# COS 318: Operating Systems

# Virtual Memory Design Issues: Address Translation

# Virtual Memory Design Issues

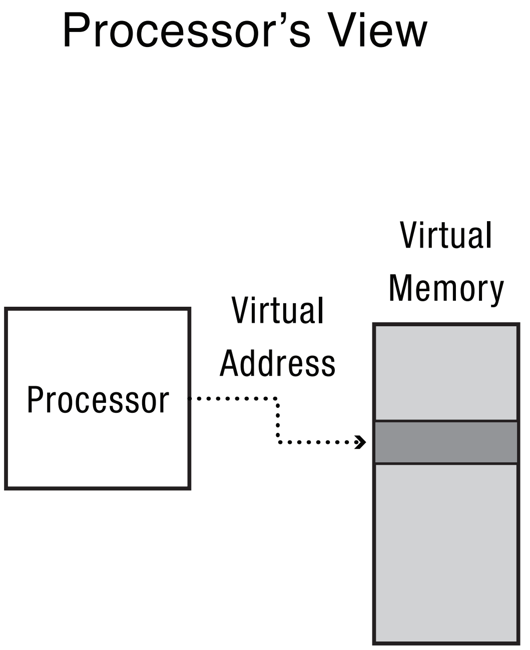
Any real design must take positions on or have solutions to:

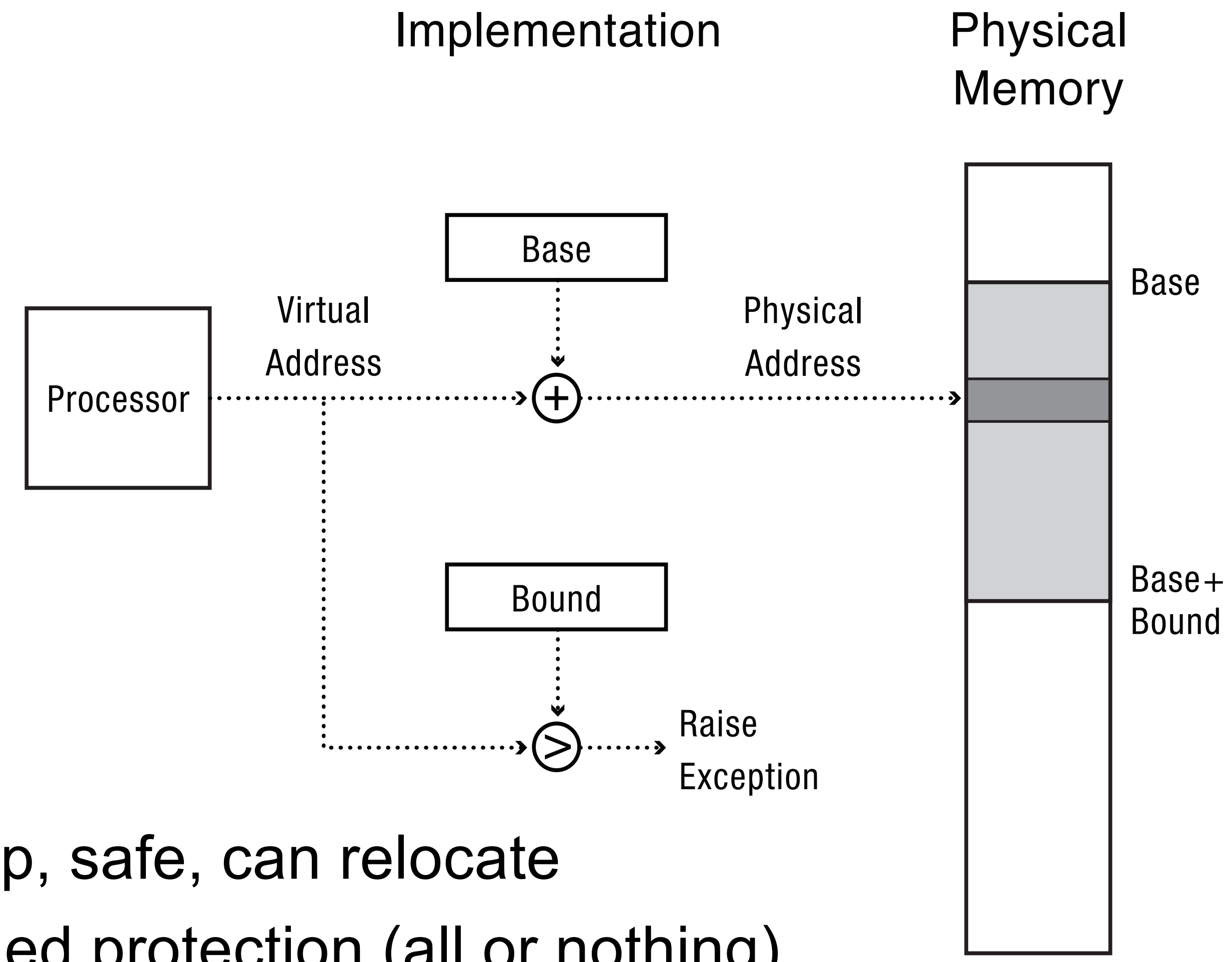
- Protection granularity
- Enabling memory sharing
  - Code, libraries, communication
- Flexibility and growth/shrinking of processes
- Efficiency
  - Translation efficiency (TLB as cache)
  - Access efficiency
    - Access time = h · memory access time + ( 1 - h ) · disk access time
    - E.g. Suppose memory access time = 100ns, disk access time = 10ms
    - If h = 90%, VM access time is 1ms!
- Process forking and copy on write

# Copy on Write

- Idea of Copy-on-Write
  - Child process inherits copy of parent's address space on fork
  - But don't really want to make a copy of all data upon fork
  - Would like to share as far as possible and make own copy only "on-demand", i.e. upon a write
- A way to do this is to protect data as read-only in both parent and child on fork
  - When a write is done by either, a protection fault occurs and a copy is made

# Recall Address translation: Base and Bound





- ◆ Pros: Simple, fast, cheap, safe, can relocate
- ◆ Cons: very coarse-grained protection (all or nothing)
  - Can't keep program from accidentally overwriting its own code
  - Can't share subsets of code/data with other processes (all or nothing)
  - Can't grow stack/heap as needed (stop program, change reg, …)

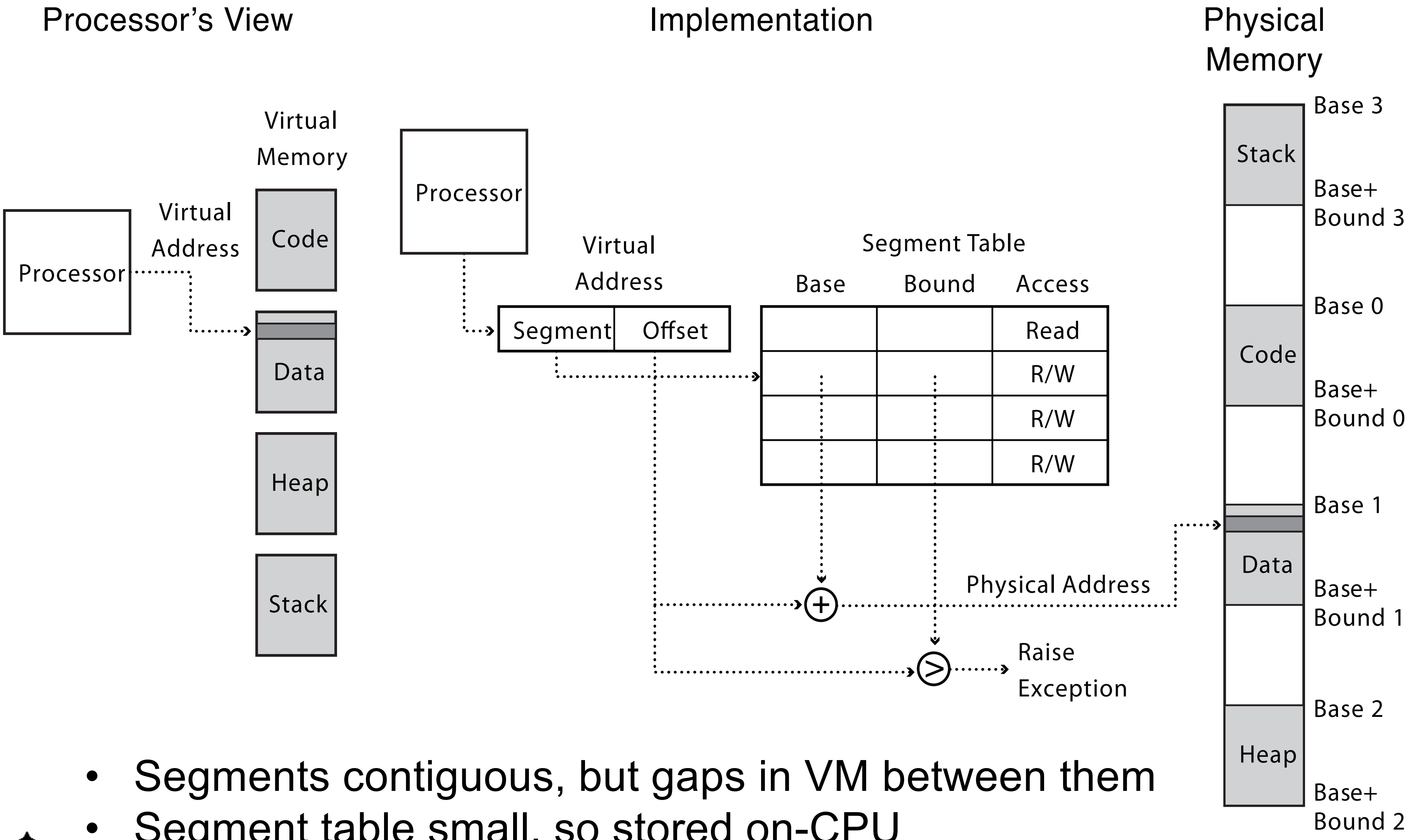
# Base and Bound

- Protection granularity: Entire process space (code+data)
  - Can’t keep program from accidentally overwriting its own code
- Sharing
  - Can’t share subsets of code/data with other processes (all or nothing)
- Growth/shrinking of processes
  - Can’t grow stack/heap as needed (stop program, change reg, …)
- Efficiency
  - Translation: fast (simple and cheap)
  - Access
    - External fragmentation leads to inefficient use of physical memory and hence high miss rates
- Process forking and copy on write
  - Protection granularity is entire process space: no benefit from copy on write

# Segmentation

- A segment is a contiguous region of *virtual* memory
- Every process has a segment table (in hardware)
  - Entry in table per segment
- Segment can be located anywhere in physical memory
  - Each segment has: start, length, access permission
- Protection is at granularity of segments

# Segmentation



- Segments contiguous, but gaps in VM between them
- Segment table small, so stored on-CPU
- Access control on per-segment basis

# Segmentation

- Protection granularity: A (user-defined) segment
  - Protects code separately from data
- Sharing
  - Processes can share segments: Same start, length, same/different access permissions
- Growth/shrinking of processes
  - Can grow segments independently, may need to relocate
- Efficiency
  - Translation: fast (few segments so table can be in hardware)
  - Access
    - Better than base+bound, but still external fragmentation due to holes
- Process forking and copy on write
  - Can do on a segment granularity: copy entire segment on first write to it

# Segments Enable Copy-on-Write

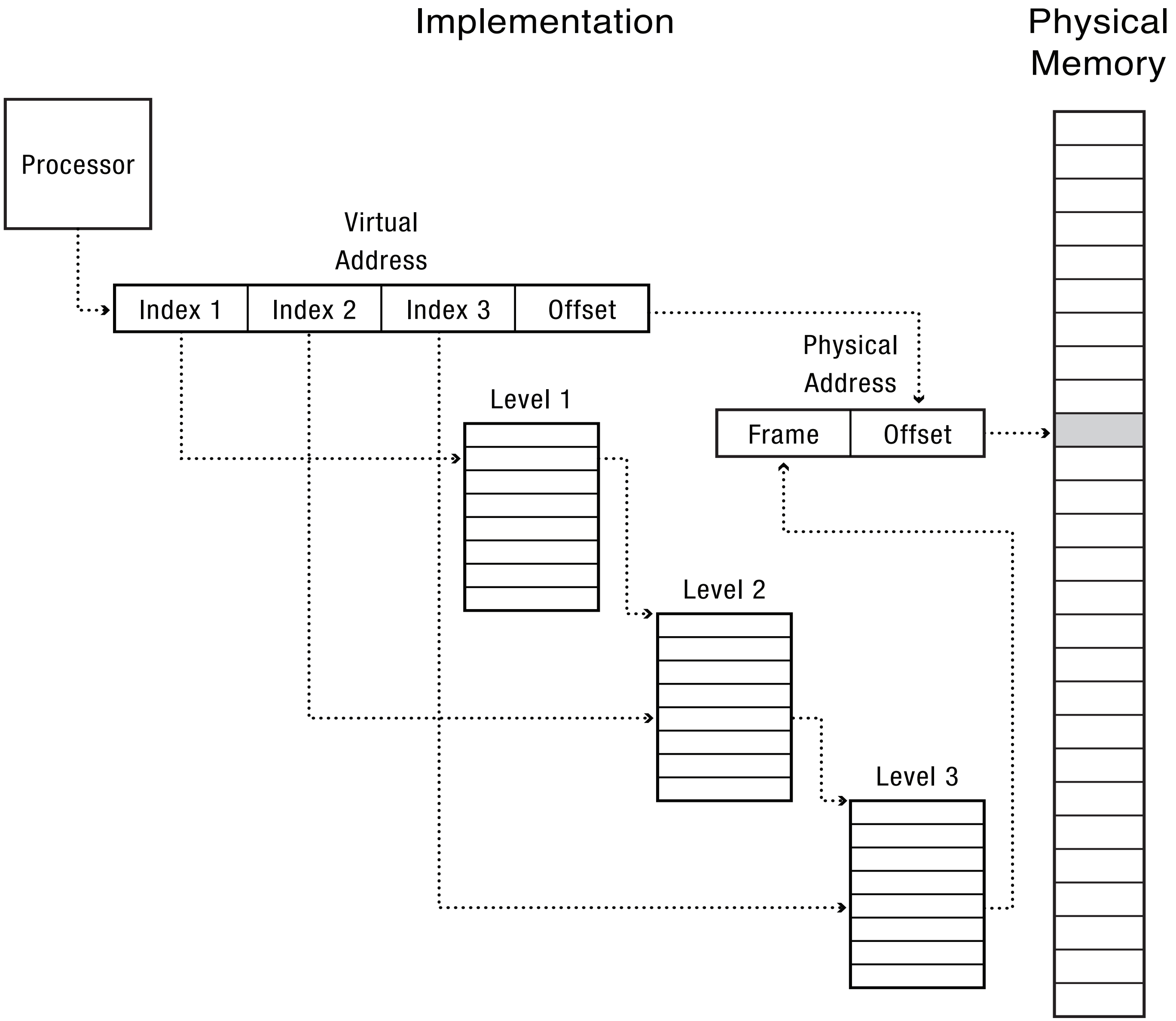
- To an extent …
  - Copy segment table into child, not entire address space
  - Mark all parent and child segments read-only
  - Start child process; return to parent
  - If child or parent writes to a segment (e.g. stack, heap)
    - Trap into kernel
    - At this point, make a copy of the data
- But segmentation has other problems too:
  - Complex memory management due to external fragmentation
    - Need to find chunk of particular size
    - Wasted space between chunks/segments
    - May need to rearrange memory from time to time to make room for new segment or to grow segment

# Paging

- Manage memory in fixed size units, or pages
- Finding a free page is easy
  - Effectively a bitmap allocation: 0011111100000001100
  - Every bit represents one physical page frame
- Every process has its own page table
  - Stored in physical memory
  - Supported by a couple of hardware registers:
    - Pointer to start of page table
    - Page table length

- Recall fancier structures: segmentation+paging, multi-level PT
  - Better for sparse virtual address spaces
  - E.g. per-processor heaps, per-thread stacks, memory mapped files, dynamically linked libraries, …
  - Eliminate need for page table entries for address space “holes”

# Multilevel Page Table

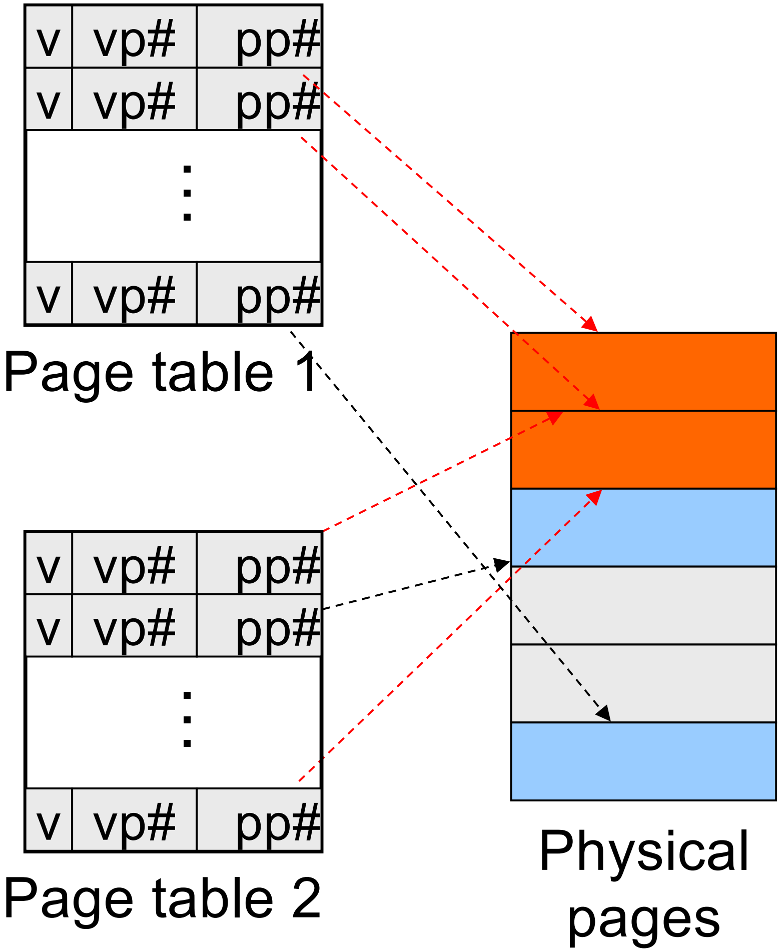


# Copy on Write with Paging

- UNIX fork with copy on write
  - Copy page table of parent into child process
  - Mark all pages (in new and old page tables) as read-only
  - Trap into kernel on write (in child or parent)
  - Copy page
  - Mark both as writeable
  - Resume execution
  - Finer grained than with segments

# Shared Pages

- PTEs from two processes share the same physical pages
  - Entries in both page tables to point to same page frames
  - What use cases?
- Implementation issues
  - What if you terminate a process with shared pages
  - Paging in/out shared pages
  - Deriving the working set for a process with shared pages
  - Pinning/unpinning shared pages



# Pinning (or Locking) Page Frames

- When do you need it?
  - When DMA is in progress, you don’t want to page the pages out to avoid CPU from overwriting the pages
- Mechanism?
  - A data structure to remember all pinned pages
  - Paging algorithm checks the data structure to decide on page replacement
  - Special calls to pin and unpin certain pages

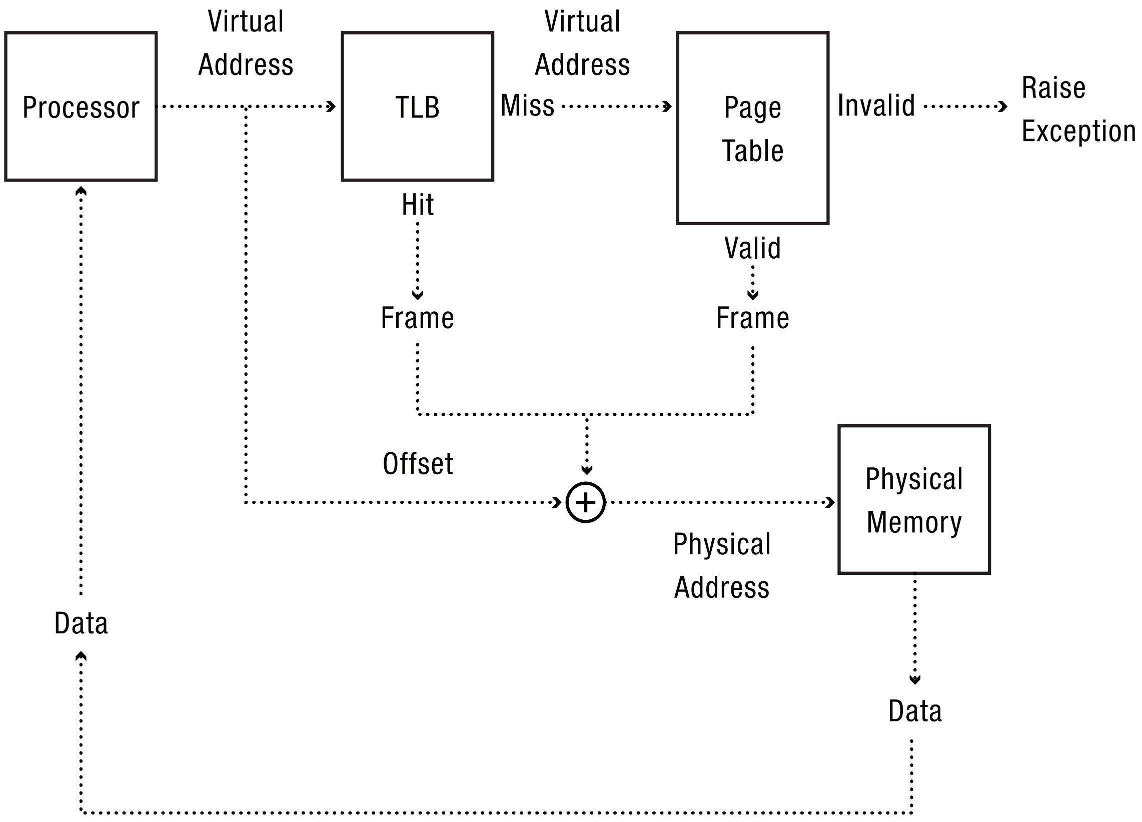
# Zeroing Pages

- Initialize pages to all zero values
  - Heap and static data are initialized
- How to implement?
  - On the first page fault on a data page or stack page, zero it
  - Or, have a special thread zeroing pages in the background

# Efficient address translation

◆ Recall translation lookaside buffer (TLB)

- Cache of recent virtual page -> physical page translations
- If cache hit, use translation
- If cache miss, walk (perhaps multi-level) page table



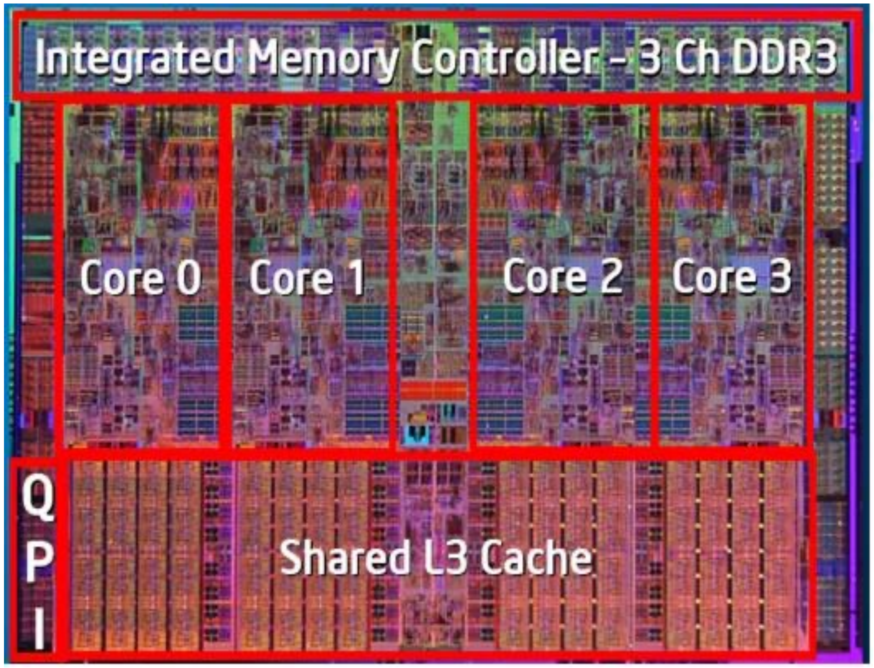
# TLB Performance

- Cost of translation =

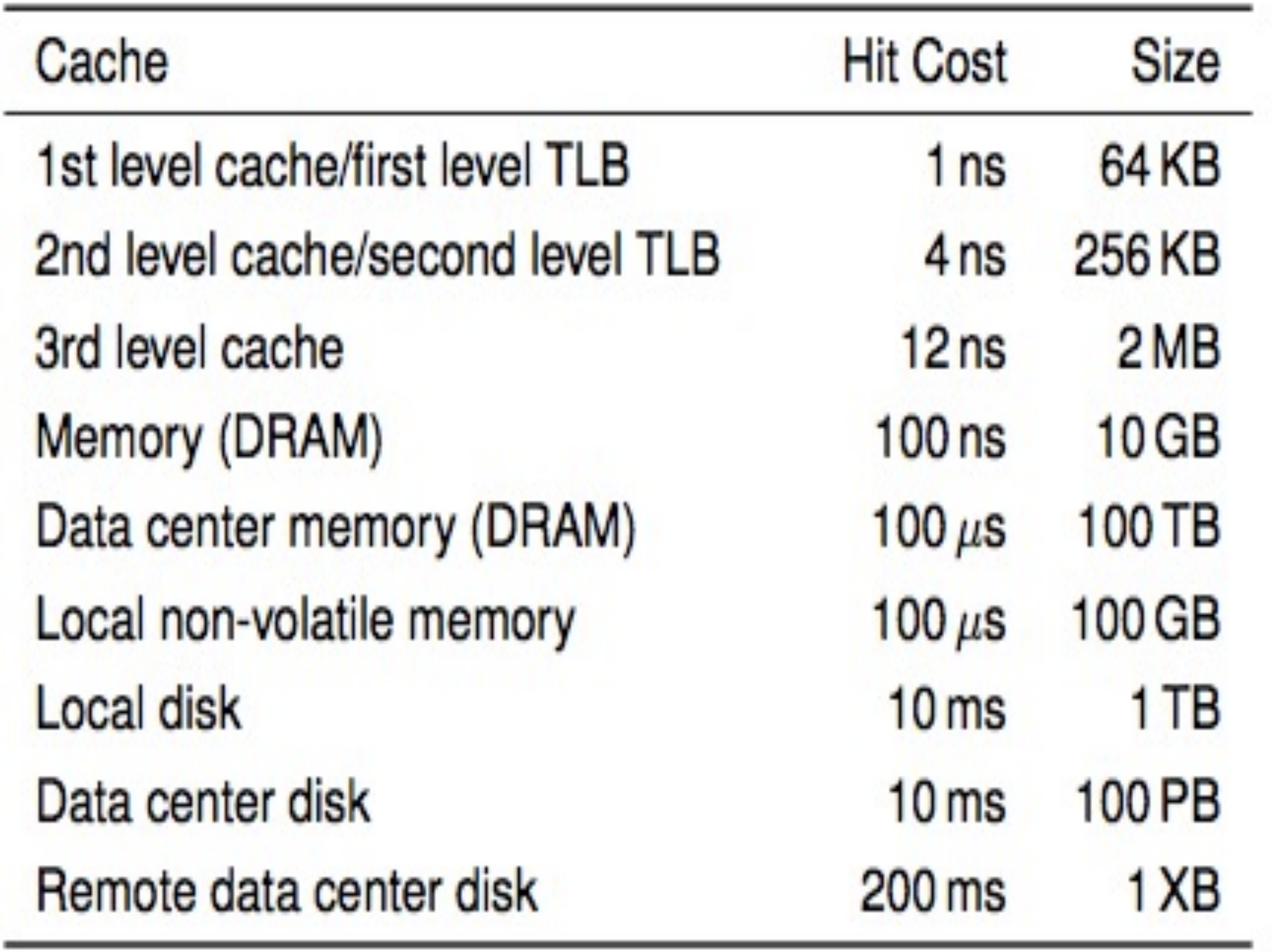
  Cost of TLB lookup + Prob(TLB miss) * cost of page table lookup
- Cost of a TLB miss on a modern processor?
  - Cost of multi-level page table walk
  - Software-controlled: plus cost of trap handler entry/exit
  - Use additional caching principles: multi-level caching, etc

TLB is important:

Intel i7 Processor Chip



# Intel i7 Memory hierarchy



| Cache | Hit Cost | Size |
|---|---|---|
| 1st level cache/first level TLB | 1 ns | 64 KB |
| 2nd level cache/second level TLB | 4 ns | 256 KB |
| 3rd level cache | 12 ns | 2 MB |
| Memory (DRAM) | 100 ns | 10 GB |
| Data center memory (DRAM) | 100 μs | 100 TB |
| Local non-volatile memory | 100 μs | 100 GB |
| Local disk | 10 ms | 1 TB |
| Data center disk | 10 ms | 100 PB |
| Remote data center disk | 200 ms | 1 XB |

i7 has 8MB as shared 3rd level cache; 2nd level cache is per-core

# Problem with Translation Slowdown

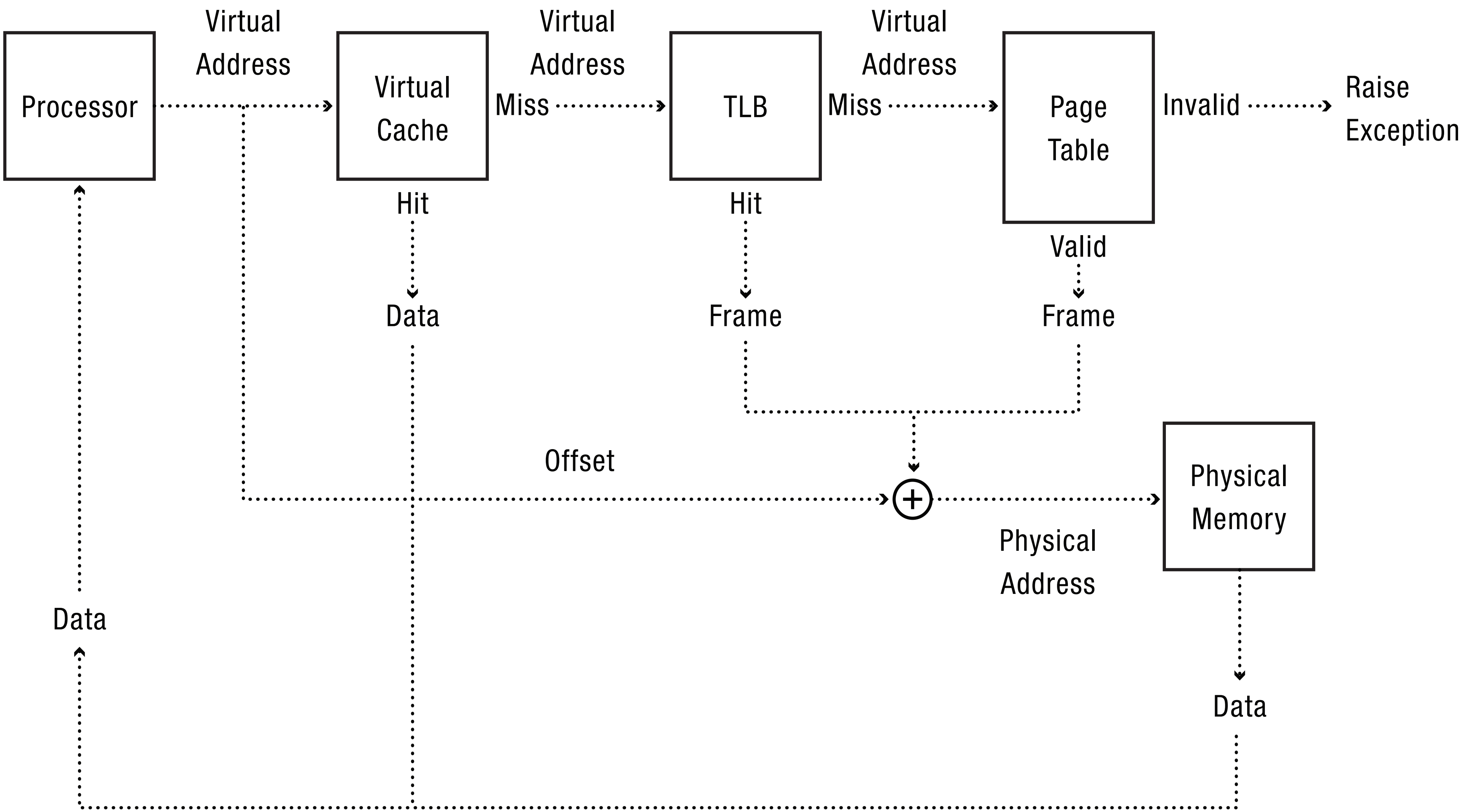
- What is the cost of a first level TLB miss?
  - Second level TLB lookup
- What is the cost of a second level TLB miss?
  - x86: 2-4 level page table walk

- Problem: Do we need to wait for the address translation in order to look up the caches (for code and data)?

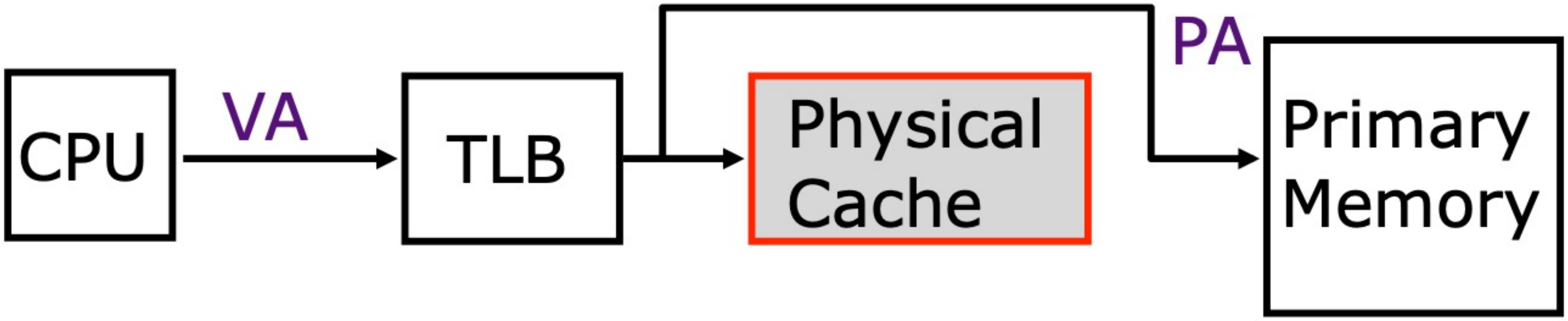
# Virtually vs. Physically Addressed Caches

- It can be too slow to first access TLB to find physical address, then look up address in the cache
- Instead, first level cache is virtually addressed
- In parallel with cache lookup using virtual address, access TLB to generate physical address in case of a cache miss

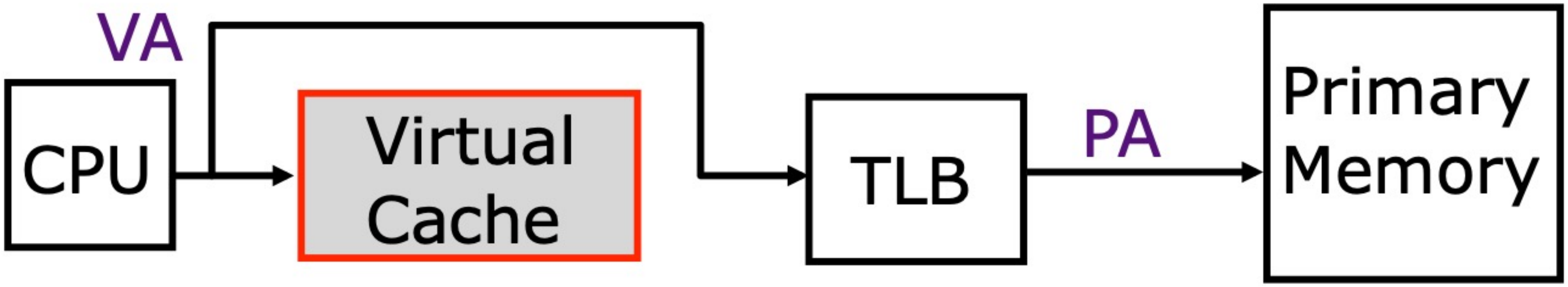
# Virtually addressed caches



# Physically vs virtually addressed cache



Physically addressed cache

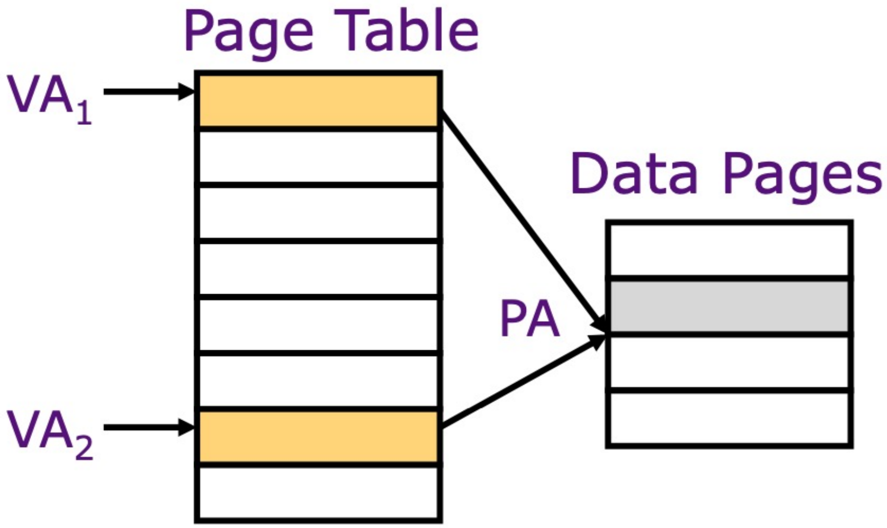


Virtually addressed cache

- Problems with virtually addressed cache?

Diagram copied

# Aliasing in virtually addressed cache



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 |
| | |

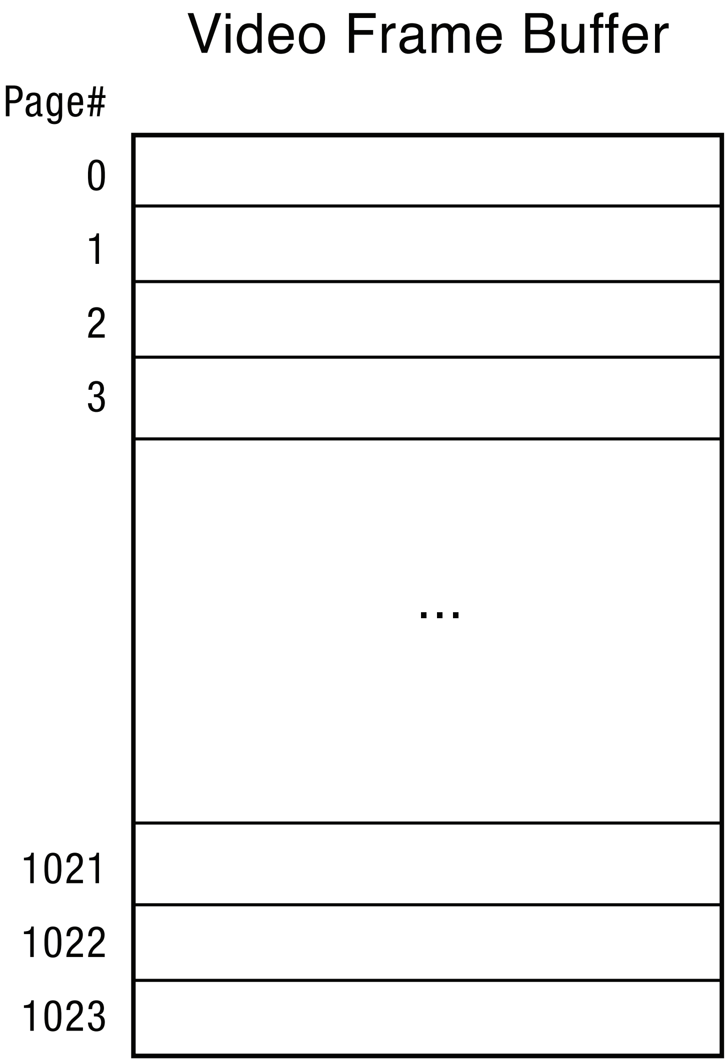
Virtual cache can have two copies of same physical data. Writes to one copy not visible to reads of other!

- Solution?

Diagram copied

# When do TLBs work/not work, Part I?

- Video Frame Buffer: 32 bits x 1K x 1K = 4MB

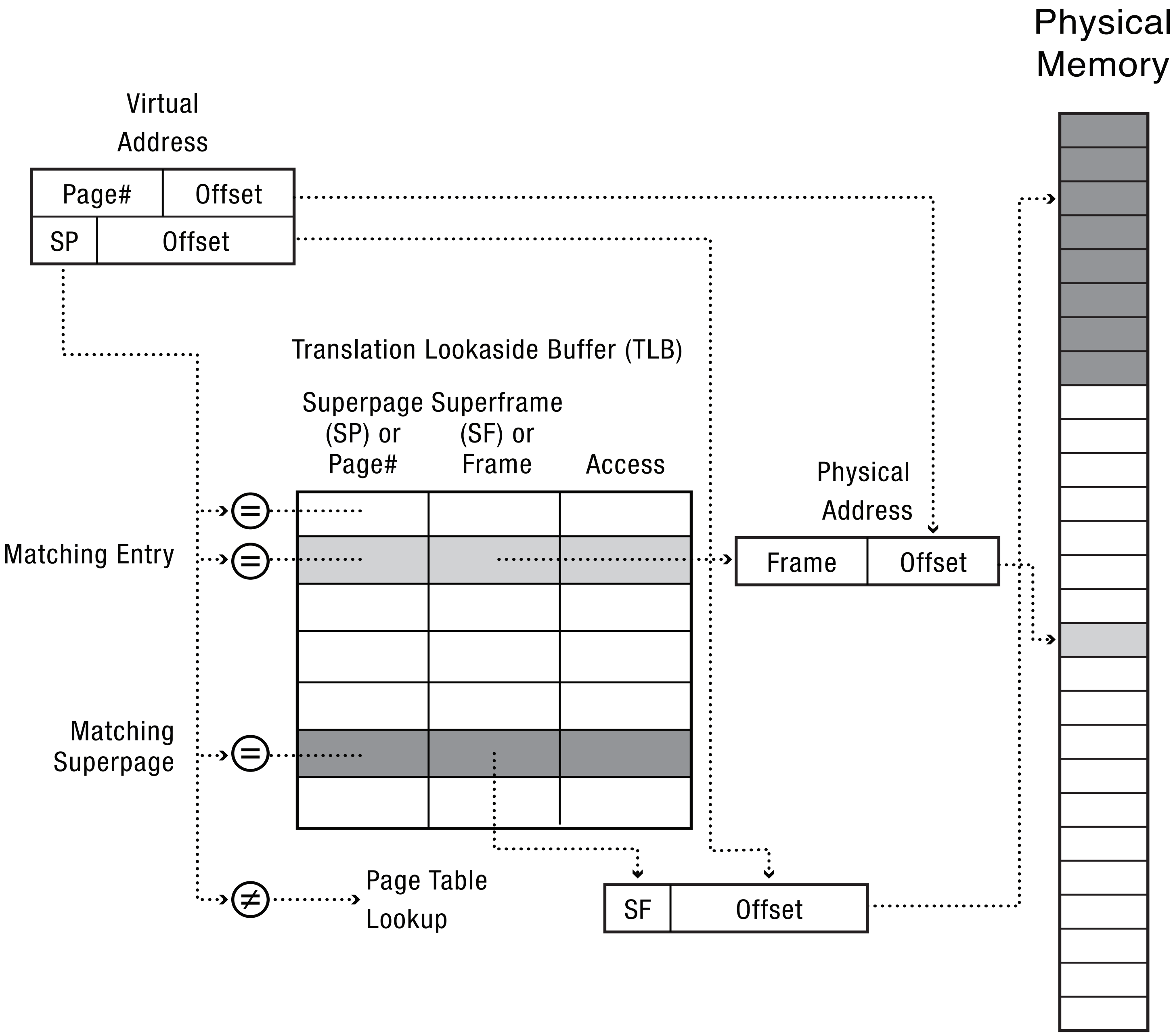


# Superpages

- On many systems, TLB entry can be
  - A page
  - A superpage: a set of contiguous pages

- x86: superpage is a set of pages with one PTE
  - x86 TLB entries
    - 4KB
    - 2MB
    - 1GB

# Superpages



Physical Memory

Virtual Address

Page# | Offset

SP | Offset

Translation Lookaside Buffer (TLB)

Superpage (SP) or Page#

Superframe (SF) or Frame

Access

Matching Entry

Matching Superpage

Page Table Lookup

Physical Address

Frame | Offset

SF | Offset

# When do TLBs Work/Not Work, Part 2

- What happens when the OS changes the permissions on a page?
  - For demand paging, copy on write, zero on reference, …
- On a single-core processor?
- On a multicore?

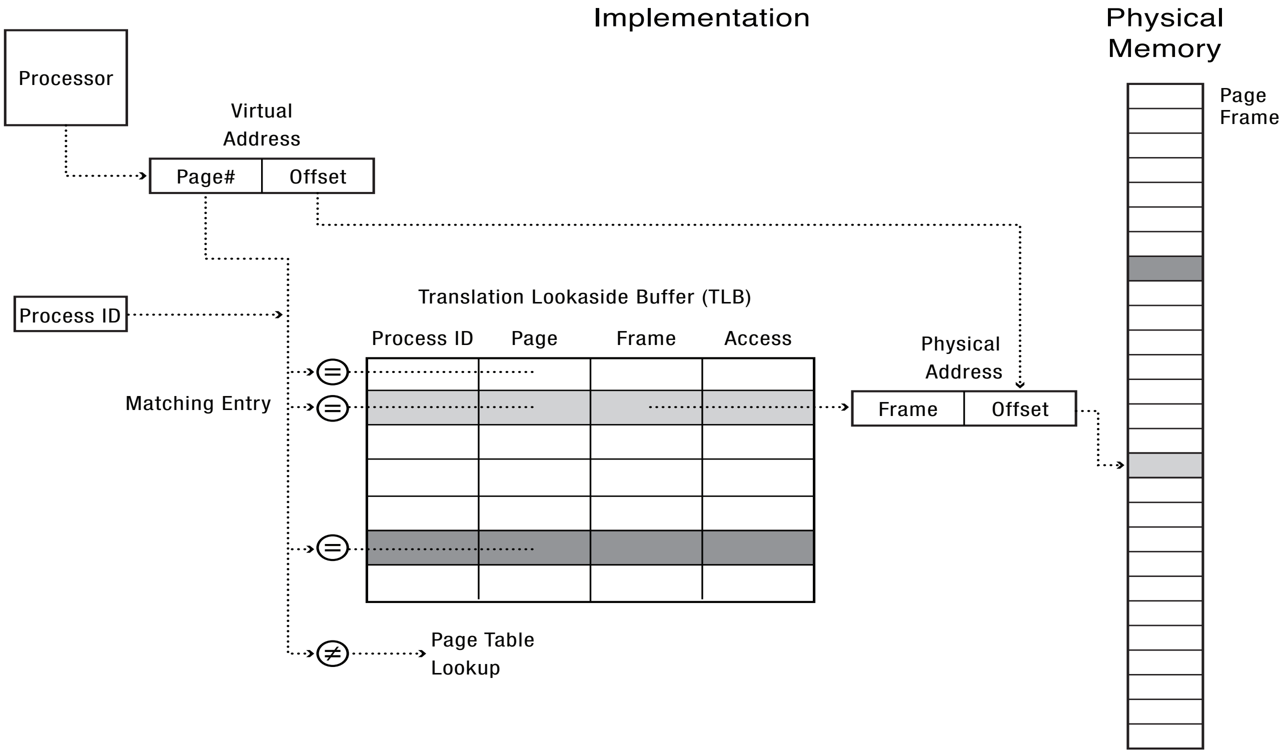
# When do TLBs Work/Not Work, Part 3

◆ What happens on a context switch?

- Keep using TLB?
- Flush TLB?

◆ Solution: Tagged TLB

- Each TLB entry has process ID
- TLB hit only if process ID matches current process



Implementation

Physical Memory

Processor

Virtual Address

Page#

Offset

Process ID

Translation Lookaside Buffer (TLB)

| Process ID | Page | Frame | Access |
|---|---|---|---|

Matching Entry

Physical Address

Frame

Offset

Page Frame

Page Table Lookup

# Summary

- Must consider many issues
  - Global and local replacement strategies
  - Management of backing store
  - Primitive operations
    - Pin/lock pages
    - Zero pages
    - Shared pages
    - Copy-on-write
- Real system designs are complex