CS107, Lecture 23
Managing The Heap, Take II

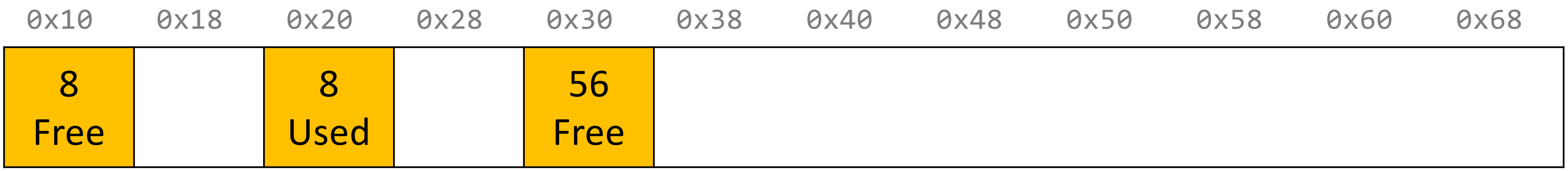
Reading: B&O 9.9 and 9.11

Ed Discussion: https://edstem.org/us/courses/65949/discussion/5698811

Based on slides created by Cynthia Lee, Chris Gregg, Jerry Cain, Lisa Yan, Nick Troccoli, and others.

Can We Do Better?

- It would be nice if we could jump *just between free blocks*, rather than all blocks, to find a block to reuse.
- **Idea:** let’s modify each header to add a pointer to the previous free block and a pointer to the next free block.



0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58 0x60 0x68

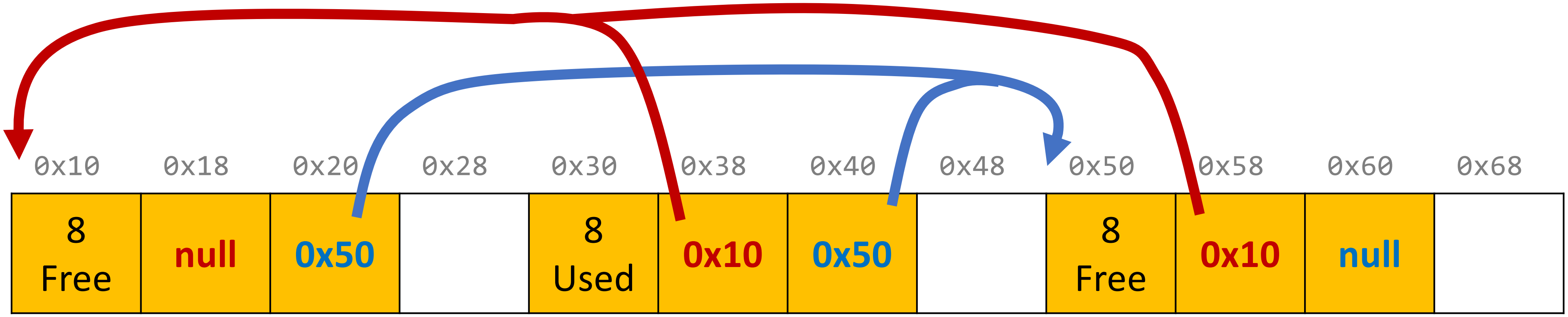
8 Free

8 Used

56 Free

Can We Do Better?

- It would be nice if we could jump *just between free blocks*, rather than all blocks, to find a block to reuse.
- **Idea:** let’s modify each header to add a pointer to the **previous** free block and a pointer to the **next** free block.

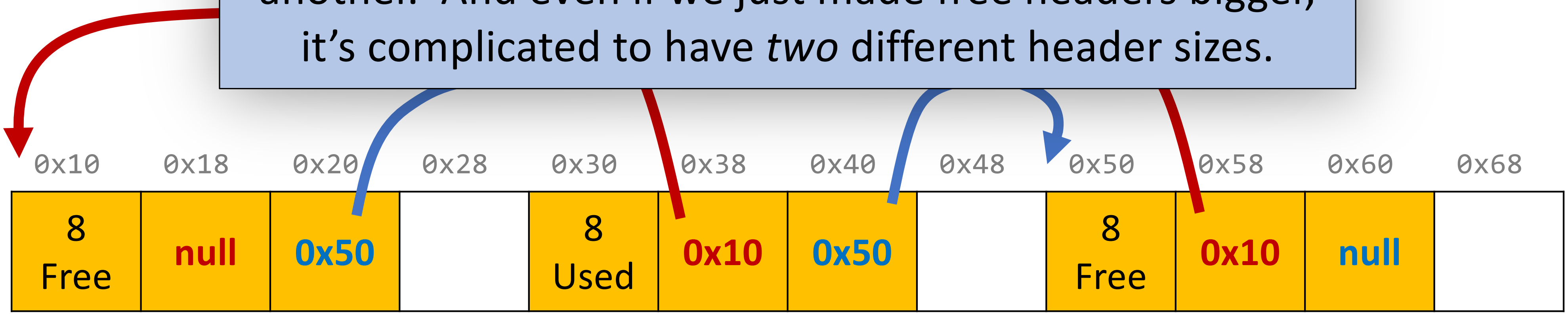


0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60	0x68
8 Free	null	0x50		8 Used	0x10	0x50		8 Free	0x10	null	

Can We Do Better?

- It would be nice if we could jump *just between free blocks*, rather than all blocks, to find a block to reuse.
- **Idea:** let’s modify each header to add a pointer to the **previous** free block and a pointer to the **next** free block.

This is inefficient – it triples the size of *every* header, when we just need to jump from one free block to another. And even if we just made free headers bigger, it’s complicated to have *two* different header sizes.



0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60	0x68
8 Free	null	0x50		8 Used	0x10	0x50		8 Free	0x10	null	

Can We Do Better?

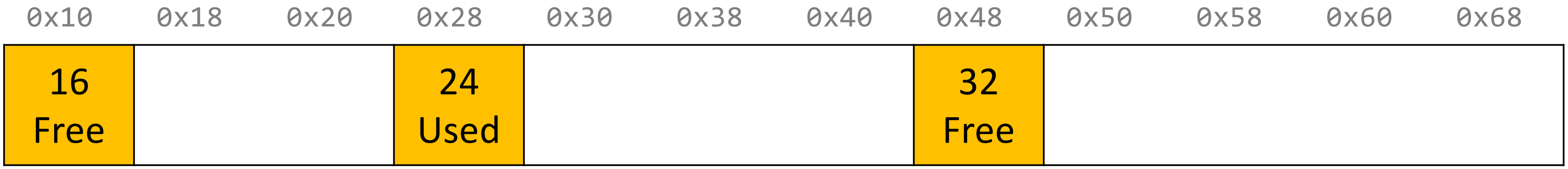
- It would be nice if we could jump *just between free blocks*, rather than all blocks, to find a block to reuse.
- **Idea:** let's modify each header to add a pointer to the previous free block and a pointer to the next free block. *This is inefficient / complicated.*
- **Where can we put these pointers to the next/previous free block?**
- **Idea:** In a separate data structure?

Can We Do Better?

- It would be nice if we could jump *just between free blocks*, rather than all blocks, to find a block to reuse.
- **Idea:** let's modify each header to add a pointer to the previous free block and a pointer to the next free block. *This is inefficient / complicated.*
- **Where can we put these pointers to the next/previous free block?**
- **Idea:** In a separate data structure? *More difficult to access in a separate place – prefer storing near blocks on the heap itself.*

Can We Do Better?

- **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 first 16 bytes of each free block’s payload!



0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60	0x68
16 Free			24 Used				32 Free				

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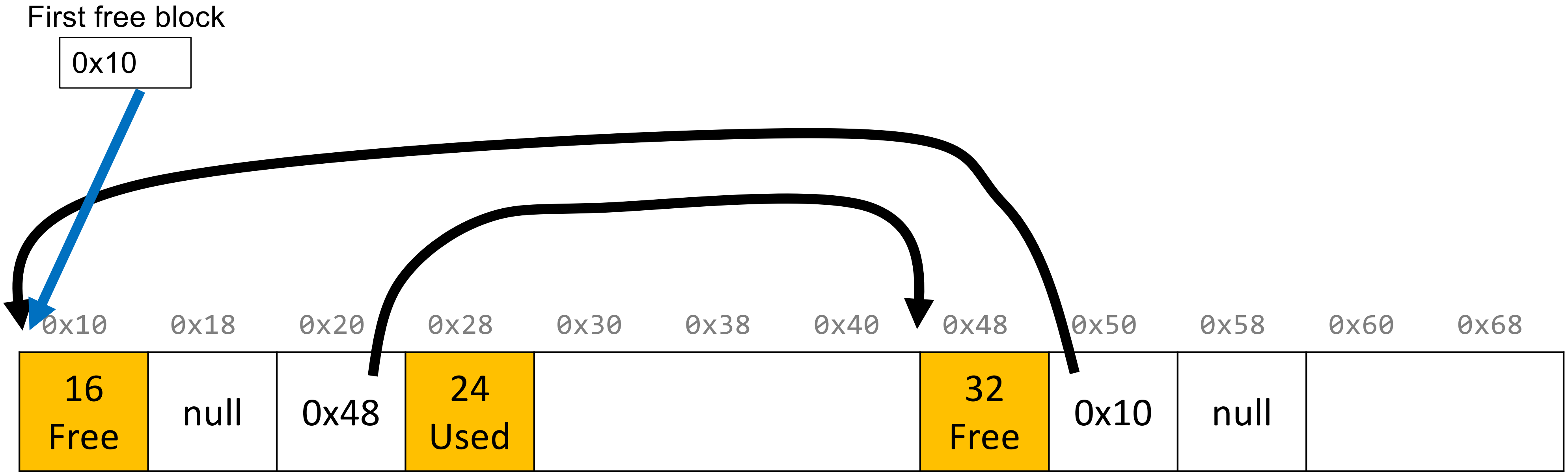
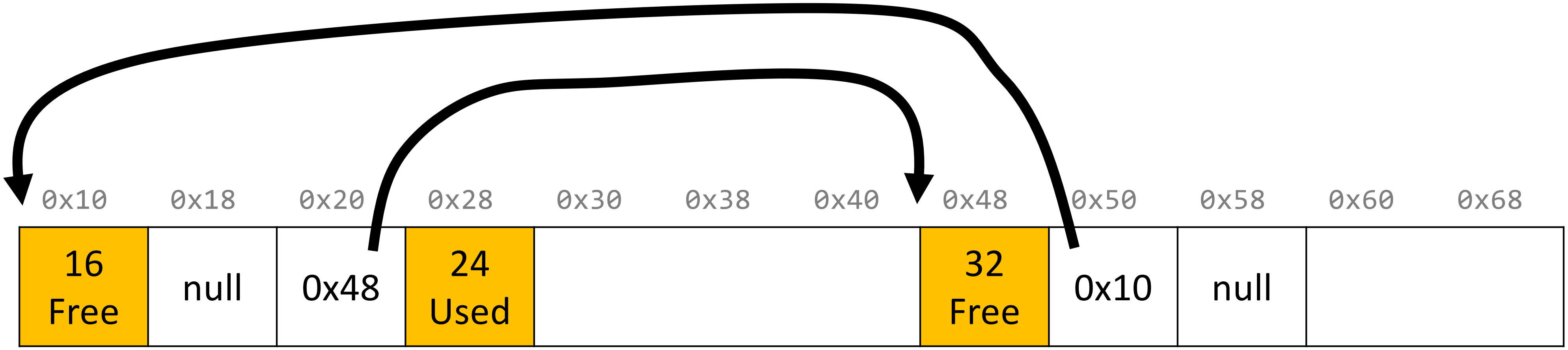


Can We Do Better?

- **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 first 16 bytes of each free block’s payload!
- This means each payload must be big enough to store 2 pointers (16 bytes). So, we must require that for every free block and every allocated one as well.



0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60	0x68
16 Free	null	0x48	24 Used				32 Free	0x10	null		

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: List Design

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

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.)

Up to you!

Better memory utilization, Linear-time free

Constant free (push recent block onto stack)

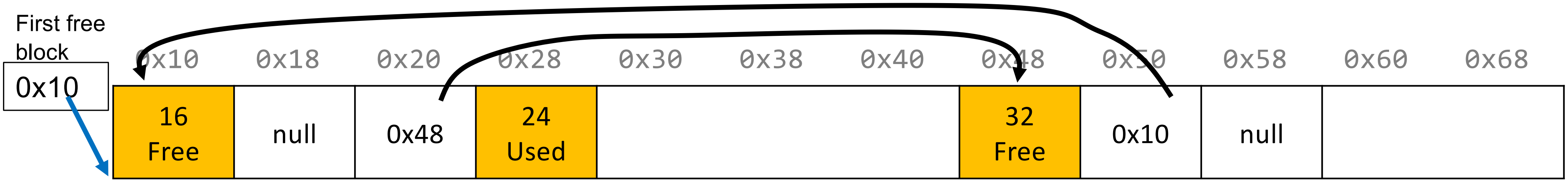
(more at end of lecture)

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



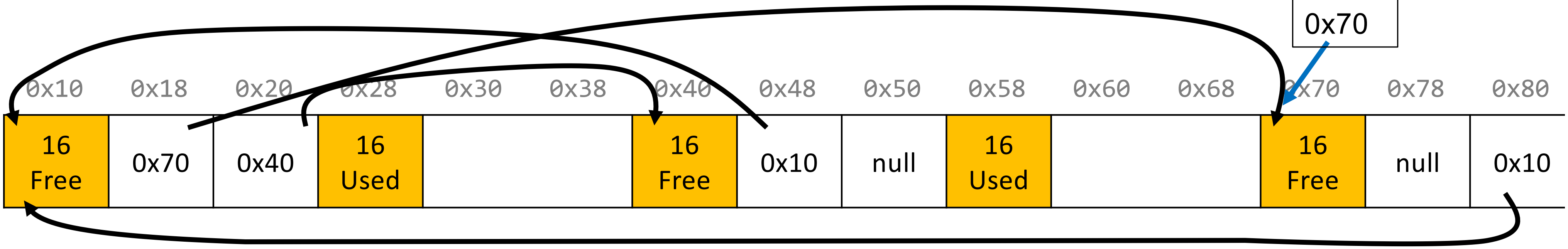
First free block

0x10

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60	0x68
16 Free	null	0x48	24 Used				32 Free	0x10	null		

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

First free block



0x70

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60	0x68	0x70	0x78	0x80
16 Free	0x70	0x40	16 Used			16 Free	0x10	null	16 Used			16 Free	null	0x10

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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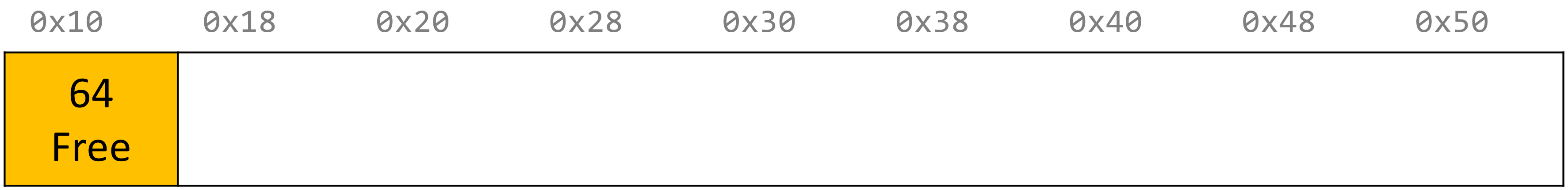
Coalescing

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

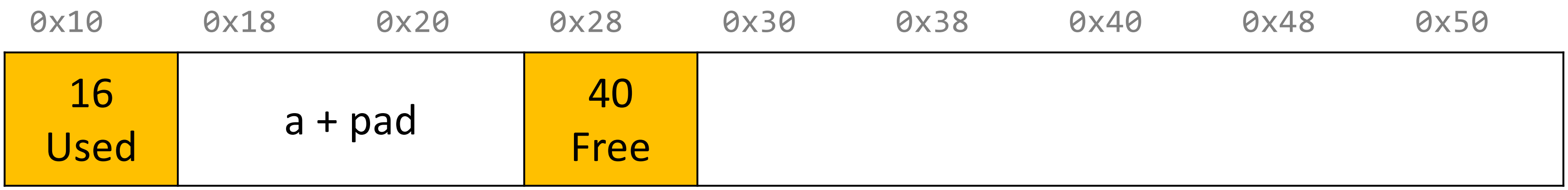


0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50

64
Free

Coalescing

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



0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50

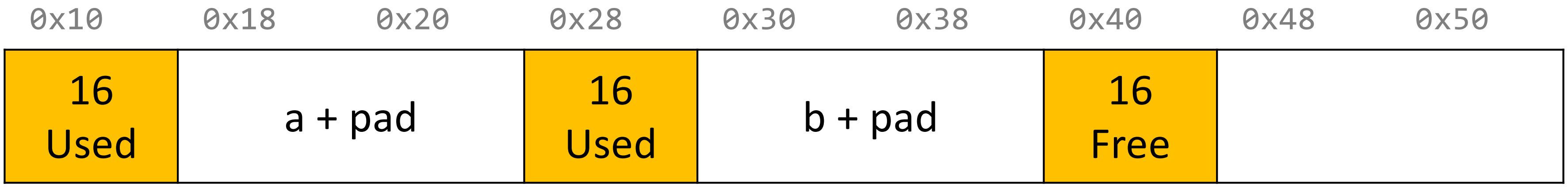
16 Used

a + pad

40 Free

Coalescing

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

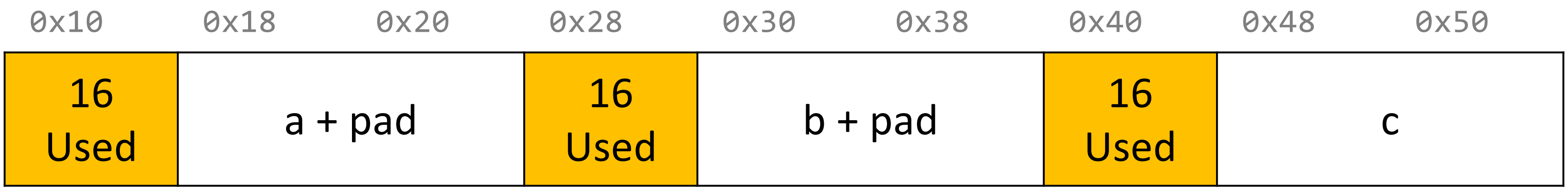


0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50

16
Used | a + pad | 16
Used | b + pad | 16
Free

Coalescing

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



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

Coalescing

```
void *a = malloc(8);
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0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50
16 Used	a + pad		16 Free	b + pad		16 Used	c	

Coalescing

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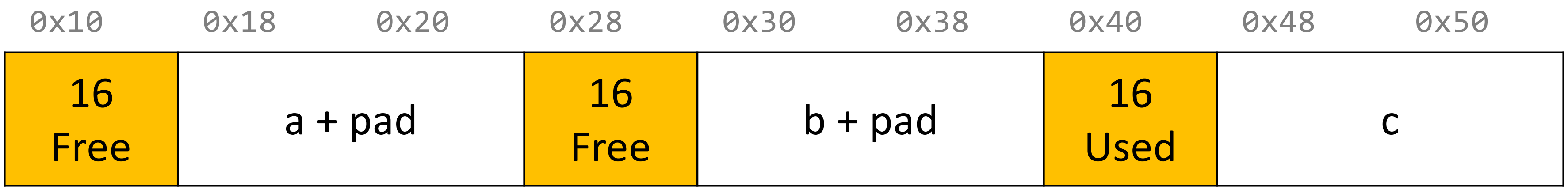

0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50

16 Free

a + pad

16 Free

b + pad

16 Used

c

Coalescing

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

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

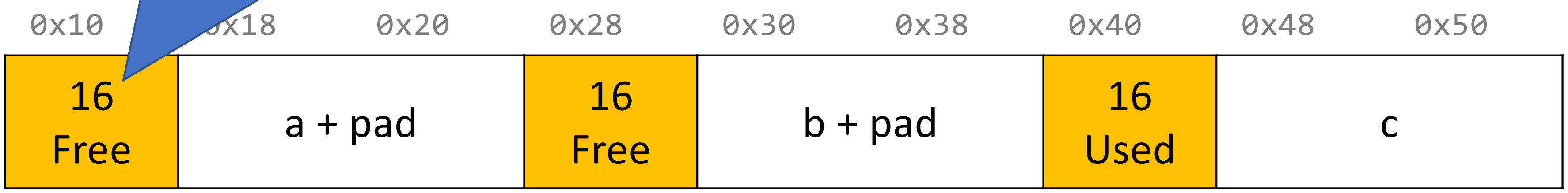
We'd like to be able to merge adjacent free blocks back together. How can we do this?

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

Coalescing

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

Hey, look! I have a free right neighbor. Let's be friends! ☺



Coalescing

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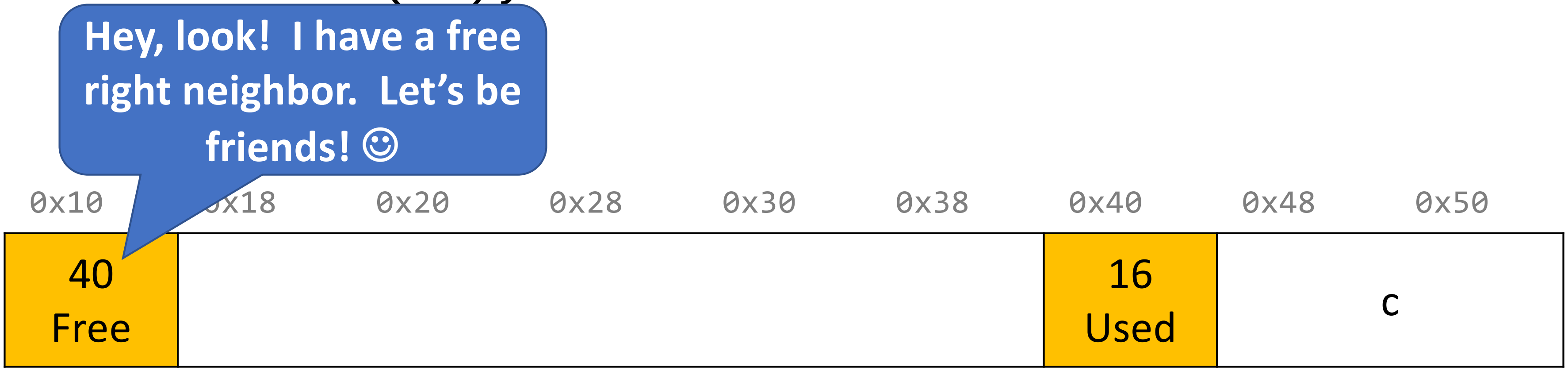

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free(b);
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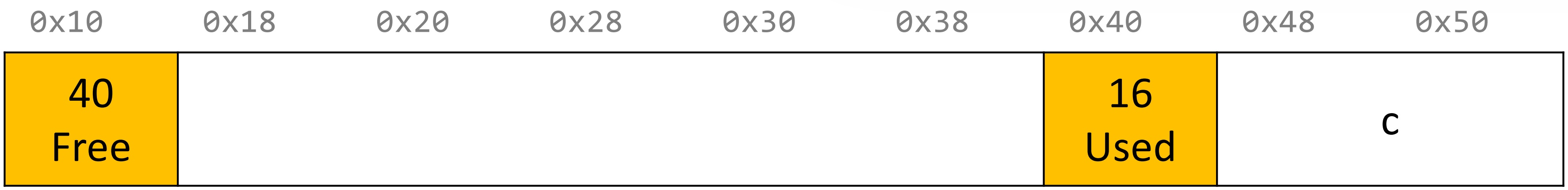
```

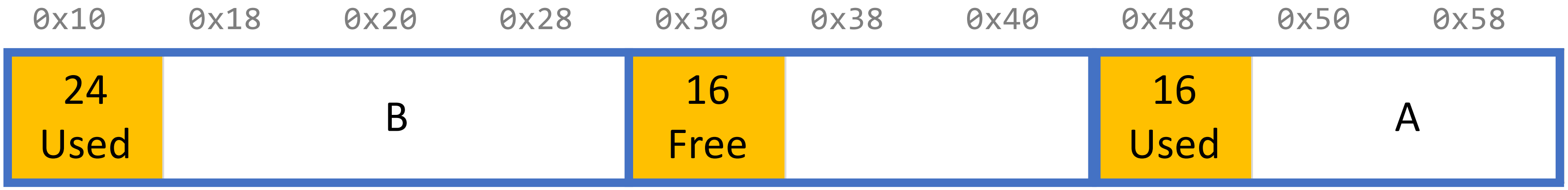
The process of combining adjacent free blocks is called *coalescing*.

For your explicit heap allocator, you should coalesce, if possible, when a block is freed. **You only need to coalesce the most immediate right neighbor.**



Practice 1: Explicit (coalesce)

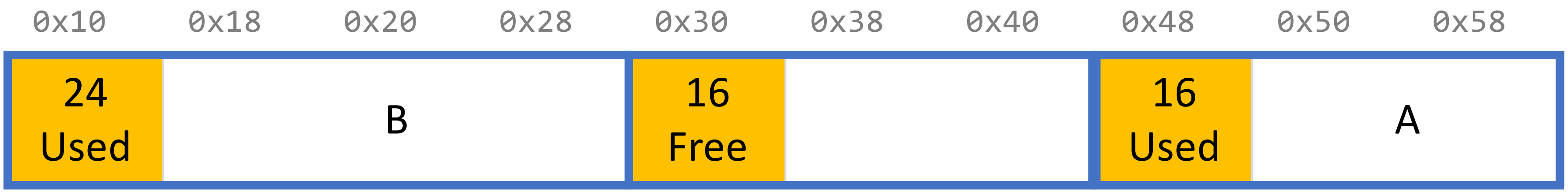
For the following heap layout, what would the heap look like after the following request is made, assuming we are using an explicit free list allocator with a **first-fit** approach and coalesce on free?



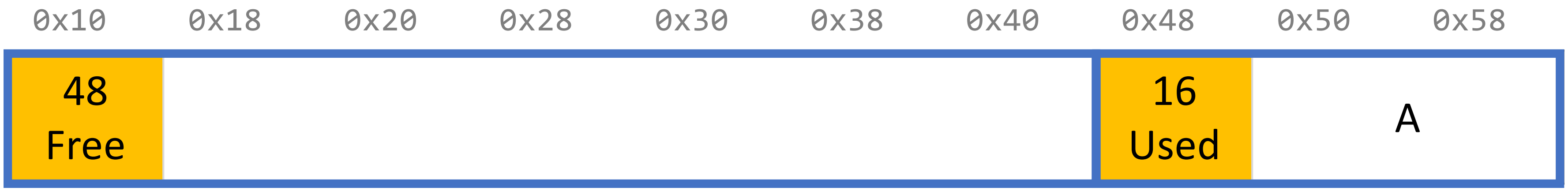
```
free(b);
```

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**?



```
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.**
2. Can we merge adjacent free blocks to keep large spaces available? **Yes! We can try to right-coalesce when calling free.**
3. Can we avoid always copying/moving data during realloc?

Revisiting Our Goals

Can we do better?

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3. **Can we avoid always copying/moving data during realloc?**

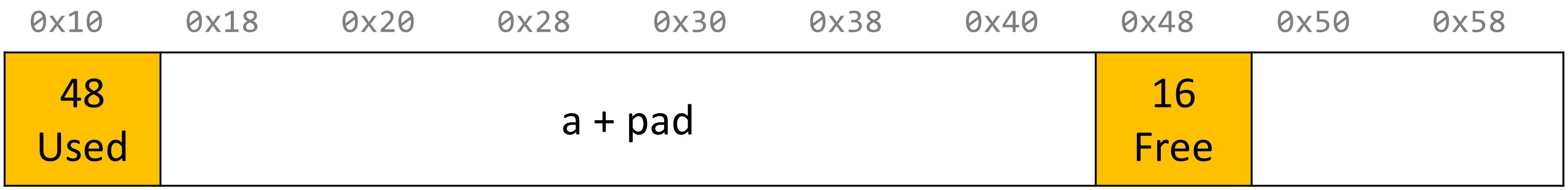
Realloc

- For the implicit allocator, we didn't worry 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.



0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58

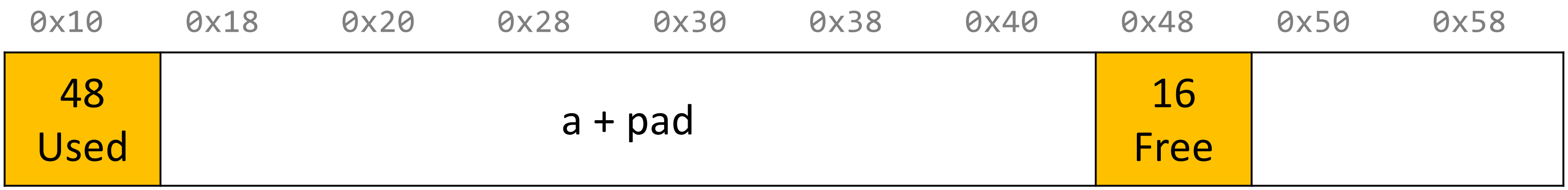
48 Used | a + pad | 16 Free |

Realloc: Growing In Place

```
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.



Realloc: Growing In Place

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

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

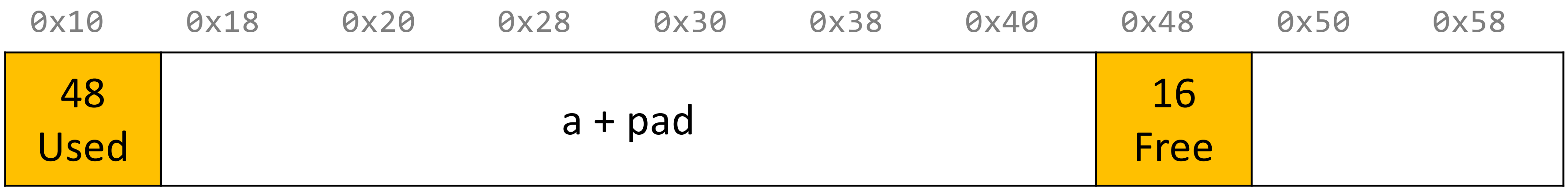
If we can, we should try to recycle the excess memory into another freed block.

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

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!



0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58

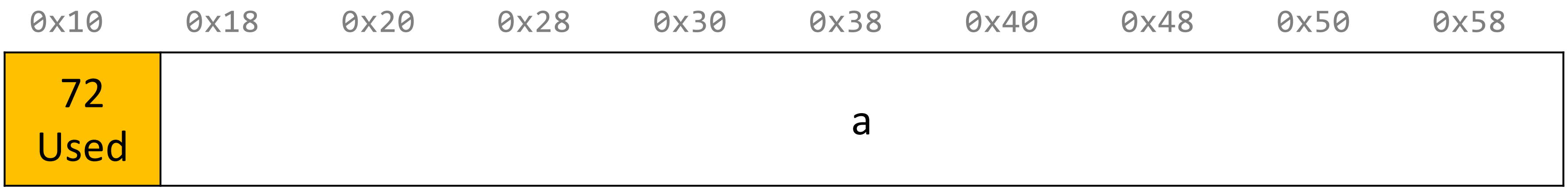
48 Used | a + pad | 16 Free |

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!

Now we can still return the same address.



0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58

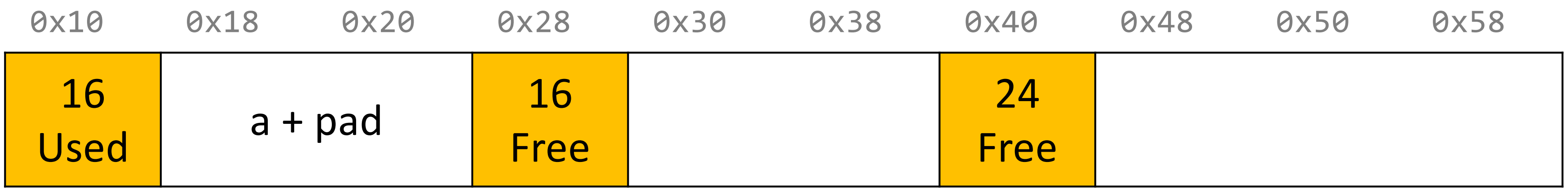
72
Used

a

Realloc: Growing In Place

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

For your project, 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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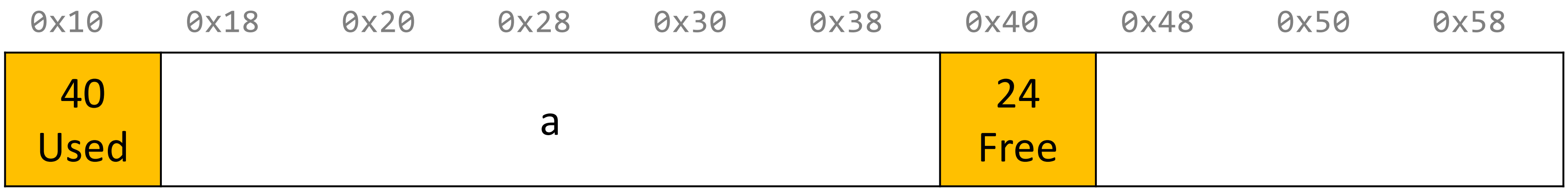


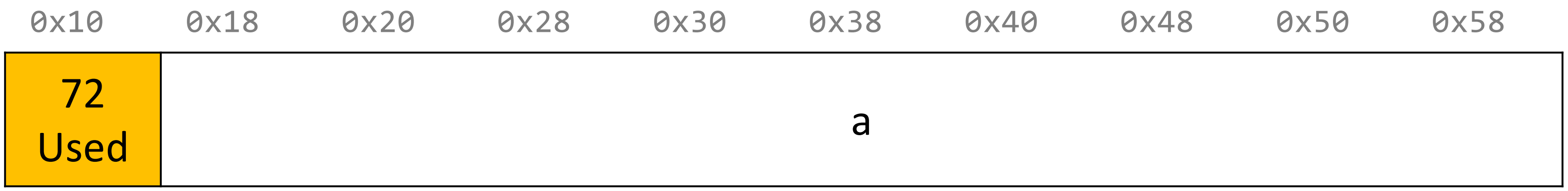
0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58

40 Used | a | 24 Free |

Realloc: Growing In Place

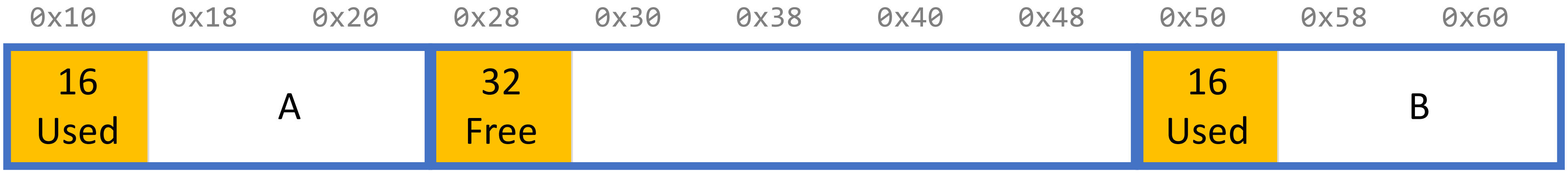
```
void *a = malloc(8);
...
void *b = realloc(a, 72);
```

For your project, 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.



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**?



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

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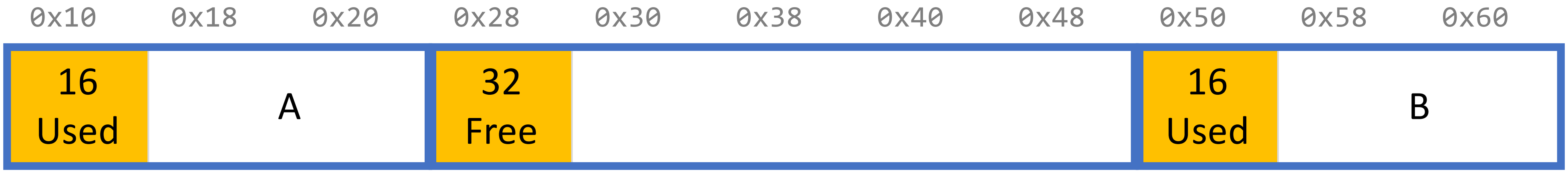
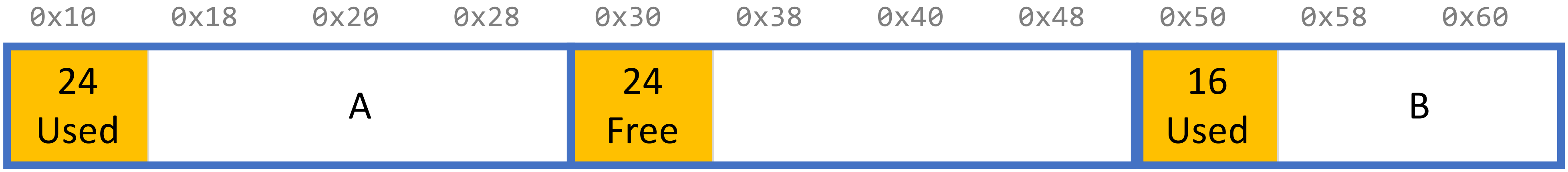


0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58 0x60

16 Used | A | 32 Free | | 16 Used | B

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

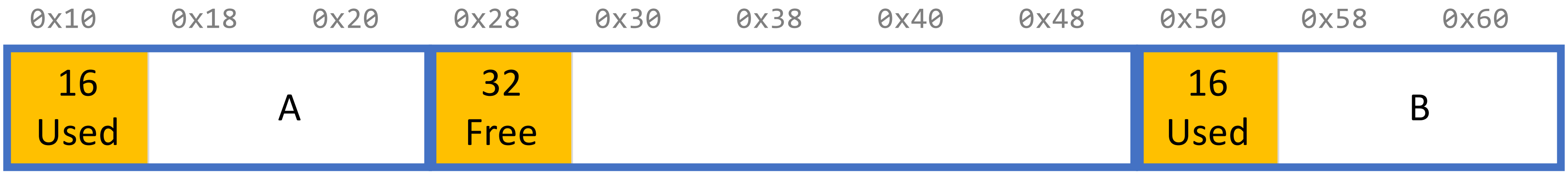


0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58 0x60

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?



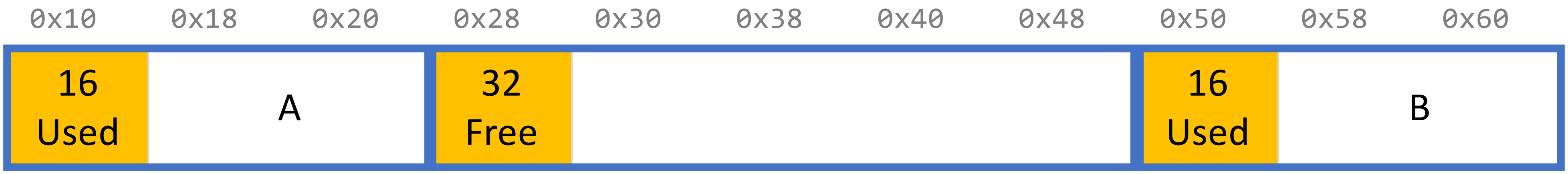
0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58 0x60

16 Used | A | 32 Free | | 16 Used | B

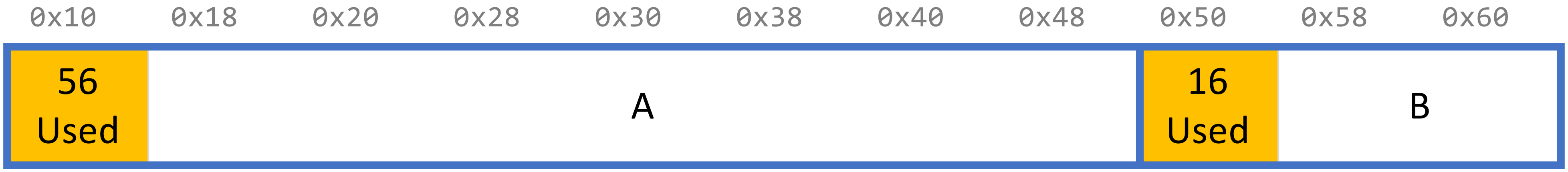
```
realloc(A, 56);
```

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?

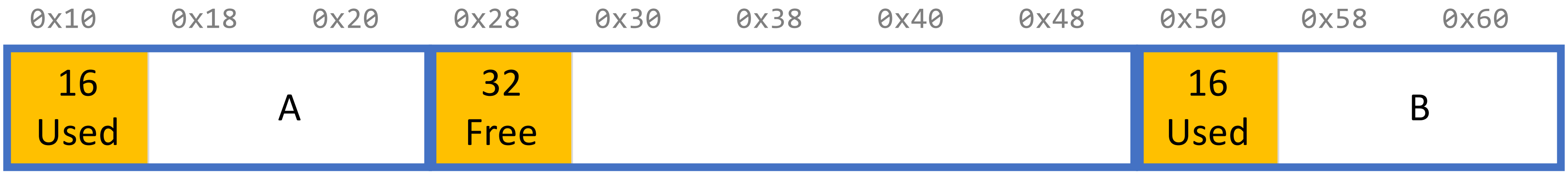


```
realloc(A, 56);
```



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**?

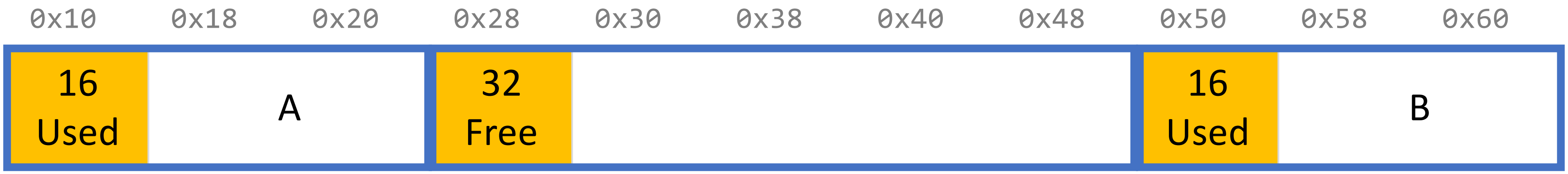


0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60
16 Used	A		32 Free					16 Used	B	

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

Practice 3: Explicit (realloc)

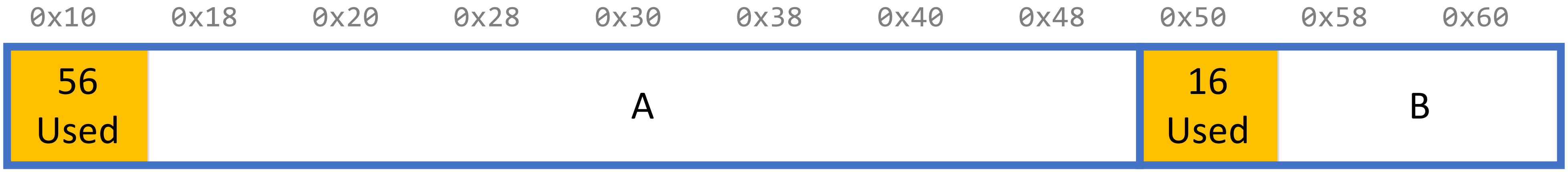
For the following heap layout, what would the heap look like after the following request is made, assuming we are using an **explicit** free list allocator with a **first-fit** approach and **coalesce on free + realloc in-place**?



0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58 0x60

16 Used | A | 32 Free | | 16 Used | B

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

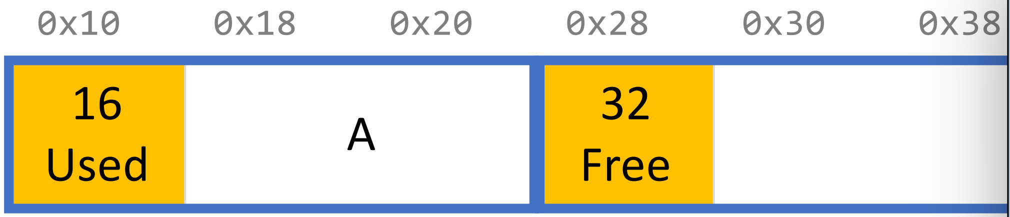


0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58 0x60

56 Used | A | 16 Used | B

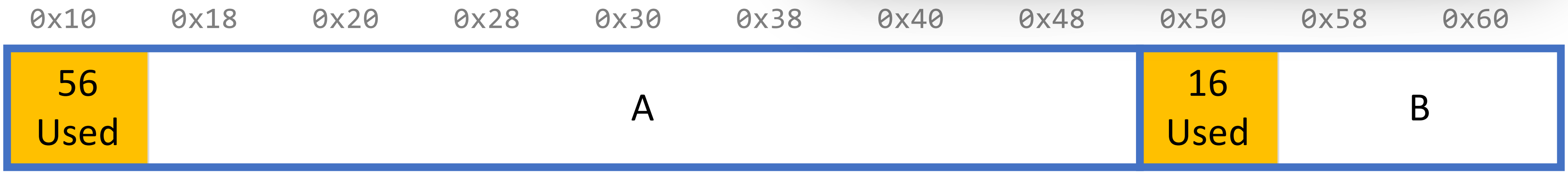
Practice 3: Explicit (realloc)

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?



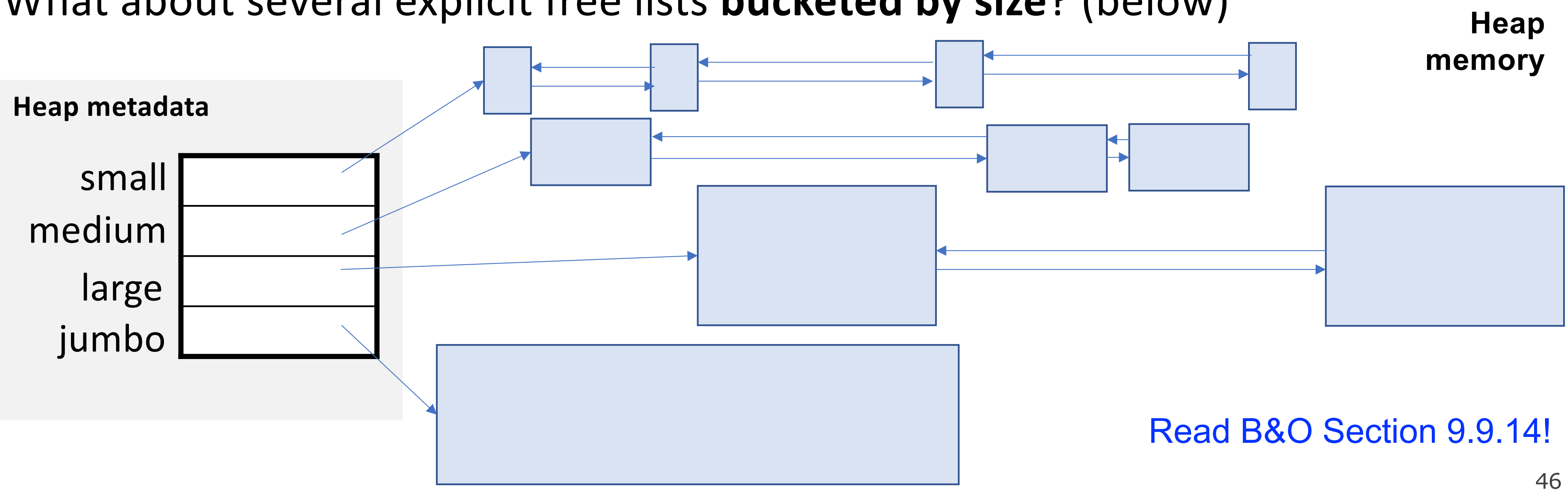
For the explicit allocator, note that we can't have payload less than 16 bytes, so here the only option for the leftover 8 bytes is to use it as padding for the existing block.

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



Going beyond: Explicit list w/size buckets

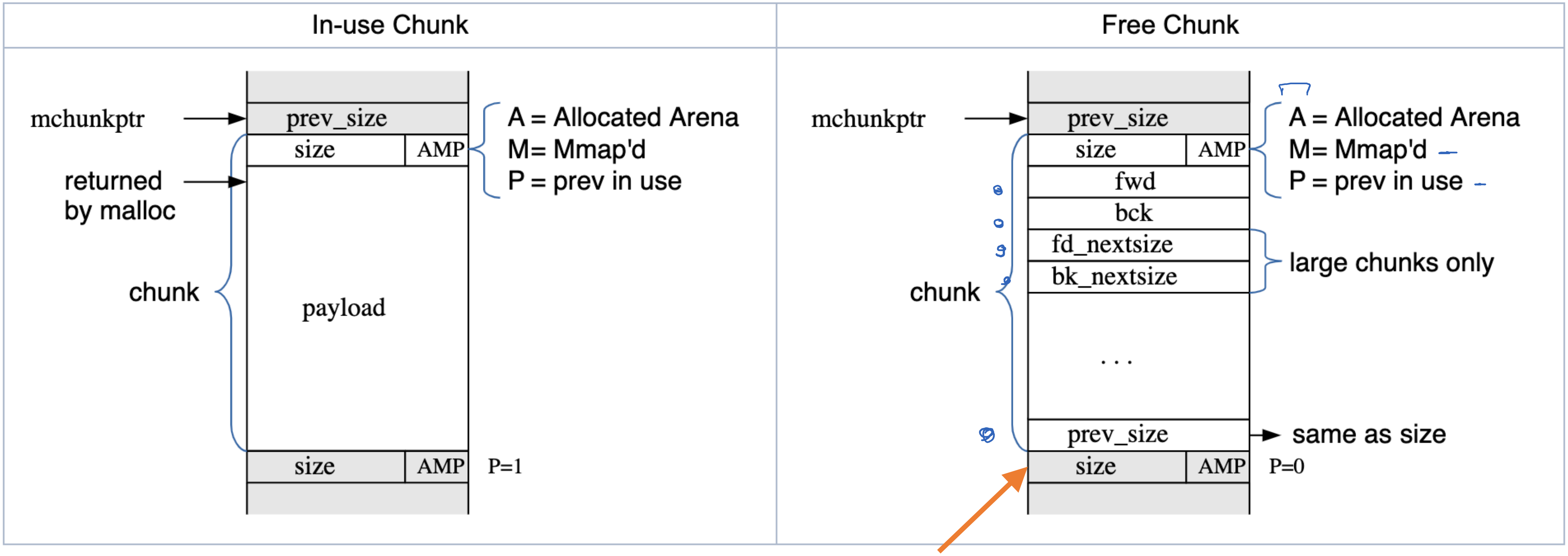
- Explicit lists are much faster than implicit lists.
- However, a first-fit placement policy is still linear in total # of free blocks.
- What about an explicit free list **sorted by size** (e.g., as a tree)?
- What about several explicit free lists **bucketed by size**? (below)



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.
- **Must** do in-place realloc when possible. 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.