Memory Allocation I

CSE 351 Autumn 2022

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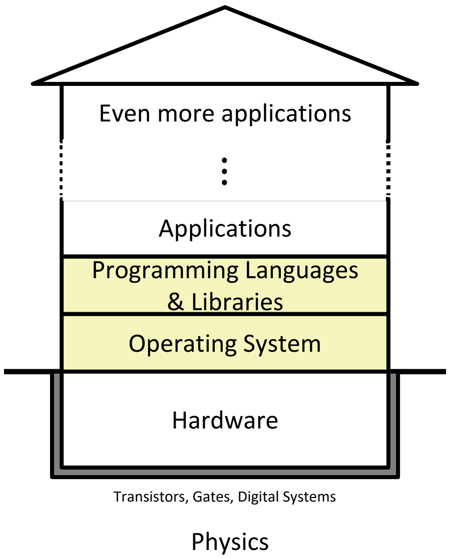
Adapted from
https://xkcd.com/1093/

Relevant Course Information

- hw22 due Wed, hw24 due Fri, hw25 due next Wed
- Lab 4 due tonight, Lab 5 released Wed
- Final Dec. 12-14
  - Structure will be very similar to the midterm
  - *Not* cumulative, focused on post-midterm material
  - Final review section on 12/8
  - Final review session planned for Zoom on 12/9
  - Regrade requests Dec. 17-18

The Hardware/Software Interface

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



- 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
- Questions from the Reading?

Multiple Ways to Store Program Data

- Static global data
  - *Fixed size* at compile-time
  - Entire *lifetime of the program* (loaded from executable)
  - 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 (*i.e.*, based on user-input)
  - Lifetime known only at runtime (long-lived data structures)

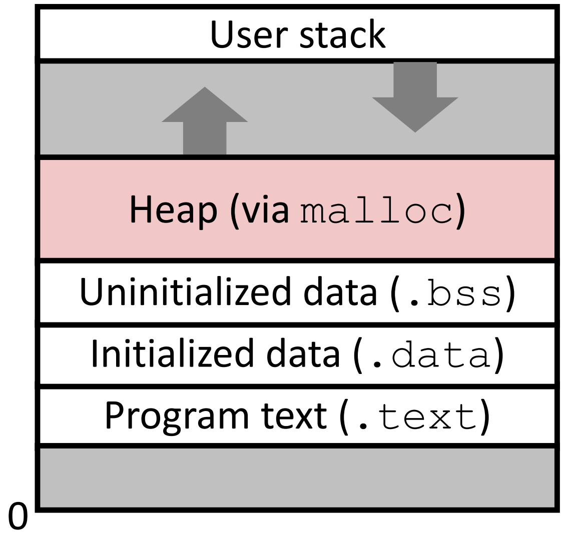
```
int array[1024];

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)

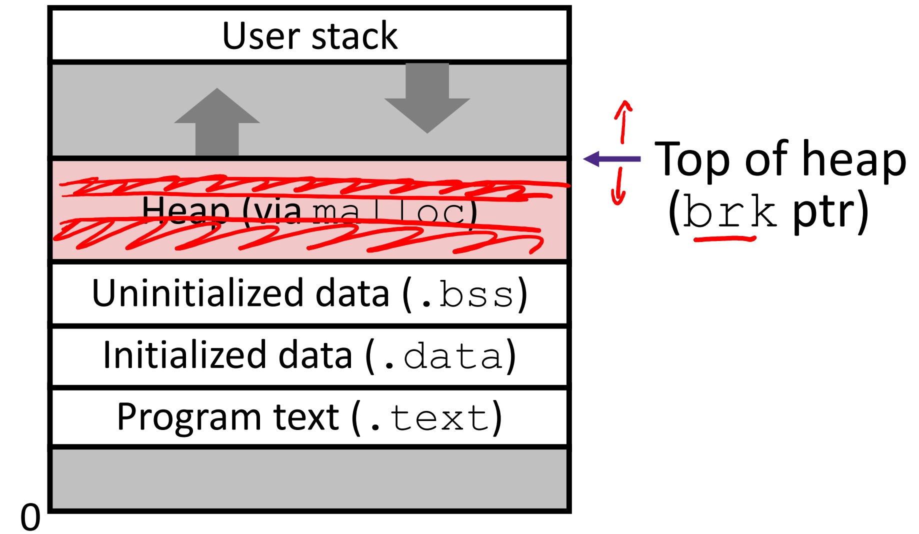
- Programmers use dynamic memory allocators to acquire virtual memory at run time
  - For data structures whose size (or lifetime) is known only at runtime
  - Manage the heap of a process' virtual memory:



- Types of allocators
  - ***Explicit* allocator:** programmer allocates and frees space
    - Example: `malloc` and `free` in C
  - ***Implicit* allocator:** programmer only allocates space (no free)
    - Example: garbage collection in Java, Caml, and Lisp

Dynamic Memory Allocation

- Allocator organizes heap as a collection of variable-sized heap *blocks*, which are either *allocated* or *free*
  - Allocator requests pages in the heap region; virtual memory hardware and OS kernel allocate these pages to the process
  - Application objects are typically smaller than pages, so the allocator manages heap blocks *within* pages
    - (Larger objects handled too; ignored here)



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
  - Returns a pointer to the beginning of the allocated block; `NULL` indicates a failed request
    - 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
- Good practices:
  - `ptr = (int*) malloc(n*sizeof(int));`
    - `sizeof` makes code more portable
    - `void*` is implicitly cast into any pointer type; explicit typecast will help you catch coding errors when pointer types don't match

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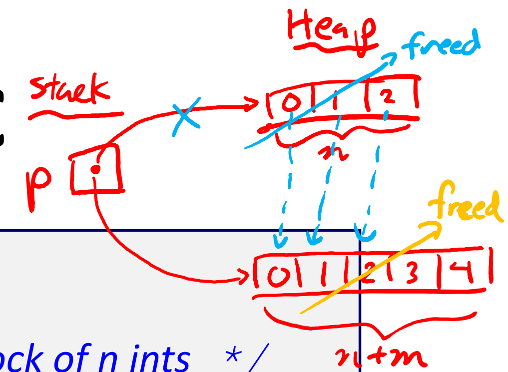
  - Different blocks not necessarily adjacent
- Related functions:
  - `void* calloc(size_t nitems, size_t size)`
    - “Zeros out” allocated block
  - `void* realloc(void* ptr, size_t size)`
    - Changes the size of a previously allocated block (if possible)
  - `void* sbrk(intptr_t increment)`
    -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

Freeing Memory in C (Review)

- Need to `#include <stdlib.h>`
- `void free(void* p)` doesn't change the pointer! (now points to deallocated memory)
  - Releases whole block pointed to by `p` to the pool of available memory
  - Pointer `p` must be the address *originally* returned by `m/c/realloc` (*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



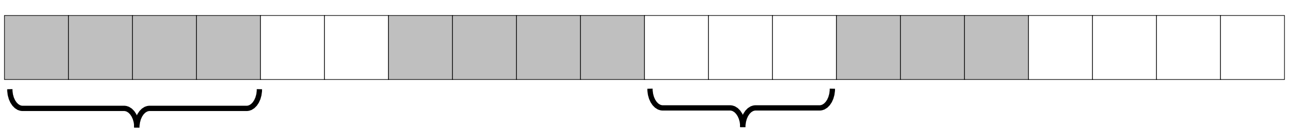

```
void foo(int n, int m) {
  int i, *p;
  p = (int*) malloc(n*sizeof(int));     /* allocate block of n ints */
  if (p == NULL) {                      /* check for allocation error */
    perror("malloc"); ← prints message related to errno
    exit(0);
  }
  for (i=0; i<n; i++)                   /* initialize int array */
    p[i] = i;
                                        /* add space for m ints to end of p block */
  p = (int*) realloc(p,(n+m)*sizeof(int));
  if (p == NULL) {                      /* check for allocation error */
    perror("realloc");
    exit(0);
  }
  for (i=n; i < n+m; i++)               /* initialize new spaces */
    p[i] = i;
  for (i=0; i<n+m; i++)                 /* print new array */
    printf("%d\n", p[i]);
  free(p);                              /* free p */
}
```

Notation

= 1 word = 8 bytes

- 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)
  - Book and old videos still use 4-byte *word*
    - Holdover from 32-bit version of textbook ☹

Heap:



Allocated block
(4 words)
32 bytes

Free block
(3 words)
24 bytes

Free word

Allocated word

Allocation Example

☐ = 8-byte word

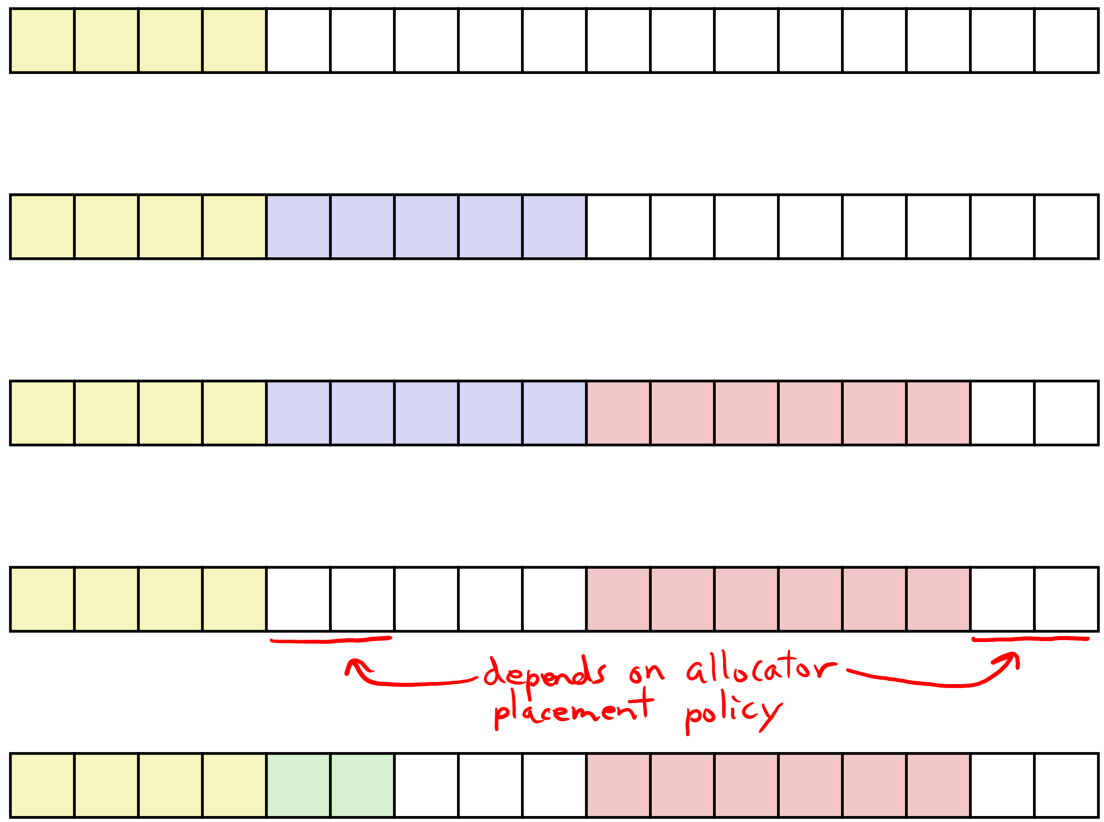
`p1 = malloc(32)`

`p2 = malloc(40)`

`p3 = malloc(48)`

`free(p2)`

`p4 = malloc(16)`



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)
  - Must allocate blocks from free memory (blocks can't overlap)
  - Must align blocks so they satisfy all alignment requirements
  - Can't move the allocated blocks (defragmentation not allowed) would break your pointers!

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?

pack fast or pack tight?

Fragmentation (Review)

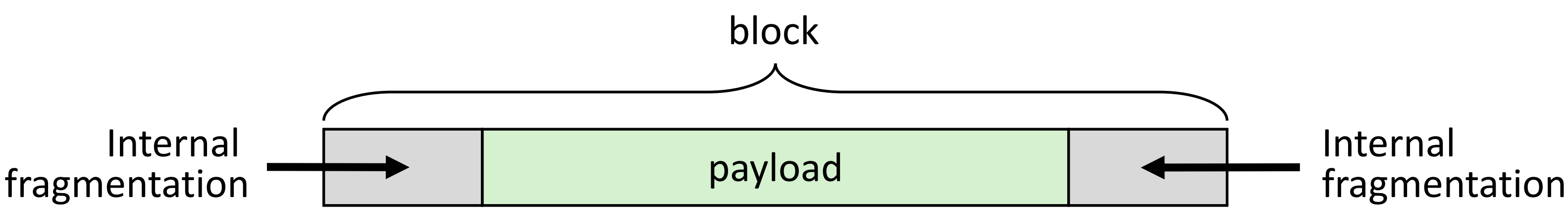
- Poor memory utilization is caused by *fragmentation*
  - Sections of memory are not used to store anything useful, but cannot satisfy allocation requests
  - Two types: *internal* and *external*

- **Recall:** Fragmentation in structs
  - 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



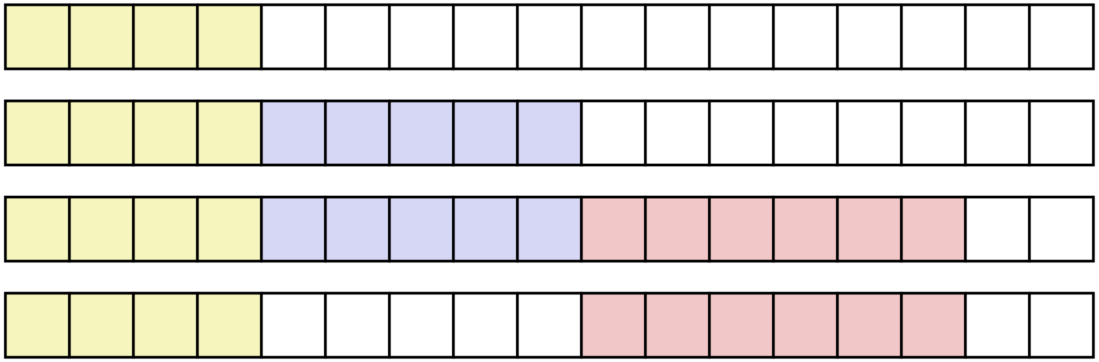
- **Causes:**
  - Padding for alignment purposes
  - Overhead of maintaining heap data structures (inside block, outside payload)
  - Explicit policy decisions (*e.g.*, return a big block to satisfy a small request) faster throughput to not individually size every block
- Easy to measure because only depends on past requests

External Fragmentation

□ = 8-byte word

- 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?
  - Vote in Ed Lessons

A. Temporary arrays should *not* be allocated on the Heap

should allocate on the Stack

B. `malloc` returns an address of a block that is filled with mystery data

allocates only; no initialization

C. Peak memory utilization is a measure of both internal and external fragmentation

$\frac{\text{aggregate payload}}{\text{heap size}}$

D. An allocation failure will cause your program to stop

just returns NULL

E. We're lost…

Implementation Issues

today

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?

next lecture

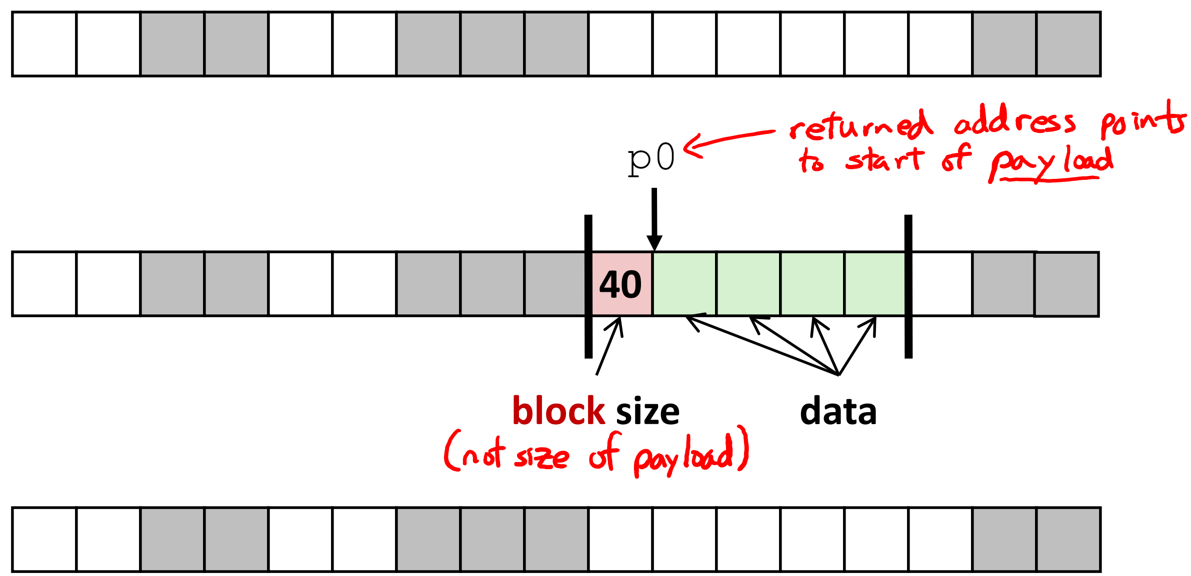
- How do we pick a block to use for allocation (when many might fit)?
- What do we do with the extra space when allocating a structure that is smaller than the free block it is placed in?
- How do we reinsert a freed block into the heap?

Knowing How Much to Free

= 8-byte word (free)

= 8-byte word (allocated)

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



`p0 = malloc(32)`

`free(p0)`

↳ read header at p0-8, free that much space

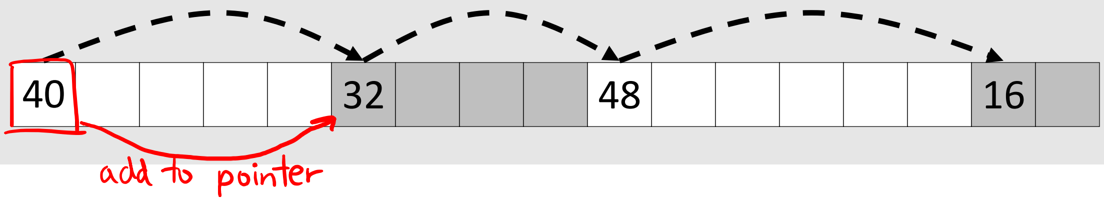
Keeping Track of Free Blocks

= 8-byte word (free)

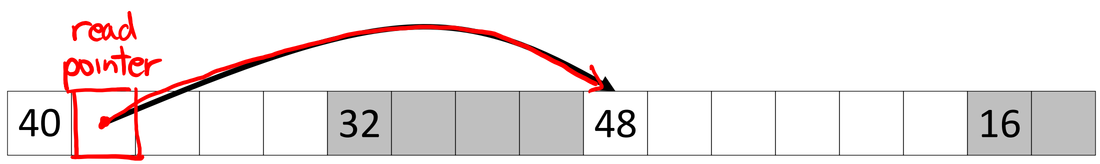
= 8-byte word (allocated)

1) *Implicit free list* using length – links all blocks using math

- No actual pointers, and must check each block if allocated or free



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



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

Implicit Free Lists

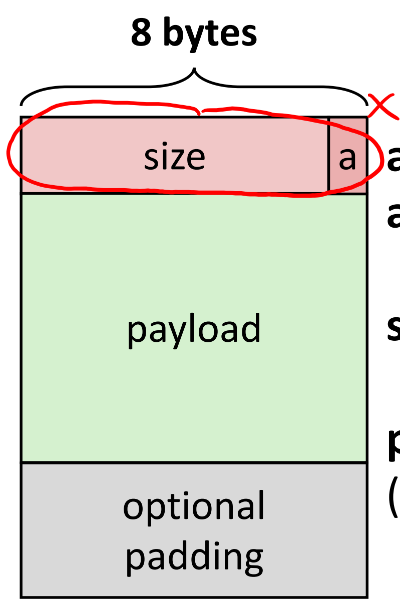
address is multiple of 8=0b1000

e.g., with 8-byte alignment, possible values for size:
- 00001000 = 8 bytes
- 00010000 = 16 bytes
- 00011000 = 24 bytes
- . . .

1 word 1 bit

- For each block we need: **`size`**, **is-allocated?**
  - Could store using two words, but 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!

Format of allocated and free blocks:



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

size: block size (in bytes)

payload: application data (allocated blocks only)

If `x` is first word (header):

or +

```
x = size | a;

a = x & 1;

size = x & ~1;
```

-2

Header Questions

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

all multiples of 16 have lowest 4 bits as zeros. ⇒ 16 = 0b10000

$\boxed{\text{4 flags}}$

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

two steps: ① mask out bit ②
② shift into LSB ①

`(header & 2) >> 1`

`(header >> 1) & 1`