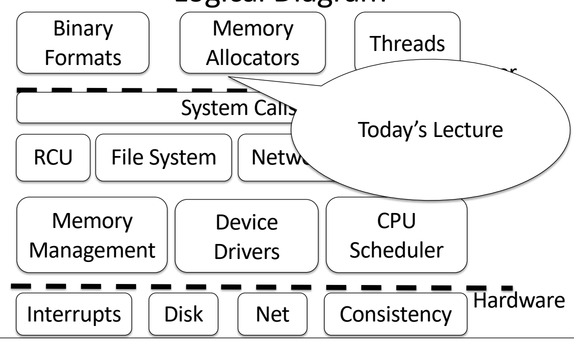
The Art and Science of Memory Allocation

Don Porter

1

Logical Diagram



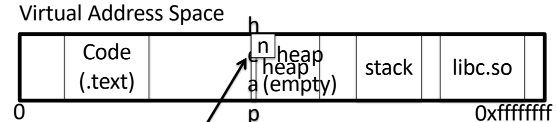
2

Lecture goal

- This lectures is about allocating small objects
  - Future lectures will talk about allocating physical pages
- Understand how memory allocators work
  - In both kernel and applications
- Understand trade-offs and current best practices

3

Big Picture




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

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

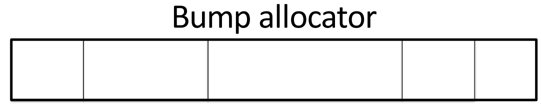

4

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

5

Bump allocator



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

6

COMP 790: OS Implementation

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

7

7

COMP 790: OS Implementation

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

8

8

COMP 790: OS Implementation

Overarching issues

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

9

9

COMP 790: OS Implementation

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?

10

10

COMP 790: OS Implementation

Hoard: Superblocks

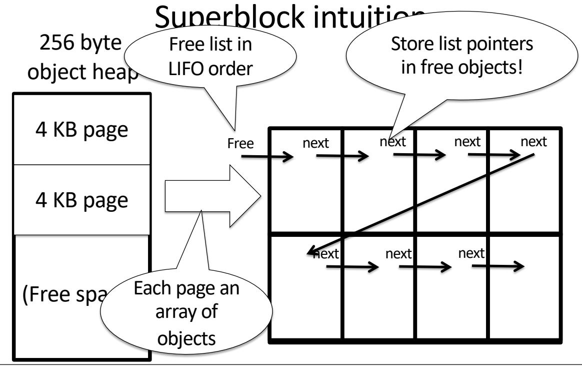
- At a high level, allocator operates on superblocks
  - Chunk of (virtually) contiguous pages
  - All objects in a superblock are the same size
- A given superblock is treated as an array of same-sized objects
  - They generalize to "powers of b > 1";
  - In usual practice, b == 2

11

11

COMP 790: OS Implementation

Superblock intuition



12

12

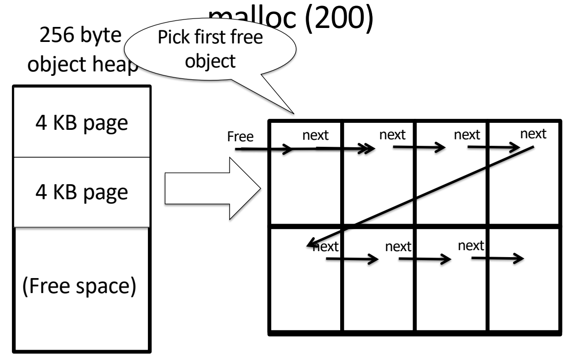
Superblock Intuition

```
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.

13

malloc (200)



14

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

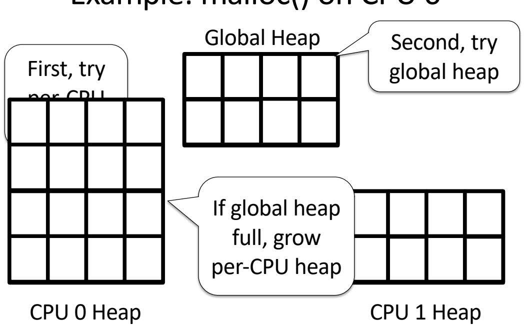
15

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
  - Why try this first?
- If that fails, get another superblock for per-CPU heap

16

Example: malloc() on CPU 0



17

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: More trouble than it is worth
    - Extra bookkeeping, potential contention, and potential bad cache behavior

18

Memory free

- Simply put back on free list within its 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!

19

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

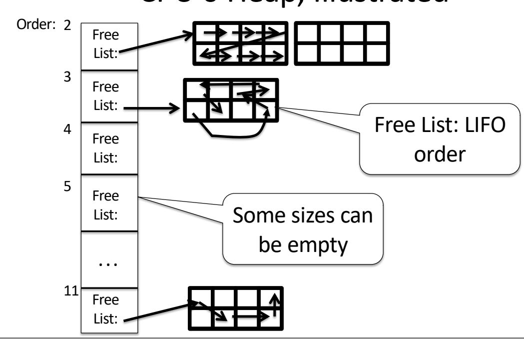
20

Hoard Simplicity

- The bookkeeping for alloc and free is straightforward
  - Many allocators are quite complex (looking at you, slab)
- Overall: (# CPUs + 1) heaps
- Per heap: 1 list of superblocks per object size (2^2—2^{11})
  - Per superblock:
    - Need to know which/how many objects are free
      - LIFO list of free blocks

21

CPU 0 Heap, Illustrated



One of these per CPU (and one shared)

22

Locking

- On alloc and free, lock superblock and per-CPU heap
- 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

23

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

24

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

25

25

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

26

26

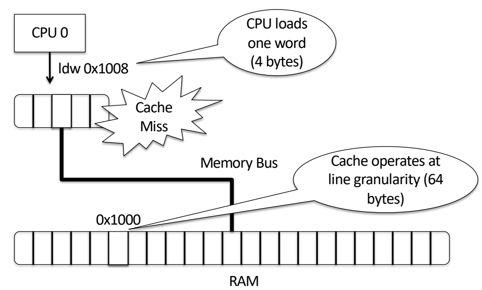
Cacheline alignment

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

27

27

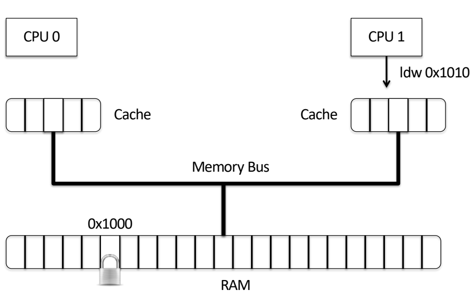
Undergrad Architecture Review



28

28

Cache Coherence (1)

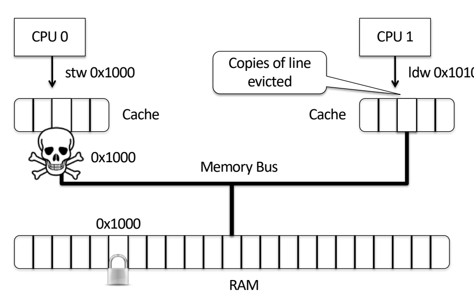


Lines shared for reading have a shared lock

29

29

Cache Coherence (2)



Lines to be written have an exclusive lock

30

30

Simple coherence model

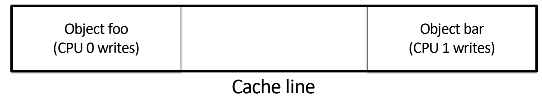
- When a memory region is cached, CPU automatically acquires a reader-writer lock on that region
  - Multiple CPUs can share a read lock
  - Write lock is exclusive
- Programmer can't control how long these locks are held
  - Ex: a store from a register holds the write lock long enough to perform the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

31

31

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
COMP 790: OS Implementation

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

32

32

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
COMP 790: OS Implementation

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

33

33

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
COMP 790: OS Implementation

Strawman

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

34

34

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
COMP 790: OS Implementation

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!

35

35

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
COMP 790: OS Implementation

Hoard summary

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

36

36

Part 2: Linux kernel allocators

- malloc() and friends, but in the kernel
- Focus today on dynamic allocation of small objects
  - Later class on management of physical pages
  - And allocation of page ranges to allocators

37

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

38

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?)

39

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

40

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

41

Small systems

- Think 4MB of RAM on a small device (thermostat)
- 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

42

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