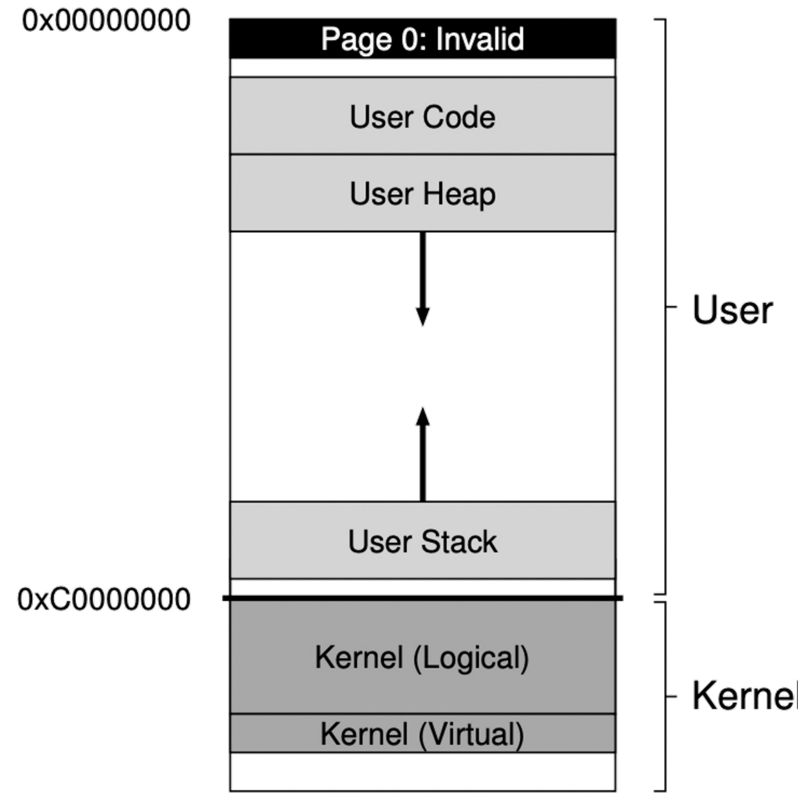
Lecture 9
Linux Memory Management

Prof. Yinqian Zhang

Fall 2024

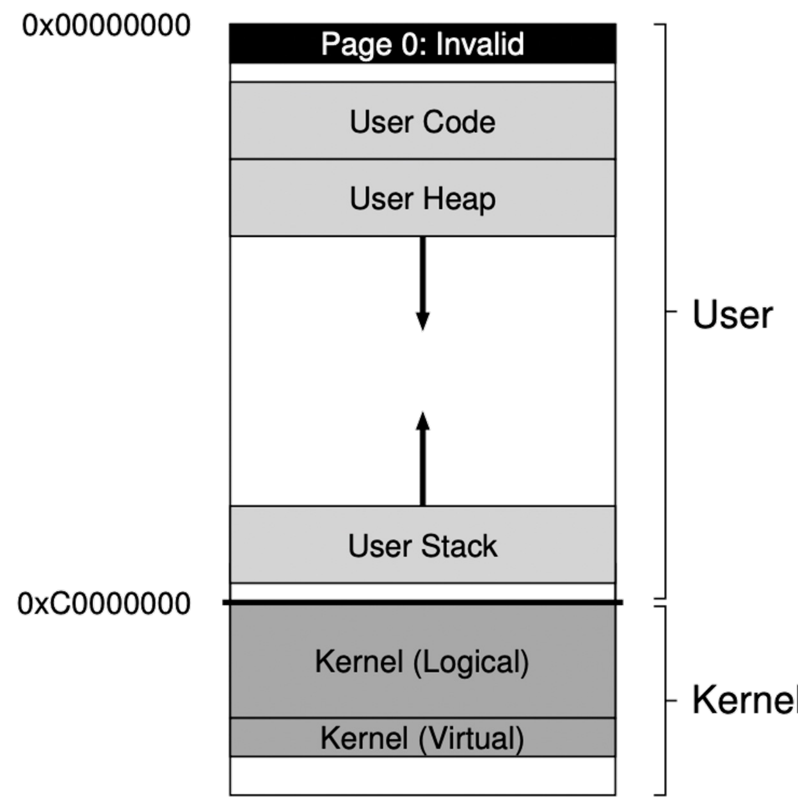
Address Space in Linux

- The virtual address space of each process is split between user and kernel portions
  - Virtual addresses 0 through 0xBFFFFFFF are user virtual addresses
    - Page 0 is invalid to detect NULL pointers
  - 0xC0000000 through 0xFFFFFFFF are in the kernel's virtual address space.
- 64-bit Linux has a similar split but at slightly different points.

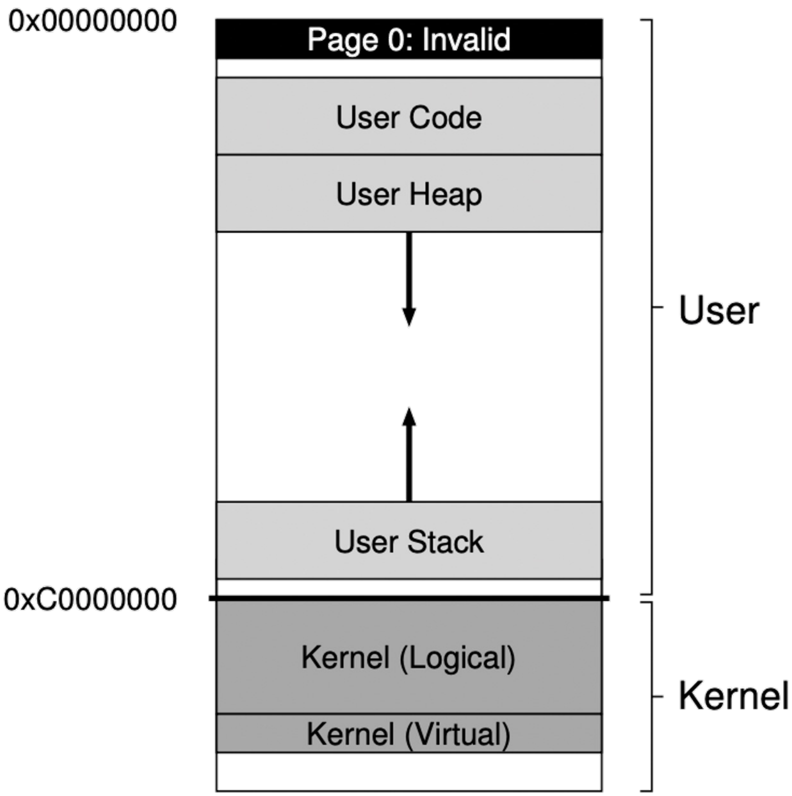


Address Space in Linux (Cont'd)

- Why is kernel memory mapped into the address space of each process?
  - No need to change page table (i.e., switch CR3) when trapped into the kernel – no TLB flush
    - system call, interrupts, exception
  - Kernel code may access user memory when needed
- The kernel memory in each address space is the same

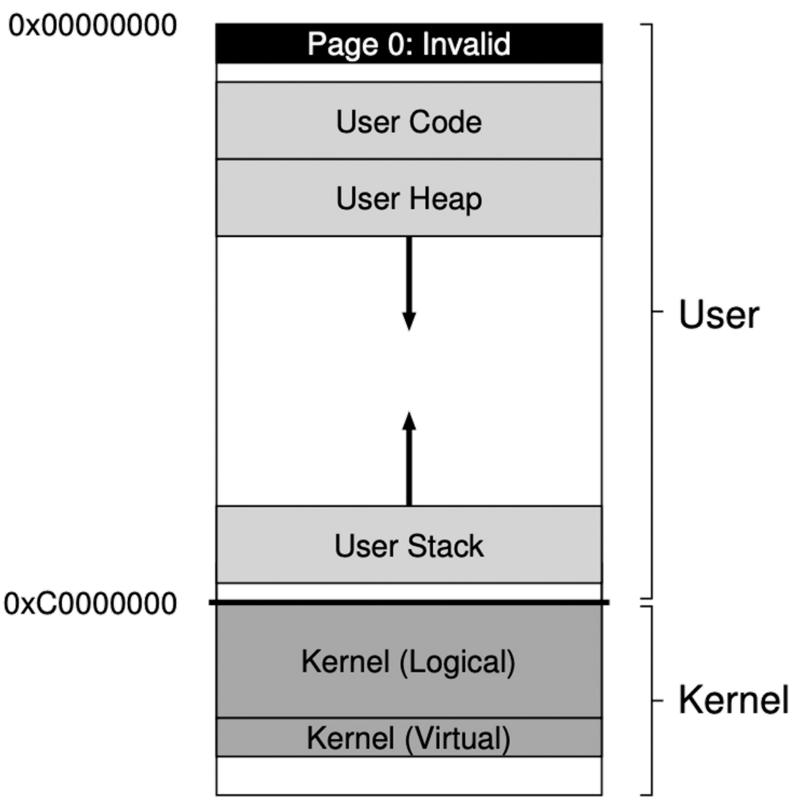


User Space and Kernel Space



- **Kernel logic addresses**
  - Most kernel data structures
    - page tables
    - per-process kernel stacks
    - kmalloc(), never swapped out
  - Starts with 0xc0000000, always map to continuous physical address starting from 0x00000000
  - Easy for DMA or other devices that requires continuous physical memory
- **Kernel virtual addresses**
  - Virtually continuous memory
  - vmalloc()

User Space and Kernel Space



- Isolation between processes
  - Not the same address space
- Isolation between user process and kernel?
  - How to protect kernel space from user process?
- Page table permission bits

63–54	53–28	27–19	18–10	9–8	7	6	5	4	3	2	1	0
Reserved	PPN[2]	PPN[1]	PPN[0]	RSW	D	A	G	U	X	W	R	V
10	26	9	9	2	1	1	1	1	1	1	1	1

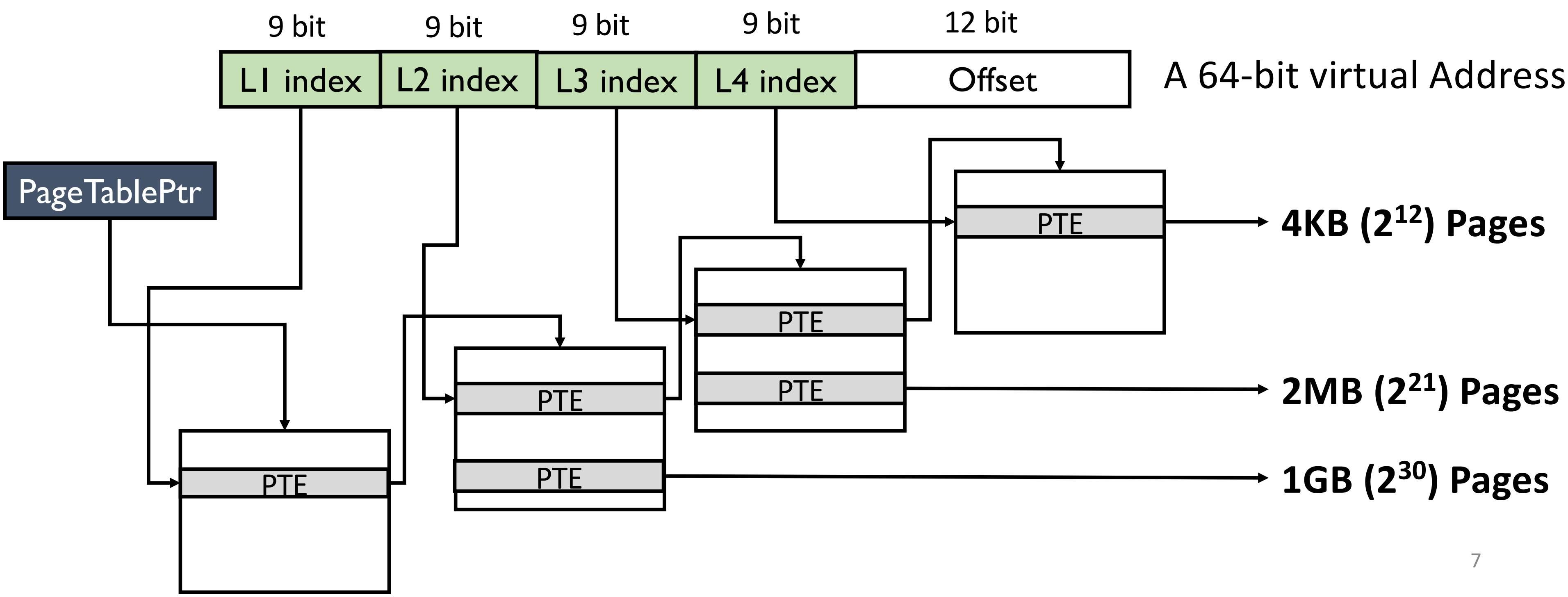
U = 1: User mode code may access this page

Large Page Support

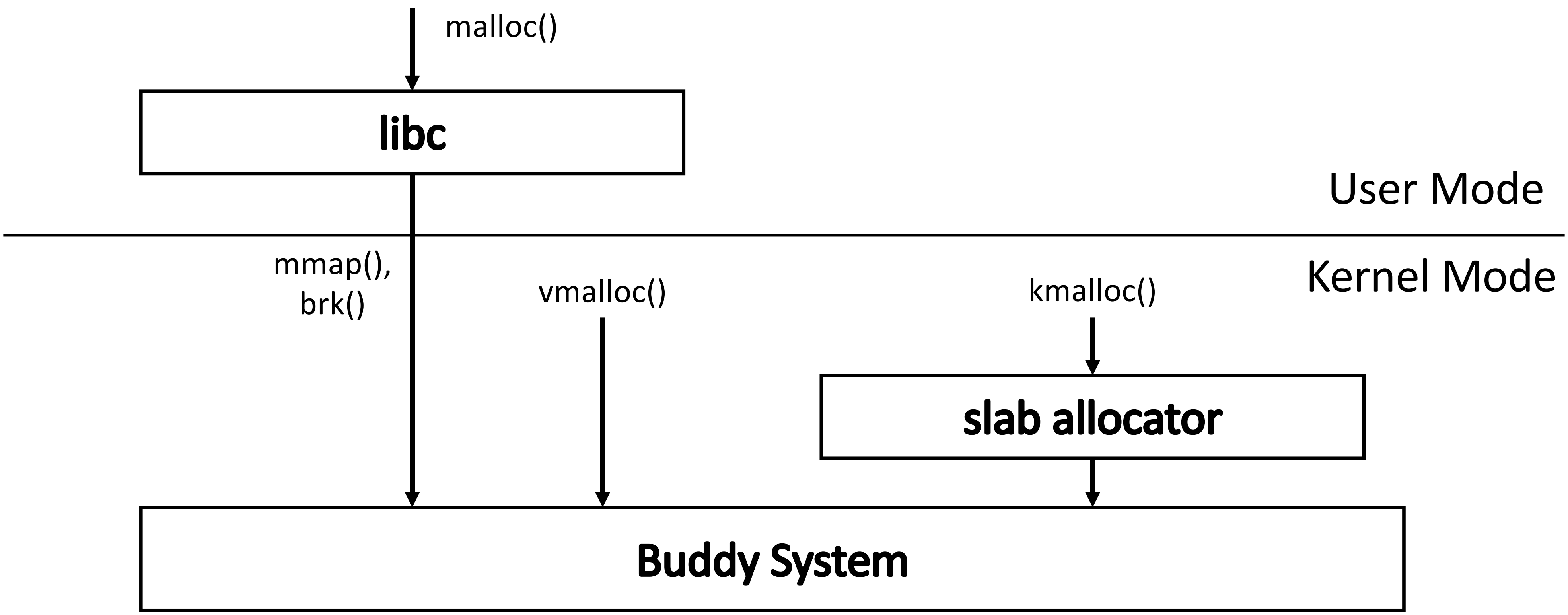
- x86 support 4KB, 2MB, 1GB pages
  - Hardware enforces page alignments
  - 4KB pages are 4KB aligned (lower 12 bits are 0)
  - 2MB pages are 2MB aligned (lower 21 bits are 0)
  - 1GB pages are 1GB aligned (lower 30 bits are 0)
- Linux also adds supports to *huge page* (Linux term)
  - Fewer TLB misses
  - Applications may need physically continuous physical memory
  - Leads to internal fragmentation

Large Page Support

- Different page size uses different level of page tables

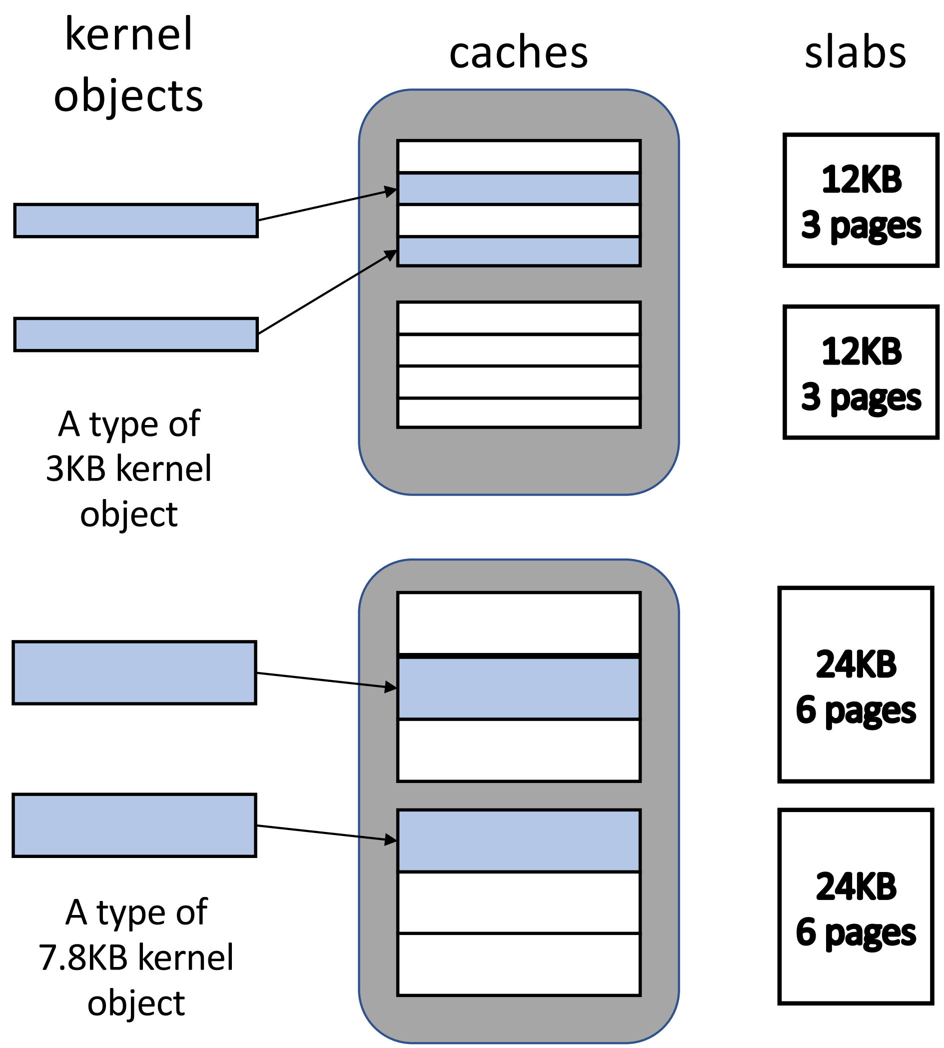


Linux Physical Memory Management



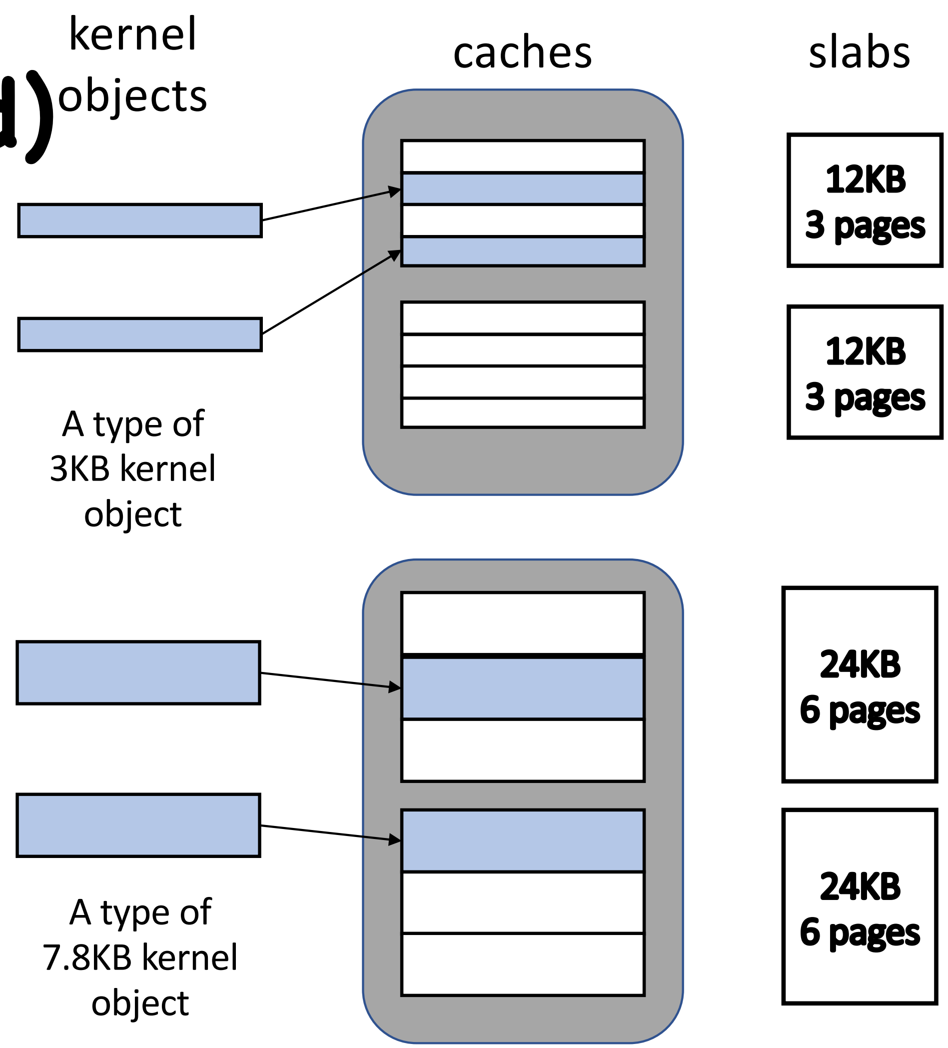
Slab Allocator

- A **slab** consists of one or more physically contiguous pages
- A **cache** consists of one or more slabs
  - One cache for each type of **kernel objects**



Slab Allocator (Cont'd)

- When a slab is allocated to a cache, objects are initialized and marked as free
- A **slab** can be in one of the following states:
  - empty: all objects are free
  - partial: some objects are free
  - full: all objects are used
- A request is first served by a partial slab, then empty slab, then a new slab can be allocated from **buddy system**

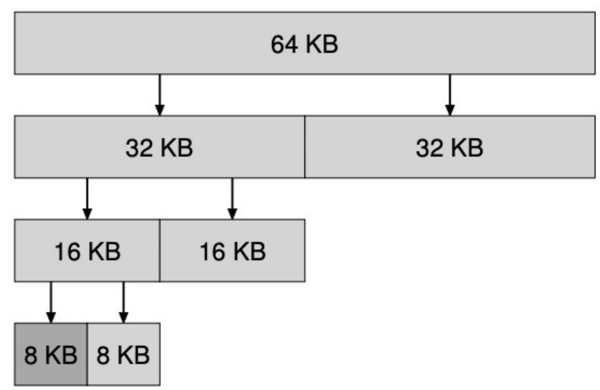


Slab Allocator (Cont'd)

- No memory is wasted due to fragmentation
  - when an object is requested, the slab allocator returns the exact amount of memory required to represent the object
  - Objects are packed tightly in the slab
- Memory requests can be satisfied quickly
  - Objects are created and initiated in advance
  - Freed object is marked as free and immediately available for subsequent requests
- Later Linux kernel also introduces Slub allocator and Slob allocators.

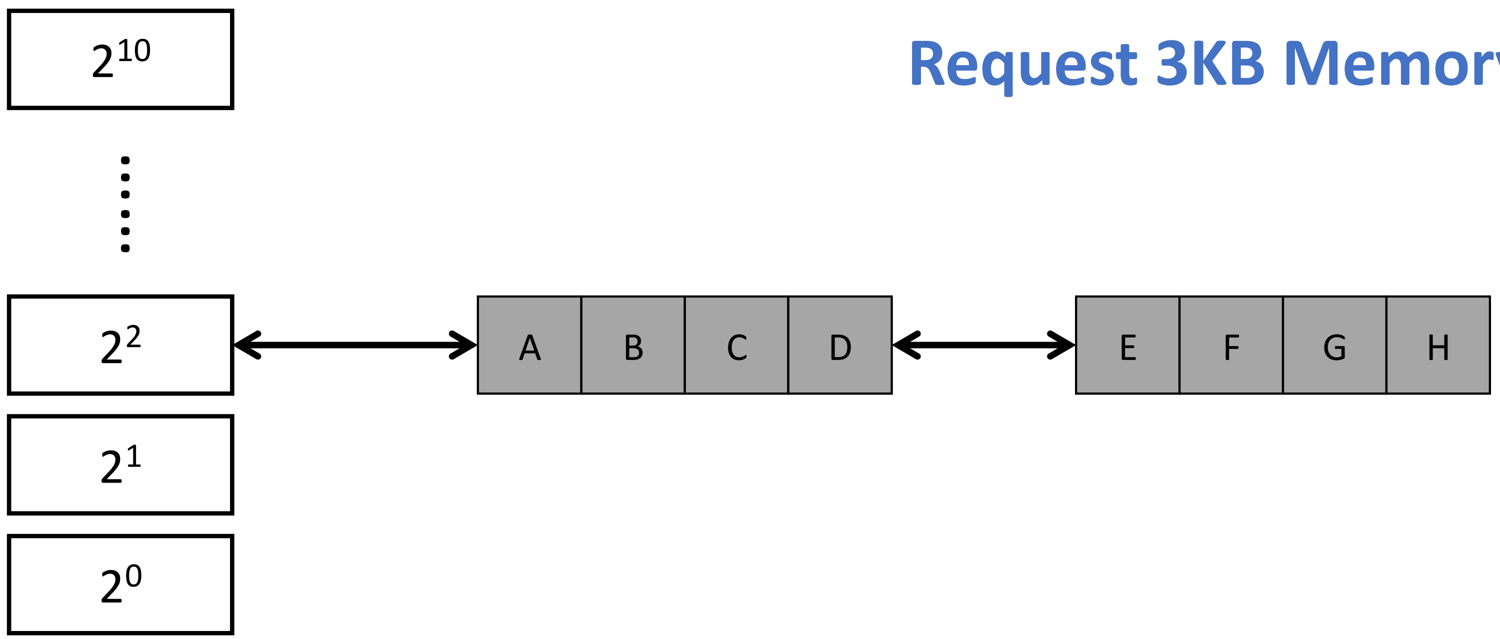
Buddy System

- Free physical memory is considered big space of size 2^N pages
- Allocation: the free space is divided by two until a block that is big enough to accommodate the request is found
  - a further split would result in a space that is too small
- Free: the freed block is recursively merged with its buddy
  - Two buddy blocks have physical addresses that differ only in 1 bit



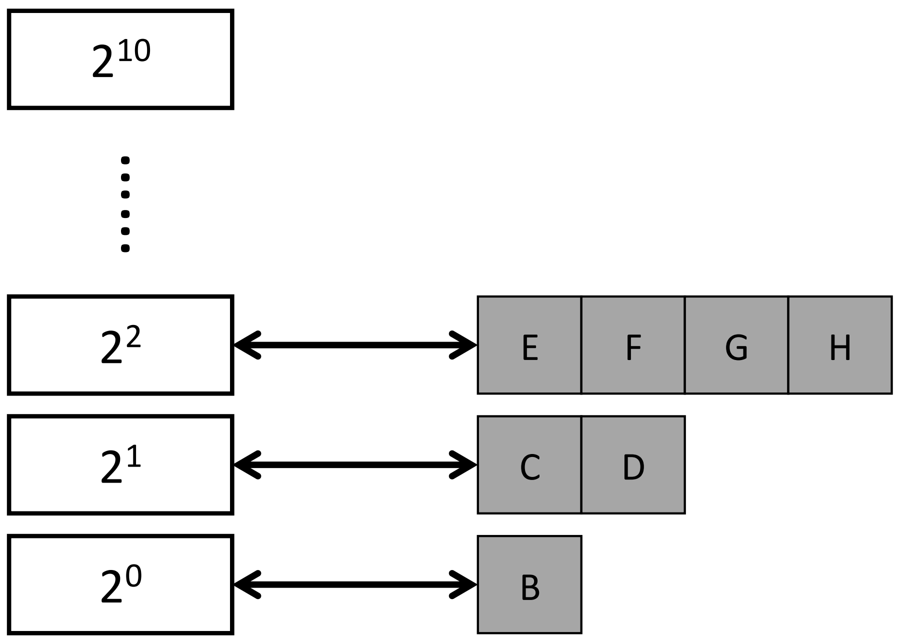
[K65] "A Fast Storage Allocator" by Kenneth C. Knowlton. Communications of the ACM, Volume 8:10, October 1965.

Buddy System Illustrated



Request 3KB Memory

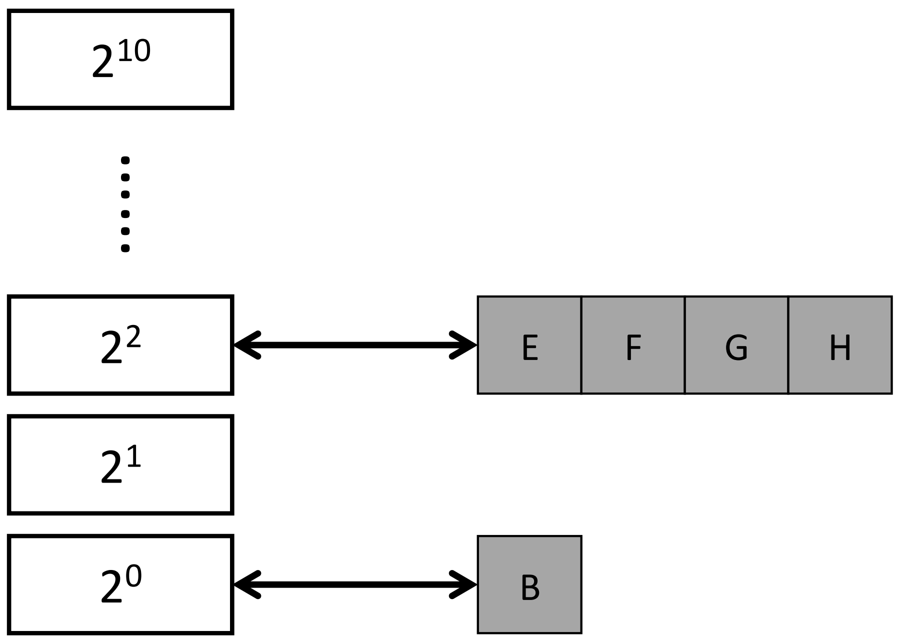
Buddy System Illustrated



Page A allocated

Request 5KB Memory

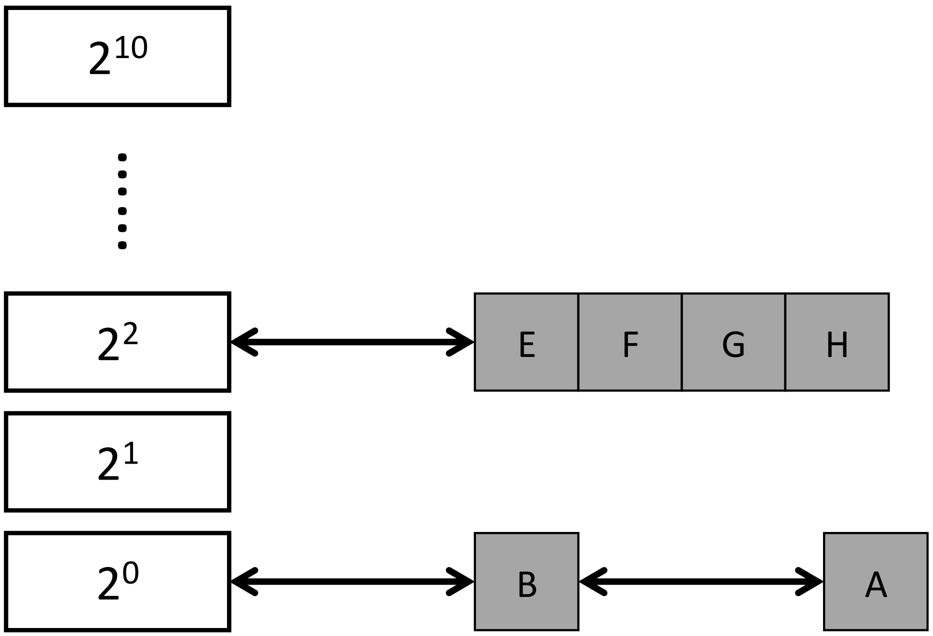
Buddy System Illustrated



Page C and D allocated

Page A freed

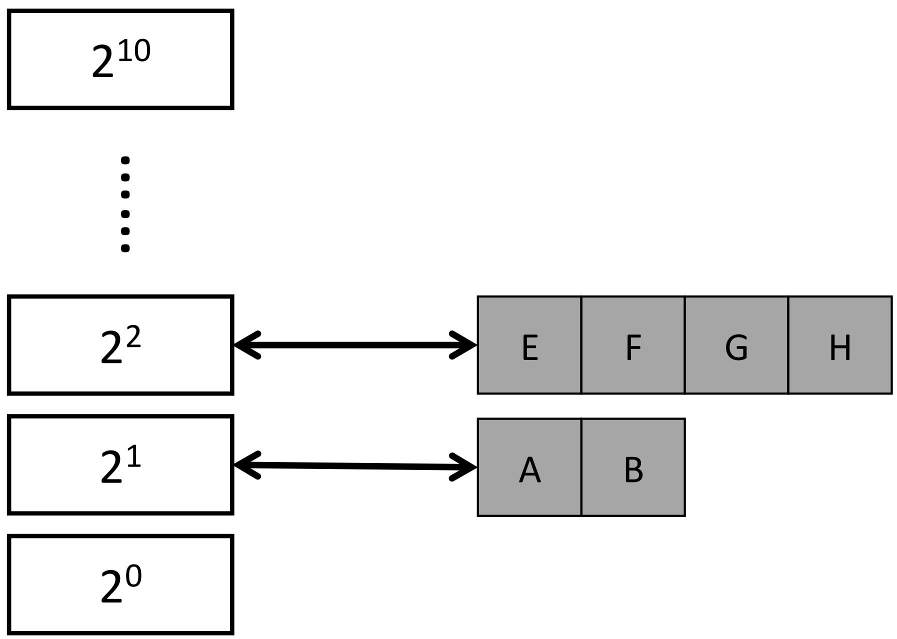
Buddy System Illustrated



Page A linked to 2^0

Check if Buddy is free

Buddy System Illustrated



Merge and move to 2^1

Thank you!