Memory Allocation I

CSE 351 Spring 2024

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Playlist: CSE 351 24Sp Lecture Tunes!

Announcements, Reminders

- Lab 3 due & Lab 4 releasing tonight
- HW17/18 due Friday, HW19 due Monday (13 May)
- Midterm due last night!
  - How’d it go?
  - Expect grades in a week-ish, more or less...
- Looking ahead: Guest lectures on May 15th and 17th

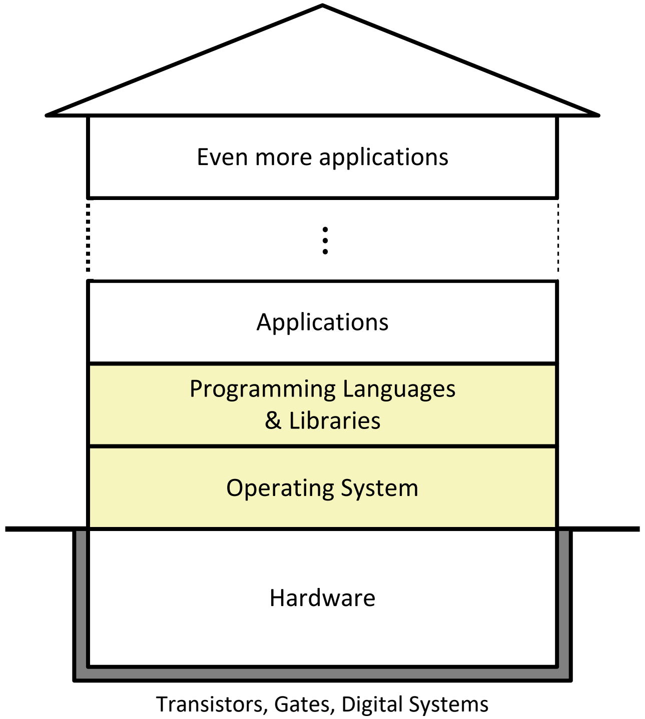
Current Events & CSE 351

- There may be interruptions to course resources:
  - Office Hours
  - Section
  - Grading

- Please bear with us as information comes in and the situation develops…

The Hardware/Software Interface

- Topic Group 3: **Scale & Coherence**
  - Caches, Processes, Virtual Memory, **Memory Allocation**


Even more applications
⋮
Applications
Programming Languages & Libraries
Operating System
Hardware
Transistors, Gates, Digital Systems

Physics

- How do we maintain logical consistency in the face of more data and more processes?
  - How do we support control flow both within many processes and things external to the computer?
  - How do we support data access, including dynamic requests, across multiple processes?

Reading Review

- Terminology:
  - Dynamically-allocated data: malloc, free
  - Allocators: implicit vs. explicit allocators, heap blocks, implicit vs. explicit free lists
  - Heap fragmentation: internal vs. external

Multiple Ways to Store Program Data

- Static global data
  - **Fixed size** at compile-time
  - **Entire lifetime of the program** (loaded from executable)
  - Accessible anywhere in program
  - A portion is read-only (*e.g.*, string literals)
- Stack-allocated data
  - Local/temporary variables
    - Can be **dynamically sized** (in some versions of C)
  - **Known lifetime** (deallocated on `return`)
- **Dynamic (heap) data**
  - **Size known only at runtime** (*e.g.*, based on user-input)
  - **Lifetime known only at runtime** due to control by programmer (*e.g.*, `malloc`/`free` in C)

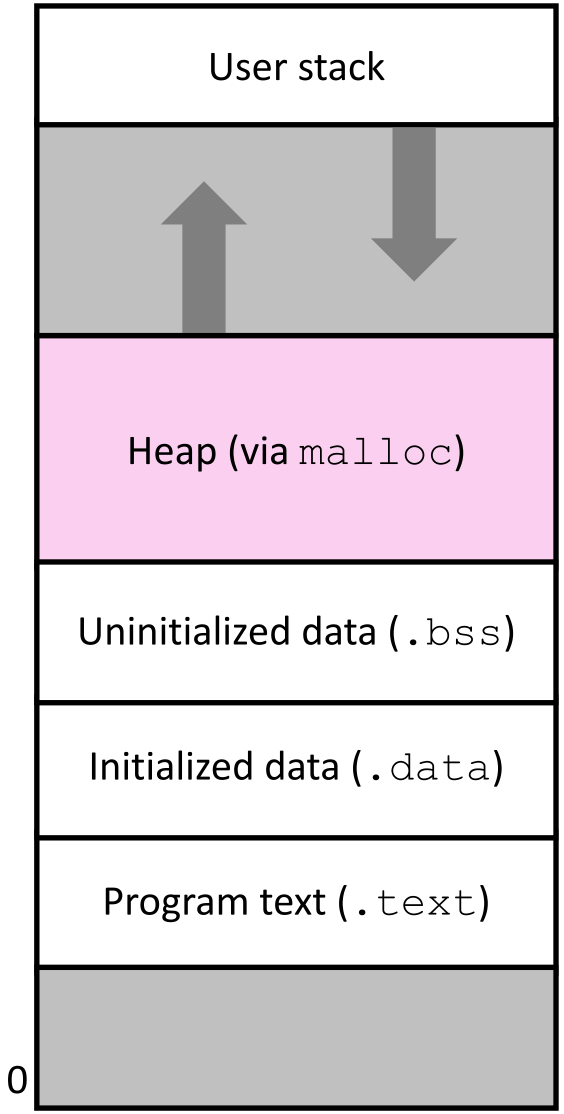
```
int array[1024];

void foo(int n) {
  int tmp;
  int local_array[n];

  int* dyn =
    (int*)malloc(n*sizeof(int));
}
```

Memory Allocation

- **Dynamic memory allocation**
  - **Introduction and goals**
  - **Allocation and deallocation (free)**
  - **Fragmentation**
- Explicit allocation implementation
  - Implicit free lists
  - Explicit free lists (Lab 5)
  - Segregated free lists
- Implicit deallocation: garbage collection
- Common memory-related bugs in C

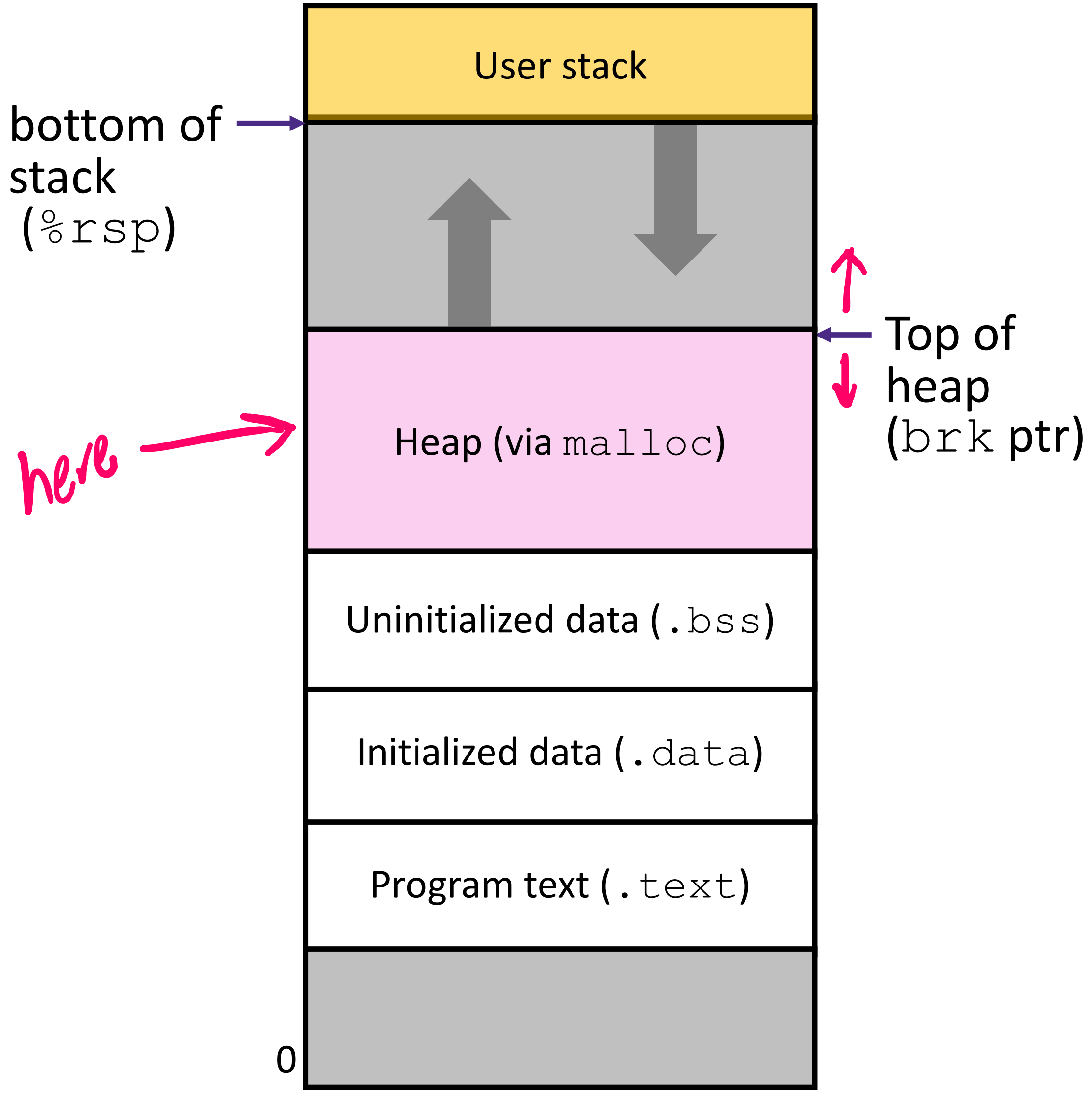
Dynamic Memory Allocation (Review)

- Programmers use **dynamic memory allocators** to acquire virtual memory at run time
  - For data structures whose size (or lifetime) is known only at runtime
  - Manage the heap of a process' virtual memory:
- Types of allocators
  - **Explicit** allocator: programmer allocates and frees space
    - Example: `malloc` and `free` in C
  - **Implicit** allocator: programmer only needs to allocate space (no free)
    - Example: use `new`, and garbage collection is done for you in Java, Ruby, and Python



Dynamic Memory Allocation

- Allocator organizes heap as a collection of variable-sized **blocks**, which are either allocated or free
- What happens if we run out of heap space?
  - Ask the OS for more memory and increment `brk`!



Allocating Memory in C (Review)

- Need to `#include <stdlib.h>`
- `void* malloc(size_t size)`
  - Allocates a continuous block of `size` bytes of uninitialized memory
  - `size_t`?! Simple `typedef` for an unsigned 8-byte integer
  - Returns a pointer to the beginning of the allocated block; `NULL` if request failed
    - Typically aligned to an 8-byte (x86) or 16-byte (x86-64) boundary
    - [Returns `NULL` if allocation failed] (also sets `errno`) or `size==0`
  - Different blocks not necessarily adjacent
- Best practices:
  - `ptr = (int*) malloc(n*sizeof(int));` // allocate space for n-many ints
    - `sizeof` makes code more portable (`int`s aren't the same size in all machines…)
    - `void*` is implicitly cast into any pointer type; explicit typecast will help you catch coding errors when pointer types don't match e.g. (int*)

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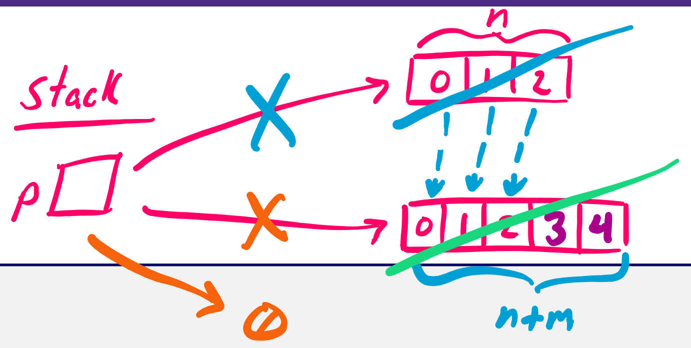
  - Different blocks not necessarily adjacent
- Related functions:
  - `void* calloc(size_t nitems, size_t size)`
    "Zeros out" allocated block
  - `void* realloc(void* ptr, size_t size)`
    - Changes the size of a previously allocated block (if possible)
  - `void* sbrk(intptr_t increment)`
    - Used internally by allocators to grow or shrink the heap

Freeing Memory in C (Review)

- Need to `#include <stdlib.h>`
- `void free(void* p)` //Note: freeing doesn't change pointer value! It will still point to (now) deallocated memory.
  - Releases whole block pointed to by `p` back to the pool of available memory
  - Pointer `p` must be the address originally returned by `(m|c|re)alloc` (*i.e.*, beginning of the block), otherwise system exception raised
  - Don't call `free` on a block that has already been released!
  - No action occurs if you call `free(NULL)`

Memory Allocation Example in C

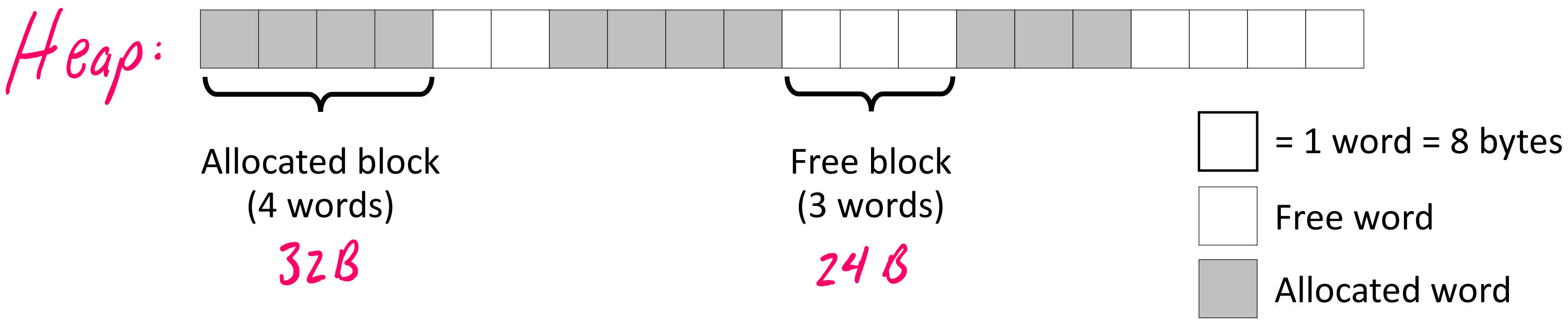


```
                 3         2
void foo(int n, int m) {
  int i, *p;
1 p = (int*) malloc(n*sizeof(int));          /* allocate block of n ints for an array */
  if (p == NULL) {                           /* check for allocation error */
    perror("malloc");
    exit(0);
  }
  for (i=0; i<n; i++)                        /* initialize int array */
    p[i] = i;

2 p = (int*) realloc(p,(n+m)*sizeof(int));   /* add space for m ints to end of p block */
  if (p == NULL) {                           /* check for allocation error */
    perror("realloc");
    exit(0);
  }
  for (i=n; i < n+m; i++)                    /* initialize new spaces only */
2.5 p[i] = i;
  for (i=0; i<n+m; i++)                      /* print new array */
    printf("%d\n", p[i]);
3 free(p);                                   /* free p */
4 p = NULL;                                  /* good practice to set p to NULL after free*/
}
```

Notation

- We will draw memory divided into **words**
  - Each word is 64 bits = 8 bytes
  - Allocations will be in sizes that are a multiple of words (*i.e.*, multiples of 8 bytes)
  - **Note:** Book and old videos still use 4-byte word
    - Holdover from 32-bit version of textbook 🙁



Heap:

Allocated block
(4 words)
32B

Free block
(3 words)
24 B

□ = 1 word = 8 bytes

□ Free word

▨ Allocated word

Allocation Example

□ = 8-byte word

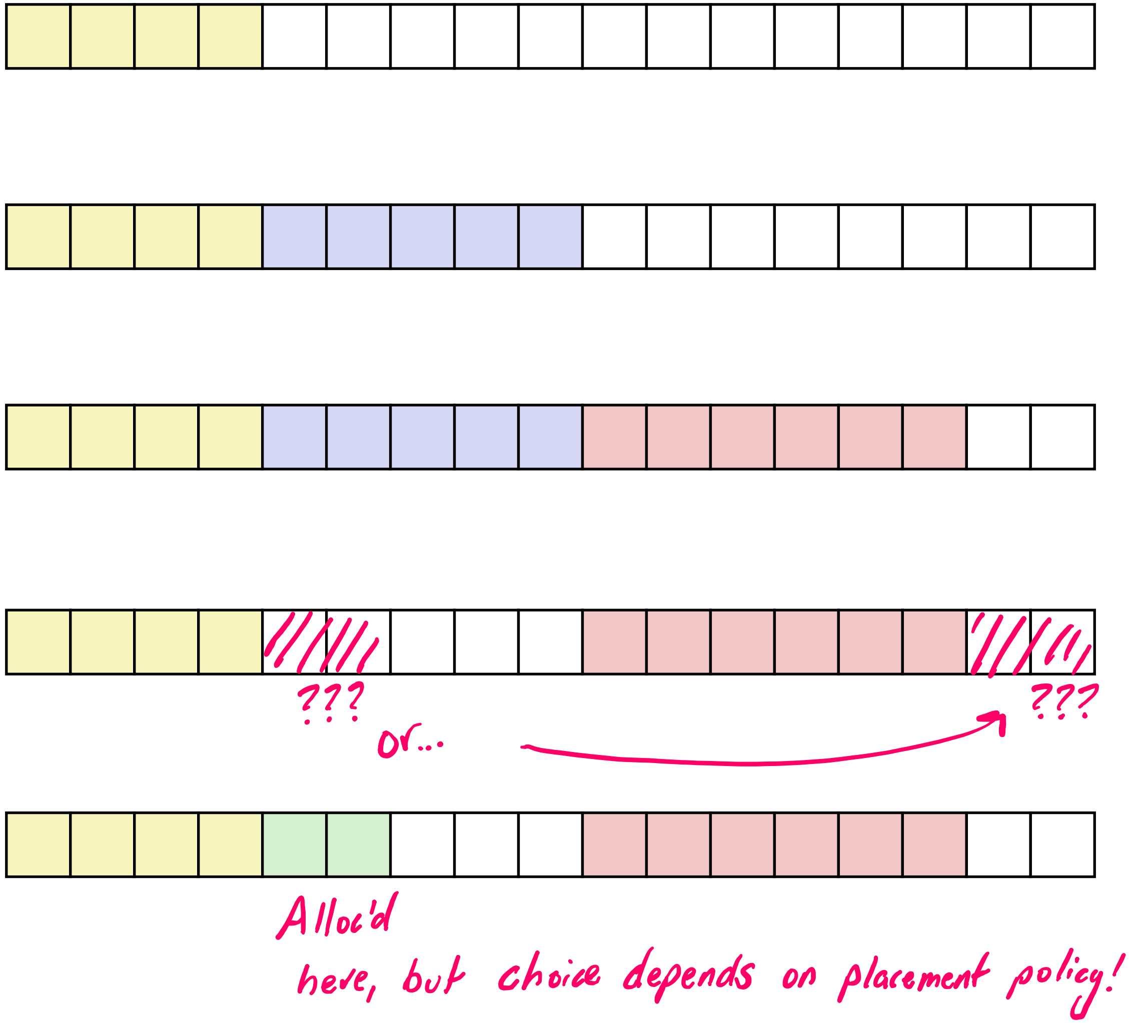
`p1 = malloc(32)`

`p2 = malloc(40)`

`p3 = malloc(48)`

`free(p2)`

`p4 = malloc(16)`



Alloc'd here, but choice depends on placement policy!

Implementation Interface (Review)

- **Applications**
  - Can issue arbitrary sequence of `malloc` and `free` requests
  - Must never access memory not currently allocated
  - Must never free memory not currently allocated
    - Also must only use `free` with previously `malloc`'ed blocks

- **Allocators**
  - Can't control number or size of allocated blocks
  - Must respond immediately to `malloc` (can't reorder or buffer them!)
  - Must allocate blocks from free memory (no overtaking or overlapping)
  - Must align blocks so they satisfy all alignment requirements
  - Can't move the allocated blocks Boo!

Performance Goals (Review)

- **Goals:** Given some sequence of `malloc` and `free` requests $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$, maximize throughput and peak memory utilization
  - These goals are often conflicting…

1) Throughput

- Number of completed requests per unit time
- Example:
  - If 5,000 `malloc` calls and 5,000 `free` calls completed in 10 seconds, then throughput is 1,000 operations/second

Performance Goals

- Definition: ***Aggregate payload*** P_k
  - `malloc(p)` results in a block with a payload of `p` bytes
  - After request R_k has completed, the aggregate payload P_k is the sum of currently allocated payloads
- Definition: ***Current heap size*** H_k
  - Assume H_k is monotonically non-decreasing
    - Allocator can increase size of heap using `sbrk`

2) Peak Memory Utilization

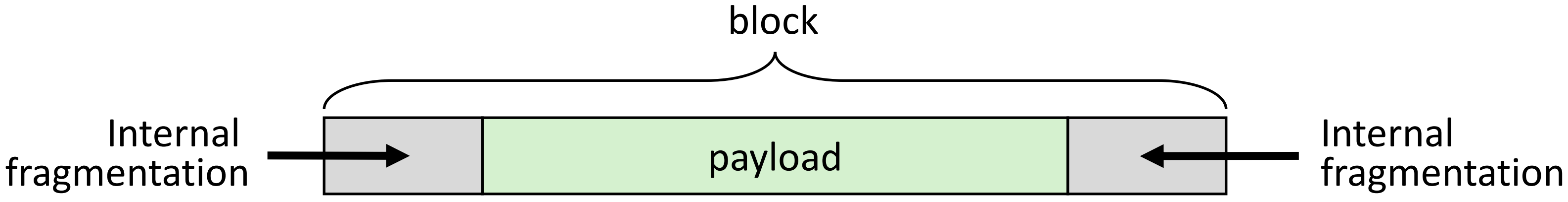
- Defined as $U_k = (\max_{i \le k} P_i)/H_k$ after k+1 requests
- Goal: maximize utilization for a sequence of requests
- Why is this hard? And what happens to throughput?

Fragmentation (Review)

- Poor memory utilization is caused by **fragmentation**
  - Sections of memory are not used to store anything useful, but cannot satisfy allocation requests
  - Two types: internal and external
- Recall: Fragmentation in `struct`s
  - Internal fragmentation was wasted space inside of the struct (between fields) due to alignment
  - External fragmentation was wasted space between struct instances (*e.g.*, in an array) due to alignment
- Now referring to wasted space in the heap inside or between allocated blocks

Internal Fragmentation

- For a given block, **internal fragmentation** occurs if payload is smaller than the block



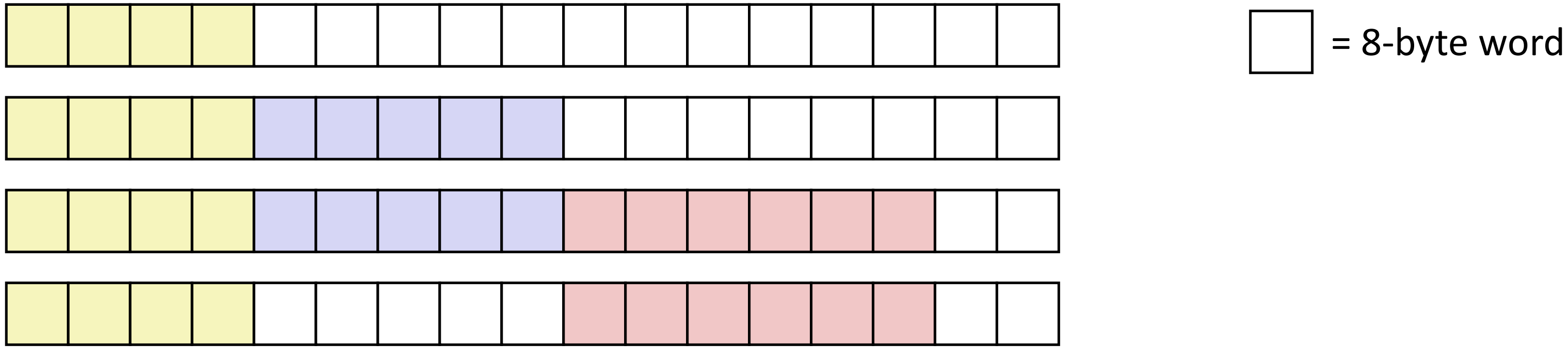
- **Causes:**
  - Padding for alignment purposes
  - Overhead of maintaining heap data structures (inside block, outside payload)
  - Explicit policy decisions (*e.g.*, return a big block to satisfy a small request)
- Easy to measure because only depends on past requests

Why? Faster in throughput, but bad for utility.

External Fragmentation

- For the heap, **external fragmentation** occurs when allocation/free pattern leaves “holes” between blocks
  - That is, the aggregate payload is non-continuous
  - Can cause situations where there is enough aggregate heap memory to satisfy request, but no single free block is large enough

```
p1 = malloc(32)
p2 = malloc(40)
p3 = malloc(48)
free(p2)
p4 = malloc(48)
```



Oh no! (What would happen now?)

- Don’t know what future requests will be
  - Difficult to impossible to know if past placements will become problematic

Polling Question

- Which of the following statements is FALSE?
  - A. Temporary arrays should not be allocated on the Heap yep, the stack!
  - B. `malloc` returns an address of a block that is filled with mystery data yep!
  - C. Peak memory utilization is a measure of both internal and external fragmentation yep!
  - [✓ D.] An allocation failure will ~~cause your program to stop~~ nah, just returns NULL
  - E. We're lost…

Implementation Issues

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?
- How do we pick a block to use for allocation (when many might fit)?
- What do we do with the extra space when allocating a structure that is smaller than the free block it is placed in?
- How do we reinsert a freed block into the heap?

Implementation Issues

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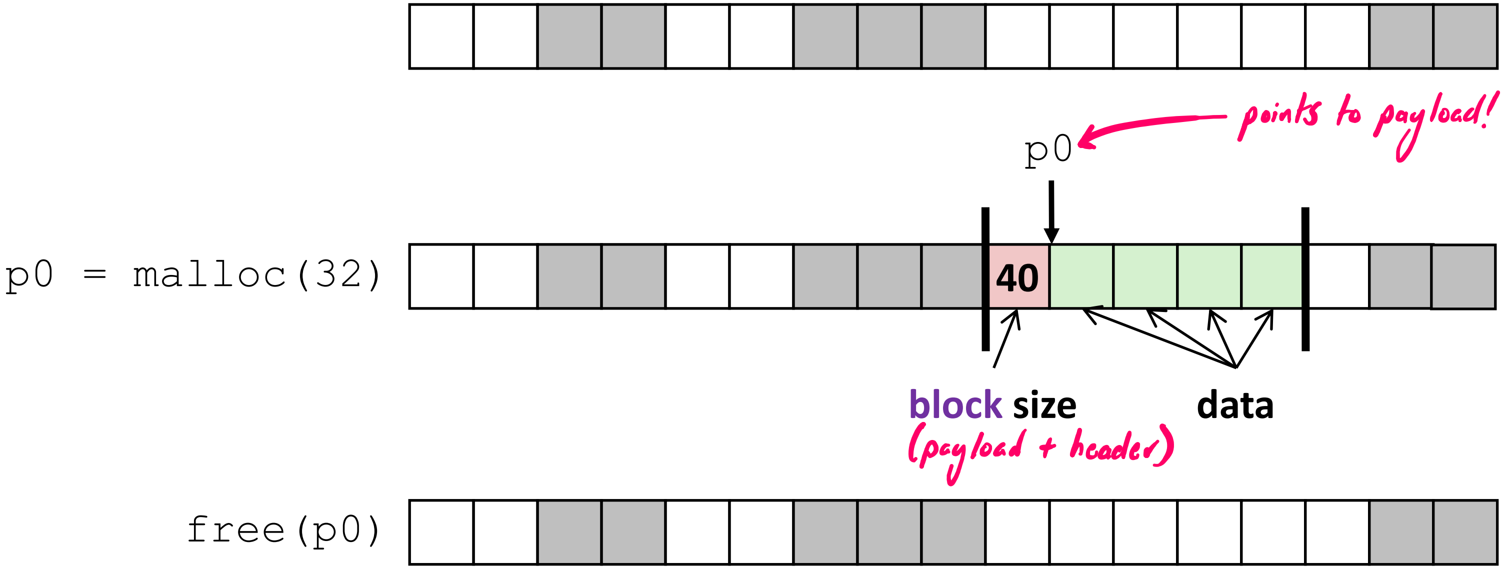
Knowing How Much to Free

- Standard method
  - Keep the length of a block in the word preceding the data
    - This word is often called the **header field** or just, **header**
  - Requires an <u>extra word for every allocated block</u>

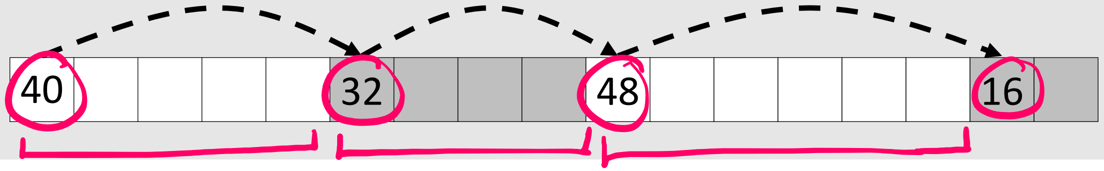
□ = 8-byte word (free)

▨ = 8-byte word (allocated)



Keeping Track of Free Blocks

1) *Implicit free list* using length – links all blocks using math
   - No actual pointers, and must check each block if allocated or free

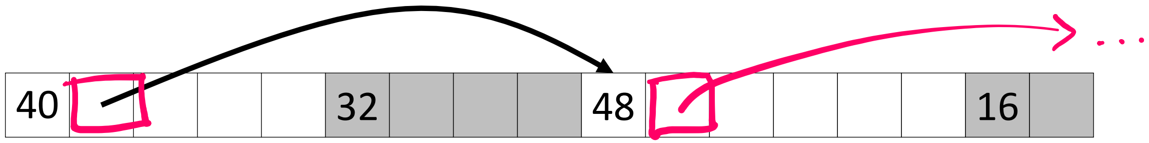


□ = 8-byte word (free)

▨ = 8-byte word (allocated)

2) *Explicit free list* among only the free blocks, using pointers

Lab 5 funness!



3) *Segregated free list*
   - Different free lists for different size "classes"

4) *Blocks sorted by size*
   - Can use a balanced binary tree (*e.g.*, red-black tree) with pointers within each free block, and the length used as a key

Out of scope of 351

Implicit Free Lists

1 word 1 bit!!

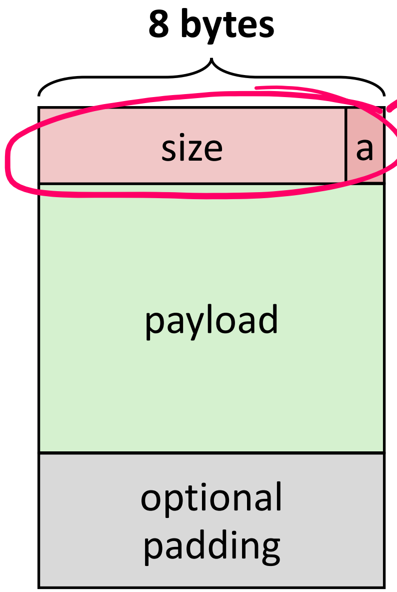
- For each block we need: **`size`**, **is-allocated?**
  - Could store using two words, but kinda wasteful…
- Standard trick
  - If blocks are aligned, some low-order bits of `size` are always 0
  - Use lowest bit as an allocated/free flag (fine as long as aligning to K>1)
  - When reading `size`, must remember to mask out this bit! Don't forget!

e.g., with 8-byte alignment, possible values for size:

```
00001000 = 8 bytes
00010000 = 16 bytes
00011000 = 24 bytes
. . .
```

Which is guaranteed!

Format of allocated and free blocks:



x

a = 1: allocated block
a = 0: free block

size: block size (in bytes)

payload: application data (allocated blocks only)

If `x` is the header:

```
x = size | a;

a = x & 1;

size = x & ~1;
```

Header Questions

- How many "flags" can we fit in our header if our allocator uses 16-byte alignment?

8-byte → 3 least significant bits are all 0, so up to 3 flags

16-byte → 4 least significant bits are all 0, so up to $\underline{4}$ flags

- If we placed a new "flag" in the second least significant bit, write out a C expression that will extract this new flag from the `header`!

Option #1: (header >> 1) & 1

Option #2: (header & 2) >> 1