CSE 506: Operating Systems

The Art and Science of Memory Allocation
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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
• 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

Overarching issues

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

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?

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, $b = 2$

Superblock Intuition

```c
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)

Pick first free
object

256 byte
object heap

4 KB page

Free

next

next

next

next

next

next

next

(1st free)

(2nd free)

(3rd free)

(4th free)

(5th free)

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
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

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

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

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

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

New topic: alignment
- Word
- Cacheline
Alignment (words)

```c
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?

• 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

  ```
  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

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Word Alignment

```c
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!

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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?

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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

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Undergrad Architecture Review

CPU loads one word (4 bytes)

CPU: 0x108

0x1000

Cache operates at line granularity (64 bytes)

0x1000

Memory Bus

CPU

Miss

RAM
Cache Coherence (1)

Lines shared for reading have a shared lock

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

False sharing

- 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

False sharing is BAD

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  - 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

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 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