Lecture 12: Dynamic Memory Allocation

601.418/618 Operating Systems

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Agenda

- Dynamic memory allocation
  - Fragmentation
  - Best fit
  - First fit
  - Buddy allocation
  - Application behavior
  - Slab allocation
  - `malloc()`/`free()`

Acknowledgments: These slides are shamelessly adapted from Prof. Ryan Huang's Fall 2022 slides, which in turn are based on Prof. David Mazières's OS lecture notes.

Memory Allocation

Static Allocation (fixed in size)

- want to create data structures that are fixed and don't need to grow or shrink
- global variables, e.g., `char name[16];`
- done at **compile time**

Dynamic Allocation (change in size)

- want to increase or decrease the size of a data structure according to different demands
- done at **run time**

Dynamic Memory Allocation

Almost every useful program uses it

- Gives wonderful functionality benefits
- Don't have to statically specify complex data structures
- Can have data grow as a function of input size
- Allows recursive procedures (stack growth)
- But, can have a huge impact on performance

Two types of dynamic memory allocation

- Stack allocation: restricted, but simple and efficient
- **Heap allocation (focus today)**: general, but difficult to implement.

Dynamic Memory Allocation

Today: how to implement dynamic heap allocation

- Lecture based on Wilson[1] (good survey from 1995)

Some interesting facts:

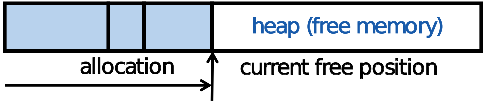
- Two or three line code change can have huge, non-obvious impact on how well allocator works (examples to come)
- Proven: impossible to construct an "always good" allocator
- Surprising result: after 27 years, memory management still poorly understood
  - *Beyond malloc efficiency to fleet efficiency: a hugepage-aware memory allocator* [OSDI '21]
- Big companies may write their own "malloc"
  - Google: TCMalloc
  - Facebook: jemalloc

[1] Wilson et. al., *Dynamic Storage Allocation: A Survey and Critical Review*

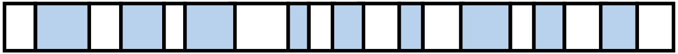
Why Is It Hard?

Satisfy arbitrary set of allocation and frees.

Easy without free: set a pointer to the beginning of some big chunk of memory (“heap”) and increment on each allocation:



Problem: free creates holes (“fragmentation”) Result? Lots of free space but cannot satisfy request!



More Abstractly

What an allocator must do?

- Track which parts of memory in use, which parts are free
- *Ideal*: no wasted space, no time overhead

What the allocator **cannot** do?

- Control order of the number and size of requested blocks
- Know the number, size, & lifetime of future allocations
- **Move allocated regions** (bad placement decisions permanent), unlike Java allocator

The core fight: minimize fragmentation

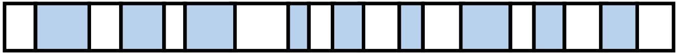
- App frees blocks in any order, creating holes in "heap"
- Holes too small? cannot satisfy future requests

What Is Fragmentation Really?

Inability to use memory that is free

Two factors required for fragmentation

1. Different lifetimes—if adjacent objects die at different times, then fragmentation:

   If all objects die at the same time, then no fragmentation:

2. Different sizes: If all requests the same size, then no fragmentation (that's why no external fragmentation with paging):

Important Decisions

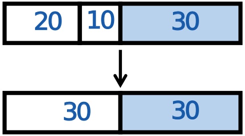
Placement choice: where in free memory to put a requested block?

- Freedom: can select any memory in the heap
- Ideal: put block where it won't cause fragmentation later (impossible in general: requires future knowledge)

Split free blocks to satisfy smaller requests?

- Fights internal fragmentation
- Freedom: can choose any larger block to split
- One way: choose block with smallest remainder (best fit)

Coalescing free blocks to yield larger blocks



- Freedom: when to coalesce (deferring can save work)
- Fights external fragmentation

Impossible to "Solve" Fragmentation

If you read allocation papers to find the best allocator

- All discussions revolve around tradeoffs

Theoretical result:

- **For any allocation algorithm**, there exist streams of allocation and deallocation requests that defeat the allocator and force it into severe fragmentation a ☹

How much fragmentation should we tolerate?

- Let M = bytes of live data, n_{min} = smallest allocation, n_{max} = largest allocation
- Bad allocator: $M \times (n_{\text{max}}/n_{\text{min}})$
  - E.g., make all allocations of size n_{max} regardless of requested size
- Good allocator: $\sim M \times \log(n_{\text{max}}/n_{\text{min}})$

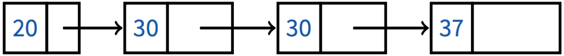
Next: two allocators (best fit, first fit) that, in practice, work pretty well

- "pretty well" = $\sim$ 20% fragmentation under many workloads

Best Fit

Strategy: minimize fragmentation by allocating space from block that leaves smallest fragment

- Data structure: heap is a list of free blocks, each has a header holding block size and a pointer to the next block



- Code: Search freelist for block closest in size to the request (exact match is ideal)
- During free: return free block, and (usually) coalesce adjacent blocks

Potential problem: Sawdust

- Remainder so small that over time left with “sawdust” everywhere
- Fortunately not a problem in practice

Best Fit Gone Wrong

Simple bad case: allocate n, m ($n < m$) in alternating orders, free all the ns, then try to allocate an $n + 1$

Example: start with 99 bytes of memory

- alloc 19, 21, 19, 21, 19

- free 19, 19, 19

- alloc 20? Fails! (wasted space = 57 bytes)

However, doesn't seem to happen in practice

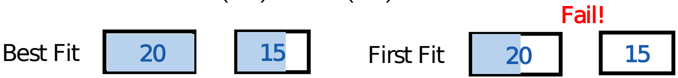
First Fit

Strategy: pick the first block that fits

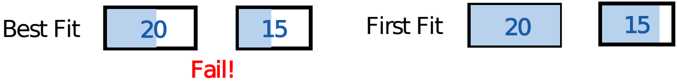
- Data structure: free list, sorted LIFO, FIFO, or by address
- Code: scan list, take the first one

Suppose memory has free blocks:

- Workload 1: alloc(10), alloc(20)



- Workload 2: alloc(8), alloc(12), alloc(12)



First Fit

LIFO: put free object on front of list.

- Simple, but causes higher fragmentation
- Potentially good for cache locality

Address sort: order free blocks by address

- Makes coalescing easy (just check if next block is free)
- Also preserves empty/idle space (locality good when paging)

FIFO: put free object at end of list

- Gives similar fragmentation as address sort, but unclear why

Some Other Ideas

Worst-fit:

- Strategy: fight against sawdust by splitting blocks to maximize leftover size
- In real life seems to ensure that no large blocks around

Next fit:

- Strategy: use first fit, but remember where we found the last thing and start searching from there
- Seems like a good idea, but tends to break down entire list

Buddy systems:

- Round up allocations to power of 2 to make management faster

Buddy Allocator Motivation

Allocation requests: frequently 2^n

- E.g., allocation physical pages in Linux
- Generic allocation strategies: overly generic

Fast search (allocate) and merge (free)

- Avoid iterating through free list

Avoid external fragmentation for req of 2^n

Used by Linux, FreeBSD

Buddy Allocator Implementation

Data structure

- $N + 1$ free lists of blocks of size $2^0, 2^1, \ldots, 2^N$

Allocation restrictions: 2^k, $0 \le k \le N$

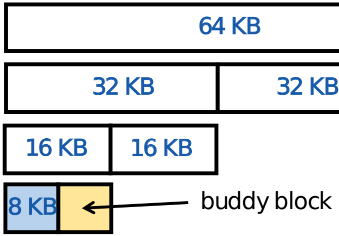
Allocation of 2^k:

- Search free lists $(k,\ k+1,\ k+2,\ \ldots)$ for appropriate size
- Recursively divide larger blocks until reach block of correct size
- Insert "buddy" blocks into free lists

Free

- recursively coalesce block with "buddy" if buddy free

Buddy Allocation



Recursively divide larger blocks until reach suitable block

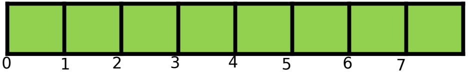
- Big enough to fit but if further splitting would be too small

Insert "buddy" blocks into free lists

- The addresses of the buddy pair only differ by one bit!

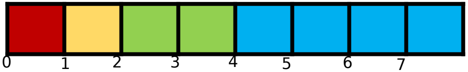
Upon free, recursively coalesce block with buddy if buddy free

Buddy Allocation Example



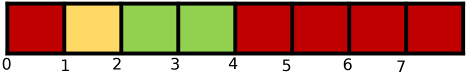
freelist[3] = {0}   (block size 2^3)

`p1 = alloc(2^0)`



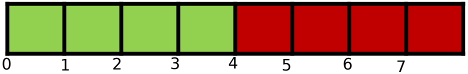
freelist[0] = {1}, freelist[1] = {2}, freelist[2] = {4}

`p2 = alloc(2^2)`



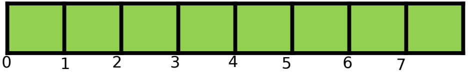
freelist[0] = {1}, freelist[1] = {2}

`free(p1)`



freelist[2] = {0}

`free(p2)`



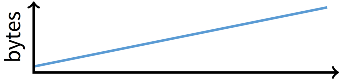
freelist[3] = {0}

Known Patterns of Real Programs

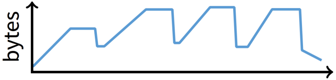
So far we've treated programs as black boxes.

Most real programs exhibit 1 or 2 (or all 3) of the following patterns of alloc/dealloc:

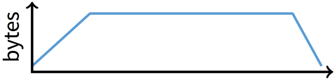
- *Ramps*: accumulate data monotonically over time



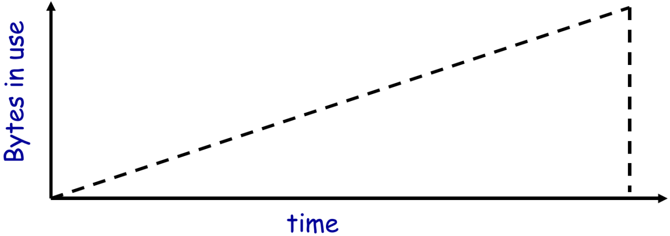
- *Peaks*: allocate many objects, use briefly, then free all



- *Plateaus*: allocate many objects, use for a long time



Pattern 1: Ramps

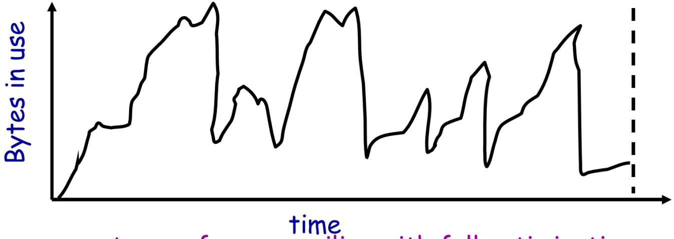


trace from an LRU simulator

In a practical sense: ramp = no free!

- Implication for fragmentation?
- What happens if you evaluate allocator with ramp programs only?

Pattern 2: Peaks



trace of gcc compiling with full optimization

Peaks: allocate many objects, use briefly, then free all

- Fragmentation a real danger
- What happens if peak allocated from contiguous memory?
- Interleave peak & ramp? Interleave two different peaks?

Exploiting Peaks

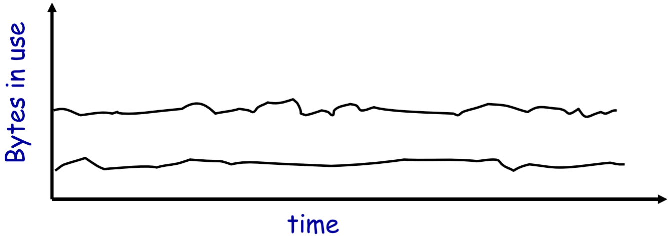
Peak phases: allocate a lot, then free everything

- Change allocation interface: alloc as before, but only support free of everything all at once
- Called "arena allocation", "obstack" (object stack)

Arena = a linked list of large chunks of memory

- Advantages: alloc is a pointer increment, free is "free"
- No wasted space for tags or list pointers
- See Pintos `threads/malloc.c`

Pattern 3: Plateaus



trace of perl running a string processing script

Plateaus: allocate many objects, use for a long time

Slab Allocation

Kernel allocates many instances of same structures

- E.g., a 1.7 KB `task_struct` for every process on system

Often want contiguous physical memory (for DMA)

Slab allocation optimizes for this case:

- A slab is multiple pages of contiguous physical memory
- A cache contains one or more slabs
- Each cache stores only one kind of object (fixed size)

Each slab is full, empty, or partial

Slab Allocation

E.g., need new `task_struct`?

- Look in the `task_struct` cache
- If there is a partial slab, pick free `task_struct` in that
- Else, use empty, or may need to allocate new slab for cache

Free memory management: bitmap

- Allocate: set bit and return slot, Free: clear bit

Advantages: speed, and no internal fragmentation

Used in FreeBSD and Linux, implemented on top of buddy page allocator

Implementing `malloc`

Getting More Space from OS

`malloc` is a library call, how does `malloc` gets free space?

- Note in Pintos, `malloc` is provided as a kernel function (see `threads/malloc.c`)

On Unix, can use sbrk and brk

- `int brk(void *p)`
  - Move the program break to address `p`
  - Return 0 if successful and -1 otherwise
- `void *sbrk(intptr_t n)`
  - Increment the program break by `n` bytes
  - If `n` is 0, then return the current location of the program break
  - Return previous break address if successful and `(void*)-1` otherwise

Implement `malloc()`

```
void *malloc(size_t n)
{
  char *p = sbrk(0);
  if (brk(p + n) == -1)
    return NULL;
  return p;
}

void free(void * p)
{
}
```

get current "program break"

set "program break" to be current plus n

Problems?

- Two system calls for every malloc!
- Freed blocks are not reused

Solutions

- Allocators request memory pool
- Keep track of free list
- If can't find free chunk, request from OS

Returning Heap Memory

Allocator can mark blocks as free when `free()` is called

- These blocks can be reused later by the process
- Problem: they are not returned to the system!
  - can cause memory pressure

Allocator can return heap memory with `brk(pBrk-n)`, but. . .

- `p` in `free(p)` is not always at the end of the heap!
- So can't reduce the heap size with `brk(pBrk-n)`

Therefore, for large allocations, `sbrk()` is a bad idea

- Can't return memory to the system

Solution: VM Mapping

```
void *mmap(void *p, size_t n, int prot, int flags, int fd, off_t offset);
```

- Creates a new mapping in the virtual address space of the calling process
- `p`: the starting address for the new mapping
- `n`: the length of the mapping
- If `p` is `NULL`, the **kernel chooses the address at which to create the mapping**
- On success, returns address of the mapped area

```
int munmap(void *p, size_t n);
```

- Deletes the mappings for the specified address range

Implement malloc() with mmap()

```c
void *malloc(size_t n) {
  size_t *p;
  if (n == 0) return NULL;
  p = mmap(NULL, n + sizeof(size_t),
           PROT_READ|PROT_WRITE,
           MAP_PRIVATE|MAP_ANONYMOUS,
           0, 0);
  if (p == (void*)-1) return NULL;

  // Store size in header
  *p = n + sizeof(size_t);
  p++;

  // Move forward from header to payload
  return p;
}
```

```c
void free(void *p) {
  if (p == NULL) return;
  size_t *x = (size_t *) p;
  x--; // Move backward from
       // payload to header
  munmap(x, *x);
}
```

A Simple First-Fit `malloc()`

https://github.com/daveho/EasySandbox/blob/master/malloc.c

Next Time

I/O and disks

Have a great Spring Break!

Heads up: Assignment 3a has been posted