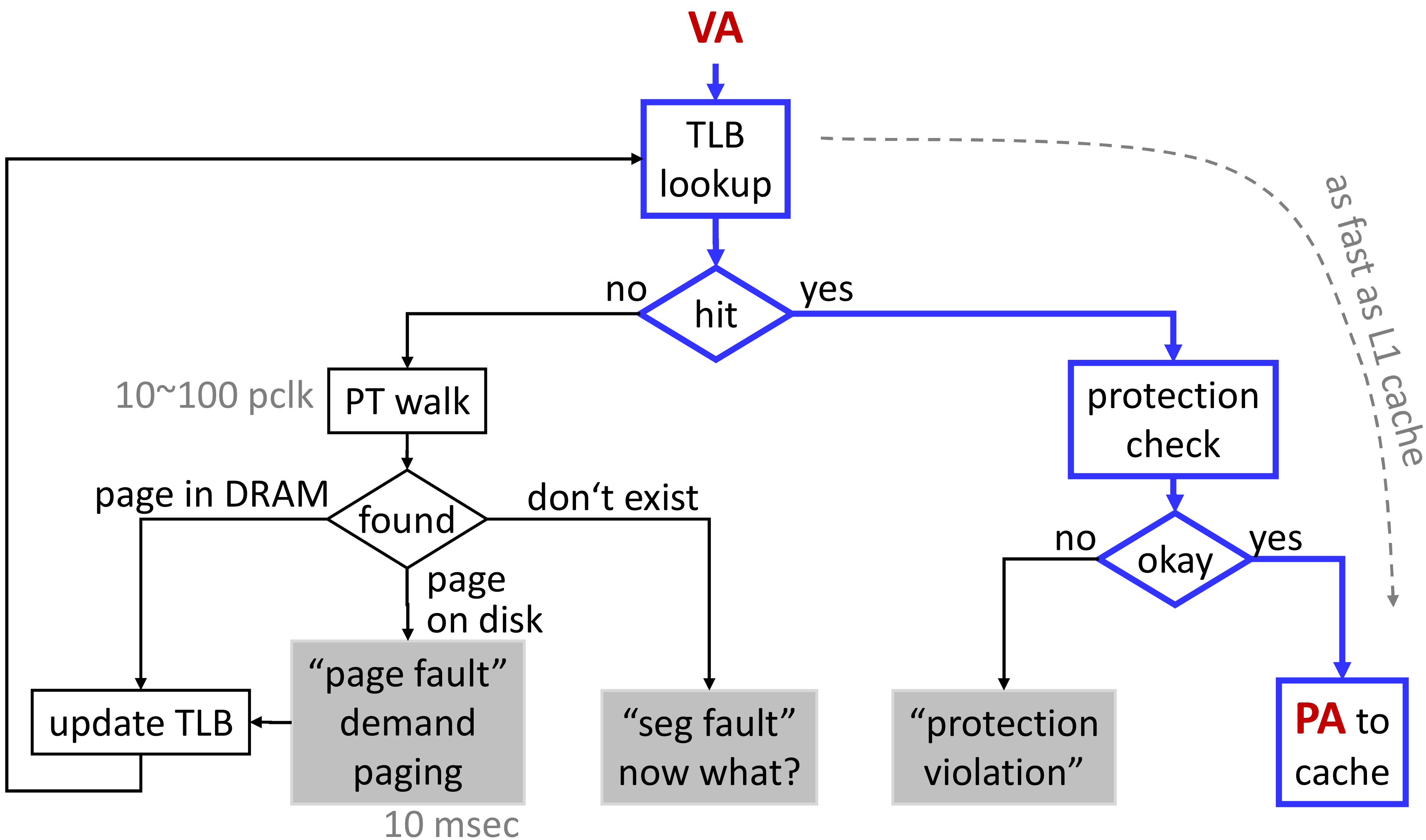
Direct-Mapped TLB (bad example)



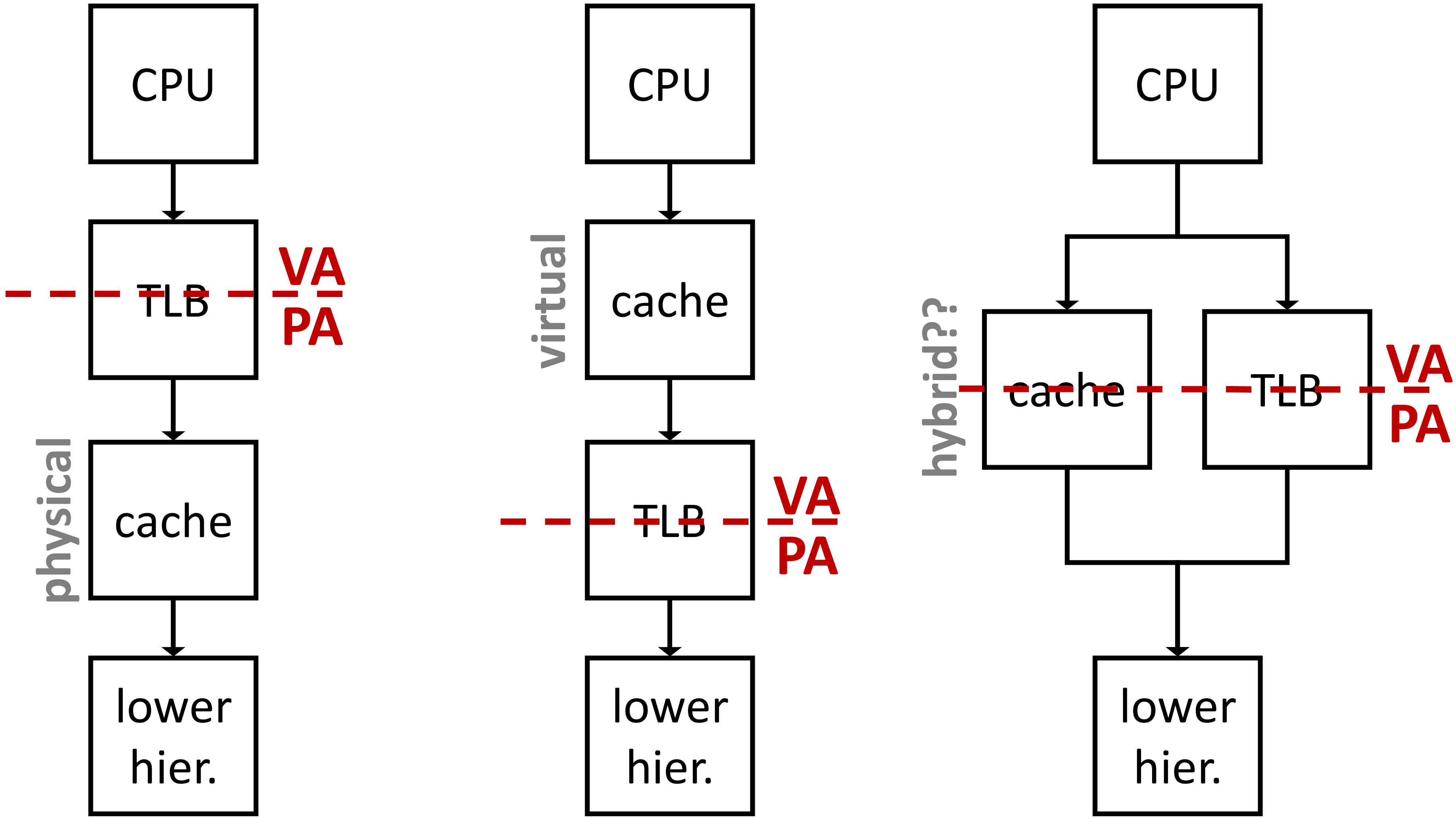
TLB Design

- C: L1 I-TLB should cover same footprint as L1 I-cache, e.g., if L1 I-cache is 64KB
  - L1 I-TLB needs minimum 16 pages but only if working set always use entire pages
  - was 32~64 entries; nowadays a few hundred
- B: after accessing a page, how likely is it to access the next page? (coarse grain spatial locality)
  - usually one PTE per TLB entry
  - exception, MIPS keeps 2 PTEs per TLB entry
- a: associativity to minimize collision?
  - in the old days, fully-associative is the norm
  - nowadays, 2~4-way-associative is more common

VA to PA Translation Flow Chart



How should VM and Cache Interact?



Only a question for L1 caches

Virtual Caches

- Even with TLB, translation takes time
- Naively, memory access time in the best case is

  TLB hit time + cache hit time
- Why not access cache with virtual addresses; only translate on a cache miss to DRAM

  make sense if TLB hit time >> cache hit time
- Virtual caches in SUN SPARC ISA, circa 1990
  - CPU fast enough for off-chip SRAM access to take multiple cycles
  - dies size large enough to include on-chip L1 caches
  - MMU and TLB still separate chip

These conditions no longer hold

Resolving Synonym and Homonym in Virtual Caches

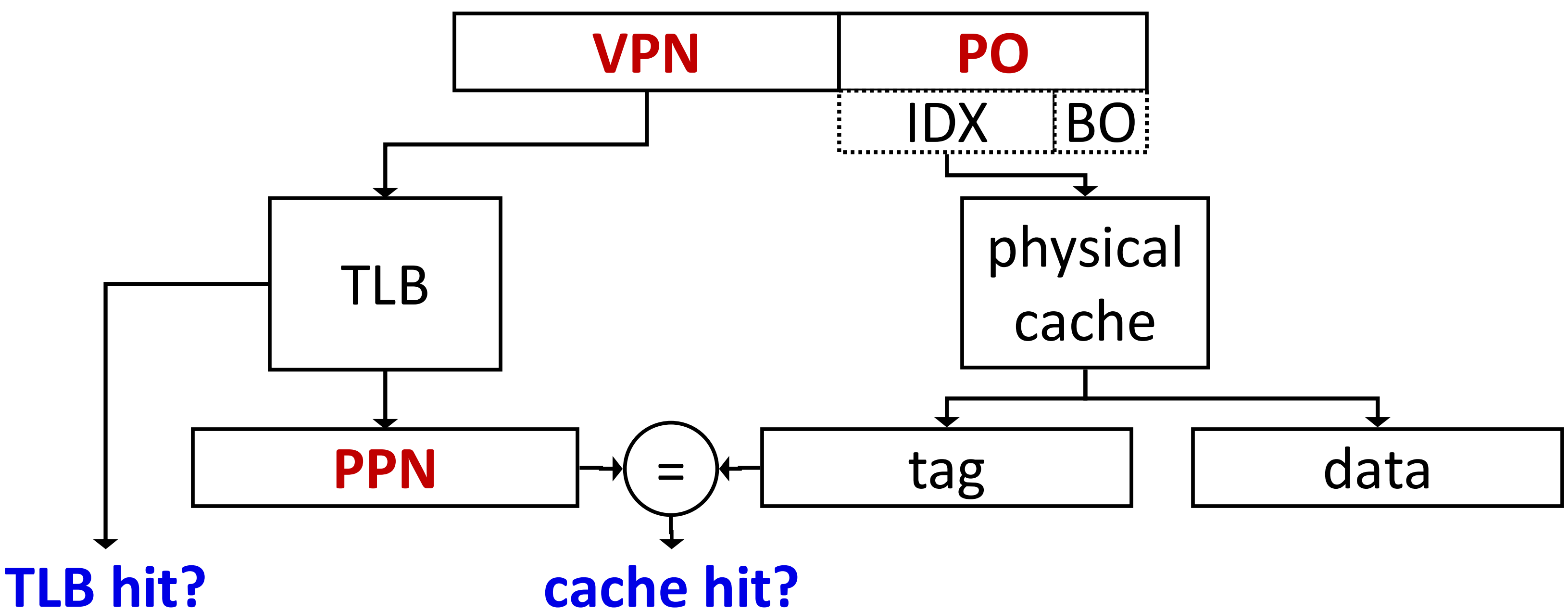
- **Homonyms**: same sound different meaning
  - same **EA** (in different processes) $\rightarrow$ different **PA**s
  - flush virtual cache between context; or include **ASID** in cache tag
- **Synonyms**: different sound same meaning
  - different **EA**s (from the same or different processes) $\rightarrow$ same **PA**
  - **PA** could be cached twice under different **EA**s
  - writes to one cached copy not reflected in the other cached copy

*Resolve by ensuring only 1 such **EA** in cache at a time*

Virtually-Indexed Physically-Tagged

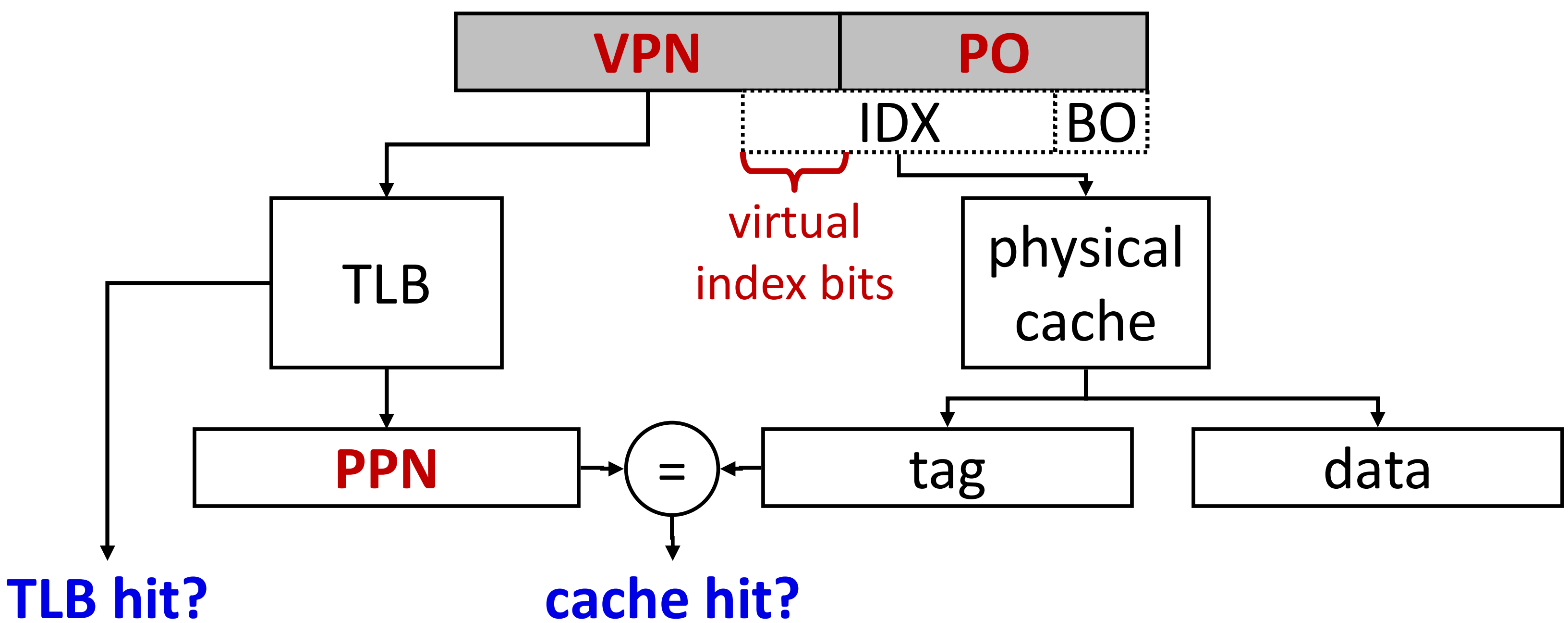
(misnomer)

- If C≤(**page_size**×**associativity**), cache index bits come only from page offset
- If both cache and TLB are on chip
  - index both SRAMs concurrently using **PO** from **VA**
  - check cache tag (physical) against TLB at the end



Large Virtually-Indexed Caches

- If **C>(page_size×associativity)**, cache index bits include **VPN** ⇒ synonyms can cause problems
- Solutions
  - increase associativity, 4KB page x 8 way =32KB
  - increase page size



R10000's Virtually Index Cache

- 32KB, 2-Way L1 D-cache
  - needs 10 bits of index + 4 bits of block offset
  - highest 2 index bits are **VA**[13:12] or **VPN**[1:0]
- Direct-mapped L2
  - L2 is inclusive of L1
  - **VPN**[1:0] is kept and checked as a part of L2 tag
- Given synonyms A_{VA} and B_{VA} that differs in **VPN**[1:0]
  - suppose A_{VA} accessed first so cached in L1 and L2
  - when accessing B_{VA} later
    1. B_{VA} indexes to a different block in L1 and misses
    2. B_{VA} indexes to the same block as A_{VA} in physical L2
    3. L2 detects synonym when comparing **VPN** portion of tag; L2 evicts A_{VA} from L1 before reloading B_{VA}

Interactions of VM and DMA

- A contiguous block in **VA**
  - is not guaranteed contiguous in **PA**
  - may not be in memory at all
- Software solutions
  - kernel copies from user buffer to pinned, contiguous buffer before DMA, or
  - user allocate special pinned and consecutive pages for zero-copy DMA
- Smarter DMA engines follow a “linked list” of commands for moving non-contiguous blocks
- Virtually-addressed I/O bus with I/O MMU

Read "Virtual memory in contemporary microprocessors" by Jacob and Mudge before coming to next Lecture!!!