

Virtual Memory 2

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Computer Science

Cornell University

Announcements

Lab3: Available today, and due by next Wednesday

HW2: Do up to Problem5 this week. Do it **now**.

Do Problem9, coding a hashtable in C, **now**.

Announcements

Next five weeks

- Week 10 (Apr 7): **Lab3** (calling convention) release
- Week 11 (Apr 14): **Proj3** (caches) release, Lab3 due Wed
- Week 12 (Apr 21): **Lab4** (virtual memory) release, due in-class, Proj3 due Fri, **HW2 due Sat**
- Week 13 (Apr 28): **Proj4** (multi-core/parallelism) release, Lab4 due in-class, **Prelim2**
- Week 14 (May 5): **Proj3 Tournament**, Proj4 design doc due

Final Project for class

- Week 15 (May 12): Proj4 due Wed

Goals for Today

Virtual Memory

- Address Translation
 - Pages, page tables, and memory mgmt unit
- Paging
- Role of Operating System
 - Context switches, working set, shared memory
- Performance
 - How slow is it
 - Making virtual memory fast
 - Translation lookaside buffer (TLB)
- Virtual Memory Meets Caching

Performance

Performance

Virtual Memory Summary

PageTable for each process:

- 4MB contiguous in physical memory, or multi-level, ...
- every load/store translated to physical addresses
- page table miss = *page fault*
load the swapped-out page and retry instruction,
or kill program if the page really doesn't exist,
or tell the program it made a mistake

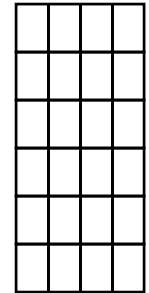
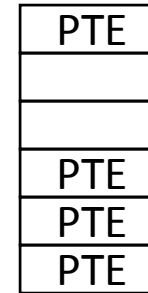
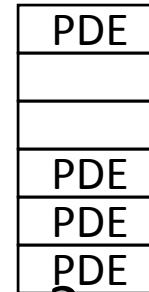
Page Table Review

x86 Example: 2 level page tables, assume...

32 bit vaddr, 32 bit paddr

4k PDir, 4k PTables, 4k Pages

PTBR



Q: How many bits for a physical page number?

Q: What is stored in each PageTableEntry?

Q: What is stored in each PageDirEntry?

Q: How many entries in a PageDirectory?

Q: How many entries in each PageTable?

Page Table Example

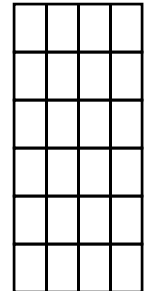
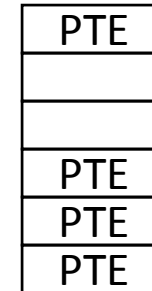
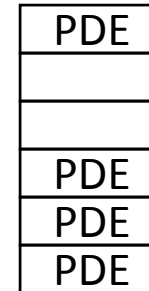
x86 Example: 2 level page tables, assume...

32 bit vaddr, 32 bit paddr

4k PDir, 4k PTables, 4k Pages

PTBR = 0x10005000 (physical)

PTBR



Write to virtual address 0x7192a44c...

Q: Byte offset in page?

PT Index?

PD Index?

(1) PageDir is at ???, so...

Fetch PDE from physical address ????

- suppose we get {0x12345, v=1, ...}

(2) PageTable is at ???, so...

Fetch PTE from physical address ???

- suppose we get {0x14817, v=1, d=0, r=1, w=1, x=0, ...}

(3) Page is at ???, so...

Write data to physical address???

Also: update PTE???

Performance

Virtual Memory Summary

PageTable for each process:

- 4MB contiguous in physical memory, or multi-level, ...
- every load/store translated to physical addresses
- page table miss: load a swapped-out page and retry instruction, or kill program

Performance?

- terrible: memory is already slow
translation makes it slower

Solution?

- A cache, of course

Making Virtual Memory Fast

The Translation Lookaside Buffer (TLB)

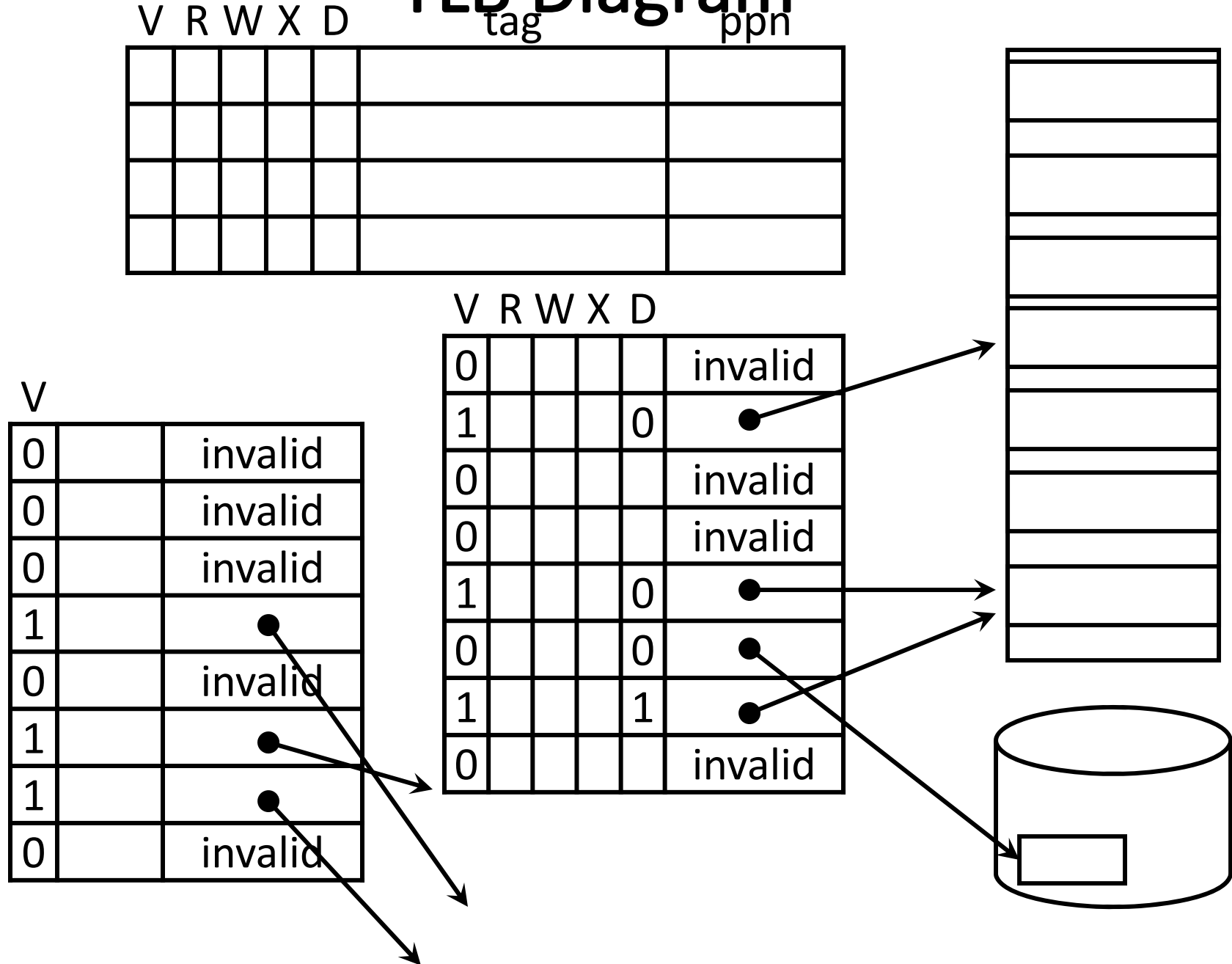
Translation Lookaside Buffer (TLB)

Hardware Translation Lookaside Buffer (TLB)

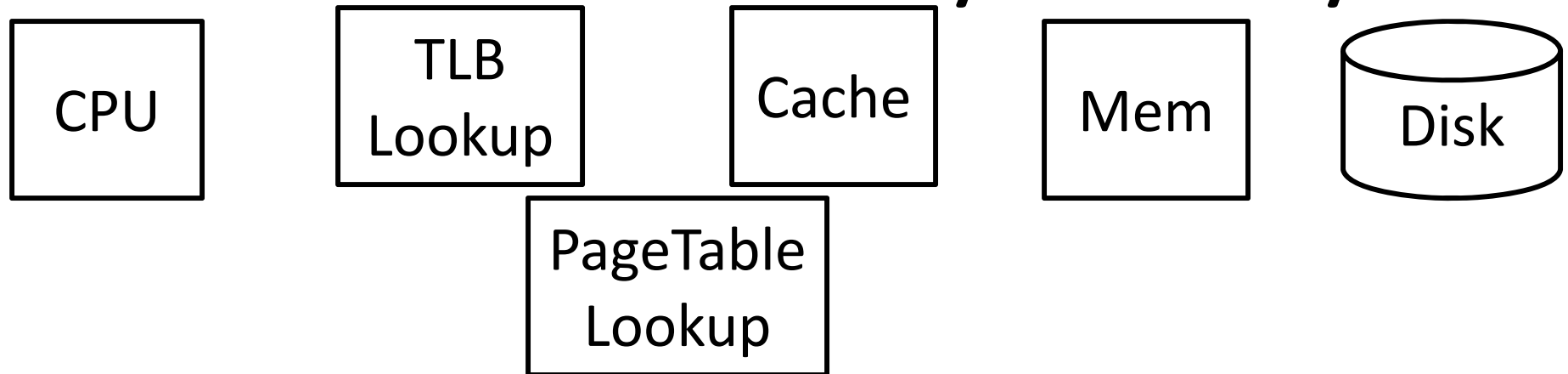
A small, very fast cache of recent address mappings

- TLB hit: avoids PageTable lookup
- TLB miss: do PageTable lookup, cache result for later

TLB Diagram



A TLB in the Memory Hierarchy



(1) Check TLB for vaddr (~ 1 cycle)

(2) TLB Hit

- compute paddr, send to cache

(2) TLB Miss: traverse PageTables for vaddr

(3a) PageTable has valid entry for in-memory page

- Load PageTable entry into TLB; try again (tens of cycles)

(3b) PageTable has entry for swapped-out (on-disk) page

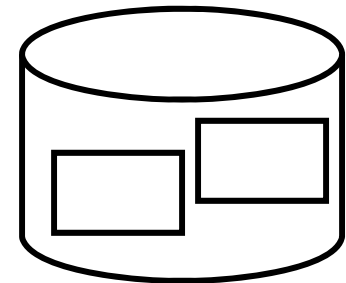
- Page Fault: load from disk, fix PageTable, try again (millions of cycles)

(3c) PageTable has invalid entry

- Page Fault: kill process

TLB Coherency

TLB Coherency: What can go wrong?



Translation Lookaside Buffers (TLBs)

When PTE changes, PDE changes, PTBR changes....

Full Transparency: TLB coherency in hardware

- Flush TLB whenever PTBR register changes
[easy – why?]
- Invalidate entries whenever PTE or PDE changes
[hard – why?]

TLB coherency in software

If TLB has a no-write policy...

- OS invalidates entry after OS modifies page tables
- OS flushes TLB whenever OS does context switch

TLB Parameters

TLB parameters (typical)

- very small (64 – 256 entries), so very fast
- fully associative, or at least set associative
- tiny block size: why?

Intel Nehalem TLB (example)

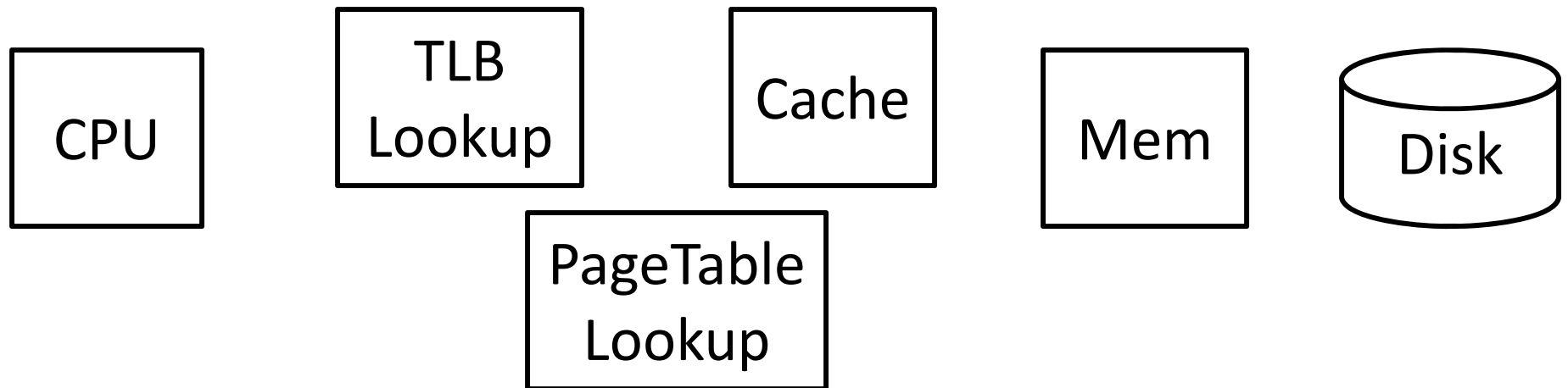
- 128-entry L1 Instruction TLB, 4-way LRU
- 64-entry L1 Data TLB, 4-way LRU
- 512-entry L2 Unified TLB, 4-way LRU

Virtual Memory meets Caching

Virtually vs. physically addressed caches

Virtually vs. physically tagged caches

Recall TLB in the Memory Hierarchy

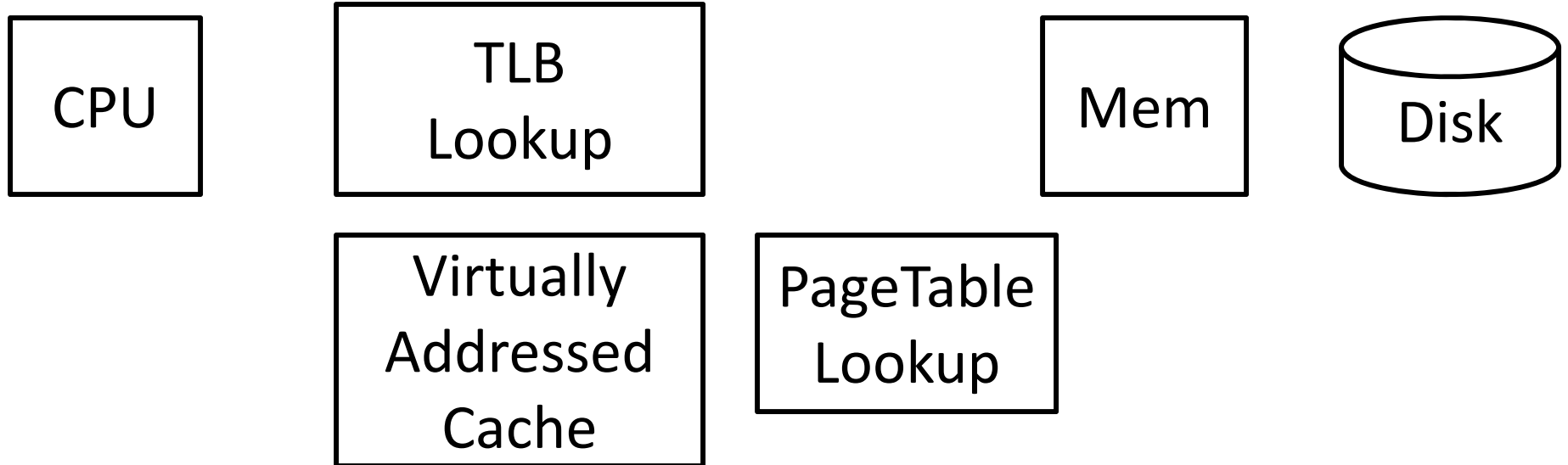


TLB is passing a physical address so we can load from memory.

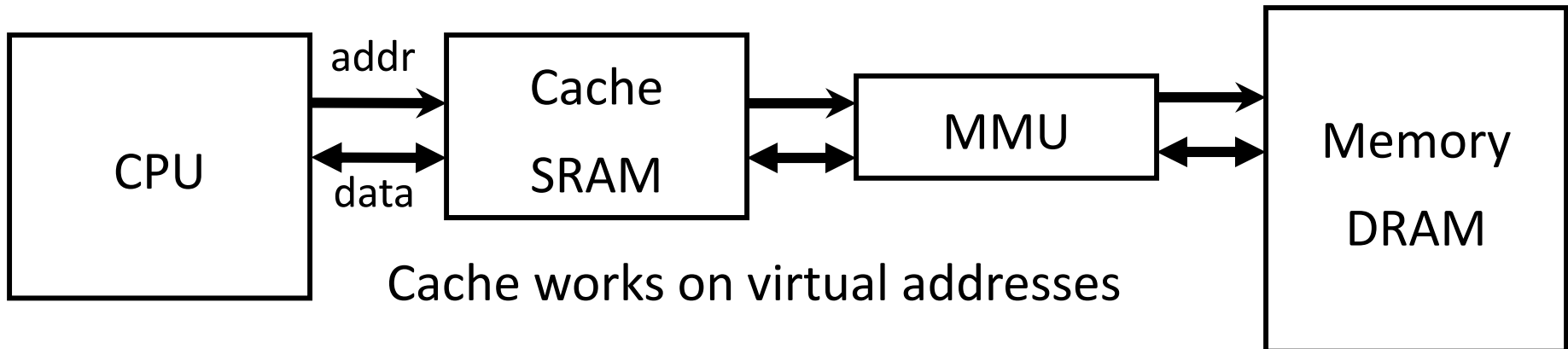
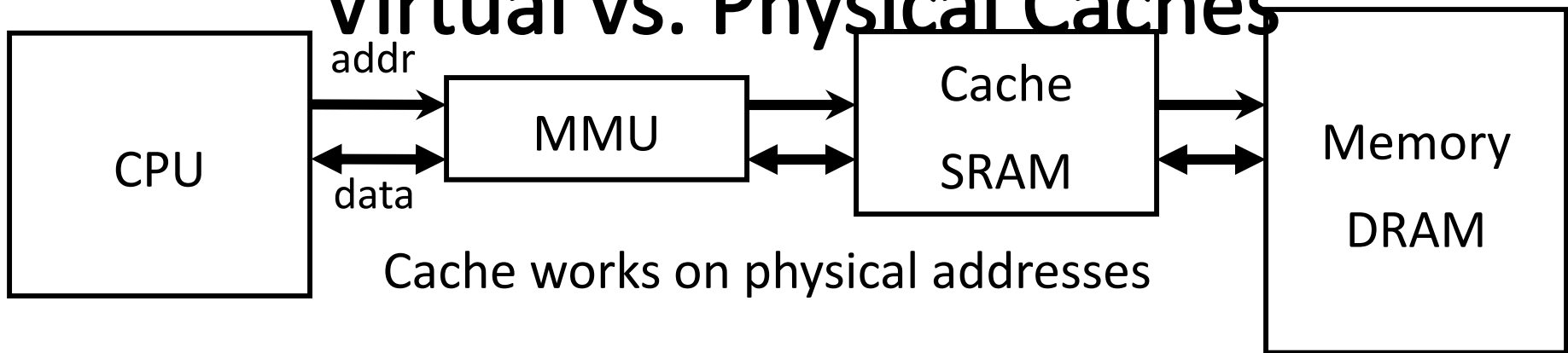
What if the data is in the cache?

Virtually Addressed Caching

Q: Can we remove the TLB from the critical path?



Virtual vs. Physical Caches



Q: What happens on context switch?

Q: What about virtual memory aliasing?

Q: So what's wrong with physically addressed caches?

Indexing vs. Tagging

Physically-Addressed Cache

- slow: requires TLB (and maybe PageTable) lookup first

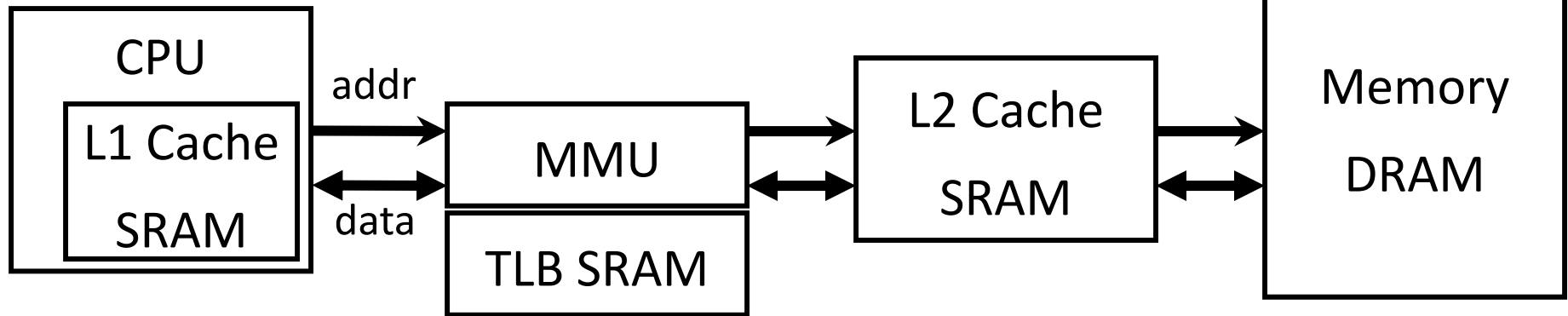
Virtually-Addressed Cache

- fast: start TLB lookup before cache lookup finishes
- PageTable changes (paging, context switch, etc.)
 - need to purge stale cache lines (how?)
- Synonyms (two virtual mappings for one physical page)
 - could end up in cache twice (very bad!)

Virtually-Indexed, Physically Tagged Cache

- ~fast: TLB lookup in parallel with cache lookup
- PageTable changes → no problem: phys. tag mismatch
- Synonyms → search and evict lines with same phys. tag

Typical Cache Setup



Typical L1: On-chip virtually addressed, physically tagged

Typical L2: On-chip physically addressed

Typical L3: On-chip ...

Design Decisions of Caches/TLBs/VM

Caches, Virtual Memory, & TLBs

Where can block be placed?

- Direct, n-way, fully associative

What block is replaced on miss?

- LRU, Random, LFU, ...

How are writes handled?

- No-write (w/ or w/o automatic invalidation)
- Write-back (fast, block at time)
- Write-through (simple, reason about consistency)

Summary of Caches/TLBs/VM

Caches, Virtual Memory, & TLBs

Where can block be placed?

- Caches:
- VM:
- TLB:

What block is replaced on miss?

How are writes handled?

- Caches:
- VM:
- TLB:

Summary of Cache Design Parameters

	L1	Paged Memory	TLB
Size (blocks)	1/4k to 4k	16k to 1M	64 to 4k
Size (kB)	16 to 64	1M to 4G	2 to 16
Block size (B)	16-64	4k to 64k	4-32
Miss rates	2%-5%	10^{-4} to $10^{-5}\%$	0.01% to 2%
Miss penalty	10-25	10M-100M	100-1000

Role of the Operating System
Context switches, working set,
shared memory

Role of the Operating System

The operating systems (OS) manages and multiplexes memory between process. It...

- Enables processes to (explicitly) increase memory: sbrk and (implicitly) decrease memory
- Enables sharing of physical memory: multiplexing memory via context switching, sharing memory, and paging
- Enables and limits the number of processes that can run simultaneously

sbrk

Suppose Firefox needs a new page of memory

(1) Invoke the Operating System

```
void *sbrk(int nbytes);
```

(2) OS finds a free page of physical memory

- clear the page (fill with zeros)
- add a new entry to Firefox's PageTable

Context Switch

Suppose Firefox is idle, but Skype wants to run

(1) Firefox invokes the Operating System

```
int sleep(int nseconds);
```

(2) OS saves Firefox's registers, load skype's

- (more on this later)

(3) OS changes the CPU's Page Table Base Register

- Cop0:ContextRegister / CR3:PDBR

(4) OS returns to Skype

Shared Memory

Suppose Firefox and Skype want to share data

(1) OS finds a free page of physical memory

- clear the page (fill with zeros)
- add a new entry to Firefox's PageTable
- add a new entry to Skype's PageTable
 - can be same or different vaddr
 - can be same or different page permissions

Multiplexing

Suppose Skype needs a new page of memory, but Firefox is hogging it all

(1) Invoke the Operating System

```
void *sbrk(int nbytes);
```

(2) OS can't find a free page of physical memory

- Pick a page from Firefox instead (or other process)

(3) If page table entry has dirty bit set...

- Copy the page contents to disk

(4) Mark Firefox's page table entry as "on disk"

- Firefox will fault if it tries to access the page

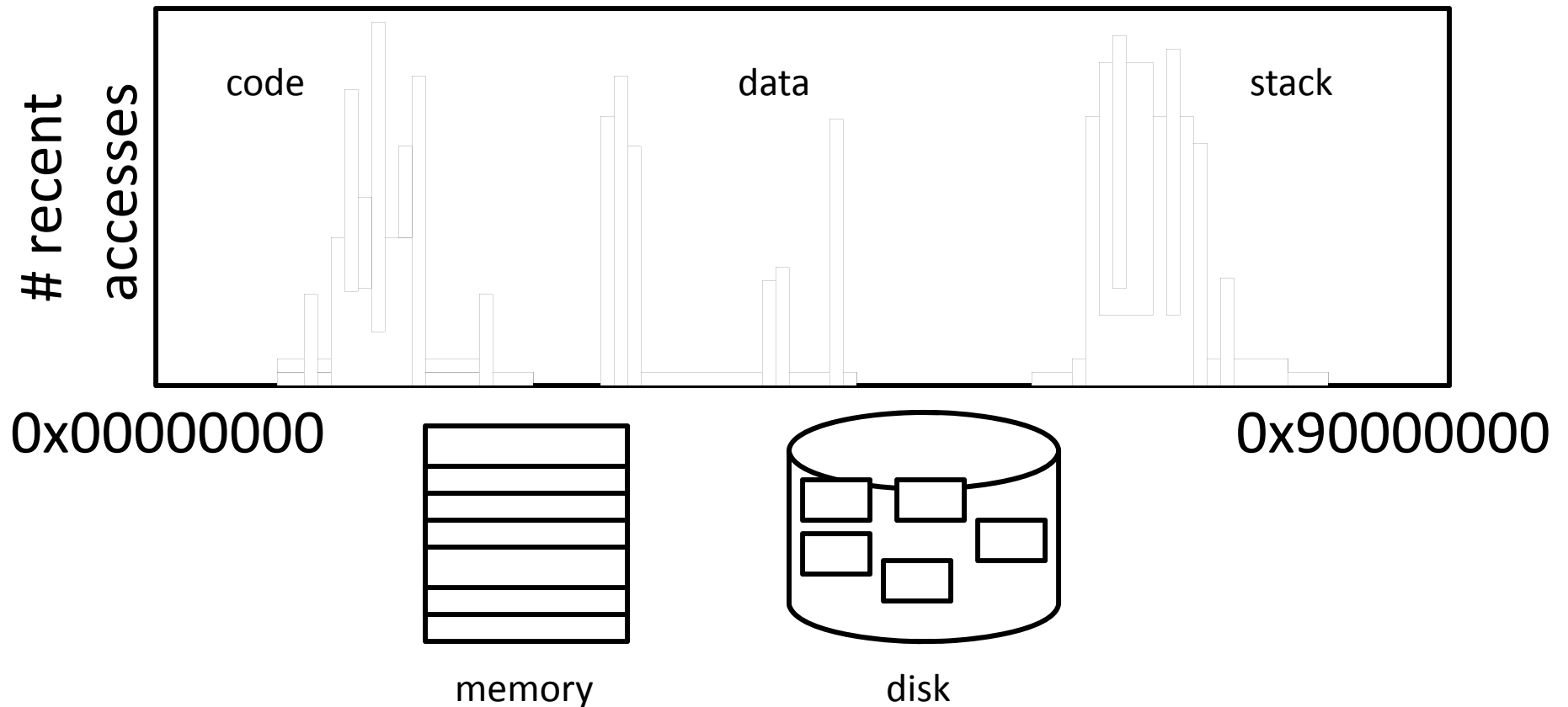
(5) Give the newly freed physical page to Skype

- clear the page (fill with zeros)
- add a new entry to Skype's PageTable

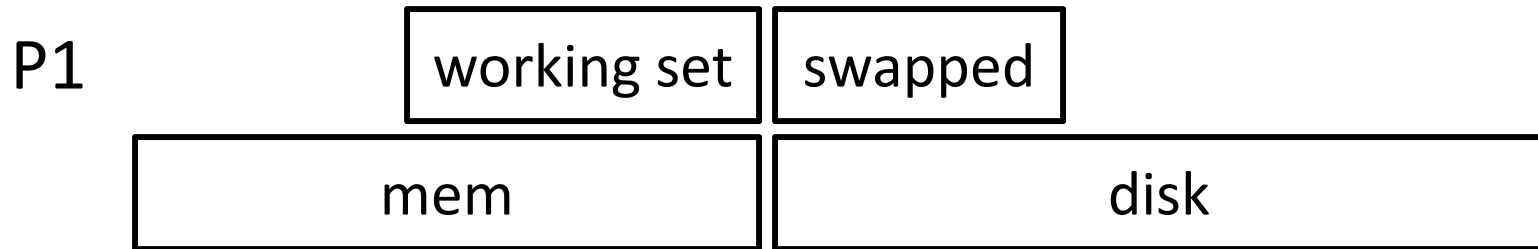
Paging Assumption 1

OS multiplexes physical memory among processes

- assumption # 1:
processes use only a few pages at a time
- working set = set of process's recently actively pages

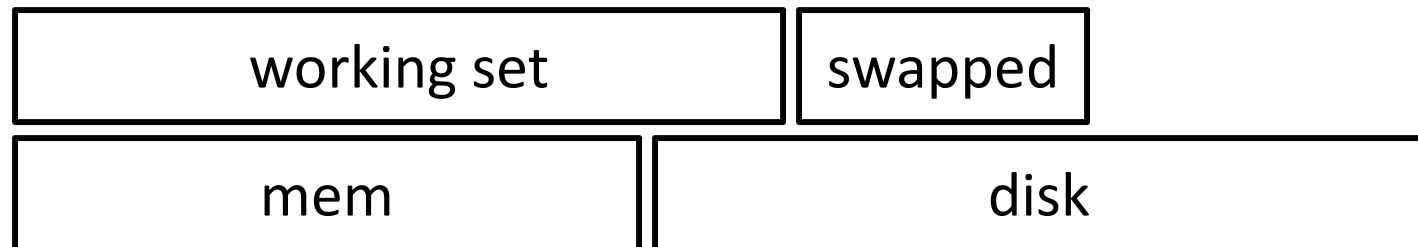


Thrashing (excessive paging)

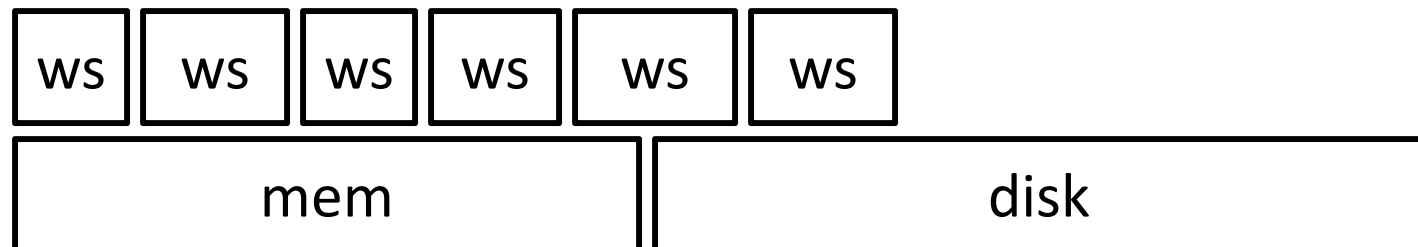


Q: What if working set is too large?

Case 1: Single process using too many pages



Case 2: Too many processes



Thrashing

Thrashing b/c working set of process (or processes) greater than physical memory available

- Firefox steals page from Skype
- Skype steals page from Firefox
- I/O (disk activity) at 100% utilization
 - But no useful work is getting done

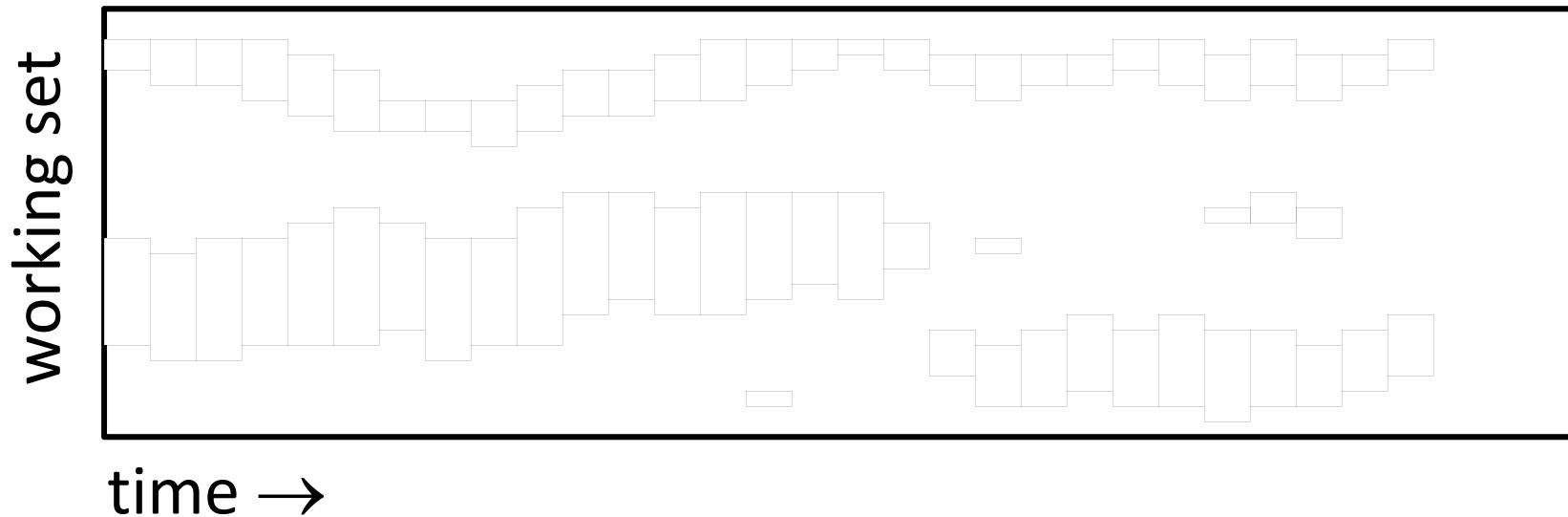
Ideal: Size of disk, speed of memory (or cache)

Non-ideal: Speed of disk

Paging Assumption 2

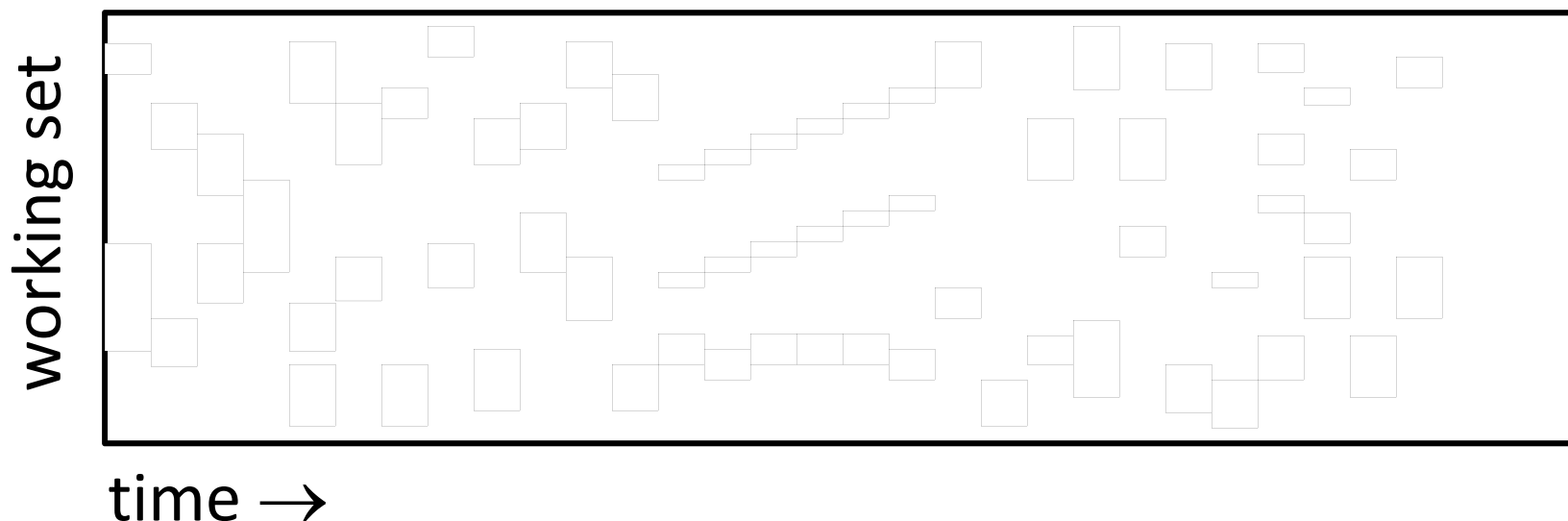
OS multiplexes physical memory among processes

- assumption # 2:
recent accesses predict future accesses
- working set usually changes slowly over time



More Thrashing

Q: What if working set changes rapidly or unpredictably?



A: Thrashing b/c recent accesses don't predict future accesses

Preventing Thrashing

How to prevent thrashing?

- User: Don't run too many apps
- Process: efficient and predictable mem usage
- OS: Don't over-commit memory, memory-aware scheduling policies, etc.

Recap

- sbrk
- Context switches
- Shared memory
- Multiplexing memory
- Working set
- Thrashing

Next: Virtual memory performance