Heap allocation: Malloc

CS 241

February 3, 2012

Announcements

Review: Why is malloc not easy?

- **Must be fast**
  - Can only perform relatively simple computation
  - Should avoid too many system calls (`sbrk()`)

- **Must be memory-efficient**
  - Can't predict what or when the user will malloc/free
  - Even if we knew sizes in advance, packing the requests into memory optimally is NP-complete, i.e., a provably hard problem!

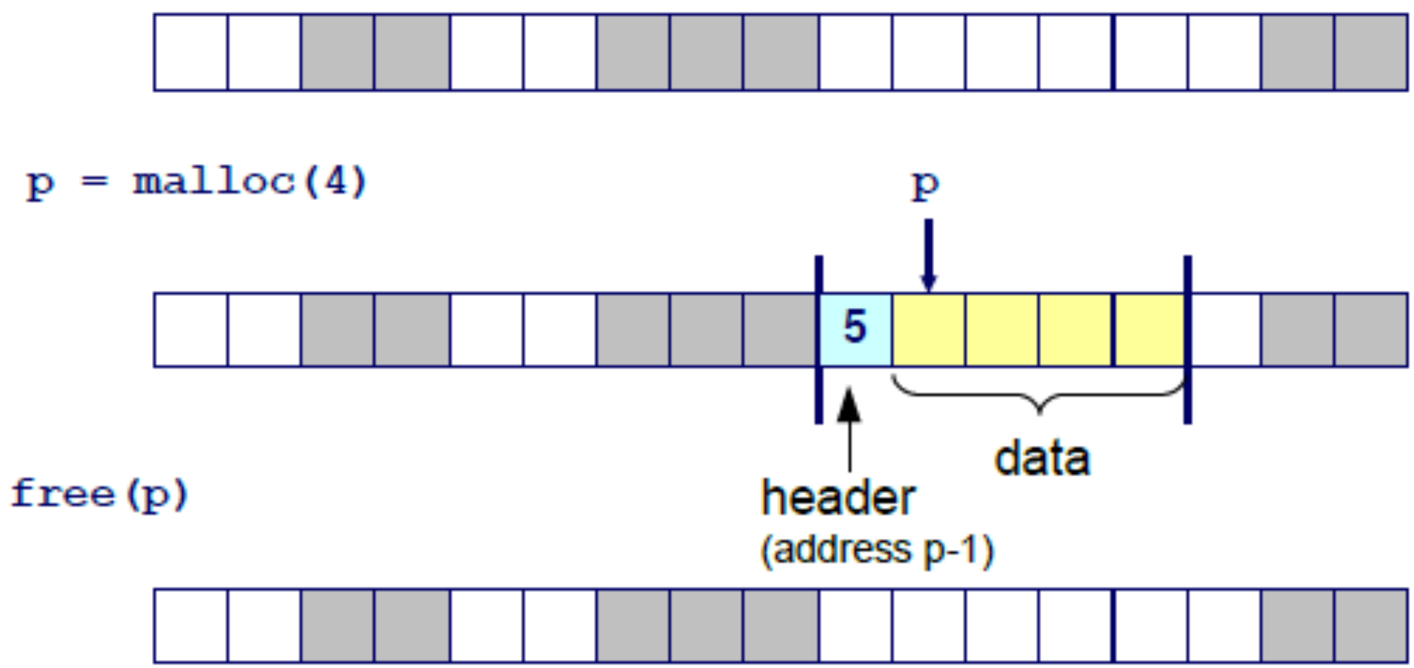
- **Must work!**
  - Easy to make mistakes with pointer & bit manipulation

Implementation Issues

- 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 the block in the header preceding the block
  - Requires an extra word for every allocated block



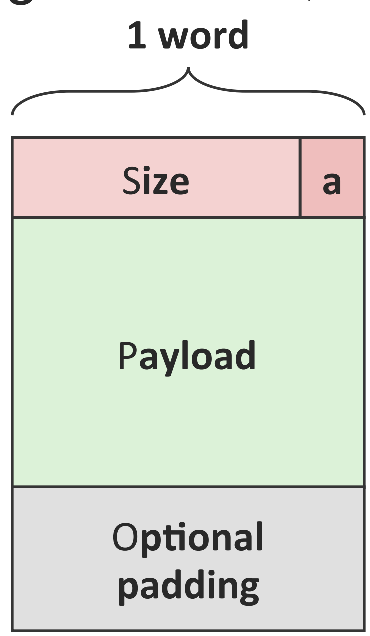
Keeping Track of Free Blocks

- One of the biggest jobs of an allocator is knowing where the free memory is
- The allocator's approach to this problem affects:
  - Throughput – time to complete a malloc() or free()
  - Space utilization – amount of extra metadata used to track location of free memory
- There are many approaches to free space management
  - Next, we will talk about one: **Implicit free lists.**

Implicit free list

- For each block we need both size and allocation status
  - Could store this information in two words: wasteful!
- Standard trick
  - If blocks are aligned, low-order address bits are always 0
  - Why store an always-0 bit? Use it as allocated/free flag!
  - When reading size word, must mask out this bit

Format of allocated and free blocks

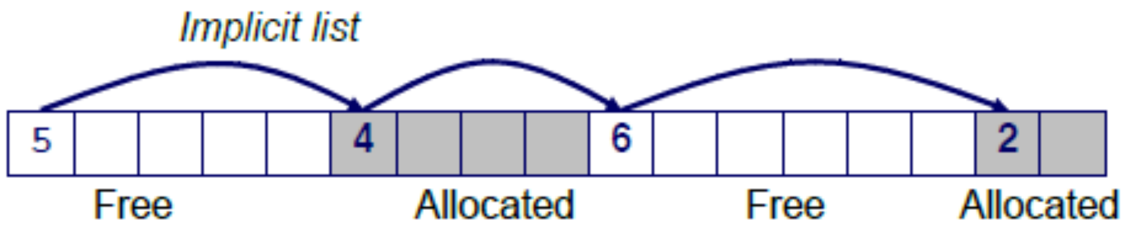


a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data (allocated blocks only)

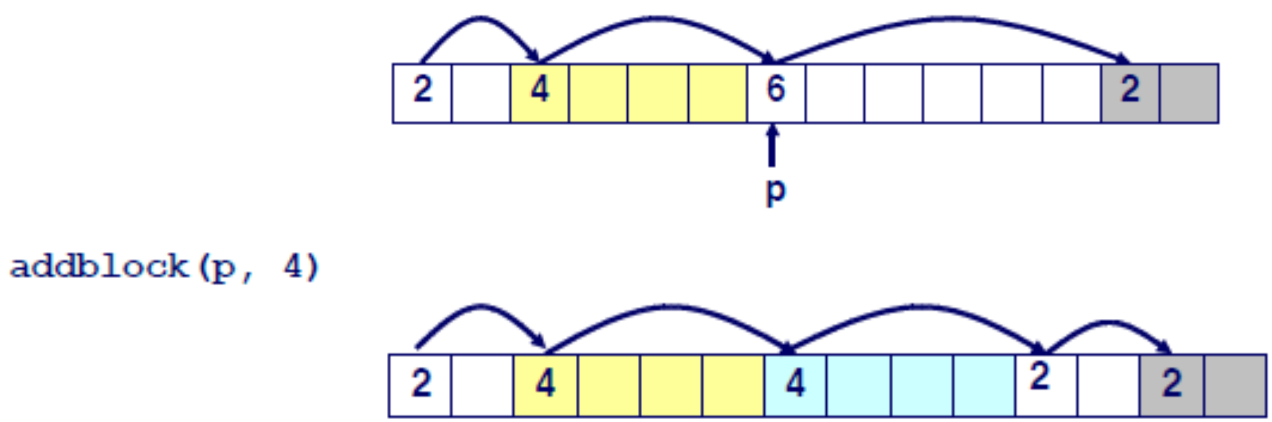
Implicit free list



- 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.
    - Could also use next fit, best fit, etc

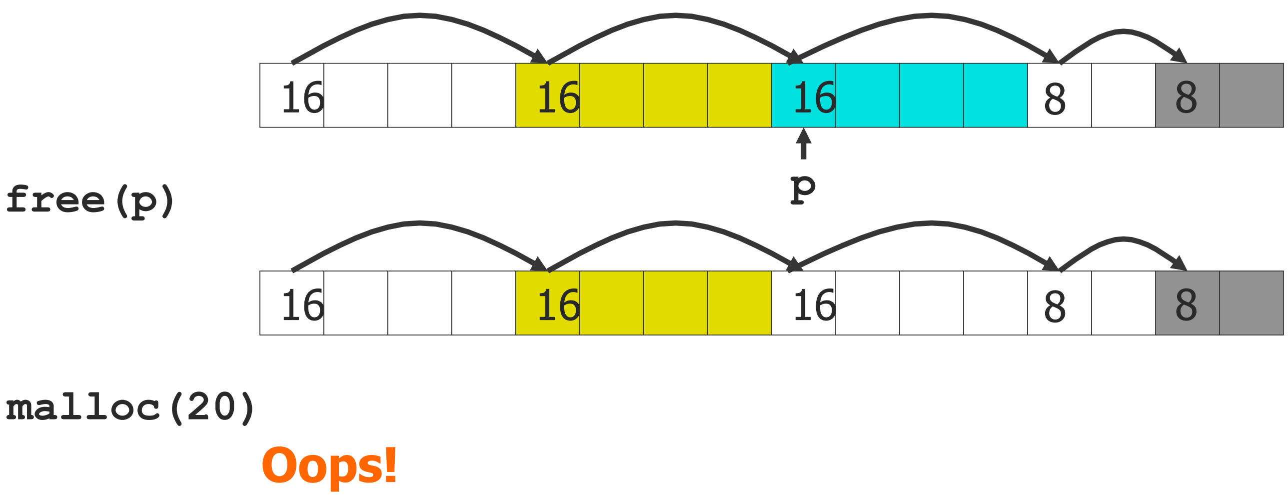
Implicit list: Allocating a Block

- 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



Implicit List: Freeing a Block

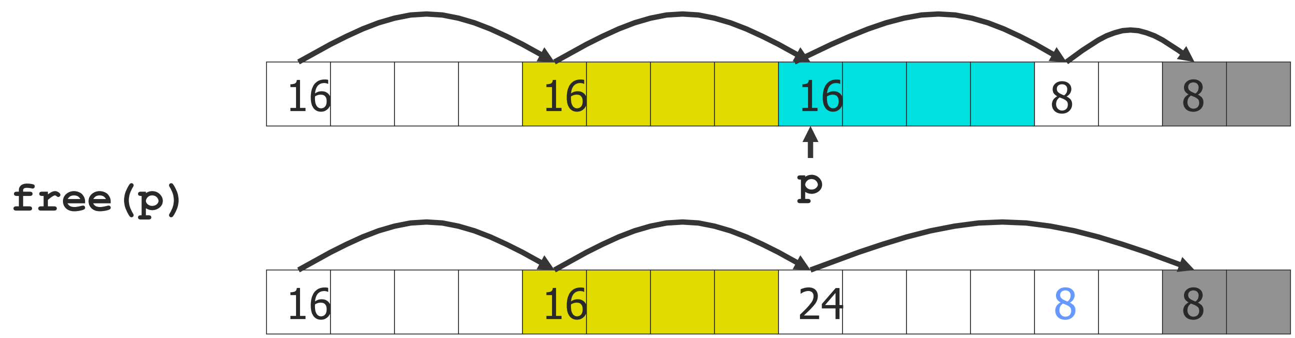
- Simplest implementation:
  - Only need to clear allocated flag
  - `void free_block(ptr p) { *p = *p & ~1; }`
- But can lead to "false fragmentation"



- There's enough free space, but allocator won't find it!

Implicit List: Coalescing

- Join (coalesce) with next and previous block if they are free
  - Coalescing with next block



- But how do we coalesce with previous block?

Implicit Lists: Summary

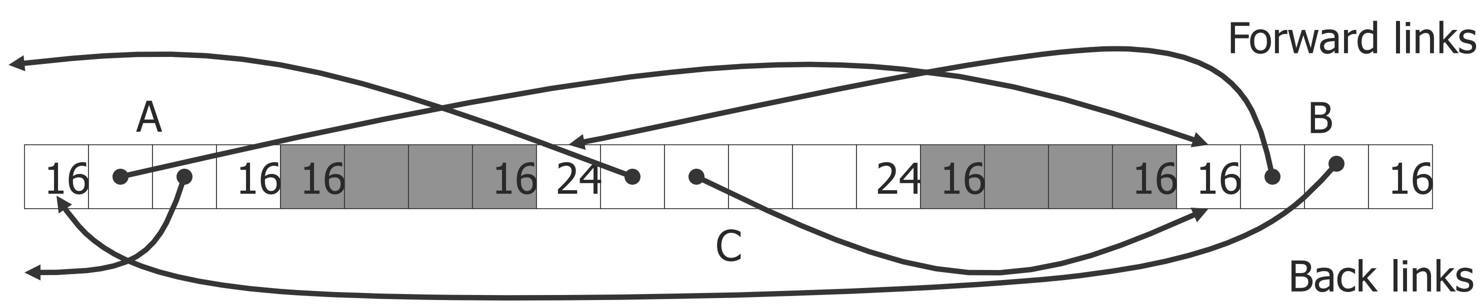
- Implementation: very simple
- Allocate: linear-time worst case
- Free: constant-time worst case—even with coalescing
- Memory usage: will depend on placement policy
  - First, next, or best fit

- Not used in practice for malloc/free because of linear-time allocate, but used in some special-purpose applications

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

Alternative: Explicit Free Lists

- Linked list among free blocks
- Use data space for link pointers
  - Typically doubly linked
  - Still need boundary tags for coalescing



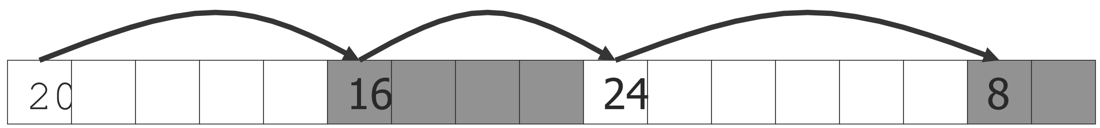
- Links aren't necessarily in same order as blocks! Advantage?

Freeing with Explicit Free Lists

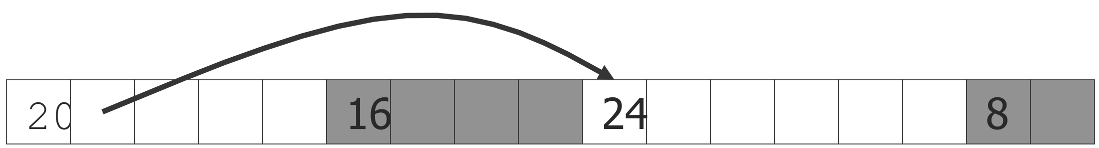
- **Insertion policy**: Where in free list to put newly freed block?
  - LIFO (last-in-first-out) policy
    - Insert freed block at beginning of free list
    - Pro: simple, and constant-time
    - Con: studies suggest fragmentation is worse than address-ordered
  - Address-ordered policy
    - Insert freed blocks so list is always in address order
      - i.e. addr(pred) < addr(curr) < addr(succ)
    - Con: requires search (using boundary tags); slow!
    - Pro: studies suggest fragmentation is better than LIFO

Summary: tracking free blocks

- *Method 1*: Implicit list using lengths -- links all blocks



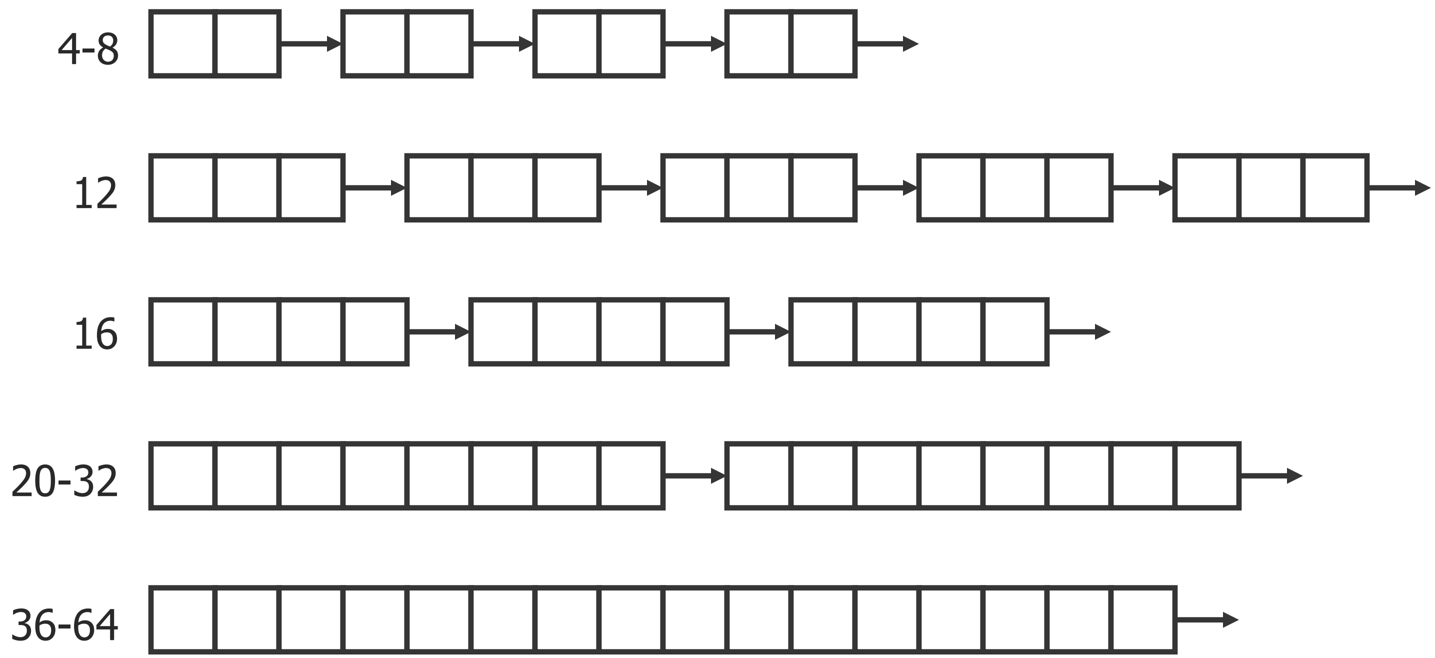
- *Method 2*: Explicit list among the free blocks using pointers within the free blocks



- *Method 3*: Segregated free list
  - Different free lists for different size classes
  - We'll talk about this one next

Segregated free lists

- Each **size class** has its own collection of blocks



  - Often separate size class for every small size (8, 12, 16, …)
  - For larger, typically have size class for each power of 2
- What is the point of having separate lists?

Buddy Allocators

- Special case of segregated free lists

- Basic idea:
  - Limited to power-of-two sizes
  - Can only coalesce with "buddy", who is other half of next-higher power of two

- Clever use of low address bits to find buddies

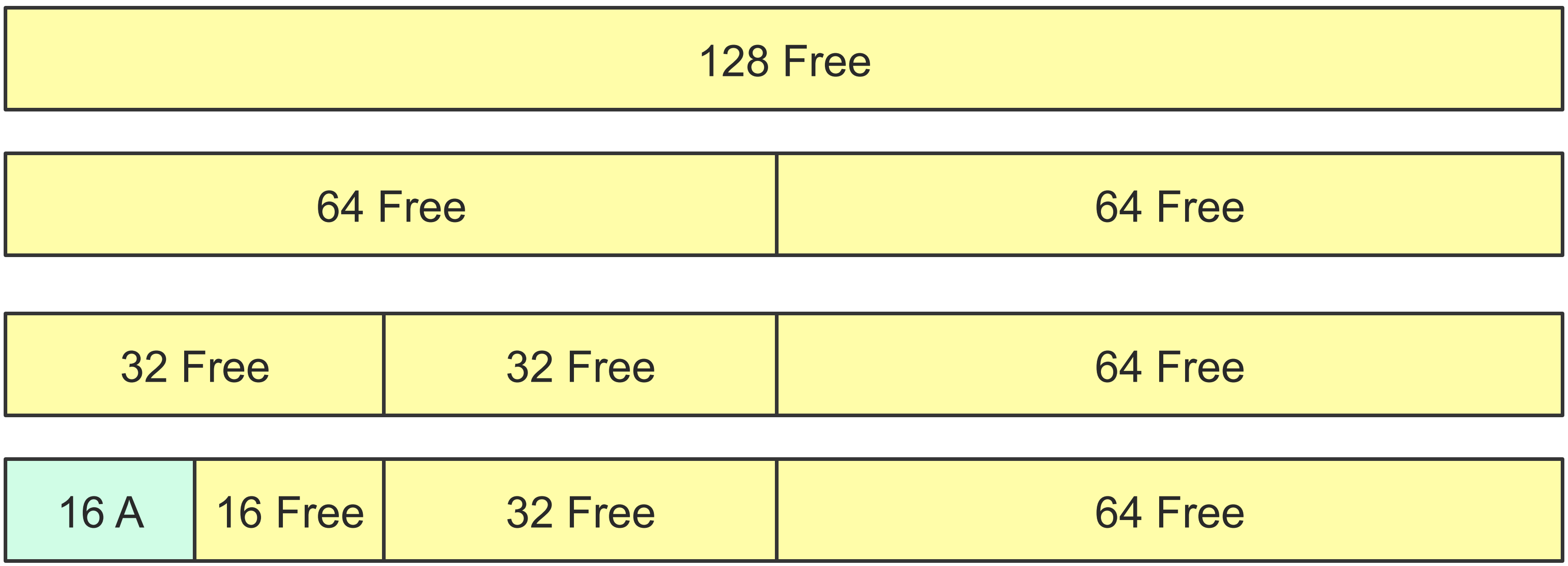
- Problem: large powers of two result in large internal fragmentation (e.g., what if you want to allocate 65537 bytes?)

Buddy System Example

128 Free

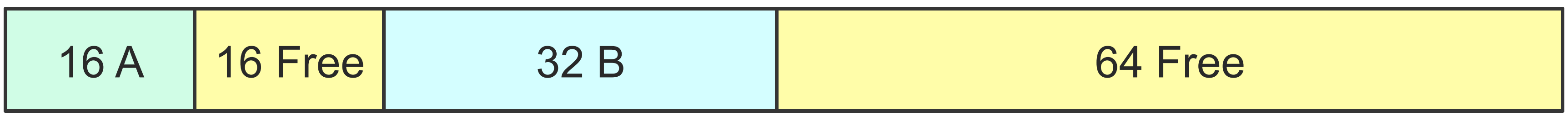
Buddy System Example

Process A requests 16



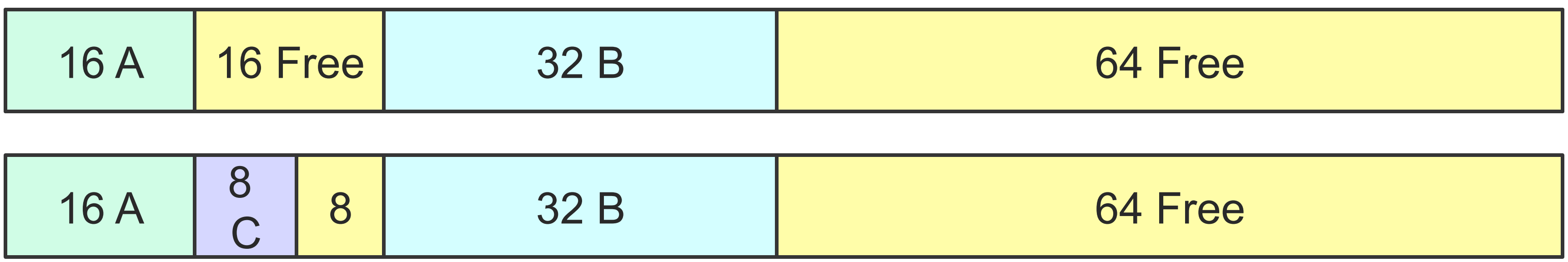
Buddy System Example

Process B requests 32



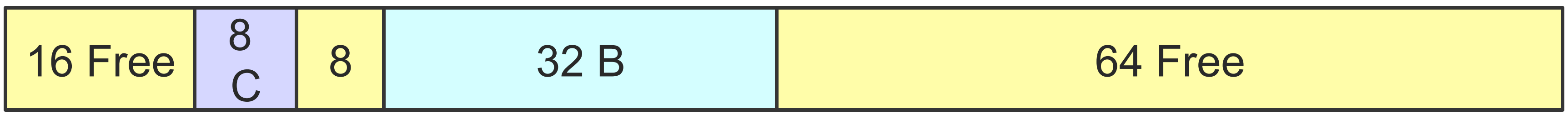
Buddy System Example

Process C requests 8



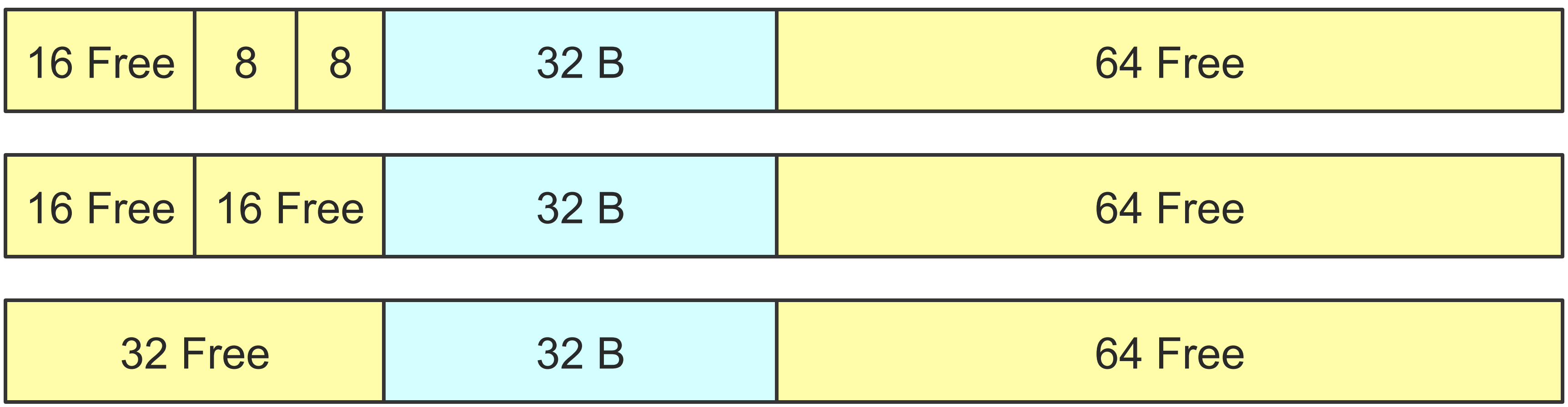
Buddy System Example

Process A exits



Buddy System Example

Process C exits



- Advantages, disadvantages?
- Advantage: Low external fragmentation
- Disadvantage: Internal fragmentation when not 2^n-sized request

So what should I do for MP2?

- Designs sketched here are reasonable
- Many other possible designs
- Implement anything you want!