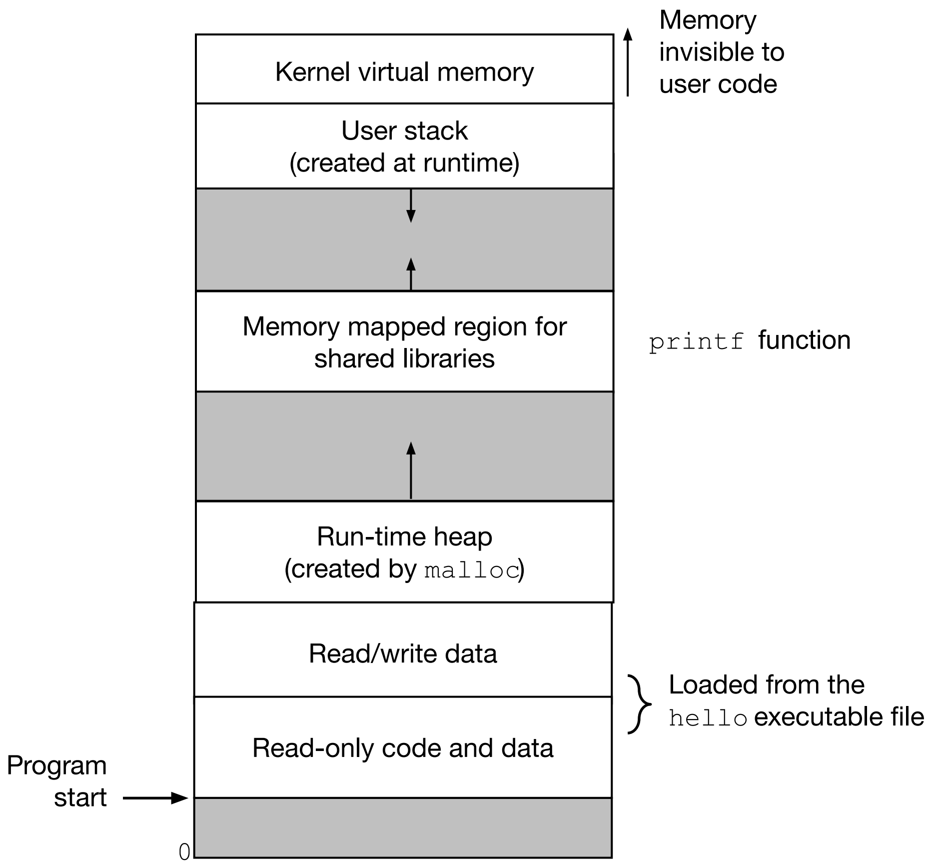
Operating Systems and C
Fall 2022
9. Heap

Slides from CSAPP3e

Virtual Memory



Each process has a view of virtual memory - its own address space.

All address spaces are structured in the same way.

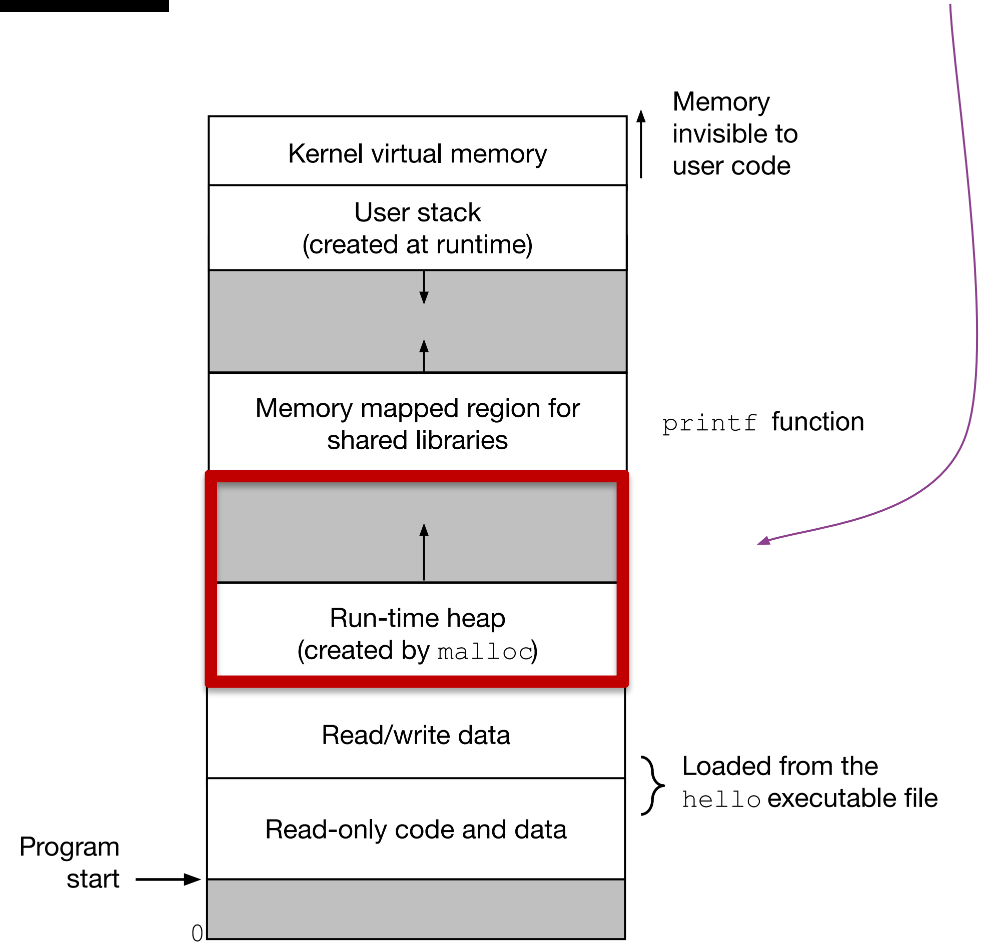
Dynamic Memory Allocation

today, we talk about the **heap**.
used for dynamic memory allocation

Programmers use *dynamic memory allocators* (such as `malloc`) to acquire VM at run time.

For data structures whose size is only known at runtime.

Dynamic memory allocators manage an area of process virtual memory known as the *heap*.



in C: data structures known
statically (compile time) in RO & RW
run time in heap.

Dynamic Memory Allocation

in every PL, you have memory allocators.

Allocator maintains heap as collection of variable sized *blocks*, which are either *allocated* or *free*

Types of allocators

Explicit allocator: application allocates and frees space

e.g., `malloc` and `free` in C

Implicit allocator: application allocates, but does not free space

e.g. garbage collection in Java, ML, and Lisp

In C, we deal with **explicit memory allocation**.

a key feature of C

malloc-lab (SWU, SD): you'll implement what's needed for malloc and free!

The `malloc` Package

#include <stdlib.h>

void *malloc(size_t size)

- Successful:
  - Returns a pointer to a memory block of at least **`size`** bytes (typically) aligned to 8-byte boundary
  - If **`size == 0`**, returns NULL
- Unsuccessful: returns NULL (0) and sets **`errno`**

void free(void *p)

- Returns the block pointed at by **`p`** to pool of available memory
- **`p`** must come from a previous call to **`malloc`** or **`realloc`**

Other functions:

- **`calloc`:** Version of **`malloc`** that initializes allocated block to zero.
- **`realloc`:** Changes the size of a previously allocated block.
- **`sbrk`:** Used internally by allocators to grow or shrink the heap

malloc never does anything to the content of the blocks unless you use something like this.

you use malloc to allocate space. then you cast that space to either struct or some basic type

Aligned malloc

going to be an issue on 64-bit machines

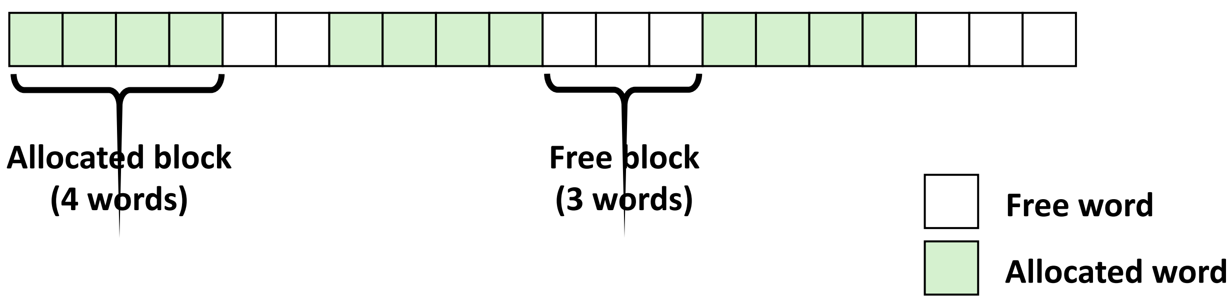
*void** **aligned_alloc**(*size_t alignment, size_t size*)

allocates a block of *size* bytes whose address is a multiple of *alignment*. The *alignment* must be a power of two and *size* must be a multiple of *alignment*.

By default malloc is word aligned: 4B on 32 bits machine, 8B on 64 bits machines.

cos

The space allocated is a multiple of word size.



malloc Example

```
void foo(int n, int m) {
    int i, *p;

    /* Allocate a block of n ints */
    p = (int *) malloc(n * sizeof(int));
    if (p == NULL) {
        perror("malloc");
        exit(0);
    }

    /* Initialize allocated block */
    for (i=0; i<n; i++)
        p[i] = i;


    /* Return p to the heap */
    free(p);
}
```

p only declared;
no memory allocated yet

we want to allocate a space
where p is going to be stored.

we allocated enough space for
this to behave as intended.
`n * sizeof(int)`

Allocation Example

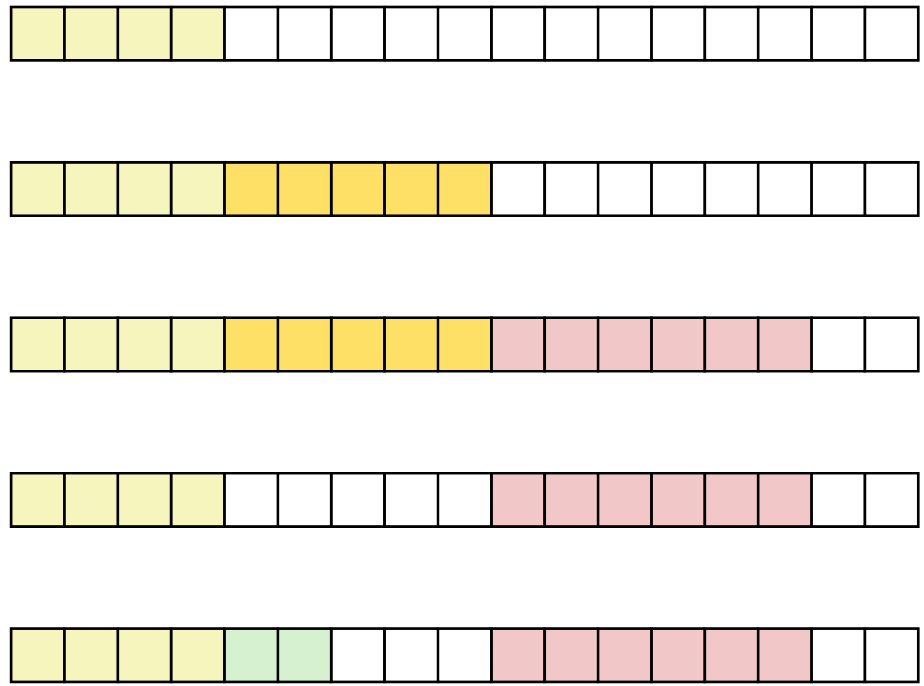
```
p1 = malloc(4)

p2 = malloc(5)

p3 = malloc(6)

free(p2)

p4 = malloc(2)
```



we have a big hole now;
we cannot “compact”;
allocator cannot do that.

Constraints

allocator must deal with any
malloc & free request
(can be any size any time)

Applications

- Can issue arbitrary sequence of **`malloc`** and **`free`** requests
- **`free`** request must be to a **`malloc`**'d block

Allocators

- Can't control number or size of allocated blocks
- Must respond immediately to **`malloc`** requests
  - *i.e.*, can't reorder or buffer requests
- Must allocate blocks from free memory
  - *i.e.*, can only place allocated blocks in free memory
- Must align blocks so they satisfy all alignment requirements
  - 8B alignment for GNU **`malloc`** (**`libc malloc`**) generally
- Can manipulate and modify only free memory
- Can't move the allocated blocks once they are **`malloc`**'d
  - *i.e.*, compaction is not allowed

Performance Goal: Throughput

we are basically going through the first part of what malloc-lab is about.

Given some sequence of `malloc` and `free` requests:

$R_0, R_1, ..., R_k, ... , R_{n-1}$

Goals: maximize throughput, and peak memory utilization

These goals are often conflicting

Throughput:

Number of completed requests per unit of time

Example:

5,000 **`malloc`** calls and 5,000 **`free`** calls in 10 seconds

Throughput is 1,000 operations/second

Performance Goal: Peak Memory Utilization

Given some sequence of `malloc` and `free` requests:

$R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$

Def: ***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

Def: ***Current heap size*** H_k

Assume H_k is monotonically nondecreasing

i.e., heap only grows when allocator uses **`sbrk`**

heap can grow, but never shrinks.

Def: ***Peak memory utilization after k requests***

$U_k = (max_{i<k} P_i) / H_k$

Fragmentation

10s

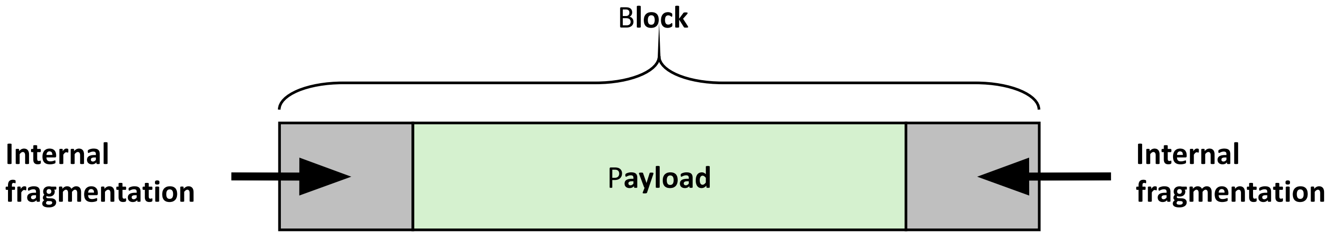
Poor memory utilization caused by *fragmentation*

- ***internal*** fragmentation
- ***external*** fragmentation

Internal Fragmentation

(within a block)

For a given block, *internal fragmentation* occurs if payload is smaller than block size



Caused by

- Overhead of maintaining heap data structures
- Padding for alignment purposes
- Explicit policy decisions
  (e.g., to return a big block to satisfy a small request)

Depends only on the pattern of *previous* requests

i.e. structure of heap at the moment

- Thus, easy to plan for

External Fragmentation

(outside blocks)

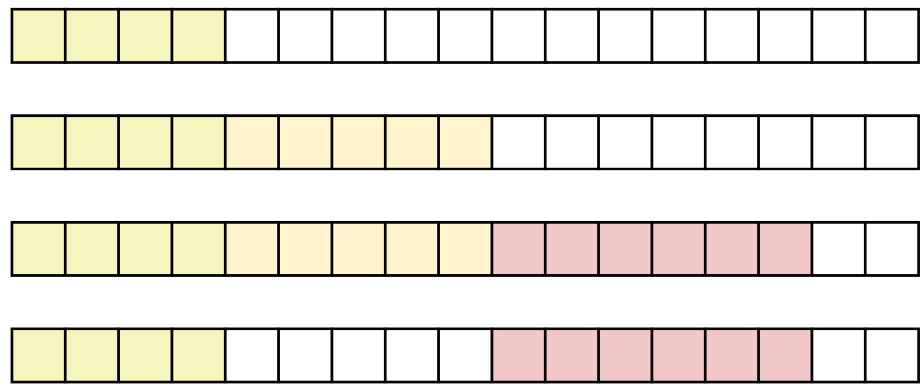
Occurs when there is enough aggregate heap memory, but no single free block is large enough

`p1 = malloc(4)`

`p2 = malloc(5)`

`p3 = malloc(6)`

`free(p2)`



`p4 = malloc(6)`

Oops! (what would happen now?)

we *have* the space, but fragmentation.

Depends on the pattern of future requests

Thus, difficult to plan for

Implementation Issues

How do we know how much memory to free given just a pointer?

How do we keep track of the free blocks?

allocator needs an internal data structure

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 pick a block to use for allocation -- many might fit?

allocator needs a policy for this

How do we reinsert freed block?

(you'll be battling pointer arithmetic like crazy)

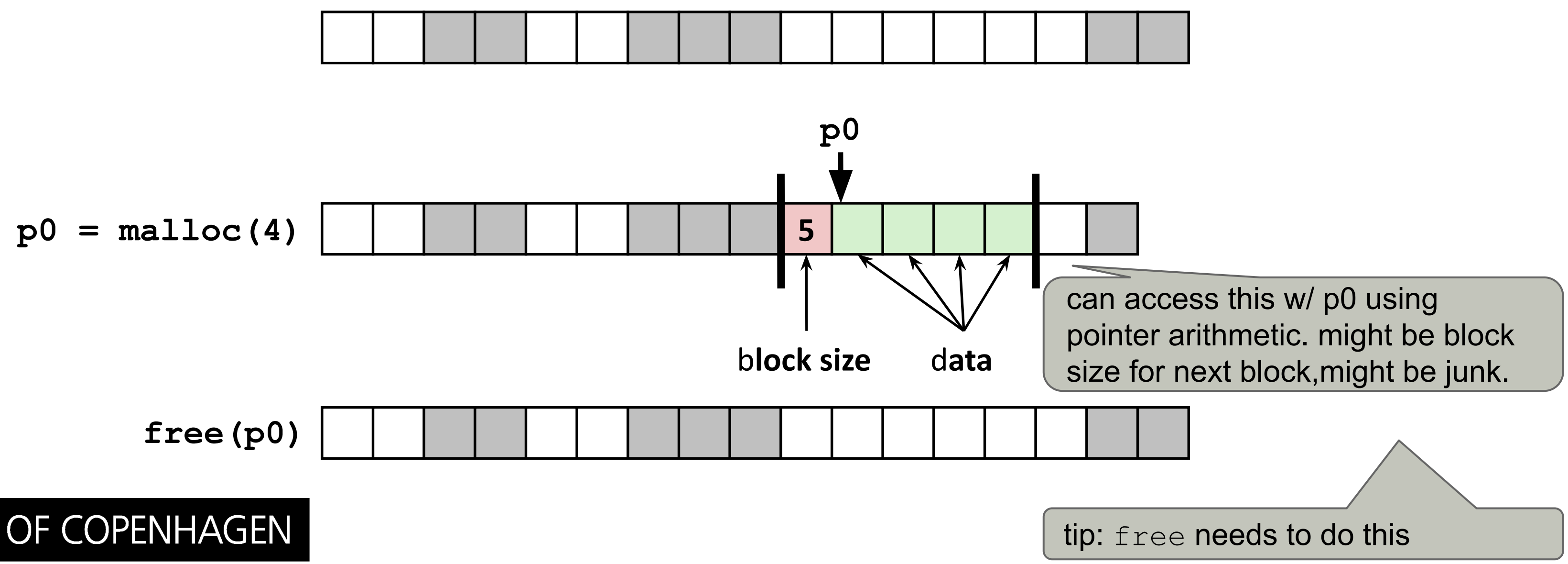
Knowing How Much to Free

Standard method

Keep the length of a block in the word preceding the block.

- This word is often called the ***header field*** or ***header***

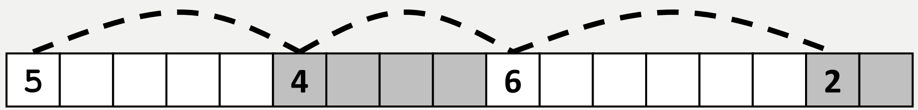
Requires an extra word for every allocated block



Keeping Track of Free Blocks

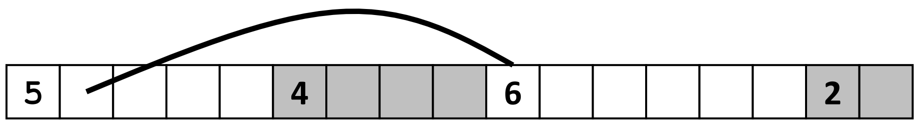
now we have to keep track of free blocks. first method: implicit list.

Method 1: *Implicit list* using length—links all blocks



finding a free block:
O(nr. of blocks **)**

Method 2: *Explicit list* among the free blocks using pointers



finding a free block:
O(nr. of *free* blocks **)**

Method 3: *Segregated free list*

Different free lists for different size classes

we'll get back to these later

Method 4: *Blocks sorted by size*

Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

let's look at method 1 and 2 in detail now.

Method 1: Implicit List

For each block we need both size and allocation status (allocated/free)

- Could store this information in two words: wasteful!

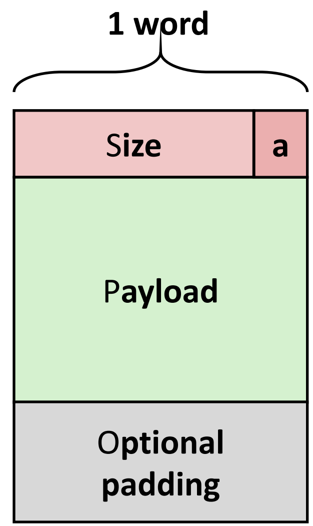
Standard trick

- If blocks are aligned, some low-order address bits are always 0
- Instead of storing an always-0 bit, use it as a allocated/free flag
- When reading size word, must mask out this bit

8-byte aligned;
last 3 bits of
(size of, & addr or)
all allocated **blocks**
are 0

mask is
1..1110 = -2

Format of allocated and free blocks



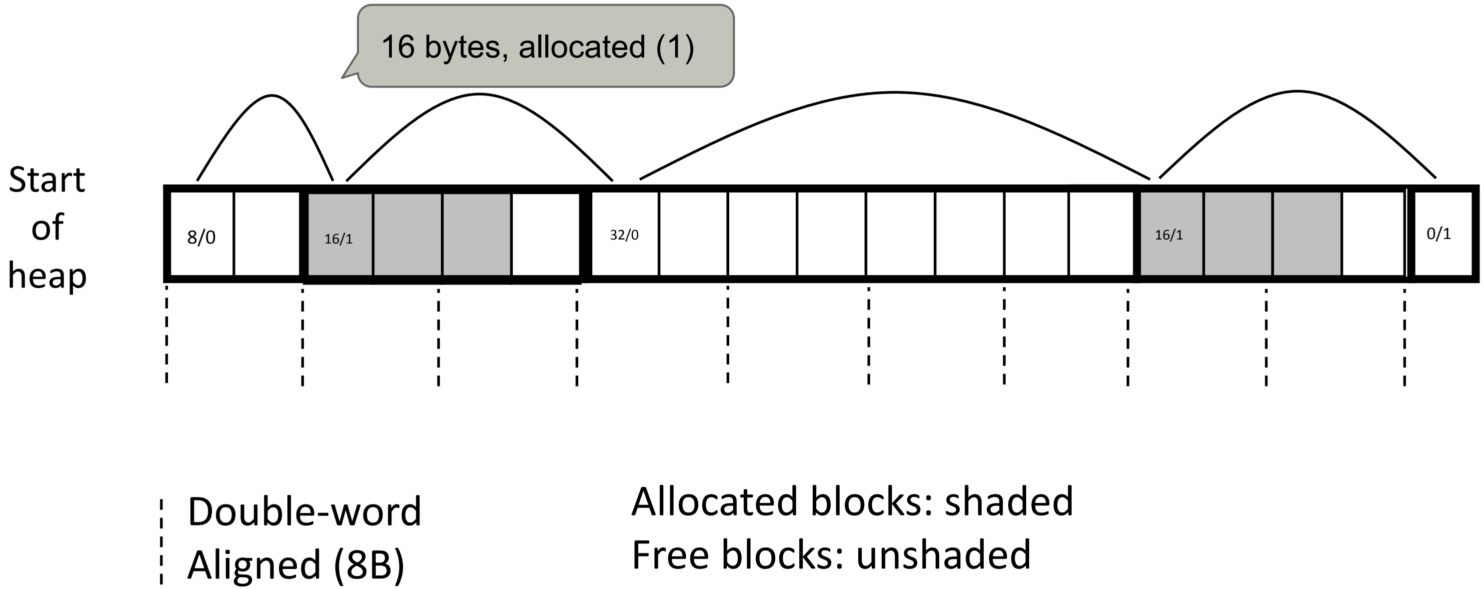
a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data (allocated blocks only)

Detailed Implicit Free List Example

10s



Allocated blocks: shaded
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit

Implicit List: Finding a Free Block

First fit:

Search list from beginning, choose ***first*** free block that fits:

```
p = start;
while ((p < end) &&                  \\ not passed end
       ((*p & 1) ||                  \\ already allocated
          (*p & -2) <= len)))        \\ too small
  p = p + (*p & -2);                 \\ goto next block (word addressed)
```

Can take linear time in total number of blocks (allocated and free)

In practice it can cause "splinters" at beginning of list

advance pointer by size of the block we are looking at

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: fits, with fewest bytes left over

Keeps fragments small—usually helps fragmentation

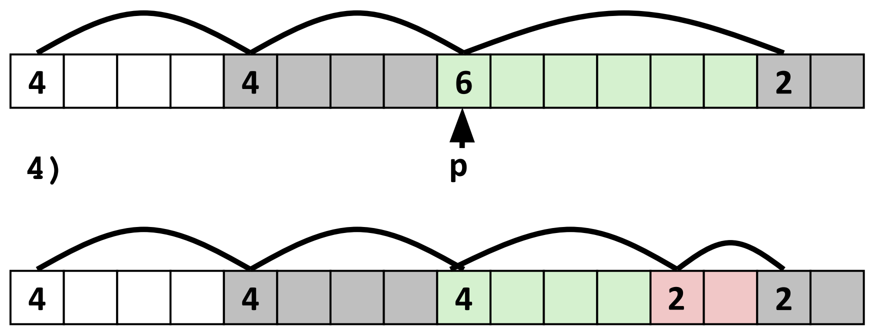
Will typically run slower than first fit

Implicit List: Allocating in Free Block

Allocating in a free block: *splitting*

Since allocated space might be smaller than free space, we might want to split the block

addblock(p, 4)




```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;   // round up to even
  int oldsize = *p & -2;                 // mask out low bit
  *p = newsize | 1;                      // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;    // set length in
remaining
}                                        //   part of block
```

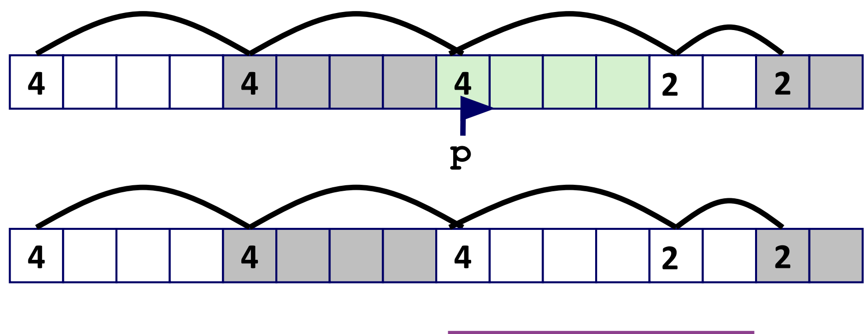
Implicit List: Freeing a Block

Simplest implementation:

Need only clear the "allocated" flag

```
void free_block(ptr p) { *p = *p & -2 }
```

But can lead to "false fragmentation"



`free(p)`

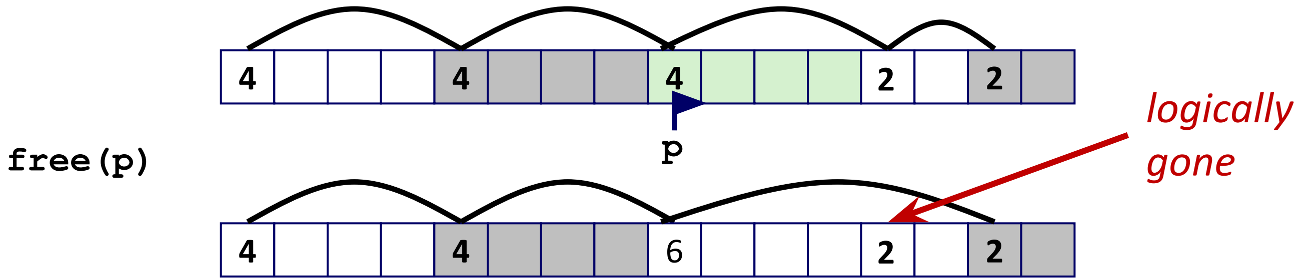
`malloc(5)` ***Oops!***

*There **is** enough free space, but the allocator won't be able to find it*

Implicit List: Coalescing

Join *(coalesce)* with next/previous blocks, if they are free

Coalescing with next block




```
void free_block(ptr p) {
    *p = *p & -2;            // clear allocated flag
    next = p + *p;           // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;       // add to this block if
}                            //    not allocated
```

This helps us coalesce space when the *next* block is free.

What about when the *previous* block is free? (see “cases” in 2 slides)

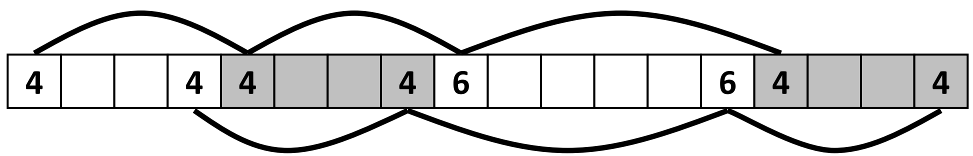
Implicit List: Bidirectional Coalescing

Boundary tags [Knuth73]

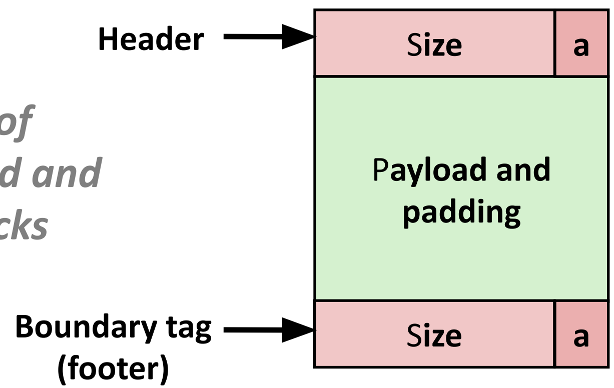
Replicate size/allocated word at “bottom” (end) of free blocks

Allows us to traverse the “list” backwards, but requires extra space

Important and general technique!



Format of allocated and free blocks

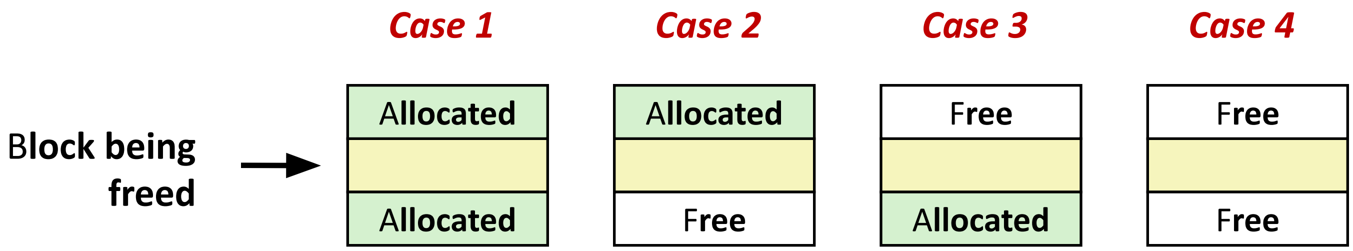


a = 1: Allocated block
a = 0: Free block

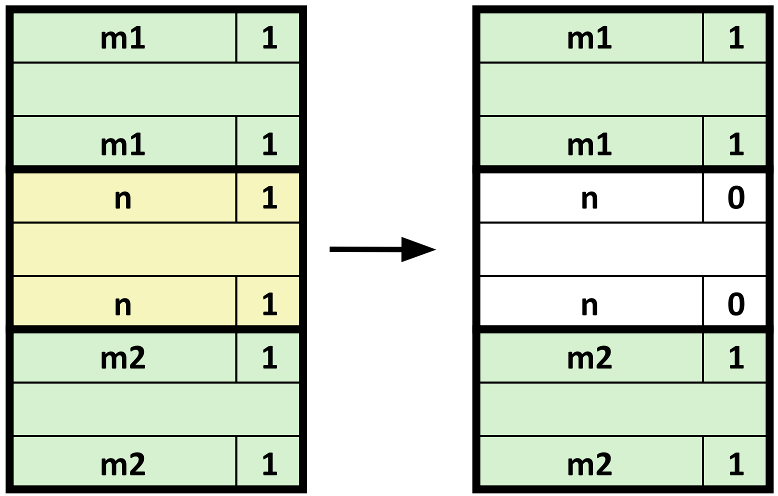
Size: Total block size

Payload: Application data (allocated blocks only)

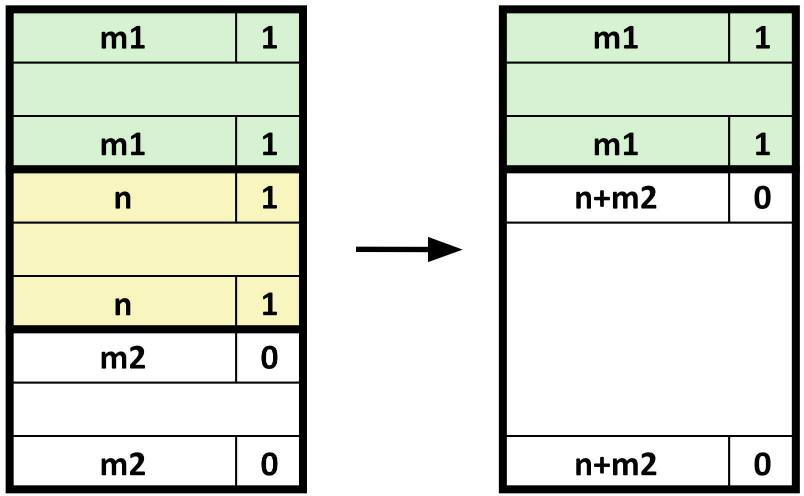
Constant Time Coalescing



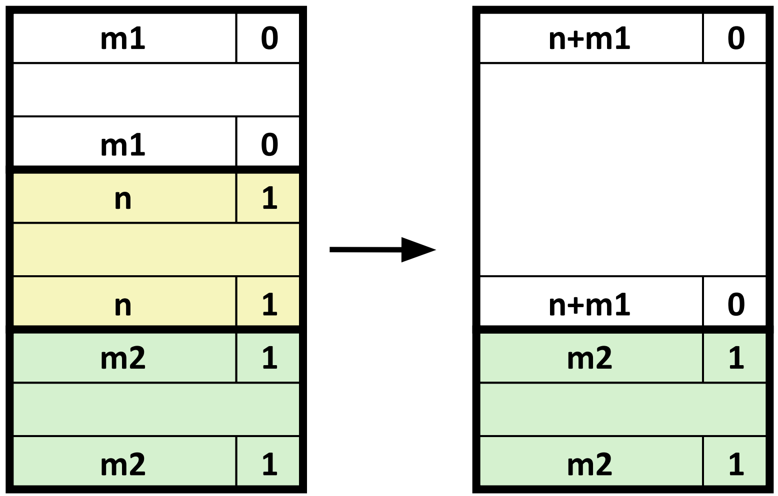
Constant Time Coalescing (Case 1)



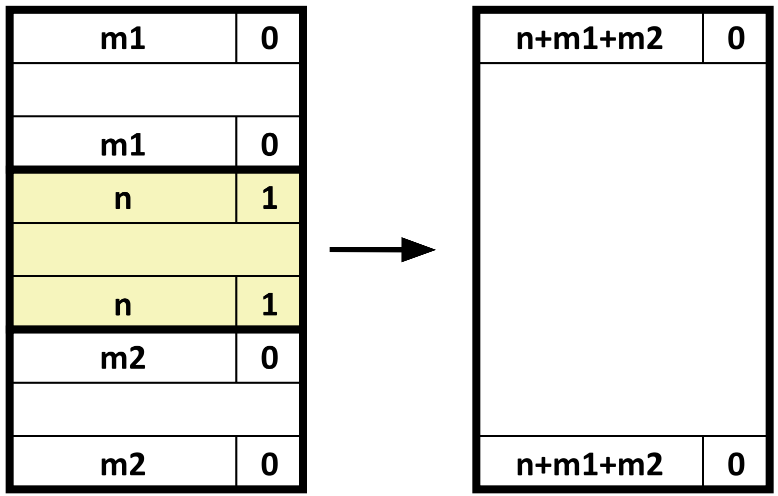
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



Summary of Key Allocator Policies

Placement policy:

- First-fit, next-fit, best-fit, etc.
- Trades off lower throughput for less fragmentation
- ***Interesting observation***: segregated free lists approximate a best fit placement policy without having to search entire free list

maintain array of free blocks; see later

Splitting policy:

- When do we go ahead and split free blocks?
- How much internal fragmentation are we willing to tolerate?

Coalescing policy:

- ***Immediate coalescing:*** coalesce each time `free` is called
- ***Deferred coalescing:*** try to improve performance of `free` by deferring coalescing until needed. Examples:
  - Coalesce as you scan the free list for `malloc`
  - Coalesce when the amount of external fragmentation reaches some threshold

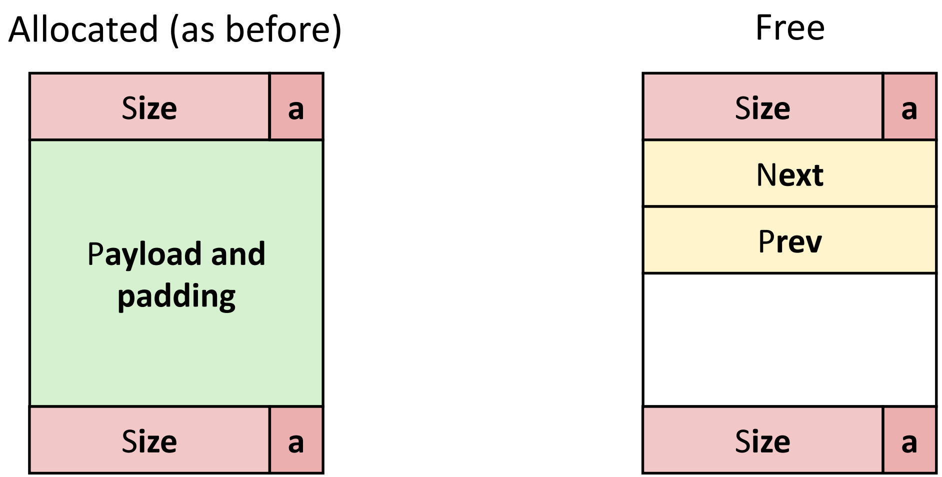
Implicit Lists: Summary

Implementation: very simple
Allocate cost:
    linear time worst case
Free cost:
    constant time worst case
  - even with coalescing
Memory usage:
    will depend on placement policy
    First-fit, next-fit or best-fit

Not used in practice for `malloc/free` because of linear-time allocation
  - used in many special purpose applications

However, the concepts of
    splitting and boundary tag coalescing
are general to *all* allocators

Explicit Free Lists



Maintain list(s) of *free* blocks, not *all* blocks

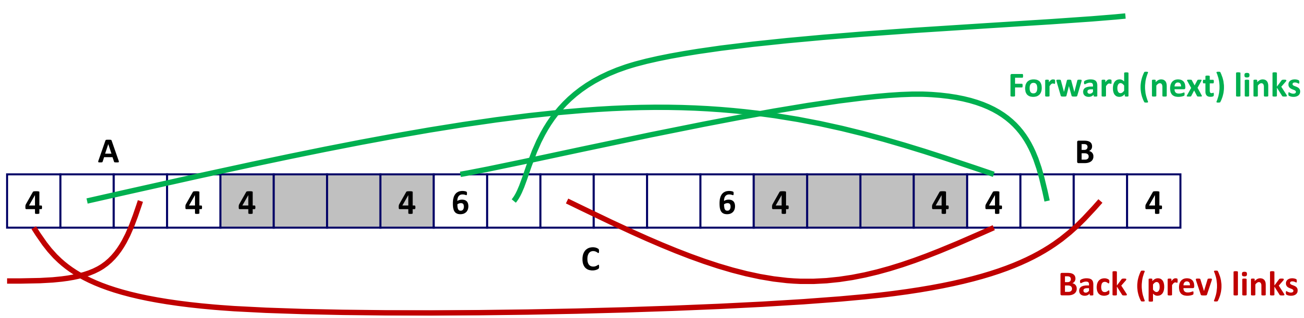
- The “next” free block could be anywhere
  - So we need to store forward/back pointers, not just sizes
- Still need boundary tags for coalescing
- Luckily we track only free blocks, so we can use payload area

because we might free a block somewhere in the middle of heap (and thus list)

Explicit Free Lists

- Logically:

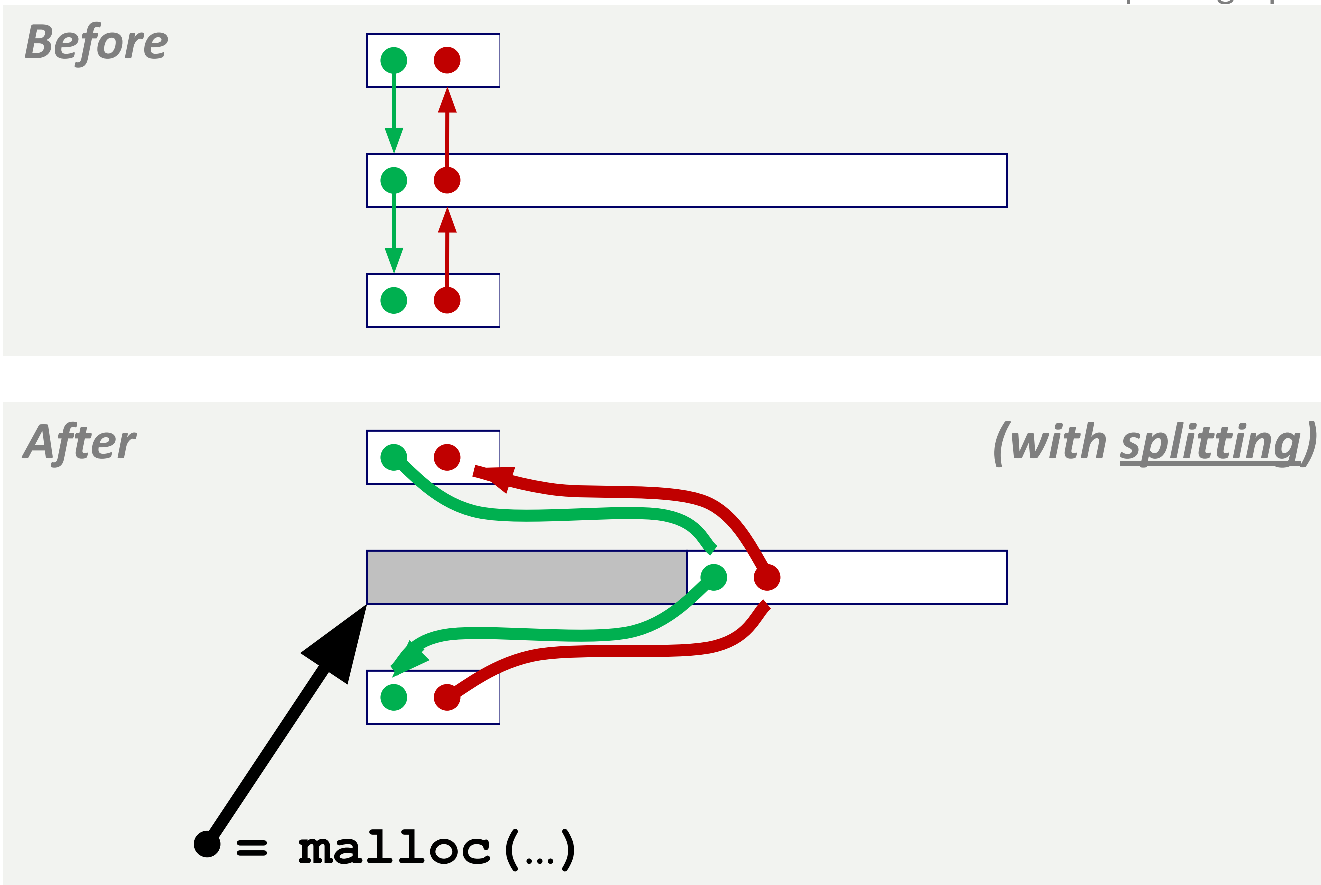
- Physically: blocks can be in any order



(*)

Allocating From Explicit Free Lists

conceptual graphic



Freeing With Explicit Free Lists

Insertion policy: Where in the free list do you put a newly freed block?

LIFO (last-in-first-out) policy

Insert freed block at the beginning of the free list

Pro: simple and constant time

Con: studies suggest fragmentation is worse than address ordered

Address-ordered policy

Insert freed blocks so that free list blocks are always in address order:

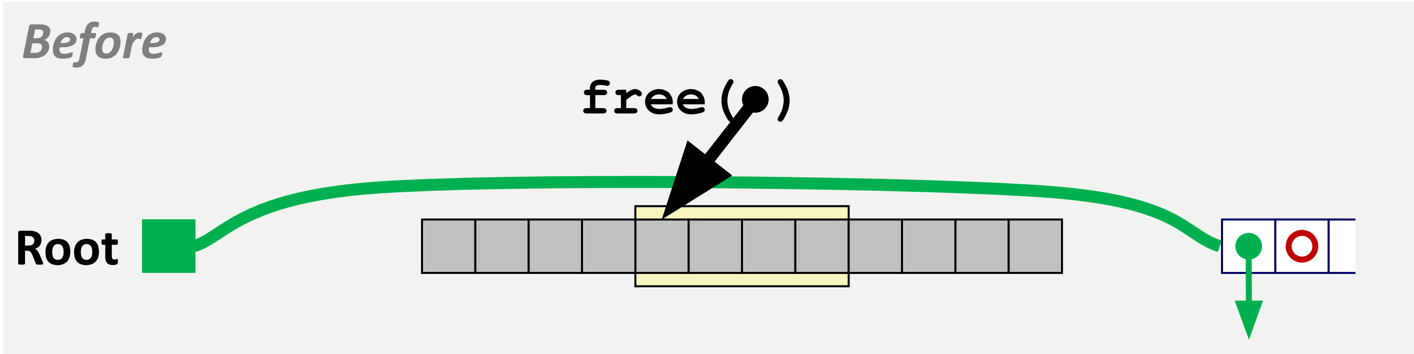
addr(prev) < addr(curr) < addr(next)

Con: requires search

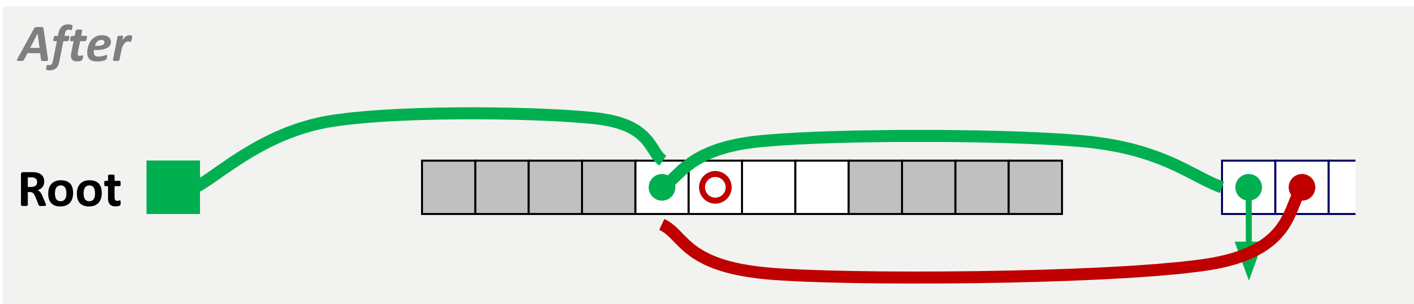
Pro: studies suggest fragmentation is lower than LIFO

Freeing With a LIFO Policy (Case 1)

conceptual graphic

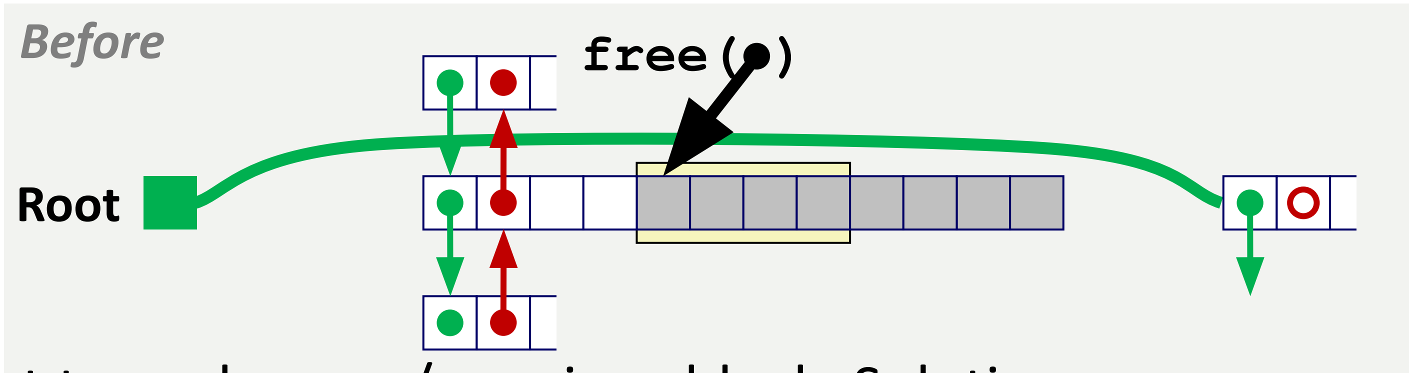


Insert the freed block at the root of the list

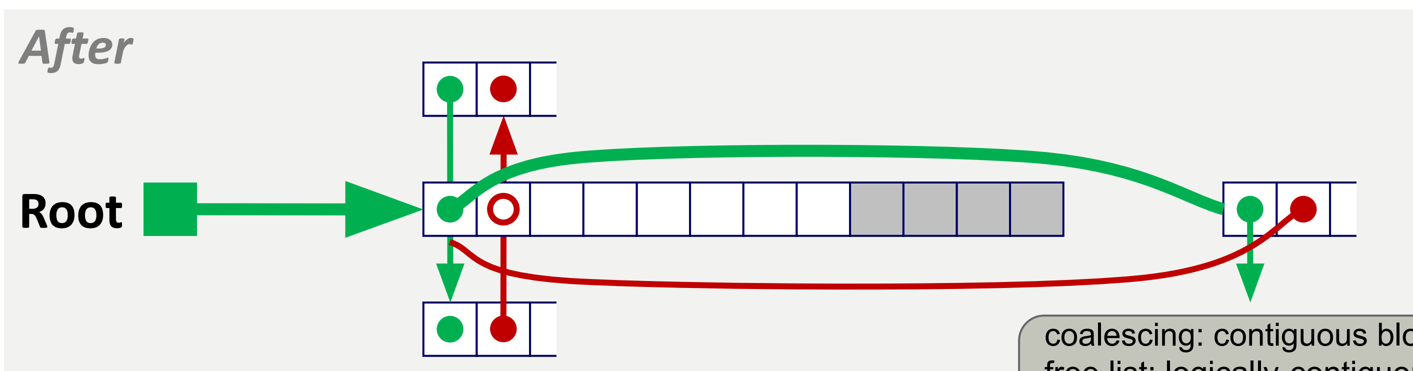


Freeing With a LIFO Policy (Case 2)

conceptual graphic



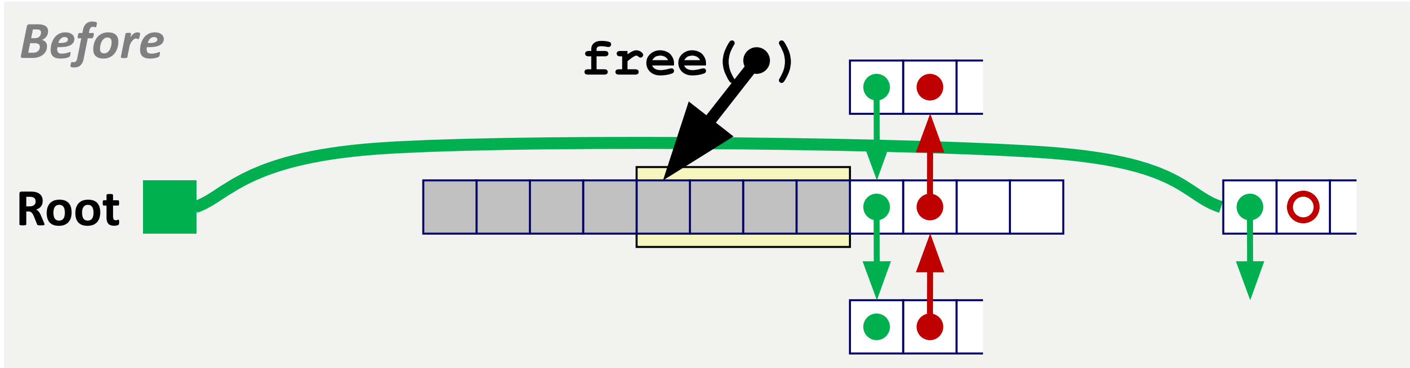
Want to coalesce w/ previous block. Solution:
Take out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list



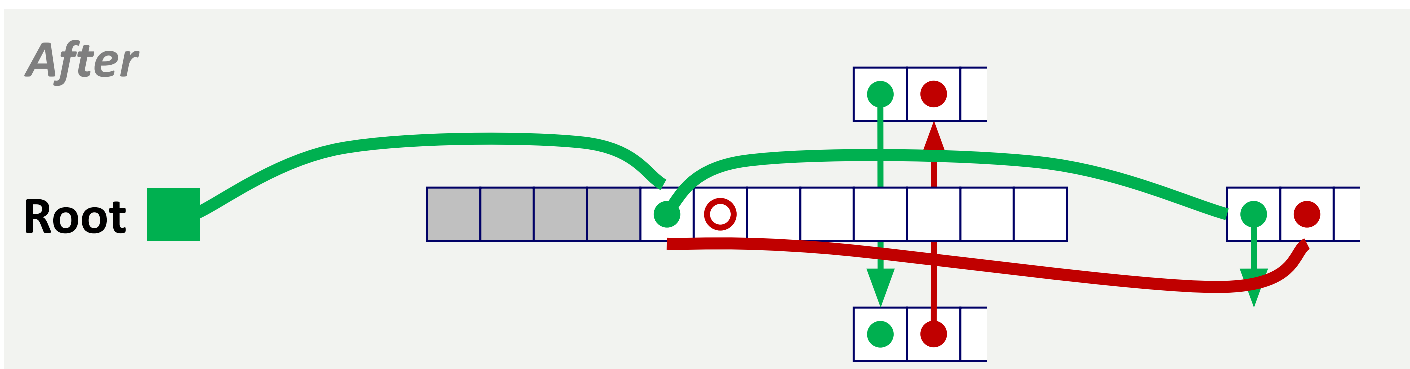
coalescing: contiguous blocks
free list: logically-contiguous blocks
consequence: coalescing function is the same for expl. & impl. free lists. **(*)**

Freeing With a LIFO Policy (Case 3)

conceptual graphic

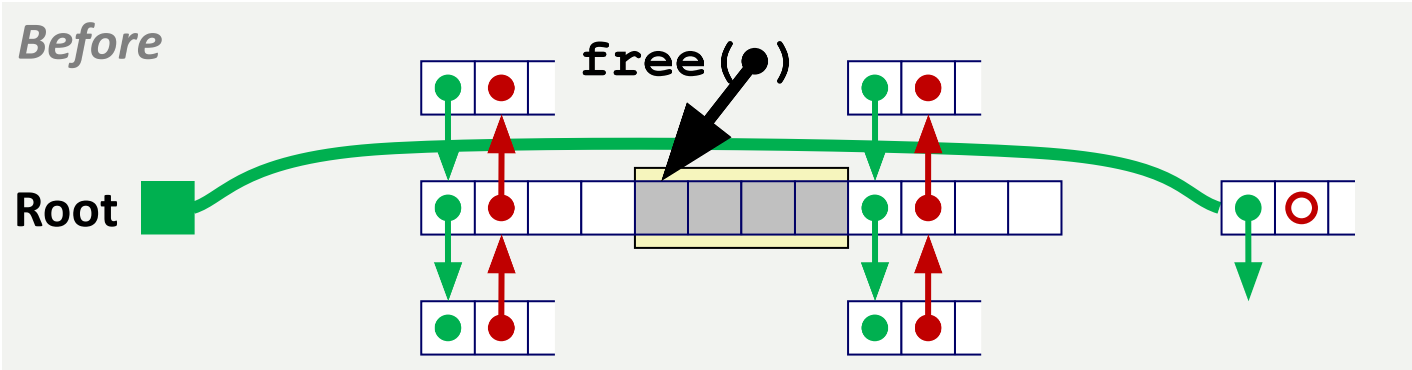


Take out successor block, coalesce both memory blocks and insert the new block at the root of the list

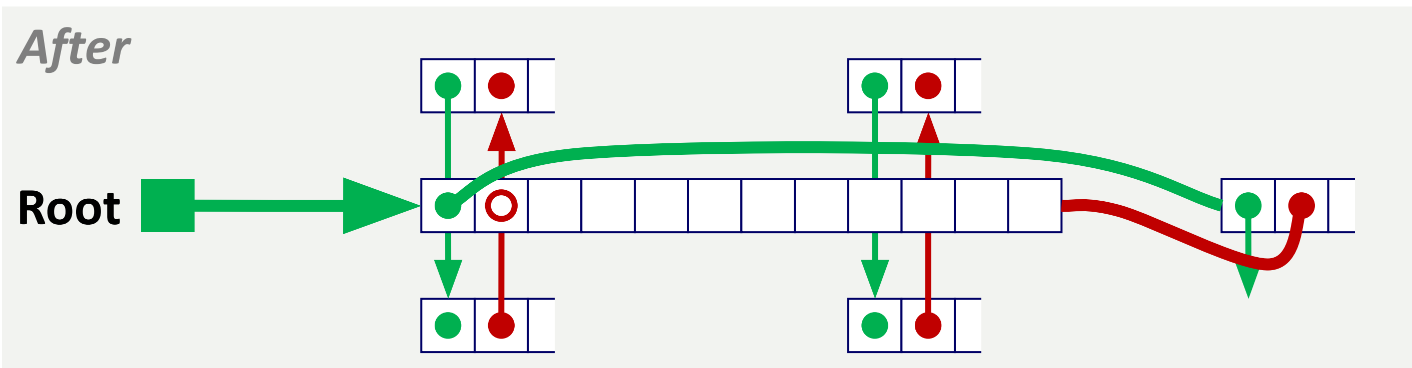


Freeing With a LIFO Policy (Case 4)

conceptual graphic



Take out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the root of the list



Explicit List Summary

(quickly summarize)

Comparison to implicit list:

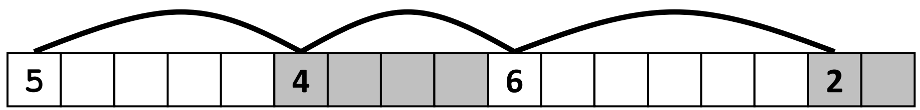
- Allocate is linear time in number of ***free*** blocks instead of ***all*** blocks
  - ***Much faster*** when most of the memory is full
- Slightly more complicated allocate and free since needs to take blocks out of the list
- Some extra space for the links (2 extra words needed for each block)
  - Does this increase internal fragmentation?

Most common use of linked lists is in conjunction with segregated free lists

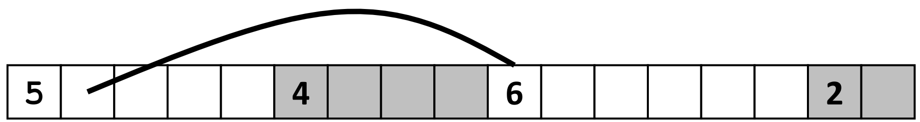
- Keep multiple linked lists of different size classes, or possibly for different types of objects

Keeping Track of Free Blocks

Method 1: *Implicit list* using length—links all blocks



Method 2: *Explicit list* among the free blocks using pointers



Method 3: *Segregated free list*

Different free lists for different size classes

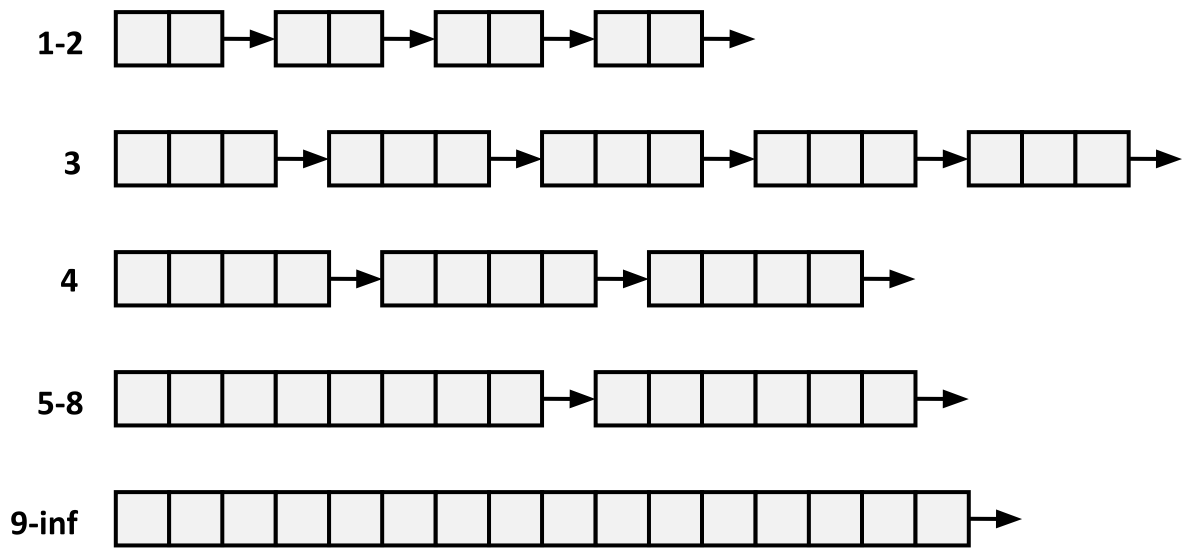
Method 4: *Blocks sorted by size*

Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Segregated List (Seglist) Allocators

10s

Each *size class* of blocks has its own free list



Often have separate classes for each small size

For larger sizes: One class for each two-power size

Seglist Allocator

(quickly summarize)

Given an array of free lists, each one for some size class

To allocate a block of size *n*:

- Search appropriate free list for block of size *m* > *n*
- If an appropriate block is found:
  - Split block and place fragment on appropriate list (optional)
- If no block is found, try next larger class
- Repeat until block is found

If no block is found:

- Request additional heap memory from OS (using **`sbrk()`**)
- Allocate block of *n* bytes from this new memory
- Place remainder as a single free block in largest size class.

Seglist Allocator (cont.)

To free a block:

- Coalesce and place on appropriate list (optional)

Advantages of seglist allocators

- Higher throughput
  - log time for power-of-two size classes
- Better memory utilization
  - First-fit search of segregated free list approximates a best-fit search of entire heap.
  - Extreme case: Giving each block its own size class is equivalent to best-fit.

More Info on Allocators

D. Knuth, "*The Art of Computer Programming*", 2nd edition, Addison Wesley, 1973

The classic reference on dynamic storage allocation

Wilson et al, "*Dynamic Storage Allocation: A Survey and Critical Review*", Proc. 1995 Int'l Workshop on Memory Management, Kinross, Scotland, Sept, 1995.

Comprehensive survey

Available from CS:APP student site (csapp.cs.cmu.edu)