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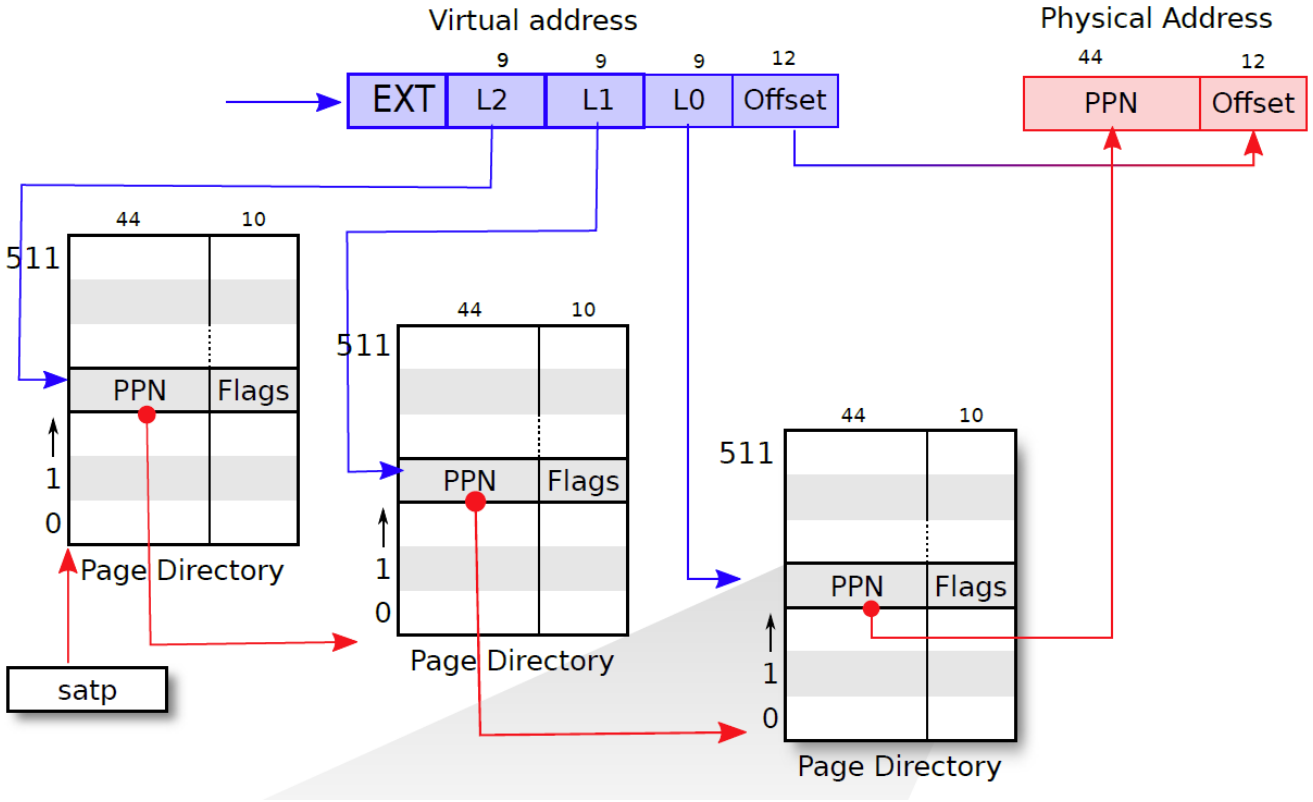
Virtual Memory Implementations

Xv6 Virtual Memory System

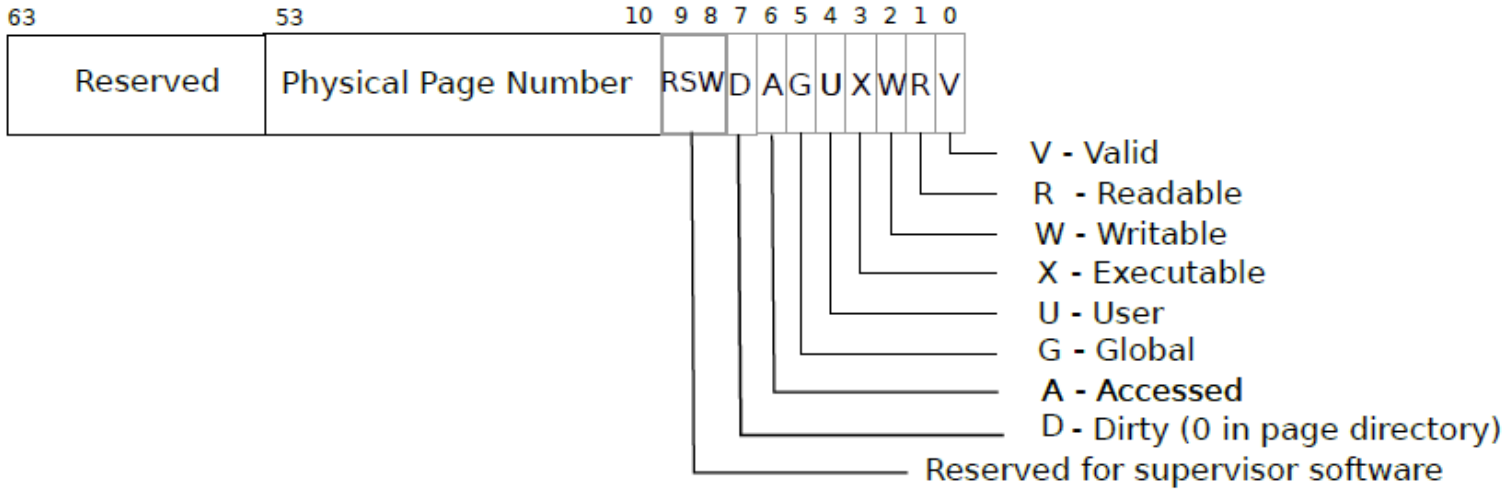
RISC-V Paging Hardware

- Sv39: page-based 39-bit virtual addressing
  - 39-bit virtual address → 56-bit physical address
  - 4KB page size
  - Three-level page table
  - `satp` register has the physical address of the root page table
  - Each CPU has its own `satp` register



RISC-V PTE

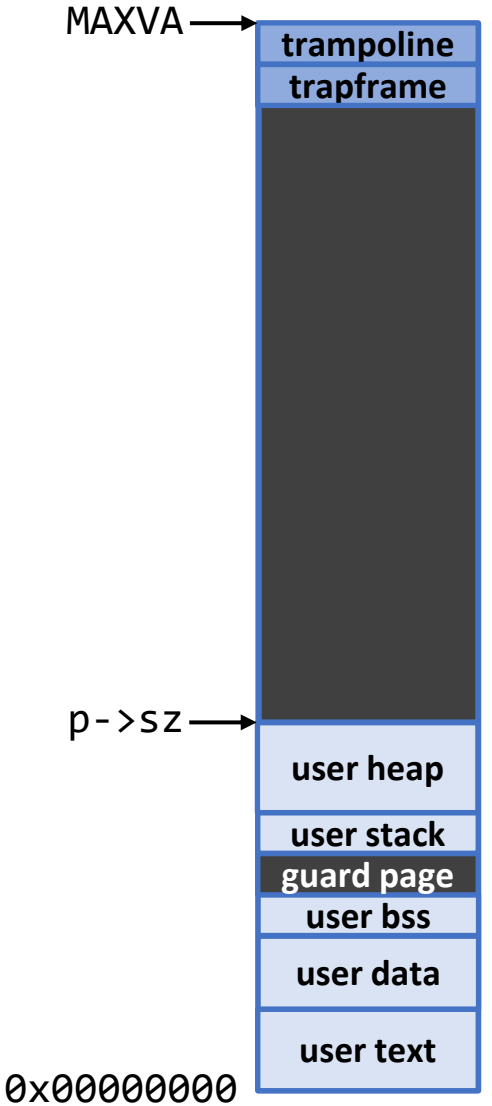
- Sv39 page table entry



- Superpage support
  - Any level of PTE may be a leaf PTE
  - 2MB "megapages"
  - 1GB "gigapages"

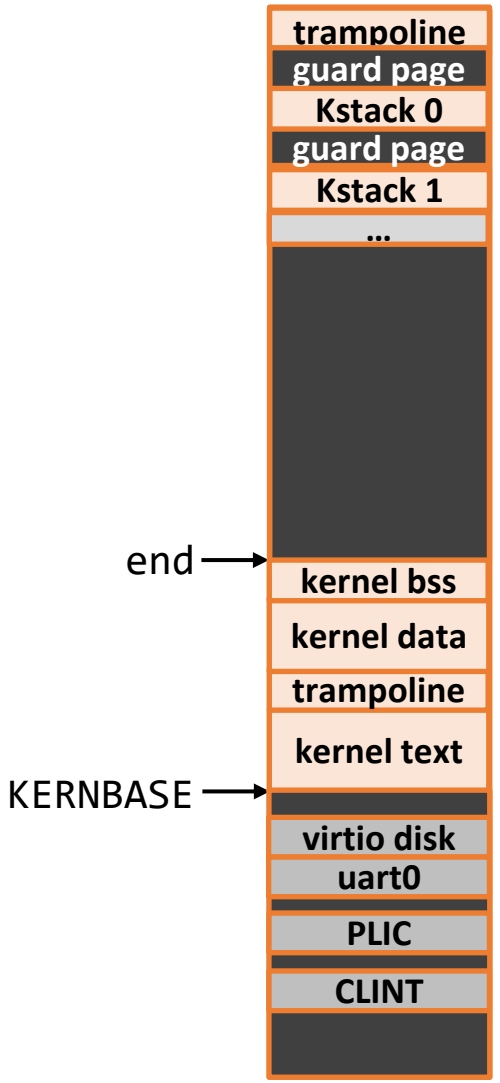
Process Address Space

- Xv6 uses only 38 bits for virtual addresses
  - `MAXVA` = $2^{38} - 1$ = `0x3fffffffff`
  - `p->pagetable` points to the address of the root page table
- Guard page: used to detect stack overflow
- Trampoline page: contains the trap handler code
  - Should be mapped at the same virtual address both in kernel page table and in every user page table
- Trapframe page: used to save user registers
  - Needs to be accessed before switching to the kernel page table
  - Mapped to a per-process trapframe (`p->tf`) page in the kernel



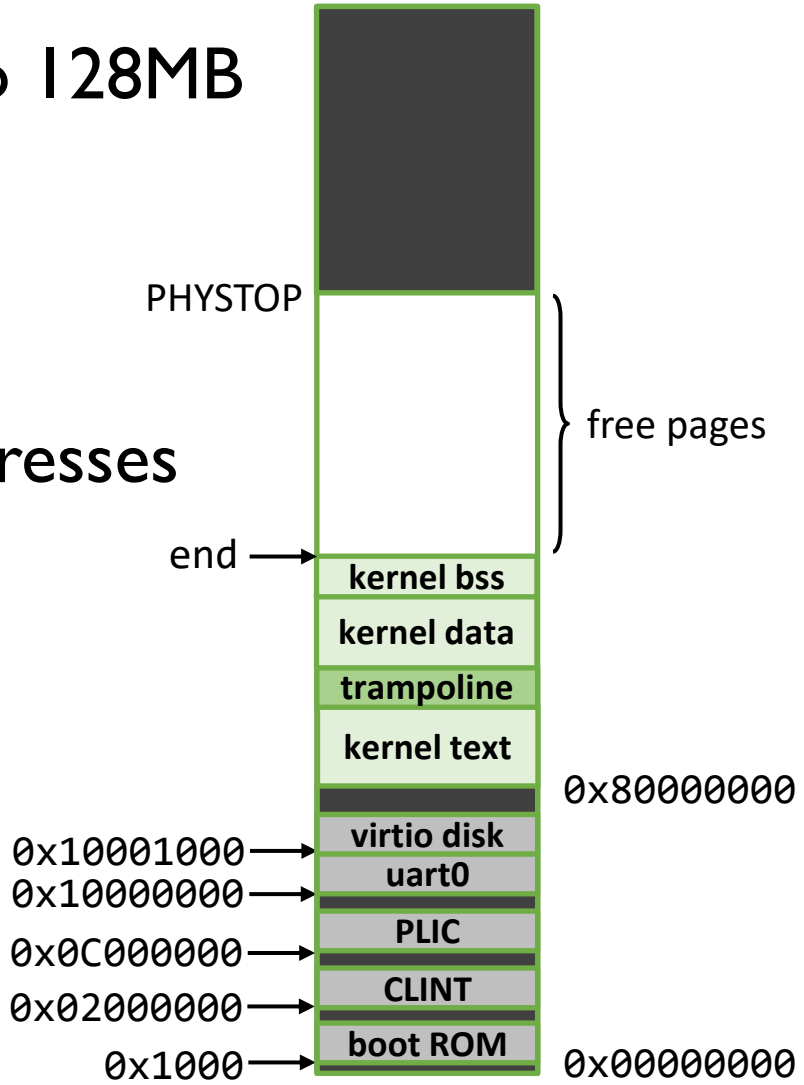
Kernel Address Space

- Xv6 uses KPTI: the kernel has its own page table
- Identity mapping: most of the kernel's address is "direct-mapped" to physical memory
  - The kernel is located at KERNBASE (`0x80000000`) in both the virtual address space and in physical memory
  - I/O devices are mapped below KERNBASE
- Trampoline page is also mapped at the top of the kernel virtual address space
- Kernel stack pages: preallocated and separated with a guard page.

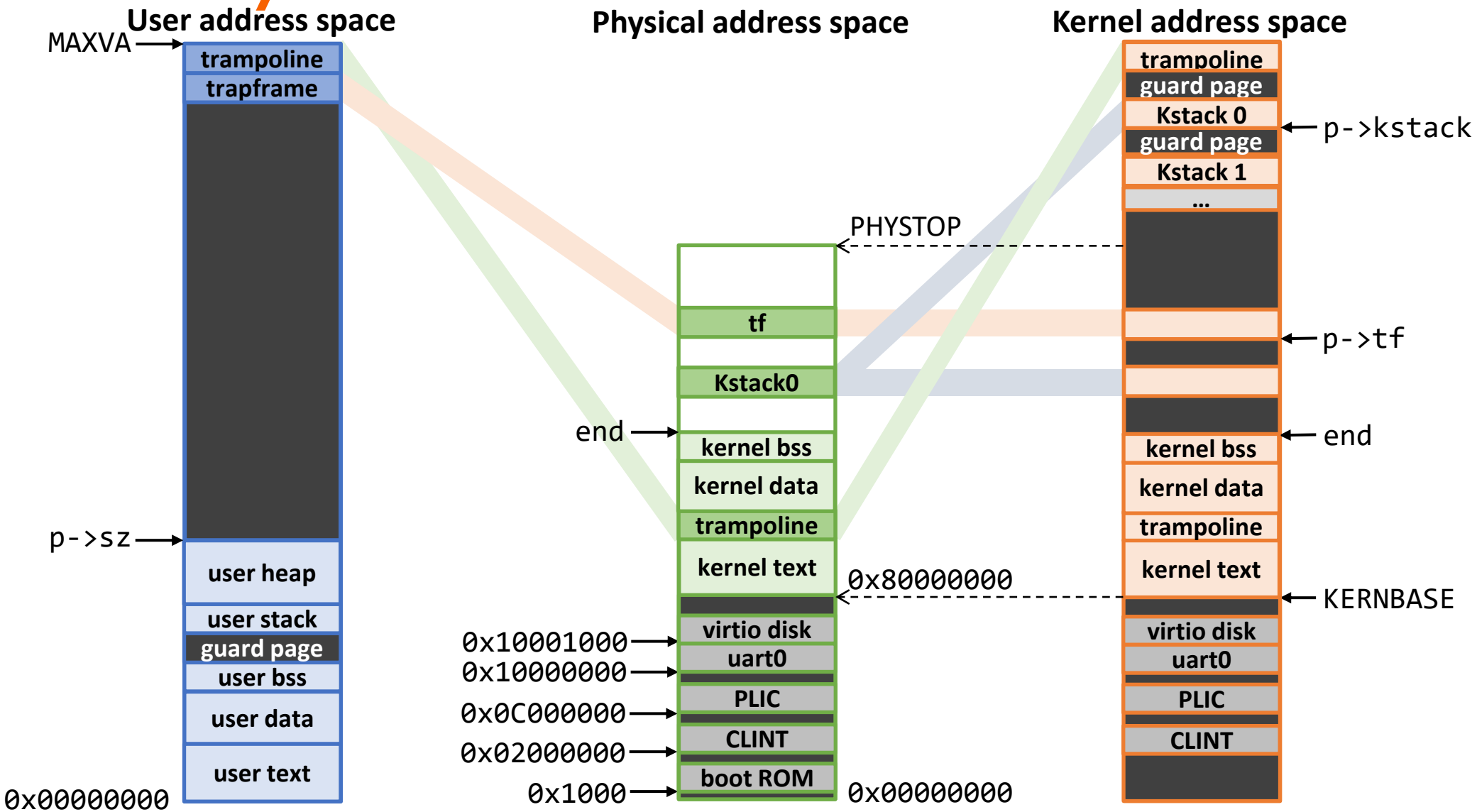


Physical Address Space

- Total amount of the physical memory is fixed to 128MB
  - PHYSTOP = KERNBASE + 128 * 1024 * 1024 (@ `kernel/memlayout.h`)
- Physical memory starts at `0x80000000`
- Various I/O devices are mapped to physical addresses below `0x80000000`
  - Boot ROM
  - Core-Local Interruptor (CLINT)
  - Platform-Level Interrupt Controller (PLIC)
  - Console (uart0)
  - Disk (virtio)



Summary


User address space
MAXVA
trampoline
trapframe
p->sz
user heap
user stack
guard page
user bss
user data
user text
0x00000000
Physical address space
PHYSTOP
tf
Kstack0
end
kernel bss
kernel data
trampoline
kernel text
0x80000000
virtio disk
uart0
PLIC
CLINT
boot ROM
0x10001000
0x10000000
0x0C000000
0x02000000
0x1000
0x00000000
Kernel address space
trampoline
guard page
Kstack 0
guard page
Kstack 1
...
p->kstack
p->tf
end
kernel bss
kernel data
trampoline
kernel text
KERNBASE
virtio disk
uart0
PLIC
CLINT

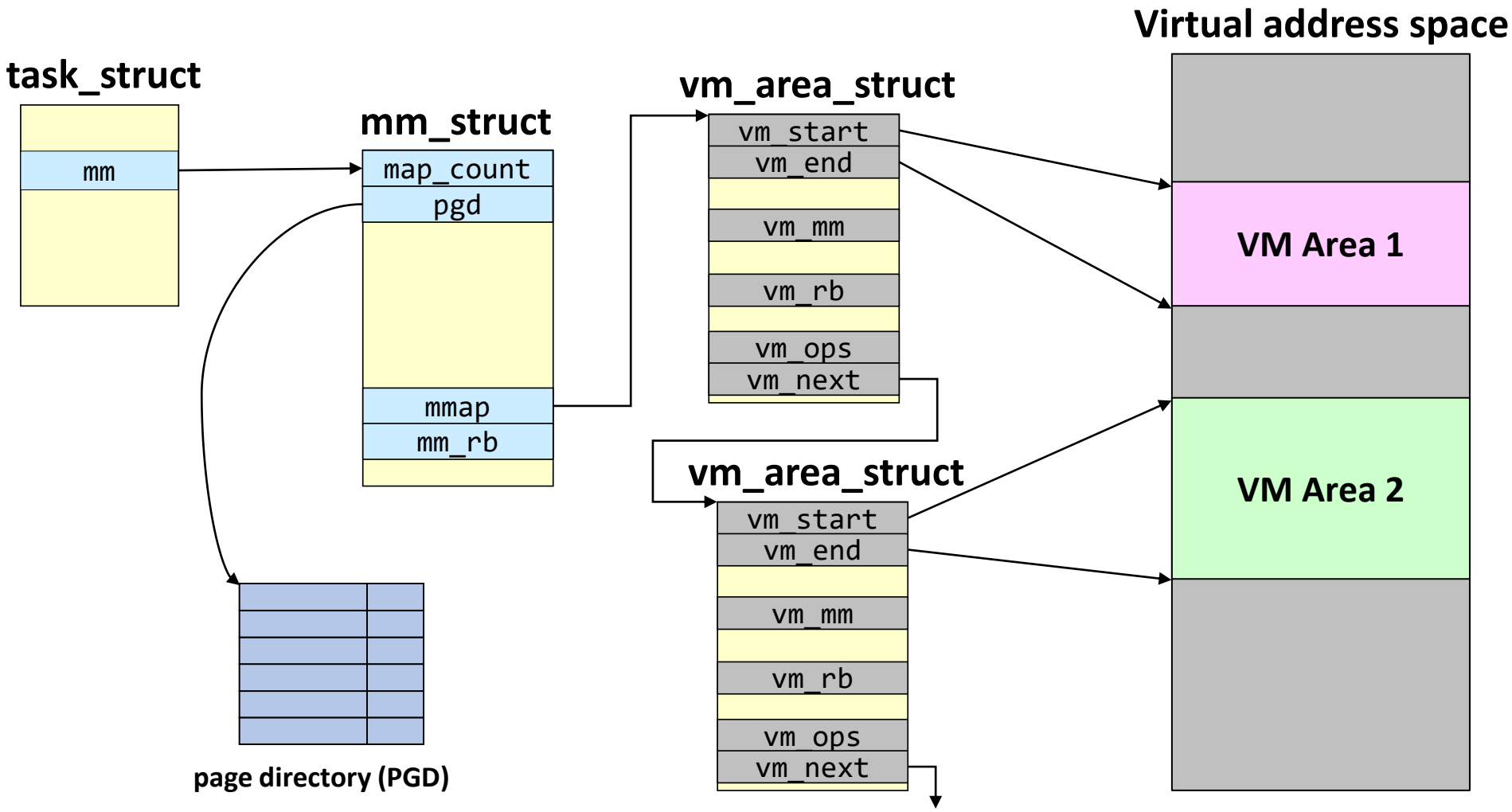
Linux Virtual Memory System

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`

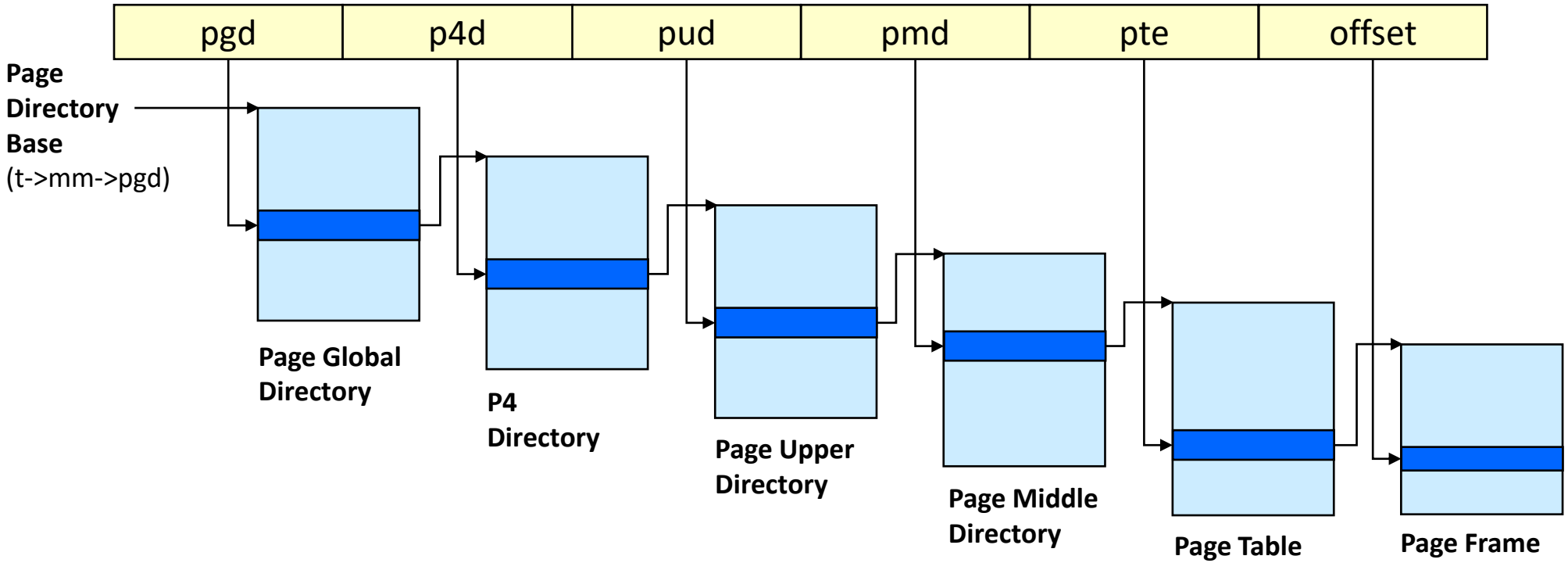
```
[sys:~-2028] cat /proc/self/maps
562a517de000-562a517e6000 r-xp 00000000 08:01 2228226                    /bin/cat
562a519e5000-562a519e6000 r--p 00007000 08:01 2228226                    /bin/cat
562a519e6000-562a519e7000 rw-p 00008000 08:01 2228226                    /bin/cat
562a52e6a000-562a52e8b000 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 Structure

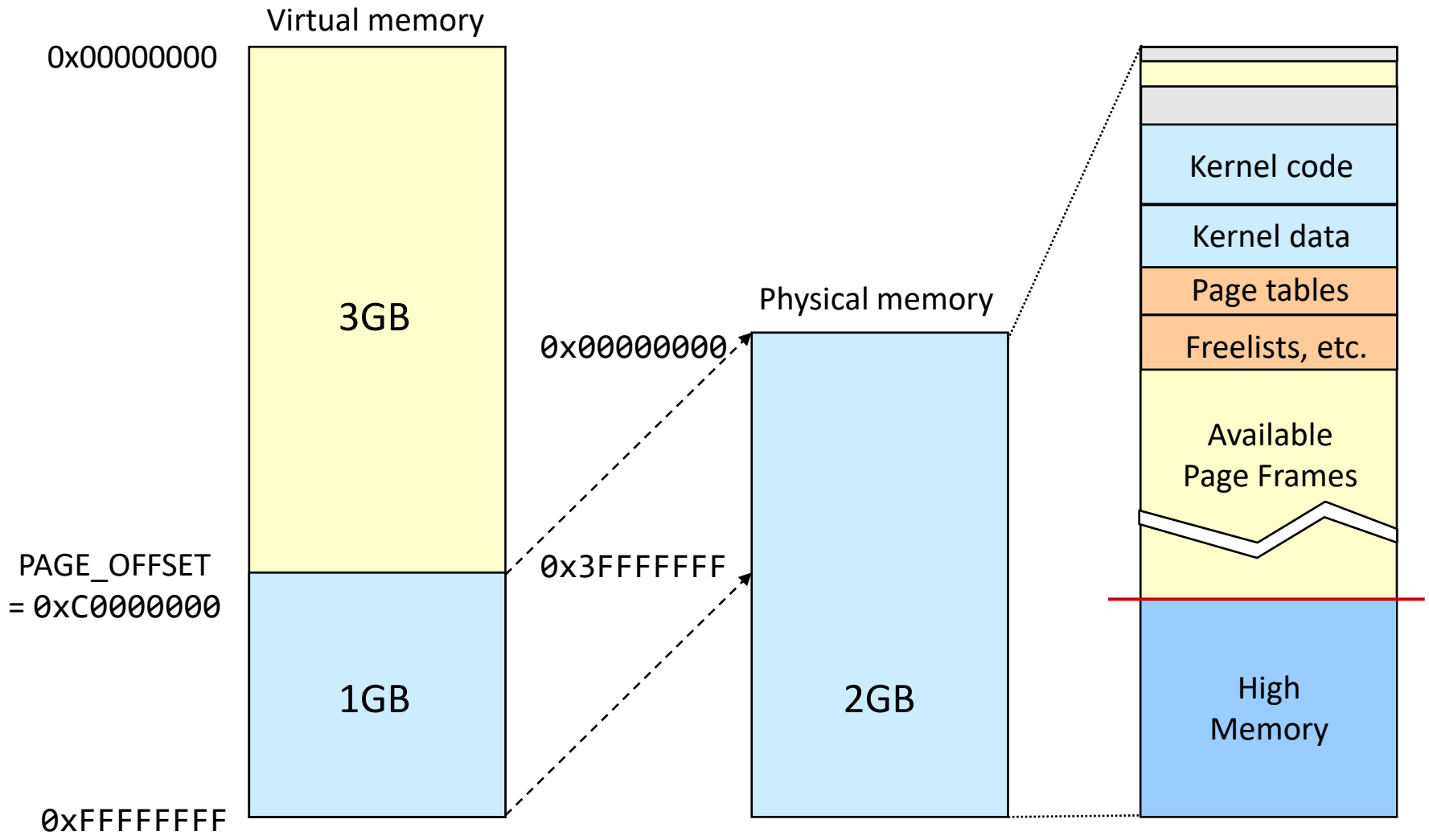


Paging in Linux

- 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



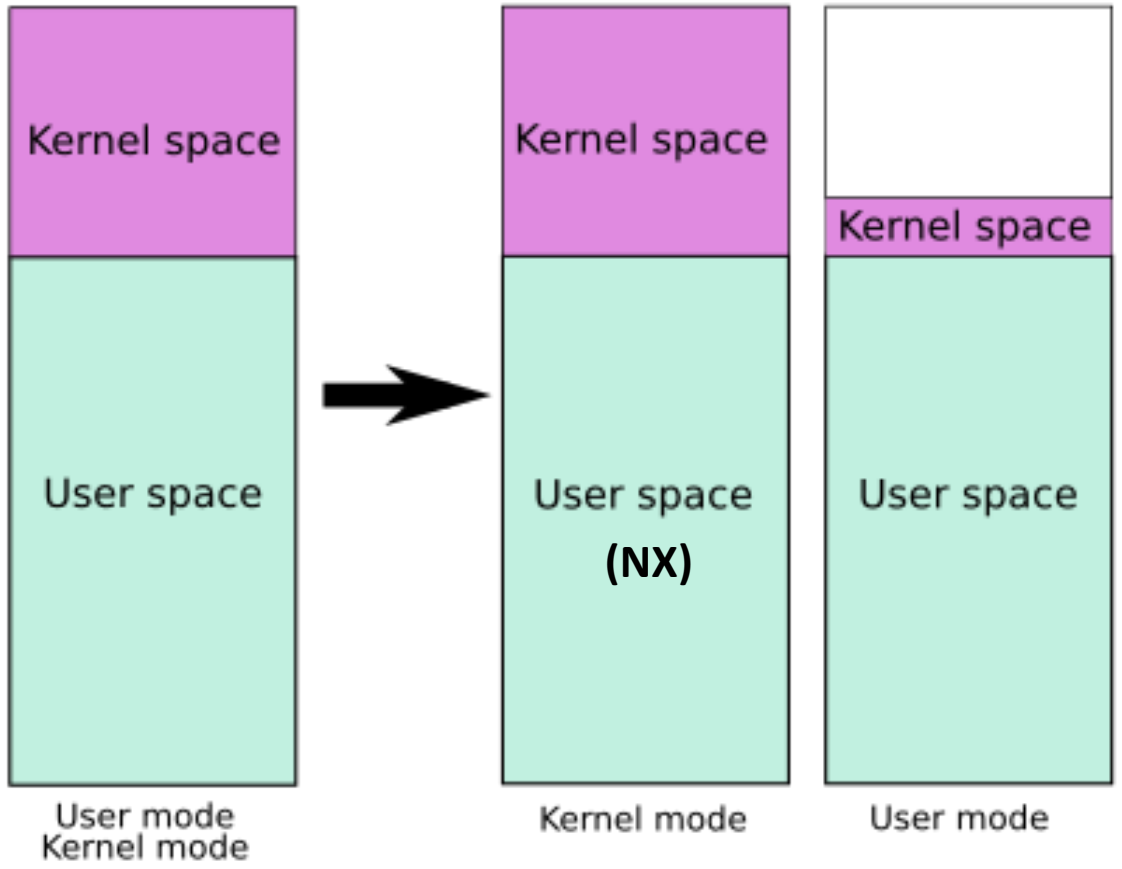
Managing Physical Memory (32-bit)



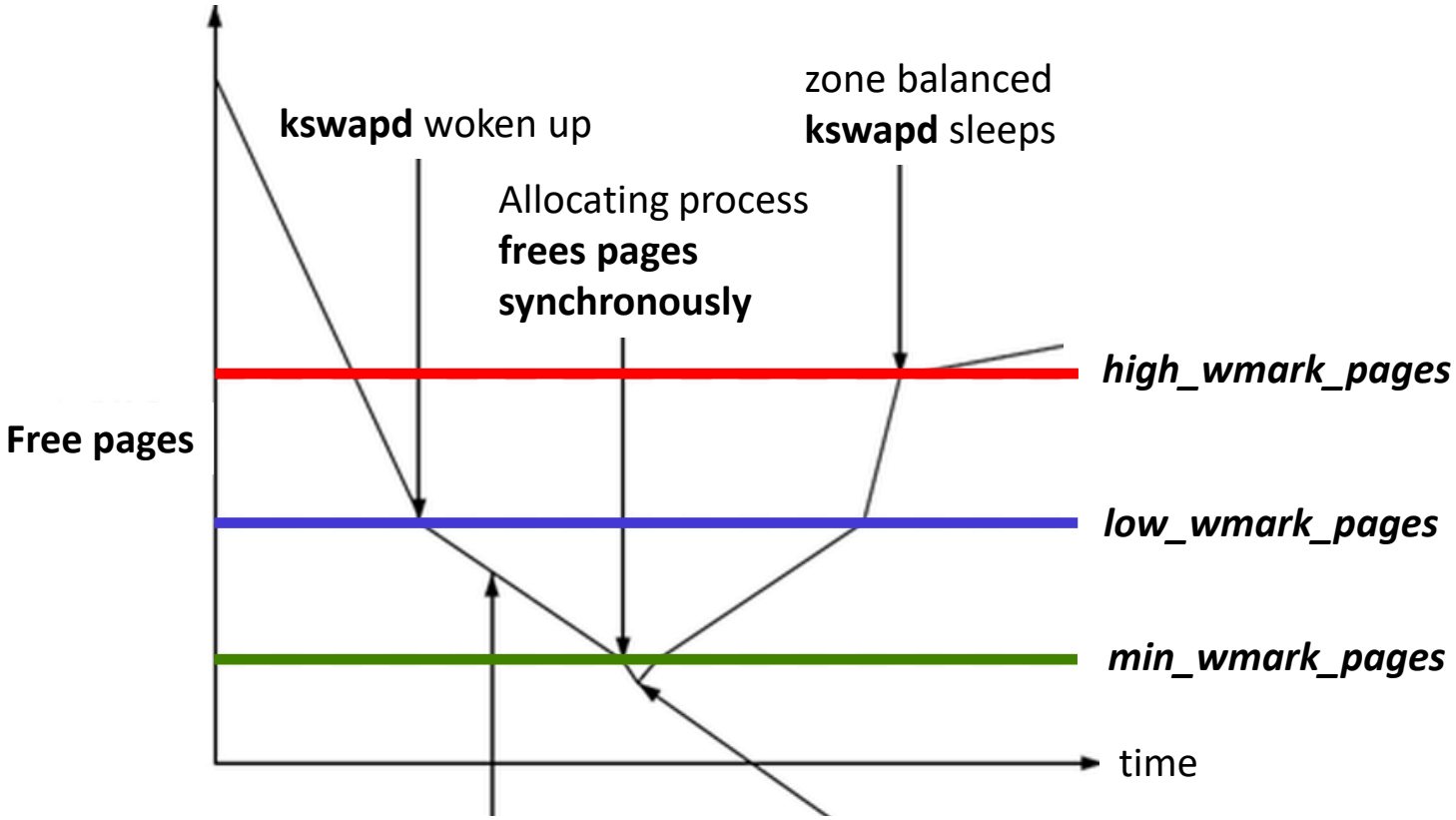
Kernel Page-Table Isolation (KPTI)

- 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



Swapping



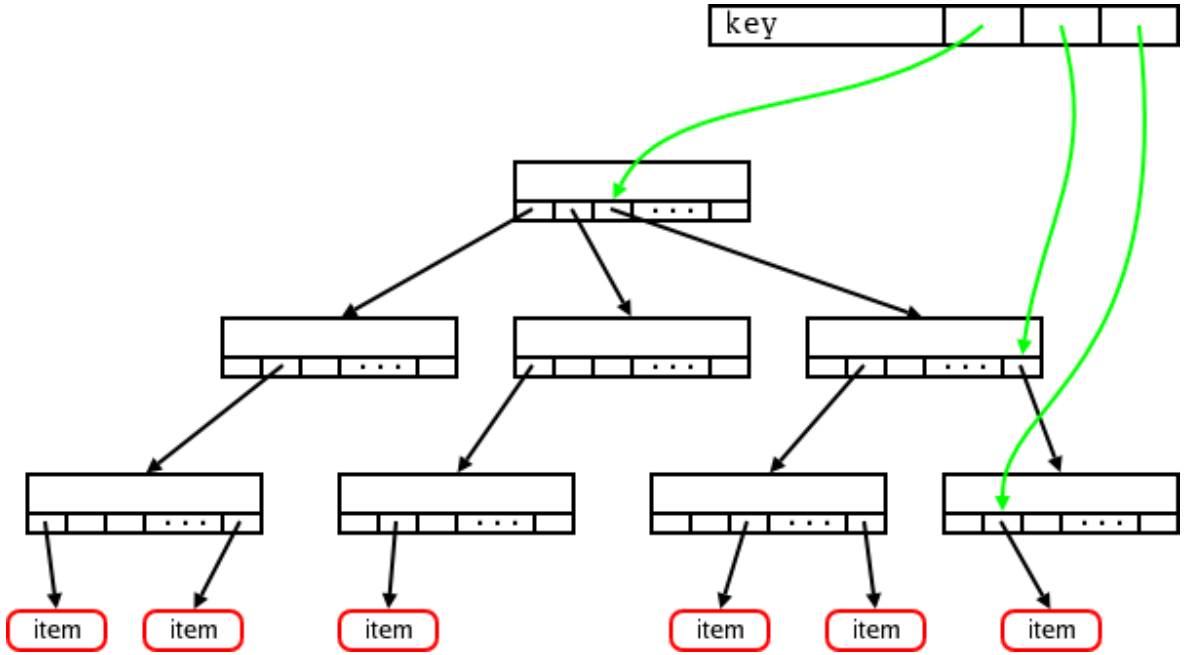
Rate of page consumption is slowed by kswapd but still allocating too fast

GFP_ATOMIC allocation can go below *min_wmark_pages(zone)*

Page Cache

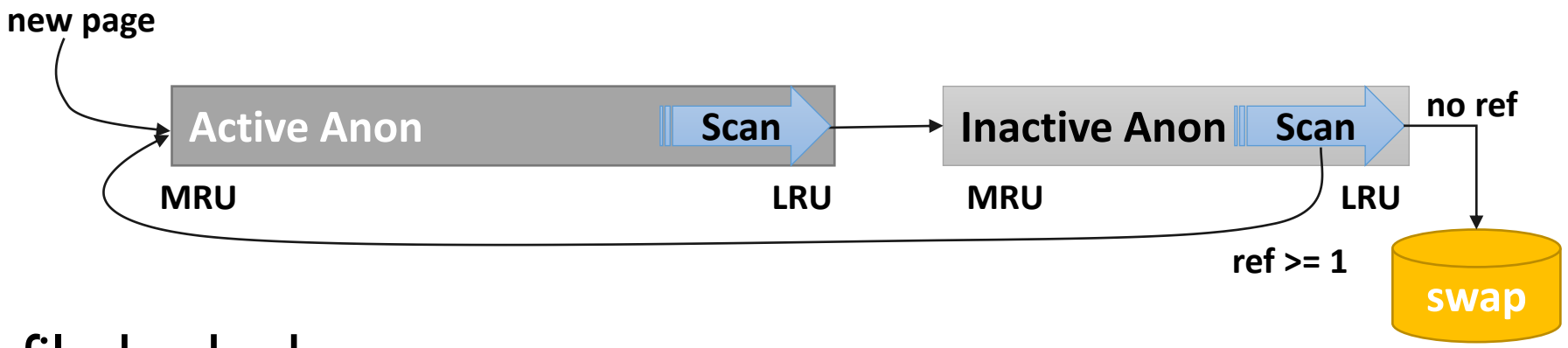
- A cache of pages in RAM
  - From reads and writes of regular filesystem files, block device files, mmap'ed files, …
  - Group cached pages belonging to the same inode

- 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)



Linux Page Replacement (v5.x)

- For anonymous pages



- For file-backed pages