

Virtual memory allocation and semaphores

Recap

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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)
- I have tried to make the slides readable, using full sentences for explanations such that you can always look through them at a later time
- There is no specific time for questions, raise hands as needed

The exercises in question

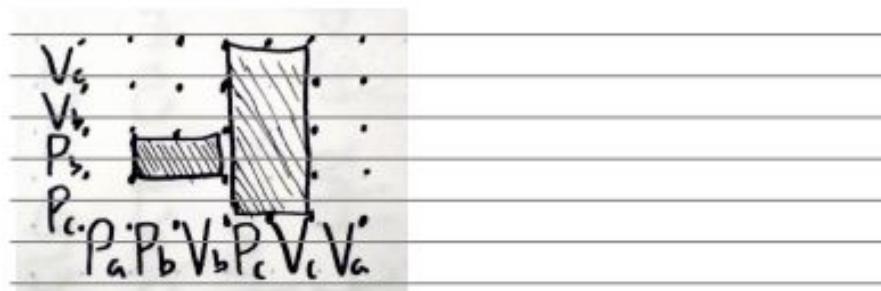
2.2 Short Questions (about 12 %)

Question 2.2.1: Consider two threads performing the following semaphores

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

Thread 1:	Thread 2:
<code>P(a);</code>	<code>P(c);</code>
<code>P(b);</code>	<code>P(b);</code>
<code>V(b);</code>	<code>V(b);</code>
<code>P(c);</code>	<code>V(c);</code>
<code>V(c);</code>	
<code>V(a);</code>	

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



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
0x12bff8	0x00000023		

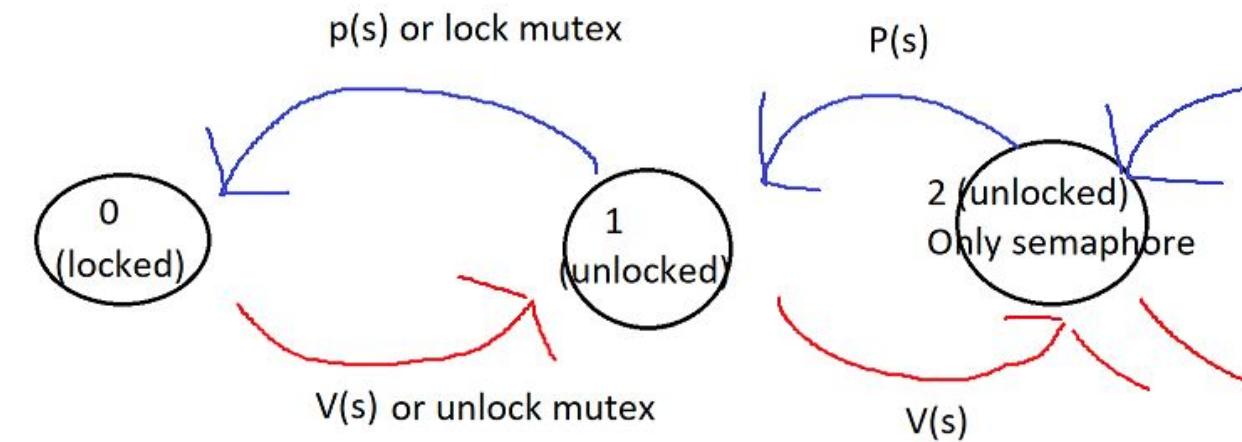
Semaphores

- 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:

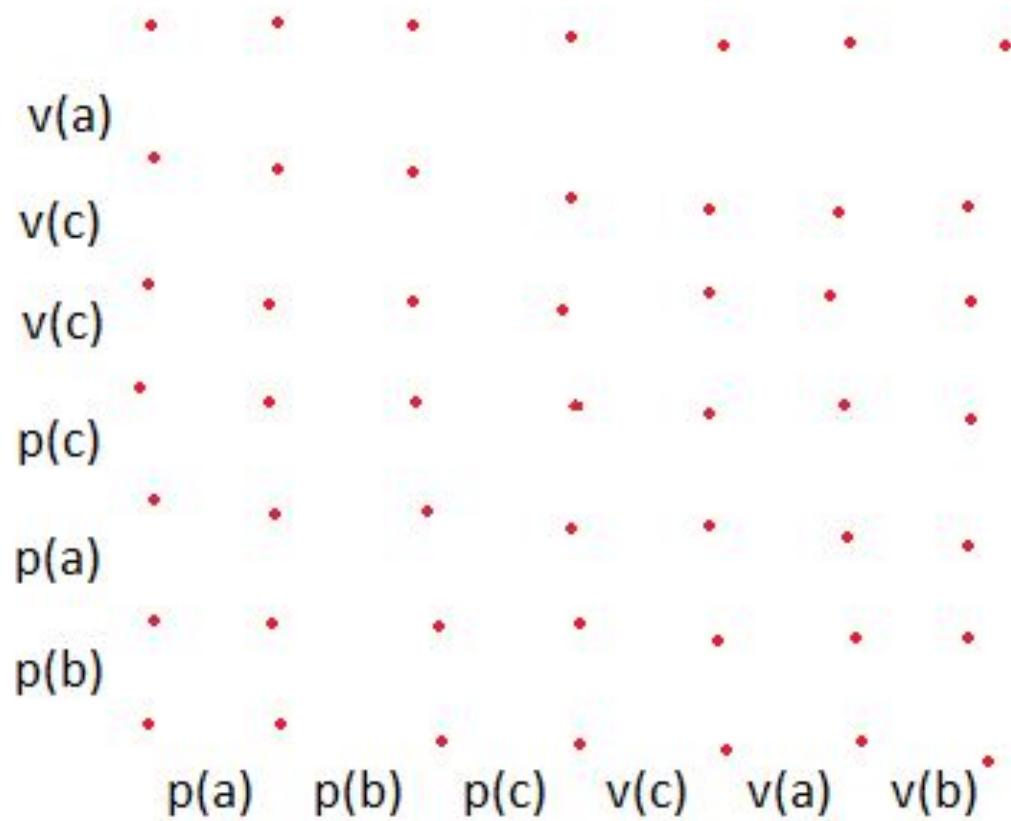
P(a);	P(b);
P(b);	P(a);
P(c);	P(c);
V(c);	V(c);
V(a);	V(b);
V(b);	V(a);

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 attach the figure as an image in the handin.)

(Warning)

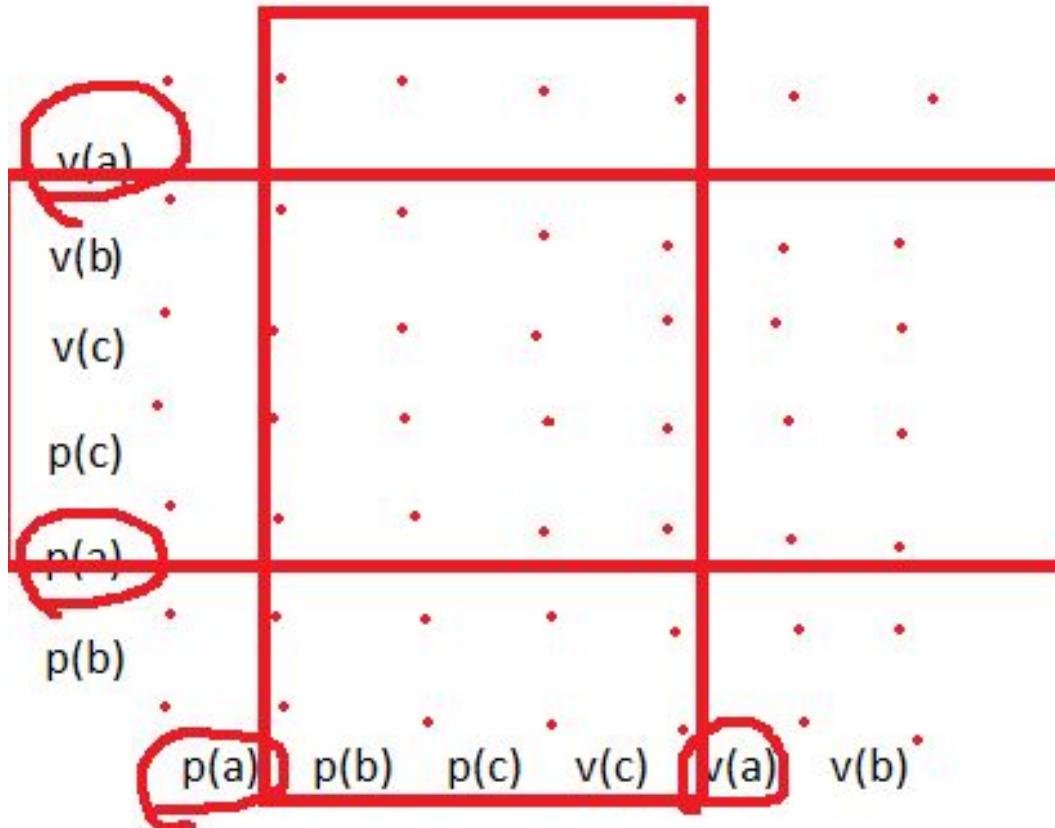
- I accidentally swapped thread 1 and thread 2 in the exercises I will show. It does not alter the correctness, just keep it in mind. You might also want to have it correct in the exam

Re-Exam 21/22 - how to solve?



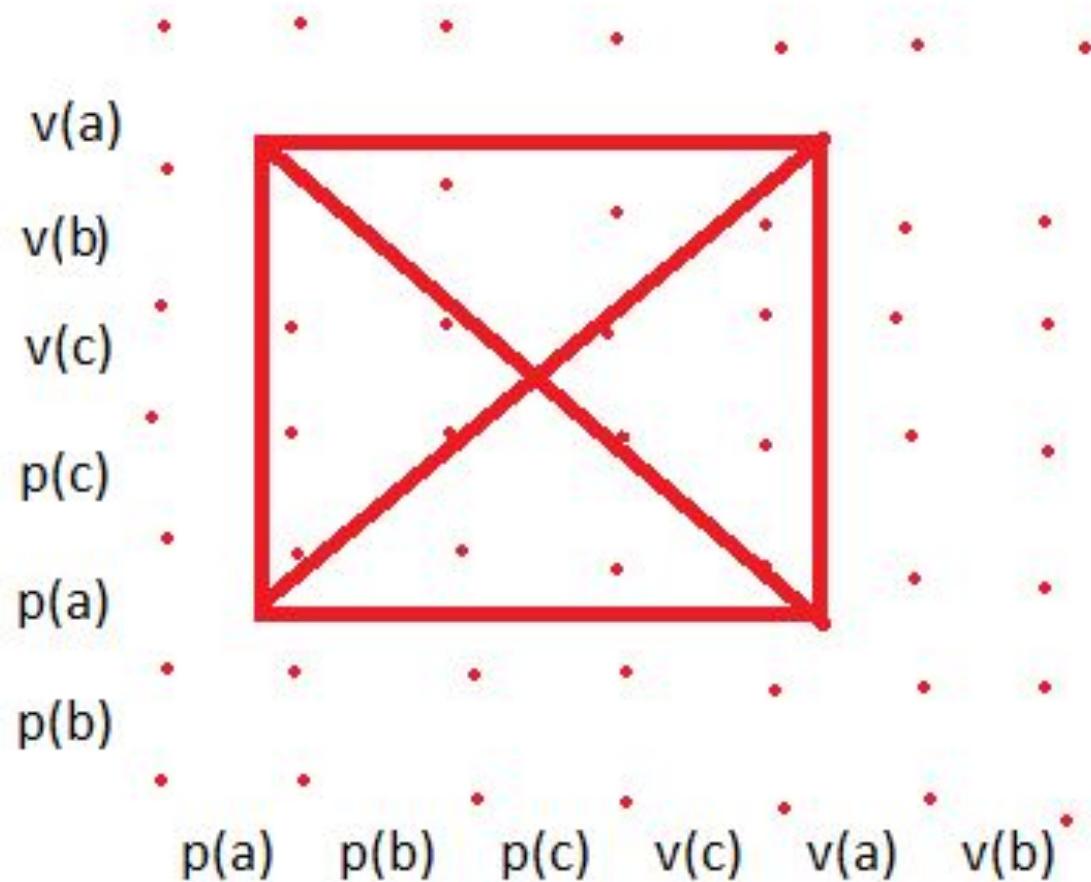
- One thread along the bottom
- The other thread along the top
- If moving right, one thread is progressing
- If moving up, the other thread is progressing
- Every p() or v() is a transition from 1 dot to another, where that action now happened

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.

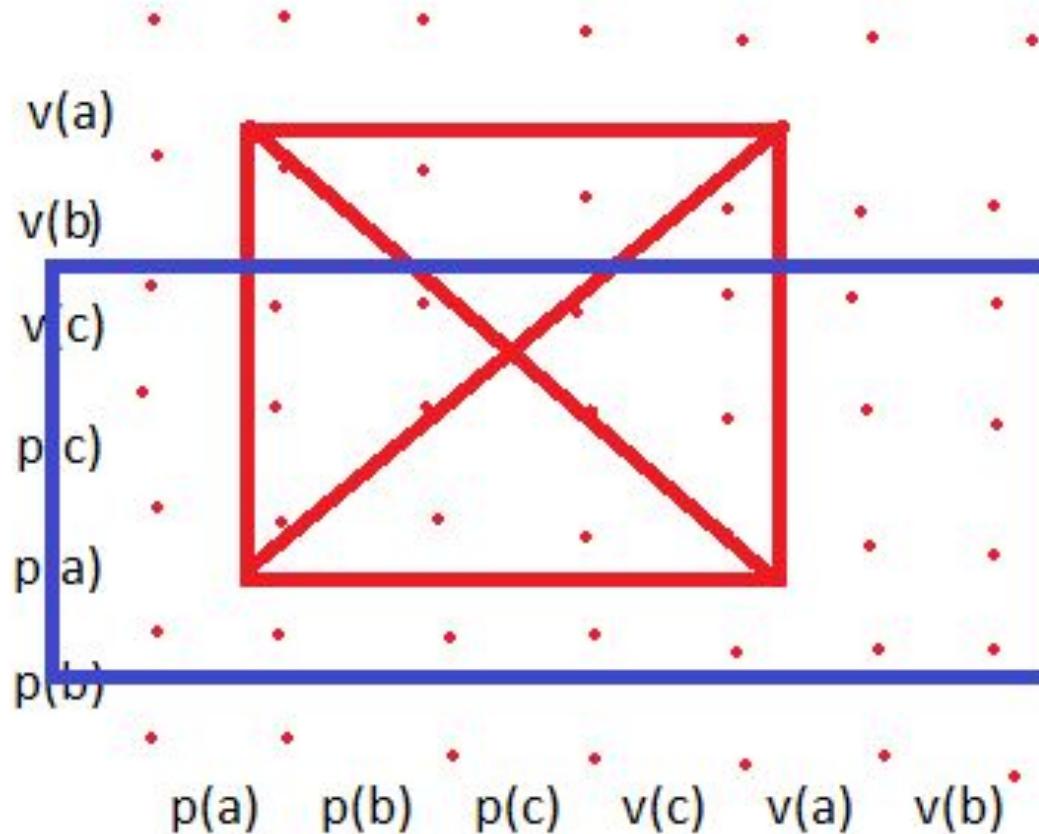
Re-Exam 21/22 - how to solve?



- Where is variable a locked?
- from $p(a)$ until $v(a)$
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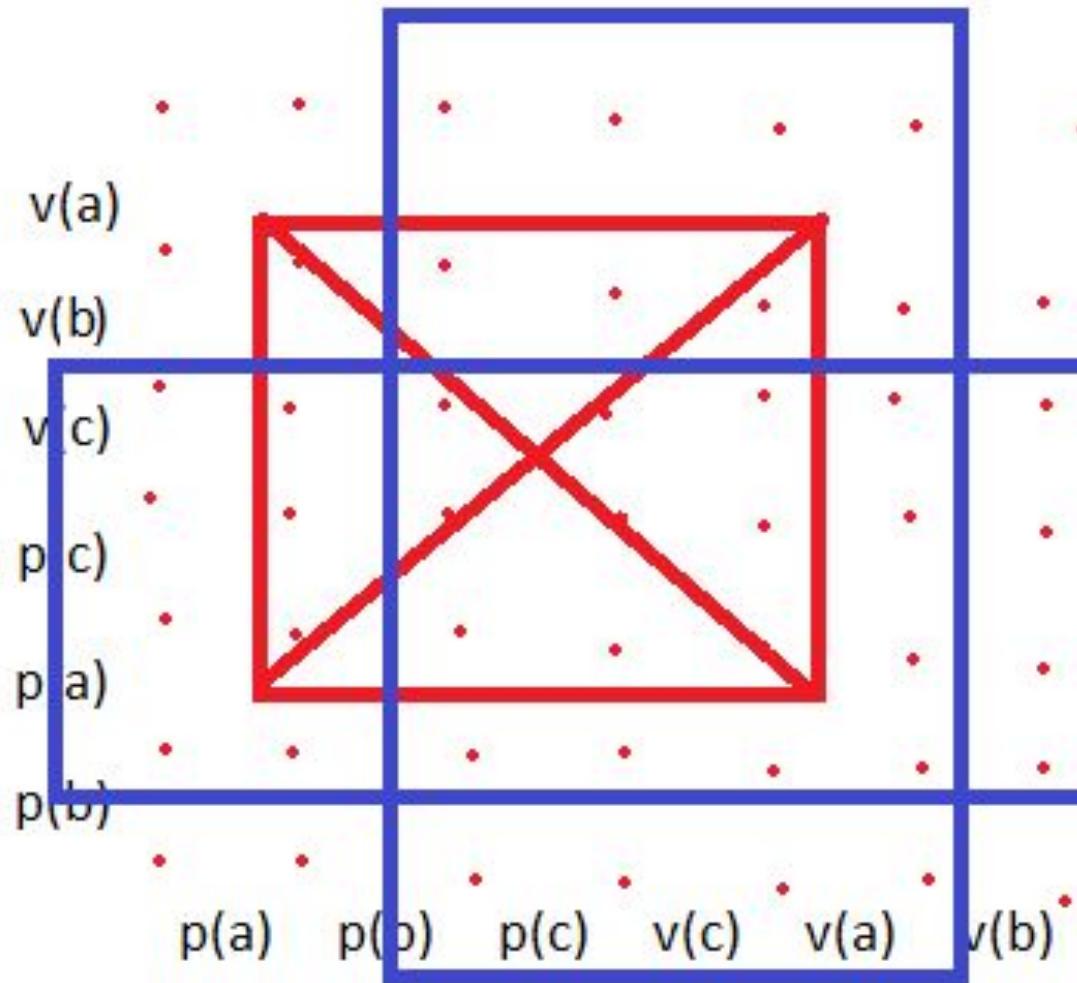
Re-Exam 21/22 - how to solve?

- Where is variable b locked?



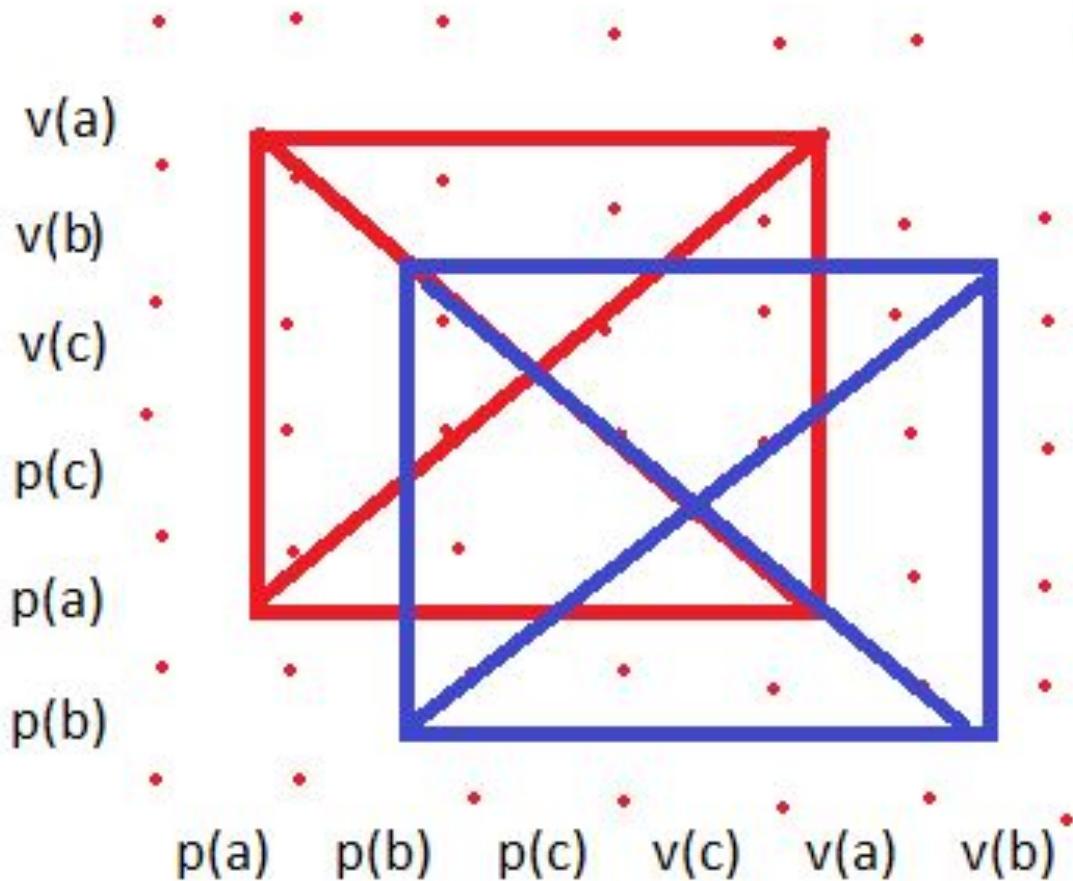
Re-Exam 21/22 - how to solve?

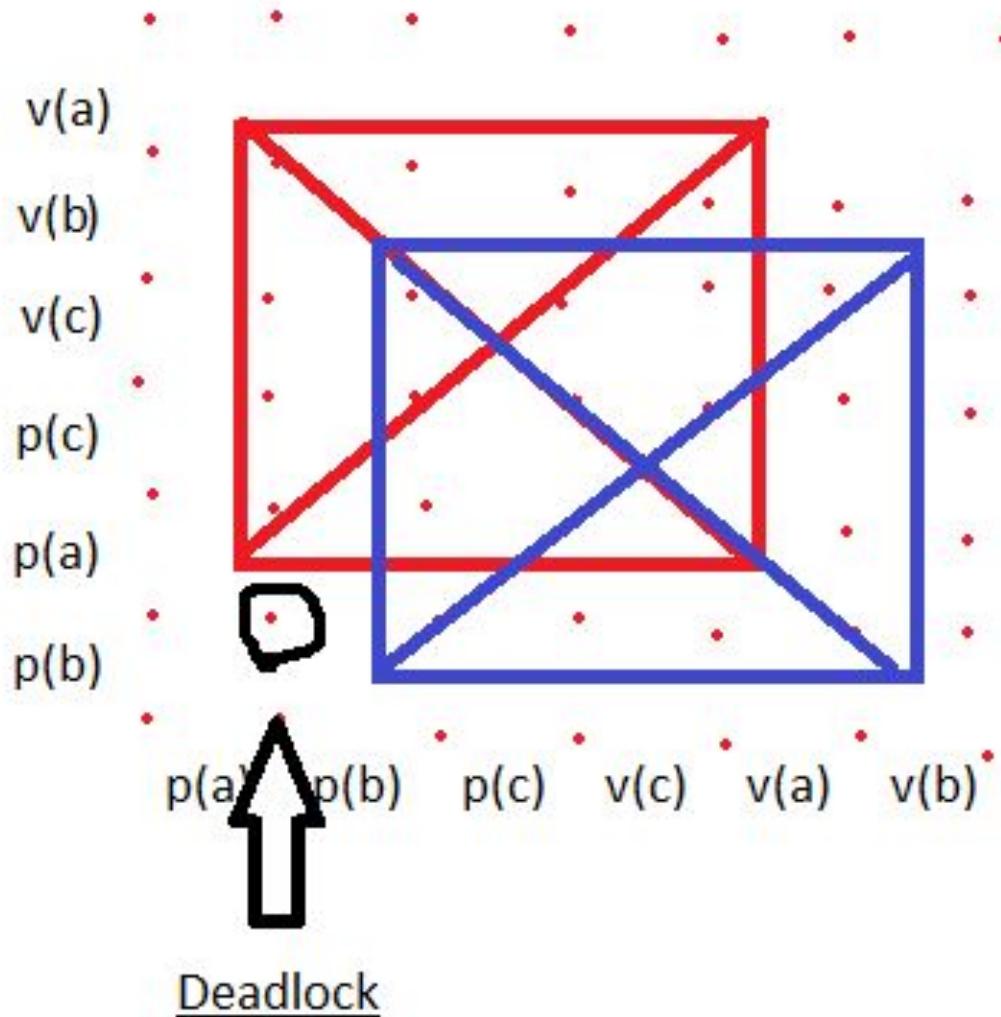
- Where is variable b locked?



Re-Exam 21/22 - how to solve?

- Where is variable b locked?

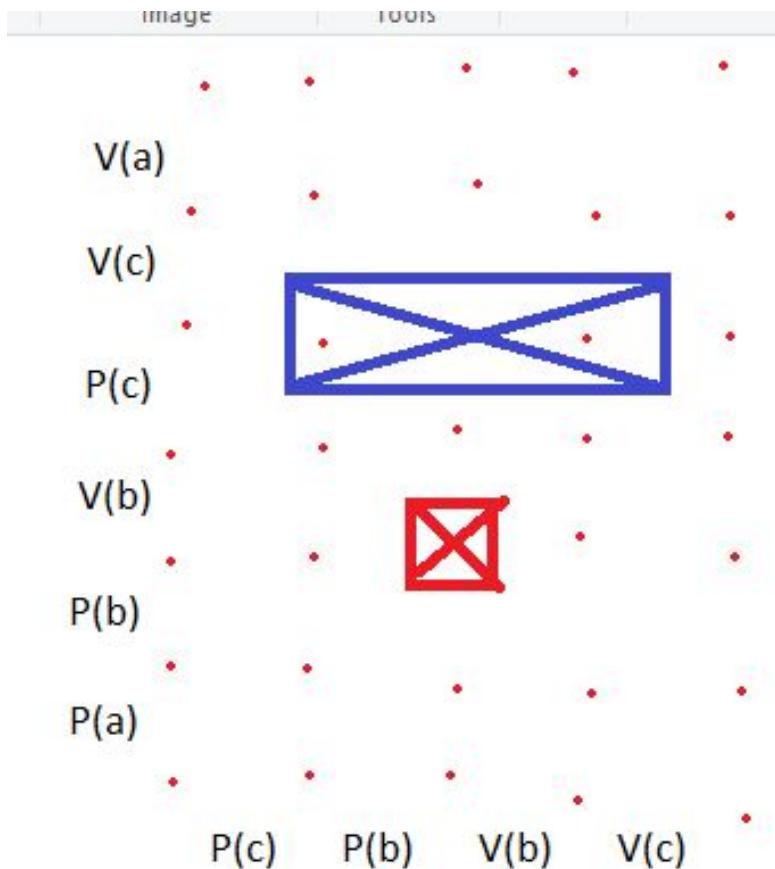




- The question was whether a deadlock existed
- Argumentation: “A deadlock is possible, as in this spot, you may go neither up nor right”
- (Checking c not necessary)

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:

$P(a);$

$P(b);$

$V(b);$

$P(c);$

$V(c);$

$V(a);$

Thread 2:

$P(c);$

$P(b);$

$V(b);$

$V(c);$

Can always proceed right

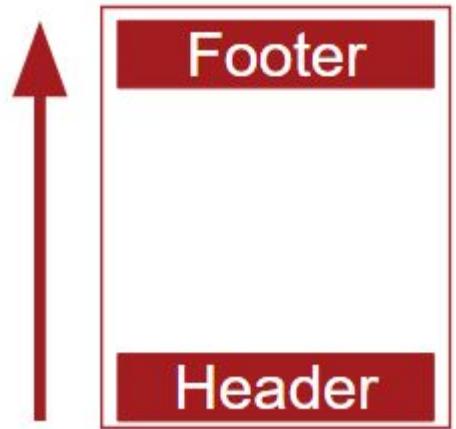
or up = no deadlock exists

(Again, I swapped the
threads, oops)

Now onto the heap

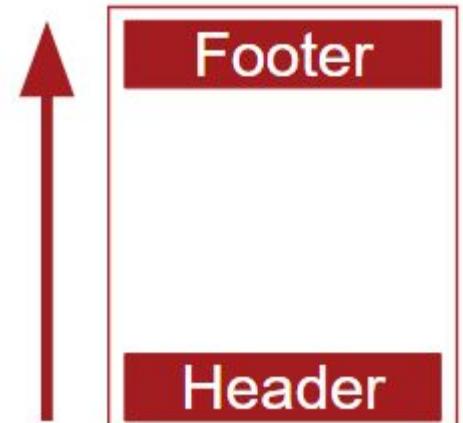
Firstly...

- The heap grows bottom-up



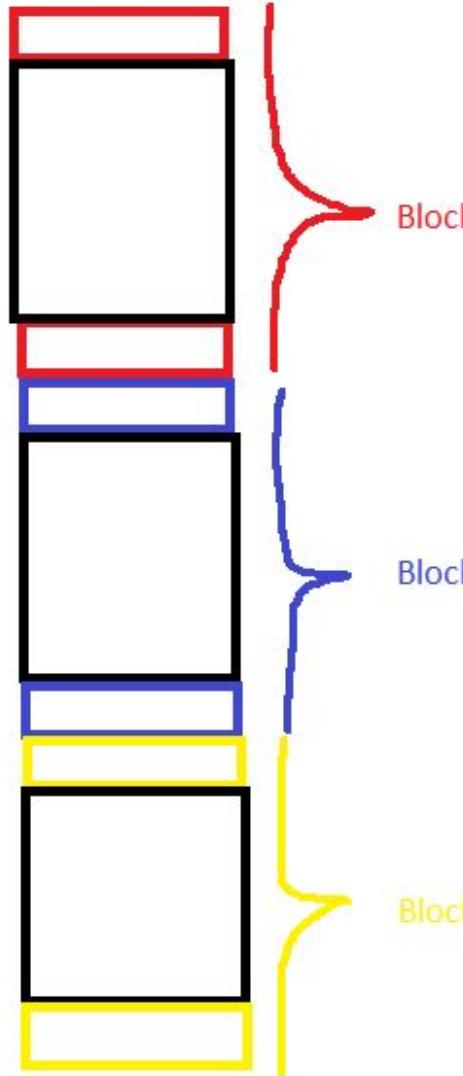
Firstly...

- 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

Footer 2->



Header 2->
Footer 1->

Header 1->
Footer 0->

Header 0 ->

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

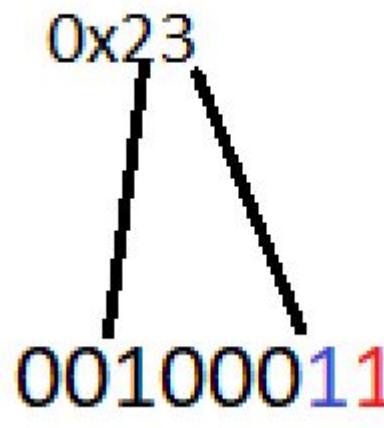
0x500bffc 0x00000013

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
- Immediate 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
- Immediate coalescing (explained more later)
- Example:

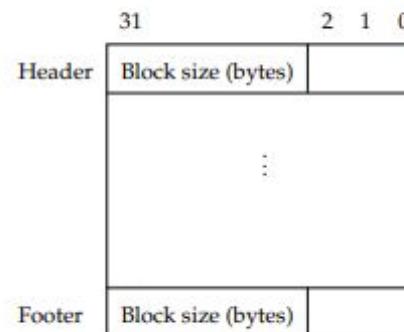


- Is allocated
- Previous is allocated
- Size is gotten by setting the 3 lower bits to 0:
00100011 -> 00100000 = 0x20 or 32
- (Size is inclusive header and footer)

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 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

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

Address	Original value	After realloc	After free
0x12c028	0x00000012		
0x12c024	0x012c611c		
0x12c020	0x012c512c		
0x12c01c	0x00000012		
0x12c018	0x00000023		
0x12c014	0x012c511c		
0x12c010	0x012c601c		
0x12c00c	0x00000000		
0x12c008	0x00000000		
0x12c004	0x012c601c		
0x12c000	0x012c511c		
0x12bfffc	0x00000023		

First element



0x12c000

Then this must
be the header



0x12bfffc

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

	Address	Original value	After realloc	After free
Footer?	0x12c028	0x00000012		
	0x12c024	0x012c611c	0x012c611c	0x012c611c
	0x12c020	0x012c512c	0x012c512c	0x012c512c
Header?	0x12c01c	0x00000012		
Footer?	0x12c018	0x00000023		
	0x12c014	0x012c511c	0x012c511c	0x012c511c
	0x12c010	0x012c601c	0x012c601c	0x012c601c
	0x12c00c	0x00000000		
	0x12c008	0x00000000		
	0x12c004	0x012c601c	0x012c601c	0x012c601c
First element	0x12c000	0x012c511c	0x012c511c	0x012c511c
Then this must be the header	0x12bfffc	0x00000023		

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

	Address	Original value	After realloc	After free
Footer?	0x12c028	0x00000012		
	0x12c024	0x012c611c		
	0x12c020	0x012c512c		
Header?	0x12c01c	0x00000012		
Footer?	0x12c018	0x00000023		
	0x12c014	0x012c511c		
	0x12c010	0x012c601c		
	0x12c00c	0x00000000		
	0x12c008	0x00000000		
	0x12c004	0x012c601c		
	0x12c000	0x012c511c		
First element	0x12c000	0x00000023		
Then this must be the header	0x12bfffc			

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
0x12bfffc	0x00000023		

0x23
00100011

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

Address	Original value
0x12c028	0x00000012
0x12c024	0x012c611c
0x12c020	0x012c512c
0x12c01c	0x00000012
0x12c018	0x00000023
0x12c014	0x012c511c
0x12c010	0x012c601c
0x12c00c	0x00000000
0x12c008	0x00000000
0x12c004	0x012c601c
0x12c000	0x012c511c
0x12bfec	0x00000023

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

After realloc After free

32

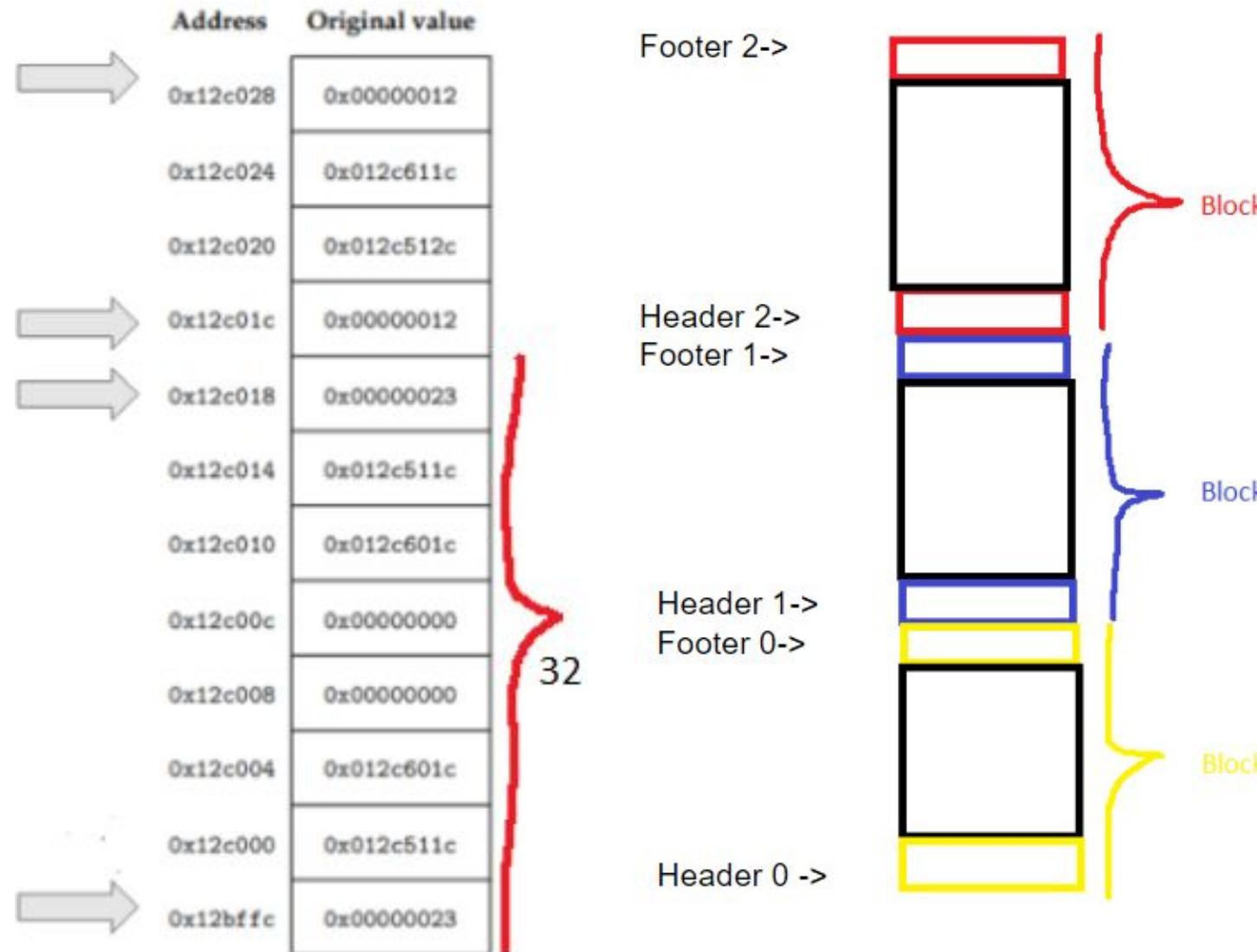
0x23
00100011

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

0x12
00010010

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

Remember - when one block ends the next one starts



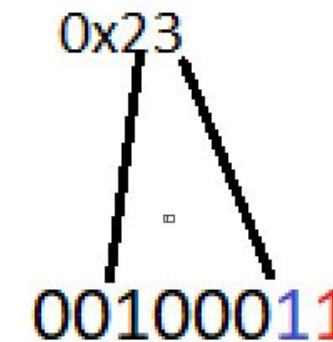
Address	Original value		
0x12c028	0x00000012		
0x12c024	0x012c611c		
0x12c020	0x012c512c		
0x12c01c	0x00000012		
0x12c018	0x00000023		
0x12c014	0x012c511c		
0x12c010	0x012c601c		
0x12c00c	0x00000000		
0x12c008	0x00000000		
0x12c004	0x012c601c		
0x12c000	0x012c511c		
0x12bffc	0x00000023		

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

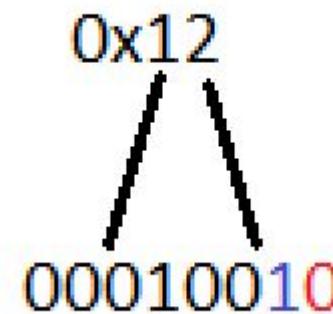
After realloc:

16

32



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



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

realloc(0x12c000, 8).

Address	Original value
0x12c028	0x00000012
0x12c024	0x012c611c
0x12c020	0x012c512c
0x12c01c	0x00000012
0x12c018	0x00000023
0x12c014	0x012c511c
0x12c010	0x012c601c
0x12c00c	0x00000000
0x12c008	0x00000000
0x12c004	0x012c601c
0x12c000	0x012c511c
0x12bfffc	0x00000023

Address	Original value
0x12c028	0x00000012
0x12c024	0x012c611c
0x12c020	0x012c512c
0x12c01c	0x00000012
0x12c018	0x00000023
0x12c014	0x012c511c
0x12c010	0x012c601c
0x12c00c	0x00000000
0x12c008	0x00000000
0x12c004	0x012c601c
0x12c000	0x012c511c
0x12bfffc	0x00000023

free(0x12c000).

0x23
00100011

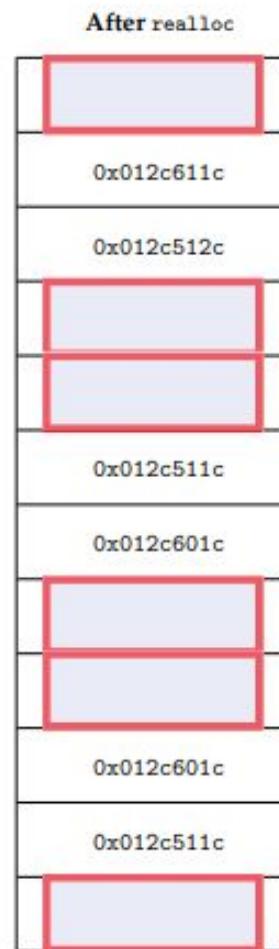
Is allocated
Previous is allocated
Size = 00100000 = 0x20 = 32

0x12
00010010

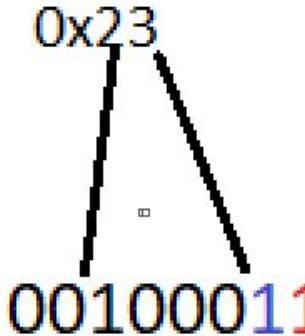
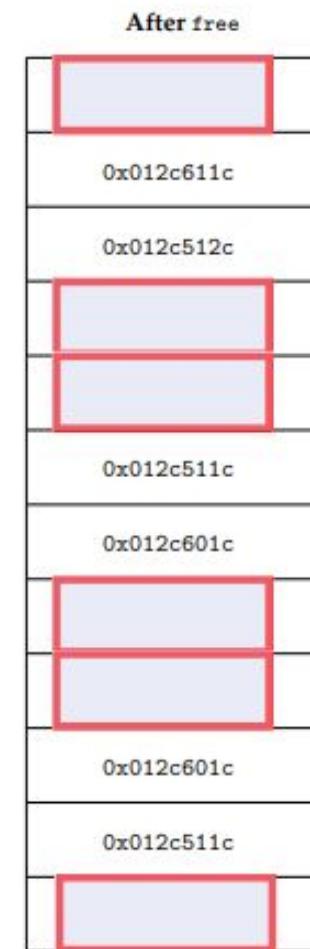
Is not allocated
Previous is allocated
Size = 00010000 = 0x10 = 16

realloc(0x12c000, 8).

Address	Original value
0x12c028	0x00000012
0x12c024	0x012c611c
0x12c020	0x012c512c
0x12c01c	0x00000012
0x12c018	0x00000023
0x12c014	0x012c511c
0x12c010	0x012c601c
0x12c00c	0x00000000
0x12c008	0x00000000
0x12c004	0x012c601c
0x12c000	0x012c511c
0x12bfffc	0x00000023



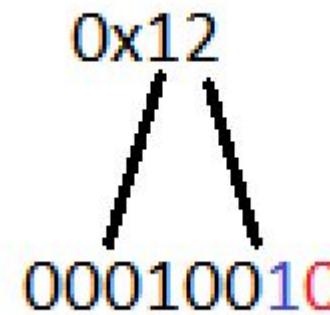
free(0x12c000).



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)

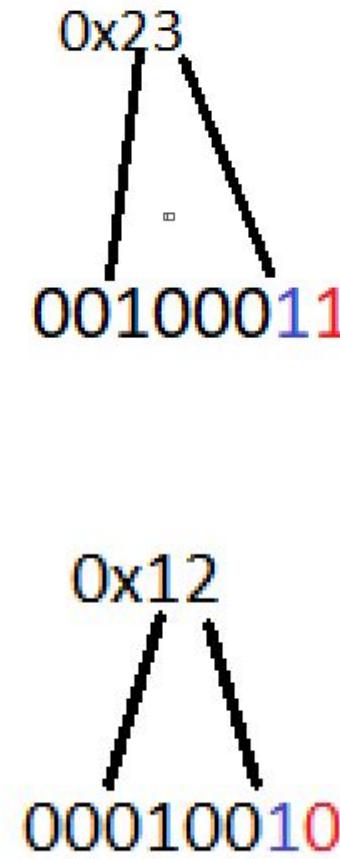
it will be allocated (via realloc())

The previous was allocated before, still will be

Size = 00010000, so: 00010011 = 0x13

	realloc(0x12c000, 8).	free(0x12c000).
Free	Address Original value After realloc	After free
0x12c028	0x00000012	0x12c611c
0x12c024	0x012c611c	0x012c512c
0x12c020	0x012c512c	0x012c512c
0x12c01c	0x00000012	0x012c511c
0x12c018	0x00000023	0x012c511c
0x12c014	0x012c511c	0x012c601c
0x12c010	0x012c601c	0x012c601c
0x12c00c	0x00000000	0x012c601c
0x12c008	0x00000000	0x012c601c
0x12c004	0x012c601c	0x012c511c
0x12c000	0x012c511c	0x12c611c
0x12bfffc	0x00000023	0x12c611c

Now free
They must
combine



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

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

realloc(0x12c000, 8).

free(0x12c000).

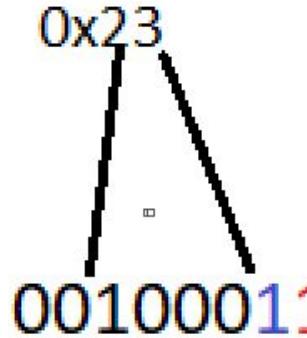
Address	Original value	After realloc
0x12c028	0x00000012	
0x12c024	0x012c611c	0x012c611c
0x12c020	0x012c512c	0x012c512c
0x12c01c	0x00000012	
0x12c018	0x00000023	
0x12c014	0x012c511c	0x012c511c
0x12c010	0x012c601c	0x012c601c
0x12c00c	0x00000000	
0x12c008	0x00000000	0x13
0x12c004	0x012c601c	0x012c601c
0x12c000	0x012c511c	0x012c511c
0x12bfffc	0x00000023	0x13

Free

Now free

They must combine

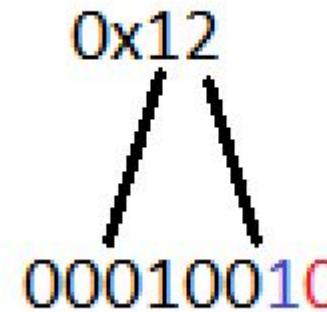
After free



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

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

Address	Original value	After realloc	After free
0x12c028	0x00000012	0x22	
0x12c024	0x012c611c		0x012c611c
0x12c020	0x012c512c		0x012c512c
0x12c01c	0x00000012	0x12	
0x12c018	0x00000023	0x23	
0x12c014	0x012c511c		0x012c511c
0x12c010	0x012c601c		0x012c601c
0x12c00c	0x00000000	0x22	
0x12c008	0x00000000	0x13	
0x12c004	0x012c601c		0x012c601c
0x12c000	0x012c511c		0x012c511c
0x12bfffc	0x00000023	0x13	

What about 0x12 and 0x23?

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

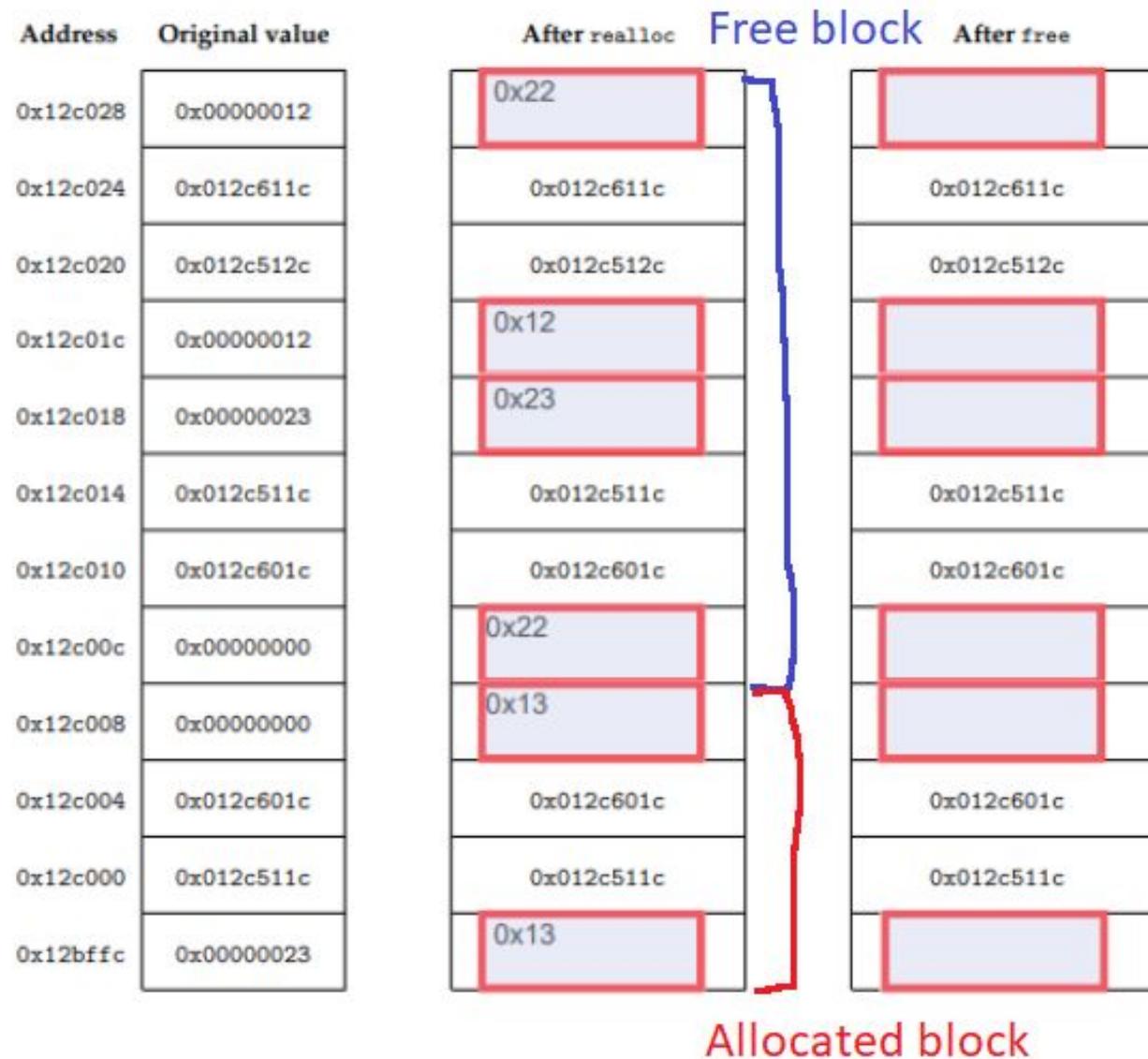
Size will be $16+16 = 32 = 00100000$

It will not be allocated

Previous is allocated (0x13 block)

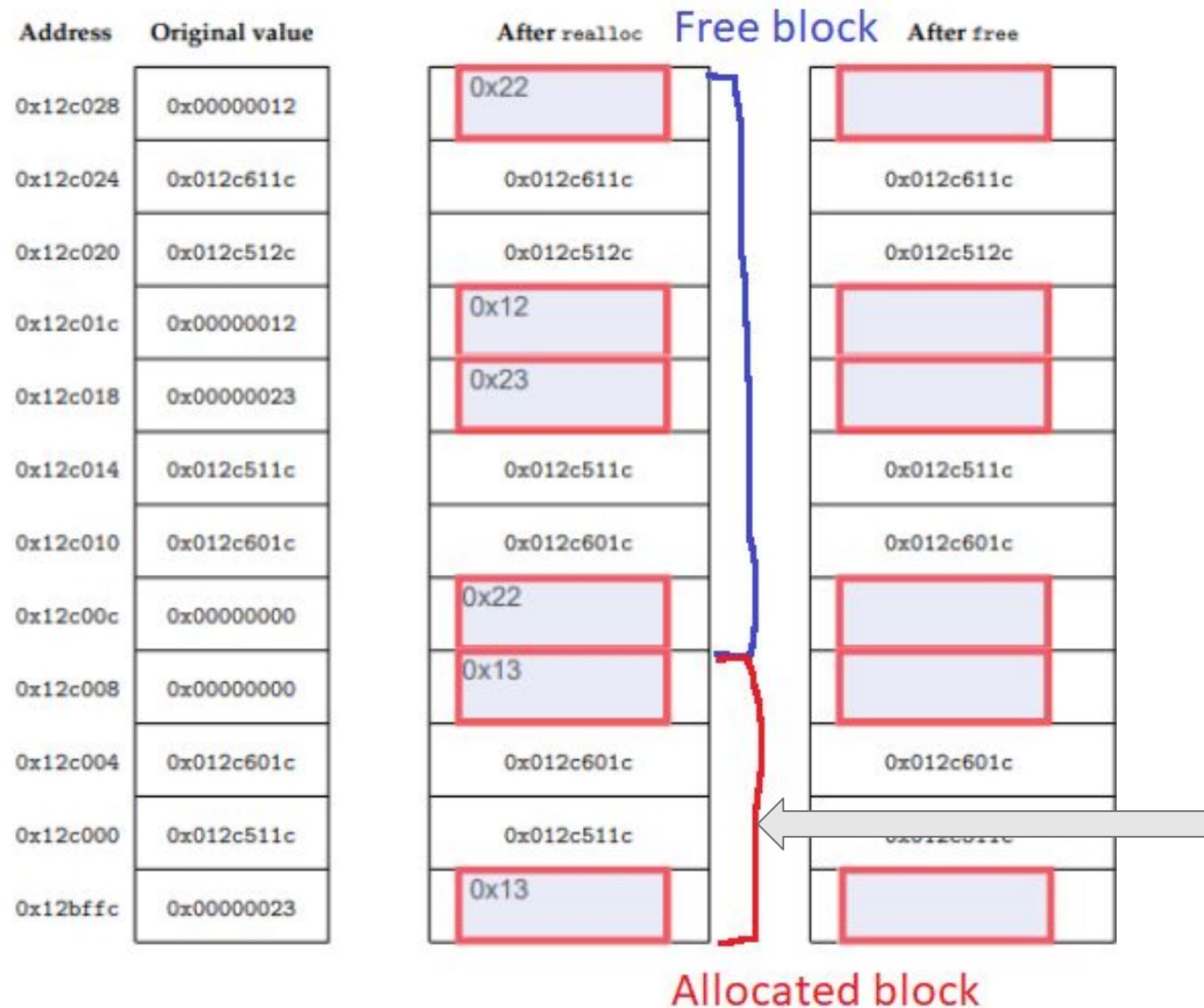
so: $001000\textcolor{blue}{1}0 = 0x22$

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



Next: free(0x12c000)

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



Next: free(0x12c000)

We free this block now

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

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

Address	After realloc
0x12c028	0x22
0x12c024	0x012c611c
0x12c020	0x012c512c
0x12c01c	0x12
0x12c018	0x23
0x12c014	0x012c511c
0x12c010	0x012c601c
0x12c00c	0x22
0x12c008	0x13
0x12c004	0x012c601c
0x12c000	0x012c511c
0x12bffc	0x13

Address	After free
0x12c028	
0x12c024	0x012c611c
0x12c020	0x012c512c
0x12c01c	
0x12c018	
0x12c014	0x012c511c
0x12c010	0x012c601c
0x12c00c	
0x12c008	
0x12c004	0x012c601c
0x12c000	0x012c511c
0x12bffc	

Next: free(0x12c000)

Free

Conclusion: Will be combined
with Immediate coalescing

Will be free

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

Address	Original value	After realloc	After free
0x12c028	0x00000012	0x22	
0x12c024	0x012c611c		0x012c611c
0x12c020	0x012c512c		0x012c512c
0x12c01c	0x00000012	0x12	
0x12c018	0x00000023	0x23	
0x12c014	0x012c511c		0x012c511c
0x12c010	0x012c601c		0x012c601c
0x12c00c	0x00000000	0x22	
0x12c008	0x00000000	0x13	
0x12c004	0x012c601c		0x012c601c
0x12c000	0x012c511c		0x012c511c
0x12bfffc	0x00000023	0x13	



realloc(0x12c000, 8).

free(0x12c000).

Address	Original value	After realloc
0x12c028	0x00000012	0x22
0x12c024	0x012c611c	0x012c611c
0x12c020	0x012c512c	0x012c512c
0x12c01c	0x00000012	0x12
0x12c018	0x00000023	0x23
0x12c014	0x012c511c	0x012c511c
0x12c010	0x012c601c	0x012c601c
0x12c00c	0x00000000	0x22
0x12c008	0x00000000	0x13
0x12c004	0x012c601c	0x012c601c
0x12c000	0x012c511c	0x012c511c
0x12bfffc	0x00000023	0x13

Address	After free
0x12c028	
0x12c024	0x012c611c
0x12c020	0x012c512c
0x12c01c	
0x12c018	
0x12c014	0x012c511c
0x12c010	0x012c601c
0x12c00c	
0x12c008	
0x12c004	0x012c601c
0x12c000	0x012c511c
0x12bfffc	

size will be $32+16 = 00110000$ (48)

It will not be allocated

Previous is still allocated (off-screen)

32

so: 00110010 = 0x32

16

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
0x12bfffc	0x00000023	0x13	0x32

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 the middle (arrows) stay unchanged, as 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
0x12bfffc	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
0x12bfffc	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

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

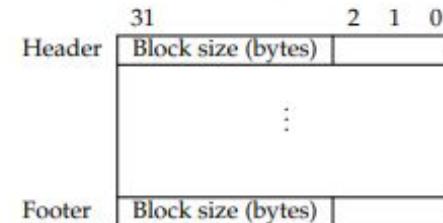
Answer:

- No, since then the uppermost block (0x12) was initially free.
And if such a free block existed, these blocks would initially have been combined due to Immediate coalescing
- (The questions are always fishing for something)

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

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

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
First element	0x500c010	0x500c601c	0x500c601c
Header of block	0x500c00c	0x00000013	0x500c601c
Footer of prev	0x500c008	0x00000013	0x500c511c
	0x500c004	0x500c601c	
	0x500c000	0x500c511c	
	0x500bff8	0x00000013	

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

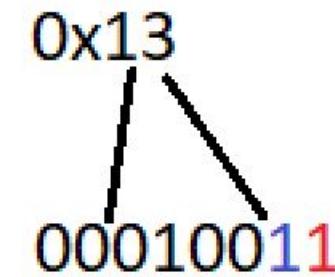
Address	Original value	After free	After realloc
0x500c028	0x00000013		
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013		
0x500c018	0x00000013		
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013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

0x13
00010011

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

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

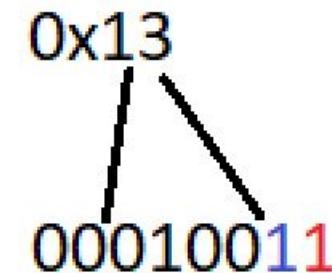
Address	Original value	After free	After realloc
0x500c028	0x00000013		
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013		
0x500c018	0x00000013		
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013		
0x500c008	0x00000013		
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bfffc	0x00000013		



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

```
free(0x500c010).realloc(0x500c000, 12) 2)
```

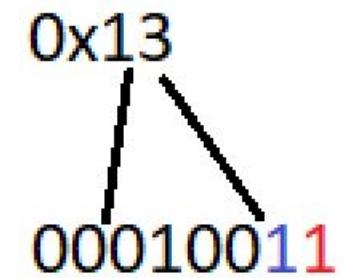
Address	Original value	After free	After realloc
0x500c028	0x00000013		
0x500c024	0x500c611c	0x500c611c	0x500c611c
0x500c020	0x500c512c	0x500c512c	0x500c512c
0x500c01c	0x00000013		
0x500c018	0x00000013		
0x500c014	0x500c511c	0x500c511c	0x500c511c
0x500c010	0x500c601c	0x500c601c	0x500c601c
0x500c00c	0x00000013		
0x500c008	0x00000013		
0x500c004	0x500c601c	0x500c601c	0x500c601c
0x500c000	0x500c511c	0x500c511c	0x500c511c
0x500bfffc	0x00000013		



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

`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:
 $00010011 \rightarrow 00010000$
 $= 0x10$ 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	

0x13
00010011

Is allocated
Previous is allocated
size is:
 $00010011 \rightarrow 00010000$
 $= 0x10$ 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).

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
0x500bfffc	0x00000013	0x13	

- Now must realloc(12)

Now
Free

Realloc (on this 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
0x500bfffc	0x00000013	0x13	

- 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

Now
Free

Realloc (on this 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	

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

Remaining Free space?

This Becomes this

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 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).

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
0x500bfffc	0x00000013	0x13	

Will-be block
with 0 payload

This
Becomes this

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	

- 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

Will-be block with 0 payload
This Becomes this

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	

We must have this:

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

This
Becomes this

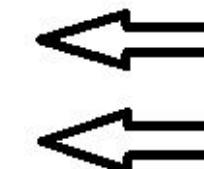
free(0x500c010). realloc(0x500c000, 12)

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
0x500bff8	0x00000013	0x13	

- 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)`

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



- Remember, these don't change due to immediate 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.
- $0x11 = 0001\ 00\textcolor{blue}{0}1$
->
 $0001\ 00\textcolor{red}{1}1 = 0x13$
- 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
0x500bfffc	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.
- $0x11 = 0001\ 00\textcolor{blue}{0}1$
->
 $0001\ 00\textcolor{red}{1}1 = 0x13$
- We also see this is exactly the same header as the original state

Correct?

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

Extra question (if time allows)

After realloc

0x13
0x500c611c
0x500c512c
0x13
0x23
0x500c511c
0x500c601c
0x12
0x13
0x500c601c
0x500c511c
0x23

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.

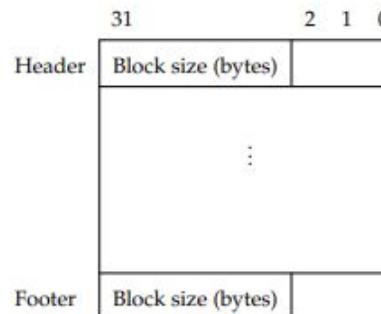
Essentially:

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	00000018	00000018
00d1c038	00000018	00000000	00000000
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021	00000022	00000022
00d1c020	00000022	00000000	00000000
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	00000000	00000000
00d1c010	00000000	00000000	00000000
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022	00000022	00000022
00d1c000	0000000b	0000000b	0000000b
00d1bfff	0000000b	0000000b	0000000b

Larger heap
= smaller text
(sorry)

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
First element	00d1c008	00000000	00000000
Header	00d1c004	00000022	00000000
Footer	00d1c000	0000000b	00000000
	00d1bfcc	0000000b	00000000

Same as always - analyse the initial state of the heap

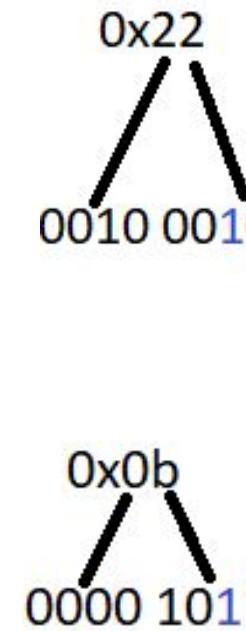
- The header is once again behind first element
- The footer of the previous block is behind that.
- We start analysing

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
First element	00d1c008	00000000	00000000
Header	00d1c004	00000022	00000000
Footer	00d1c000	0000000b	0000000b
	00d1bfcc	0000000b	0000000b

0x22
0010 0010

- Not allocated (makes sense, since we will malloc it)
- Previous 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	(red box)	(red box)
00d1c040	00000021	(red box)	(red box)
00d1c03c	0000001d	(red box)	(red box)
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021	(red box)	(red box)
00d1c020	00000022	(red box)	(red box)
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	(red box)	(red box)
00d1c010	00000000	(red box)	(red box)
00d1c00c	00000000	00000000	00000000
First element	00d1c008	00000000	00000000
Header	00d1c004	00000022	00000000
Footer	00d1c000	0000000b	0000000b
	00d1bfcc	0000000b	0000000b



- Not allocated (makes sense, since we will malloc it)
- Previous 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.

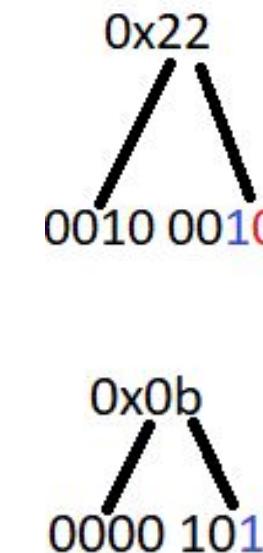
Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	(red box)	(red box)
00d1c040	00000021	(red box)	(red box)
00d1c03c	0000001d	(red box)	(red box)
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021	(red box)	(red box)
00d1c020	00000022	(red box)	(red box)
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	(red box)	(red box)
00d1c010	00000000	(red box)	(red box)
00d1c00c	00000000	00000000	00000000
First element	00d1c008	00000000	00000000
Header	00d1c004	00000022	00000000
Footer	00d1c000	0000000b	0000000b
	00d1bfcc	0000000b	0000000b

0x22
0010 0010

0x0b
0000 1011

- Not allocated (makes sense, since we will malloc it)
- Previous 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

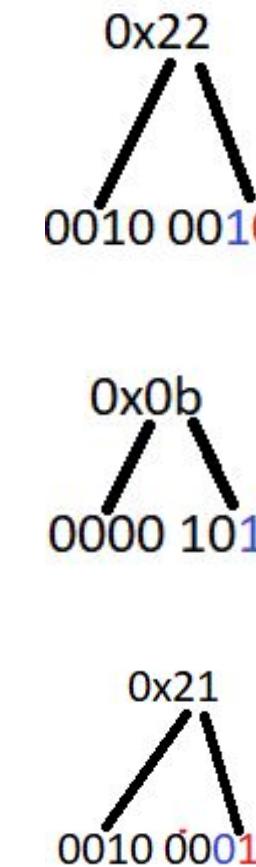
Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	000000100	000000100	000000100
00d1c048	000000020	000000020	000000020
00d1c044	000000042		
00d1c040	000000021		
00d1c03c	00000001d		
00d1c038	000000018	000000018	000000018
00d1c034	000000000	000000000	000000000
00d1c030	000000000	000000000	000000000
00d1c02c	000000000	000000000	000000000
00d1c028	00000001d	00000001d	00000001d
00d1c024	000000021	000000021	
00d1c020	000000022	000000022	
00d1c01c	000000000	000000000	000000000
00d1c018	000000000	000000000	000000000
00d1c014	000000000	000000000	000000000
00d1c010	000000000	000000000	000000000
00d1c00c	000000000	000000000	000000000
00d1c008	000000000	000000000	000000000
00d1c004	000000022		
00d1c000	00000000b		
00d1bfff	00000000b		



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

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

Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	000000100	000000100	000000100
00d1c048	000000020	000000020	000000020
00d1c044	000000042		
00d1c040	000000021		
00d1c03c	00000001d		
00d1c038	000000018	000000018	000000018
00d1c034	000000000	000000000	000000000
00d1c030	000000000	000000000	000000000
00d1c02c	000000000	000000000	000000000
00d1c028	00000001d	00000001d	00000001d
00d1c024	000000021	000000021	
00d1c020	000000022	000000022	
00d1c01c	000000000	000000000	000000000
00d1c018	000000000	000000000	000000000
00d1c014	000000000	000000000	000000000
00d1c010	000000000	000000000	000000000
00d1c00c	000000000	000000000	000000000
00d1c008	000000000	000000000	000000000
00d1c004	000000022		
00d1c000	00000000b		
00d1bfff	00000000b		

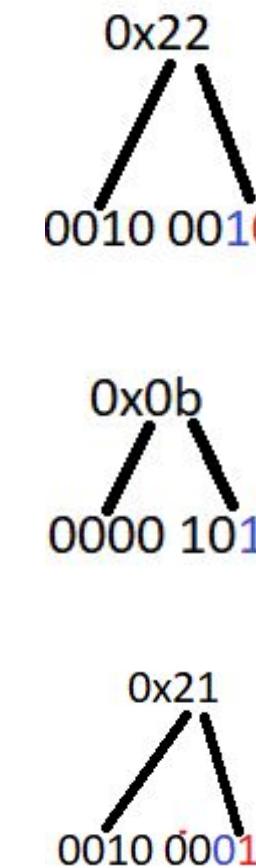


- Not allocated (makes sense, since we will malloc it)
- Previous allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32

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

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

Address	Original value	0xd1c008	free(0xd1c028)
		After malloc	After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	Header 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	00000022	00000022
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	00000000	00000000
00d1c010	00000000	00000000	00000000
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022	00000022	00000022
00d1c000	0000000b	0000000b	0000000b
00d1bffc	0000000b	0000000b	0000000b

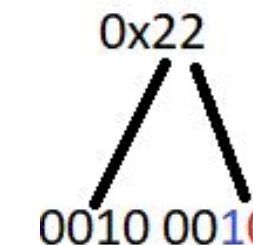


- Not allocated (makes sense, since we will malloc it)
- Previous allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32

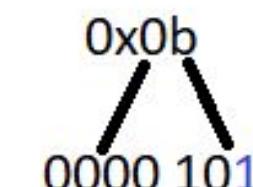
- Allocated
- Previous is allocated
- size = 0000 1011 -> 0000 1000 = 0x08 = 8

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

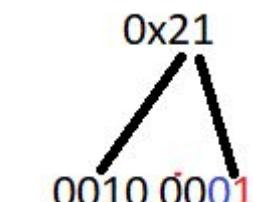
Address	Original value	0xd1c008	free(0xd1c028)
		After malloc	After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	Header 00000042	00000042
00d1c040	00000021	00000021	00000021
00d1c03c	0000001d	0000001d	0000001d
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	00000000	00000000	00000000
00d1c028	0000001d	0000001d	0000001d
00d1c024	00000021	00000021	00000021
00d1c020	00000022	00000022	00000022
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	00000000	00000000
00d1c010	00000000	00000000	00000000
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022	00000022	00000022
00d1c000	0000000b	0000000b	0000000b
00d1bfcc	0000000b	0000000b	0000000b



32



32



32

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- Not allocated (makes sense, since we will malloc it)

- Previous allocated

size = 0010 0010 -> 0010 0000 = 0x20 = 32

- Allocated

Previous is allocated

size = 0000 1011 -> 0000 1000 = 0x08 = 8

- Allocated

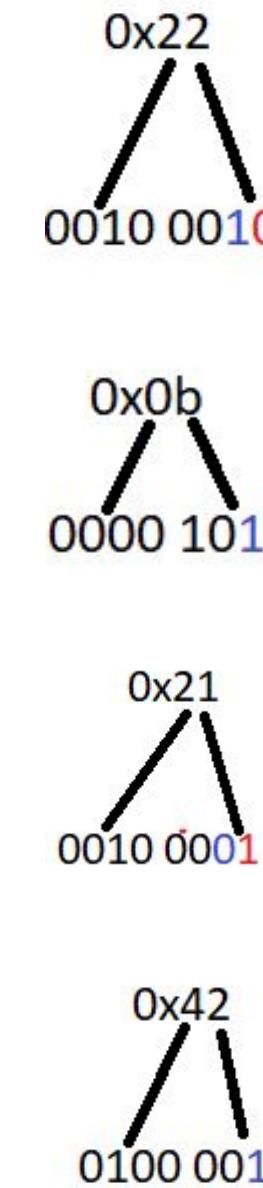
Previous is not allocated

size = 0010 0001 -> 0010 0000 = 0x20 = 32

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

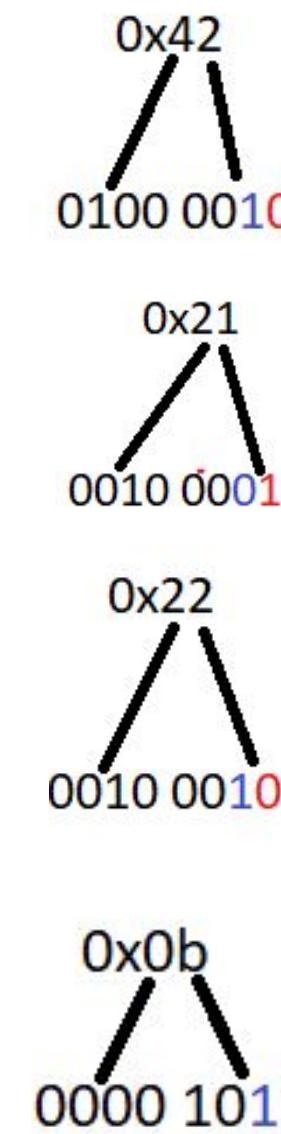
- Some parts of the heap may lie outside the area shown.

Address	Original value	0xd1c008 After malloc	free(0xd1c028) After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	Header 00000042	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	Header 00000021	00000021
00d1c020	00000022	00000022	00000022
00d1c01c	00000000	00000000	00000000
00d1c018	00000000	00000000	00000000
00d1c014	00000000	Header 00000000	00000000
00d1c010	00000000	00000000	00000000
00d1c00c	00000000	00000000	00000000
00d1c008	00000000	00000000	00000000
00d1c004	00000022	Header 00000022	00000022
00d1c000	0000000b	0000000b	0000000b
00d1bfcc	0000000b	0000000b	0000000b



- Not allocated (makes sense, since we will malloc it)
- Previous 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

Address	Original value	0xd1c008	free(0xd1c028)
		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		
00d1bfec	0000000b		
00d1bfff	0000000b		



- 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 allocated
- size = 0010 0010 -> 0010 0000 = 0x20 = 32
- Allocated
- Previous is allocated
- size = 0000 1011 -> 0000 1000 = 0x08 = 8

Address	Original value	0xd1c008	free(0xd1c028)
		After malloc	After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	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		
00d1bfec	0000000b		

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

0xd1c008 free(0xd1c028)

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	0x13	
00d1c000	0000000b	0xb	
00d1bffc	0000000b	0xb	

Sorry I need space, try to remember the rest

We malloc(8) here, meaning $8 + \text{header} + \text{footer} = 16$

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

Unaffected by the change

0xd1c008 free(0xd1c028)

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	0x13	0xb
00d1c000	0000000b		0xb
00d1bffc	0000000b		

Sorry I need space, try to remember the rest

We malloc(8) here, meaning $8 + \text{header} + \text{footer} = 16$

- 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 0010 -> 0x12

	0xd1c008	free(0xd1c028)	
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	0x12	
00d1c020	00000022		
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	

Sorry I need space, try to remember the rest

We malloc(8) here, meaning $8 + \text{header} + \text{footer} = 16$

- 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 0010 -> 0x12

	0xd1c008	free(0xd1c028)	
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	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	

Sorry I need space, try to remember the rest

We malloc(8) here, meaning $8 + \text{header} + \text{footer} = 16$

- 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 0010 -> 0x12

What now?

0xd1c008 free(0xd1c028)

Address	Original value	After malloc	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	
00d1bfcc	0000000b	0xb	



(not a real header.
Nothing changes)

Size unchanged, previous still
unallocated. stays the same

0xd1c008 free(0xd1c028)

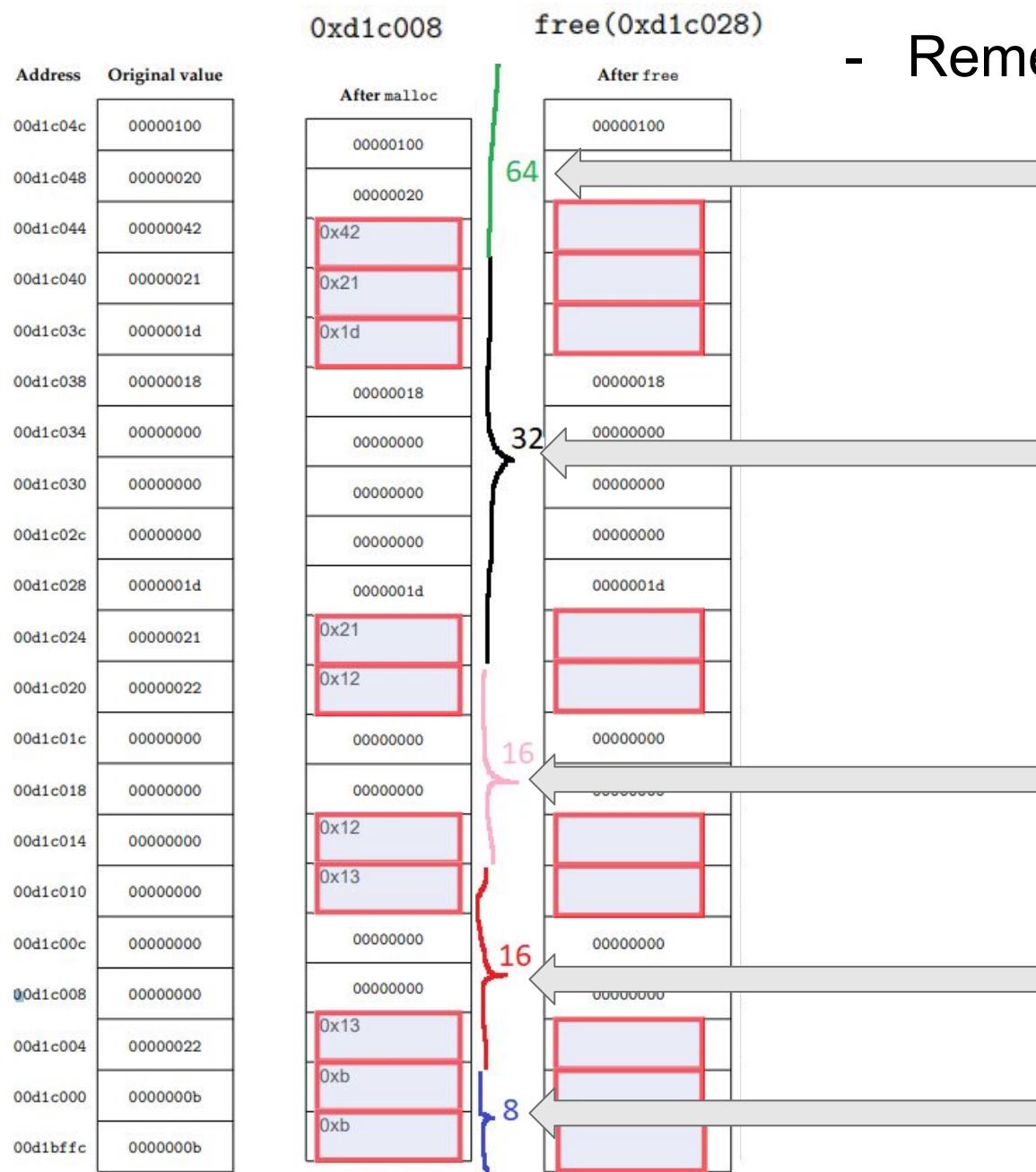
Address	Original value	After malloc	After free
00d1c04c	00000100	00000100	00000100
00d1c048	00000020	00000020	00000020
00d1c044	00000042	0x42	
00d1c040	00000021	0x21	
00d1c03c	0000001d	0x1d	
00d1c038	00000018	00000018	00000018
00d1c034	00000000	00000000	00000000
00d1c030	00000000	00000000	00000000
00d1c02c	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	
00d1bfcc	0000000b	0xb	

Stays the same

0x21 Footer

(not a real header.
Nothing changes)

Size unchanged, previous still
unallocated. Stays the same



- Remember:

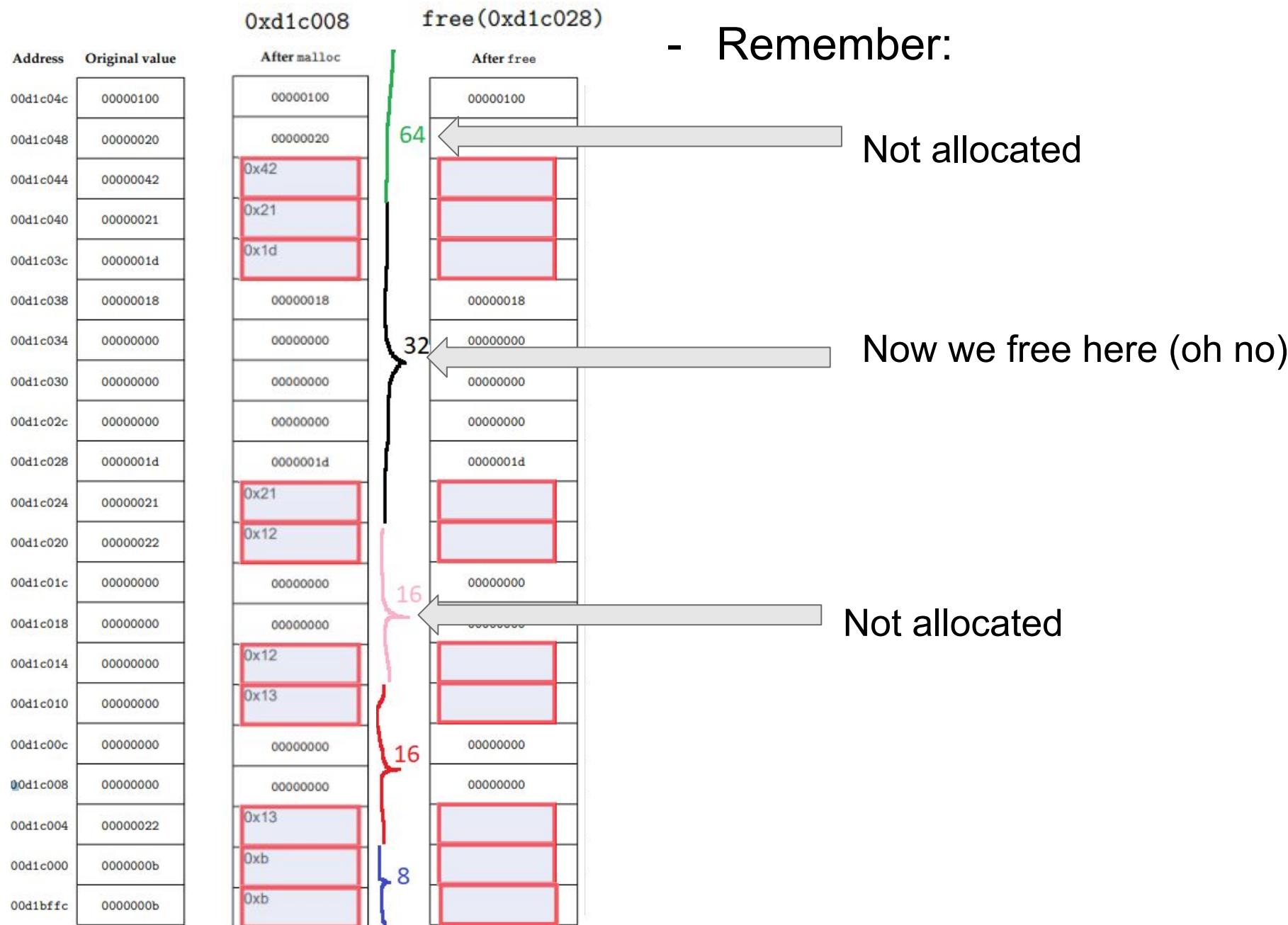
Not allocated

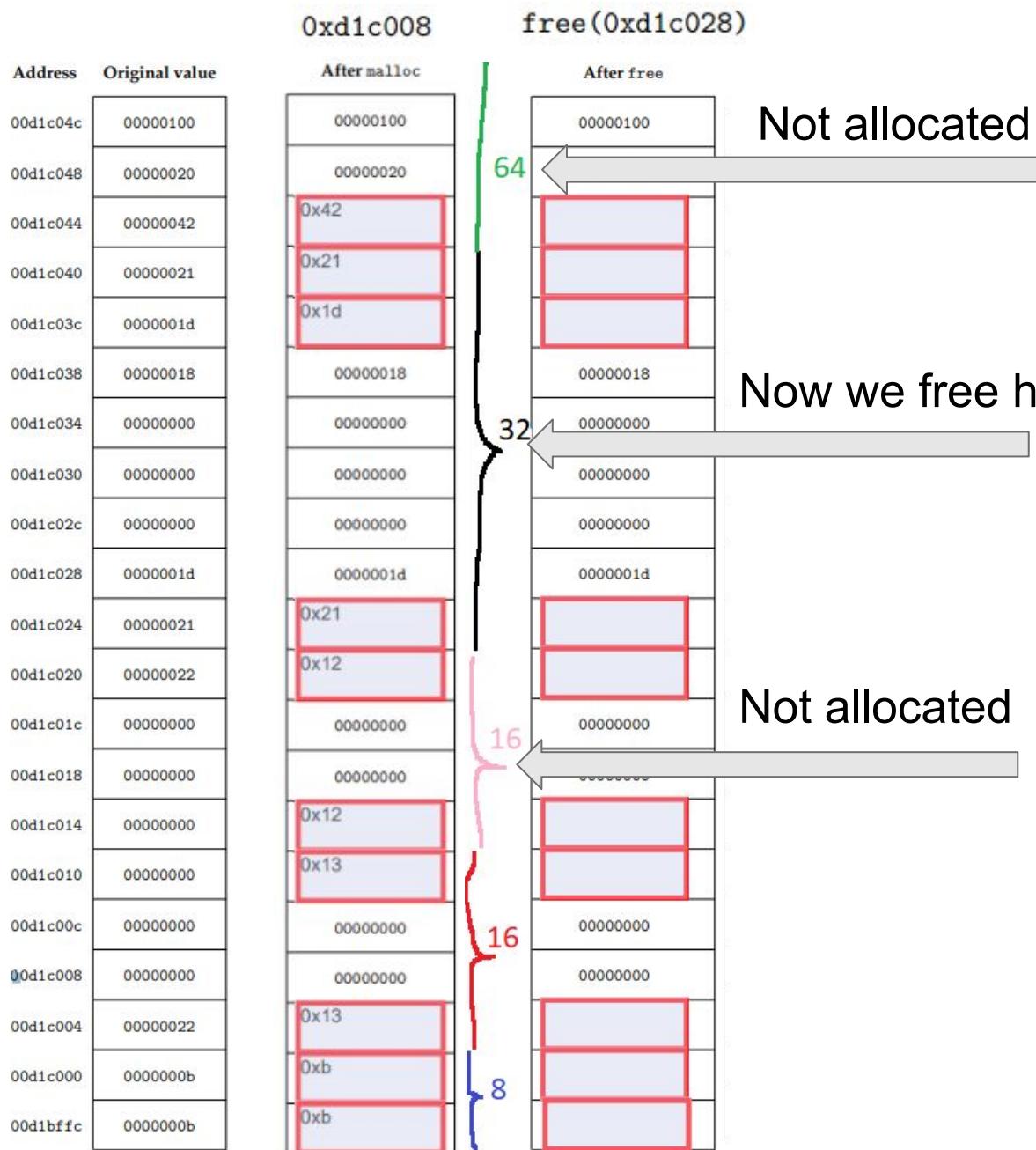
Allocated

Not allocated

Allocated (now)

Allocated





- 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

Address	Original value	0xd1c008	free(0xd1c028)
		After malloc	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	

It will not be allocated

Its neighbour will be allocated

Size = 16+32+64 = 0111 0000

So: 0111 00**10** = 0x72

Address	Original value	After malloc	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	

It will not be allocated
 Its neighbour will be allocated
 Size = 16+32+64 = 0111 0000
 So: 0111 0010 = 0x72

Address	Original value	0xd1c008	free(0xd1c028)
		After malloc	After free
00d1c04c	000000100	000000100	000000100
00d1c048	000000020	000000020	000000020
00d1c044	000000042	0x42	0x42
00d1c040	000000021	0x21	0x21
00d1c03c	00000001d	0x1d	0x1d
00d1c038	000000018	000000018	000000018
00d1c034	000000000	000000000	000000000
00d1c030	000000000	000000000	000000000
00d1c02c	000000000	000000000	000000000
00d1c028	00000001d	00000001d	00000001d
00d1c024	000000021	0x21	0x21
00d1c020	000000022	0x12	0x12
00d1c01c	000000000	000000000	000000000
00d1c018	000000000	000000000	000000000
00d1c014	000000000	0x12	0x72
00d1c010	000000000	0x13	0x13
00d1c00c	000000000	000000000	000000000
00d1c008	000000000	000000000	000000000
00d1c004	000000022	0x13	0x13
00d1c000	0000000b	0xb	0xb
00d1bfffc	0000000b	0xb	0xb

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
00dic04c	00000100	00000100	00000100
00dic048	00000020	00000020	00000020
00dic044	00000042	0x42	0x42
00dic040	00000021	0x21	0x21
00dic03c	0000001d	0x1d	0x1d
00dic038	00000018	00000018	00000018
00dic034	00000000	00000000	00000000
00dic030	00000000	00000000	00000000
00dic02c	00000000	00000000	00000000
00dic028	0000001d	0000001d	0000001d
00dic024	00000021	0x21	0x21
00dic020	00000022	0x12	0x12
00dic01c	00000000	00000000	00000000
00dic018	00000000	00000000	00000000
00dic014	00000000	0x12	0x72
00dic010	00000000	0x13	0x13
00dic00c	00000000	00000000	00000000
00dic008	00000000	00000000	00000000
00dic004	00000022	0x13	0x13
00dic000	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 process graph tips

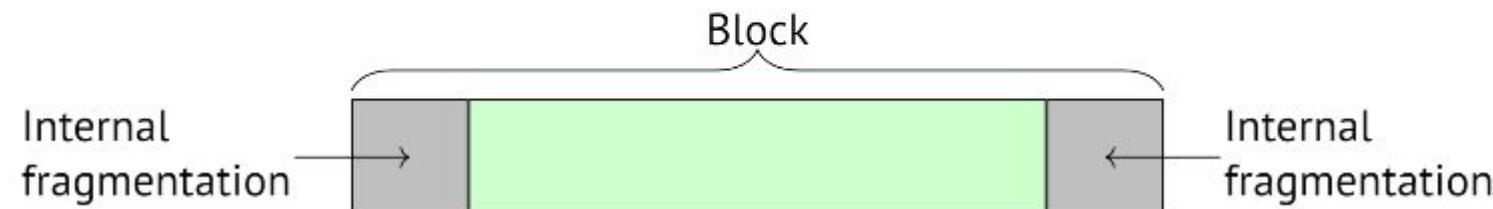
- If both lock same place, this is no-go zone
- Draw no-go zones
- If at any point can go neither up nor right. This is a deadlock
- Else not deadlock

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

Internal fragmentation occurs when the payload is smaller than the block size.

*(Shamelessly stolen from Troels slides
Virtual memory ii)*

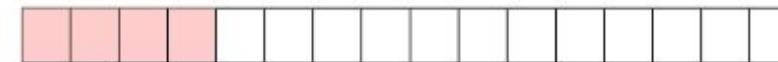


External fragmentation

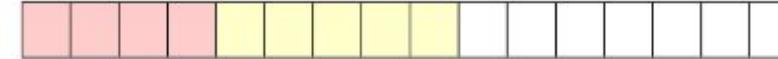
- External fragmentation is when a heap with a lot of allocating and deallocating, after long time will be a mess. What was once a heap with blocks neatly adjacent is now a lot of blocks everywhere with inconvenient space in between.

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

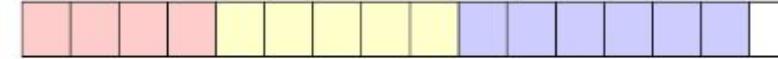
```
p1 = malloc(4*4);
```



```
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)

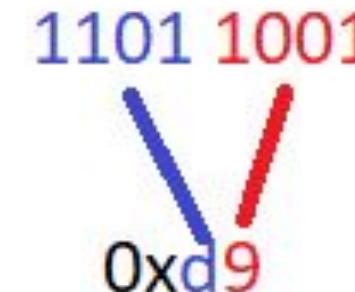
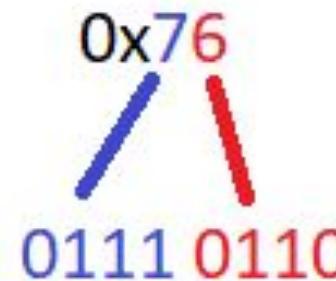
← We kind of wish the blue block could easily be moved 5 to the left for some nice adjacency.

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.