Lecture 9
Linux Memory Management

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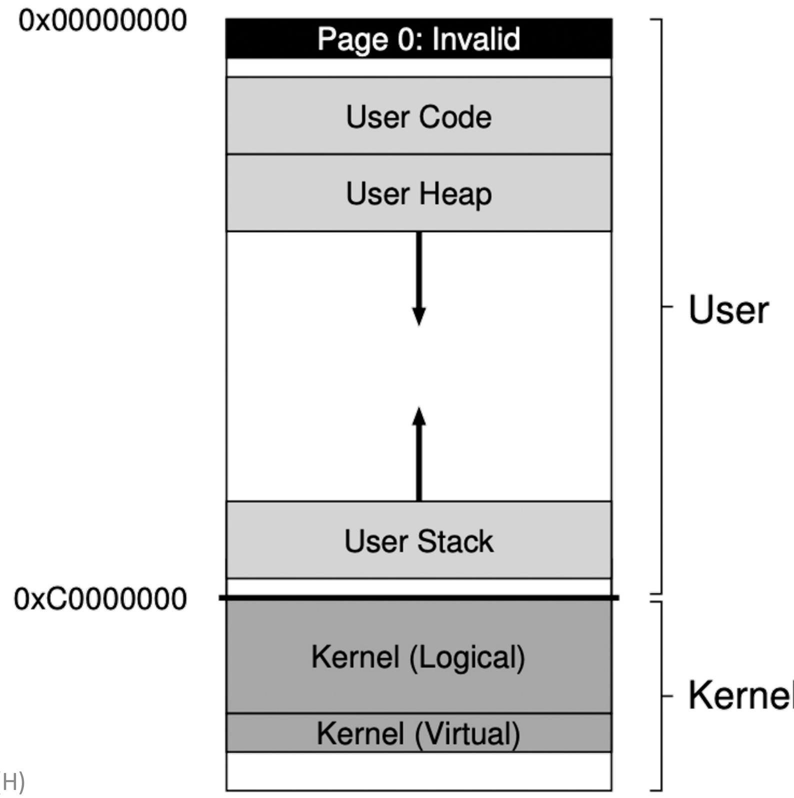
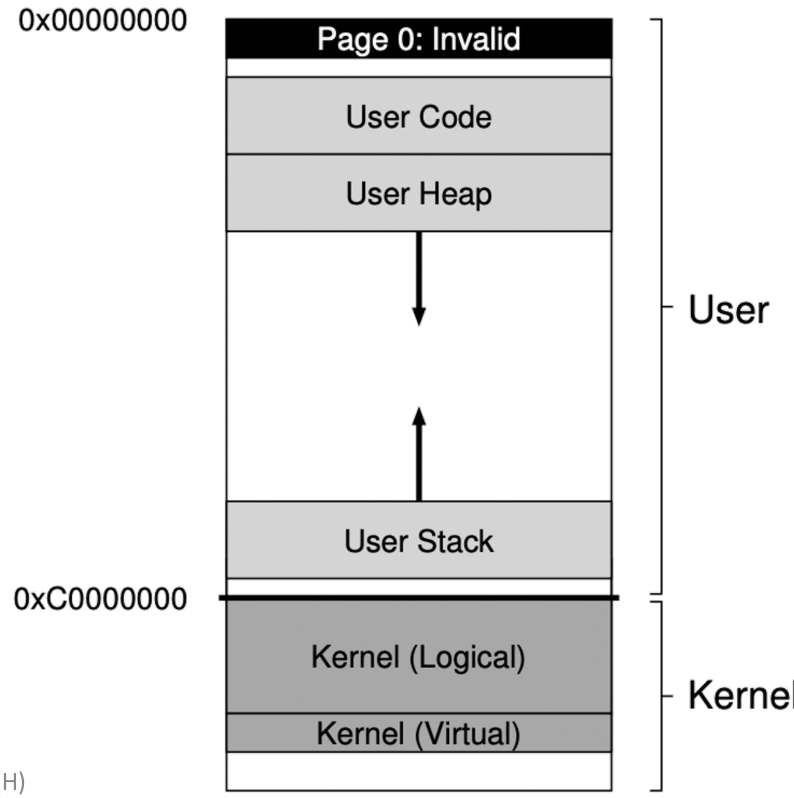
Address Space in Linux

- 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.

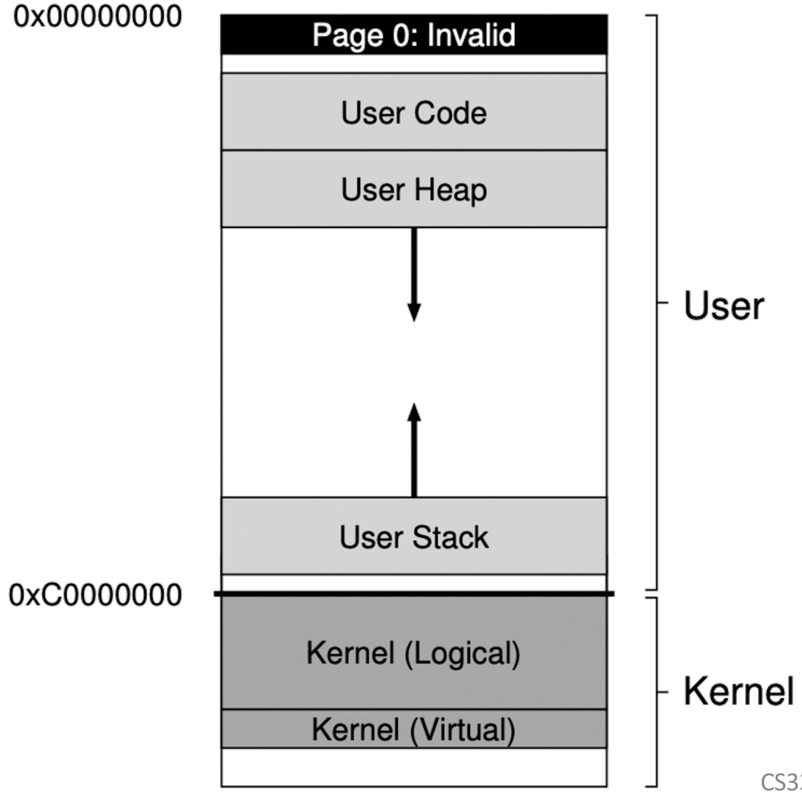


Address Space in Linux (Cont'd)

- 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

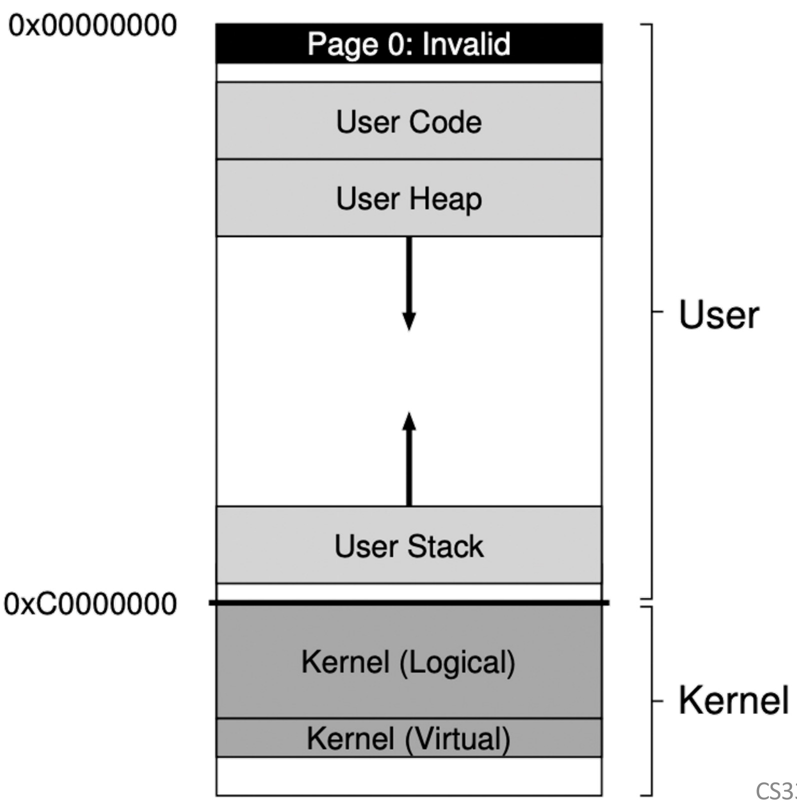


User Space and Kernel Space



- **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

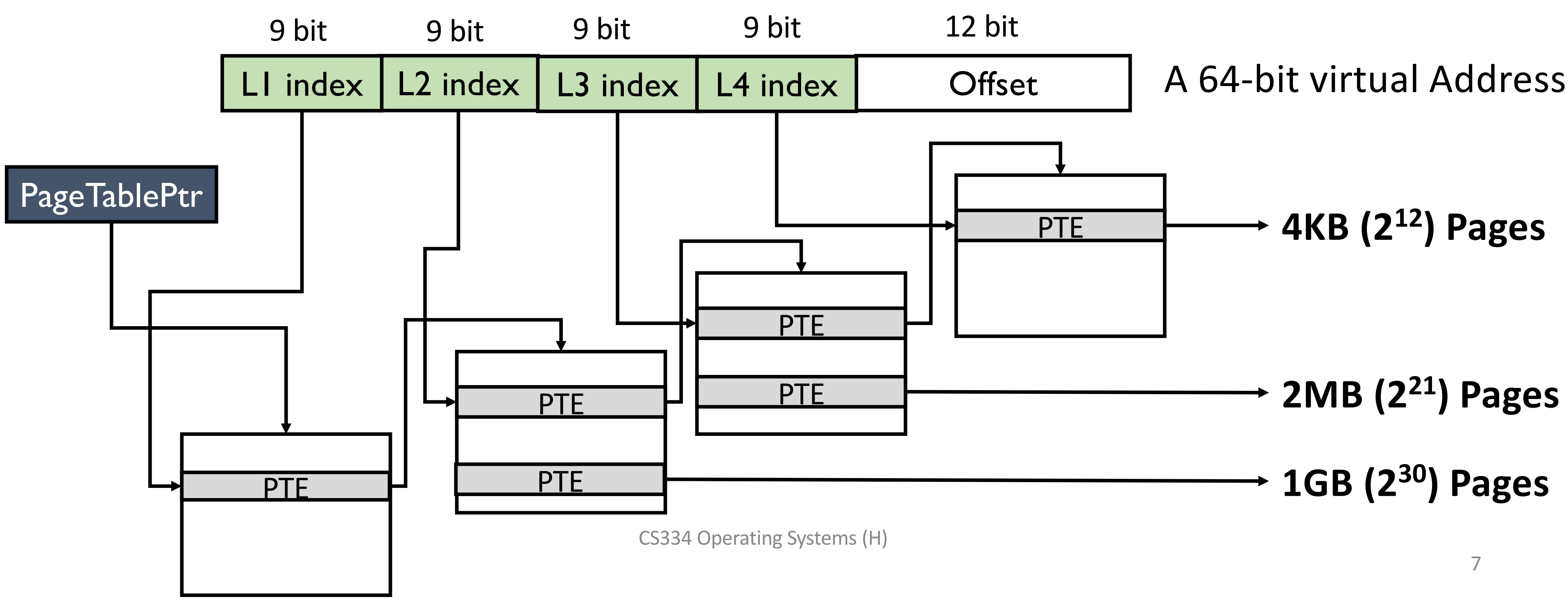
U = 1: User mode code may access this page

Large Page Support

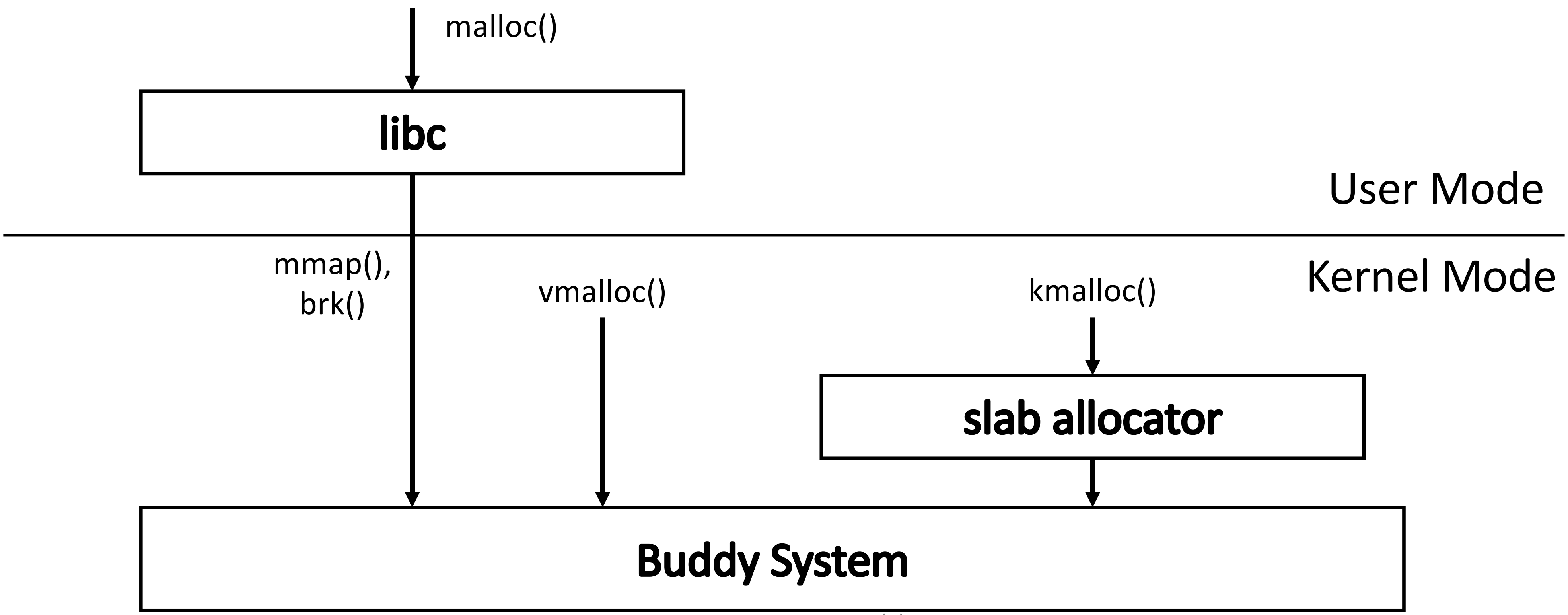
- x86 support 4KB, 2MB, 1GB pages
  - Hardware enforces page alignments
  - 4KB pages are 4KB aligned (lower 12 bits are 0)
  - 2MB pages are 2MB aligned (lower 21 bits are 0)
  - 1GB pages are 1GB aligned (lower 30 bits are 0)
- Linux also adds supports to *huge page* (Linux term)
  - Fewer TLB misses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

Large Page Support

- Different page size uses different level of page tables

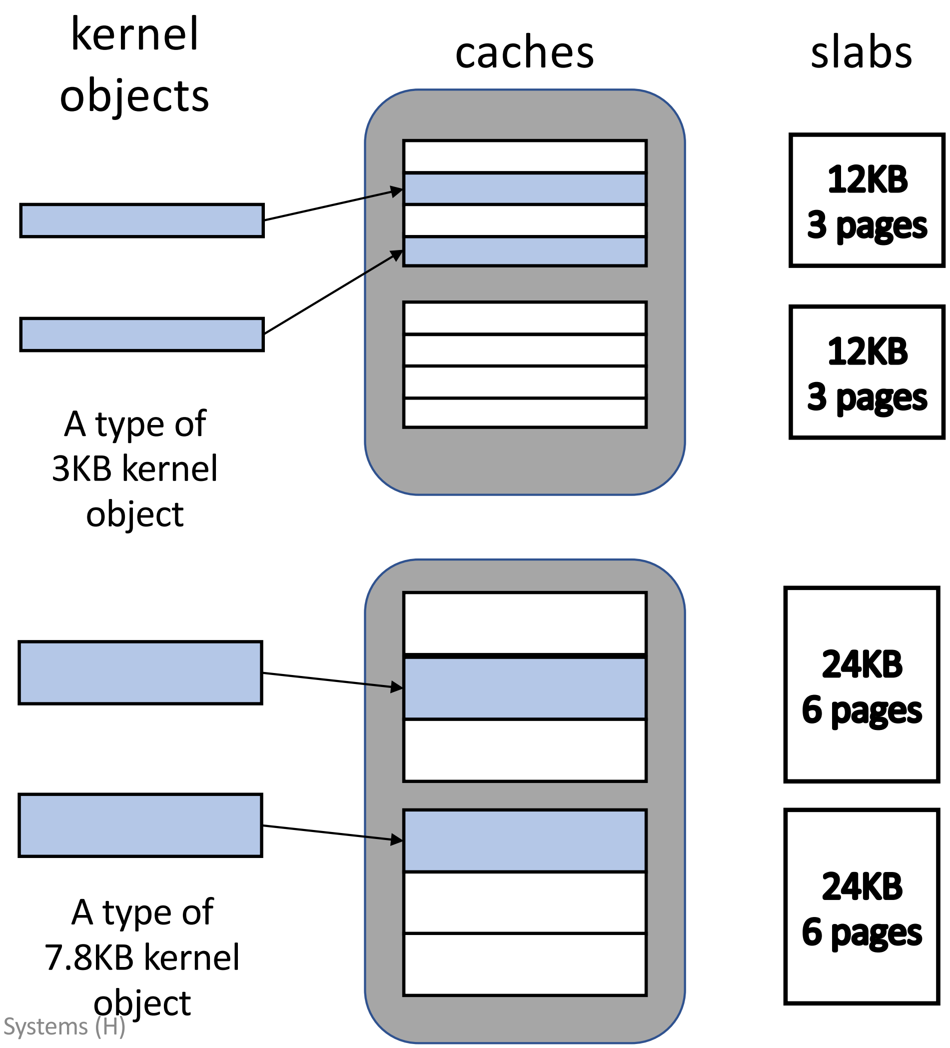


Linux Physical Memory Management



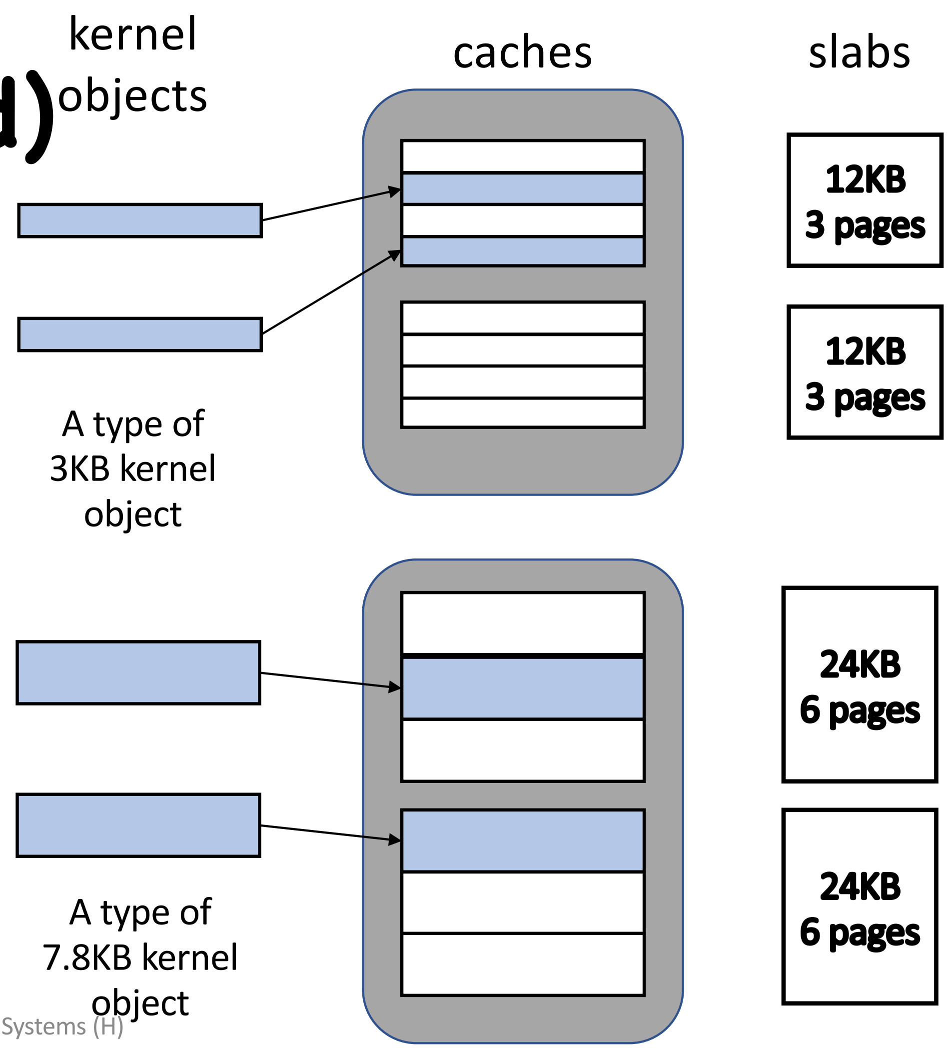
Slab Allocator

- 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**

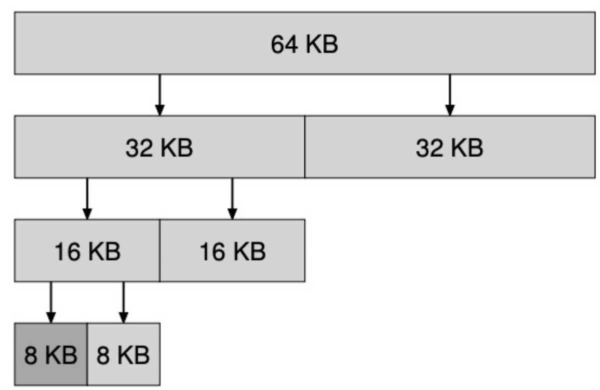


Slab Allocator (Cont'd)

- 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.

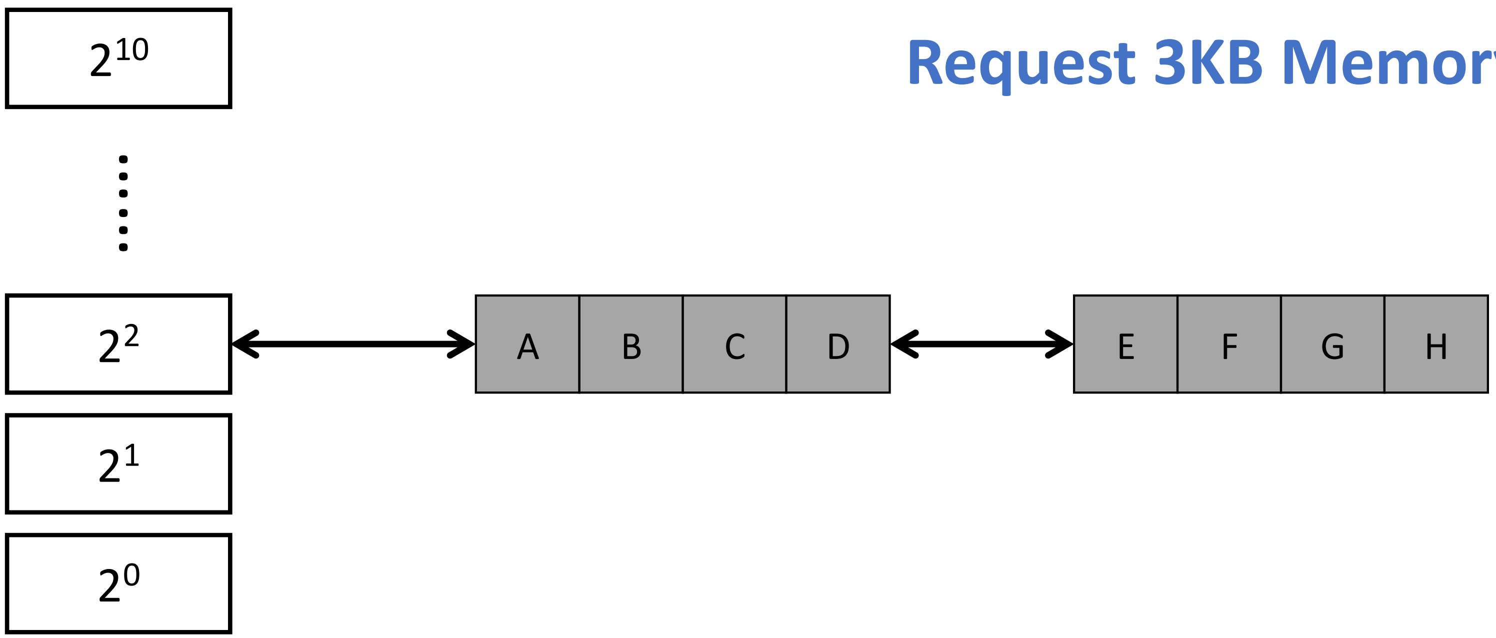
Buddy System

- 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



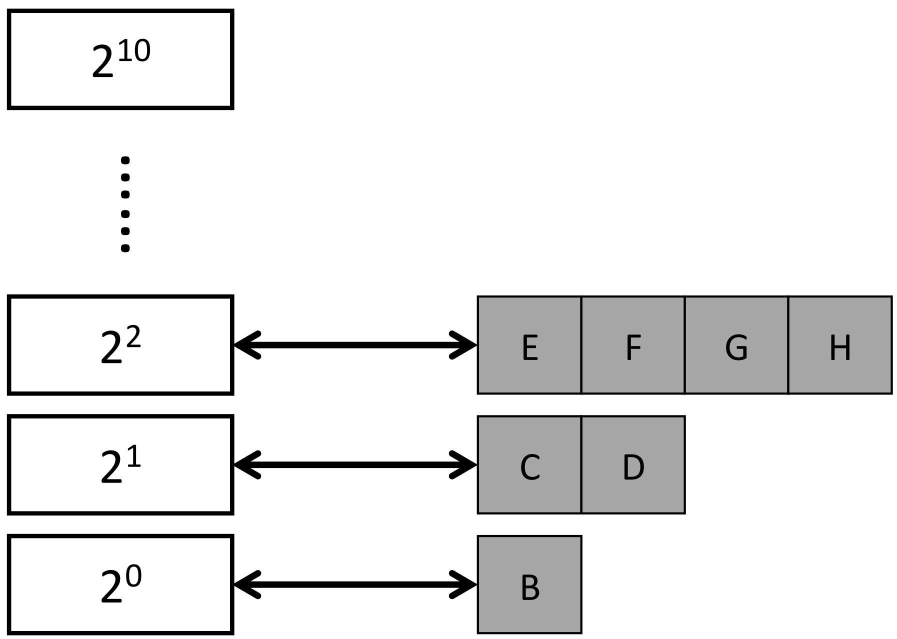
[K65] "A Fast Storage Allocator" by Kenneth C. Knowlton. Communications of the ACM, Volume 8:10, October 1965.

Buddy System Illustrated



Request 3KB Memory

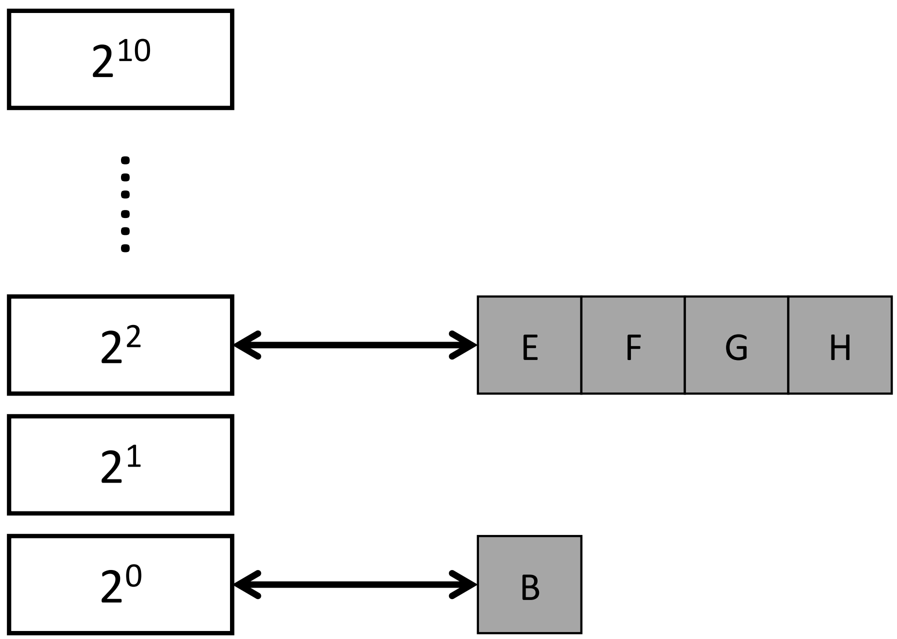
Buddy System Illustrated



Page A allocated

Request 5KB Memory

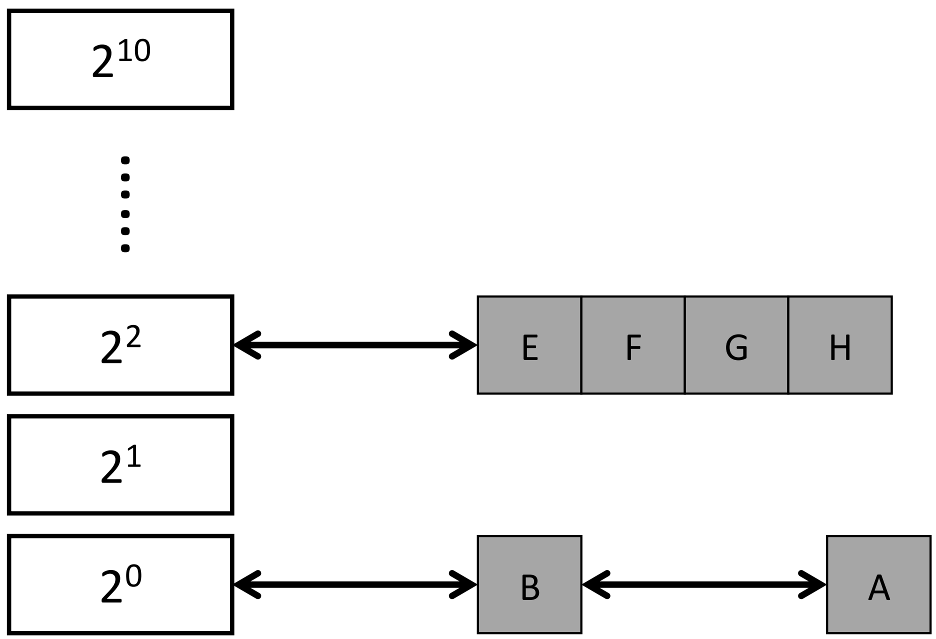
Buddy System Illustrated



Page C and D allocated

Page A freed

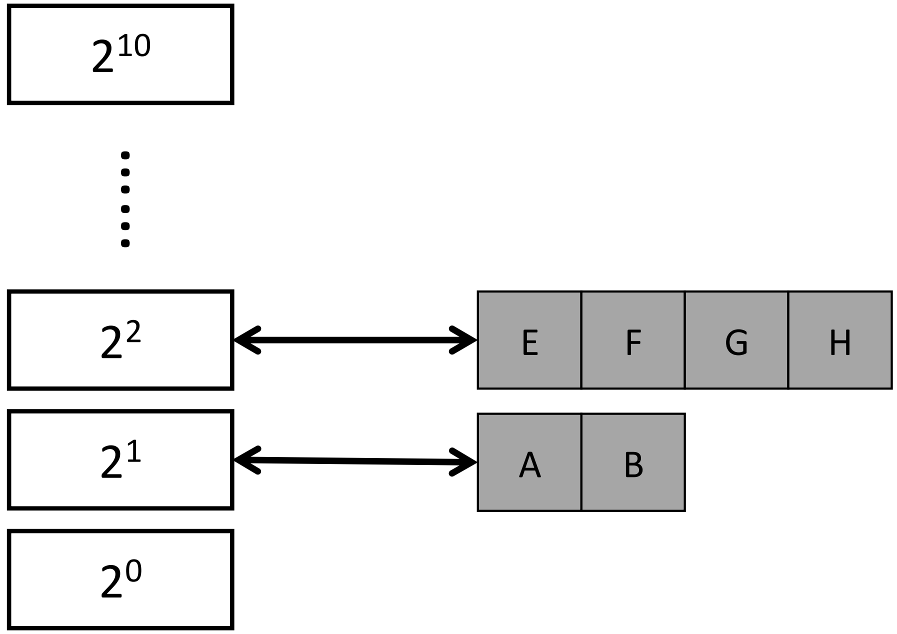
Buddy System Illustrated



Page A linked to 2^0

Check if Buddy is free

Buddy System Illustrated



Merge and move to 2^1

Page Cache

- Page cache: an area of physical memory to hold data that are stored on a hard disk or other permanent storage
  - memory-mapped files: all binaries and dynamic libraries
  - anonymous memory: stacks and heaps that are stored in swap space
- The page cache tracks if entries are clean or dirty
  - Dirty pages are periodically written back to disk (pdflush)

```
0000000000400000    372K r-x-- tcsh
00000000019d5000   1780K rw---   [anon ]
00007f4e7cf06000   1792K r-x-- libc-2.23.so
00007f4e7d2d0000     36K r-x-- libcrypt-2.23.so
00007f4e7d508000    148K r-x-- libtinfo.so.5.9
00007f4e7d731000    152K r-x-- ld-2.23.so
00007f4e7d932000     16K rw---   [stack ]
```

Page Cache (Cont'd)

- Page replacement policy for page cache
  - Use 2Q replacement
  - LRU may perform poorly in certain corner cases
    - e.g., when a large file is accessed sequentially, all other files will be evicted
- 2Q replacement policy
  - Two lists: inactive list and active list (LRU **queues**)
    - When accessed for the first time, a page is placed in inactive list
    - When it is re-referenced, the page is promoted to the active list
  - Replacement takes place in the inactive list
    - Linux periodically moves some page from the bottom of active list to inactive list, keeping active list 2/3 of the size of page cache
    - Clock algorithm used to approximate LRU

Data Execution Prevention (DEP)

- Buffer overflow is a well-known software vulnerability
  - Attacker provides input to an application (possibly from remote)
  - After a stack overflow, a function is returned to instructions on the stack (also provided by the attacker)
- DEP is a security feature that prevents data pages to be executed by software
  - A page is either writable or executable (NX bit in PTE)
  - Stacks are not executable

```
int some_function(char *input) {
  char dest_buffer[100];
  strcpy(dest_buffer, input); // oops, unbounded copy!
}
```

Address Space Layout Randomization

- Return-to-libc attacks and its successor - Return Oriented Programming (ROP) attacks
  - Stack overflow leads to returns to functions in libc or gadgets in libc
  - Gadgets are short code snippets that can be chained together
- Address space layout randomization (ASLR)
  - Randomize virtual address of stacks, heaps, and libraries so libc and stack/heap address are not known

```
int main(int argc, char *argv[]) {
    int stack = 0;
    printf("%p\n", &stack);
    return 0;
}
```

```
prompt> ./random
0x7ffd3e55d2b4
prompt> ./random
0x7ffe1033b8f4
prompt> ./random
0x7ffe45522e94
```

Thank you!