National Yang Ming Chiao Tung University
Computer Architecture & System Lab

# Memory Allocation

## IOC5226 Operating System Capstone

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# Acknowledgements and Disclaimer

- Slides were developed in the reference with
  - MIT 6.828 Operating system engineering class, 2018
  - MIT 6.004 Operating system, 2018
  - Remzi H. Arpaci-Dusseau etl. , Operating systems: Three easy pieces. WISC

# Outline

- Dynamic memory allocation
- Buddy memory allocator
- Slab memory allocator

# Dynamic memory allocation

- How does the OS manage memory of a single process ?
    - Each process has contiguous logical address space
- **Static (compile-time) allocation** is not always a good choice
    - Recursive procedures
        - Data dependencies are hard to predict
    - Complex data structures
        - Link-list, tree, graph (ptr = malloc(x); free(ptr))
- **Dynamic allocation**
    - Stack allocation
    - Heap allocation

# Stack organization

- Stack grows happens via
  - **mremap ()** : remap a virtual memory address
- When is it useful ?
  - Memory allocation and freeing are partially predictable
  - Examples
    - Procedure call frames, tree traversal, recursion
- Advantages
  - Keeps all the free space contiguous
  - Simple and efficient to implement
- Disadvantages
  - Not appropriate for all data structures

alloc(A)
alloc(B)
alloc(C)
free(C)
free(B)
free(A)

# Heap organization


- Allocate from random locations
    - Memory contains **allocated** areas and **free** areas
- When is it useful ?
    - Allocation and release are unpredictable
    - Arbitrary list structures, complex data organizations
        - E.g. new in C++, malloc() in C
- Advantage: works on arbitrary allocation and free patterns
- Disadvantage: End up with small chunks of free space

# Stack vs heap allocation

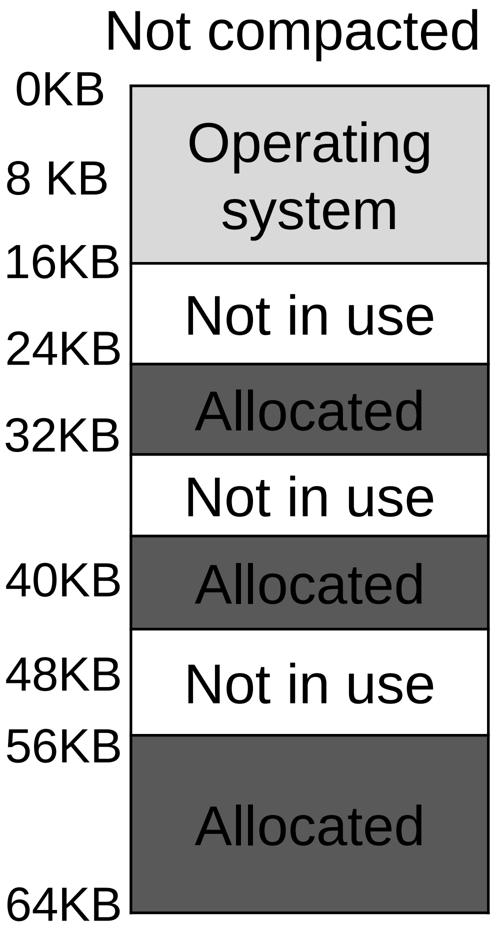
| Parameter | Stack | Heap |
| --- | --- | --- |
| Basic | Allocated in a contiguous block | Allocated in a random order |
| Allocation | Automatic by compiler | Manual by programmer |
| Main issue | Storage of memory | Memory fragmentation |
| Safety | Thread safe, data only accessed by owner | Not thread-safe, data stored visible to all threads |
| Flexibility | Fixed-size | Resizing is possible |
| Access time | Fast | Slow |

# Fragmentation

- **Internal fragmentation**
  - Waste space when you round an allocation up
- **External fragmentation**
  - When you end up with small chunks of free memory that are too small to be useful

# External fragmentation

- **External fragmentation**
  - Full of little holes of free space
  - Have a number of segments per process
  - Each segment might be a different size
  - It is difficult to allocate new segments
- **Compact physical memory**
  - Rearranging the existing segments
  - Compaction is expansive
  - Best-fit, worst-fit, first-fit, buddy algorithm



# External fragmentation (cont.)

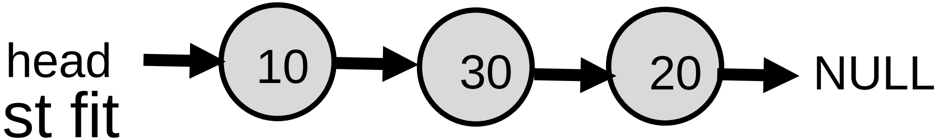
- **When does external fragmentation occur ?**
  - The free space consists of variable-sized units
  - This arises in a user-level memory allocation library (malloc())
  - Chops segments into little pieces of different sizes
- **Problems of the external fragmentation**
  - No single contiguous space that can satisfy the request
  - Even the total amount of free space exceeds the size of requests
  - E.g. A request 15 bytes will fail even though there are 20 bytes free

# Memory allocation strategies

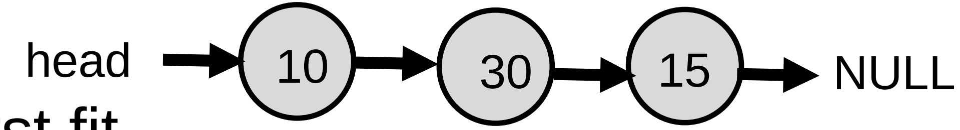
- **Best fit**
  - Return a block that is close to what the user asks
  - Try to reduce wasted space
  - Perform an exhaustive search for the correct free block penalty
- **First fit**
  - Find the first block that is big enough and returns the requested amount to the user
  - Has the advantage of speed – no exhaustive search
  - How the allocator manages the free list’s order becomes an issue ?

# Case study: memory block fitting

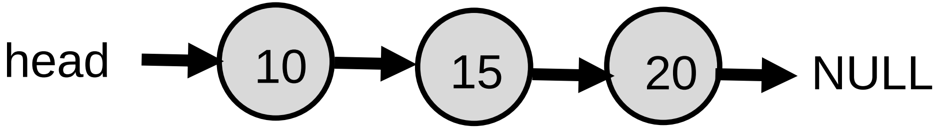
- Envision a free list with three elements on it
    - Assume an allocation request of size 15




- Best fit
    - Search the entire list and find that 20 was the best fit




- First fit
    - Find the first free block that can satisfy the request



# Designing memory allocator issues

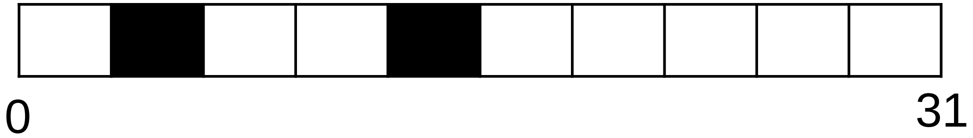
- How to keep track of the size of a block ?
- How to keep track of which blocks are in use and free ?
- How to align memory space if a block is smaller than the free block we find ?
- How to pick a block to use for allocation ?
- How do re-insert freed block ?

# Buddy allocator

- Fast, simple allocation for blocks that are $2^n$ bytes
- Allocation restrictions
  - Block sizes: $2^n$
- Allocation strategy for k bytes
  - Raise allocation request to the nearest $2^n$
  - Search free list for appropriate size
    - Recursively divide large blocks until reach block of correct size
  - Free strategy
    - Recursively coalesce block with buddy if buddy free
    - May coalesce lazily to avoid overhead

# Buddy allocator issues

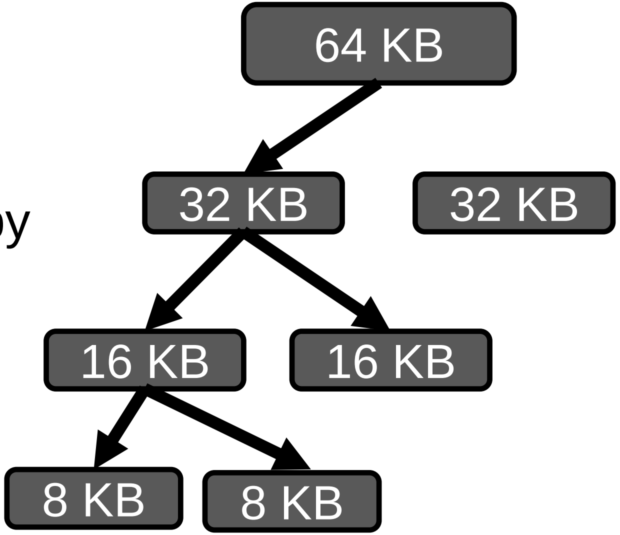
- **Memory fragmentation**
  - Buddy allocator still leads to few reserved pages that prevent the allocation of larger contiguous blocks
- **Performance**
  - Very fast, since the simple binary shift or bit change arithmetic




Memory layout of the buddy allocator

# Buddy allocation

- **Binary buddy allocator**
  - Free memory as one big space of size $2^N$
  - Recursive search by dividing free space by two until a block that is big enough to accommodate the request is found
  - **Internal fragmentation** as only allowed to power-of-two-sized block
  - Check whether the “buddy” 8KB is free when returning the 8KB block to the free list
  - Keep coalescing when the buddy is still free
  - Making coalescing simple



# Case study: buddy allocation

## Memory blocks

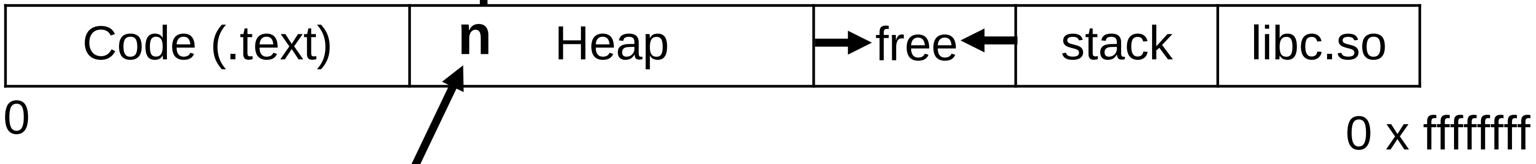
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |

- In a memory
  - Block 0, 4, 5, 6, 7 is used
  - Will buddy allocator merges block 1 and 2 if both of them are free ?
    - No !! Block 1 and 2 are not buddy

```
static inline unsigned long _find_buddy_pfn
                              (unsigned long page_pfn, unsigned int order)
{
        return page_pfn ^ (1 << order);
}
```

# How to allocate memory ?

## Virtual address space




```
int main () {
        struct foo *x = malloc(sizeof(struct foo));
        ….
}
```

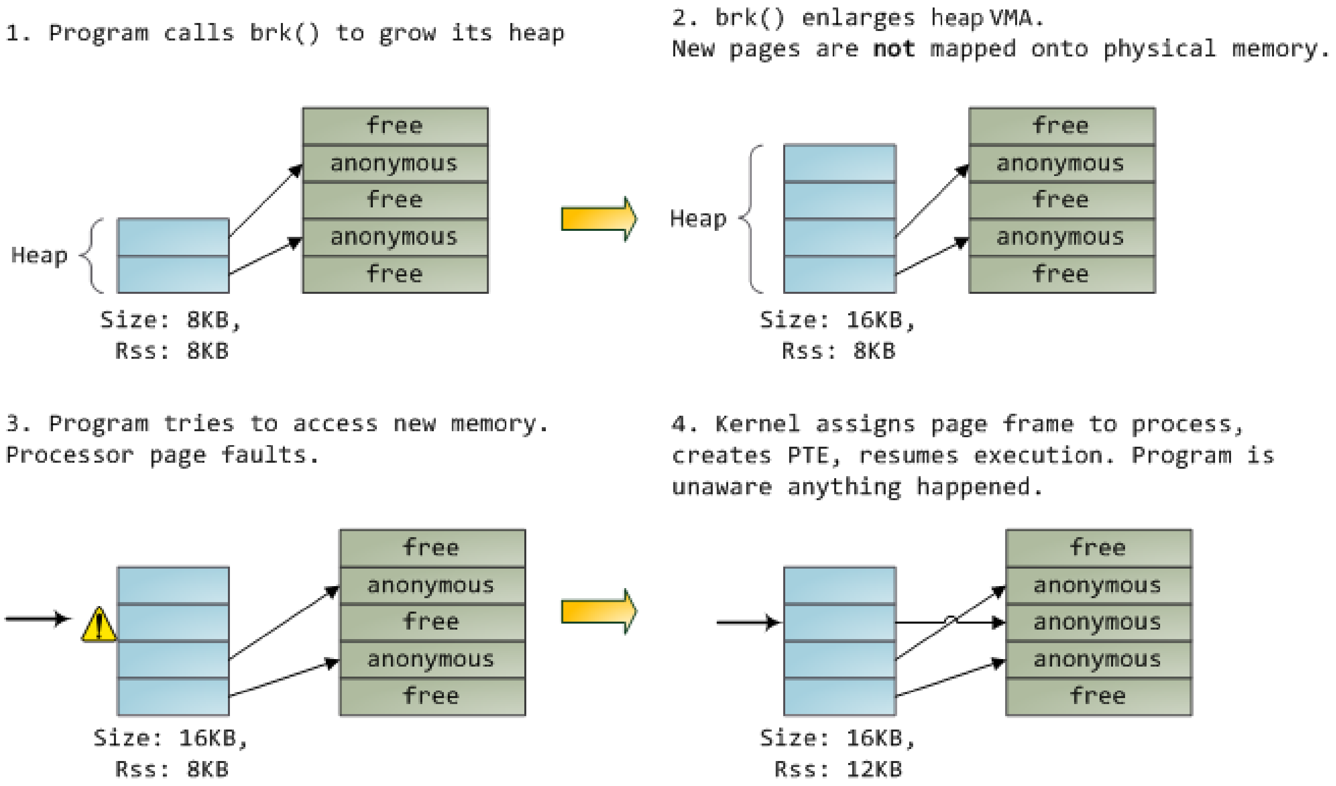
```
void* malloc (ssize_t n) {
        if(heap empty)
                mmap(); // add pages to heap and find a free block of size n
}
```

# malloc() issues

- How to implement malloc() or new ?
  - Calls **sbrk()** to request more contiguous memory from OS
  - Add small header to each block of memory
    - Pointer to next free block

https://pages.cs.wisc.edu/~eli/537/lectures/lecture12.2x2.pdf

# Enlarge VMA




*Source: http://duartes.org/gustavo/blog/post/how-the-kernel-manages-your-memory/*

https://pages.cs.wisc.edu/~eli/537/lectures/lecture12.2x2.pdf

# Reclaiming free memory

- When can dynamically-allocated memory be freed ?
  - Explicitly call free()
  - Hard, can't be recycled until all sharers are finished
    - Sharing is indicated by the presence of pointers to the data
- Two possible problems
  - **Dangling pointers**
    - Recycle storage while it's still being used
  - **Memory leaks**
    - Forget to free storage even when can't be used again
    - Not a problem for short-lived user processes
    - Issue for operating systems and long-running applications

# Garbage collection

- **Idea**
  - No free() operation
  - Storage freed implicitly when no longer referenced
- **Approach**
  - When system needs storage, examine and collect free memory
- **Advantages**
  - Makes life easier on the application programmer

https://pages.cs.wisc.edu/~eli/537/lectures/lecture12.2x2.pdf

# Mark and sweep

- Requirements
  - Must be able to find all objects
  - Must be able to find all pointers to objects
  - Compiler must cooperate by marking type of data in memory
- **Two passes**
  - **Pass 1: Mark**
    - Start with all statically-allocated and procedure-local variables (on stack)
    - Mark each object
    - Recursively mark all objects can reach with a pointer
  - **Pass 2: Sweep**
    - Go through all objects, free those that aren’t marked

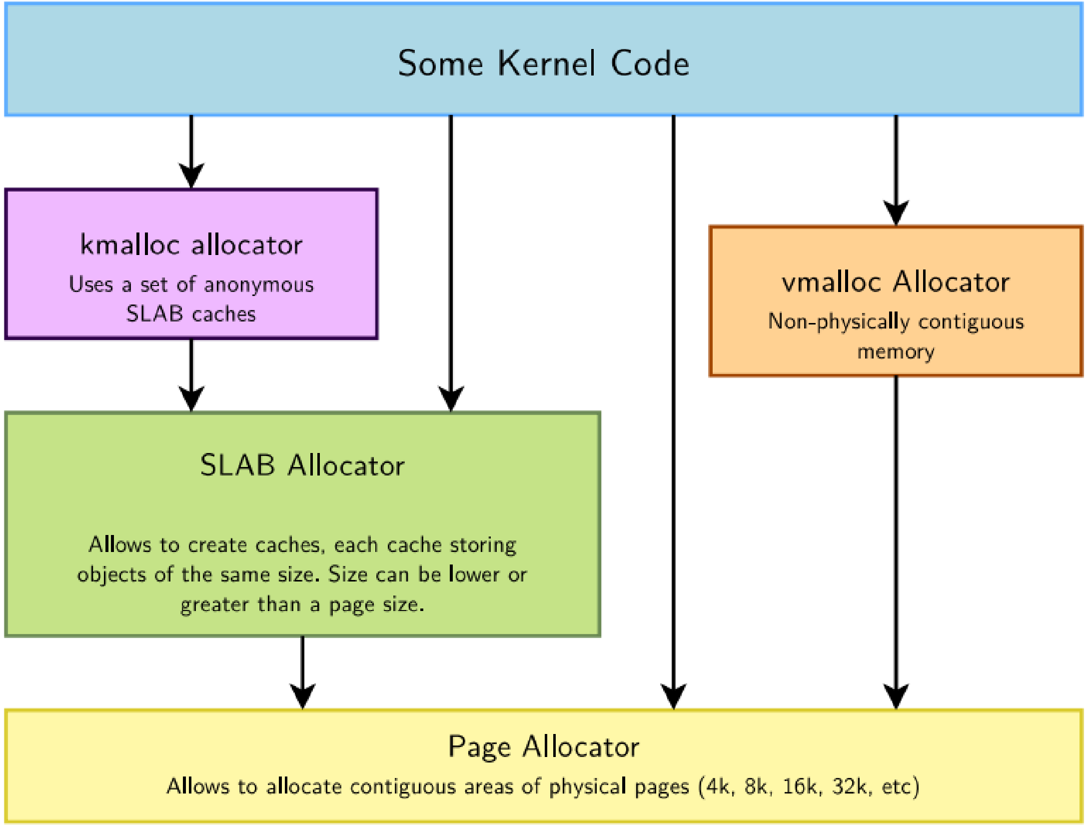
https://pages.cs.wisc.edu/~eli/537/lectures/lecture12.2x2.pdf

# Garbage collection in practice

- **Disadvantages**
  - **Expansive**: 20% or more of CPU
  - **Difficult to implement**
    - Execute program during garbage collection (incremental)
- Languages with garbage collection
  - LISP
  - Java

https://bootlin.com/doc/training/linux-kernel/linux-kernel-slides.pdf

# Linux kernel allocators



# Page allocator

- Appropriate for medium-size allocations
- A page is usually **4KB** that is dependent to the hardware
- **Buddy allocator strategy**
  - Only allocations of power of two numbers of pages such as 1, 2, 4, 8, 16 pages, etc.
  - Typical maximum size is 8192 KB
  - The allocated area is contiguous in the kernel virtual address space
  - Maps to physically contiguous pages
  - The large areas may not be available due to physical memory fragmentation

# Motivation of the slab allocator

- **The kernel needs**
  - Many different **temporary objects**
  - Such as the mm_struct, inode, files_struct structures
- **Temporary kernel objects**
  - Very small and very large size
  - They are often allocated and freed
  - Require to perform object allocation efficiently
- **Drawbacks of the buddy allocator**
  - Its free areas are composed of entire frames of memory (too large for various object size)
  - Align objects with power of two size has a negative impact on the use of the process cache

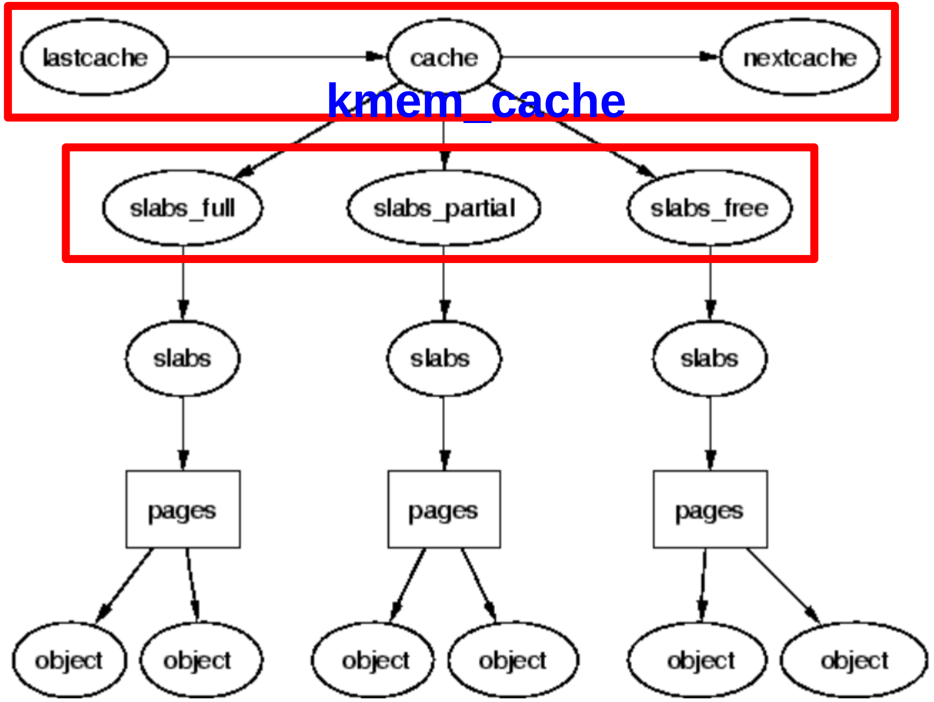
# Principle of the slab allocator

- The allocation of **small memory blocks**
  - Eliminate internal fragmentation caused by a binary buddy allocator
  - Two caches of small memory buffers (32 – 131072 bytes)
  - kmalloc() is provided for allocate objects in these small cache buffers
- The **caching** of commonly used objects
  - The system doesn’t waste time allocating, initializing and destroying objects
- **The better utilization of hardware cache**
  - aligning objects to the L1 or L2 caches

# What is slab ?

**Cache chain**

**Slab state**




https://www.kernel.org/doc/gorman/html/understand/understand011.html

- **Slab**
  - a chunk of contiguous pages
  - A container of objects
  - Allocates a number of objects to the slabs associated with that cache
- **Cache chain**
  - A variable number of caches linked on a doubly linked circular list
  - Kmem_cache_s manages objects such as mm_struct or fs_cache

# What is slab ? (cont.)

- The slab allocator manages the objects in a cache
  - A slab contains one or more pages, divided into equal-sized objects
  - When cached created, allocate a slab, divided the slab into free objects
  - If a slab is full of used objects, next object comes from an empty/new slab
- **Benefits**
  - No fragmentation and fast memory allocation
  - Some of the object fields may be reusable; no need to initialize again

# Alternative slab allocators

- **SLOB allocator**
  - Designed for small systems
  - As compact as possible
- **SLAB allocator**
  - As cache friendly as possible
- **SLUB allocator**
  - Designed for large systems
  - Minimize memory overhead
  - Execution time friendly

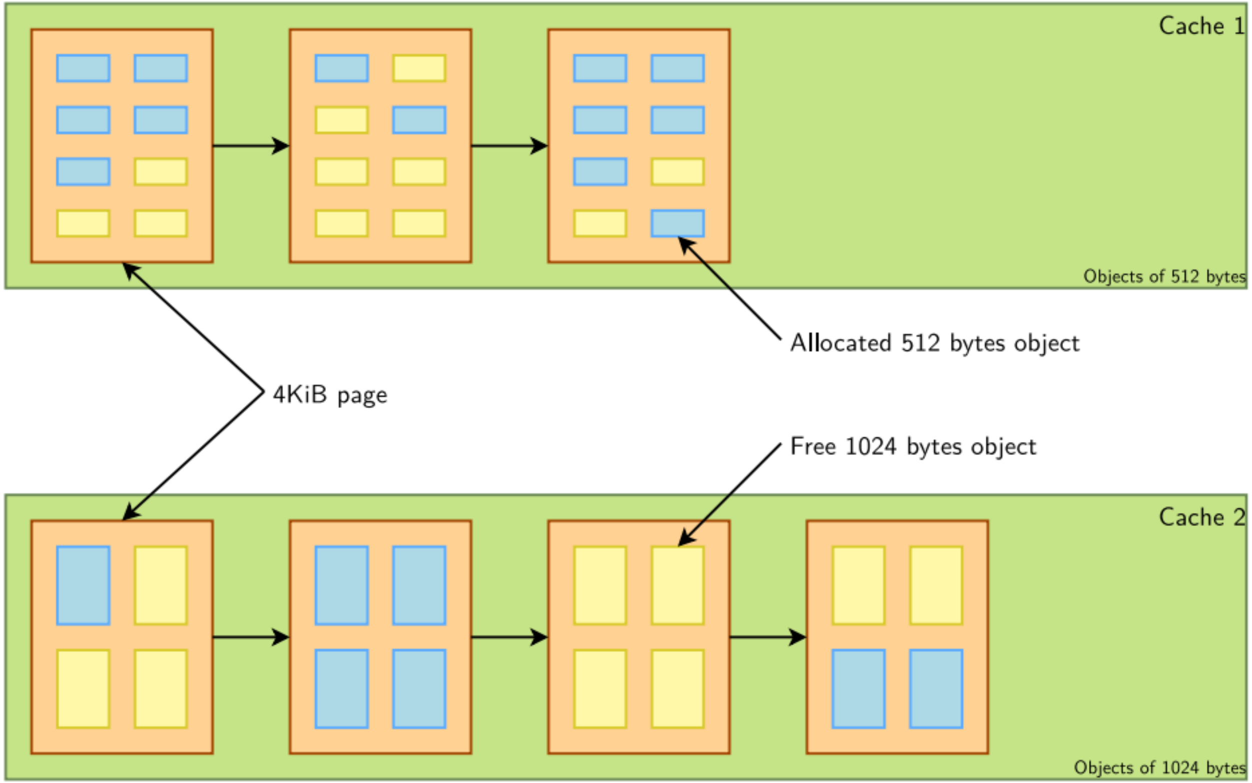
# The slab allocator

- **The slab allocator**
  - The default cache allocator (at least as of early Linux kernel 2.6, Solaris)
  - A given cache allocates a specific type of object
    - E.g. a cache for file descriptors, a cache for inodes
  - **Motivation**
    - The kernel often **spends much of its time on allocating, initializing and freeing the same object**
    - Reduce the number of references to the buddy allocator
  - **Basic idea**
    - Have **caches** of commonly used objects kept in an initialized state for use by the kernel

# The slab allocator (cont.)

- The SLAB allocator
  - Allow to **create caches**, which contain a set of objects of the same size
  - The object size can be smaller or greater than the page size
  - Takes care of growing or reducing the size of cache as needed
  - Uses the page allocator to allocate and free pages
  - SLAB caches are used for data structures that are present in kernel instances
    - Directory entries, file objects, network packet descriptors etc..
    - See /proc/slabinfo

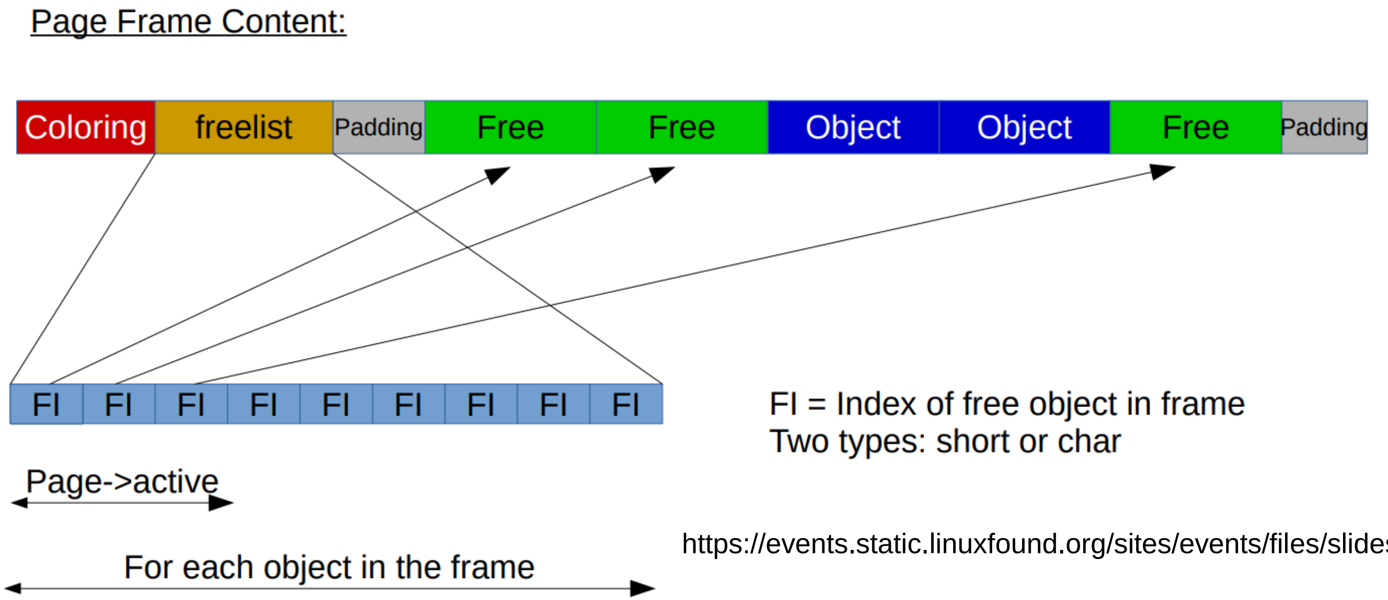
# The slab allocator(cont.)




https://bootlin.com/doc/training/linux-kernel/linux-kernel-slides.pdf

# SLAB per frame freelist management

- Multiple requests for free objects can be satisfied from the same cache line without touching the object contents

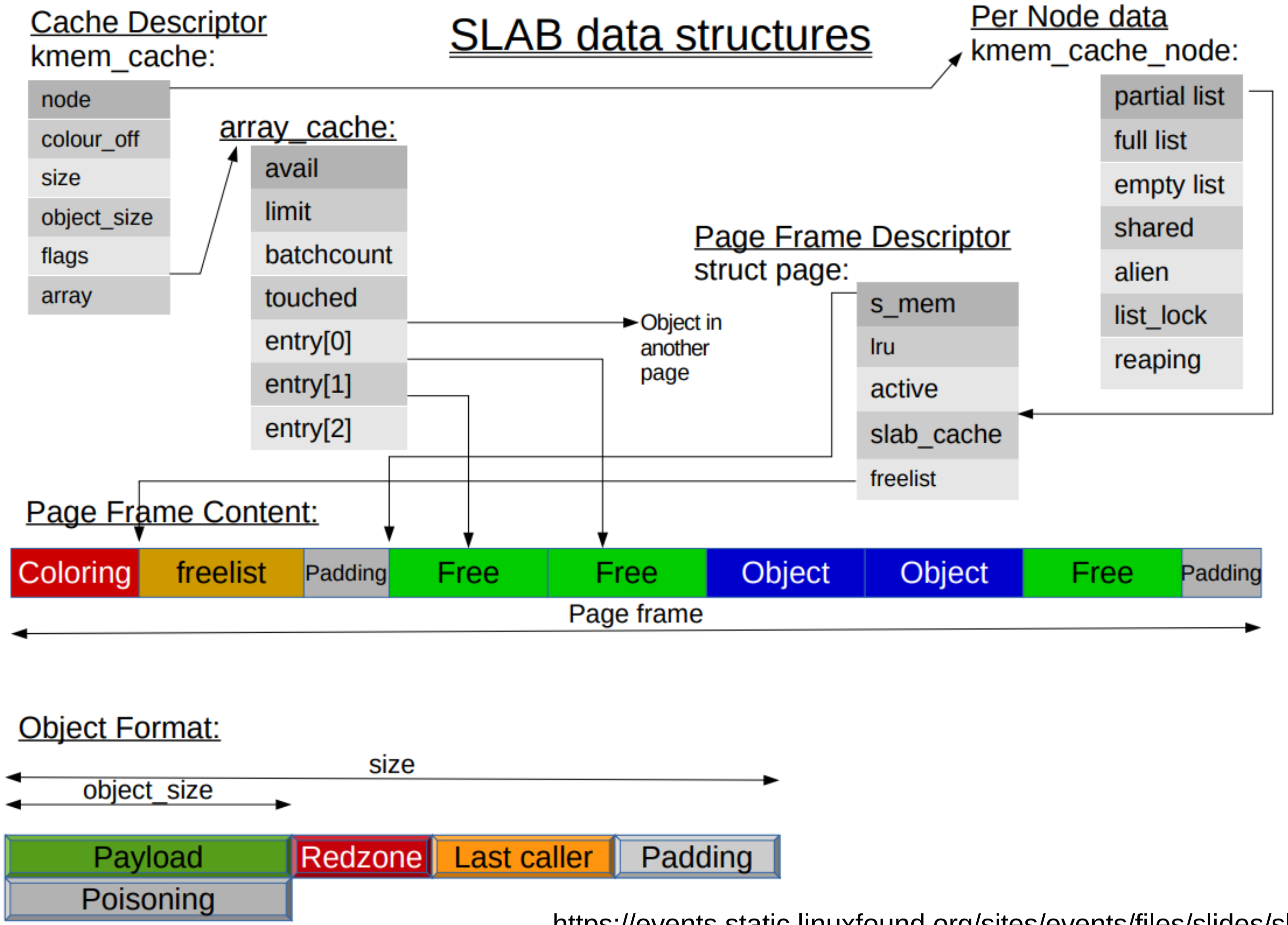



https://events.static.linuxfound.org/sites/events/files/slides/slaballocators.pdf

# SLAB allocator – data structure

- **Red zone**
  - Used to detect writes after the object
- **Poisoning**
  - If the object is inactive then the bytes contain **poison** values
- **Padding**
  - An unused data to fill up the space to get the next object properly aligned
- **Coloring**
  - A scheme that attempts to have objects in different slabs use different lines in the cache
  - Objects use different cache lines ensure objects from the same slab cache will be unlikely to flush each other

# SLAB data structures




https://events.static.linuxfound.org/sites/events/files/slides/slaballocators.pdf

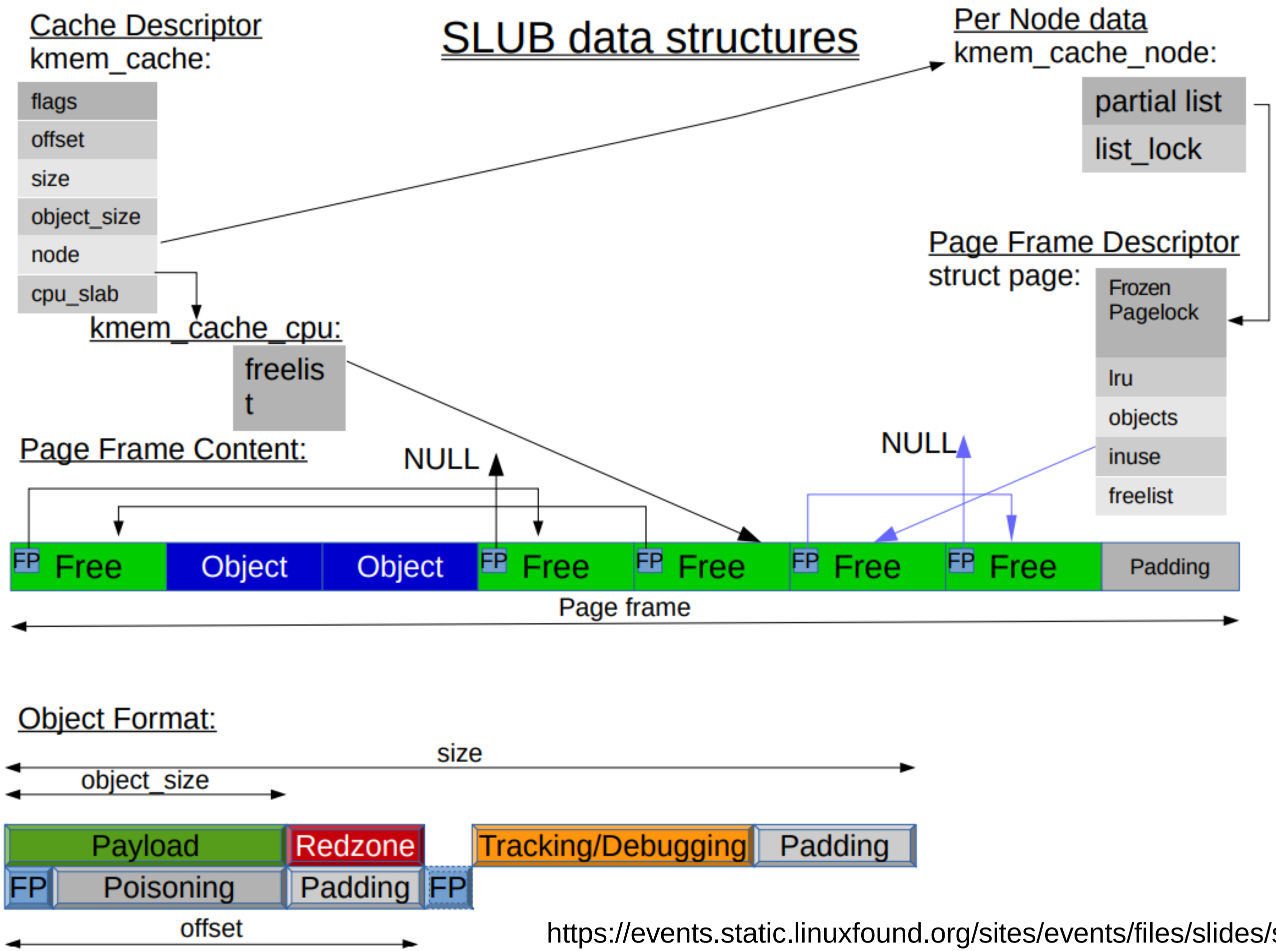
# SLOB allocator

- **Small systems**
  - The bookkeeping overheads become critical on tiny memory system such as embedded systems
- **Simple list of blocks (SLOB)**
  - Just keep a free list of each available chunk and its size
  - Currently uses a first-fit algorithm
  - Grab the first one big enough to work
  - Split block if leftover bytes
  - No internal fragmentation
  - External fragmentation? Yes. Trade for low overheads

# SLUB allocator

- **Large system**
  - The number of SLAB queues can make allocation fast but add complexity and storage overhead in large systems
- **The unqueue slab allocator (SLUB)**
  - All objects of same size from same slab
  - **Simple free list per slab – no per-slab metadata**
  - Add new fields in struct page to guide the search of free objects
    - void *freelist; // points to the first free object within a slab
    - short unsigned int inuse; // the number of objects allocated from the slab
    - short unsigned int offset; // tells the allocator where to find the pointer to the next free object

# SLUB data structures




https://events.static.linuxfound.org/sites/events/files/slides/slaballocators.pdf

# kmalloc allocator

- **kmalloc()**
  - Allocate memory for the kernel from general purpose caches
  - For small sizes, it relies on generic SLAB caches (see /proc/slabinfo)
  - For large sizes, it relies on the page allocator
  - The allocated area is guaranteed to be physical contiguous
  - The allocated area size is rounded up to the size of the smallest SLAB cache in which it can fit

# kmalloc API

- #include <linux/slab.h>
- void ***kmaloc**(size_t size, int flags);
  - Allocate size bytes and return a pointer to the area (virtual address)
  - Size: number of bytes to allocate
  - Flags: same flags as the page allocator (GFP_KERNEL, GFP_ATOMIC, GFP_DMA, etc. )
- void **kfree**(const void *objp);
  - Free an allocated area

```
struct ib_port_attr *tprops;
tprops = kmalloc(sizeof *tprops,
GFP_KERNEL);
…
kfree(tprops);
```

drivers/infiniband/core/cache.c

# vmalloc allocator

- The **vmalloc()** allocator
  - Used to obtain memory zones that are **contiguous in the virtual addressing space**, but not made out of physically contiguous pages
  - The allocated area is in the kernel space part of the address space
  - Allocations of fairly large areas is possible
  - Physical memory fragmentation is not an issue
  - Areas **cannot be used for DMA**, since DMA usually requires physically contiguous buffers
  - API in **include/linux/vmalloc.h**
  - void *vmalloc(unsigned long size); // return a virtual address

# Conclusion

- Dynamic memory allocation
  - Fit for arbitrary complex data structure
- Buddy memory allocation
  - Simple, fast for power of two blocks
  - Fragmentation
- Slab memory allocator
  - Caching the commonly used objects