HARVARD
School of Engineering and Applied Sciences

Dynamic Memory Allocation

CS61, Lecture 10

Prof. Stephen Chong

October 4, 2011

Announcements 1/2

- Assignment 4: Malloc
  - Will be released today
  - May work in groups of one or two
    - Please go to website and enter your group by **Sunday 11:59PM**
      - Every group must do this (i.e., even if you are working individually)
  - Two deadlines:
    - Design checkpoint: Thursday October 13, 10pm
    - Final submission: Thursday October 20, 11:59pm
  - Encourage you to use version control
- Assignment 3 (Buffer bomb) due Thursday

Announcements 2/2

- Give us feedback on when you'd like office hours
  - http://tinyurl.com/689seas
  - Link posted on website

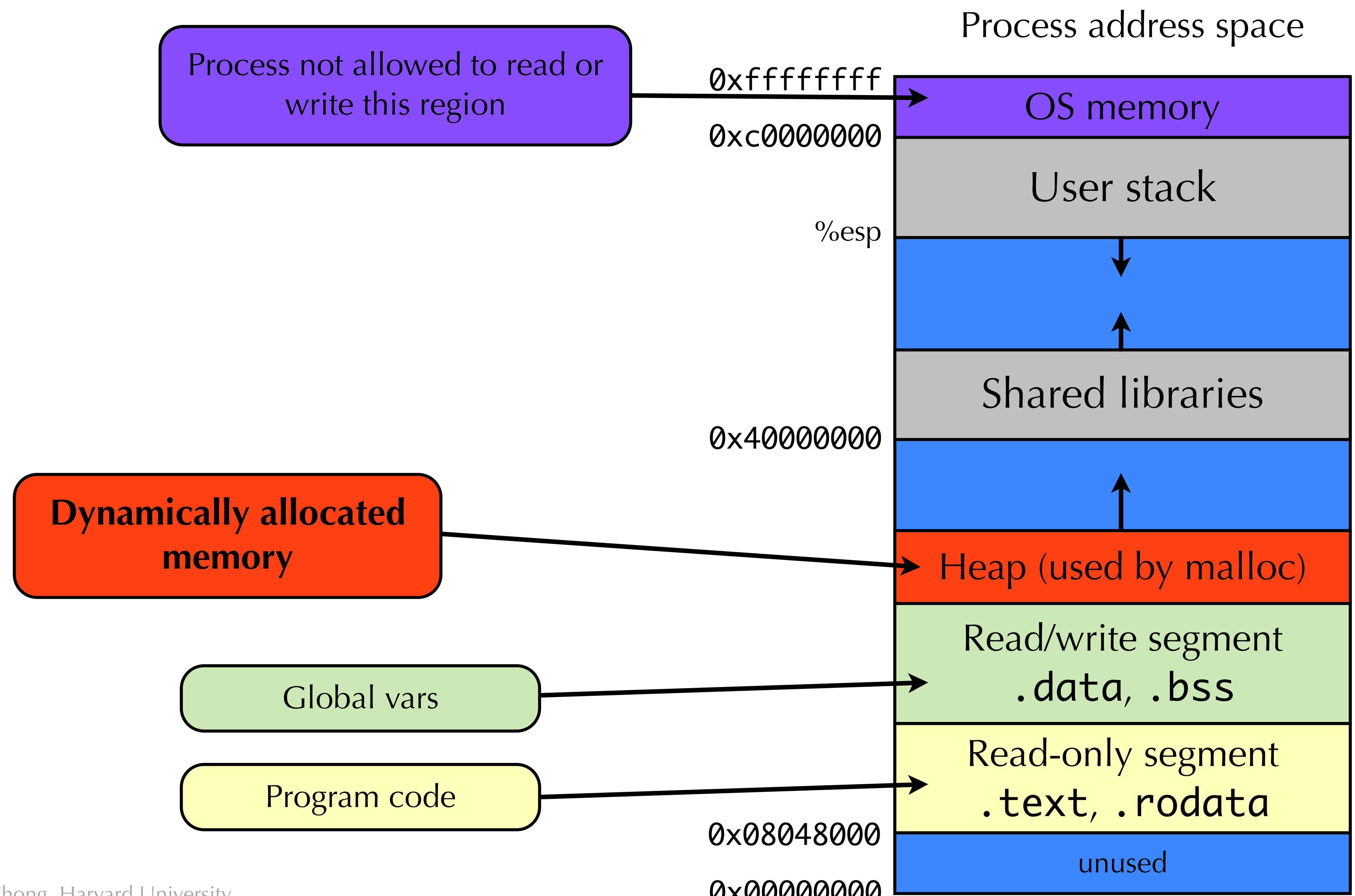
Topics for today

- Dynamic memory allocation
  - Implicit vs. explicit memory management
- Performance goals
- Fragmentation
- Free block list management
  - Implicit free list
  - Explicit free list
  - Segregated lists
  - Tradeoffs

Harsh Reality: Memory Matters!

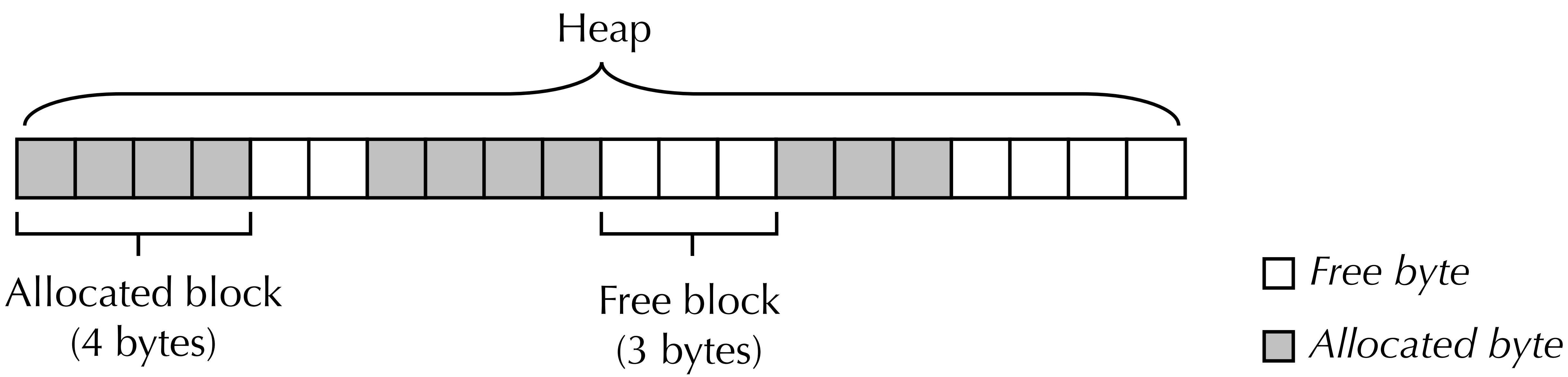
- Memory is not unlimited!
  - It must be allocated and managed
  - Many applications are memory dominated
    - Especially those based on complex, graph algorithms
- Memory referencing bugs especially pernicious
  - Effects are distant in both time and space
- Memory performance is not uniform
  - Cache and virtual memory effects can greatly affect program performance
  - Adapting program to characteristics of memory system can lead to major speed improvements

A process's view of memory



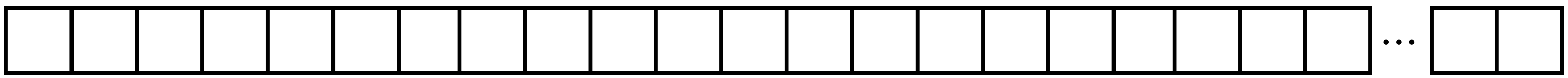
The heap

- The **heap** is the region of a program's memory used for dynamic allocation.
- Program can allocate and free blocks of memory within the heap.

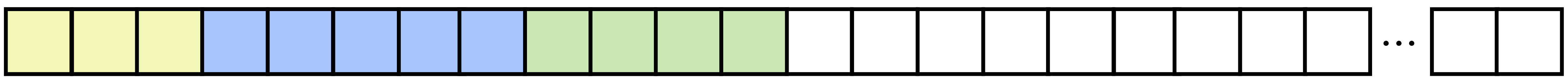


Free blocks, and allocated blocks

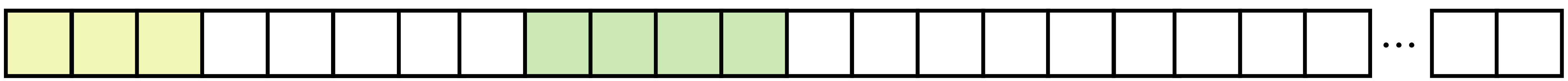
- Heap starts out as a single big “free block” of some fixed size (say a few MB)



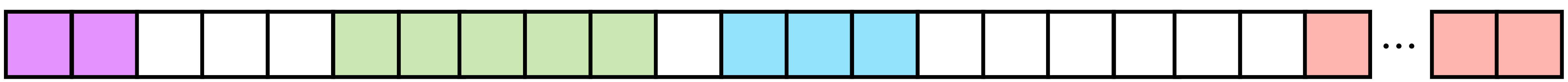
- Program may request memory, which splits up the the free space.



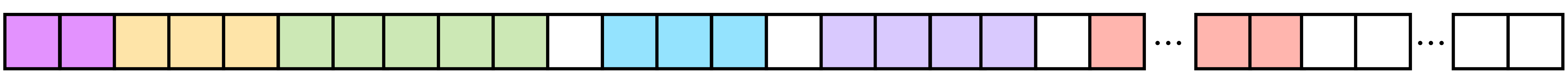
- Program may free up some memory, which increases the free space



- Over time the heap will contain a mixture of free and allocated blocks.



- Heap may need to grow in size (but typically never shrinks)
  - Program can grow the heap if it is too small to handle an allocation request.
  - On UNIX, the `sbrk()` system call is used to expand the size of the heap.



Dynamic Memory Management

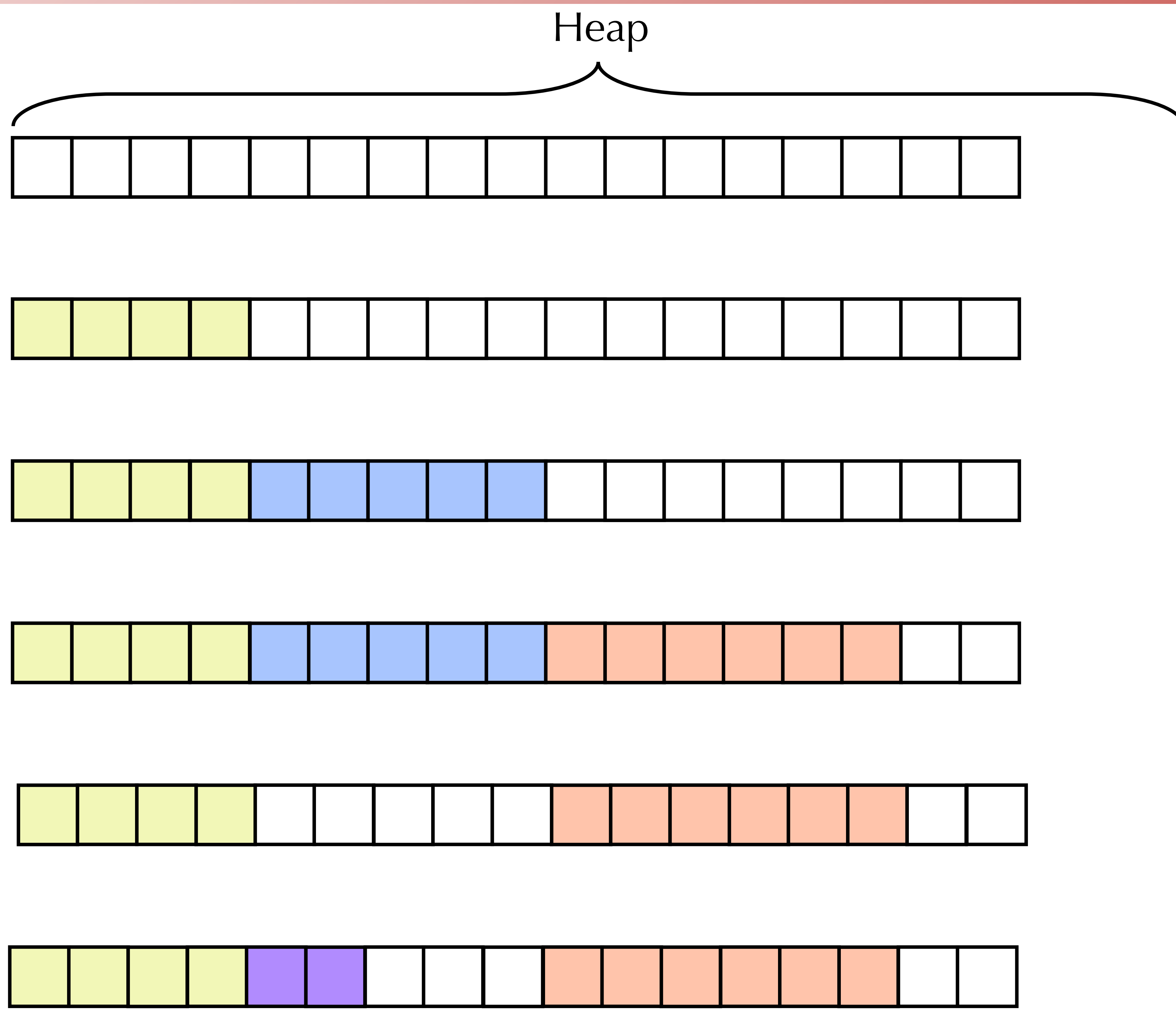
- How do we decide when do expand the heap (using `sbrk()`)?
- How do we manage allocating and freeing bytes on the heap?
- There are two broad classes of memory management schemes:
- Explicit memory management
  - Application code responsible for both explicitly **allocating** and **freeing** memory.
  - Example: `malloc()` and `free()`
- Implicit memory management
  - Application code can allocate memory, but **does not explicitly free memory**
  - Rather, rely on **garbage collection** to “clean up” memory objects no longer in use
  - Used in languages like Java, Python, OCaml

Malloc Package

- `#include <stdlib.h>`
- `void *malloc(size_t size)`
  - If successful:
    - Returns a pointer to a memory block of at least `size` bytes
    - If `size == 0`, returns `NULL`
  - If unsuccessful: returns `NULL`.
- `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`.
- `void *realloc(void *p, size_t size)`
  - Changes size of block `p` and returns pointer to new block.
  - Contents of new block unchanged up to min of old and new size.

Allocation Examples

```
p1 = malloc(4)
p2 = malloc(5)
p3 = malloc(6)
free(p2)
p4 = malloc(2)
```



Constraints

- Application code must obey following constraints:
  - Allowed to issue arbitrary sequence of allocation and free requests
  - Free requests must correspond to an allocated block
- Memory management code must obey following constraints:
  - Can't control number or size of requested blocks
  - Must respond immediately to all allocation 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
  - Can't mess around with allocated memory
    - Can only manipulate and modify free memory
    - Can't move the allocated blocks once they are allocated (i.e., compaction is not allowed)

Topics for today

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  - Implicit vs. explicit memory management
- Performance goals
- Fragmentation
- Free block list management
  - Implicit free list
  - Explicit free list
  - Segregated lists
  - Tradeoffs

What do we want?

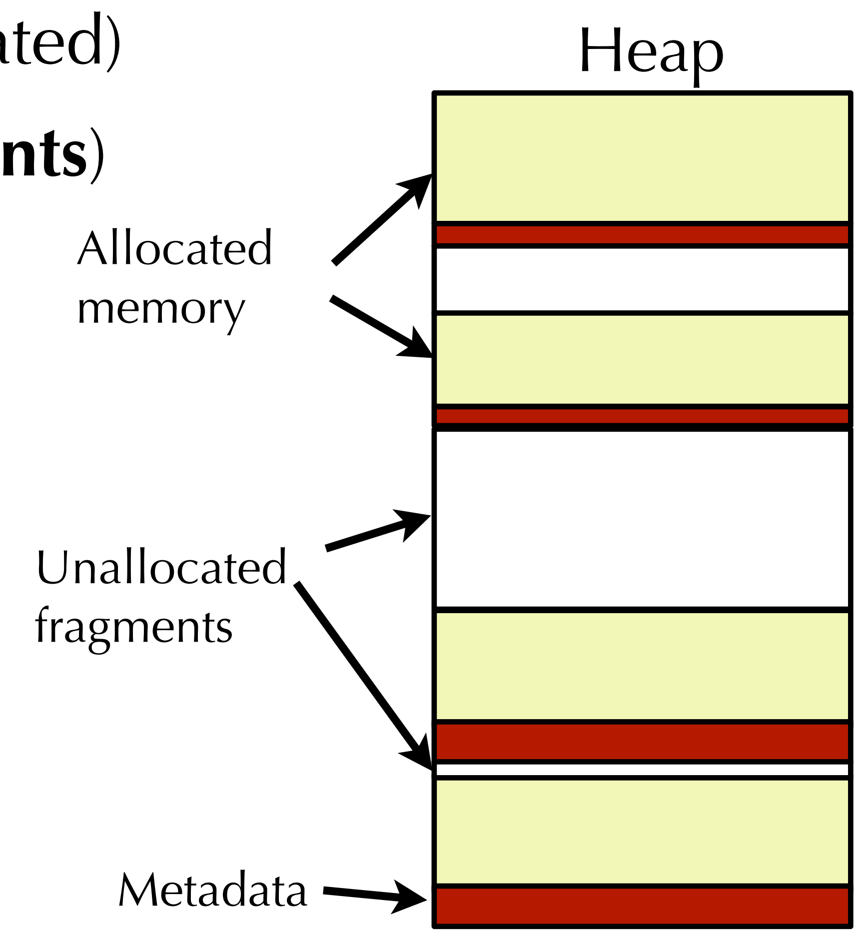
- Want our memory management to be:
  - Fast
    - Minimize overhead of allocation and deallocation operations.
  - Efficient
    - Don’t waste memory space

Performance Goals: Allocation overhead

- Want our memory allocator to be fast!
  - Minimize the overhead of both allocation and deallocation operations.
- One useful metric is **throughput**:
  - Given a series of allocate or free requests
  - Maximize the number of completed requests per unit time
- Example:
  - 5,000 malloc calls and 5,000 free calls in 10 seconds
  - Throughput is 1,000 operations/second.

Performance Goals: Memory Utilization

- Allocators rarely do a perfect job of managing memory.
  - Usually there is some "waste" involved in the process.
- Examples of waste...
  - Extra metadata or internal structures used by the allocator itself (example: Keeping track of where free memory is located)
  - Chunks of heap memory that are unallocated (**fragments**)
- We define **memory utilization** as...
  - The **total amount of memory allocated to the application** divided by the **total heap size**
- Ideally, we'd like utilization to be to 100%
  - In practice this is not possible, but want to be as close as possible



Conflicting performance goals

- High throughput and good utilization are difficult to achieve simultaneously.
- A fast allocator may not be efficient in terms of memory utilization.
  - Faster allocators tend to be “sloppier” with their memory usage.
- Likewise, a space-efficient allocator may not be very fast
  - To keep track of memory waste (i.e., tracking fragments), the allocation operations generally take longer to run.
- Trick is to balance these two conflicting goals.

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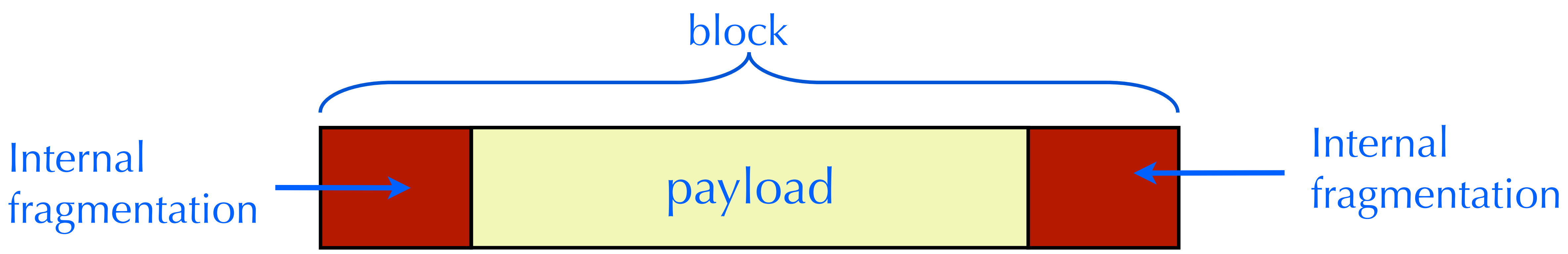
  - Segregated lists
  - Tradeoffs
- Alignment

Internal Fragmentation

- Poor memory utilization caused by **fragmentation**.
  - Comes in two forms: **internal** and **external** fragmentation
- **Internal fragmentation**
  - Internal fragmentation is the difference between block size and payload size.

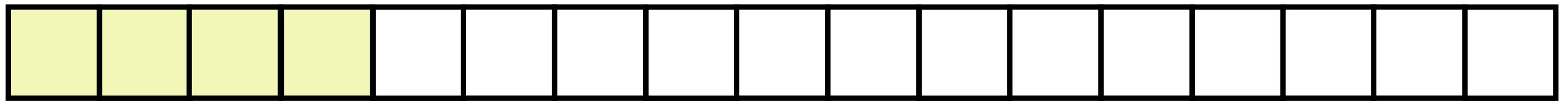


  - Caused by overhead of maintaining heap data structures, padding for alignment purposes, or the policy used by the memory allocator
  - Example: Say the allocator always "rounds up" to next highest power of 2 when allocating blocks.
    - So `malloc(1025)` will actually allocate 2048 bytes of heap space!

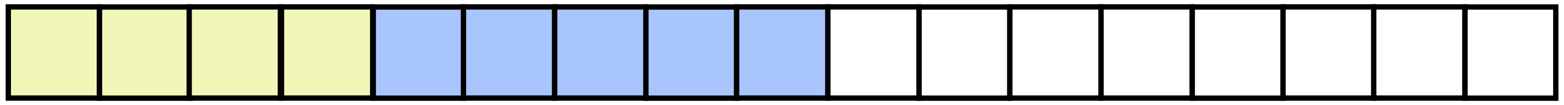
External Fragmentation

- Occurs when there is enough aggregate heap memory, but no single free block is large enough to satisfy a given request.

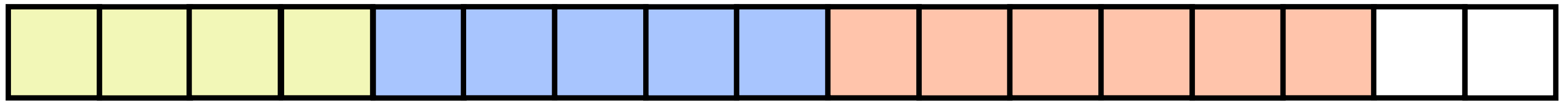
`p1 = malloc(4)`



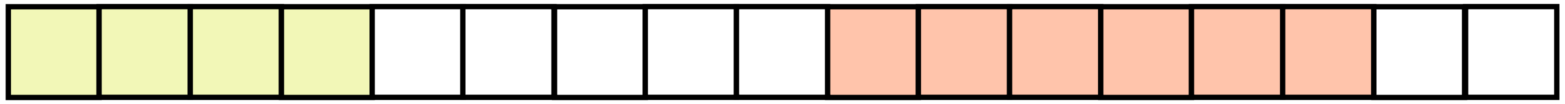
`p2 = malloc(5)`



`p3 = malloc(6)`



`free(p2)`



`p4 = malloc(6)`

No free block big enough!

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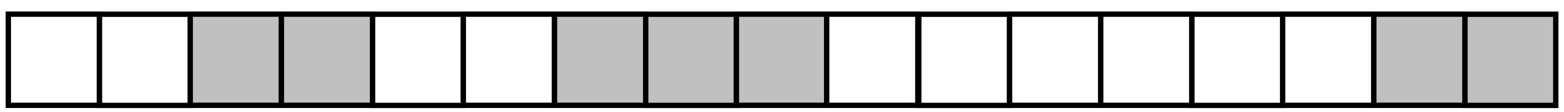
Free block list management

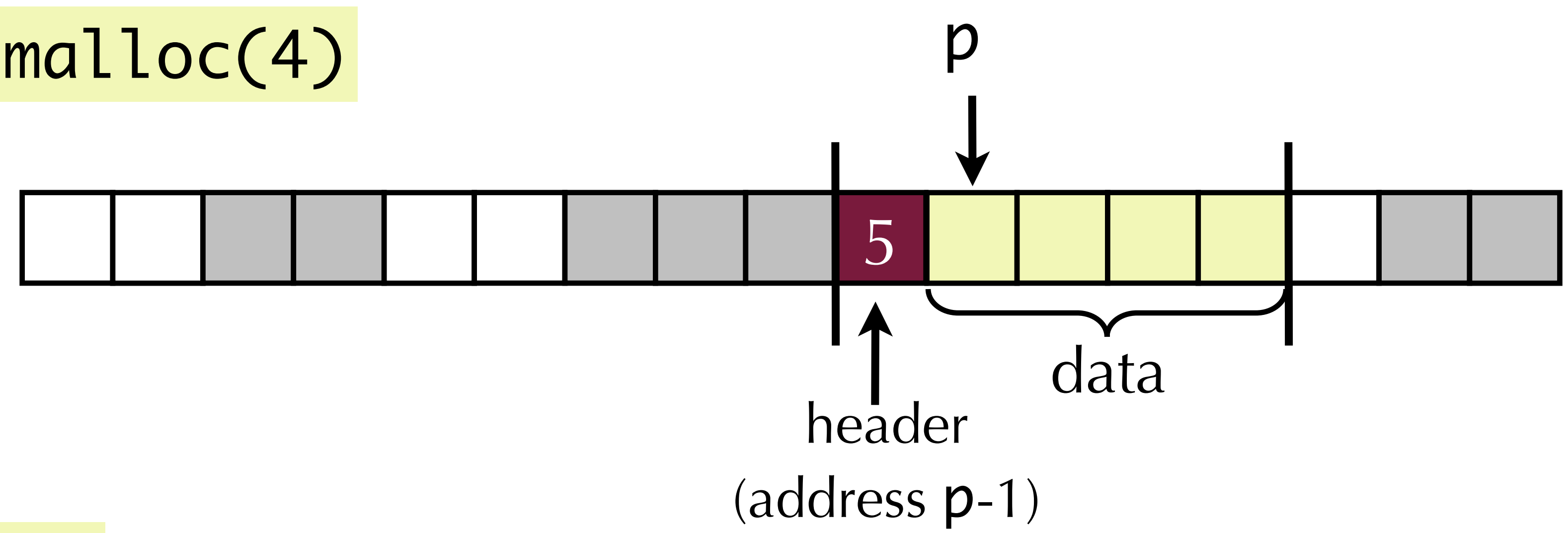
- How do we know how much memory to free just given a pointer?
- How do we keep track of the free blocks?
- What do we do with the extra space when allocating a memory block that is smaller than the free block it is placed in?
- How do we pick which free block to use for allocation?

Knowing how much to free

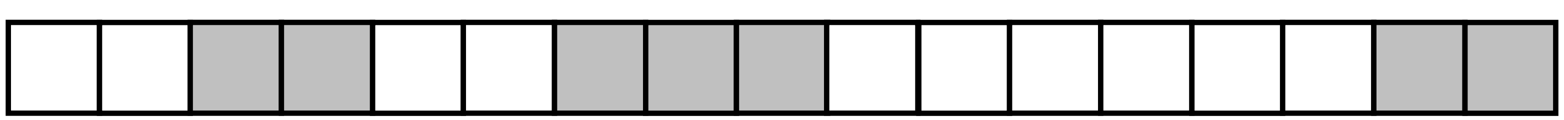
- Standard method
  - Keep the length of a block in a header preceding the block.
  - Requires an extra word for every allocated block



```
p = malloc(4)
```




```
free(p)
```

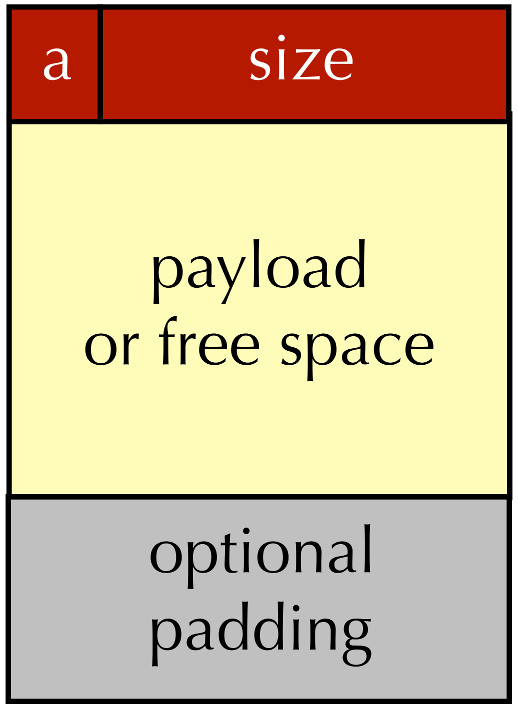


Keeping Track of Free Blocks

- One of the biggest jobs of an allocator is knowing where the free memory is.
  - Affects throughput and utilization
- Many approaches to free block management.
  - Today, we will talk about three techniques
    - Implicit free lists
    - Explicit free lists
    - Segregated free lists
  - There are other approaches

Implicit free list

- Idea: Each block contains a **header** with some extra information.
  - **Allocated bit** indicates whether block is allocated or free.
  - **Size field** indicates entire size of block (including the header)
  - Trick: Allocation bit is just the high-order bit of the size word
- For this lecture, assume header size is 1 byte.
  - Makes later pictures easier to understand.
  - This means the block size is only 7 bits, so max. block size is 127 bytes (2^7-1).
  - Clearly a real implementation would want to use a larger header (e.g., 4 bytes).

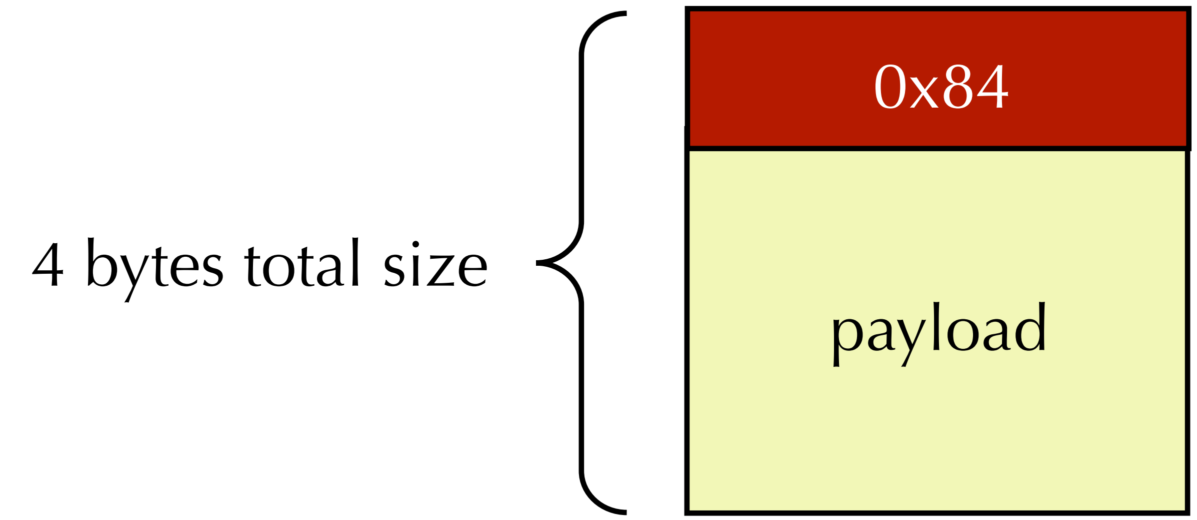


a = 1: block is allocated
a = 0: block is free

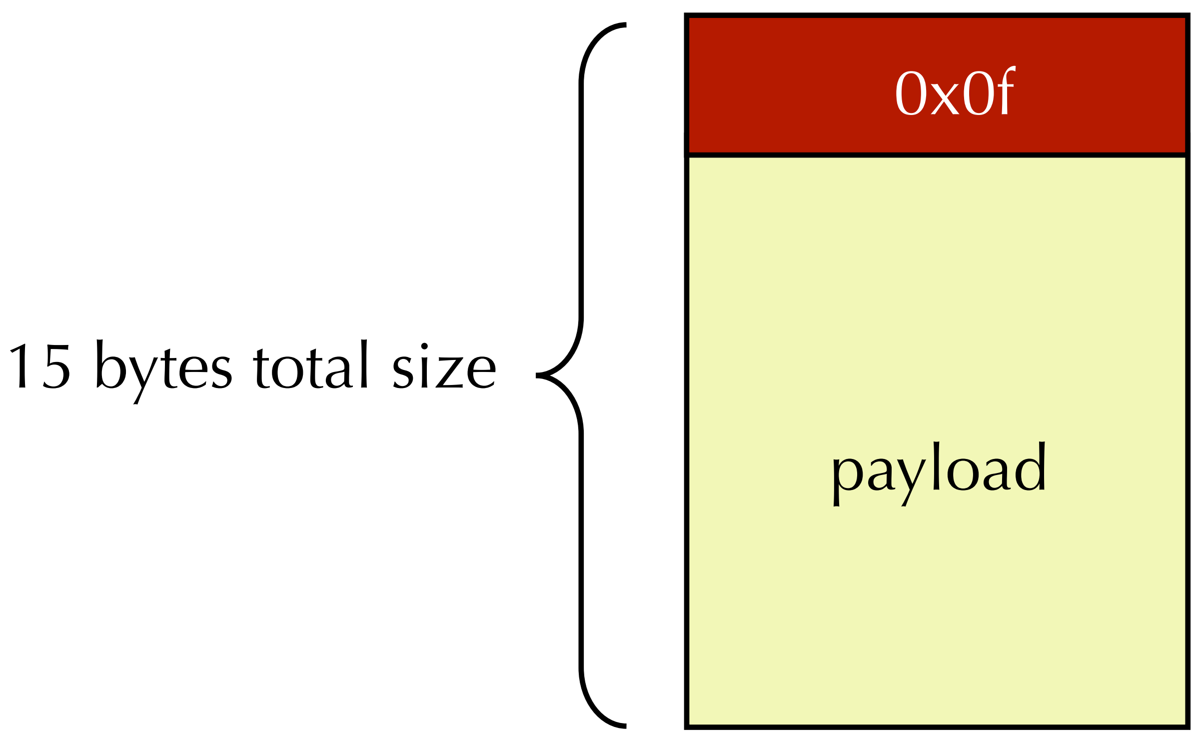
size: block size

payload: application data

Examples

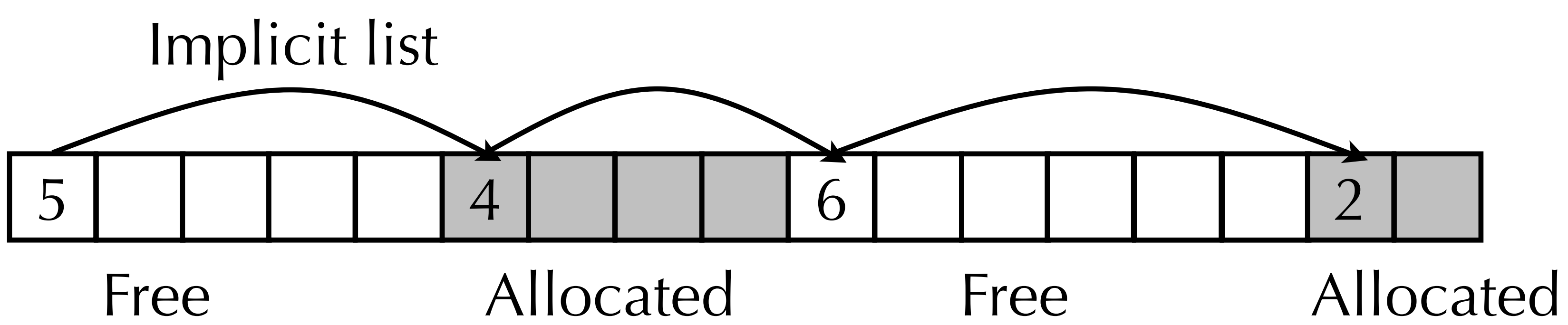


0x84 in binary: 1000 0100
allocated = 1
size = 000 0100 = 0x4 = 4 bytes



0x0f in binary: 0000 1111
allocated = 0
size = 000 1111 = 0xf = 15 bytes

Implicit free list



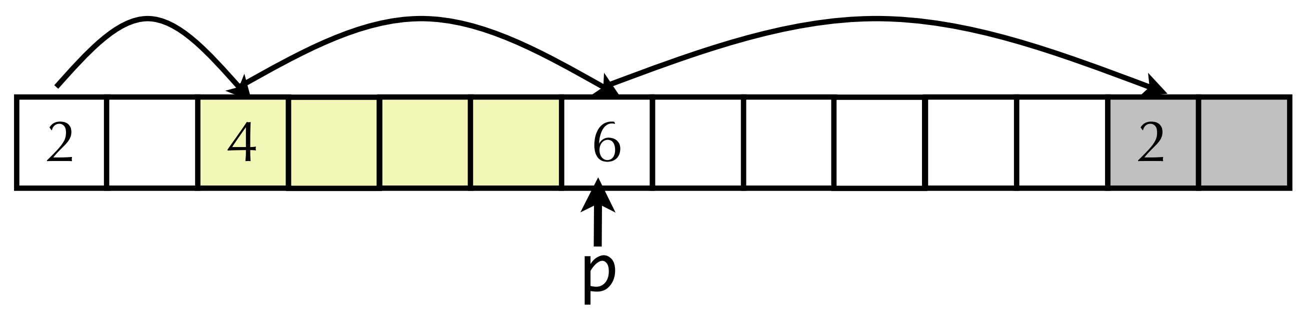
- No **explicit** structure tracking location of free/allocated blocks.
  - Rather, the size word (and allocated bit) in each block form an **implicit** "block list"
- How do we find a free block in the heap?
  - Start scanning from the beginning of the heap.
  - Traverse each block until (a) we find a free block and (b) the block is large enough to handle the request.
  - This is called the **first fit** strategy.

Implicit List: Finding a Free Block

- **First fit** strategy:
  - Search list from beginning, choose first free block that fits
  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause “splinters” at beginning of list
- **Next fit** strategy:
  - Like first-fit, but search list from location of end of previous search
  - Research suggests that fragmentation is worse than first-fit
- **Best fit** strategy:
  - Search the list, choose the free block with the closest size that fits
  - Keeps fragments small — usually helps fragmentation
  - Runs slower than first- or next-fit, since the entire list must be searched each time

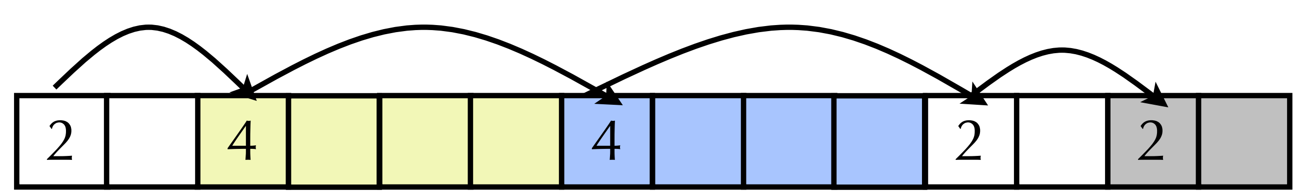
Implicit List: Allocating in Free Block

- Splitting free blocks
  - Since allocated space might be smaller than free space, we may need to **split** the free block that we're allocating within
  - E.g., `malloc(3)`




```
void addblock(ptr_t p, int len) {
  int oldsize = *p;              // Get old size of free block
  *p = len | 0x80;               // Set new size + alloc bit
  if (len < oldsize)
    *(p+len) = oldsize - len;  // Set size of remaining
}                                //   part of free block
```

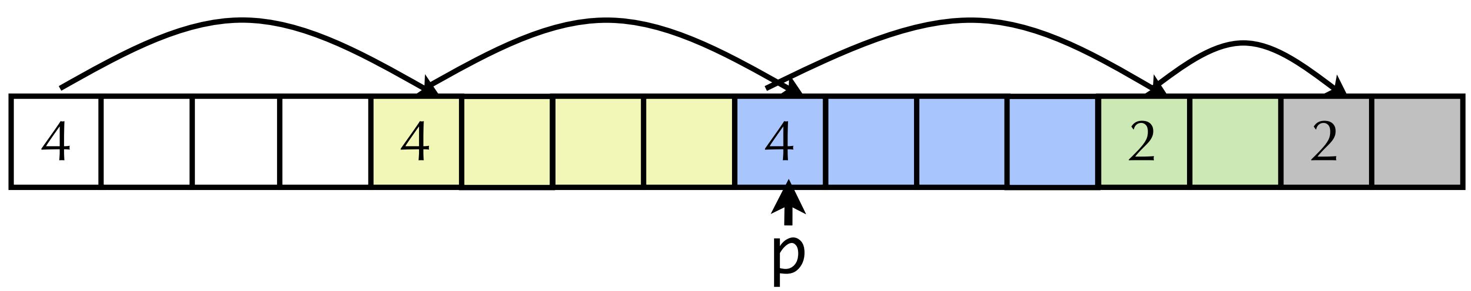
`addblock(p, 4)`



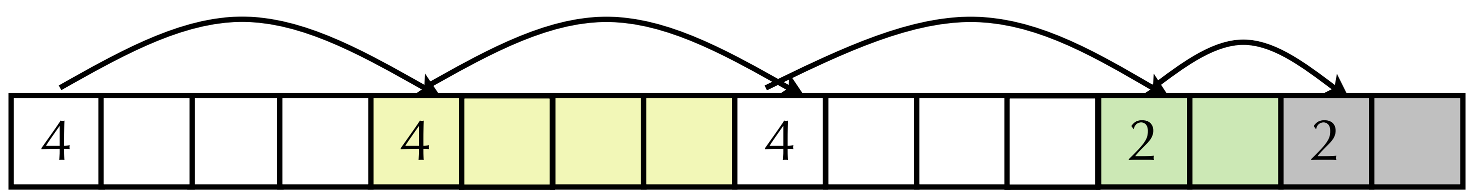
Implicit List: Freeing a Block

- Simplest implementation:
  - Simply clear the allocated bit in the header

```
/* Here, p points to the block header. */
/* This sets the high-order bit to 0. */
void free_block(ptr_t p) { *p = *p & 0x7f; }
```



free(p+1)

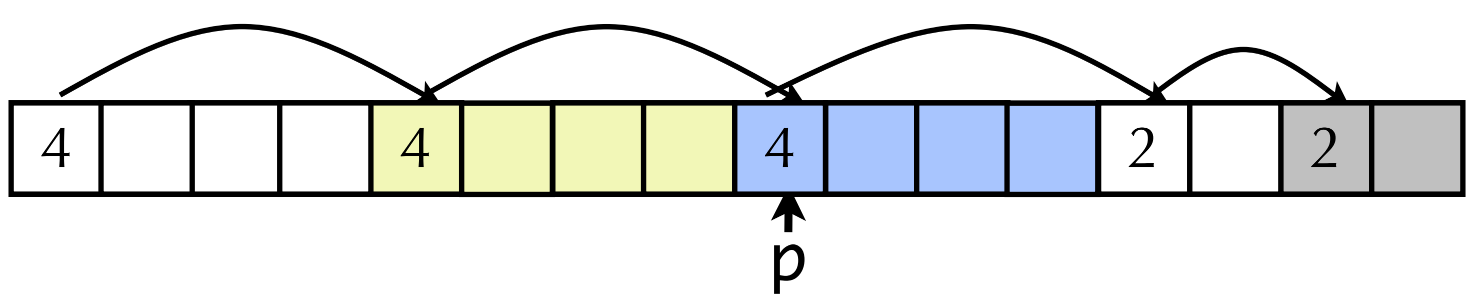


Implicit List: Freeing a Block

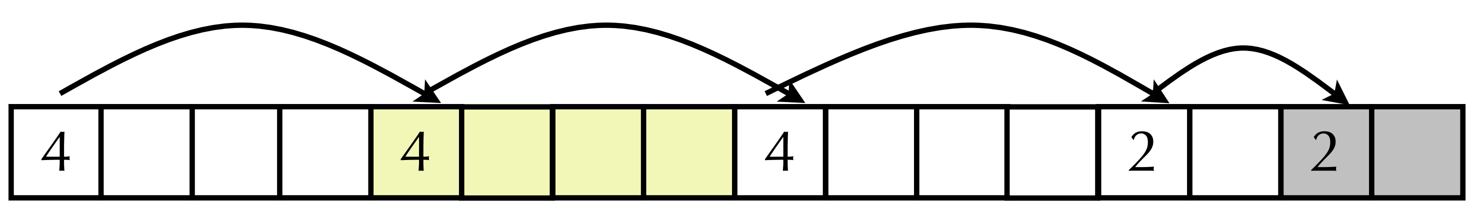
- Simplest implementation:
  - Simply clear the allocated bit in the header

```
/* Here, p points to the block header. */
/* This sets the high-order bit to 0. */
void free_block(ptr_t p) { *p = *p & ~0x80; }
```

  - But can lead to “false fragmentation”



`free(p+1)`



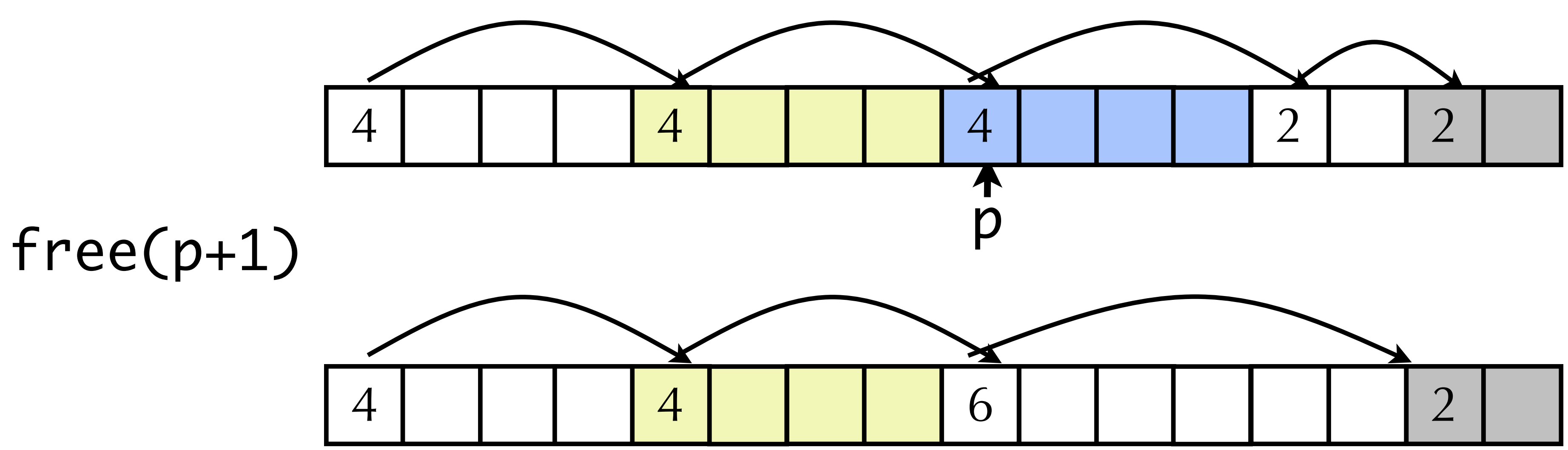
`malloc(5)`

  - There is enough free space, but the allocator won’t be able to find it!

Implicit List: Coalescing

- **Coalesce** with adjacent block(s) if they are free

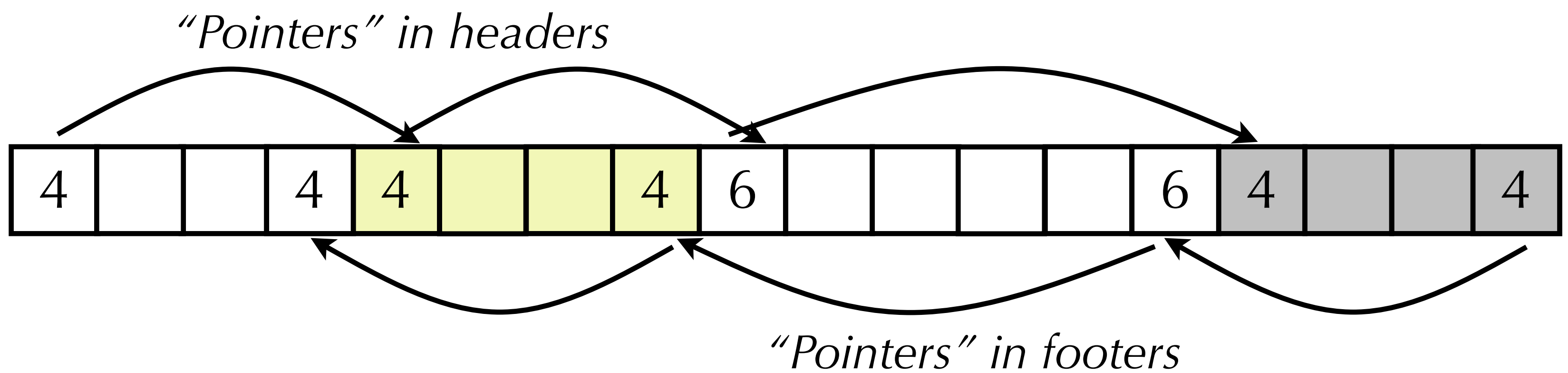
```
void free_block(ptr_t p) {
    *p = *p & 0x7f;        // Clear allocated bit
    next = p + *p;          // Find next block
    if ((*next & 0x80) == 0)
      *p = *p + *next;      // Add to this block if
}                           //    next is also free
```



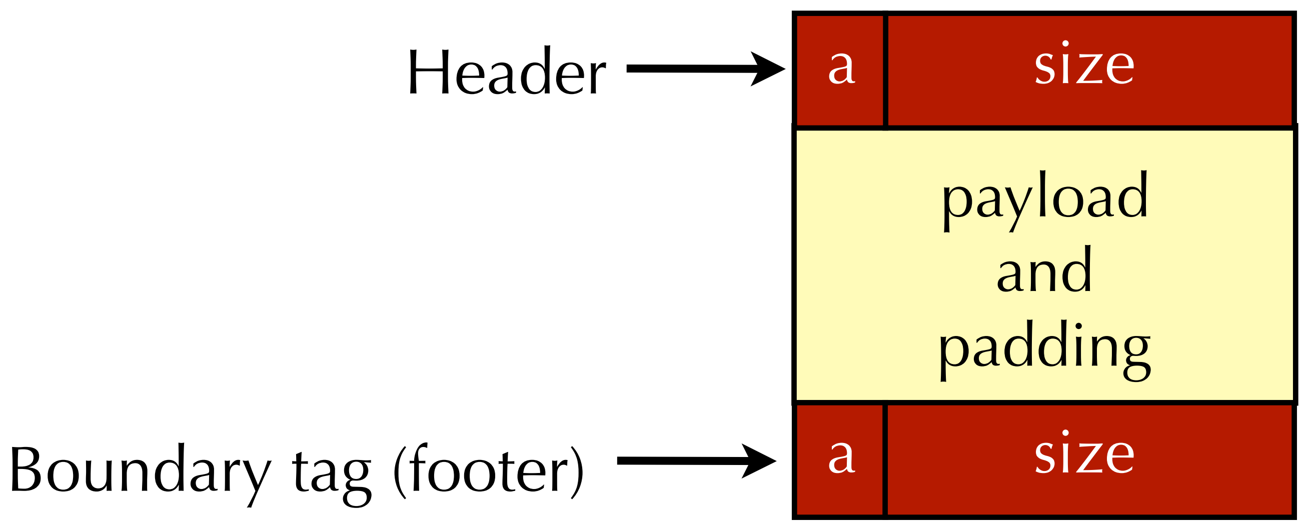
- This is coalescing with the next free block.
- How would we coalesce with the previous free block?

Implicit List: Bidirectional Coalescing

- **Boundary tags** [Knuth73]
  - Also maintain the size/allocated word at end of free blocks (a footer)



  - Allows us to traverse the "block list" backwards, but requires extra space



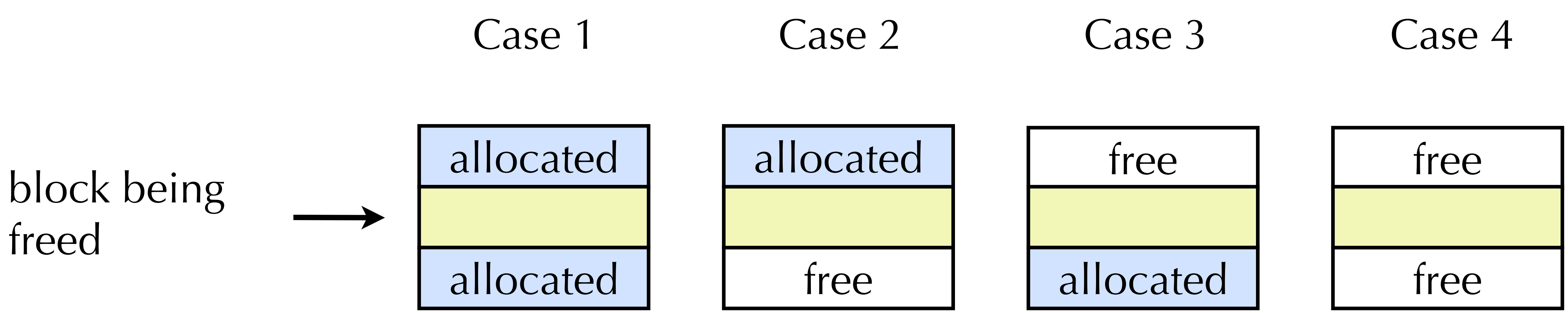
a = 1: block is allocated
a = 0: block is free

size: total block size

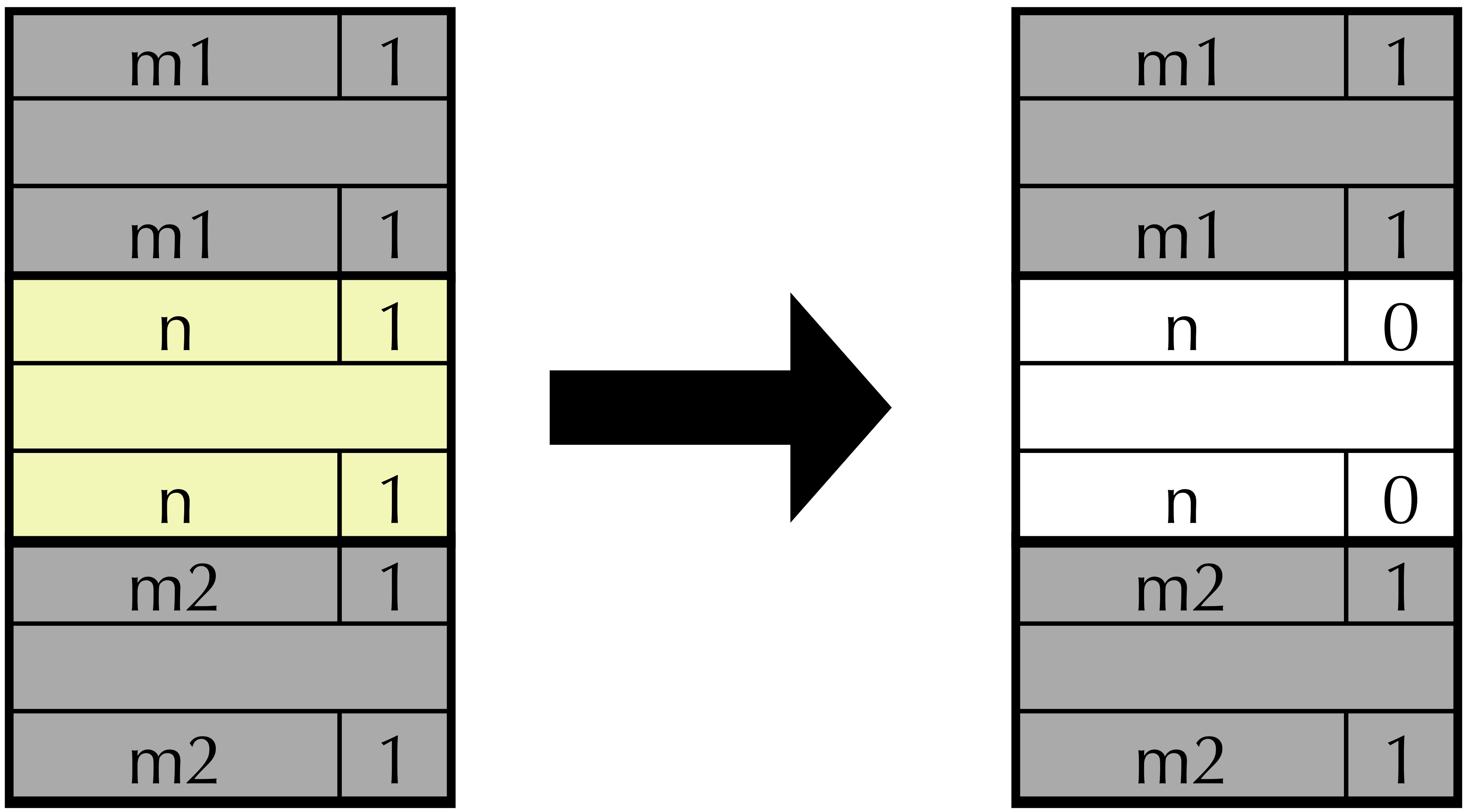
payload: application data

  - Important and general technique!

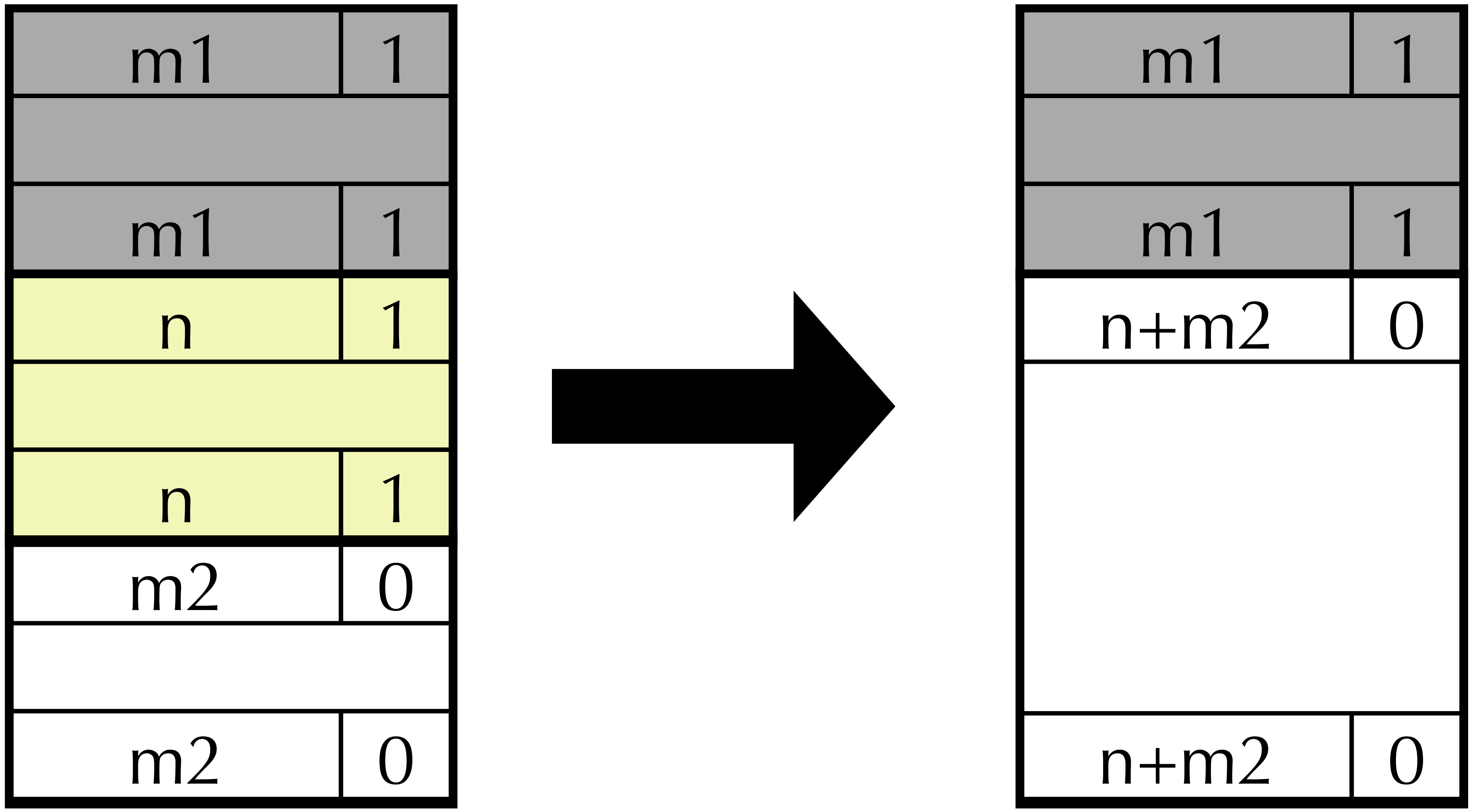
Constant Time Coalescing



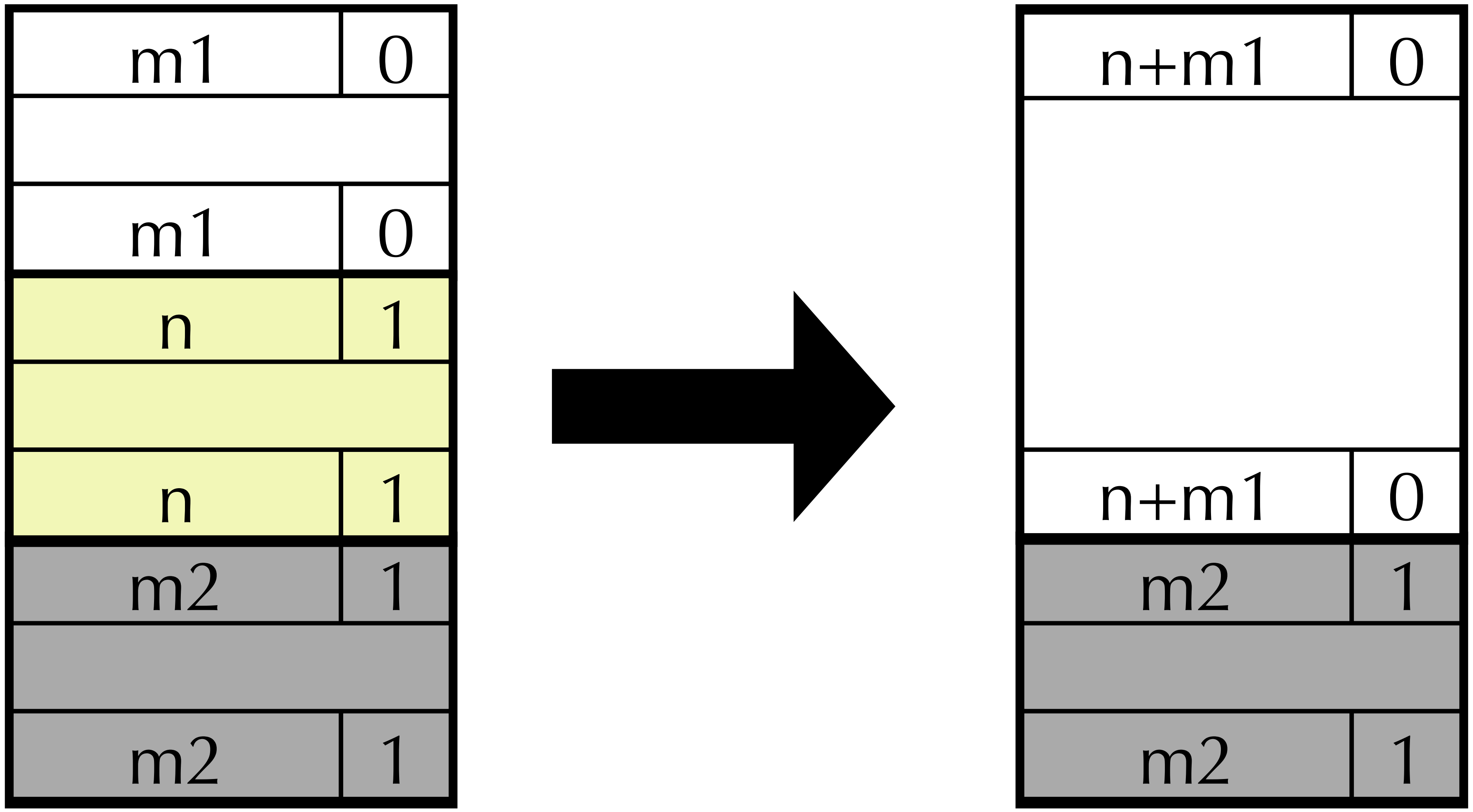
Constant Time Coalescing (Case 1)



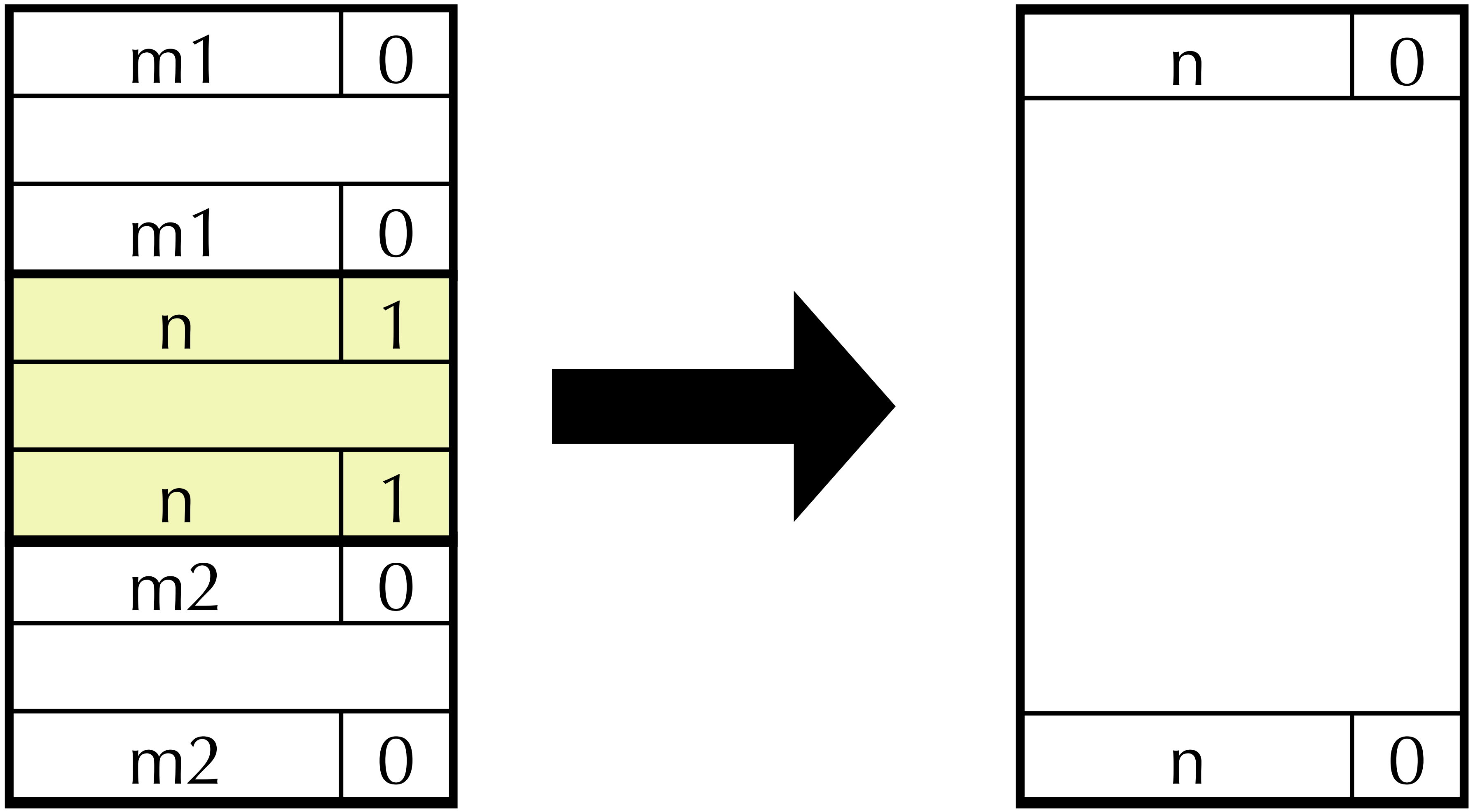
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



Implicit Lists: Summary

- Implementation: Very simple.
- Allocation cost: Linear time worst case
- Free cost: Constant time, even with coalescing
- Memory usage: Depends on placement policy
  - First fit, next fit, or best fit
- Not used in practice for `malloc/free` because of linear time allocation.

- The concepts of splitting and boundary tag coalescing are general to *all* allocators.

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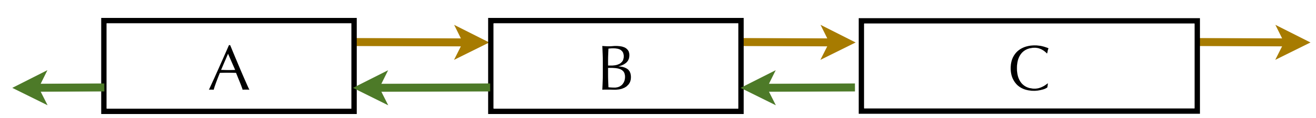
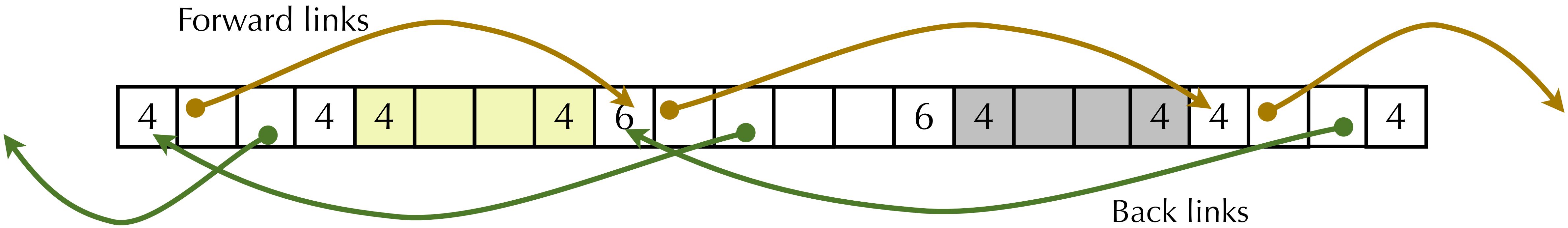
  - Segregated lists
  - Tradeoffs

Explicit Free Lists

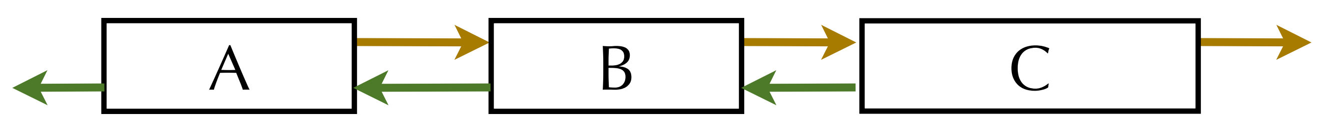
- Use an **explicit** data structure to track the free blocks
  - Just a doubly-linked list.
  - No pointers to or from allocated blocks: Can put the pointers into the payload!
  - Still need boundary tags, in order to perform free block coalescing.

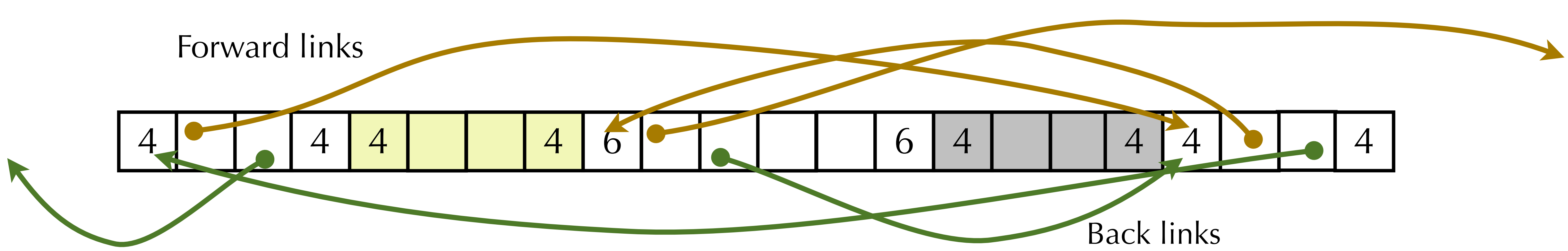




Explicit Free Lists

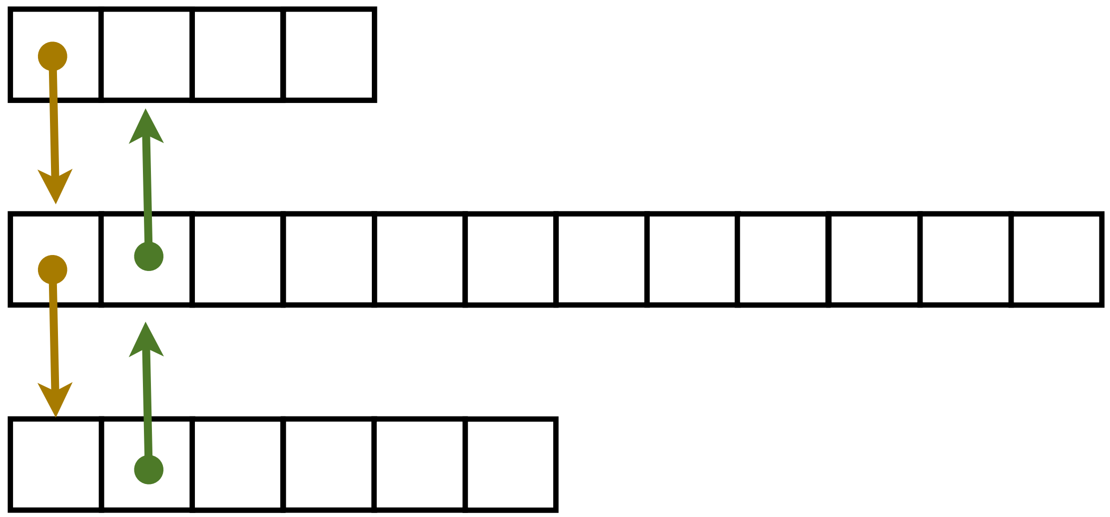
- Note that free blocks need not be linked in the same order
they appear in memory!
  - Free blocks can be chained together in any order.





Allocation using an explicit free list

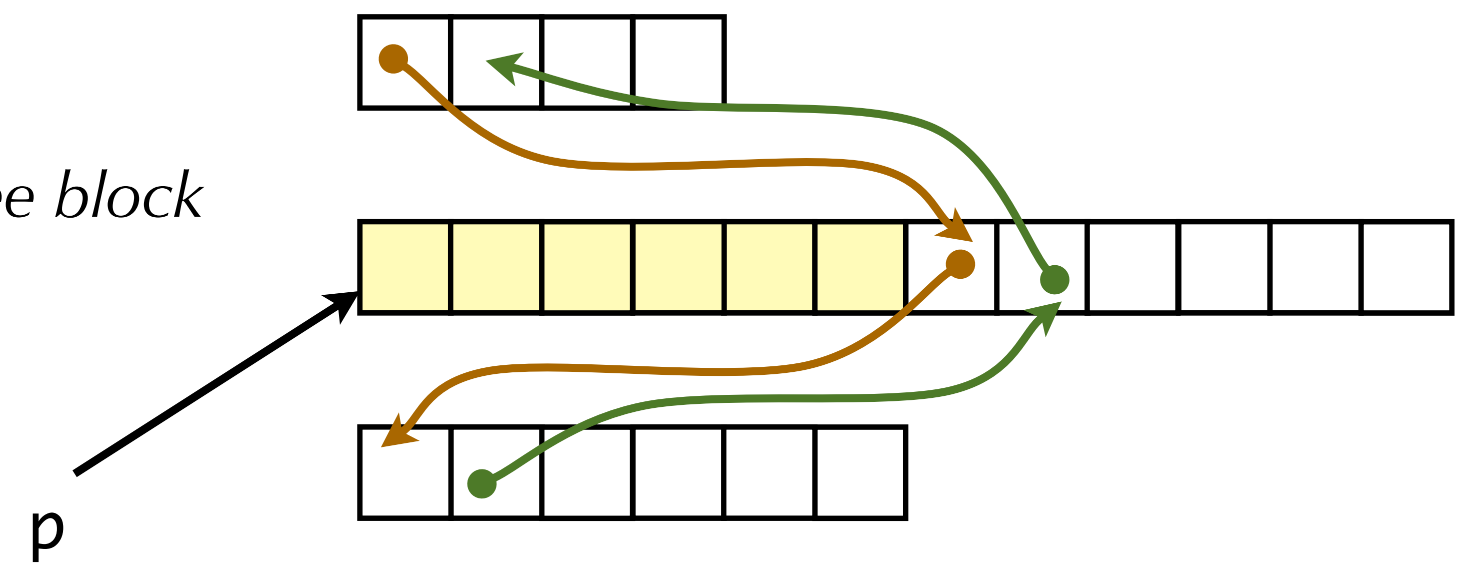
Before:



`p = malloc(size);`

After:

split 2nd free block

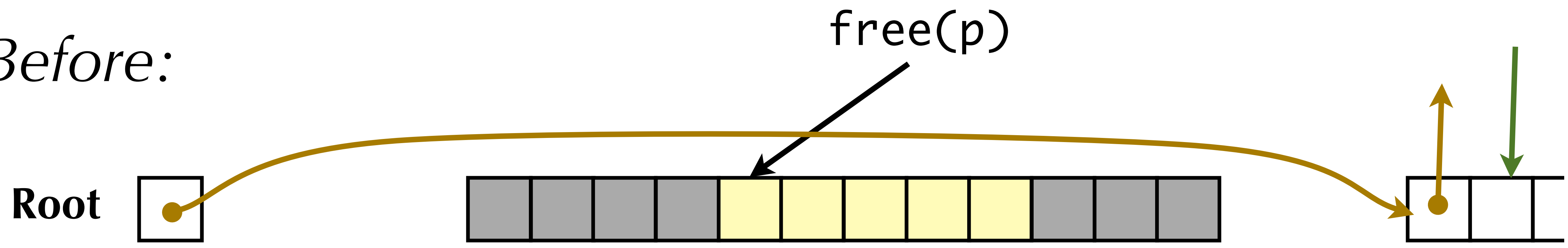


Deallocation with an explicit free list

- Same idea as previously
  - Step 1: Mark block as free
  - Step 2: Coalesce adjacent free blocks
  - Step 3: Insert free block into the free list
- Where in the free list do we put a newly freed block?
  - LIFO (last-in-first-out) policy
    - Insert freed block at the beginning of the free list
    - Simple and constant time
  - Address-ordered policy
    - Insert freed blocks so that free list blocks are always in address order
    - Con: requires search
    - Pro: studies suggest fragmentation is lower than LIFO

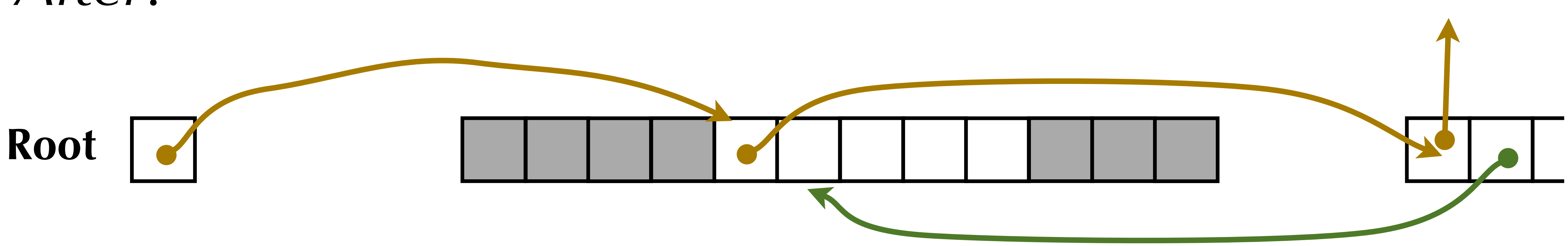
Freeing With a LIFO Policy (Case 1)

Before:

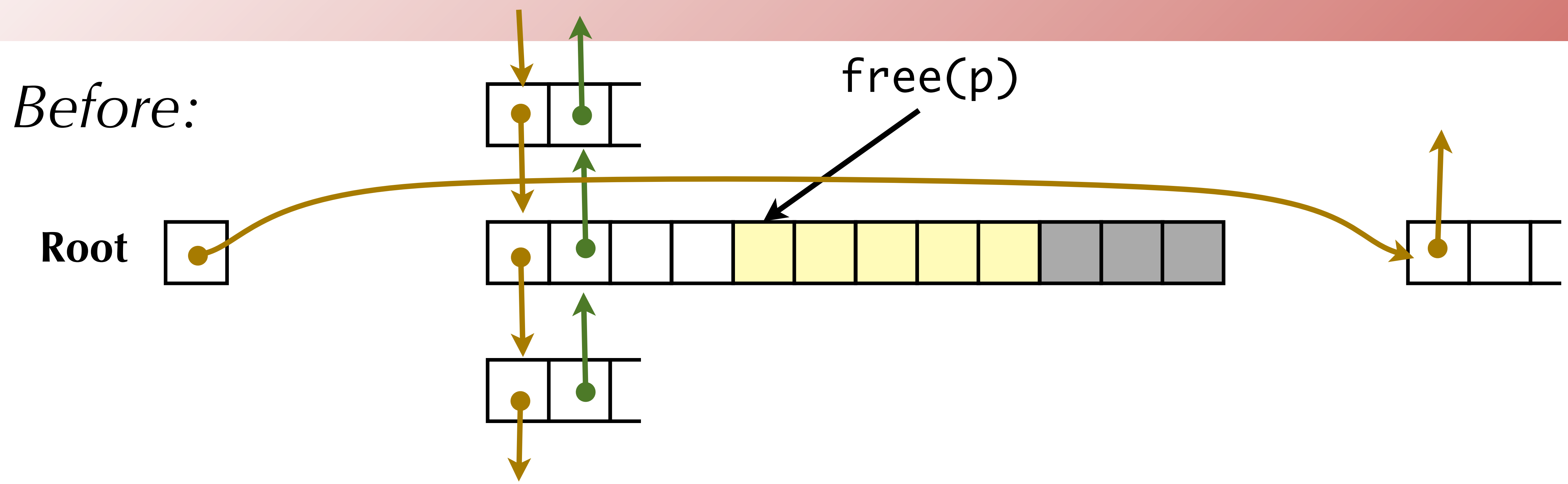


- Insert the freed block at the root of the free block list

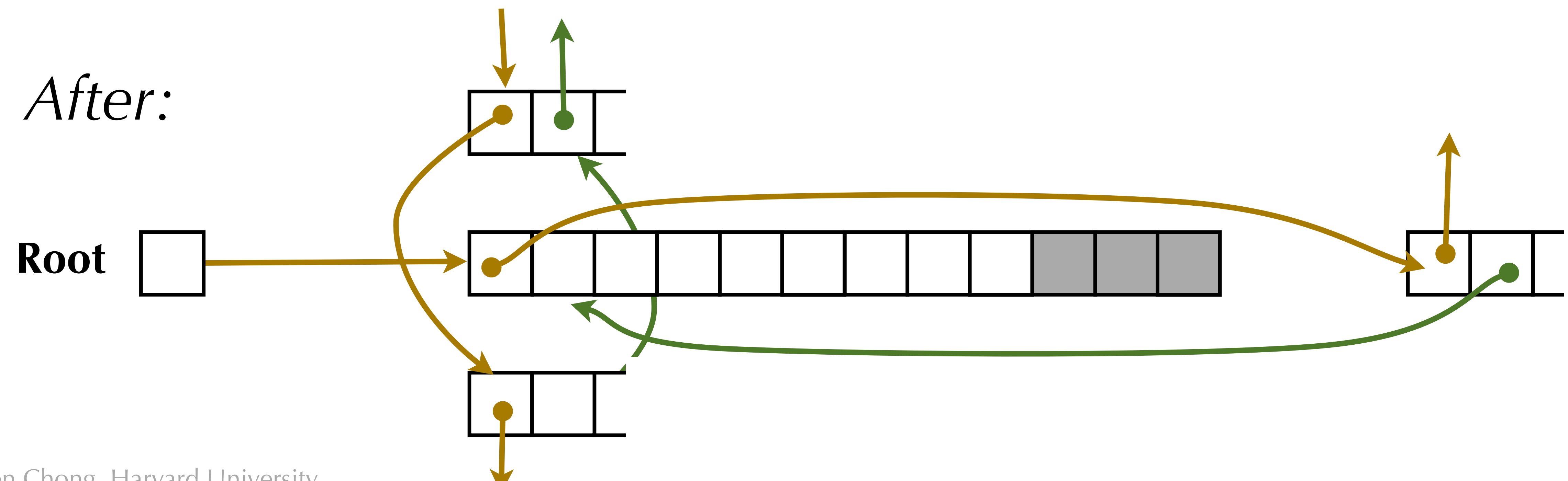
After:



Freeing With a LIFO Policy (Case 2)

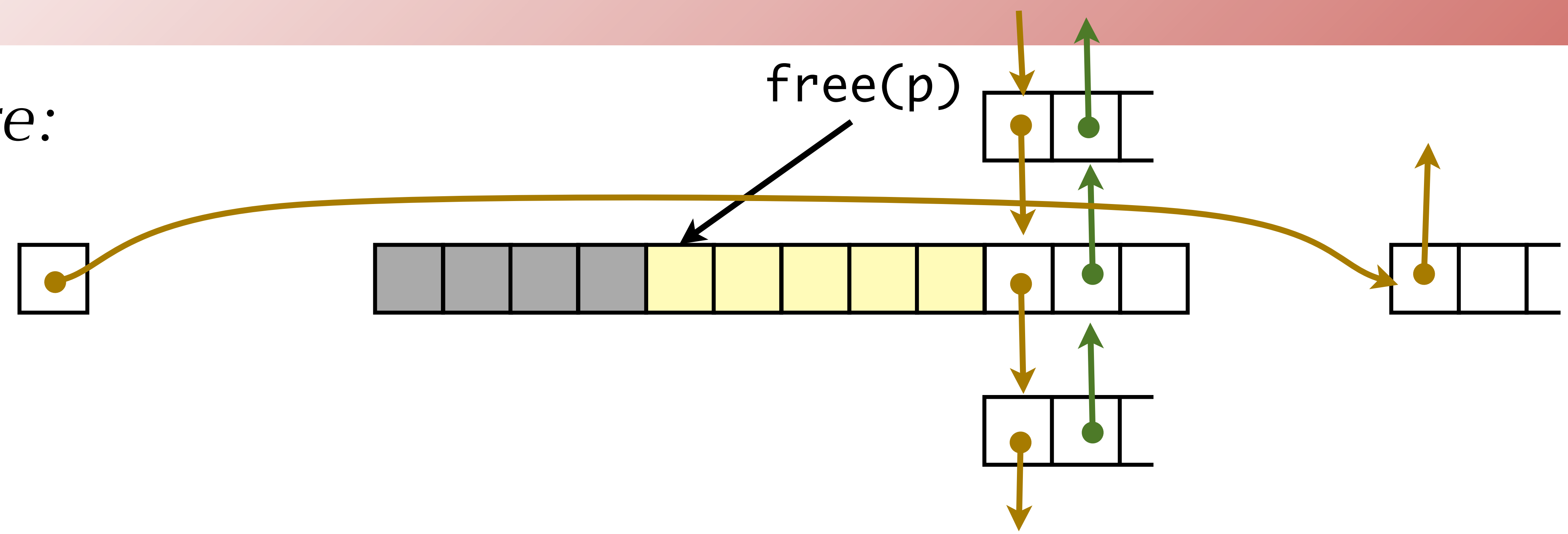


- Splice out predecessor block, coalesce both memory blocks and insert the new block at the root of the list



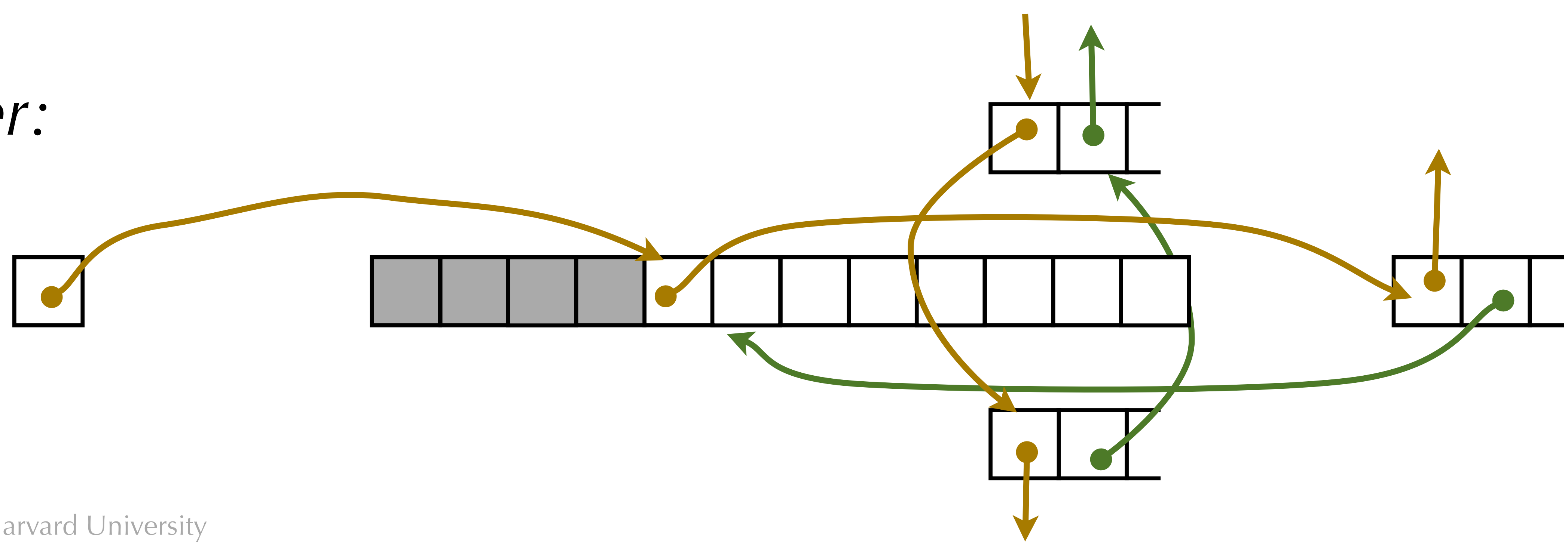
Freeing With a LIFO Policy (Case 3)

Before:



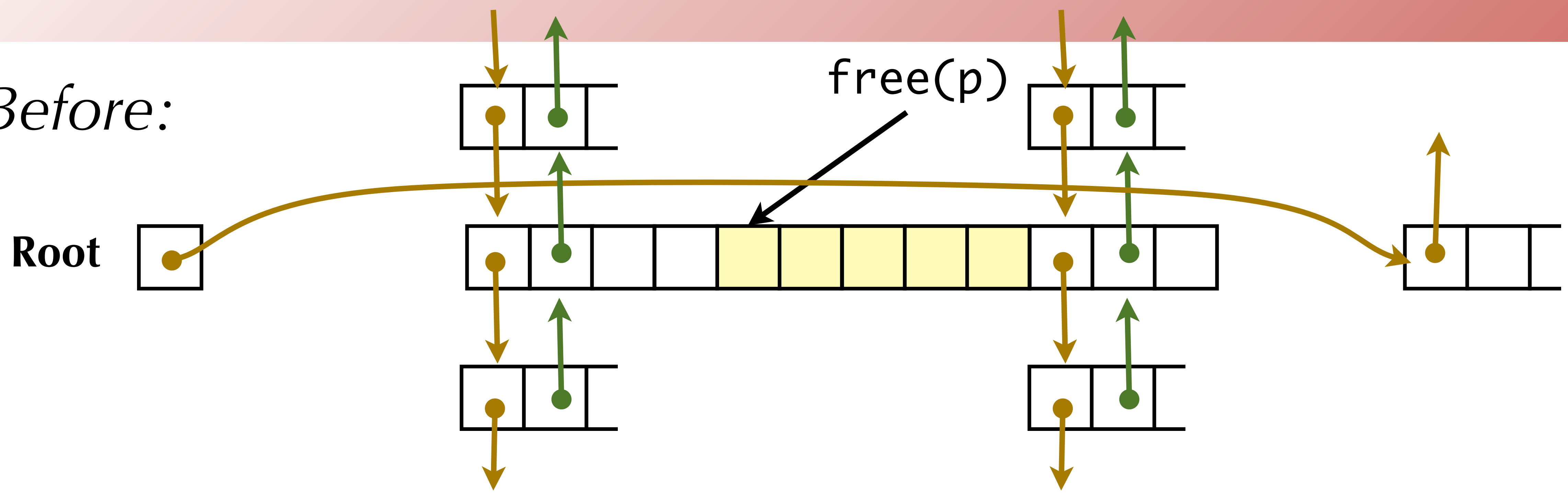
- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list

After:



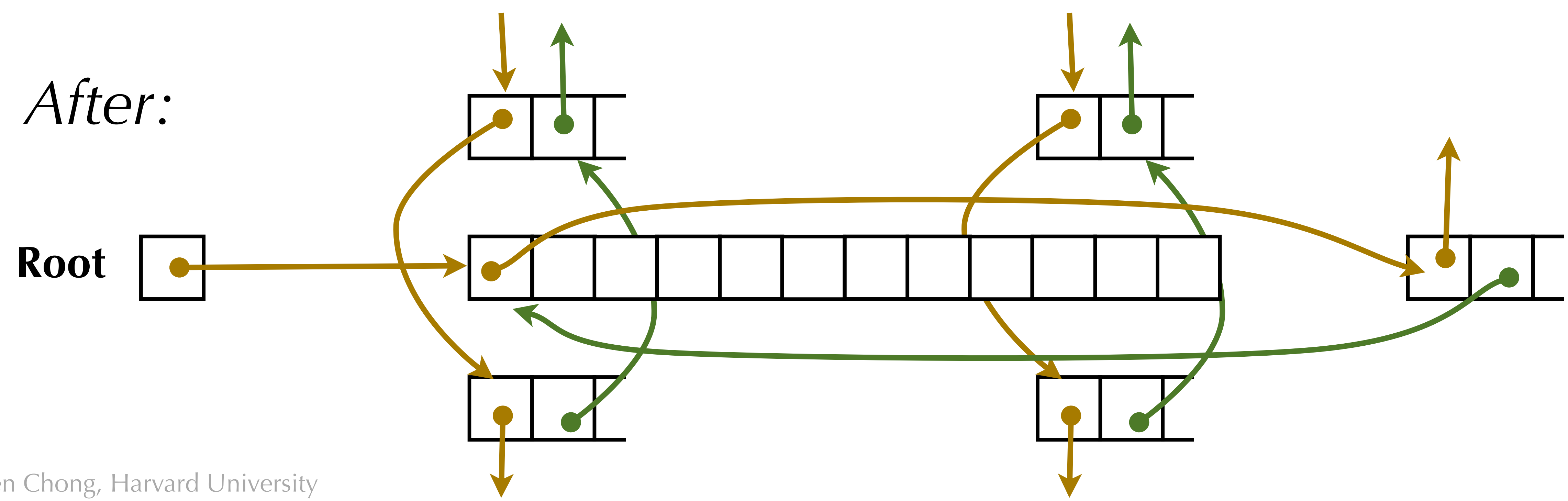
Freeing With a LIFO Policy (Case 4)

Before:



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

After:



Explicit List Summary

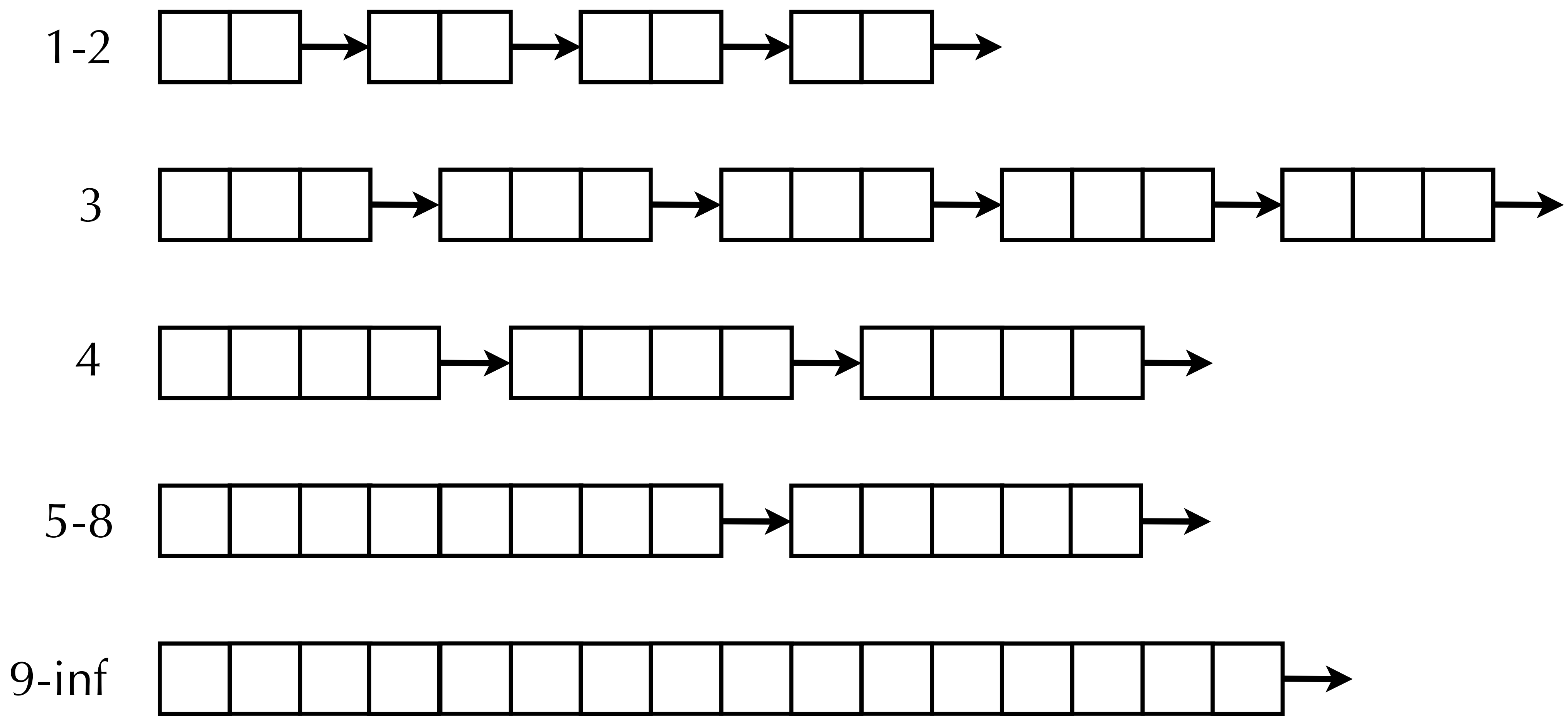
- Comparison to implicit list:
    - Allocation is linear time in number of **free blocks**
    - Implicit list allocation is linear time in the number of **total blocks**
- Slightly more complicated allocate and free since need to splice blocks in and out of the list
- Need some extra space for the links
    - 2 extra words needed for each free block
    - But these can be stored in the payload, since only needed for free blocks.

Topics for today

- Dynamic memory allocation
  - Implicit vs. explicit memory management
- Performance goals
- Fragmentation
- Free block list management
  - Implicit free list
  - Explicit free list
  - Segregated lists
  - Tradeoffs

Segregated List (seglist) Allocators

- Use a different free list for blocks of different sizes!



  - Often have separate size class for every small size (4,5,6,…)
  - For larger sizes typically have a size class for each power of 2

Seglist Allocator

- To allocate a block of size *n*:
  - Determine correct free list to use
  - Search that free list for block of size $m \geq n$
  - If an appropriate block is found:
    - Split block and place fragment on appropriate list
  - If no block is found, try next larger class
  - Repeat until block is found
- If no free block is found:
  - Request additional heap memory from OS (using `sbrk()` system call)
  - Allocate block of *n* bytes from this new memory
  - Place remainder as a single free block in largest size class.

Freeing with Seglist

- To free a block:
  - Mark block as free
  - Coalesce (if needed)
  - Place free block on appropriate sized list

Seglist advantages

- Advantages of seglist allocators
  - Higher throughput
    - Faster to find appropriate sized block: Look in the right list.
  - Better memory utilization
    - First-fit search of segregated free list approximates a best-fit search of entire heap.
    - Extreme case: Giving each size its own segregated list is equivalent to best-fit.

Topics for today

- Dynamic memory allocation
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  - Implicit free list
  - Explicit free list
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Allocation Policy Tradeoffs

- Data structure for free lists
  - Implicit lists, explicit lists, segregated lists
  - Other structures possible, e.g.explicit free blocks in binary tree, sorted by size
- Placement policy: First fit, next fit, or best fit
  - Best fit has higher overhead, but less fragmentation.
- Splitting policy: When do we split free blocks?
  - Splitting leads to more internal fragmentation, since each block needs its own header.
- Coalescing policy: When do we coalesce free blocks?
  - **Immediate coalescing**: Coalesce each time free is called
  - **Deferred coalescing**: Improve free performance by deferring coalescing until needed.
    - E.g., While scanning the free list for `malloc()`, or when external fragmentation reaches some threshold.

Topics for next time

- Allocation requirements
- Common memory bugs
- Implicit memory management: Garbage collection