Memory Allocation I

CSE 351 Summer 2021

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

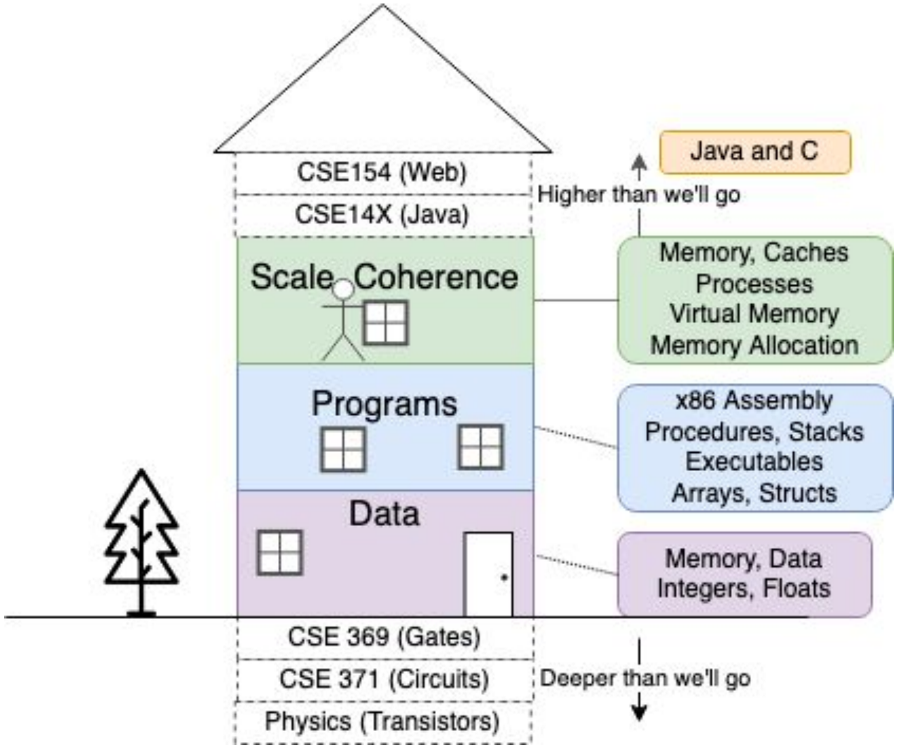
Gentle, Loving reminders

- hw18, 19 due tonight!
- hw20 due Friday (8/13)
- hw21 due Monday (8/16)

- Lab 5 is out!
  - Section tomorrow should help!
  - Lecture Friday should help too!
  - *If you're using late days, send us an email! We need to submit final grades!*

Unit 3: Scale, Coherence

- Caches, Process, Virtual Memory
  - Multiple programs? Larger programs?
- Metrics & Structures
- **Memory Allocation**



New topic, what's implicit?

Malloc: Everything all at once

- Both technically, and sociotechnically!
  - Builds on alignment, memory access, pointer arithmetic, structs
- Memory allocation is structural
  - *Much like this entire course!*
  - Historic, ideological

- Y'all will probably experience more historic structures, built from ideology & metrics
  - I want to make sure y'all have practice with analysis
  - Ideally yours, not mine

Let’s try a new thing!

- For this lecture (and beyond, if you so choose), if you see something, say something!
  - Use 🤖, or 🏡
- I’ll lovingly ask you to explain what’s implicit, what’s assumed
  - This, at some level, is a personal interpretation
  - How you’re feeling about the material, now.
- *Disclaimer: I really don’t know how this will go!*
  - We can try it together?

Socio-Technical Callouts

- **Embedded values:** CS tends to emphasize efficiency, performance, minimalism, ruggedness
  - *We shape our tools, and our tools shape us*
- **Ideology:** What's taken as fact, so much so that we don't even need to ask?
  - *Neoliberalism*: individualism, self-sufficiency, self-reliance, emphasize individuals over structures
  - Building upon structures without examining them!
- **Access:** What structures exist? Who were they designed for? Who can use them?
- **Metrics:** Choice of metric is ideological, and shapes structures; optimizing for the average case harms people, knowledge & positivism

Sound good?
Feel ok?
Anything you'd like to be different?

Back to memory allocation!

Learning Objectives

Understanding this lecture means you can:

- Differentiate between explicit and implicit memory allocators, and utilize C's memory allocation interface
- Define throughput and utilization, how fragmentation affects utilization, and how both determine allocator implementations
- Understand implicit free lists allocators
- Point out ideological assumptions in this lecture, with some help!

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)

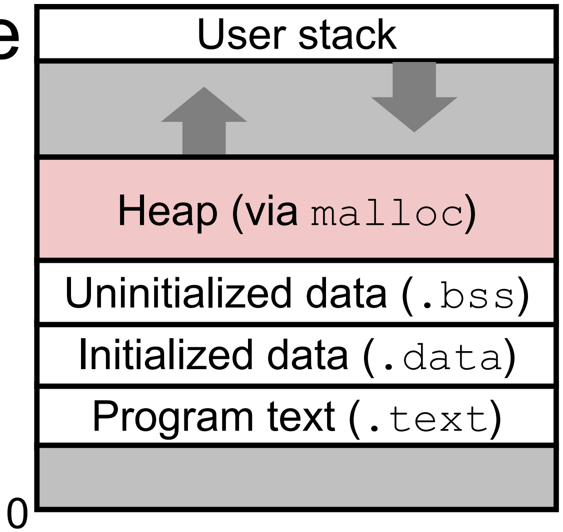
```
int array[1024];

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

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

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
- Common memory-related bugs in C

Dynamic Memory Allocation

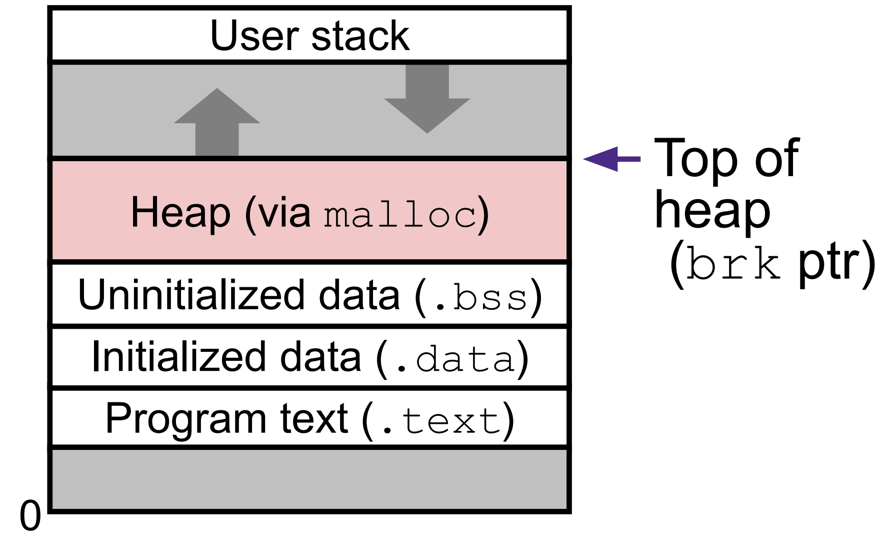
- Programmers use dynamic memory allocators to acquire virtual memory at run time
  - For data structures whose size (or lifetime) is known only at runtime
  - Manage the heap of a process' virtual memory:



- Types of allocators
  - ***Explicit* allocator:** programmer allocates & frees space
    - Example: `malloc` and `free` in C
  - ***Implicit* allocator:** programmer only allocates space
    - Example: garbage collection in Java, Caml, and Lisp

Dynamic Memory Allocation

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



Allocating Memory in C

- 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 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

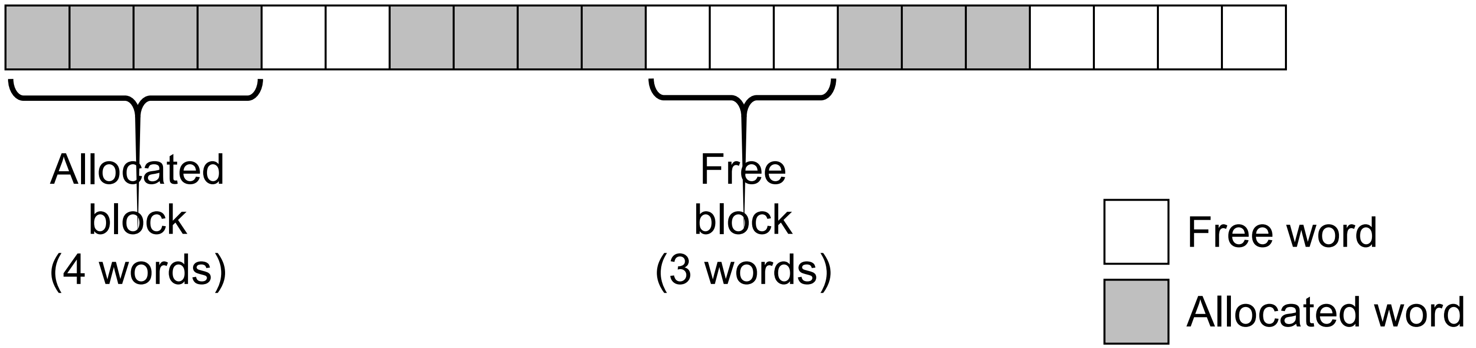
- Need to `#include <stdlib.h>`
- `void free(void* p)`
  - Releases whole block ref'd by `p` to the pool of available memory
  - Pointer `p` must be the address *originally* returned by `m/c/realloc` (*i.e.* beginning of the block), otherwise system exception raised
  - Don't call `free` on a block that has already been released or on `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");
    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

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



Allocation Example

☐ = 8-byte word

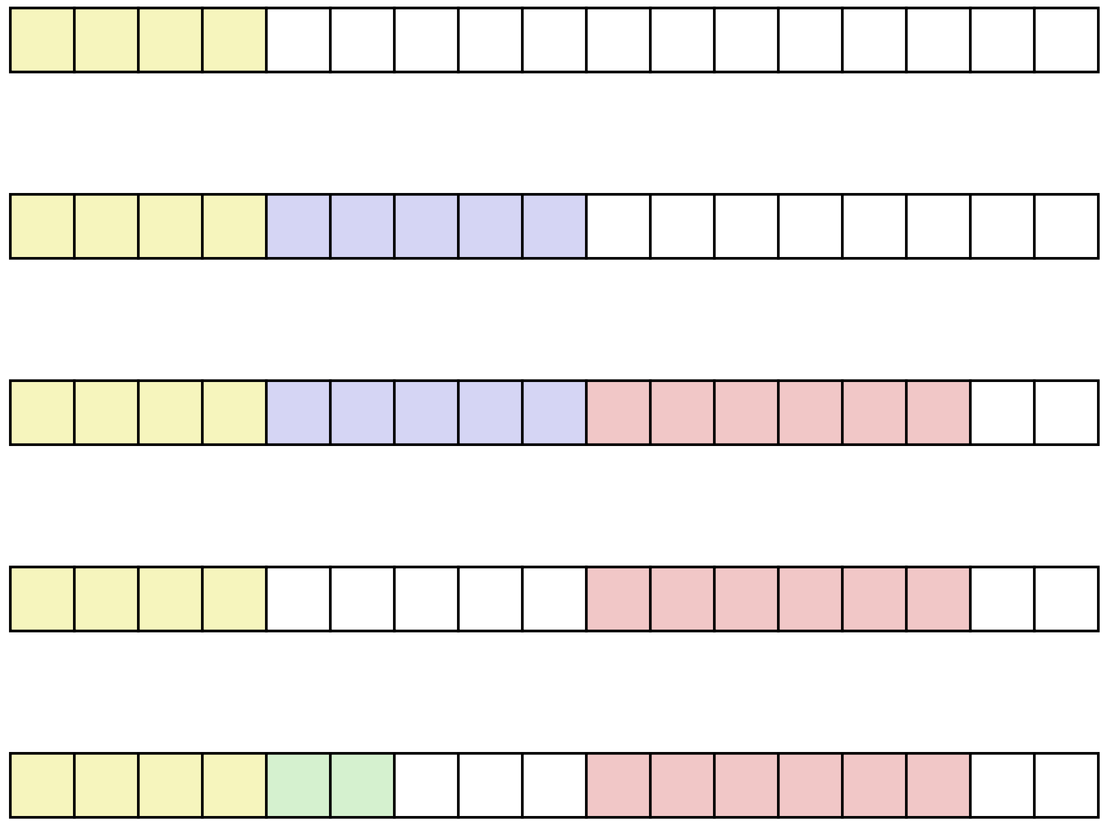
```
p1 = malloc(32)

p2 = malloc(40)

p3 = malloc(48)

free(p2)

p4 = malloc(16)
```



Implementation Interface

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

- **Allocators**
  - Can't control number or size of allocated blocks
  - Must respond immediately to `malloc`
  - Must allocate blocks from free memory
  - Must align blocks so they satisfy alignment requirements
  - Can't move the allocated blocks

Performance Goals

- **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

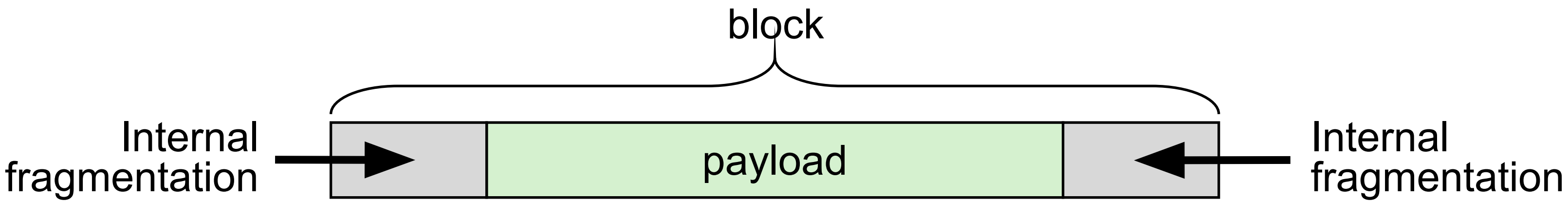
- Defined as $U_k = (\max_{i \le k} P_i)/H_k$ after k+1 requests
- Goal: maximize utilization for a sequence of requests
- Why is this hard? And what happens to throughput?

Fragmentation

- Poor memory utilization 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



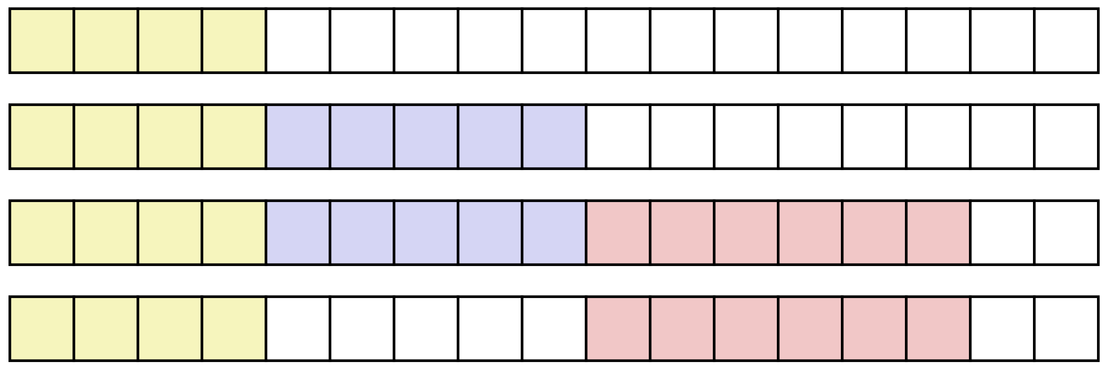
- **Causes:**
  - Padding for alignment purposes
  - Overhead of maintaining heap data structures (inside block, outside payload)
  - Explicit policy decisions (*e.g.* return a big block to satisfy a small request)
- Easy to measure because only depends on past requests

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

Checking in!

- Which of the following statements is FALSE?
  - 🐶 **Arrays that are sized at runtime should be stored on the heap**
  - 🐈 **`malloc` returns an address of a block that is filled with garbage**
  - 🐑 **Peak memory utilization is a measure of both internal and external fragmentation**
  - 🦄 **An allocation failure will cause your program to stop**
  - 🥶 **Help!**

Principles of memory allocation, feeling ok?

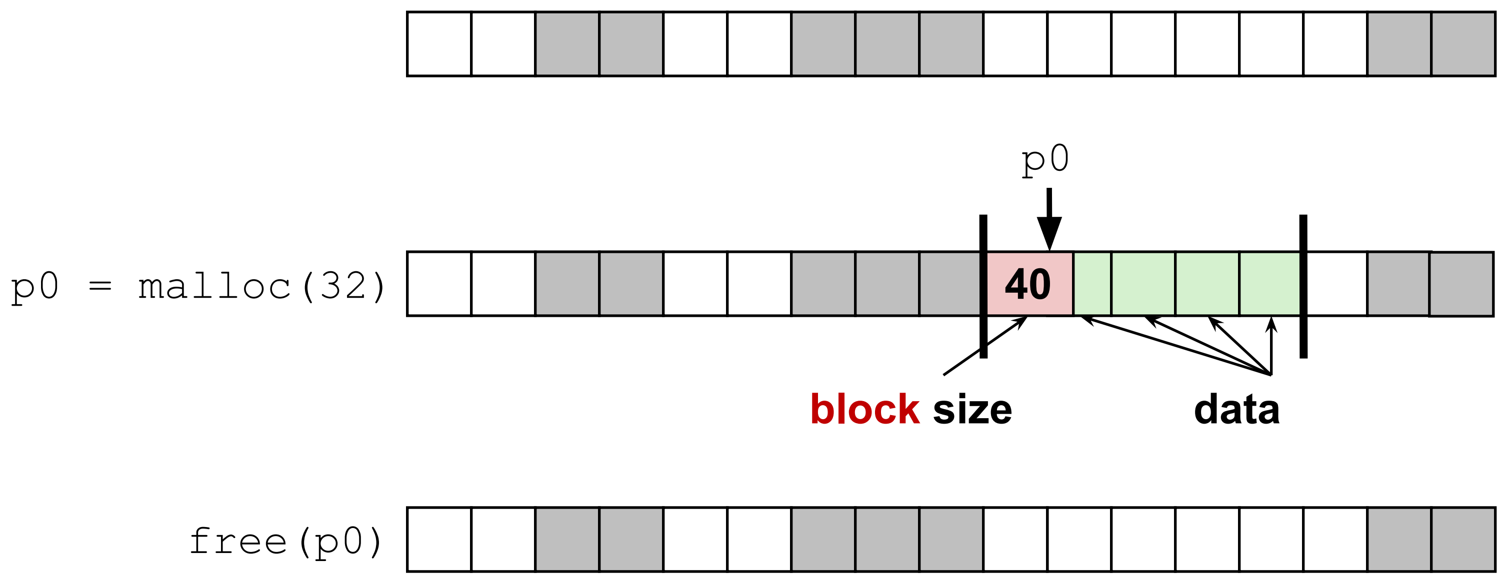
Implementation Issues

- 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?

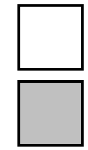
Knowing How Much to Free

□ = 8-byte word (free)
■ = 8-byte word (allocated)

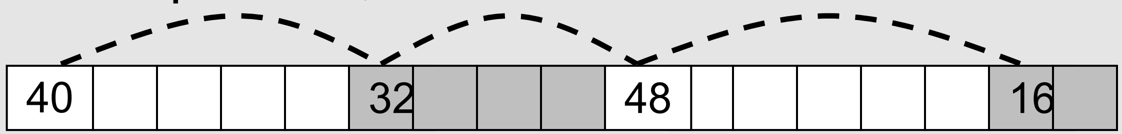
- Standard method
  - Keep block length in the word preceding the data
    - This word is often called the ***header field*** or ***header***
  - Requires an extra word for every allocated block



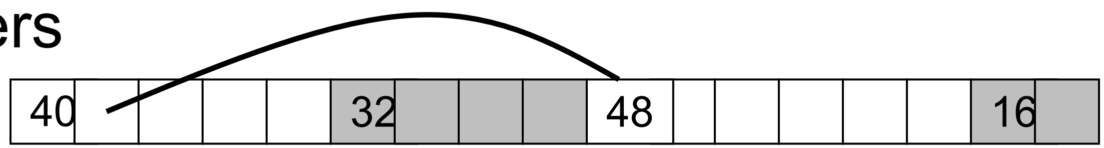
Tracking Free Blocks


= 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



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

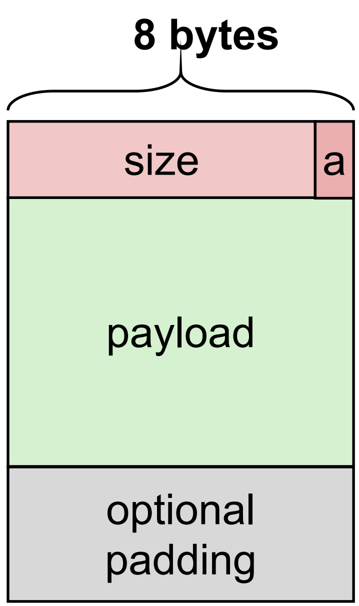
Implicit Free Lists

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

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

- 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)

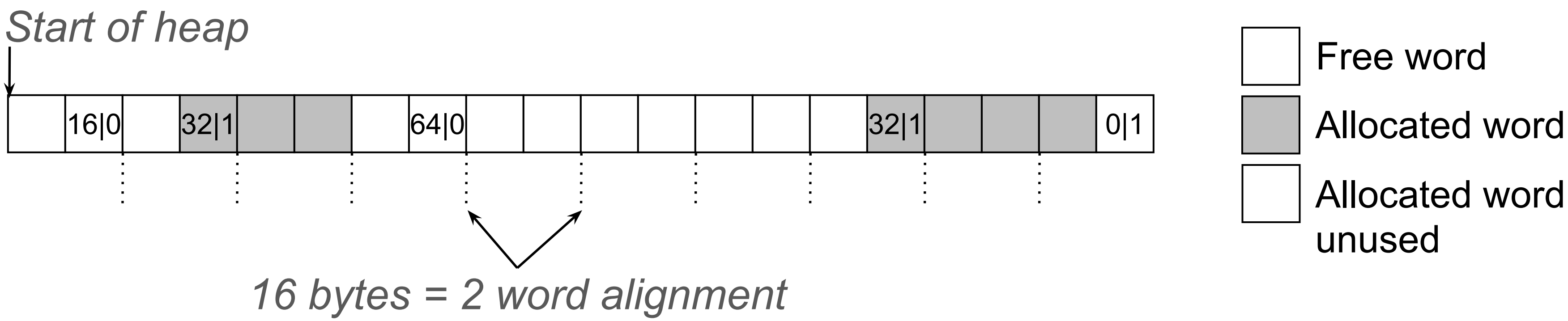
payload: application data (allocated blocks only)

Let X=header (first word)

```
x = size | a;
a = x & 1;
size = x & ~1;
```

Implicit Free List Example

- Each block begins with header (size in bytes and allocated bit)
- Sequence of blocks in heap (`size|allocated`): 16|0, 32|1, 64|0, 32|1



- 16-byte alignment for *payload*
  - May require initial padding (internal fragmentation)
  - Note `size`: padding is considered part of *previous* block
- Special one-word marker (0|1) marks end of list
  - Zero `size` is distinguishable from all other blocks

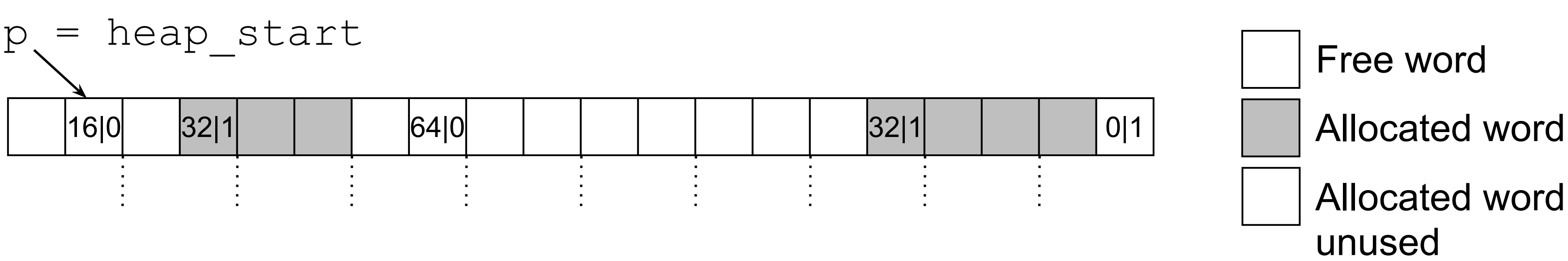
Finding a Free Block

(*p) gets the block *header*
(*p & 1) extracts the `allocated` bit
(*p & -2) extracts the `size`

- *First fit*
  - **Search list from beginning**, choose first free block

```
p = heap_start;
while ((p < end) &&        // not past end
       ((*p & 1) ||        // already allocated
        (*p <= len))) {    // too small
  p = p + (*p & -2);       // go to next block (UNSCALED +)
}                          // p points to selected block or end
```

  - Can take time linear in total number of blocks
  - In practice can cause "splinters" at beginning of list



Implicit List: Finding a Free Block

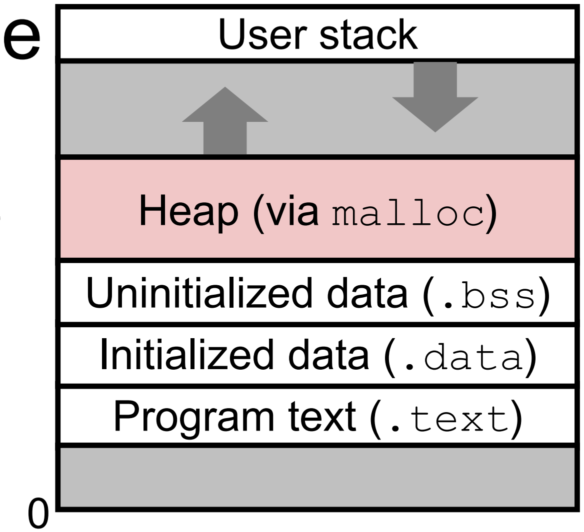
- *Next fit*
  - Like first-fit, but **search list starting where previous search finished**
  - Should often be faster than first-fit: avoids re-scanning unhelpful blocks
  - Some research suggests that fragmentation is worse
- *Best fit*
  - Search the list, choose the ***best*** free block: large enough AND with fewest bytes left over
  - Keeps fragments small—usually helps fragmentation
  - Usually worse throughput

Implicit free lists ok?

A few thoughts on allocators

Dynamic Memory Allocation

- 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:



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