Memory Allocation I

CSE 351 Autumn 2021

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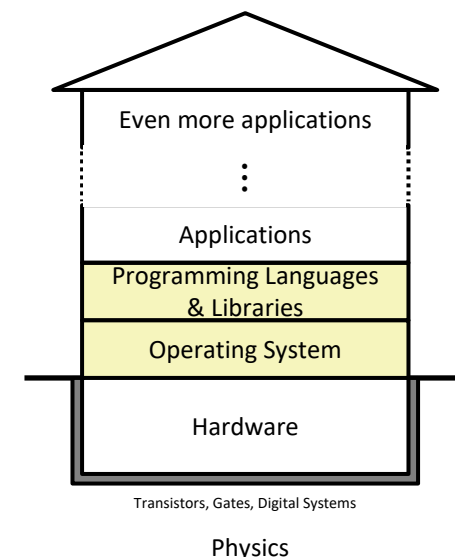
Sanjana Chintalapati

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

Relevant Course Information

❖ hw23 due Wed, hw25 due Fri, hw26 due next Wed

❖ Lab 4 due tonight, Lab 5 released Tue

❖ Final Dec. 13-15
  ▪ Structure will be very similar to the midterm
  ▪ *Not* cumulative, focused on post-midterm material
  ▪ Final review section on 12/9
  ▪ Regrade requests Dec. 18-19

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

❖ 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));
}
```
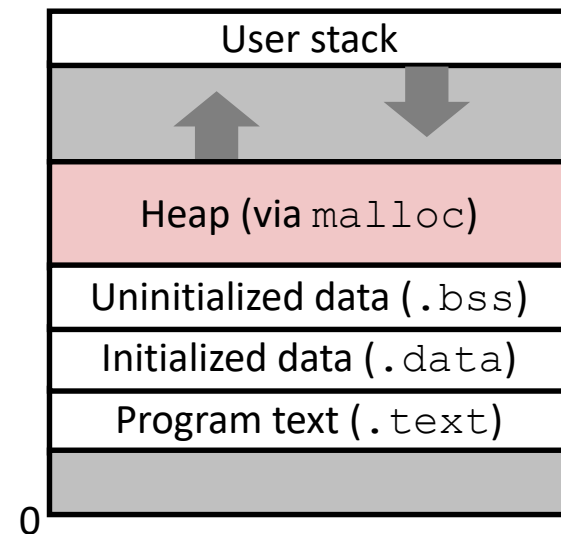
Memory Allocation

- ❖ **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:

User stack
↑   ↓
Heap (via `malloc`)
Uninitialized data (`.bss`)
Initialized data (`.data`)
Program text (`.text`)

0

❖ Types of allocators

   ▪ ***Explicit* allocator:** programmer allocates and frees space
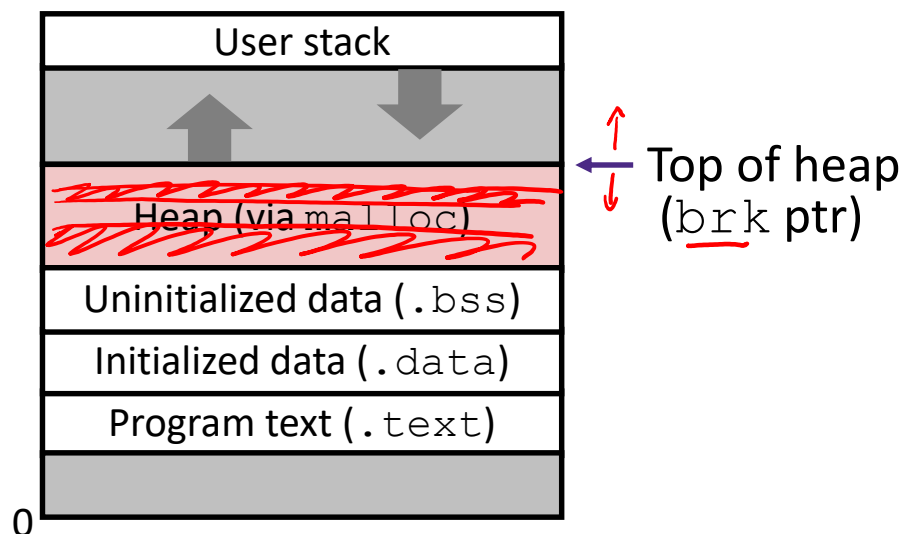
      • Example: `malloc` and `free` in C

   ▪ ***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 *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)

User stack
Heap (via `malloc`)
Uninitialized data (`.bss`)
Initialized data (`.data`)
Program text (`.text`)

← Top of heap (`brk` ptr)

0

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

Allocating Memory in C (Review)

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❖ 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)`
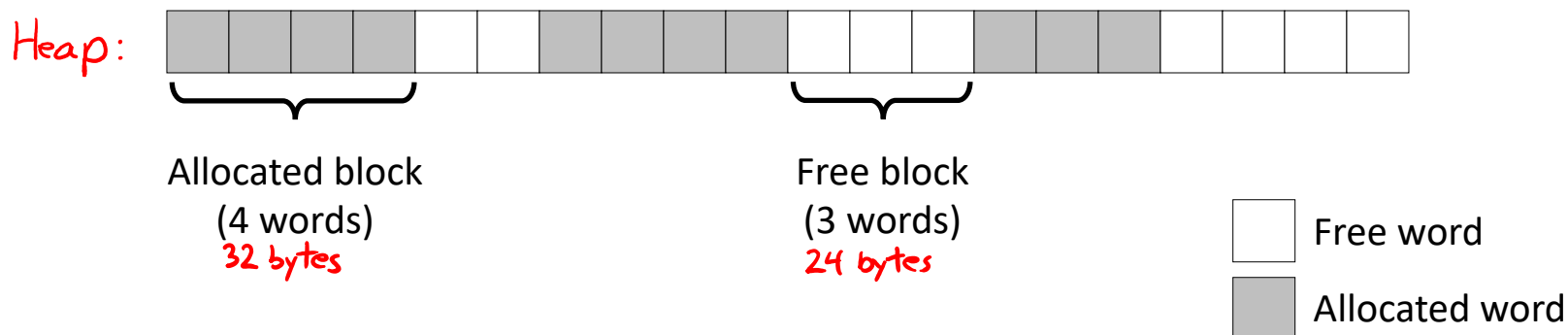
Memory Allocation Example in C

[handwritten annotations: Heap, freed, stack, p, n+m, freed, boxes labeled 0 1 2 and 0 1 2 3 4]
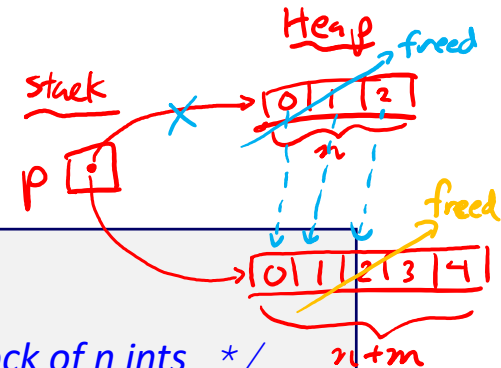
```c
void foo(int n, int m) {
  int i, *p;
  p = (int*) malloc(n*sizeof(int));  /* allocate block of n ints */
  if (p == NULL) {                   /* check for allocation error */
    perror("malloc");
    exit(0);
  }
  for (i=0; i<n; i++)                /* initialize int array */
    p[i] = i;

                                     /* 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 */
}
```

[handwritten: ① ② ③ numbered markers; "prints message related to errno" pointing to perror("malloc")]
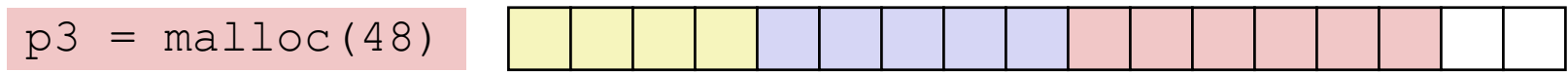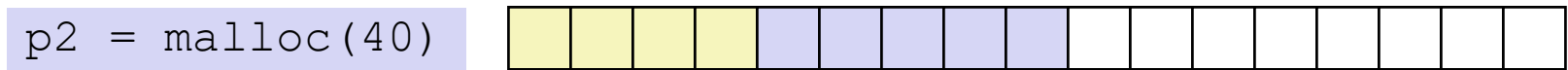
Notation

□ = 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:

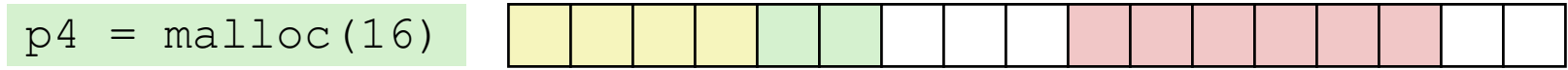Allocated block
(4 words)
32 bytes

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)

depends on allocator placement policy

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 <u>alignment</u> 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

  ▪ <u>Example</u>:

    • If 5,000 `malloc` calls and 5,000 `free` calls completed in 10 seconds, then throughput is 1,000 operations/second

Performance Goals

❖ <u>Definition</u>: *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

❖ <u>Definition</u>: *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: <u>maximize utilization</u> 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

block

Internal fragmentation → [   ] [payload] [   ] ← Internal fragmentation
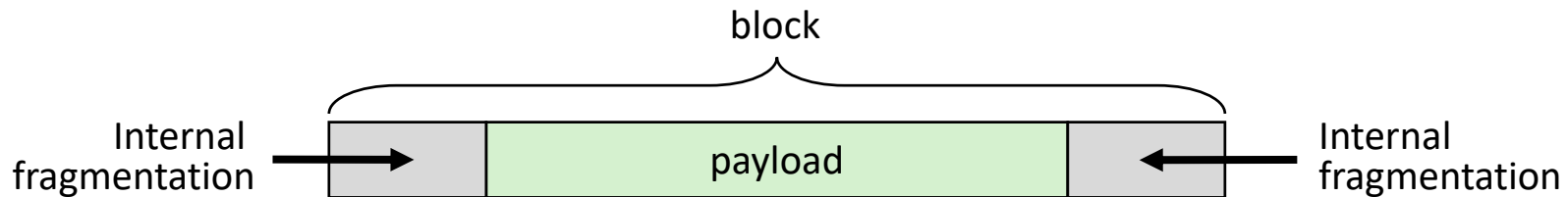
❖ **Causes:**
- ▪ <u>Padd</u>ing for alignment purposes
- ▪ Overhead of maintaining heap data structures (inside block, outside payload)
- ▪ Explicit policy decisions (*e.g.*, return a big block to satisfy a small request) *faster throughput to not individually size every block*

❖ Easy to measure because only depends on past requests

External Fragmentation
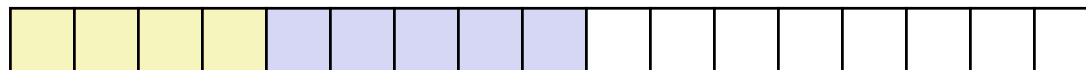
☐ = 8-byte word

❖ 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
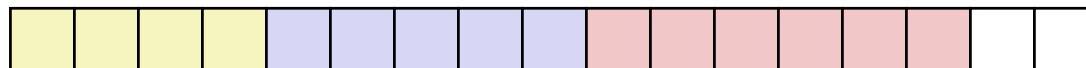
p1 = malloc(32)

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**

  aggregate payload / heap size

  D. **An allocation failure will cause your program to stop**

  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?
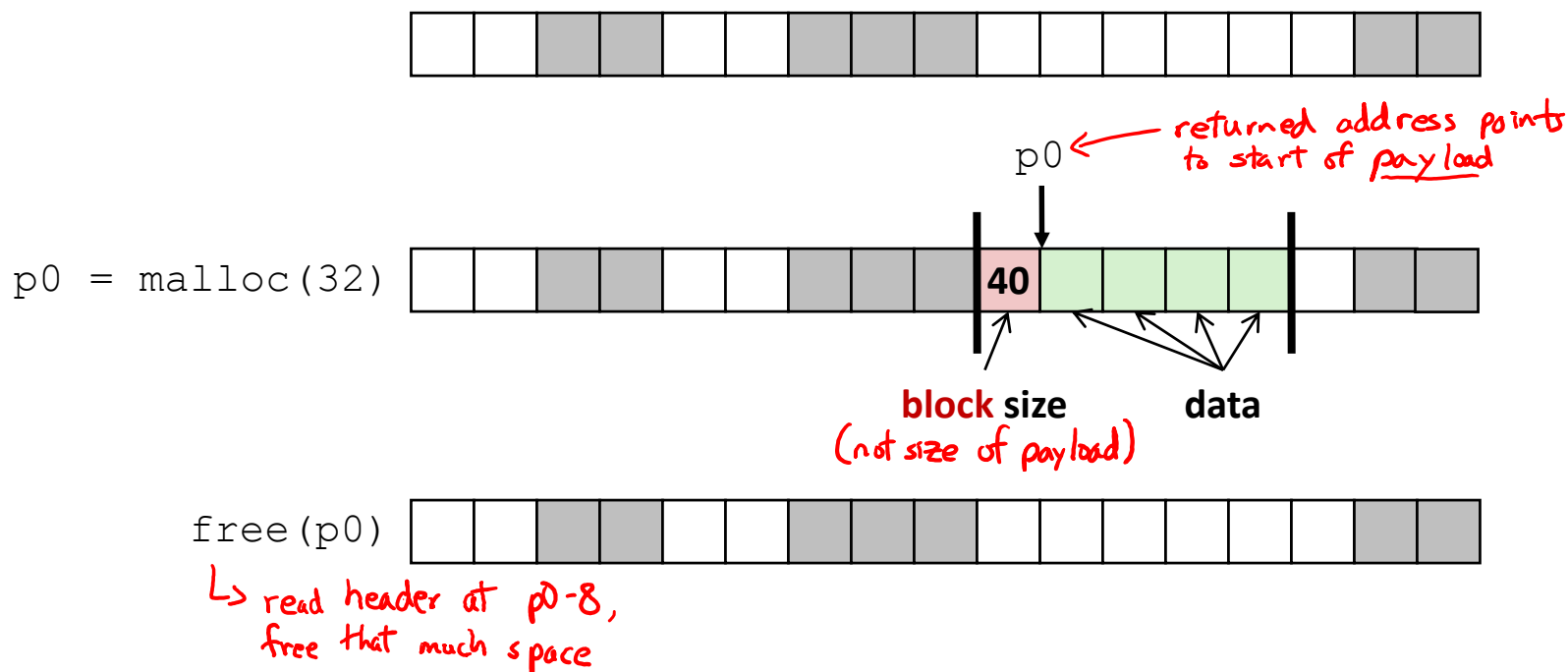
❖ How do we reinsert a freed block into the heap?

today

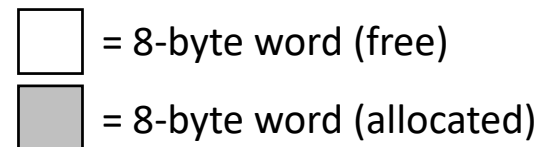*next lecture*

Knowing How Much to Free

☐ = 8-byte word (free)

▨ = 8-byte word (allocated)
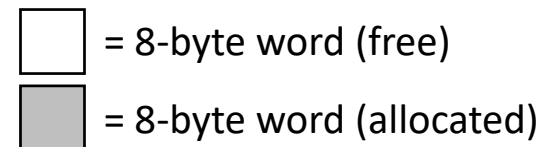
❖ Standard method

  ▪ 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

returned address points to start of payload

p0 = malloc(32)

40

block size
(*not size of payload*)

data

free(p0)

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

Keeping Track of Free Blocks

☐ = 8-byte word (free)

▨ = 8-byte word (allocated)
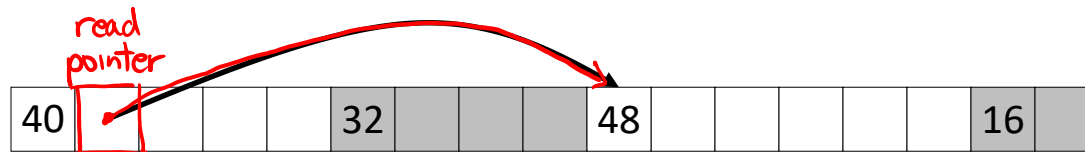
1) *Implicit free list* using length – links <u>all</u> blocks using <u>math</u>
   - No actual pointers, and must check each block if allocated or free

40   32   48   16

add to pointer
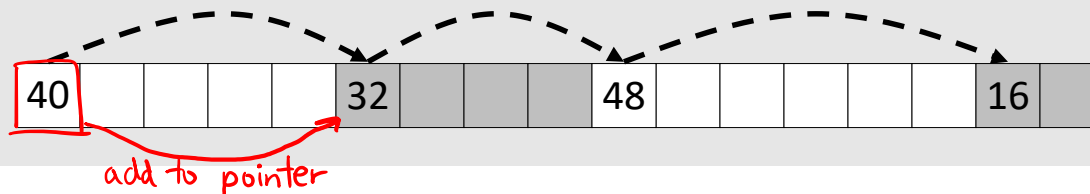
2) *Explicit free list* among <u>only the free blocks</u>, using pointers

(linked list!)

read pointer

40   32   48   16

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:
00001**000** = 8 bytes
00010**000** = 16 bytes
00011**000** = 24 bytes
. . .

❖ For each block we need: **size**, **is-allocated?**
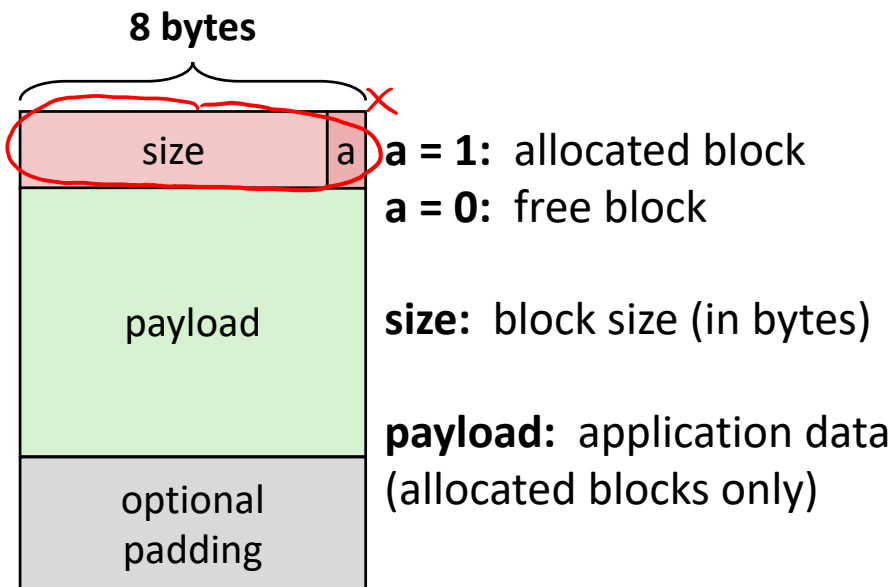
1 word   *1 bit*

  ▪ 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!

8 bytes

Format of allocated and free blocks:

size	a
payload	
optional padding	

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

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

❖ 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

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