Virtual memory allocation and semaphores

Recap

Lucas Yri

KØBENHAVNS UNIVERSITET

Plan for this recap

- Semaphores (10-15 minutes)
  - Quick explanation of semaphores
  - Semaphore exercise
  - Additional semaphore exercise (if time allows)
- Heap allocation (The rest)
  - Explaining the basics
  - 2.3.1 from exam 21/22
  - 2.3.1 from exam 20/21
  - 2.3.1 from exam 22/23 (if time)
- Why?
- (Warning, made in paint)

- There is no specific time for questions, raise hands as needed

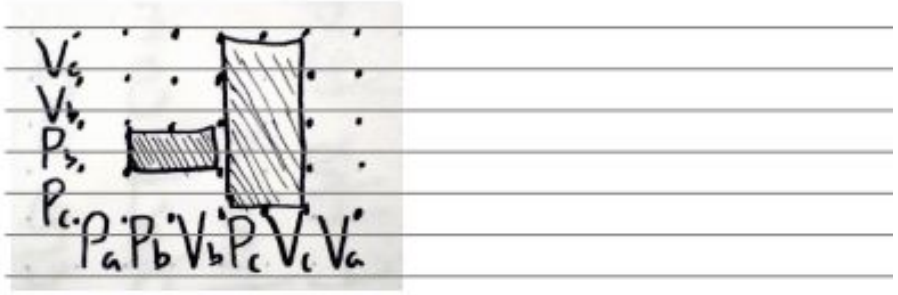
The exercises in question

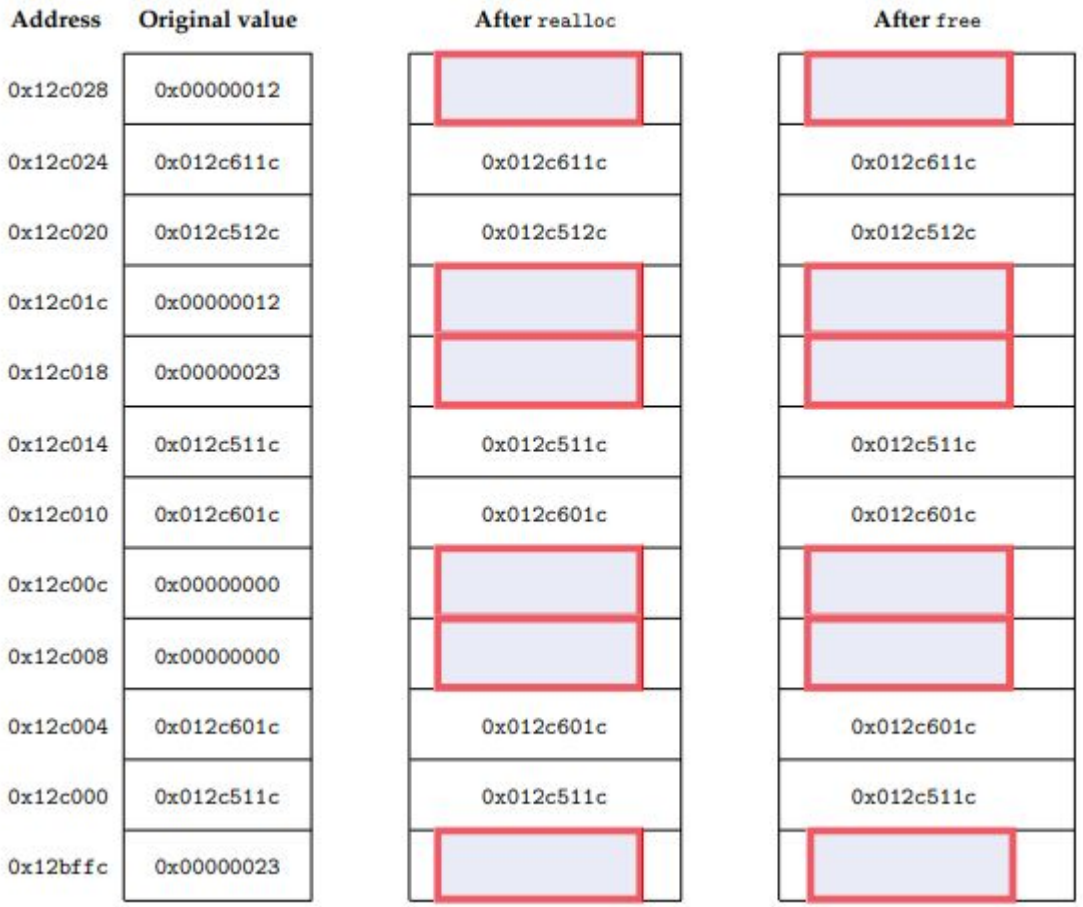
2.2 Short Questions (about 12 %)

Question 2.2.1: Consider two threads performing the following semapho

```
Initially: a = 1; b = 1; c = 1;

Thread 1:        Thread 2:
P(a);            P(c);
P(b);            P(b);
V(b);            V(b);
P(c);            V(c);
V(c);
V(a);
```

Draw a process graph with thread 1 along the horizontal axis and thr
show the forbidden regions, and argue whether this means deadlocks are





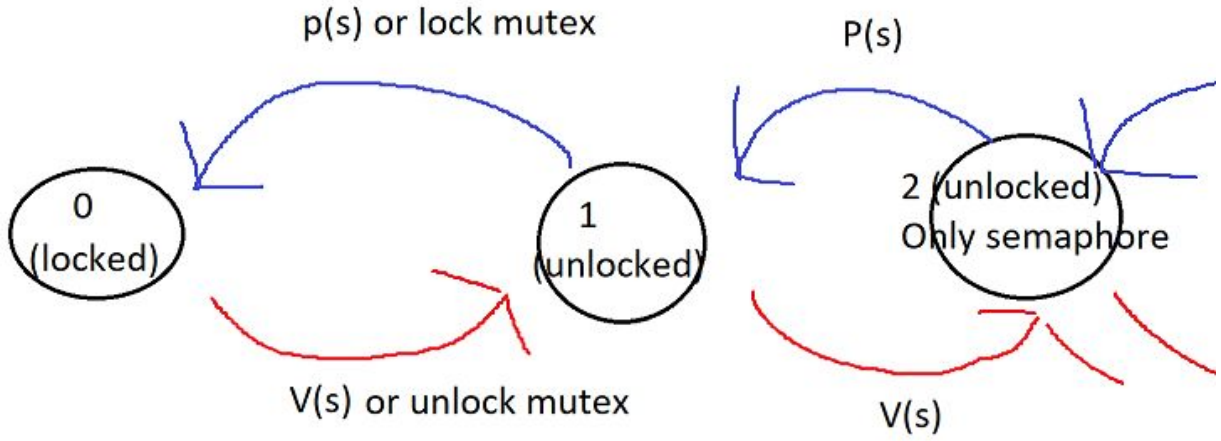
Semaphores

- Kind of like a combination of a mutex and a counter
- P(s) decrements
- V(s) increments
- Locked if 0 (memory is inaccessible)
- For example if the semaphore is 5, it would need 5 calls of P(s) to become locked.
- A mutex is a type of semaphore that is only 0 (locked) or 1 (unlocked).

```
wait (S) {  // originally called P(S)
    while ( S ≤ 0 ) do no-op;
    S --;
}
```

Generally implemented without busy waiting using *sleep()* and *wakeup()*.

```
signal (S) { // originally called V(S)
    S++;
}
```



Re-Exam 21/22 - how to solve?

2.2 Short Questions (about 12 %)

Question 2.2.1: Consider two threads performing the following semaphore operations.

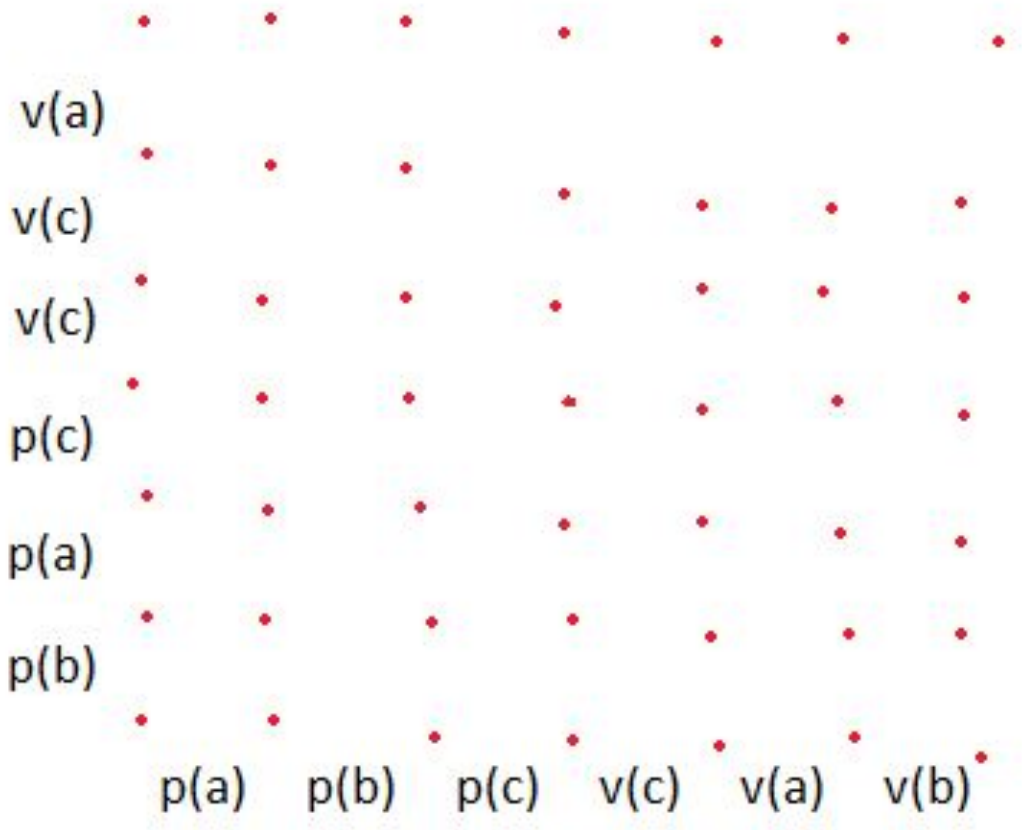
```
Initially: a = 1; b = 1; c = 1;

Thread 1:        Thread 2:
P(a);            P(b);
P(b);            P(a);
P(c);            P(c);
V(c);            V(c);
V(a);            V(b);
V(b);            V(a);
```

Draw a process graph with thread 1 along the horizontal axis and thread 2 along the vertical axis, show the forbidden regions, and argue whether this means deadlocks are possible or not. (You are welcome to attached the figure as an image in the handin.)

(Warning)

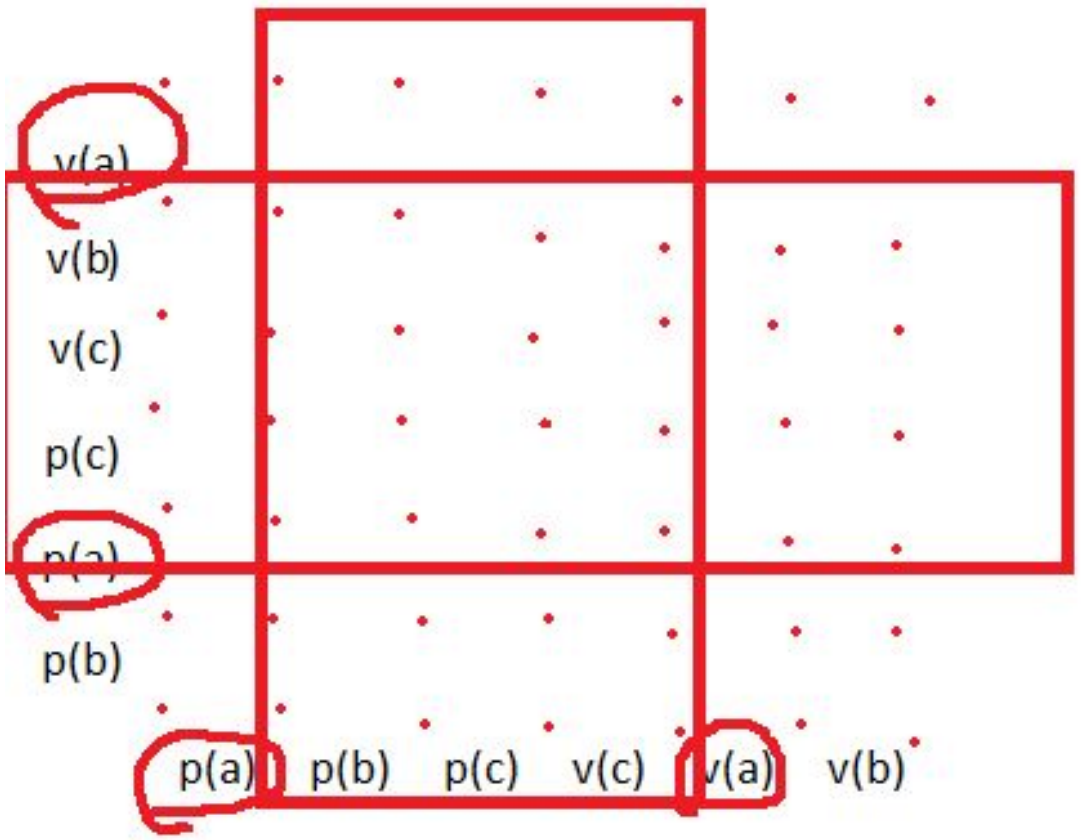
- I accidentally swapped thread 1 and thread 2 in the exercises I will show. It does not alter the correctness, just keep it in mind. You might also want to have it correct in the exam

Re-Exam 21/22 - how to solve?



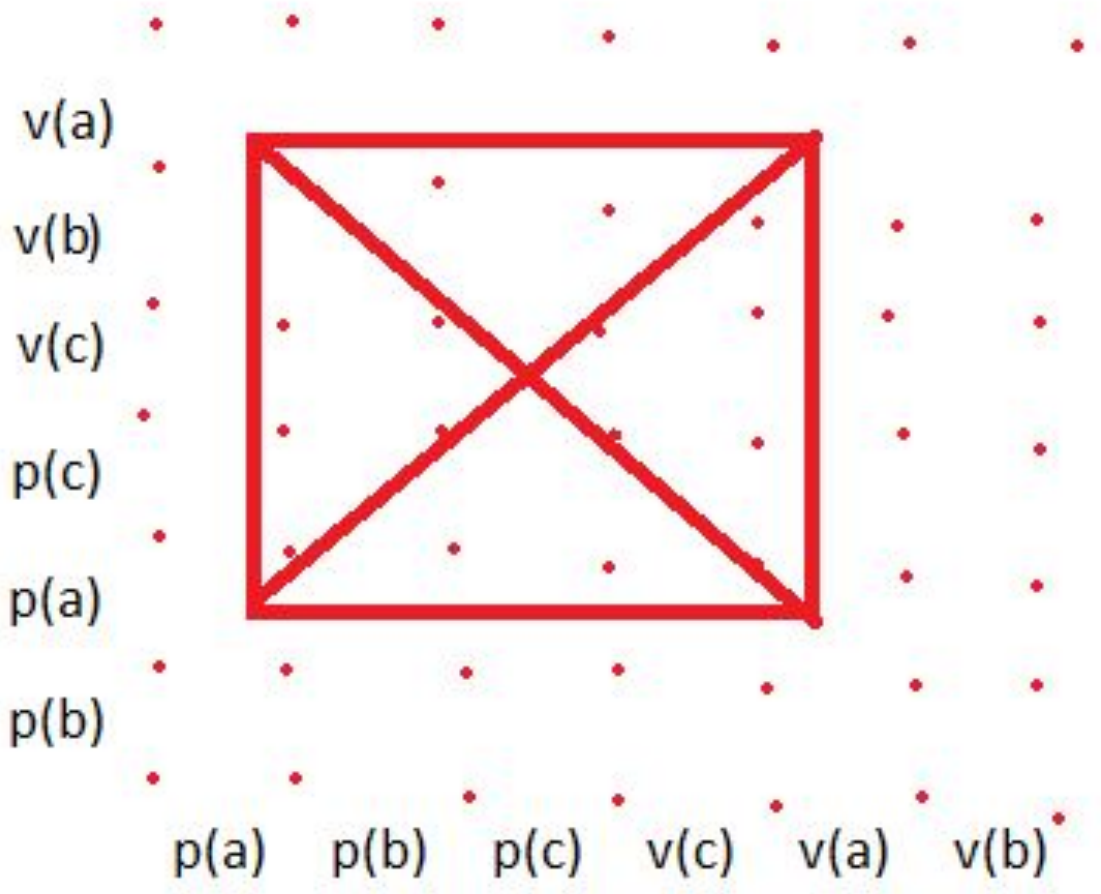
- One thread along the bottom
- The other thread along the top
- If moving right, one thread is progressing
- If moving up, the other thread is progressing
- Every p() or v() is a transition from 1 dot to another, where that action now happened

Re-Exam 21/22 - how to solve?



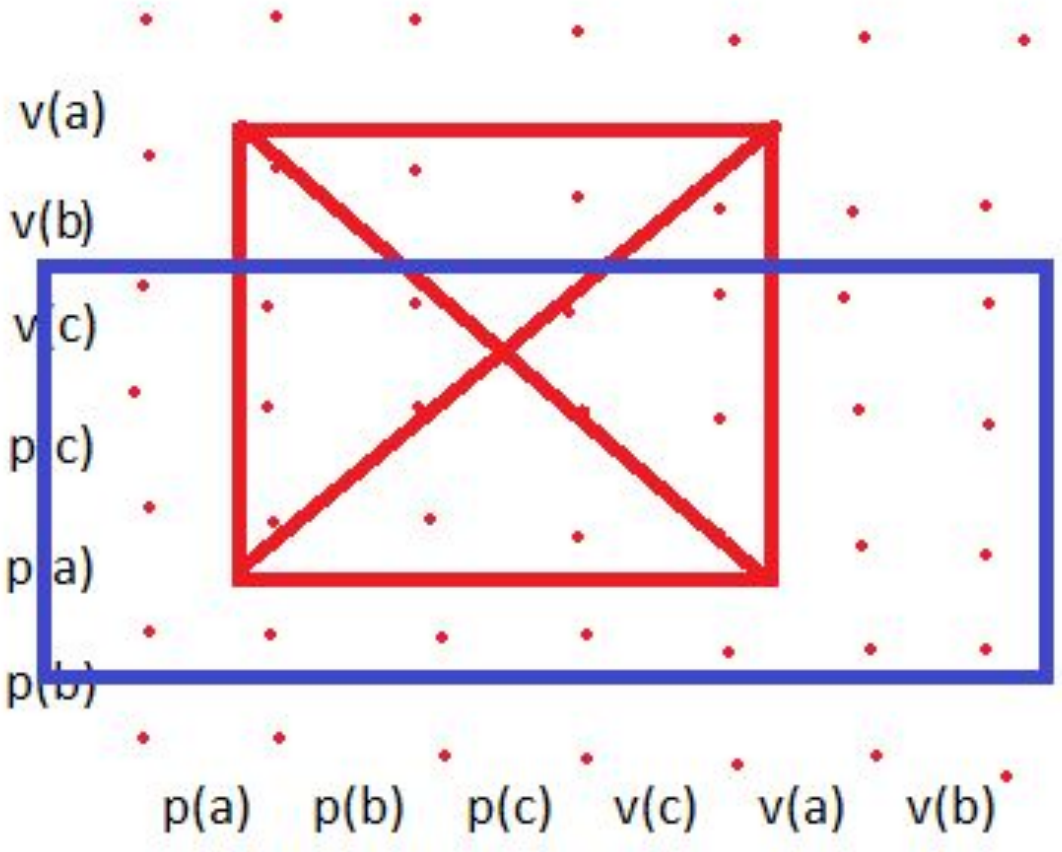
- Where is variable a locked?
- from p(a) until v(a)
- The place where both of them lock variable a is forbidden, simply put, we cannot go there on the graph as the semaphore does not allow 2 to access at the same time.

Re-Exam 21/22 - how to solve?



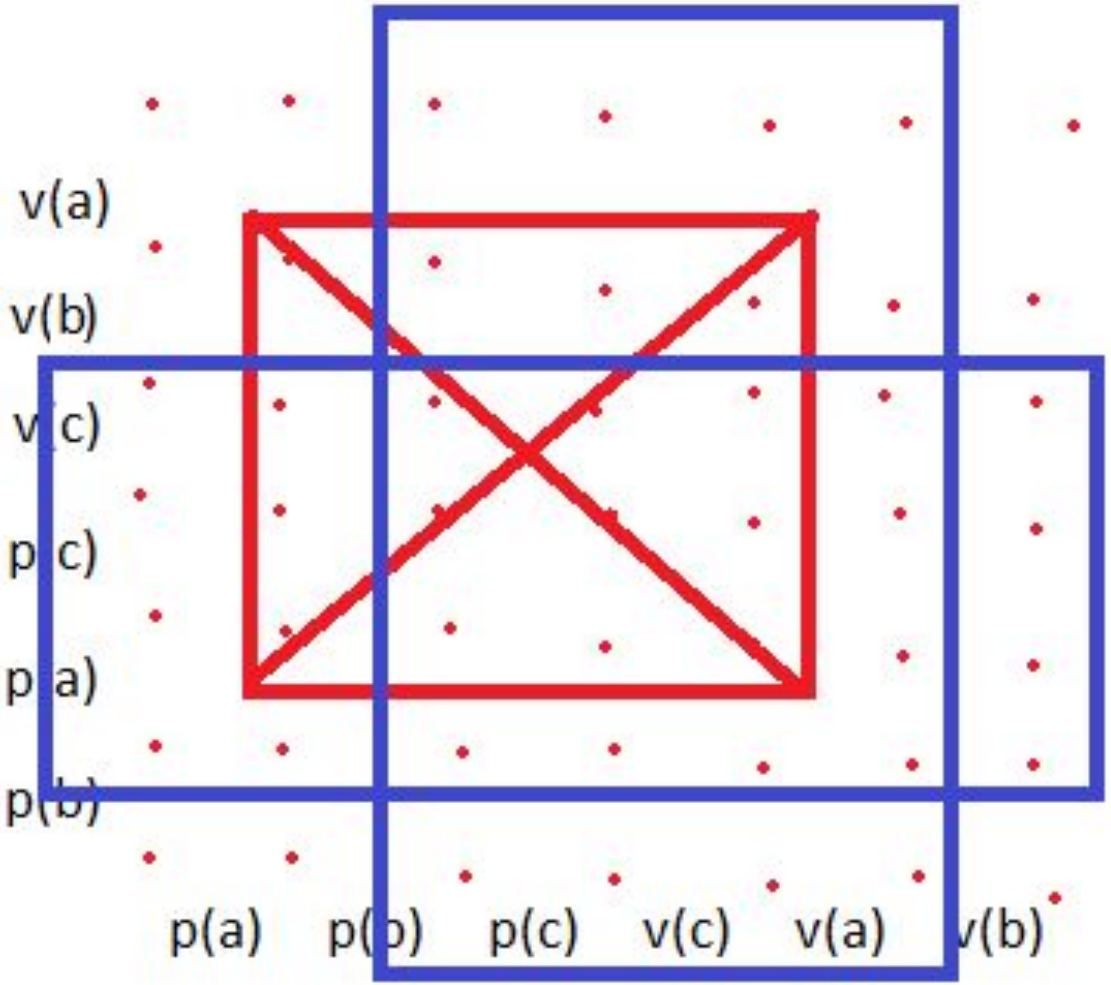
- Where is variable a locked?
- from p(a) until v(a)
- The place where both of them lock variable a is forbidden, simply put, we cannot go there on the graph as the semaphore does not allow 2 to access at the same time.

Re-Exam 21/22 - how to solve?



- Where is variable b locked?

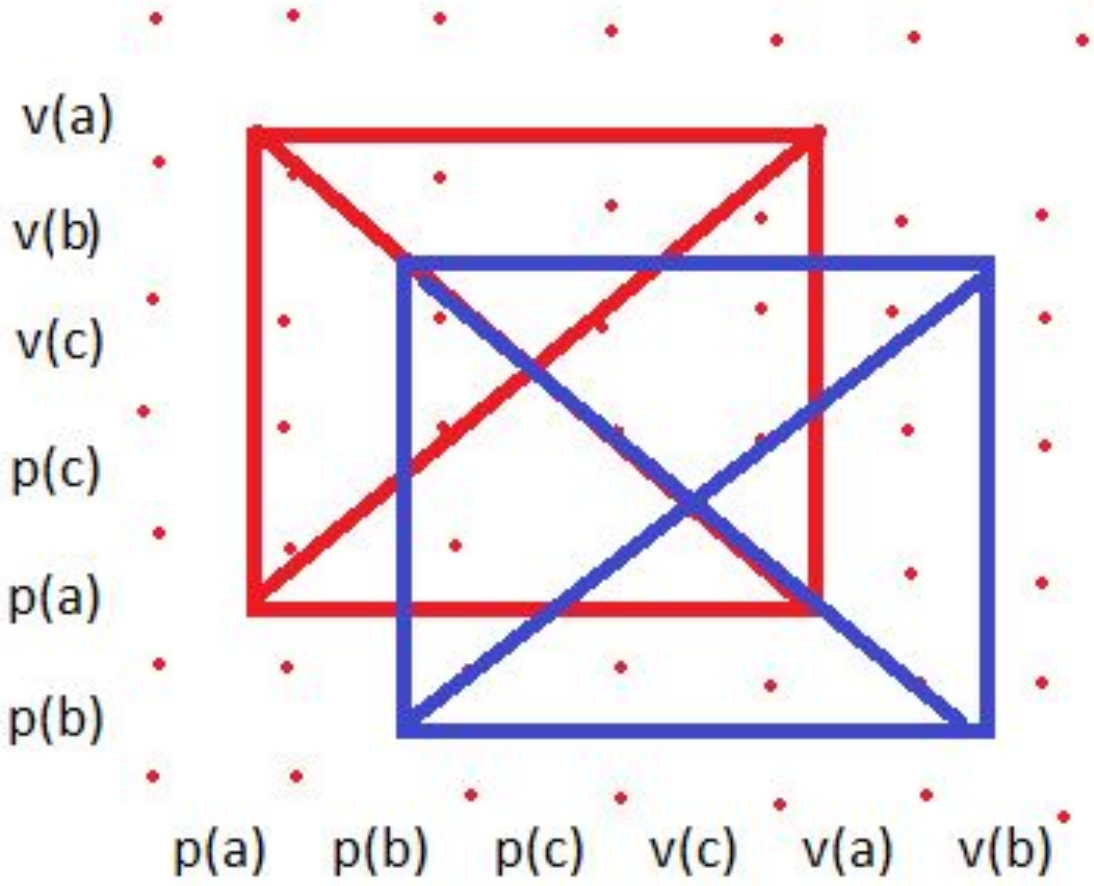
Re-Exam 21/22 - how to solve?

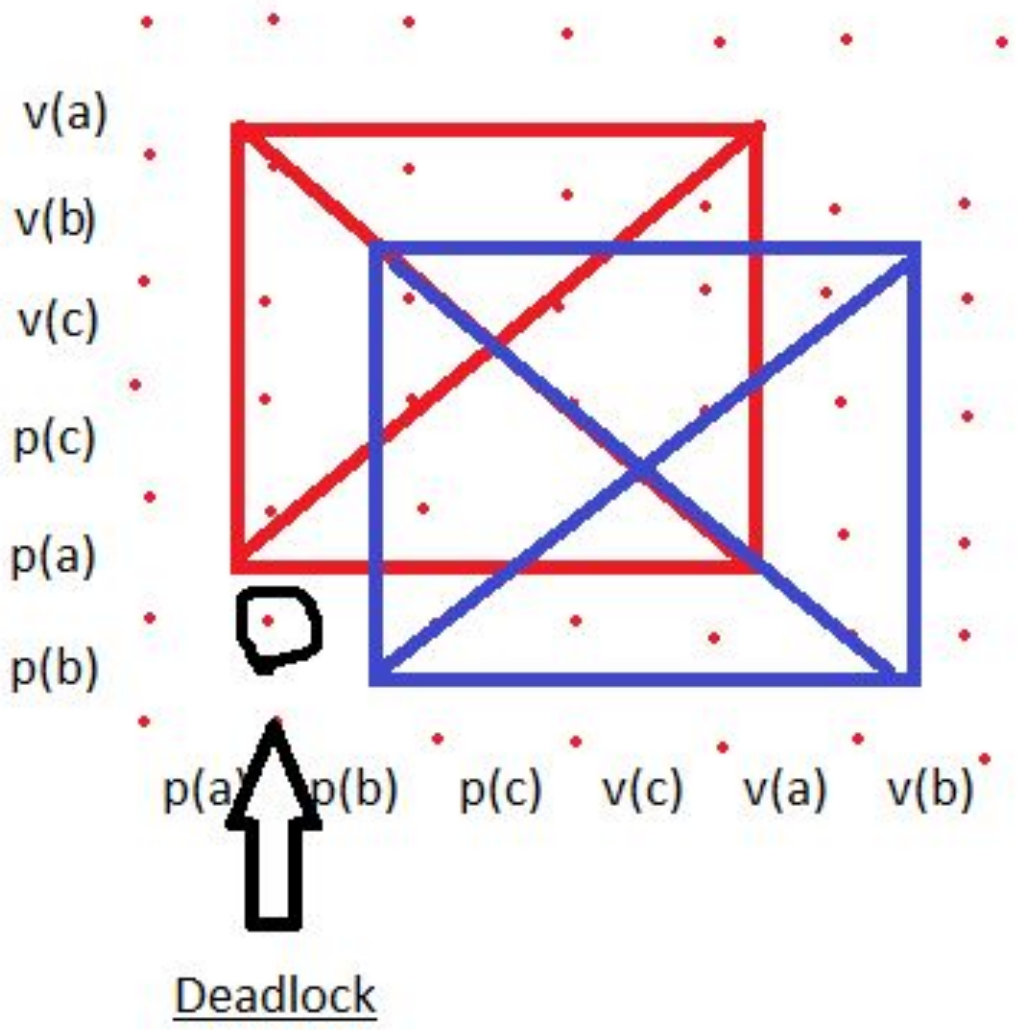


- Where is variable b locked?

Re-Exam 21/22 - how to solve?

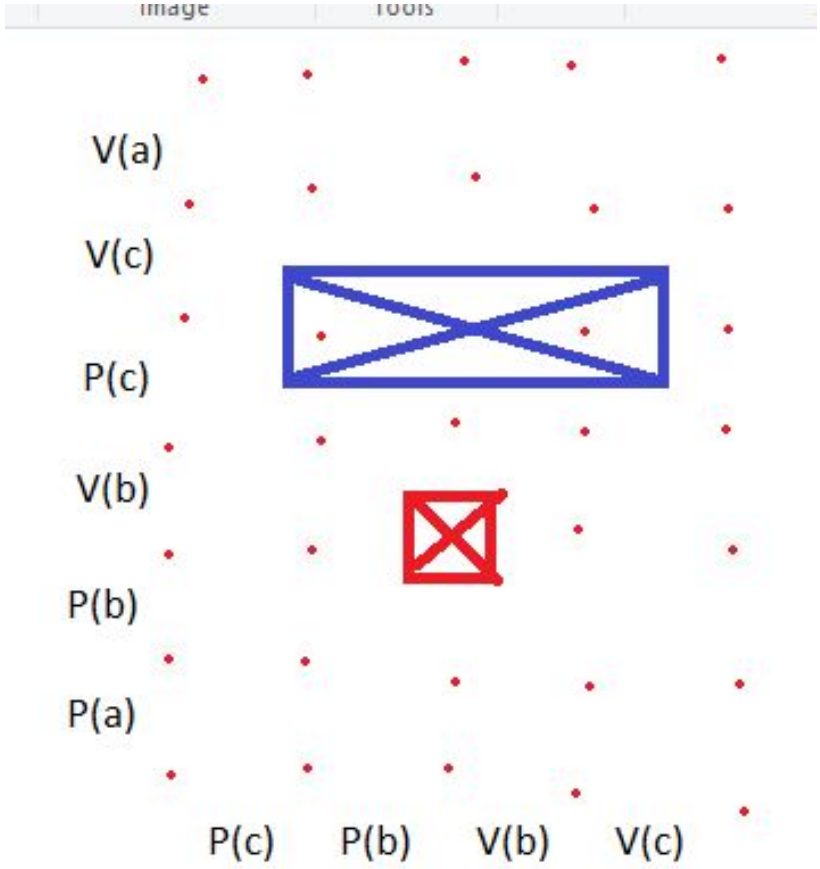
- Where is variable b locked?





- The question was whether a deadlock existed
- Argumentation: “A deadlock is possible, as in this spot, you may go neither up nor right”
- (Checking c not necessary)

Another (quick) example from exam 21/22



2.2 Short Questions (about 12 %)

Question 2.2.1: Consider two threads per

Initially: a = 1; b = 1; c = 1;

Thread 1:	Thread 2:
P(a);	P(c);
P(b);	P(b);
V(b);	V(b);
P(c);	V(c);
V(c);	
V(a);	

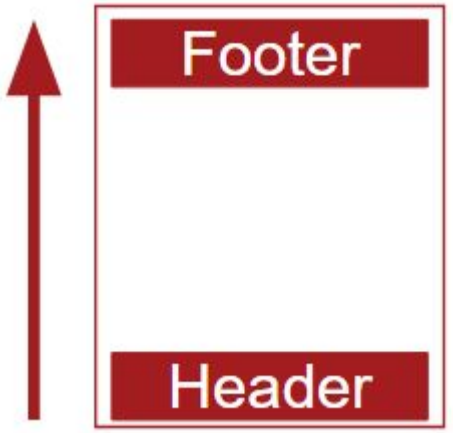
Can always proceed right or up = no deadlock exists

(Again, I swapped the threads, oops)

Now onto the heap

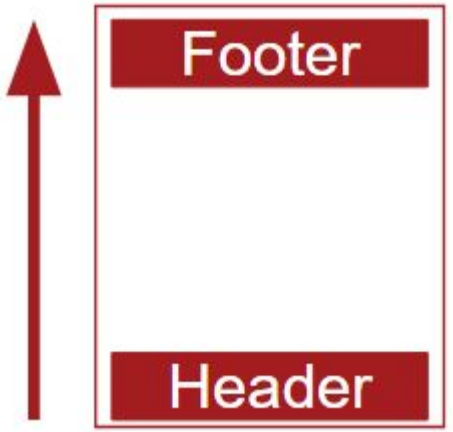
Firstly…

- The heap grows bottom-up

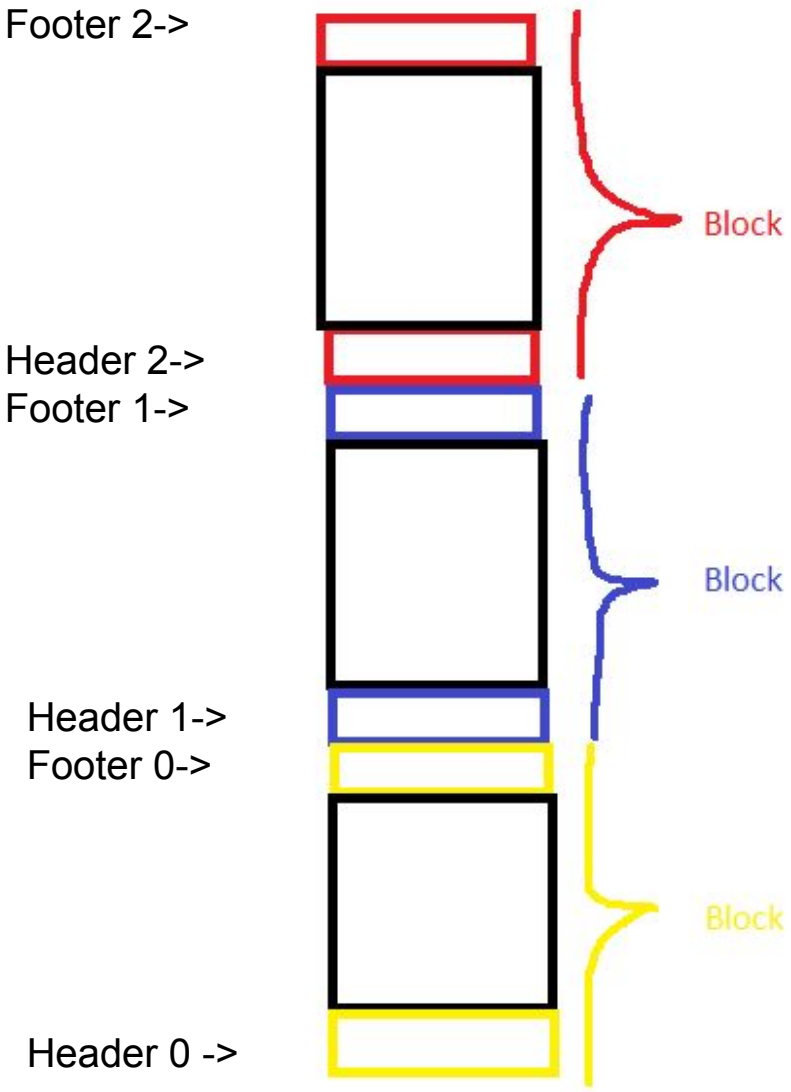


Firstly…

- The heap grows bottom-up
- The footer and header contain information about the block including its size. Since they represent the same block the footer and header have the same value
- The size of a block is always a multiple of 8
- Each address represents 4 bytes of space



A heap might look like this



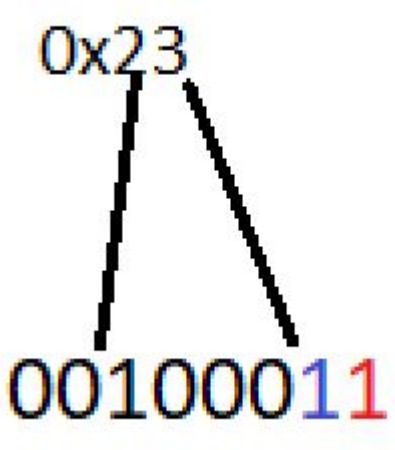
Address	Original value
0x500c028	0x00000013
0x500c024	0x500c611c
0x500c020	0x500c512c
0x500c01c	0x00000013
0x500c018	0x00000013
0x500c014	0x500c511c
0x500c010	0x500c601c
0x500c00c	0x00000013
0x500c008	0x00000013
0x500c004	0x500c601c
0x500c000	0x500c511c
0x500bffc	0x00000013

What do the bits represent?

- (In general always check the rules, they might change)
- Bit 0 represents whether the current block is allocated'
- Bit 1 represents whether the previous block is allocated
- Bit 2 is always 0
- Instant coalescing (explained more later)
- Example:

What do the bits represent?

- (In general always check the rules, they might change)
- Bit 0 represents whether the current block is allocated'
- Bit 1 represents whether the previous block is allocated
- Bit 2 is always 0
- Instant coalescing (explained more later)
- Example:



- Is allocated
- Previous is allocated
- Size is gotten by setting the 3 lower bits to 0:

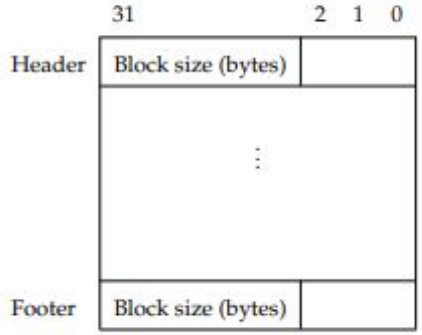
  00100011 -> 00100000 = 0x20 or 32

- (Size is inclusive header and footer)

Let's get started (Exam 21/22)

2.3 Long Questions (about 14 %)

Question 2.3.1: Consider an allocator that uses an implicit free list and immediate coalescing of neighbouring free blocks. The layout of each allocated and free memory block is as follows, with one 32-bit word per row:



Each memory block, either allocated or free, has a size that is a multiple of eight bytes, rounding up allocations if necessary. Thus, only the 29 higher order bits in the header and footer are needed to record block size, which includes the header and footer. The usage of the remaining 3 lower order bits is as follows:

- `bit 0` indicates the use of the current block: 1 for allocated, 0 for free.
- `bit 1` indicates the use of the previous adjacent block: 1 for allocated, 0 for free.
- `bit 2` is unused and is always set to be 0.

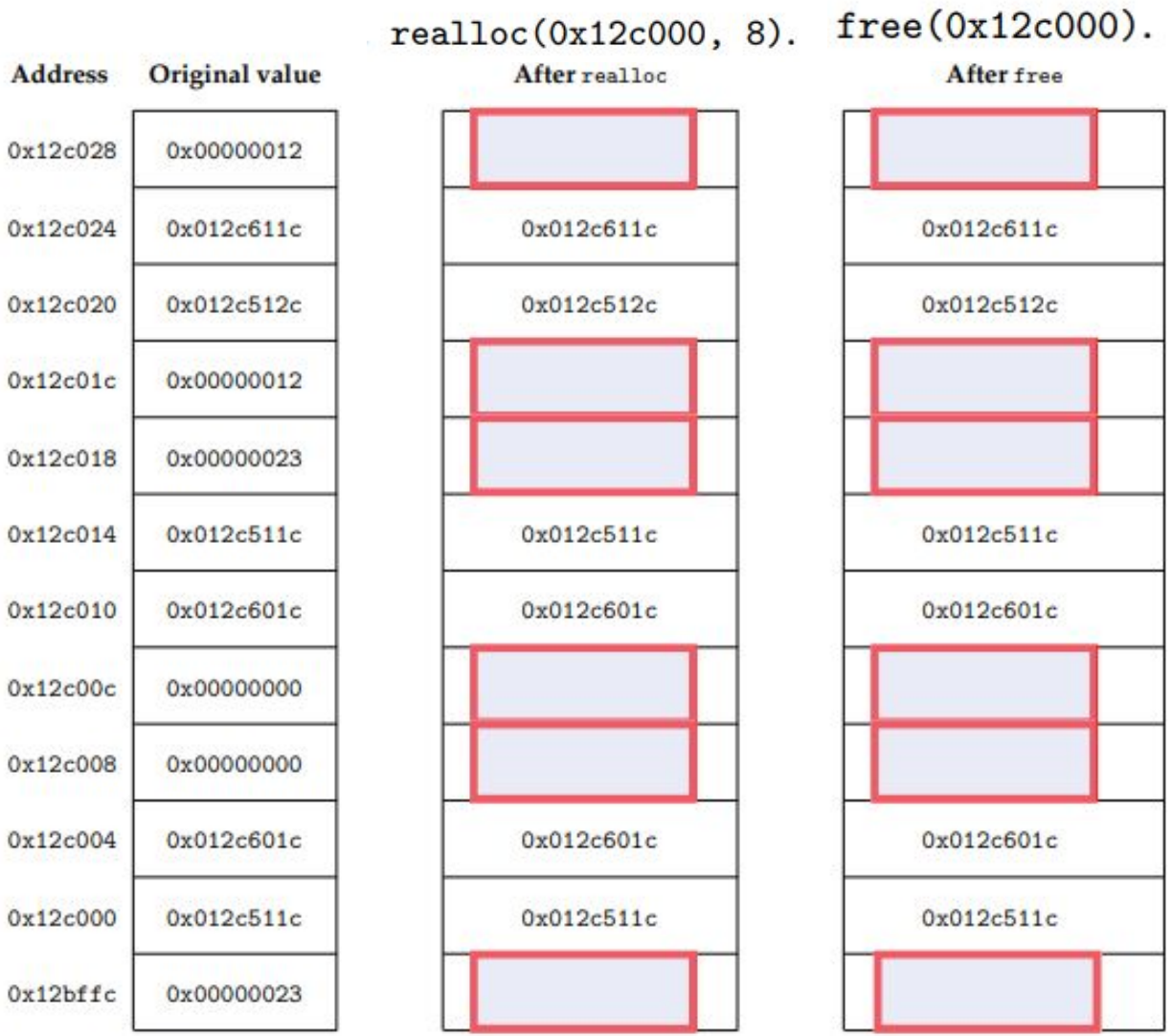
Important: We must *never* create blocks with zero payload (i.e. we must *never* create blocks with size 8).

Given the heap shown on the left, show the new heap contents after *consecutive* calls to

1. `realloc(0x12c000, 8)`. Assume the the return value is `0x12c000`, and that the existing allocation is resized to be as small as possible.
2. `free(0x12c000)`.

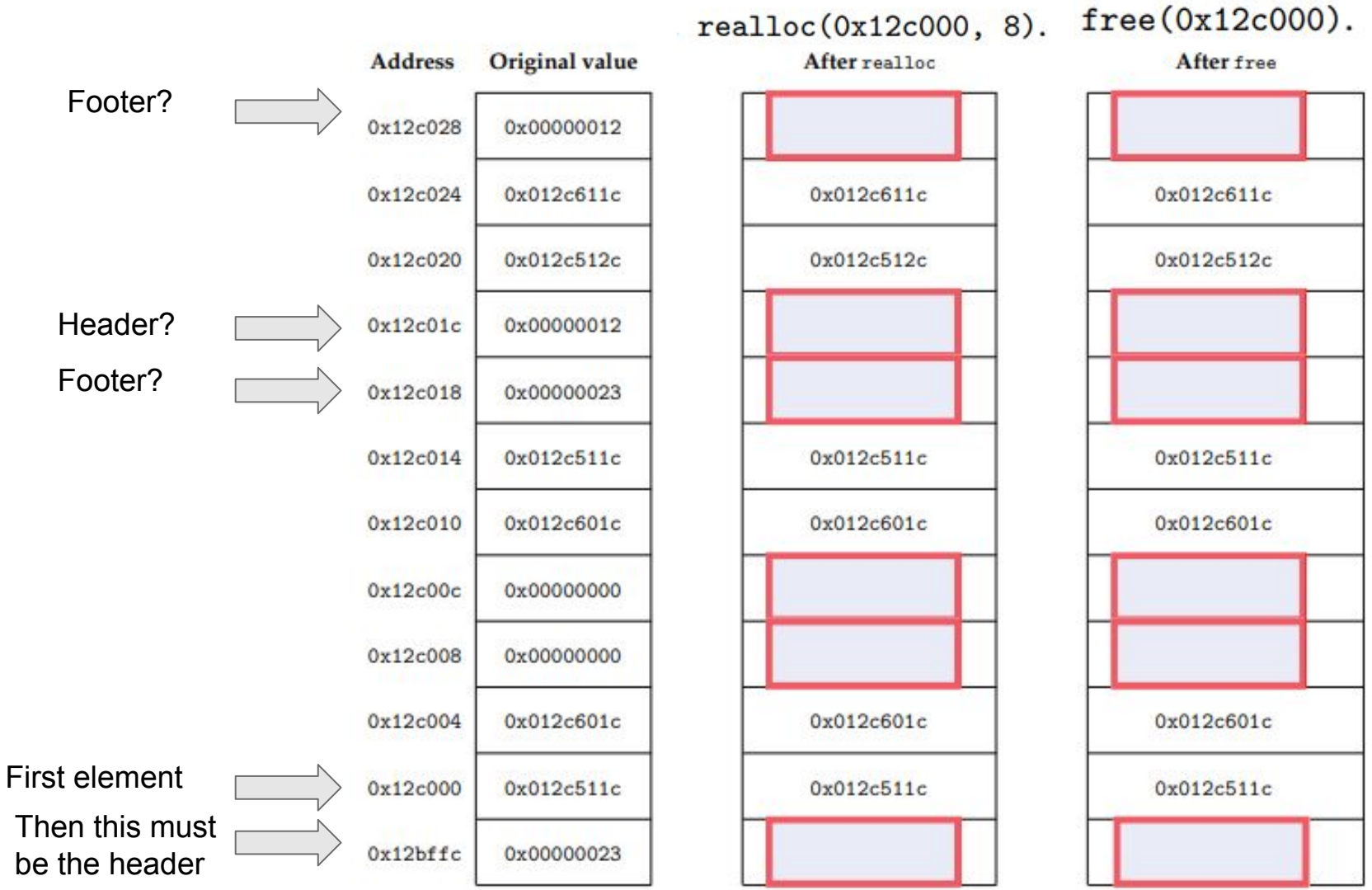
Your answers should be given as hex values. Note that the address grows from bottom up. Assume that the allocator uses immediate coalescing, that is, adjacent free blocks are merged immediately each time a block is freed.

- You are given a realloc() free() or malloc()
- Given this information, along with an initial heap, transform the heap accordingly



First element

Then this must be the header


realloc(0x12c000, 8).
free(0x12c000).
Address
Original value
After realloc
After free
Footer?
Header?
Footer?
First element
Then this must be the header
0x12c028 0x00000012
0x12c024 0x012c611c
0x12c020 0x012c512c
0x12c01c 0x00000012
0x12c018 0x00000023
0x12c014 0x012c511c
0x12c010 0x012c601c
0x12c00c 0x00000000
0x12c008 0x00000000
0x12c004 0x012c601c
0x12c000 0x012c511c
0x12bffc 0x00000023

Footer?

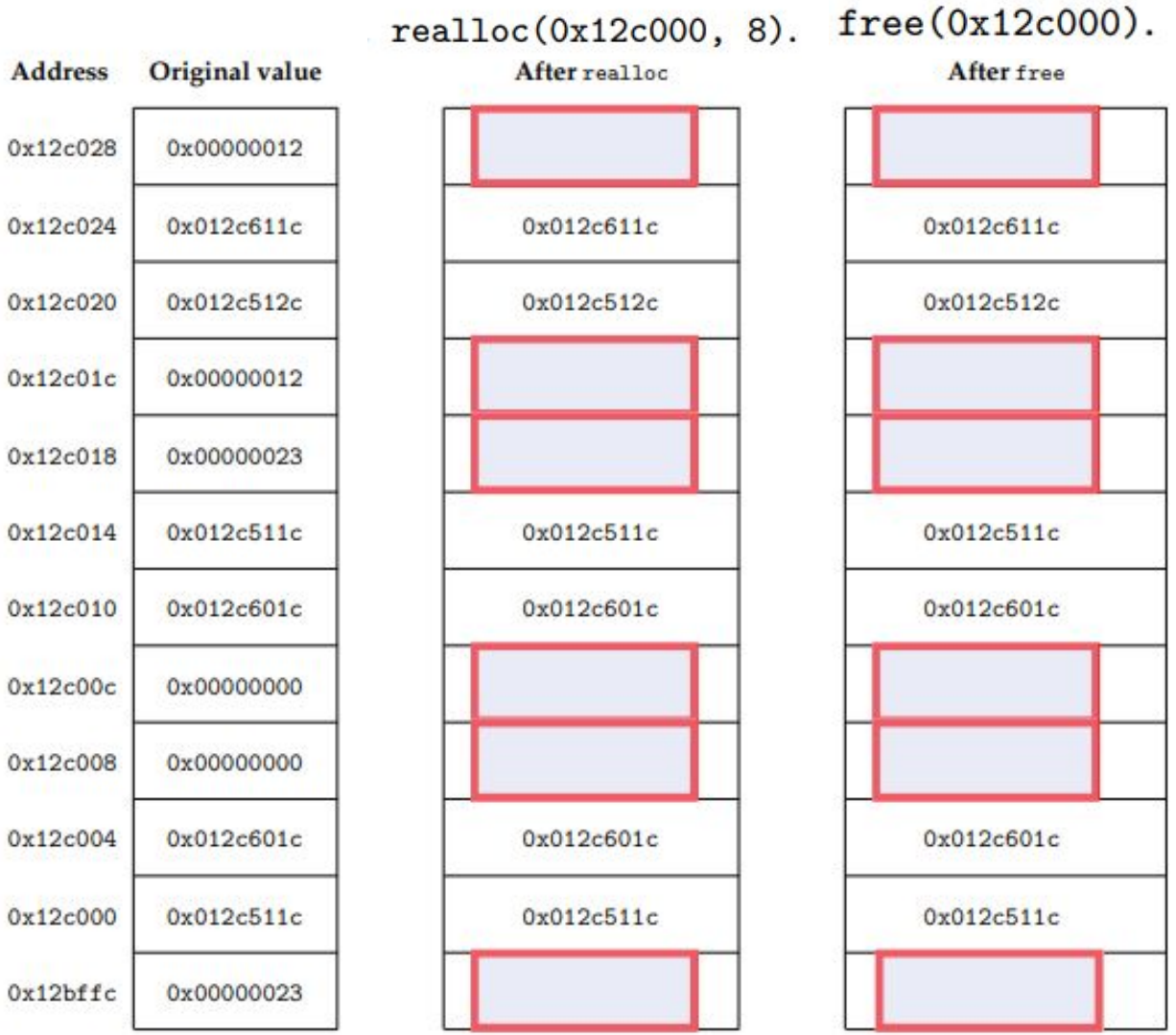
Header?

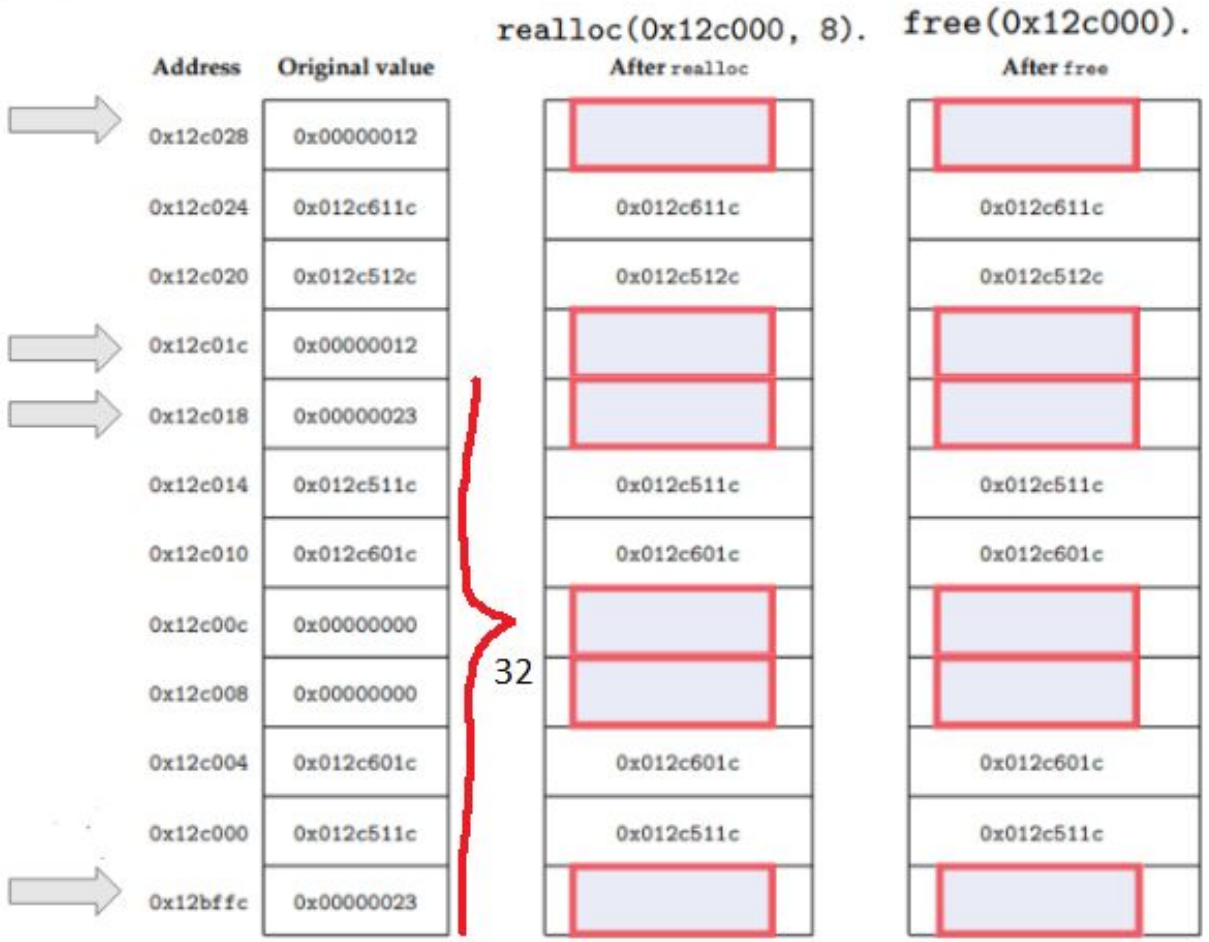
Footer?

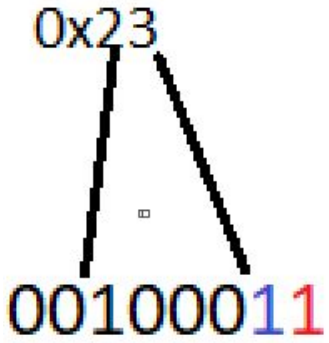
Watch out for traps, try to be certain by looking at the size instead of just guessing

First element

Then this must be the header



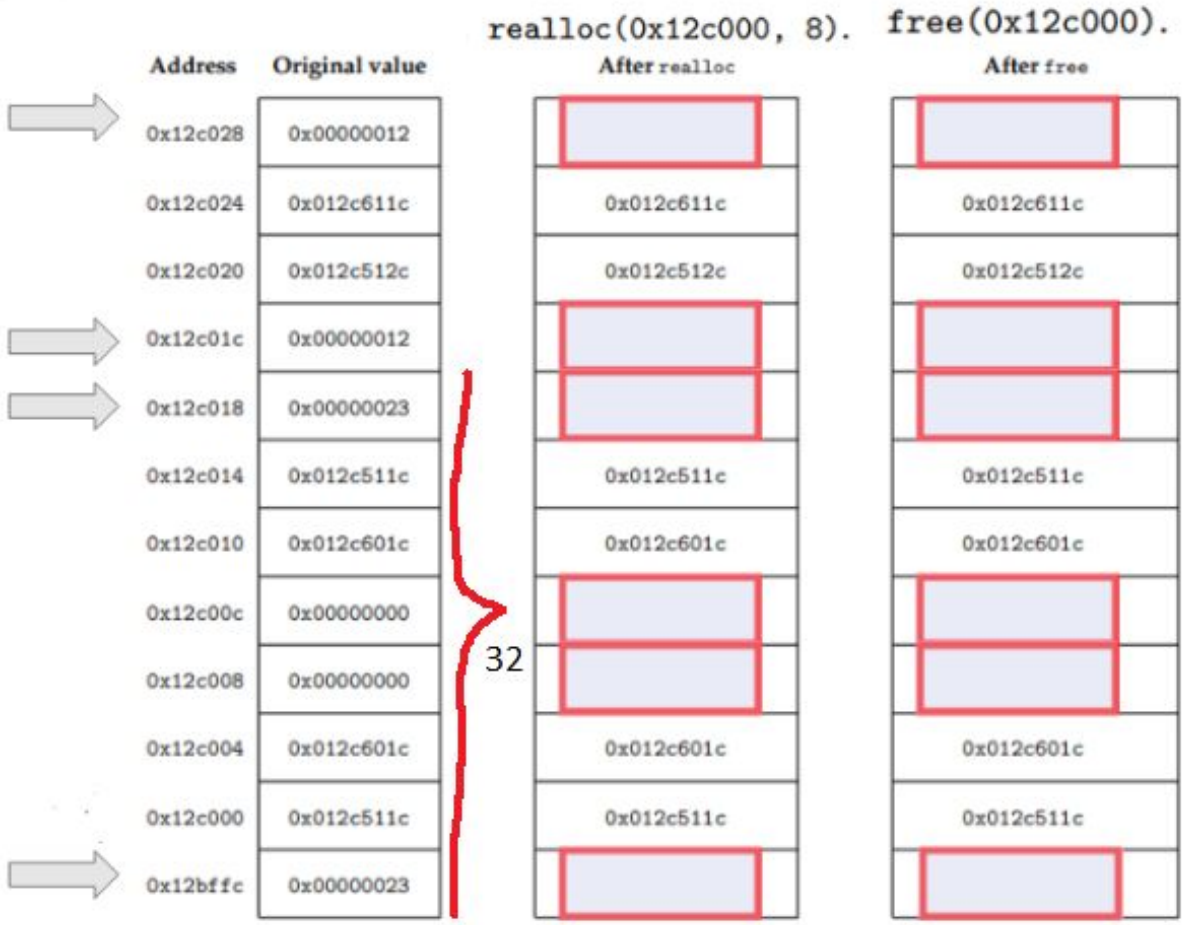


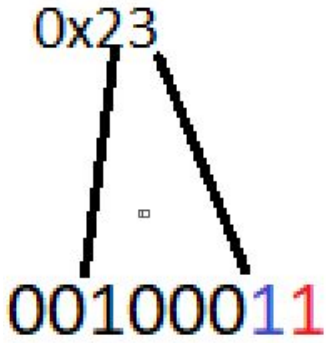


Is allocated

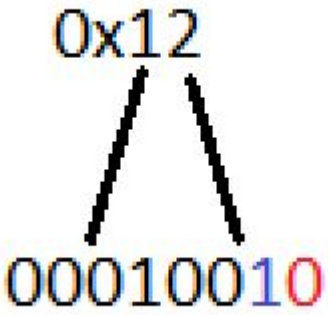
Previous is allocated

Size = 00100000 = 0x23 = 32

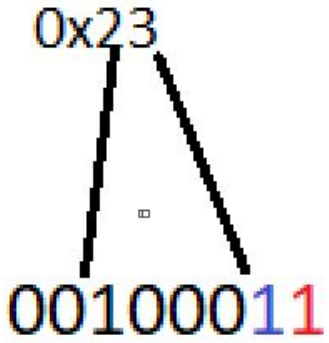




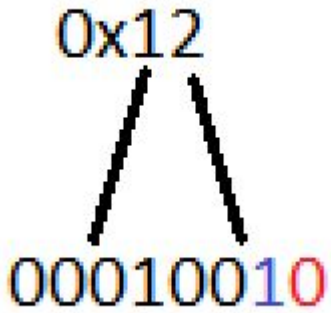
Is allocated
Previous is allocated
Size = 00100000 = 0x20 = 32



Is not allocated
Previous is allocated
Size = 00010000 = 0x10 = 16



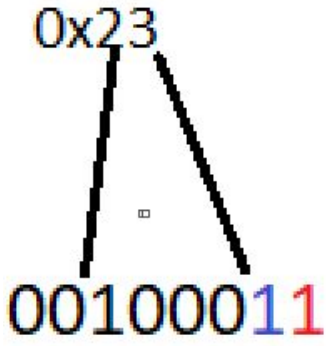
Is allocated
Previous is allocated
Size = 00100000 = 0x20 = 32



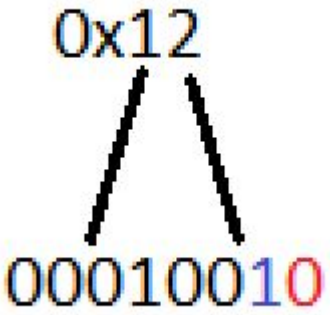
Is not allocated
Previous is allocated
Size = 00010000 = 0x10 = 16

`realloc(0x12c000, 8).` `free(0x12c000).`

Address	Original value	After `realloc`	After `free`
0x12c028	0x00000012		
0x12c024	0x012c611c	0x012c611c	0x012c611c
0x12c020	0x012c512c	0x012c512c	0x012c512c
0x12c01c	0x00000012		
0x12c018	0x00000023		
0x12c014	0x012c511c	0x012c511c	0x012c511c
0x12c010	0x012c601c	0x012c601c	0x012c601c
0x12c00c	0x00000000		
0x12c008	0x00000000		
0x12c004	0x012c601c	0x012c601c	0x012c601c
0x12c000	0x012c511c	0x012c511c	0x012c511c
0x12bffc	0x00000023		



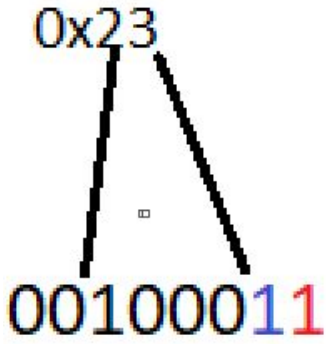
Is allocated
Previous is allocated
Size = 00100000 = 0x20 = 32



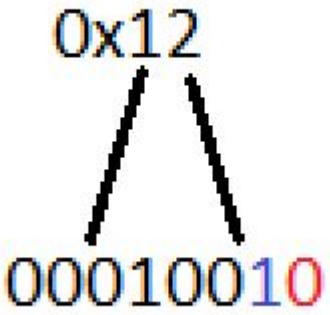
Is not allocated
Previous is allocated
Size = 00010000 = 0x10 = 16

`realloc(0x12c000, 8).` `free(0x12c000).`

Address	Original value	After realloc	After free
0x12c028	0x00000012		
0x12c024	0x012c611c	0x012c611c	0x012c611c
0x12c020	0x012c512c	0x012c512c	0x012c512c
0x12c01c	0x00000012		
0x12c018	0x00000023		
0x12c014	0x012c511c	0x012c511c	0x012c511c
0x12c010	0x012c601c	0x012c601c	0x012c601c
0x12c00c	0x00000000		
0x12c008	0x00000000		
0x12c004	0x012c601c	0x012c601c	0x012c601c
0x12c000	0x012c511c	0x012c511c	0x012c511c
0x12bffc	0x00000023		



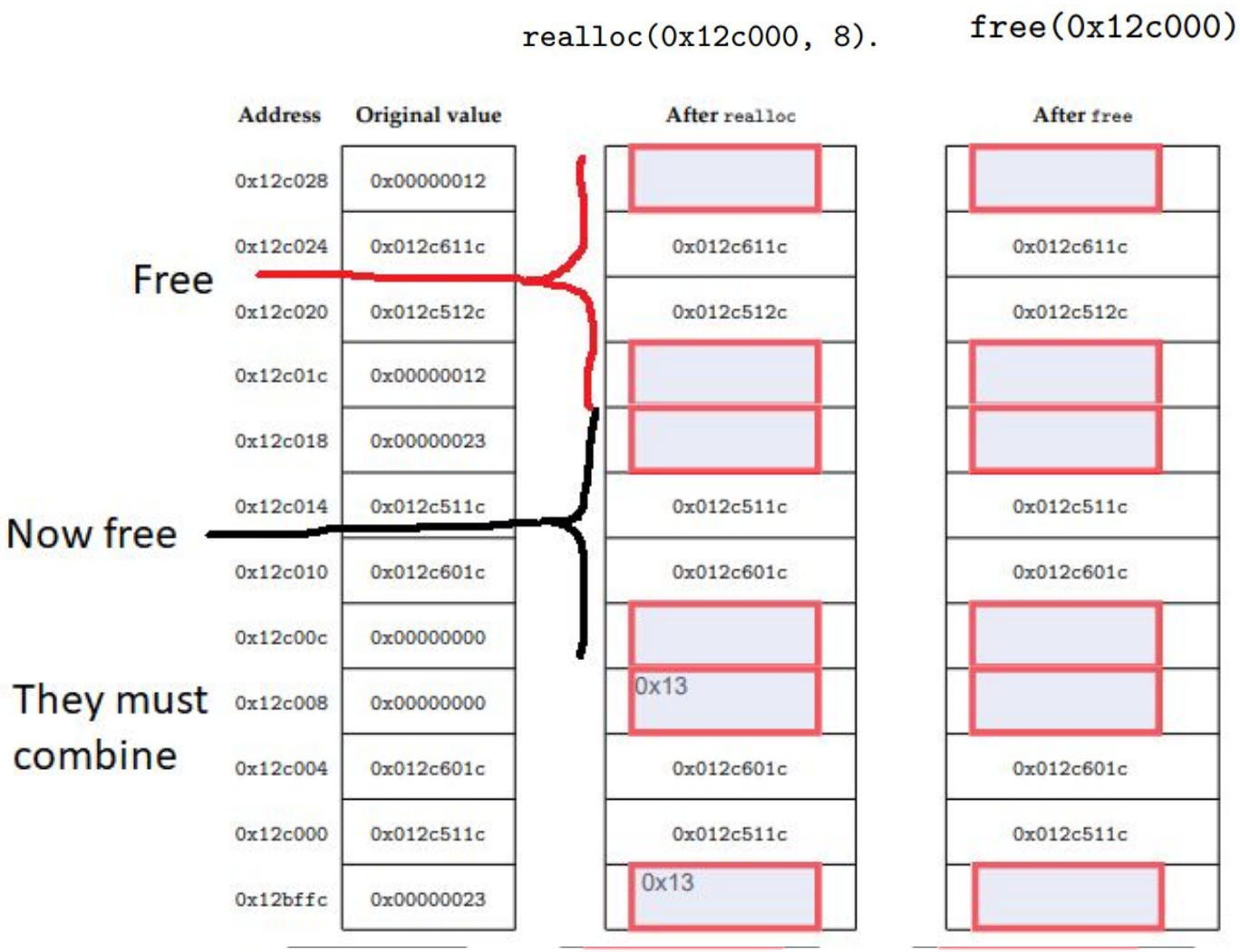
Is allocated
Previous is allocated
Size = 00100000 = 0x20 = 32

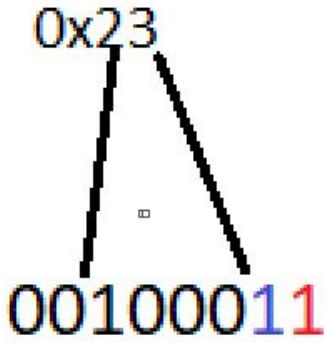


Is not allocated
Previous is allocated
Size = 00010000 = 0x10 = 16

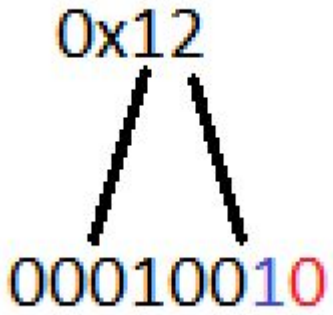
new size is 16, (8 + header/footer)
it will be allocated (via realloc())
The previous was allocated before, still will be

Size = 00010000, so: 00010011 = 0x13





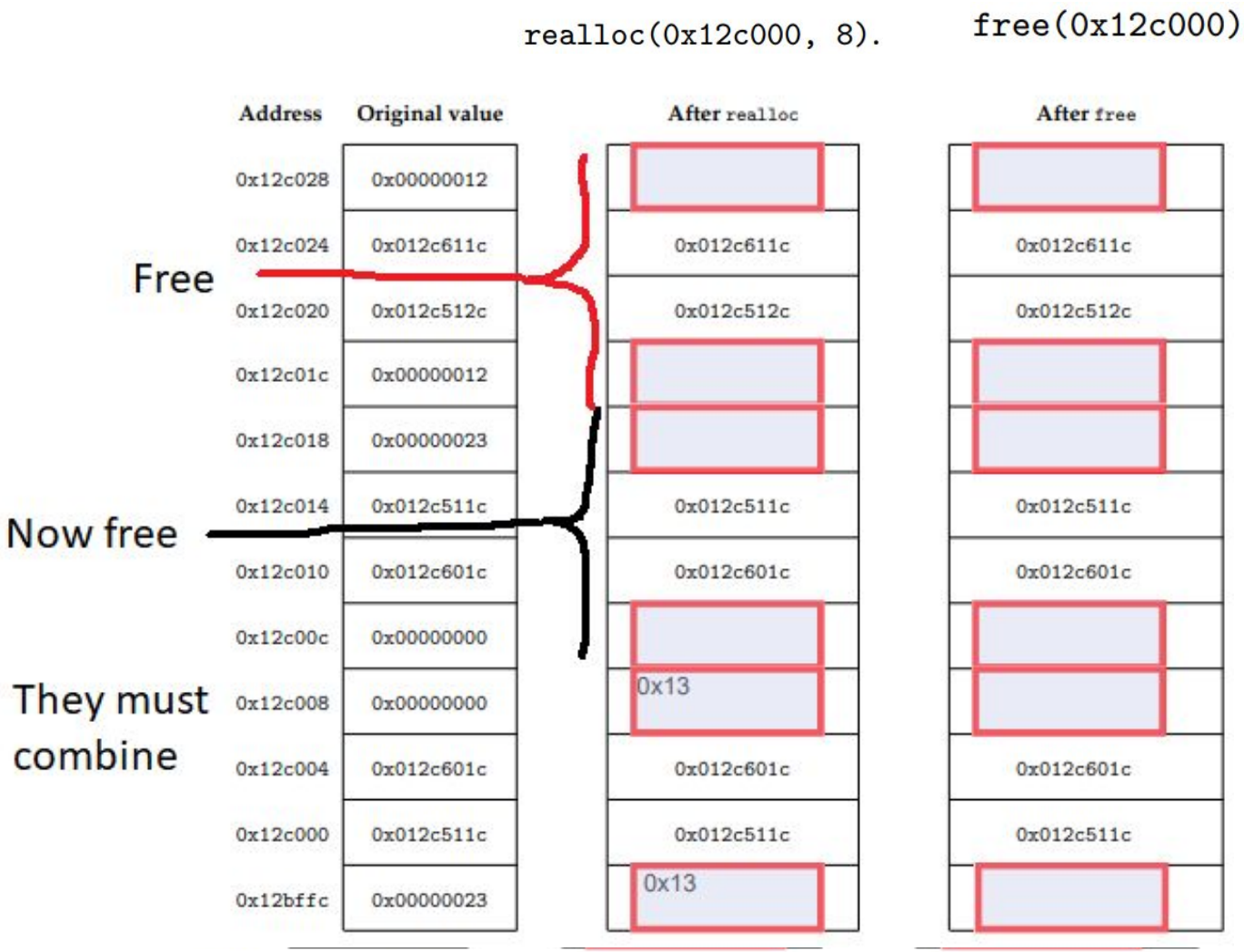
Is allocated
Previous is allocated
Size = 00100000 = 0x20 = 32

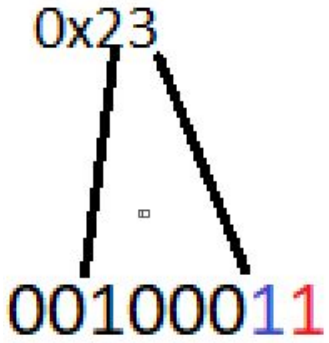


Is not allocated
Previous is allocated
Size = 00010000 = 0x10 = 16

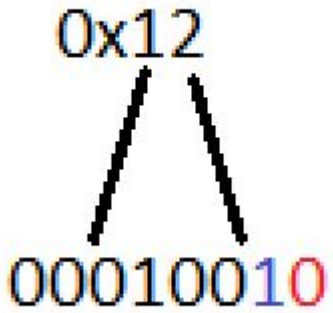
new size is 16, (8 + header/footer)
it will be allocated (via realloc())
The previous was allocated before, still will be

Size = 00010000, so: 00010011 = 0x13





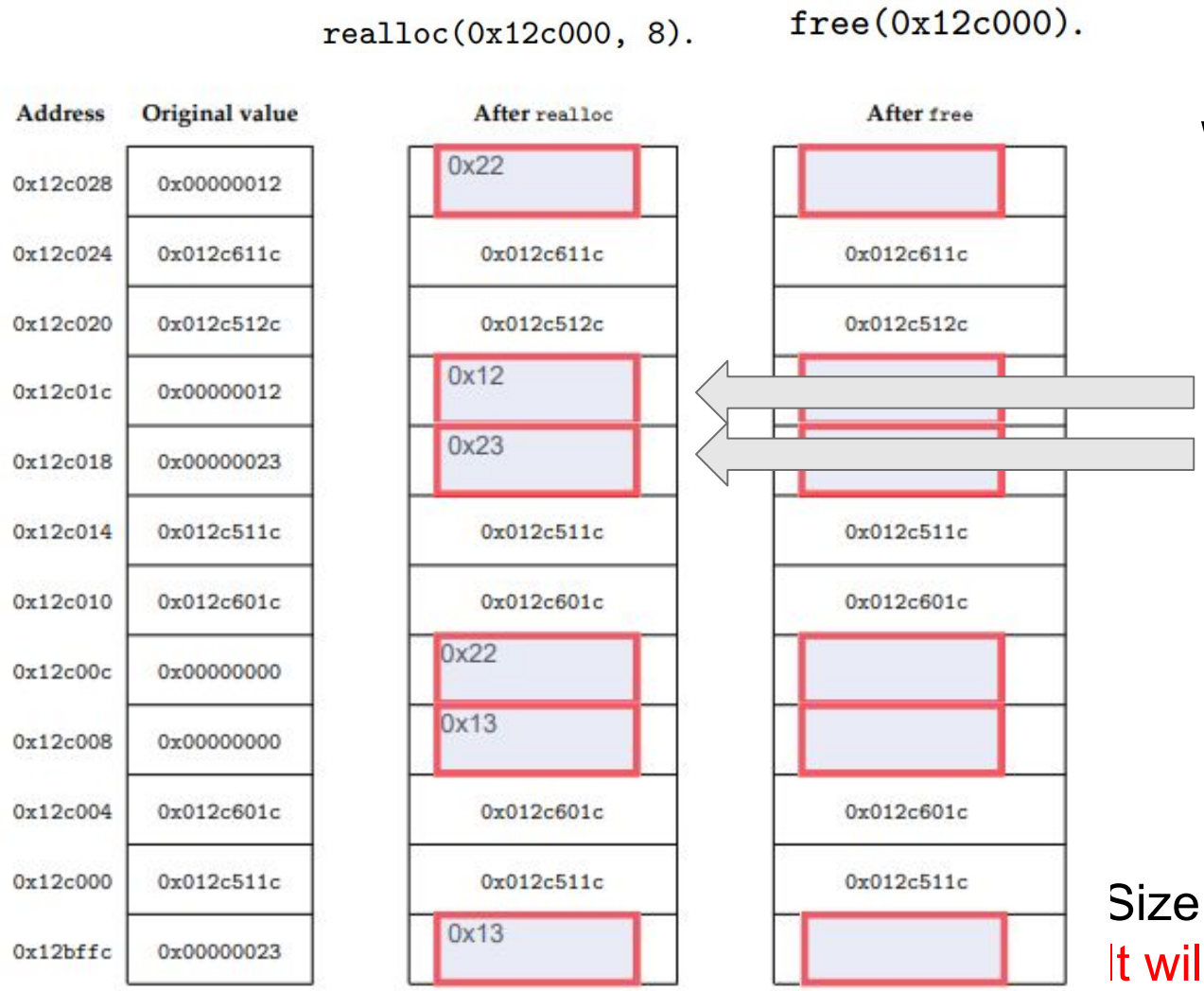
Is allocated
Previous is allocated
Size = 00100000 = 0x20 = 32



Is not allocated
Previous is allocated
Size = 00010000 = 0x10 = 16

Size will be 16+16 = 32 = 00100000
It will not be allocated
Previous is allocated (0x13 block)

so: 00100010 = 0x22

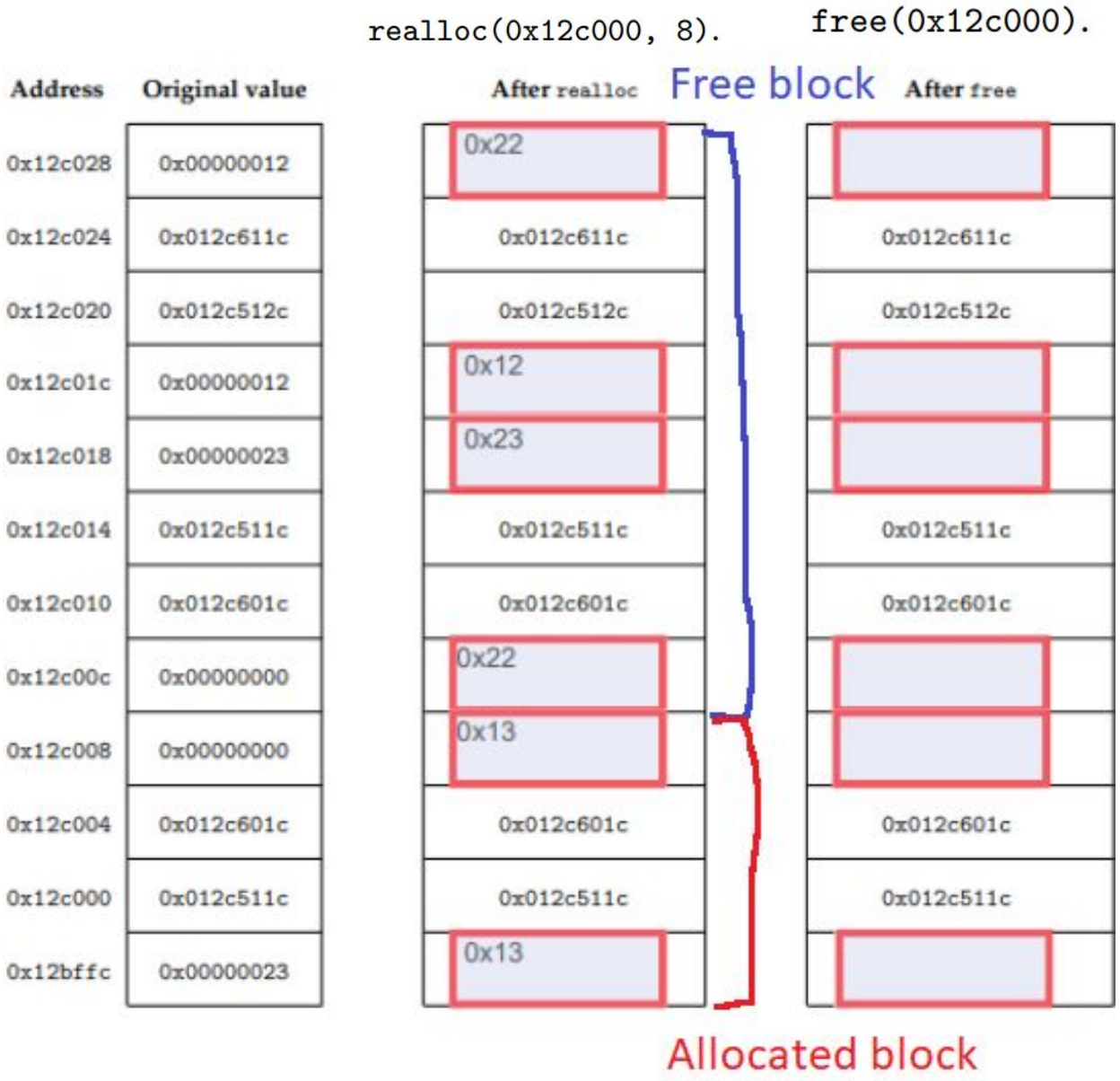


What about 0x12 and 0x23?

- They stay the same in c, we do not need to change them, so we do not. They are now essentially garbage values that are not allocated

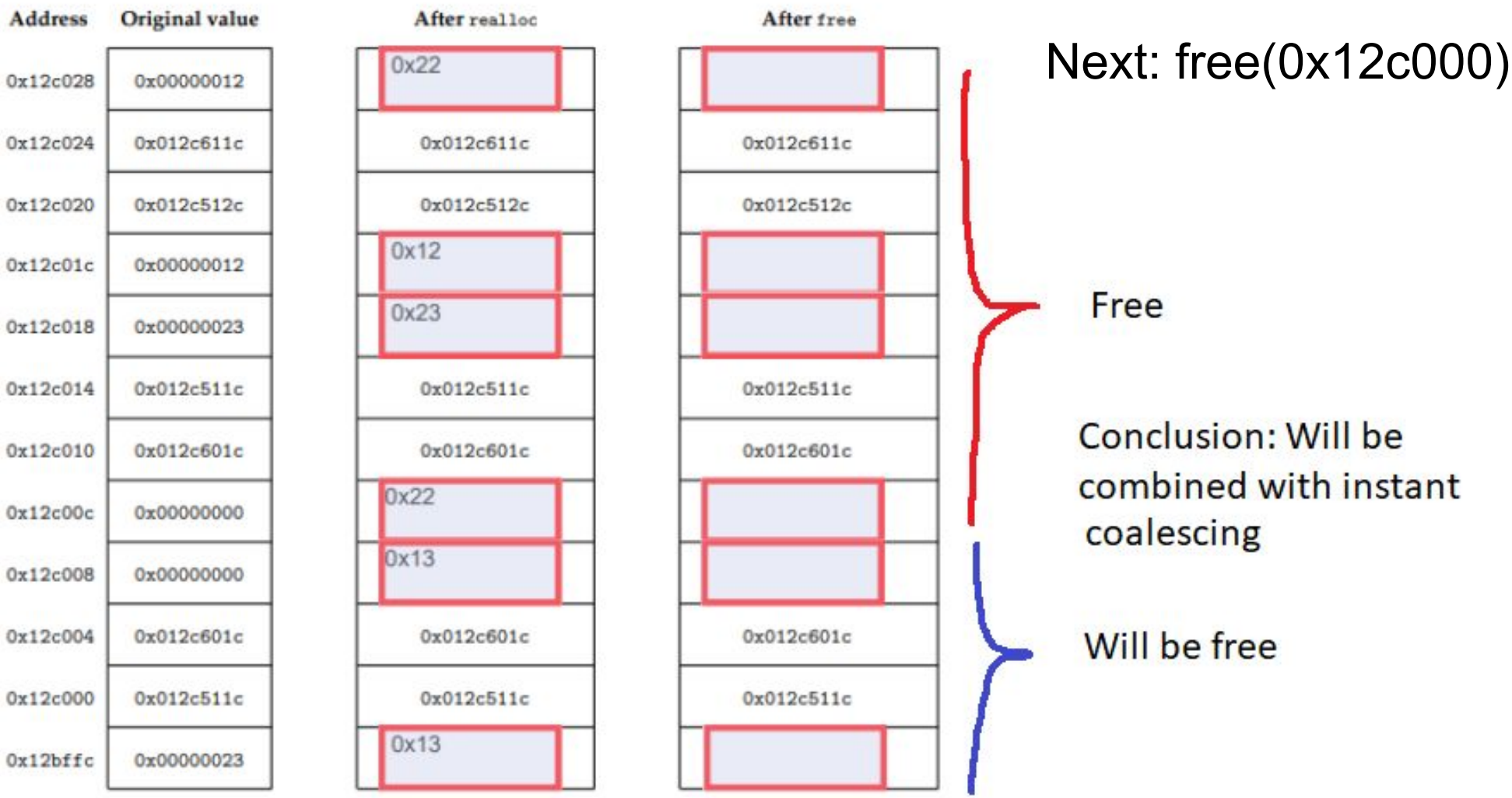
Size will be 16+16 = 32 = 00100000
It will not be allocated
Previous is allocated (0x13 block)

so: 00100010 = 0x22



Next: free(0x12c000)

`realloc(0x12c000, 8).` `free(0x12c000).`



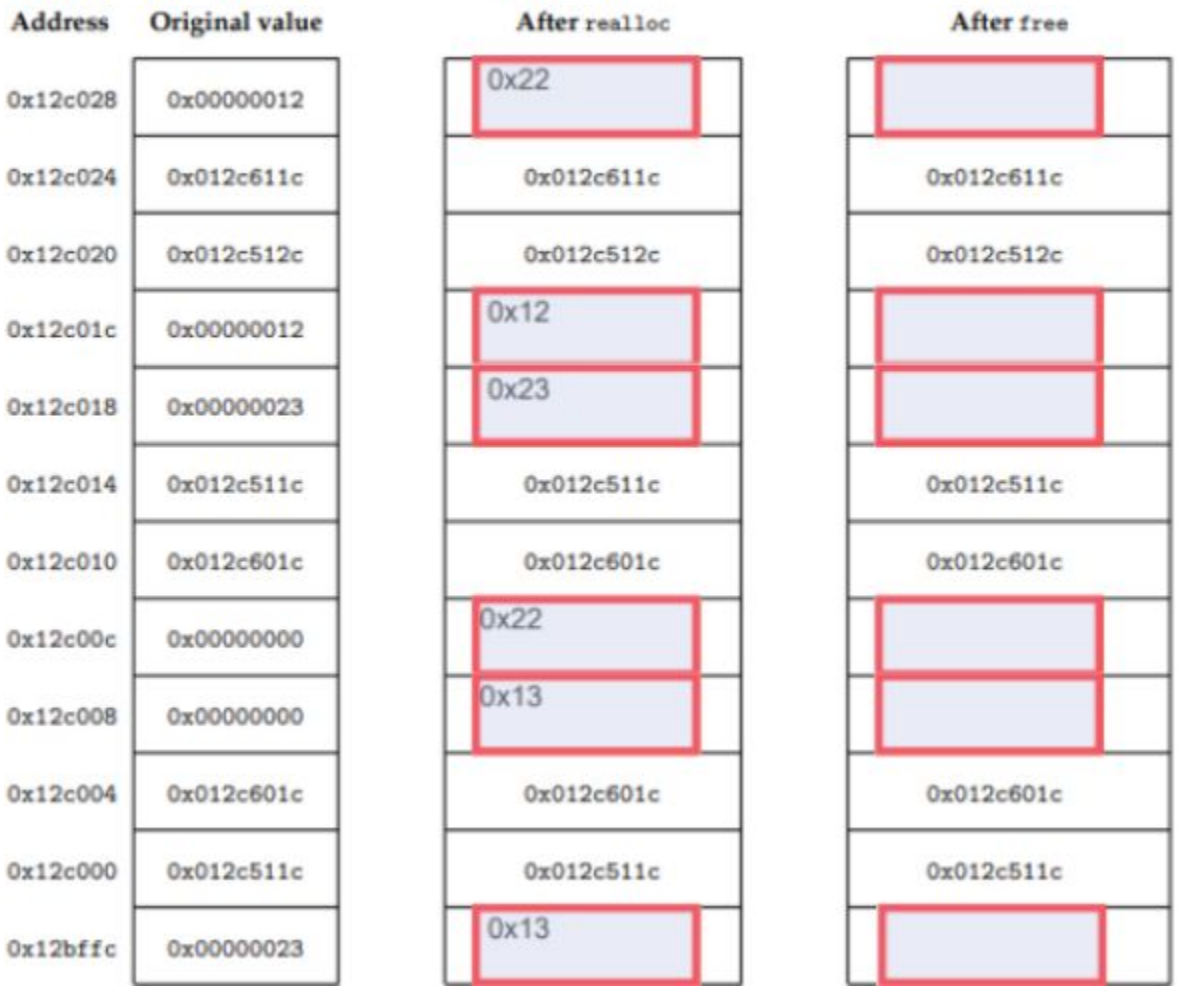
Next: free(0x12c000)

Free

Conclusion: Will be combined with instant coalescing

Will be free

`realloc(0x12c000, 8).` `free(0x12c000).`



size will be 32+16 = 00110000 (48)

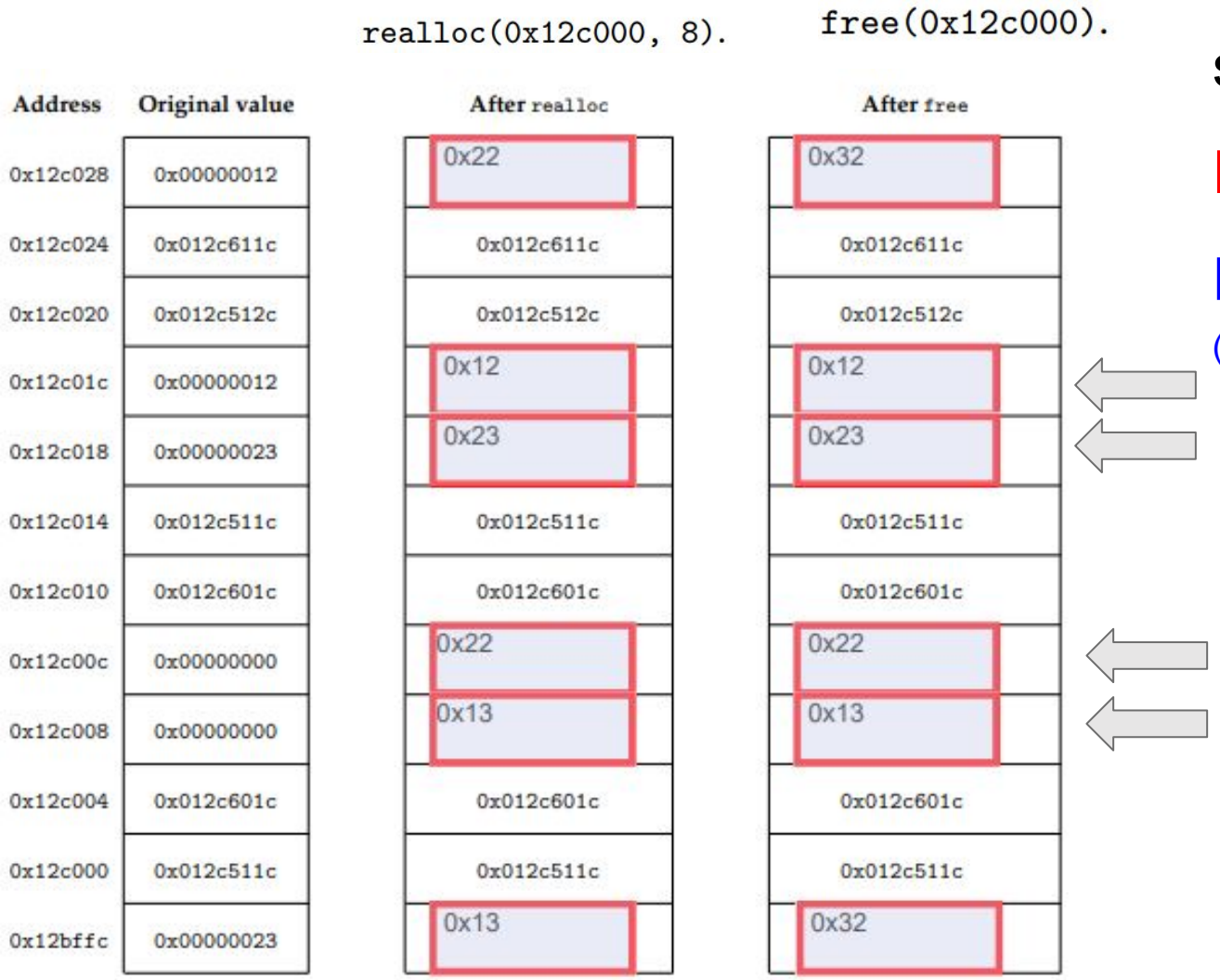
It will not be allocated

Previous is still allocated (off-screen)

32

so: 00110010 = 0x32

16



size will be 32+16 = 00110000 (48)

It will not be allocated

Previous is still allocated

(under, off-screen)

so: 00110010 = 0x32

- Previous headers and footers in th
  middle (arrows) stay unchanged, a
  they do not need to change

`realloc(0x12c000, 8).` `free(0x12c000).`

Address	Original value	After `realloc`	After `free`
0x12c028	0x00000012	0x22	0x32
0x12c024	0x012c611c	0x012c611c	0x012c611c
0x12c020	0x012c512c	0x012c512c	0x012c512c
0x12c01c	0x00000012	0x12	0x12
0x12c018	0x00000023	0x23	0x23
0x12c014	0x012c511c	0x012c511c	0x012c511c
0x12c010	0x012c601c	0x012c601c	0x012c601c
0x12c00c	0x00000000	0x22	0x22
0x12c008	0x00000000	0x13	0x13
0x12c004	0x012c601c	0x012c601c	0x012c601c
0x12c000	0x012c511c	0x012c511c	0x012c511c
0x12bffc	0x00000023	0x13	0x32

Address	Original value	After `realloc`	After `free`
0x12c028	0x00000012	0x22	0x32
0x12c024	0x012c611c	0x012c611c	0x012c611c
0x12c020	0x012c512c	0x012c512c	0x012c512c
0x12c01c	0x00000012	0x12	0x12
0x12c018	0x00000023	0x23	0x23
0x12c014	0x012c511c	0x012c511c	0x012c511c
0x12c010	0x012c601c	0x012c601c	0x012c601c
0x12c00c	0x00000000	0x22	0x22
0x12c008	0x00000000	0x13	0x13
0x12c004	0x012c601c	0x012c601c	0x012c601c
0x12c000	0x012c511c	0x012c511c	0x012c511c
0x12bffc	0x00000023	0x13	0x32

Also

Also answer the following: Would it be possible for a free block to start at address 0x12c02C?

Address	Original value	After realloc	After free
0x12c028	0x00000012	0x22	0x32
0x12c024	0x012c611c	0x012c611c	0x012c611c
0x12c020	0x012c512c	0x012c512c	0x012c512c
0x12c01c	0x00000012	0x12	0x12
0x12c018	0x00000023	0x23	0x23
0x12c014	0x012c511c	0x012c511c	0x012c511c
0x12c010	0x012c601c	0x012c601c	0x012c601c
0x12c00c	0x00000000	0x22	0x22
0x12c008	0x00000000	0x13	0x13
0x12c004	0x012c601c	0x012c601c	0x012c601c
0x12c000	0x012c511c	0x012c511c	0x012c511c
0x12bffc	0x00000023	0x13	0x32

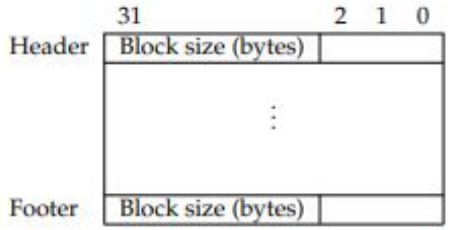
Answer:

- No, since then the uppermost block (0x12) was free. And if this was the case the block would initially have been combined with it due to instant coalescing

Exam 20/21

2.3 Long Questions (about 15 %)

Question 2.3.1: Consider an allocator that uses an implicit free list. The layout of each allocated and free memory block is as follows, with one 32-bit word per row:



Each memory block, either allocated or free, has a size that is a multiple of eight bytes, rounding up allocations if necessary. Thus, only the 29 higher order bits in the header and footer are needed to record block size, which includes the header and footer. The usage of the remaining 3 lower order bits is as follows:

- `bit 0` indicates the use of the current block: 1 for allocated, 0 for free.
- `bit 1` indicates the use of the previous adjacent block: 1 for allocated, 0 for free.
- `bit 2` is unused and is always set to be 0.

Important: We must *never* create blocks with zero payload (i.e. we must *never* create blocks with size 8).

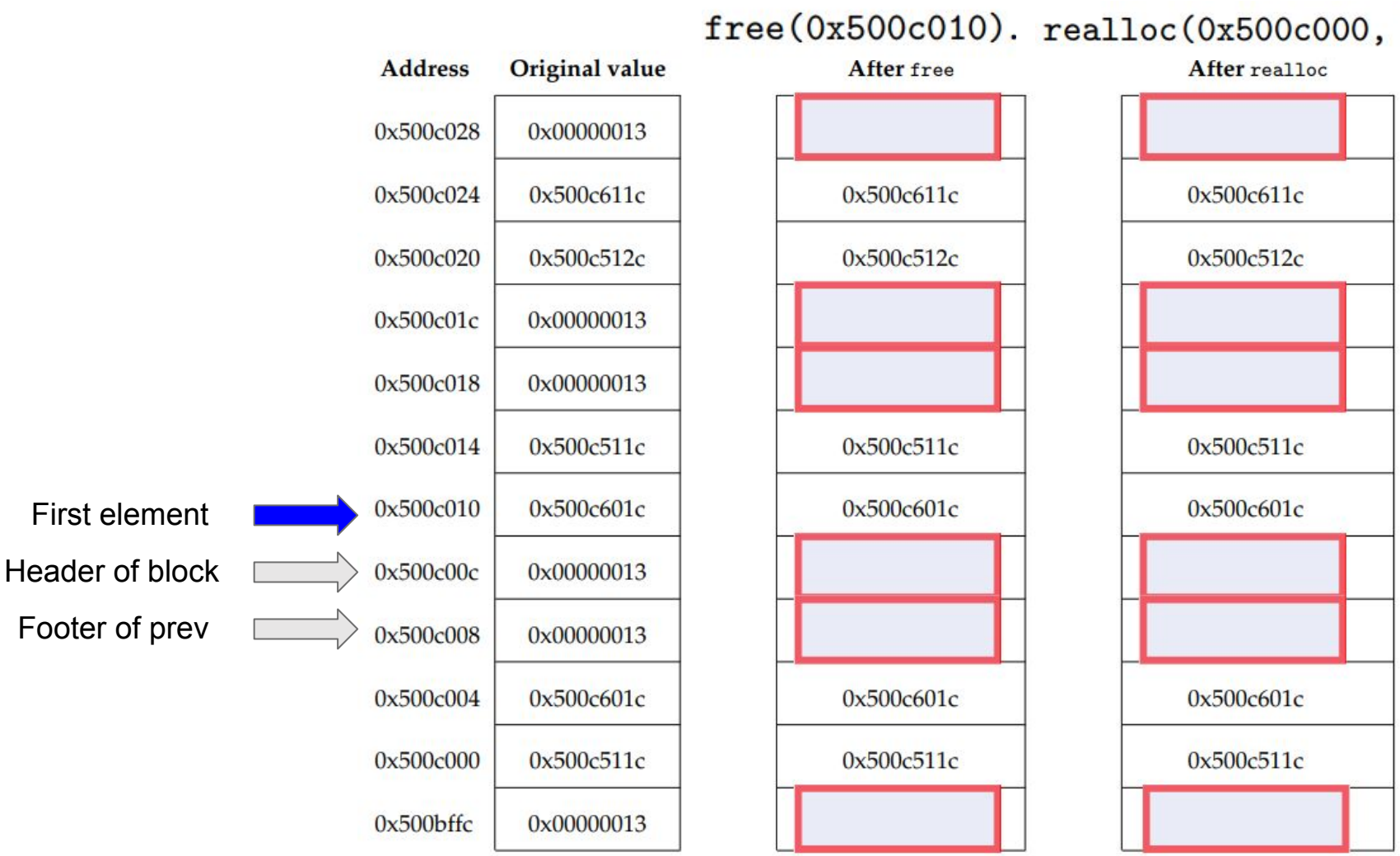
Given the heap shown on the left, show the new heap contents after *consecutive* calls to

1. `free(0x500c010)`.
2. `realloc(0x500c000, 12)`. Assume the the return value is `0x500c000`, meaning that the existing allocation is resized.

Your answers should be given as hex values. Note that the address grows from bottom up. Assume that the allocator uses immediate coalescing, that is, adjacent free blocks are merged immediately each time a block is freed.

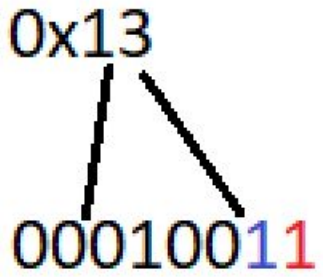
Address	Original value	After `free`	After `realloc`
0x500c028	0x00000013		
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013		
0x500c018	0x00000013		
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013		
0x500c008	0x00000013		
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bffc	0x00000013		

`free(0x500c010). realloc(0x500c000, 12).`



`free(0x500c010). realloc(0x500c000, 12).`

Address	Original value	After `free`	After `realloc`
0x500c028	0x00000013		
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013		
0x500c018	0x00000013		
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013		
0x500c008	0x00000013		
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bffc	0x00000013		



Is allocated

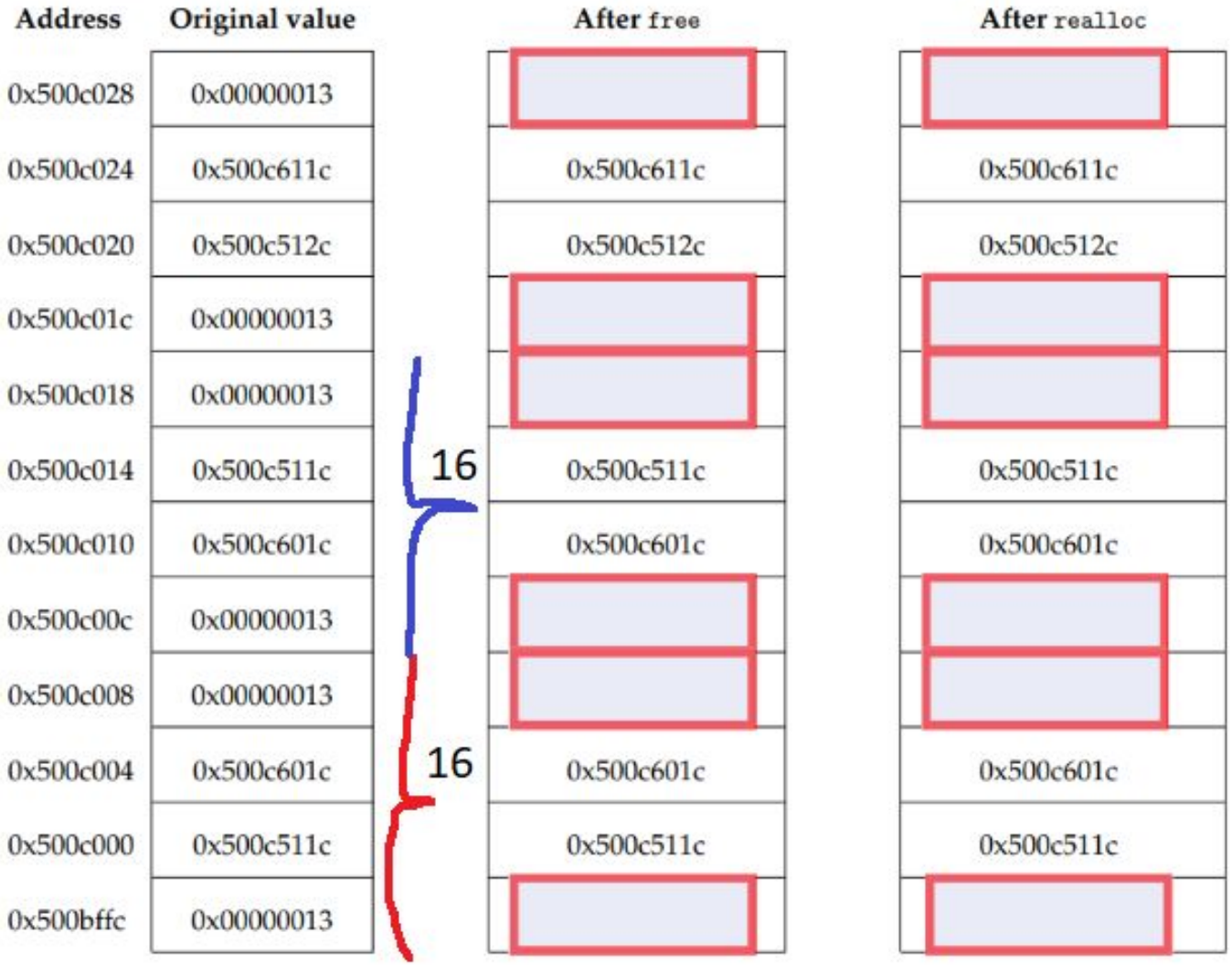
Previous is allocated

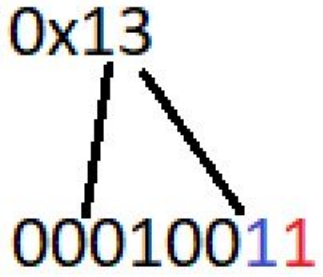
size is:

00010011 -> 00010000

= 0x10 or 16

`free(0x500c010).realloc(0x500c000, 12)`





Is allocated

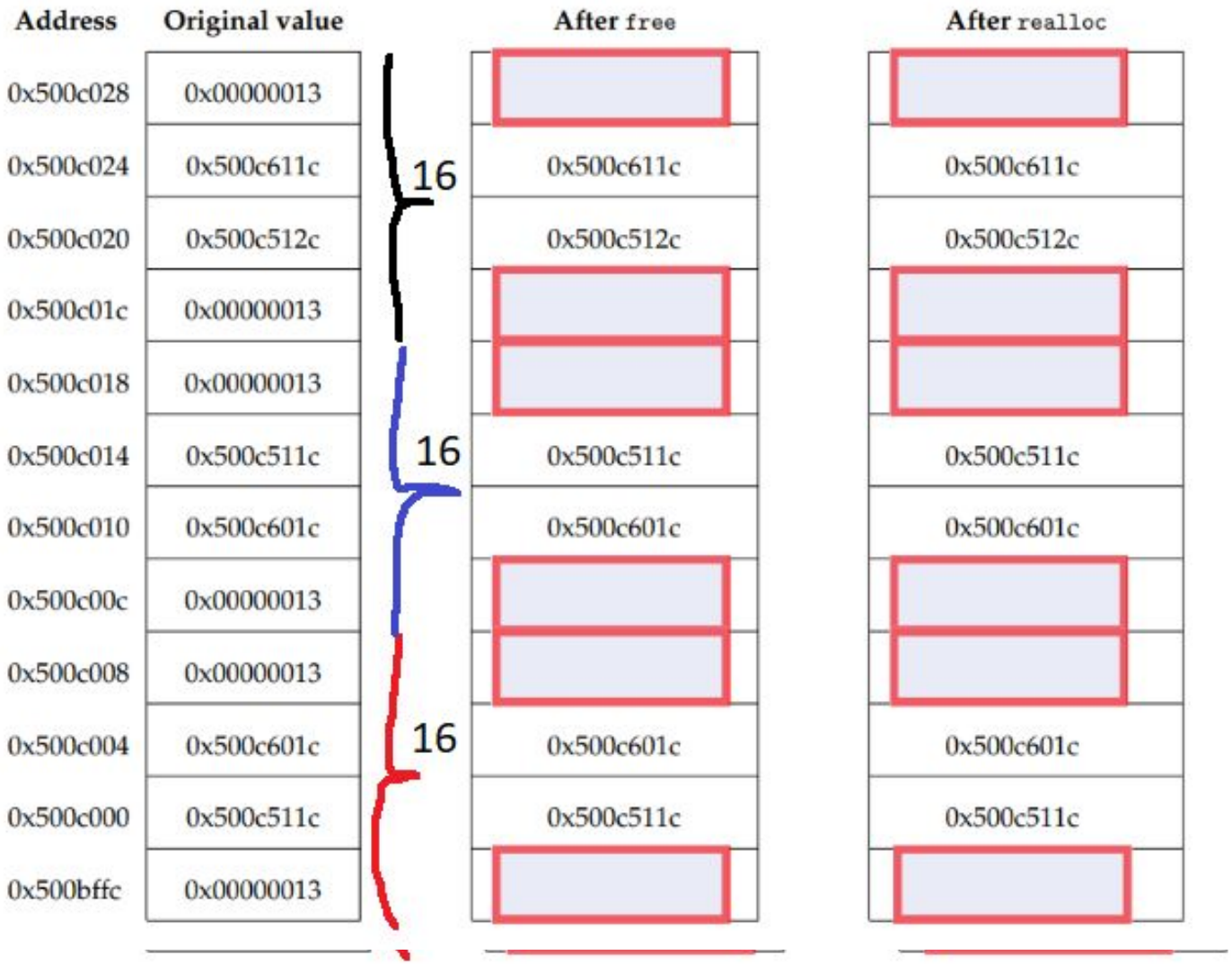
Previous is allocated

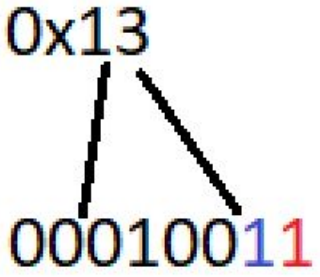
size is:

00010011 -> 00010000

= 0x10 or 16

free(0x500c010).realloc(0x500c000, 12)[2]





Is allocated

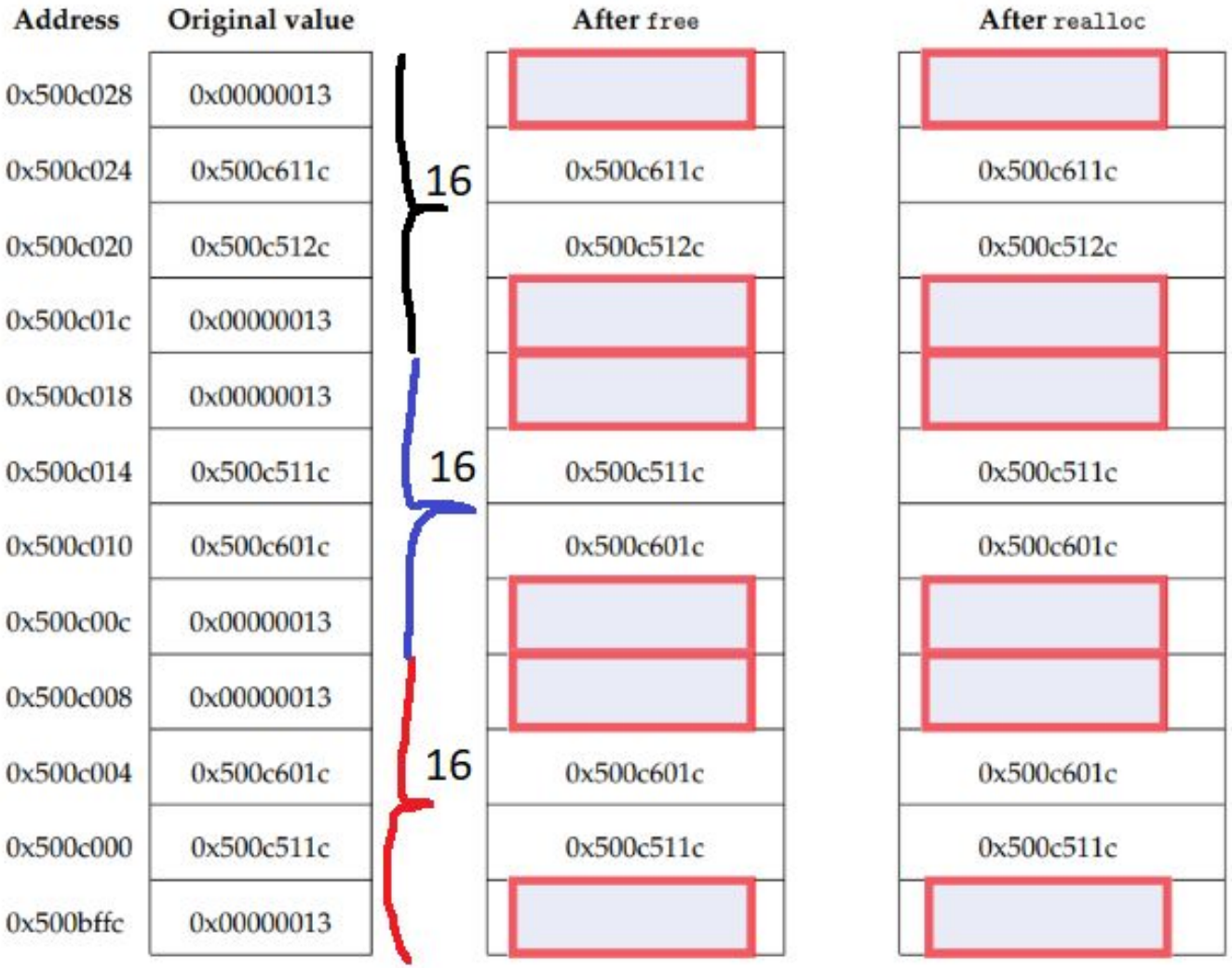
Previous is allocated

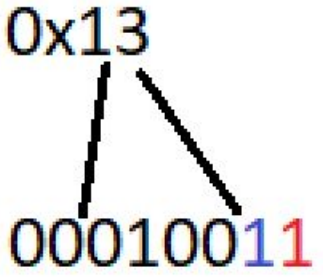
size is:

00010000 -> 00010000

= 0x10 or 16

free(0x500c010).realloc(0x500c000, 12)



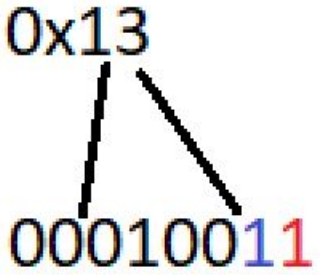


Is allocated
Previous is allocated
size is:
00010011 -> 00010000
= 0x10 or 16

- Here, as no coalescing will occur this is simply changing bit 0 which says that it is allocated
- Remember to also change bit 1 of the next block

`free(0x500c010).` `realloc(0x500c000, 12).`

Address	Original value	After `free`	After `realloc`
0x500c028	0x00000013	0x11	
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013	0x11	
0x500c018	0x00000013	0x12	
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013	0x12	
0x500c008	0x00000013	0x13	
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bffc	0x00000013	0x13	



Is allocated
Previous is allocated
size is:
00010011 -> 00010000
= 0x10 or 16

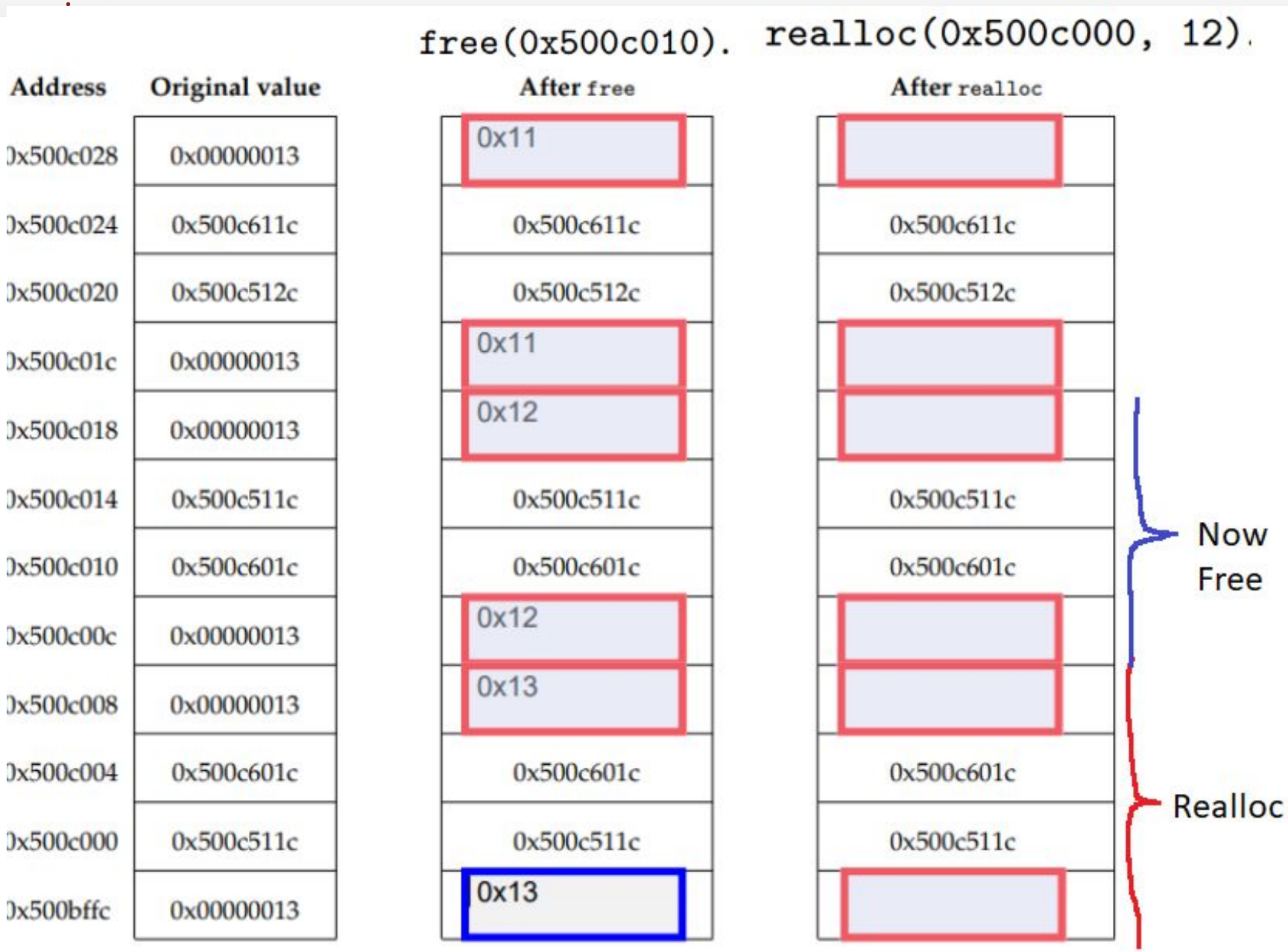
- Here, as no coalescing will occur this is simply changing bit 0 which says that it is allocated
- Remember to also change bit 1 of the next block

- 000010010 = 0x12
- 000010001 = 0x11

`free(0x500c010).` `realloc(0x500c000, 12).`

(on this block)

- Now must realloc(12)



- Now must realloc(12)
- Problem is that 12 is not a multiple of 8, so we have to round up resulting realloc(16)
- Additionally, remember that 16 is the amount of space we want, excluding the header and footer

`free(0x500c010).` `realloc(0x500c000, 12).`

- New problem: The alloc will leave the free space as a block of size 8.
- Remember the rule?

Each memory block, either allocated or free, has a size that is a multiple of eight bytes, rounding up allocations if necessary. Thus, only the 29 higher order bits in the header and footer are needed to record block size, which includes the header and footer. The usage of the remaining 3 lower order bits is as follows:

- `bit 0` indicates the use of the current block: 1 for allocated, 0 for free.
- `bit 1` indicates the use of the previous adjacent block: 1 for allocated, 0 for free.
- `bit 2` is unused and is always set to be 0.

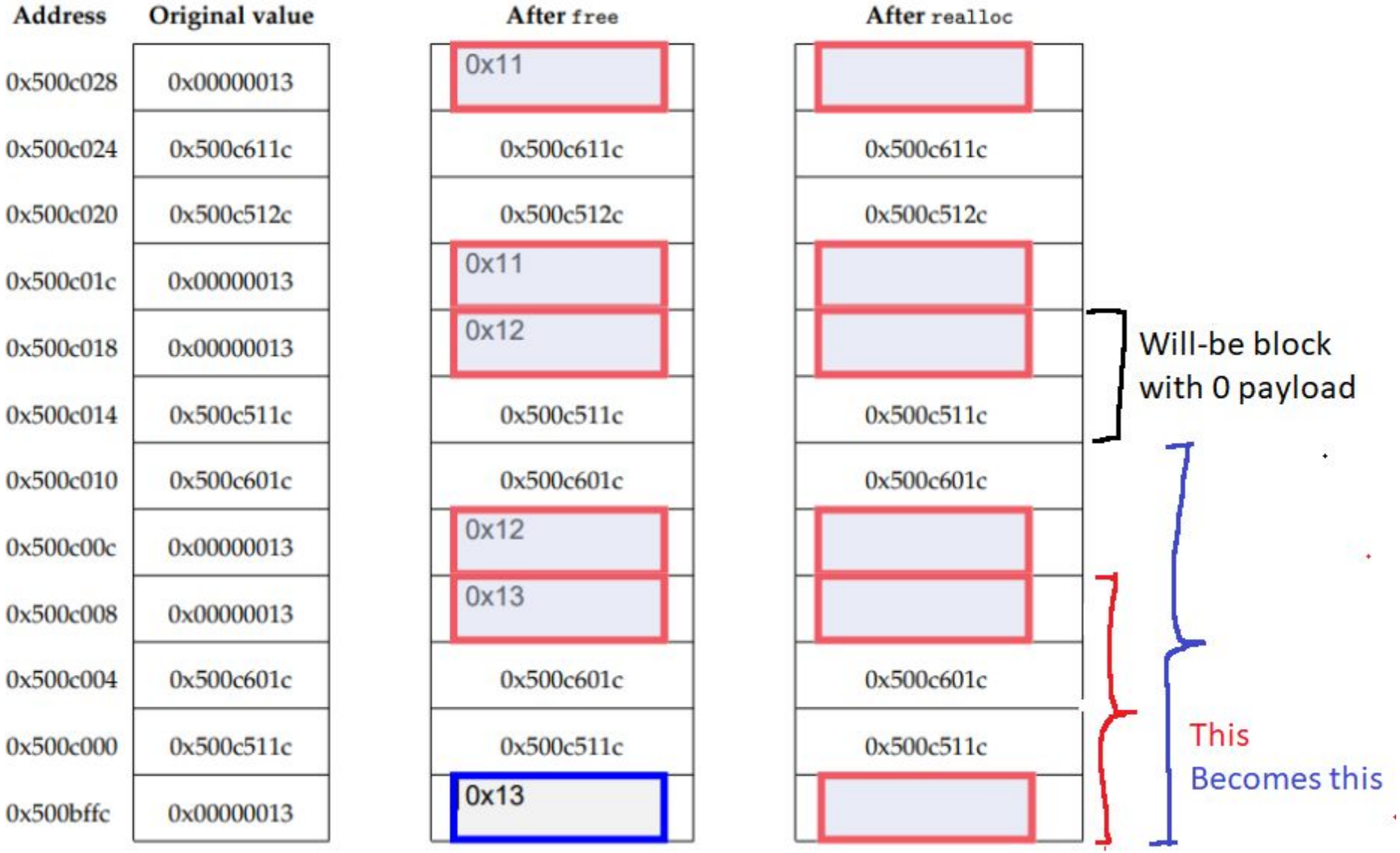
Important: We must *never* create blocks with zero payload (i.e. we must *never* create blocks with size 8).

Given the heap shown on the left, show the new heap contents after *consecutive* calls to

1. `free(0x500c010)`.
2. `realloc(0x500c000, 12)`. Assume the the return value is `0x500c000`, meaning that the existing allocation is resized.

Your answers should be given as hex values. Note that the address grows from bottom up. Assume that the allocator uses immediate coalescing, that is, adjacent free blocks are merged immediately each time a block is freed.

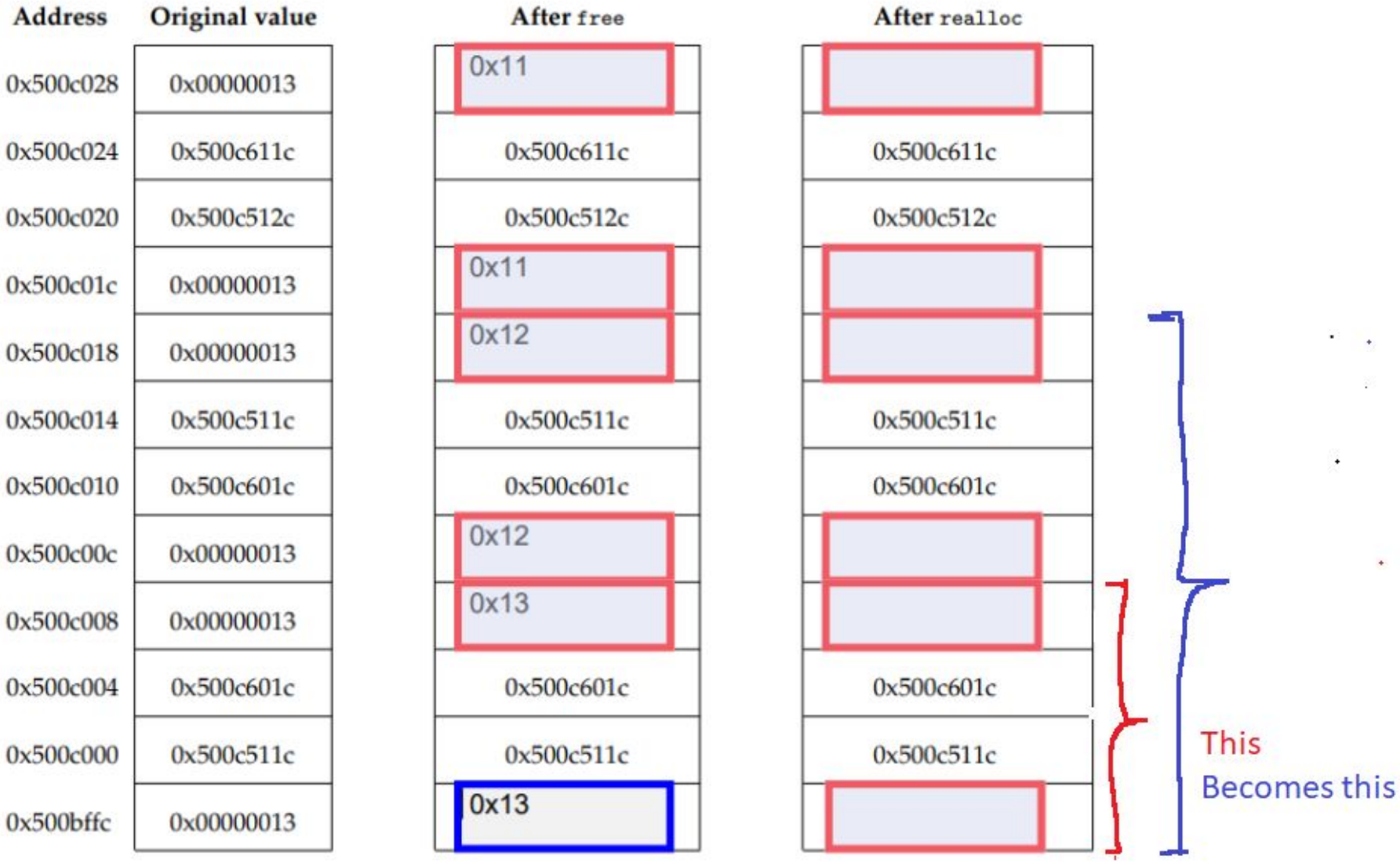
`free(0x500c010).` `realloc(0x500c000, 12).`



- Solution?
- Even more internal fragmentation

- Essentially, since the remaining free space is too small, the only choice is for this to be taken by the realloc aswell… so

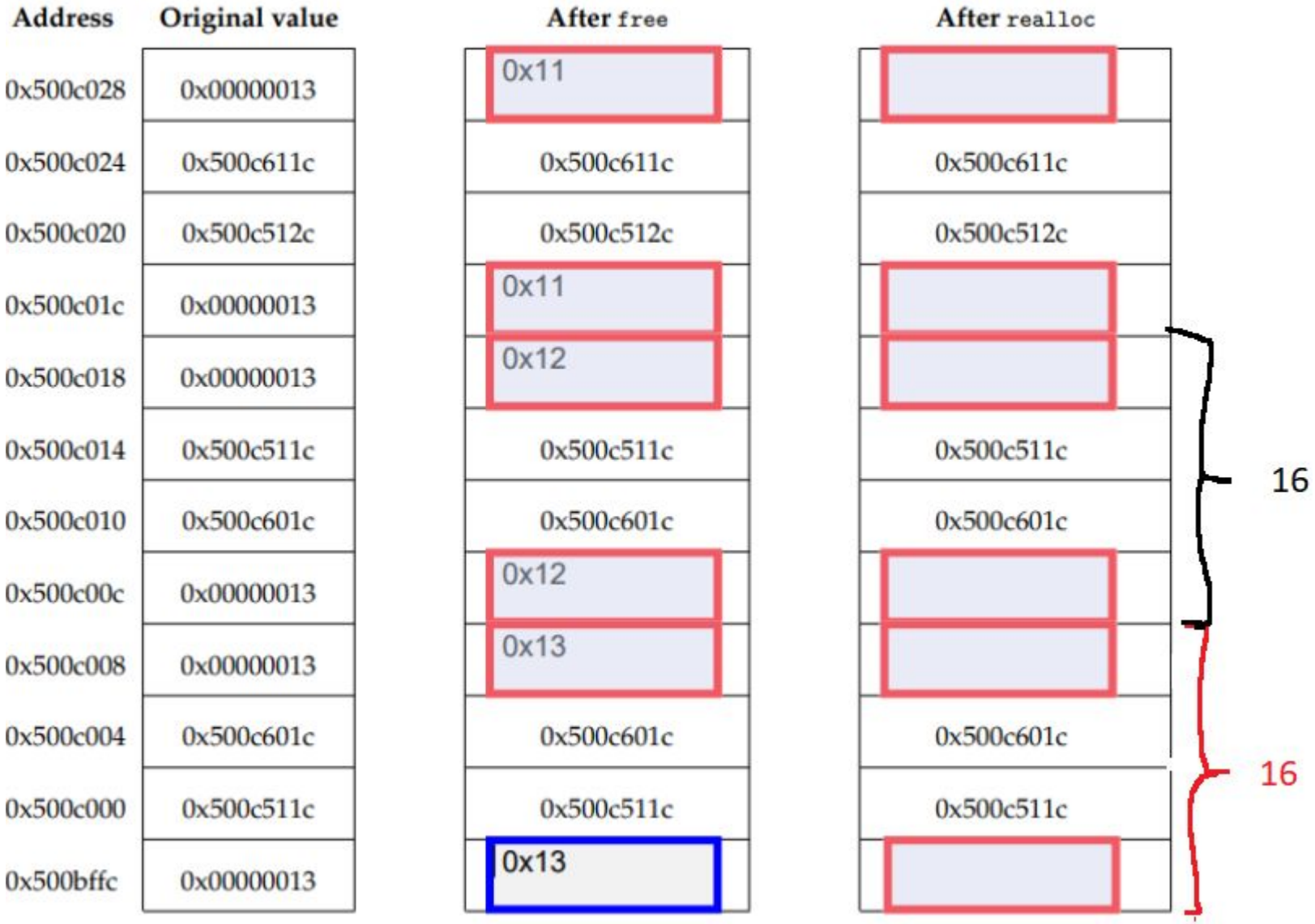
`free(0x500c010).` `realloc(0x500c000, 12).`



We must have this:

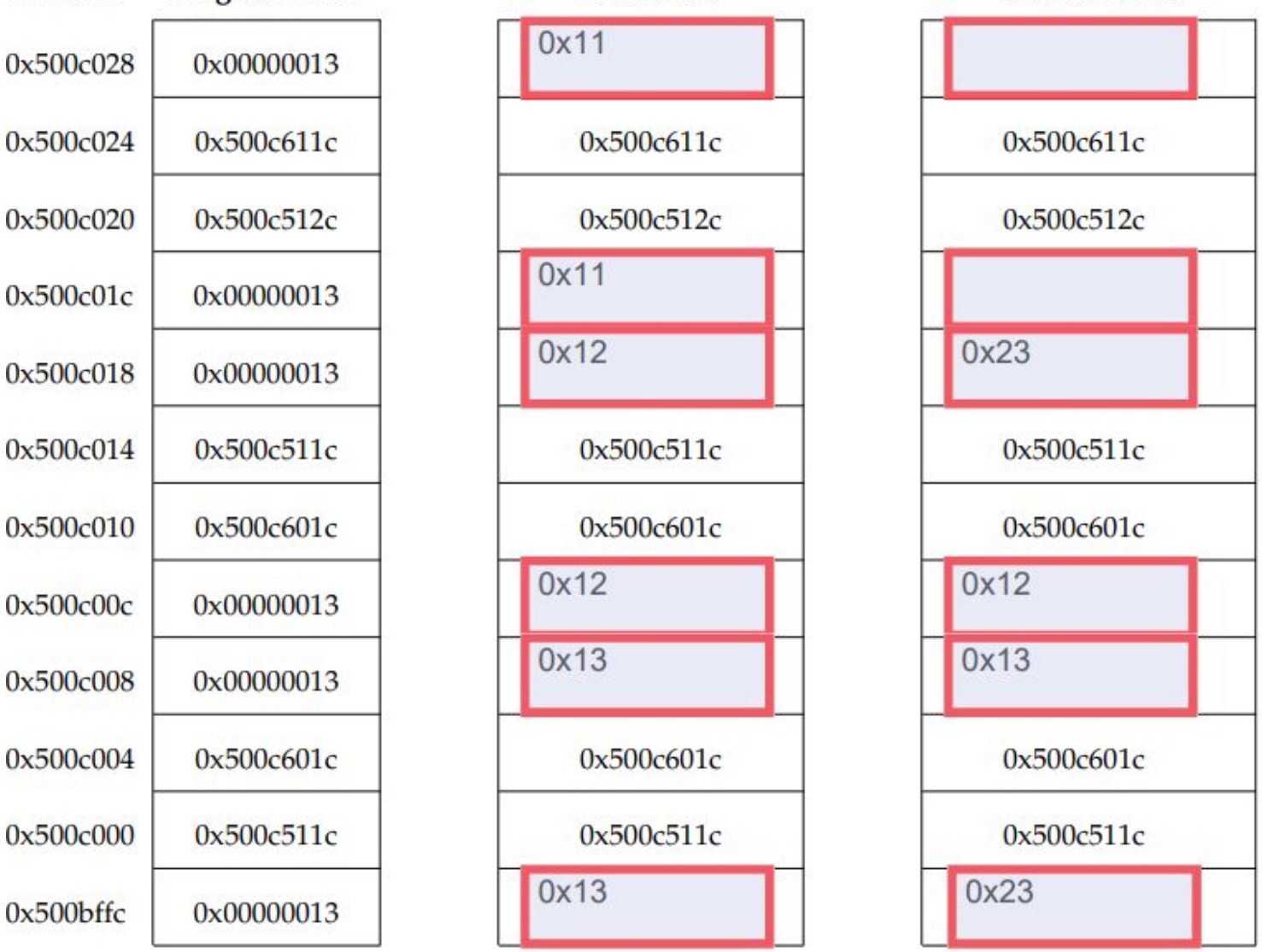
Now, after solving the puzzle, we fill in the fields

`free(0x500c010).` `realloc(0x500c000, 12)`



- What will the header of the block be?
- Will be allocated
- Previous is still allocated
- Size is 16+16 = 32 = 0010 0000
- So we get: 0010 0011 = 0x23

`free(0x500c010).` `realloc(0x500c000, 12)`



- Remember, these don’t change due to instant coalescing

`free(0x500c010).` `realloc(0x500c000, 12)`

Address	Original value	After `free`	After `realloc`
0x500c028	0x00000013	0x11	
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013	0x11	
0x500c018	0x00000013	0x12	0x23
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013	0x12	0x12
0x500c008	0x00000013	0x13	0x13
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bffc	0x00000013	0x13	0x23

- And of the last block?
- Not much changes. Except now the previous is allocated again, so bit 1 changes back to 1.
- 0x11 = 0001 0001
  ->
  0001 0011 = 0x13
- We also see this is exactly the same header as the original state

`free(0x500c010).` `realloc(0x500c000, 12)`

Address	Original value	After `free`	After `realloc`
0x500c028	0x00000013	0x11	0x13
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013	0x11	0x13
0x500c018	0x00000013	0x12	0x23
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013	0x12	0x12
0x500c008	0x00000013	0x13	0x13
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bffc	0x00000013	0x13	0x23

- And of the last block?
- Not much changes. Except now the previous is allocated again, so bit 1 changes back to 1.
- 0x11 = 0001 0001
  ->
  0001 0011 = 0x13
- We also see this is exactly the same header as the original state

Correct?

Address	Original value	After `free`	After `realloc`
0x500c028	0x00000013	0x11	0x13
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013	0x11	0x13
0x500c018	0x00000013	0x12	0x23
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013	0x12	0x12
0x500c008	0x00000013	0x13	0x13
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bffc	0x00000013	0x13	0x23

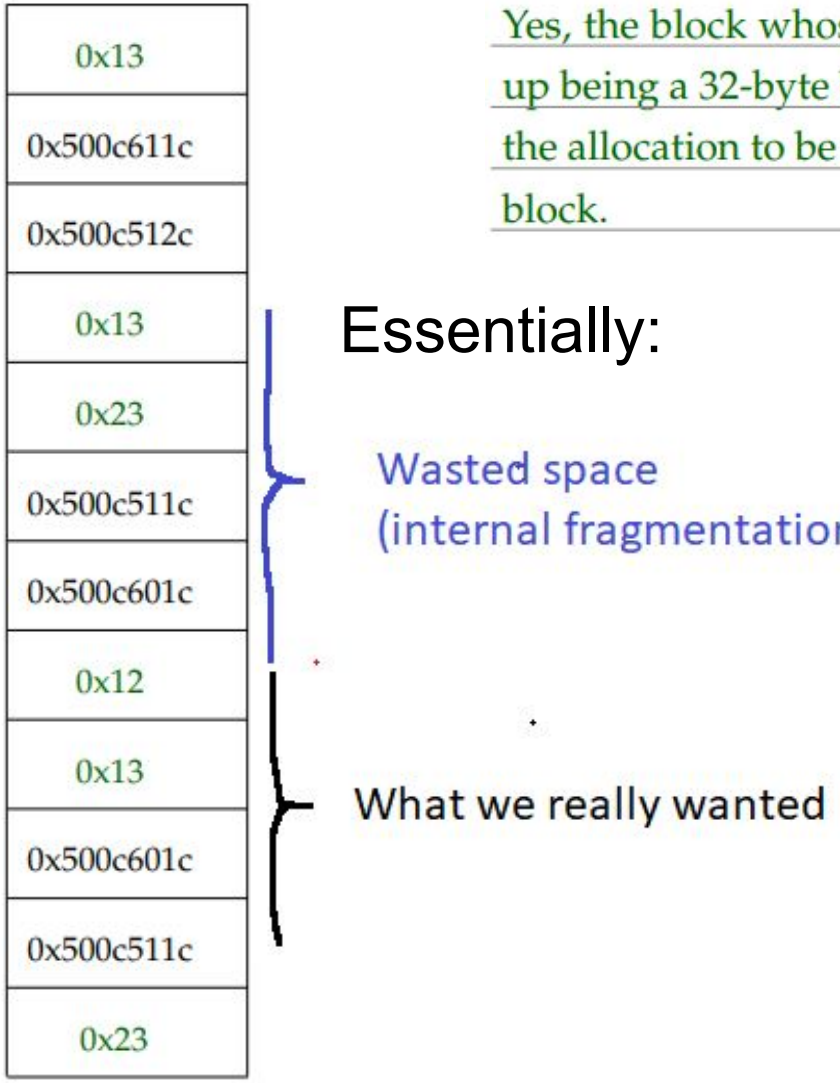
Address	Original value	After `free`	After `realloc`
0x500c028	0x00000013	0x11	0x13
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013	0x11	0x13
0x500c018	0x00000013	0x12	0x23
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013	0x12	0x12
0x500c008	0x00000013	0x13	0x13
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bffc	0x00000013	0x13	0x23

Extra question (if time allows)

Also answer the following: Does the resulting heap exhibit internal or external fragmentation? Explain your answer.

Yes, the block whose payload starts at 0x500c000 was asked to contain 12 bytes of payload, but ended up being a 32-byte block due to the 8 bytes of headers/footers (necessary), but also having to round up the allocation to be a multiple of 8 bytes, and then further expanding to avoid a following zero-payload block.

After `realloc`



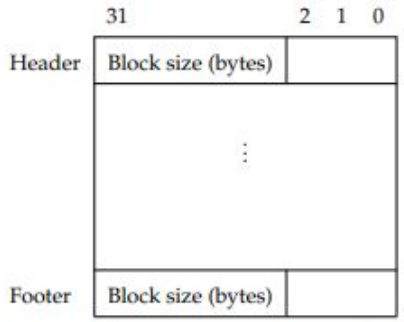
Essentially:

Wasted space
(internal fragmentation)

What we really wanted

Exam 22/23

Question 2.3.1: Consider an allocator that uses an implicit free list and immediate coalescing of neighbouring free blocks. The layout of each allocated and free memory block is as follows, with one 32-bit word per row:



Each memory block, either allocated or free, has a size that is a multiple of eight bytes, rounding up allocations if necessary. Thus, only the 29 higher order bits in the header and footer are needed to record block size, which includes the header and footer. The minimum block size is 8. The usage of the remaining 3 lower order bits is as follows:

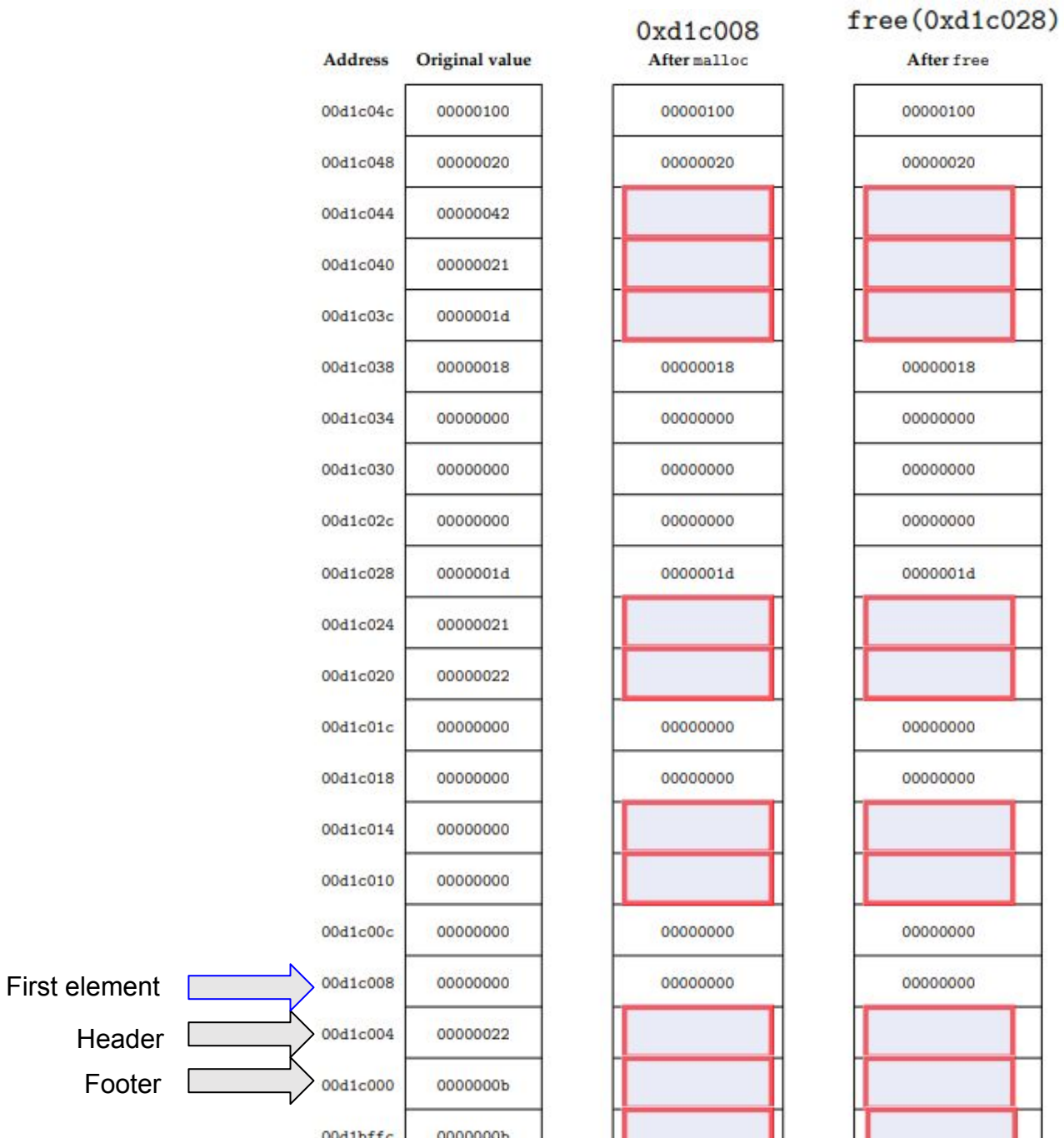
- Bit 0 indicates the use of the current block: 1 for allocated, 0 for free.
- Bit 1 indicates the use of the previous adjacent block: 1 for allocated, 0 for free.
- Bit 2 is unused and is always set to be 0.

Given the partial contents of the heap shown on the left, show the new contents of the heap after a call to `malloc(8)` is executed that returns `0xd1c008` (in the middle column), followed by a call `free(0xd1c028)` (rightmost column).

- All numbers are hexadecimal, and so should your answers be.
- Note that the address grows from bottom up.
- Some parts of the heap may lie outside the area shown.
- Assume that the allocator uses immediate coalescing, that is, adjacent free blocks are merged immediately each time a block is freed.
- Perform the minimum number of memory changes required.

Address	Original value	After `malloc`	After `free`
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042		
00d1c040	00000021		
00d1c03c	0000001d		
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021		
00d1c020	00000022		
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000		
00d1c010	00000000		
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022		
00d1c000	0000000b		
00d1bffc	0000000b		

Larger heap = smaller text (sorry)



Same as always - analyse the initial state of the heap

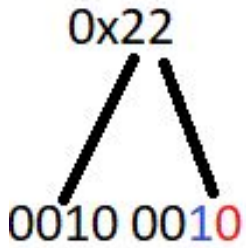
- The header is once again behind first element
- The footer of the previous block is behind that.
- We start analysing

Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042		
00d1c040	00000021		
00d1c03c	0000001d		
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021		
00d1c020	00000022		
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000		
00d1c010	00000000		
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022		
00d1c000	0000000b		
00d1bffc	0000000b		

First element

Header

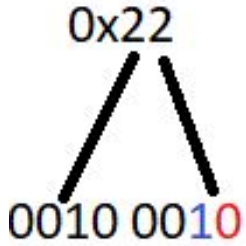
Footer



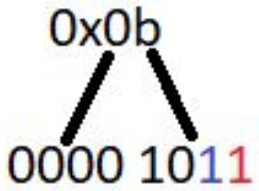
- Not allocated (makes sense, since we will malloc it)
- Previous not allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32

Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042		
00d1c040	00000021		
00d1c03c	0000001d		
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021		
00d1c020	00000022		
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000		
00d1c010	00000000		
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022		
00d1c000	0000000b		
00d1bffc	0000000b		

First element
Header
Footer



- Not allocated (makes sense, since we will malloc it)
- Previous not allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32



- Allocated
- Previous is allocated
- size = 0000 1011 -> 0000 1000 = 0x08 = 8

But that's not allowed? Right?

Be careful! Rules change

Each memory block, either allocated or free, has a size that is a multiple of eight bytes, rounding up allocations if necessary. Thus, only the 29 higher order bits in the header and footer are needed to record block size, which includes the header and footer. The minimum block size is 8. The usage of the remaining 3 lower order bits is as follows:

- Bit 0 indicates the use of the current block: 1 for allocated, 0 for free.
- Bit 1 indicates the use of the previous adjacent block: 1 for allocated, 0 for free.
- Bit 2 is unused and is always set to be 0.

Given the partial contents of the heap shown on the left, show the new contents of the heap after a call to `malloc(8)` is executed that returns `0xd1c008` (in the middle column), followed by a call `free(0xd1c028)` (rightmost column).

- All numbers are hexadecimal, and so should your answers be.
- Note that the address grows from bottom up.
- Some parts of the heap may lie outside the area shown.
- Assume that the allocator uses immediate coalescing, that is, adjacent free blocks are merged immediately each time a block is freed.
- Perform the minimum number of memory changes required.

Rule stating:

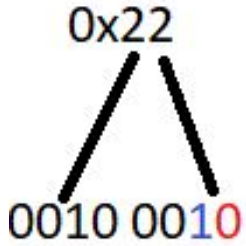
"**Important**: We must never create blocks with zero payload (i.e. we must never create blocks with size 8)."

Is no longer present. It was changed.

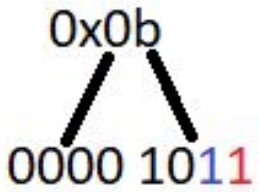
- Read carefully

Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042		
00d1c040	00000021		
00d1c03c	0000001d		
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021		
00d1c020	00000022		
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000		
00d1c010	00000000		
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022		
00d1c000	0000000b		
00d1bffc	0000000b		

First element
Header
Footer

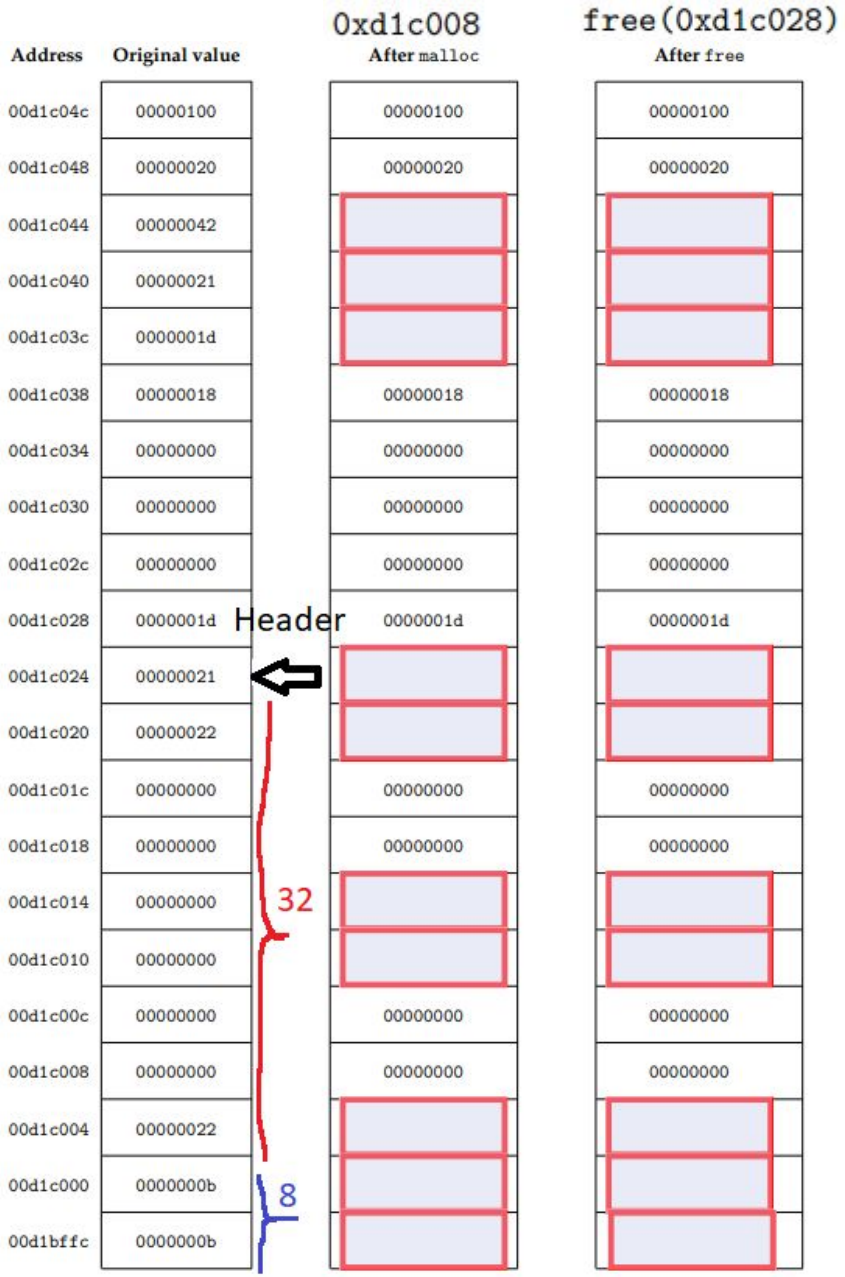


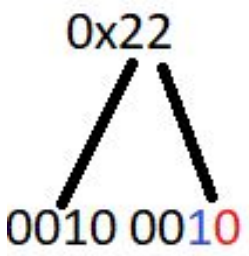
- Not allocated (makes sense, since we will malloc it)
- Previous not allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32



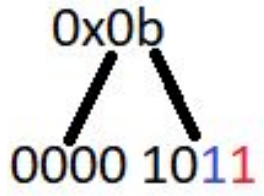
- Allocated
- Previous is allocated
- size = 0000 1011 -> 0000 1000 = 0x08 = 8

- Also, last year it appears they tried to make just guessing the headers / footers a bit harder

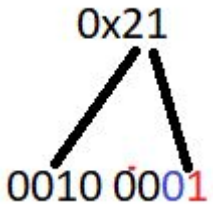




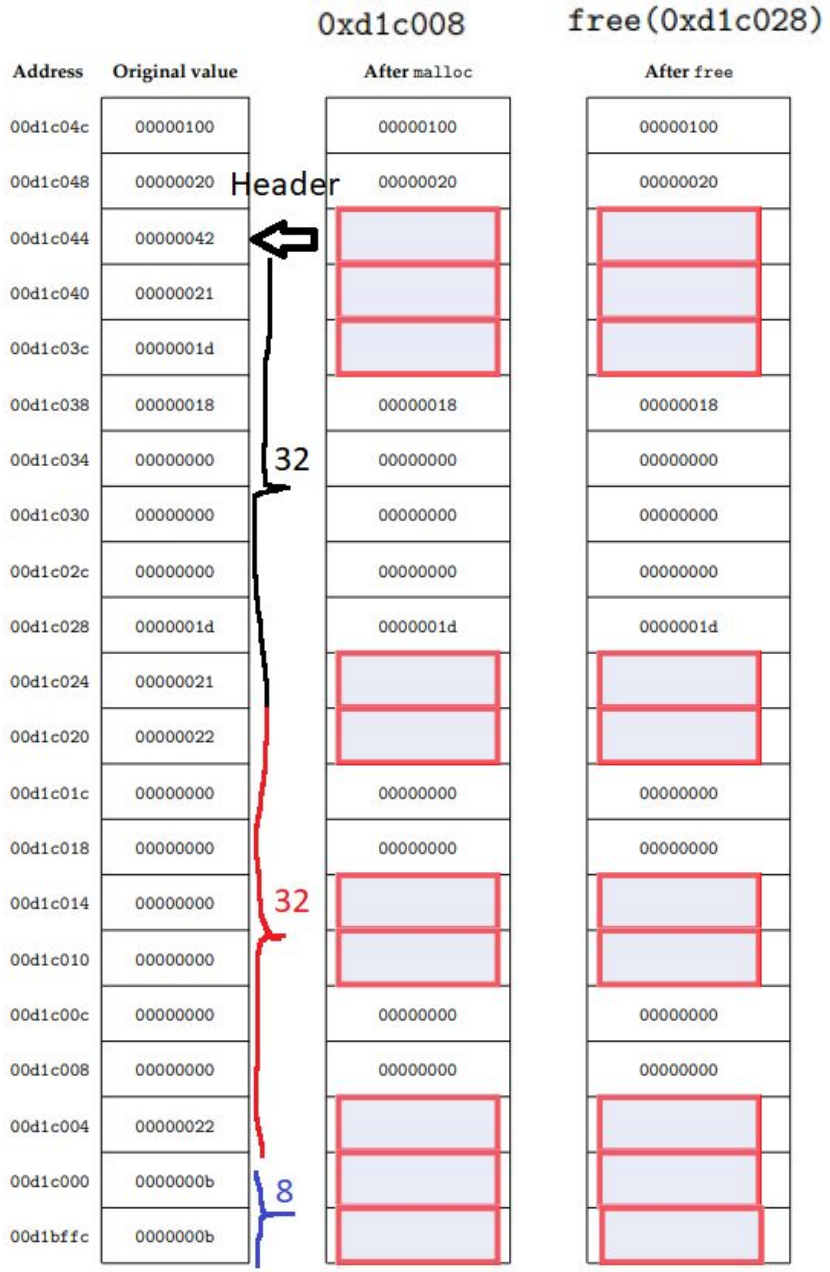
- Not allocated (makes sense, since we will malloc it)
- Previous not allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32

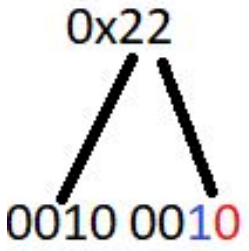


- Allocated
- Previous is allocated
- size = 0000 1011 -> 0000 1000 = 0x08 = 8

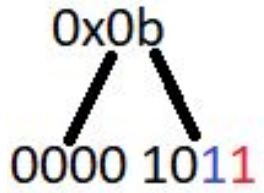


- Allocated
- Previous is not allocated
- size = 0010 0001 -> 0010 0000 = 0x20 = 32

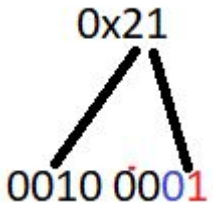




- Not allocated (makes sense, since we will malloc it)
- Previous not allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32



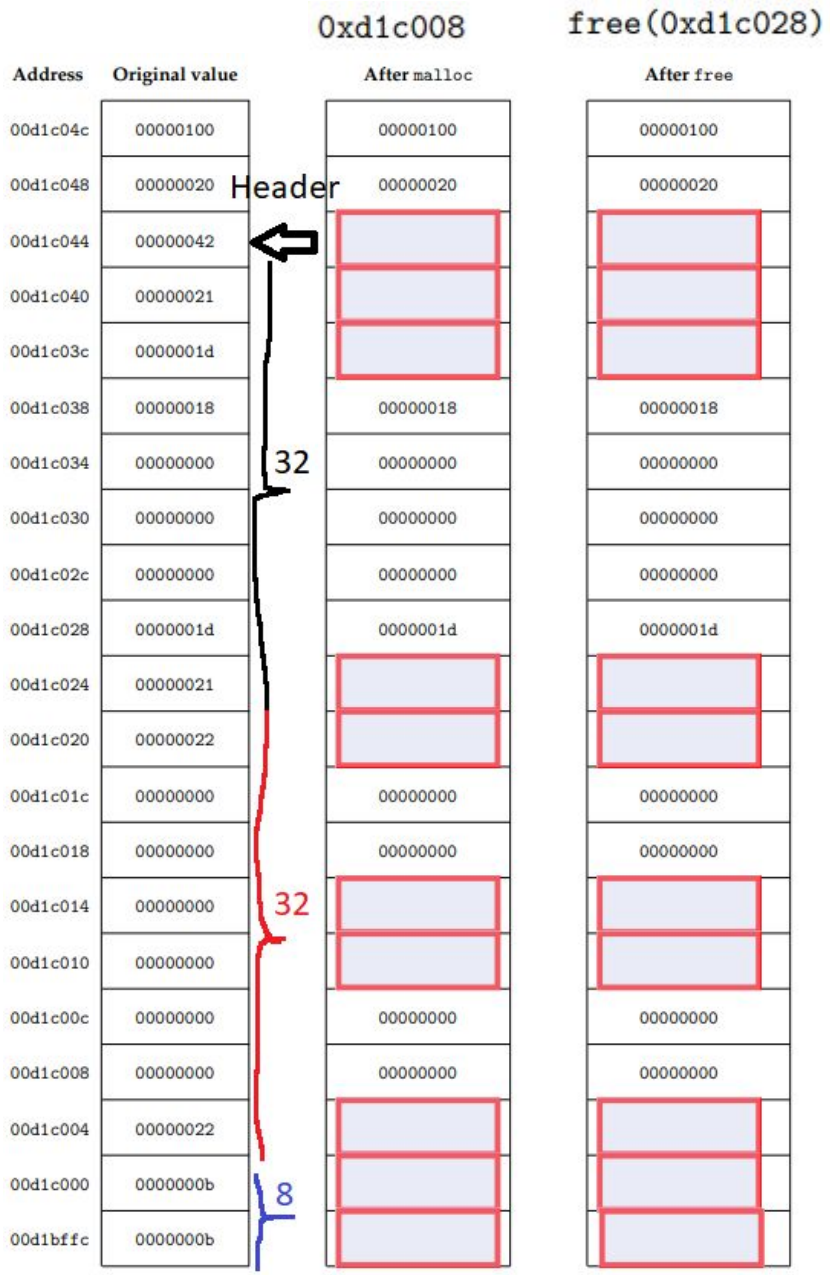
- Allocated
- Previous is allocated
- size = 0000 1011 -> 0000 1000 = 0x08 = 8

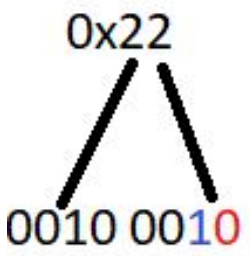


- Allocated
- Previous is not allocated
- size = 0010 0001 -> 0010 0000 = 0x20 = 32

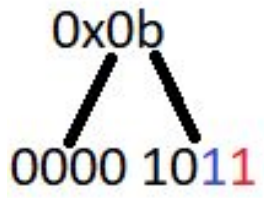
That's quite a large number, feels like it will go beyond the visible heap

- Some parts of the heap may lie outside the area shown.

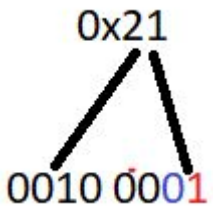




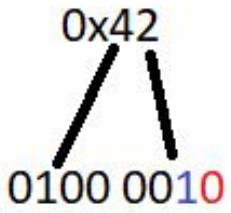
- Not allocated (makes sense, since we will malloc it)
- Previous not allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32



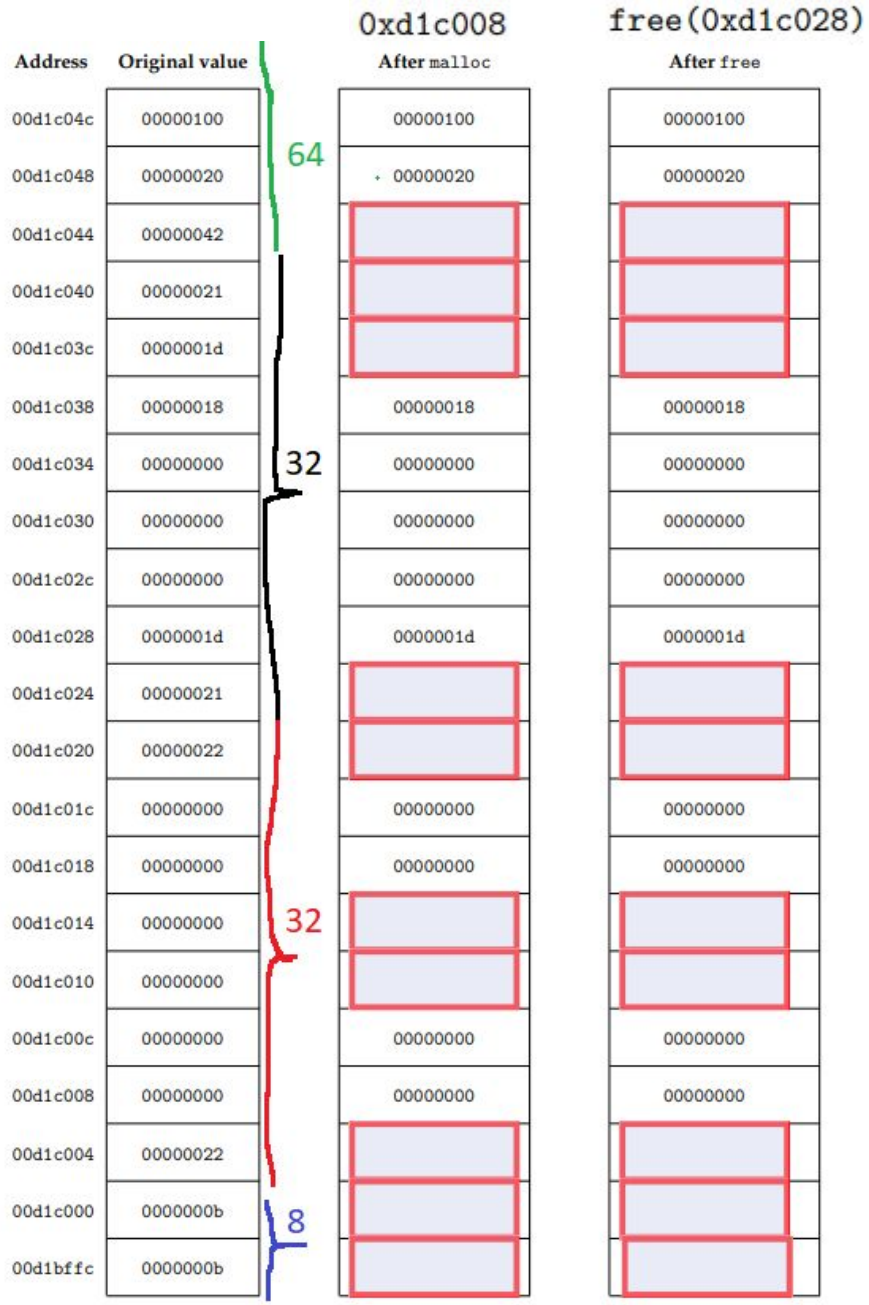
- Allocated
- Previous is allocated
- size = 0000 1011 -> 0000 1000 = 0x08 = 8

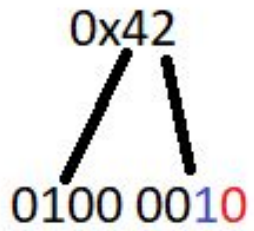


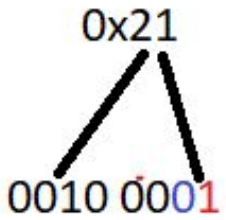
- Allocated
- Previous is not allocated
- size = 0010 0001 -> 0010 0000 = 0x20 = 32

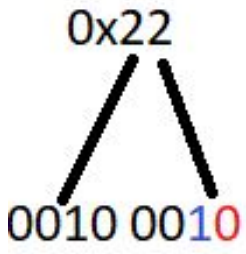


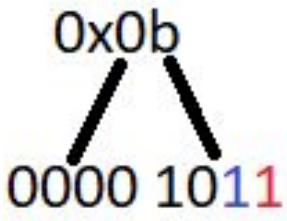
- Not allocated
- Previous is allocated
- size = 0100 0010 -> 0100 0000 = 0x40 = 64
- Way outside the heap, important later



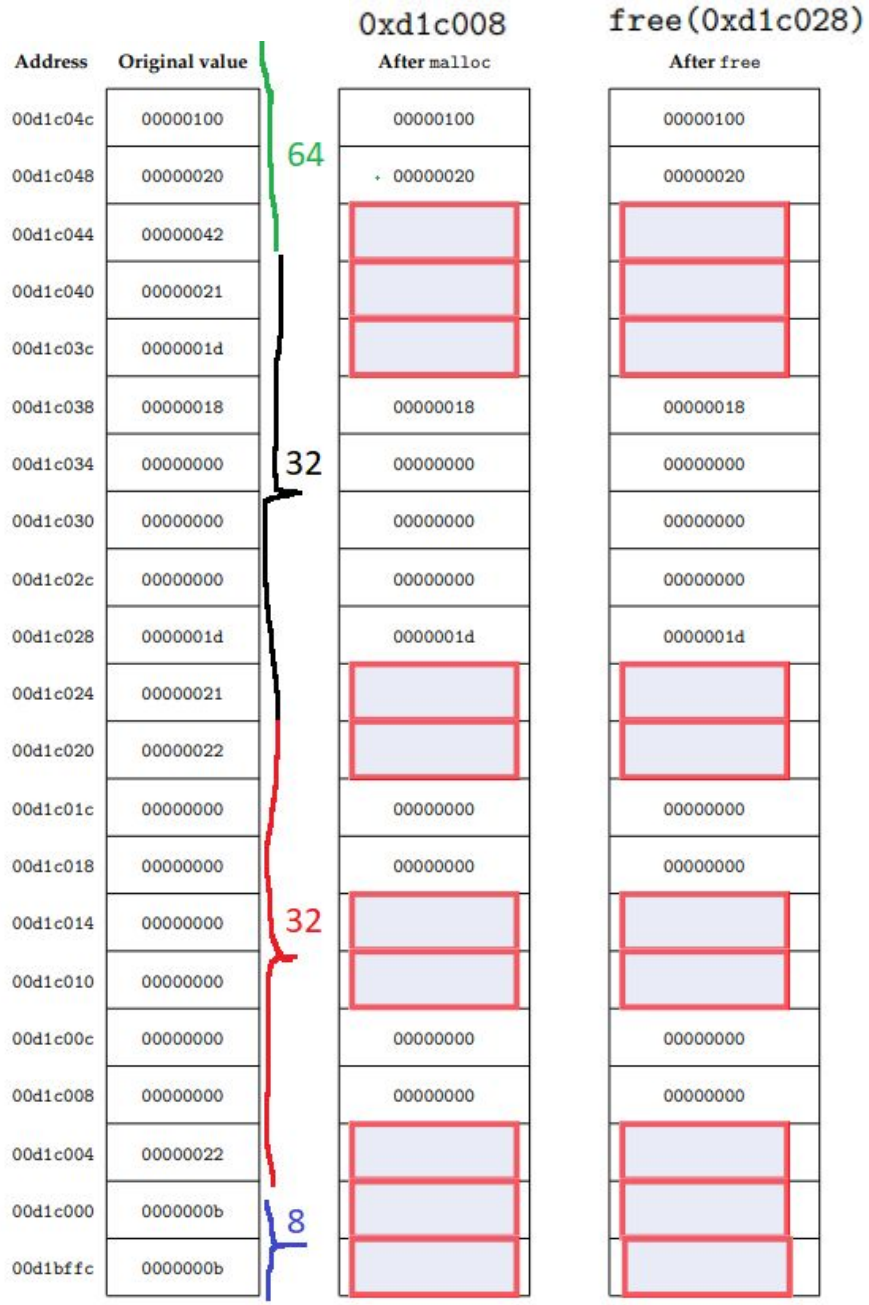








- Not allocated
- Previous is allocated
- size = 0100 0010 -> 0100 0000 = 0x40 = 64
- Way outside the heap, important later
  - Allocated
  - Previous is not allocated
  - size = 0010 0001 -> 0010 0000 = 0x20 = 32
- Not allocated (makes sense, since we will malloc it)
- Previous not allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32
- Allocated
- Previous is allocated
- size = 0000 1011 -> 0000 1000 = 0x08 = 8



Sorry I need space, try to remember the rest

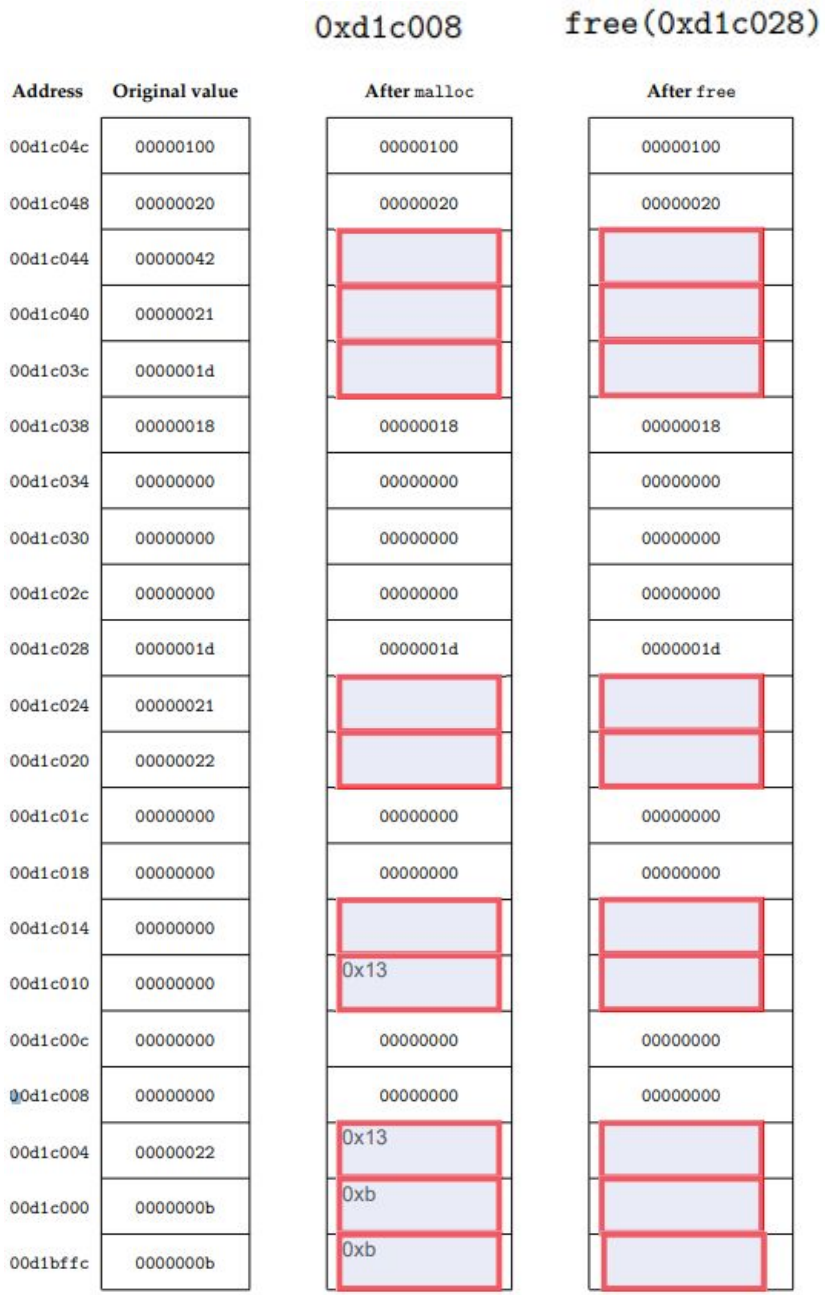
We malloc(8) here, meaning 8 + header + footer = 16

- It will be allocated
- Previous will be allocated (0xb)
- Size = 16 = 0001 0000
- So -> 0001 0011 -> 0x13

Sorry I need space, try to remember the rest

We malloc(8) here, meaning 8 + header + footer = 16

- It will be allocated
- Previous will be allocated (0xb)
- Size = 16 = 0001 0000
- So -> 0001 0011 -> 0x13



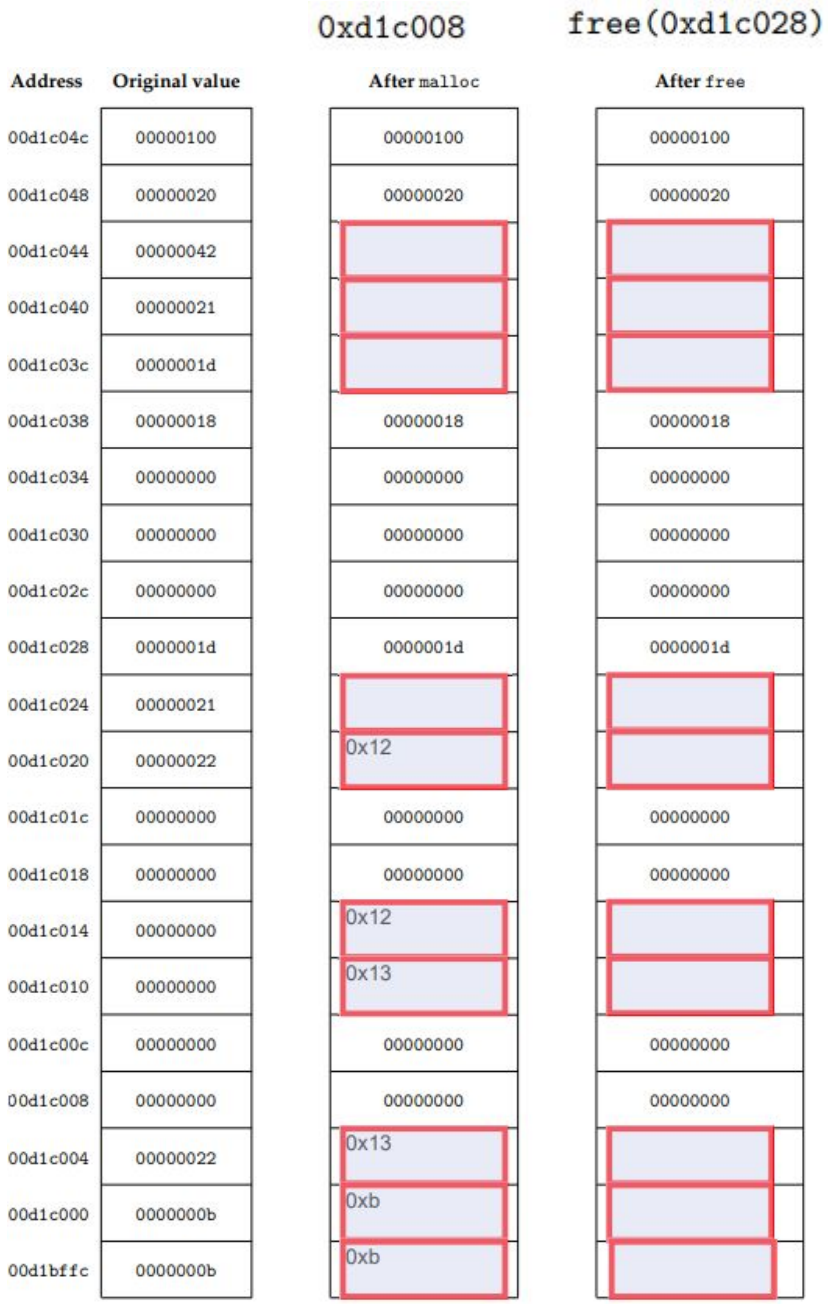
Sorry I need space, try to remember the rest

We malloc(8) here, meaning 8 + header + footer = 16

- It will be allocated
- Previous will be allocated (0xb)
- Size = 16 = 0001 0000
- So -> 0001 0011 -> 0x13

What about the rest of the free block? (just above)

- It will not be be allocated
- Previous will be allocated
- Size = 32-16 = 16 = 0001 0000
- So -> 0001 0011 -> 0x12



Sorry I need space, try to remember the rest

We malloc(8) here, meaning 8 + header + footer = 16

- It will be allocated
- Previous will be allocated (0xb)
- Size = 16 = 0001 0000
- So -> 0001 0011 -> 0x13

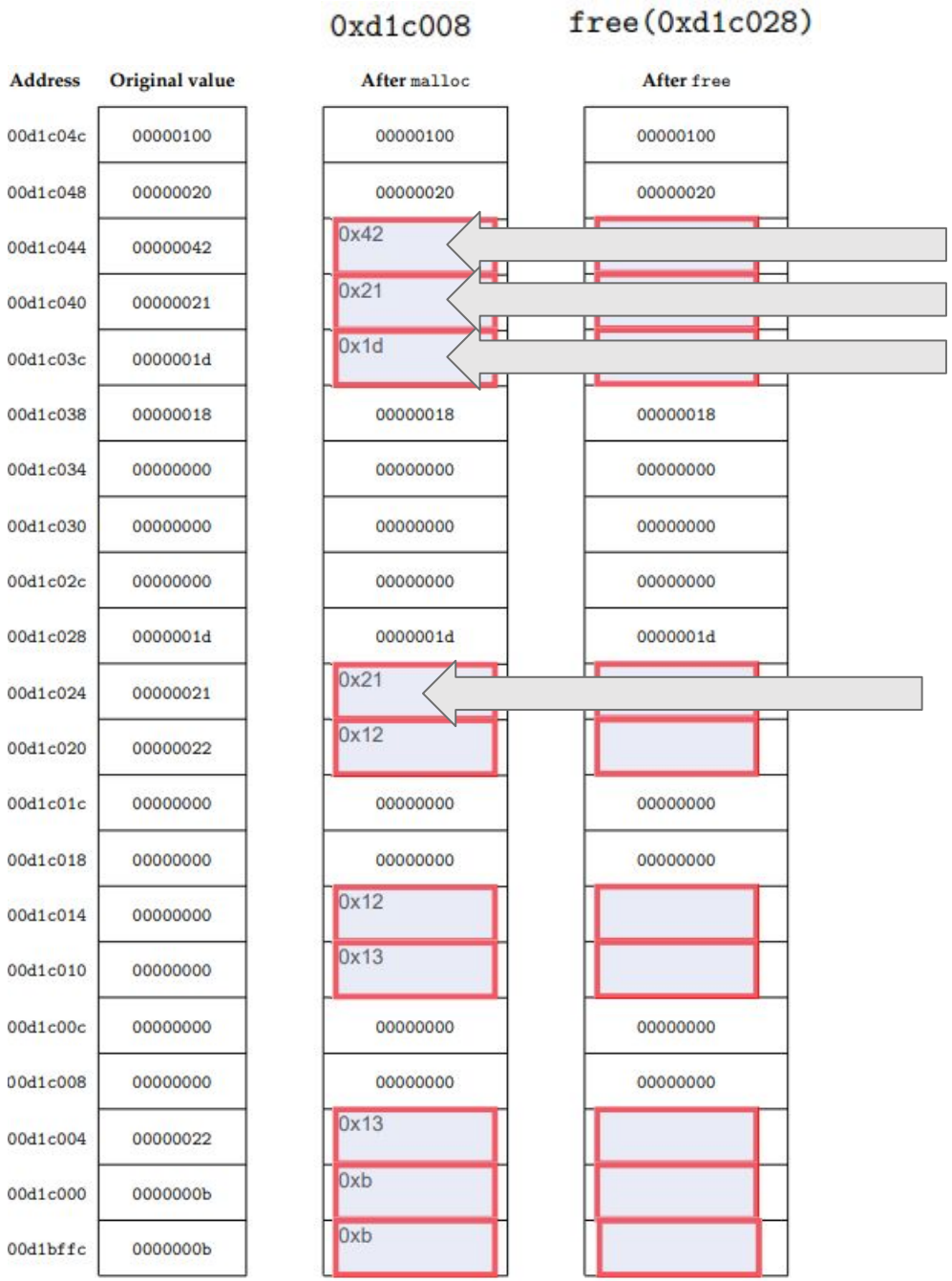
What about the rest of the free block? (just above)

- It will not be be allocated
- Previous will be allocated
- Size = 32-16 = 16 = 0001 0000
- So -> 0001 0011 -> 0x12

Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	0x42	
00d1c040	00000021	0x21	
00d1c03c	0000001d	0x1d	
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021	0x21	
00d1c020	00000022	0x12	
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	0x12	
00d1c010	00000000	0x13	
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022	0x13	
00d1c000	0000000b	0xb	
00d1bffc	0000000b	0xb	

(not a real header.
Nothing changes)

Size unchanged, previous still unallocated. stays the same

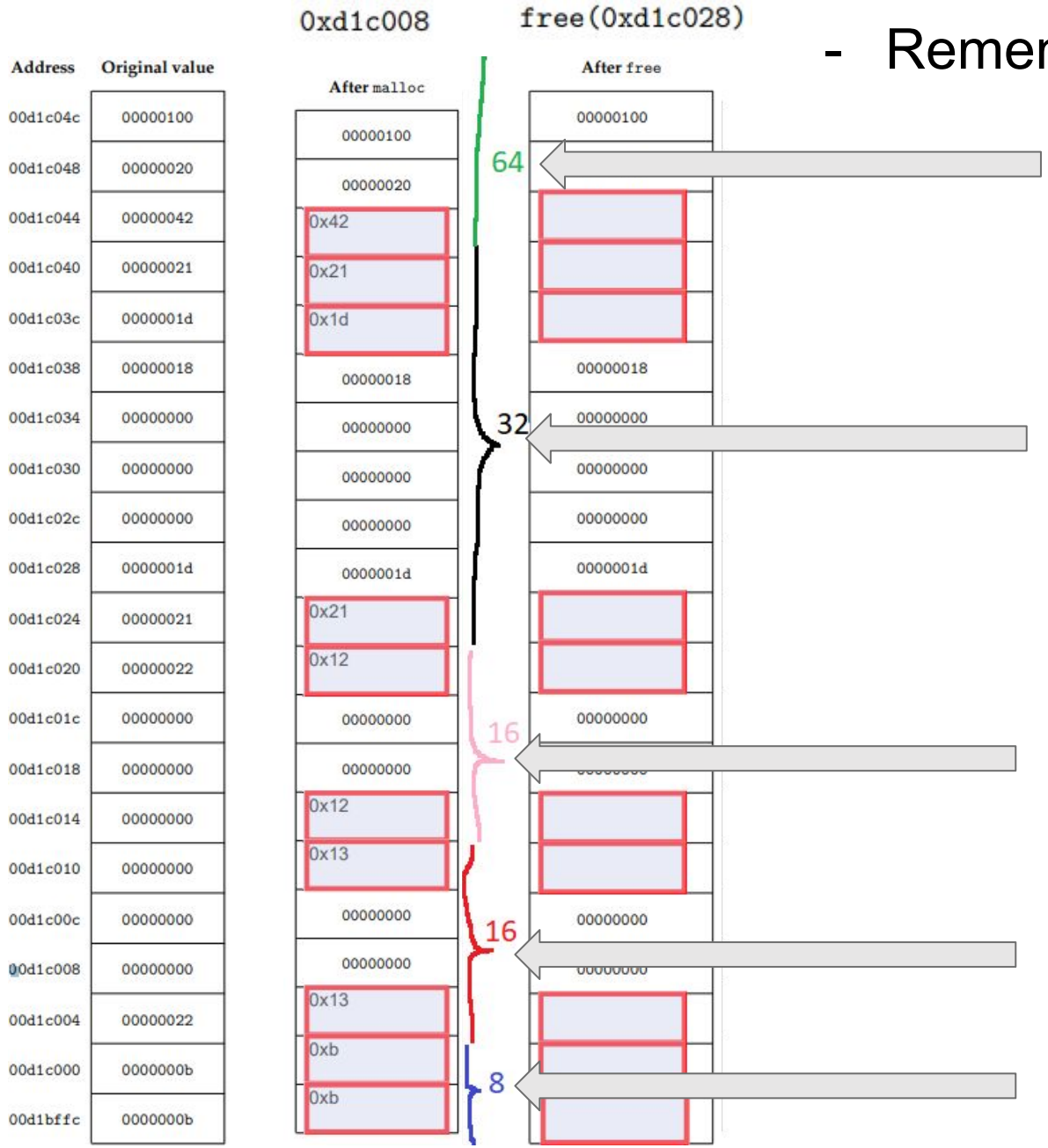


Stays the same

0x21 Footer

(not a real header. Nothing changes)

Size unchanged, previous still unallocated. Stays the same



- Remember:

Not allocated

Allocated

Not allocated

Allocated (now)

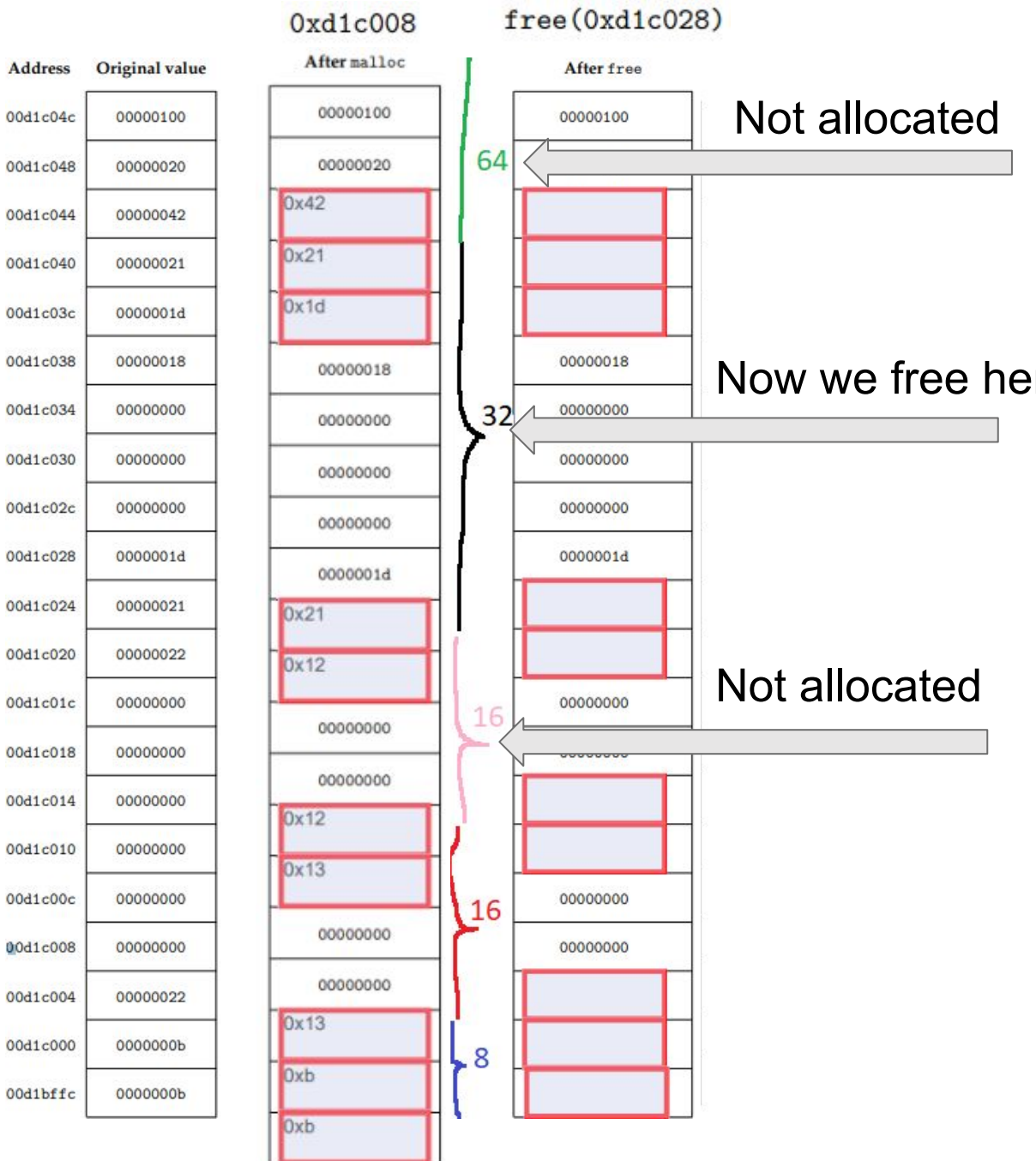
Allocated

- Remember:

Not allocated

Now we free here (oh no)

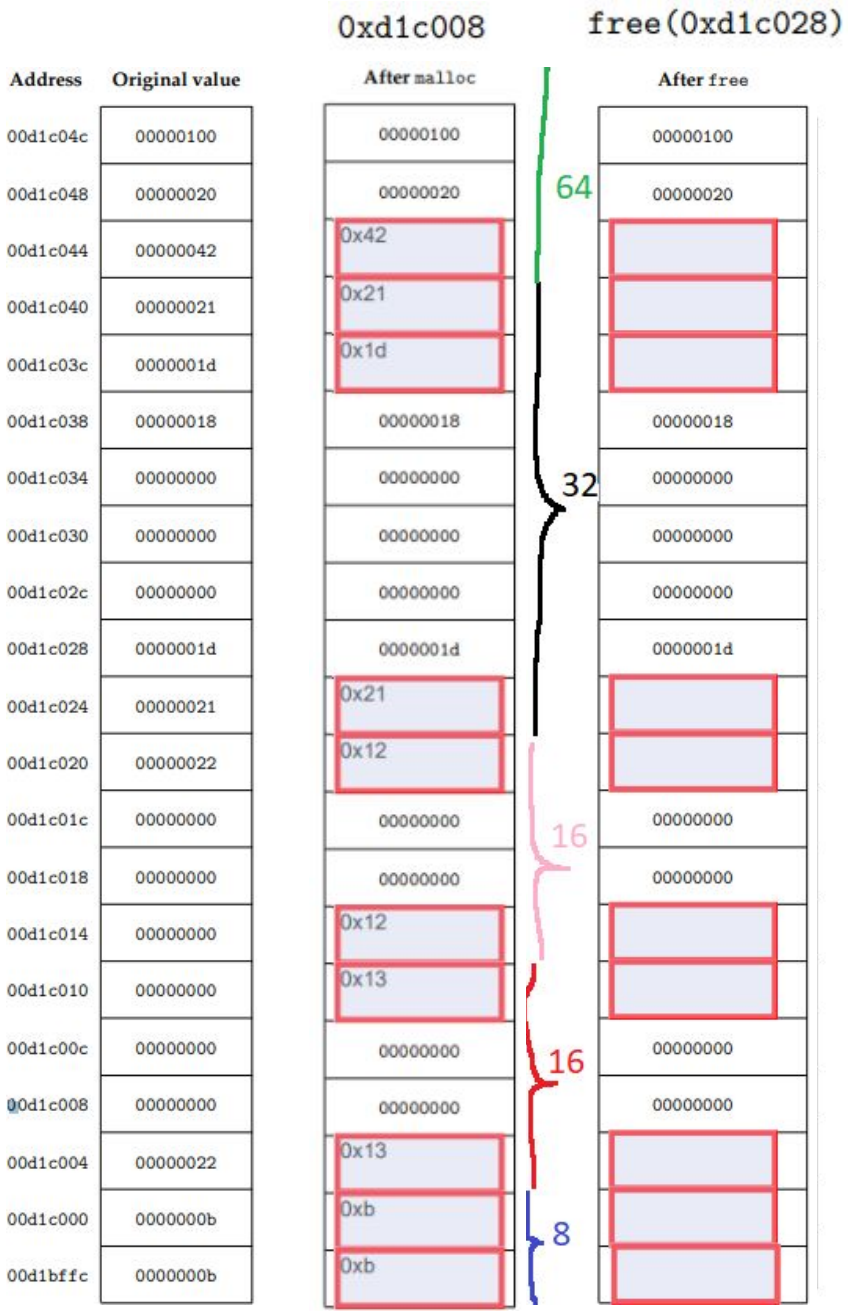
Not allocated



- But how? The block above is not even on the heap.

- Twofold: We solve the size using simple math, trusting the bits even if we cannot see the footer. And we do not change the footer, since it is not possible.

  Simply, the heap we see must be correct for the exercise. We are not concerned with the non-visible heap



It will not be allocated

Its neighbour will be allocated

Size = 16+32+64 = 0111 0000

So: 0111 0010 = 0x72

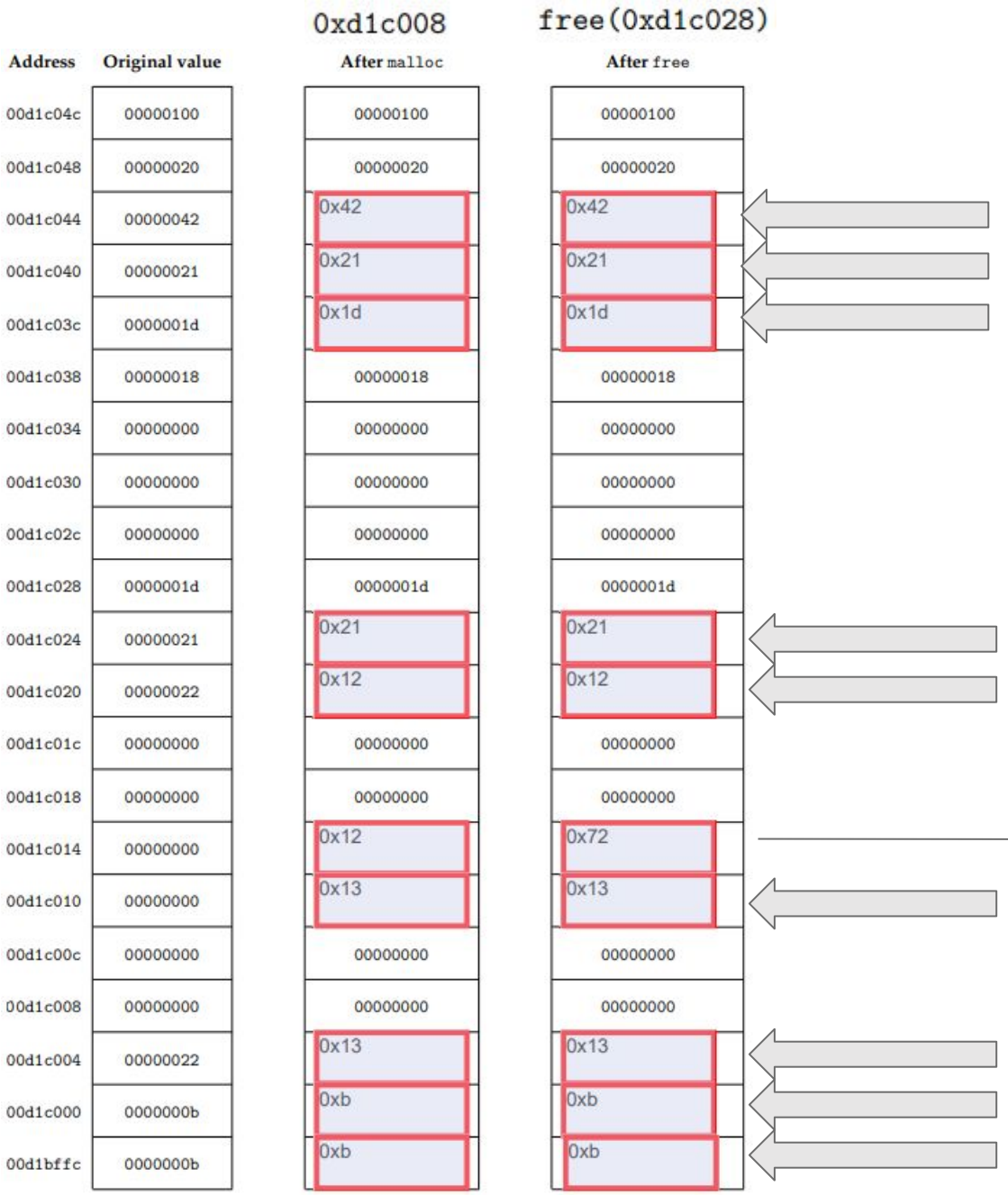
Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	0x42	0x42
00d1c040	00000021	0x21	0x21
00d1c03c	0000001d	0x1d	0x1d
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021	0x21	0x21
00d1c020	00000022	0x12	0x12
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	0x12	0x72
00d1c010	00000000	0x13	0x13
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022	0x13	0x13
00d1c000	0000000b	0xb	0xb
00d1bffc	0000000b	0xb	0xb

It will not be allocated

Its neighbour will be allocated

Size = 16+32+64 = 0111 0000

So: 0111 0010 = 0x72



Unchanged, again, because of immediate coalescing. They do not need to be changed so they just remain the same value, but now unallocated.

There was even a hint/specification for this, this time:

- Perform the minimum number of memory changes required.

Unchanged, unaffected by changes in any way

Correct?

Address	Original value	After `malloc`	After `free`
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	0x42	0x42
00d1c040	00000021	0x21	0x21
00d1c03c	0000001d	0x1d	0x1d
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021	0x21	0x21
00d1c020	00000022	0x12	0x12
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	0x12	0x72
00d1c010	00000000	0x13	0x13
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022	0x13	0x13
00d1c000	0000000b	0xb	0xb
00d1bffc	0000000b	0xb	0xb

Address	Original value	After `malloc`	After `free`
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	00000042	00000042
00d1c040	00000021	00000021	00000021
00d1c03c	0000001d	0000001d	0000001d
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021	00000021	00000021
00d1c020	00000022	00000012	00000012
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	00000012	00000072
00d1c010	00000000	00000013	00000013
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022	00000013	00000013
00d1c000	0000000b	0000000b	0000000b
00d1bffc	0000000b	0000000b	0000000b

No bonus question

Likely due to a change in the format

From a 8-hour take home exam to a 4 hour written exam

Extra

Either for reading or in case I have extra extra time

General Heap tips

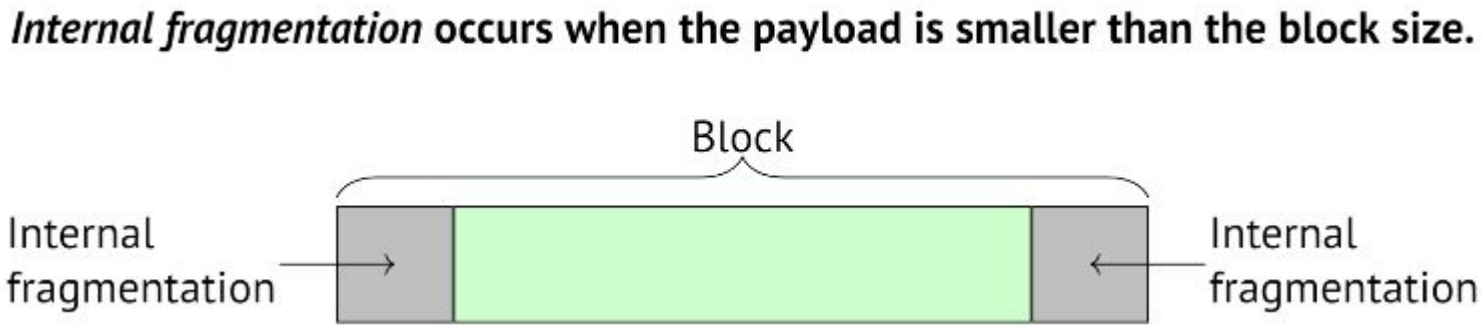
- There will almost always be some trick, such that you actually have to understand the heap to be able to complete the exercise
- Even with that, this becomes easily manageable with enough practice.
- At the first step, always analyse the entire initial heap, before doing any of the heap functions
- Even if it is recommended to analyse the length of a block to see where the next block starts, in case of time trouble, and/or having good intuition of block lengths (hexadecimal is not that far from decimal, especially in low numbers) you may be able to guess which are headers and which are not
- Read. The. Stated. Rules

Semaphore tips

- If both lock same place, this is no-go zone
- Draw no-go zones
- If at any point can go neither up nor right. This is a deadlock
- Else not deadlock

Internal fragmentation

- Internal fragmentation we saw in our second example, and is the result of standards (such as a block being a multiple of 8 bytes or needing to eat up a block that cannot exist on its own)
- The fragmentation is, then, the extra space taken up that is not needed



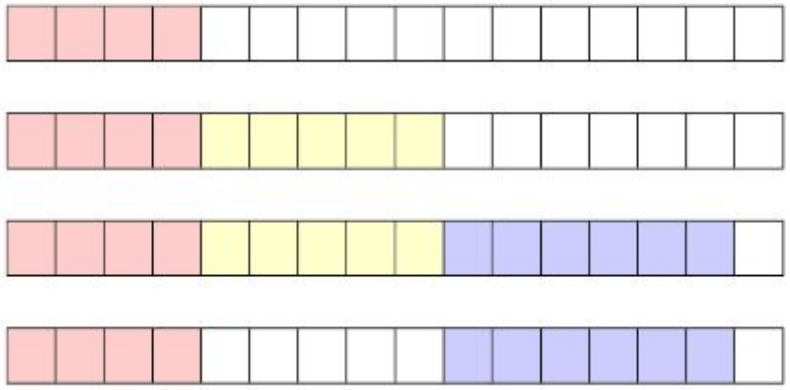
(Shamelessly stolen from Troels slides Virtual memory ii)

External fragmentation

- External fragmentation is when a heap with a lot of allocating and deallocating, after long time will be a mess. What was once a heap with blocks neatly adjacent is now a lot of blocks everywhere with inconvenient space in between.

Occurs when there is enough aggregate heap memory, but no single free block is large enough.

```
p1 = malloc(4*4);
p2 = malloc(5*4);
p3 = malloc(6*4);
free(p2);
p4 = malloc(6*4);
```



No free block with room for six words.

Depends on future requests, so difficult to measure.

(Shamelessly stolen from Troels slides - Virtual memory ii)

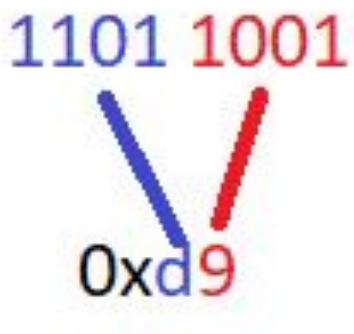
← We kind of wish the blue block could easily be moved 5 to the left for some nice adjacency.

Fragmentation Intuition

- Internal and external fragmentation are called so, because internal fragmentation exists within blocks and external fragmentation happens outside (between) blocks. This can be a way to remember them.

How to convert between hexadecimal, binary, and decimal

- https://www.youtube.com/watch?v=D_YC6DSPpQE
- No, yeah, there already exists a great resource I won't be trying to beat.
- But essentially the big thing is that since a hexadecimal digit can represent 16 different values, and the same is the case with 4 binary digits (since 2^4 = 16) then translating between them is really easy, just from least to most take the 4 binary digits and each is a hexadecimal digit, and reversed. For example:



Fin.