The Art and Science of Memory Allocation

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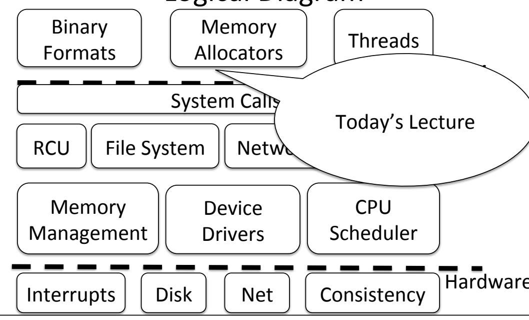
Logical Diagram



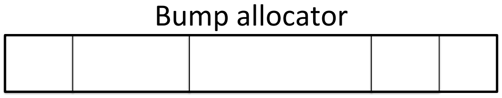
Lecture goal

- Understand how memory allocators work
  - In both kernel and applications
- Understand trade-offs and current best practices

Today's Lecture

- How to implement **`malloc`**() or **`new`**
  - Note that **`new`** is essentially malloc + constructor
  - **`malloc`**() is part of libc, and executes in the application
- **`malloc()`** gets pages of memory from the OS via **`mmap()`** and then sub-divides them for the application
- The next lecture will talk about how the kernel manages physical pages
  - For internal use, or to allocate to applications

Bump allocator



- malloc (6)
- malloc (12)
- malloc(20)
- malloc (5)

Bump allocator

- Simply "bumps" up the free pointer
- How does free() work? It doesn't
  - Well, you could try to recycle cells if you wanted, but complicated bookkeeping
- Controversial observation: This is ideal for simple programs
  - You only care about free() if you need the memory for something else

Assume memory is limited

- Hoard: best-of-breed concurrent allocator
  - User applications
  - Seminal paper
- We'll also talk about how Linux allocates its own memory

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Overarching issues

- Fragmentation
- Allocation and free latency
  - Synchronization/Concurrency
- Implementation complexity
- Cache behavior
  - Alignment (cache and word)
  - Coloring

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Fragmentation

- Undergrad review: What is it? Why does it happen?
- What is
  - Internal fragmentation?
    - Wasted 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
- Which kind does our bump allocator have?

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Hoard: Superblocks

- At a high level, allocator operates on superblocks
  - Chunk of (virtually) contiguous pages
  - All objects in a superblock are the same size
- A given superblock is treated as an array of same-sized objects
  - They generalize to "powers of b > 1";
  - In usual practice, b == 2

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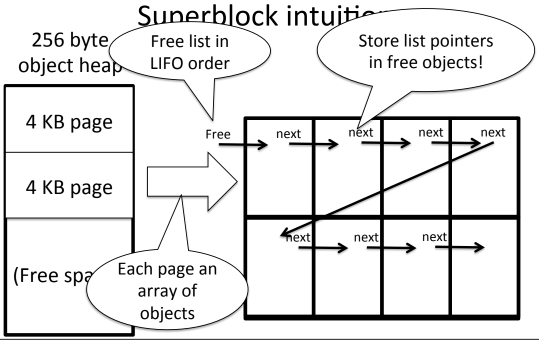
Superblock intuiti



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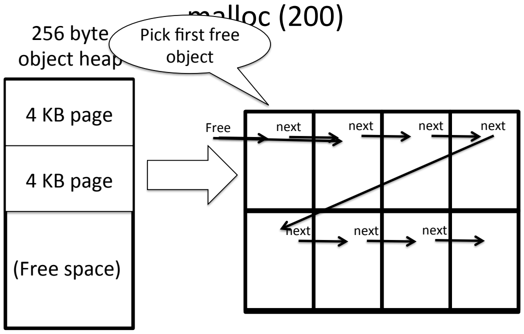
Superblock Intuition

```
malloc (8);
```

1) Find the nearest power of 2 heap (8)
2) Find free object in superblock
3) Add a superblock if needed. Goto 2.

malloc (200)



Superblock example

- Suppose my program allocates objects of sizes:
  – 4, 5, 7, 34, and 40 bytes.
- How many superblocks do I need (if b ==2)?
  – 3 – (4, 8, and 64 byte chunks)
- If I allocate a 5 byte object from an 8 byte superblock, doesn't that yield internal fragmentation?
  – Yes, but it is bounded to < 50%
  – Give up some space to bound worst case and complexity

Memory free

- Simple most-recently-used list for a superblock
- How do you tell which superblock an object is from?
  – Suppose superblock is 8k (2pages)
    - And always mapped at an address evenly divisible by 8k
  – Object at address 0x431a01c
  – Just mask out the low 13 bits!
  – Came from a superblock that starts at 0x431a000
- Simple math can tell you where an object came from!

Big objects

- If an object size is bigger than half the size of a superblock, just mmap() it
  – Recall, a superblock is on the order of pages already
- What about fragmentation?
  – Example: 4097 byte object (1 page + 1 byte)
  – Argument (preview): More trouble than it is worth
    - Extra bookkeeping, potential contention, and potential bad cache behavior

LIFO

- Why are objects re-allocated most-recently used first?
  – Aren't all good OS heuristics FIFO?
  – More likely to be already in cache (hot)
  – Recall from undergrad architecture that it takes quite a few cycles to load data into cache from memory
  – If it is all the same, let's try to recycle the object already in our cache

High-level strategy

- Allocate a heap for each processor, and one shared heap
  – Note: not threads, but CPUs
  – Can only use as many heaps as CPUs at once
  – Requires some way to figure out current processor
- Try per-CPU heap first
- If no free blocks of right size, then try global heap
- If that fails, get another superblock for per-CPU heap

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Simplicity

- The bookkeeping for alloc and free is pretty straightforward; many allocators are quite complex (slab)
  - Overall: Need a simple array of (# CPUs + 1) heaps
- Per heap: 1 list of superblocks per object size
- Per superblock:
  - Need to know which/how many objects are free
    - LIFO list of free blocks

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Locking

- On alloc and free, superblock and per-CPU heap are locked
- Why?
  - An object can be freed from a different CPU than it was allocated on
- Alternative:
  - We could add more bookkeeping for objects to move to local superblock
  - Reintroduce fragmentation issues and lose simplicity

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How to find the locks?

- Again, page alignment can identify the start of a superblock
- And each superblock keeps a small amount of metadata, including the heap it belongs to
  - Per-CPU or shared Heap
  - And heap includes a lock

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Locking performance

- Acquiring and releasing a lock generally requires an atomic instruction
  - Tens to a few hundred cycles vs. a few cycles
- Waiting for a lock can take thousands
  - Depends on how good the lock implementation is at managing contention (spinning)
  - Blocking locks require many hundreds of cycles to context switch

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Performance argument

- Common case: allocations and frees are from per-CPU heap
- Yes, grabbing a lock adds overheads
  - But better than the fragmented or complex alternatives
  - And locking hurts scalability only under contention
- Uncommon case: all CPUs contend to access one heap
  - Had to all come from that heap (only frees cross heaps)
  - Bizarre workload, probably won't scale anyway

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New topic: alignment

- Word
- Cacheline

Alignment (words)

```
struct foo {
    char x;
    int32_t y;
};
```

- Naïve layout: 1 byte for x, followed by 4 bytes for y
- ISA tools for loading from memory:
  - Load byte
  - Load 4 bytes (starting at address divisible by 4)
  - Load 8 bytes (starting at address divisible by 8)
  - And so on

How to load foo.y in assembly?

How to load foo.y in assembly?

- I'd like to do something like this:
  - `movw %eax, (&foo.y)`
- Problems?
  - Word-aligned mov expects foo.y to be at a word boundary
- I can solve this:

  for i in (0..4)

    Load byte foo.y[i] into eax

    Shift eax left 8 bits

Caveat: Most ISAs (e.g., ARM) only do word-aligned loads.

x86 implements (slower) unaligned loads in hardware with a similar loop

My solution is obviously undesirable

Word Alignment

```
struct foo {
    byte x;
    int32_t y;
};
```

- Compiler generally pads this out
  - Waste 24 bits after x
  - Save a ton of code reinventing simple arithmetic
    - Code takes space in memory too!
- Code will still break if foo isn't aligned to a word boundary!

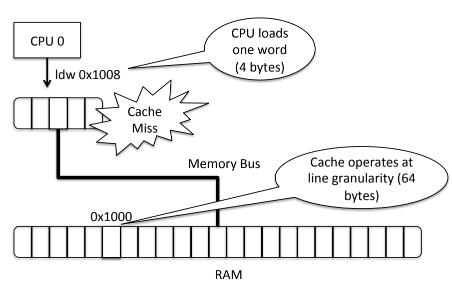
Memory allocator + alignment

- Compiler and allocator have a contract that malloc() and friends will return addresses that are word aligned
- This contract often dictates a degree of fragmentation
  - See the appeal of 2^n sized objects yet?

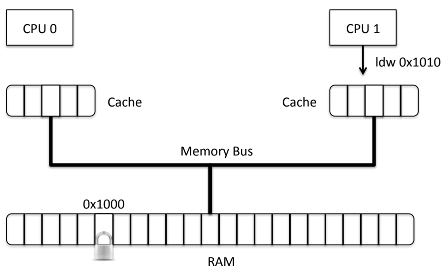
Cacheline alignment

- Different issue, similar name
- Cache lines are bigger than words
  - Word: 32-bits or 64-bits
  - Cache line – 64—128 bytes on most CPUs
- Lines are the basic unit at which memory is cached

Undergrad Architecture Review



Cache Coherence (1)



Lines shared for reading have a shared lock

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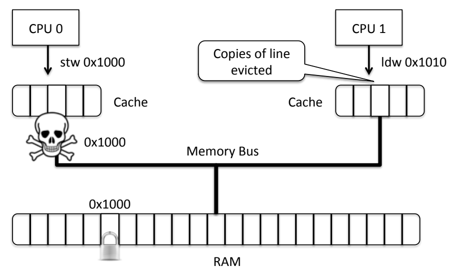
Cache Coherence (2)



Lines to be written have an exclusive lock

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Simple coherence model

- When a memory region is cached, CPU automatically acquires a reader-writer lock on that region
  - Multiple CPUs can share a read lock
  - Write lock is exclusive
- Programmer can't control how long these locks are held
  - Ex: a store from a register holds the write lock long enough to perform the write; held from there until the next CPU wants it

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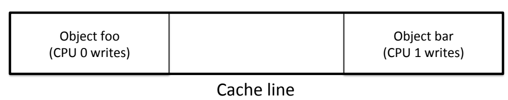
False sharing



- These objects have nothing to do with each other
  - At program level, private to separate threads
- At cache level, CPUs are fighting for a write lock

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False sharing is **BAD**

- Leads to pathological performance problems
  - Super-linear slowdown in some cases
- Rule of thumb: any performance trend that is more than linear in the number of CPUs is probably caused by cache behavior

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Strawman

- Round everything up to the size of a cache line
- Thoughts?
  - Wastes too much memory; a bit extreme

Hoard strategy (pragmatic)

- Rounding up to powers of 2 helps
  - Once your objects are bigger than a cache line
- Locality observation: things tend to be used on the CPU where they were allocated
- For small objects, always return free to the original heap
  - Remember idea about extra bookkeeping to avoid synchronization: some allocators do this
    - Save locking, but introduce false sharing!

Hoard summary

- Really nice piece of work
- Establishes nice balance among concerns
- Good performance results

Linux kernel allocators

- Focus today on dynamic allocation of small objects
  - Later class on management of physical pages
  - And allocation of page ranges to allocators

kmem_caches

- Linux has a kmalloc and kfree, but caches preferred for common object types
- Like Hoard, a given cache allocates a specific type of object
  - Ex: a cache for file descriptors, a cache for inodes, etc.
- Unlike Hoard, objects of the same size not mixed
  - Allocator can do initialization automatically
  - May also need to constrain where memory comes from

Caches (2)

- Caches can also keep a certain “reserve” capacity
  - No guarantees, but allows performance tuning
  - Example: I know I’ll have ~100 list nodes frequently allocated and freed; target the cache capacity at 120 elements to avoid expensive page allocation
  - Often called a **memory pool**
- Universal interface: can change allocator underneath
- Kernel has kmalloc and kfree too
  - Implemented on caches of various powers of 2 (familiar?)

Superblocks to slabs

- The default cache allocator (at least as of early 2.6) was the slab allocator
- Slab is a chunk of contiguous pages, similar to a superblock in Hoard
- Similar basic ideas, but substantially more complex bookkeeping
  - The slab allocator came first, historically

Complexity backlash

- I'll spare you the details, but slab bookkeeping is complicated
- 2 groups upset: (guesses who?)
  - Users of very small systems
  - Users of large multi-processor systems

Small systems

- Think 4MB of RAM on a small device/phone/etc.
- As system memory gets tiny, the bookkeeping overheads become a large percent of total system memory
- How bad is fragmentation really going to be?
  - Note: not sure this has been carefully studied; may just be intuition

SLOB allocator

- Simple List Of Blocks
- Just keep a free list of each available chunk and its size
- Grab the first one big enough to work
  - Split block if leftover bytes
- No internal fragmentation, obviously
- External fragmentation? Yes. Traded for low overheads

Large systems

- For very large (thousands of CPU) systems, complex allocator bookkeeping gets out of hand
- Example: slabs try to migrate objects from one CPU to another to avoid synchronization
  - Per-CPU * Per-CPU bookkeeping

SLUB Allocator

- The Unqueued Slab Allocator
- A much more Hoard-like design
  - All objects of same size from same slab
  - Simple free list per slab
  - No cross-CPU nonsense
- Now the default Linux cache allocator

Conclusion

- Different allocation strategies have different trade-offs
  - No one, perfect solution
- Allocators try to optimize for multiple variables:
  - Fragmentation, low false conflicts, speed, multi-processor scalability, etc.
- Understand tradeoffs: Hoard vs Slab vs. SLOB

Misc notes

- When is a superblock considered free and eligible to be move to the global bucket?
  - See figure 2, free(), line 9
  - Essentially a configurable "empty fraction"
- Is a "used block" count stored somewhere?
  - Not clear, but probably