Virtual Memory Part 3

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Acknowledgements

- Some of the slides in the deck were provided by Profs. Luis Ceze (Washington), Nima Horanmand (Stony Brook), Mark Hill, David Wood, Karu Sankaralingam (Wisconsin), Abhishek Bhattacharjee(Yale).

- Development of this course is partially supported by funding from Western Digital corporations.

CoLT : Coalesced Large reach TLB

- Observations:
  - Often a few contiguous VA pages maps to contiguous PA pages, naturally (e.g., 32KB)
  - Can use a single TLB entry to map it
- COLT:
  - Dynamically coalesce TLB entries when opportunity exists
  - Transparent to software –only hardware changes

- Reading assignment: “CoLT: Coalesced Large-Reach TLBs” –by Pham et. al.

Segmentation with paging

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  - Virtual address is first translated via segment registers (CS,DS,ES etc.) to linear address
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- 64-bit x86 mostly got rid of segmentation

Agenda

What is virtual memory?

Hardware implementations of virtual memory

Software management of virtual memory

Research opportunity in virtual memory

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Journey so far….Next up

Mostly H/W

- Virtual memory basics
- Address mapping and translation

Mostly S/W

- Virtual address allocation
- Physical memory allocation and page table creation

Virtual address allocation

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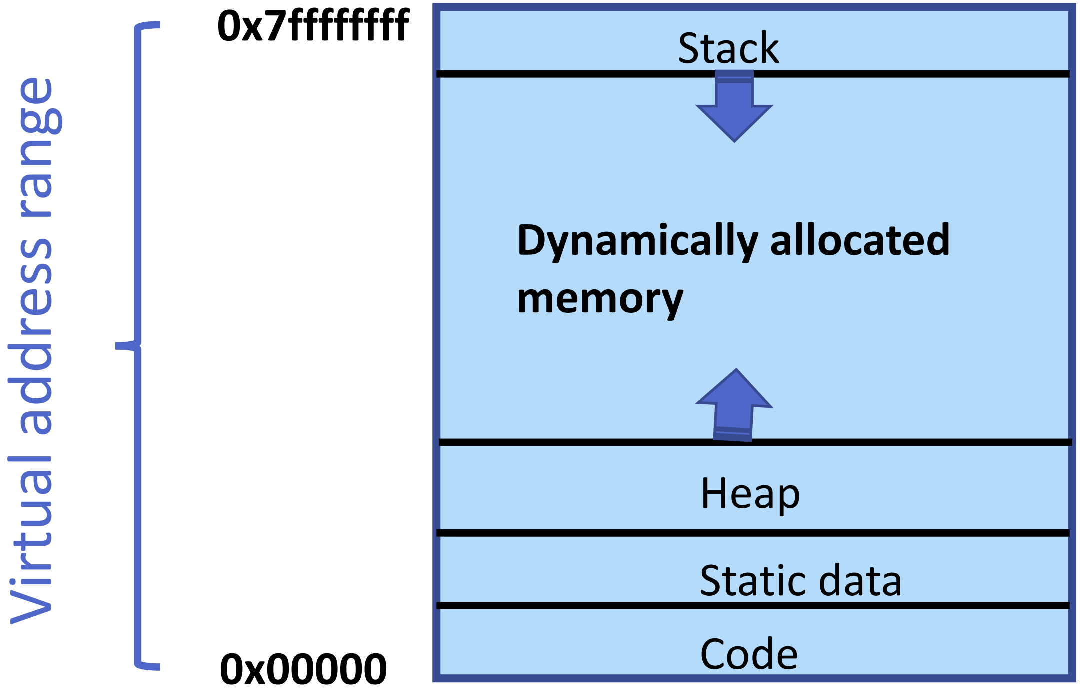
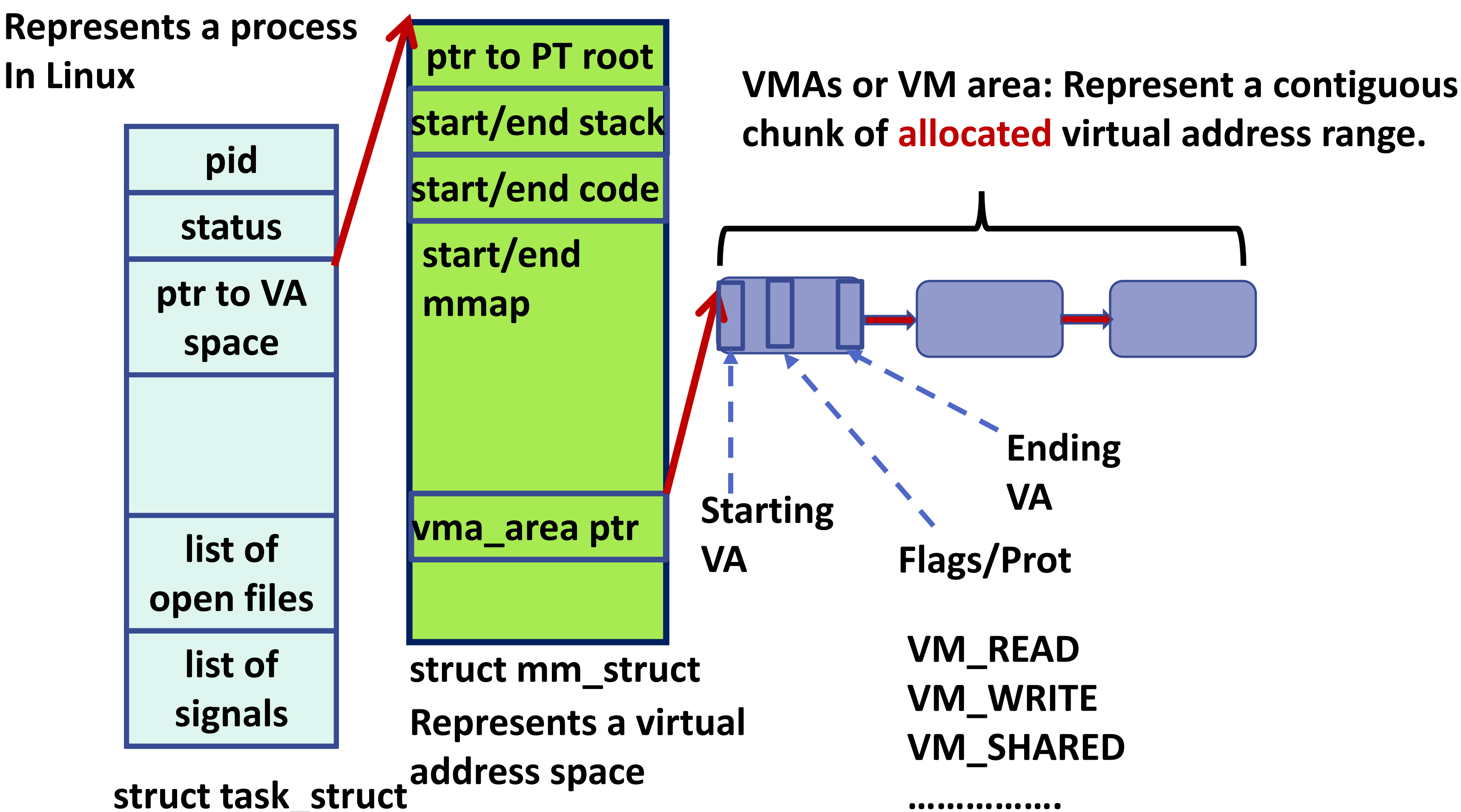


Virtual address space

Typical virtual address layout of a process in Linux

Representation of VA (in Linux)



Dynamically allocating VA

- User application or library requests VA allocation via system calls

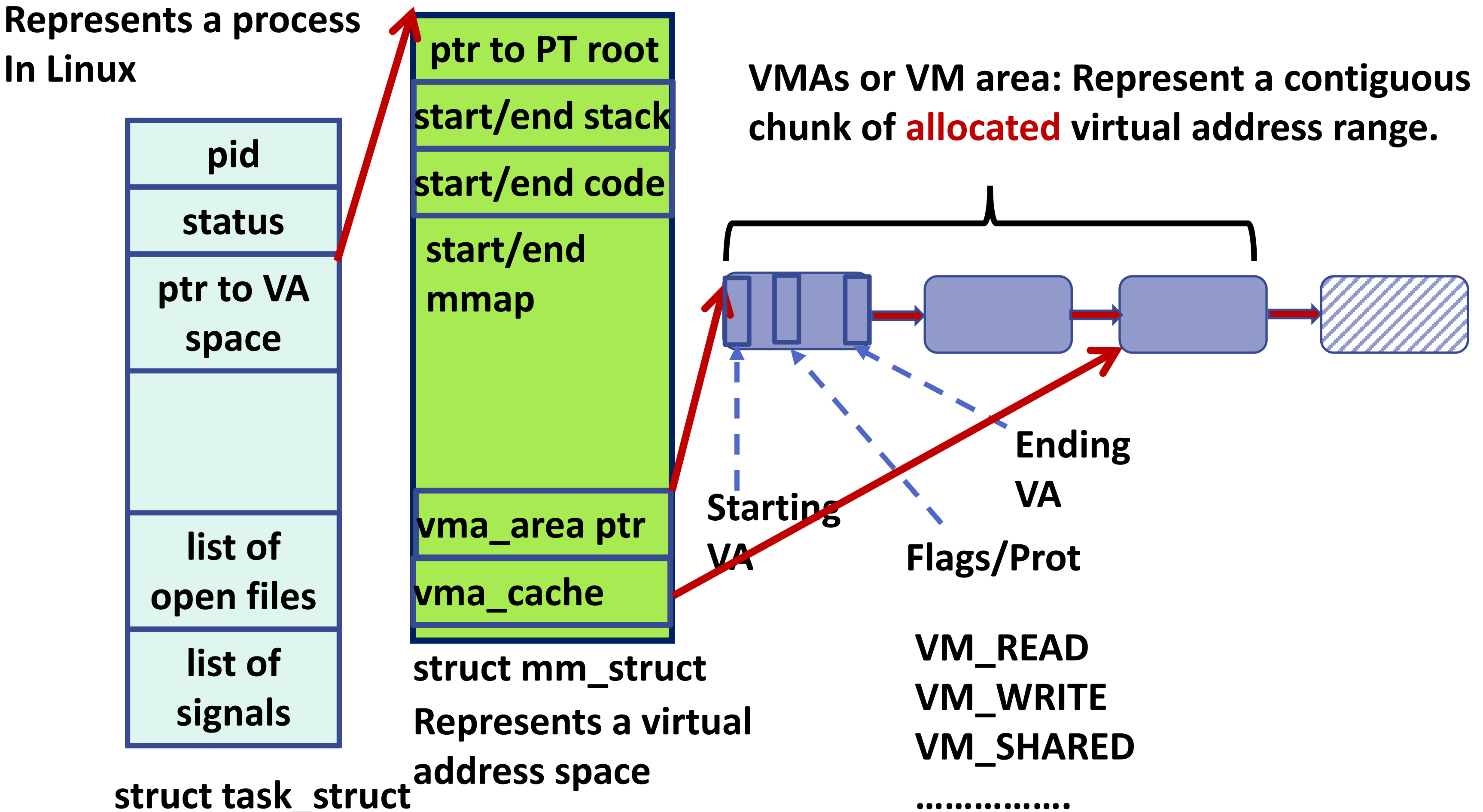
void *mmap(void *addr, size_t length, int prot, int flags, int fd, off_t offset);

Length has to be multiple of 4KB

Prot → PROT_NONE, PROT_READ, PROT_WRITE…

Flags→ MAP_ANONYMOUS, MAP_SHARED, MAP_PRIVATE, MAP_SHARED

What happens on dynamic memory allocation (e.g., mmap())?

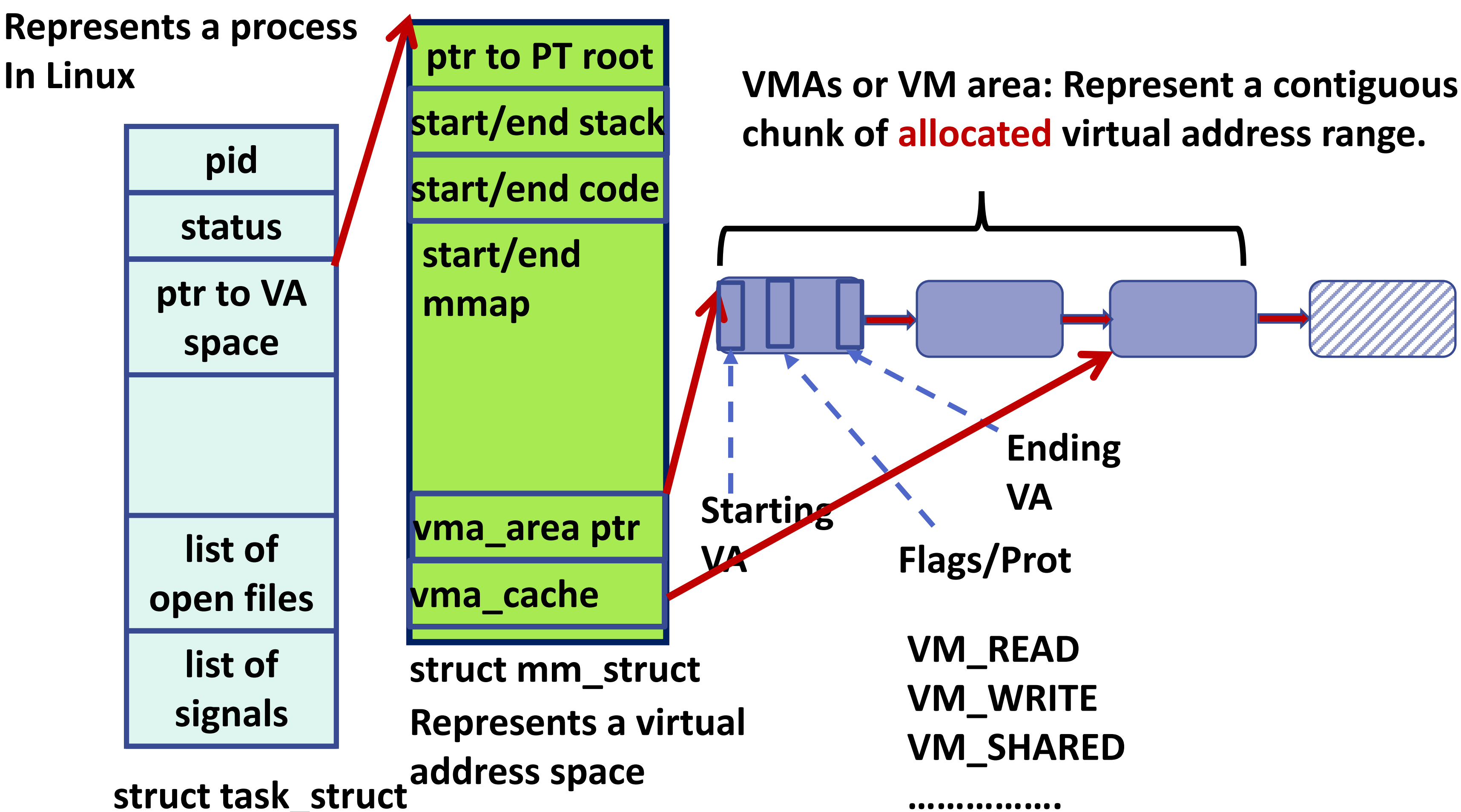


Extending heap memory

- **Heap**: Special type of dynamically allocated contiguous memory region that grows in upwards

- System calls in Linux to extend heap
  - int sbrk (increment _bytes)

Extending heap via *sbrk*



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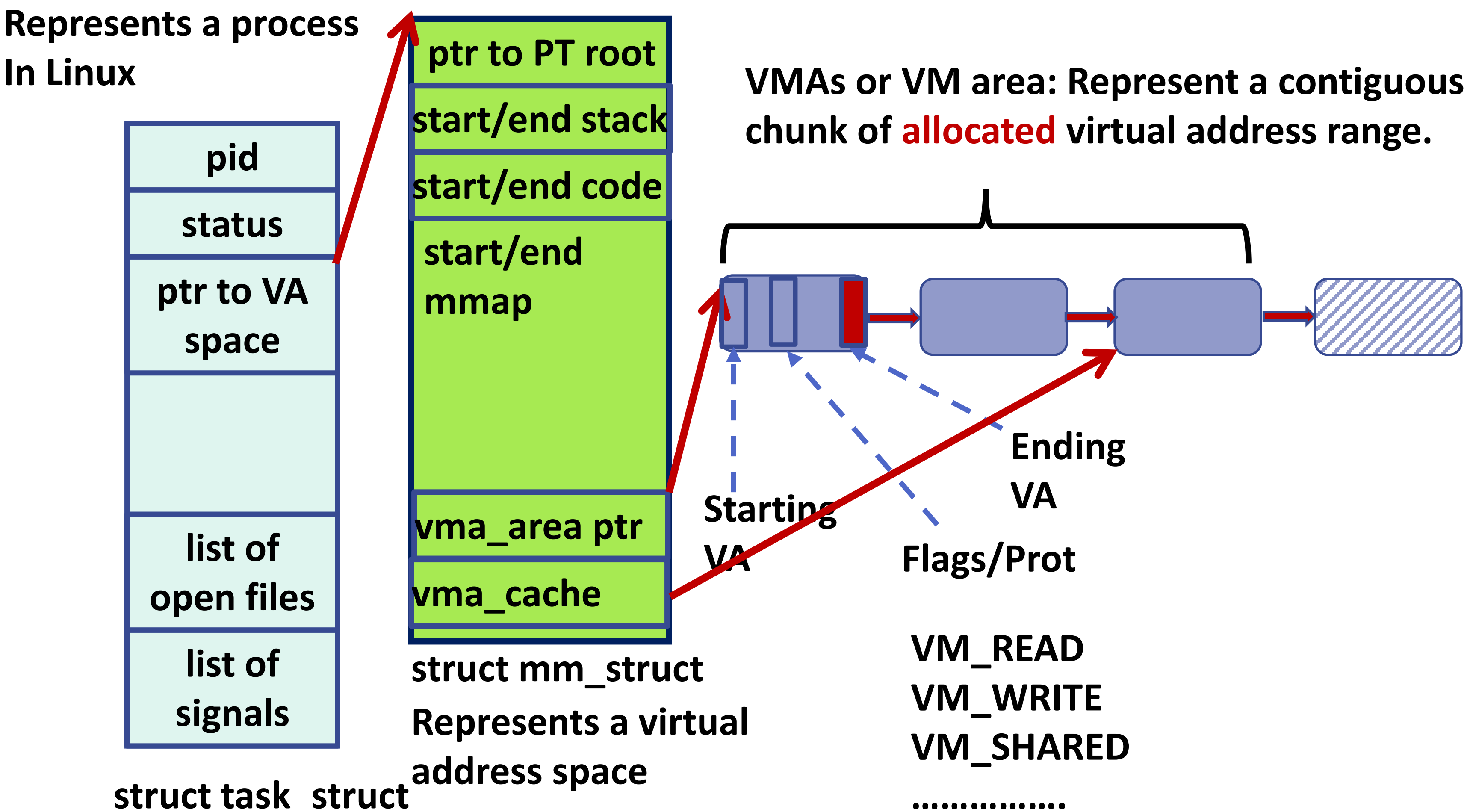

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- Why? Virtual address is in abundance; but physical memory is scarce resource.
- Allocate physical memory for when the virtual **address is accessed first time**
- Lazily allocating physical memory is called *demand paging*
- Advantage: Commits physical memory only if used

Page fault in demand paging

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- Page fault can also happen due to insufficient permission (e.g., write access to read-only page) → protection fault

Servicing a page fault

- Page fault routine is implemented inside the OS
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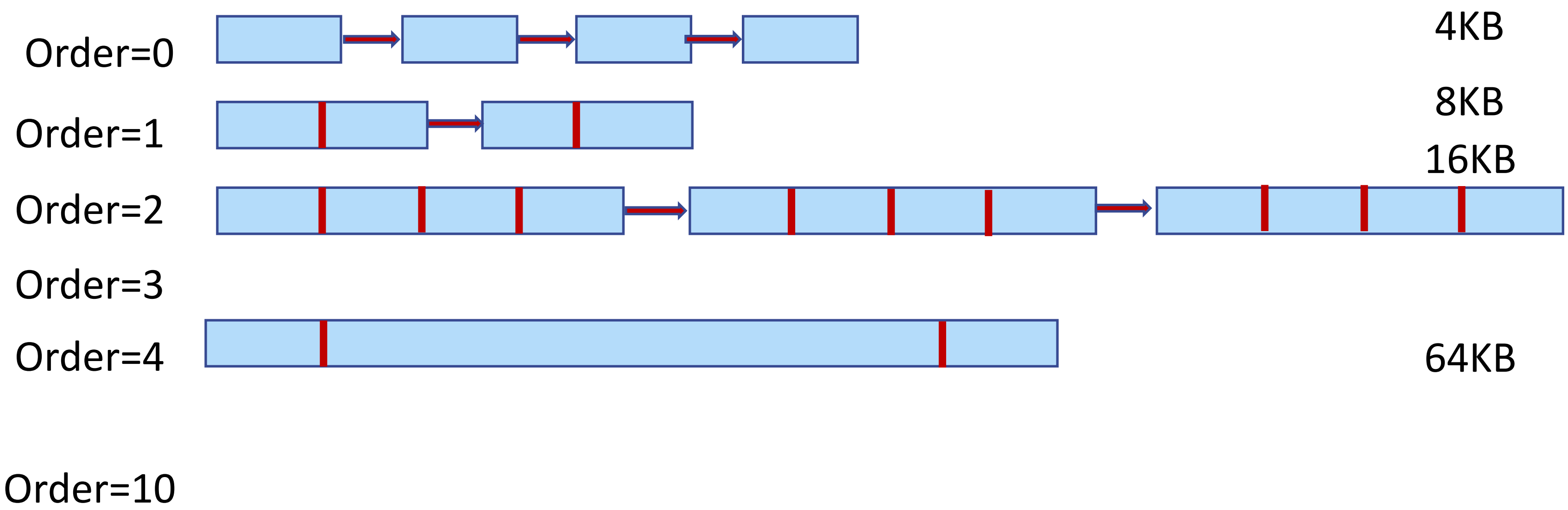

Buddy allocator operation

- Allocate from a free list which has smallest units that fits the requested allocation size
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- Merge two contiguous blocks of physical memory in a free list and add the merged block in next higher order free list

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  - Minimum granularity of VA allocation is a page (4KB)
  - But applications often allocates in chunks less than 4KB
- malloc() maintains free list of small allocations
- If free memory is available in malloc()'s free list, no need to got to the OS
- malloc() with large size (e.g., >32KB) converts to mmap

Where does *malloc() fits in* ?

- Two key goals of a malloc library:
  - Reduce memory bloat, i.e., reduce any additional allocated memory than what application asked
  - Reduce the number of system calls to OS (e.g., mmap())
  - System calls are slow

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  - Reduce the number of system calls to OS (e.g., mmap())
  - System calls are slow
- Many approaches to create malloc library
  - Best fit, first fit, worst fit
- Many malloc() libraries
  - glibc-malloc, tc-malloc, dl-malloc
- You can write your own malloc() library !

The overall picture of memory management

Application

The overall picture of memory management

malloc()

Application

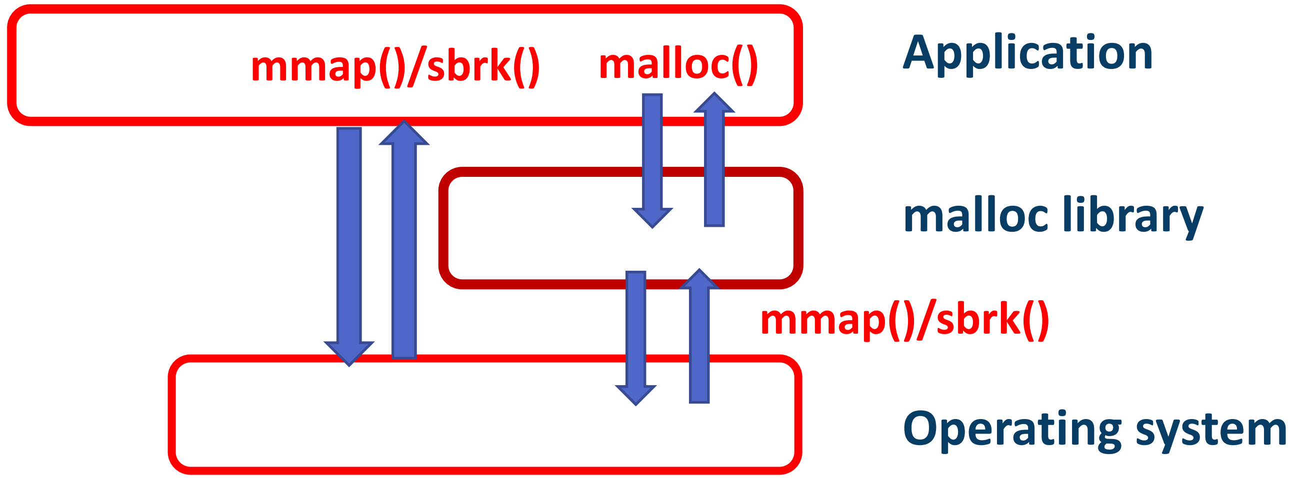
Small VA allocation

malloc library

The overall picture of memory management

Small VA allocation

VA allocations
Page fault
PA allocations



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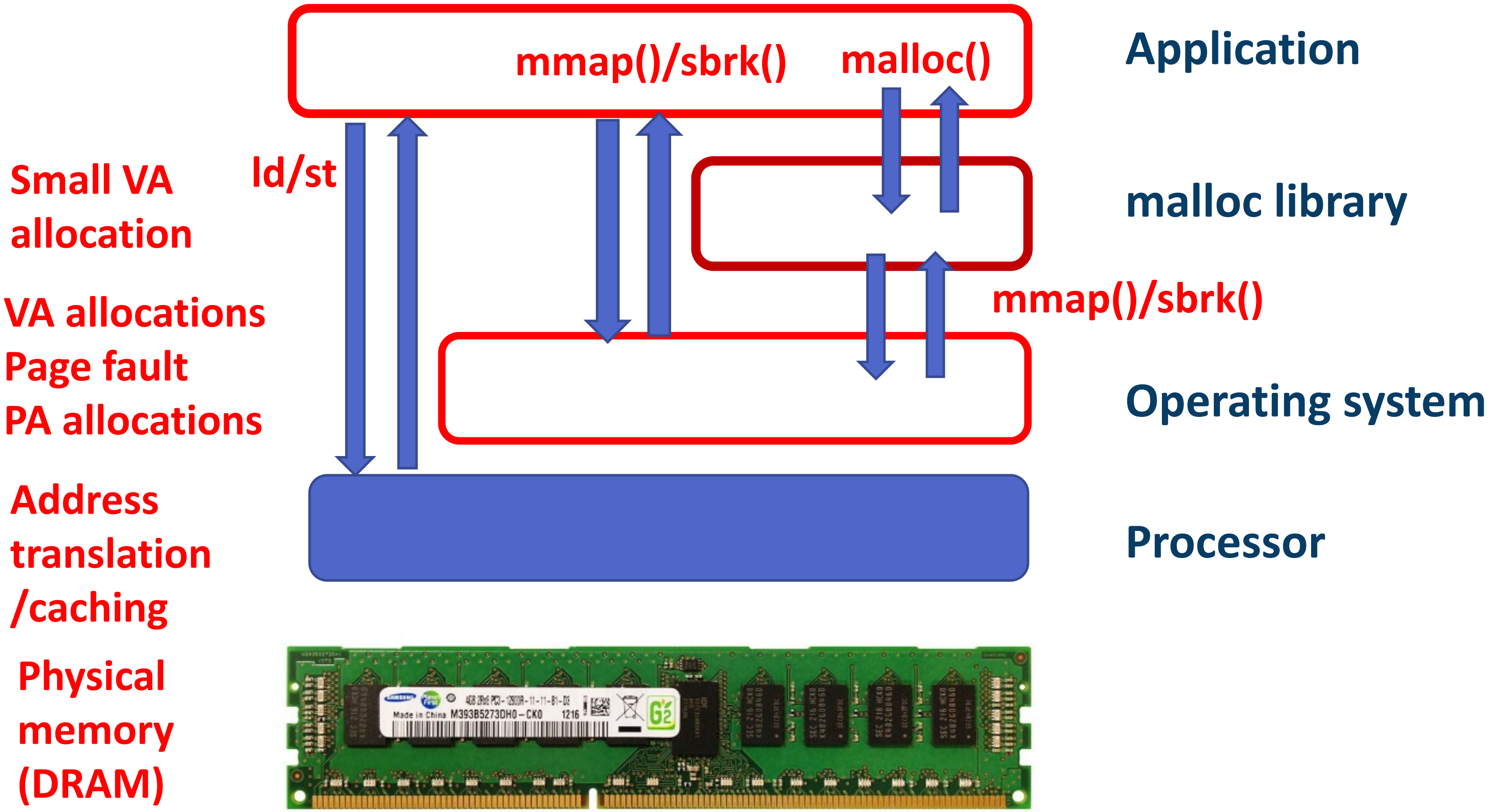

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6. H/W page table walker walks the page table
7. Desired entry not found on PTE (why?)
8. H/W generates a page fault to OS

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9. OS’a page fault handler checks VMA regions to ensure it’s a legal access
10. Page fault handler finds a free physical page frame to map the VA page from the buddy allocator
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11. Updates page table to note new VA to PA mapping and return
12. Application retries the same instruction
13. This time page table walker finds it in page table and loads it into TLB
14. Next time if same page is accessed it may hit in TLB (→ no page walk)

Miscellaneous related topics

Swapping

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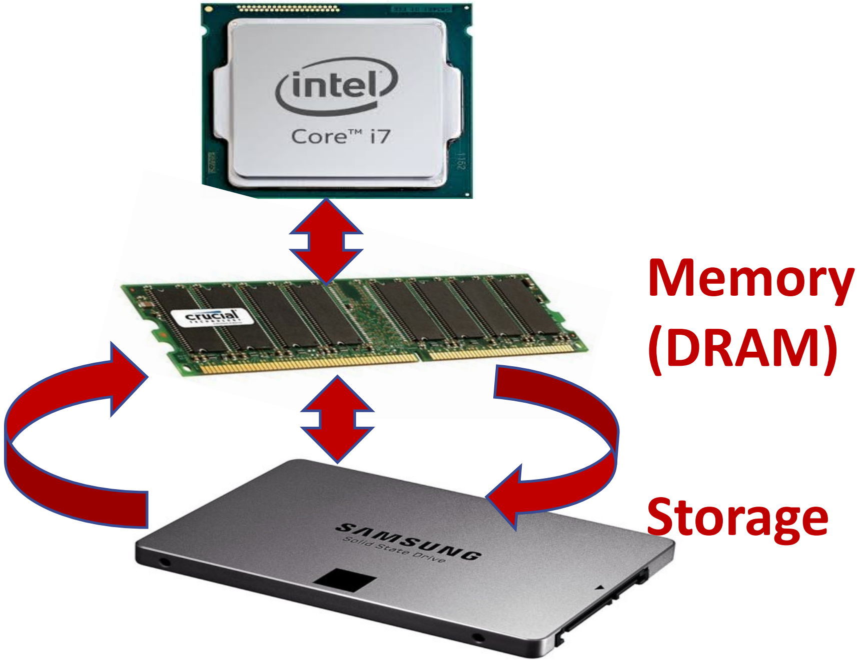

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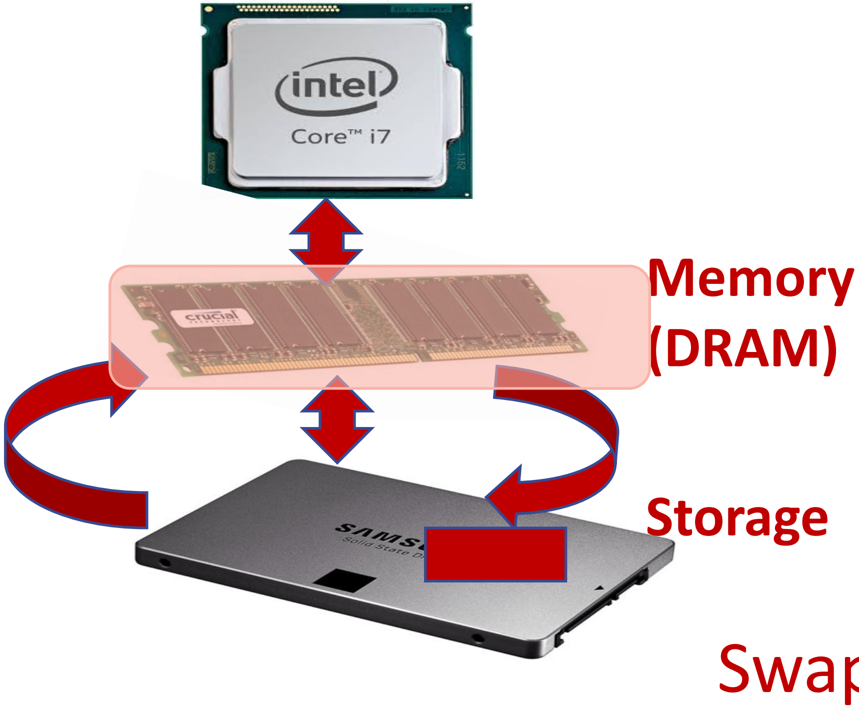

How swapping work?

- OS attempts to figure out which pages in memory are not actively used
  - Use access bit ("A" bit) in the PTE
  - OS periodically unsets "A" bits of pages in memory
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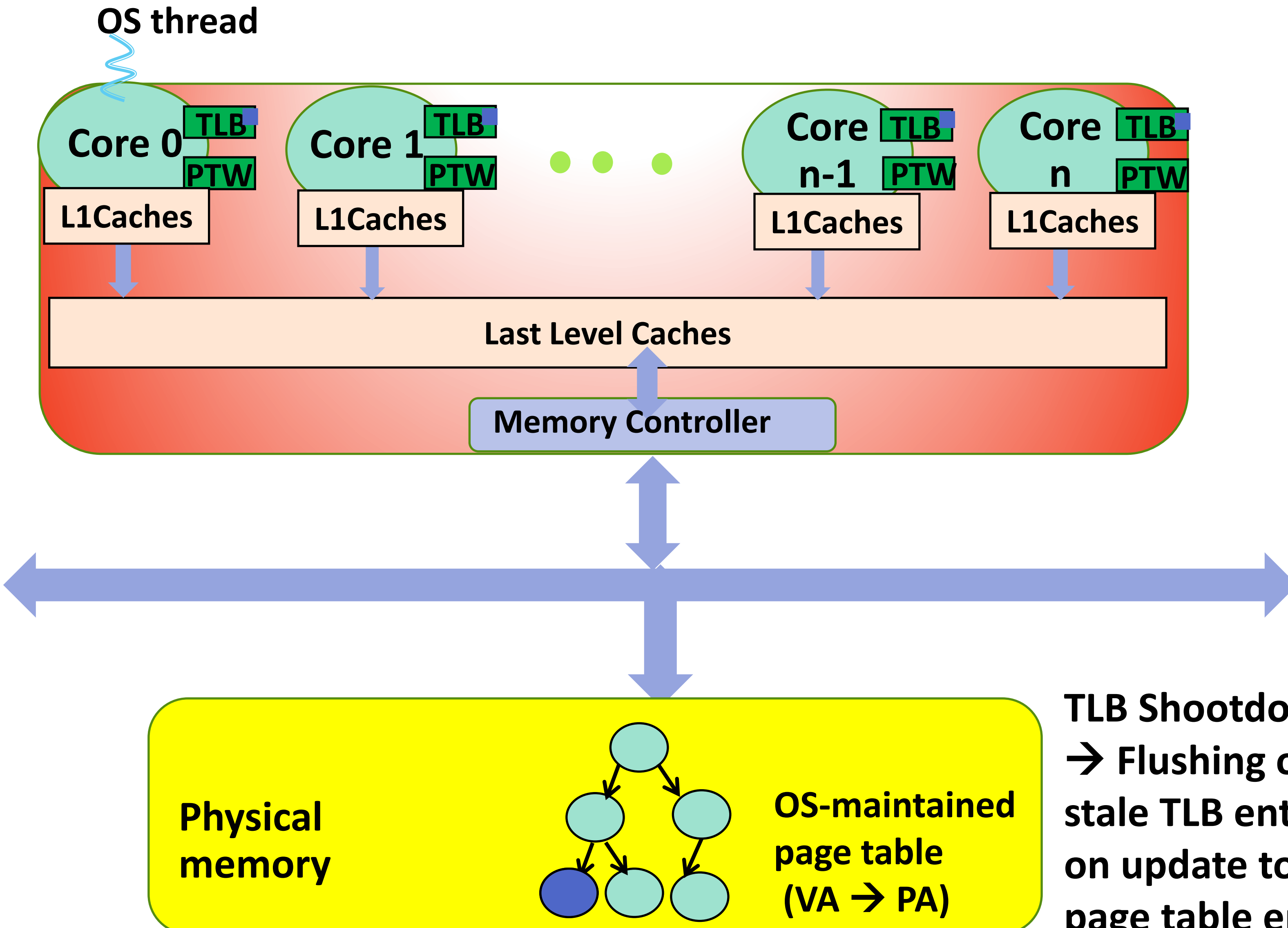
- OS writes back data of the page to swap file
- Update PTE to unset present ("p") bit

How swapping work?

- There will be page fault if an application accesses a page that is swapped out
  - Because “p” bit is unset
- OS page fault handler figures out the page had been swapped out
- Page fault handler brings the page into memory
- Application retries the faulting instruction.

TLB shootdown (invalidation)



TLB Shootdown → Flushing of stale TLB entries on update to page table entry.

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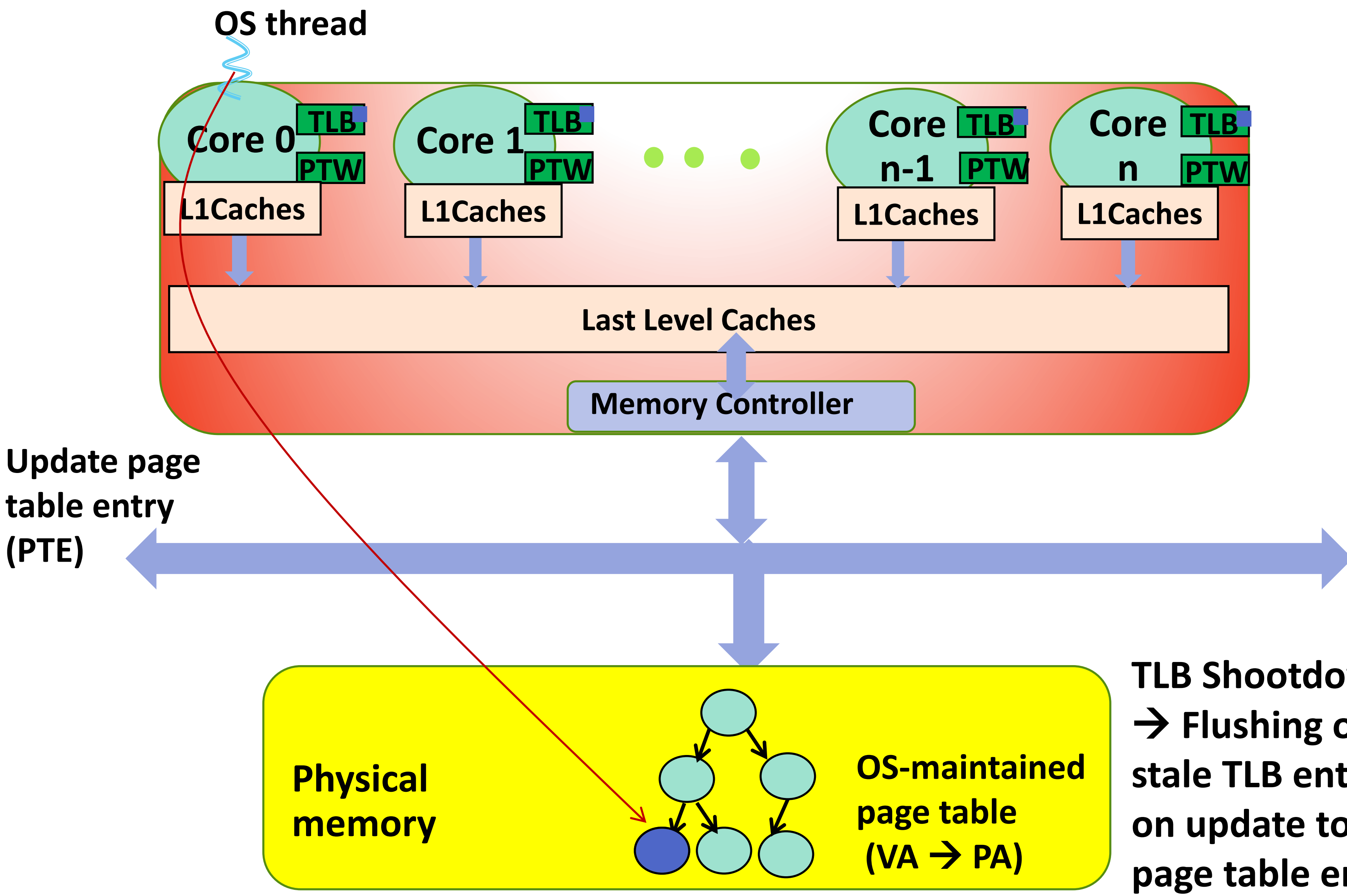

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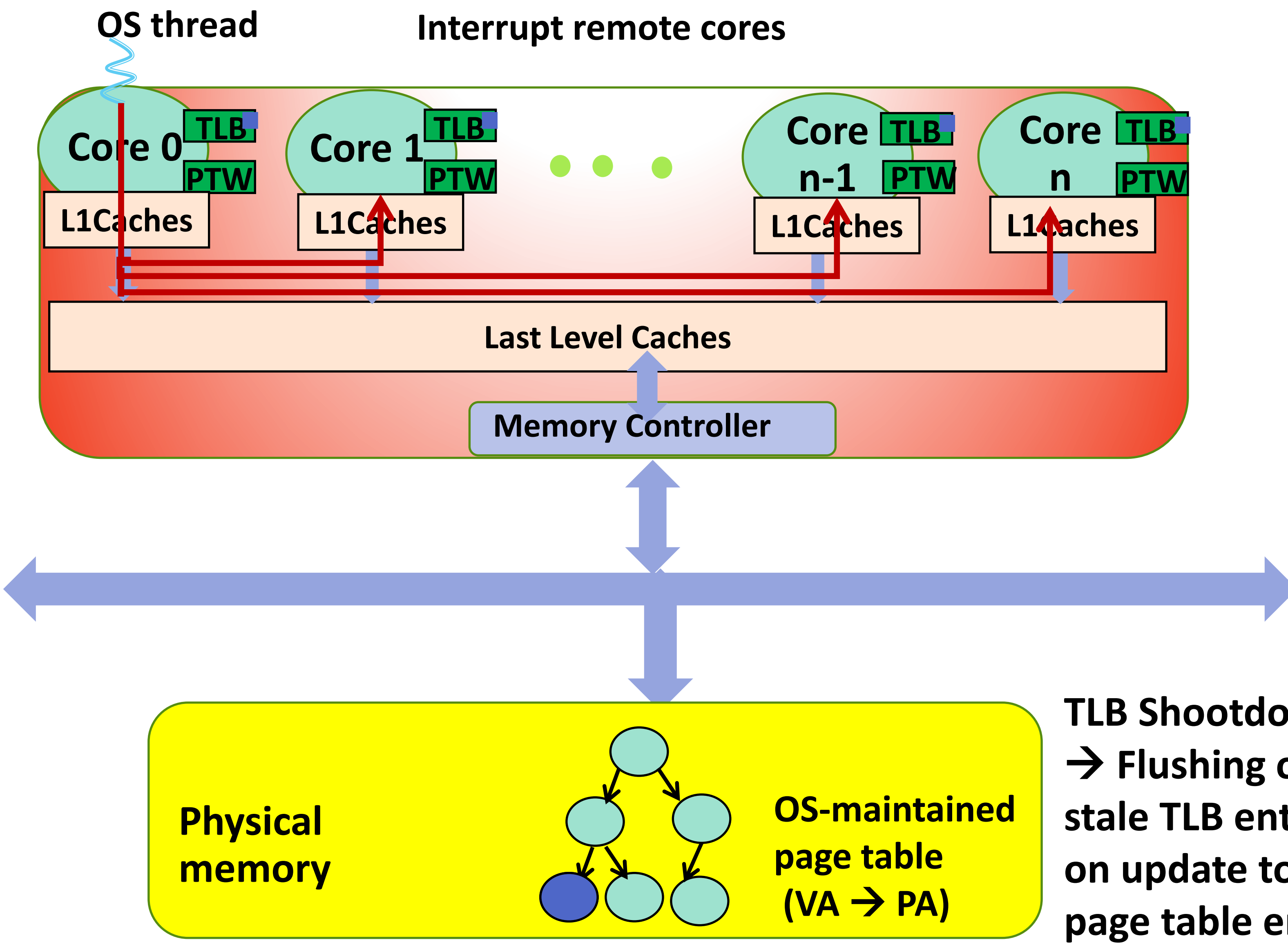

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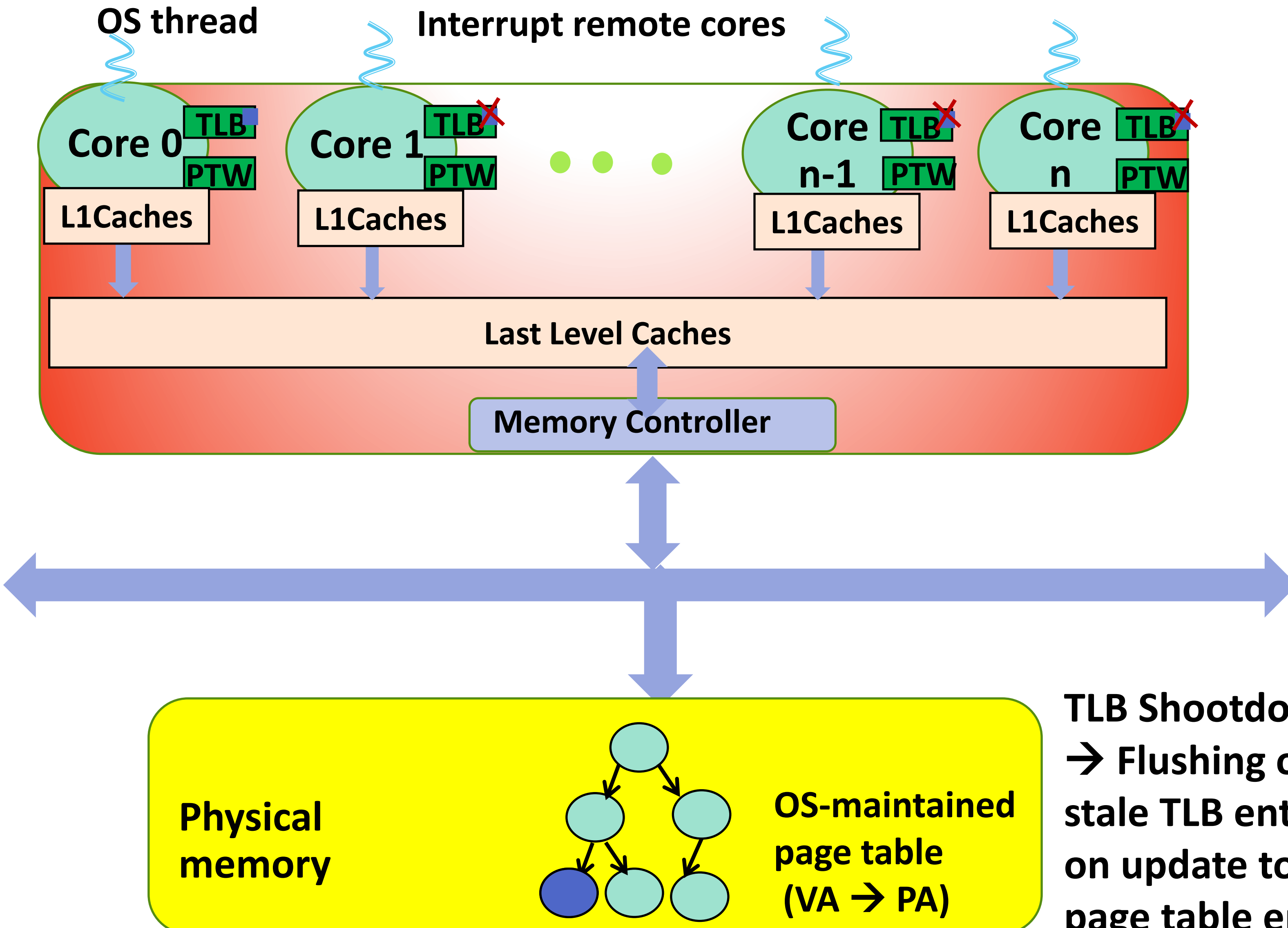

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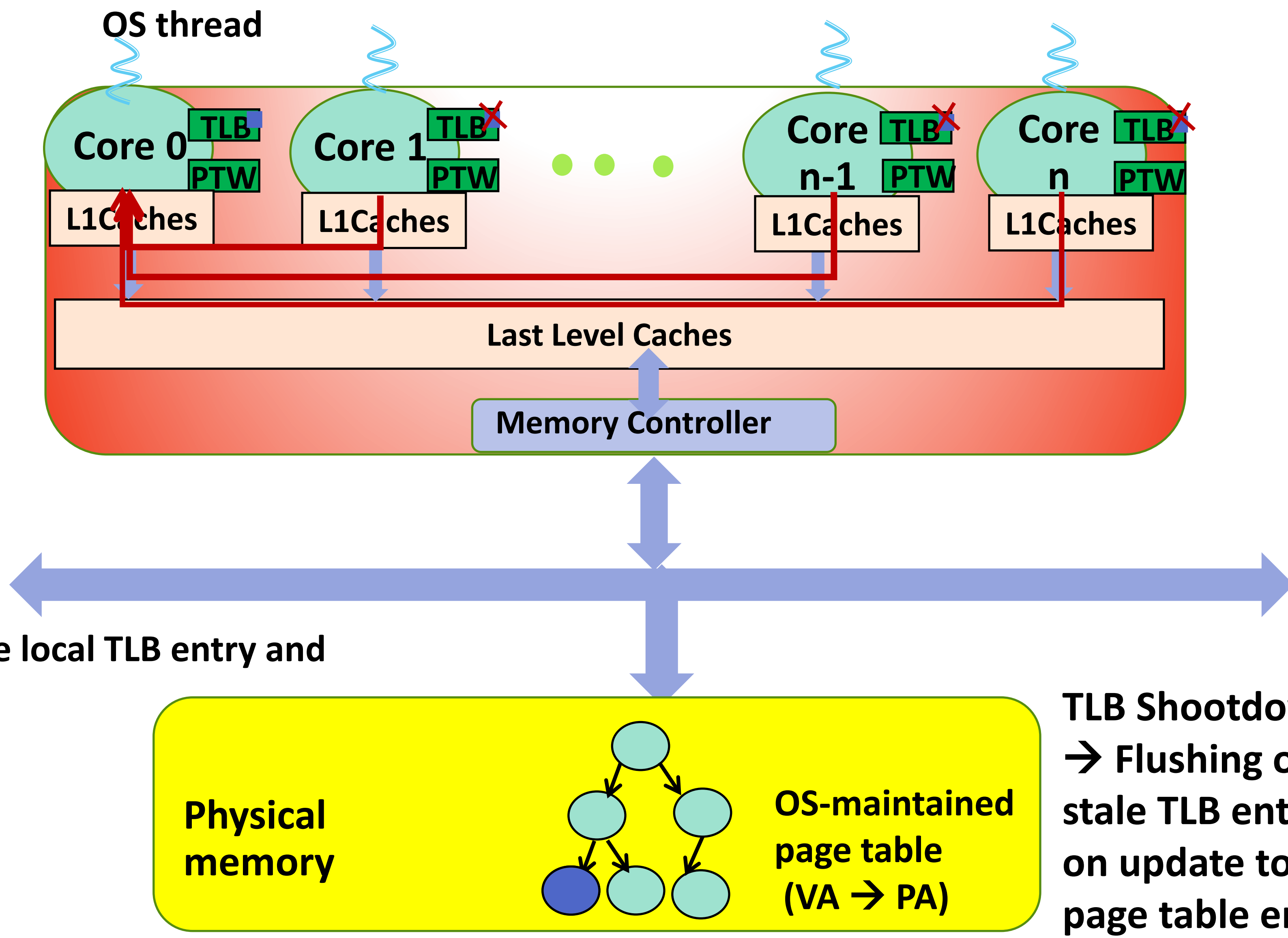

Invalidate local TLB entry and send Ack

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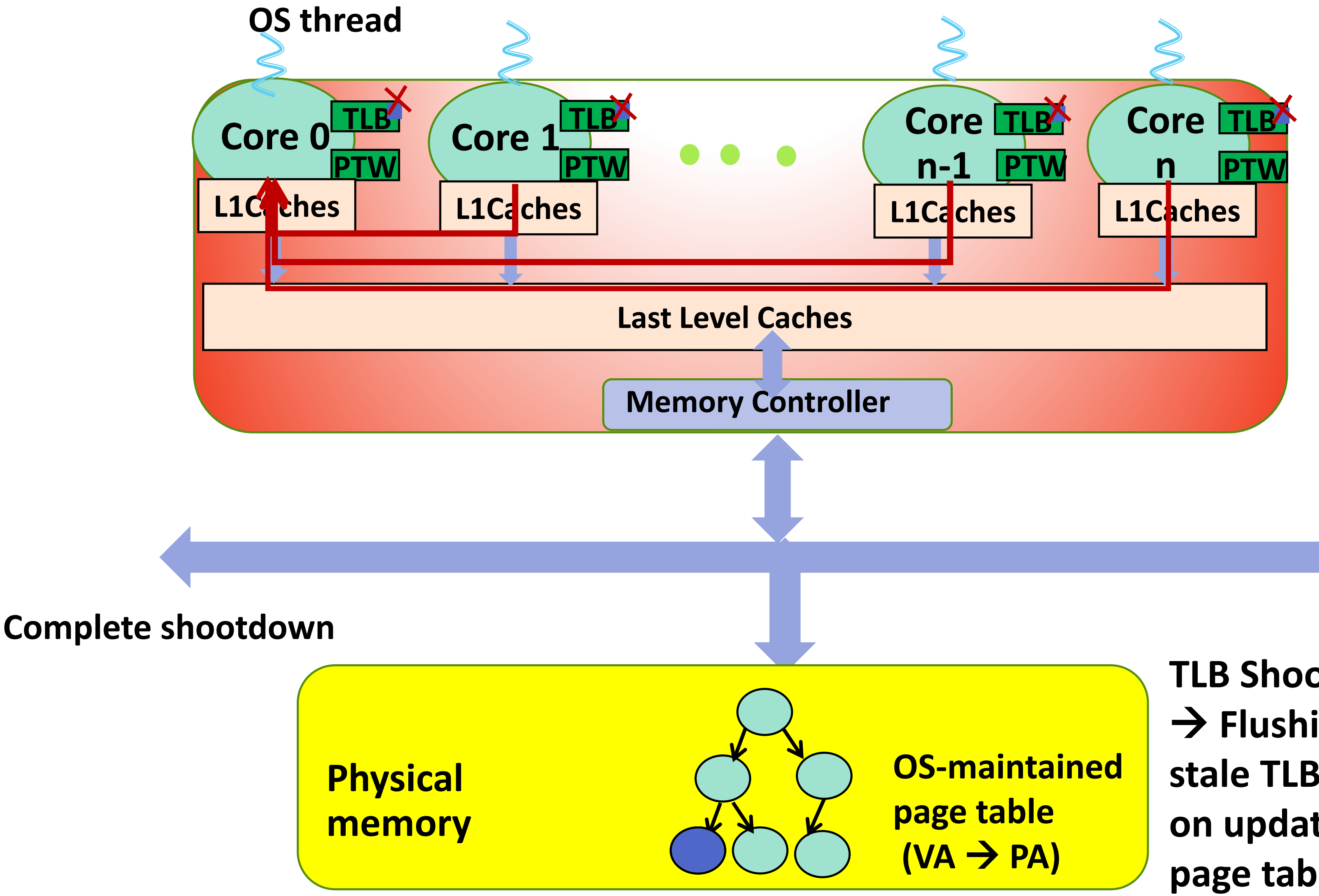

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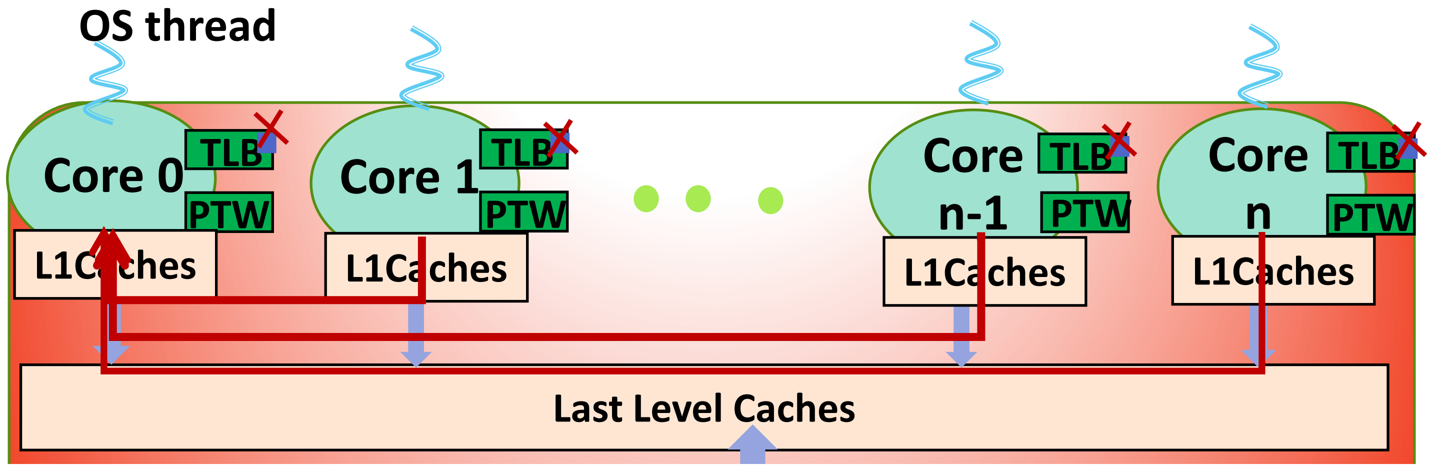
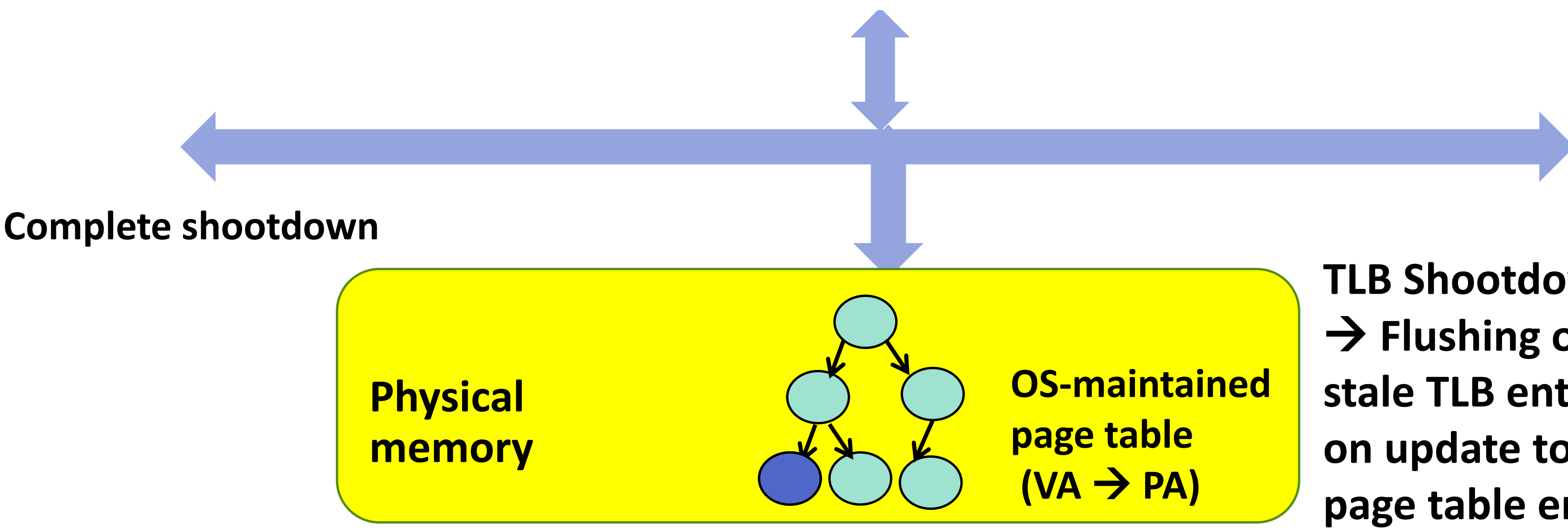


A shootdown on a x86-64 CPU could take 10s of micro-seconds



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