Jin-Soo Kim
(*jinsoo.kim@snu.ac.kr*)

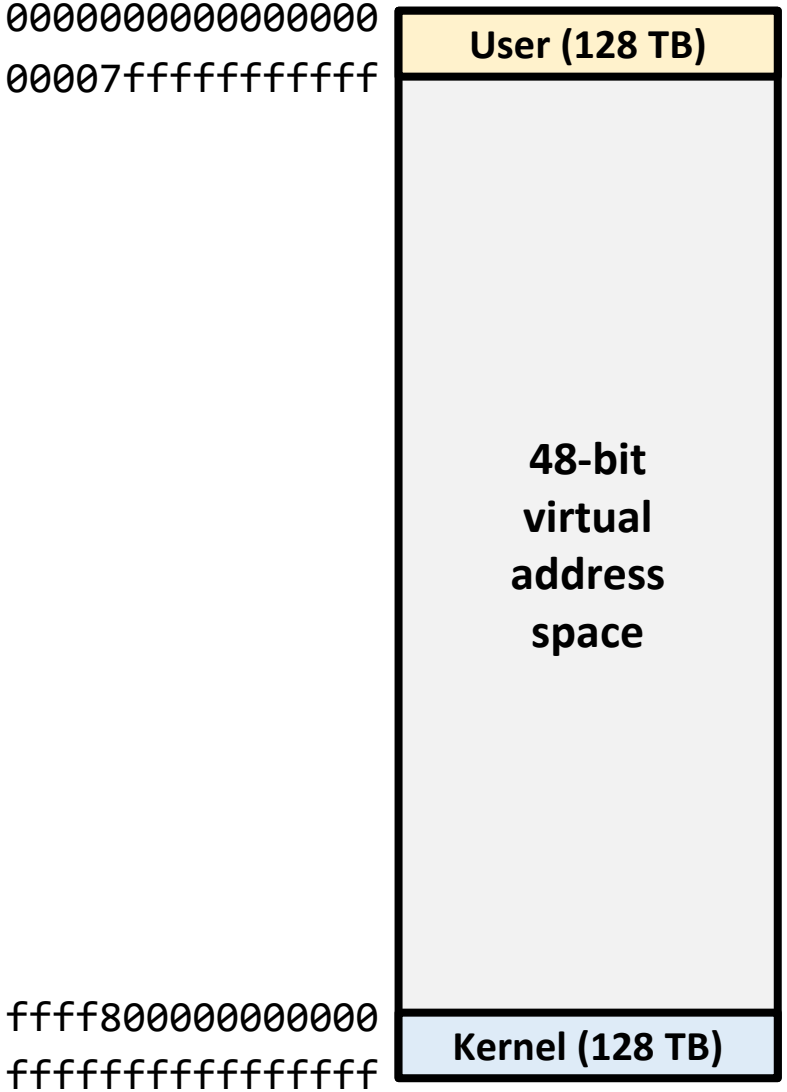
Systems Software &
Architecture Lab.

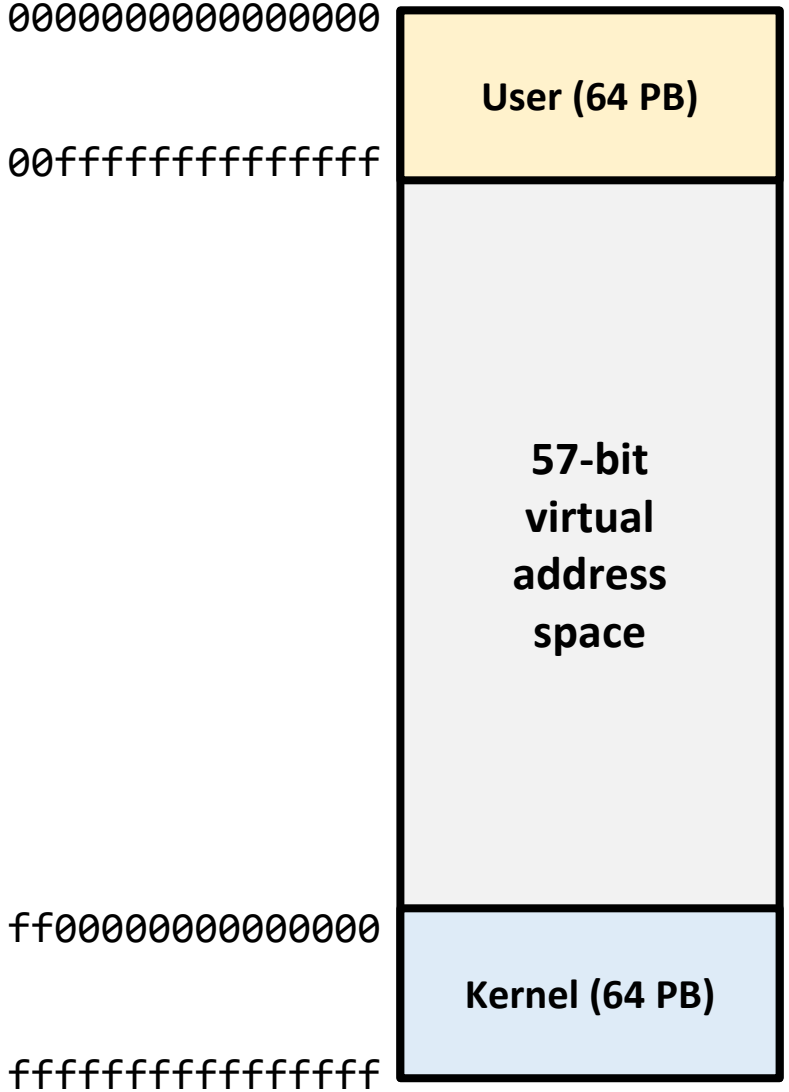
Seoul National University

Fall 2022

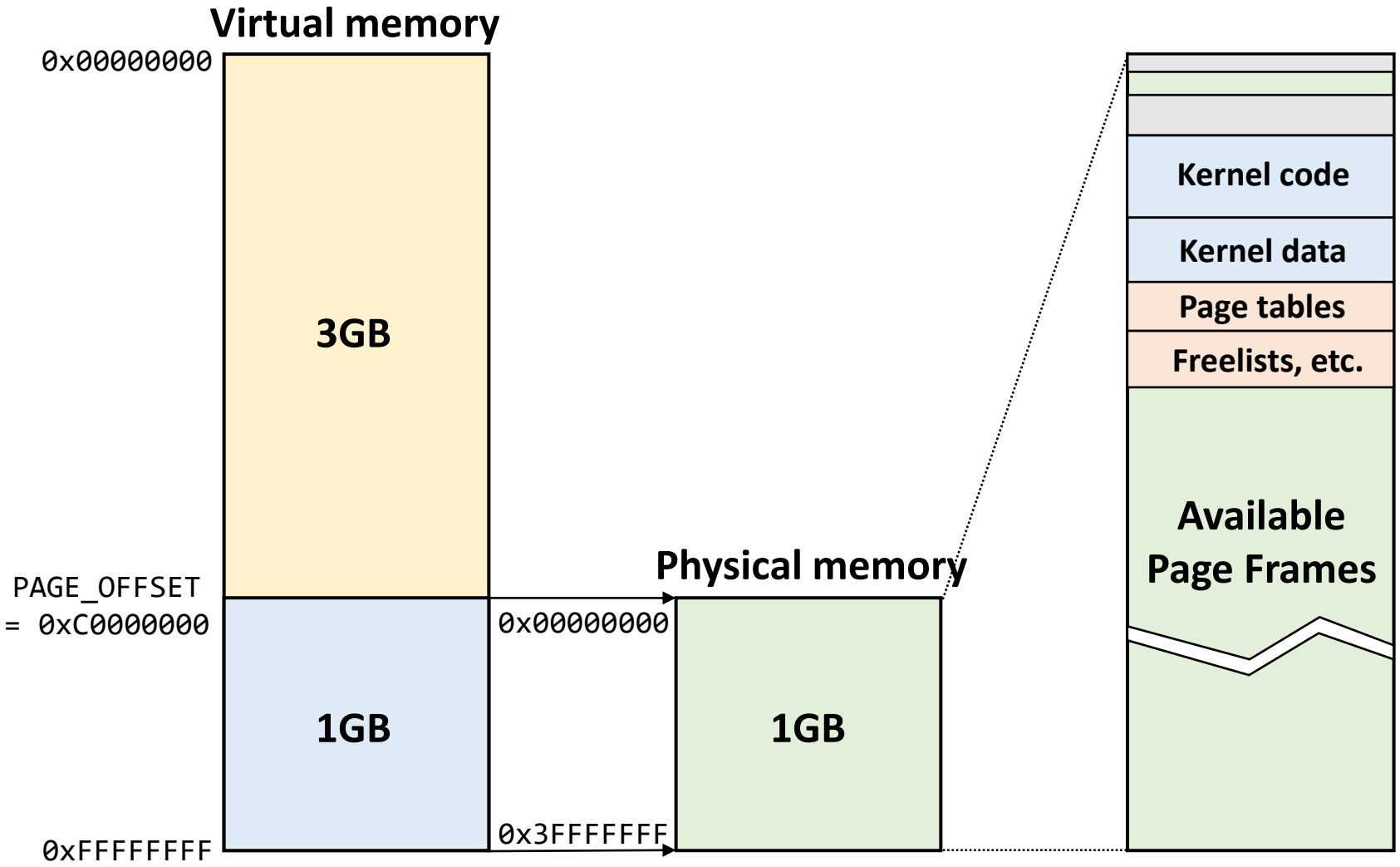
Linux
Virtual Memory

Virtual Address Map

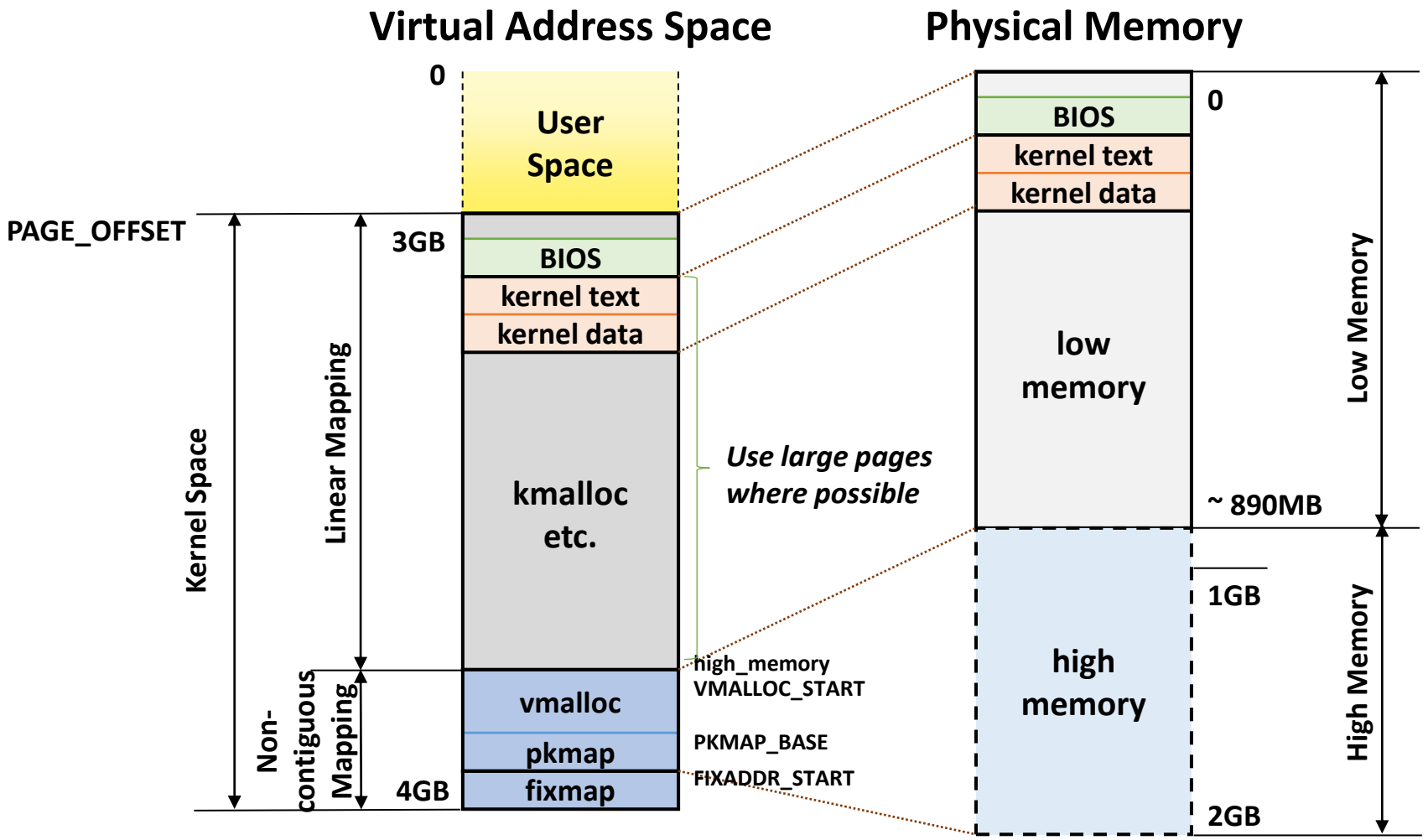




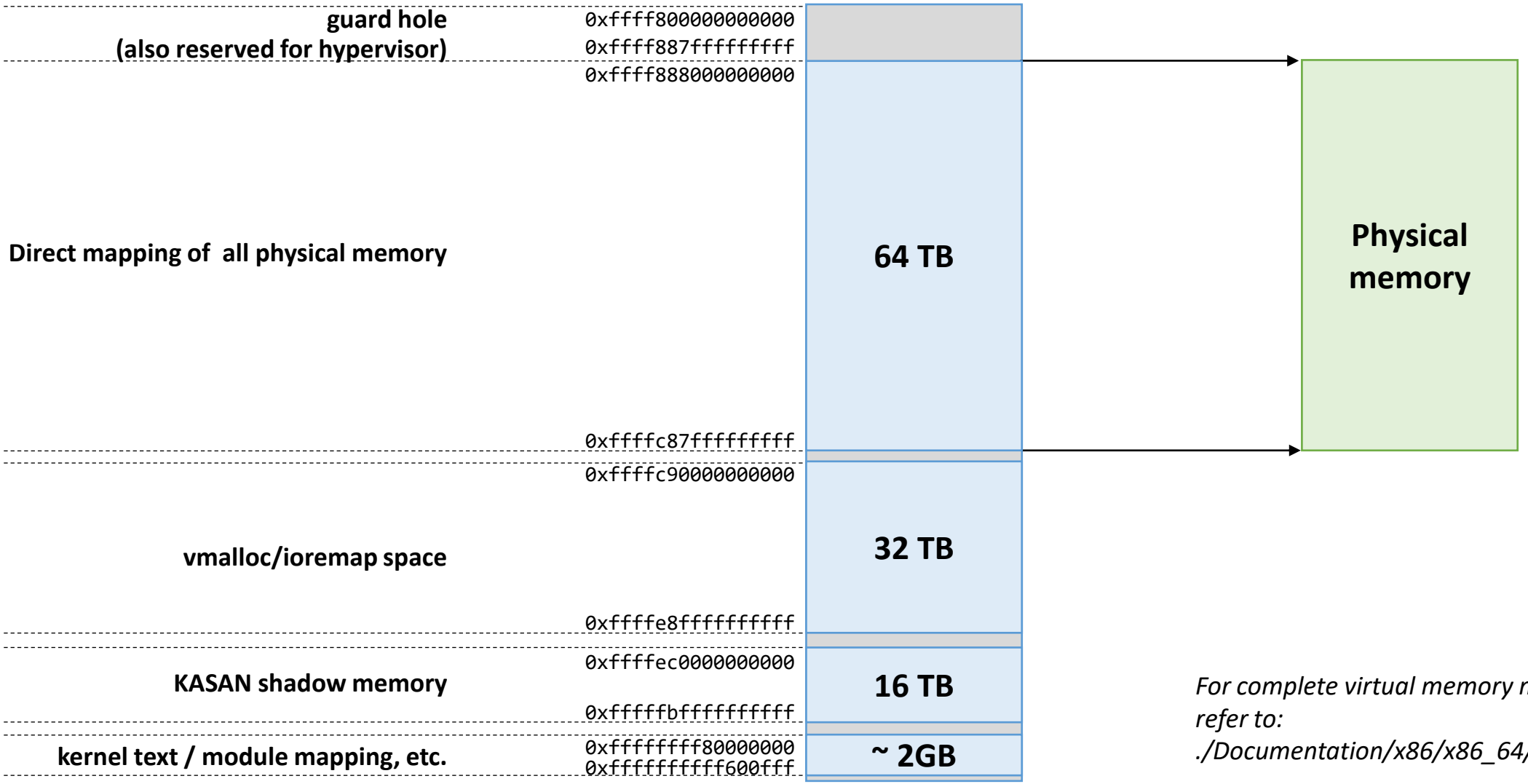
Kernel Address Space (i386, <1GB)



Kernel Address Space (i386)



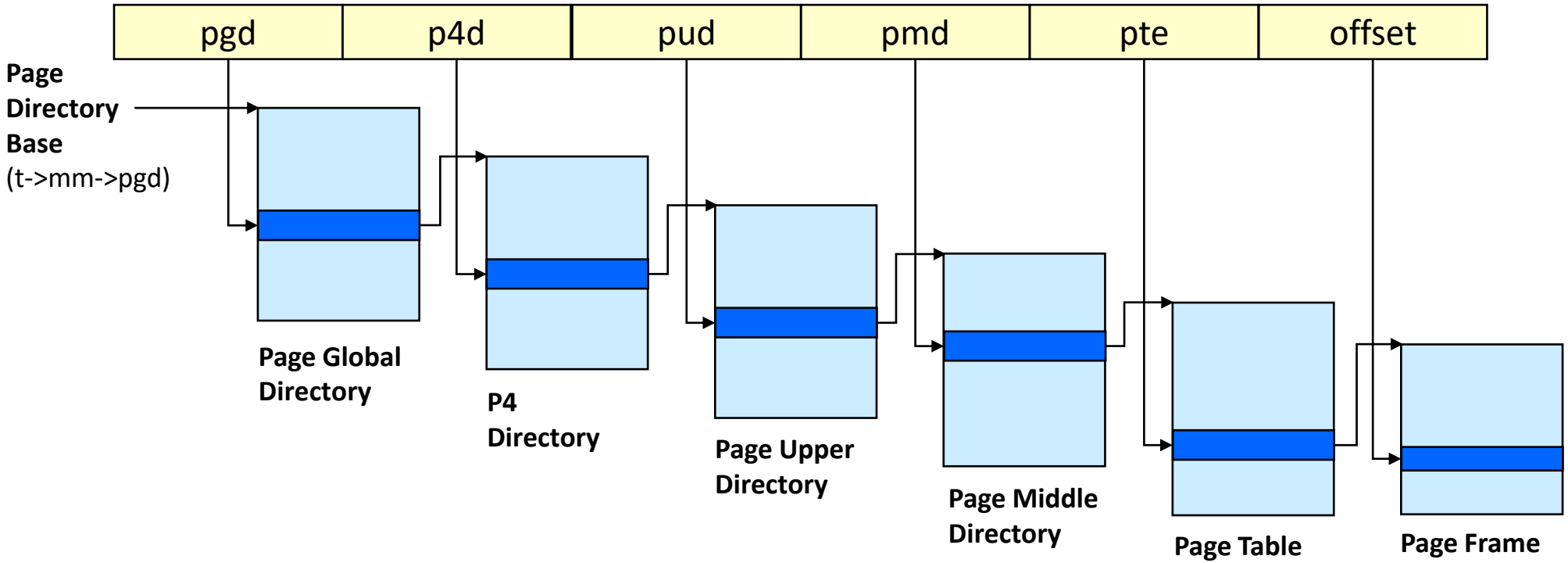
Kernel Address Space (x86_64, 48-bit)



For complete virtual memory map, refer to: ./Documentation/x86/x86_64/mm.rst

Paging in Linux

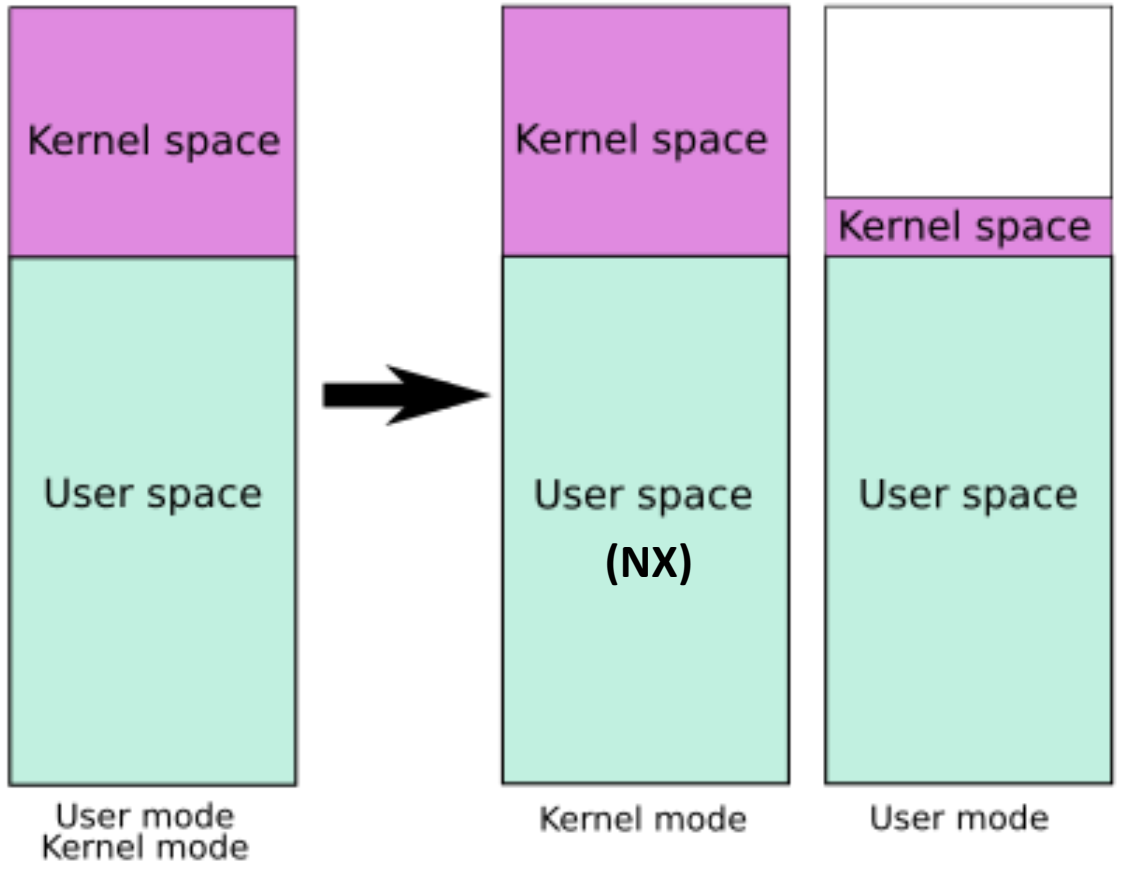
- Five-level address translation
  - 5-level paging for Intel "Ice Lake" processors and beyond (57-bit virtual address)
  - For 48-bit virtual address, the size of P4D is set to 1



Kernel Page-Table Isolation (KPTI)

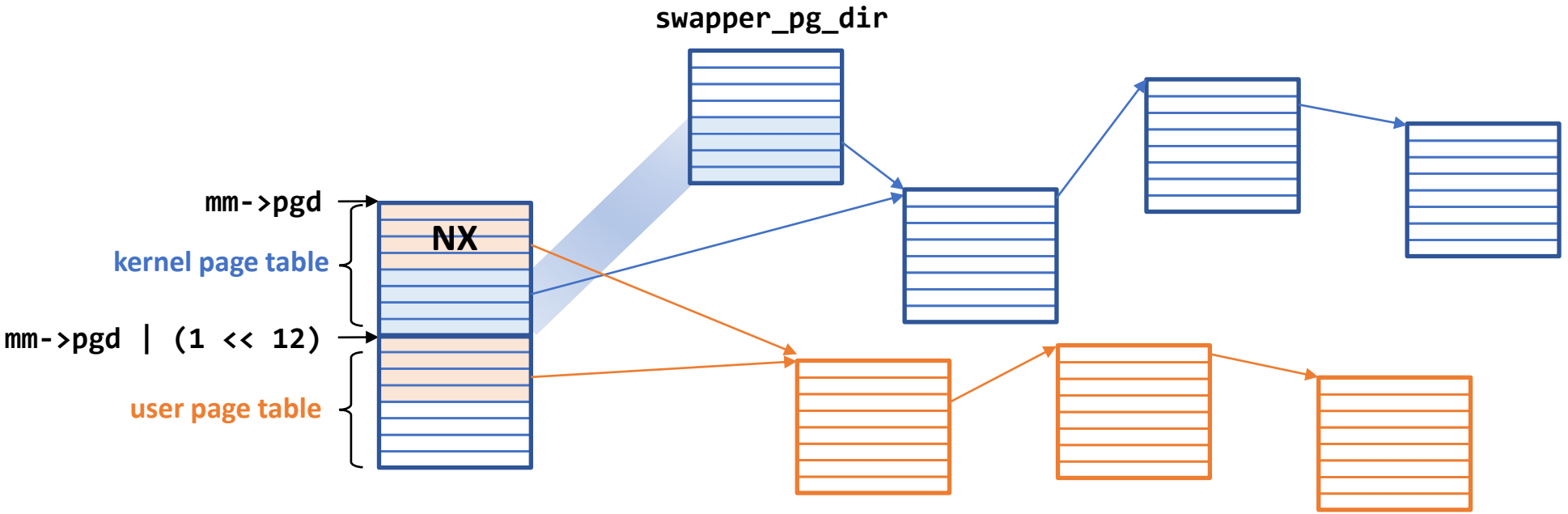
- To mitigate Meltdown vulnerability
- Separate page table for kernel
- Minimal kernel space for syscall, page fault & interrupt handling

- Merged in 4.15
- `CONFIG_PAGE_TABLE_ISOLATION=y`
- Disabled by '`nopti`' at boot time
- ASID becomes critical to the performance



Page Table Allocation

- When KPTI is enabled, two PGDs are allocated (@ `_pgd_alloc()`)
  - PGD_ALLOCATION_ORDER = 1 (8KB in size and 8KB-aligned)
  - One for kernel address space, the other for user address space
  - User portion of the kernel page table is set with the NX bit



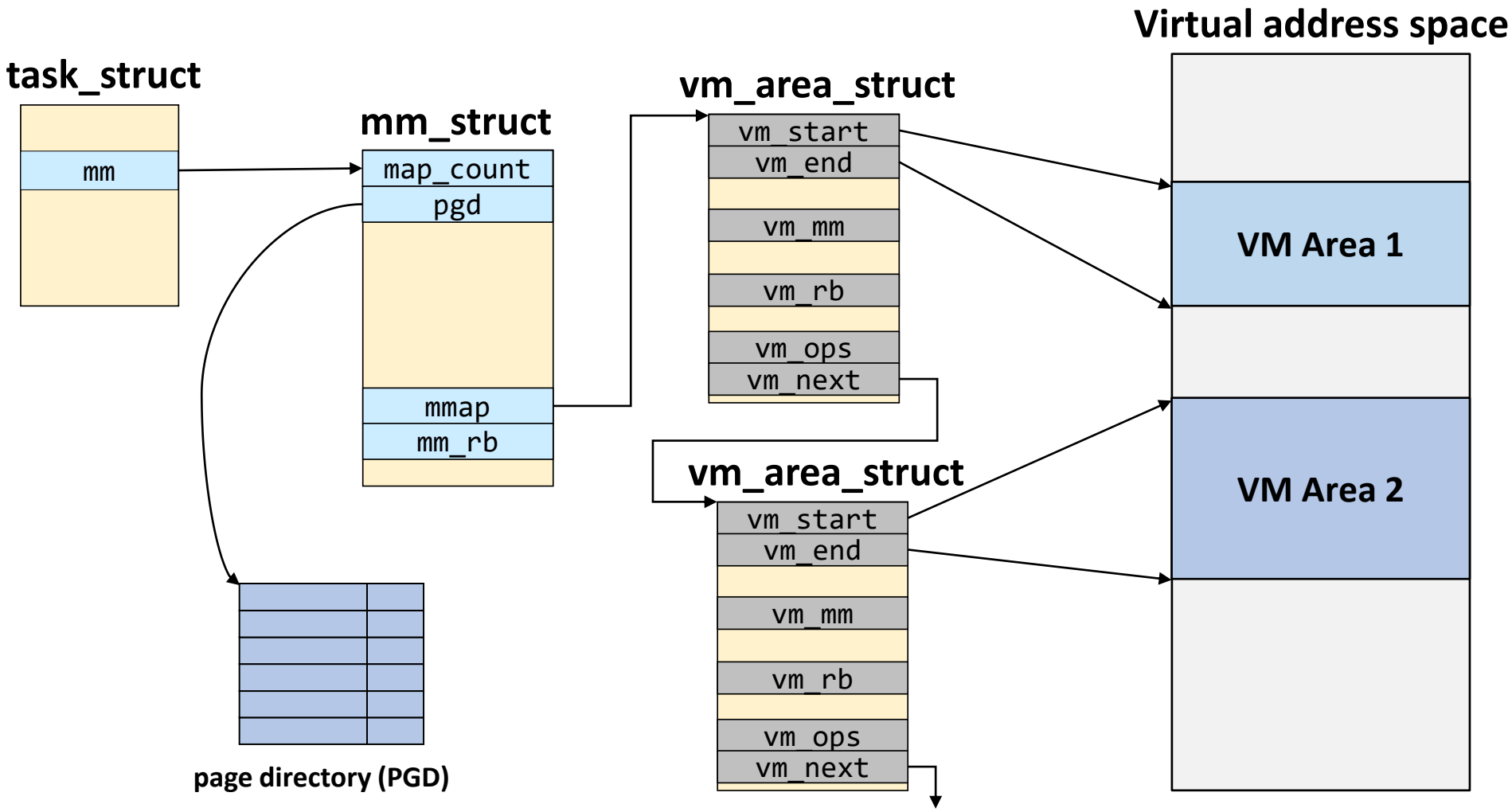
VMA

- Virtual Memory Area
  - A contiguous, page-aligned subset of the virtual address space
  - VMAs are linked with a red-black tree for fast lookup of the region corresponding to any virtual address
  - Described by a `vm_area_struct`
  - Either file-backed or anonymous
  - `/proc/PID/maps`

```
[sys:~-2028] cat /proc/self/maps
562a517de000-562a517e6000 r-xp 00000000 08:01 2228226                    /bin/cat
562a519e5000-562a519e6000 r--p 00007000 08:01 2228226                    /bin/cat
562a519e6000-562a519e7000 rw-p 00008000 08:01 2228226                    /bin/cat
562a52e6a000-562a52e8b000 rw-p 00000000 00:00 0                          [heap]
7f2244bd0000-7f2244db7000 r-xp 00000000 08:01 14286948                   /lib/x86_64-linux-gnu/libc-2.27.so
7f2244db7000-7f2244fb7000 ---p 001e7000 08:01 14286948                   /lib/x86_64-linux-gnu/libc-2.27.so
7f2244fb7000-7f2244fbb000 r--p 001e7000 08:01 14286948                   /lib/x86_64-linux-gnu/libc-2.27.so
7f2244fbb000-7f2244fbd000 rw-p 001eb000 08:01 14286948                   /lib/x86_64-linux-gnu/libc-2.27.so
7f2244fbd000-7f2244fc1000 rw-p 00000000 00:00 0
7f2244fc1000-7f2244fe8000 r-xp 00000000 08:01 14286873                   /lib/x86_64-linux-gnu/ld-2.27.so
7f224500e000-7f2245030000 rw-p 00000000 00:00 0
7f2245030000-7f22451cb000 r--p 00000000 08:01 262169                     /usr/lib/locale/locale-archive
7f22451cb000-7f22451cd000 rw-p 00000000 00:00 0
7f22451e8000-7f22451e9000 r--p 00027000 08:01 14286873                   /lib/x86_64-linux-gnu/ld-2.27.so
7f22451e9000-7f22451ea000 rw-p 00028000 08:01 14286873                   /lib/x86_64-linux-gnu/ld-2.27.so
7f22451ea000-7f22451eb000 rw-p 00000000 00:00 0
7fffdbb92000-7fffdbbb3000 rw-p 00000000 00:00 0                          [stack]
7fffdbbea000-7fffdbbed000 r--p 00000000 00:00 0                          [vvar]
7fffdbbed000-7fffdbbef000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

VMA *permission* *offset* *device* *i-node* *mapped file name*

VMA Structure



Lazy TLB Flushing

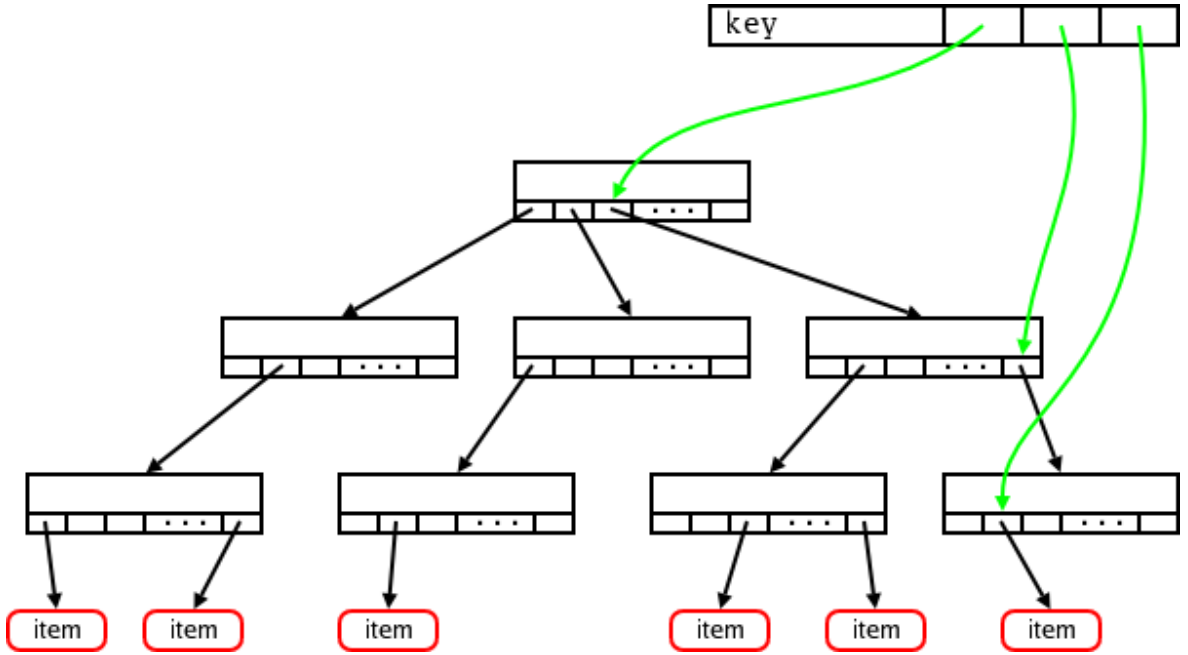
- TLB flush is expensive
- No need to flush TLB for a task without user virtual address space (i.e., kernel threads)

- Implementation
  - (`task_struct *`) `t->mm`: virtual address space of a process
  - (`task_struct *`) `t->active_mm`: the effective mm
  - Normally, `t->active_mm == t->mm`
  - On context switch, `t->active_mm->pgd` is stored into CR3
  - If the next task's `mm` is NULL, use previous task's `active_mm` to avoid TLB flush

Page Cache

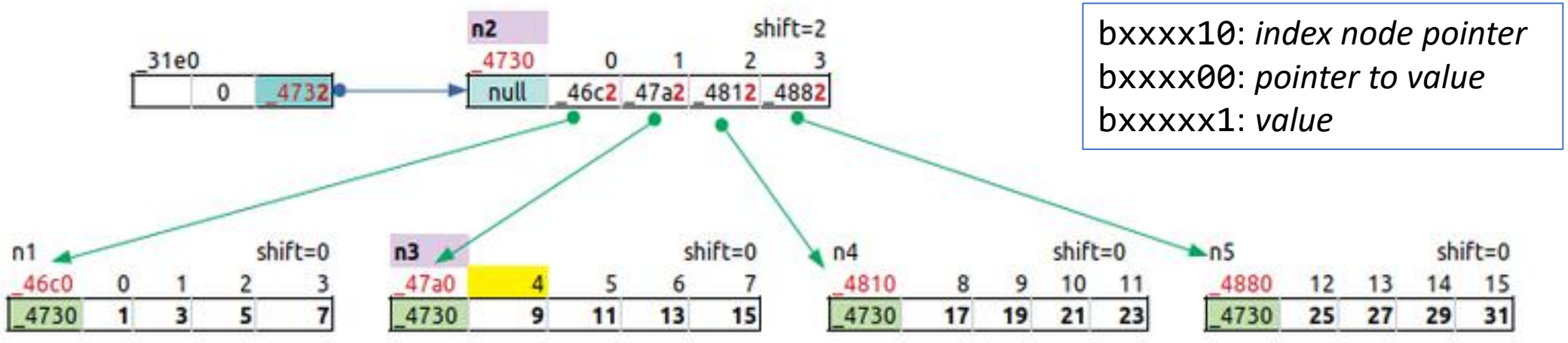
- A cache of pages in RAM
  - From reads and writes of regular filesystem files, block device files, mmap'ed files, …
  - Group cached pages belonging to the same inode

- Page cache lookup
  - Each inode has a unique radix tree
  - Key: <inode, page offset>
  - The radix tree points to the cached page
  - Fanout: 64
    (16 for small system)



Xarray (eXtensible Array)

- An abstract data type which behaves like a very large array of pointers
  - Radix tree is replaced with XArray since 4.19 (by Matthew Wilcox)
  - Can go to the next or previous entry in a cache-efficient manner compared to a hash
  - No need to copy data or change MMU mappings compared to a resizable array
  - More memory-efficient, parallelizable and cache-friendly than a doubly-linked list
  - Perform lookups without locking using RCU



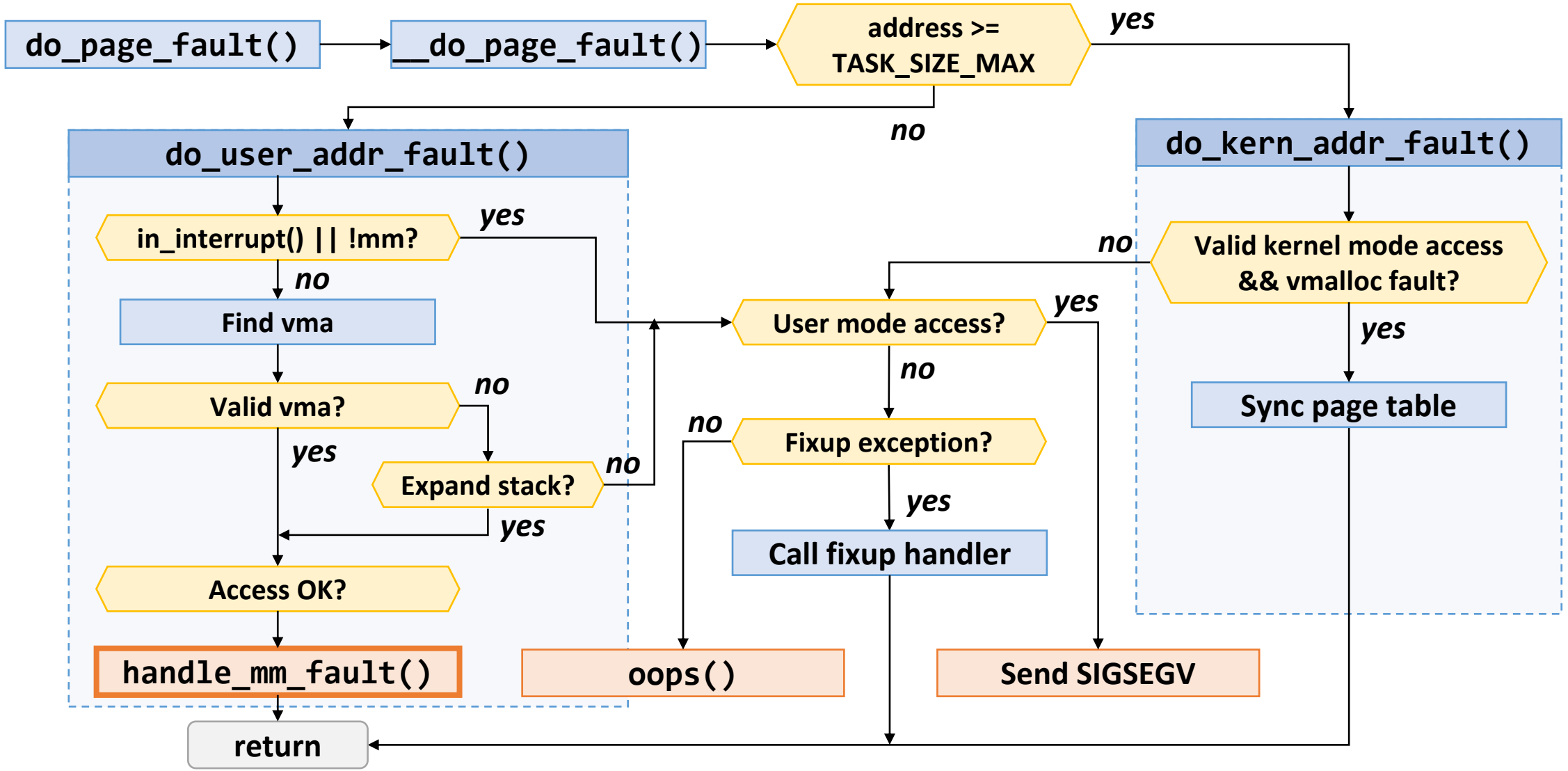
bxxxx10: *index node pointer*
bxxxx00: *pointer to value*
bxxxxx1: *value*

Source: https://www.kernel.bz/boardPost/118679/19

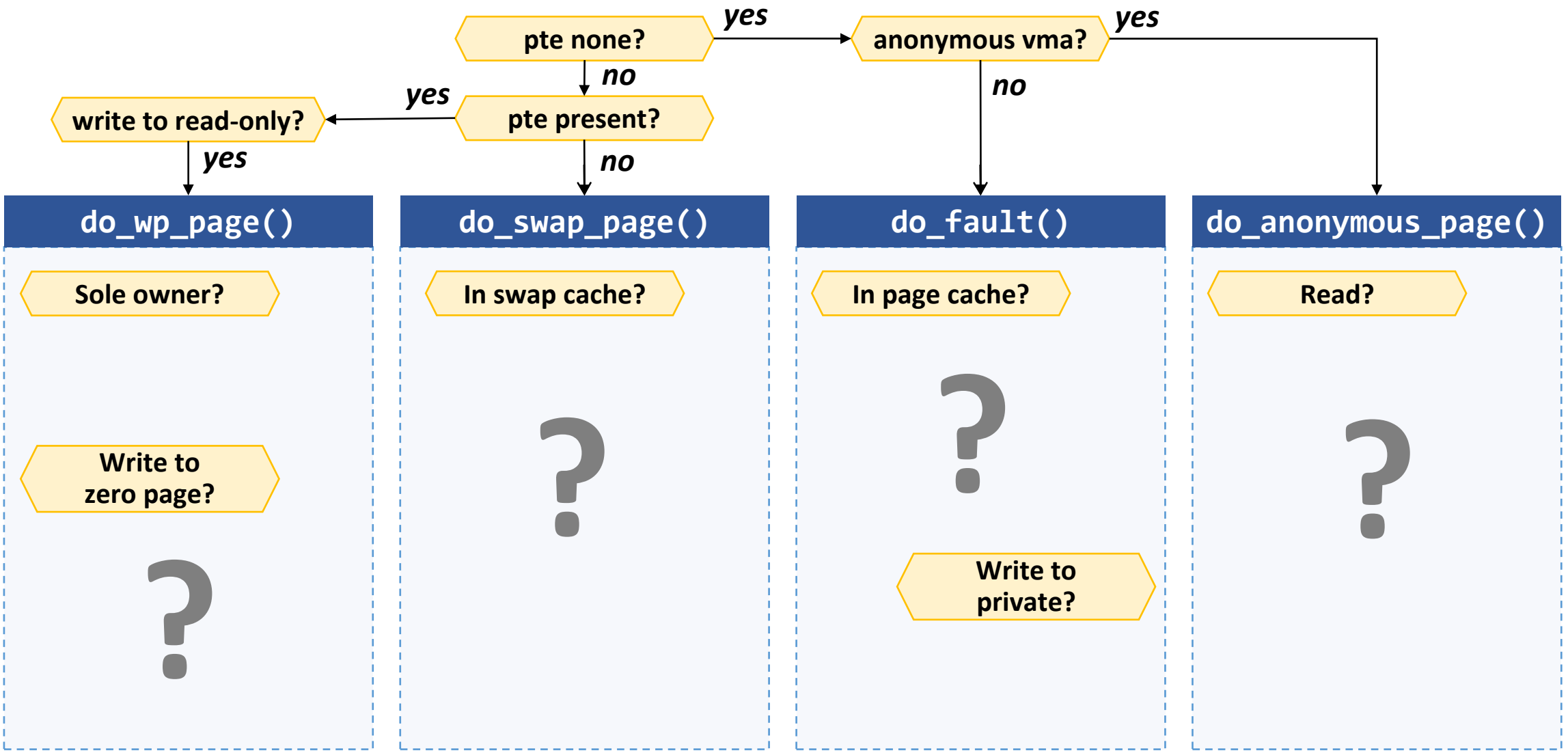
Classifying Page Faults

	User address	Kernel address
User mode	Invalid user address: SIGSEGV Valid user address: Normal page faults	Invalid kernel address: SIGSEGV
Kernel mode	Fixup address: Jump to the fixup handler Kernel bug: OOPS	Inconsistent PGD: Synchronize PGD Fixup address: Jump to the fixup handler Kernel bug: OOPS

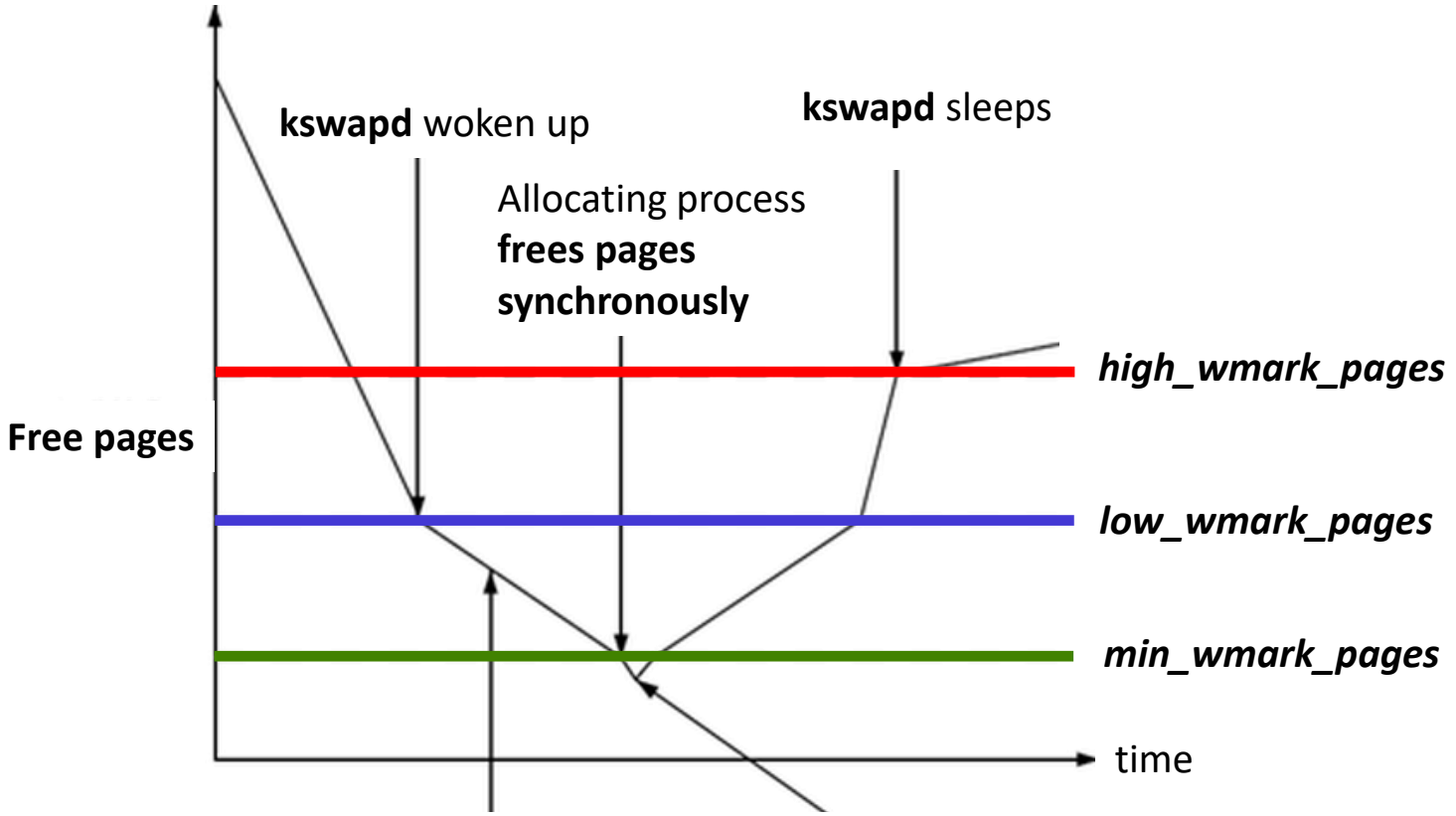
Page Fault Handling



Handling Normal Page Faults



Swapping in Linux

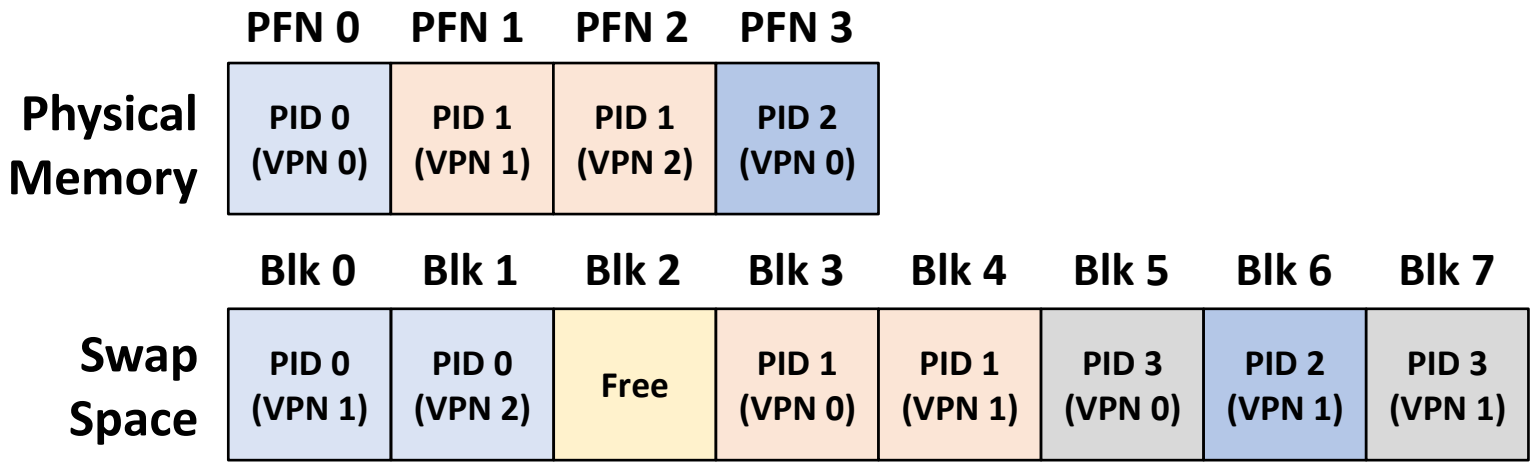


Rate of page consumption is slowed by kswapd but still allocating too fast

GFP_ATOMIC allocation can go below *min_wmark_pages*

Where to Swap

- Swap space
  - Disk space reserved for moving pages back and forth
  - The size of the swap space determines the maximum number of memory pages that can be in use
  - Block size is same as the page size
  - Can be a dedicated partition or a file in the file system



What to Swap

- What happens to each type of page frame on low mem?
  - Kernel code → **Not swapped**
  - Kernel data → **??**
  - Page tables for user processes → **Not swapped**
  - Kernel stack for user processes → **??**
  - User code pages → **Dropped**
  - User data pages → **??**
  - User heap/stack pages → **Swapped**
  - Files mmap'ed to user processes → **??**
  - Page cache pages → **Dropped** or **go to file system**
- Page replacement policy chooses the pages to evict

Replacement Algorithms

- I/O buffer cache replacement
  - "Page hit" is known to OS
  - Uses block I/O traces
  - LRU, LRU-2, 2Q, SEQ, LRFU, EELRU, MQ, LIRS, ARC, …

- VM page replacement
  - "Page hit" is only known to hardware, not to OS
  - Hardware sets the Reference / Dirty bits in the PTE
  - LRU approximation
  - Uses memory reference traces
  - CLOCK, WSClock, GCLOCK, CAR, CLOCK-Pro, …

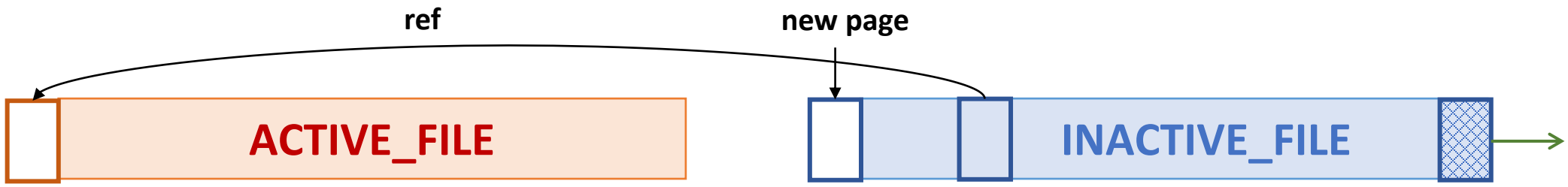
LRU Lists

- `LRU_INACTIVE_ANON`: for inactive anonymous pages
- `LRU_ACTIVE_ANON`: for active anonymous pages
- `LRU_INACTIVE_FILE`: for inactive file-backed pages
- `LRU_ACTIVE_FILE`: for active file-backed pages
- `LRU_UNEVICTABLE`: for unevictable pages (ramfs, locked pages, etc.)

- Why separate lists for ANON and FILE pages?
  - Page cache pages may be hidden behind lots of anonymous pages on the LRU
  - The kernel scans over pages that should not be evicted
    (e.g., scanning anonymous pages when there is no swap)

Refault Distance

- Inactive_age: total # of pages removed from INACTIVE_FILE
  = # of pages evicted from INACTIVE_FILE +
  # of pages promoted from INACTIVE_FILE to ACTIVE_FILE
- *E* = inactive_age(t_e) when a page is evicted from memory
- *R* = inactive_age(t_r) when the page is fetched to memory again
- Refault distance = *R* – *E*: total # of pages removed from INACTIVE_FILE while the page was outside of memory



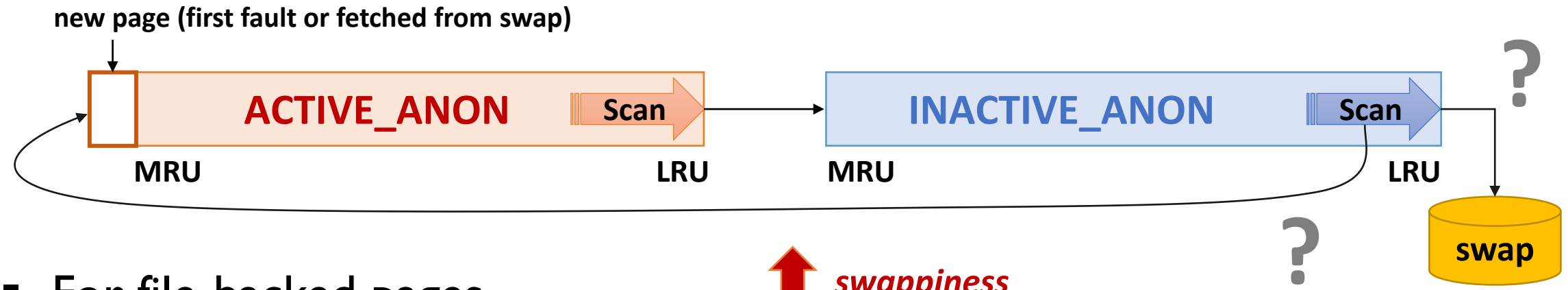
Promotion using Refault Distance

- Minimum access distance D = (R – E) + *nr_inactive*(t_r)
- Check whether D <= *nr_inactive*(t_r) + *nr_active*(t_r) or (R – E) <= *nr_active*(t_r)
- If (R – E) <= *nr_active*(t_r) then the page goes to ACTIVE_FILE
  Otherwise, it goes to INACTIVE_FILE

- Implementation
  - Page cache maintains shadow entries for evicted pages
  - The shadow entry records inactive age (E)
  - On refault, compare (R – E) with *nr_active*

Page Reclaim

- For anonymous pages



- For file-backed pages

swappiness