Memory Allocation I

CSE 351 Spring 2019

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

Administrivia

- Homework 5, due Friday (5/31)
  - Processes and Virtual Memory
- Lab 5, coming soon, due Friday (6/7)
  - Memory Allocation
  - Recommended that you watch the Lab 5 helper videos

- **Final Exam:** Wed, 6/12, 12:30-2:20 pm in KNE 130

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

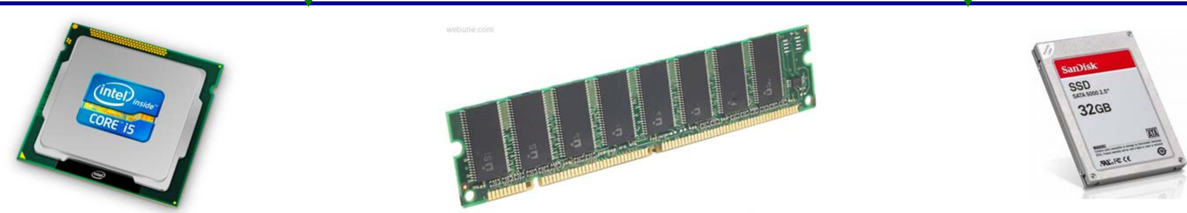
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10 OS X Yosemite

Computer system:



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)

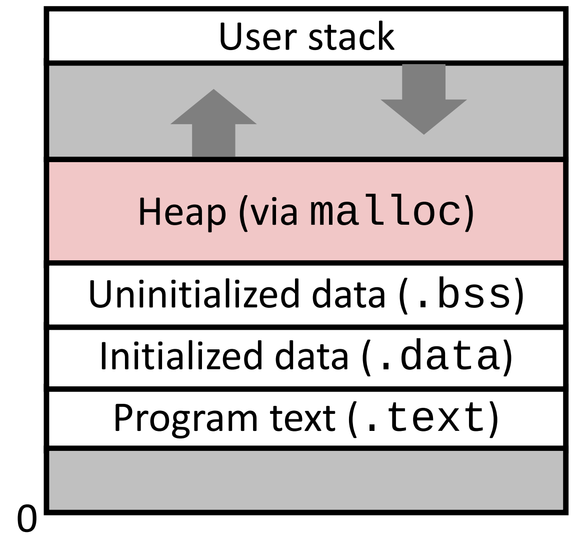
```
int array[1024];

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

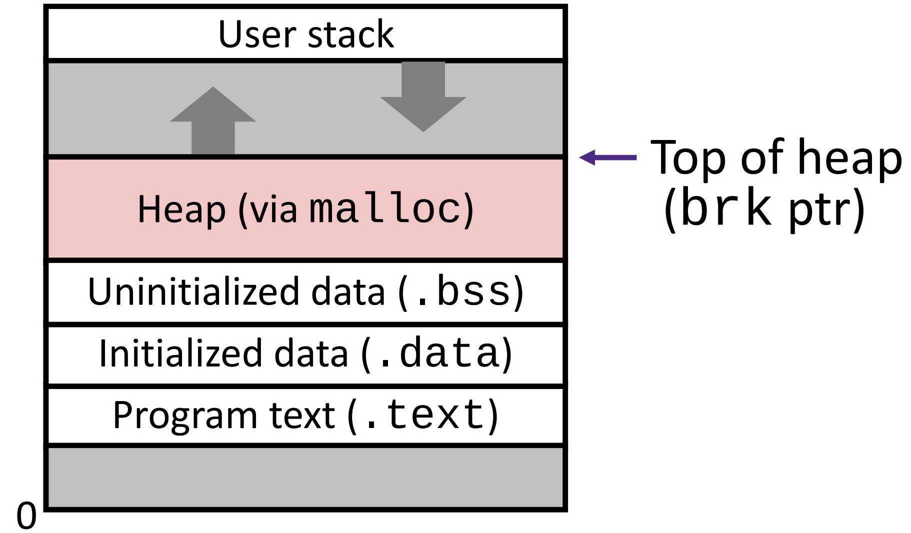
- Programmers use dynamic memory allocators to acquire virtual memory at run time
  - For data structures whose size (or lifetime) is known only at runtime
    user inputed data or data that changes continuously
  - Manage the heap of a process' virtual memory:



- 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 *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 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)` 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 or on `NULL`

Memory Allocation Example in C

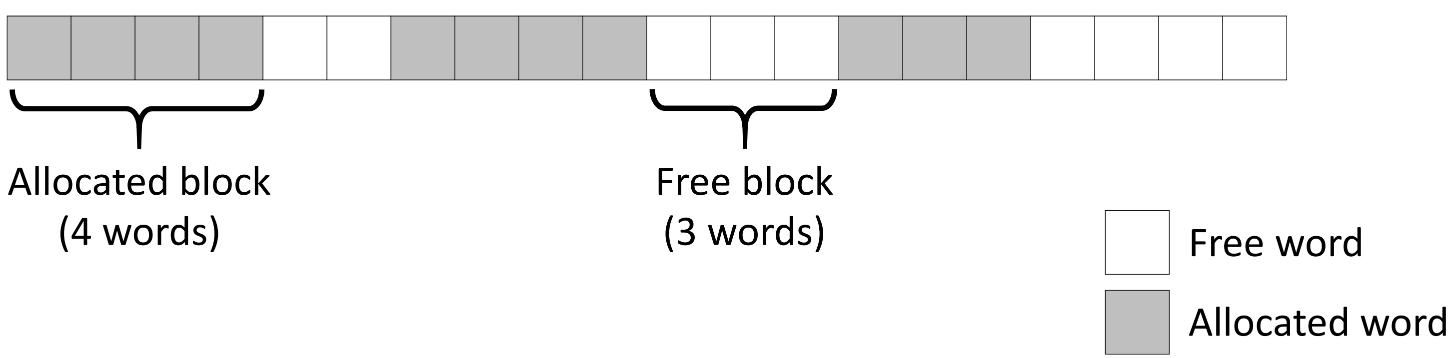
changes the amount of space in an already allocated block

```
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

= 1 word = 8 bytes

- We will draw memory divided into *words*
  - Each *word* can hold an 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 use 4-byte *word* instead of 8-byte *word*
    - Holdover from 32-bit version of textbook ☹



Allocation Example

= 8-byte word

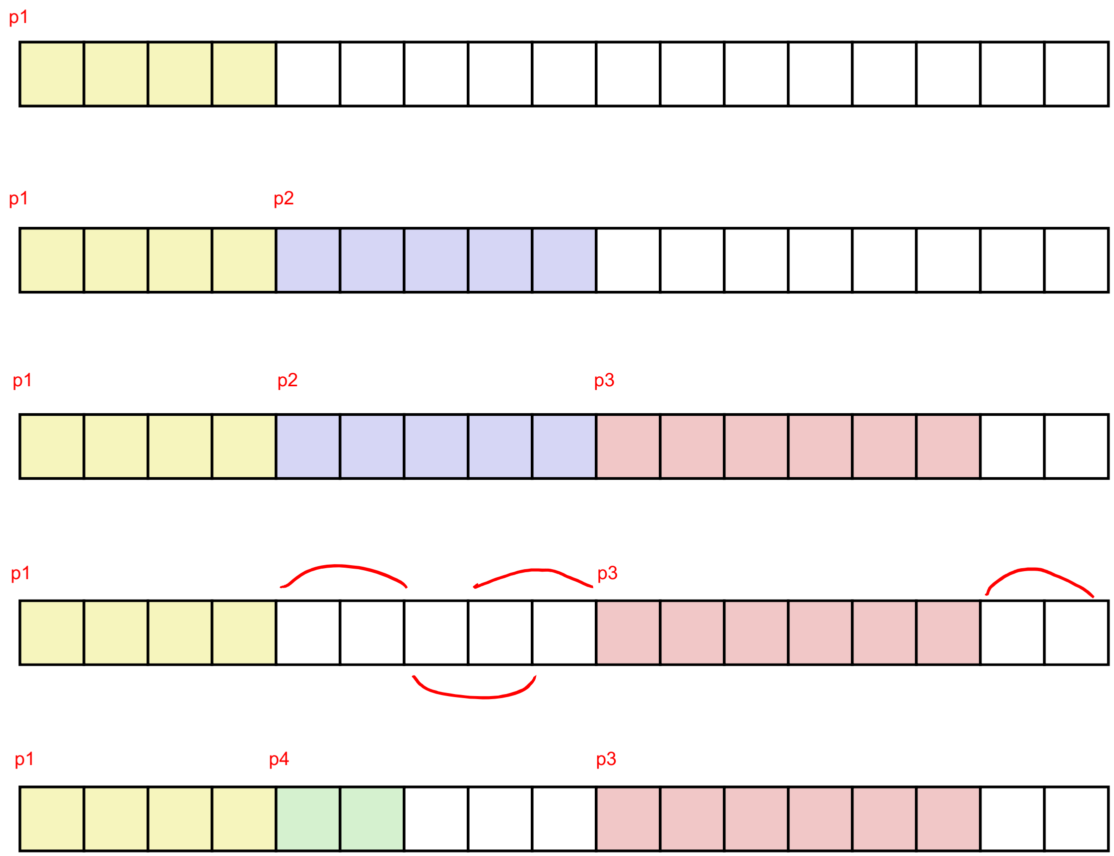
`p1 = malloc(32)`

`p2 = malloc(40)`

`p3 = malloc(48)`

`free(p2)`

`p4 = malloc(16)`



Implementation Interface

- **Applications**
  - 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

- **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

Not exactly max percentage of heap being used, as the heap grows. Instead it is the maximum percentage of the heap used CONSIDERING the MAXIMUM size of the heap (size at final timestep)

- 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

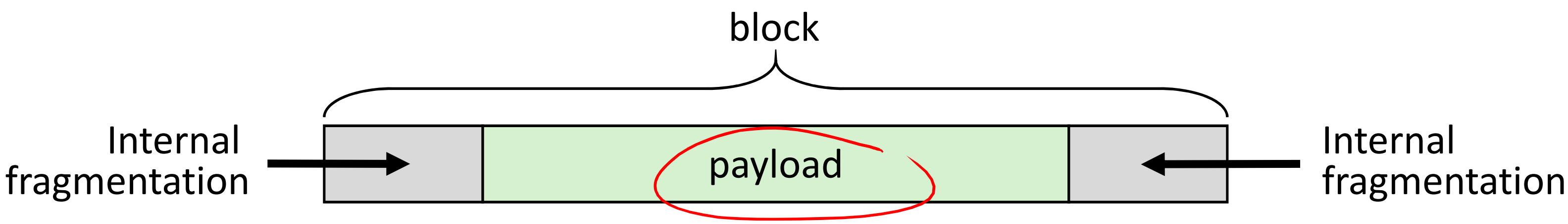
- Poor memory utilization is caused by *fragmentation*
  - Sections of memory are not used to store anything useful, but cannot satisfy allocation requests lots of small free blocks that are too small to fit anything
  - Two types: *internal* and *external*

- **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



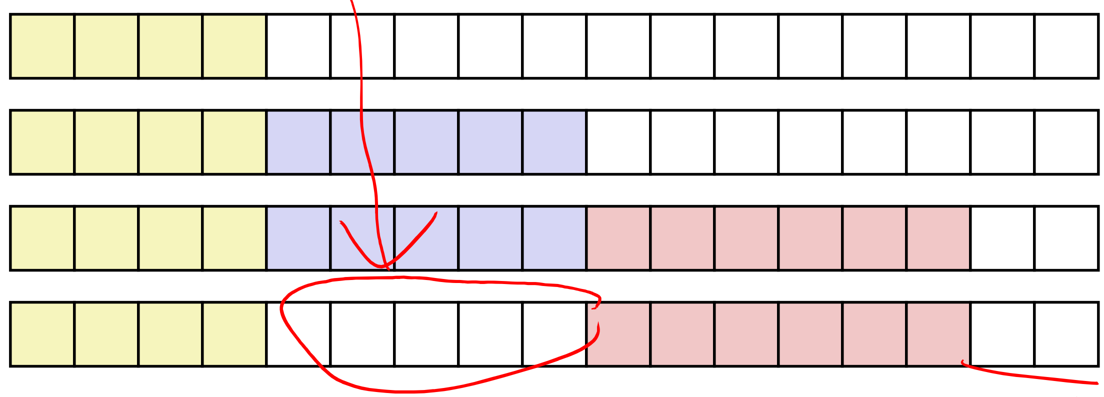
- **Causes:**
  - Padding for alignment purposes
  - Overhead of maintaining heap data structures (inside block, outside payload)
  - Explicit policy decisions (*e.g.* return a big block to satisfy a small request)
- Easy to measure because only depends on past requests

= 8-byte word

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?)

not

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

e.g. plenty of free space, but it is too spread out to be useful! Not a lot of contiguous space

Peer Instruction Question

- Which of the following statements is FALSE?
  - Vote at http://pollev.com/rea

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

should allocate on the Stack

T B. `malloc` returns an address of a block that is filled with garbage

allocates only; no initialization

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

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

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

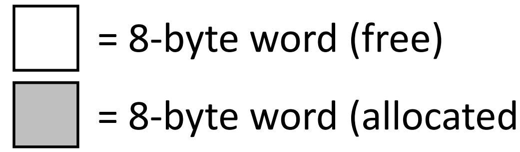
just returns NULL

E. We're lost…

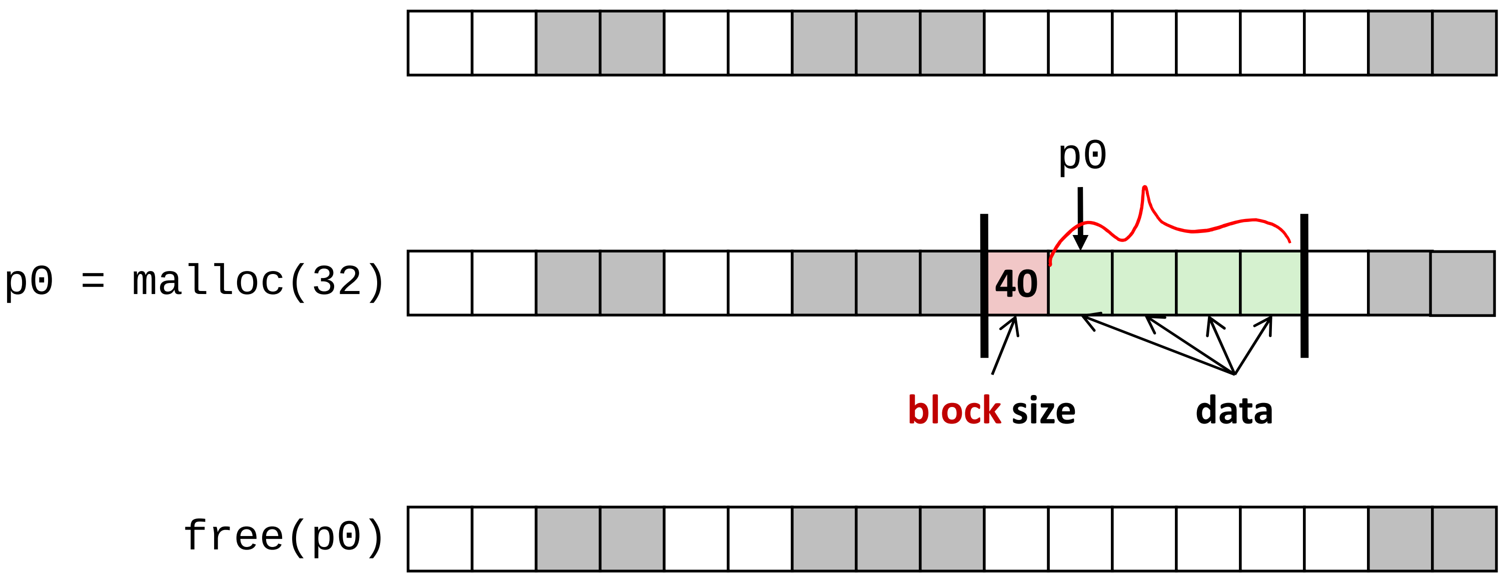
Implementation Issues

- 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?

Knowing How Much to Free



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



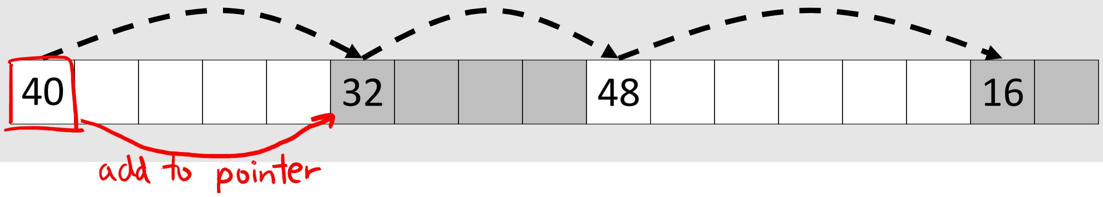
Keeping Track of Free Blocks

= 8-byte word (free)

= 8-byte word (allocated)

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

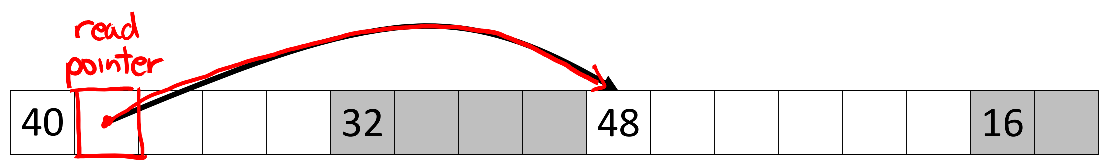
- No actual pointers, and must check each block if allocated or free



header just stores the size of a given block, so we can jump block to block just by reading the headers

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

(linked list!)



header stores the address of the next free block (can be more work to maintain when blocks are allocated.

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

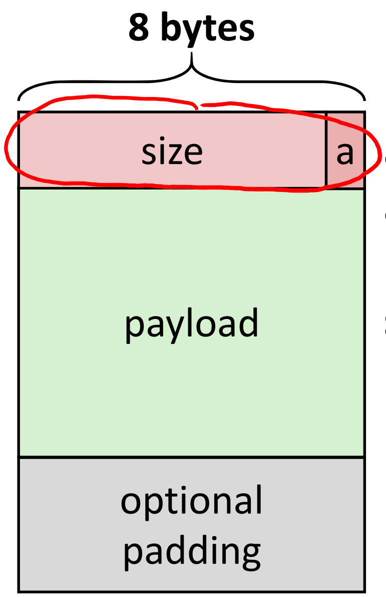
- For each block we need: **`size`, is-allocated?**
  - Could store using two words, but wasteful
- Standard trick
  - If blocks are aligned, some low-order bits of `size` are always 0
  - Use lowest bit as an allocated/free flag (fine as long as aligning to K>1)
  - When reading `size`, must remember to mask out this bit!

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
. . .

If it's a multiple of 8, the last 3 digits are always zero so why bother storing them?

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):

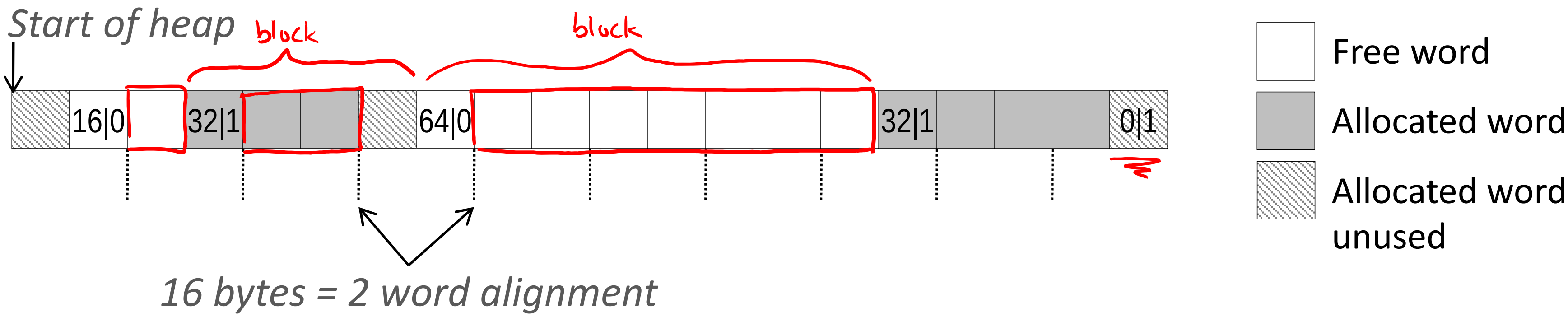
or +

```
x = size | a;

a = x & 1;

size = x & ~1;
```

-2

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 33 64 33 ← actual header data



- 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

Implicit List: 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 that fits:

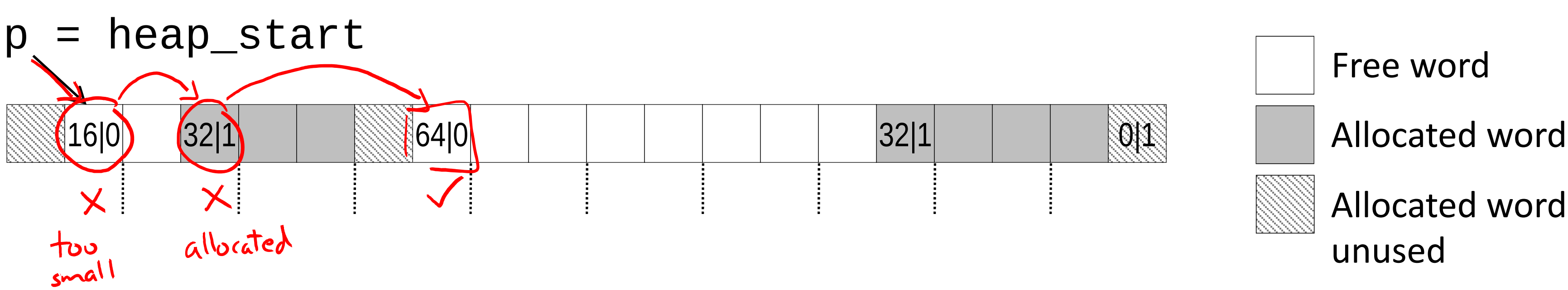
```
p = heap_start;
while ((p < end) &&        // not past end
       ((*p & 1) ||        // already allocated
        (*p <= len))) {    // too small
  p = p + (*p & -2);       // go to next block (UNSCALED +)
}                          // p points to selected block or end
```

equivalent to pointer arithmetic with char *

after loop exits

O(n)

  - 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