Optimizing Dynamic Memory Management

Goals of this Lecture

- Help you learn about:
  - Details of K&R heap mgr
  - Heap mgr optimizations related to Assignment #5
    - Faster `free()` via doubly-linked list, redundant sizes, and status bits
    - Faster `malloc()` via binning
  - Other heap mgr optimizations
    - Best/good fit block selection
    - Selective splitting
    - Deferred coalescing
    - Segregated data
    - Segregated meta-data
    - Memory mapping

Part 1:
Details of the K&R Heap Manager

An Implementation Challenge

Problem:

- Need information about each free block
  - Starting address of the block of memory
  - Length of the free block
  - Pointer to the next block in the free list
- Where should this information be stored?
  - Number of free blocks is not known in advance
  - So, need to store the information on the *heap*
- But, wait, this code is what *manages* the heap!!!
  - Can't call **`malloc()`** to allocate storage for this information
  - Can't call **`free()`** to deallocate the storage, either

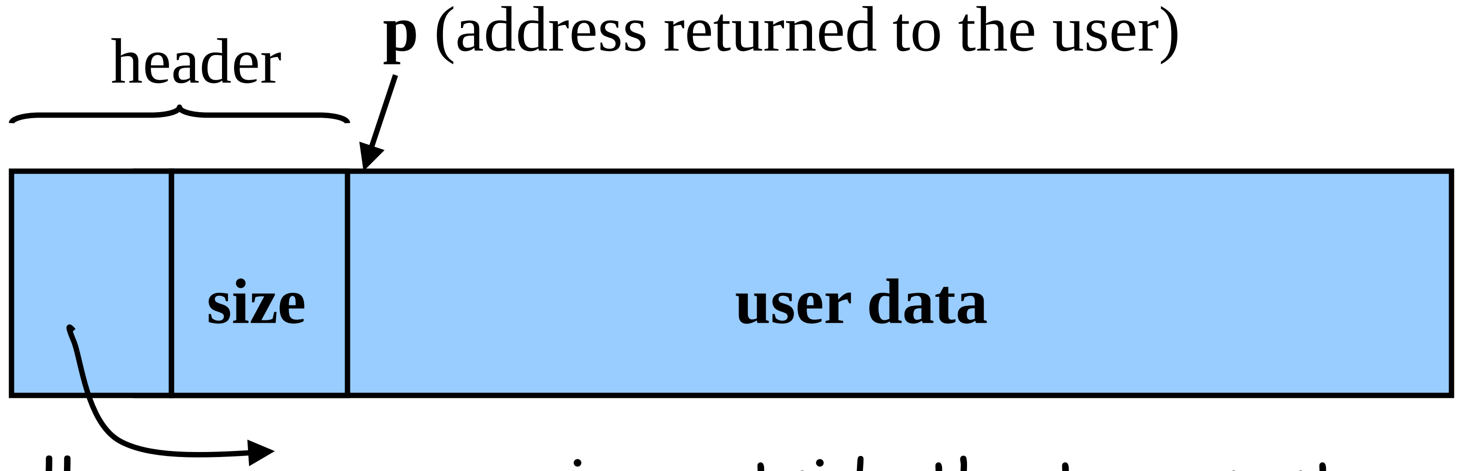
Store Information in the Free Block

Solution:

- Store the information directly in the block
  - Since the memory isn't being used for anything anyway
  - And allows data structure to grow and shrink as needed

Block Headers

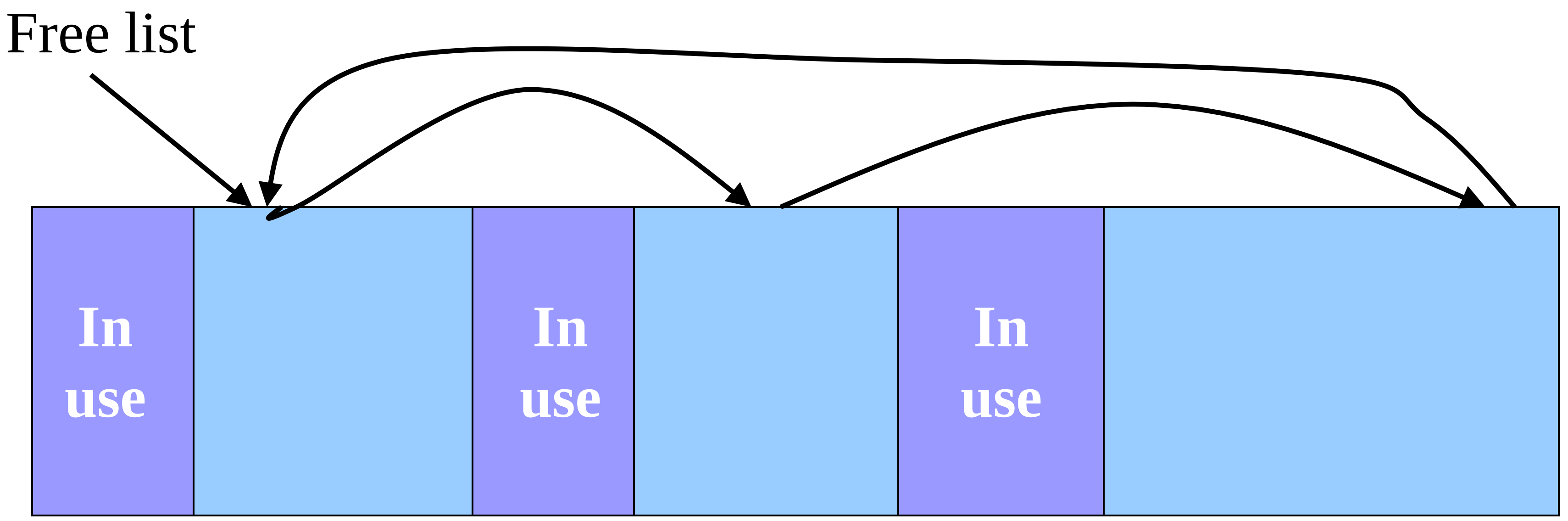
- Every free block has a **header**, containing:
  - Pointer to (i.e., address of) the next free block
  - Size of the free block



- Challenge: programming outside the type system

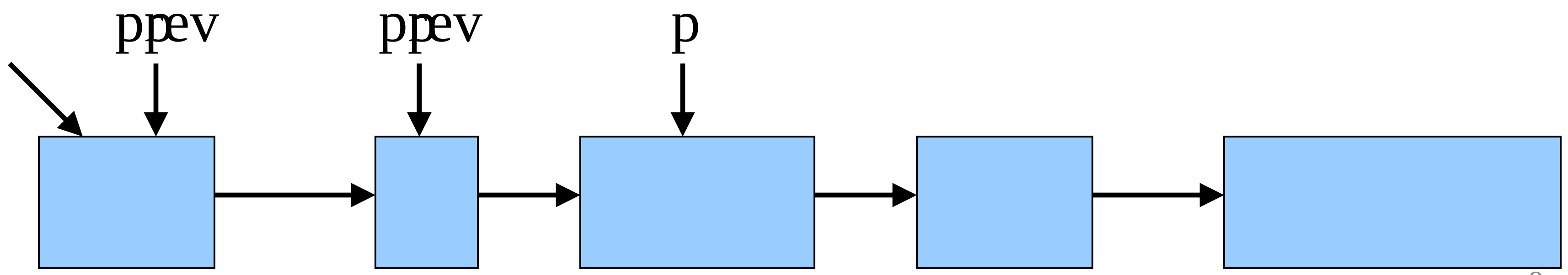
Free List: Circular Linked List

- Free blocks, linked together
  - Example: circular linked list
- Keep list in order of increasing addresses
  - Makes it easier to coalesce adjacent free blocks



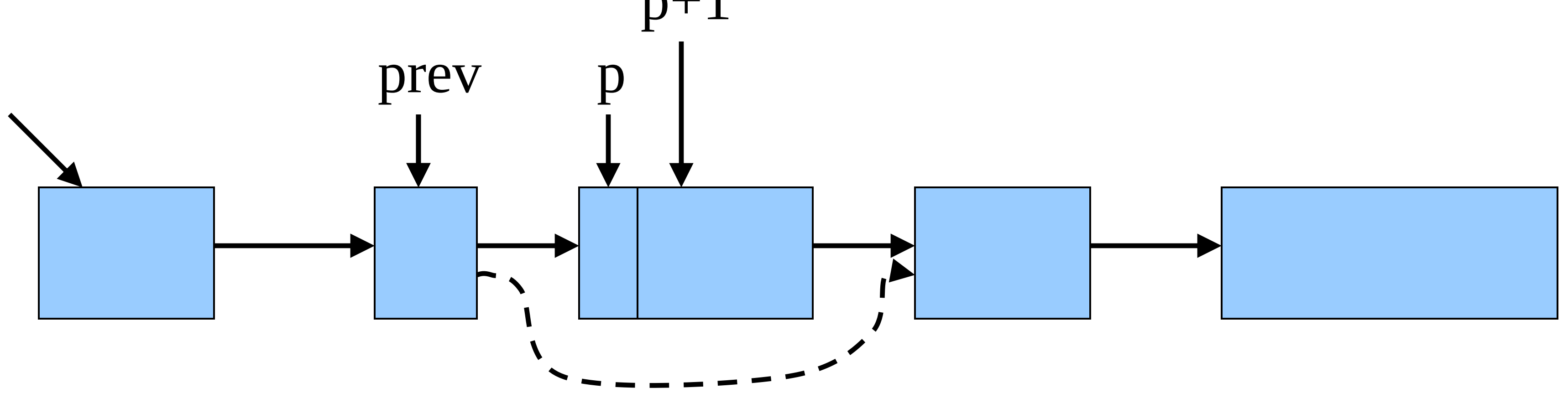
Malloc: First-Fit Algorithm

- Start at the beginning of the list
- Sequence through the list
  - Keep a pointer to the previous element
- Stop when reaching first block that is big enough
  - Patch up the list
  - Return a pointer to the user



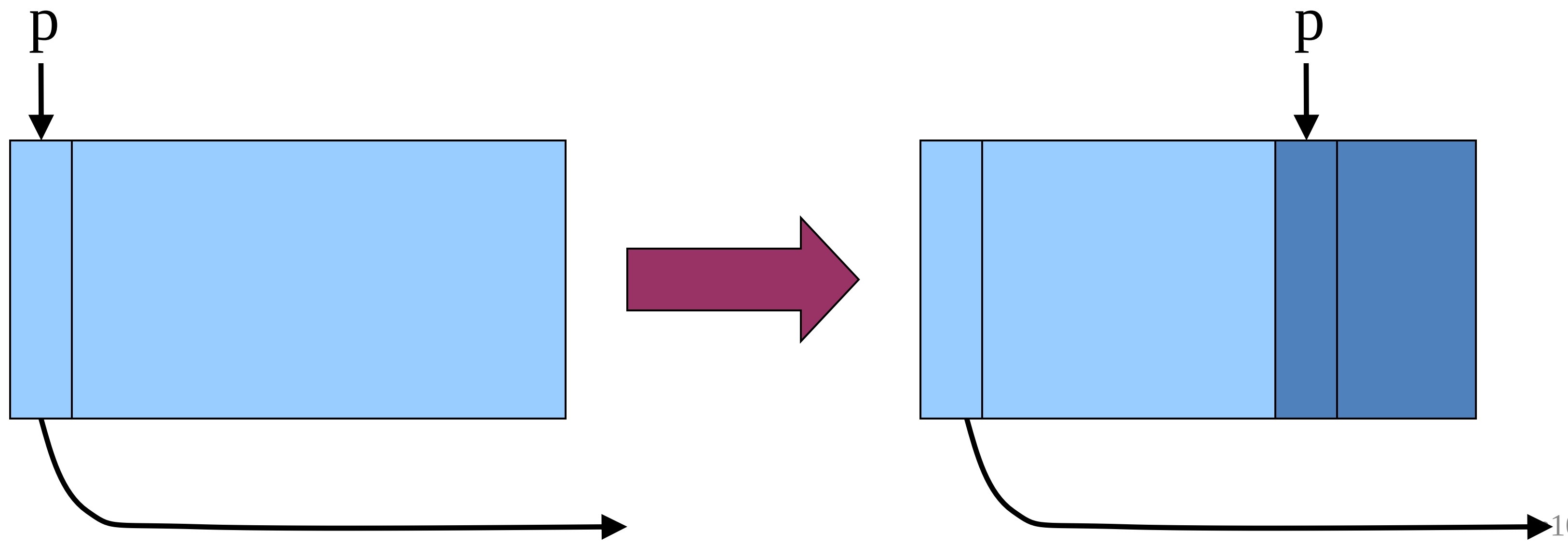
Malloc: First Case: Perfect Fit

- Suppose the first fit is a perfect fit
  - Remove the block from the list
  - Link the previous free block with the next free block
  - Return the current to the user (skipping header)



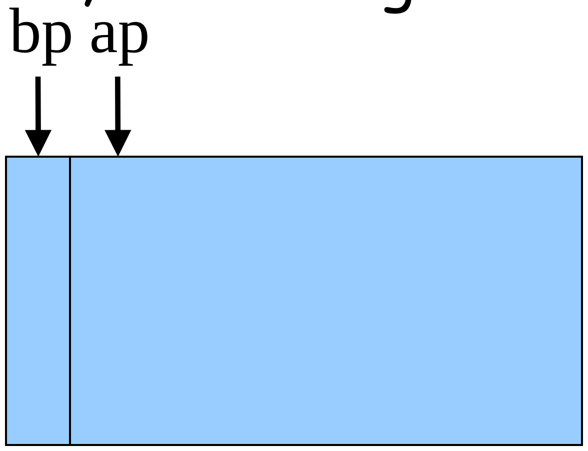
Malloc: Second Case: Big Block

- Suppose the block is bigger than requested
  - Divide the free block into two blocks
  - Keep first (now smaller) block in the free list
  - Allocate the second block to the user
  - Bonus: No need to manipulate links



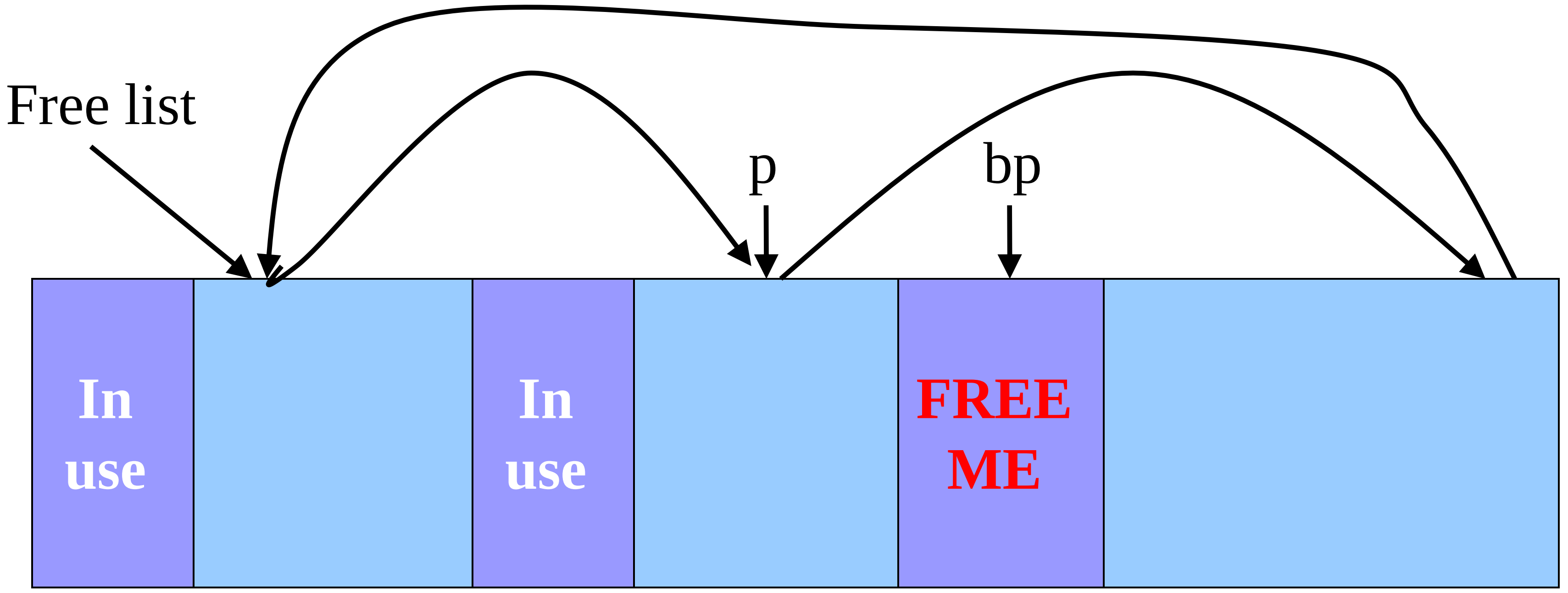
Free

- User passes a pointer to the memory block
  - `void free(void *ap);`
- `free()` function inserts block into the list
  - Identify the start of entry
  - Find the location in the free list
  - Add to the list, coalescing entries, if needed



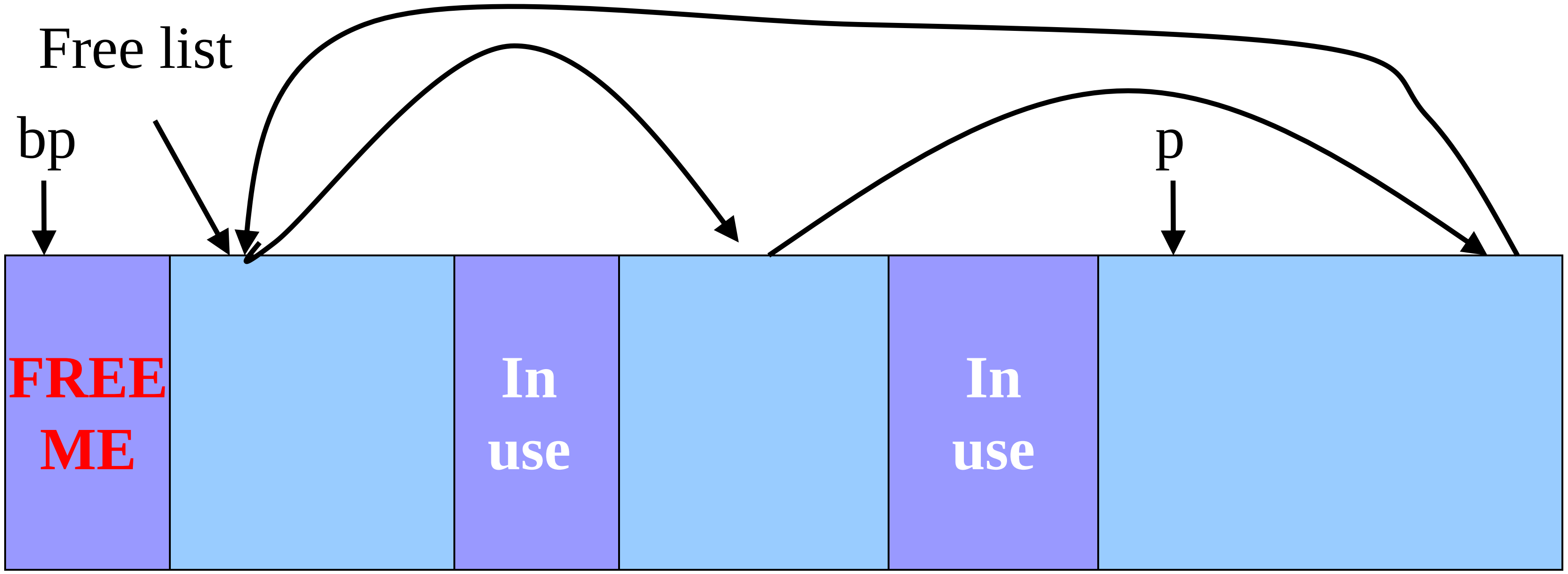
Free: Finding Location to Insert

- Start at the beginning
- Sequence through the list
- Stop at last entry before the to-be-freed element



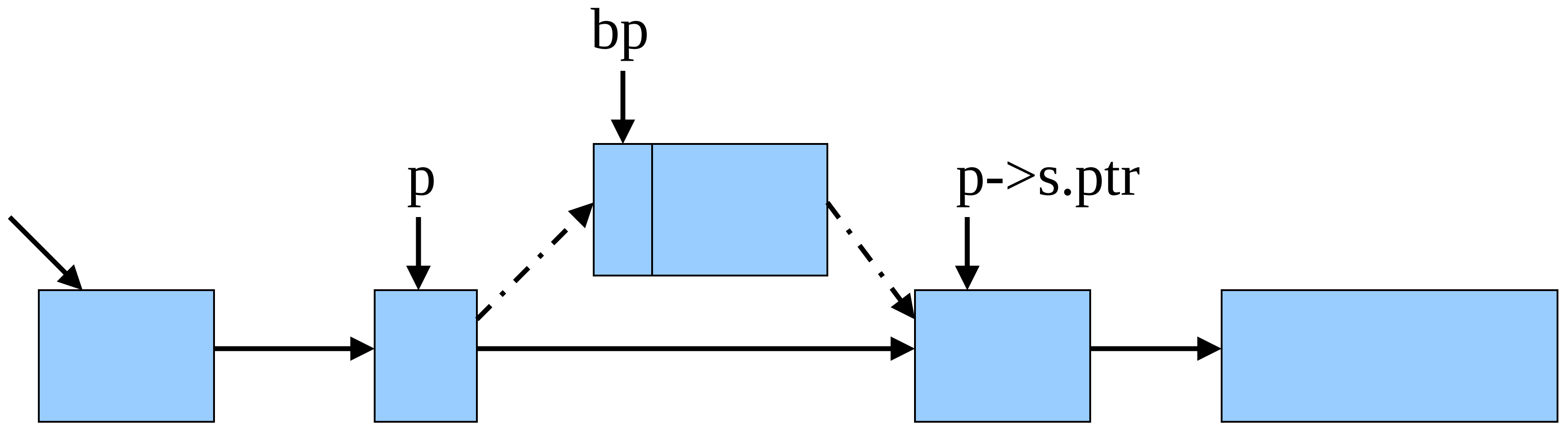
Free: Handling Corner Cases

- Check for wrap-around in memory
  - To-be-freed block is before first entry in the free list, or
  - To-be-freed block is after the last entry in the free list



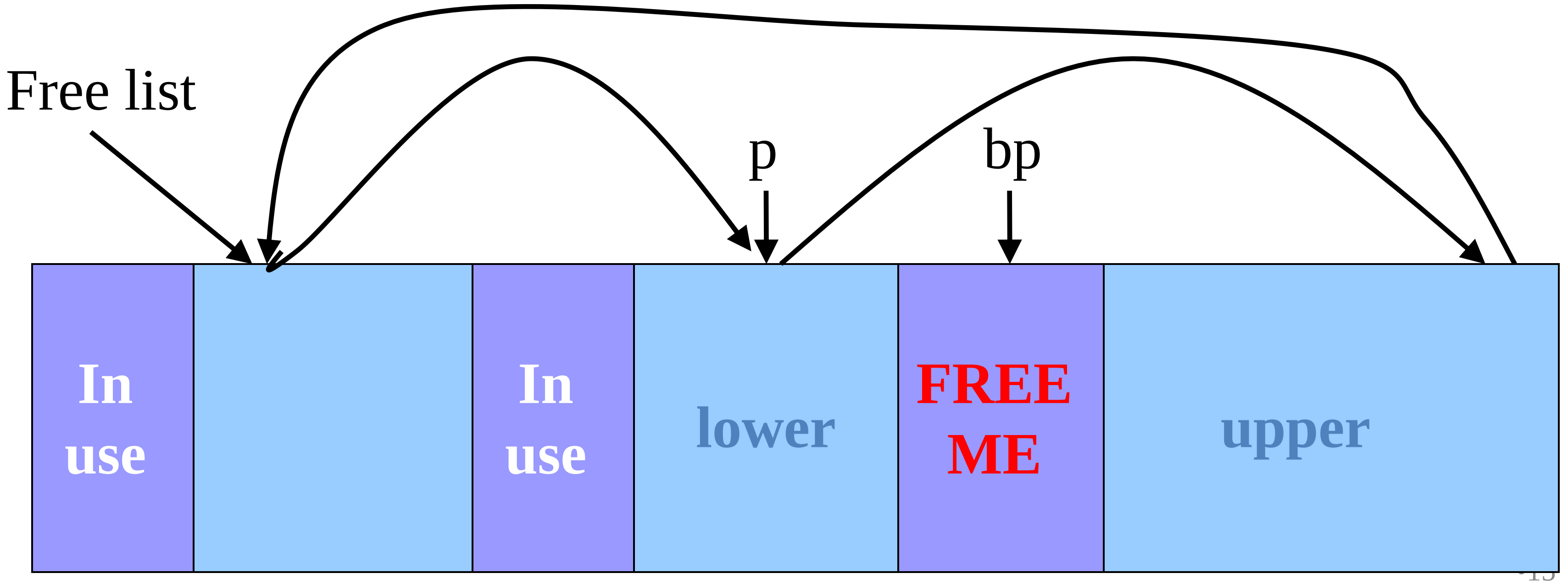
Free: Inserting Into Free List

- New element to add to free list
- Insert in between previous and next entries
- But, there may be opportunities to coalesce



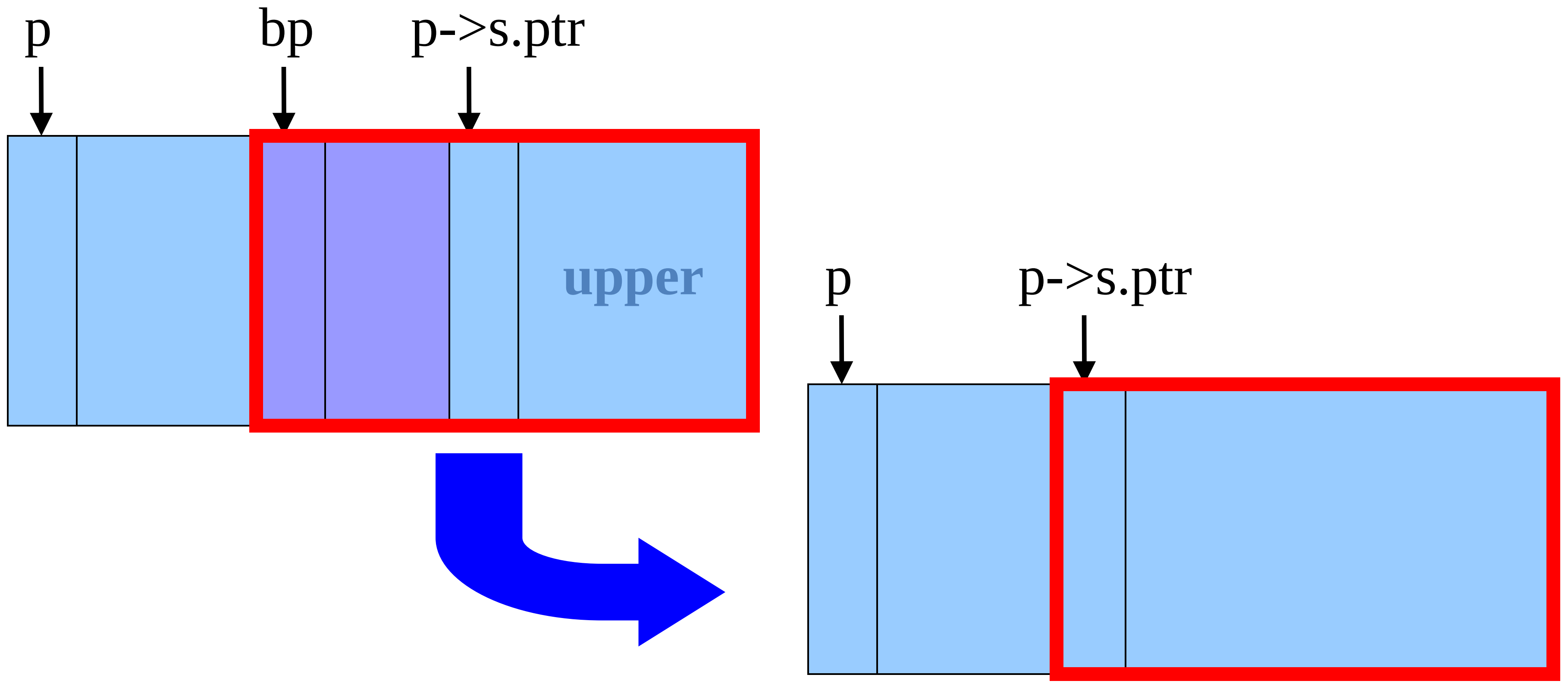
Coalescing With Neighbors

- Scanning the list finds the location for inserting
  - Pointer to to-be-freed element: **`bp`**
  - Pointer to previous element in free list: **`p`**
- Coalescing into larger free blocks
  - Check if contiguous to upper and lower neighbors



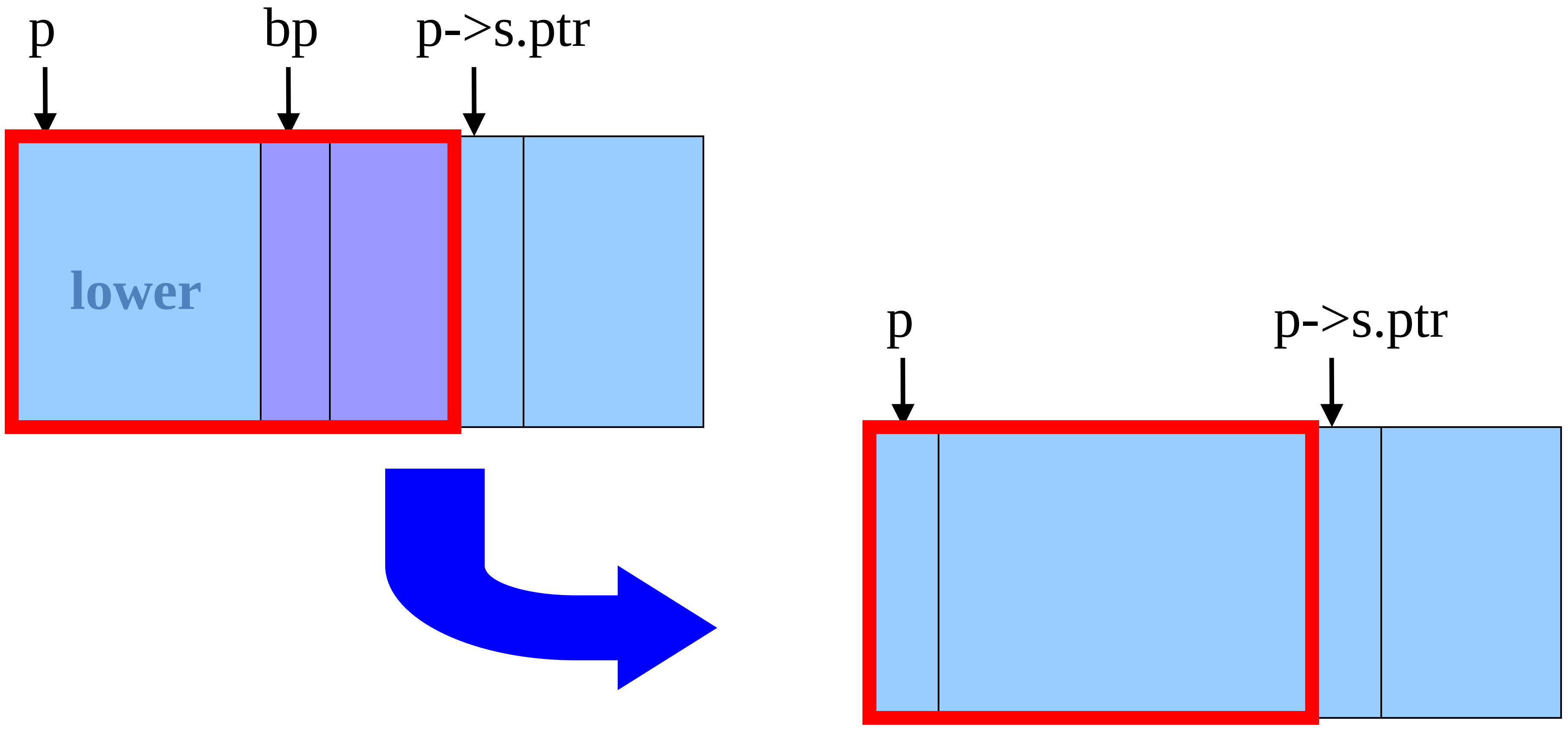
Coalesce With Upper Neighbor

- Check if next part of memory is in the free list
- If so, make into one bigger block
- Else, simply point to the next free element



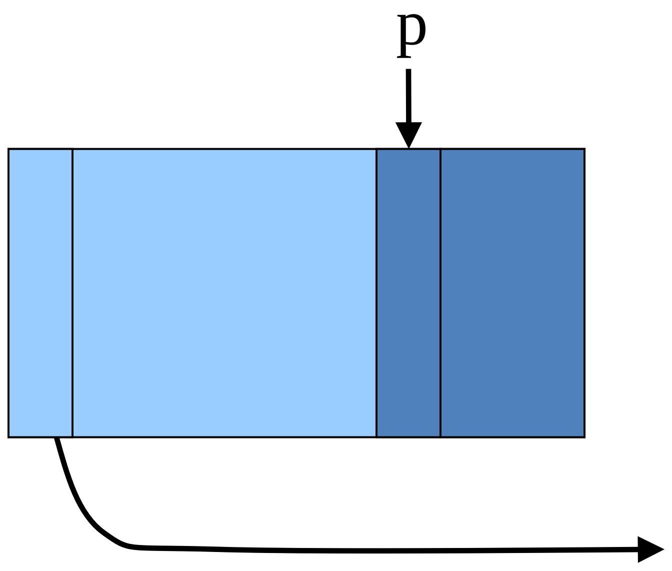
Coalesce With Lower Neighbor

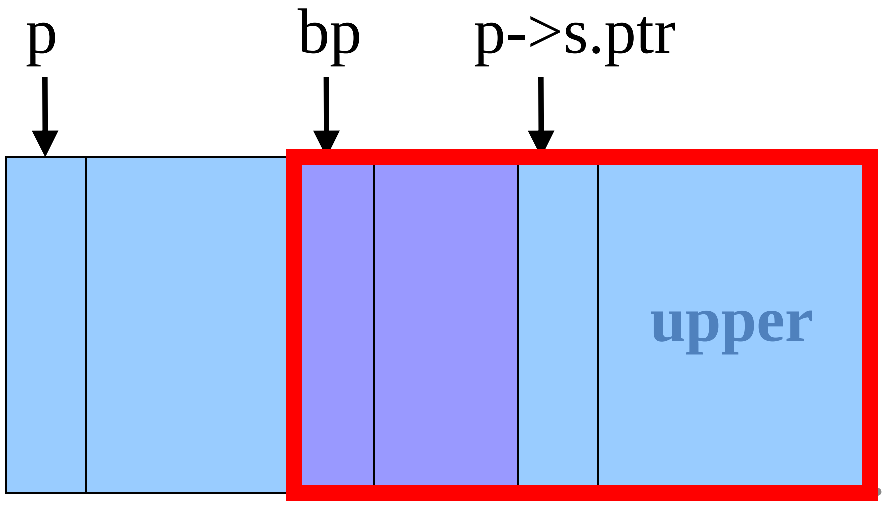
- Check if previous part of memory is in the free list
- If so, make into one bigger block



Strengths of K&R Approach

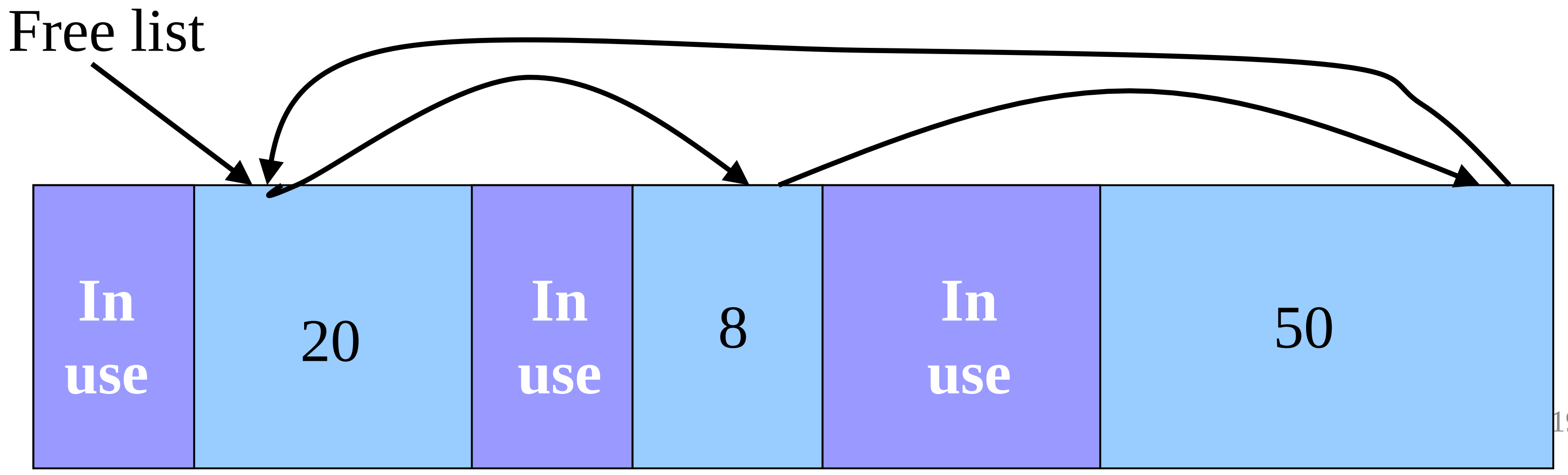
- Advantages
  - Simplicity of the code
- Optimizations to **`malloc()`**
  - Splitting large free block to avoid wasting space
- Optimization to **`free()`**
  - Roving free-list pointer is left at the last place a block was allocated
  - Coalescing contiguous free blocks to reduce fragmentation





Weaknesses of K&R Approach

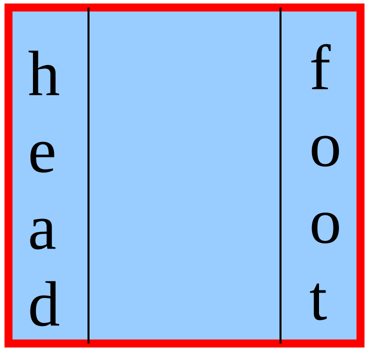
- Inefficient use of memory: fragmentation
  - First-fit policy can leave lots of "holes" of free blocks in memory
- Long execution times: linear-time overhead
  - **`malloc()`** scans the free list to find a big-enough block
  - **`free()`** scans the free list to find where to insert a block
- Accessing a wide range of memory addresses in free list
  - Can lead to large amount of paging to/from the disk



Part 2:
Optimizations Related to Assignment 5

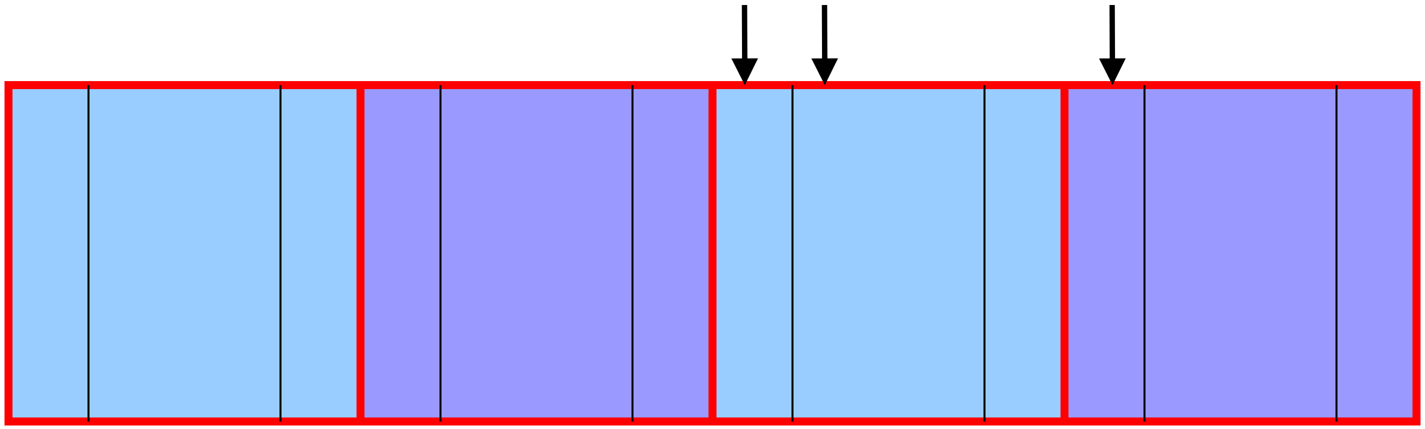
Faster Free

- Performance problems with K&R **`free()`**
  - Scanning the free list to know where to insert
  - Keeping track of the "previous" node to do the insertion
- Doubly-linked, non-circular list
  - Header
    - Size of the block (in # of units)
    - Flag indicating whether the block is free or in use
    - If free, a pointer to the next free block
  - Footer
    - Size of the block (in # of units)
    - If free, a pointer to the previous free block



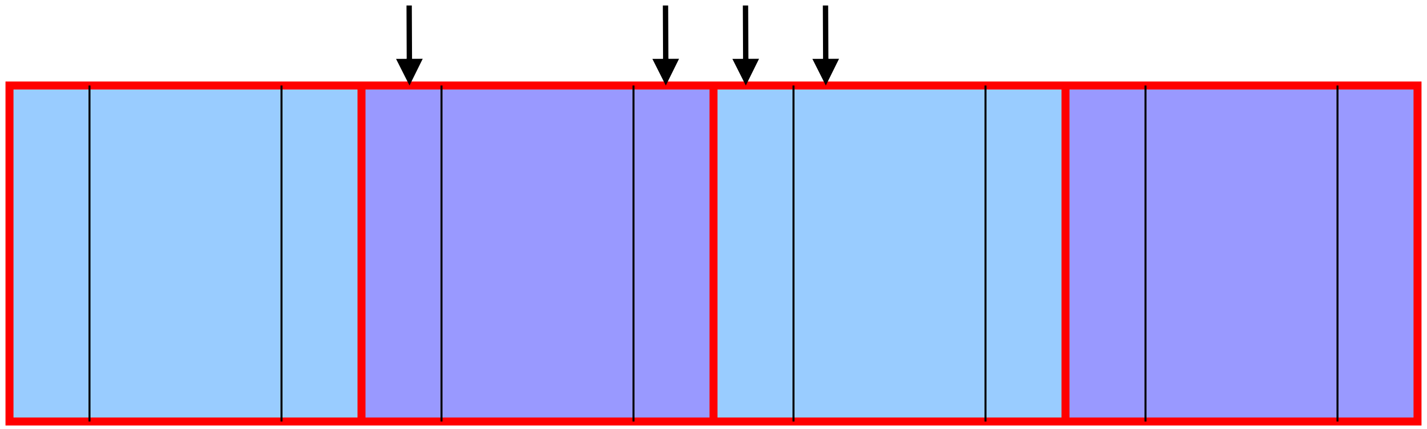
Size: Finding Next Block

- Go quickly to next block in memory
  - Start with the user's data portion of the block
  - Go backwards to the head of the block
    - Easy, since you know the size of the header
  - Go forward to the head of the next block
    - Easy, since you know the size of the current block



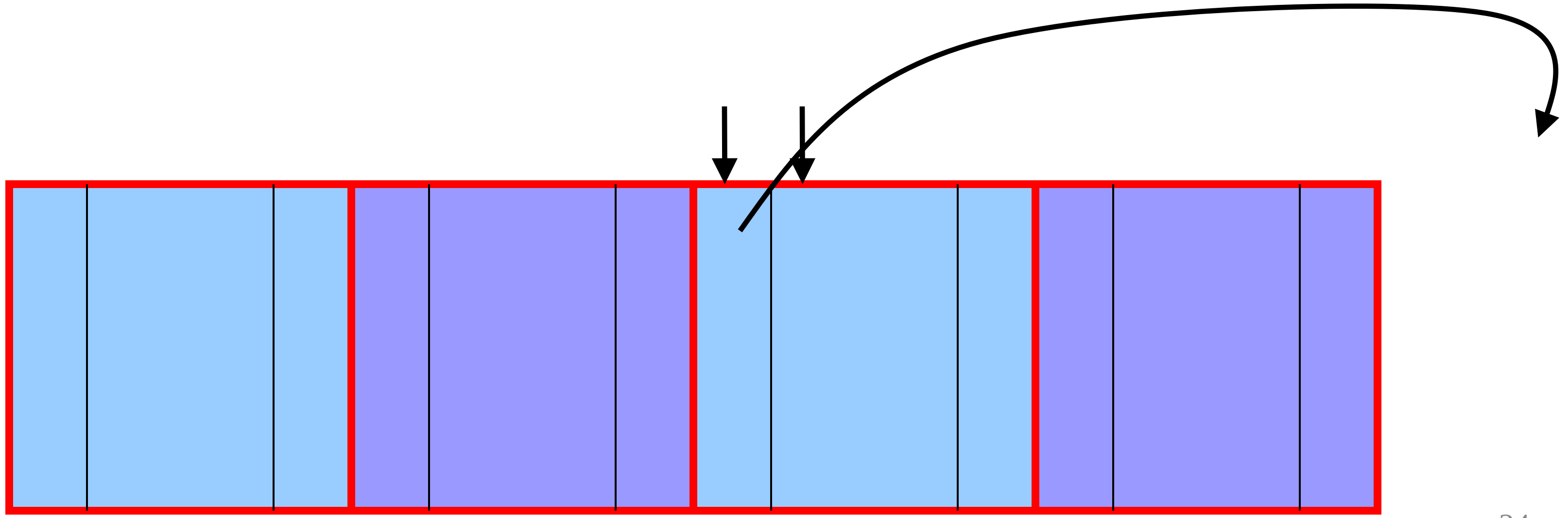
Size: Finding Previous Block

- Go quickly to previous chunk in memory
  - Start with the user's data portion of the block
  - Go backwards to the head of the block
    - Easy, since you know the size of the header
  - Go backwards to the footer of the previous block
    - Easy, since you know the size of the footer
  - Go backwards to the header of the previous block
    - Easy, since you know the size from the footer



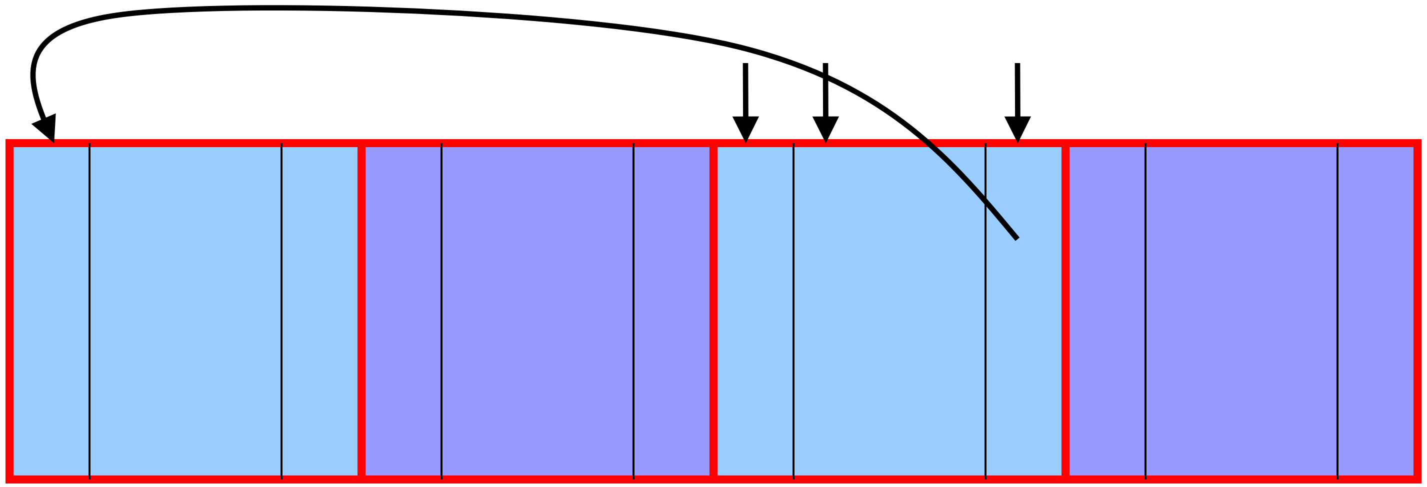
Pointers: Next Free Block

- Go quickly to next free block in memory
  - Start with the user's data portion of the block
  - Go backwards to the head of the block
    - Easy, since you know the size of the header
  - Go forwards to the next free block
    - Easy, since you have the next free pointer



Pointers: Previous Free Block

- Go quickly to previous free block in memory
  - Start with the user's data portion of the block
  - Go backwards to the head of the block
    - Easy, since you know the size of the header
  - Go forwards to the footer of the block
    - Easy, since you know the block size from the header
  - Go backwards to the previous free block
    - Easy, since you have the previous free pointer

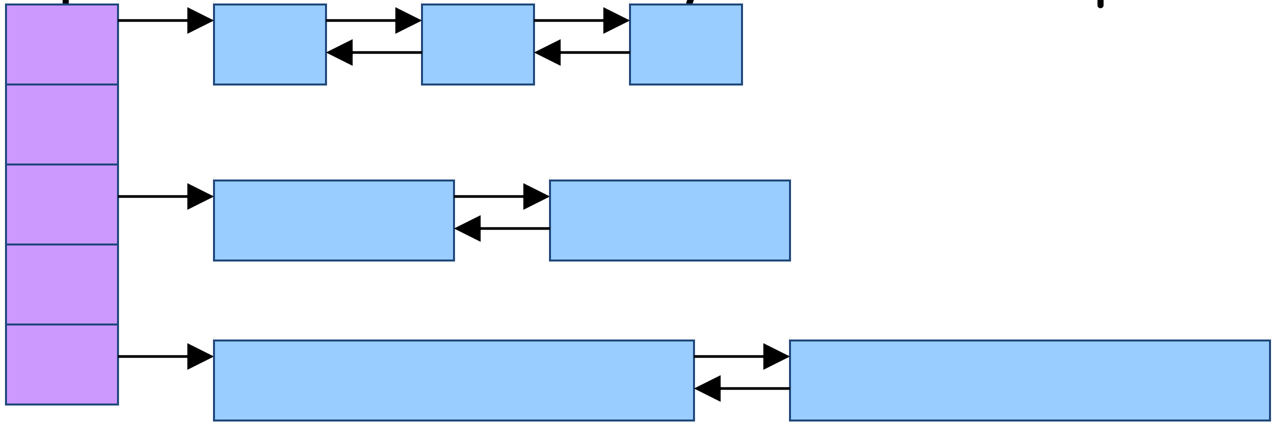


Efficient Free

- Before: K&R
  - Scan the free list till you find the place to insert
    - Needed to see if you can coalesce adjacent blocks
  - Expensive for loop with several pointer comparisons
- After: with header/footer and doubly-linked list
  - Coalescing with the previous block in memory
    - Check if previous block in memory is also free
    - If so, coalesce
  - Coalescing with the next block in memory the same way
  - Add the new, larger block to the front of the linked list

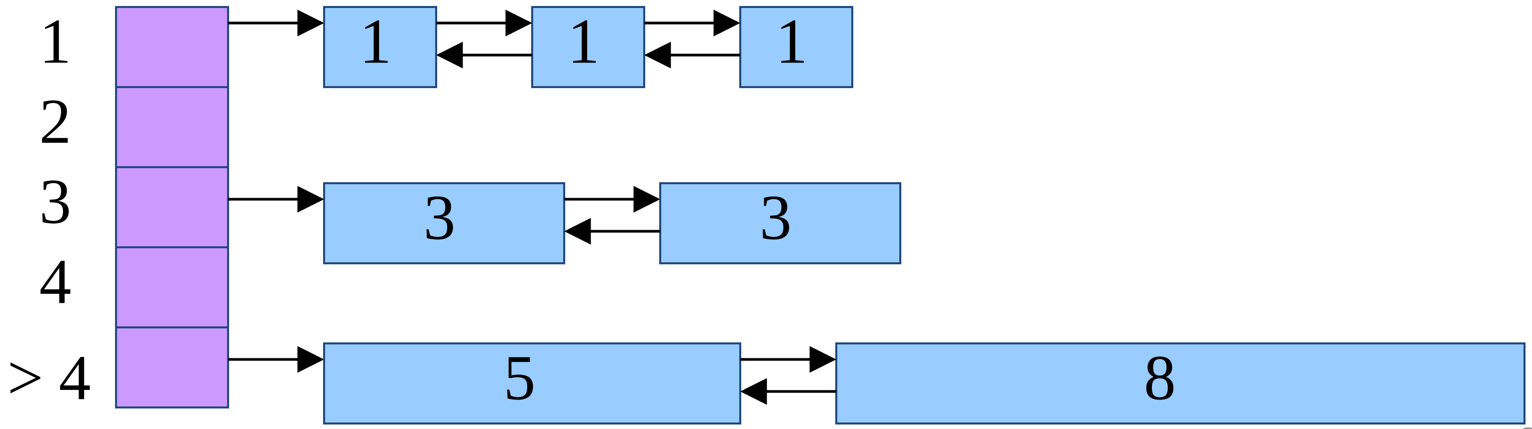
But Malloc is Still Slow…

- Still need to scan the free list
  - To find the first, or best, block that fits
- Root of the problem
  - Free blocks have a wide range of sizes
- Solution: binning
  - Separate free lists by block size
  - Implemented as an array of free-list pointers



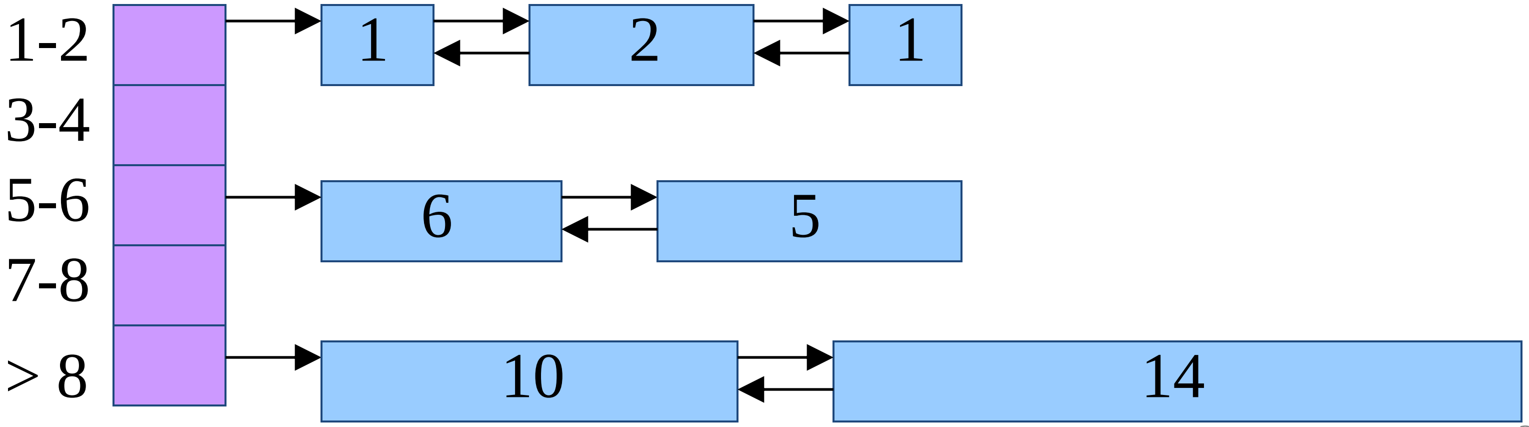
Binning Strategies: Exact Fit

- Have a bin for each block size, up to a limit
  - Advantages: no search for requests up to that size
  - Disadvantages: many bins, each storing a pointer
- Except for a final bin for all larger free blocks
  - For allocating larger amounts of memory
  - For splitting to create smaller blocks, when needed



Binning Strategies: Range

- Have a bin cover a range of sizes, up to a limit
  - Advantages: fewer bins
  - Disadvantages: need to search for a big enough block
- Except for a final bin for all larger free chunks
  - For allocating larger amounts of memory
  - For splitting to create smaller blocks, when needed



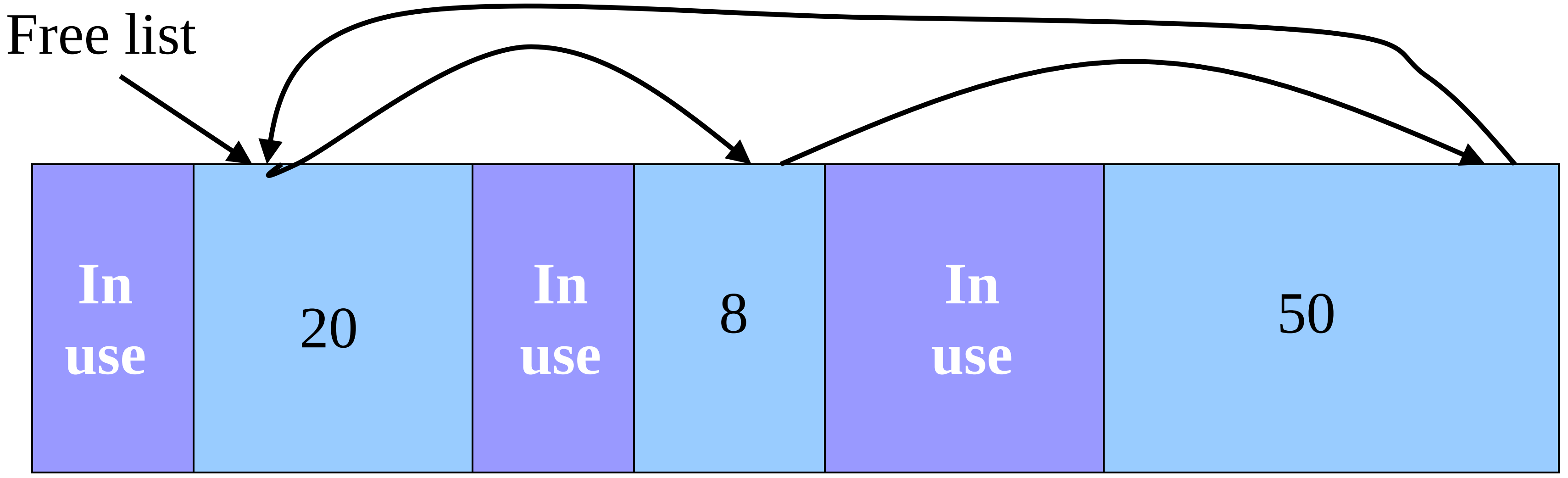
Suggestions for Assignment #5

- Debugging memory management code is hard
  - A bug in your code might stomp on the headers or footers
  - … making it very hard to understand where you are in memory
- Suggestion: debug carefully as you go along
  - Write little bits of code at a time, and test as you go
  - Use assertion checks very liberally to catch mistakes early
  - Use functions to apply higher-level checks on your list
    - E.g,. all free-list blocks are marked as free
    - E.g., each block pointer is within the heap range
    - E.g., the block size in header and footer are the same
- Suggestion: draw lots and lots of pictures

Part 3:
Other Optimizations

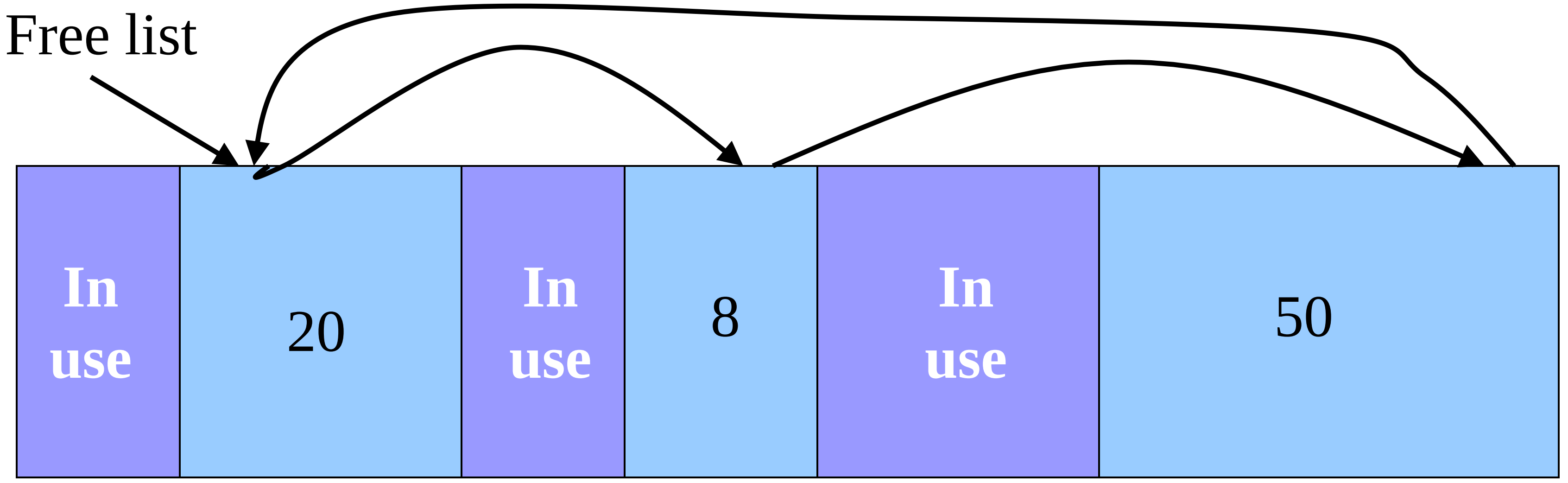
Best/Good Fit Block Selection

- Observation:
  - K&R uses "first fit" (really, "next fit") strategy
  - Example: `malloc(8)` would choose the 20-byte block
- Alternative: "**best fit**" or "**good fit**" strategy
  - Example: `malloc(8)` would choose the 8-byte block
  - Applicable if not binning, or if a bin has blocks of variable sizes
  - **Pro**: Minimizes internal fragmentation and splitting
  - **Con**: Increases cost of choosing free block



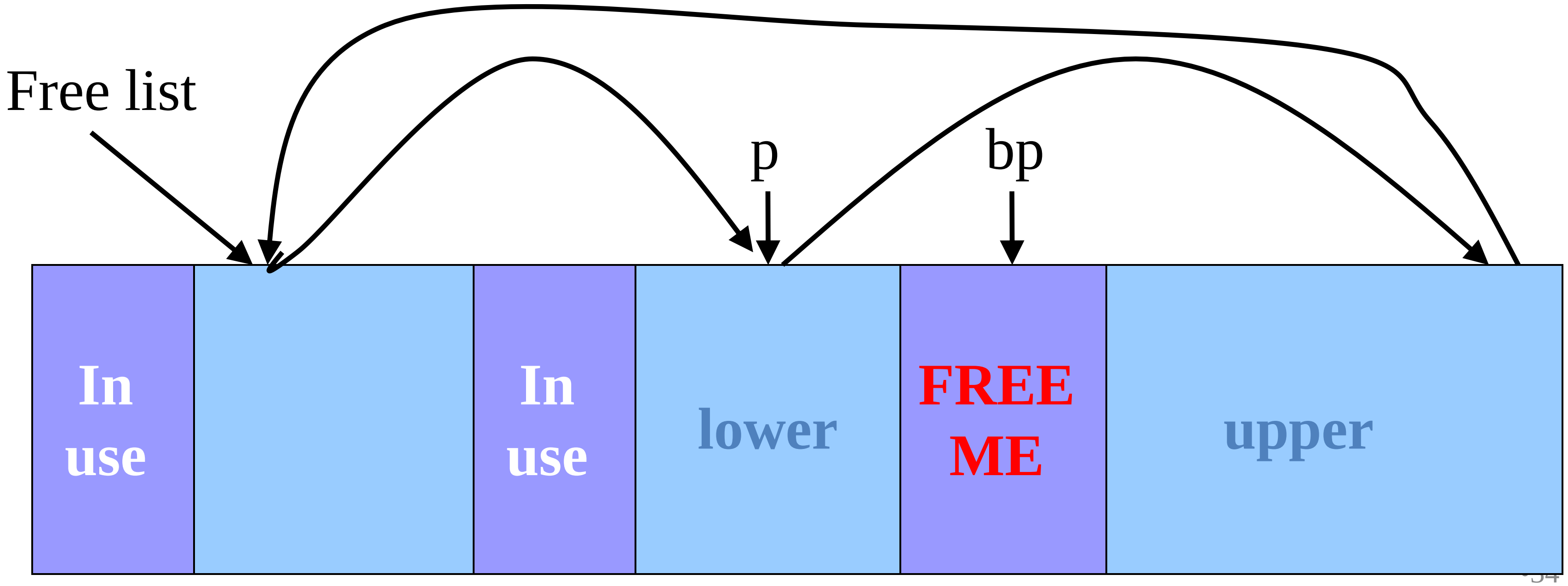
Selective Splitting

- Observation:
  - K&R `malloc()` splits whenever chosen block is too big
  - Example: `malloc(14)` splits the 20-byte block
- Alternative: **selective splitting**
  - Split only when the saving is big enough
  - Example: `malloc(14)` allocates the entire 20-byte block
  - **Pro**: Reduces external fragmentation
  - **Con**: Increases internal fragmentation



Deferred Coalescing

- Observation:
  - K&R does coalescing in `free()` whenever possible
- Alternative: **deferred coalescing**
  - Wait, and coalesce many blocks at a later time
  - **Pro**: Handles "`malloc(x);free();malloc(x)`" sequences well
  - **Con**: Complicates algorithms



Segregated Data

- Observation:
  - Splitting and coalescing consume lots of overhead
- Problem:
  - How to eliminate that overhead?
- Solution: **Segregated data**
  - **Make use of the virtual memory concept…**
  - Store each bin's blocks in a distinct (segregated) virtual memory page
  - Elaboration…

Segregated Data (cont.)

- Segregated data
  - Each bin contains blocks of fixed sizes
    - E.g. 32, 64, 128, …
  - All blocks within a bin are from same **virtual memory** page
  - Malloc never splits! Examples:
    - Malloc for 32 bytes => provide 32
    - Malloc for 5 bytes => provide 32
    - Malloc for 100 bytes => provide 128
  - Free never coalesces!
    - Free block => examine address, infer virtual memory page, infer bin, insert into that bin
  - **Pro**: Completely eliminates splitting and coalescing overhead
  - **Pro**: Eliminates most meta-data; only forward links are required (no backward links, sizes, status bits, footers)
  - **Con**: Some usage patterns cause excessive external fragmentation

Segregated Meta-Data

- Observations:
  - Meta-data (block sizes, status flags, links, etc.) are scattered across the heap, interspersed with user data
  - Heap mgr often must traverse meta-data
- Problem 1:
  - User error easily can corrupt meta-data
- Problem 2:
  - Frequent traversal of meta-data can cause excessive page faults
- Solution: **Segregated meta-data**
  - **Make use of the virtual memory concept…**
  - Store meta-data in a distinct (segregated) virtual memory page from user data

Memory Mapping

- Observations:
  - Heap mgr might want to release heap memory to OS (e.g. for use as stack)
  - Heap mgr can call `brk(currentBreak-x)` to release freed memory to OS, but…
  - Difficult to know when memory at high end of heap is free, and…
  - Often freed memory is not at high end of heap!
- Problem:
  - How can heap mgr effectively release freed memory to OS?
- Solution: **Memory mapping**
  - **Make use of virtual memory concept…**
  - Allocate memory via `mmap()` system call
  - Free memory via `munmap()` system call

`mmap()` and `munmap()`

- Typical call of **`mmap()`**

```
p = mmap(NULL, size, PROT_READ|PROT_WRITE,
             MAP_PRIVATE|MAP_ANON, 0, 0);
```

  - Asks the OS to map a new private read/write area of virtual memory containing **`size`** bytes
  - Returns the virtual address of the new area on success, NULL on failure
- Typical call of **`munmap()`**

```
status = munmap(p, size);
```

  - Unmaps the area of virtual memory at virtual address **`p`** consisting of **`size`** bytes
  - Returns 1 on success, 0 on failure
- See Bryant & O'Hallaron book and man pages for details

Using `mmap()` and `munmap()`

Typical strategy:

- Allocate **small** block =>
  - Call **`brk()`** if necessary
  - Manipulate data structures described earlier in this lecture
- Free **small** block =>
  - Manipulate data structures described earlier in this lecture
  - Do not call **`brk()`**

- Allocate **large** block =>
  - Call **`mmap()`**
- Free **large** block =>
  - Call **`munmap()`**

Summary

- Details of K&R heap manager
- Heap mgr optimizations related to Assignment #5
  - Faster `free()` via doubly-linked list, redundant sizes, and status bits
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- Other heap mgr optimizations
  - Best/good fit block selection
  - Selective splitting
  - Deferred coalescing
  - Segregated data
  - Segregated meta-data
  - Memory mapping