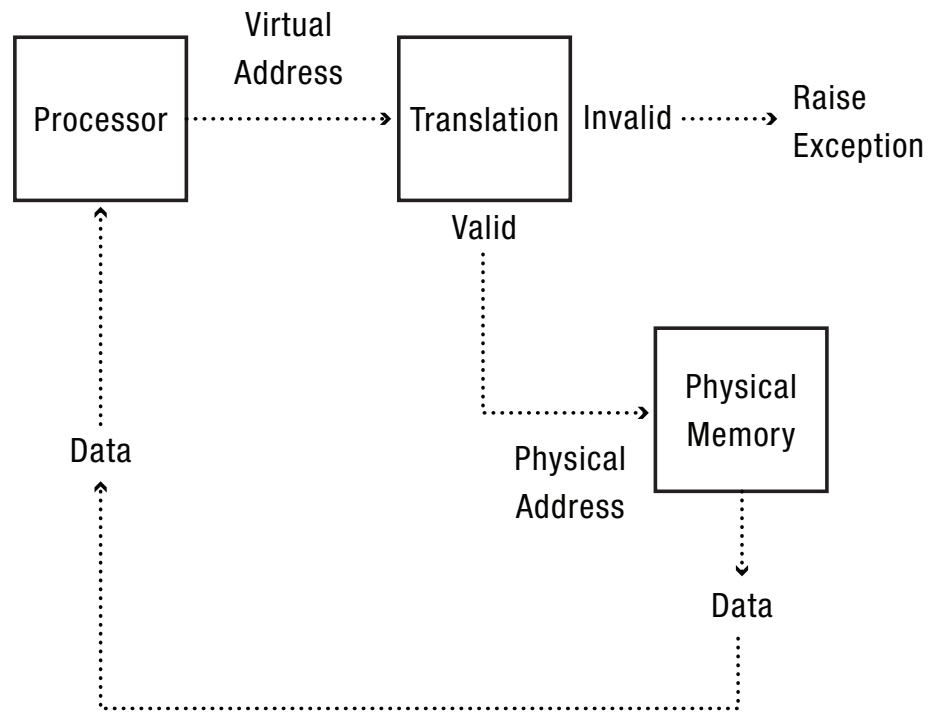


Address Translation

Main Points

- Address Translation Concept
 - How do we convert a virtual address to a physical address?
- Flexible Address Translation
 - Base and bound
 - Segmentation
 - Paging
 - Multilevel translation
- Efficient Address Translation
 - Translation Lookaside Buffers
 - Virtually and physically addressed caches

Address Translation Concept



Address Translation Goals

- Memory protection
- Memory sharing
 - Shared libraries, interprocess communication
- Sparse addresses
 - Multiple regions of dynamic allocation (heaps/stacks)
- Efficiency
 - Memory placement
 - Runtime lookup
 - Compact translation tables
- Portability

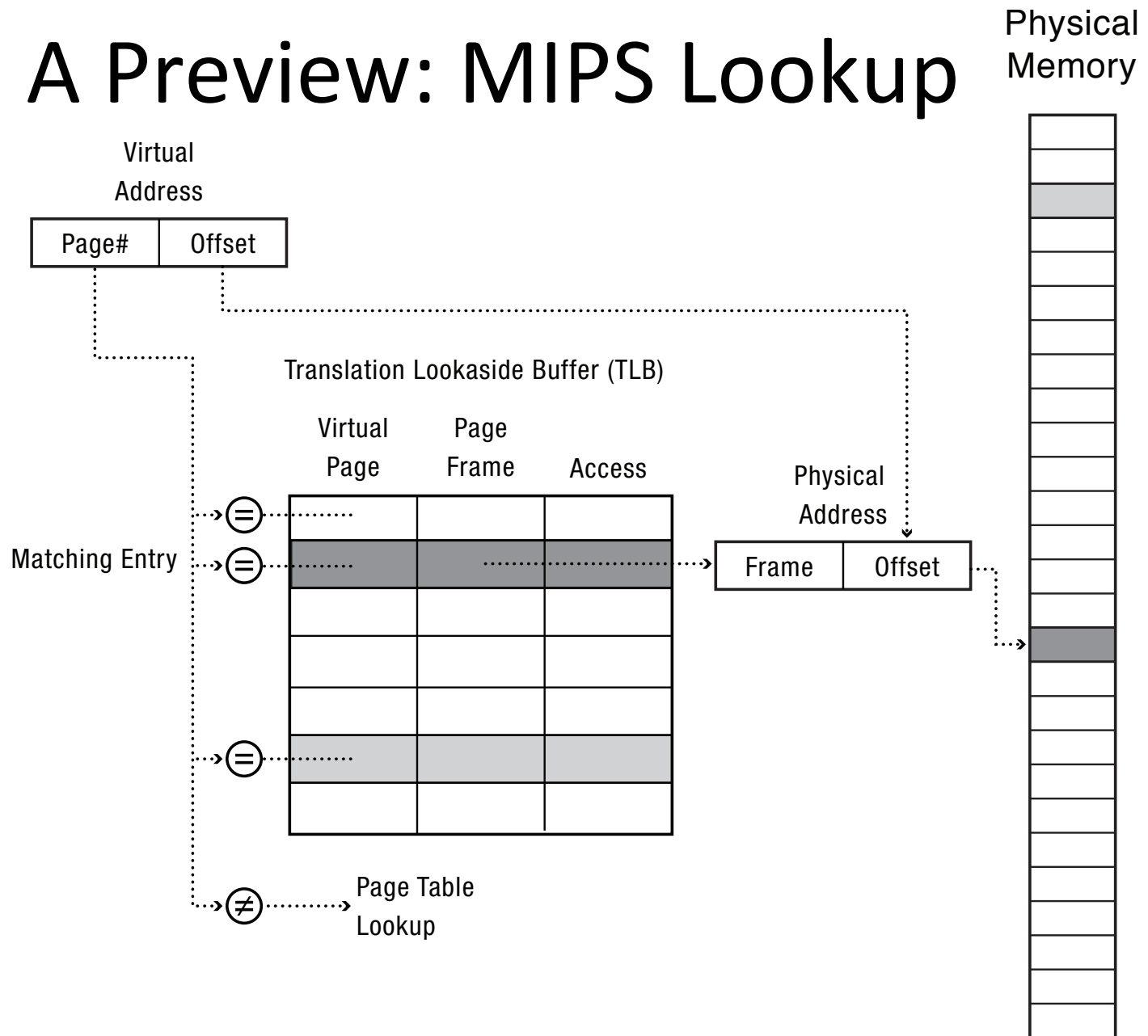
Bonus Feature

- What can you do if you can (selectively) gain control whenever a program reads or writes a particular virtual memory location?
- Examples:
 - Copy on write
 - Zero on reference
 - Fill on demand
 - Demand paging
 - Memory mapped files
 - ...

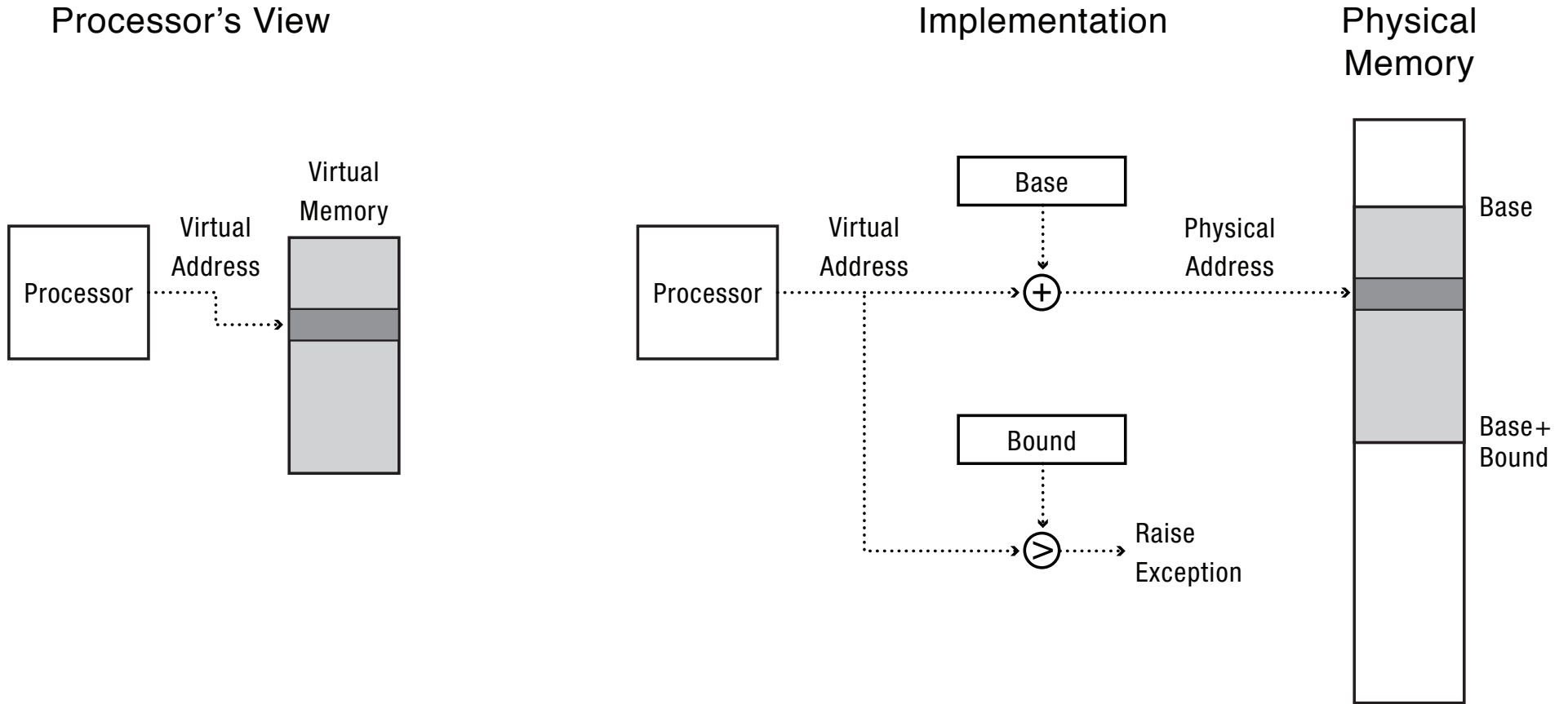
A Preview: MIPS Address Translation

- Software-Loaded Translation lookaside buffer (TLB)
 - Cache of virtual page -> physical page translations
 - If TLB hit, physical address
 - If TLB miss, trap to kernel
 - Kernel fills TLB with translation and resumes execution
- Kernel can implement *any* page translation
 - Page tables
 - Multi-level page tables
 - Inverted page tables
 - ...

A Preview: MIPS Lookup



Virtually Addressed Base and Bounds



Question

- With virtually addressed base and bounds, what is saved/restored on a process context switch?

Virtually Addressed Base and Bounds

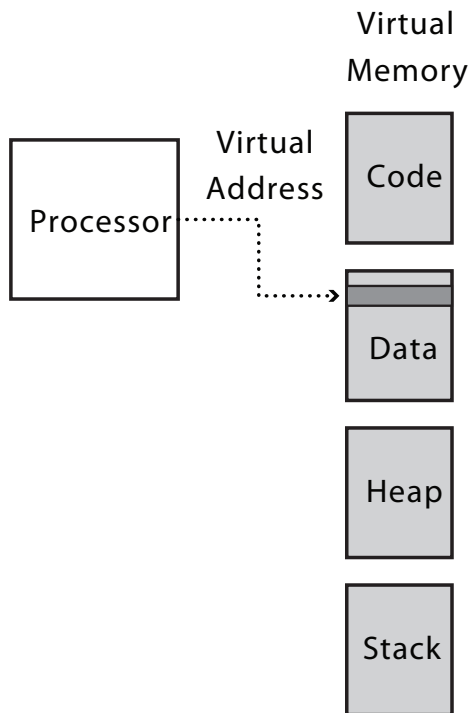
- Pros?
 - Simple
 - Fast (2 registers, adder, comparator)
 - Safe
 - Can relocate in physical memory without changing process
- Cons?
 - Can't keep program from accidentally overwriting its own code
 - Can't share code/data with other processes
 - Can't grow stack/heap as needed

Segmentation

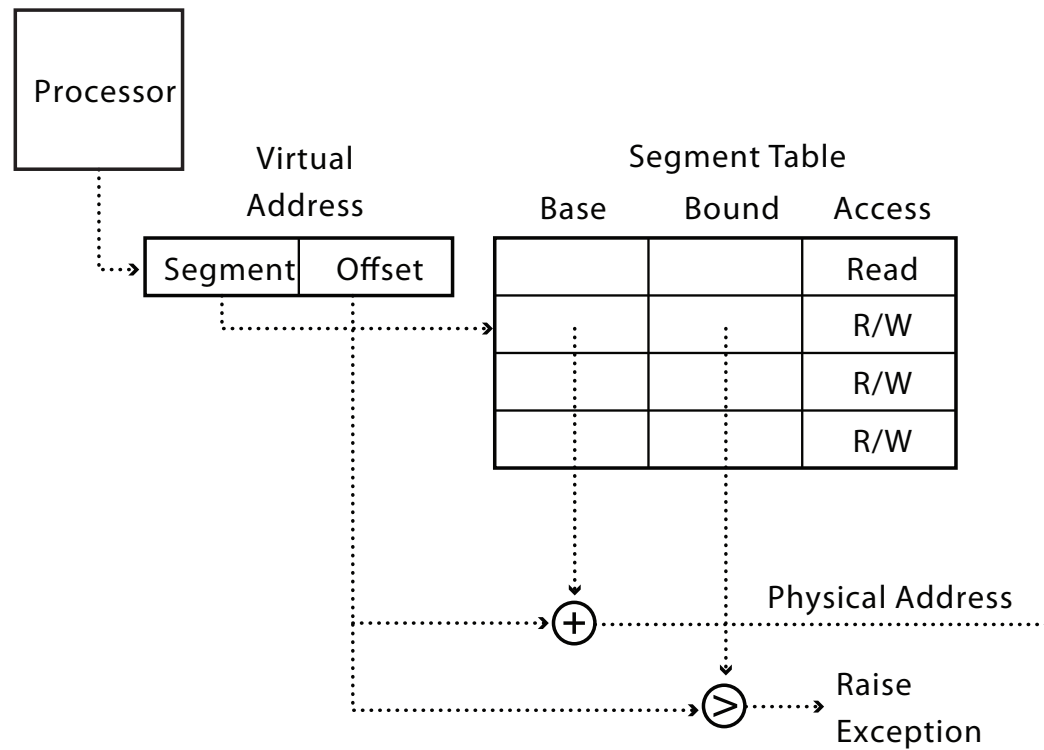
- Segment is a contiguous region of *virtual* memory
- Each process has a segment table (in hardware)
 - Entry in table = segment
- Segment can be located anywhere in physical memory
 - Each segment has: start, length, access permission
- Processes can share segments
 - Same start, length, same/different access permissions

Segmentation

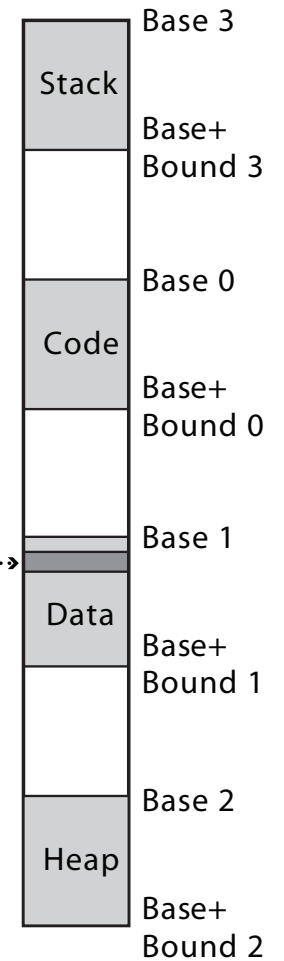
Processor's View



Implementation



Physical Memory



		Segment start	length	
2 bit segment #	code	0x4000	0x700	
12 bit offset	data	0	0x500	
	heap	-	-	
Virtual Memory	stack	0x2000	0x1000	Physical Memory

main: 240	store #1108, r2	x: 108	a b c \0
244	store pc+8, r31	...	
248	jump 360	main: 4240	store #1108, r2
24c		4244	store pc+8, r31
...		4248	jump 360
strlen: 360	loadbyte (r2), r3	424c	
...
420	jump (r31)	strlen: 4360	loadbyte (r2),r3
...		...	
x: 1108	a b c \0	4420	jump (r31)
...		...	

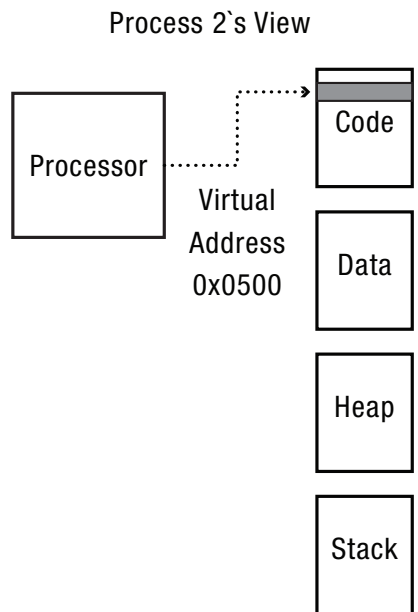
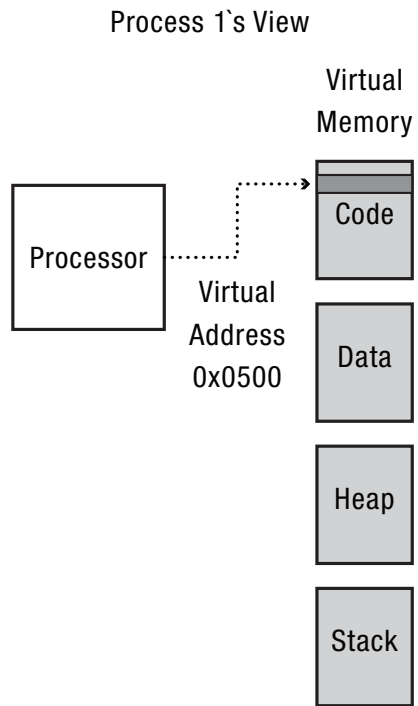
Question

- With segmentation, what is saved/restored on a process context switch?

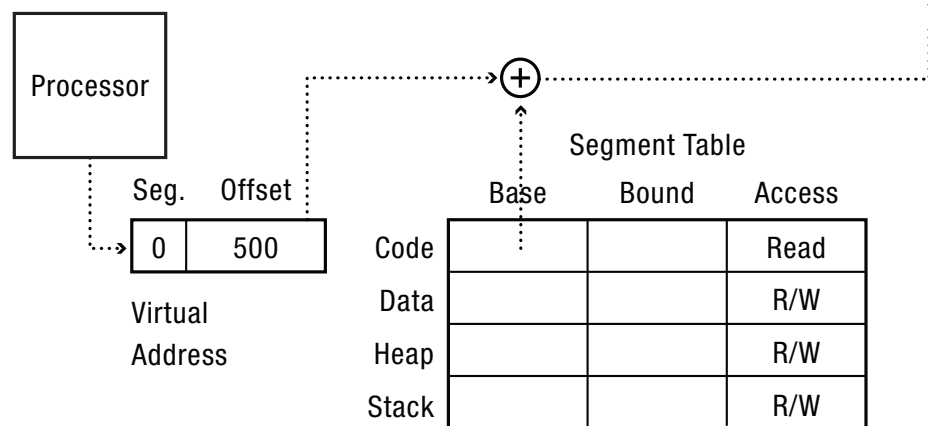
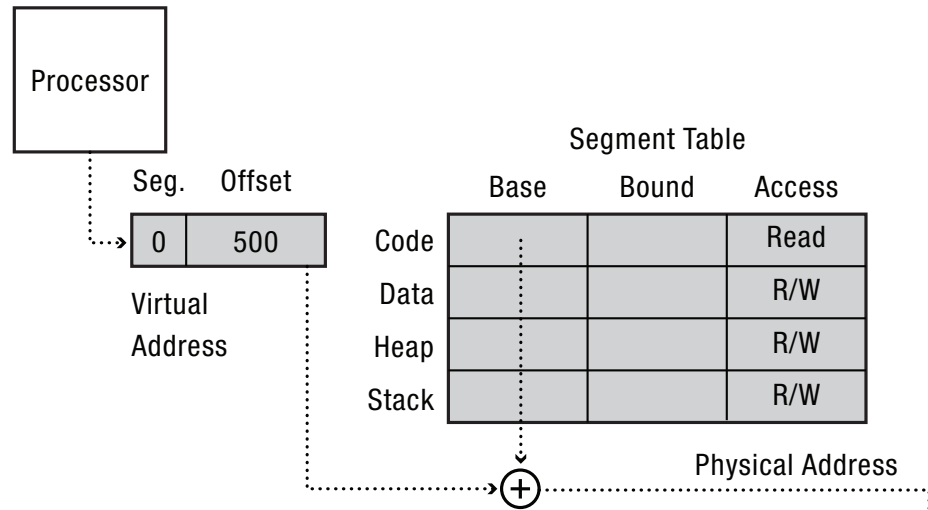
UNIX fork and Copy on Write

- UNIX fork
 - Makes a complete copy of a process
- Segments allow a more efficient implementation
 - Copy segment table into child
 - Mark parent and child segments read-only
 - Start child process; return to parent
 - If child or parent writes to a segment (ex: stack)
 - trap into kernel
 - make a copy of the segment and resume

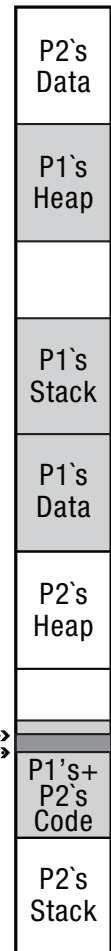
Processor's View



Implementation



Physical Memory



Question

- How much physical memory is needed for the stack or heap?

Expand Stack on Reference

- When program references memory beyond end of stack
 - Segmentation fault into OS kernel
 - Kernel allocates some additional memory
 - How much?
 - Zeros the memory
 - avoid accidentally leaking information!
 - Modify segment table
 - Resume process

Segmentation

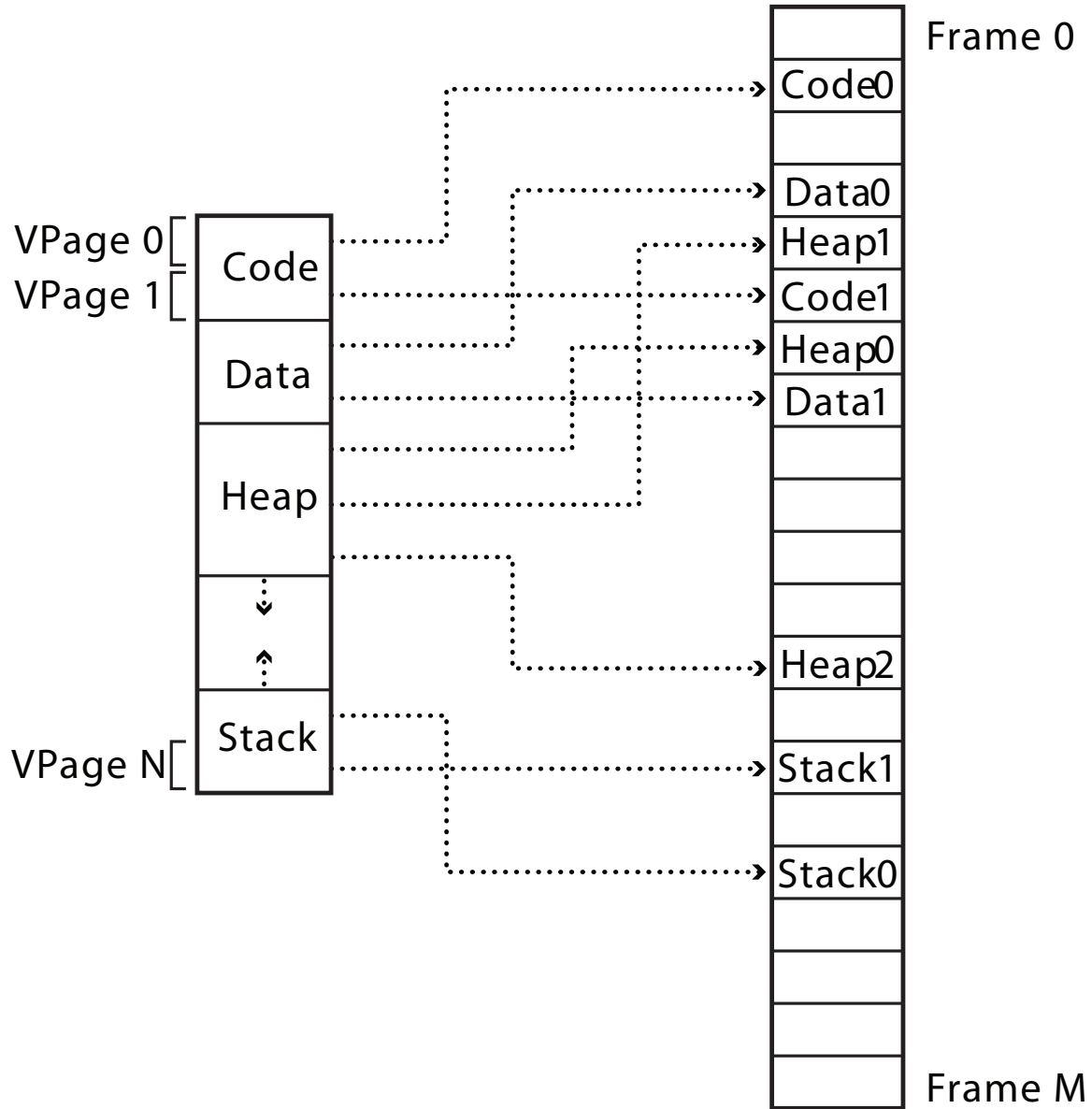
- Pros?
 - Can share code/data segments between processes
 - Can protect code segment from being overwritten
 - Can transparently grow stack/heap as needed
 - Can detect if need to copy-on-write
- Cons? Complex memory management
 - Need to find chunk of a particular size
 - May need to rearrange memory to make room for new segment or growing segment
 - External fragmentation: wasted space between chunks

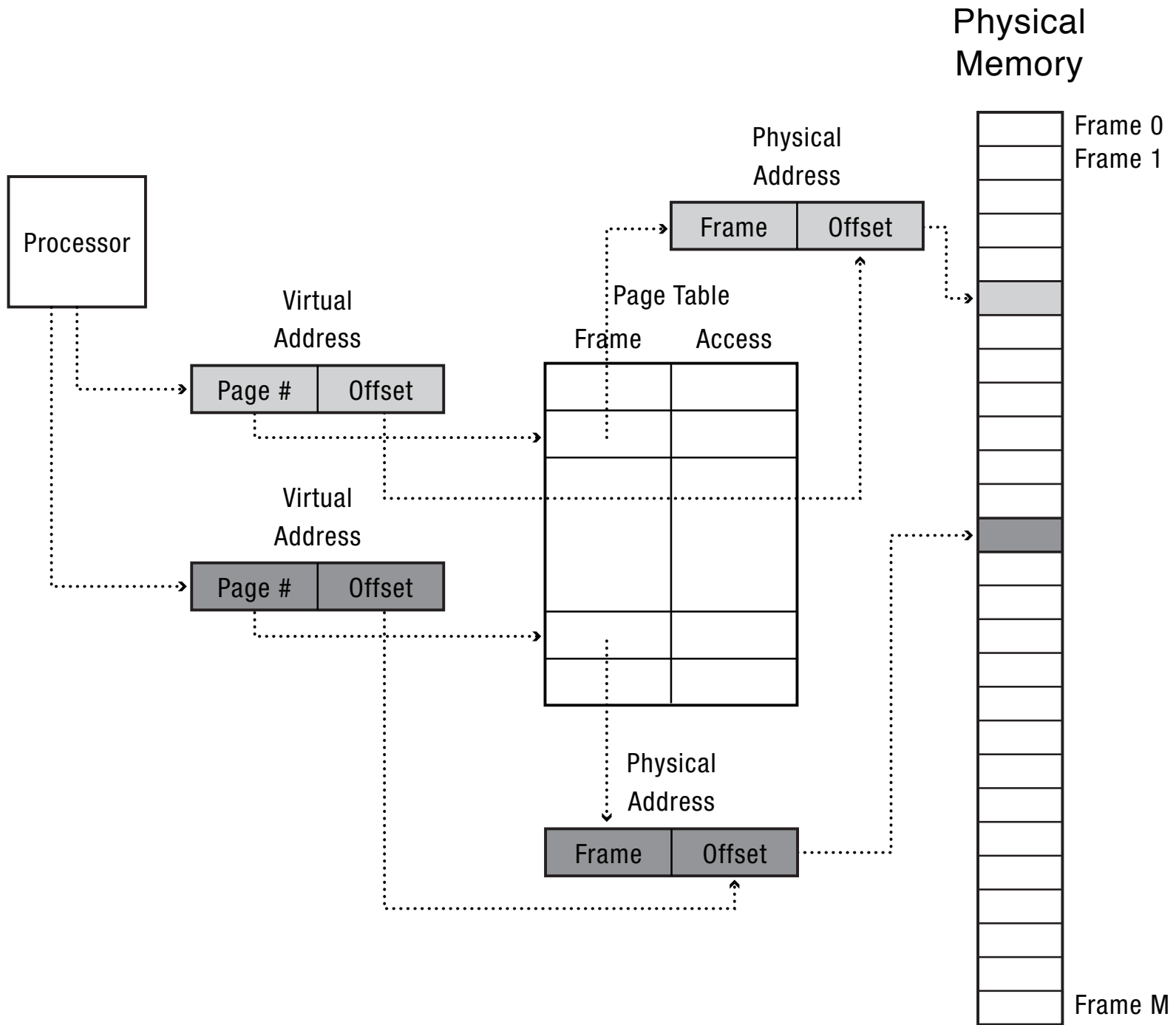
Paged Translation

- Manage memory in fixed size units, or pages
- Finding a free page is easy
 - Bitmap allocation: 00111111000000001100
 - Each bit represents one physical page frame
- Each process has its own page table
 - Stored in physical memory
 - Hardware registers
 - pointer to page table start
 - page table length

Processor's View

Physical Memory





Process View

A
B
C
D
E
F
G
H
I
J
K
L

Physical Memory

I
J
K
L
E
F
G
H
A
B
C
D

Page Table

4
3
1

Paging Questions

- With paging, what is saved/restored on a process context switch?
 - Pointer to page table, size of page table
 - Page table itself is in main memory
- What if page size is very small?
- What if page size is very large?
 - Internal fragmentation: if we don't need all of the space inside a fixed size chunk

Paging and Sharing

- Can we share memory between processes?
- Set both page tables point to same page frames
- Need *core map*
 - Array of information about each physical page frame
 - Set of processes pointing to that page frame
 - When zero, can reclaim!

Paging and Copy on Write

- UNIX fork
 - 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

Question

- Can I run a program when only some of its code is in physical memory?

Fill On Demand

- Set all page table entries to invalid
- When a page is referenced for first time, kernel trap
- Kernel brings page in from disk
- Resume execution
- Remaining pages can be transferred in the background while program is running

A Case for Sparse Address Spaces

- Might want many separate segments
 - Per-processor heaps
 - Per-thread stacks
 - Memory-mapped files
 - Dynamically linked libraries
- What if virtual address space is large?
 - 32-bits, 4KB pages => 500K page table entries
 - 64-bits => 4 quadrillion page table entries

Multi-level Translation

- Tree of translation tables
 - Paged segmentation
 - Multi-level page tables
 - Multi-level paged segmentation
- All have pages as lowest level; why?

Fixed Size Pages at Lowest Level

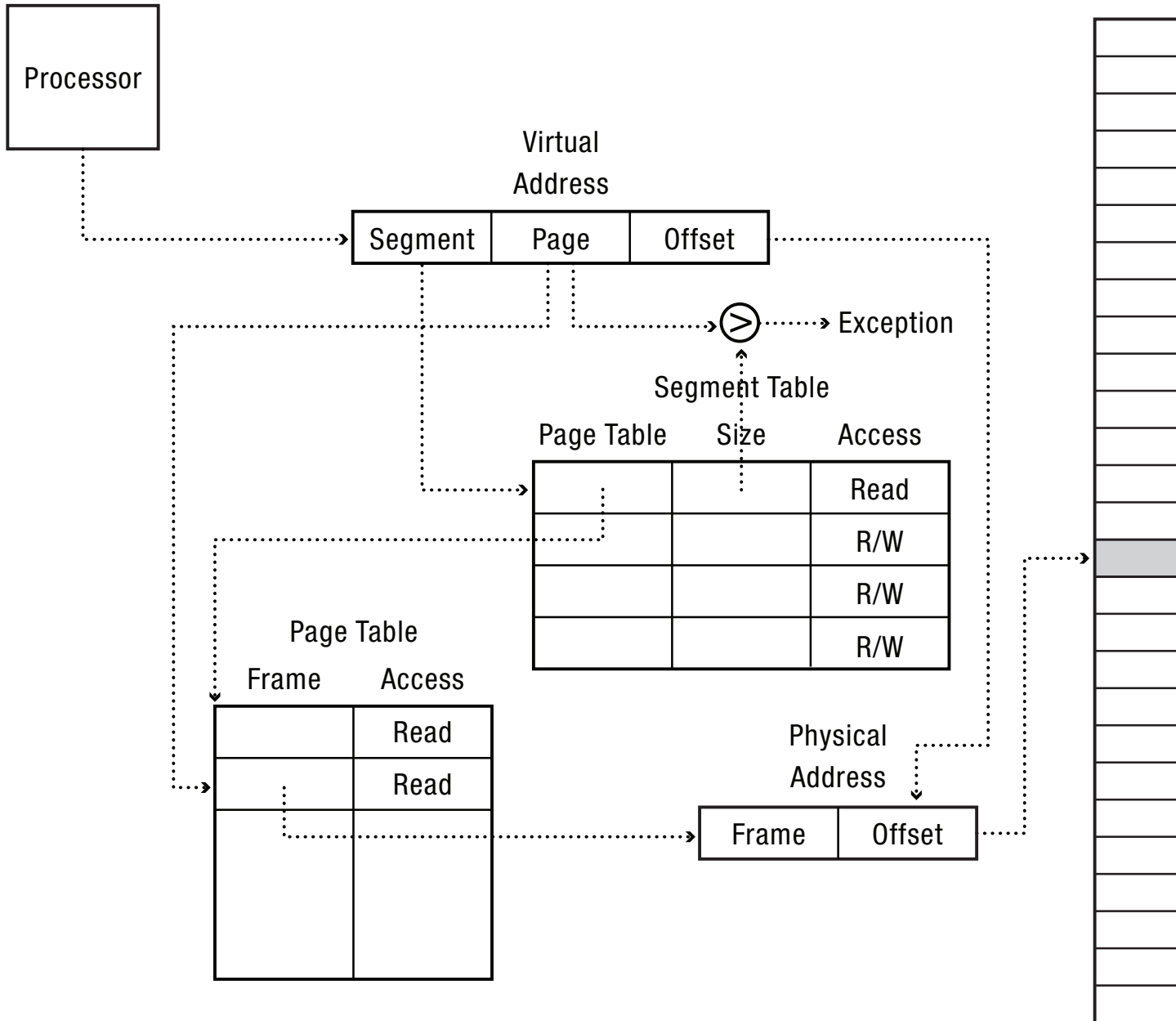
- Efficient memory allocation (vs. segments)
- Efficient for sparse addresses (vs. paging)
- Efficient disk transfers (fixed size units)
- Easier to build translation lookaside buffers
- Efficient reverse lookup (from physical -> virtual)
- Variable granularity for protection/sharing

Paged Segmentation

- Process memory is segmented
- Segment table entry:
 - Pointer to page table
 - Page table length (# of pages in segment)
 - Access permissions
- Page table entry:
 - Page frame
 - Access permissions
- Share/protection at either page or segment-level

Implementation

Physical Memory



Question

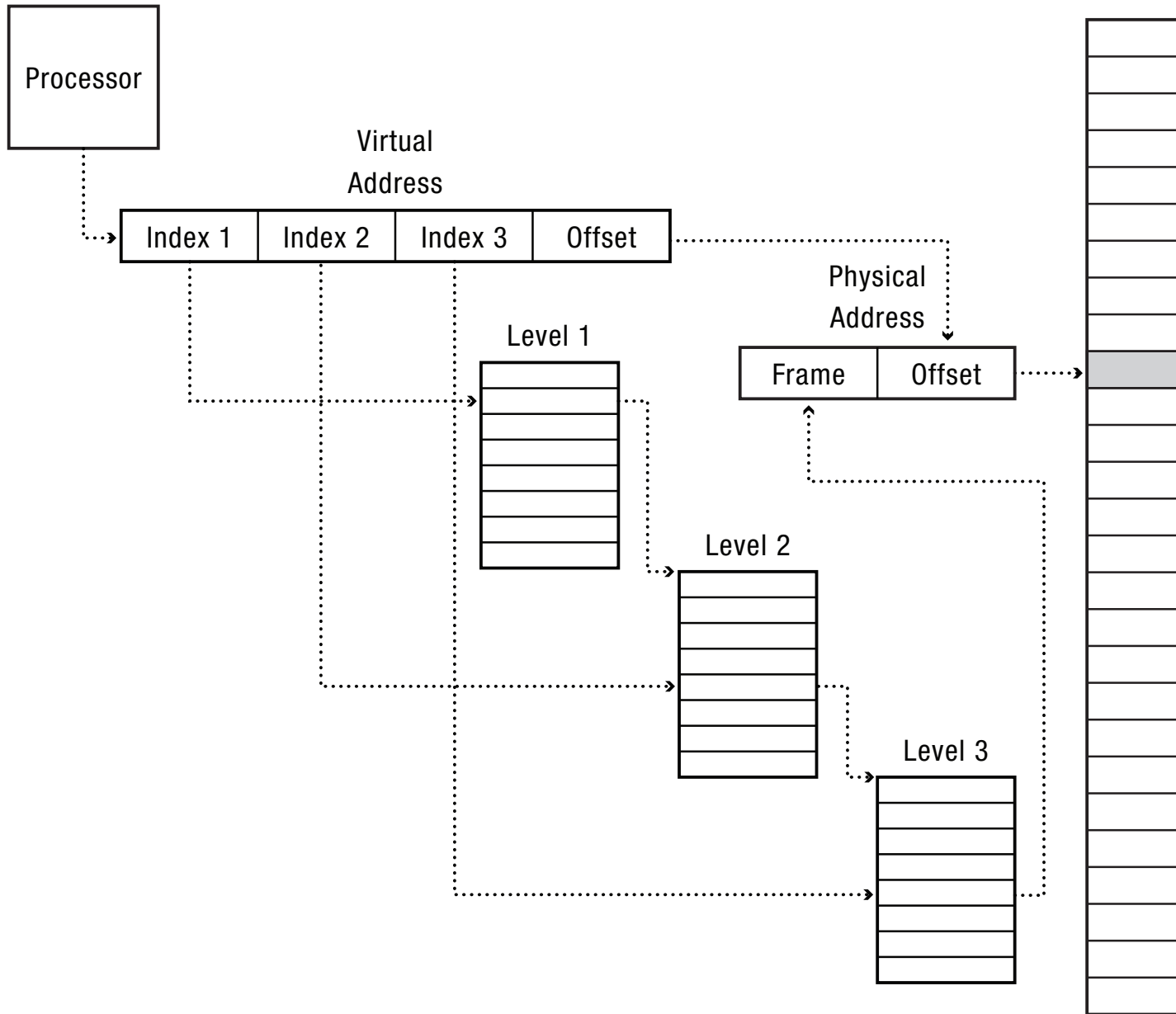
- With paged segmentation, what must be saved/restored across a process context switch?

Multilevel Paging

What if each page table points to a page table?

Implementation

Physical Memory



Question

- Write pseudo-code for translating a virtual address to a physical address for a system using 3-level paging, with 8 bits of address per level

x86 Multilevel Paged Segmentation

- Global Descriptor Table (segment table)
 - Pointer to page table for each segment
 - Segment length
 - Segment access permissions
 - Context switch: change global descriptor table register (GDTR, pointer to global descriptor table)
- Multilevel page table
 - 4KB pages; each level of page table fits in one page
 - 32-bit: two level page table (per segment)
 - 64-bit: four level page table (per segment)
 - Omit sub-tree if no valid addresses

Multilevel Translation

- Pros:
 - Allocate/fill only page table entries that are in use
 - Simple memory allocation
 - Share at segment or page level
- Cons:
 - Space overhead: one pointer per virtual page
 - Multiple lookups per memory reference

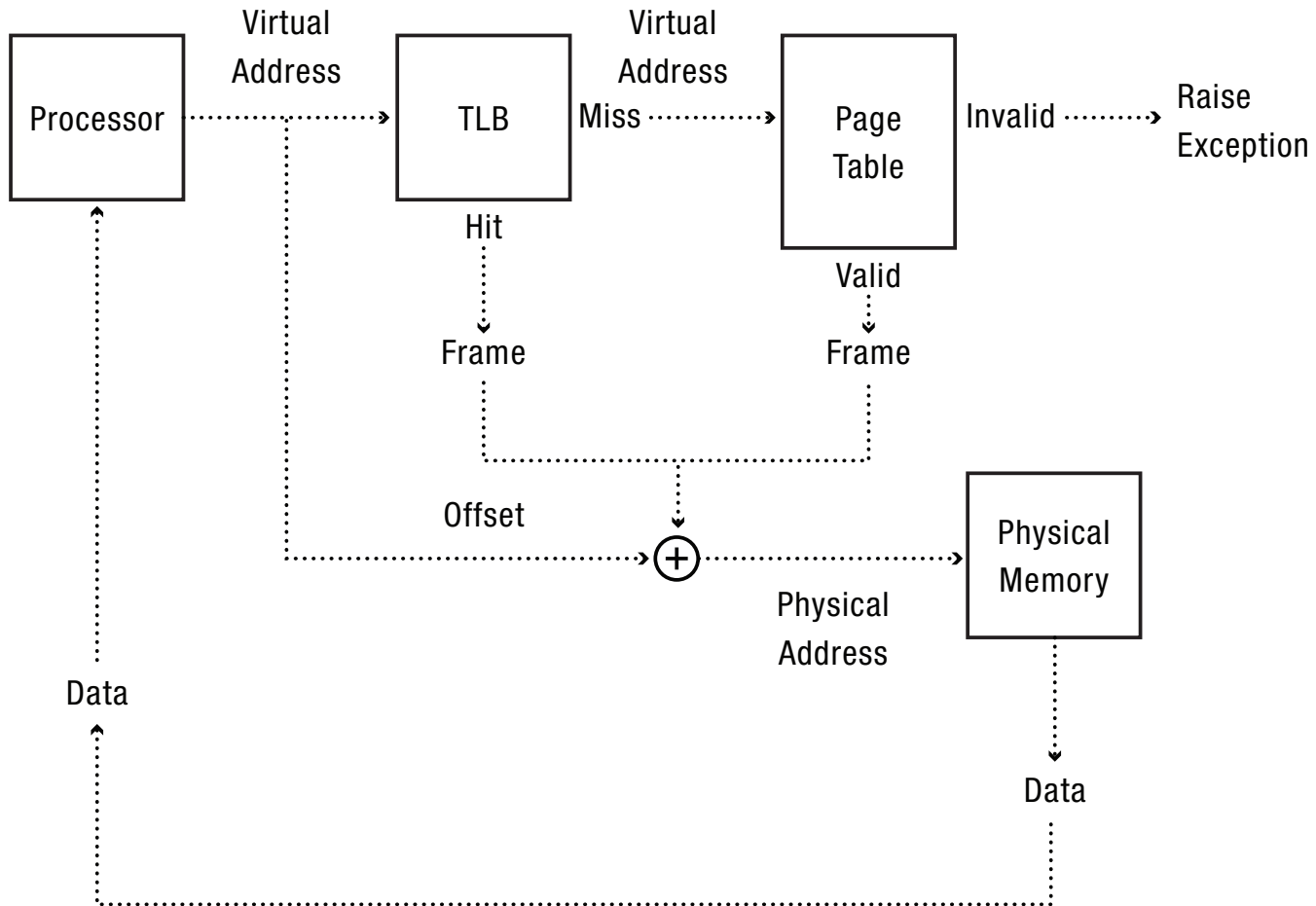
Page Translation in the OS

- OS's need to keep their own data structures
 - List of memory objects (segments)
 - Virtual page -> physical page frame
 - Physical page frame -> set of virtual pages
- An option: Inverted page table
 - Hash from virtual page -> physical page
 - Space proportional to # of physical pages
- Why not just reuse the hardware page tables?

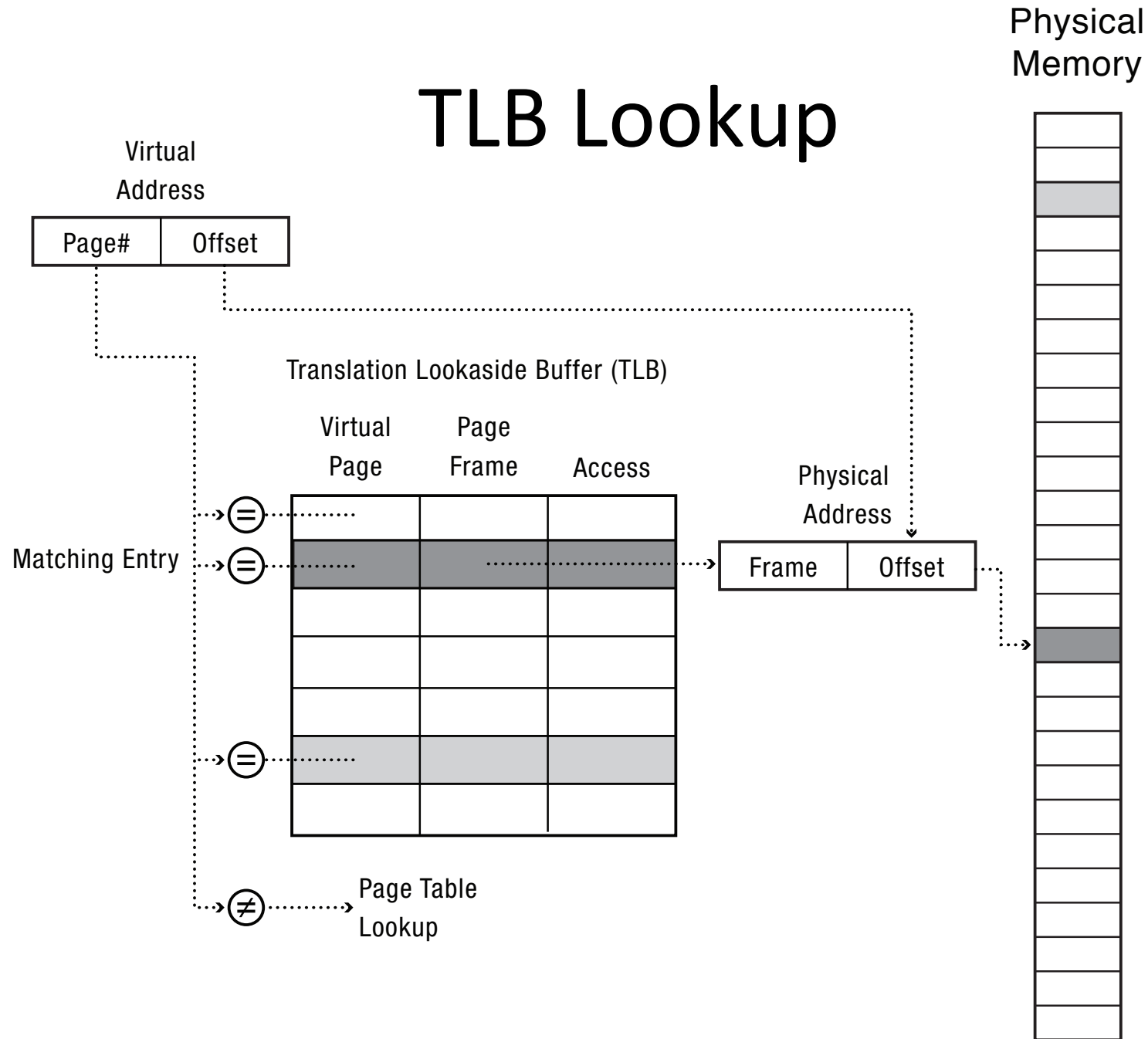
Efficient Address Translation

- Translation lookaside buffer (TLB)
 - Cache of recent virtual page \rightarrow physical page translations
 - If cache hit, use translation
 - If cache miss, walk multi-level page table
- Cost of translation =
Cost of TLB lookup +
 $\text{Prob}(\text{TLB miss}) * \text{cost of page table lookup}$

TLB and Page Table Translation



TLB Lookup



MIPS Software Loaded TLB

- Software defined translation tables
 - If translation is in TLB, ok
 - If translation is not in TLB, trap to kernel
 - Kernel computes translation and loads TLB
 - Kernel can use whatever data structures it wants
- Pros/cons?

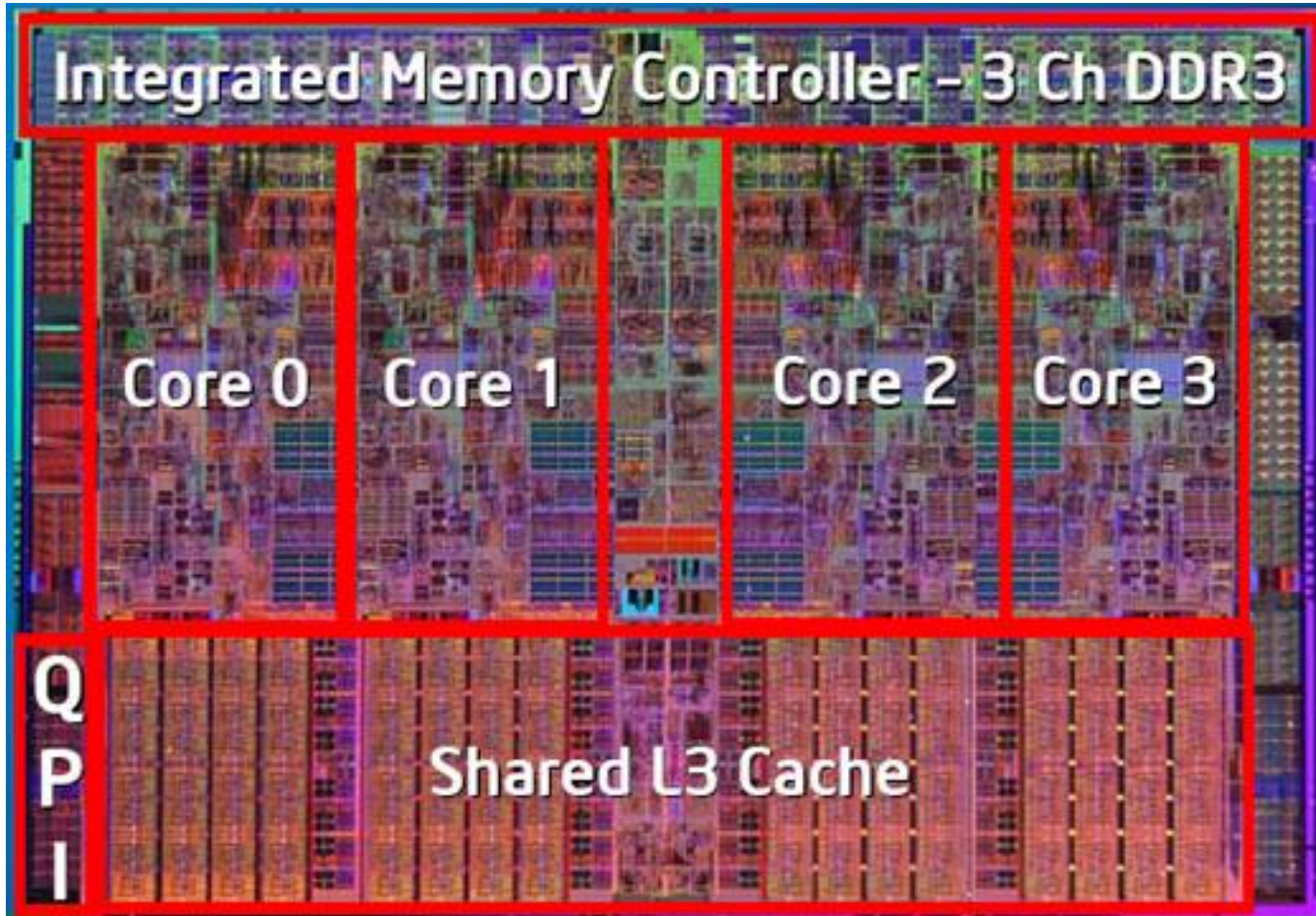
Question

- What is the cost of a TLB miss on a modern processor?
 - Cost of multi-level page table walk
 - MIPS: plus cost of trap handler entry/exit

Hardware Design Principle

The bigger the memory, the slower the memory

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 μ s	100 TB
Local non-volatile memory	100 μ s	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

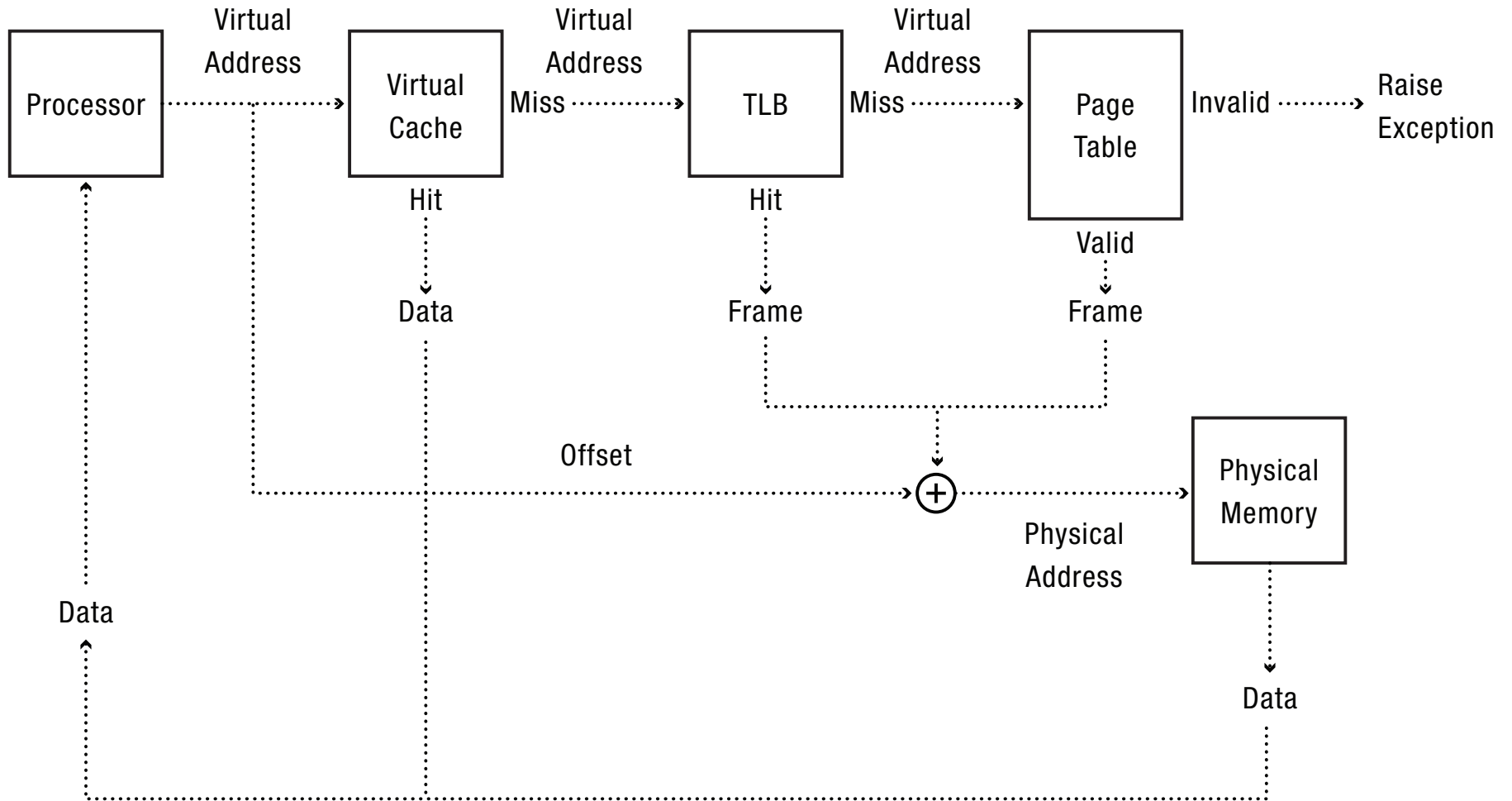
Question

- 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
- How expensive is a 4-level page table walk on a modern processor?

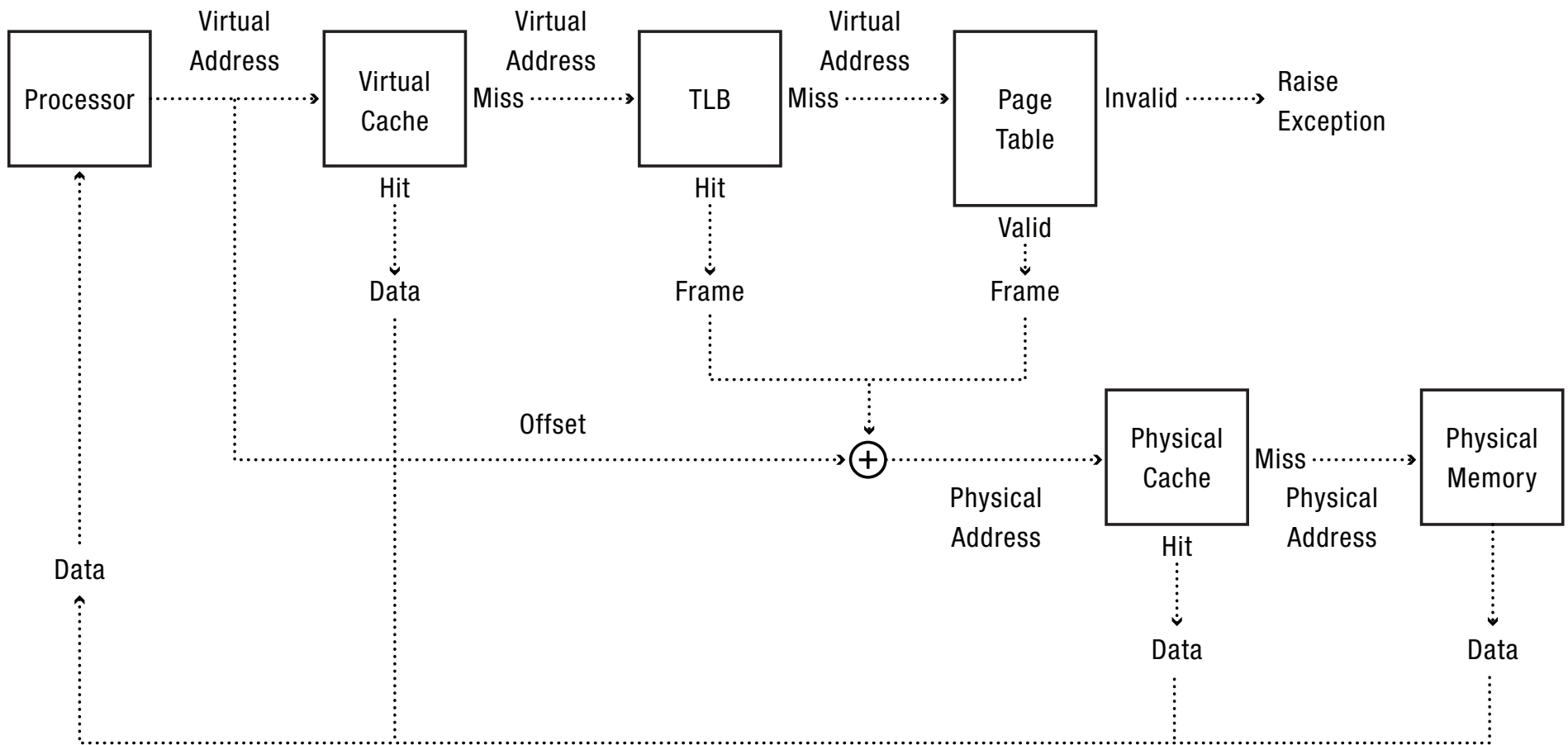
Virtually Addressed vs. Physically Addressed Caches

- 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, access TLB to generate physical address in case of a cache miss

Virtually Addressed Caches

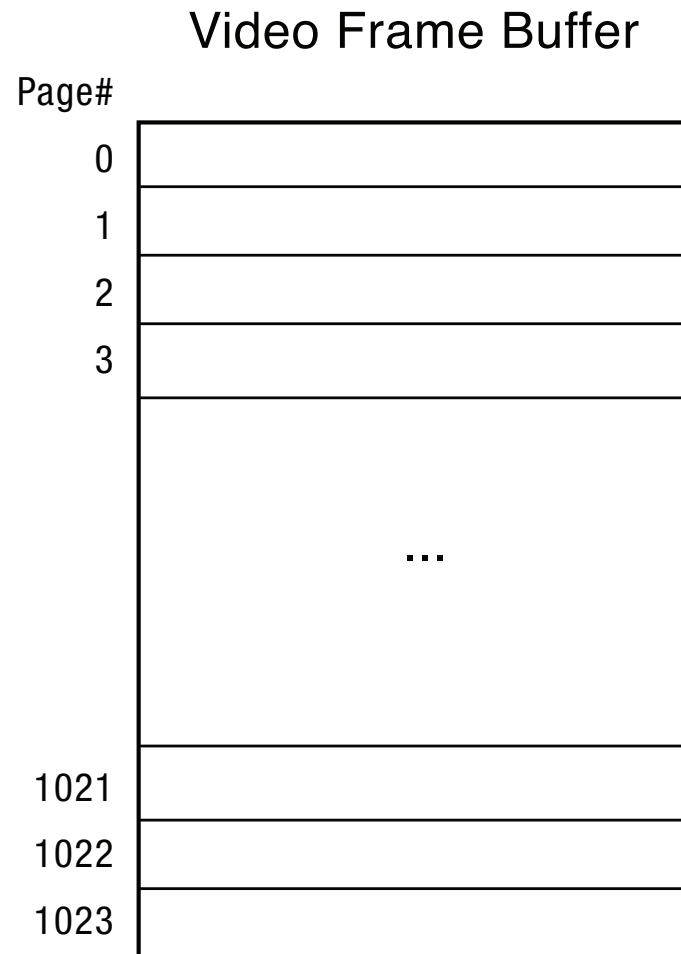


Physically Addressed Cache



When Do TLBs Work/Not Work?

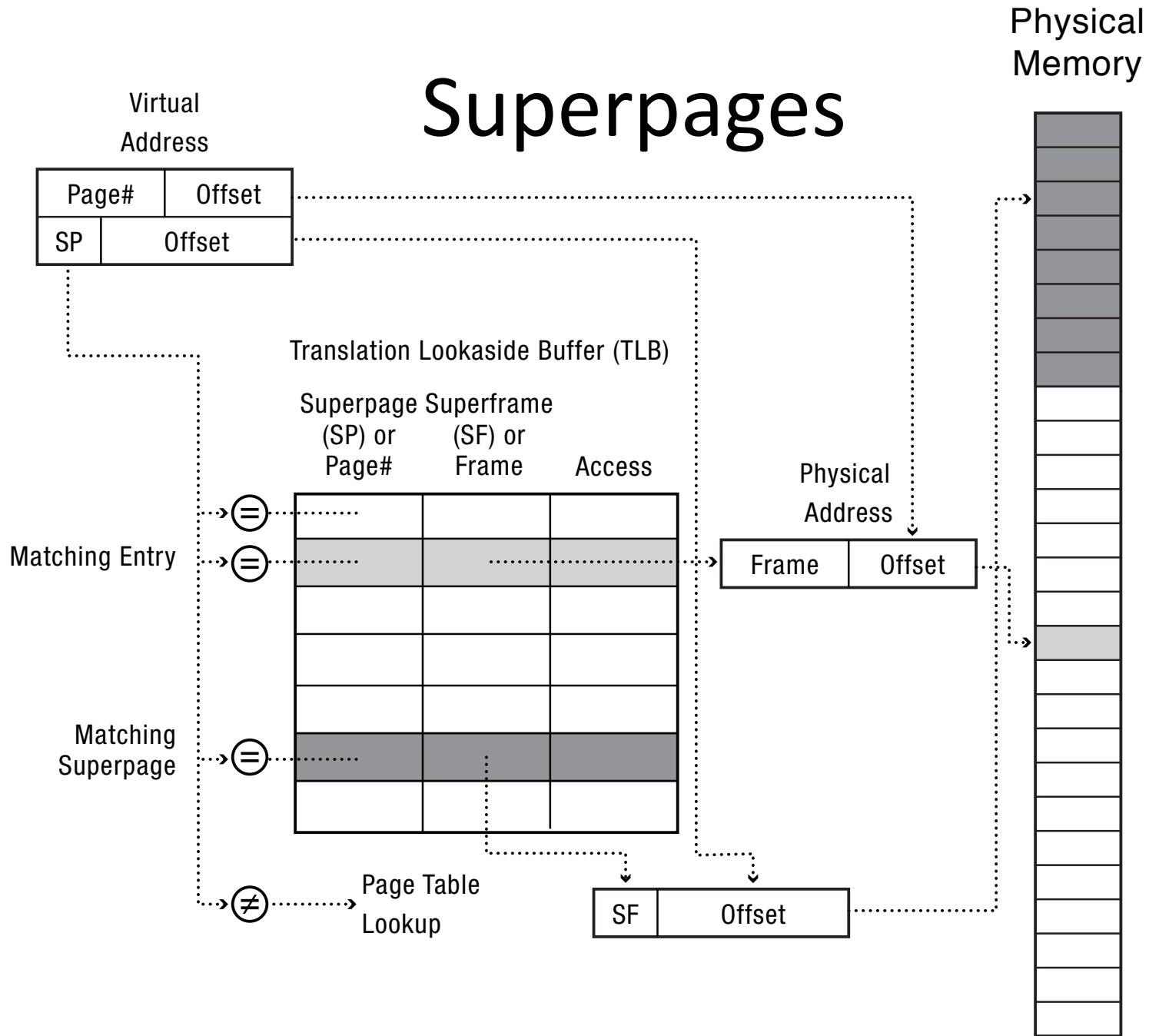
Video Frame Buffer:
32 bits x 1K x 1K =
4MB



Superpages

- On many systems, TLB entry can be
 - A page
 - A superpage: a set of contiguous, aligned pages
- x86: superpage is set of pages in one page table
 - One page: 4KB
 - One page table: 2MB
 - One page table of page tables: 1GB
 - One page table of page tables of page tables: 0.5TB

Superpages



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, ...
- TLB may contain old translation
 - OS must ask hardware to purge TLB entry
- On a multicore: TLB shutdown
 - OS must ask each CPU to purge TLB entry

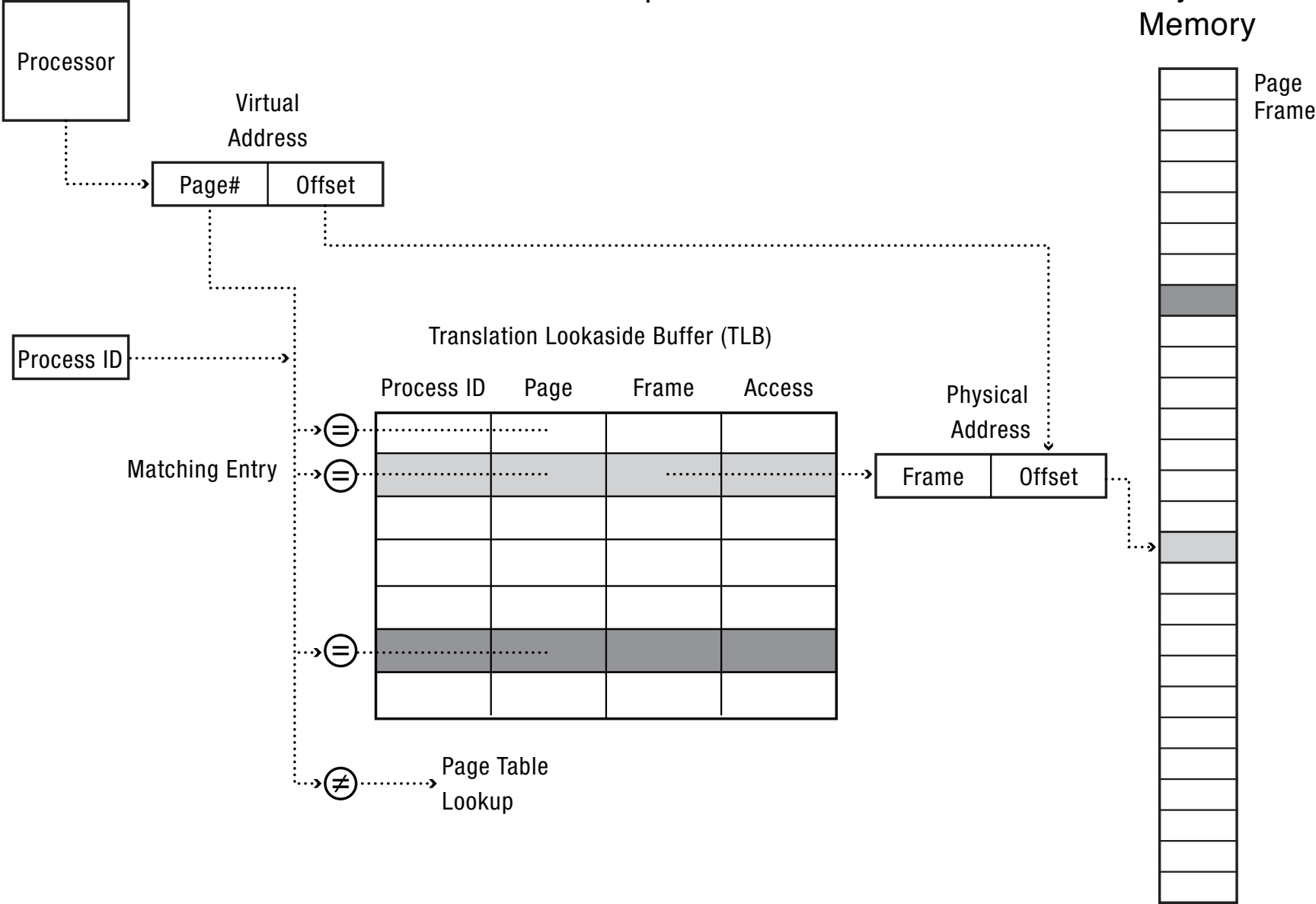
TLB Shutdown

	Process				
	ID	VirtualPage	PageFrame	Access	
Processor 1 TLB	=	0	0x0053	0x0003	R/W
	=	1	0x40FF	0x0012	R/W
Processor 2 TLB	=	0	0x0053	0x0003	R/W
	=	0	0x0001	0x0005	Read
Processor 3 TLB	=	1	0x40FF	0x0012	R/W
	=	0	0x0001	0x0005	Read

When Do TLBs Work/Not Work, part 3

- What happens on a context switch?
 - Reuse TLB?
 - Discard TLB?
- Solution: Tagged TLB
 - Each TLB entry has process ID
 - TLB hit only if process ID matches current process

Implementation



Question

- With a virtual cache, what do we need to do on a context switch?

Aliasing

- Alias: two (or more) virtual cache entries that refer to the same physical memory
 - A consequence of a tagged virtually addressed cache!
 - A write to one copy needs to update all copies
- Typical solution
 - Keep both virtual and physical address for each entry in virtually addressed cache
 - Lookup virtually addressed cache and TLB in parallel
 - Check if physical address from TLB matches multiple entries, and update/invalidate other copies

Multicore and Hyperthreading

- Modern CPU has several functional units
 - Instruction decode
 - Arithmetic/branch
 - Floating point
 - Instruction/data cache
 - TLB
- Multicore: replicate functional units (i7: 4)
 - Share second/third level cache, second level TLB
- Hyperthreading: logical processors that share functional units (i7: 2)
 - Better functional unit utilization during memory stalls
- No difference from the OS/programmer perspective
 - Except for performance, affinity, ...

Address Translation Uses

- Process isolation
 - Keep a process from touching anyone else's memory, or the kernel's
- Efficient interprocess communication
 - Shared regions of memory between processes
- Shared code segments
 - E.g., common libraries used by many different programs
- Program initialization
 - Start running a program before it is entirely in memory
- Dynamic memory allocation
 - Allocate and initialize stack/heap pages on demand

Address Translation (more)

- Cache management
 - Page coloring
- Program debugging
 - Data breakpoints when address is accessed
- Zero-copy I/O
 - Directly from I/O device into/out of user memory
- Memory mapped files
 - Access file data using load/store instructions
- Demand-paged virtual memory
 - Illusion of near-infinite memory, backed by disk or memory on other machines

Address Translation (even more)

- Checkpointing/restart
 - Transparently save a copy of a process, without stopping the program while the save happens
- Persistent data structures
 - Implement data structures that can survive system reboots
- Process migration
 - Transparently move processes between machines
- Information flow control
 - Track what data is being shared externally
- Distributed shared memory
 - Illusion of memory that is shared between machines