

CSI 62
Operating Systems and
Systems Programming
Lecture 14

Caching and TLBs (Finished),
Demand Paging

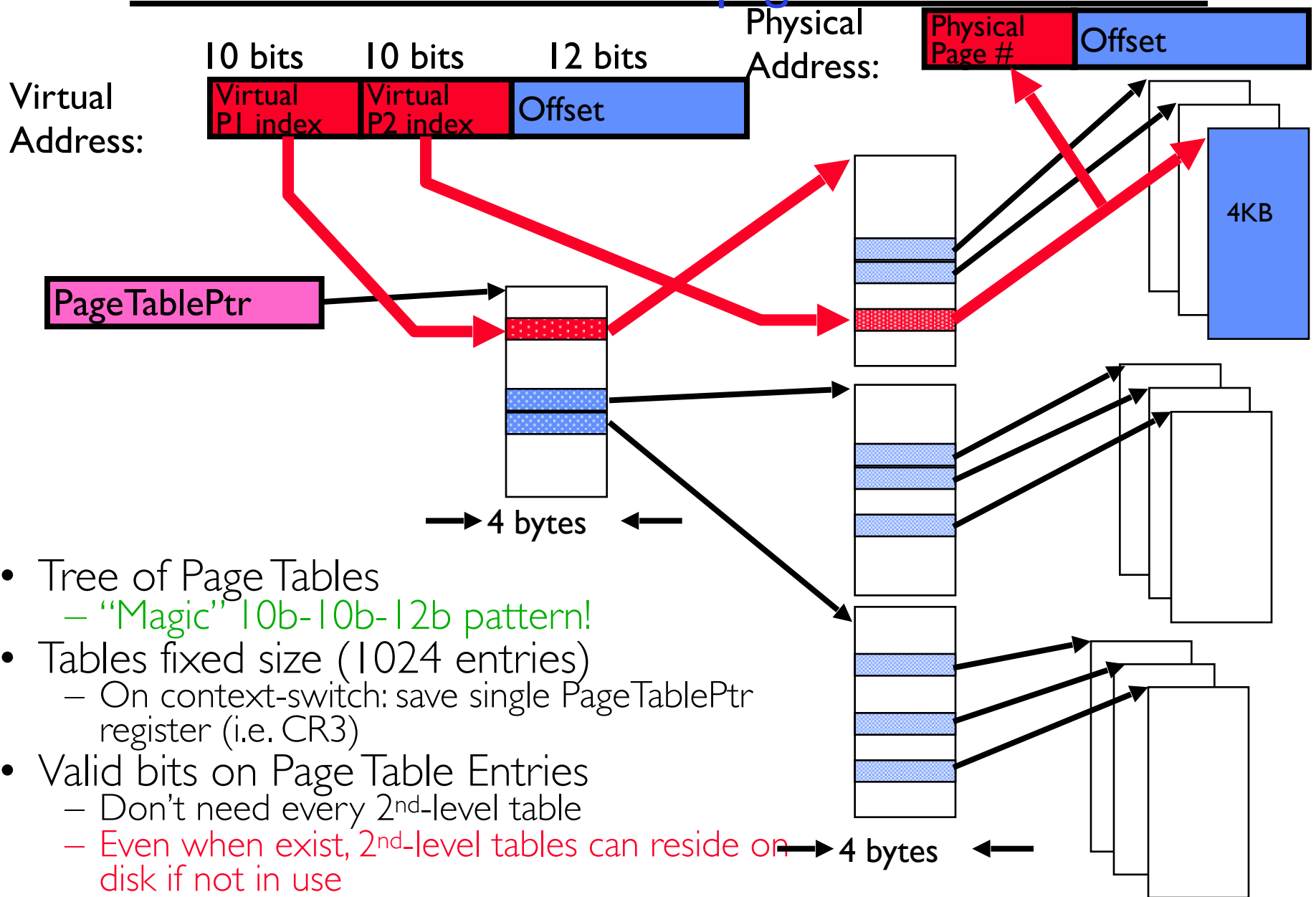
March 12th, 2020

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<http://cs162.eecs.Berkeley.edu>

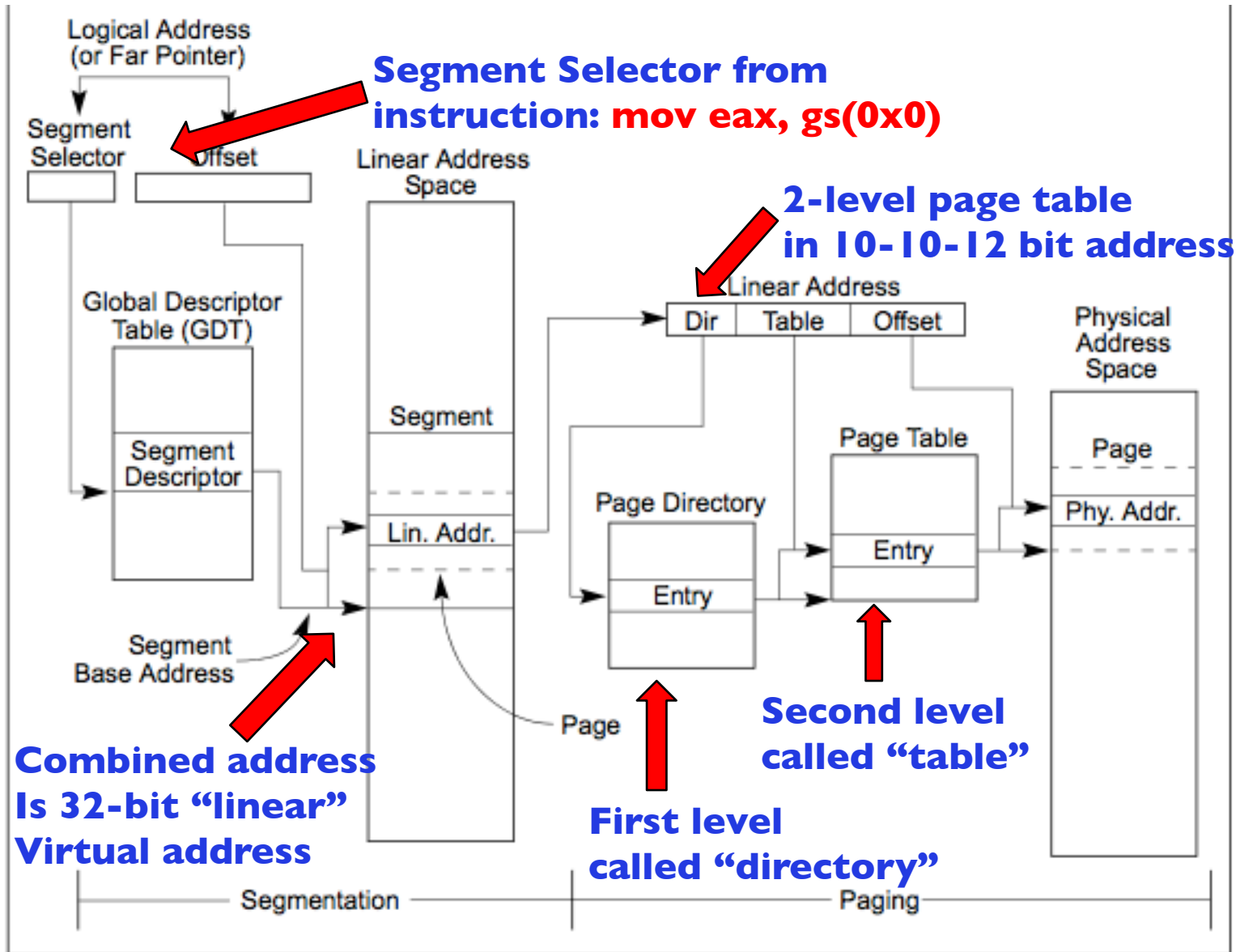
Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiawicz at Berkeley, with few minor updates/changes. When slides are obtained from other sources, a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.

Recall: Fix for sparse address space: The two-level page table



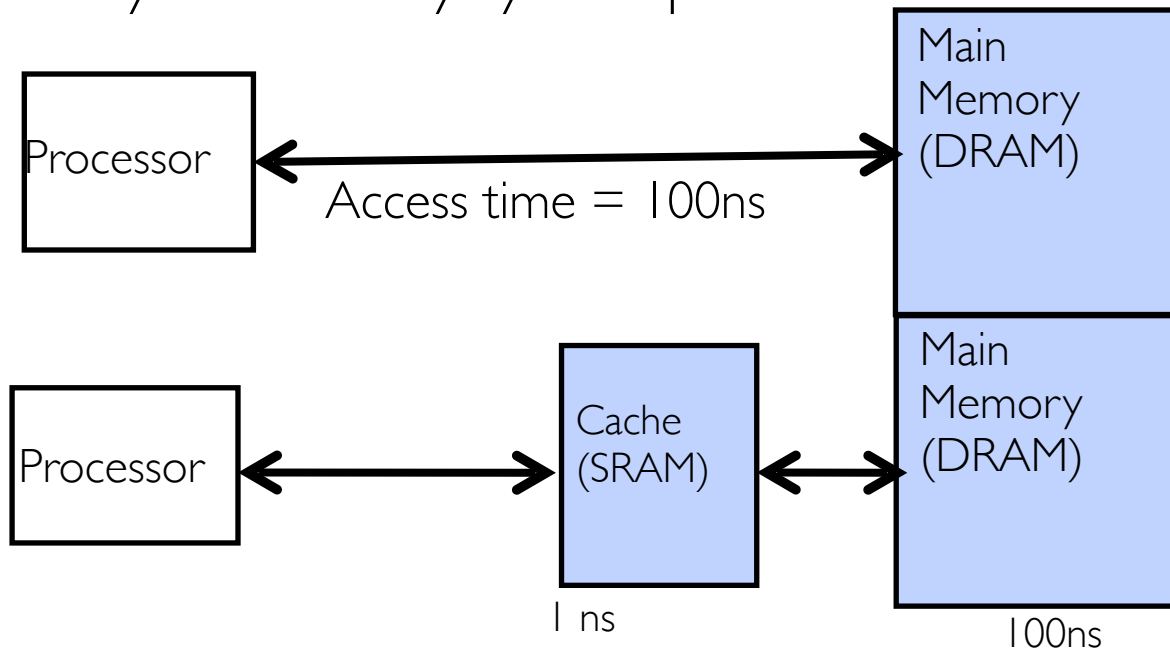
- Tree of Page Tables
 - “Magic” 10b-10b-12b pattern!
- Tables fixed size (1024 entries)
 - On context-switch: save single PageTablePtr register (i.e. CR3)
- Valid bits on Page Table Entries
 - Don't need every 2nd-level table
 - Even when exist, 2nd-level tables can reside on disk if not in use

Recall: Making it real:
X86 Memory model with segmentation (16/32-bit)



Recall: In Machine Structures (eg. 6 | C) ...

- Caching is the key to memory system performance



Average Memory Access Time (AMAT)

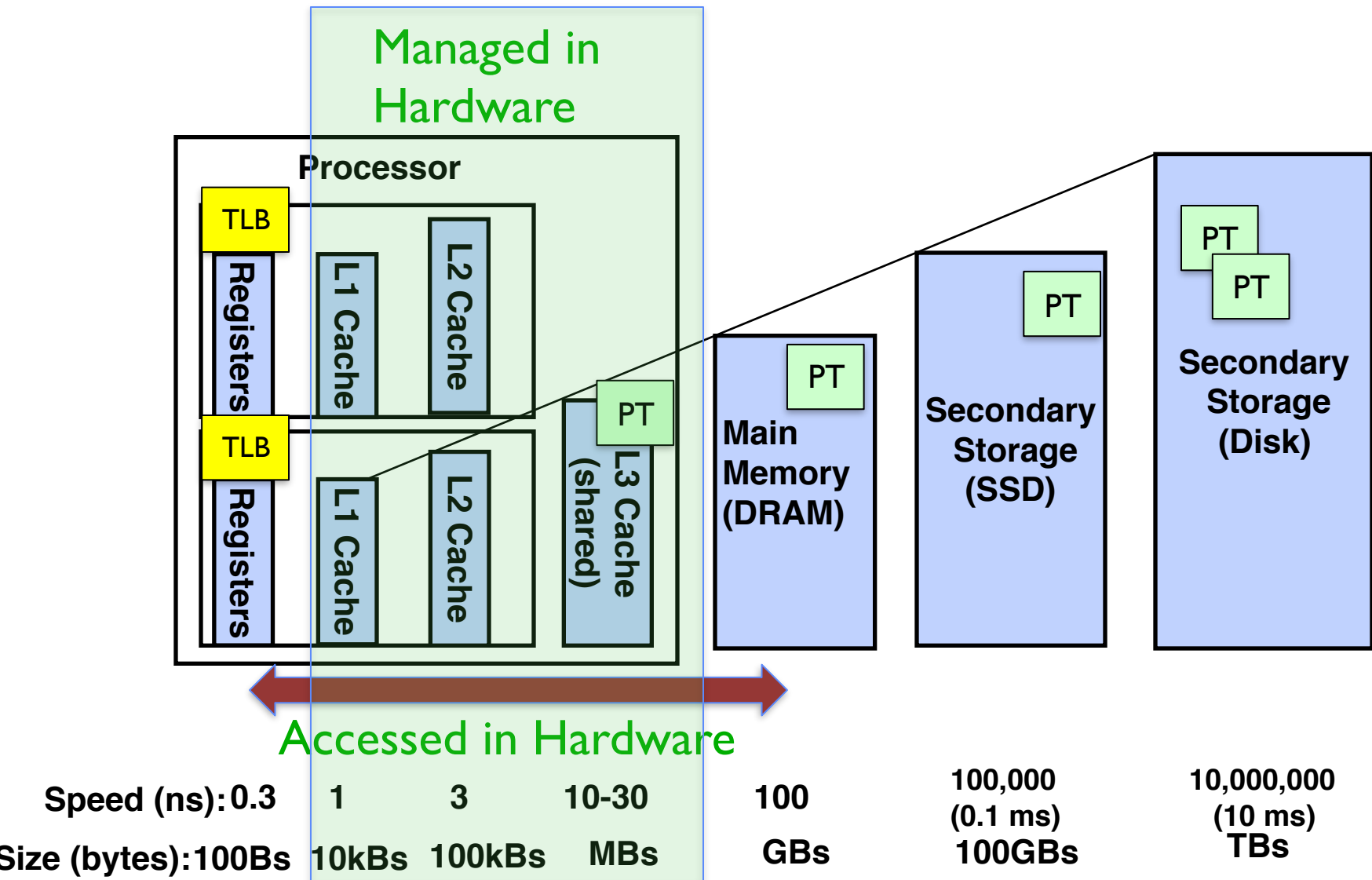
$$= (\text{Hit Rate} \times \text{HitTime}) + (\text{Miss Rate} \times \text{MissTime})$$

Where $\text{HitRate} + \text{MissRate} = 1$

$$\text{HitRate} = 90\% \Rightarrow \text{AMAT} = (0.9 \times 1) + (0.1 \times 101) = 11.1 \text{ ns}$$

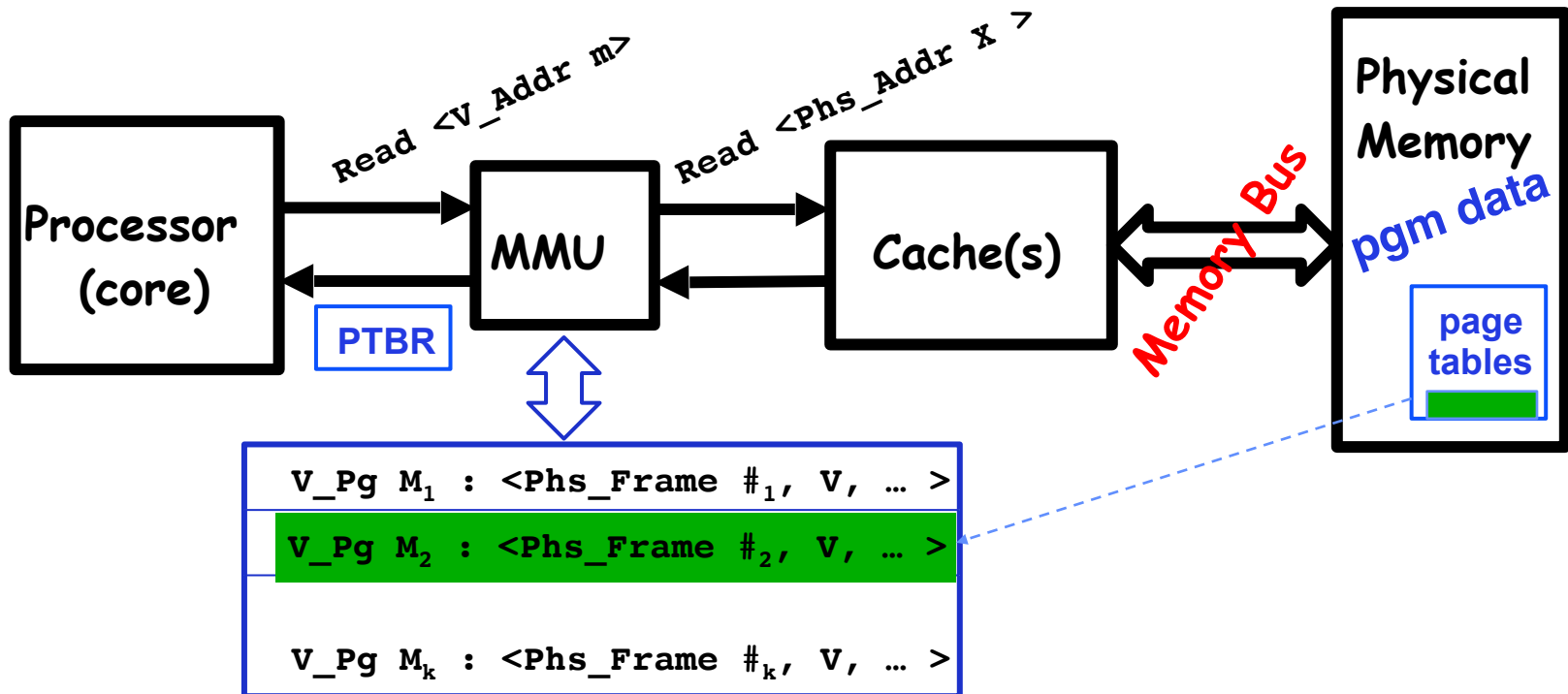
$$\text{HitRate} = 99\% \Rightarrow \text{AMAT} = (0.99 \times 1) + (0.01 \times 101) = 2.01 \text{ ns}$$

Recall: The Memory Hierarchy



Recall: How to make Address Translation Fast?

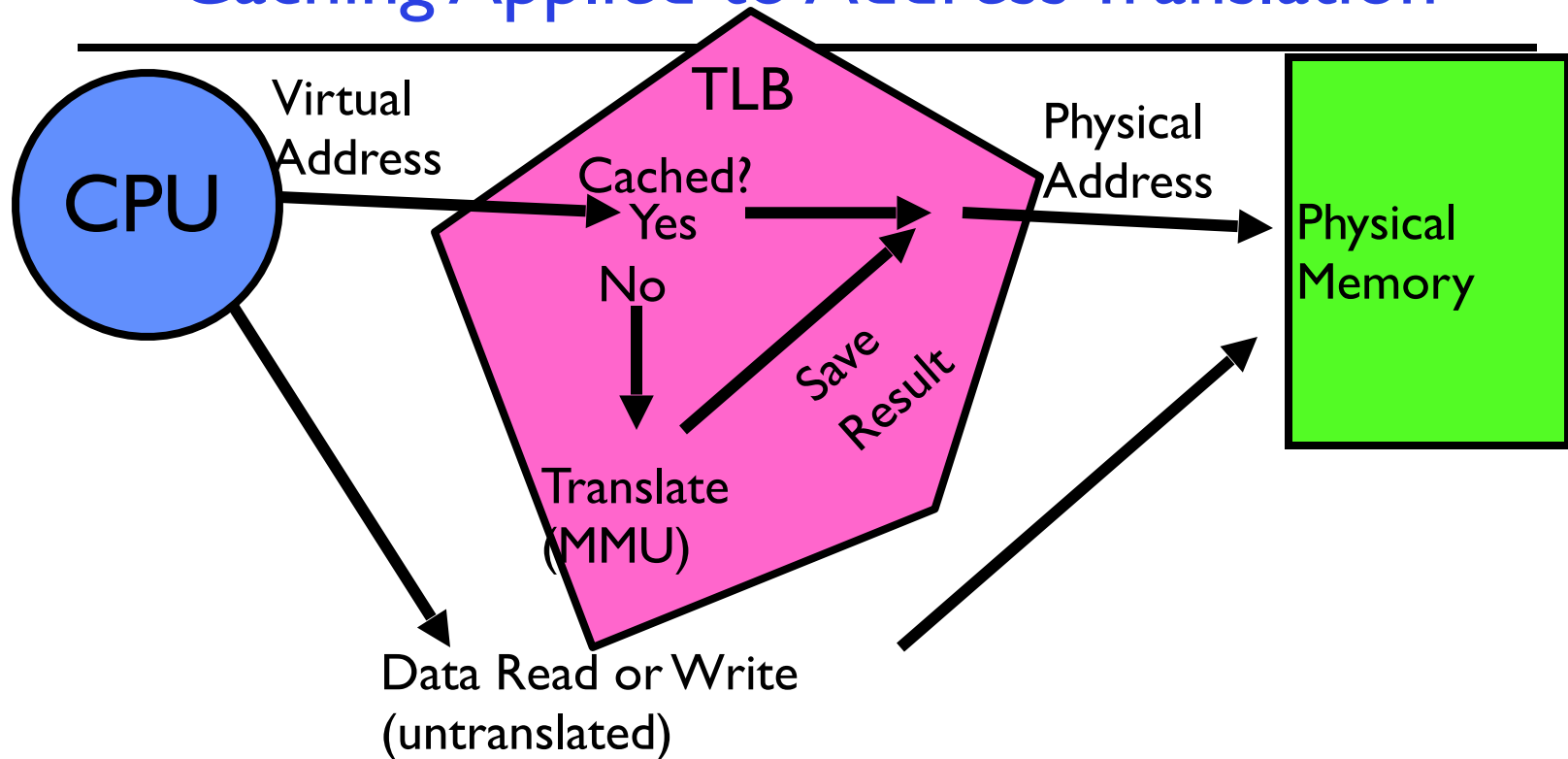
- Cache results of recent translations !
 - Different from a traditional cache
 - Cache Page Table Entries using Virtual Page # as the key



Translation Look-Aside Buffer

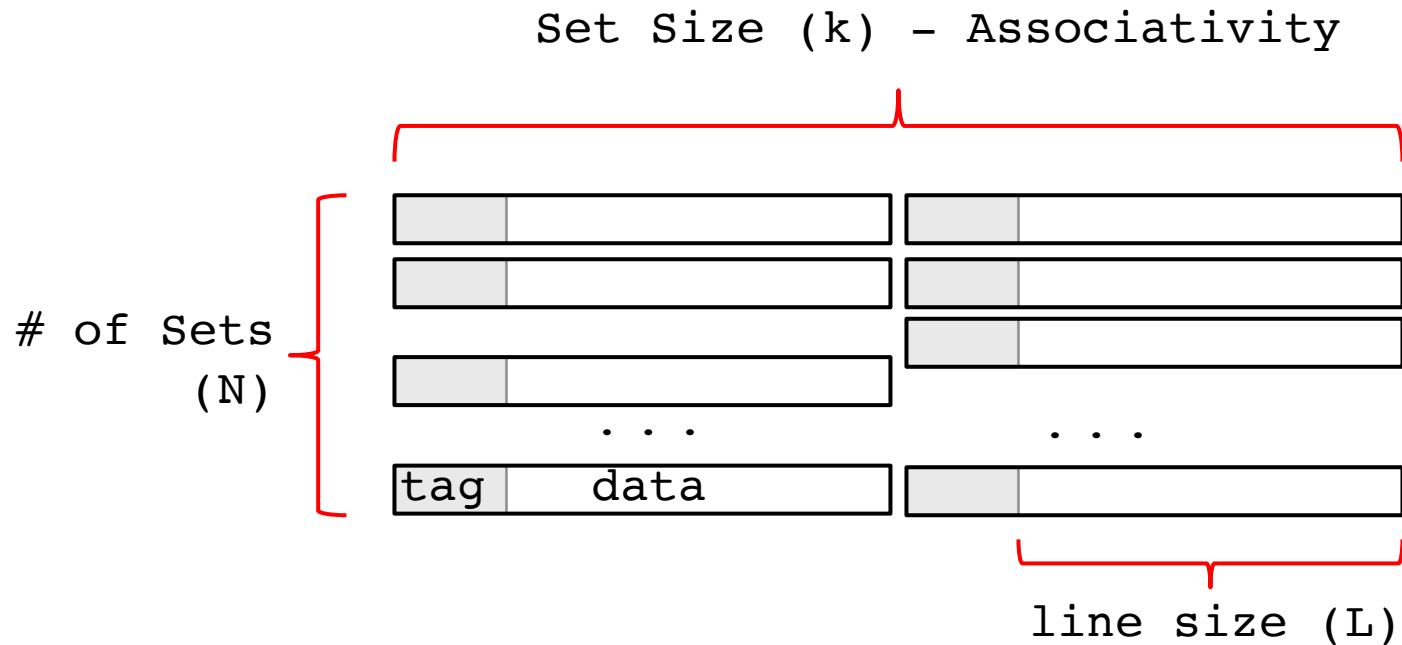
- TLB is a cache of translations:
 - Record recent Virtual Page # to Physical Frame # translation
- If present, get the physical address from TLB without reading any of the page tables !!!
 - Even if the translation involved multiple levels
 - Caches the end-to-end result
- Was invented by Sir Maurice Wilkes – *prior to caches*
 - People realized “if it’s good for page tables, why not the rest of the data in memory?”
- On a *TLB miss*, the page tables may be cached, so only go to memory when both miss
 - Ultimately invokes page table walk

Caching Applied to Address Translation



- Question is one of page locality: does it exist?
 - Instruction accesses spend a lot of time on the same page (since accesses sequential)
 - Stack accesses have definite locality of reference
 - Data accesses have less page locality, but still some...
- Can we have a TLB hierarchy?
 - Sure: multiple levels at different sizes/speeds

What kind of Cache for TLB?



- Remember all those cache design parameters and trade-offs?
 - Amount of Data = $N * L * K$
 - Tag is portion of address that identifies line (w/o line offset)
 - Write Policy (write-thru, write-back), Eviction Policy (LRU, ...)

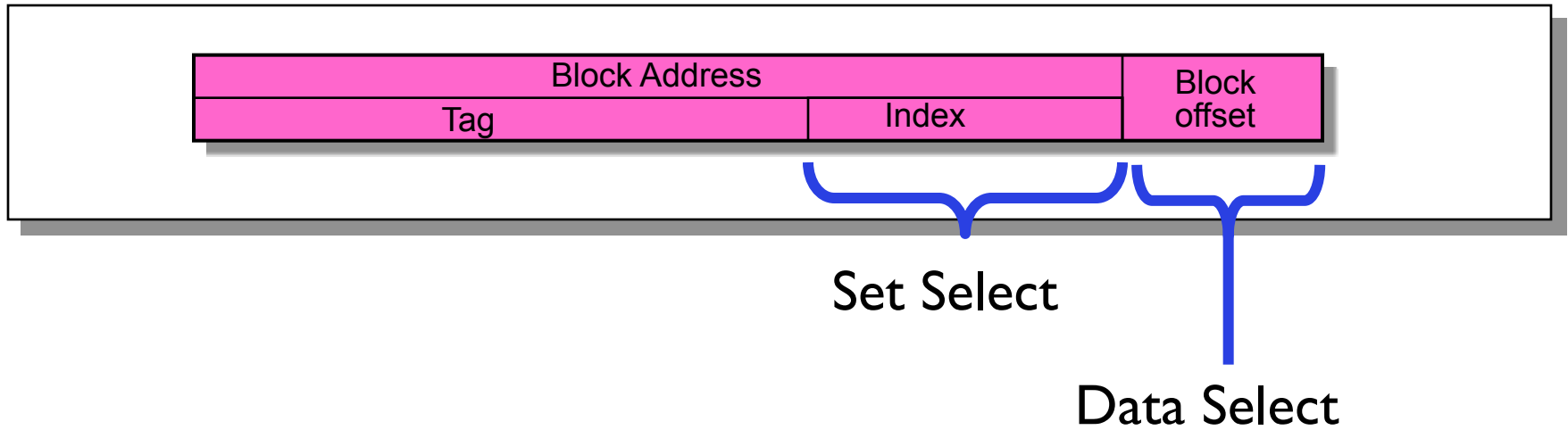
How might organization of TLB differ from that of a conventional instruction or data cache?

- Let's do some review ...

A Summary on Sources of Cache Misses

- **Compulsory** (cold start or process migration, first reference): first access to a block
 - “Cold” fact of life: not a whole lot you can do about it
 - Note: If you are going to run “billions” of instruction, Compulsory Misses are insignificant
- **Capacity**:
 - Cache cannot contain all blocks access by the program
 - Solution: increase cache size
- **Conflict** (collision):
 - Multiple memory locations mapped to the same cache location
 - Solution 1: increase cache size
 - Solution 2: increase associativity
- **Coherence** (Invalidation): other process (e.g., I/O) updates memory

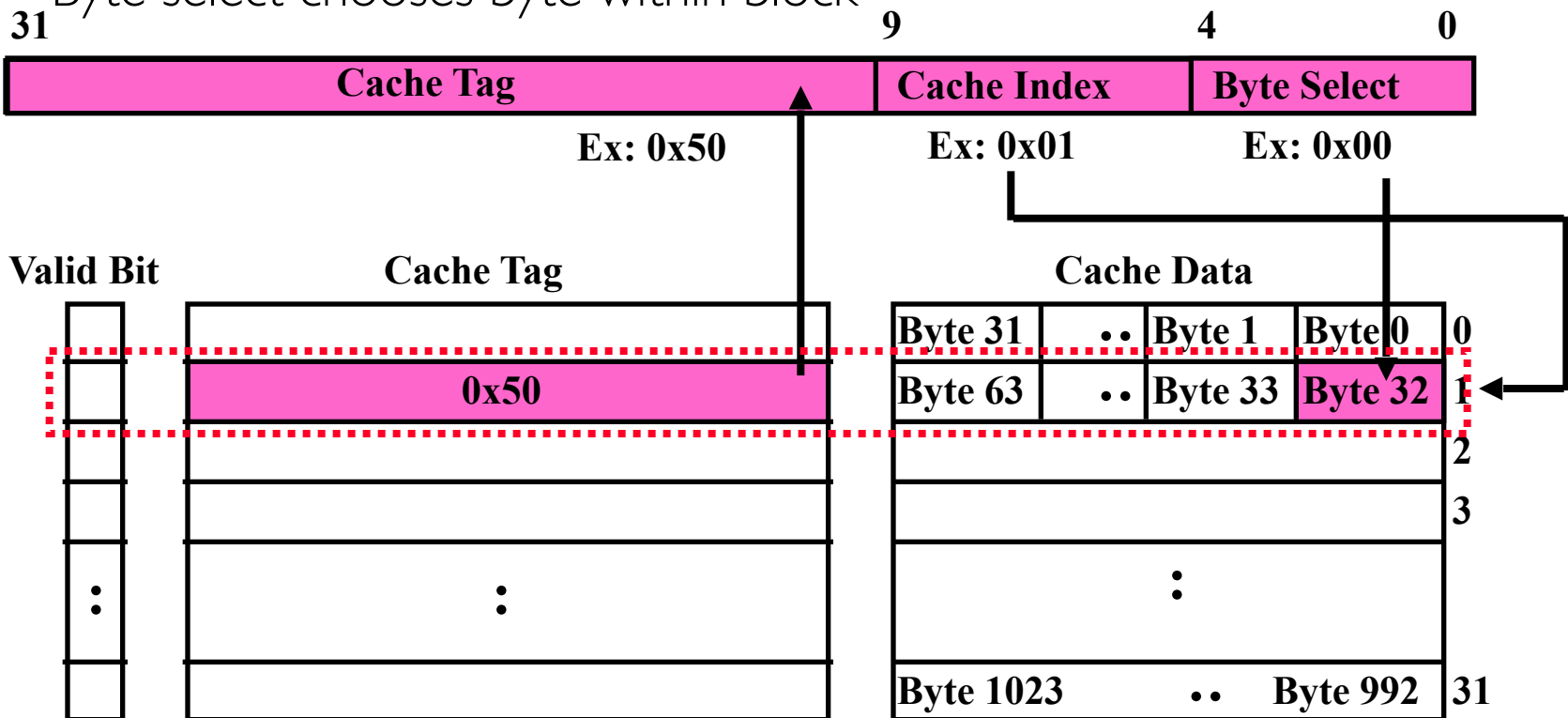
How is a Block found in a Cache?



- **Block** is minimum quantum of caching
 - Data select field used to select data (byte) within block
 - Many caching applications don't have data select field
- **Index** Used to Lookup Candidates in Cache
 - Index identifies the set
- **Tag** used to identify actual copy
 - If no candidates match, then declare cache miss

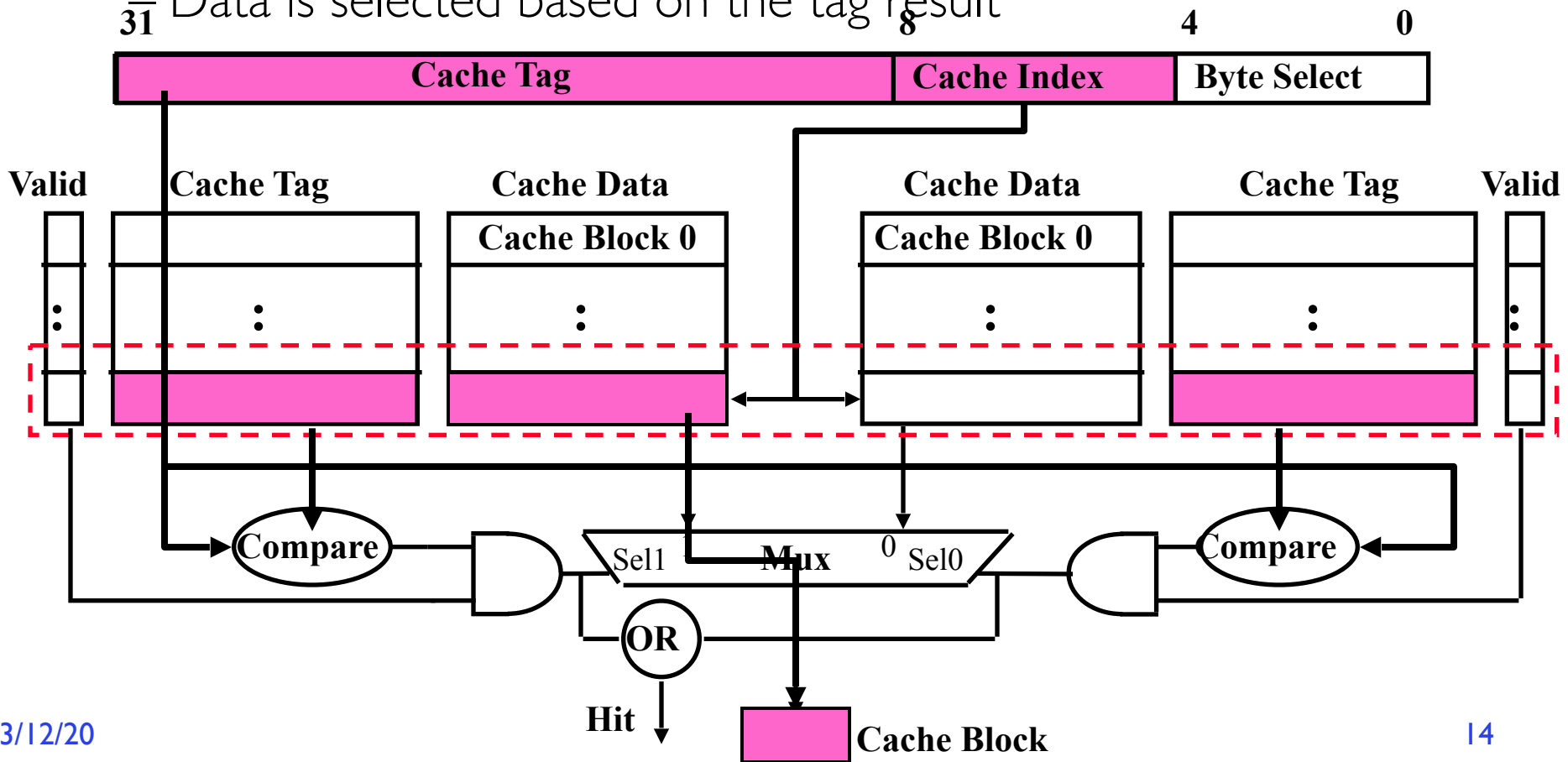
Review: Direct Mapped Cache

- **Direct Mapped 2^N byte cache:**
 - The uppermost $(32 - N)$ bits are always the Cache Tag
 - The lowest M bits are the Byte Select (Block Size = 2^M)
- Example: 1 KB Direct Mapped Cache with 32 B Blocks
 - Index chooses potential block
 - Tag checked to verify block
 - Byte select chooses byte within block



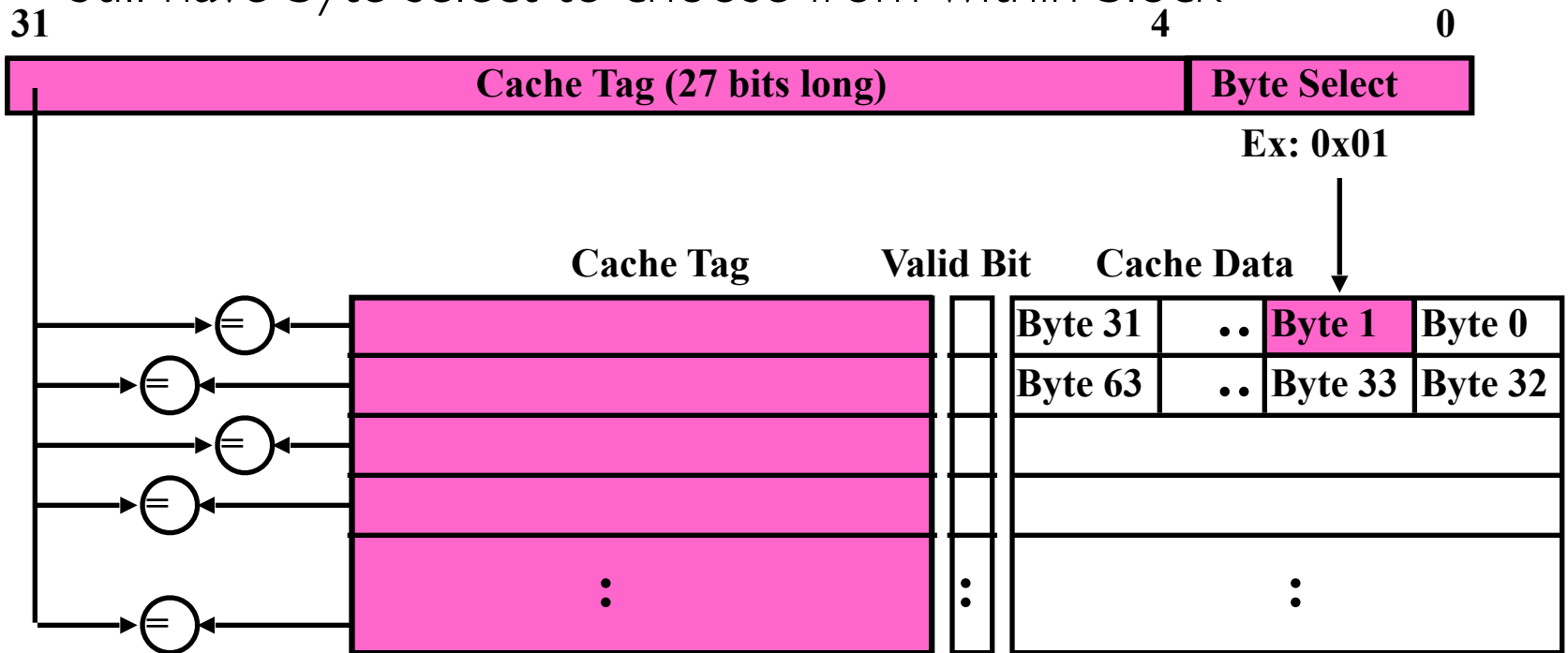
Review: Set Associative Cache

- **N-way set associative**: N entries per Cache Index
 - N direct mapped caches operates in parallel
- Example: Two-way set associative cache
 - Cache Index selects a “set” from the cache
 - Two tags in the set are compared to input in parallel
 - Data is selected based on the tag result



Review: Fully Associative Cache

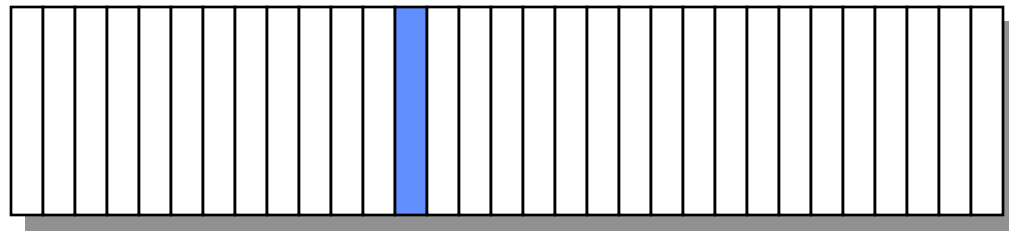
- **Fully Associative**: Every block can hold any line
 - Address does not include a cache index
 - Compare Cache Tags of all Cache Entries in Parallel
- Example: Block Size=32B blocks
 - We need N 27-bit comparators
 - Still have byte select to choose from within block



Where does a Block Get Placed in a Cache?

- Example: Block 12 placed in 8 block cache

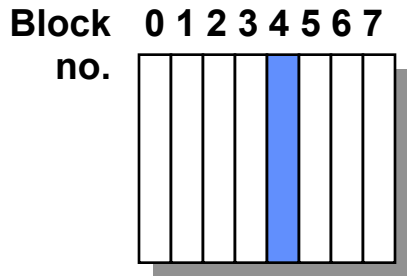
32-Block Address Space:



Block no. 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

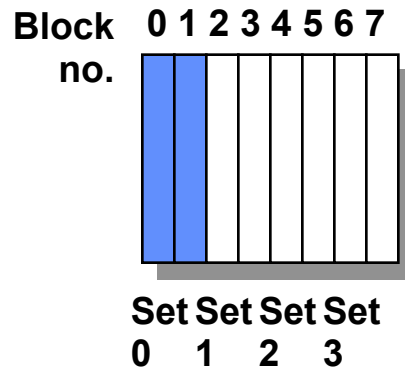
Direct mapped:

block 12 can go only into block 4
($12 \bmod 8$)



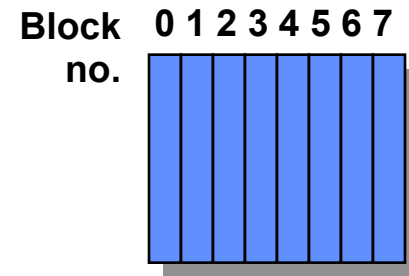
Set associative:

block 12 can go anywhere in set 0
($12 \bmod 4$)



Fully associative:

block 12 can go anywhere



Which block should be replaced on a miss?

- Easy for Direct Mapped: Only one possibility
- Set Associative or Fully Associative:
 - Random
 - LRU (Least Recently Used)

- Miss rates for a workload:

Size	2-way		4-way		8-way	
	LRU	Random	LRU	Random	LRU	Random
16 KB	5.2%	5.7%	4.7%	5.3%	4.4%	5.0%
64 KB	1.9%	2.0%	1.5%	1.7%	1.4%	1.5%
256 KB	1.15%	1.17%	1.13%	1.13%	1.12%	1.12%

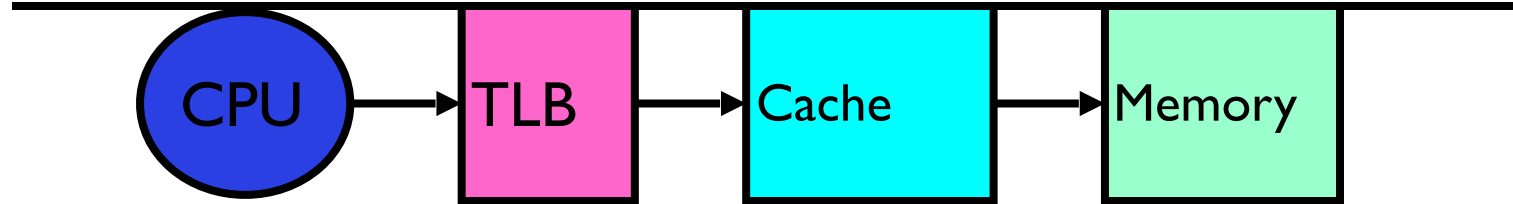
Review: What happens on a write?

- **Write through**: The information is written to both the block in the cache and to the block in the lower-level memory
- **Write back**: The information is written only to the block in the cache
 - Modified cache block is written to main memory only when it is replaced
 - Question is block clean or dirty?
- Pros and Cons of each?
 - WT:
 - » PRO: read misses cannot result in writes
 - » CON: Processor held up on writes unless writes buffered
 - WB:
 - » PRO: repeated writes not sent to DRAM
processor not held up on writes
 - » CON: More complex
Read miss may require writeback of dirty data

Impact of caches on Operating Systems

- Dealing with cache effects
 - Maintaining the correctness of various caches
 - E.g., TLB consistency:
 - » With PT across context switches ?
 - » Across updates to the PT ?
- Process scheduling
 - Which and how many processes are active ? Priorities ?
 - Large memory footprints versus small ones ?
 - Shared pages mapped into VAS of multiple processes ?
- Impact of thread scheduling on cache performance
 - Rapid interleaving of threads (small quantum) may degrade cache performance
 - » Increase average memory access time (AMAT) !!!
- Designing operating system data structures for cache performance

What TLB Organization Makes Sense?



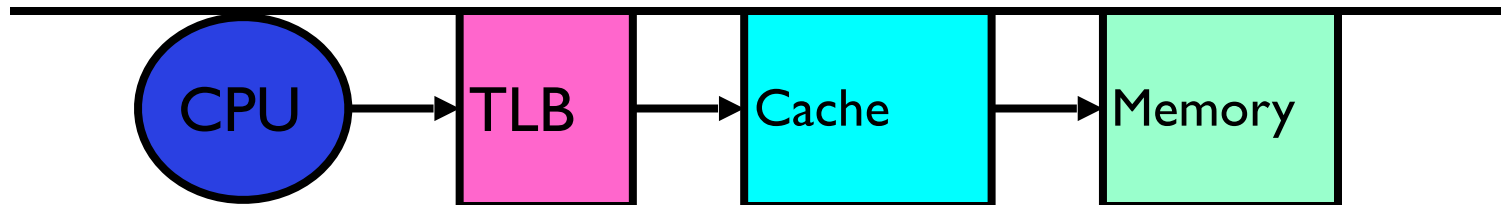
- Needs to be really fast
 - Critical path of memory access
 - » In simplest view: before the cache
 - » Thus, this adds to access time (reducing cache speed)
 - Seems to argue for Direct Mapped or Low Associativity
- However, needs to have very few conflicts!
 - With TLB, the Miss Time extremely high! (PT traversal)
 - Cost of Conflict (Miss Time) is high
 - Hit Time – dictated by clock cycle
- Thrashing: continuous conflicts between accesses
 - What if use low order bits of page as index into TLB?
 - » First page of code, data, stack may map to same entry
 - » Need 3-way associativity at least?
 - What if use high order bits as index?
 - » TLB mostly unused for small programs

TLB organization: include protection

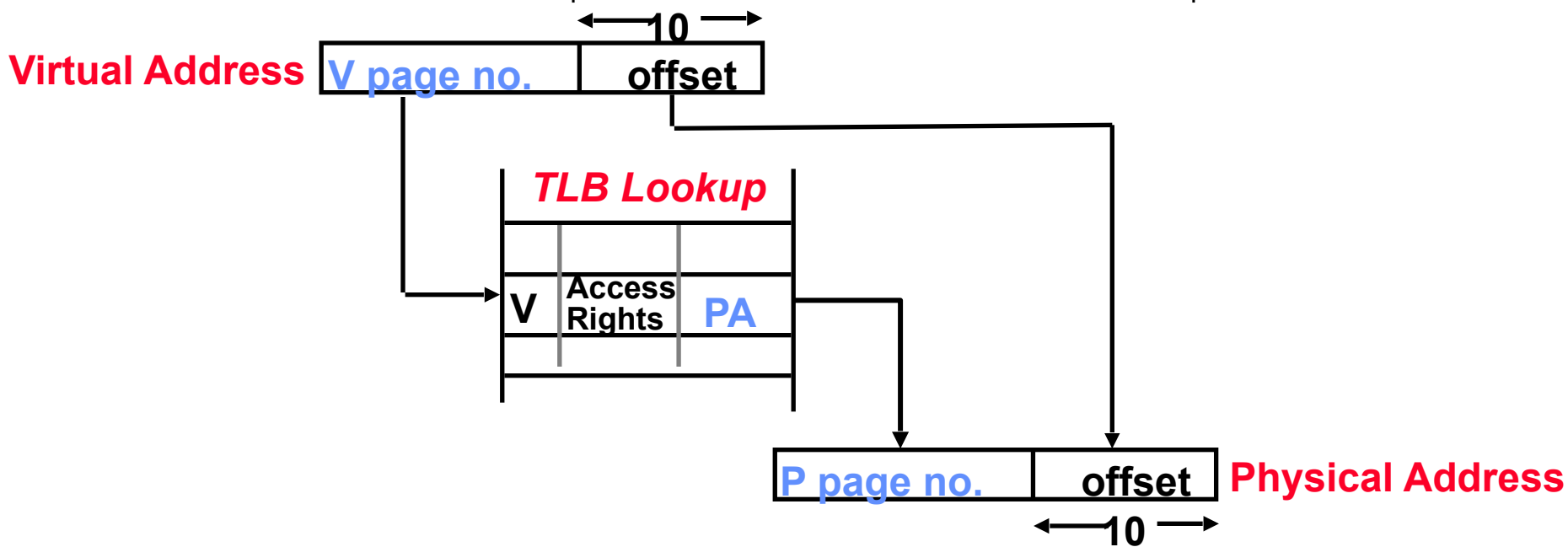
- How big does TLB actually have to be?
 - Usually small: 128-512 entries (larger now)
 - Not very big, can support higher associativity
- **Small TLBs usually organized as fully-associative cache**
 - Lookup is by Virtual Address
 - Returns Physical Address + other info
- What happens when fully-associative is too slow?
 - Put a small (4-16 entry) direct-mapped cache in front
 - Called a “TLB Slice”
- Example for MIPS R3000:

Virtual Address	Physical Address	Dirty	Ref	Valid	Access	ASID
0xFA00	0x0003	Y	N	Y	R/W	34
0x0040	0x0010	N	Y	Y	R	0
0x0041	0x0011	N	Y	Y	R	0

Reducing translation time further



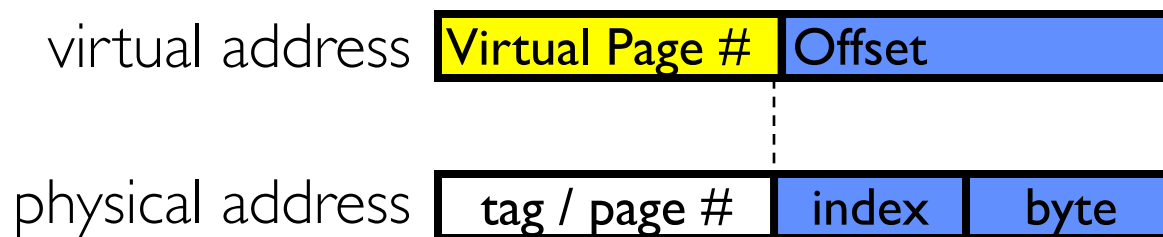
- As described, TLB lookup is in serial with cache lookup:



- Machines with TLBs go one step further: they overlap TLB lookup with cache access.
 - Works because offset available early

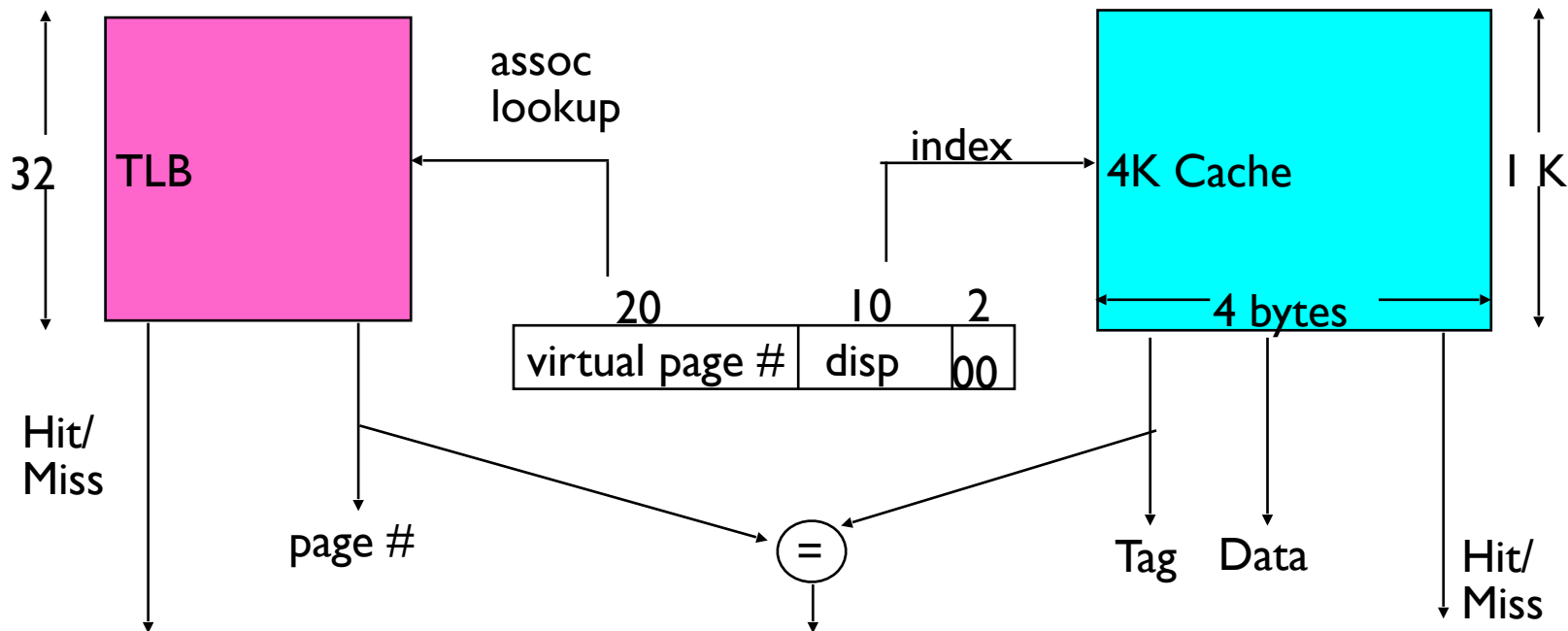
Overlapping TLB & Cache Access (1/2)

- Main idea:
 - Offset in virtual address exactly covers the “cache index” and “byte select”
 - Thus can select the cached byte(s) in parallel to perform address translation



Overlapping TLB & Cache Access

- Here is how this might work with a 4K, direct-mapped cache:



- This gets much more interesting if you want a larger cache
 - Increase page size (obvious, but not entirely desirable)
 - Increase associativity of cache (thereby decreasing index)
 - Start looking up in multiple chunks of cache, pick when TLB lookup is finished.

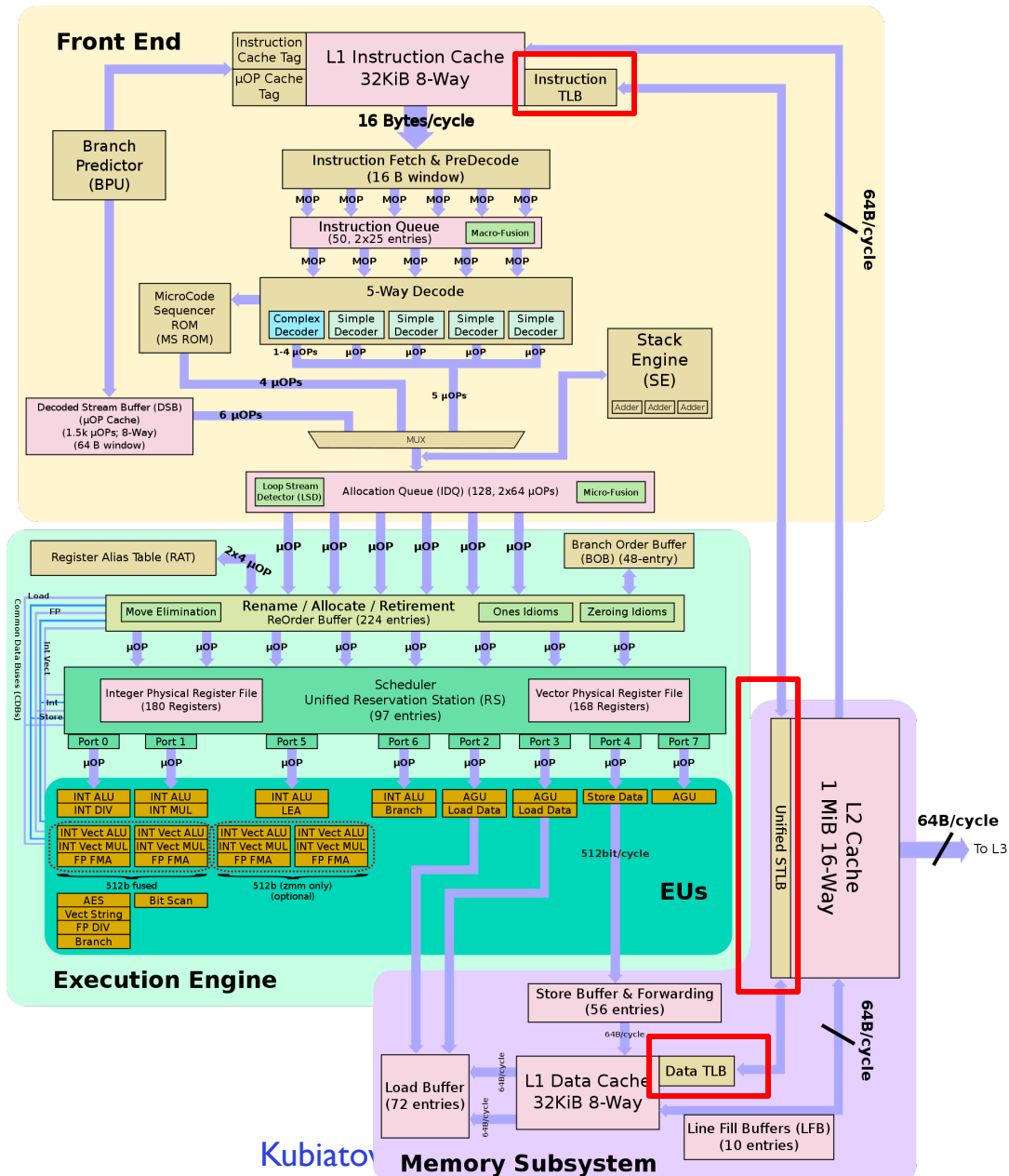
Example TLB Sizes: Pentium-M TLBs (2003)

- Four different TLBs
 - Instruction TLB for 4K pages
 - » 128 entries, 4-way set associative
 - Instruction TLB for large pages
 - » 2 entries, fully associative
 - Data TLB for 4K pages
 - » 128 entries, 4-way set associative
 - Data TLB for large pages
 - » 8 entries, 4-way set associative
- All TLBs use LRU replacement policy
- Why different TLBs for instruction, data, and page sizes?

Intel Nahelem (2008)

- L1 DTLB
 - 64 entries for 4 K pages and
 - 32 entries for 2/4 M pages,
- L1 ITLB
 - 128 entries for 4 K pages using 4-way associativity and
 - 14 fully associative entries for 2/4 MiB pages
- unified 512-entry L2 TLB for 4 KiB pages, 4-way associative.

Current Intel x86 (Skylake, Cascade Lake)



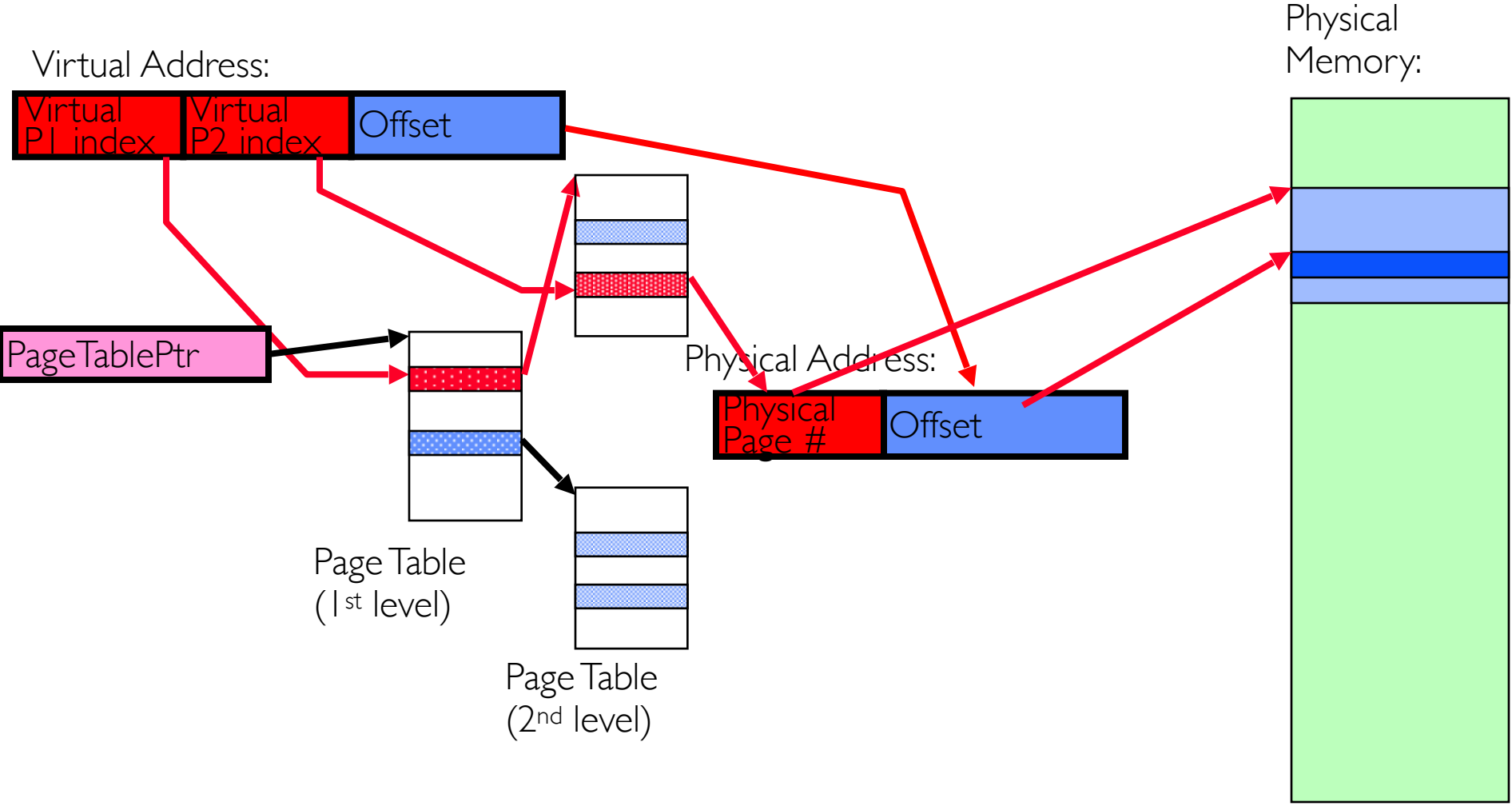
Current Example: Memory Hierarchy

- Caches (all 64 B line size)
 - L1 I-Cache: 32 KiB/core, 8-way set assoc.
 - L1 D Cache: 32 KiB/core, 8-way set assoc., 4-5 cycles load-to-use, Write-back policy
 - L2 Cache: 1 MiB/core, 16-way set assoc., Inclusive, Write-back policy, 14 cycles latency
 - L3 Cache: 1.375 MiB/core, 11-way set assoc., shared across cores, Non-inclusive victim cache, Write-back policy, 50-70 cycles latency
- TLB
 - L1 ITLB, 128 entries; 8-way set assoc. for 4 KB pages
 - » 8 entries per thread; fully associative, for 2 MiB / 4 MiB page
 - L1 DTLB 64 entries; 4-way set associative for 4 KB pages
 - » 32 entries; 4-way set associative, 2 MiB / 4 MiB page translations:
 - » 4 entries; 4-way associative, 1 G page translations:
 - L2 STLB: 1536 entries; 12-way set assoc. 4 KiB + 2 MiB pages
 - » 16 entries; 4-way set associative, 1 GiB page translations:

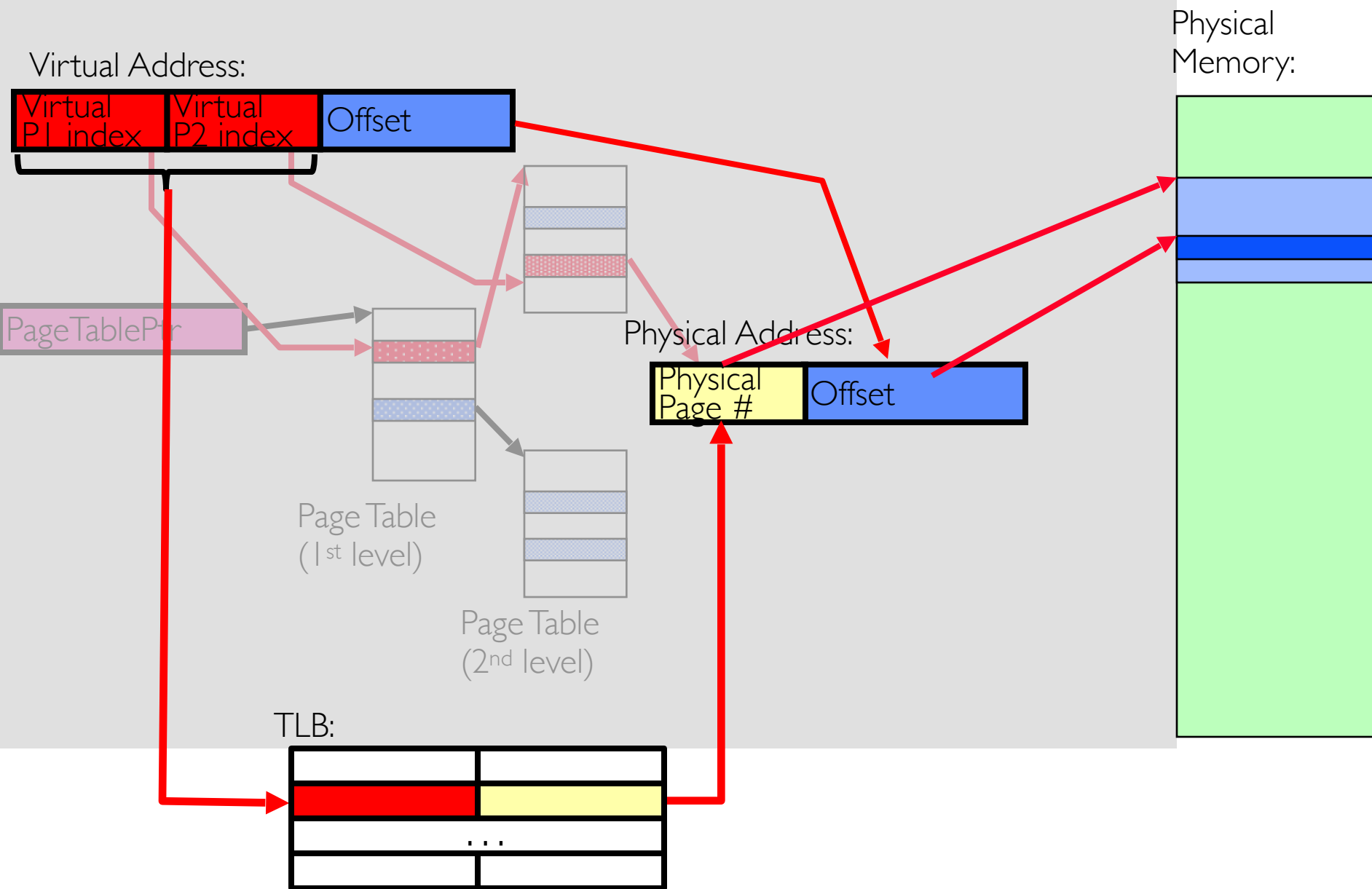
What happens to TLB on Context Switch?

- Need to do something, since TLBs map virtual addresses to physical addresses
 - Address Space just changed, so TLB entries no longer valid!
- Options?
 - Invalidate TLB: simple but might be expensive
 - » What if switching frequently between processes?
 - Include ProcessID in TLB
 - » This is an architectural solution: needs hardware
- What if translation tables change?
 - For example, to move page from memory to disk or vice versa...
 - Must invalidate TLB entry!
 - » Otherwise, might think that page is still in memory!
 - Called “TLB Consistency”

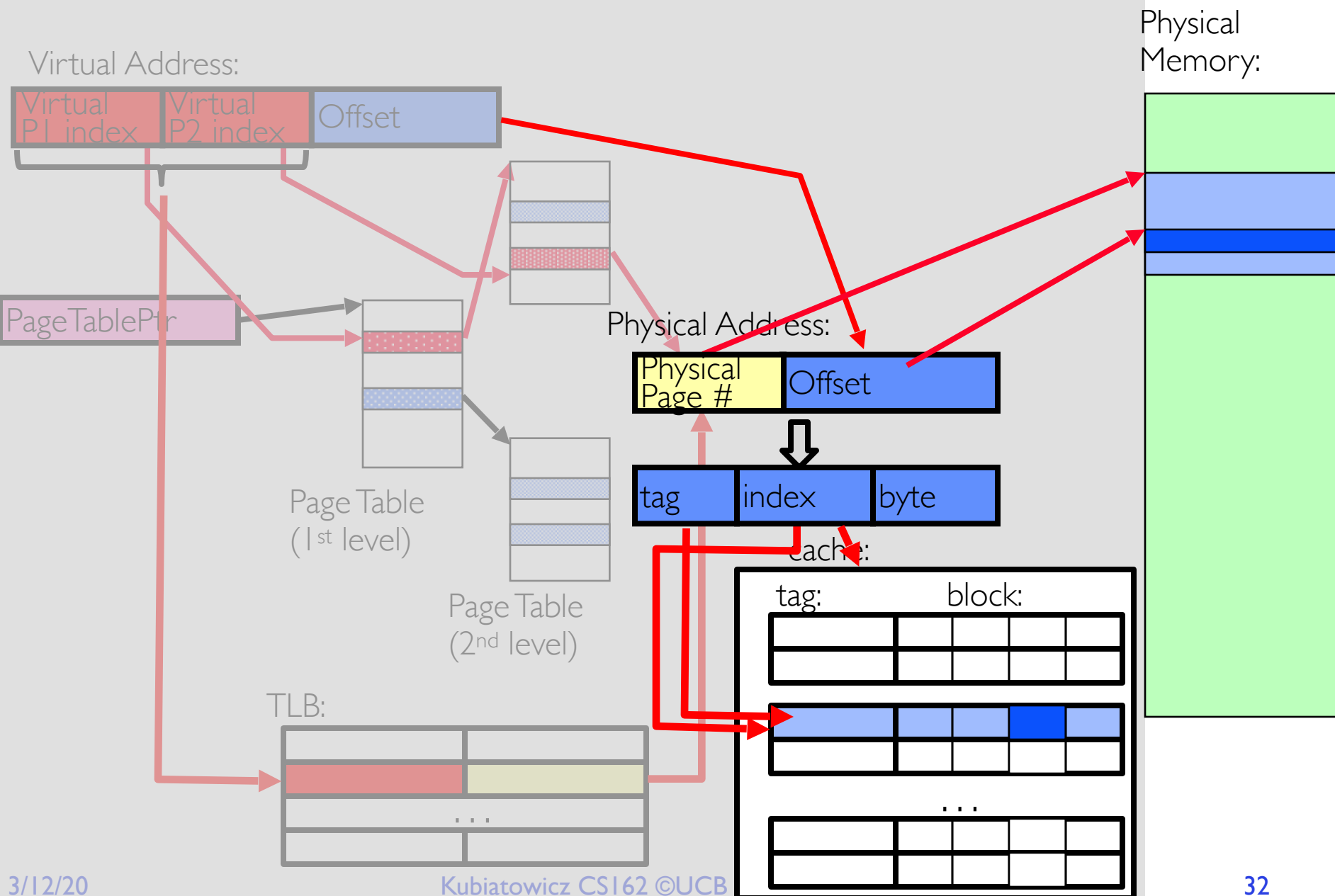
Putting Everything Together: Address Translation



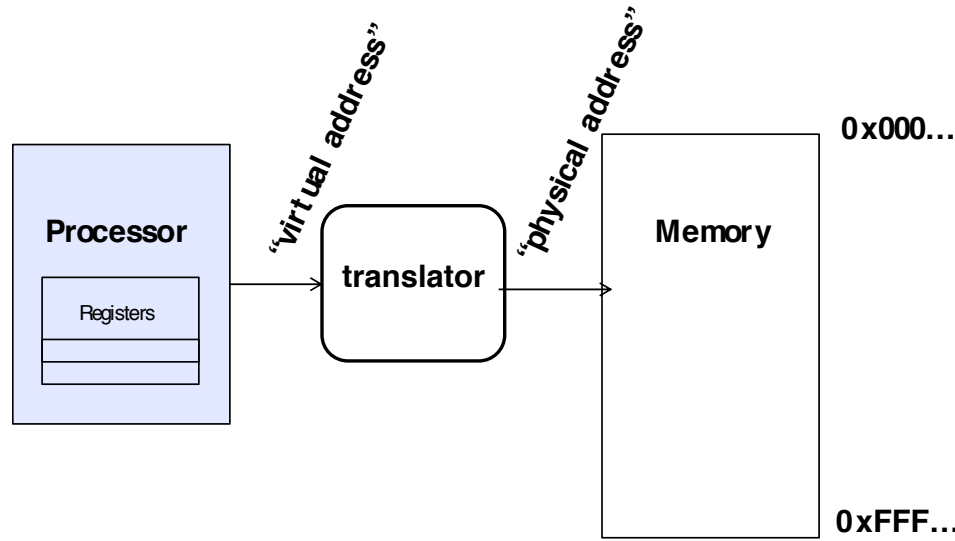
Putting Everything Together: TLB



Putting Everything Together: Cache



Recall: Two Critical Issues in Address Translation



- How to translate addresses fast enough?
 - Every instruction fetch
 - Plus every load / store
 - EVERY MEMORY REFERENCE !
 - More than one translation for EVERY instruction
- Next: What to do if the translation fails?
 - Page fault! This is a synchronous exception!

Recall: User→Kernel: (Exceptions: Traps & Interrupts)

- A system call instruction causes a synchronous exception (or “trap”)
 - In fact, often called a software “trap” instruction
- Other sources of **Synchronous Exceptions (“Trap”)**:
 - Divide by zero, Illegal instruction, Bus error (bad address, e.g. unaligned access)
 - Segmentation Fault (address out of range)
 - Page Fault (for illusion of infinite-sized memory)
- Interrupts are **Asynchronous Exceptions**:
 - Examples: timer, disk ready, network, etc....
 - **Interrupts can be disabled, traps cannot!**
- On system call, exception, or interrupt:
 - Hardware enters kernel mode with interrupts disabled
 - Saves PC, then jumps to appropriate handler in kernel
 - Some processors (e.g. x86) also save registers, changes stack
- Handler does any required state preservation not done by CPU:
 - Might save registers, other CPU state, and switches to kernel stack

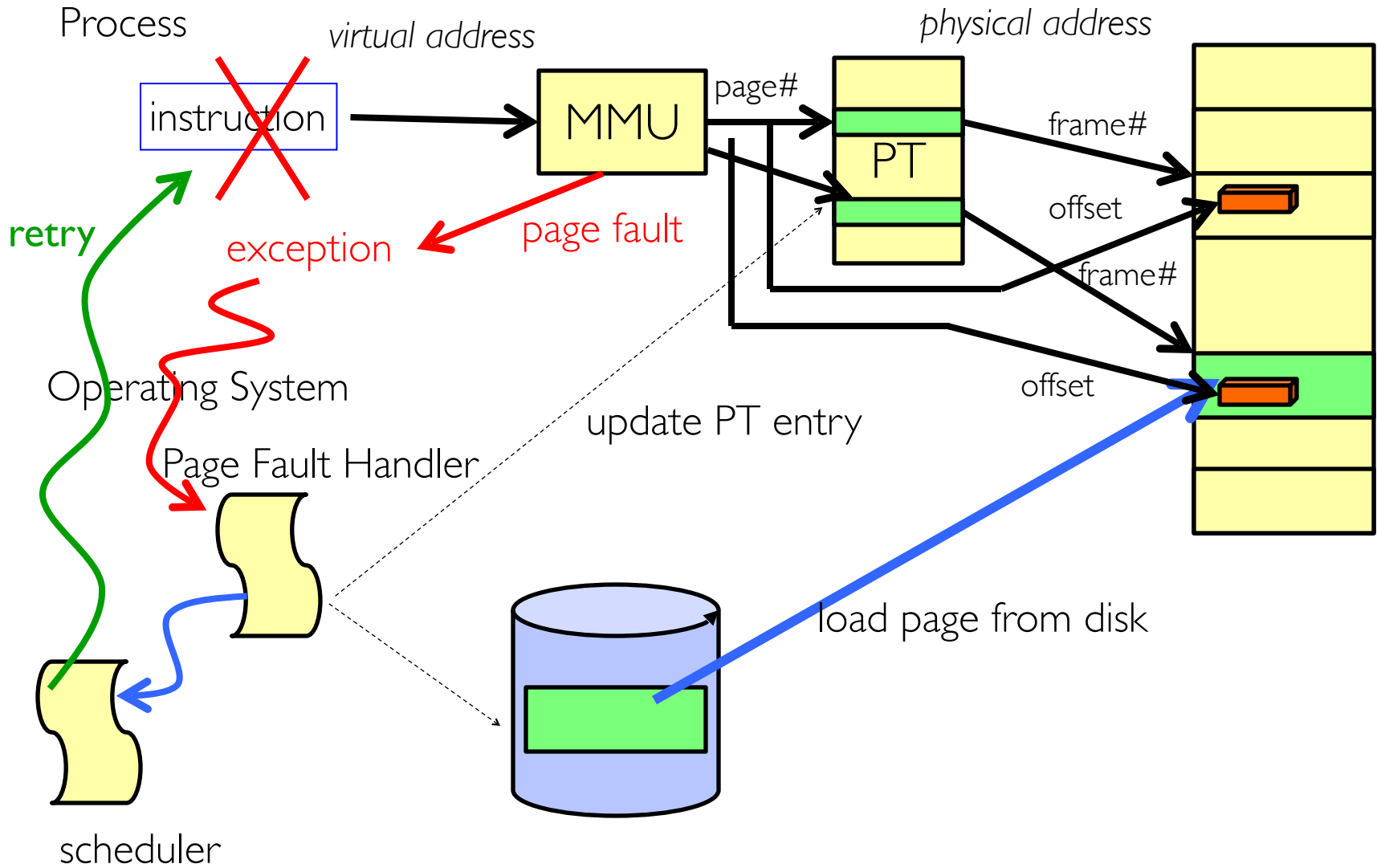
Precise Exceptions

- Precise \Rightarrow state of the machine is preserved as if program executed up to the offending instruction
 - All previous instructions **completed**
 - Offending instruction and all following instructions act **as if they have not even started**
 - Same system code will work on different implementations
 - Difficult in the presence of pipelining, out-of-order execution, ...
- Imprecise \Rightarrow system software has to figure out what is where and put it all back together
- Performance goals may lead designers to forsake precise interrupts
 - system software developers, user, markets etc. usually wish they had not done this
- **Modern techniques for out-of-order execution and branch prediction help implement precise interrupts**

Page Fault is a Synchronous Exception

- The Virtual-to-Physical Translation fails
 - PTE marked invalid (at whatever level of page table), Privilege-Level Violation, Access violation
- Causes a Fault / Trap
 - Not an interrupt because synchronous to instruction execution!
 - May occur on instruction fetch or data access
 - Protection violations typically terminate the instruction in a way that is restartable (more later)
- Page Faults engage operating system to fix the situation and retry the instruction
 - Allocate an additional stack page, or
 - Make the page accessible - Copy on Write,
 - Bring page in from secondary storage – demand paging
- Protection violations that cannot be resolved \Rightarrow terminate process (possibly “dumping core” image for debugging)
- Fundamental inversion of the hardware / software boundary

Next Up: What happens when ...



Inversion of the Hardware / Software Boundary

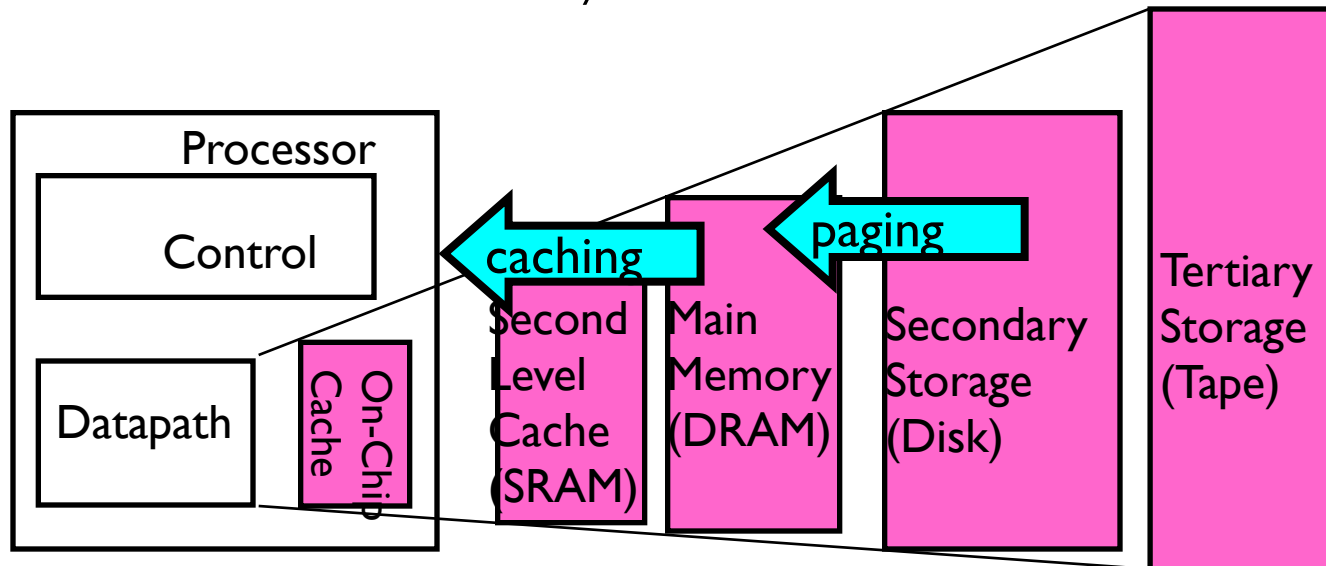
- In order for an instruction to complete ...
- It requires the intervention of operating system software
- Receive the page fault, remedy the situation
 - Load the page, create the page, copy-on-write
 - Update the PTE entry so the translation will succeed
- Restart (or resume) the instruction
 - This is one of the huge simplifications in RISC instructions sets
 - Can be very complex when instruction modify state (x86)

Demand Paging as Caching, ...

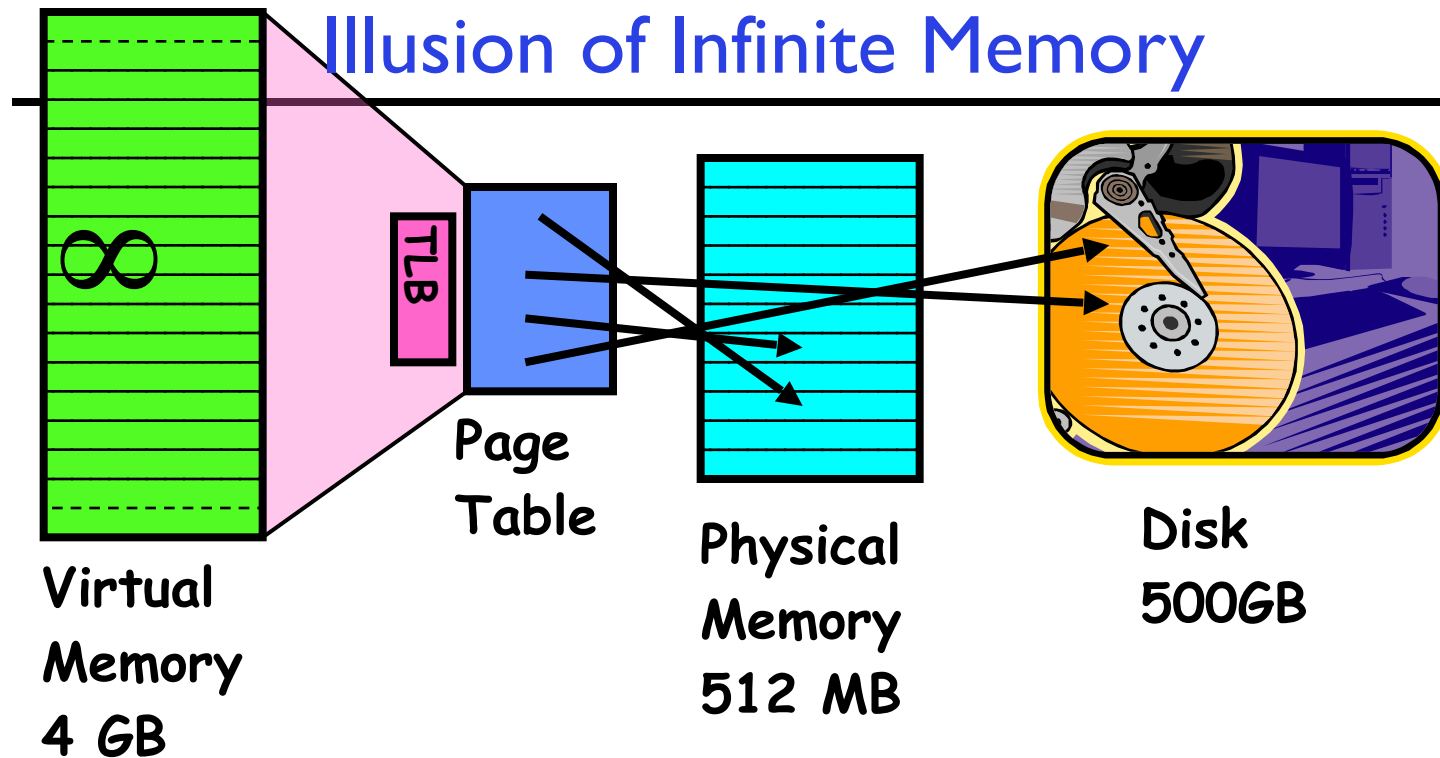
- What “block size”? - 1 page (e.g, 4 KB)
- What “organization” ie. direct-mapped, set-assoc., fully-associative?
 - Any page in any frame of memory, i.e., fully associative: arbitrary virtual → physical mapping
- How do we locate a page?
 - First check TLB, then page-table traversal
- What is page replacement policy? (i.e. LRU, Random...)
 - This requires more explanation... (kinda LRU)
- What happens on a miss?
 - Go to lower level to fill miss (i.e. disk)
- What happens on a write? (write-through, write back)
 - Definitely write-back – need dirty bit!

Demand Paging

- Modern programs require a lot of physical memory
 - Memory per system growing faster than 25%-30%/year
- But they don't use all their memory all of the time
 - 90-10 rule: programs spend 90% of their time in 10% of their code
 - Wasteful to require all of user's code to be in memory
- Solution: use main memory as “cache” for disk



Illusion of Infinite Memory



- Disk is larger than physical memory \Rightarrow
 - In-use virtual memory can be bigger than physical memory
 - Combined memory of running processes much larger than physical memory
 - » More programs fit into memory, allowing more concurrency
- Principle: **Transparent Level of Indirection** (page table)
 - Supports flexible placement of physical data
 - » Data could be on disk or somewhere across network
 - Variable location of data transparent to user program
 - » Performance issue, not correctness issue

Review: What is in a PTE?

- What is in a Page Table Entry (or PTE)?
 - Pointer to next-level page table or to actual page
 - Permission bits: valid, read-only, read-write, write-only
- Example: Intel x86 architecture PTE:
 - 2-level page tabler (10, 10, 12-bit offset)
 - Intermediate page tables called “Directories”



P: Present (same as “valid” bit in other architectures)

W: Writeable

U: User accessible

PWT: Page write transparent: external cache write-through

PCD: Page cache disabled (page cannot be cached)

A: Accessed: page has been accessed recently

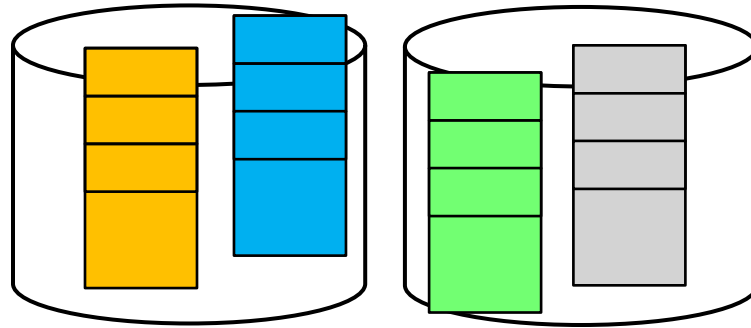
D: Dirty (PTE only): page has been modified recently

PS: Page Size: PS=1 ⇒ 4MB page (directory only).

Bottom 22 bits of virtual address serve as offset

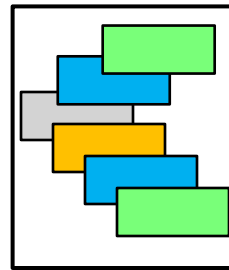
Origins of Paging

Keep most of the address space on disk



Disks provide most of the storage

Actively swap pages to/from



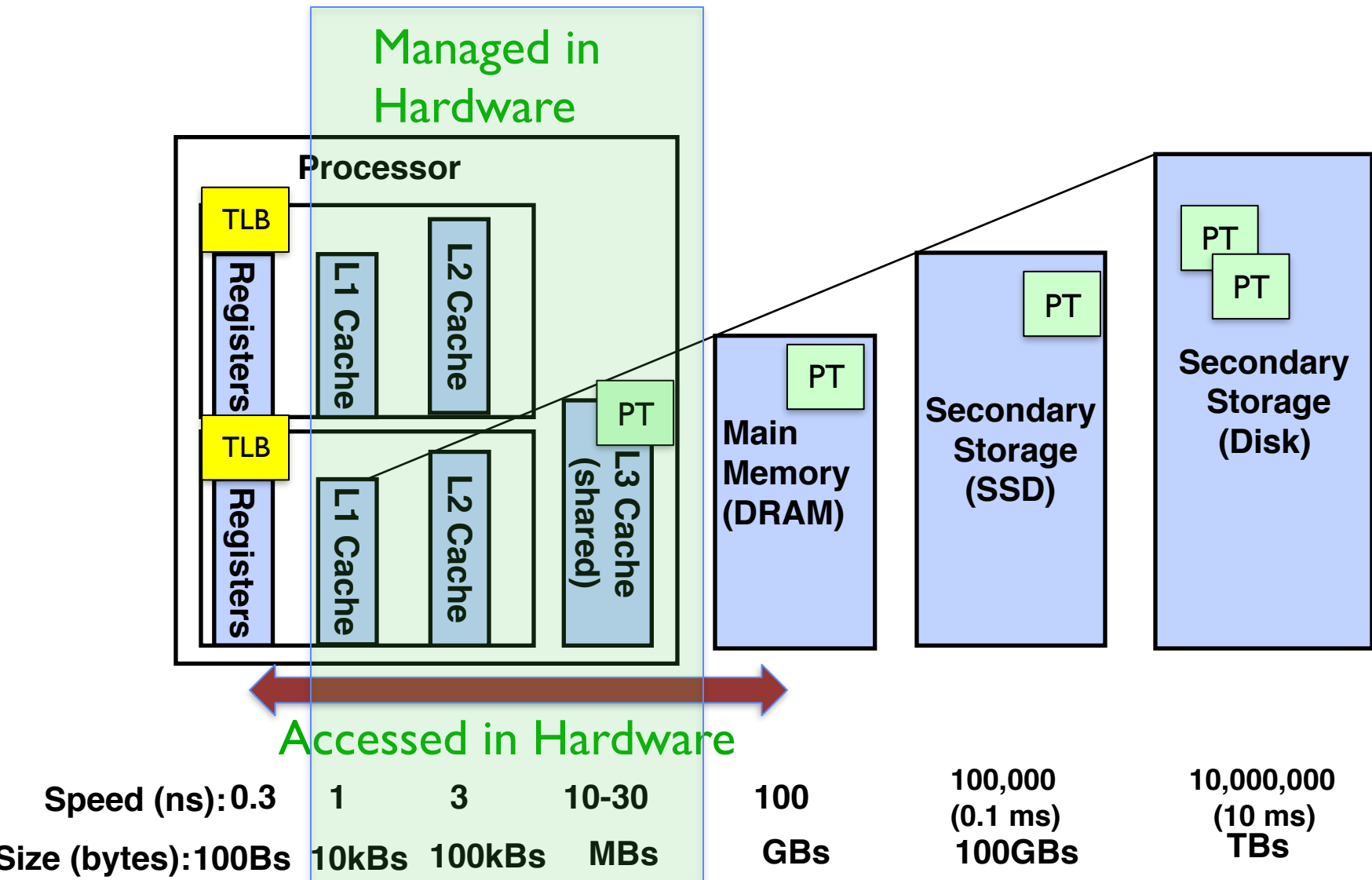
Relatively small memory, for many processes

Keep memory full of the frequently accesses pages

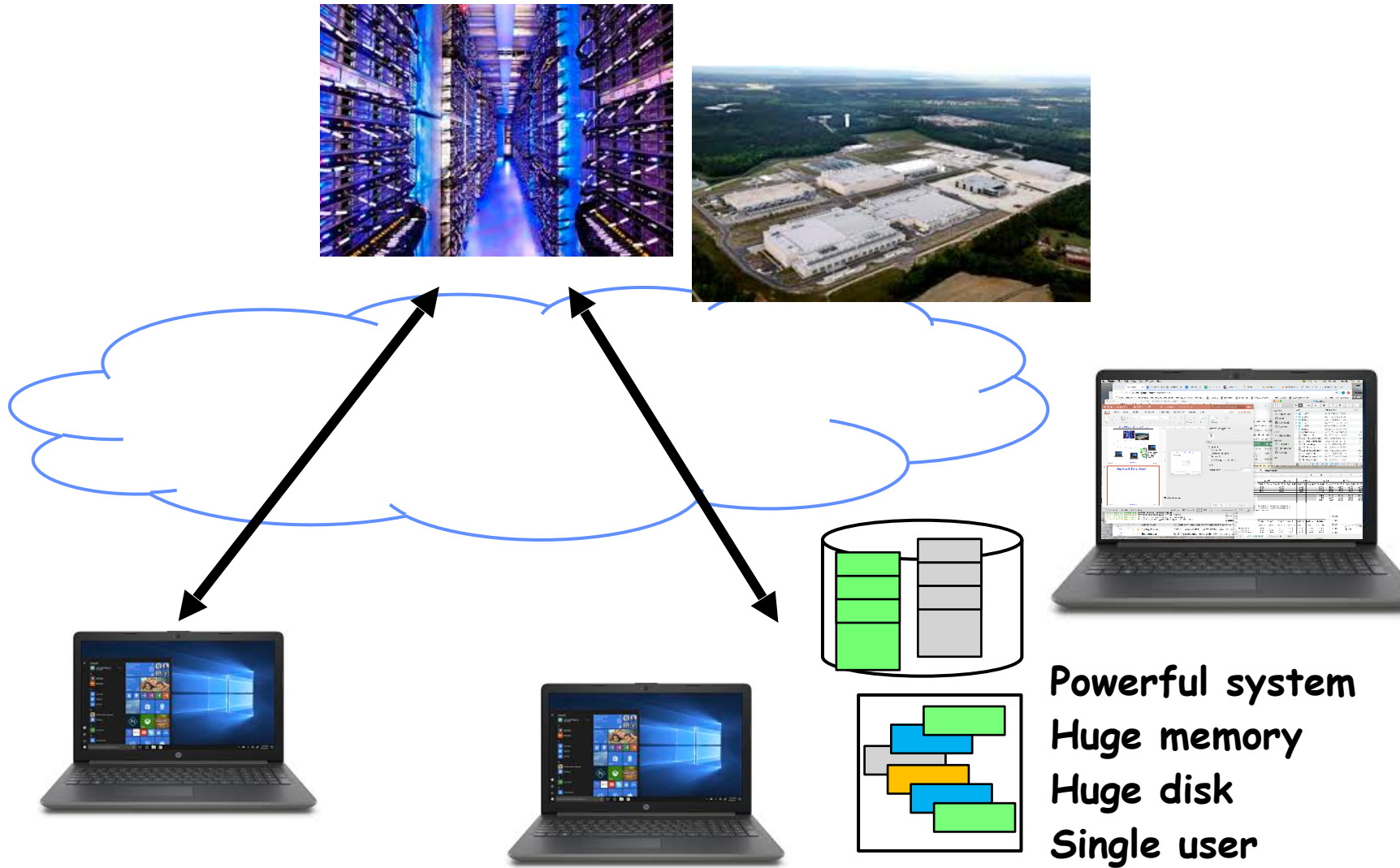


Many clients on dumb terminals running different programs

Recall: The Memory Hierarchy



Very Different Situation Today



A Picture on one machine

```
Processes: 407 total, 2 running, 405 sleeping, 2135 threads                22:10:39
Load Avg: 1.26, 1.26, 0.98 CPU usage: 1.35% user, 1.59% sys, 97.5% idle
SharedLibs: 292M resident, 54M data, 43M linkedit.
MemRegions: 155071 total, 4489M resident, 124M private, 1891M shared.
PhysMem: 13G used (3518M wired), 2718M unused.
VM: 1819G vsize, 1372M framework vsize, 68020510(0) swapins, 71200340(0) swapouts.
Networks: packets: 40629441/21G in, 21395374/7747M out.
Disks: 17026780/555G read, 15757470/638G written.
```

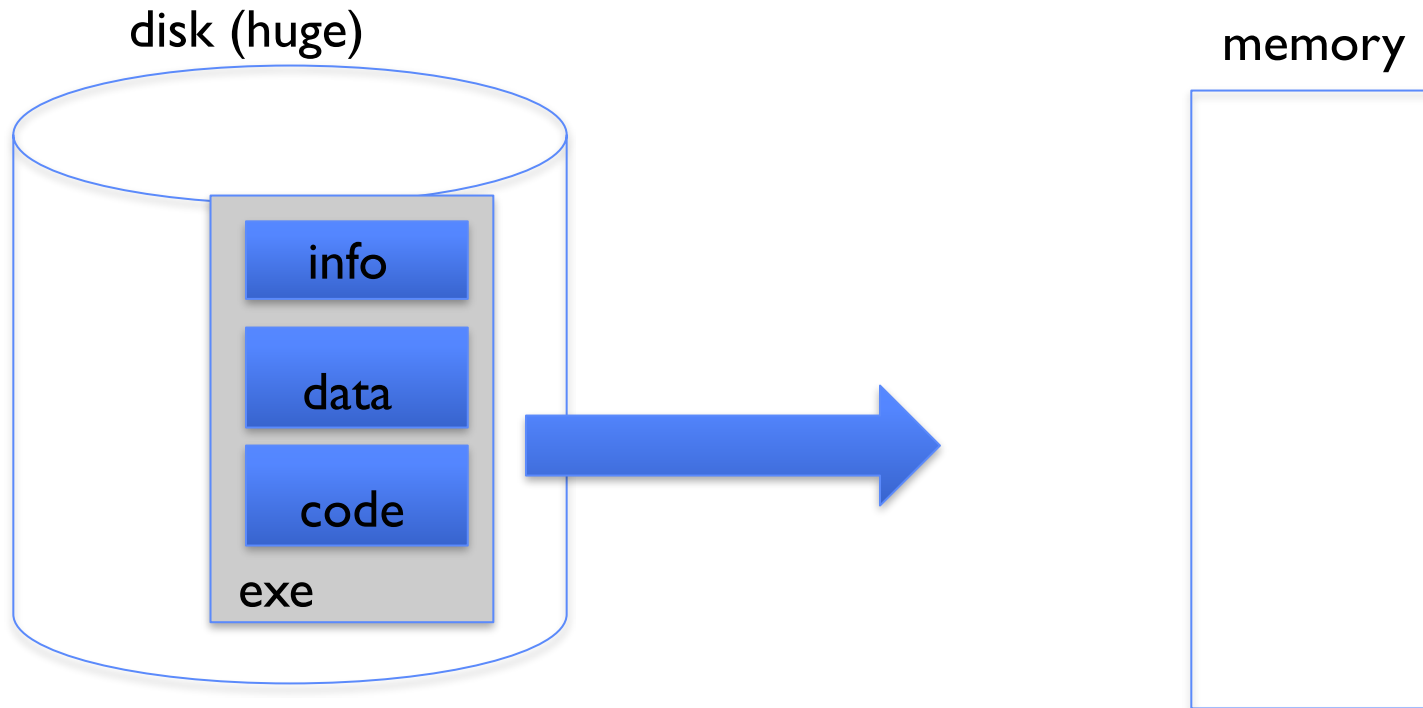
PID	COMMAND	%CPU	TIME	#TH	#WQ	#PORTS	MEM	PURG	CMPRS	PGRP	PPID	STATE
90498	bash	0.0	00:00.41	1	0	21	1080K	0B	564K	90498	90497	sleeping
90497	login	0.0	00:00.10	2	1	31	1236K	0B	1220K	90497	90496	sleeping
90496	Terminal	0.5	01:43.28	6	1	378-	103M-	16M	13M	90496	1	sleeping
89197	siriknowledg	0.0	00:00.83	2	2	45	2664K	0B	1528K	89197	1	sleeping
89193	com.apple.DF	0.0	00:17.34	2	1	68	2688K	0B	1700K	89193	1	sleeping
82655	LookupViewSe	0.0	00:10.75	3	1	169	13M	0B	8064K	82655	1	sleeping
82453	PAH_Extensio	0.0	00:25.89	3	1	235	15M	0B	7996K	82453	1	sleeping
75819	tzlinkd	0.0	00:00.01	2	2	14	452K	0B	444K	75819	1	sleeping
75787	MTLCompilerS	0.0	00:00.10	2	2	24	9032K	0B	9020K	75787	1	sleeping
75776	secd	0.0	00:00.78	2	2	36	3208K	0B	2328K	75776	1	sleeping
75098	DiskUnmountW	0.0	00:00.48	2	2	34	1420K	0B	728K	75098	1	sleeping
75093	MTLCompilerS	0.0	00:00.06	2	2	21	5924K	0B	5912K	75093	1	sleeping
74938	ssh-agent	0.0	00:00.00	1	0	21	908K	0B	892K	74938	1	sleeping
74063	Google Chrom	0.0	10:48.49	15	1	678	192M	0B	51M	54320	54320	sleeping

- Memory stays about 75% used, 25% for dynamics
- A lot of it is shared 1.9 GB

Many Uses of "Demand Paging" ...

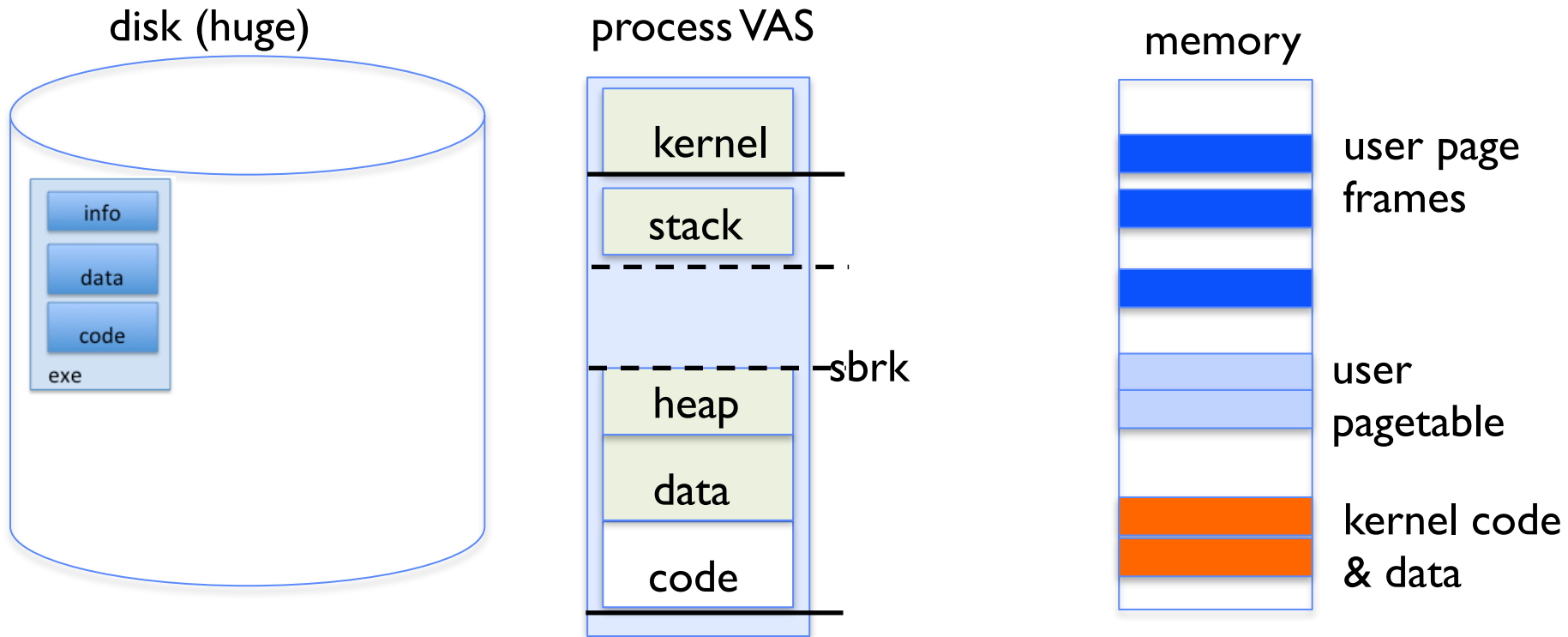
- Extend the stack
 - Allocate a page and zero it
- Extend the heap (sbrk of old, today mmap)
- Process Fork
 - Create a copy of the page table
 - Entries refer to parent pages – NO-WRITE
 - Shared read-only pages remain shared
 - Copy page on write
- Exec
 - Only bring in parts of the binary in active use
 - Do this on demand
- MMAP to explicitly share region (or to access a file as RAM)

Classic: Loading an executable into memory



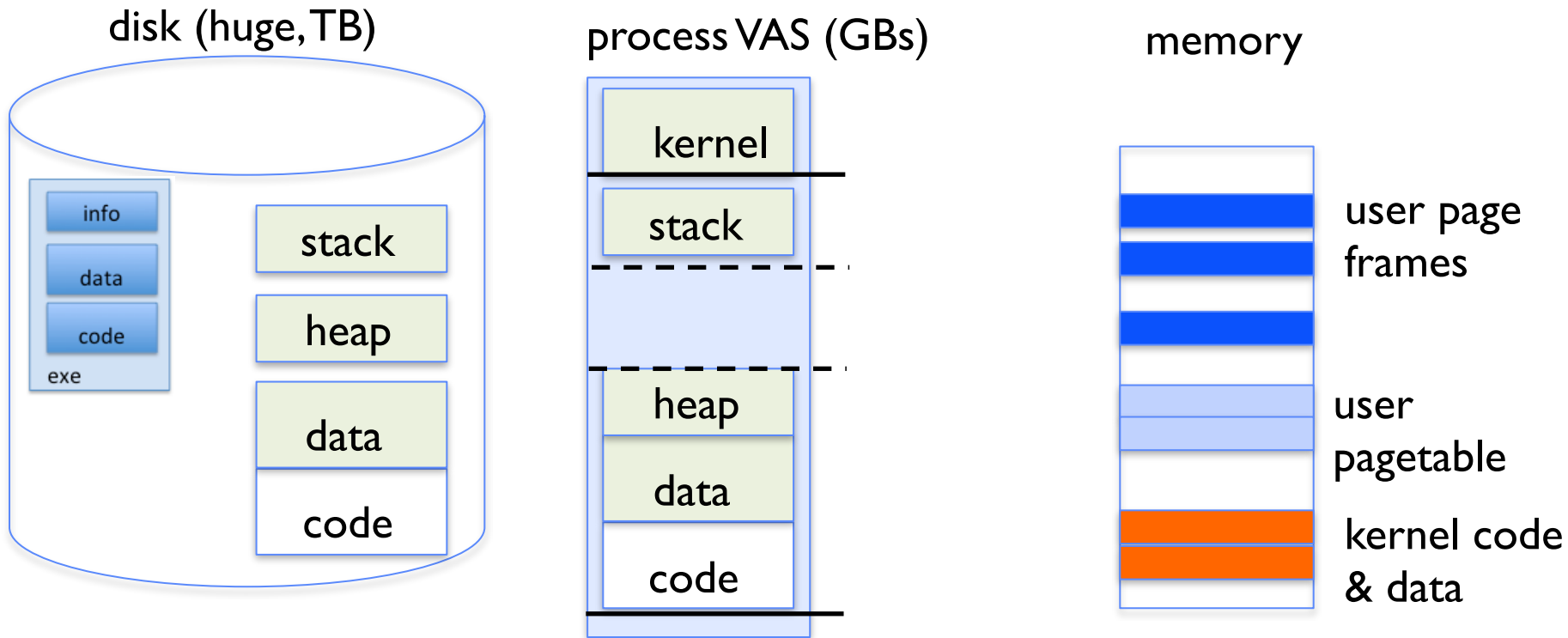
- .exe
 - lives on disk in the file system
 - contains contents of code & data segments, relocation entries and symbols
 - OS loads it into memory, initializes registers (and initial stack pointer)
 - program sets up stack and heap upon initialization:
`crt0` (C runtime init)

Create Virtual Address Space of the Process



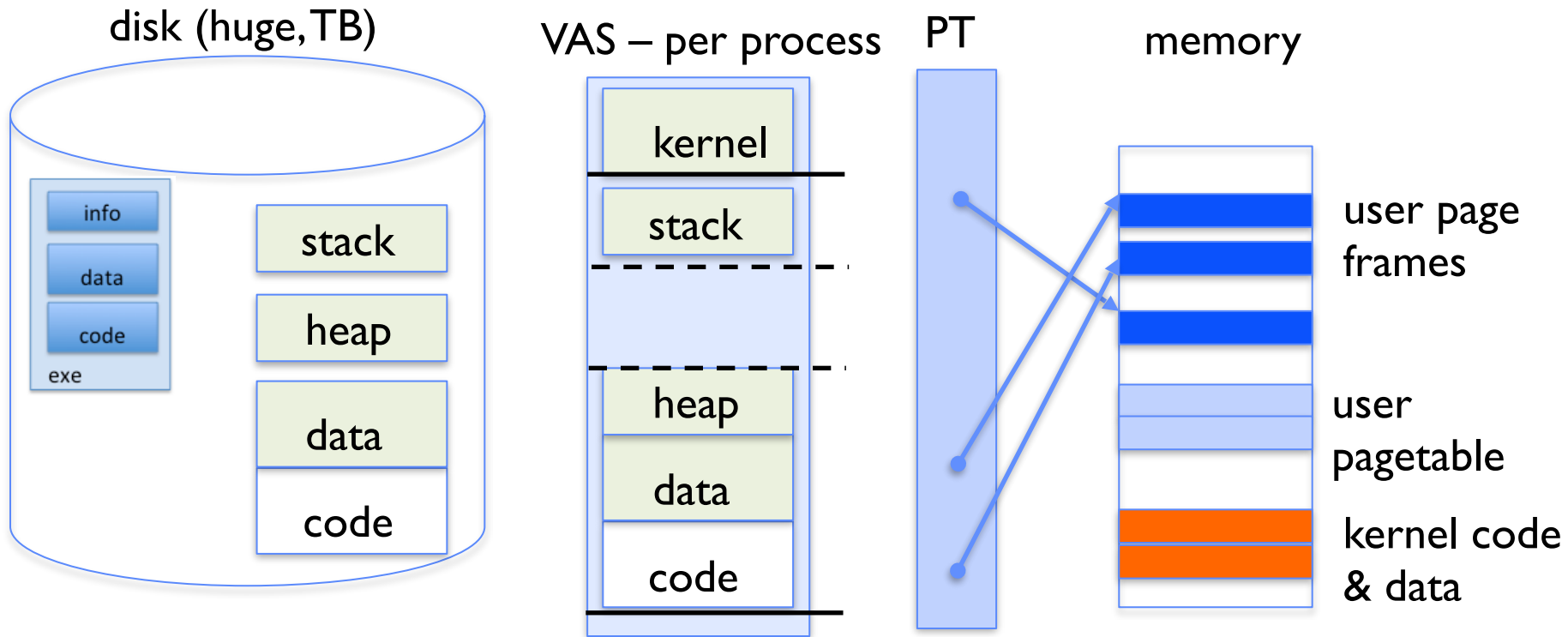
- Utilized pages in the VAS are backed by a page block on disk
 - Called the backing store or swap file
 - Typically in an optimized block store, but can think of it like a file

Create Virtual Address Space of the Process



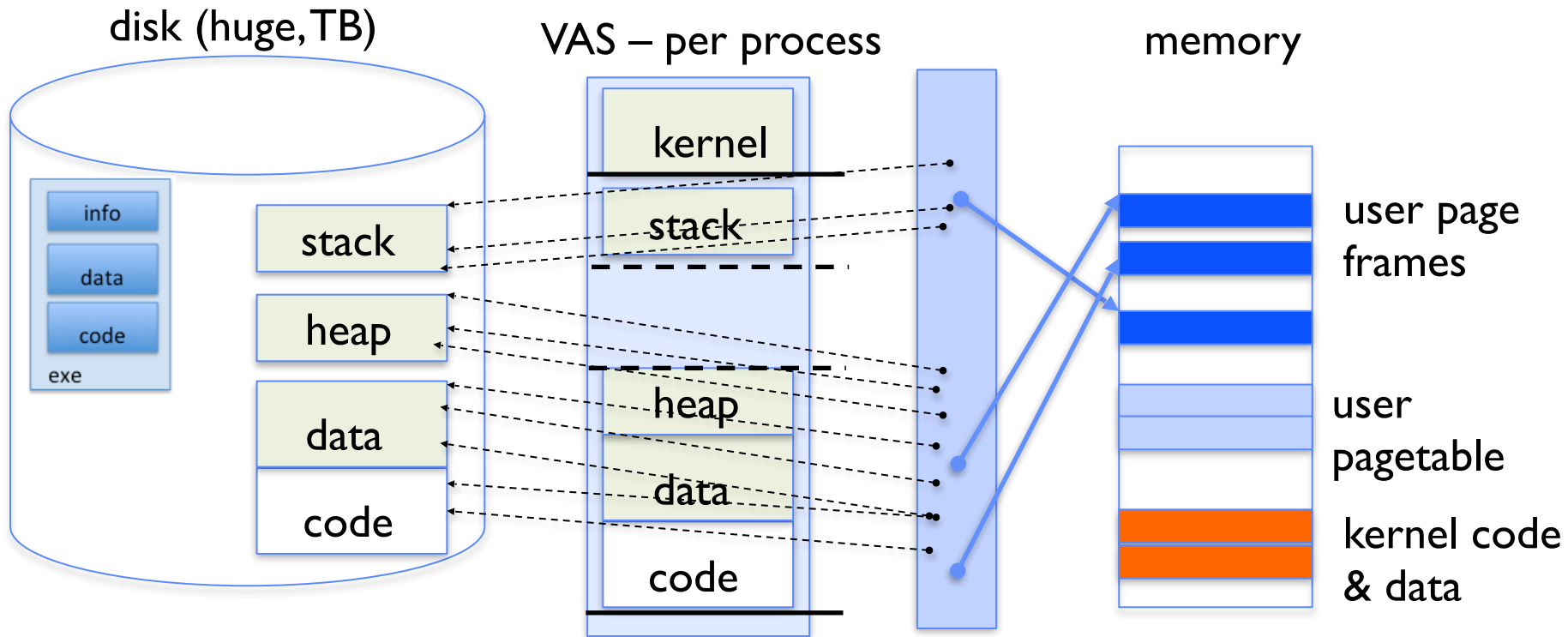
- User Page table maps entire VAS
- All the utilized regions are backed on disk
 - swapped into and out of memory as needed
- For every process

Create Virtual Address Space of the Process



- User Page table maps entire VAS
 - Resident pages to the frame in memory they occupy
 - The portion of it that the HW needs to access must be resident in memory

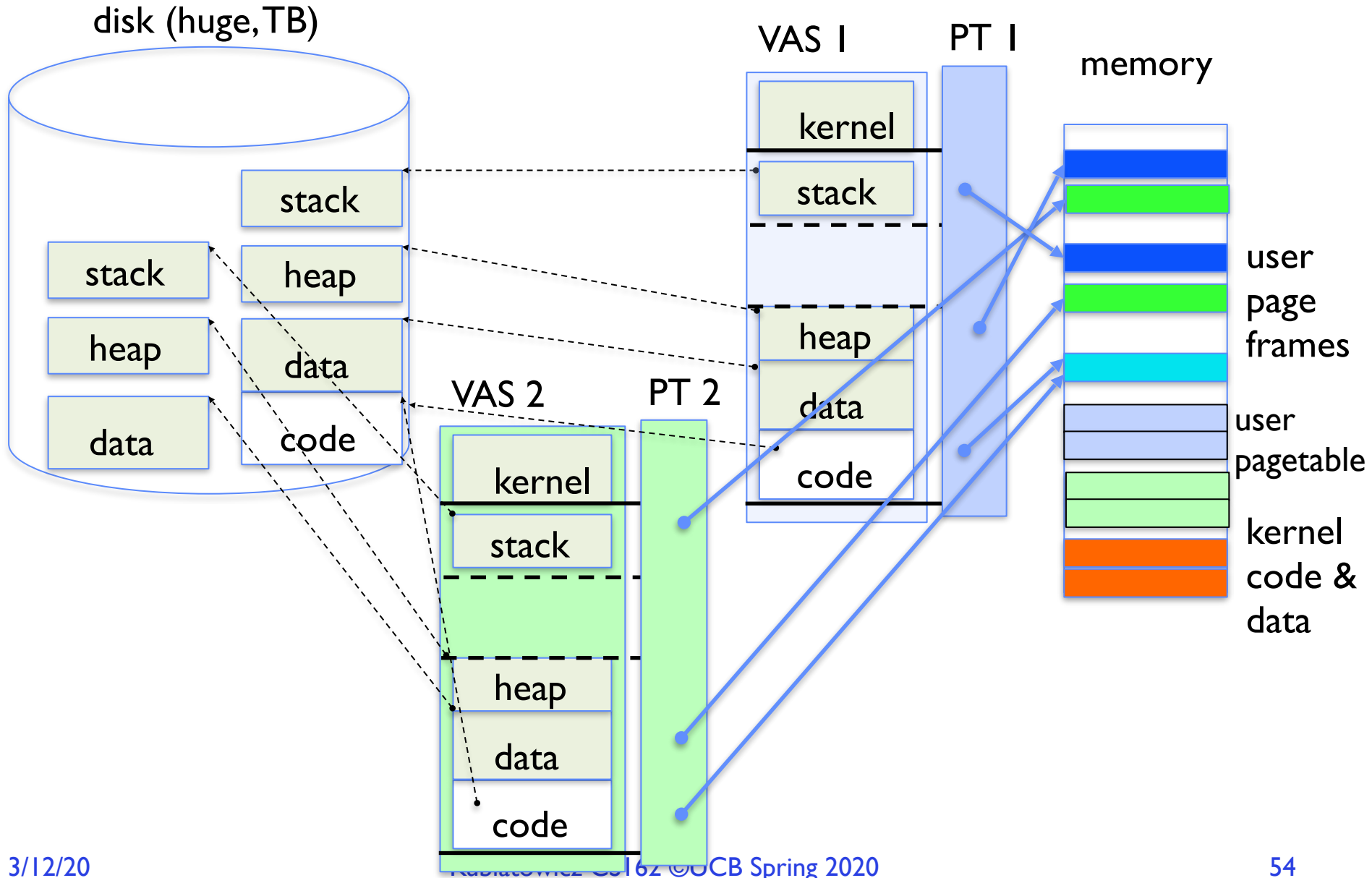
Provide Backing Store for VAS



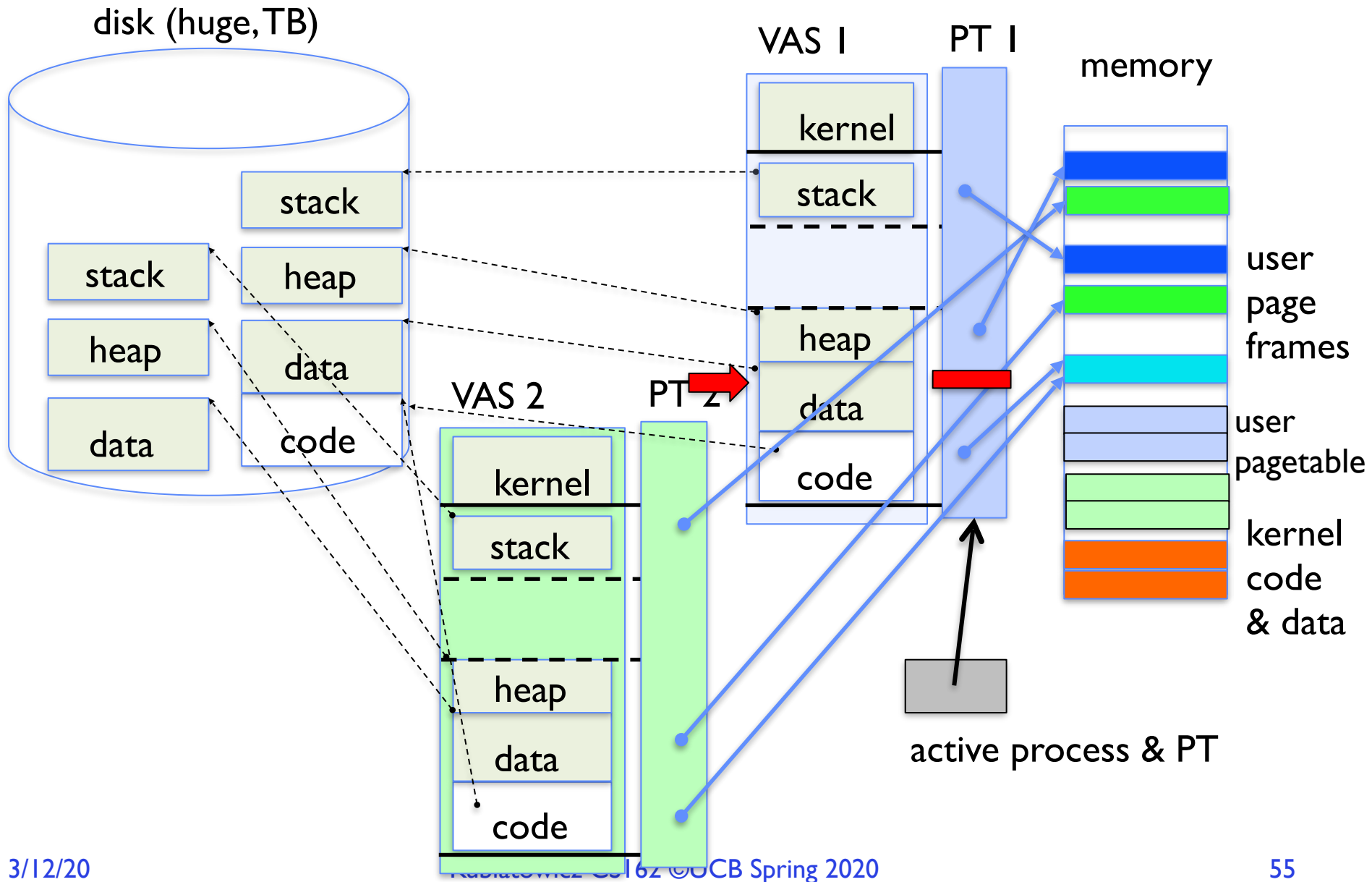
- User Page table maps entire VAS
- Resident pages mapped to memory frames
- For all other pages, OS must record where to find them on disk

- `FindBlock(PID, page#) → disk_block`
 - Some OSs utilize spare space in PTE for paged blocks
 - Like the PT, but purely software
- Where to store it?
 - In memory – can be compact representation if swap storage is contiguous on disk
 - Could use hash table (like Inverted PT)
- Usually want backing store for resident pages too
- May map code segment directly to on-disk image
 - Saves a copy of code to swap file
- May share code segment with multiple instances of the program

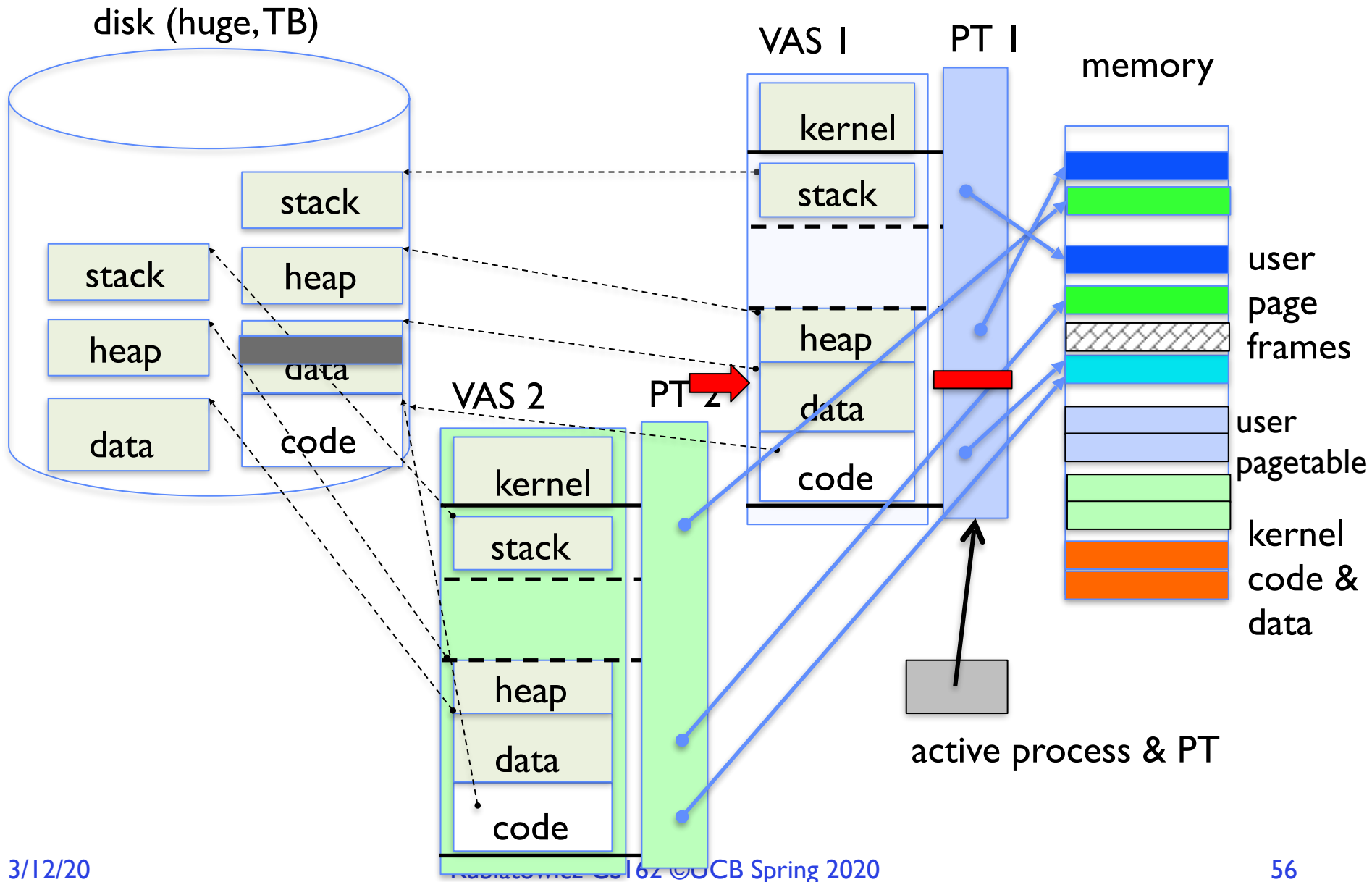
Provide Backing Store for VAS



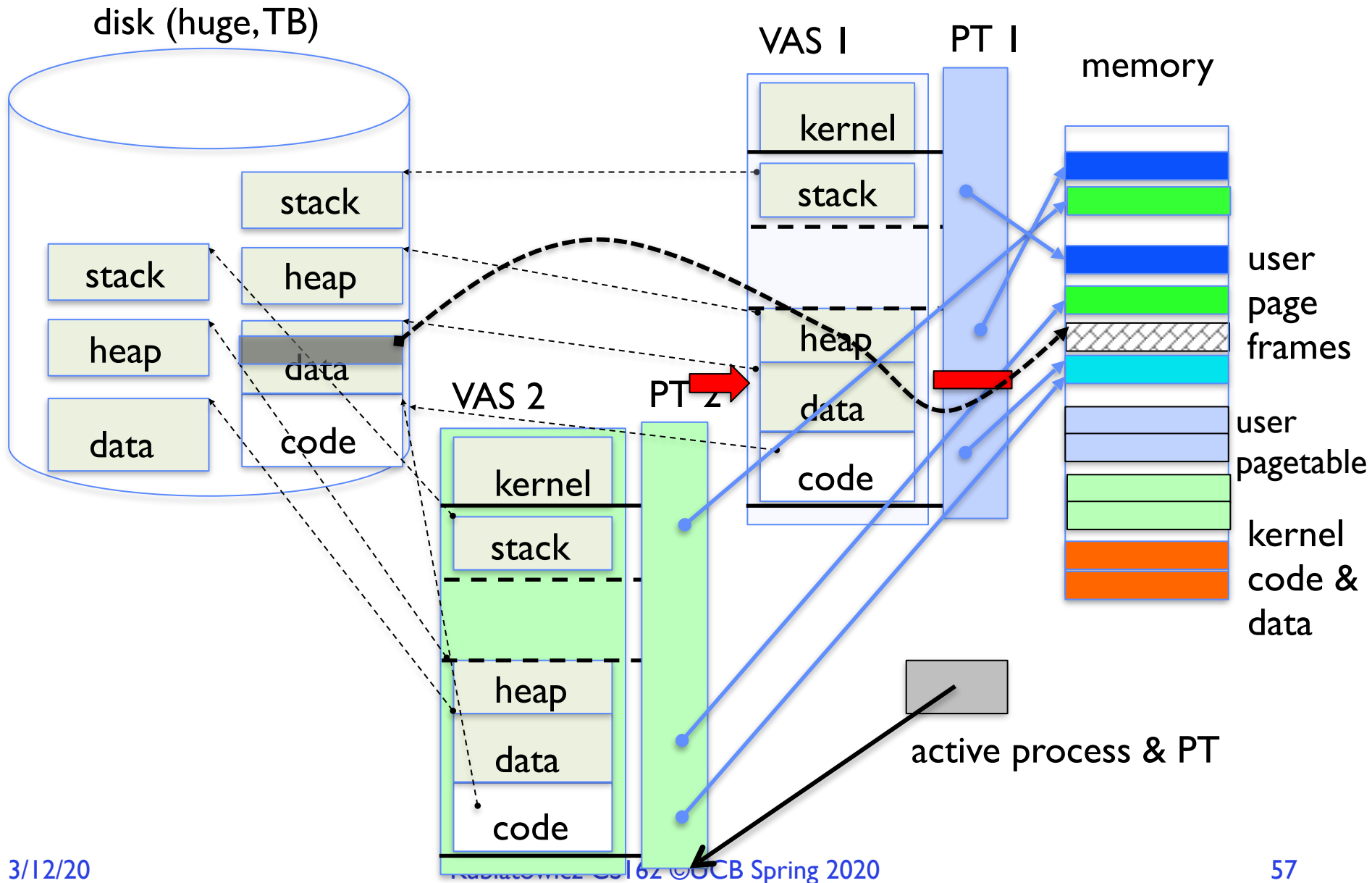
On page Fault ...



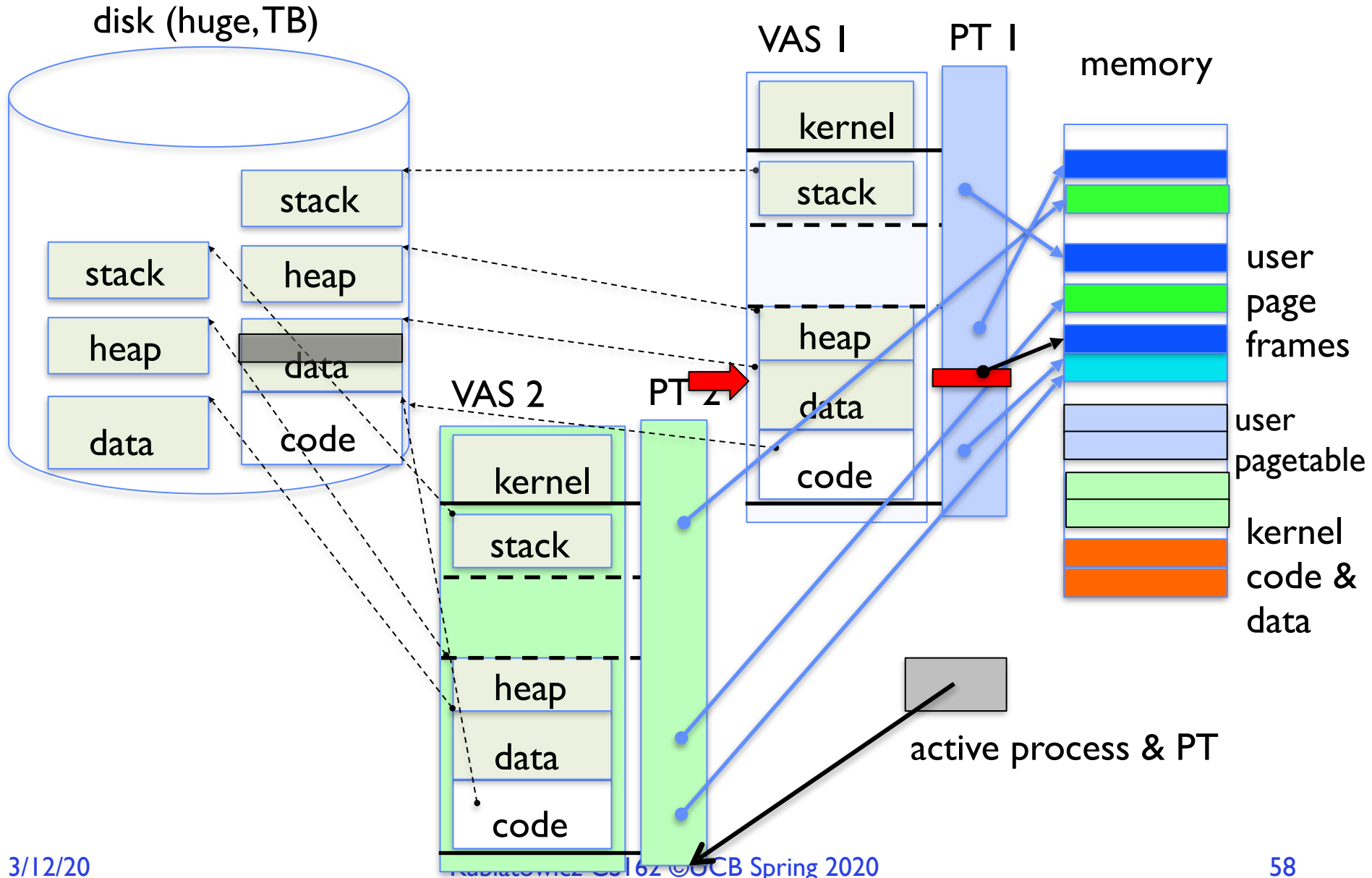
On page Fault ... find & start load



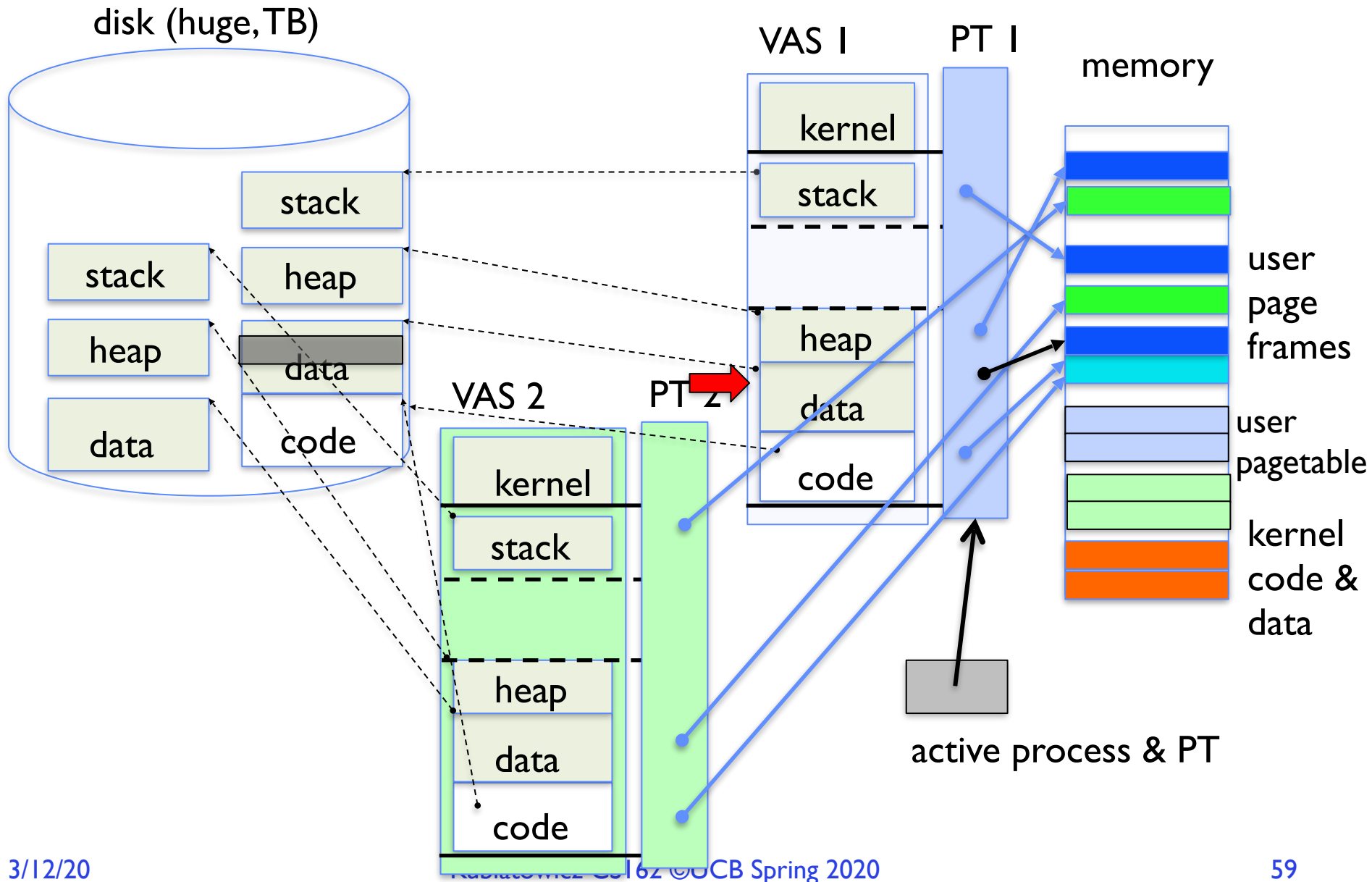
On page Fault ... schedule other P or T



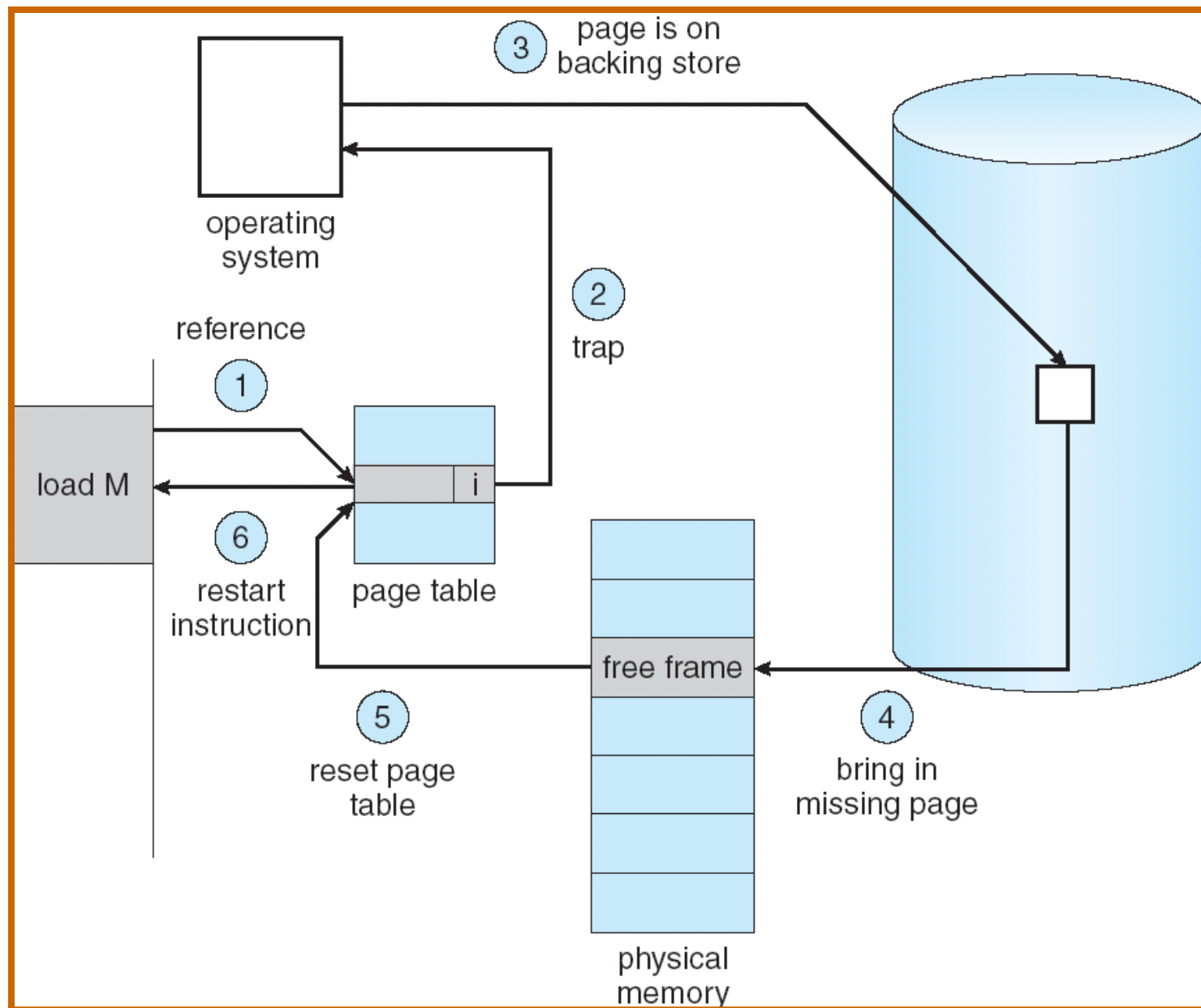
On page Fault ... update PTE



Eventually reschedule faulting thread



Summary: Steps in Handling a Page Fault



Demand Paging Mechanisms

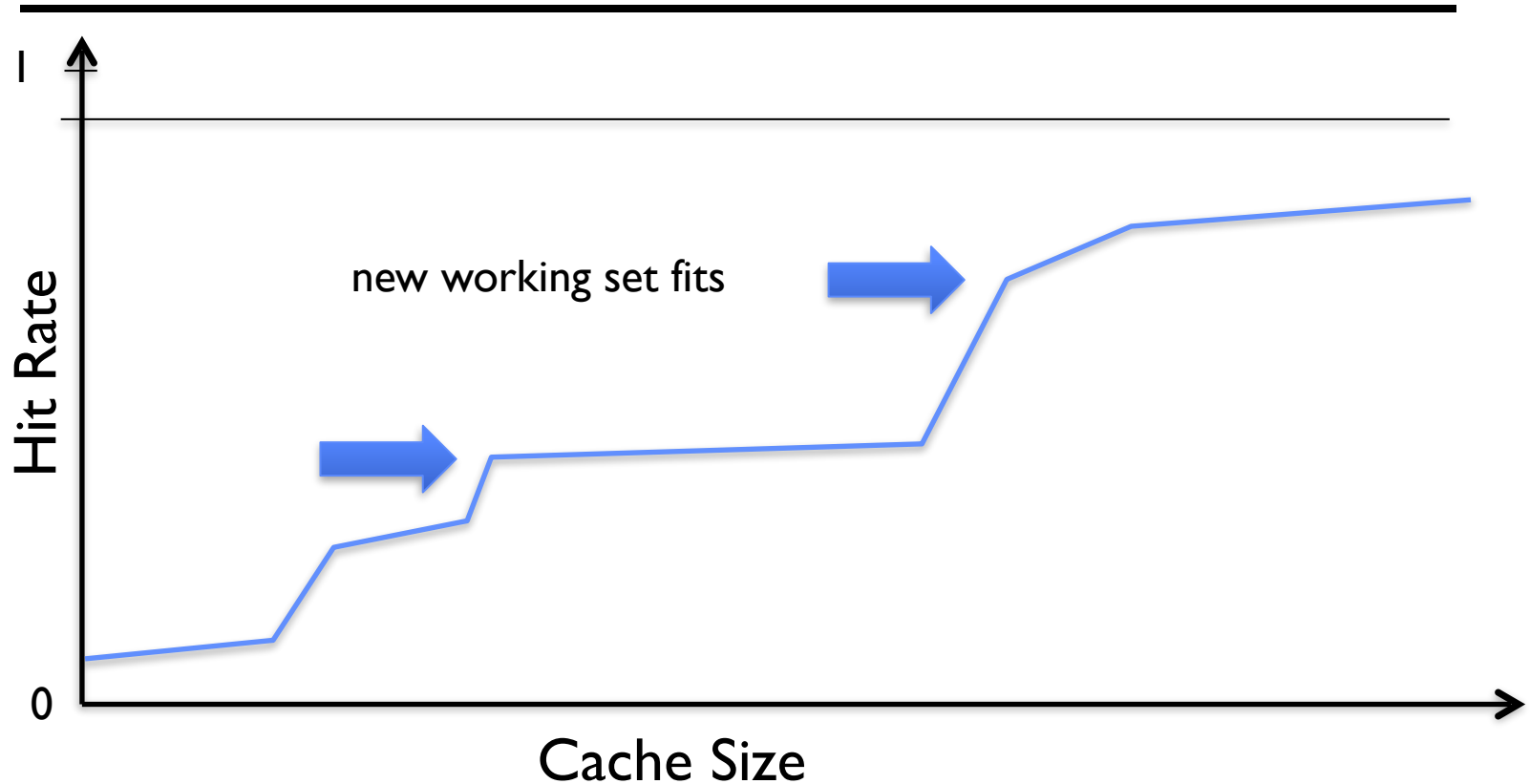
- PTE makes demand paging implementable
 - Valid \Rightarrow Page in memory, PTE points at physical page
 - Not Valid \Rightarrow Page not in memory; use info in PTE to find it on disk when necessary
- Suppose user references page with invalid PTE?
 - Memory Management Unit (MMU) traps to OS
 - » Resulting trap is a “Page Fault”
 - What does OS do on a Page Fault?:
 - » Choose an old page to replace
 - » If old page modified (“D=I”), write contents back to disk
 - » Change its PTE and any cached TLB to be invalid
 - » Load new page into memory from disk
 - » Update page table entry, invalidate TLB for new entry
 - » Continue thread from original faulting location
 - TLB for new page will be loaded when thread continued!
 - While pulling pages off disk for one process, OS runs another process from ready queue
 - » Suspended process sits on wait queue

Cache

Some questions we need to answer!

- During a page fault, where does the OS get a free frame?
 - Keeps a free list
 - Unix runs a “reaper” if memory gets too full
 - » Schedule dirty pages to be written back on disk
 - » Zero (clean) pages which haven’t been accessed in a while
 - As a last resort, evict a dirty page first
- How can we organize these mechanisms?
 - Work on the replacement policy
- How many page frames/process?
 - Like thread scheduling, need to “schedule” memory resources:
 - » Utilization? fairness? priority?
 - Allocation of disk paging bandwidth

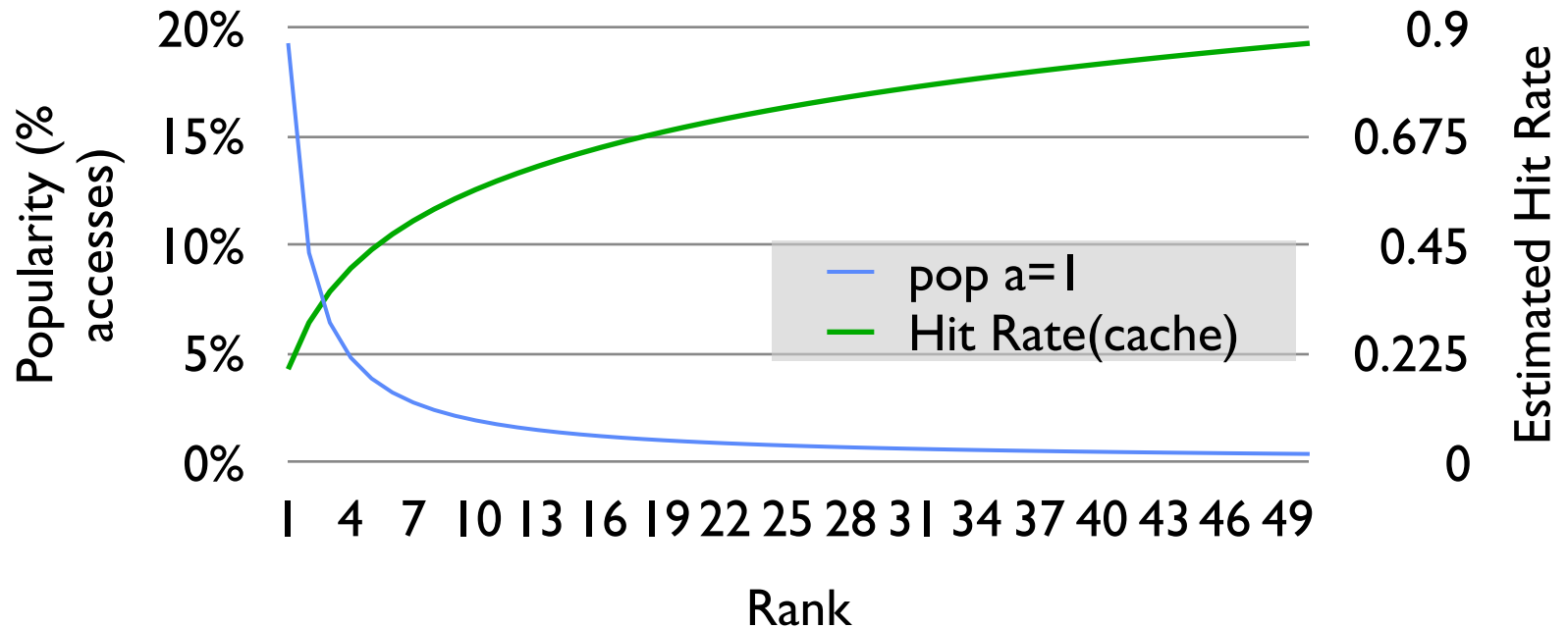
Cache Behavior under WS model



- Amortized by fraction of time the Working Set is active
- Transitions from one WS to the next
- Capacity, Conflict, Compulsory misses
- Applicable to memory caches and pages. Others ?

Another model of Locality: Zipf

$$P \text{ access}(\text{rank}) = 1/\text{rank}$$



- Likelihood of accessing item of rank r is $\alpha 1/r^a$
- Although rare to access items below the top few, there are so many that it yields a “heavy tailed” distribution
- Substantial value from even a tiny cache
- Substantial misses from even a very large cache

Demand Paging Cost Model

- Since Demand Paging like caching, can compute average access time! (“Effective Access Time”)
 - $EAT = \text{Hit Rate} \times \text{Hit Time} + \text{Miss Rate} \times \text{Miss Time}$
 - $EAT = \text{Hit Time} + \text{Miss Rate} \times \text{Miss Penalty}$
- Example:
 - Memory access time = 200 nanoseconds
 - Average page-fault service time = 8 milliseconds
 - Suppose p = Probability of miss, $1-p$ = Probability of hit
 - Then, we can compute EAT as follows:
$$\begin{aligned} EAT &= 200\text{ns} + p \times 8 \text{ ms} \\ &= 200\text{ns} + p \times 8,000,000\text{ns} \end{aligned}$$
- If one access out of 1,000 causes a page fault, then $EAT = 8.2 \mu\text{s}$:
 - This is a slowdown by a factor of 40!
- What if want slowdown by less than 10%?
 - $200\text{ns} \times 1.1 < EAT \Rightarrow p < 2.5 \times 10^{-6}$
 - This is about 1 page fault in 400,000!

What Factors Lead to Misses in Page Cache?

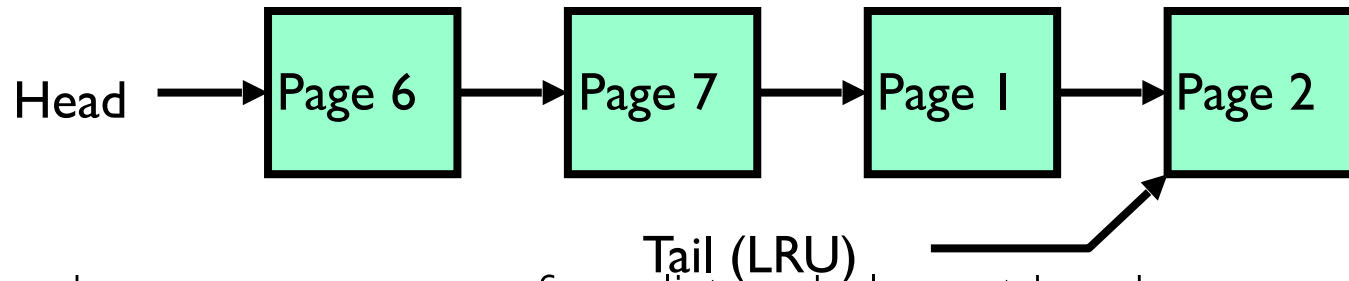
- **Compulsory Misses:**
 - Pages that have never been paged into memory before
 - How might we remove these misses?
 - » Prefetching: loading them into memory before needed
 - » Need to predict future somehow! More later
- **Capacity Misses:**
 - Not enough memory. Must somehow increase available memory size.
 - Can we do this?
 - » One option: Increase amount of DRAM (not quick fix!)
 - » Another option: If multiple processes in memory: adjust percentage of memory allocated to each one!
- **Conflict Misses:**
 - Technically, conflict misses don't exist in virtual memory, since it is a “fully-associative” cache
- **Policy Misses:**
 - Caused when pages were in memory, but kicked out prematurely because of the replacement policy
 - How to fix? Better replacement policy

Page Replacement Policies

- Why do we care about Replacement Policy?
 - Replacement is an issue with any cache
 - Particularly important with pages
 - » The cost of being wrong is high: must go to disk
 - » Must keep important pages in memory, not toss them out
- FIFO (First In, First Out)
 - Throw out oldest page. Be fair – let every page live in memory for same amount of time.
 - Bad – throws out heavily used pages instead of infrequently used
- RANDOM:
 - Pick random page for every replacement
 - Typical solution for TLB's. Simple hardware
 - Pretty unpredictable – makes it hard to make real-time guarantees
- MIN (Minimum):
 - Replace page that won't be used for the longest time
 - Great (provably optimal), but can't really know future...
 - *But past is a good predictor of the future ...*

Replacement Policies (Con't)

- LRU (Least Recently Used):
 - Replace page that hasn't been used for the longest time
 - Programs have locality, so if something not used for a while, unlikely to be used in the near future.
 - Seems like LRU should be a good approximation to MIN.
- How to implement LRU? Use a list!



- On each use, remove page from list and place at head
 - LRU page is at tail
- Problems with this scheme for paging?
 - Need to know immediately when each page used so that can change position in list...
 - Many instructions for each hardware access
- In practice, people **approximate** LRU (more later)

Example: FIFO (strawman)

- Suppose we have 3 page frames, 4 virtual pages, and following reference stream:
 - A B C A B D A D B C B
- Consider FIFO Page replacement:

Ref:	A	B	C	A	B	D	A	D	B	C	B
Page:											
1	A					D				C	
2		B					A				
3			C						B		

- FIFO: 7 faults
- When referencing D, replacing A is bad choice, since need A again right away

Example: MIN / LRU

- Suppose we have the same reference stream:
 - A B C A B D A D B C B
- Consider MIN Page replacement:

Ref:	A	B	C	A	B	D	A	D	B	C	B
Page:											
1	A									C	
2		B									
3			C			D					

- MIN: 5 faults
 - Where will D be brought in? Look for page not referenced farthest in future
- What will LRU do?
 - Same decisions as MIN here, but won't always be true!

Is LRU guaranteed to perform well?

- Consider the following: A B C D A B C D A B C D
- LRU Performs as follows (same as FIFO here):

Ref:	A	B	C	D	A	B	C	D	A	B	C	D
Page:												
1	A			D			C			B		
2		B			A			D			C	
3			C			B			A			D

- Every reference is a page fault!
- Fairly contrived example of working set of $N+1$ on N frames

When will LRU perform badly?

- Consider the following: A B C D A B C D A B C D
- LRU Performs as follows (same as FIFO here):

Ref:	A	B	C	D	A	B	C	D	A	B	C	D
Page:												
1	A			D			C			B		
2		B			A			D			C	
3			C			B			A			D

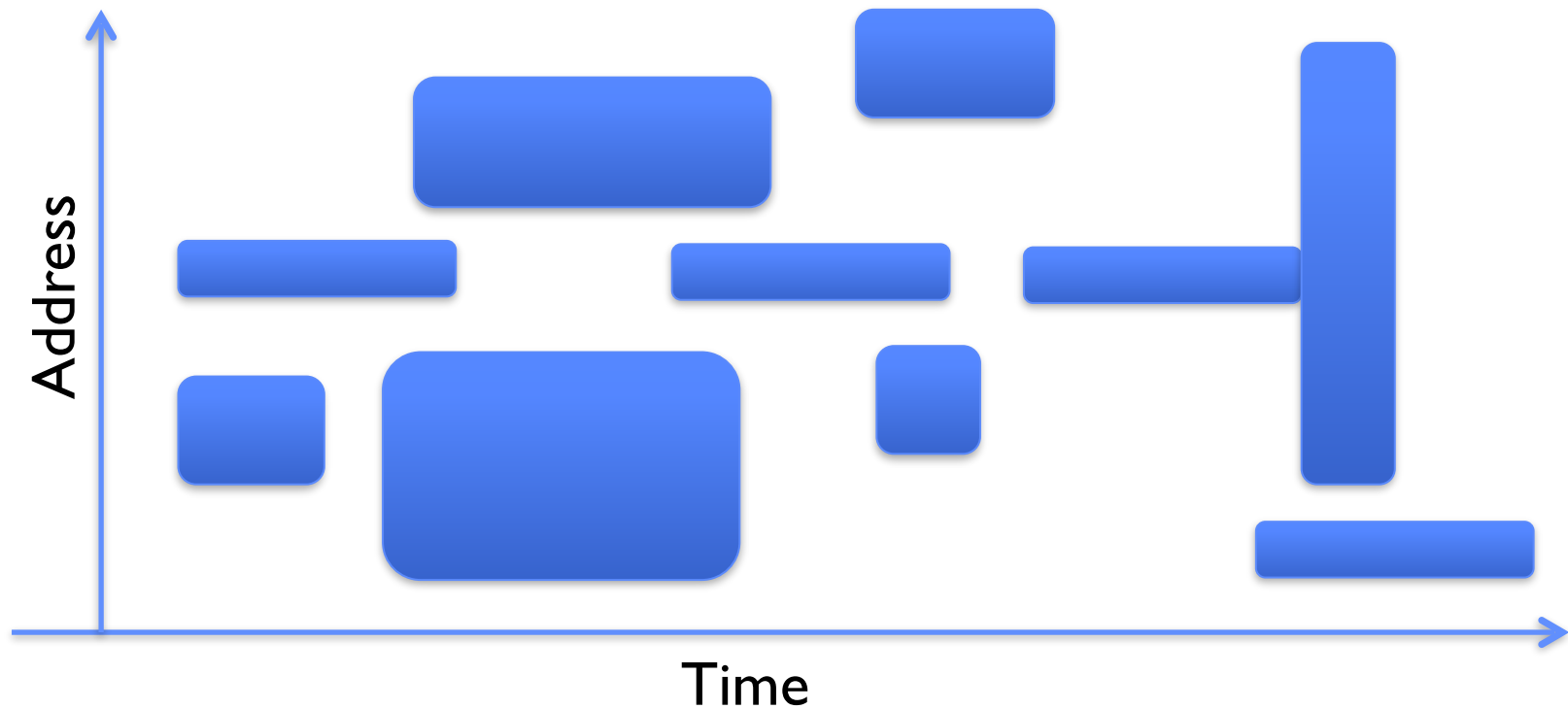
– Every reference is a page fault!

- MIN Does much better:

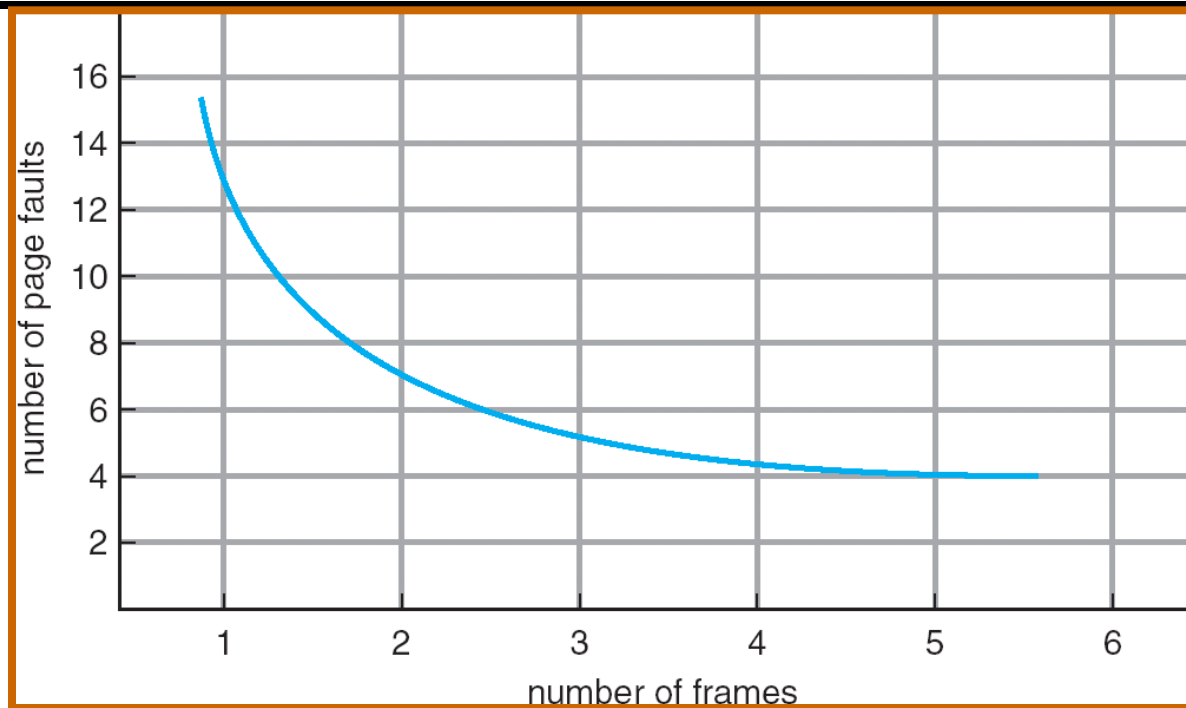
Ref:	A	B	C	D	A	B	C	D	A	B	C	D
Page:												
1	A									B		
2		B					C					
3			C	D								

Why it works in Practice: Working Set Model

- As a program executes it transitions through a sequence of “working sets” consisting of varying sized subsets of the address space



Graph of Page Faults Versus The Number of Frames



- One desirable property: When you add memory the miss rate drops (stack property)
 - Does this always happen?
 - Seems like it should, right?
- No: Bélády's anomaly
 - Certain replacement algorithms (FIFO) don't have this obvious property!

Adding Memory Doesn't Always Help Fault Rate

- Does adding memory reduce number of page faults?
 - Yes for LRU and MIN
 - Not necessarily for FIFO! (Called Bélády's anomaly)

Ref: Page:	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E					
2		B			A					C		
3			C			B					D	

Ref: Page:	A	B	C	D	A	B	E	A	B	C	D	E
1	A						E				D	
2		B						A				E
3			C						B			
4				D						C		

- After adding memory:
 - With FIFO, contents can be completely different
 - In contrast, with LRU or MIN, contents of memory with X pages are a subset of contents with $X+1$ Page

Summary (1/2)

- The Principle of Locality:
 - Program likely to access a relatively small portion of the address space at any instant of time.
 - » **Temporal Locality:** Locality in Time
 - » **Spatial Locality:** Locality in Space
- Three (+ 1) Major Categories of Cache Misses:
 - **Compulsory Misses:** sad facts of life. Example: cold start misses.
 - **Conflict Misses:** increase cache size and/or associativity
 - **Capacity Misses:** increase cache size
 - **Coherence Misses:** Caused by external processors or I/O devices
- Cache Organizations:
 - Direct Mapped: single block per set
 - Set associative: more than one block per set
 - Fully associative: all entries equivalent

Summary (2/2)

- “Translation Lookaside Buffer” (TLB)
 - Small number of PTEs and optional process IDs (< 512)
 - Fully Associative (Since conflict misses expensive)
 - On TLB miss, page table must be traversed and if located PTE is invalid, cause Page Fault
 - On change in page table, TLB entries must be invalidated
 - TLB is logically in front of cache (need to overlap with cache access)
- Precise Exception specifies a single instruction for which:
 - All previous instructions have completed (committed state)
 - No following instructions nor actual instruction have started
- Can manage caches in hardware or software or both
 - Goal is highest hit rate, even if it means more complex cache management