CS107, Lecture 24

Explicit Free List Allocator

Reading: B&O 9.9, 9.11, 5 (Optimization)

😷 masks recommended

CS107 Topic 6

<u>How do the core malloc/realloc/free memory-allocation operations work?</u>

Why is answering this question important?

- Combines techniques from across the quarter (bits/bytes, pointers, memory, generics, assembly, efficiency, testing, and more) to understand a real-world system that you have relied on all quarter!
- Learning about the design and tradeoffs in a real-world large system gives us a great example of how to evaluate different designs when there's no one "right" answer.

assign6: implement two different possible designs for a heap allocator, implementing malloc/realloc/free.

Learning Goals

- Learn about how we can implement coalescing of blocks and in-place realloc
- Understand the tradeoffs between bump, implicit and explicit free list allocators

Lecture Plan

- **Recap:** heap allocators so far
- Method 2: Explicit Free List Allocator

Lecture Plan

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- Method 2: Explicit Free List Allocator

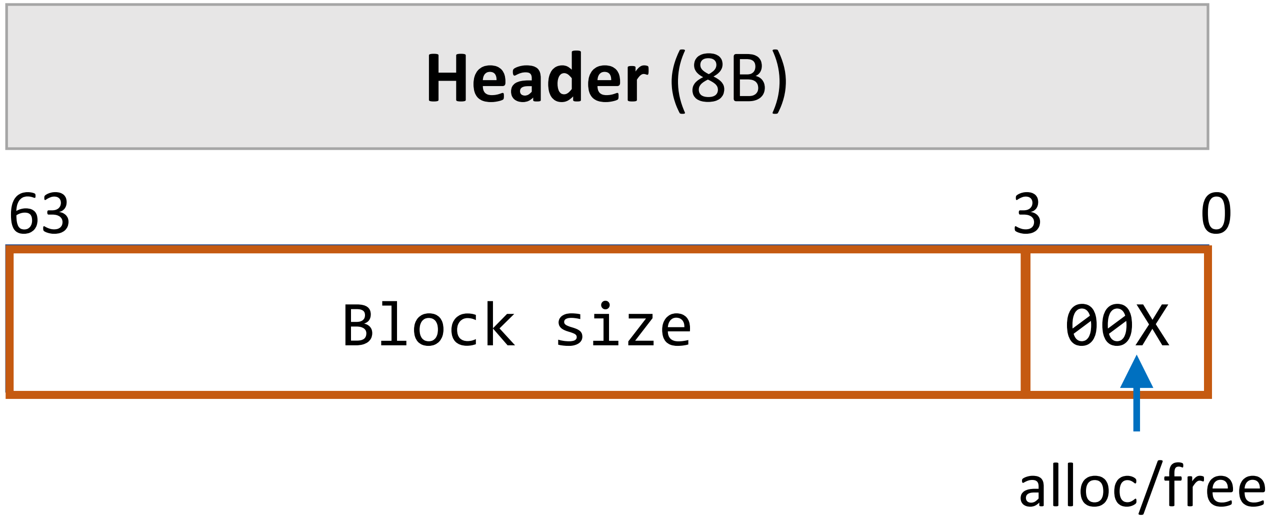
Bump Allocator

- A **bump allocator** is a heap allocator design that simply allocates the next available memory address upon an allocate request and does nothing on a free request.
- Throughput: each **malloc** and **free** execute only a handful of instructions:
  - It is easy to find the next location to use
  - Free does nothing!
- Utilization: we use each memory block at most once. No freeing at all, so no memory is ever reused. ☹
- We provide a bump allocator implementation as part of the final assignment as a code reading exercise.

Implicit Free List Allocator

For **all blocks**,

- Have a header that stores size and status.
- Our list links *all* blocks, allocated (A) and free (F).



Keeping track of free blocks:

- **Improves memory utilization** (vs bump allocator)
- **Decreases throughput** (worst case allocation request has O(A + F) time)
- Increases design complexity ☺

Final Assignment: Implicit Allocator

- **Must have** headers that track block information (size, status in-use or free) – you must use the 8 byte header size, storing the status using the free bits (this is larger than the 4 byte headers specified in the book, as this makes it easier to satisfy the alignment constraint and store information).
- **Must have** free blocks that are recycled and reused for subsequent malloc requests if possible
- **Must have** a malloc implementation that searches the heap for free blocks via an implicit list (i.e. traverses block-by-block).

- **Does not need to** have coalescing of free blocks
- **Does not need to** support in-place realloc

(Note: these could be part of an implicit allocator, it's just not a requirement for this assignment)

Lecture Plan

- **Recap:** heap allocators so far
- **Method 2: Explicit Free List Allocator**
  - **Explicit Allocator**
  - Coalescing
  - In-place realloc

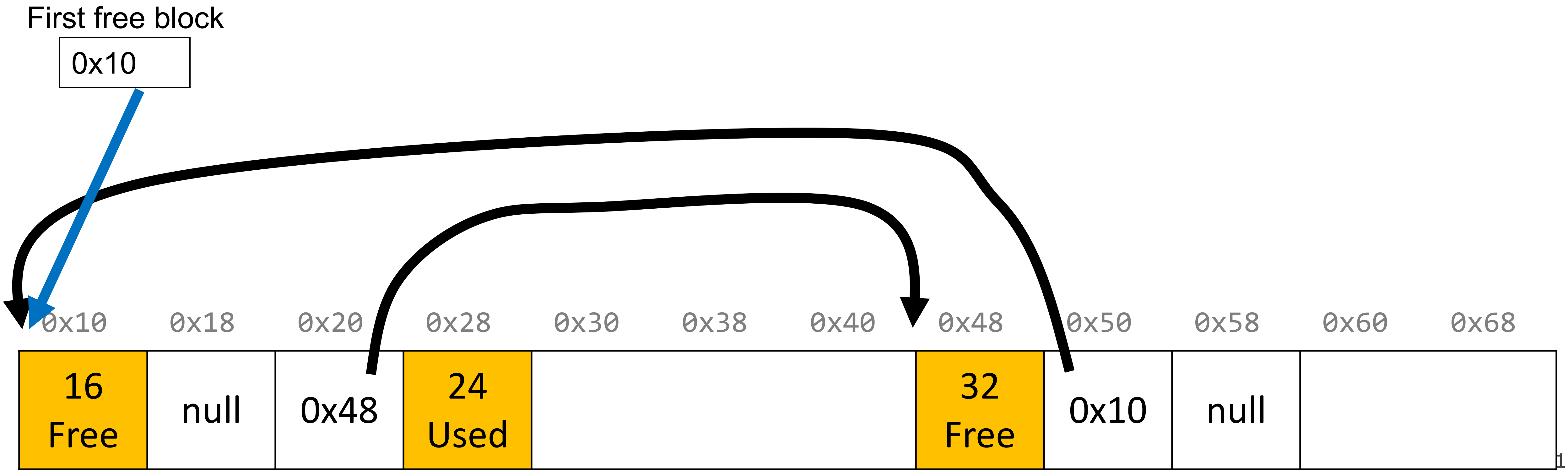
Explicit Free List Allocator

- This design builds on the implicit allocator, but also stores pointers to the next and previous free block inside each free block's payload.
- When we allocate a block, we look through just the free blocks using our linked list to find a free one, and we update its header and the linked list to reflect its allocated size and that it is now allocated.
- When we free a block, we update its header to reflect it is now free and update the linked list.

This **explicit** list of free blocks increases request throughput, with some costs (design and internal fragmentation)

Explicit Free List Allocator

- **Key Insight:** the payloads of the free blocks aren't being used, because they're free.
- **Idea:** since we only need to store these pointers for free blocks, let's store them in the <u>first 16 bytes of each free block's payload!</u>



Explicit Free List: List Design

How do you want to organize your explicit free list? (compare utilization/throughput)

Up to you!

A. Address-order (each block's address is less than successor block's address)
B. Last-in first-out (LIFO)/like a stack, where newly freed blocks are at the beginning of the list
C. Other (e.g., by size, etc.)

Better memory util, Linear free

Constant free (push recent block onto stack)

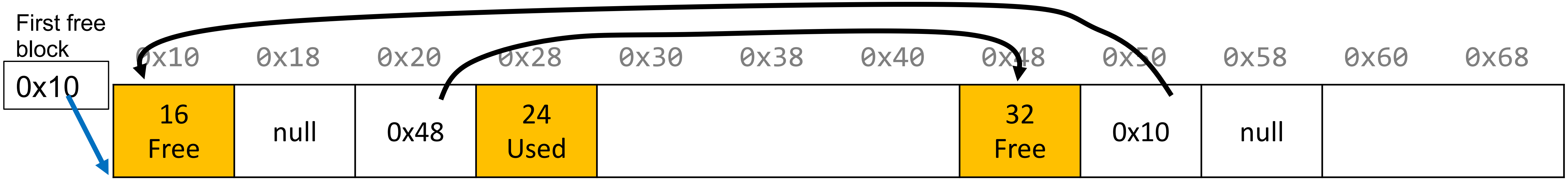
(more at end of lecture)

Explicit free list design

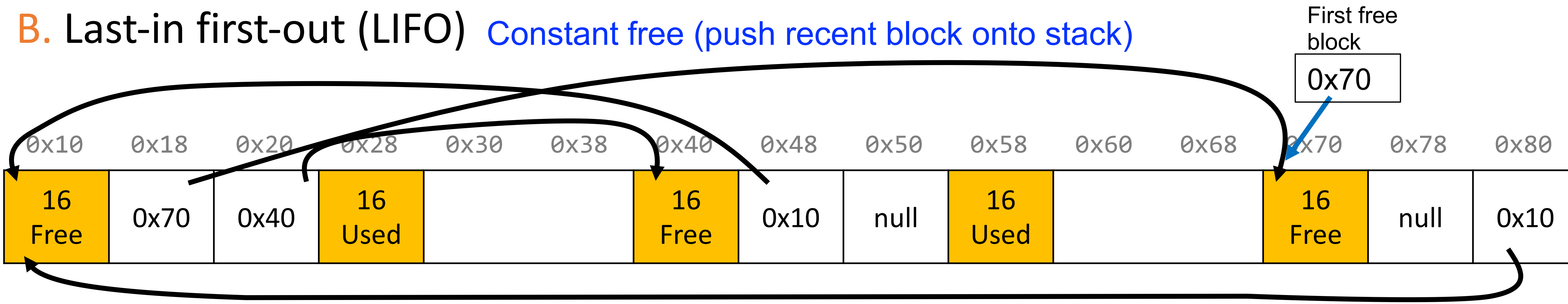
Up to you!

How do you want to organize your explicit free list?(utilization/throughput)

A. Address-order Better memory util, linear free



B. Last-in first-out (LIFO) Constant free (push recent block onto stack)



C. Other (e.g., by size, etc.) (see textbook)

Implicit vs. Explicit: So Far

Implicit Free List

- 8B header for size + alloc/free status
- Allocation requests are worst-case linear in total number of blocks
- Implicitly address-order

Explicit Free List

- 8B header for size + alloc/free status
- Free block payloads store prev/next free block pointers
- Allocation requests are worst-case linear in number of free blocks
- Can choose block ordering

Revisiting Our Goals

Can we do better?

1. Can we avoid searching all blocks for free blocks to reuse? **Yes! We can use a doubly-linked list.**
2. Can we merge adjacent free blocks to keep large spaces available?
3. Can we avoid always copying/moving data during realloc?

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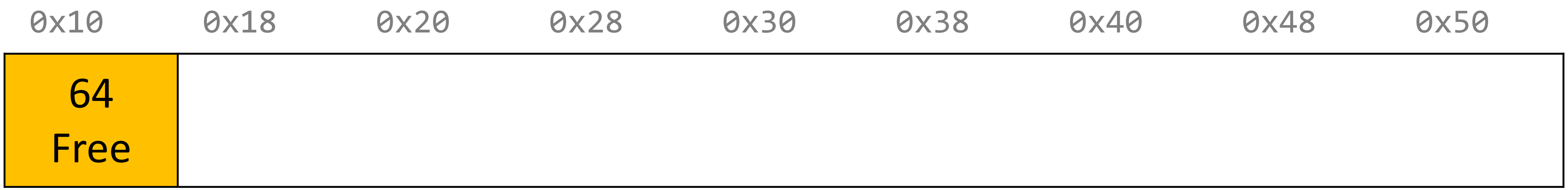
Lecture Plan

- **Recap:** heap allocators so far
- **Method 2: Explicit Free List Allocator**
  - Explicit Allocator
  - **Coalescing**
  - In-place realloc

Coalescing

```
void *a = malloc(8);
void *b = malloc(8);
void *c = malloc(16);
free(b);
free(a);
void *d = malloc(32);
```



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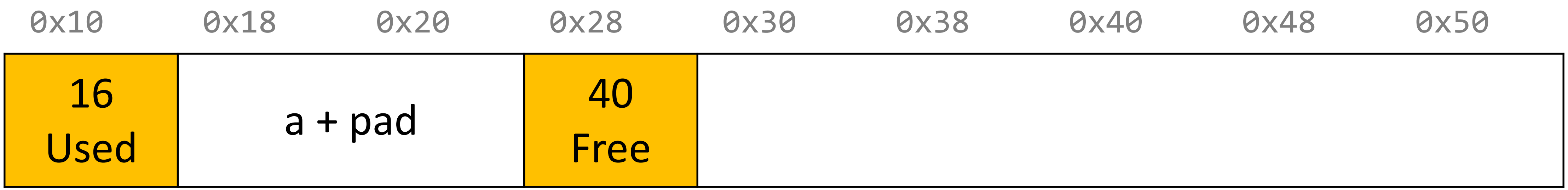

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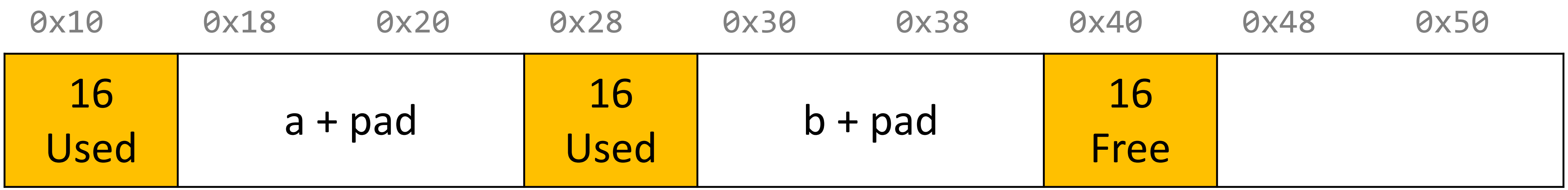

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```

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50
16 Used	a + pad		16 Used	b + pad		16 Used	c	

Coalescing

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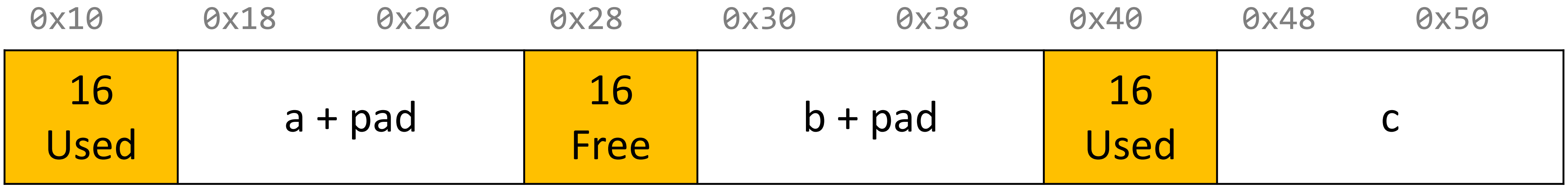

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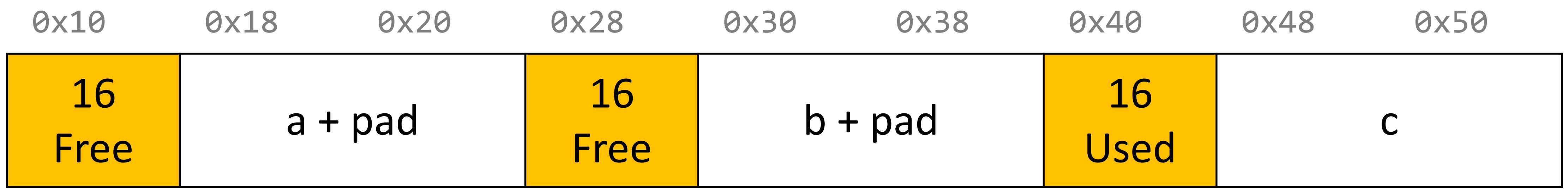

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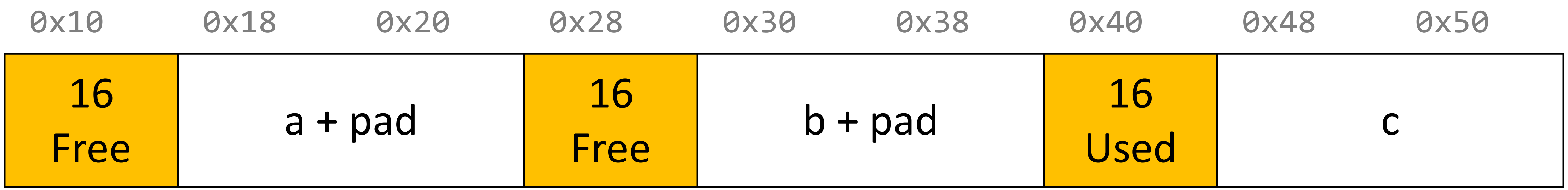
We have enough memory space, but it is fragmented into free blocks sized from earlier requests!

We'd like to be able to merge adjacent free blocks back together. How can we do this?



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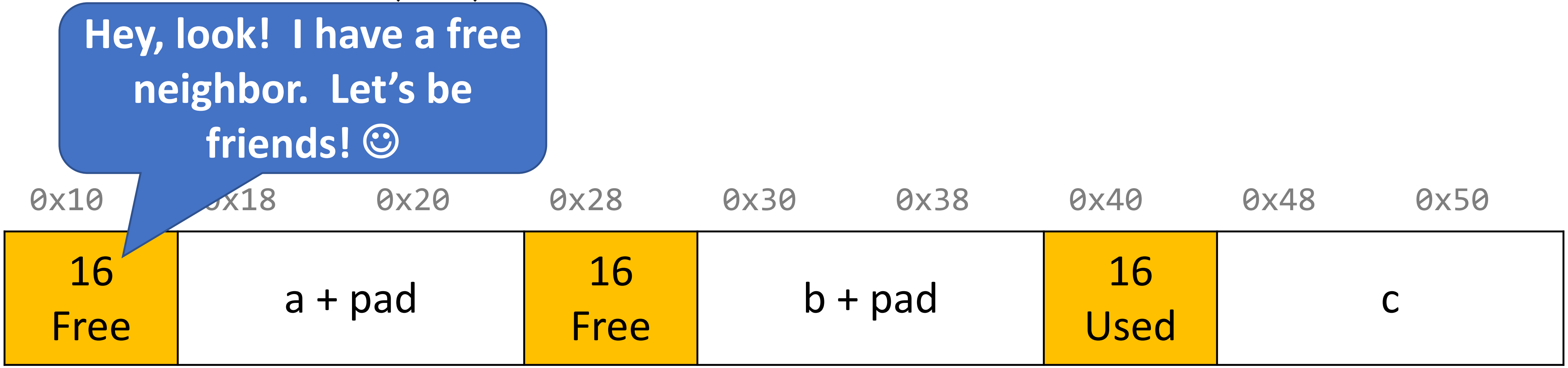

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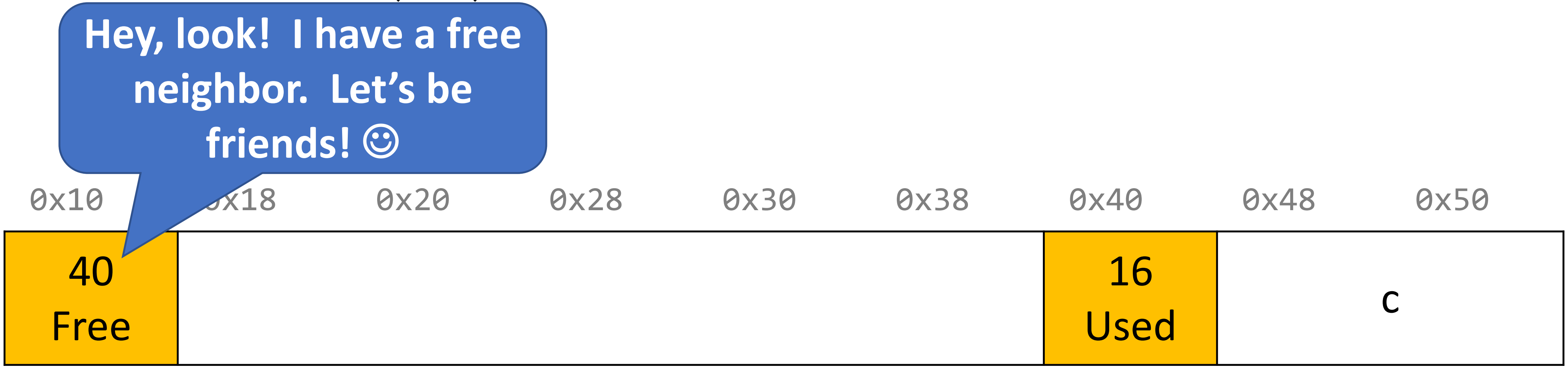

Coalescing

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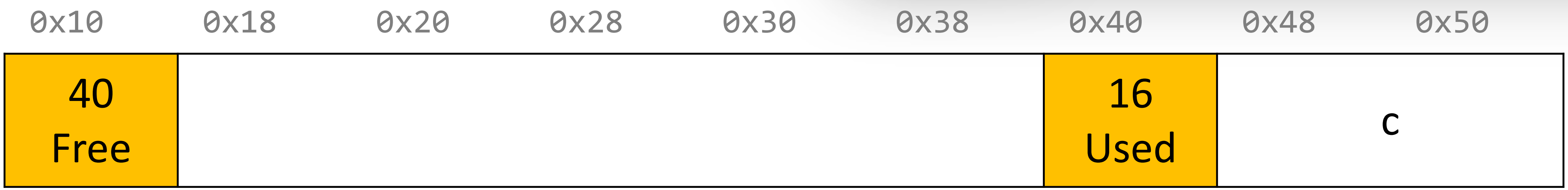
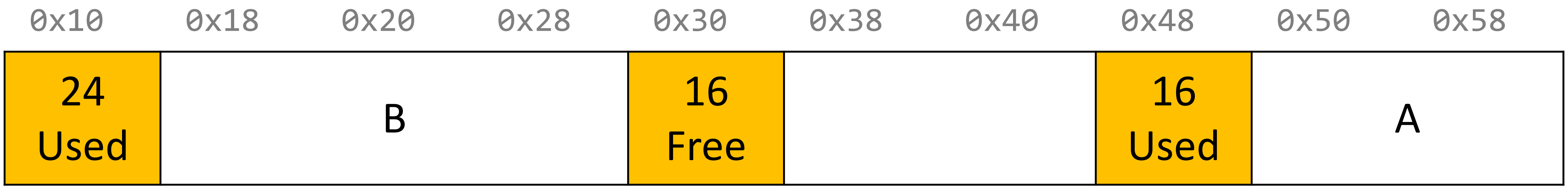
The process of combining adjacent free blocks is called *coalescing*.

For your explicit heap allocator only (not required for implicit), you should coalesce if possible when a block is freed. **You only need to coalesce the most immediate right neighbor.**



Practice 1: Explicit (coalesce)

For the following heap layout, what would the heap look like after the following request is made, assuming we are using an **explicit** free list allocator with a **first-fit** approach and **coalesce on free**?

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free(b);
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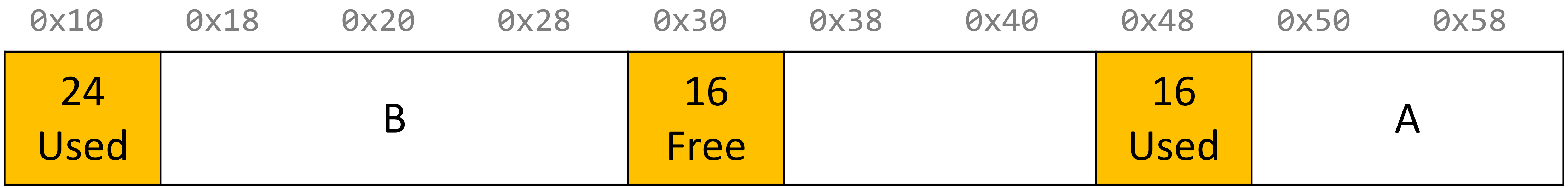


```
free(b);
```

Revisiting Our Goals

Can we do better?

1. Can we avoid searching all blocks for free blocks to reuse? **Yes! We can use a doubly-linked list.**
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3. Can we avoid always copying/moving data during realloc?

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  - Explicit Allocator
  - Coalescing
  - **In-place realloc**

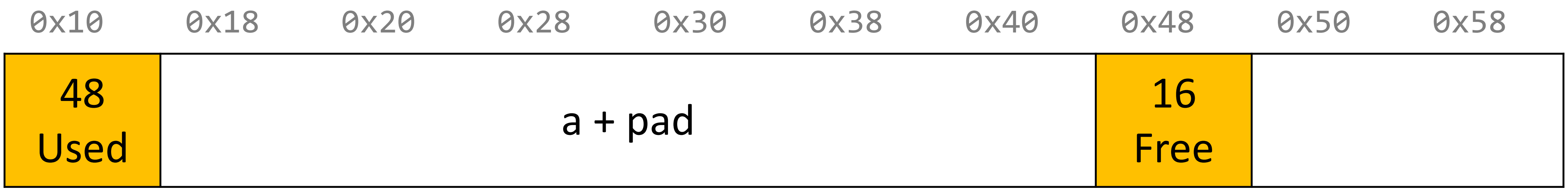
Realloc

- For the implicit free list allocator, we didn't worry too much about realloc. We always moved data when they requested a different amount of space.
  - Note: realloc can grow *or* shrink the data size.
- But sometimes we may be able to keep the data in the same place. How?
  - **Case 1:** size is growing, but we added padding to the block and can use that
  - **Case 2:** size is shrinking, so we can use the existing block
  - **Case 3:** size is growing, and current block isn't big enough, but adjacent blocks are free.

Realloc: Growing In Place

```
void *a = malloc(42);
...
void *b = realloc(a, 48);
```

a's earlier request was too small, so we added padding. Now they are requesting a larger size we can satisfy with that padding! So realloc can return the same address.



Realloc: Growing In Place

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void *a = malloc(42);
...
void *b = realloc(a, 16);
```
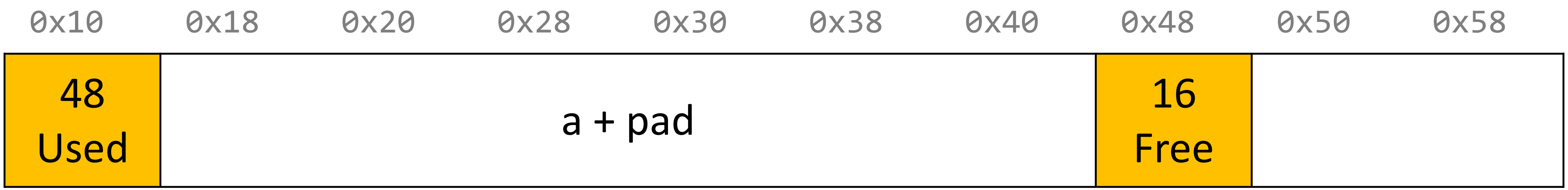

If a realloc is requesting to shrink, we can still use the same starting address.

If we can, we should try to recycle the now-freed memory into another freed block.



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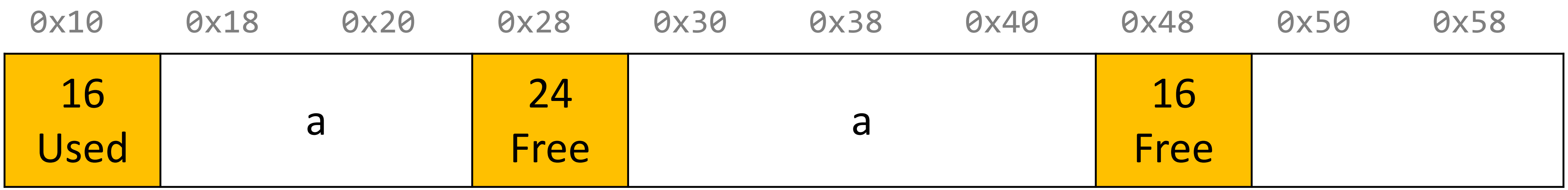
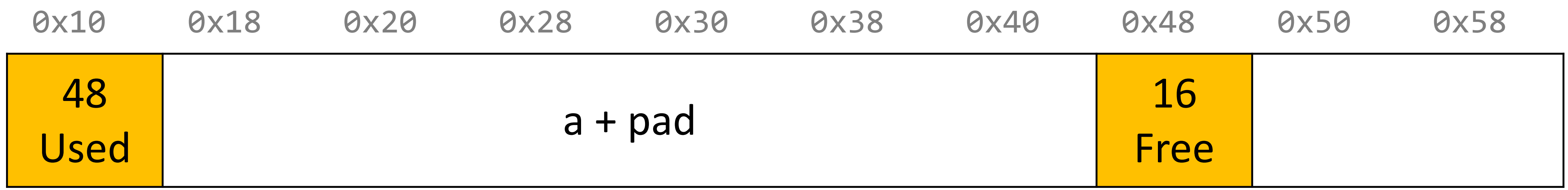


Realloc: Growing In Place

```
void *a = malloc(42);
...
void *b = realloc(a, 72);
```

Even with the padding, we don’t have enough space to satisfy the larger size. But we have an adjacent neighbor that is free – let’s team up!



Realloc: Growing In Place

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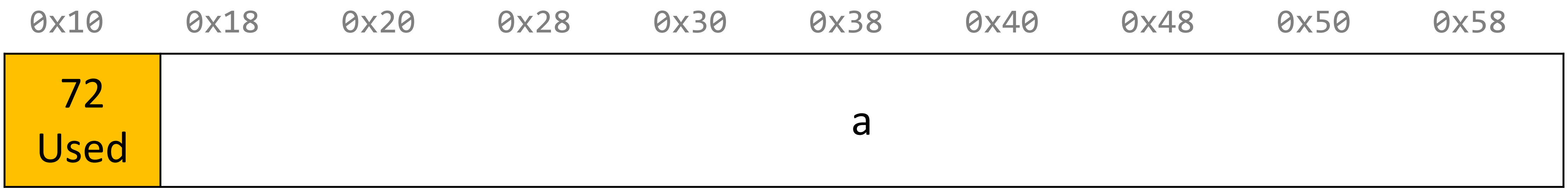
Now we can still return the same address.



Realloc: Growing In Place

```
void *a = malloc(8);
...
void *b = realloc(a, 72);
```

For your project (explicit only), you should combine with your *right* neighbors as much as possible until we get enough space, or until we know we cannot get enough space.

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
16 Used	a + pad		16 Free			24 Free			

Realloc: Growing In Place

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0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
40 Used	a					24 Free			

Realloc: Growing In Place

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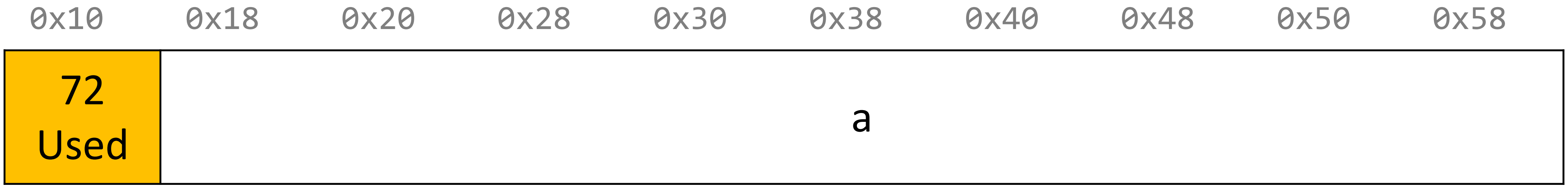

Realloc

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  - **Case 3:** size is growing, and current block isn't big enough, but adjacent blocks are free.
- If you can't do an in-place realloc, then you should move the data elsewhere.

Practice 1: Explicit (realloc)

For the following heap layout, what would the heap look like after the following request is made, assuming we are using an explicit free list allocator with a **first-fit** approach and **coalesce on free + realloc in-place**?

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60
16 Used	A		32 Free					16 Used	B	

```
realloc(A, 24);
```

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For the following heap layout, what would the heap look like after the following request is made, assuming we are using an explicit free list allocator with a **first-fit** approach and **coalesce on free** + **realloc in-place**?

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60
16 Used	A		32 Free					16 Used	B	

```
realloc(A, 24);
```

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60
24 Used	A			24 Free				16 Used	B	

Practice 2: Explicit (realloc)

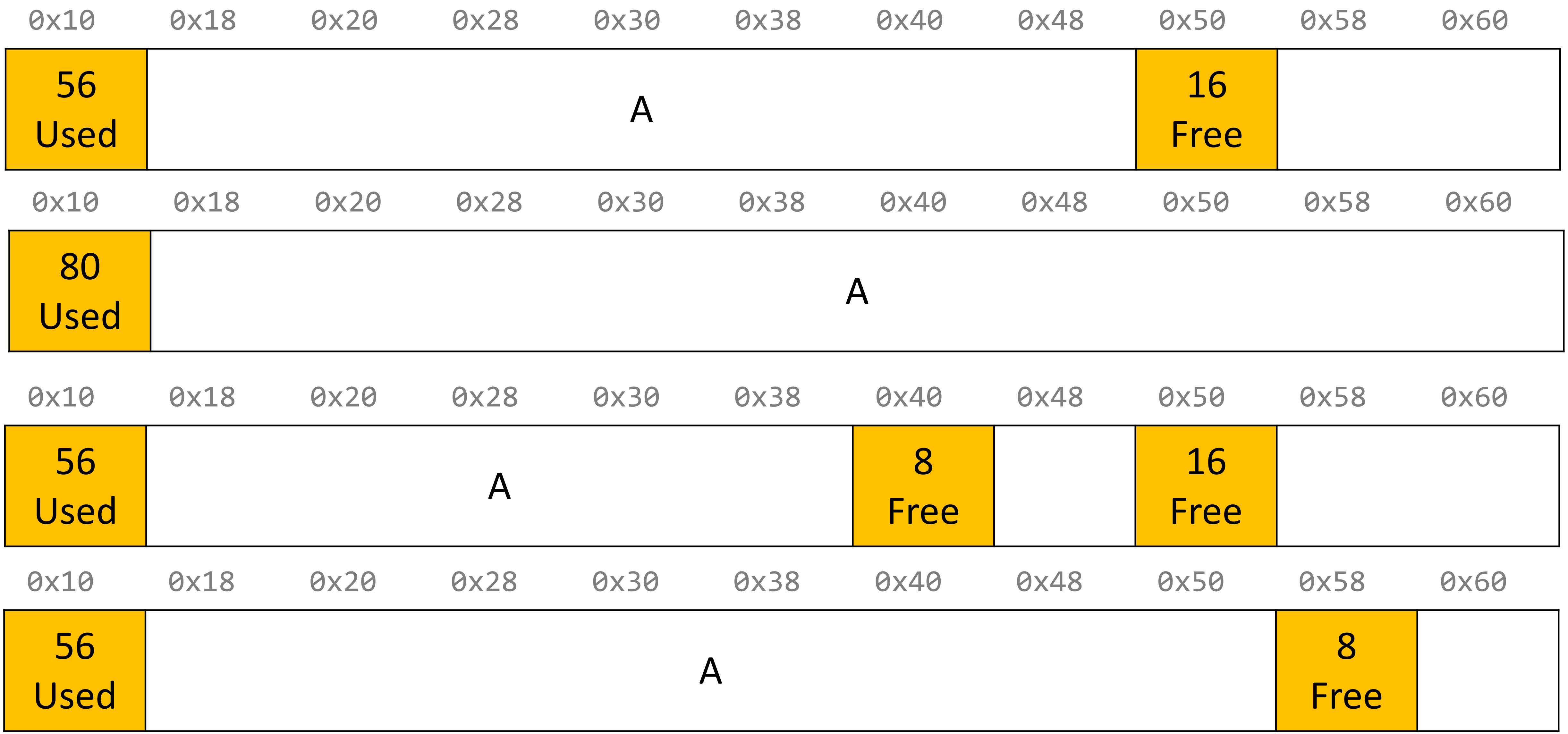
For the following heap layout, what would the heap look like after the following request is made, assuming we are using an **explicit** free list allocator with a **first-fit** approach and **coalesce on free + realloc in-place**?

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60
16 Used	A		32 Free					16 Free		

```
realloc(A, 56);
```

Input your answer on PollEv:
pollev.com/cs107 or text CS107 to 22333 once to join.

Practice 2: Explicit: Options



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16 Used	A		32 Free					16 Free		

```
realloc(A, 56);
```

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60
56 Used	A							16 Free		

Practice 3: Explicit (realloc)

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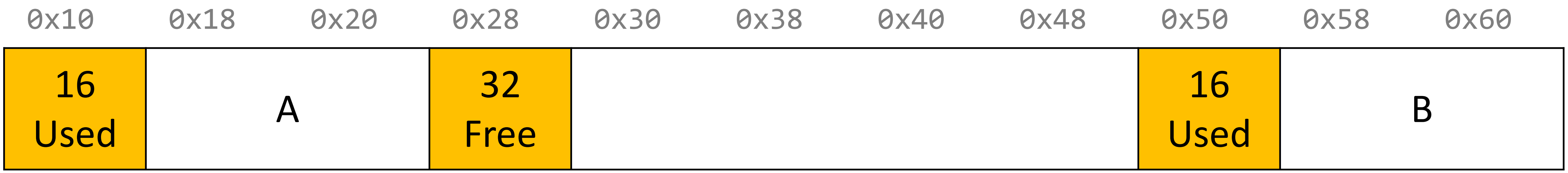
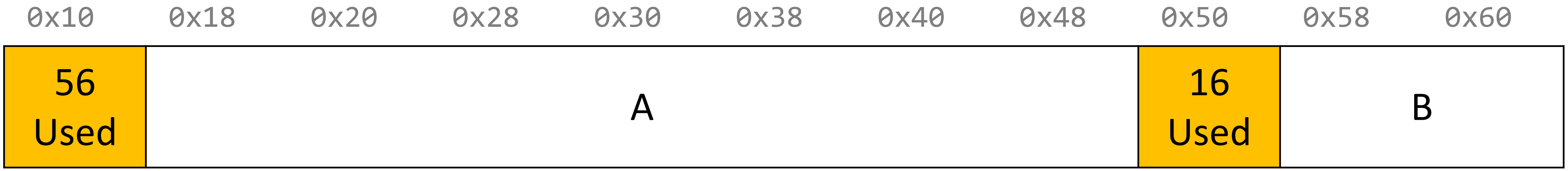
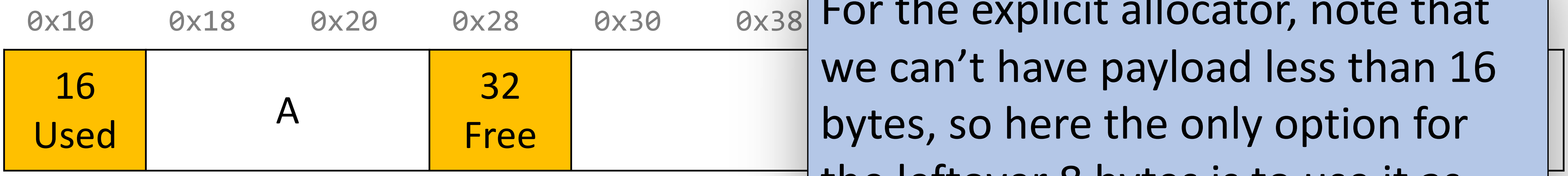



```
realloc(A, 48);
```



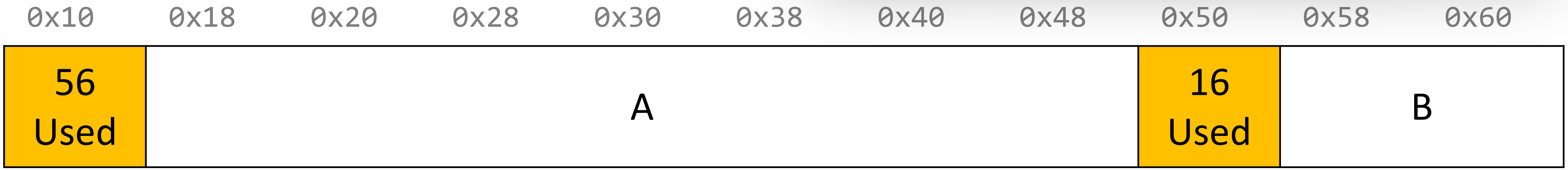
Practice 3: Explicit (realloc)

For the following heap layout, what would the heap look like after the following request is made, assuming we are using an **explicit** free list allocator with a **first-fit** approach and **coalesce on free + realloc in-place**?



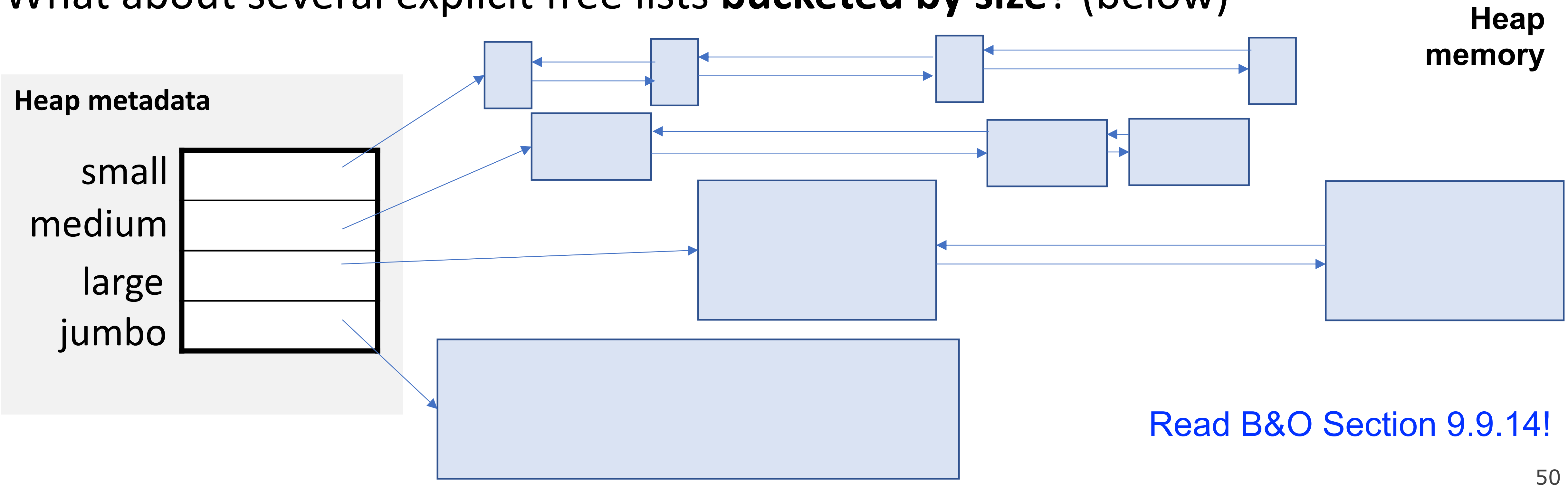
For the explicit allocator, note that we can't have payload less than 16 bytes, so here the only option for the leftover 8 bytes is to use it as padding for the existing block.

```
realloc(A, 48);
```



Going beyond: Explicit list w/size buckets

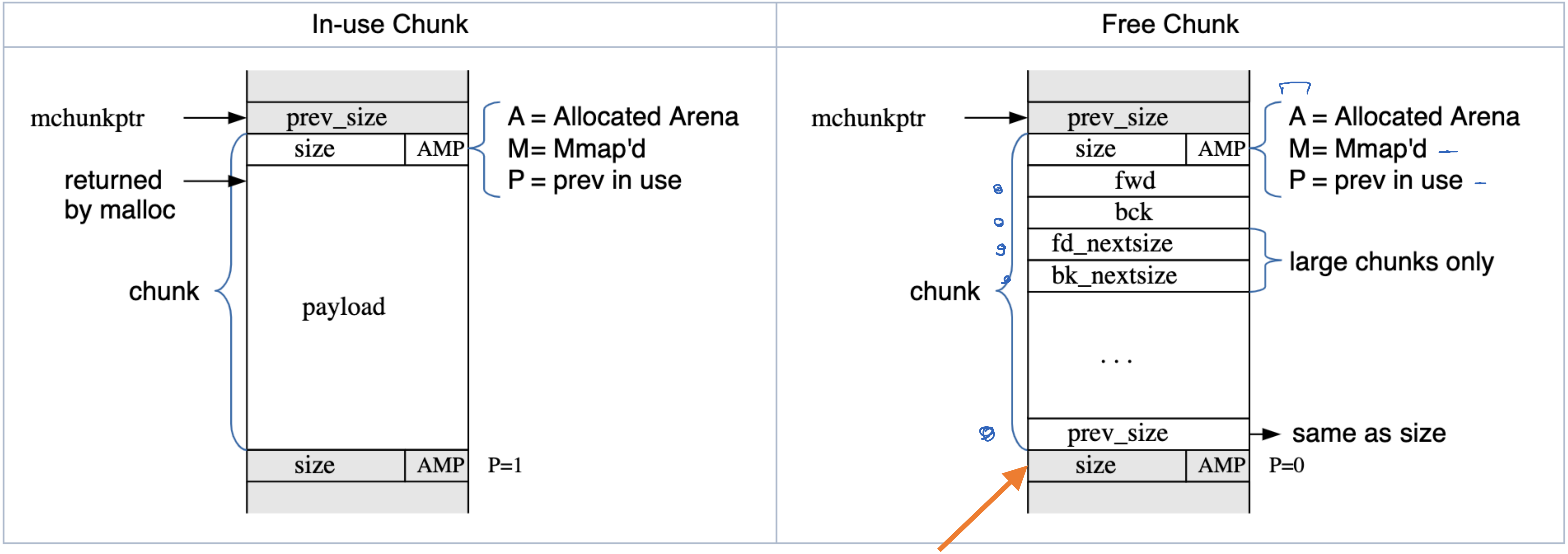
- Explicit lists are much faster than implicit lists.
- However, a first-fit placement policy is still linear in total # of free blocks.
- What about an explicit free list **sorted by size** (e.g., as a tree)?
- What about several explicit free lists **bucketed by size**? (below)



Read B&O Section 9.9.14!

In the wild: glibc allocator

- https://sourceware.org/glibc/wiki/MallocInternals



Footer/Boundary tag (see textbook)

Final Assignment: Explicit Allocator

- **Must have** headers that track block information like in implicit (size, status in-use or free) – you can copy from your implicit version
- **Must have** an explicit free list managed as a doubly-linked list, using the first 16 bytes of each free block's payload for next/prev pointers.
- **Must have** a malloc implementation that searches the explicit list of free blocks.
- **Must** coalesce a free block in free() whenever possible with its immediate right neighbor. (only required for explicit)
- **Must** do in-place realloc when possible (only required for explicit). Even if an in-place realloc is not possible, you should still absorb adjacent right free blocks as much as possible until you either can realloc in place or can no longer absorb and must realloc elsewhere.

Final Project Tips

Read B&O textbook.

- Offers some starting tips for implementing your heap allocators.
- Make sure to cite any design ideas you discover.

Honor Code/collaboration

- All non-textbook code is off-limits.
- Please do not discuss discuss code-level specifics with others.
- Your code should be designed, written, and debugged by you independently.

Helper Hours

- We will provide good debugging techniques and strategies!
- Come and discuss design tradeoffs!

Recap

- **Recap:** heap allocators so far
- Method 2: Explicit Free List Allocator

Lecture 24 takeaway: The explicit free list allocator uses headers and also stores pointers to free blocks in free block payloads. Allocators can support techniques like realloc-in-place and coalesce-on-free (both only required for your explicit allocator) to try and better handle requests.

Next time: optimization