CSCI-UA.0201

Computer Systems Organization

Memory Management – Dynamic Allocation

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Why dynamic allocator?

- We've discussed two types of data allocation so far:
  - Global variables
  - Stack-allocated local variables

- Not sufficient!
  - How to allocate data whose size is only known at runtime?
    - E.g. when reading variable-sized input from network, file etc.
  - How to control lifetime of allocated data?
    - E.g. a linked list that grows and shrinks as items are inserted/deleted

Why dynamic memory allocation?

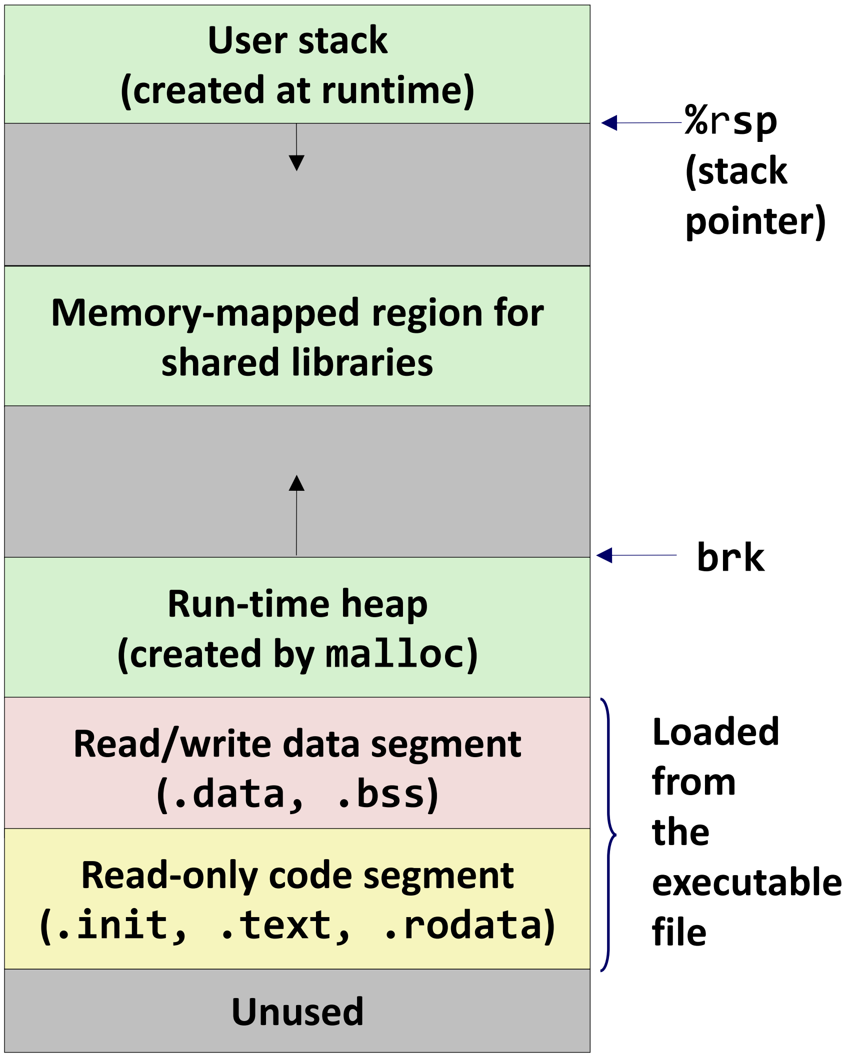
Allocation size is unknown until the program runs (at runtime).

```
int main(void) {
  int *array, i, n;

  scanf("%d", &n);
  array = (int*) malloc(n*sizeof(int));

  for (i = 0; i < n; i++)
    scanf("%d", &array[i]);

  return 0;
}
```

Dynamic allocation on heap

Question: can one dynamically allocate memory on stack?

Answer: Yes, but space is freed upon function return



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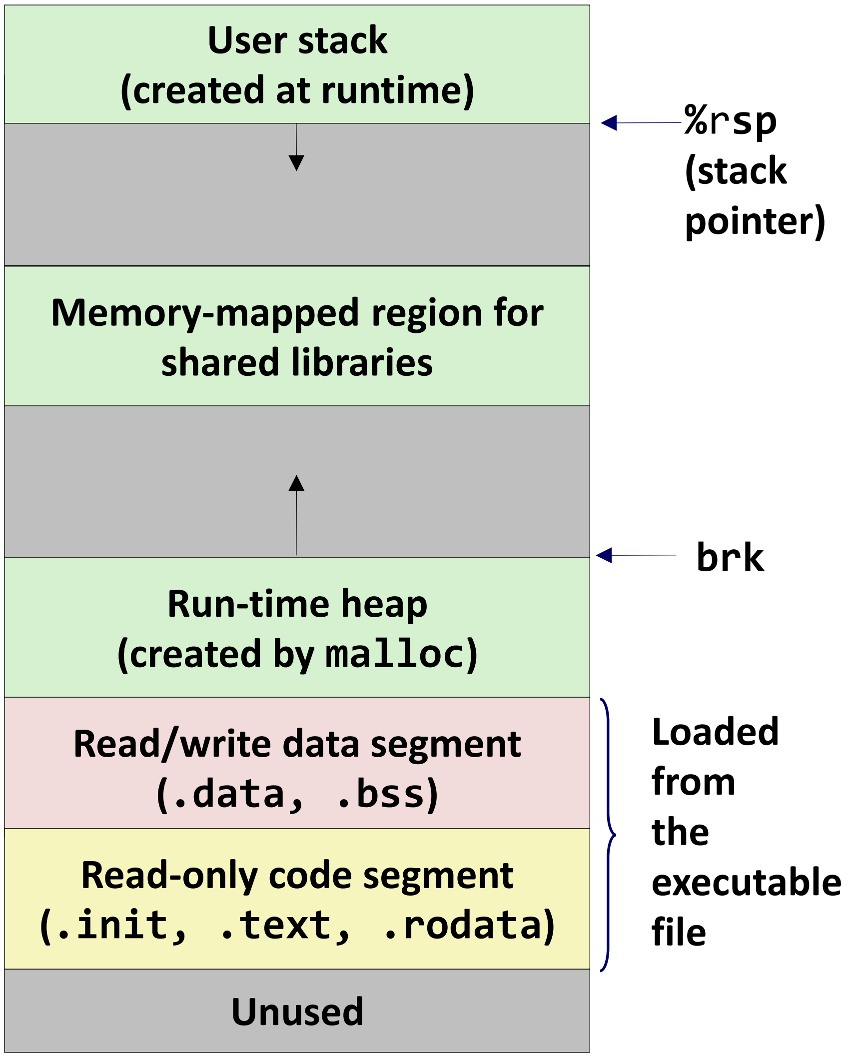


Dynamic allocation on heap

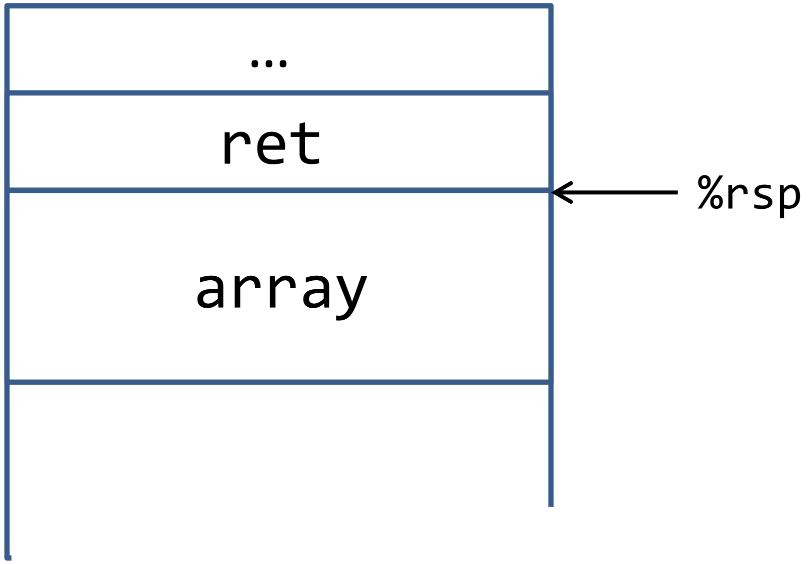
Question: can one dynamically allocate memory on stack?

Answer: Yes, but space is freed upon function return

```
#include <stdlib.h>
void *alloca(size_t size);

void func(int n) {
  int* array = alloca(n);
}
```

stack




```
subq $n,%rsp
```

Not good practice!

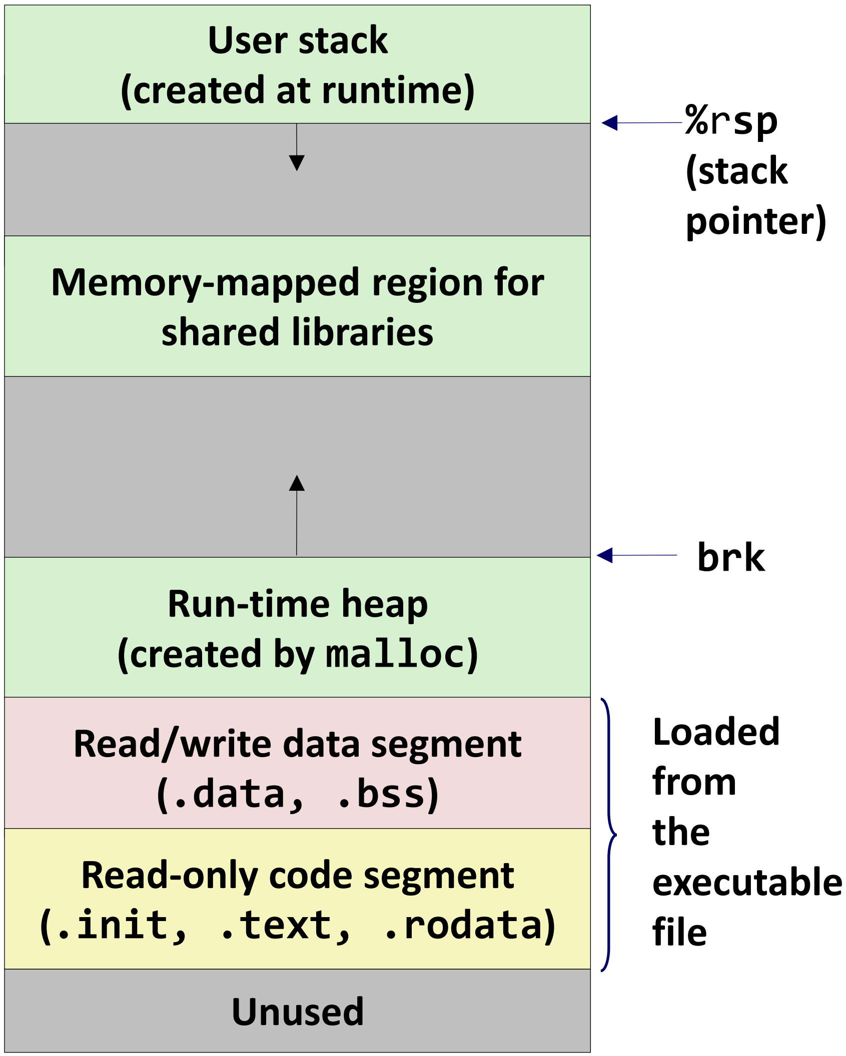
Dynamic allocation on heap

Question: how to allocate memory on the heap?

Ask OS for allocation on the heap via system calls

```
void *sbrk(intptr_t size);
```

It increases the top of heap by `size` and returns a pointer to the base of new storage. The `size` can be a negative number.



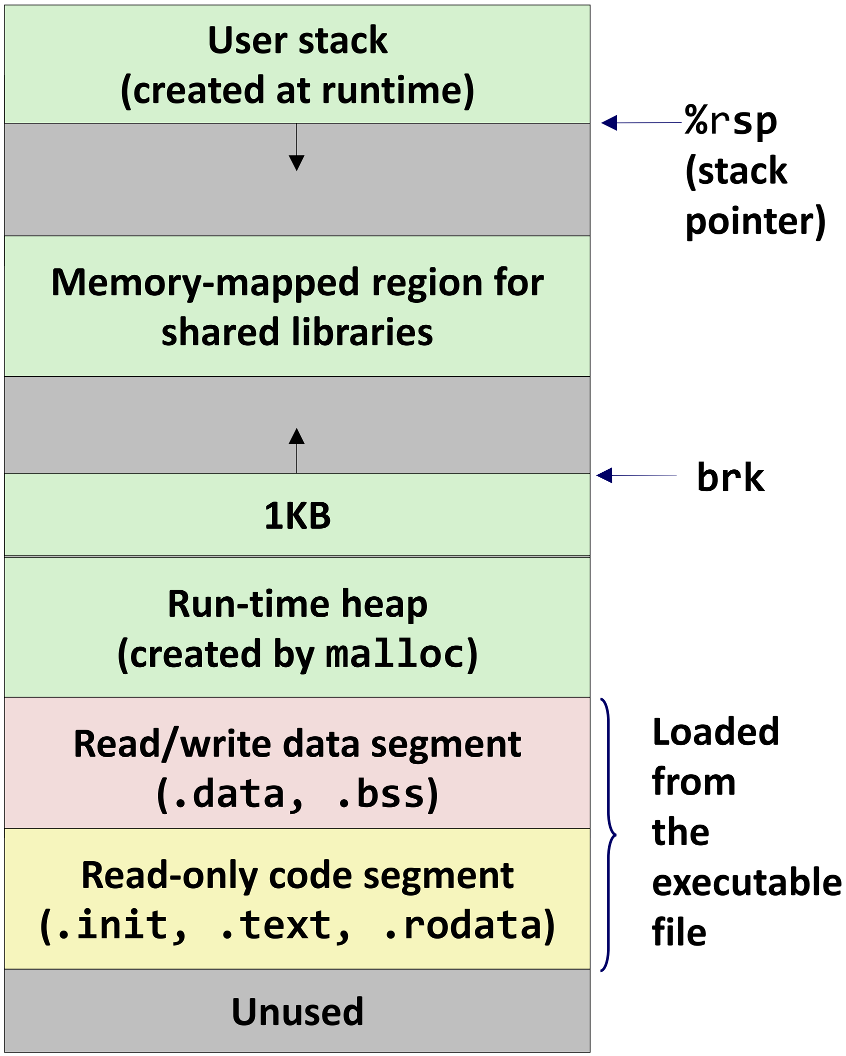
Dynamic allocation on heap

Question: how to allocate memory on the heap?

Ask OS for allocation on the heap via system calls

```
void *sbrk(intptr_t size);

p = sbrk(1024)   //allocate 1KB
```



Dynamic allocation on heap

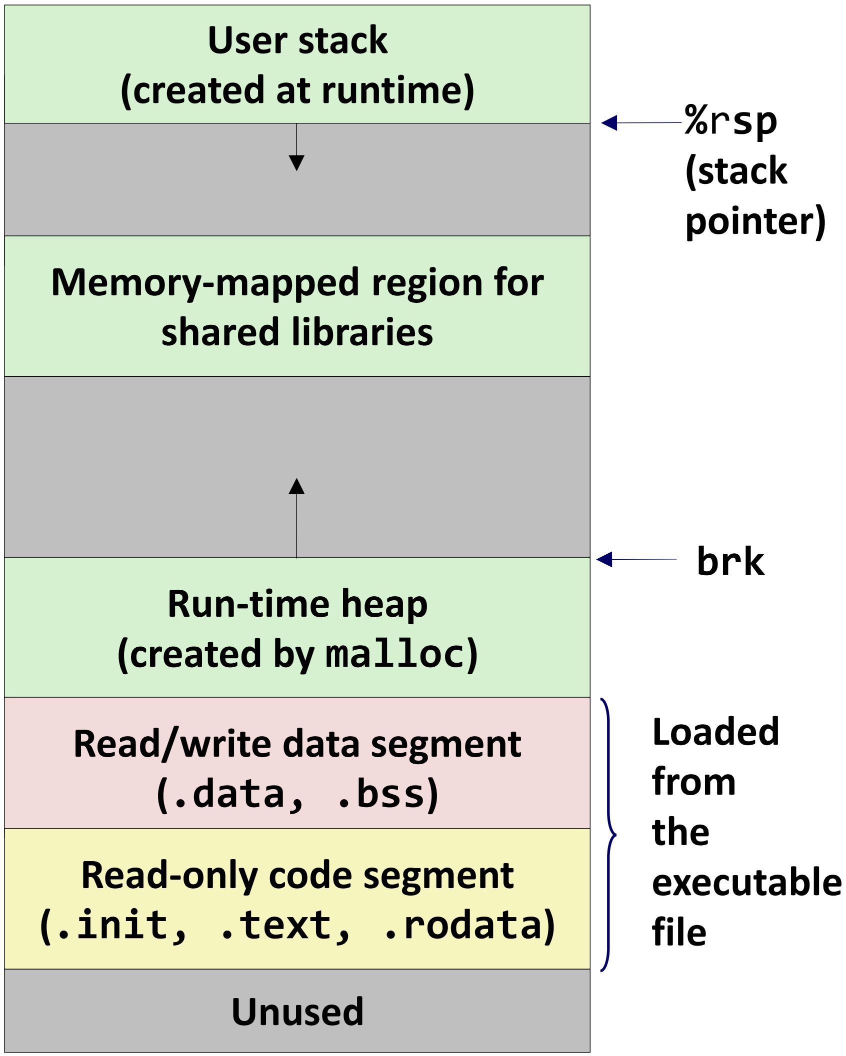
Question: how to allocate memory on the heap?

Ask OS for allocation on the heap via system calls

```
void *sbrk(intptr_t size);
```

```
p = sbrk(1024)   //allocate 1KB
```

```
sbrk(-1024)   // free p
```



Dynamic allocation on heap

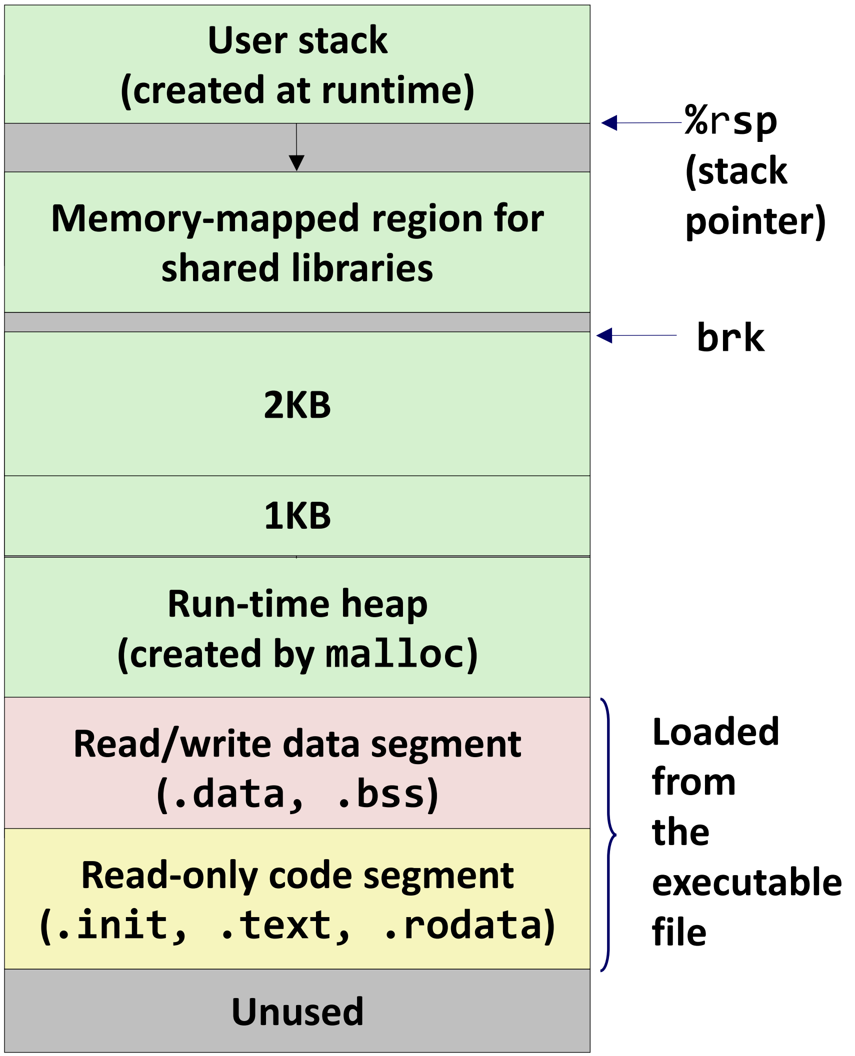
Question: how to allocate memory on the heap?

Issue I – can only free the memory on the top of heap

```
void *sbrk(intptr_t size);
```

```
p1 = sbrk(1024)   //allocate 1KB
p2 = sbrk(2048)   //allocate 2KB

// free p1?
```



Dynamic allocation on heap

Question: how to allocate memory on the heap?

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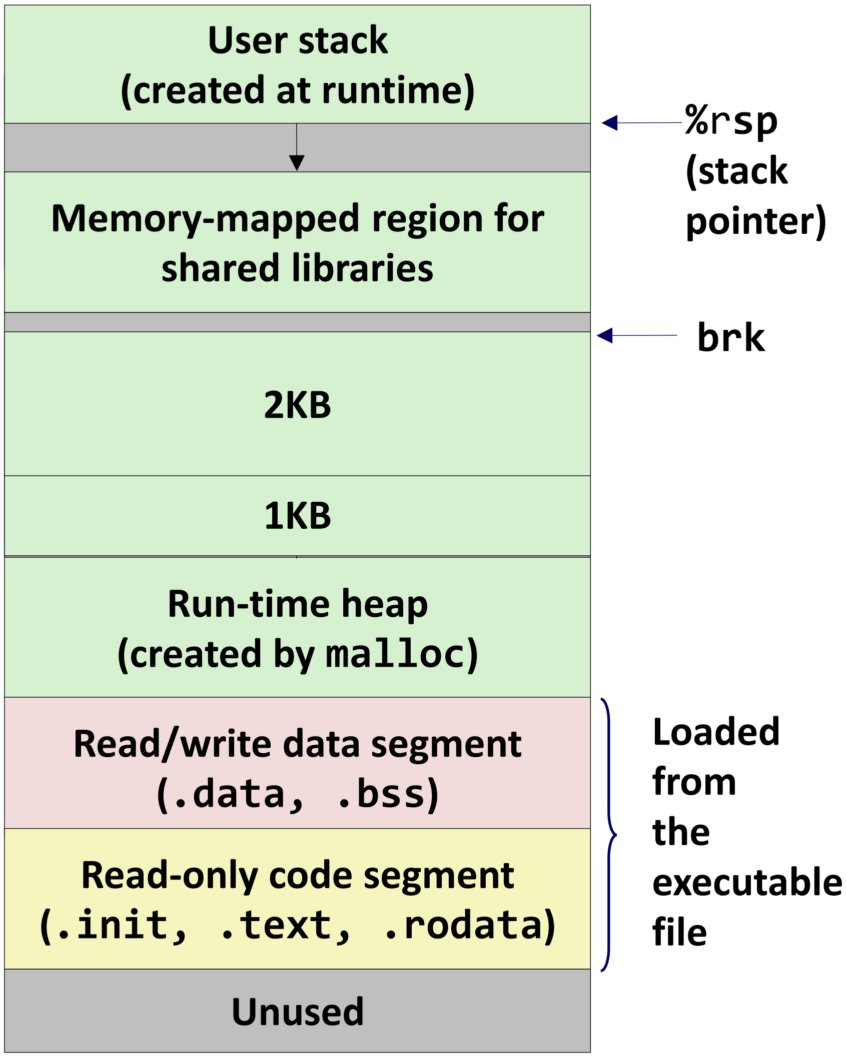

Dynamic allocation on heap

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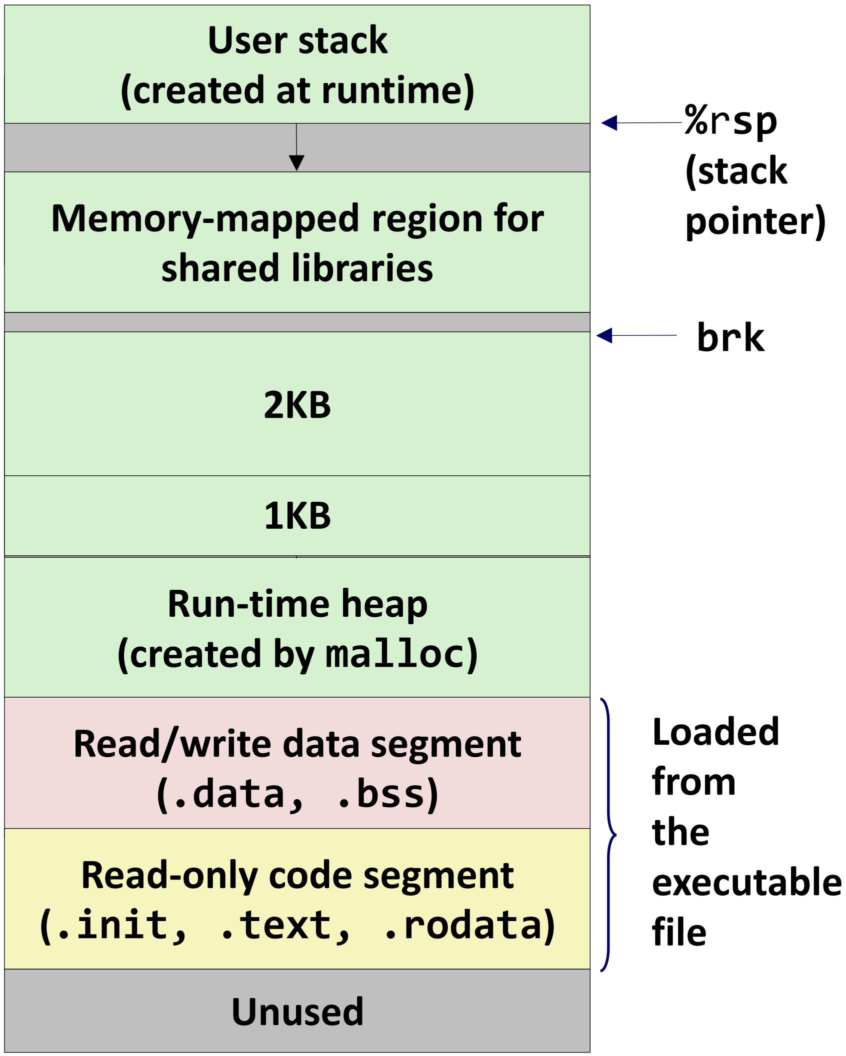
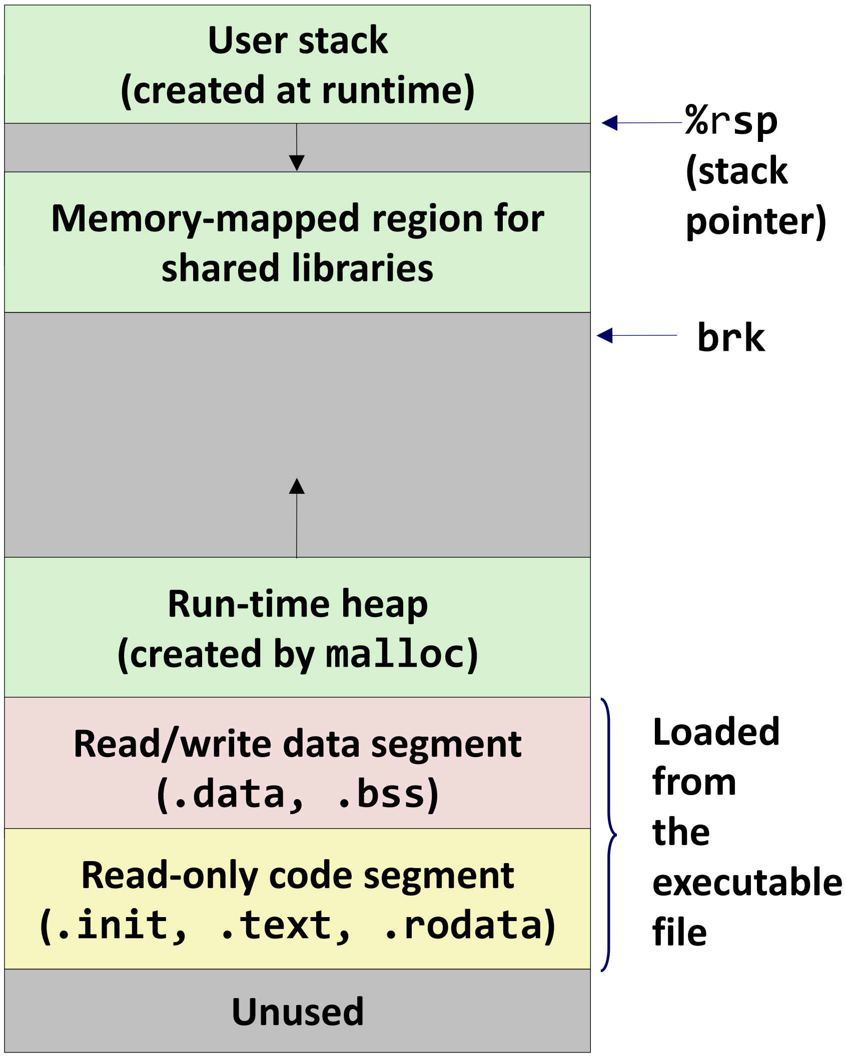


Dynamic allocation on heap

Question: how to allocate memory on the heap?

Issue I – can only free the memory on the top of heap

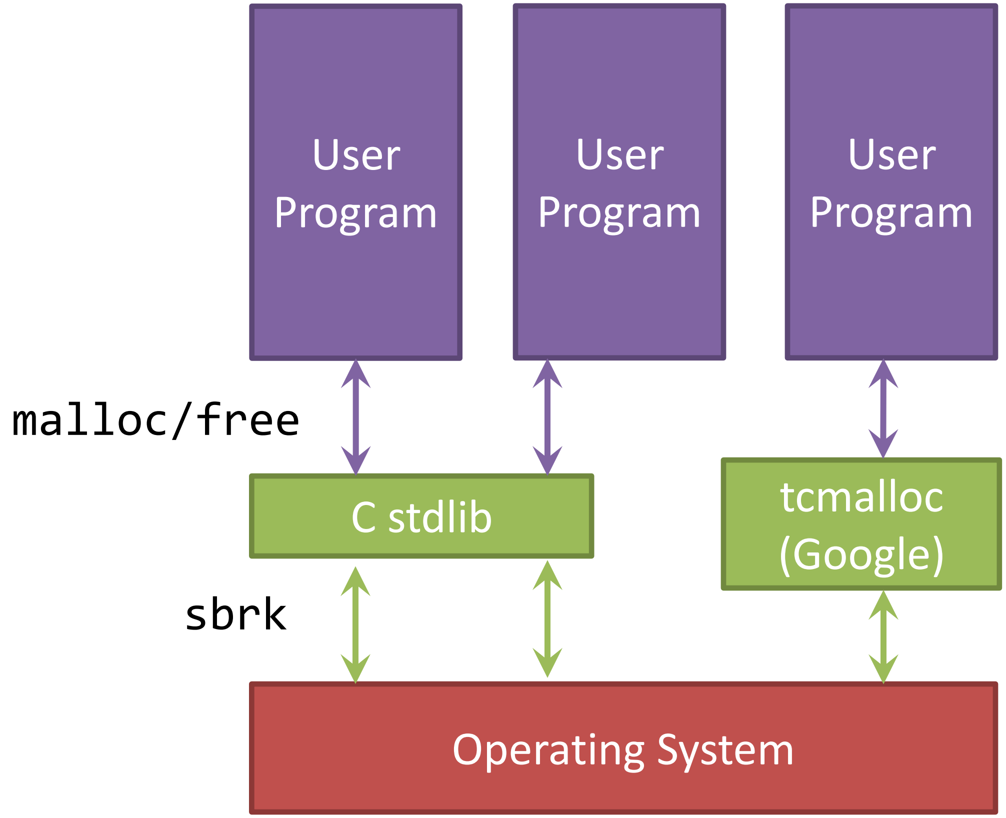
Issue II – system call has high performance cost > 10X



Dynamic allocation on heap

Question: How to efficiently allocate memory on heap?

Basic idea – request a large memory region on heap from OS once, then manage this memory region by itself.



⇒ Allocator is implemented in a user-level library

Types of Dynamic Memory Allocator

- Explicit allocator (used by C/C++): application allocates and frees space
  - `malloc` and `free` in C
  - `new` and `delete` in C++

Will concentrate on this

- Implicit allocator (used by Java,…): application allocates, but does not free space
  - Garbage collection in Java, Python etc.

Challenges facing a memory allocator

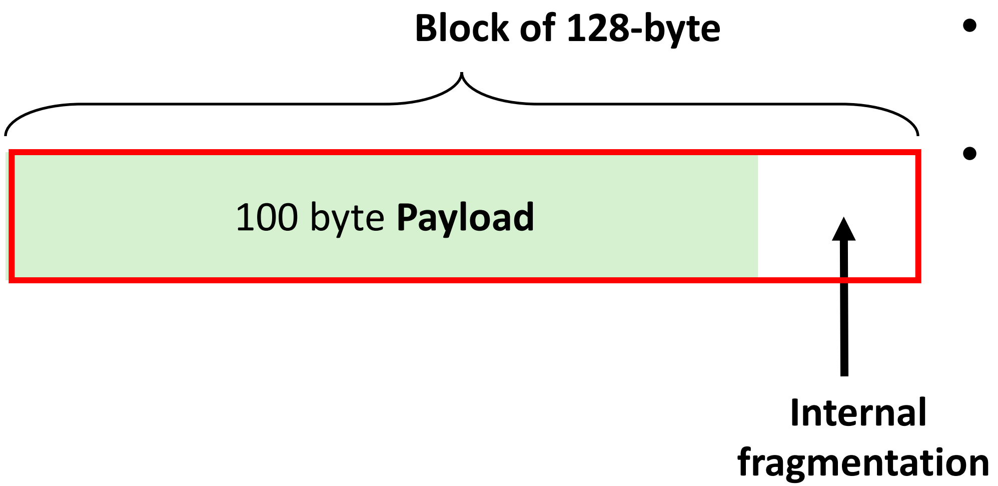
- Achieve good memory utilization
  - Apps issue arbitrary sequence of `malloc/free` requests of arbitrary sizes
  - Utilization = sum of `malloc`'d data / size of heap
- Achieve good performance
  - `malloc/free` calls should return quickly
  - Throughput = # ops/sec
- Constraints:
  - Cannot touch/modify `malloc`'d memory
  - Can't move the allocated blocks once they are `malloc'd`
    - *i.e.*, compaction is not allowed

Fragmentation

- Poor memory utilization caused by *fragmentation*
  - ***internal*** fragmentation
  - ***external*** fragmentation

Internal Fragmentation

- Malloc allocates data from blocks of certain sizes.
- *Internal fragmentation* occurs if payload is smaller than block size

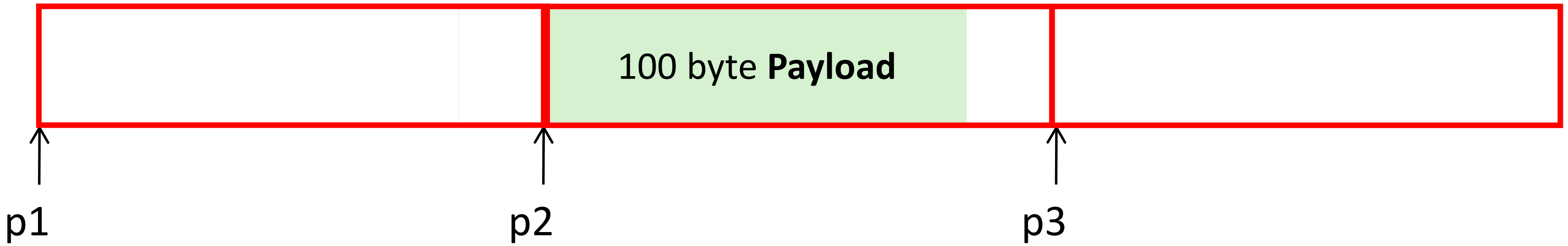


- Block size decided by allocator's designer.
- Payload is the number of bytes you want when you call `malloc()`, …

- May be caused by
  - Limited choices of block sizes
  - Padding for alignment purposes
  - Other space overheads…

External Fragmentation

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



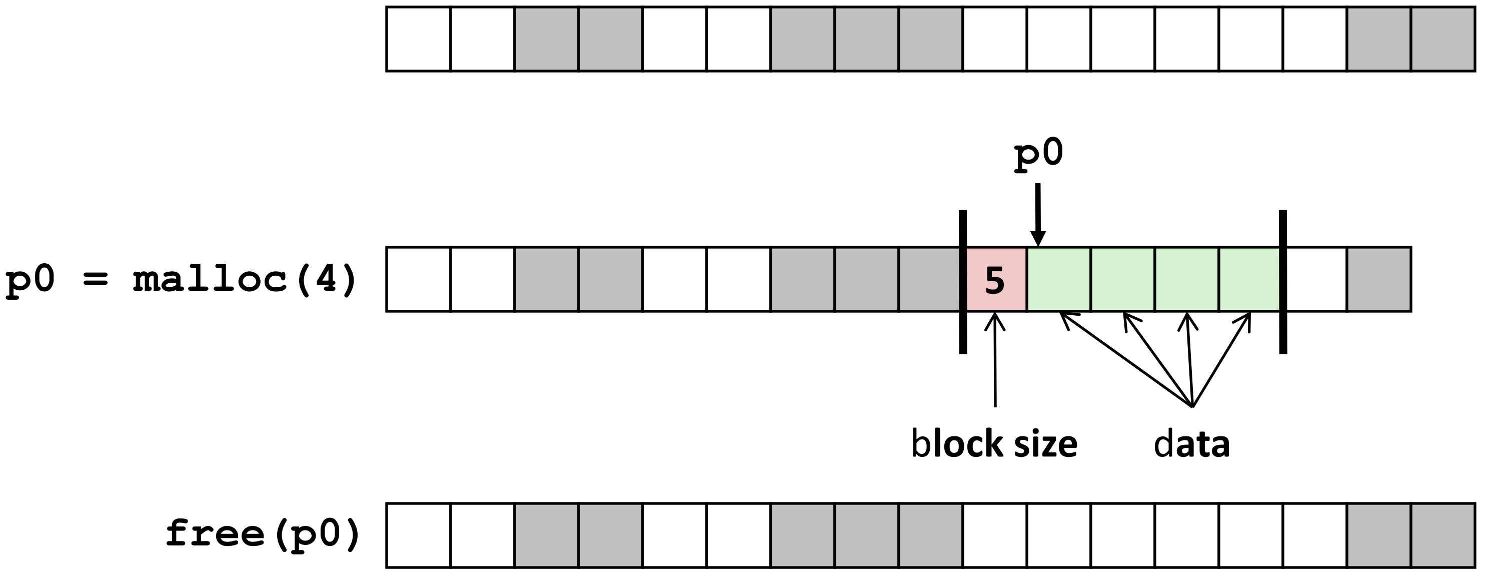

```
p1 = malloc(100);
p2 = malloc(100);
p3 = malloc(100);
free(p1);
free(p3);
malloc(200)?
```

Malloc design choices

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?
- What do we do with the extra space when allocating a space that is smaller than the free block it is placed in?
- How do we pick a block to use for allocation -- many might fit?
- How do we reinsert freed block?

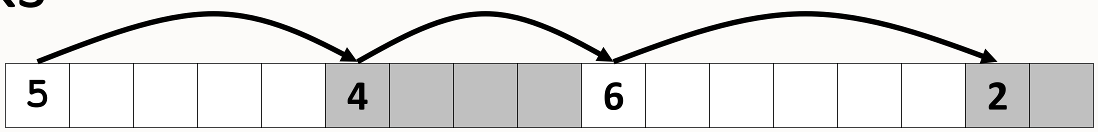
Knowing How Much to Free

- Standard method
  - Keep the length of a block in the header field preceding the block.
  - Requires header overhead for every allocated block

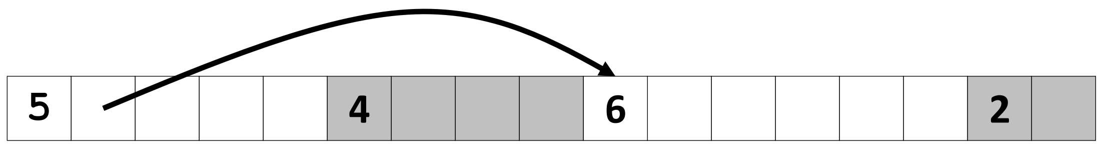


Keeping Track of Free Blocks

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



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

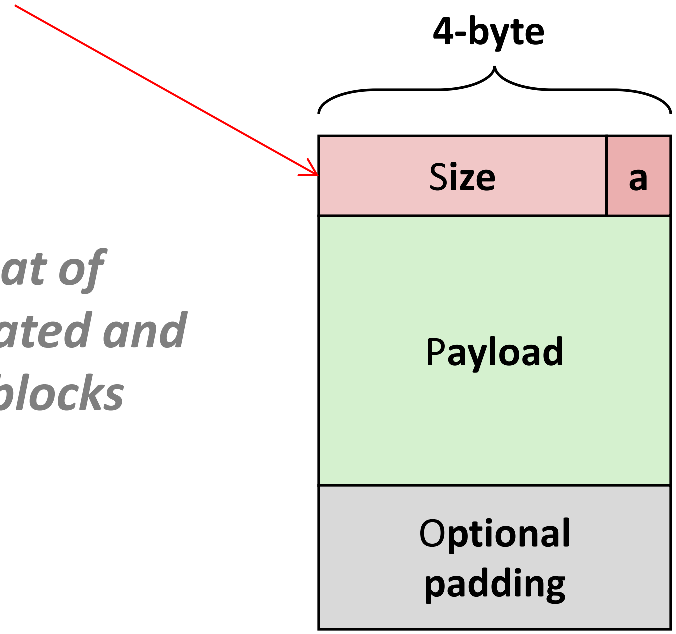


- Method 3: *Segregated free list*
  - Different free lists for different size classes

Method 1: Implicit List

- Malloc grows a contiguous region of heap by calling sbrk()
- Heap is divided into variable-sized blocks
- For each block, we need both size and allocation status

header + payload + padding



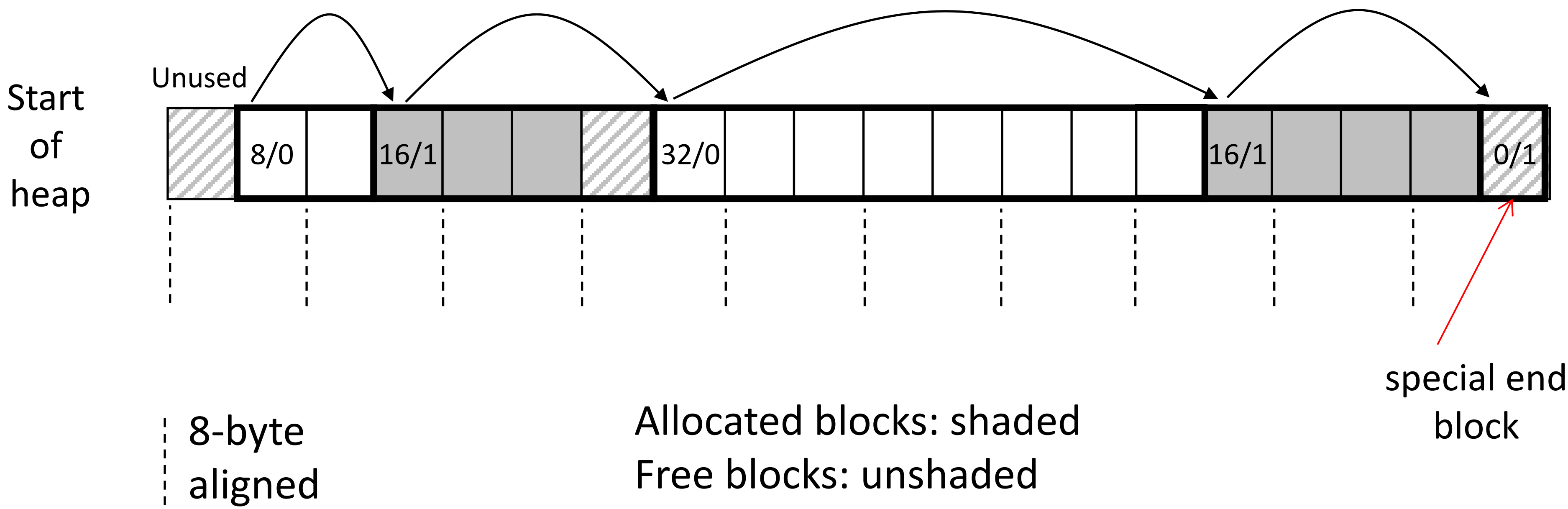
Format of allocated and free blocks

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

Size: block size

Payload: application data (allocated blocks only)

Detailed Implicit Free List Example



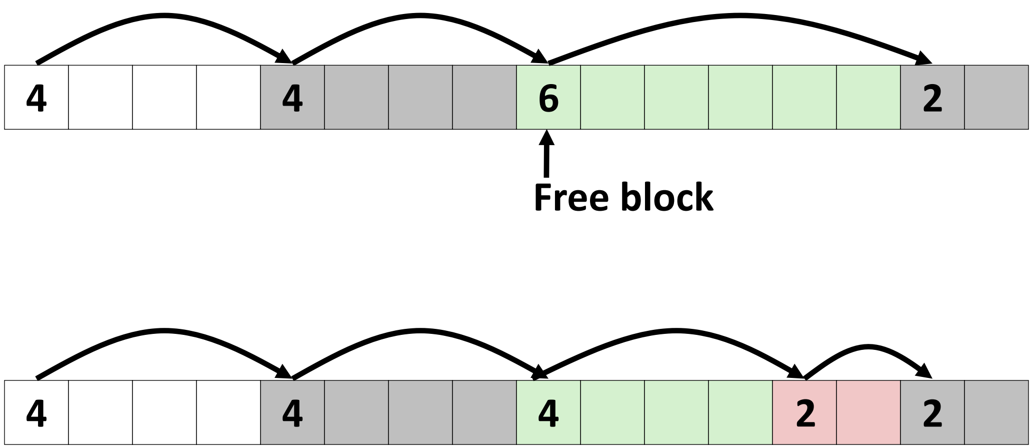
Allocated blocks: shaded
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit
Each square represents 4 bytes

Implicit List: Finding a Free Block

- *First fit:*
  - Search from beginning, choose ***first*** free block that fits:
- *Next fit:*
  - Like first fit, except search starts where previous search finished
- *Best fit:*
  - Search the list, choose the ***best*** free block: fits, with fewest bytes left over (i.e. pick the smallest block that is big enough for the payload)
  - Keeps fragments small
  - 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

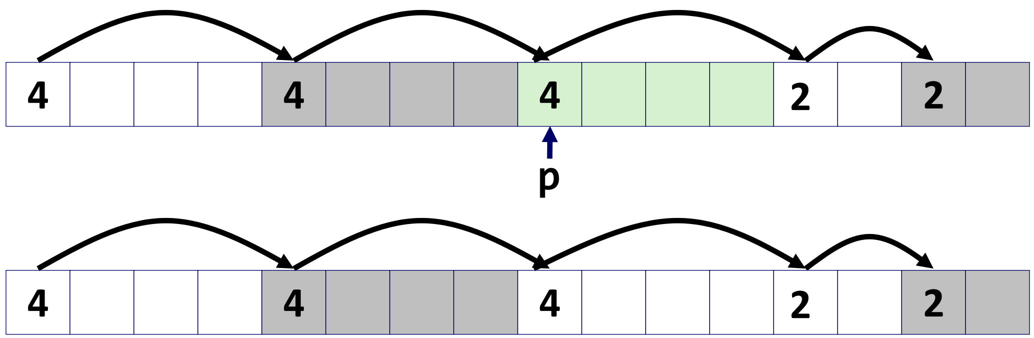


After malloc(4)

Implicit List: Freeing a Block

- Simplest implementation:
  - Need only clear the "allocated" flag
  - But can lead to "false fragmentation"

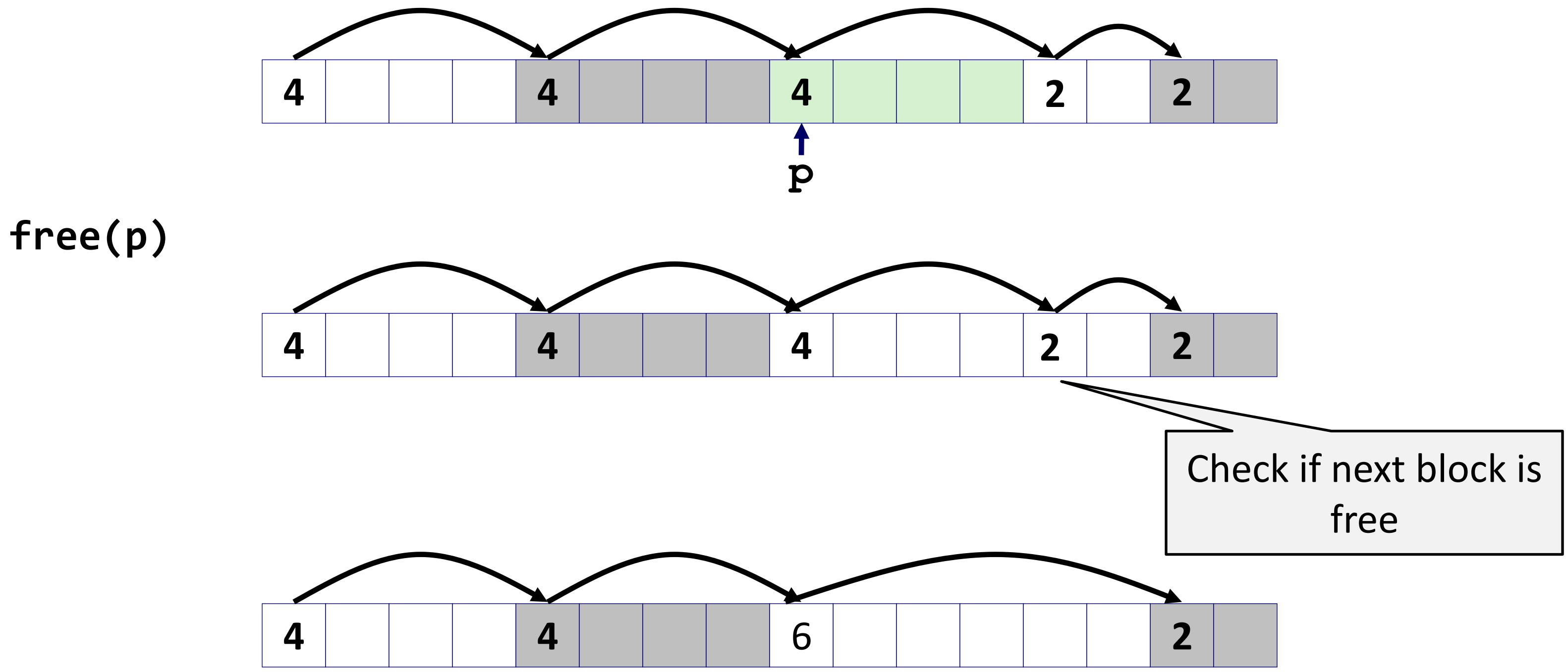
`free(p)`



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

Implicit List: Coalescing

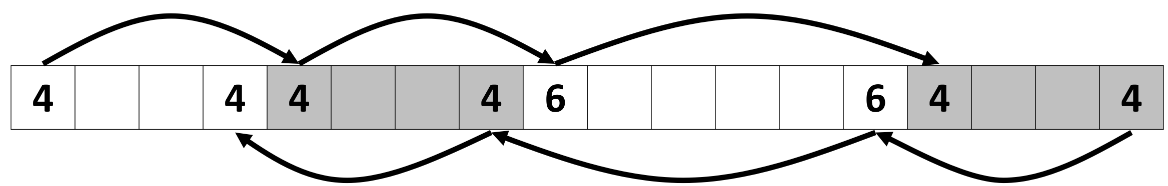
- Join *(coalesce)* with next/previous blocks, if they are free
  - Coalescing with next block



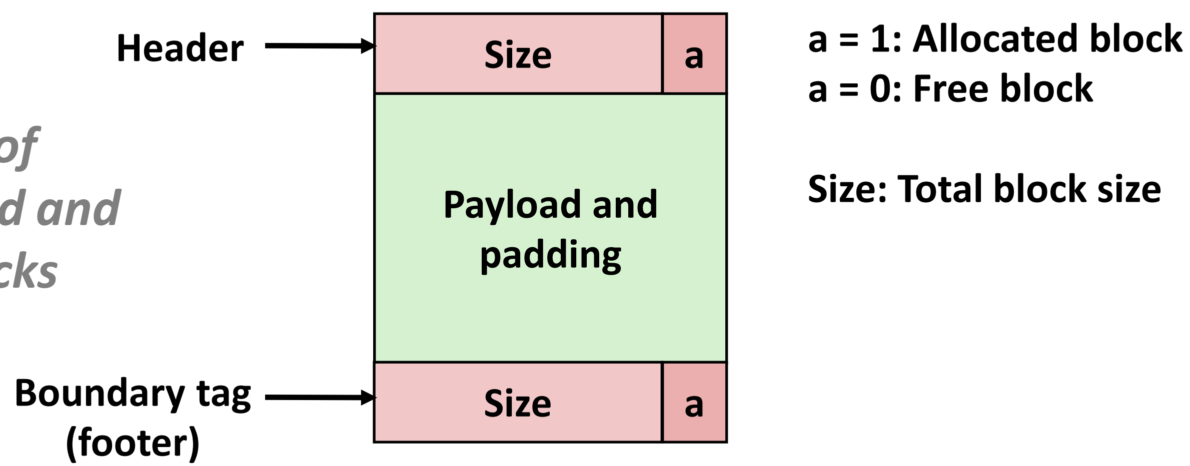
How to coalesce with a previous block?

Implicit List: Bidirectional Coalescing

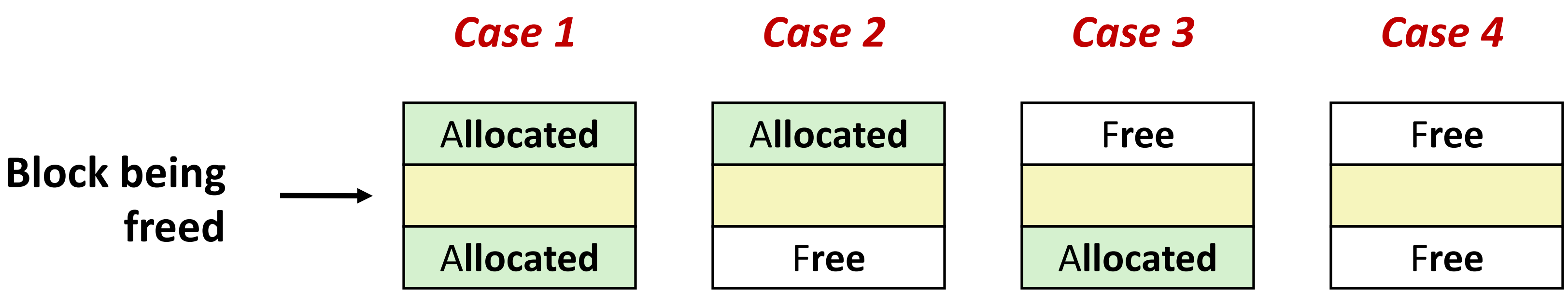
- ***Boundary tags*** [Knuth73]
  - Replicate size/allocated header at "bottom" (end) of blocks
  - Allows us to traverse the "list" backwards, but requires extra space



Format of allocated and free blocks

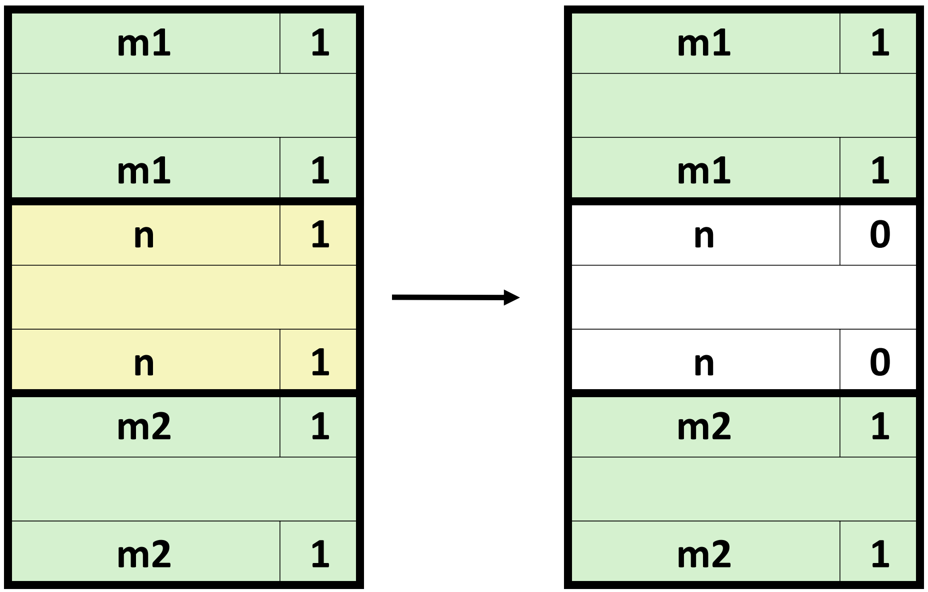


Coalescing

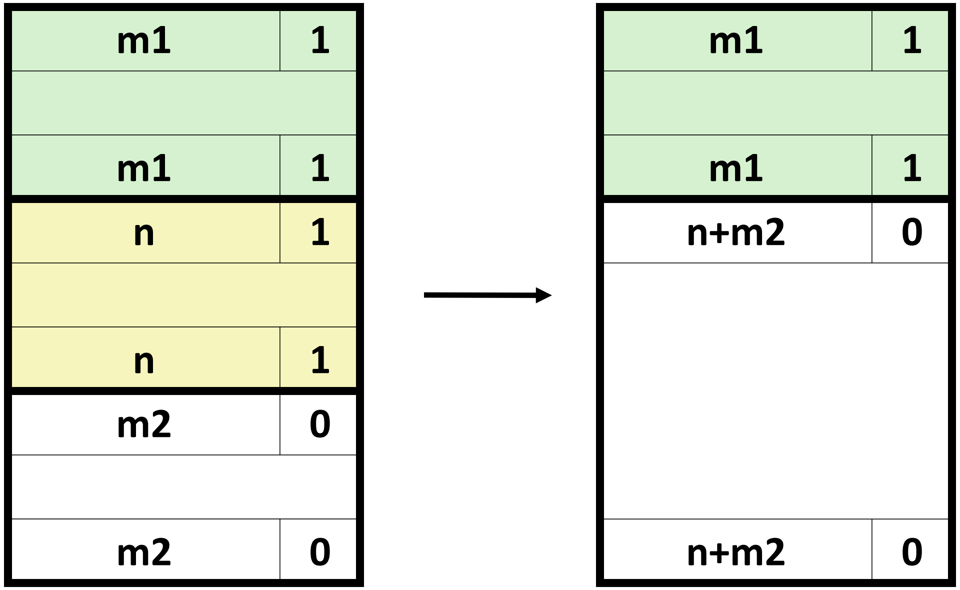


Case 1
Case 2
Case 3
Case 4
Block being freed
Allocated
Allocated
Allocated
Free
Free
Allocated
Free
Free

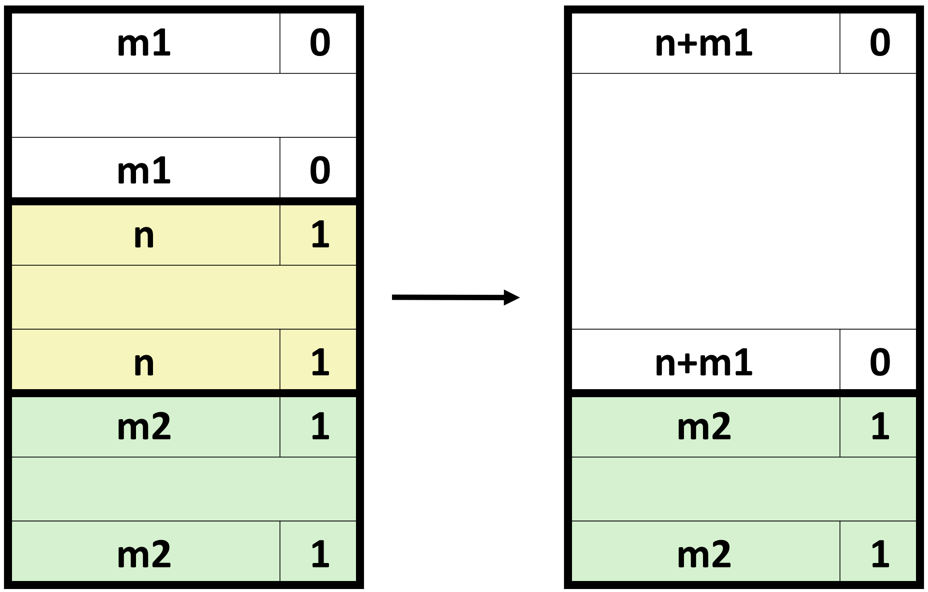
Coalescing (Case 1)



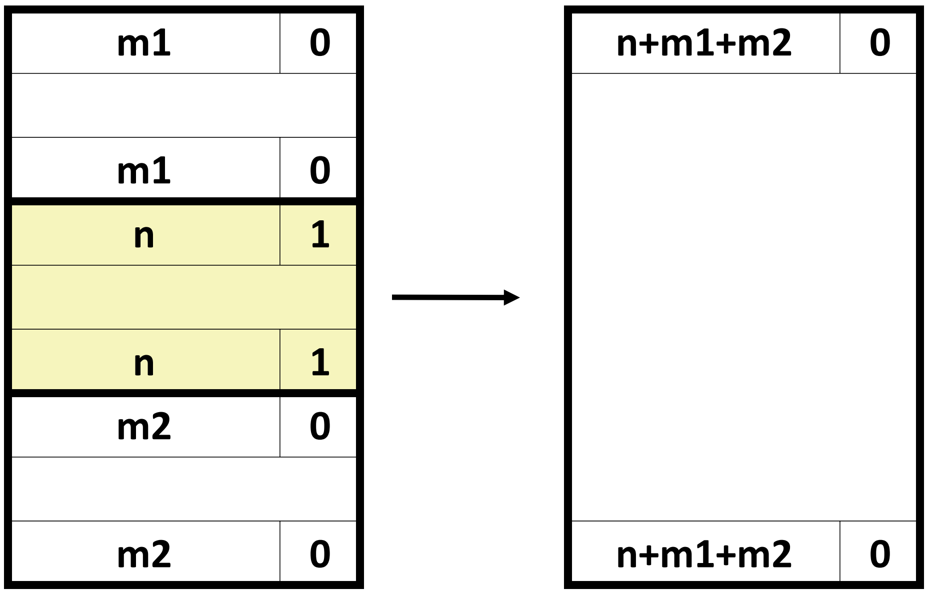
Coalescing (Case 2)



Coalescing (Case 3)



Coalescing (Case 4)



When to coalesce?

- 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 first-fit, next-fit or best-fit

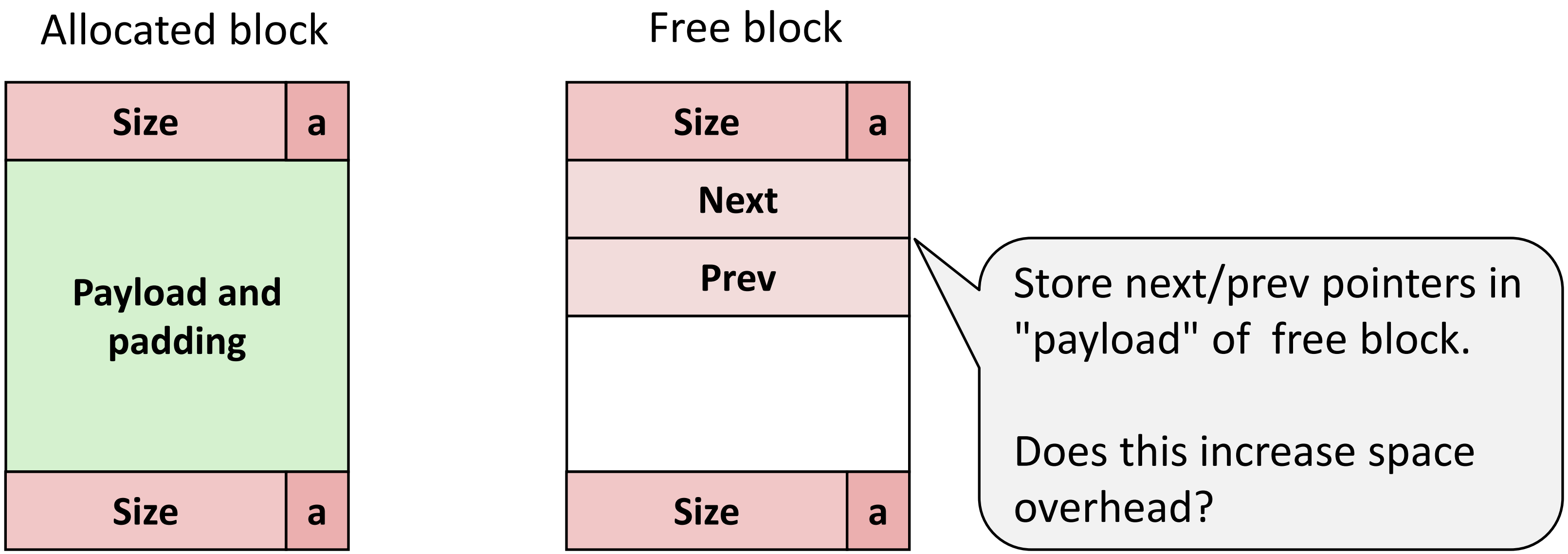
- Not used in practice for `malloc/free` because of linear-time allocation
  - used in many special purpose applications

Explicit Free list

- Maintain list(s) of free blocks instead of all blocks

- Need to store forward/back pointers in each free block, not just sizes
  - because free blocks may not be contiguous in heap.

Explicit Free Lists



Freeing With Explicit Free Lists

- Where in the free list to put a newly freed block?
  - Insert freed block at the beginning of the free list (LIFO)
    - ***Pro:*** simple and constant time
  - Insert freed blocks to maintain address order:

    addr(prev) < addr(curr) < addr(next)
    - ***Pro:*** may lead to less fragmentation than LIFO

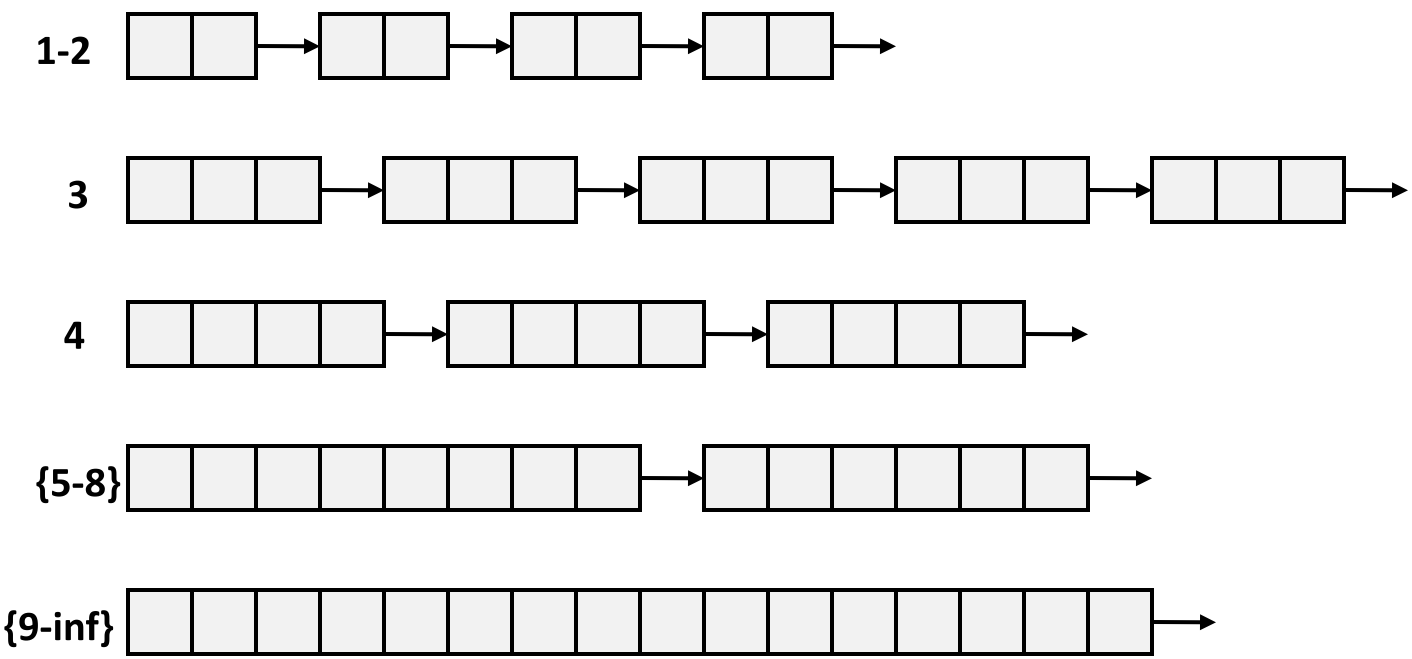
Explicit List

✓ Allocation is linear time in # of ***free*** blocks instead of ***all*** blocks

- Still expensive to find a free block that fits
  – How about keeping multiple linked lists of different size classes?

Segregated List (Seglist) Allocators

- Multiple free lists each linking free blocks of similar sizes



Seglist Allocator

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

- To allocate a block of size *n*:
  - Search in appropriate free list containing size n
  - Split found block and place fragment on appropriate list
  - try next larger class if no blocks found

- If no block is found:
  - Request additional heap memory from OS
  - 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
- Advantages of seglist allocators
  - Fast allocation
  - Better memory utilization
    - First-fit search of segregated free list approximates a best-fit search of entire heap

A Word About Garbage Collection

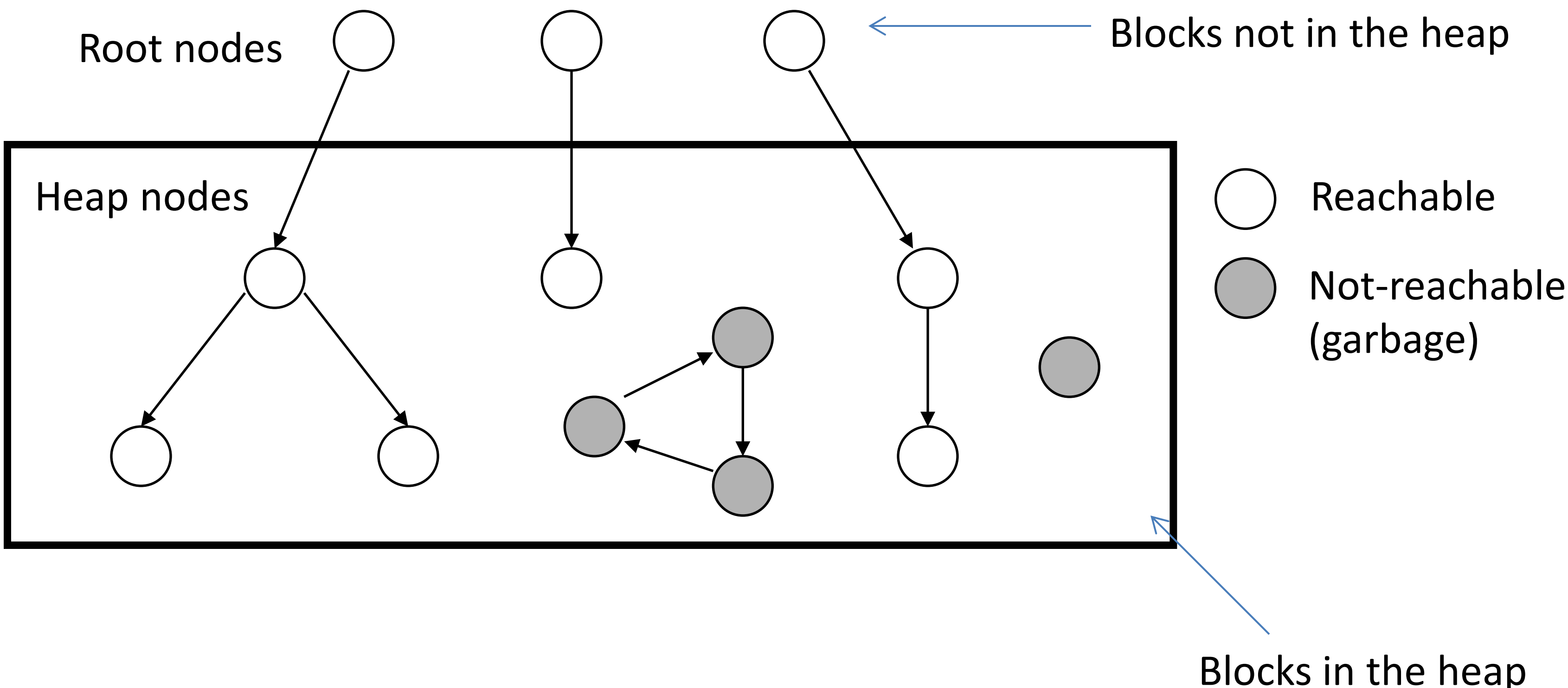
- In C, it is the programmer's responsibility to free any memory allocated by malloc/calloc/…
- A garbage collection is a dynamic storage allocator that automatically frees allocated blocks that are no longer needed by the program.
- Allocated blocks that are no longer needed are called garbage.

A Word About Garbage Collection

- In systems that support garbage collection (e.g. Java, Perl, Mathematica, …)
  - Applications explicitly allocate heap blocks
  - But never free them!
- The garbage collector periodically identifies garbage and make appropriate calls to free.

How does the garbage collector recognizes blocks that are no longer needed?

A Word About Garbage Collection



Reachability Graph

Conclusions

- Dynamic memory allocator manages the heap.
- Dynamic memory allocator is part of the user-space
- The allocator has two main goals:
  - reaching higher throughput (operations per second)
  - better memory utilization (i.e. reduces fragmentation).

Conclusions (cont'd)

- Explicit allocator
  - Works in terms of blocks
  - Keeping track of free blocks
    - Implicit list
    - Explicit list
    - segregated list
    - blocks sorted by size
- Implicit allocator