Memory Allocation I

CSE 351 Spring 2018

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

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();
```

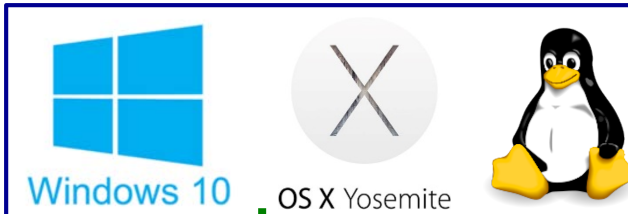
Assembly language:

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

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



Computer system:

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

Multiple Ways to Store Program Data

- Static global data
  - *Fixed size* at compile-time
  - Entire *lifetime of the program* (loaded from executable)
  - Some is writable, some not (e.g. string literals read-only)
- Stack-allocated data
  - Local/temporary variables
    - *Can* be dynamically sized (in some versions of C) but usually isn't
  - *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)

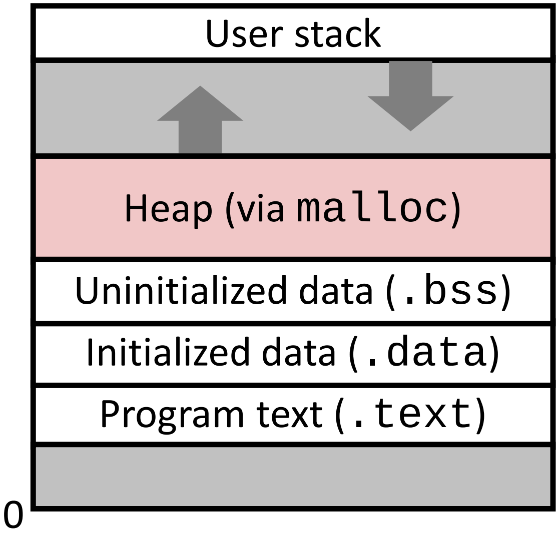
```
int array[1024];

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

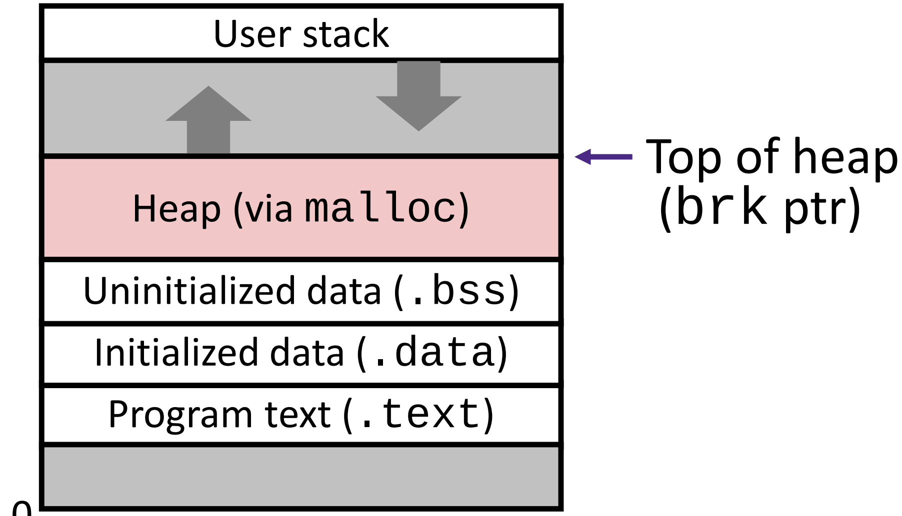
- Programmers use dynamic memory allocators to acquire virtual memory at run time
  - For data structures whose size or lifetime is known only at runtime
  - Manage the heap of a process' virtual memory:



- 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, OCaml, and Racket

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
  - **`size_t`** is just a **`typedef`** for some length unsigned number type
  - 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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- 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, else move*
  - `void* sbrk(intptr_t increment)`
    - Used internally by allocators to grow or shrink the heap

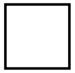
Freeing Memory in C

- Need to `#include <stdlib.h>`
- `void free(void* p)`
  - Releases whole block pointed to by `p` 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 throws system exception
  - Don't call `free` on a block that has already been released or on `NULL`

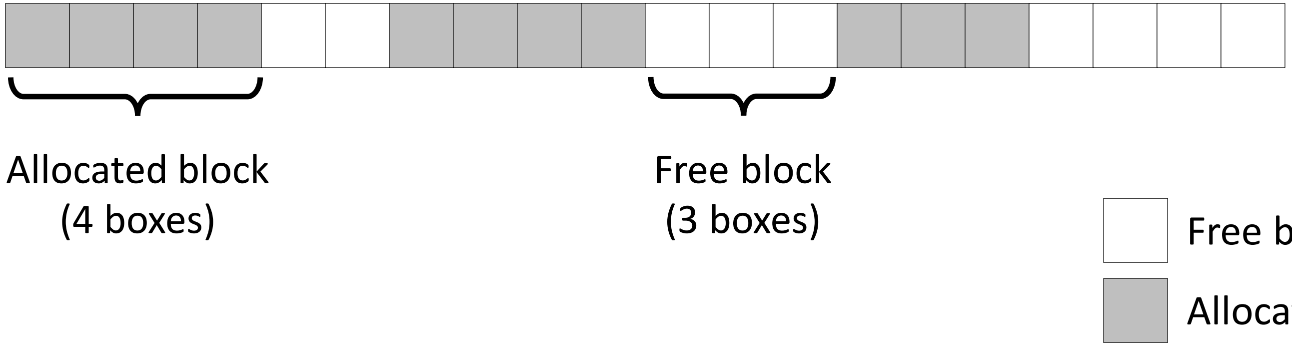
Memory Allocation Example in C

```
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 *boxes*
  - Each *box* can hold an `int` (32 bits/4 bytes)
  - Allocations will be in sizes that are a multiple of boxes, i.e. multiples of 4 bytes
  - Book and old videos use *word* instead of *box*
    - Holdover from 32-bit version of textbook ☹



Allocation Example

☐ = 4-byte box

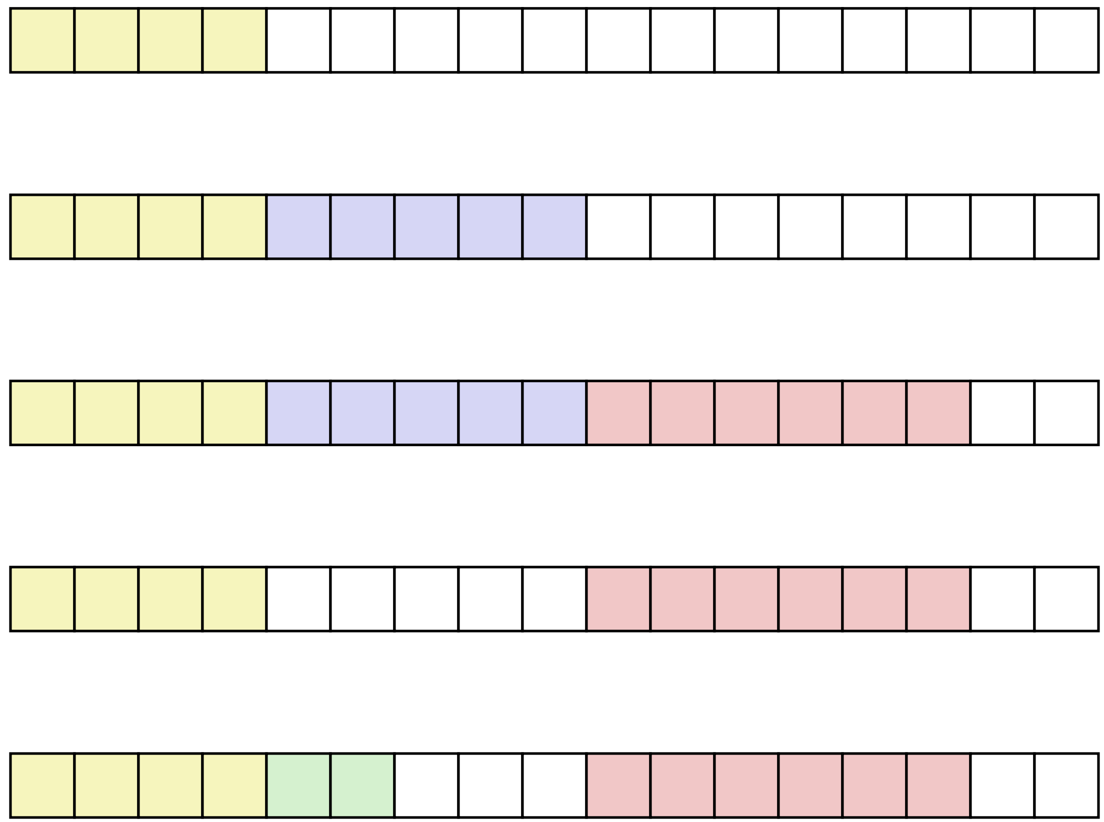
```
p1 = malloc(16)

p2 = malloc(20)

p3 = malloc(24)

free(p2)

p4 = malloc(8)
```



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`
  - Must allocate blocks from free memory
  - Must align blocks so they satisfy all 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

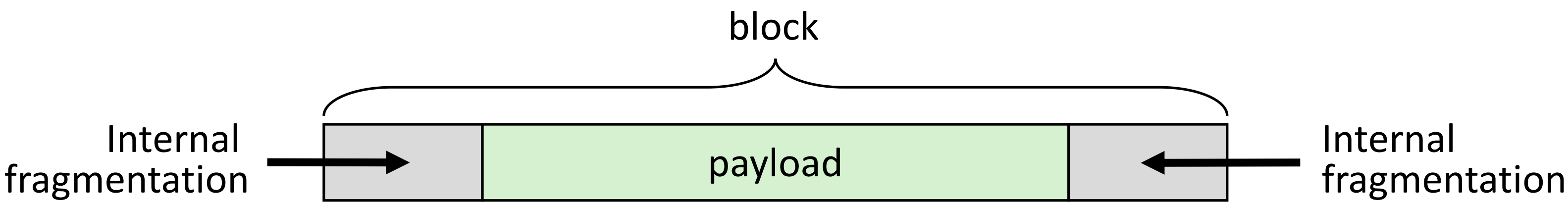
- Poor memory utilization is caused by *fragmentation*
  - Sections of memory are not used to store anything useful, but cannot satisfy allocation requests
  - Two types: *internal* and *external*

- **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



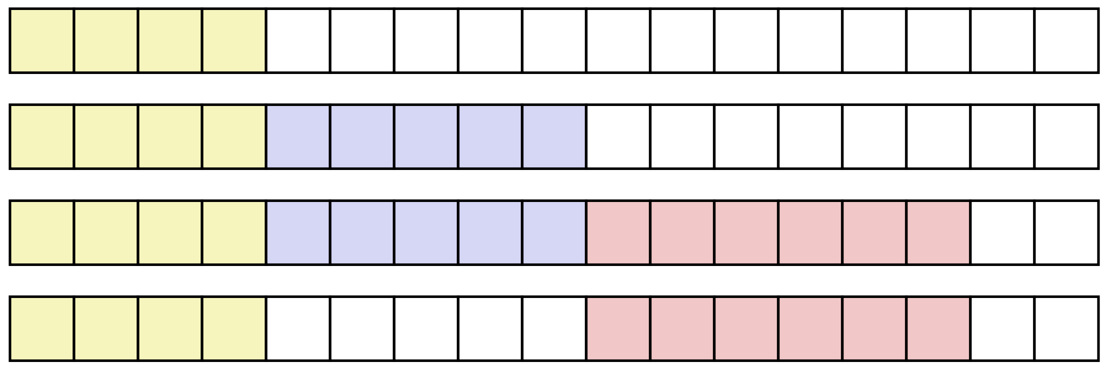
- **Causes:**
  - Padding for alignment purposes
  - Overhead of maintaining heap data structures (inside block, outside payload)
  - Explicit policy decisions (e.g. return a big block to satisfy a small request)
- Easy to measure because only depends on past requests

External Fragmentation

= 4-byte box

- 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(16)
p2 = malloc(20)
p3 = malloc(24)
free(p2)
p4 = malloc(24)
```



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

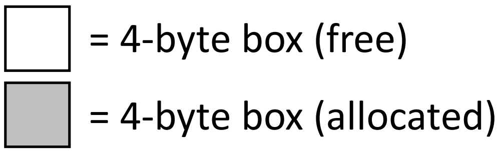
Peer Instruction Question

- Which of the following statements is FALSE?
  - A. Temporary arrays should *not* be allocated on the Heap
  - B. `malloc` returns an address filled with garbage
  - C. Peak memory utilization is a measure of both internal and external fragmentation
  - D. An allocation failure will cause your program to stop
  - E. We're lost…

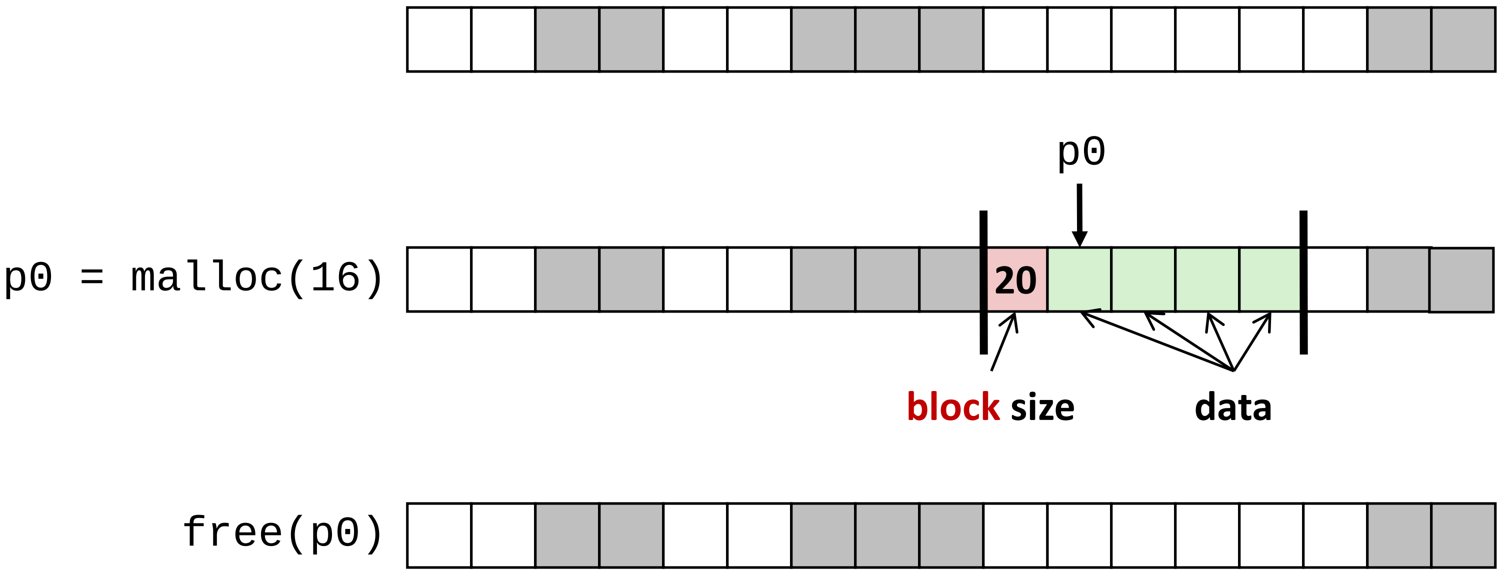
Implementation Issues

- 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?

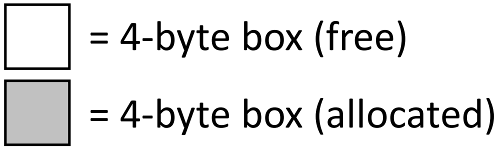
Knowing How Much to Free



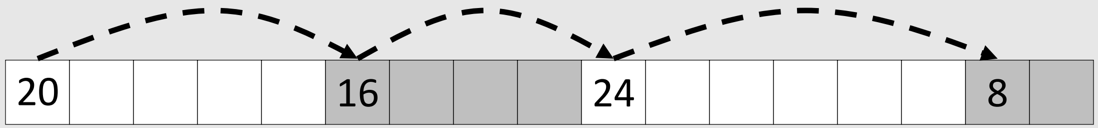
- Standard method
  - Keep the length of a block in the box preceding the block
    - This box is often called the ***header field*** or ***header***
  - Requires an extra box for every allocated block



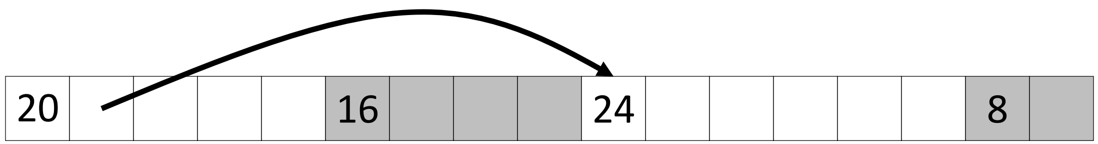
Keeping Track of Free Blocks



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



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



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

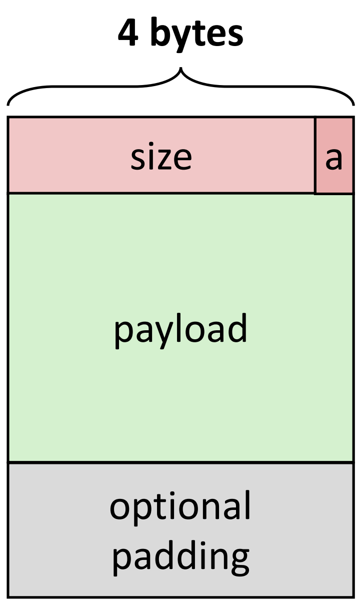
4) *Blocks sorted by size*
   - Can use a balanced binary tree (e.g., AVL tree) with pointers within each free block, and the length used as a key

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 boxes, 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 header box:

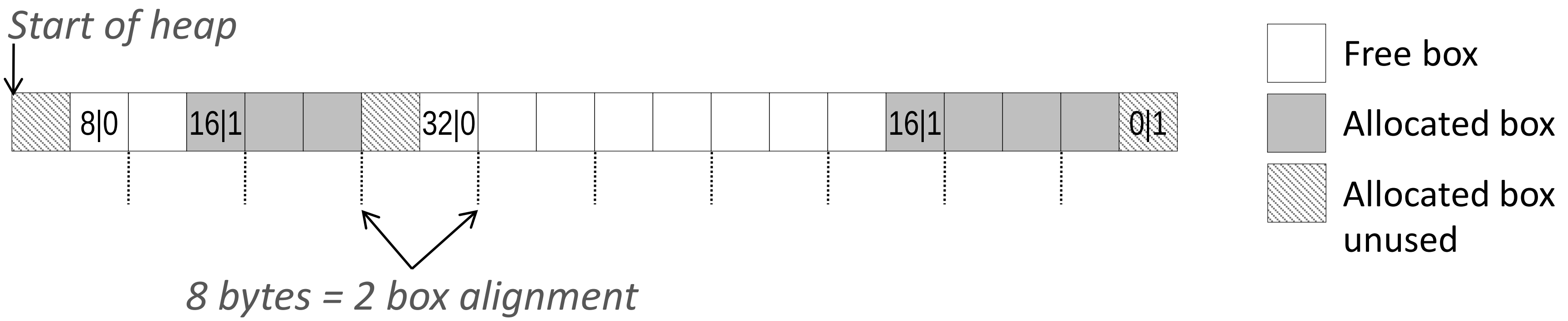
```
x = size | a;

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`):
  8|0, 16|1, 32|0, 16|1



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

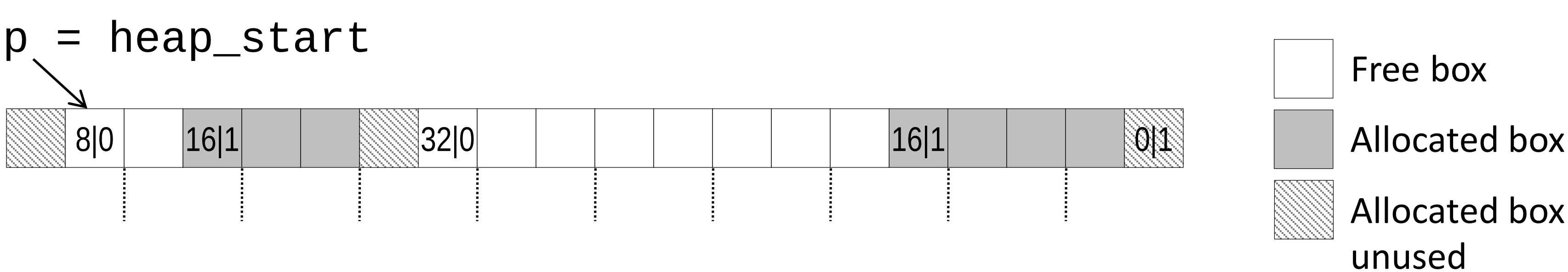
Implicit List: Finding a Free Block

(*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
```

  - 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

Peer Instruction Question

- Which allocation strategy and requests remove *external* fragmentation in this Heap? B3 was the last fulfilled request.

(A) Best-fit:
`malloc(50),malloc(50)`

(B) First-fit:
`malloc(50),malloc(30)`

(C) Next-fit:
`malloc(30),malloc(50)`

(D) Next-fit:
`malloc(50),malloc(30)`