CS107, Lecture 15
Managing The Heap

Reading: B&O 9.9, 9.11

CS107 Topic 7: How do the core `malloc`/`realloc`/`free` memory-allocation operations work?

How do malloc/realloc/free work?

Pulling together all of our CS107 topics this quarter:

- Testing
- Efficiency
- Bit-level manipulation
- Memory management
- Pointers
- Generics
- Assembly
- And more…

Learning Goals

- Learn the restrictions, goals and assumptions of a heap allocator
- Understand the conflicting goals of utilization and throughput
- Learn about 3 different ways to implement a heap allocator
- Learn about how we can optimize our compiled code

Plan For Today

- Recap: the heap
- What is a heap allocator?
- Heap allocator requirements and goals
- Method 1: Bump Allocator
- **Break:** Announcements
- Method 2: Implicit Free List Allocator
- Method 3: Explicit Free List Allocator
- Optimization

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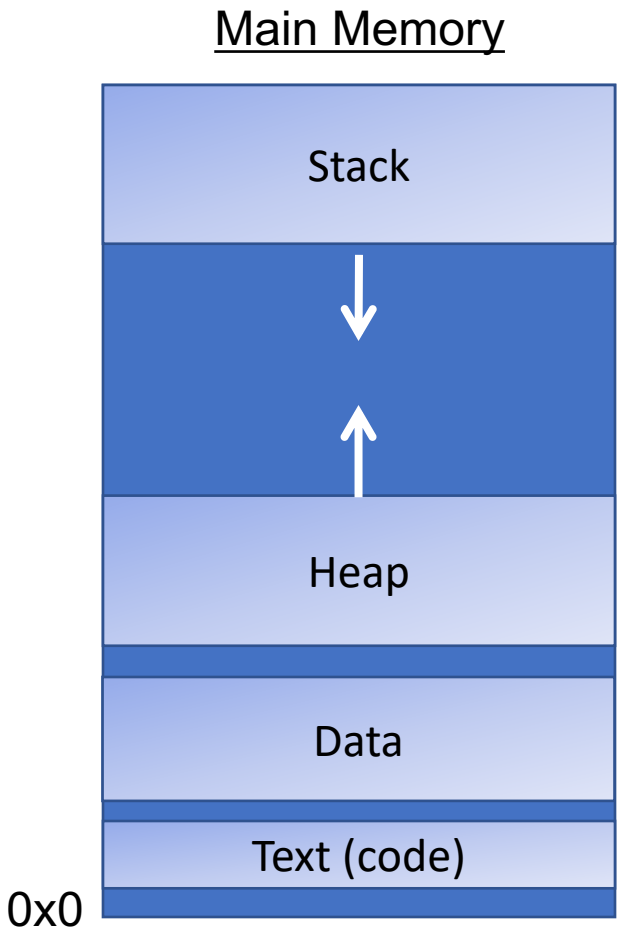
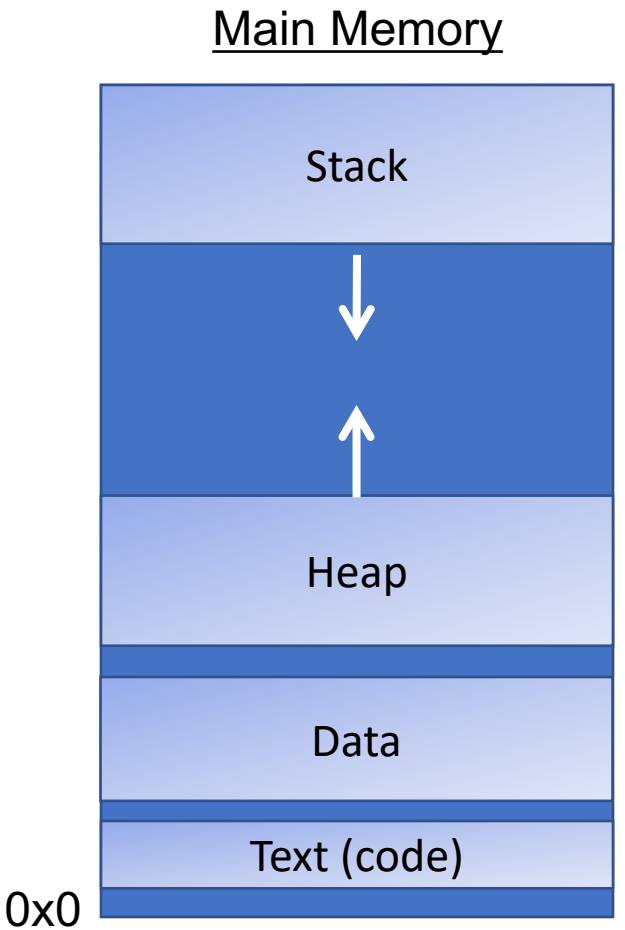
The Heap



The Heap

- The heap is an area of memory below the stack that grows up towards higher addresses.
- Unlike the stack, where memory goes away when a function finishes, the heap provides memory that persists until the caller is done with it.



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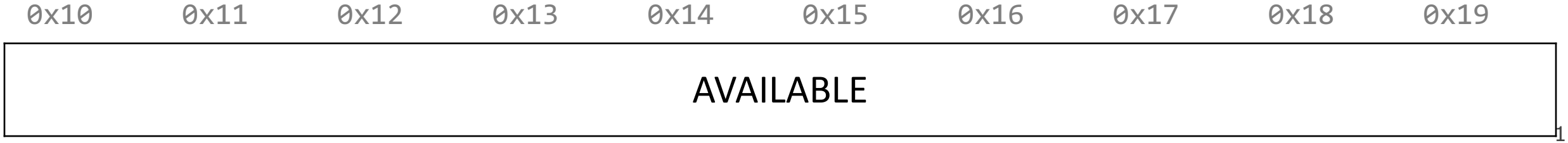

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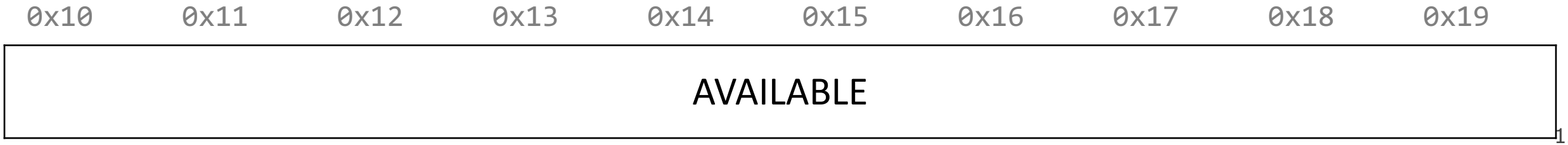
Request 1: Hi! May I please have 2 bytes of heap memory?

Allocator: Sure, I've given you address 0x10.



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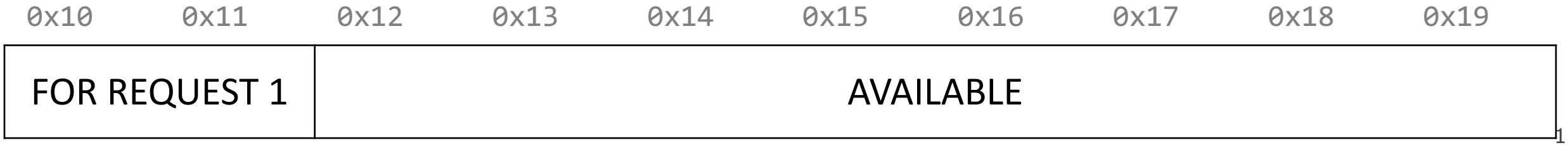

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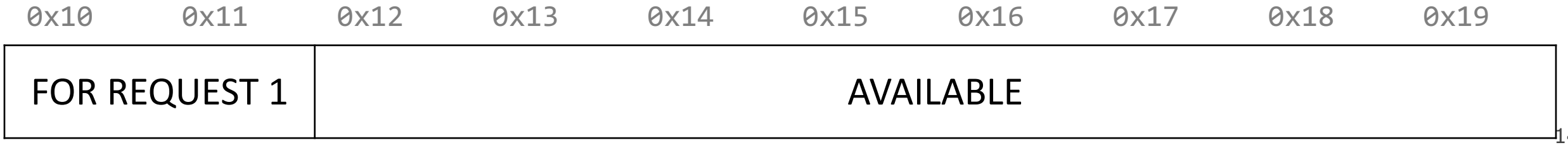
Request 2: Howdy! May I please have 3 bytes of heap memory?

Allocator: Sure, I've given you address 0x12.



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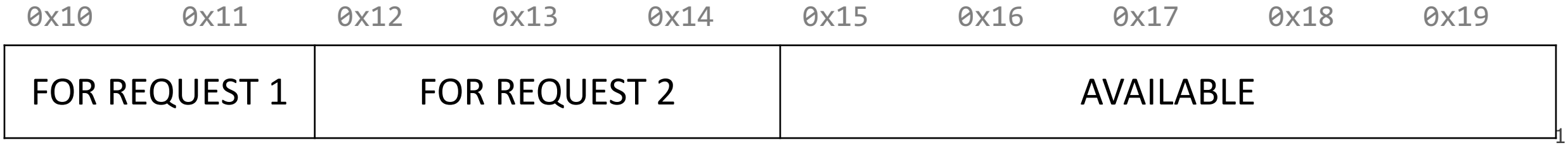

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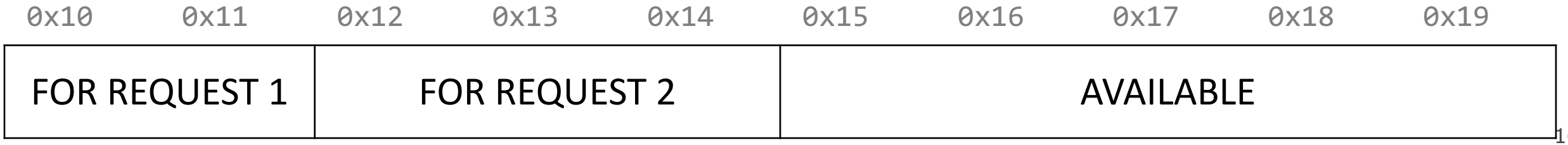

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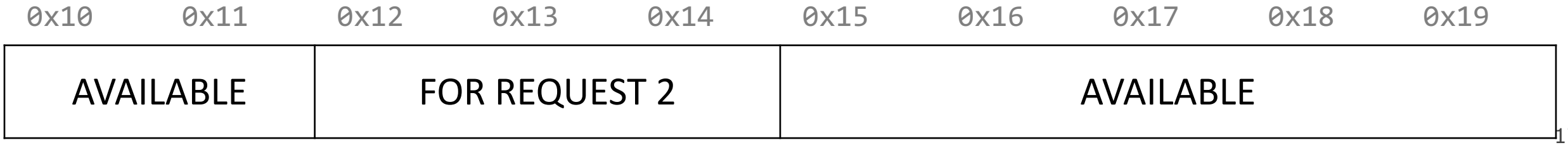

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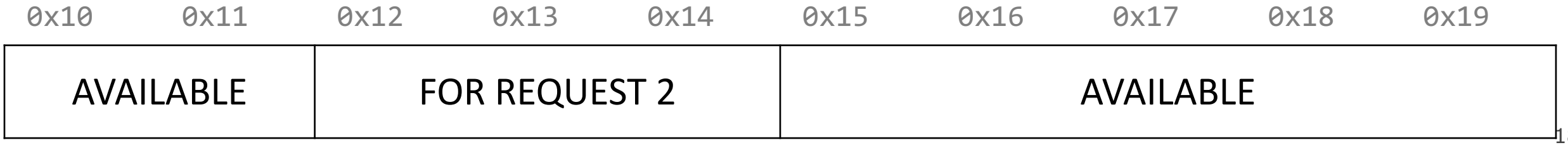

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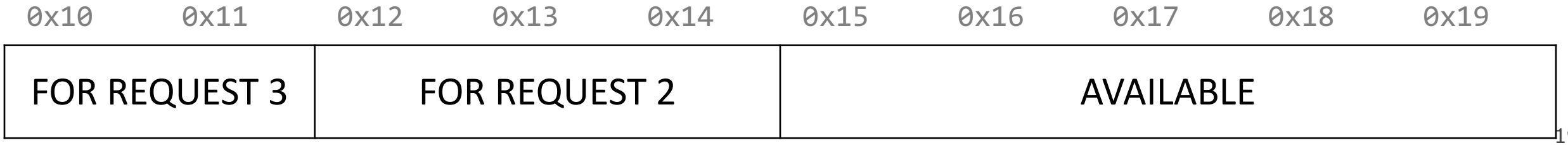

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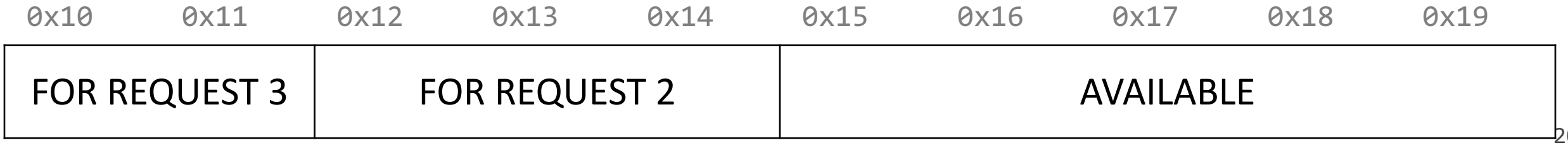
Request 3: Hi again! I'd like to request the region of memory at 0x10 be reallocated to 4 bytes.

Allocator: Sure thing. I've given you address 0x15.



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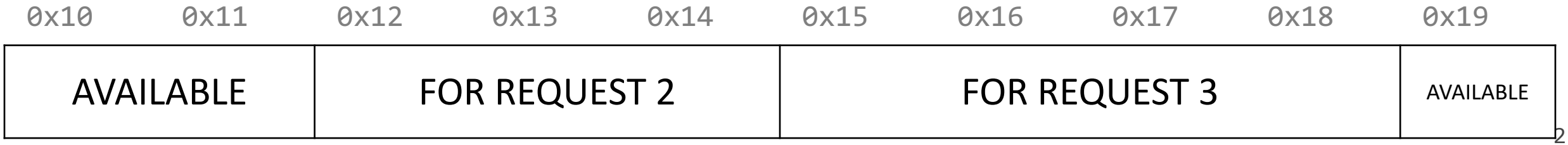

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You Are the "Heap Hotel Concierge"

Heap Allocator Functions

```
void *malloc(size_t size);
```

Returns a pointer to a block of heap memory of at least size bytes, or NULL if an error occurred.

```
void free(void *ptr);
```

Frees the heap-allocated block starting at the specified address.

```
void *realloc(void *ptr, size_t size);
```

Changes the size of the heap-allocated block starting at the specified address to be the new specified size. Returns the address of the new, larger allocated memory region.

Heap Allocator Requirements

A heap allocator must…

1. Handle arbitrary request sequences of allocations and frees
2. Keep track of which memory is allocated and which is available
3. Decide which memory to provide to fulfill an allocation request
4. Immediately respond to requests without delay

Heap Allocator Requirements

A heap allocator must…

1. **Handle arbitrary request sequences of allocations and frees**
2. Keep track of which memory is allocated and which is available
3. Decide which memory to provide to fulfill an allocation request
4. Immediately respond to requests without delay

A heap allocator cannot assume anything about the order of allocation and free requests, or even that every allocation request is accompanied by a matching free request.

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A heap allocator must…

1. Handle arbitrary request sequences of allocations and frees
2. **Keep track of which memory is allocated and which is available**
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A heap allocator marks memory regions as **allocated** or **available**. It must remember which is which so as to properly provide memory to clients.

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A heap allocator must…

1. Handle arbitrary request sequences of allocations and frees
2. Keep track of which memory is allocated and which is available
3. **Decide which memory to provide to fulfill an allocation request**
4. Immediately respond to requests without delay

A heap allocator may have options for which memory to use to fulfill an allocation request. It must decide this based on a variety of factors.

Heap Allocator Requirements

A heap allocator must…

1. Handle arbitrary request sequences of allocations and frees
2. Keep track of which memory is allocated and which is available
3. Decide which memory to provide to fulfill an allocation request
4. **Immediately respond to requests without delay**

A heap allocator must respond immediately to allocation requests, and should not e.g. prioritize or reorder certain requests to improve performance.

Heap Allocator Requirements

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1. Handle arbitrary request sequences of allocations and frees
2. Keep track of which memory is allocated and which is available
3. Decide which memory to provide to fulfill an allocation request
4. Immediately respond to requests without delay
5. **Return addresses that are 8-byte-aligned (must be multiples of 8).**

Heap Allocator Goals

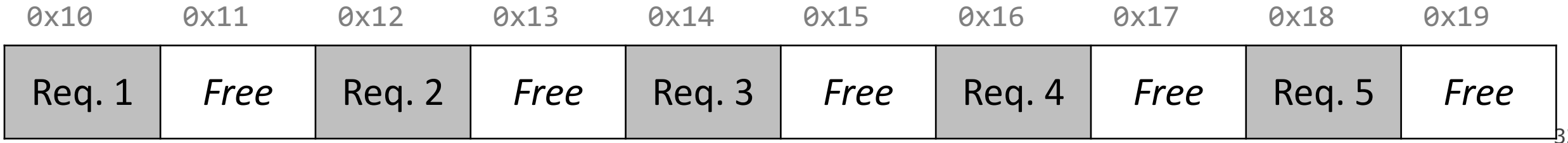
- Goal 1: Maximize **throughput**, or the number of requests completed per unit time. This means minimizing the average time to satisfy a request.
- Goal 2: Maximize memory **utilization**, or how efficiently we make use of the limited heap memory to satisfy requests.

Utilization

- The primary cause of poor utilization is **fragmentation**. **Fragmentation** occurs when otherwise unused memory is not available to satisfy allocation requests.
- In this example, there is enough aggregate free memory to satisfy the request, but no single free block is large enough to handle the request.
- In general: we want the largest address used to be as low as possible.

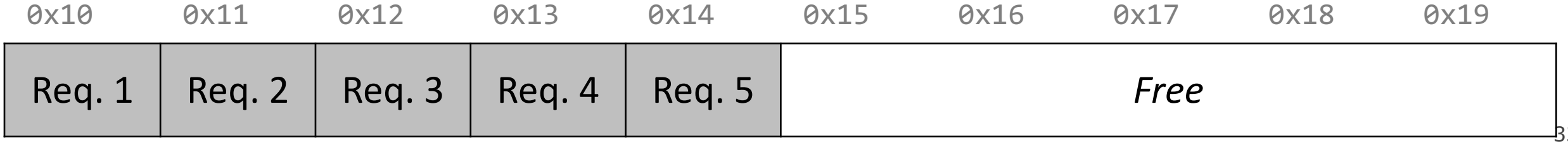
Request 6: Hi! May I please have 4 bytes of heap memory?

Allocator: I'm sorry, I don't have a 4 byte block available…



Utilization

- Question: what if we shifted these blocks down to make more space? Can we do this?
- **No!** We have already guaranteed these addresses to the client. We cannot move allocated memory around, since this will mean the client will now have incorrect pointers to their memory!



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.

These are seemingly conflicting goals – for instance, it may take longer to better plan out heap memory use for each request.

Heap allocators must find an appropriate balance between these two goals!

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Bump Allocator

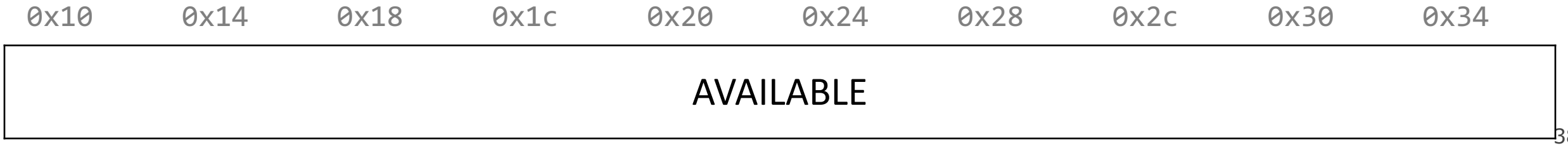
- Let’s approach designing our first heap allocator implementation.
- Let’s say we want to prioritize throughput as much as possible, and do not care about utilization at all. This means we do not care about reusing memory. How could we do this?

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 assign7 as a code reading exercise.

Bump Allocator

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



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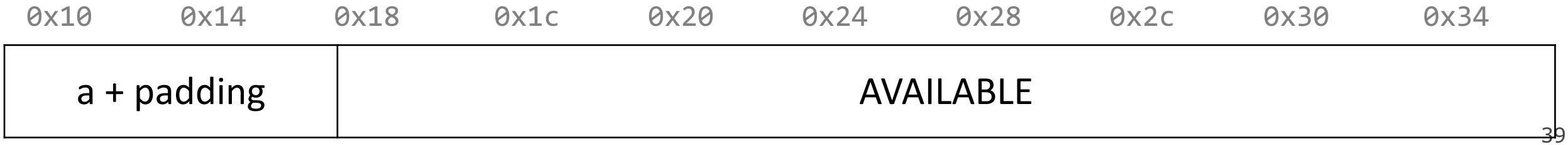
Variable	Value
a	0x10



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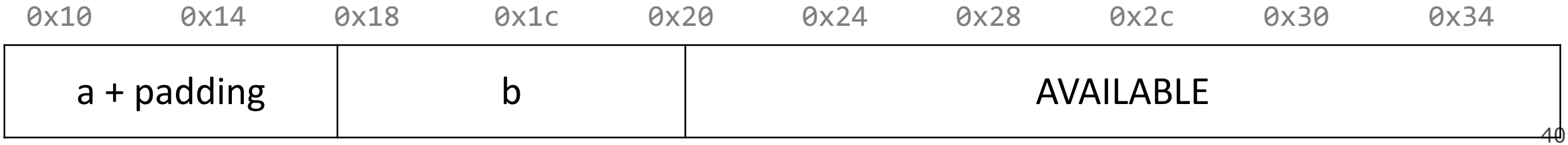
void *c = malloc(24);
free(b);
void *d = malloc(4);
```

Variable	Value
a	0x10
b	0x18



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free(b);
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```

Variable	Value
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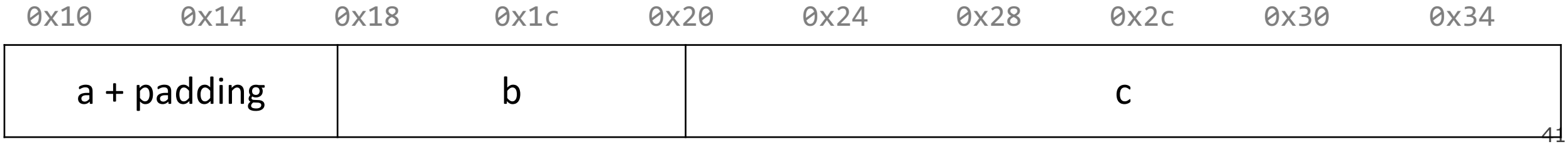
b	0x18
c	0x20



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```

Variable	Value
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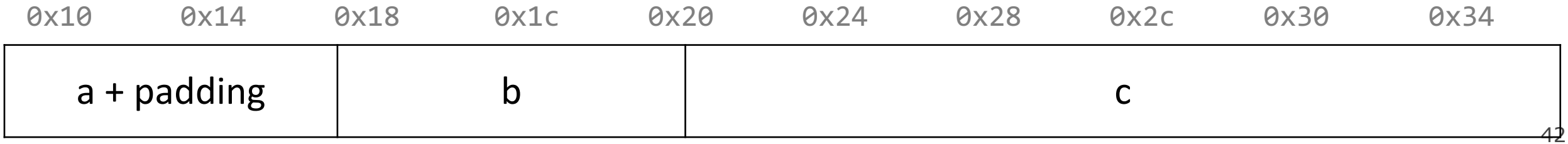
b	0x18
c	0x20



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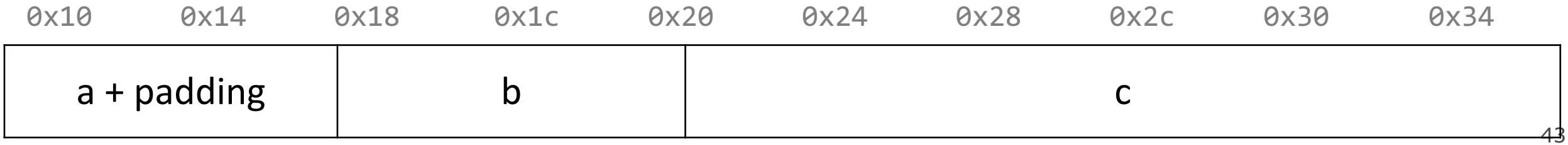

Variable	Value
a	0x10
b	0x18
c	0x20
d	NULL



Summary: Bump Allocator

- A bump allocator is an extreme heap allocator – it optimizes only for **throughput**, not **utilization**.
- Better allocators strike a more reasonable balance. How can we do this?

Questions to consider:

1. How do we keep track of free blocks?
2. How do we choose an appropriate free block in which to place a newly allocated block?
3. After we place a newly allocated block in some free block, what do we do with the remainder of the free block?
4. What do we do with a block that has just been freed?

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Announcements

- Last lab (**lab8**) next week on optimization and efficiency. Useful to fine tune your heap allocator!
- Heap allocator assignment is due **Wed. 3/14 at 11:59PM PST**. There is **no grace period** for this assignment.
  - We will be releasing it *early* this weekend for those who would like to get started.
  - For heap allocator, we will not be looking at code during office hours.
    - This assignment highly emphasizes debugging and *incremental development*, just like we've been practicing all quarter. You can do it!
    - We're eager to help with assignment and code questions, but are not able to look through your code with you to resolve issues. Instead, let's talk/sketch/sample code!
  - We will be releasing an additional video this weekend covering more important concepts for heap allocator that we don't have time to get through today.
- All midterm regrade requests have been completed.
- Office hours schedule as normal over the 3 day weekend.

Break-time thoughts: can we do better?

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2. How do we choose an appropriate free block in which to place a newly allocated block?
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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).

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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```
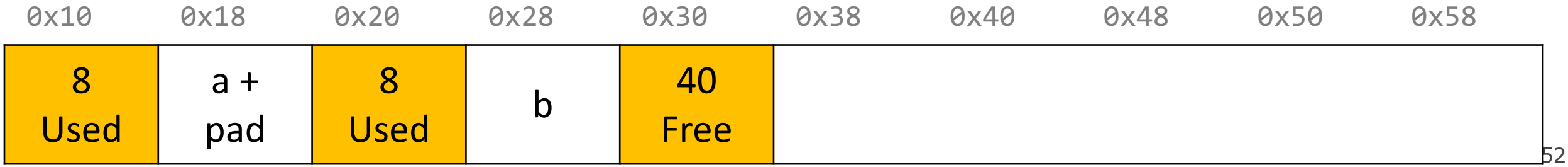

Variable	Value
a	0x18
b	0x28



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);
```

Variable	Value
a	0x18
b	0x28
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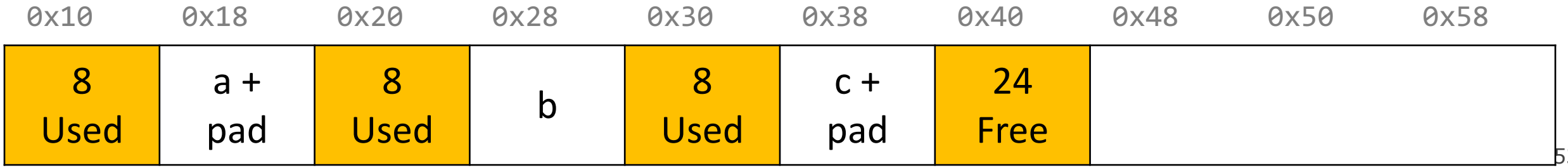

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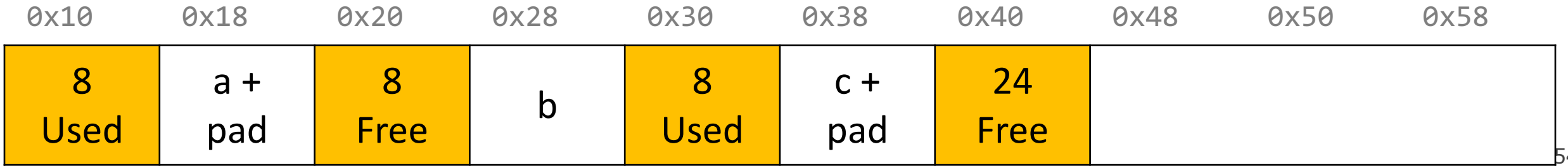

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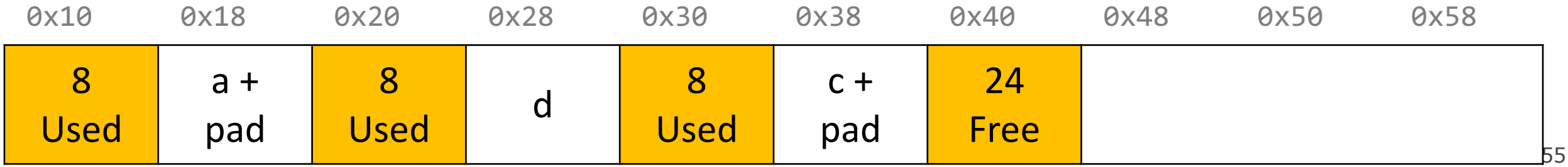

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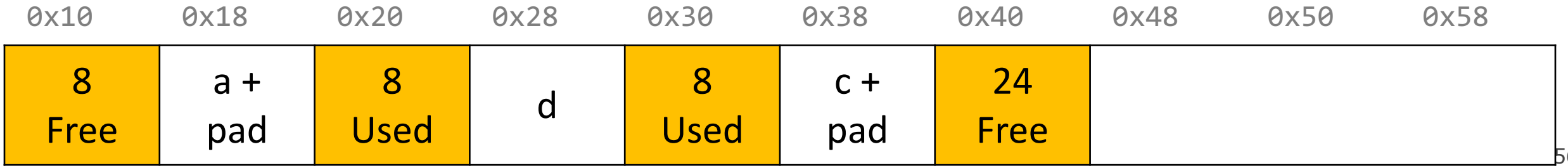

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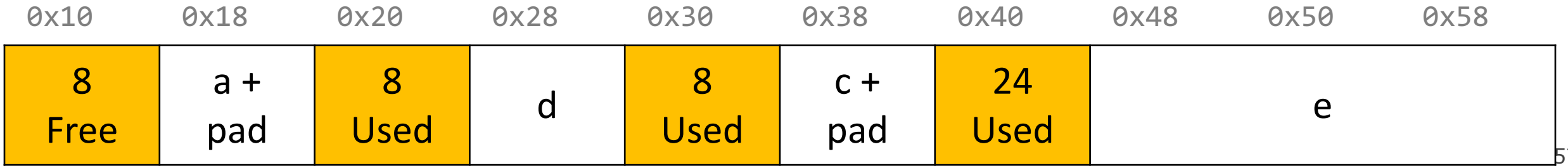
```

Variable	Value
a	0x18
b	0x28
c	0x38
d	0x28
e	0x48



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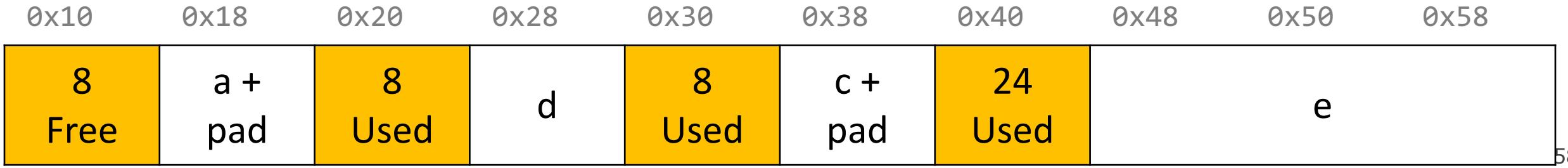


Representing Headers

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

Int for size, int for bytes? **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

For assignment 7, you may use this approach, or another approach, but remember that header sizes affect utilization!

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.

- What are the pros/cons of this approach?

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!**

Assignment 7: Implicit Allocator

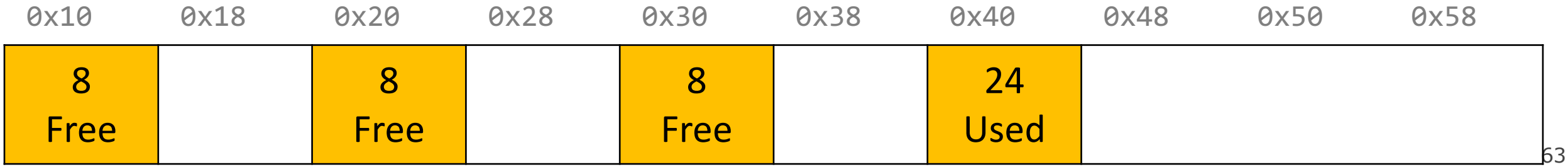
- **Must have** headers that track block information (size, status in-use or free) - we recommend using headers larger than the 4 byte headers specified in the book, as this makes it easier to satisfy the alignment constraint and store information.
- **Must have** free blocks that are recycled and reused 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

Coalescing

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

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).



In-Place Realloc

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

In-Place Realloc

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

Variable	Value
a	0x18

In-Place Realloc

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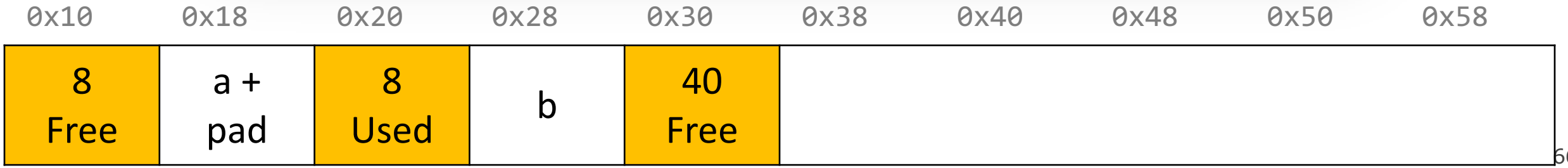
```

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).



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?

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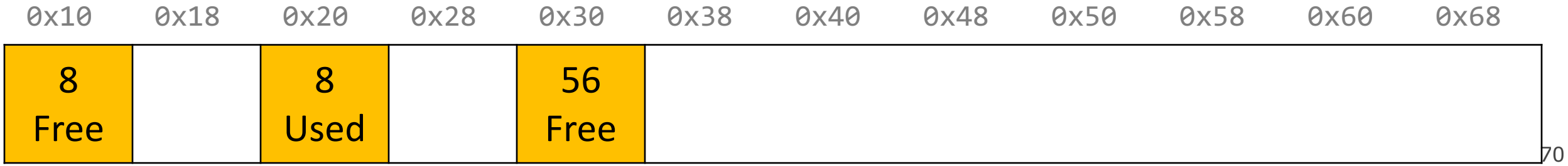
Can We Do Better?

- 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 next free block and a pointer to the previous free block.



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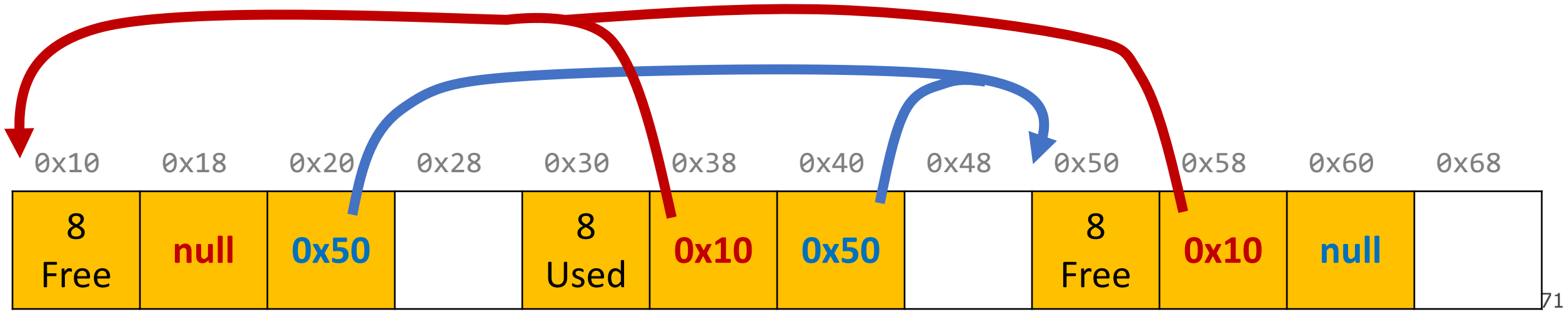

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- It would be nice if we could jump *just between free blocks*, rather than all blocks, to find a block to reuse.
- **Idea:** let's modify each header to add a pointer to the **previous** free block and a pointer to the **next** free block.

This is inefficient – it triples the size of *every* header, when we really 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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- **Where can we put these pointers to the next/previous free block?**

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- **Idea:** In a separate data structure?

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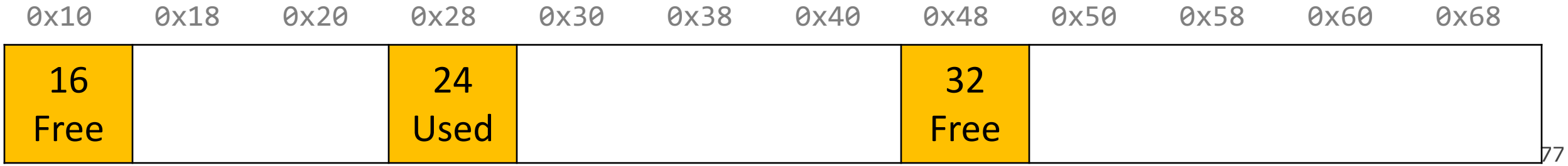
- It would be nice if we could jump *just between free blocks*, rather than all blocks, to find a block to reuse.
- **Idea:** let's modify each header to add a pointer to the next free block and a pointer to the previous free block. *This is inefficient / complicated.*
- **Where can we put these pointers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



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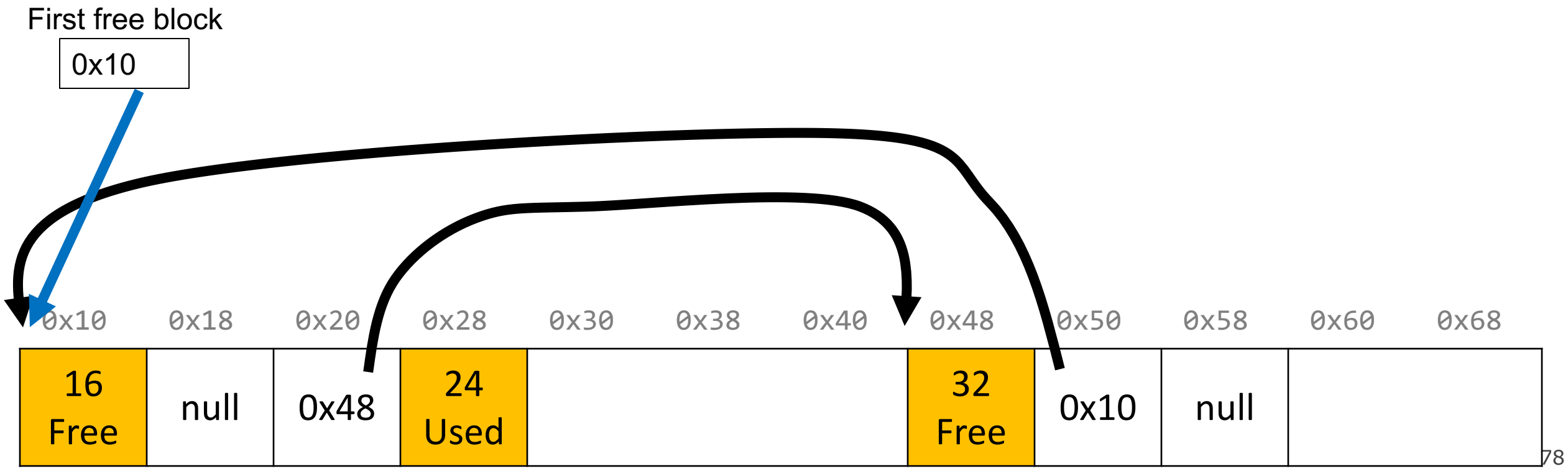

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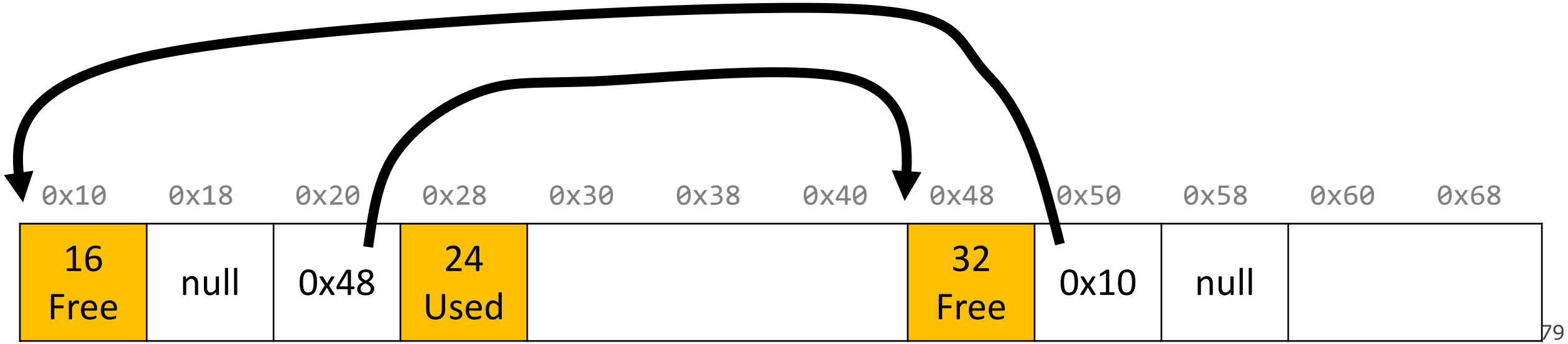
- **Idea:** since we only need to store these pointers for free blocks, let's store them in the first 16 bytes of each free block's payload!
- This means each payload must be big enough to store 2 pointers (16 bytes). So we must require that for every block, free and allocated. (why?)

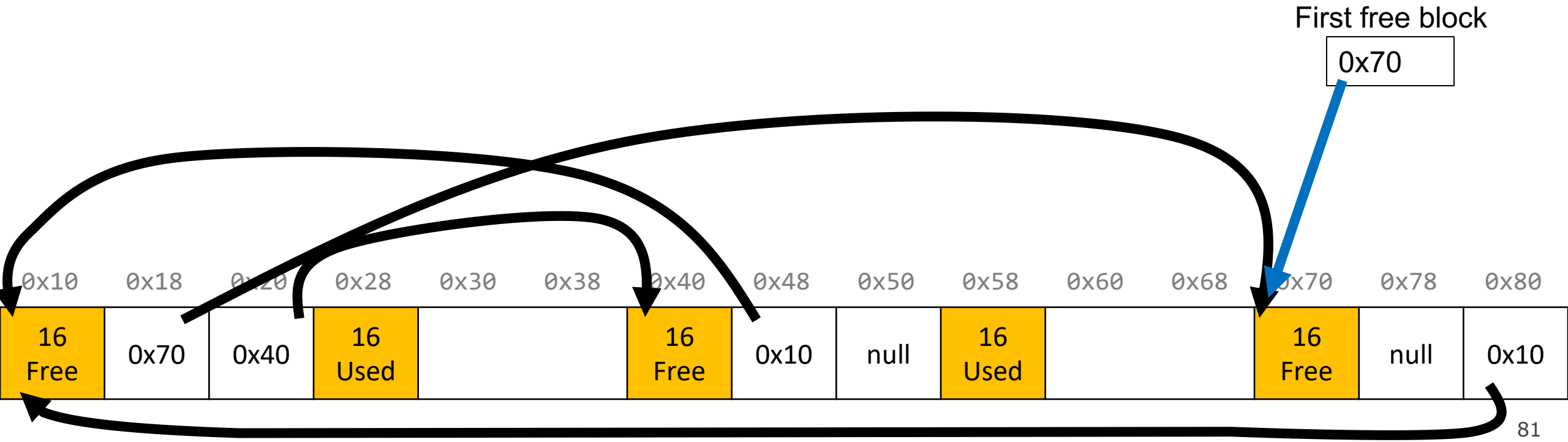


Explicit Free List Allocator

- 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.

Explicit Free List Allocator

- Note that the doubly-linked list *does not have to be in address order*.
- You should build up your linked list as efficiently as possible (e.g. where is it most efficient to add to a linked list?)
- When you allocate a block, you must update your linked list pointers.



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1. Can we avoid searching all blocks for free blocks to reuse? **Yes! We can use a doubly-linked list.**
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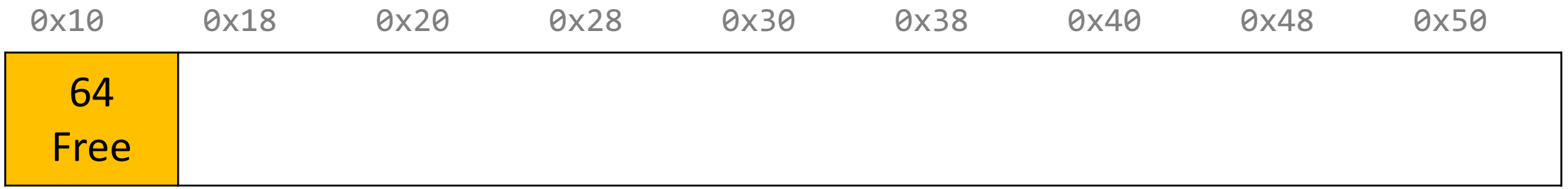

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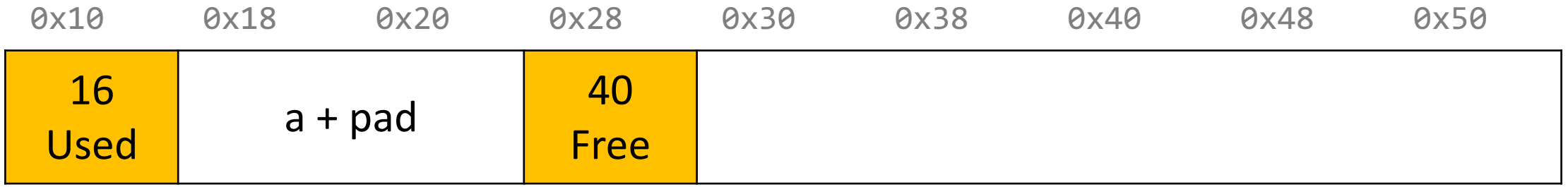

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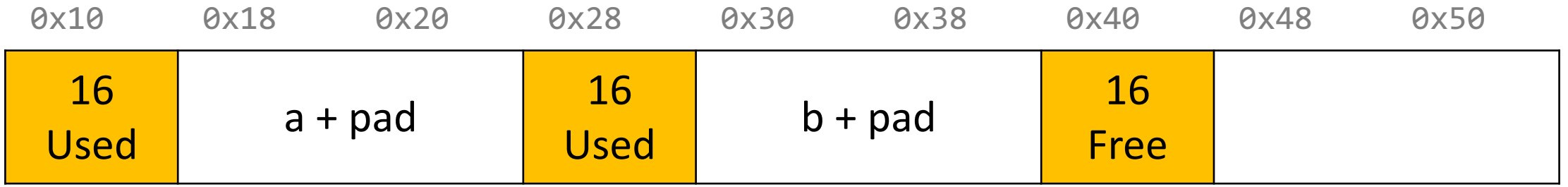

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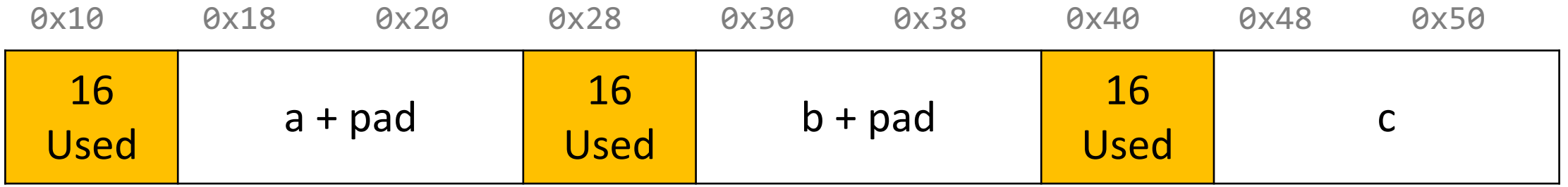

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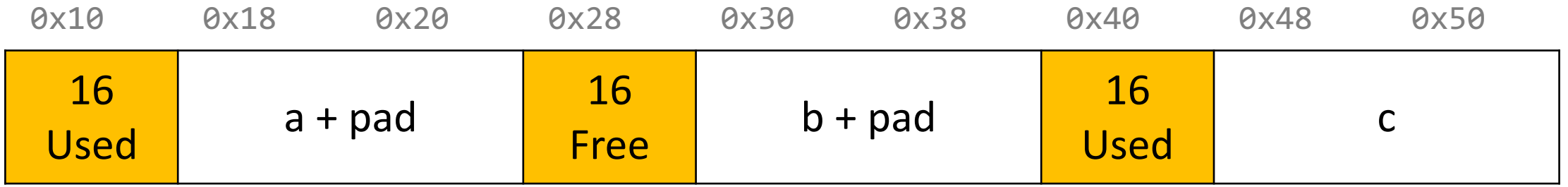

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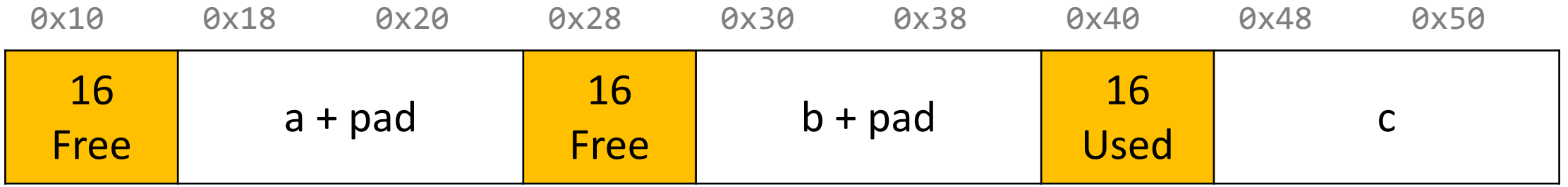

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```
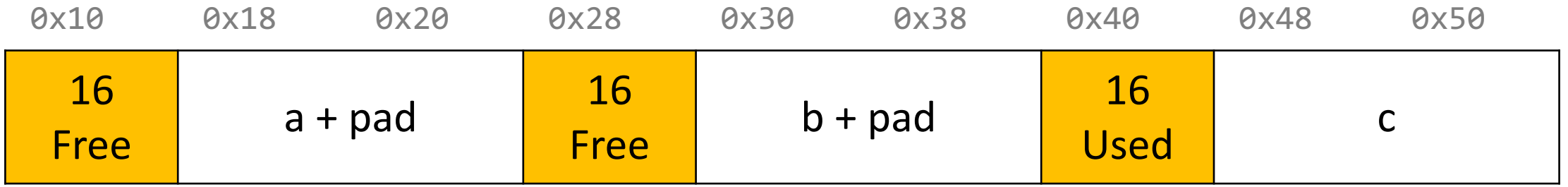

We have enough memory space, but it is fragmented into free blocks sized from earlier requests!

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



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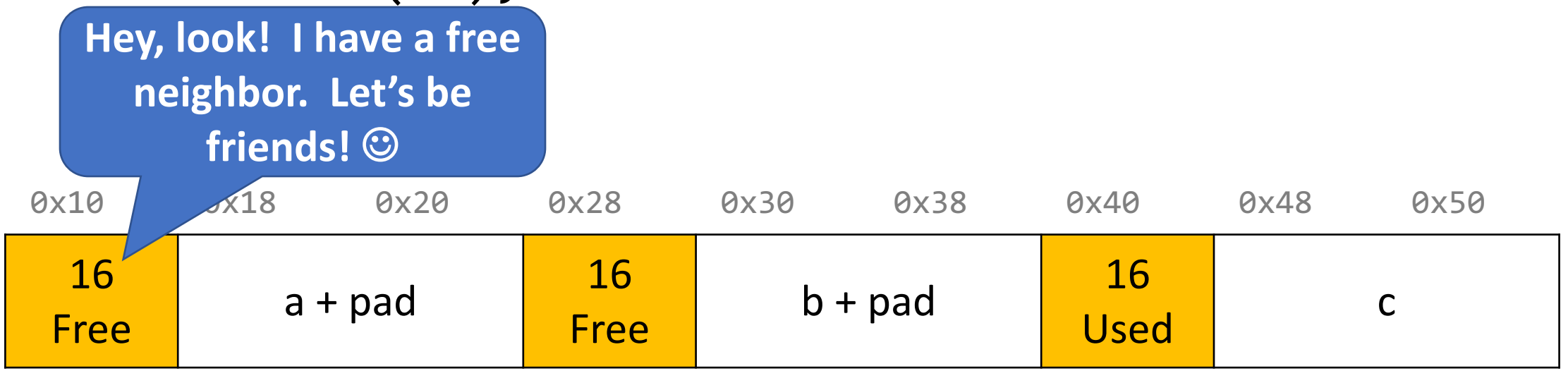

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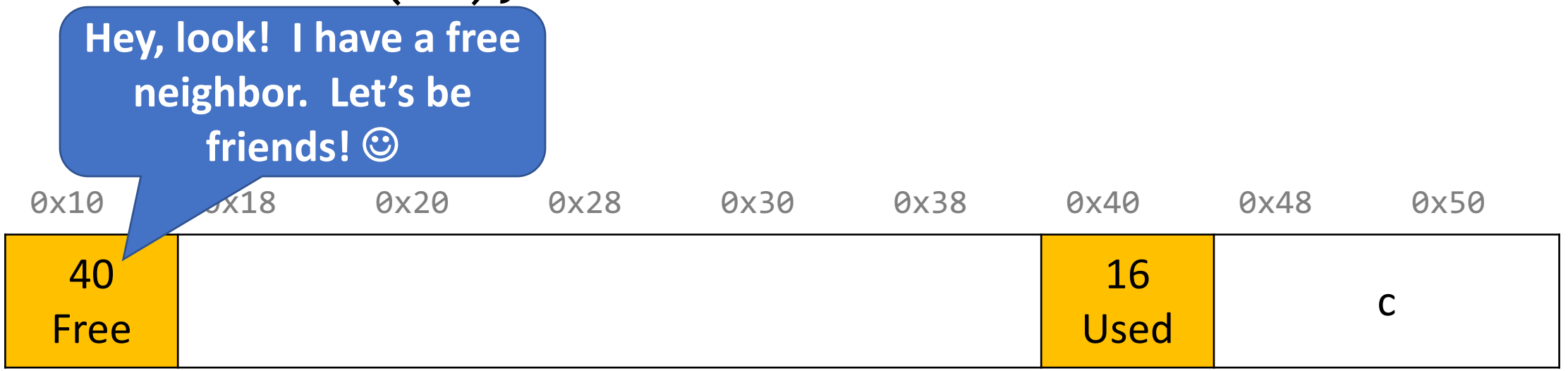

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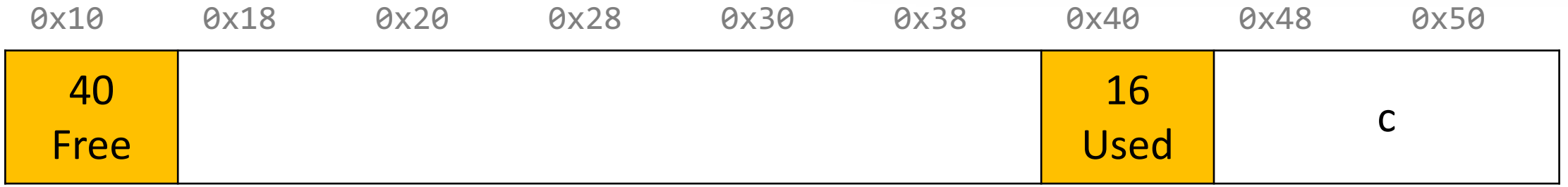
The process of combining adjacent free blocks is called *coalescing*.

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.**



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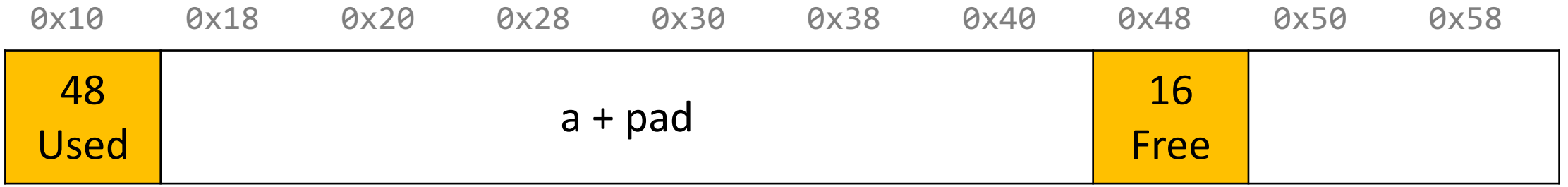
Realloc

- For the implicit 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.

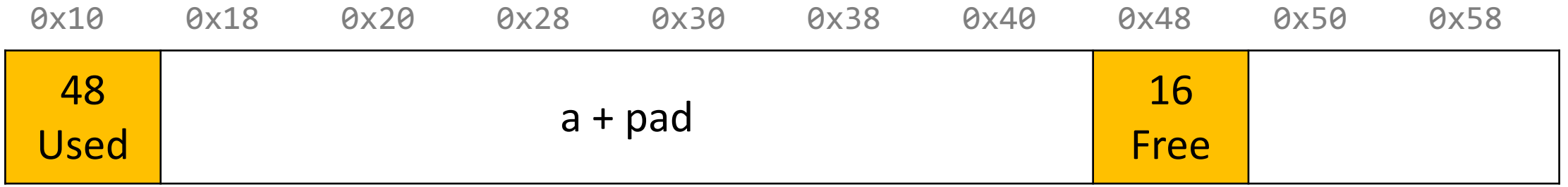


Realloc: Growing In Place

```
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.



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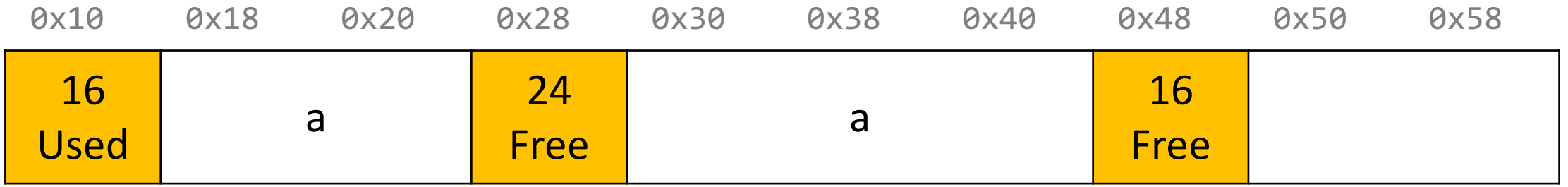
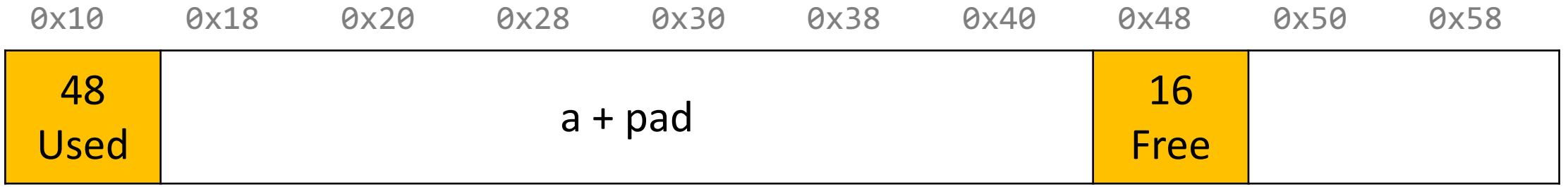


Realloc: Growing In Place

```
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!



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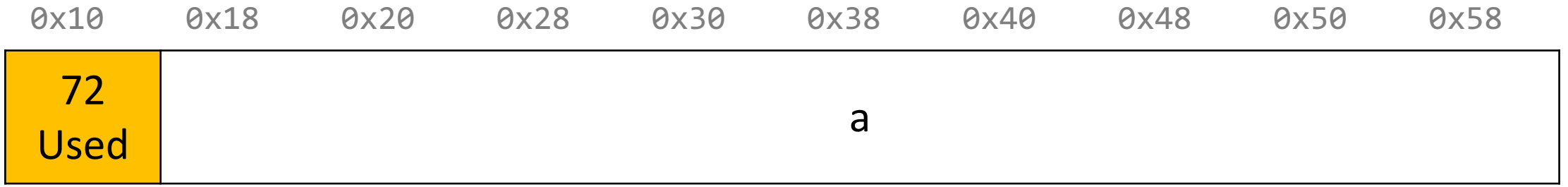
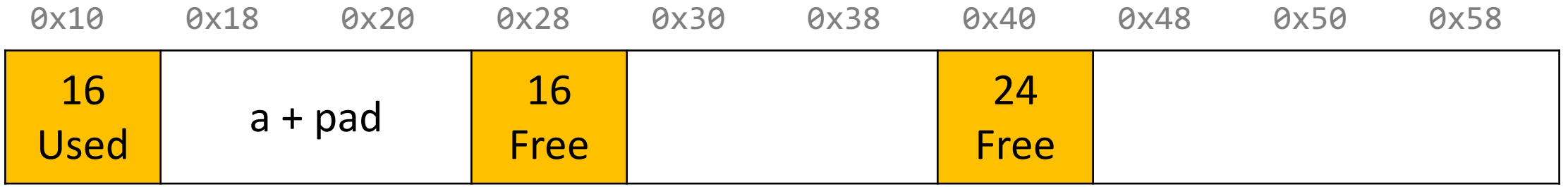
Now we can still return the same address.



Realloc: Growing In Place

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

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.



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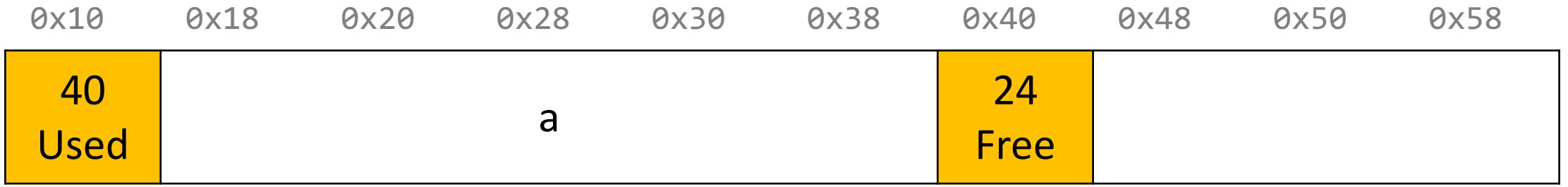

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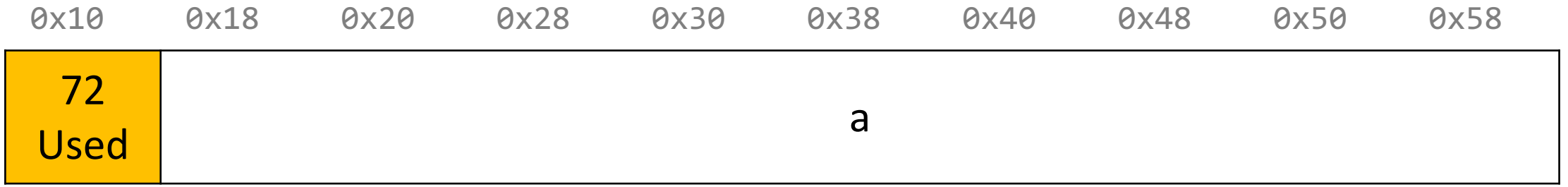

Realloc

- For the implicit 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.
- If you can't do an in-place realloc, then you should move the data elsewhere.

Assignment 7: Explicit Allocator

- **Must have** headers that track block information (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.

Plan For Today

- Recap: the heap
- What is a heap allocator?
- Heap allocator requirements and goals
- Method 1: Bump Allocator
- **Break:** Announcements
- Method 2: Implicit Free List Allocator
- Method 3: Explicit Free List Allocator
- Optimization

Optimization

- Optimization is the task of making your program faster or more efficient with space or time. You've seen explorations of efficiency with Big-O notation!
- *Targeted, intentional* optimizations to alleviate bottlenecks can result in big gains. But it's important to only work to optimize where necessary.

Optimization

Most of what you need to do with optimization can be summarized in 3 easy steps:

1) If doing something seldom and only on small inputs, do whatever is simplest to code, understand, and debug
2) If doing things thing a lot, or on big inputs, make the primary algorithm's Big-O cost reasonable
3) **Let gcc do its magic from there**

GCC Optimization

- Today, we'll be comparing two levels of optimization in the gcc compiler:
  - `gcc –O0  //mostly just literal translation of C`
  - `gcc –O2  //enable nearly all reasonable optimizations`
  - (we use –Og, like –O0 but with less needless use of the stack)

- There are other custom and more aggressive levels of optimization, e.g.:
  - `-O3     //more aggressive than O2, trade size for speed`
  - `-Os     //optimize for size`
  - `-Ofast  //disregard standards compliance (!!)`

- Exhaustive list of gcc optimization-related flags:
  - https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html

Example: Matrix Multiplication

Here's a standard matrix multiply, a triply-nested for loop:

```
void mmm(double a[][DIM], double b[][DIM], double c[][DIM], int n) {
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < n; j++) {
            for (int k = 0; k < n; k++) {
                c[i][j] += a[i][k]*b[k][j];
            }
        }
    }
}
```

```
./mult          // -O0 (no optimization)
matrix multiply  25^2: cycles   0.44M
matrix multiply  50^2: cycles   3.13M
matrix multiply 100^2: cycles  24.80M
```

```
./mult_opt     // -O2 (with optimization)
matrix multiply  25^2: cycles   0.11M (opt)
matrix multiply  50^2: cycles   0.47M (opt)
matrix multiply 100^2: cycles   3.67M (opt)
```

GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling
- Psychic Powers

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- ~~Psychic Powers~~ (kidding.)

Constant Folding

Constant Folding pre-calculates constants at compile-time where possible.

```
int seconds = 60 * 60 * 24 * n_days;
```

What is the consequence of this for you as a programmer? What should you do differently or the same knowing that compilers can do this for you?

Constant Folding

```
int CF(int param) {
    char arr[0x55];

    int a = 0x107;
    int b = a * sizeof(arr);
    int c = sqrt(2.0);
    return a*param + (a + 0x15/c + strlen("hello")*b - 0x37)/4;
}
```

Constant Folding: Before (-O0)

```
0000000000400726 <CF>:
  400726:       55                      push   %rbp
  400727:       53                      push   %rbx
  400728:       48 83 ec 08             sub    $0x8,%rsp
  40072c:       89 fd                   mov    %edi,%ebp
  40072e:       f2 0f 10 05 ba 05 00    movsd  0x5ba(%rip),%xmm0
  400735:       00
  400736:       e8 c5 fe ff ff          callq  400600 <sqrt@plt>
  40073b:       f2 0f 2c c8             cvttsd2si %xmm0,%ecx
  40073f:       69 ed 07 01 00 00       imul   $0x107,%ebp,%ebp
  400745:       b8 15 00 00 00          mov    $0x15,%eax
  40074a:       99                      cltd
  40074b:       f7 f9                   idiv   %ecx
  40074d:       8d 98 07 01 00 00       lea    0x107(%rax),%ebx
  400753:       bf e4 0c 40 00          mov    $0x400ce4,%edi
  400758:       e8 73 fe ff ff          callq  4005d0 <strlen@plt>
  40075d:       48 69 c0 53 57 00 00    imul   $0x5753,%rax,%rax
  400764:       48 63 db                movslq %ebx,%rbx
  400767:       48 8d 44 18 c9          lea    -0x37(%rax,%rbx,1),%rax
  40076c:       48 c1 e8 02             shr    $0x2,%rax
  400770:       01 e8                   add    %ebp,%eax
  400772:       48 83 c4 08             add    $0x8,%rsp
  400776:       5b                      pop    %rbx
  400777:       5d                      pop    %rbp
  400778:       c3                      retq
```

Constant Folding: After (-O2)

```
0000000000400800 <CF>:
  400800:       69 c7 07 01 00 00       imul   $0x107,%edi,%eax
  400806:       05 61 6d 00 00          add    $0x6d61,%eax
  40080b:       c3                      retq
```

Common Sub-Expression Elimination

Common Sub-Expression Elimination prevents the recalculation of the same thing many times by doing it once and saving the result.

```
int a = (param2 + 0x107);
int b = param1 * (param2 + 0x107) + a;
return a * (param2 + 0x107) + b * (param2 + 0x107);
```

Strength Reduction

Strength reduction changes divide to multiply, multiply to add/shift, and mod to AND to avoid using instructions that cost many cycles (multiply and divide).

Assignment 7: Optimization

- Explore various optimizations you can make to your code to reduce instruction count.
  - More efficient Big-O for your algorithms
  - Explore other ways to reduce instruction count
    - Look for hotspots using callgrind
    - Optimize using –O2
    - And more…

Recap

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- **Next time:** additional topics