CS107, Lecture 16
Heap Allocators

Reading: B&O 9.9, 9.11

Attendance

https://forms.gle/KwgK9A2KP3eF7APd7

Recap: Heap Allocator Goals

- Goal 1: Maximize **throughput**, or the number of requests completed per unit time. This means minimizing the average time to satisfy a request.

- Goal 2: Maximize memory **utilization**, or how efficiently we make use of the limited heap memory to satisfy requests.

Recap: Fragmentation

- The primary cause of poor utilization is **fragmentation**. **Fragmentation** occurs when otherwise unused memory is not available to satisfy allocation requests.

  - **External Fragmentation**: no single space is large enough to satisfy a request, even though enough aggregate free memory is available

  - **Internal Fragmentation**: space allocated for a block is larger than needed (more later).

Lecture Plan

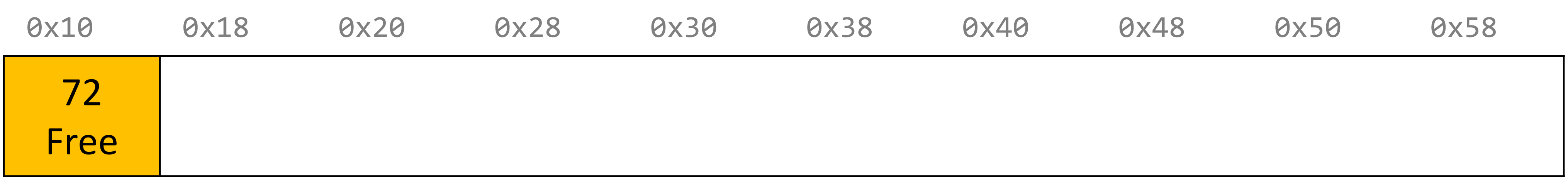
- **Method 1: Implicit Free List Allocator**
- Method 2: Explicit Free List Allocator

Implicit Free List Allocator

- **Key idea:** in order to reuse blocks, we need a way to track which blocks are allocated and which are free.
- We could store this information in a separate global data structure, but this is inefficient.
- Instead: let's allocate extra space before each block for a **header** storing its payload size and whether it is allocated or free.
- When we allocate a block, we look through the blocks to find a free one, and we update its header 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.
- The header should be 8 bytes (or larger).
- By storing the block size of each block, we *implicitly* have a *list* of free blocks.

Implicit Free List Allocator

```
void *a = malloc(4);
void *b = malloc(8);
void *c = malloc(4);
free(b);
void *d = malloc(8);
free(a);
void *e = malloc(24);
```



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```

Variable	Value
a	0x18

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
8 Used	a + pad	56 Free							

Implicit Free List Allocator

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Variable	Value
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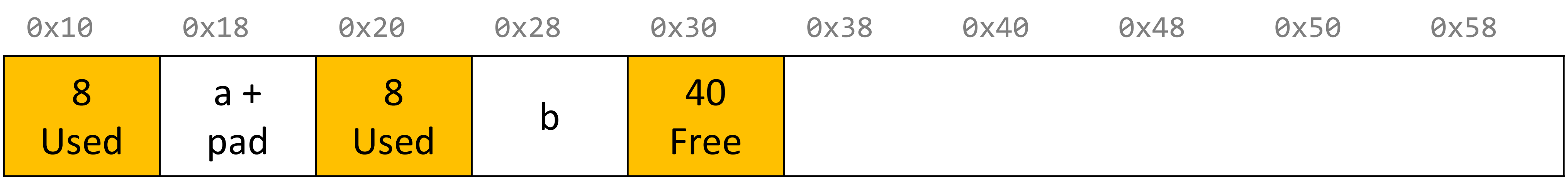

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8 Free	a + pad	8 Used	d	8 Used	c + pad	24 Used	e		

Representing Headers

How can we store both a size and a status (Free/Allocated) in 8 bytes?

Int for size, int for status? **no! malloc/realloc use size_t for sizes!**

Key idea: block sizes will *always be multiples of 8*. (Why?)

- Least-significant 3 bits will be unused!
- *Solution:* use one of the 3 least-significant bits to store free/allocated status

Implicit Free List Allocator

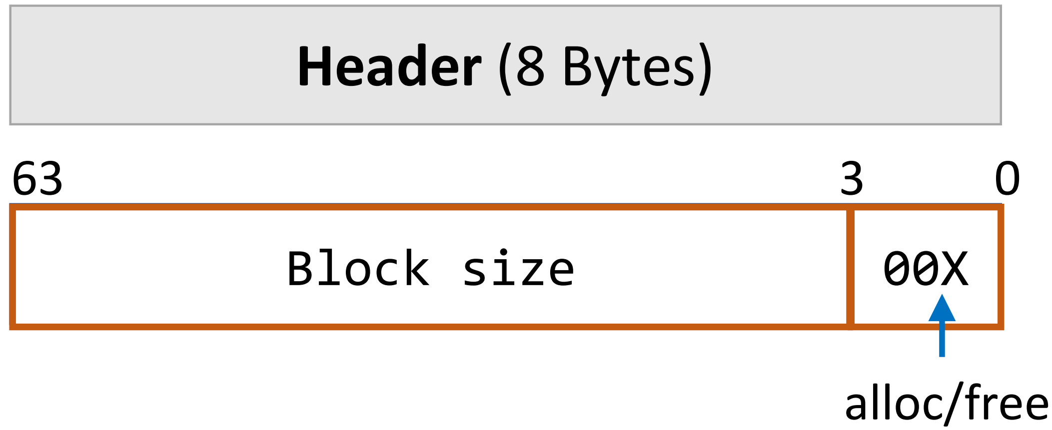
- How can we choose a free block to use for an allocation request?
  - **First fit:** search the list from beginning each time and choose first free block that fits.
  - **Next fit:** instead of starting at the beginning, continue where previous search left off.
  - **Best fit:** examine every free block and choose the one with the smallest size that fits.

- First fit/next fit easier to implement
- What are the pros/cons of each approach?

Implicit Free List Summary

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 ☺

Up to you!

Implicit free list header design

Should we store the **block size** as
(A) payload size, or
(B) header + payload size?

Up to you! Your decision affects how you traverse the list (be careful of off-by-one)

Up to you!

Splitting Policy

```
...
void *e = malloc(16);
```

So far, we have seen that a reasonable allocation request splits a free block into an allocated block and a free block with remaining space. **What about edge cases?**

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
8 Free	a + pad	8 Used	d	8 Used	c + pad	24 Free			

Up to you!

Splitting Policy

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0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
8 Free	a + pad	8 Used	d	8 Used	c + pad	16 Used	e		???

Up to you!

Splitting Policy

```
...
void *e = malloc(16);
```

So far, we have seen that a reasonable allocation request splits a free block into an allocated block and a free block with remaining space. **What about edge cases?**

A. Throw into allocation for e as extra padding? *Internal fragmentation – unused bytes because of padding*

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
8 Free	a + pad	8 Used	d	8 Used	c + pad	24 Used	e + pad		

Up to you!

Splitting Policy

```
...
void *e = malloc(16);
```

So far, we have seen that a reasonable allocation request splits a free block into an allocated block and a free block with remaining space. **What about edge cases?**

A. Throw into allocation for e as extra padding?

B. Make a “zero-byte free block”? *External fragmentation – unused free blocks*

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
8 Free	a + pad	8 Used	d	8 Used	c + pad	16 Used	e		0 Free

Revisiting Our Goals

Questions we considered:

1. How do we keep track of free blocks? **Using headers!**
2. How do we choose an appropriate free block in which to place a newly allocated block? **Iterate through all blocks.**
3. After we place a newly allocated block in some free block, what do we do with the remainder of the free block? **Try to make the most of it!**
4. What do we do with a block that has just been freed? **Update its header!**

Practice 1: Implicit (first-fit)

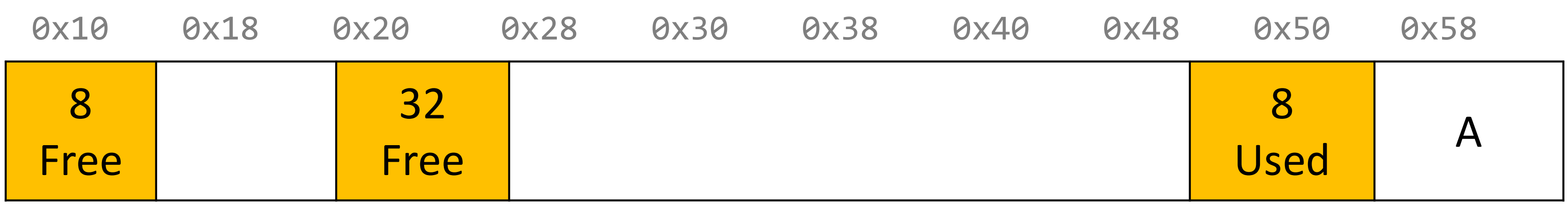
For the following heap layout, what would the heap look like after the following request is made, assuming we are using an **implicit** free list allocator with a **first-fit** approach?

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
8 Free		32 Free						8 Used	A

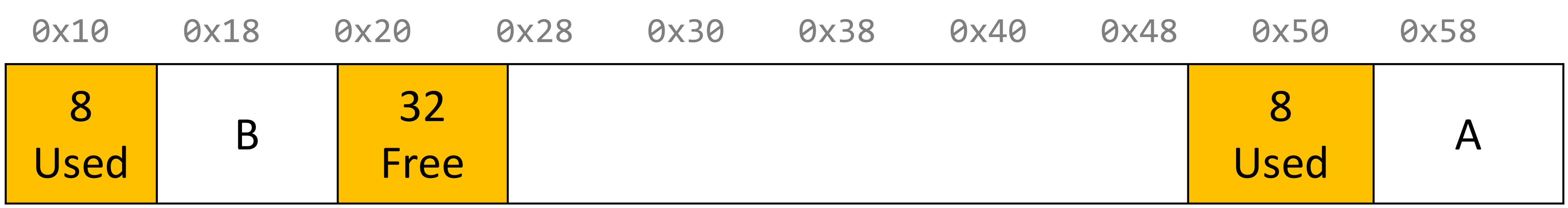
```
void *b = malloc(8);
```

Practice 1: Implicit (first-fit)

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

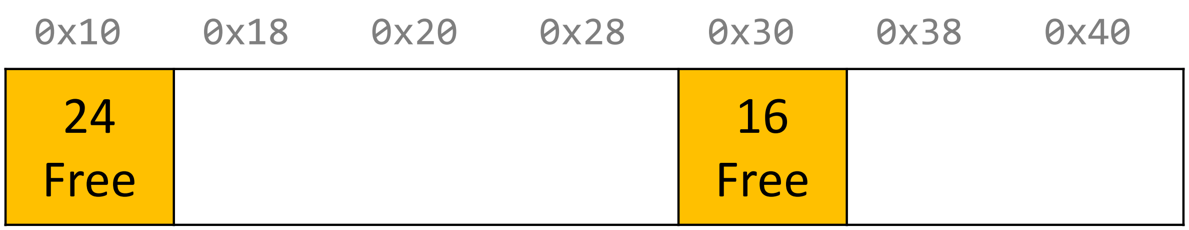



```
void *b = malloc(8);
```



Practice 2: Implicit (first-fit)

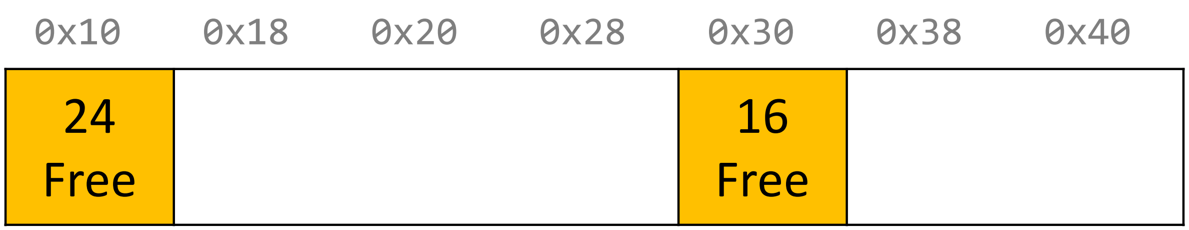
For the following heap layout, what would the heap look like after the following request is made, assuming we are using an **implicit** free list allocator with a **first-fit** approach?



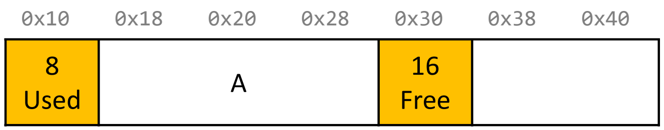

```
void *a = malloc(8);
```

Practice 2: Implicit (first-fit)

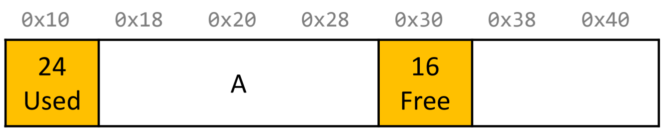
For the following heap layout, what would the heap look like after the following request is made, assuming we are using an **implicit** free list allocator with a **first-fit** approach?



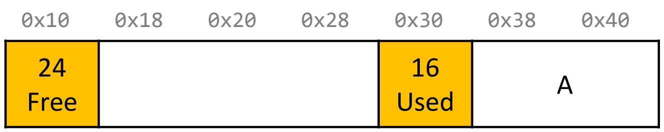

```
void *a = malloc(8);
```



✗ *Space not tracked correctly*



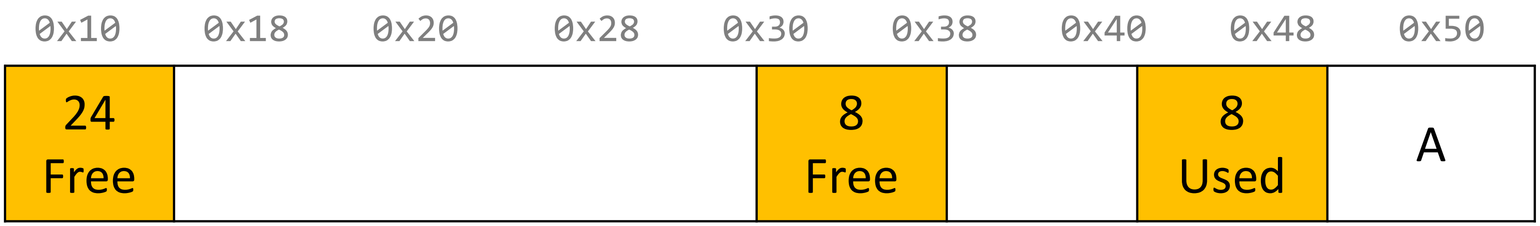
✗ *We can save extra for later*



✗ *First fit chooses first available*

Practice 3: Implicit (best-fit)

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




```
void *b = malloc(8);
```

Practice 3: Implicit (best-fit)

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

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

24 Free		8 Free		8 Used	A

```
void *b = malloc(8);
```

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

24 Free		8 Used	B	8 Used	A

Final Assignment: Implicit Allocator

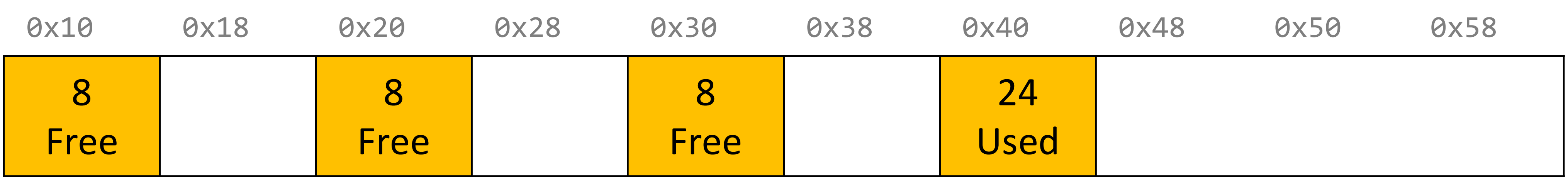
- **Must have** headers that track block information (size, status in-use or free) – you must use the 8 byte header size, storing the status using the free bits (this is larger than the 4 byte headers specified in the book, as this makes it easier to satisfy the alignment constraint and store information).
- **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)*

Coalescing

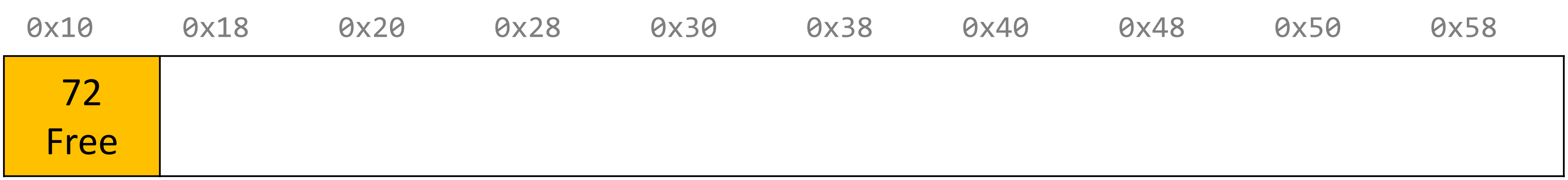
```
void *e = malloc(24);   // returns NULL!
```



Coalescing

```
void *a = malloc(4);
```

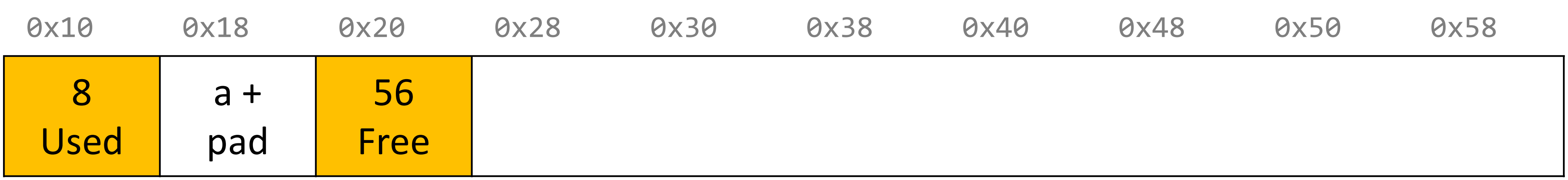
You do not need to worry about this problem for the implicit allocator, but this is a requirement for the *explicit* allocator! (More about this later).



Realloc

```
void *a = malloc(4);
void *b = realloc(a, 8);
```

Variable	Value
a	0x18



Realloc

```
void *a = malloc(4);
void *b = realloc(a, 8);
```

Variable	Value
a	0x10
b	0x28

The implicit allocator can always move memory to a new location for a realloc request. The *explicit* allocator must support in-place realloc (more on this later).

0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
8 Free	a + pad	8 Used	b	40 Free					

Summary: Implicit Allocator

An implicit allocator is a more efficient implementation that has reasonable **throughput** and **utilization** due to its recycling of blocks.

Can we do better?

1. Can we avoid searching all blocks for free blocks to reuse?
2. Can we merge adjacent free blocks to keep large spaces available?
3. Can we avoid always copying/moving data during realloc?

Checkpoint Review

Heap allocator terminology: What do the below terms mean/imply?

- Payload, Header, Free/Used(Allocated) status
- Splitting policy
- Memory utilization vs Throughput
- Bump allocator, Implicit free list Allocator
- First-fit approach, Best-fit approach
- Coalescing
- Realloc in place
- Fragmentation

Lecture Plan

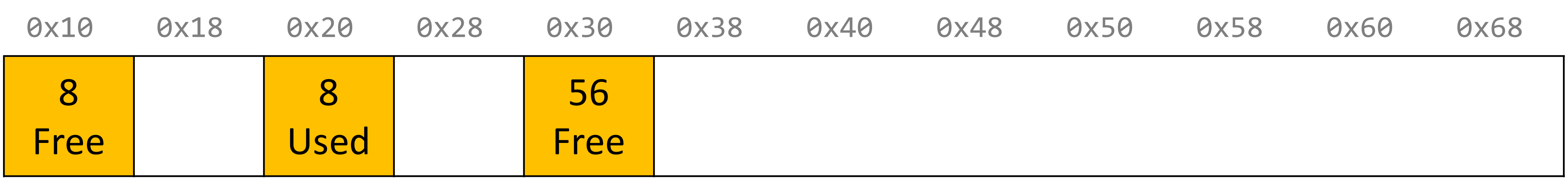
- Method 1: Implicit Free List Allocator
- **Method 2: Explicit Free List Allocator**

Lecture Plan

- Method 1: Implicit Free List Allocator
- **Method 2: Explicit Free List Allocator**
  - **Explicit Allocator**
  - Coalescing
  - In-place realloc

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.



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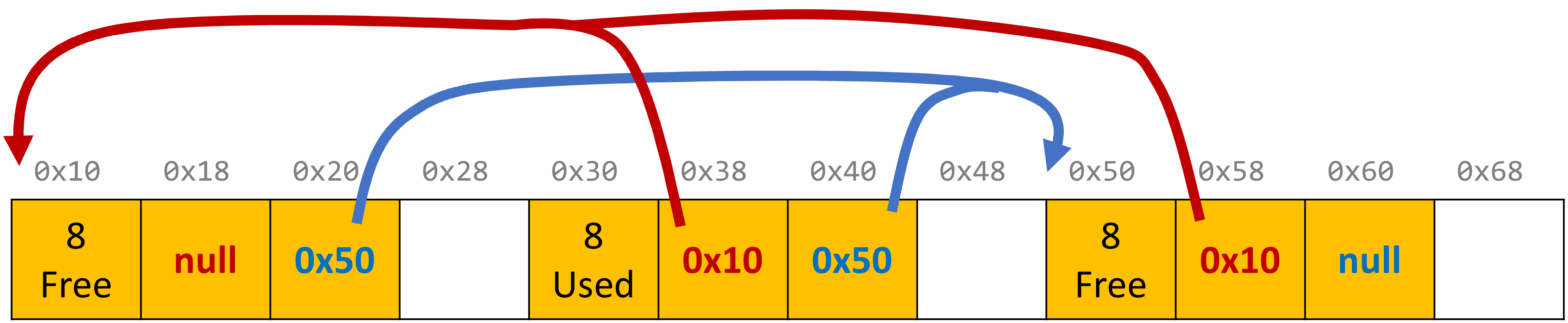

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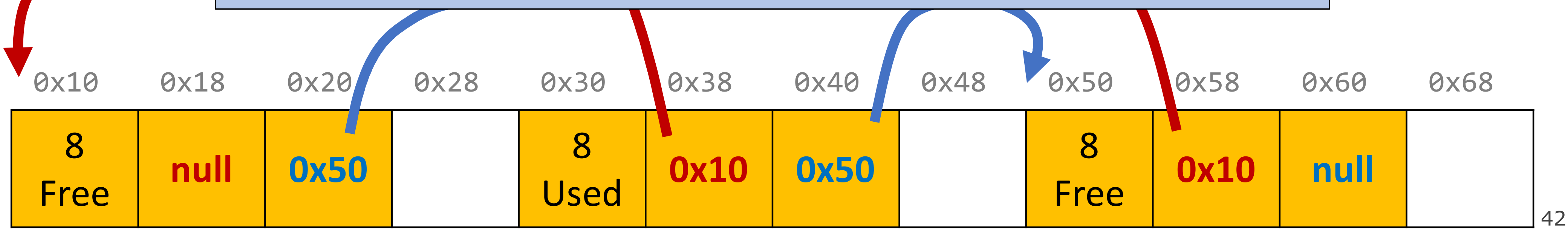
This is inefficient – it triples the size of *every* header, when we just need to jump from one free block to another. And even if we just made free headers bigger, it's complicated to have *two* different header sizes.



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- **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?

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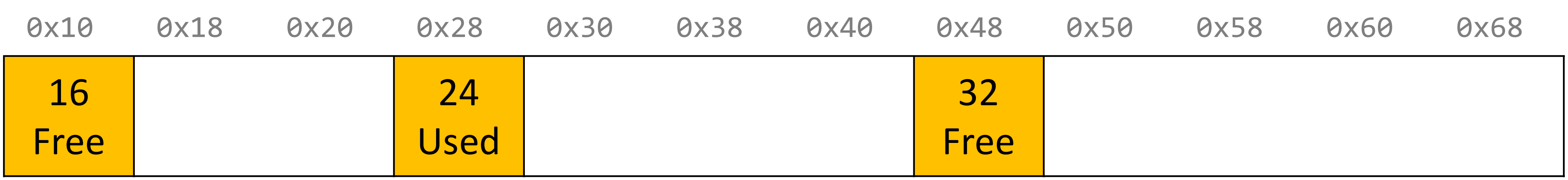
- **Idea:** let's modify each header to add a pointer to the previous free block and a pointer to the next free block. *This is inefficient / complicated.*
- **Where can we put these pointers to the next/previous free block?**
- **Idea:** In a separate data structure? *More difficult to access in a separate 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 <u>first 16 bytes of each free block's payload!</u>



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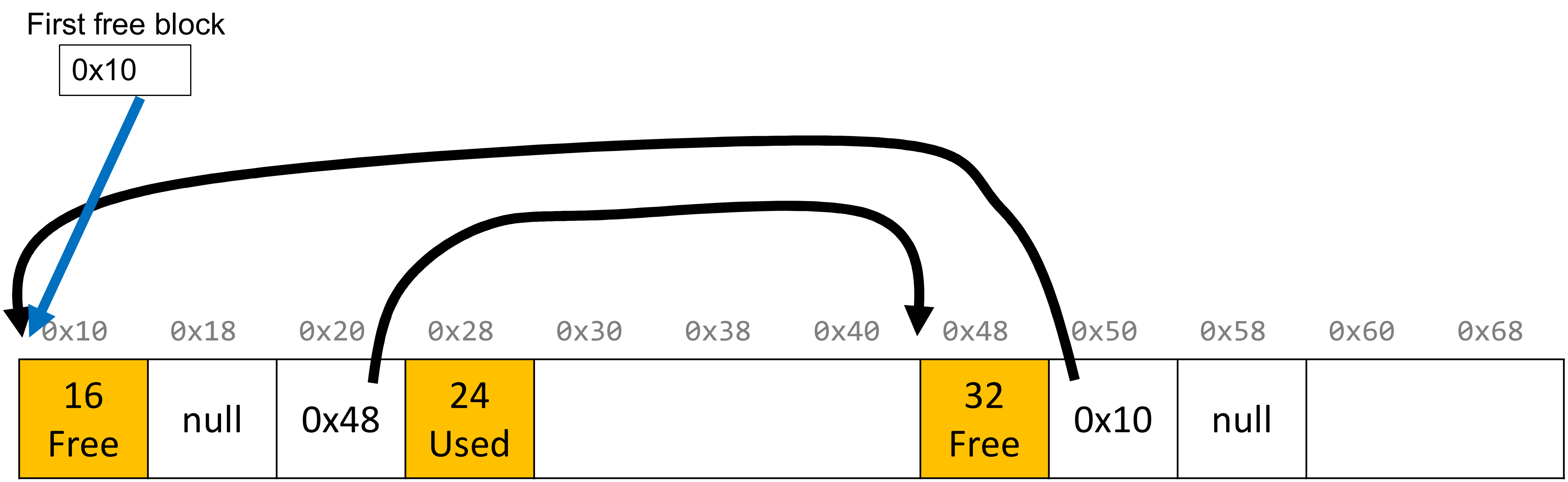

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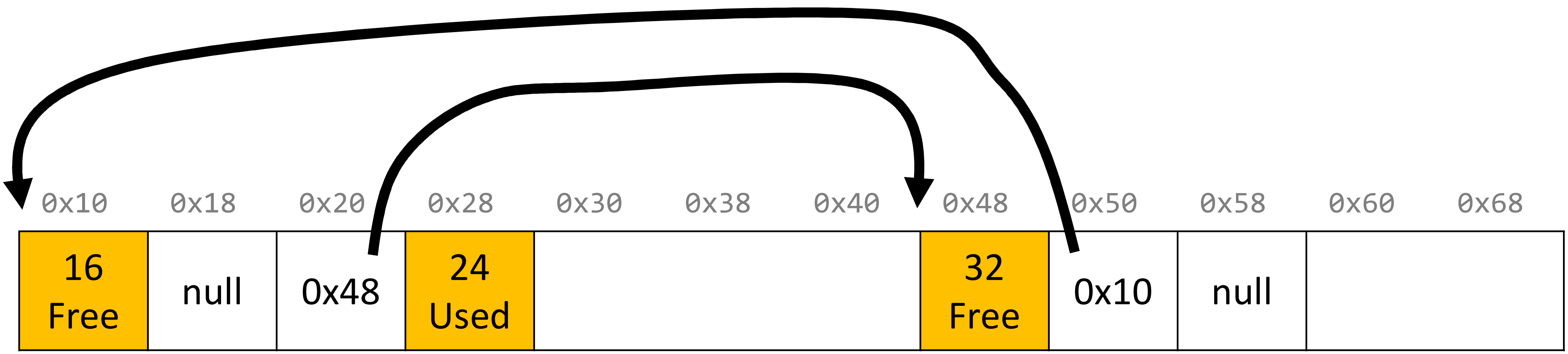
- **Key Insight:** the payloads of the free blocks aren't being used, because they're free.
- **Idea:** since we only need to store these pointers for free blocks, let's store them in the first 16 bytes of each free block's payload!
- This means each payload must be big enough to store 2 pointers (16 bytes). So we must require that for every block, free and allocated. (why?)



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 util, Linear free

Constant free (push recent block onto stack)

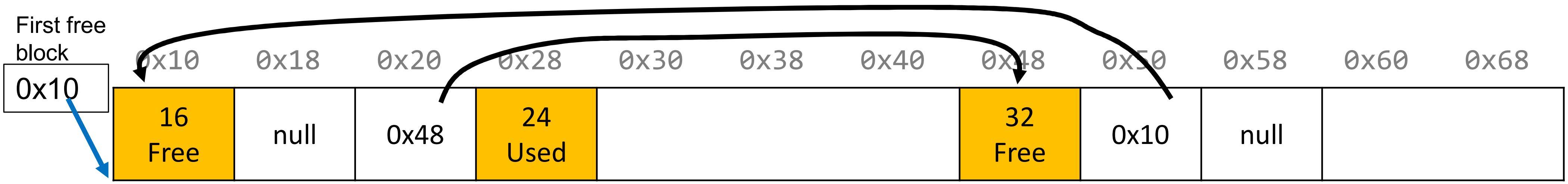
(more at end of lecture)

Explicit free list design

Up to you!

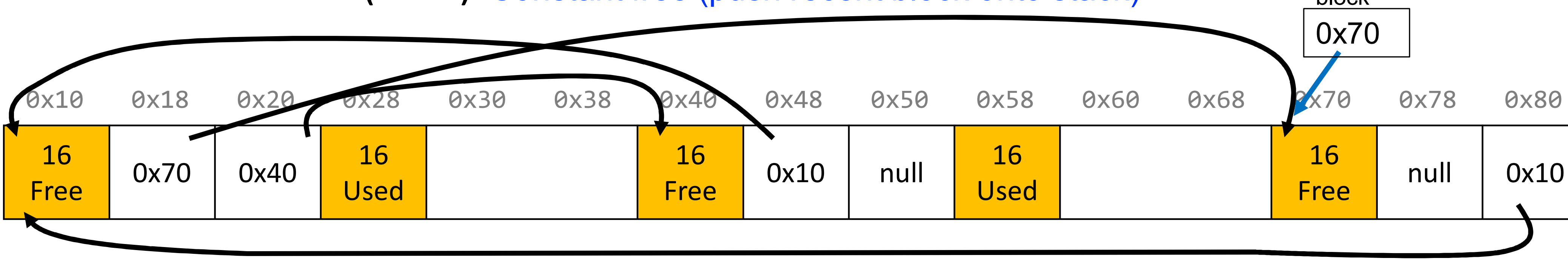
How do you want to organize your explicit free list?(utilization/throughput)

A. Address-order Better memory util, linear free



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

First free block



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?

Revisiting Our Goals

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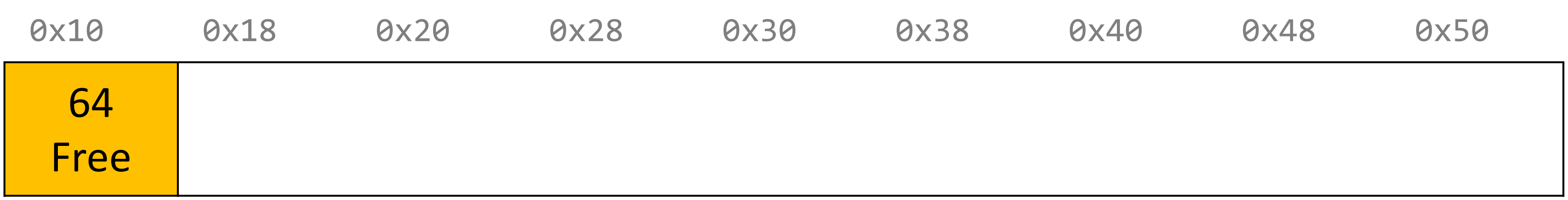
Lecture Plan

- Method 1: Implicit Free List Allocator
- **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);
```



Coalescing

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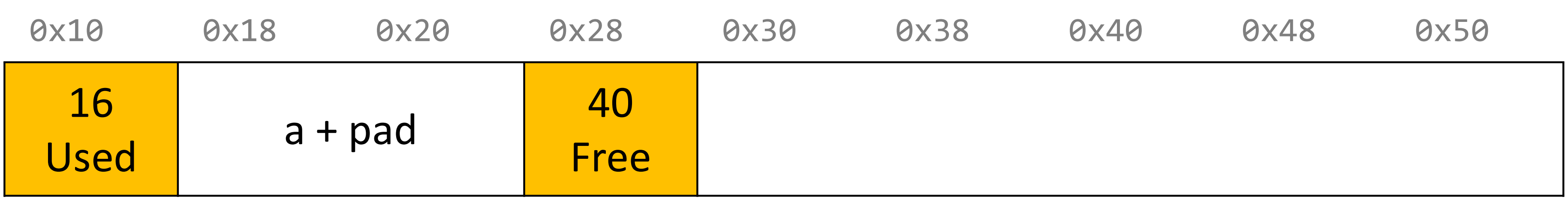
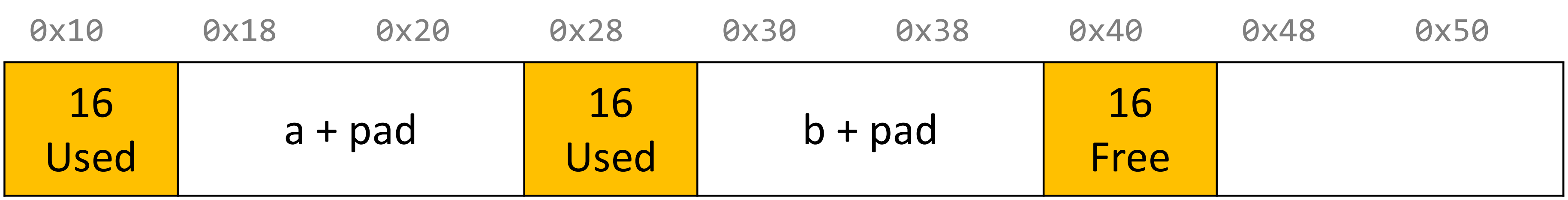



Coalescing

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



Coalescing

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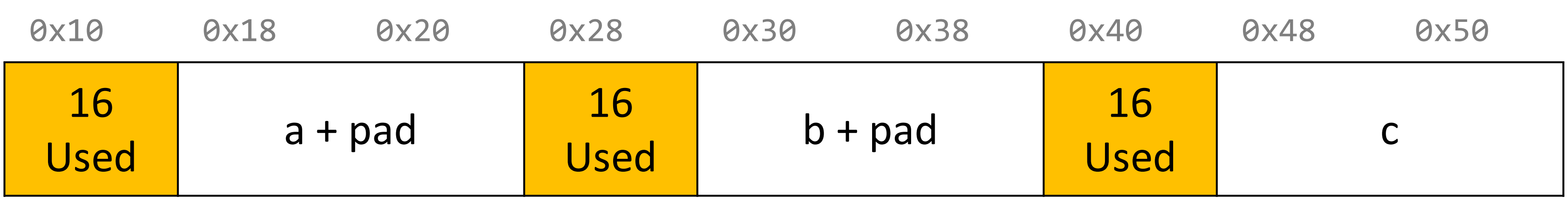



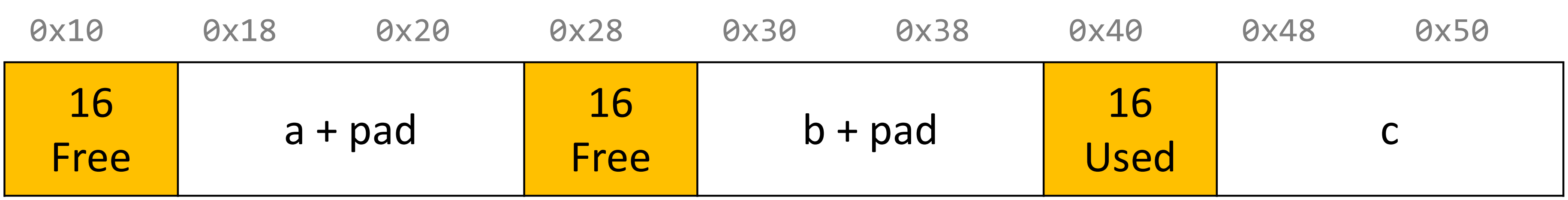
Coalescing

```
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
16 Used	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);
```

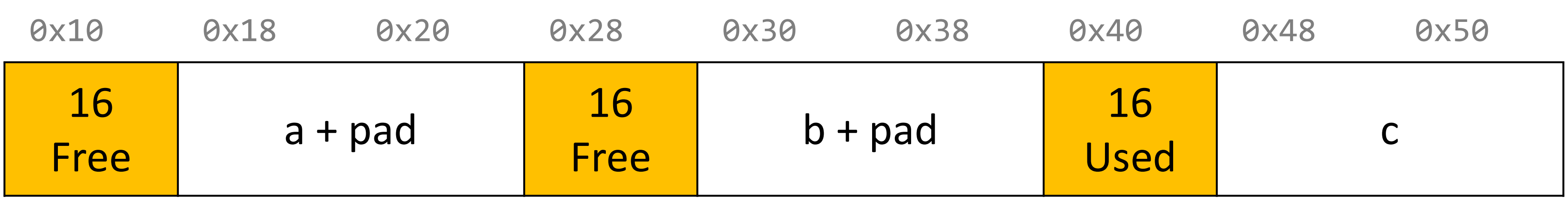


Coalescing

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



Coalescing

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

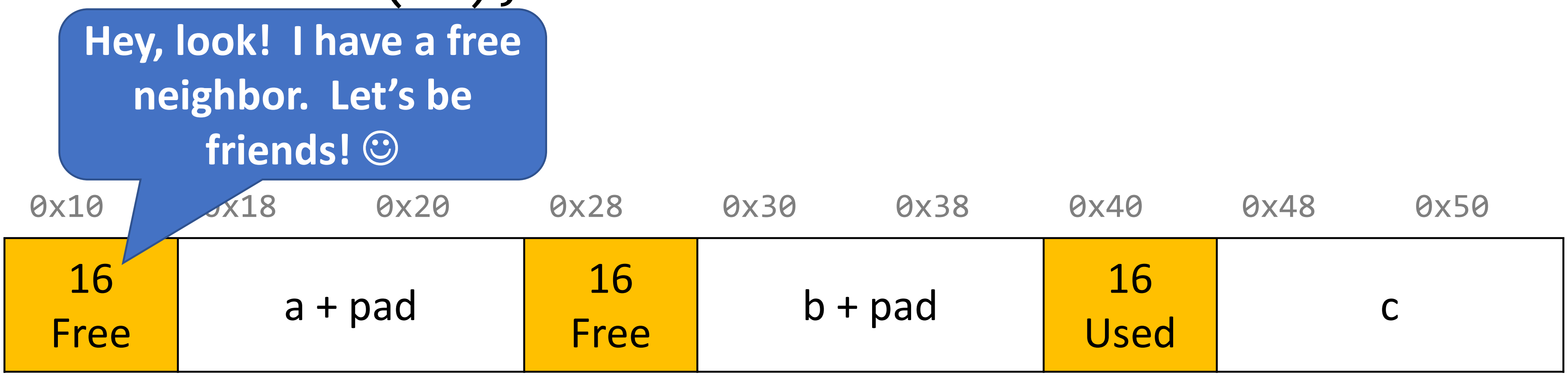

Coalescing

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free(a);
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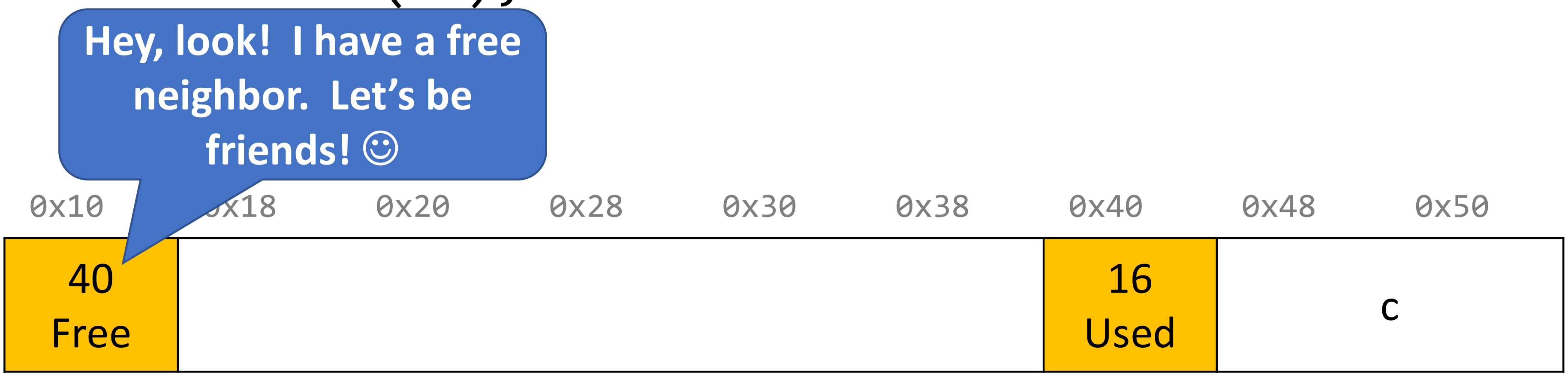
```

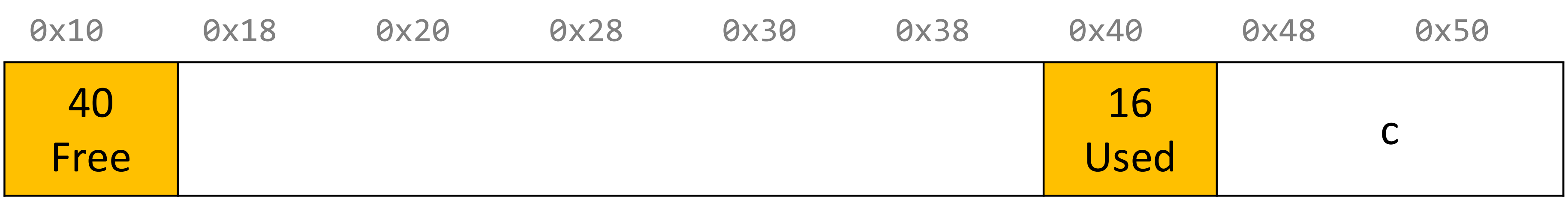


Coalescing

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

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**?

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

```
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**?

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

```
free(b);
```

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

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 coalesce on free().**
3. Can we avoid always copying/moving data during realloc?

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 coalesce on free().**
3. **Can we avoid always copying/moving data during realloc?**

Lecture Plan

- Method 1: Implicit Free List Allocator

- **Method 2: Explicit Free List Allocator**
  - Explicit Allocator
  - Coalescing
  - **In-place realloc**

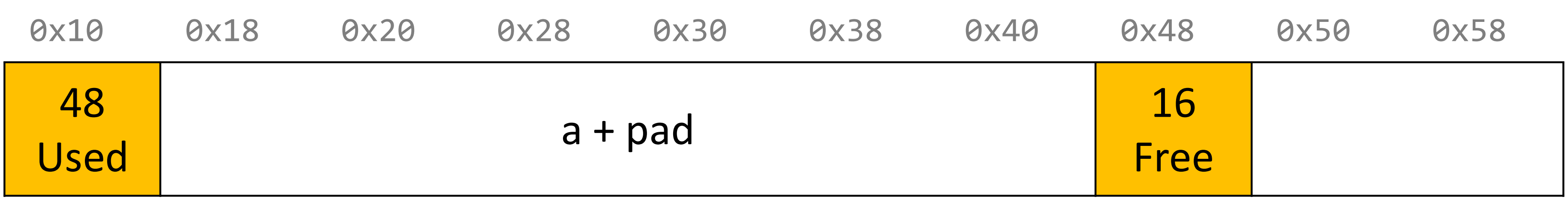
Realloc

- 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.

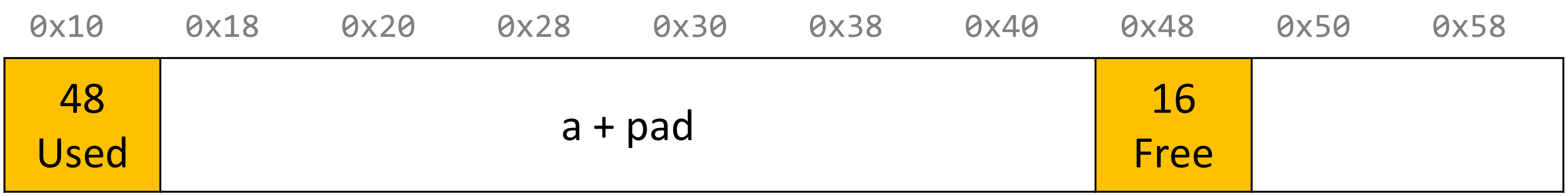


Realloc: Growing In Place

```
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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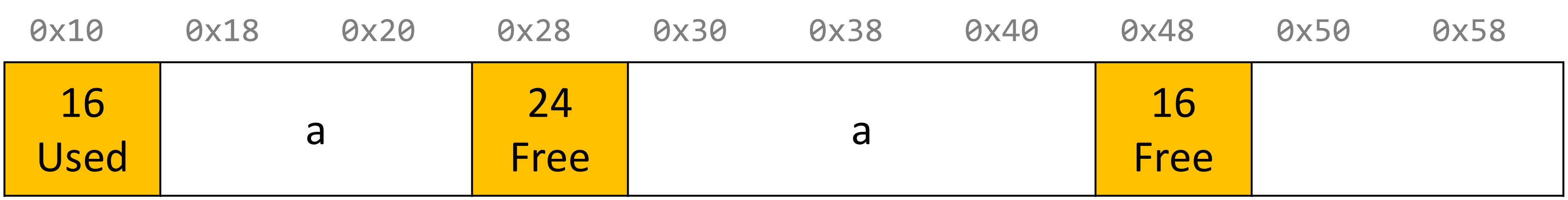
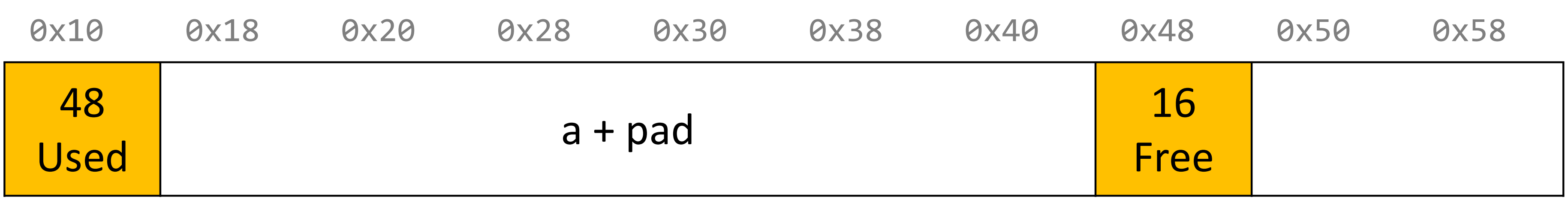


Realloc: Growing In Place

```
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!

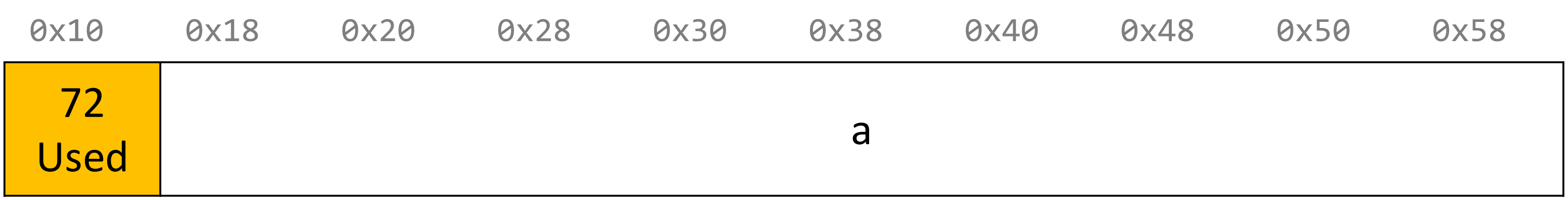


Realloc: Growing In Place

```
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!

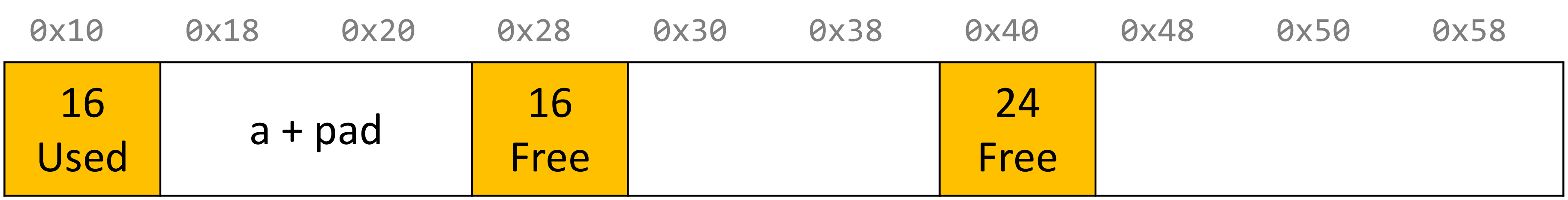
Now we can still return the same address.



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.



Realloc: Growing In Place

```
void *a = malloc(8);
...
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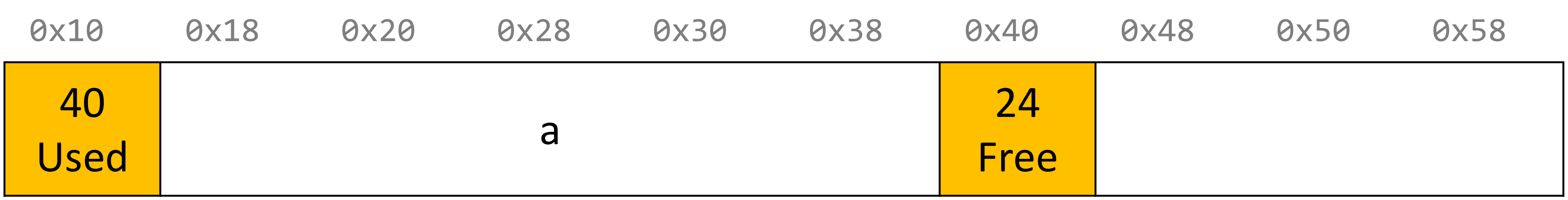

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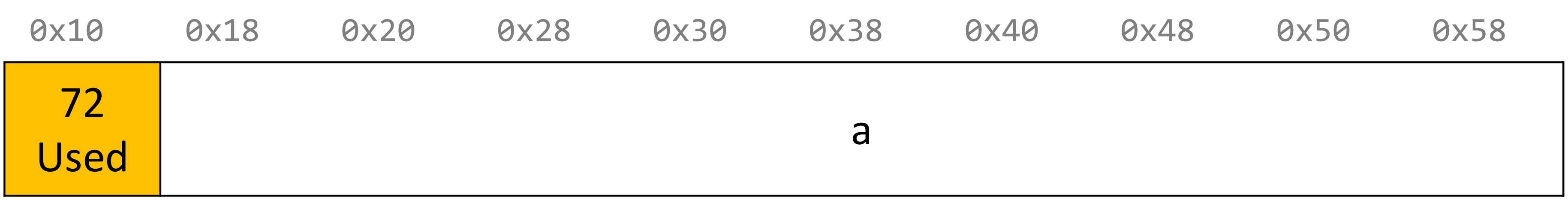
For your project (explicit only), you should combine with your *right* neighbors as much as possible until we get enough space, or until we know we cannot get enough space.



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.
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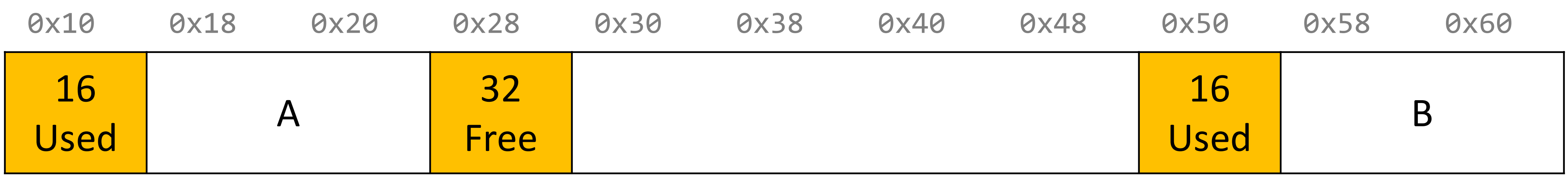
  - **Case 1:** size is growing, but we added padding to the block and can use that
  - **Case 2:** size is shrinking, so we can use the existing block
  - **Case 3:** size is growing, and current block isn't big enough, but adjacent blocks are free.
- If you can't do an in-place realloc, then you should move the data elsewhere.

Practice 1: Explicit (realloc)

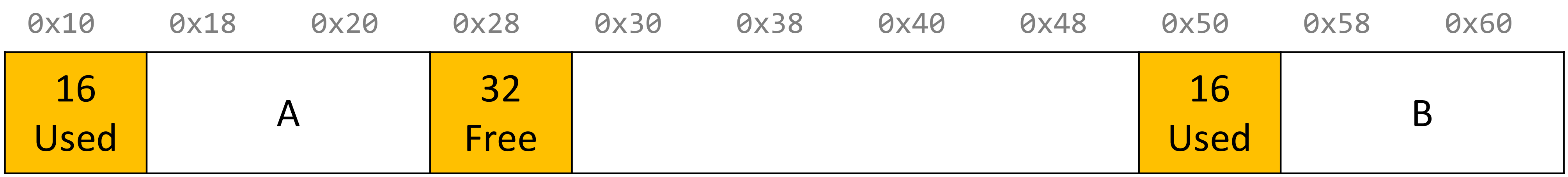
For the following heap layout, what would the heap look like after the following request is made, assuming we are using an explicit free list allocator with a **first-fit** approach and **coalesce on free + realloc in-place**?



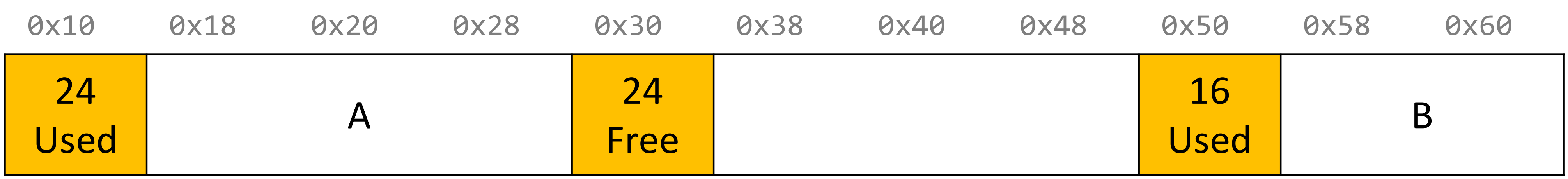

```
realloc(A, 24);
```

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**?

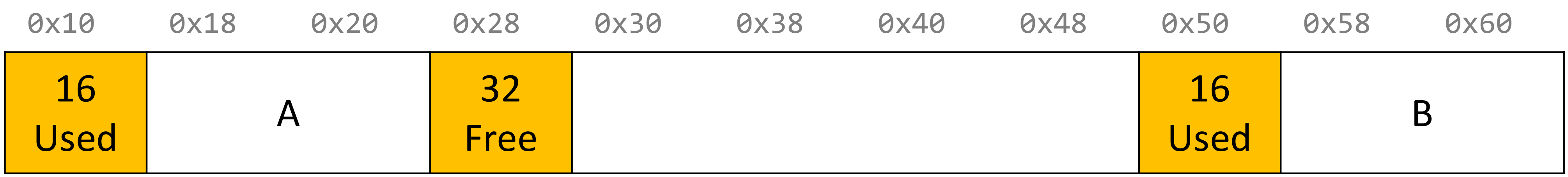



```
realloc(A, 24);
```



Practice 2: Explicit (realloc)

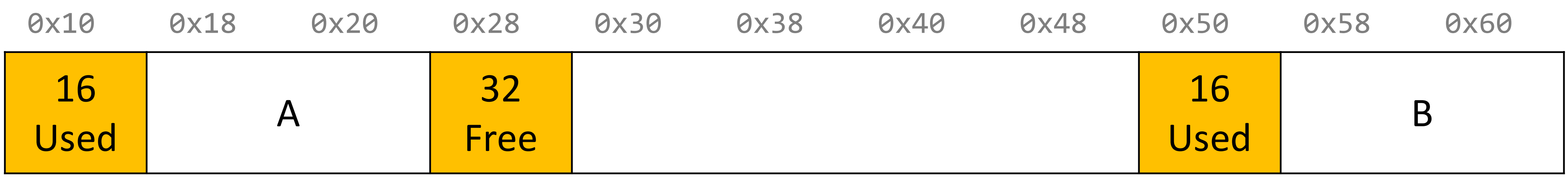
For the following heap layout, what would the heap look like after the following request is made, assuming we are using an **explicit** free list allocator with a **first-fit** approach and **coalesce on free + realloc in-place**?



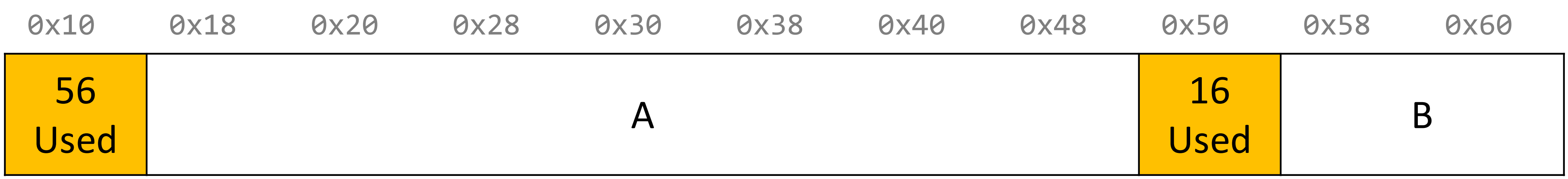

```
realloc(A, 56);
```

Practice 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**?

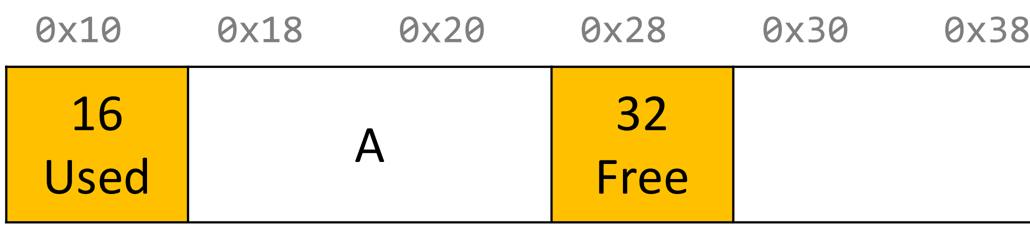
0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58	0x60
16 Used	A		32 Free					16 Used	B	

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

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

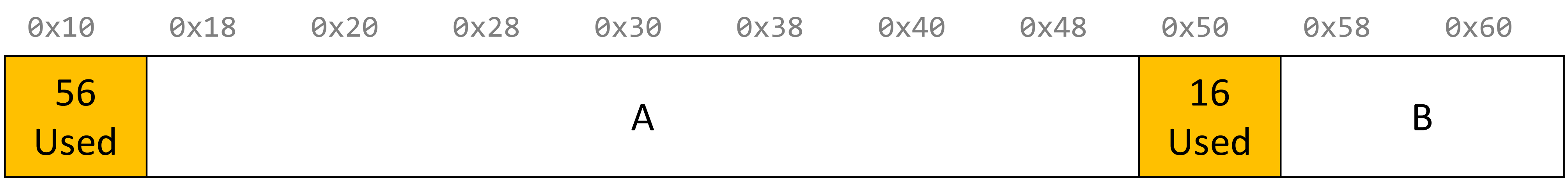
Practice 3: Explicit (realloc)

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);
```



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

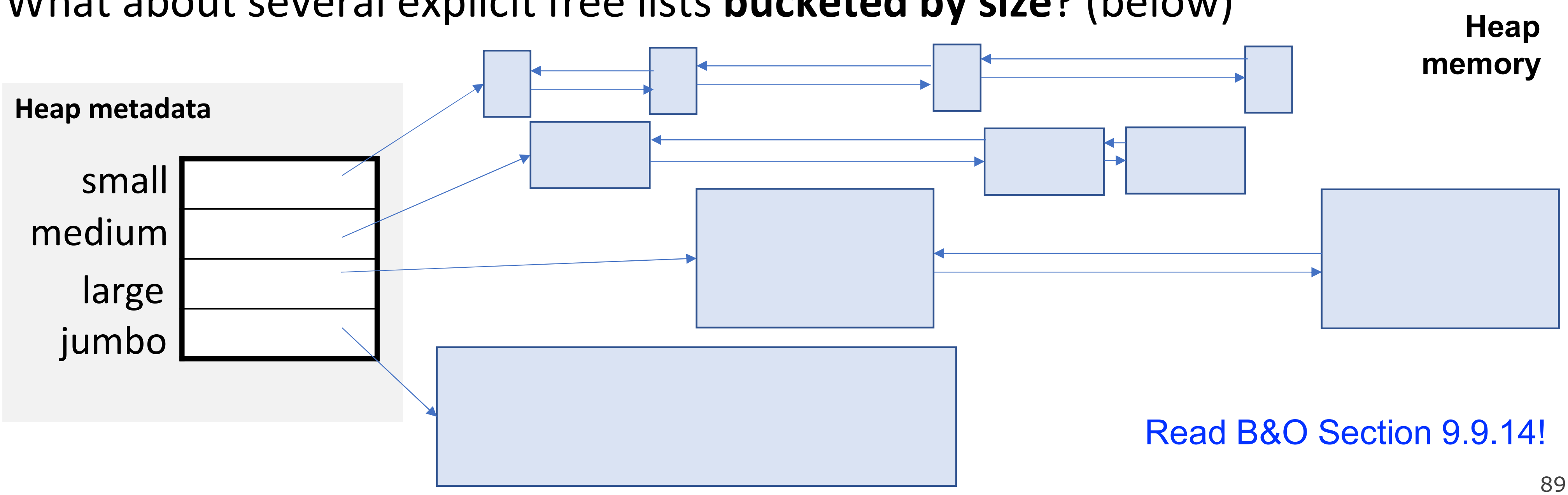
- All non-textbook code is off-limits.
- Please do not discuss discuss code-level specifics with others.
- Your code should be designed, written, and debugged by you independently.

Helper Hours

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

Going beyond: Explicit list w/size buckets

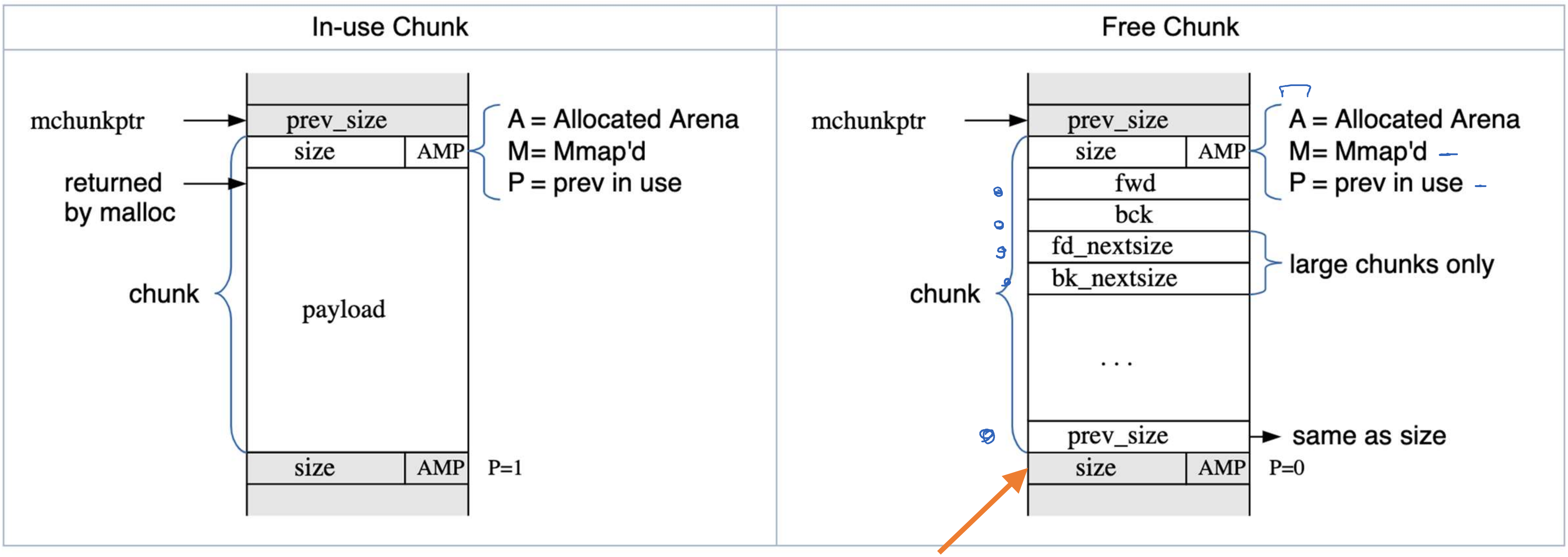
- Explicit lists are much faster than implicit lists.
- However, a first-fit placement policy is still linear in total # of free blocks.
- What about an explicit free list **sorted by size** (e.g., as a tree)?
- What about several explicit free lists **bucketed by size**? (below)



Read B&O Section 9.9.14!

In the wild: glibc allocator

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



Footer/Boundary tag (see textbook)