• Lab 2 due next Saturday
  - If you haven’t started yet, please do now.
  - Otherwise you won’t be able to complete the lab.

• Next Tuesday’s class is cancelled, working on lab 2

• Next next Tuesday (October 22\textsuperscript{nd}) is Midterm
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]

• 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 35 years, memory management still poorly understood
    • Mallacc: Accelerating Memory Allocation: ASPLOS 2017 Highlights
  - Big companies may write their own “malloc”
    • Google: TCMalloc
    • Facebook: jemalloc
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:

![Diagram showing heap (free memory), allocation, and current free position.]

• 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:

   ![Diagram showing fragmentation due to different lifetimes]

   - 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):

   ![Diagram showing no fragmentation due to different sizes]
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

20 10 30

30 30
Impossible to “Solve” Fragmentation

• If you read allocation papers to find the best allocator
  - All discussions revolve around tradeoffs
  - The reason? There cannot be a best allocator

• Theoretical result:
  - For any allocation algorithm, there exist streams of allocation and deallocation requests that defeat the allocator and force it into severe fragmentation 😞

• How much fragmentation should we tolerate?
  - Let $M = \text{bytes of live data}$, $n_{\text{min}} = \text{smallest allocation}$, $n_{\text{max}} = \text{largest allocation}$
  - Bad allocator: $M \cdot \left(\frac{n_{\text{max}}}{n_{\text{min}}}\right)$
    • E.g., make all allocations of size $n_{\text{max}}$ regardless of requested size
  - Good allocator: $\sim M \cdot \log\left(\frac{n_{\text{max}}}{n_{\text{min}}}\right)$
Pathological Examples

• Suppose heap currently has 7 20-byte chunks
  
  ![20 20 20 20 20 20 20]

  - What’s a bad stream of frees and then allocates?

• Next: two allocators (best fit, first fit) that, in practice, work pretty well
  
  - “pretty well” = ~20% fragmentation under many workloads
Pathological Examples

• Suppose heap currently has 7 20-byte chunks

- What’s a bad stream of frees and then allocates?
- Free every other chunk, then alloc 21 bytes

• Next: two allocators (best fit, first fit) that, in practice, work pretty well
  - “pretty well” = ~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 $n$s, 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**: 20 15

  - Workload 1: alloc(10), alloc(20)
    - Best Fit: 20 15  First Fit: 20 15  Fail!

  - Workload 2: alloc(8), alloc(12), alloc(12)
    - Best Fit: 20 15  First Fit: 20 15  Fail!
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
Subtle Pathology: LIFO FF

• Storage management example of subtle impact of simple decisions

• LIFO first fit seems good:
  - Put object on front of list (cheap), hope same size used again (cheap + good locality)

• But, has big problems for simple allocation patterns:
  - E.g., repeatedly intermix short-lived $2n$-byte allocations, with long-lived $(n + 1)$-byte allocations

    alloc(8), free(8), alloc(5), alloc(8), free(8), alloc(5), alloc(8), free(8), ...

  - Each time large object freed, a small chunk will be quickly taken, leaving useless fragment. Pathological fragmentation
First Fit: Nuances

• First fit sorted by address order, in practice
  - Blocks at front preferentially split, ones at back only split when no larger one found before them
  - Result? Seems to roughly sort free list by size
  - So? Makes first fit operationally similar to best fit: a first fit of a sorted list = best fit!

• Problem: sawdust at beginning of the list
  - Sorting of list forces a large requests to skip over many small blocks. Need to use a scalable heap organization
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 $2^n$**

- **Keep physical pages contiguous**

- **Used by Linux, FreeBSD**
Buddy Allocator Implementation

- **Data structure**
  - $N$ free lists of blocks of size $2^0$, $2^1$, ..., $2^N$

- **Allocation restrictions**: $2^k$, $0 \leq k \leq N$

- **Allocation of $2^k$**:
  - Search free lists $(k, k+1, k+2, ...)$ 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

p1 = alloc(2^0)

p2 = alloc(2^2)

free(p1)

free(p2)

Note: 2^3

freelist[3] = {0}


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

freelist[2] = {0}

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

- In a practical sense: ramp = no free!
  - Implication for fragmentation?
  - What happens if you evaluate allocator with ramp programs only?
Pattern 2: Peaks

- 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: allocate as before, but only support free of everything all at once
  - Called “arena allocation”, “obstack” (object stack), or alloca/procedure call (by compiler people)

• 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

- Plateaus: allocate many objects, use for a long time
  - What happens if overlap with peak or different plateau?
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
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 0 if successful and (void*)-1 otherwise
Implement `malloc()`

```c
void *malloc(size_t n)
{
    char *p = sbrk(0);  // get current "program break"
    if (brk(p + n) == -1)  // set "program break" to be current plus n
        return NULL;
    return p;
}

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

Problem?
- 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 \texttt{free()} is called**
  - But these blocks can be reused later by the process
  - i.e., they are not returned to the system!
  - Can cause memory pressure

• **Allocator can return heap memory with \texttt{brk(pBrk-n), but...**
  - \texttt{p} in \texttt{free(p)} is not always at the end of the heap!
  - So can’t reduce the heap size with \texttt{brk(pBrk-n)}

• **Therefore, for large allocations, \texttt{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;
    *p = n + sizeof(size_t); // Store size in header
    p++; // Move forward from header to payload
    return p;
}
```

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

• Midterm Review
Simple, Fast Segregated Free Lists

- Array of free lists for small sizes, tree for larger
  - Place blocks of same size on same page
  - Have count of allocated blocks: if goes to zero, can return page

- Pro: segregate sizes, no size tag, fast small alloc

- Con: worst case waste: 1 page per size even w/o free, After pessimal free: waste 1 page per object

- TCMalloc [Ghemawat] is a well-documented malloc like this
Typical Space Overheads

- Free list bookkeeping and alignment determine minimum allocatable size:
- If not implicit in page, must store size of block
- Must store pointers to next and previous freelist element

![Diagram of memory alignment](image)

- Allocator doesn’t know types
  - Must align memory to conservative boundary