Memory Management

6

CS/COE 0449
Introduction to
Systems Software

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(with content borrowed from Vinicius Petrucci
and Jarrett Billingsley)

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Our Story So Far

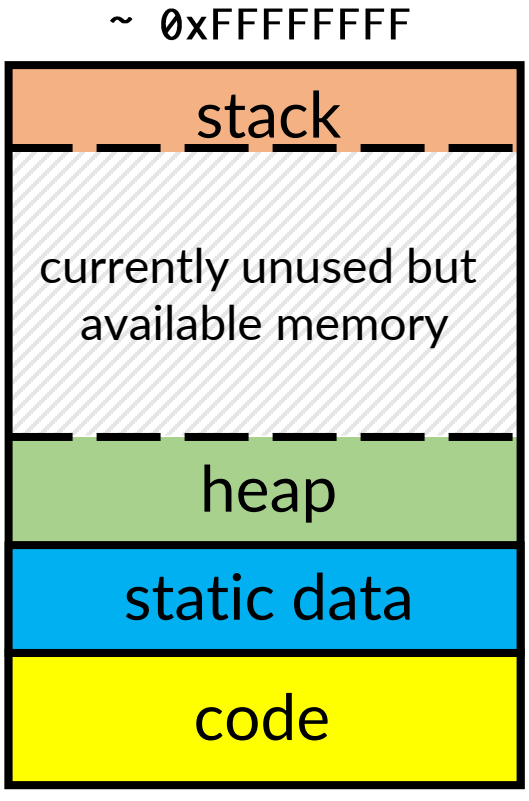
You Hear a Voice Whisper: “The Memory Layout is a Lie”

Reallocating our thoughts

- A program has several sections:
  - Code
  - Static data
  - Stack
  - Heap

- Today, we take a deeper dive at how dynamic memory is allocated in the heap.

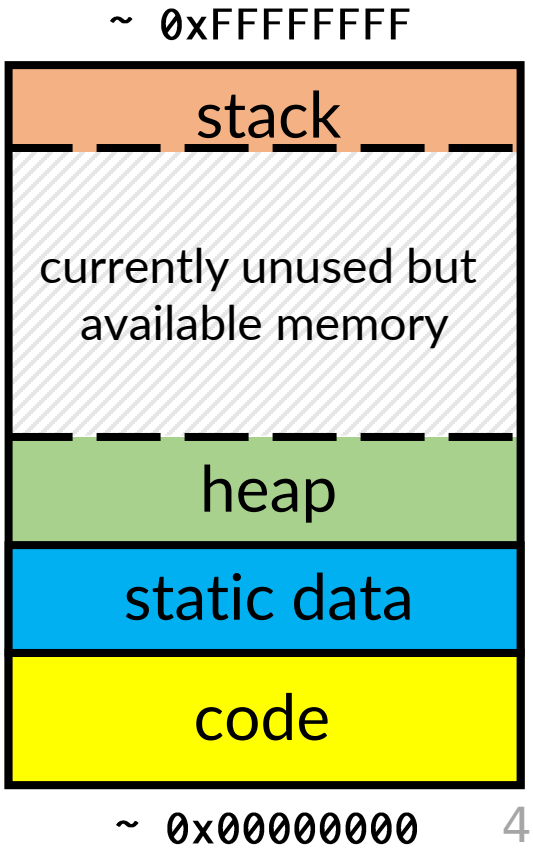
Potential Layout
(32-bit addresses)



Reallocating our thoughts

- We have looked at `malloc` and `calloc`.
- They stake out space in the heap and return an address.
- Right now, we live in a nice ideal world.
  - No other programs are running.
  - We have access to all of the memory.
    - Muhahahaha!!
- The OS is lying to our program.
  - This memory is… virtual… reality.
  - We will investigate this lie later in the course.

Potential Layout
(32-bit addresses)



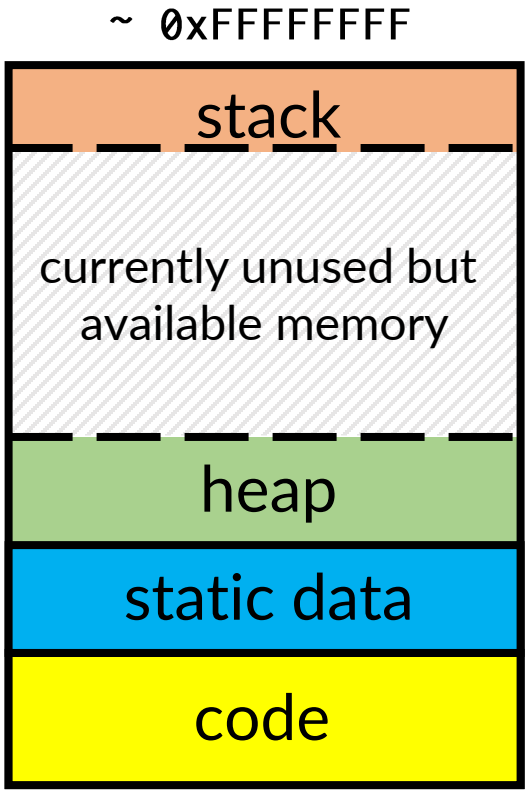
The World of Allocation

It is a puzzle without any optimal solution. Welcome to computers!

A heap of possibilities

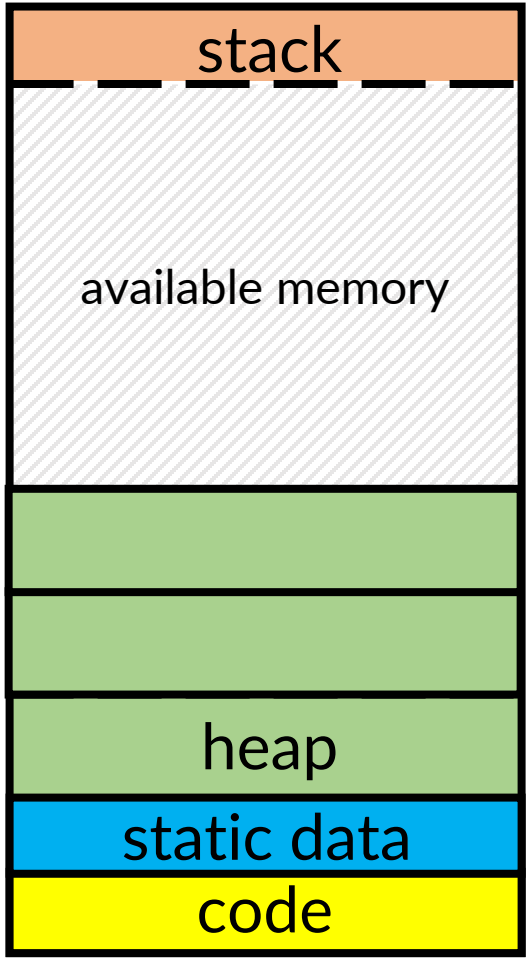
- **Stack access often does not deviate much.**
  - We allocate a little bit at a time.
  - We allocate and free the memory VERY often.
- **Heap allocations have many access patterns that are possible.**
  - You might allocate a lot at a time and keep it around for a long time. Or a short time.
  - You might allocate a lot of small things, instead.
  - Maybe you do a little bit of everything?
- **Often, such patterns are not easy to predict.**
  - Do you get a big file as input? A small file?

Potential Layout
(32-bit addresses)



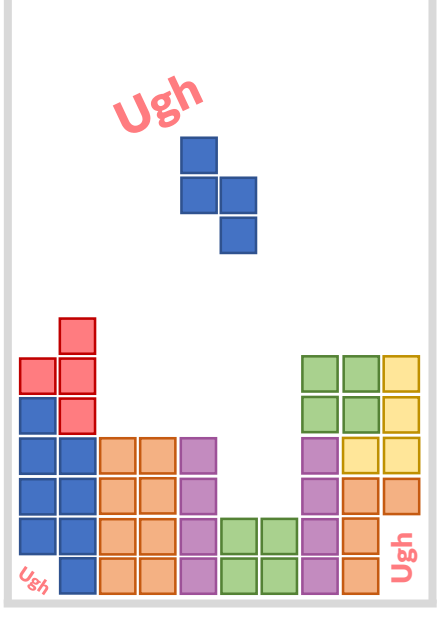
A heaping helping of good luck

- Allocations could happen in a nice order.
- When something is allocated, it can be allocated after everything else.
- When freed, it makes room for new things.
- **IF ONLY**.
  - I mean, it's possible… but like…
    - the heap and stack are different things for a reason.



Digital potholes… as annoying as real ones

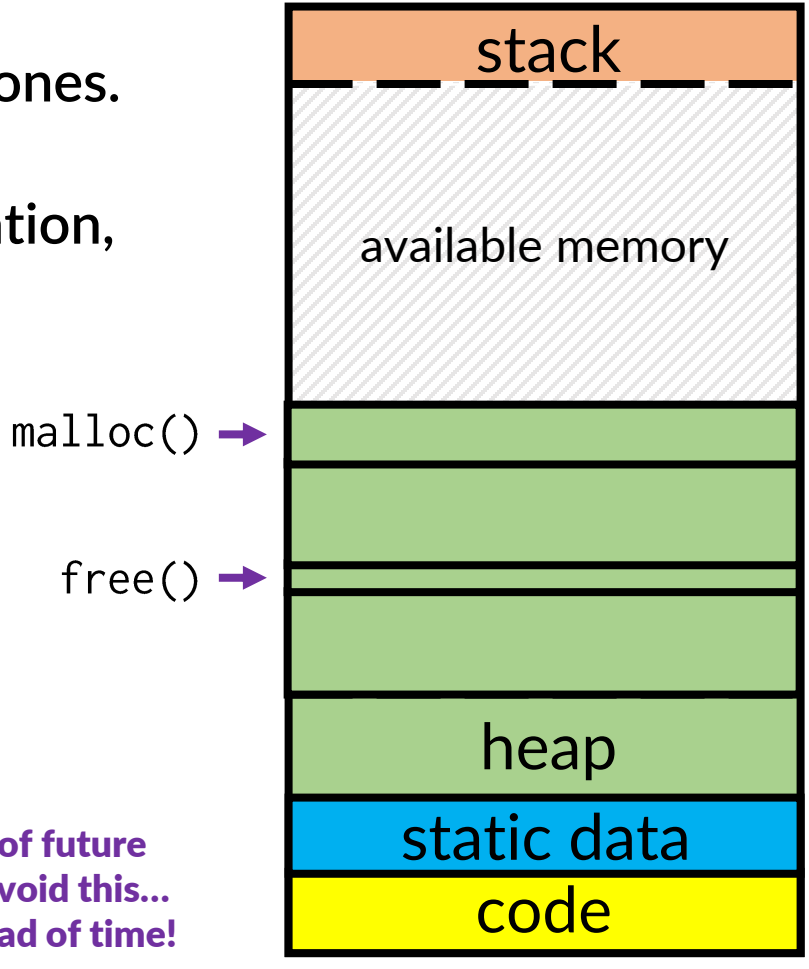
- Small allocations interfere with large ones.
- When small gaps interfere with allocation, this is called ***fragmentation***.



NEXT ALLOCATION

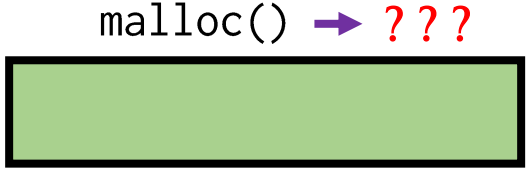
?

if we had omniscience of future allocations, we could avoid this… but we can't know ahead of time!



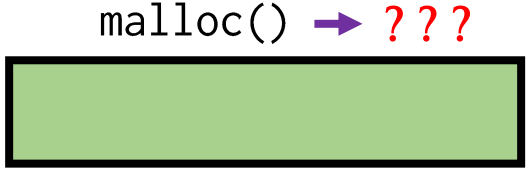
The worst case

- When you allocate a lot of small things…
  - Free every other one…
  - And then attempt to allocate a bigger thing…
- Even though there is technically enough memory…
  - There is no continuous space.
  - Therefore, our naïve `malloc` will fail.
- We have to come up with some strategy.

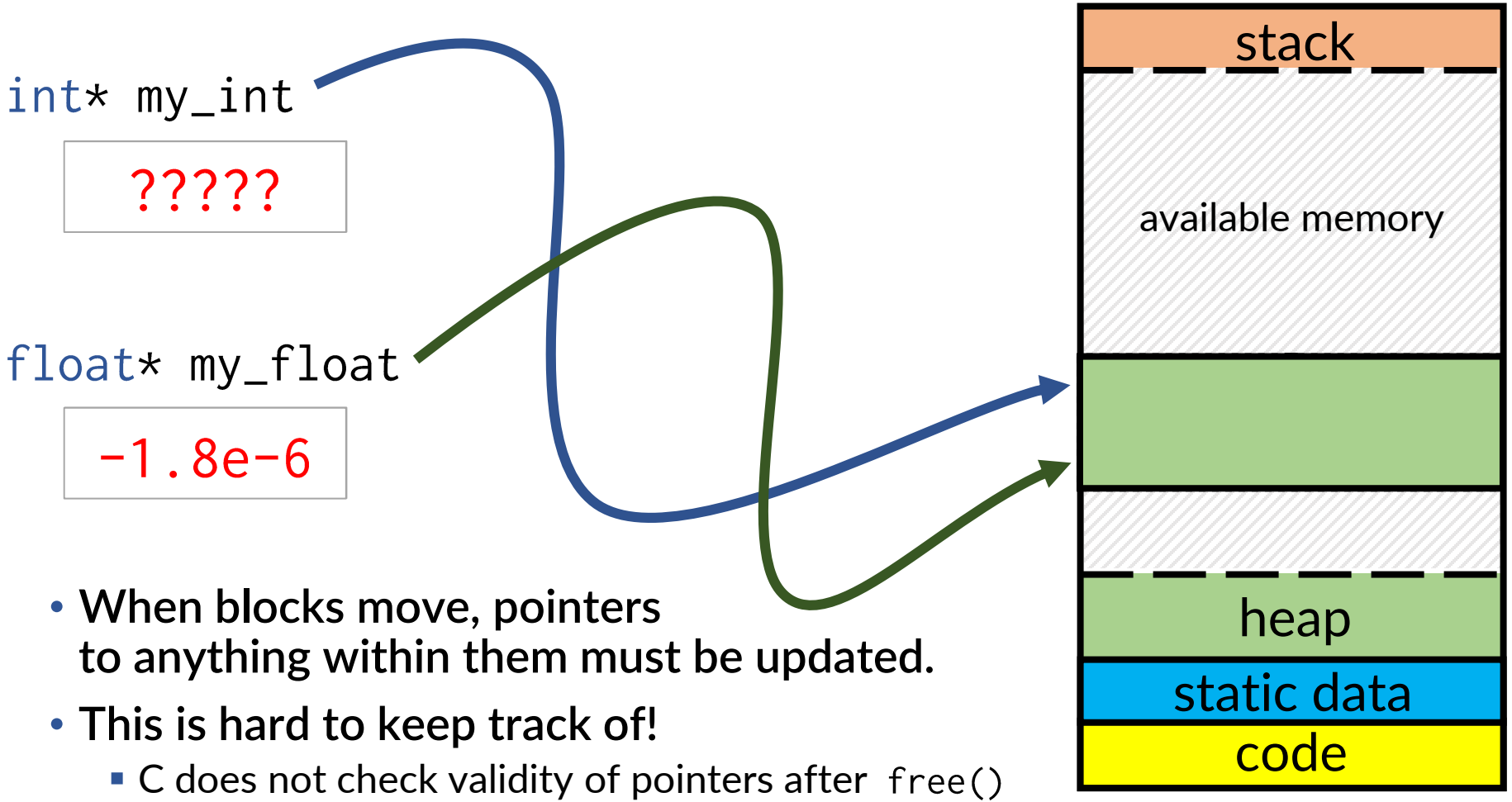


Moving is never easy

- Why not move things around??
  - A ***defragmentation*** process/algorithm
- Moving around something in the heap is hard!
  - Any pointers referring to data within a block must be updated.
  - Finding these pointers automatically is effectively as difficult as garbage collection.
- Because of this, moving blocks around is discouraged. (Easier to solve it another way.)



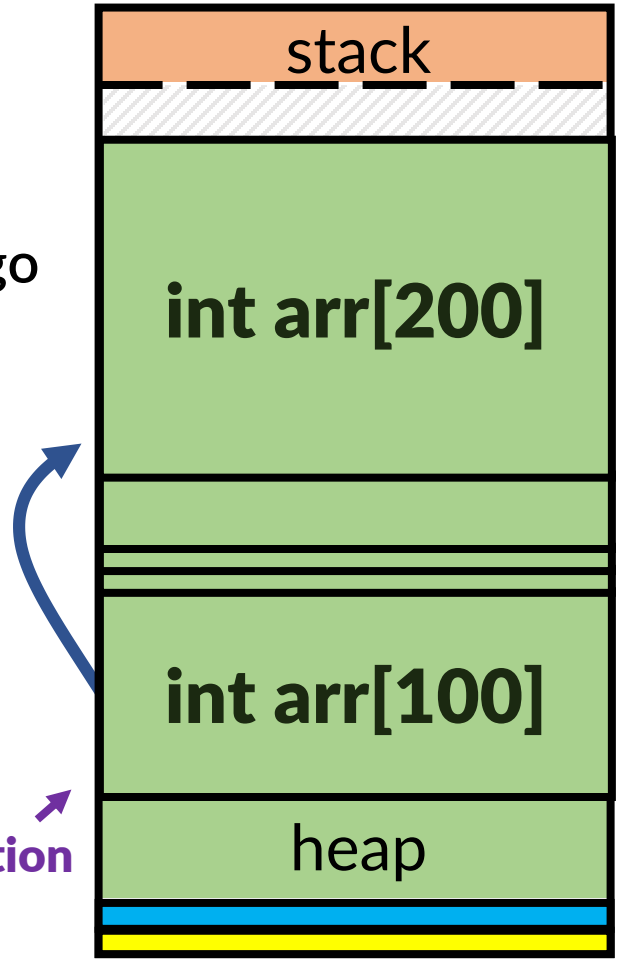
Moving is NEVER easy



- When blocks move, pointers to anything within them must be updated.
- This is hard to keep track of!
  - C does not check validity of pointers after `free()`

Stressing it out

- If we allocate a large array it will be allocated on the heap somewhere.
- Other allocations can also happen, and they go "above" that array.
- What happens when you need to append a 101st element to this array?
  - Uh oh!
- You will need to allocate more space.
  - And then copy the array contents.
  - Free the old array.
  - How long does that take?

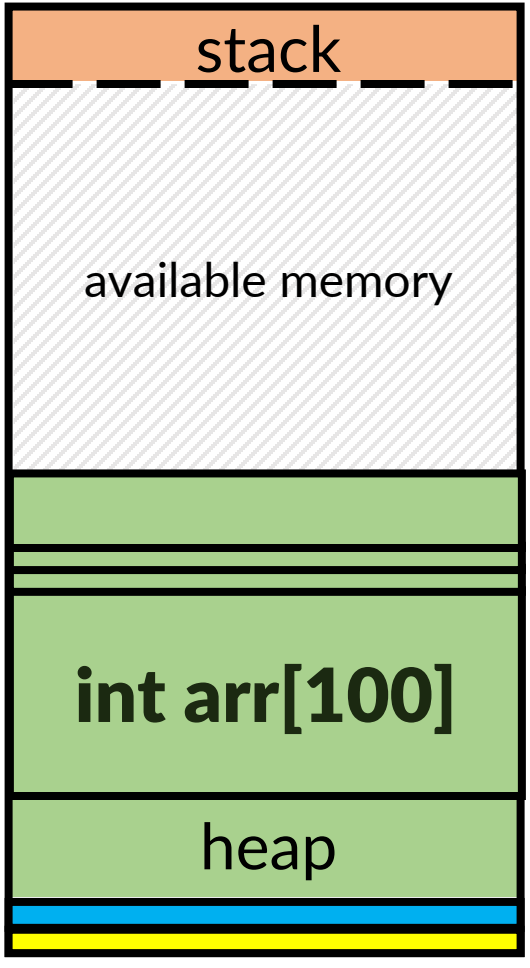


Stressing it out: Big Arrays

- This happens in very practical situations!
  - Reallocating means getting rid of a small thing
  - And replacing it with a larger thing.
  - You could have TiBs of memory and this will be a problem.

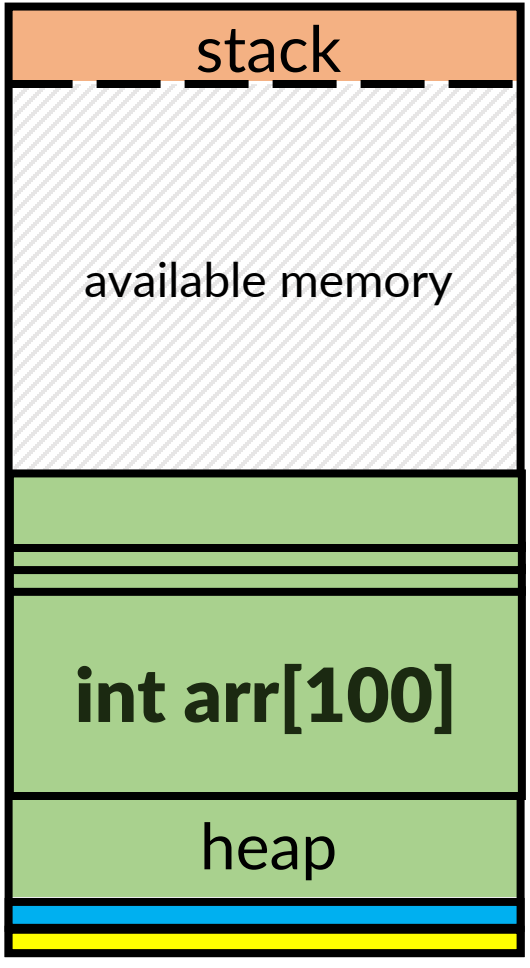
- This affects performance: (in terms of writes:)
  - Appending item arr[0]: $O(1)$
  - Appending item arr[1]: $O(1)$
  - …
  - Appending item arr[99]: $O(1)$
  - Appending item arr[100]: $O(n+1)$ oh no!

- When you would overflow the buffer…
  - You then need to copy all previous values as well.



Stressing it out: Performance Consistency

- Big arrays want to be continuous.
  - Ensuring continuous space is difficult when you do not know how much you will ultimately need.
- This is exactly why ***linked lists*** exist!
- Since a linked list allocates on every append.
  - Each append takes the same amount of time.
- However, everything is a trade-off.
  - Dang it!!!
  - One cost is extra overhead for metadata.
  - Linked list traversal can stress memory caches.
    - It means traversing the array is slower.
    - However, we will mostly ignore this for now.



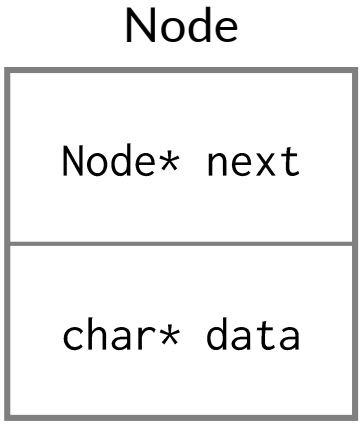
The Linked List

A story about trade-offs.

What is a linked list?

- A **linked list** is a non-continuous data structure representing an ordered list.

- Each item in the linked list is represented by metadata called a node.
  - This metadata indirectly refers to the actual data.
  - Furthermore, it indirectly refers to at least one other item in the list.



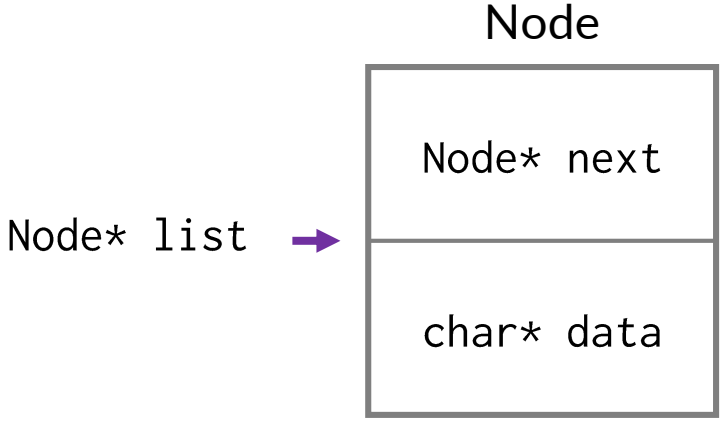

```
typedef struct _Node {
  struct _Node* next;
  char* data;
} Node;
```

"struct" required since Node is not technically defined until after it is defined! 😱

Keeping ahead of the list.

- Creation of a list occurs when one allocates a single node and tracks it in a pointer. This is the head of our list (first element.)

```
Node* list = (Node*)malloc(sizeof(Node));
list->next = NULL; // NULL is our end-of-list marker
list->data = NULL; // Allocate/copy the data you want
```

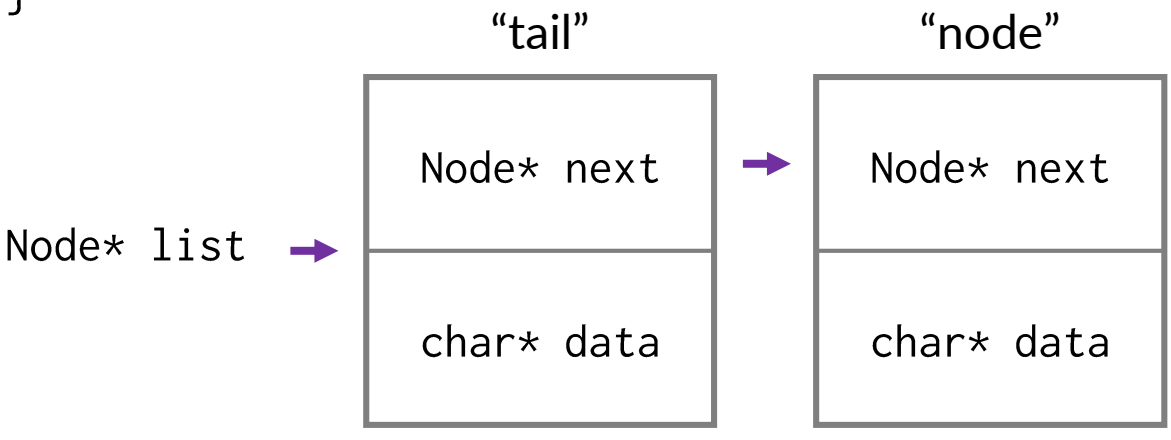


Adding some links to our chain

- If we want to append an item, we can add a node anywhere!

```
void append(Node* tail, const char* value) {
  Node* node = (Node*)malloc(sizeof(Node));
  node->next = NULL; // The new end of our list
  tail->next = node; // We attach this node to the old last node
  node->data = (char*)malloc(strnlen(value, 100) + 1);
  strncpy(node->data, value, 100);
}
```

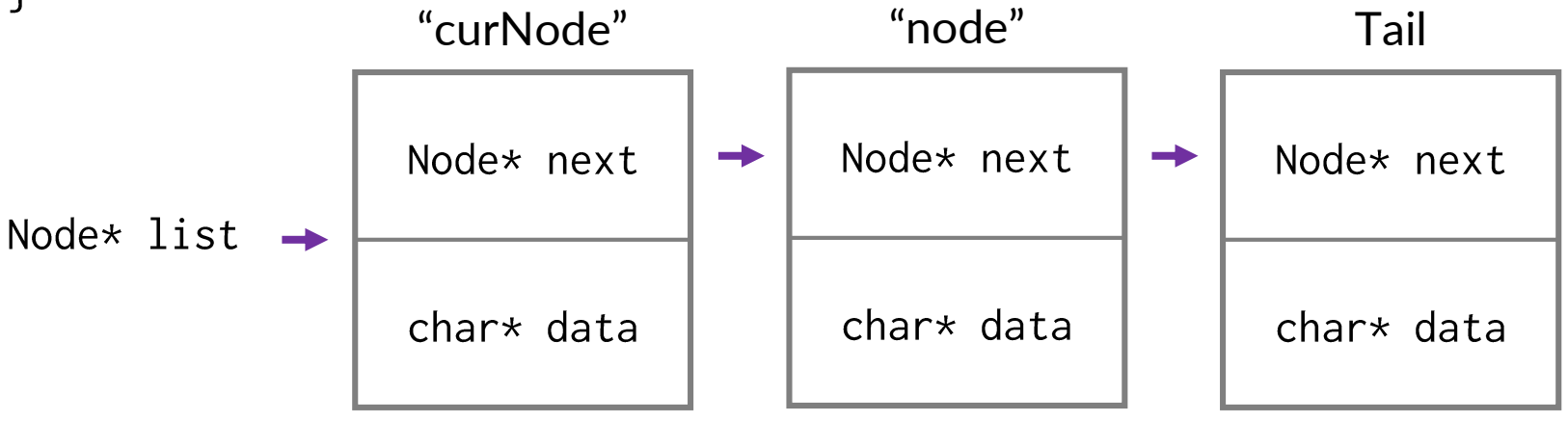
Remember the '\0' sentinel!



We can add them anywhere!!

- Consider what happens if we update our append to take any Node:

```
void linkedListAppend(Node* curNode, const char* value) {
  Node* node = (Node*)malloc(sizeof(Node));
  node->next = curNode->next;
  curNode->next = node;
  node->data = (char*)malloc(strnlen(value, 100) + 1);
  strncpy(node->data, value, 100);
}
```



We can add them anywhere!!

- This function has very consistent performance (constant time):

```
void linkedListAppend(Node* curNode, const char* value) {
  Node* node = (Node*)malloc(sizeof(Node));
  node->next = curNode->next;
  curNode->next = node;
  node->data = (char*)malloc(strnlen(value, 100) + 1);
  strncpy(node->data, value, 100);
}
```

- The append *always* allocates the same amount.
- It *always* copies the same amount.
- Compare to a big array where you may have to copy the entire thing to append something new!

Traversal… on the other hand…

- **Accessing an array element is generally very simple.**
  - `arr[42]` is the same as `*(arr + 42)` because its location is very well-known!
  - This is because array items are continuous in memory. Not true for linked lists!

- **Here is a function that performs the equivalent for linked lists:**

```
Node* linkedListGet(Node* head, size_t index) {
  Node* curNode = head;
  while(curNode && index) {
    index--;
    curNode = curNode->next;
  }
  return curNode;
}
```

Q: How many times is memory accessed relative to the requested index?

Removing… on the other, other hand!

```
Node* linkedListDelete(Node* head, size_t index) {
  Node* lastNode = NULL;
  Node* curNode = head;
  while(curNode && index) {
      index--;
      lastNode = curNode;
      curNode = curNode->next;
  }
  if (!curNode)
      return head;
  if (!lastNode)
      head = curNode->next; // New head is next item
  else
      lastNode->next = curNode->next; // Orphans item
  free(curNode->data);
  free(curNode);
  return head;
}
```

Can't find item at index.

We are deleting the head.

Returns new head (or old head if unchanged).

- One nice thing about linked lists is their flexibility to changing shape.
  - I used to be able to bend a lot better, too, when I was in my 20s. Alas.
- Since we don't have a way to go "backward"
  - We first find the node we want to delete (`curNode`)
  - Keeping track of the node of `index - 1` (`lastNode`)
  - Rewire `lastNode` to cut out `curNode`.

Removing… on the other, other hand!

```
Node* linkedListDelete(Node* head, size_t index) {
  Node* lastNode = NULL;
  Node* curNode = head;
  while(curNode && index) {
      index--;
      lastNode = curNode;
      curNode = curNode->next;
  }
  if (!curNode)
      return head;
  if (!lastNode)
      head = curNode->next; // New head is next item
  else
      lastNode->next = curNode->next; // Orphans item
  free(curNode->data);
  free(curNode);
  return head;
}
```

- **This looks complex, but it really is a simple traversal.**
  - So it takes $O(n)$ to find the item.
  - And it performs a simple update and deallocation. (quick to do)
- **A big array, on the other hand.**
  - It can find the element to remove immediately.
  - However, removing it means shifting over every item after it left.
  - That can be an expensive update! (Memory is slow!!)

On your own!

Think about the code you would need to do any of the following:

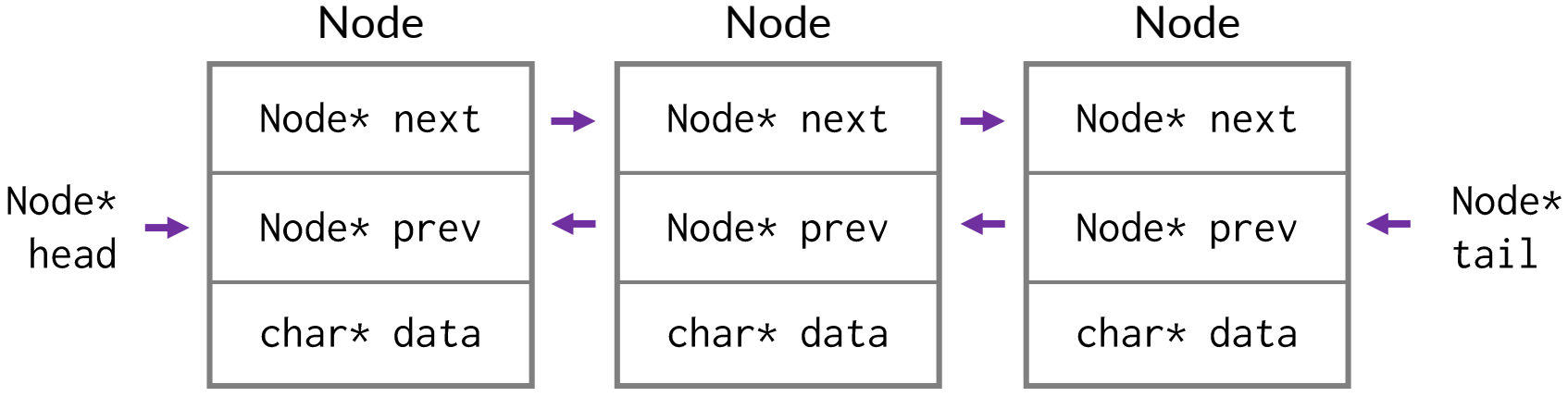
- Delete/free the entire linked list.
- Sort a linked list.
- Append a linked list to an existing one.
- Copy a subset of a linked list to a new list.

Often, operations can be abstracted in such a way that all of these can be written relatively simply.

Consider the performance of these operations compared to an Array.

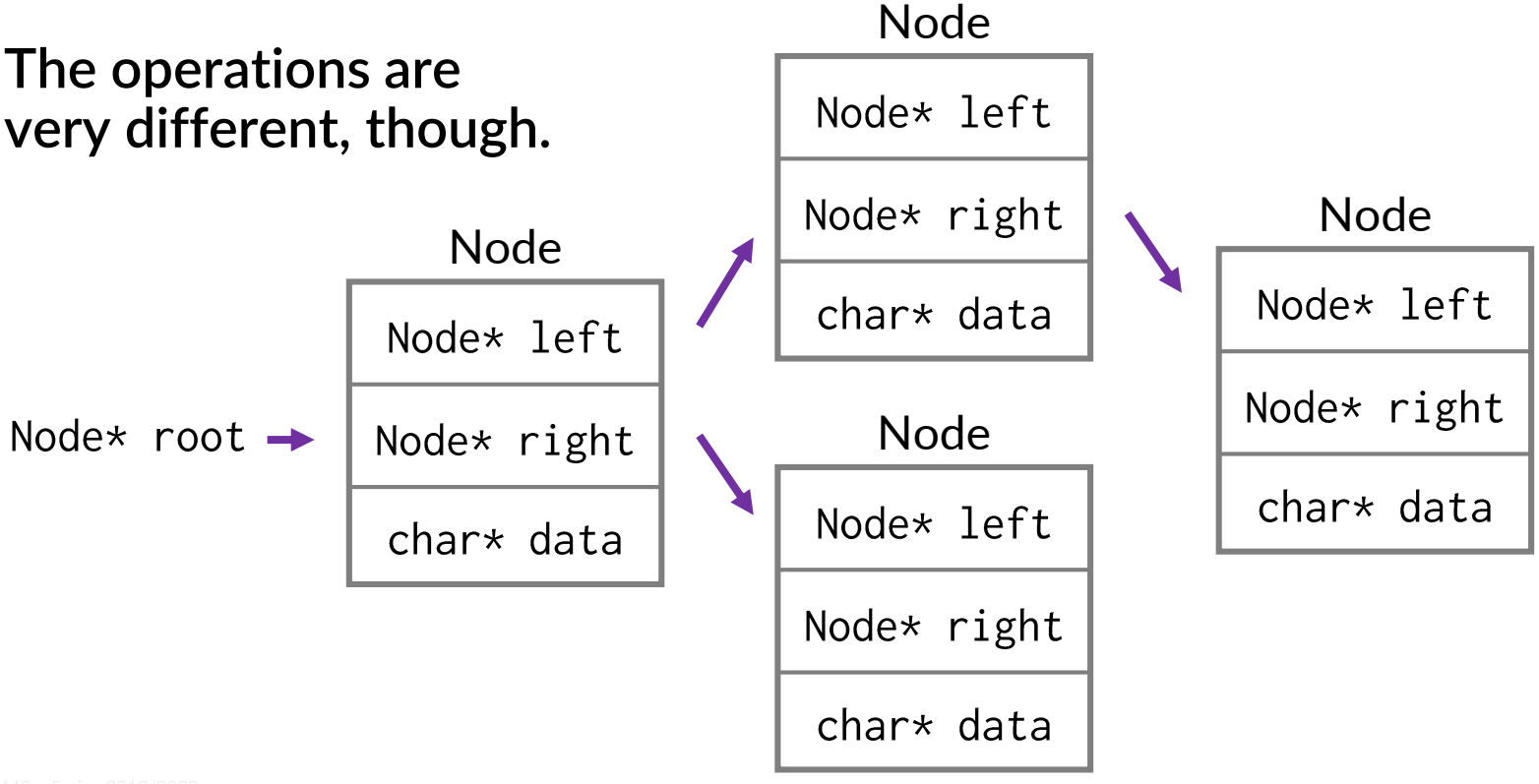
Linked lists … link you … to the world!

- Consider how much cleaner you can make certain operations if you tracked the previous node as well.
  - This is a **doubly linked list**.
  - This is typically "double-ended" as well: keeping track of both head and tail.



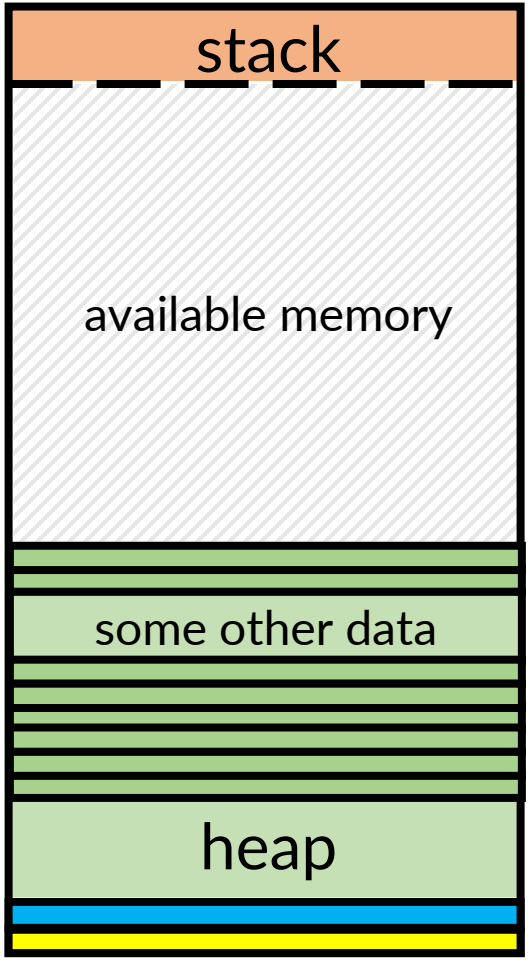
Seeing the trees through the forest

- A **binary tree** can be represented by the same nodes as a linked list.
  - In this case, you have a left and right child node instead of next and prev.
- The operations are very different, though.



De-Stressing it out: Linked Lists

- We know big arrays want to be continuous.
  - However, ensuring continuous space is difficult when you do not know how much you will ultimately need.
- Linked lists allocate very small chunks of metadata.
  - These chunks can be allocated easily on-demand.
  - And then deallocated without creating wide gaps.
- This reduces fragmentation.
  - Deallocating always leaves a small amount of room.
  - It is always the exact amount needed to append!
  - However, it is all at the expense of complexity!
  - And traversal can be expensive (but we can find ways to deal with that.)



Implementing Malloc

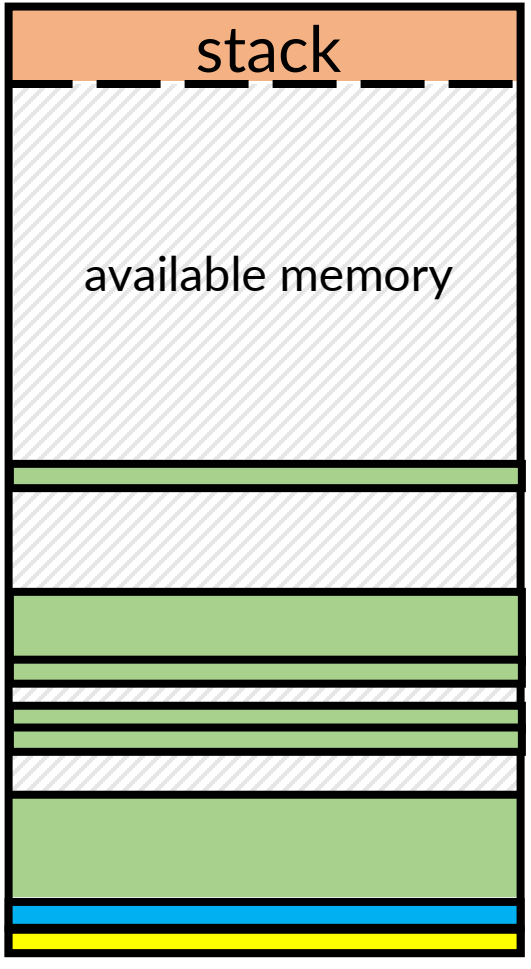
It really sounds like some kind of He-Man or She-Ra villain of the week.

The malloc essentials

- The `malloc(size_t size)` function does the following:
  - Allocates memory of at least `size` bytes.
  - Returns the address to that block of memory (or `NULL` on error)

- Essentially, your program has a potentially large chunk of memory.
  - The `malloc` function tears off a piece of the chunk.
  - Also `free` must then allow that chunk to be reused.
  - The job of `malloc` is to do so in the "best" way to reduce fragmentation.

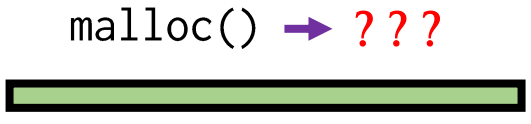
We want to avoid fragmentation

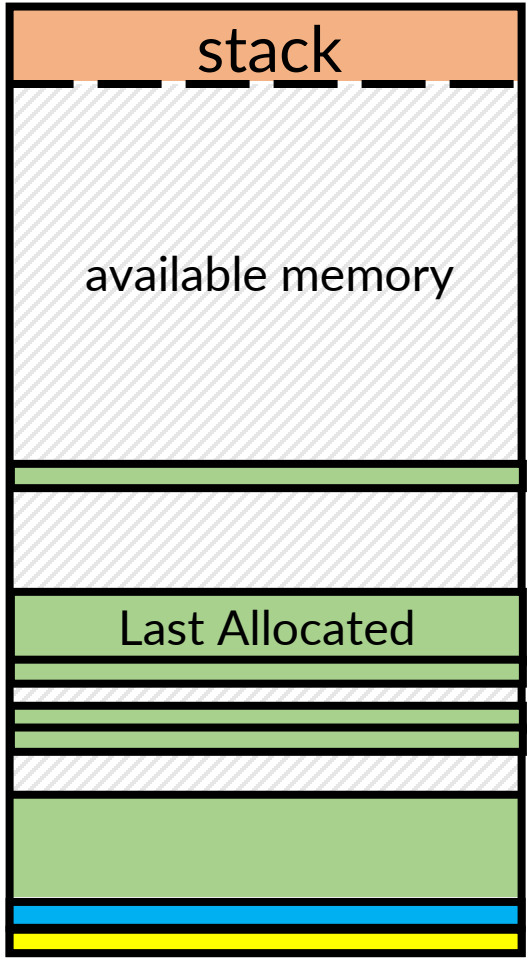


Choosing where to allocate

- Our first problem is, when `malloc` is called, where do we tear off a chunk?

- We can do a few simple things:
  - **First-Fit**: start at lowest address, find first available section.
    - Fast, but small blocks clog up the works.
  - **Next-fit**: Do "First-Fit" but start where we last allocated.
    - Fast and spreads small blocks around a little better.
  - **Best-Fit**: laboriously look for the smallest available section to divide up.
    - Slow, but limits fragmentation.



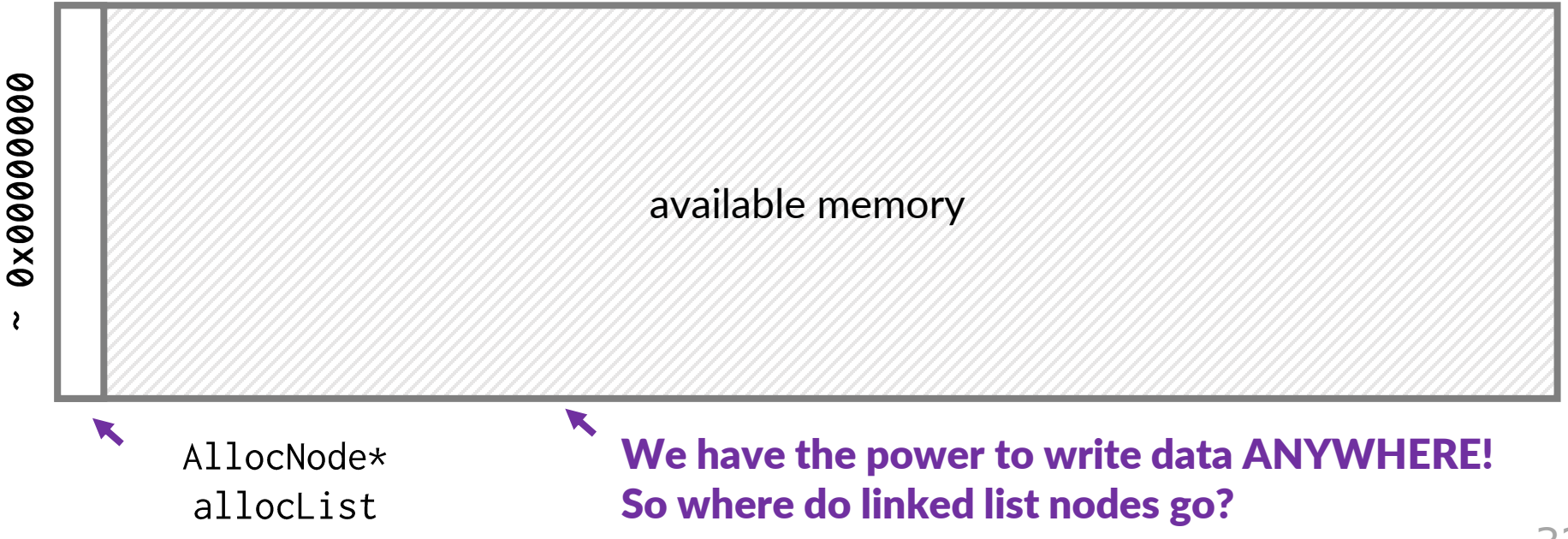


Managing that metadata!

- You have a whole section of memory to divide up.
- You need to keep track of what is allocated and what is free.
- One of the least complicated ways of doing so is to use… hmm…
  - A linked list! (or two!) We know how to do this!!
- We can treat each allocated block (and each empty space) as a node in a linked list.
  - Allocating memory is just appending a node to our list.
- The trick is to think about how we want to split up the nodes representing available memory.

Tracking memory: Our fresh new world.

- Let's orient our memory visually horizontally.
  - We have control over EVERY byte of it. We can place metadata ANYWHERE.
- Every `malloc` is responsible for allocating a block of memory.
  - How, then, do we manage where things are allocated and where is empty space?
  - We can have "allocation" reduce to creating a new node in a linked list.

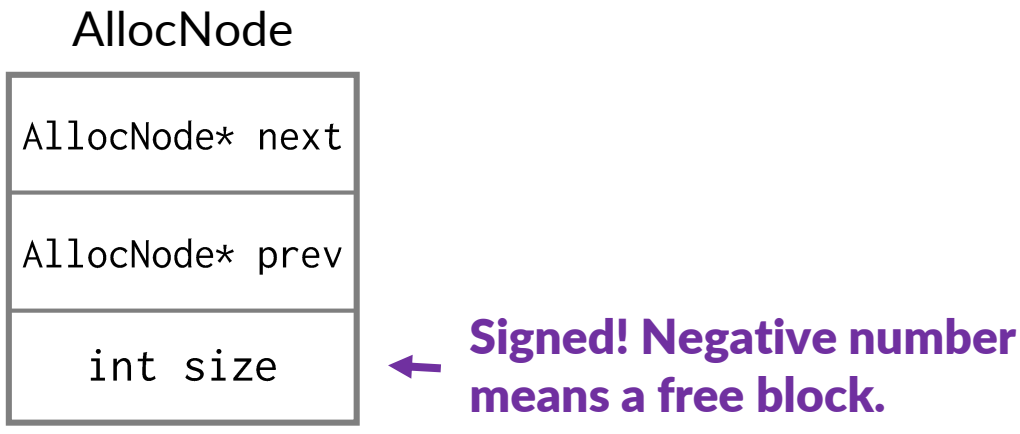


Linked lists are our friend, here

- We will augment our normal doubly linked list to be useful for tracking the size of the block it represents. (an **explicit list** allocator)

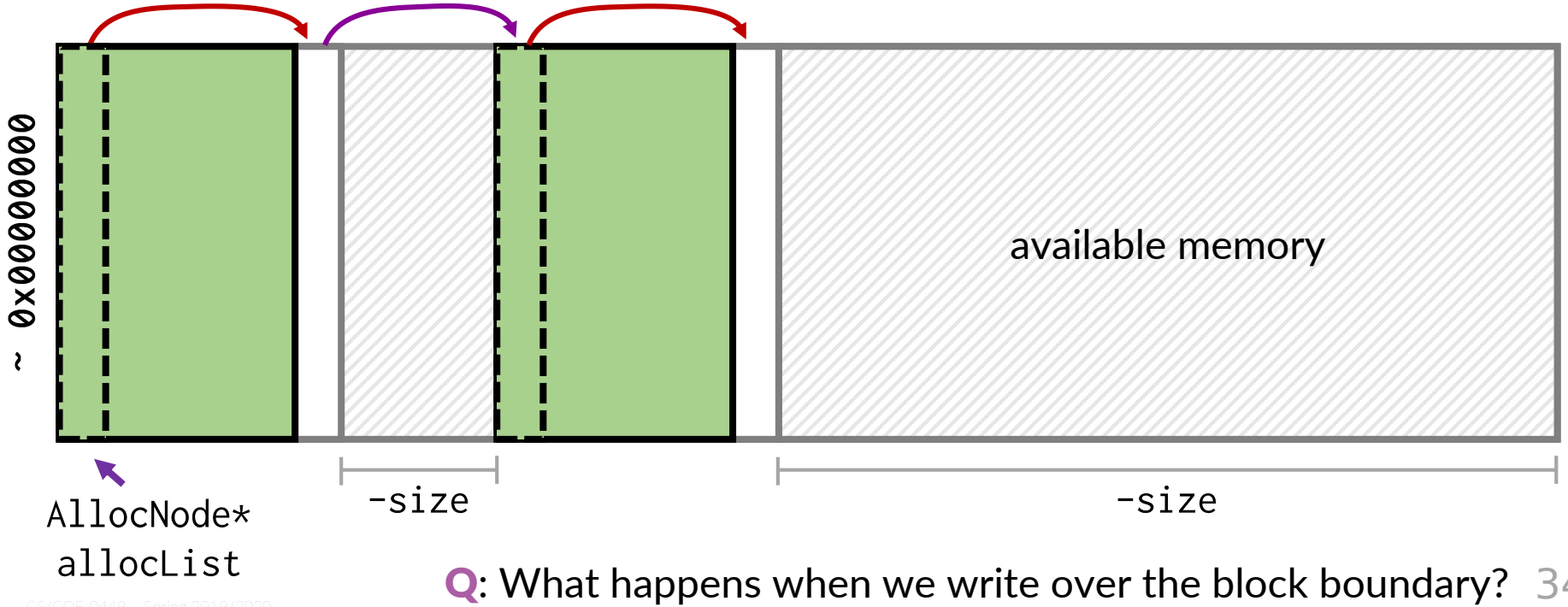
- Here, we will maintain a single linked lists of all allocated or free blocks.
  - The size field denotes how big the block is (how much is used/available.)
  - We need to know when a block represents allocated space or if it is free.
  - Hmm… we could use a single bit to denote that. Or… negativity!
    - The `size` is *NEVER* `0`. In fact, `malloc` fails when requesting size of `0`.

We can make other clever space optimizations, but we will start with this.



Tracking memory: High level metadata

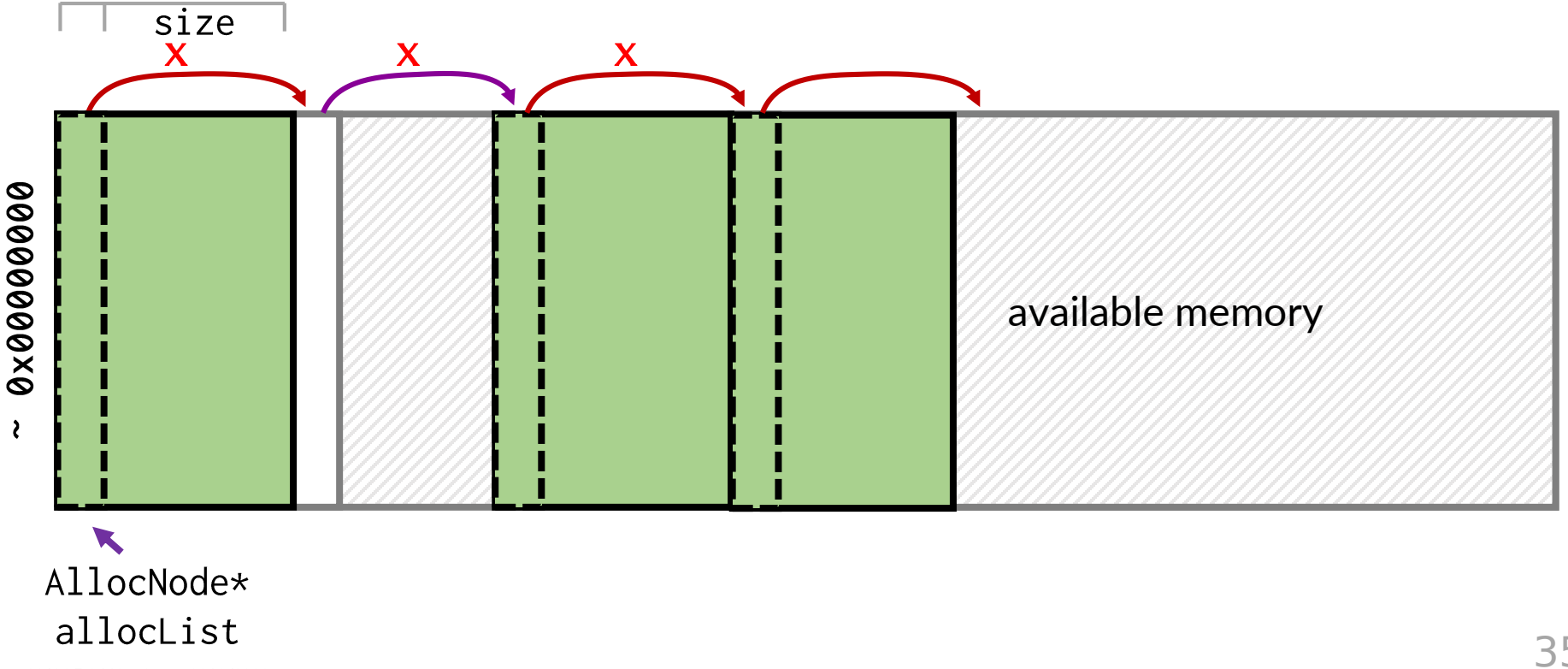
- We can keep track of used/empty spaces cheaply by having linked list nodes at the beginning of them. The nodes track the size of the space.
  - Here we have an allocated block followed by a free and then allocated block.
  - The metadata for the linked list is just smashed into the block itself.



Q: What happens when we write over the block boundary?

Implementing `malloc`

- To allocate some amount of space, we find a free block that is at least that size + metadata size. (Which one? Well, first-fit and friends apply!)
  - Then we will want to split that free block.



Implementing `malloc`

```
AllocNode* allocList;
void* malloc(size_t size) {
    int wantedSize = -(int)(size + sizeof(AllocNode));
    AllocNode* current = allocList;
    while(current &&
          current->size > wantedSize) {
          current = current->next;
    }
    if (!current)
        return NULL; // No free memory!
    // Split the block
    AllocNode* freeBlock = (AllocList*)(((char*)current) + size);
    freeBlock->next = current->next;
    freeBlock->size = current->size + (int)size + sizeof(AllocNode);
    current->next = freeBlock;
    current->size = size;
    return (void*)(current + 1);
}
```

Carefully negate size

Linked list traversal; $O(n)$

Linked list append; $O(1)$

Positive means non-free.

Think about it!

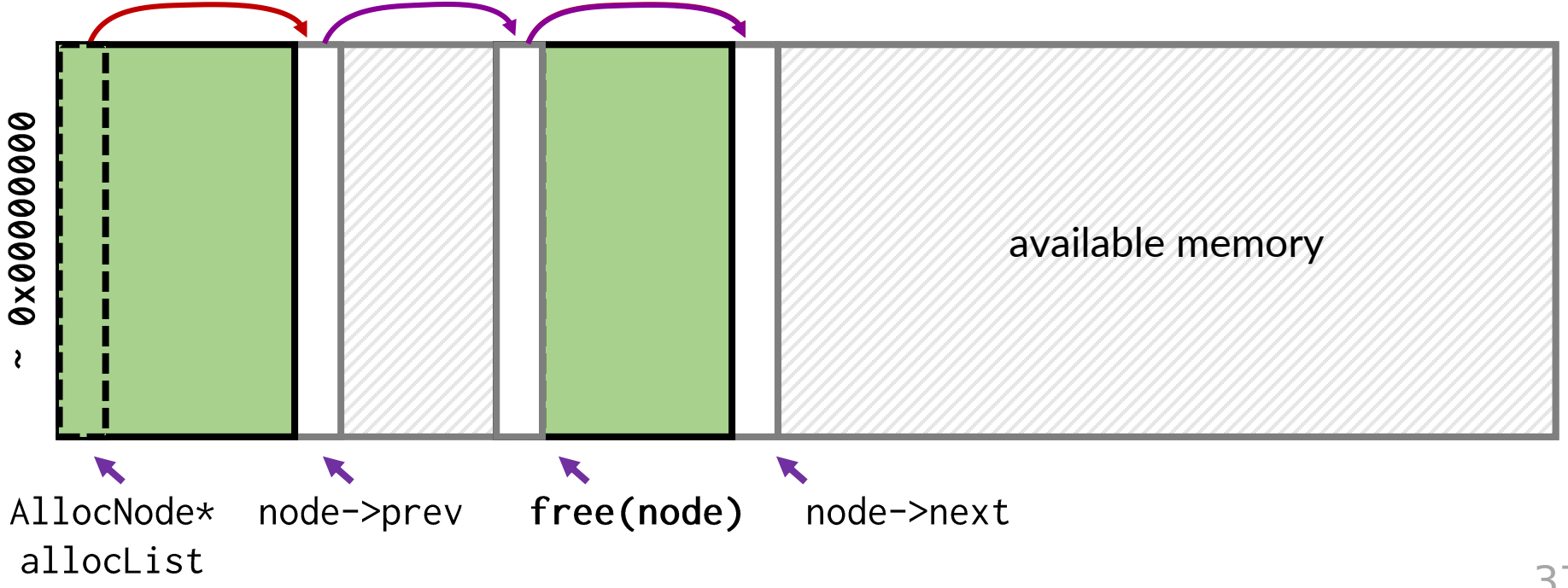
- Allocating means finding a free block big enough.
  - Including the metadata size.
- Then splitting it into a used block and a smaller free block.
- This is incomplete. (Why?)
  - (you don't always split)

Recall that we made size negative for a free block. `current->size` **is negative.**

Q: This is first-fit. What should be added to implement next-fit? Best-fit?

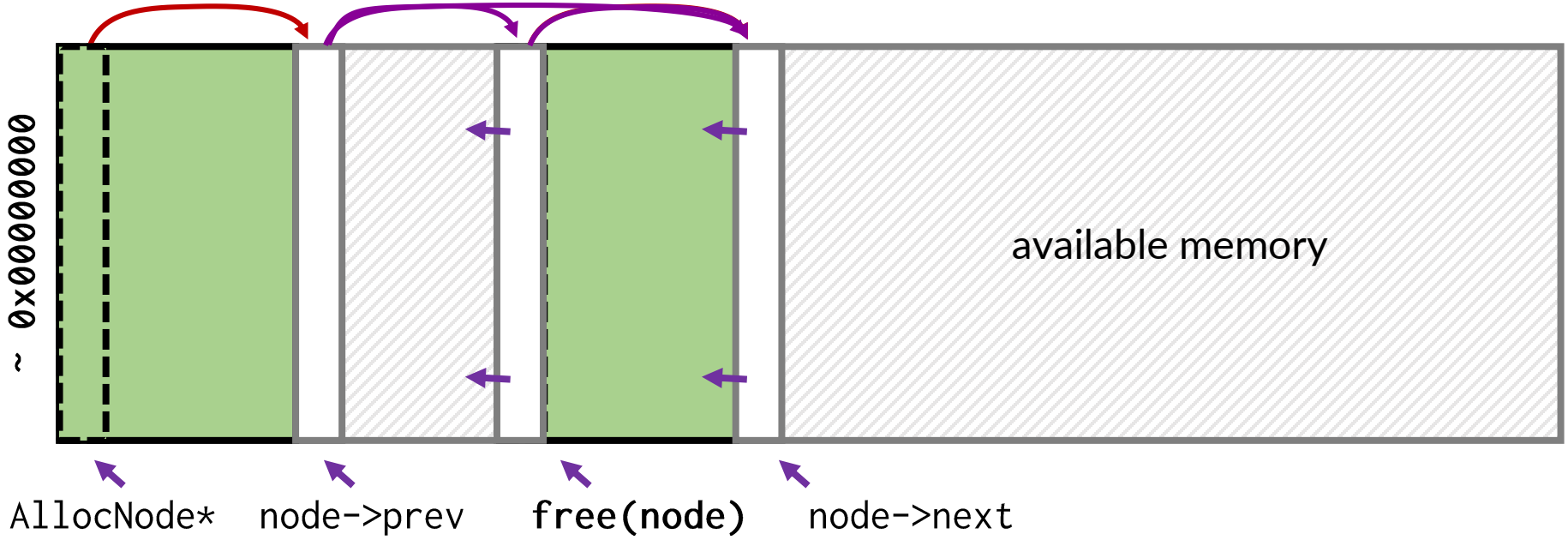
Implementing `free`

- When freeing the middle block, you will create empty space.
- Consider allocations… it's somewhat difficult to see the empty space.
  - You have "*false fragmentation*," so you will want to merge adjacent free blocks.



Implementing `free`

- So, when we free blocks, we look to the left. We look to the right.
  - We **coalesce** the newly free block with ANY adjacent free blocks.
  - First one…
  - Then the other. (And it is linked list node removal; a constant time operation!)



Implementing `free`

```
AllocNode* allocList;

void free(void* ptr) {
    AllocNode* header = ((AllocNode*)ptr) - 1;
    AllocNode* prev = header->prev;
    AllocNode* next = header->next;
    header->size = -header->size;
    if (prev->size < 0) { // prev is free, coalesce
        prev->size -= sizeof(AllocNode) + -header->size;
        prev->next = header->next; header->next->prev = prev;
        header = prev;
    }
    if (next->size < 0) { // next is free, coalesce
        header->size -= sizeof(AllocNode) + -next->size;
        header->next = next->next;
        header->next->prev = header;
    }
}
```

Header is just before ptr

Resembles linked list delete; $O(1)$

However it subtracts from size (which makes reflect a *larger* space)

- Finding the header metadata node is simple.
  - Look at our `malloc`'s `return`.
- `free` is slightly less complex.
  - It does not have to search.
- Where `malloc` splits nodes
  - `free` merges them.
- Whenever a block is freed next to an existing one…
  - It should merge them!
- Consider how much a doubly linked list helped.

Q: Are any changes required here for best-fit?

Thinking about next-fit

- **With a typical first-fit version of the malloc function…**
  - We can now consider simple improvements.
  - Traversing the list is expensive! $O(n)$!
- **Next-fit helps because we start from the last allocated item.**
  - Generally, what do you think comes after the last allocated item.
  - Consider the normal operation…
    - It splits the node and creates free space.
- **Therefore, seems likely free space will exist near the last allocation.**
  - Perhaps causing the average case for malloc to bias itself toward $O(1)$
  - However, all strategies have their own worst-case!!
    - Think about what that might be.

Thinking about best-fit

- **Best-fit, on the other hand, is not about avoiding traversal.**
  - Instead, we focus on fragmentation.
- **Allocating anywhere means worst-case behavior splits nodes poorly.**
  - If we find a PERFECT fit, we *remove* fragmentation.
- **Traversal is still bad… and we brute force the search…**
  - But, hey, solve one problem, cause another. That's systems!
  - Fragmentation may indeed be a major issue on small memory systems.
- **What is the best of both worlds? Next-fit + Best-fit?**
  - Hmm.
  - Works best if you keep large areas open.

Other thoughts

- Don't need `next` pointers since adding size to the block's address will also move there. (unusually, the linked list is always ordered!)

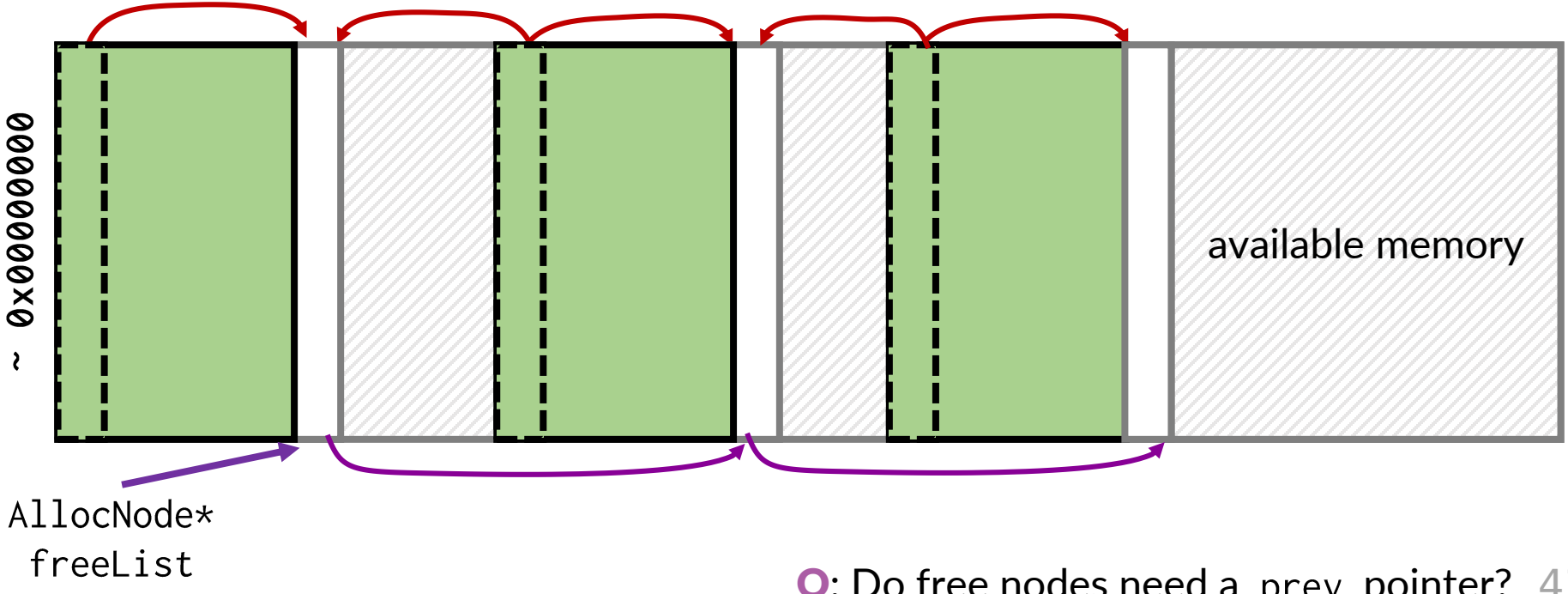
- You don't need to keep the used blocks in the list.
  - More complex to understand but removes implementation complexity.
  - Free nodes point to the next and previous free nodes. Used nodes point to their neighbors. Traversal is improved since it only visits free nodes; still $O(n)$

- The idea is to only keep track of necessary metadata.
  - You only coalesce when free blocks are adjacent.
  - With a list of only free blocks, you can easily tell when that condition is met…
    - just see if `node->next` is the same address as `(char*)(node + 1) + node->size`

- The only other concern is getting from a used block you want to free to its neighboring free block. So those have normal pointers.

Explicit free lists: giving you VIP access

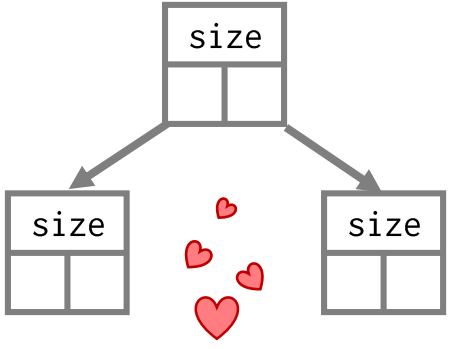
- When you allocate, you go through the free list.
  - You don't care about allocated nodes.
- When you free, you only care about coalescing neighbors.



Q: Do free nodes need a `prev` pointer?

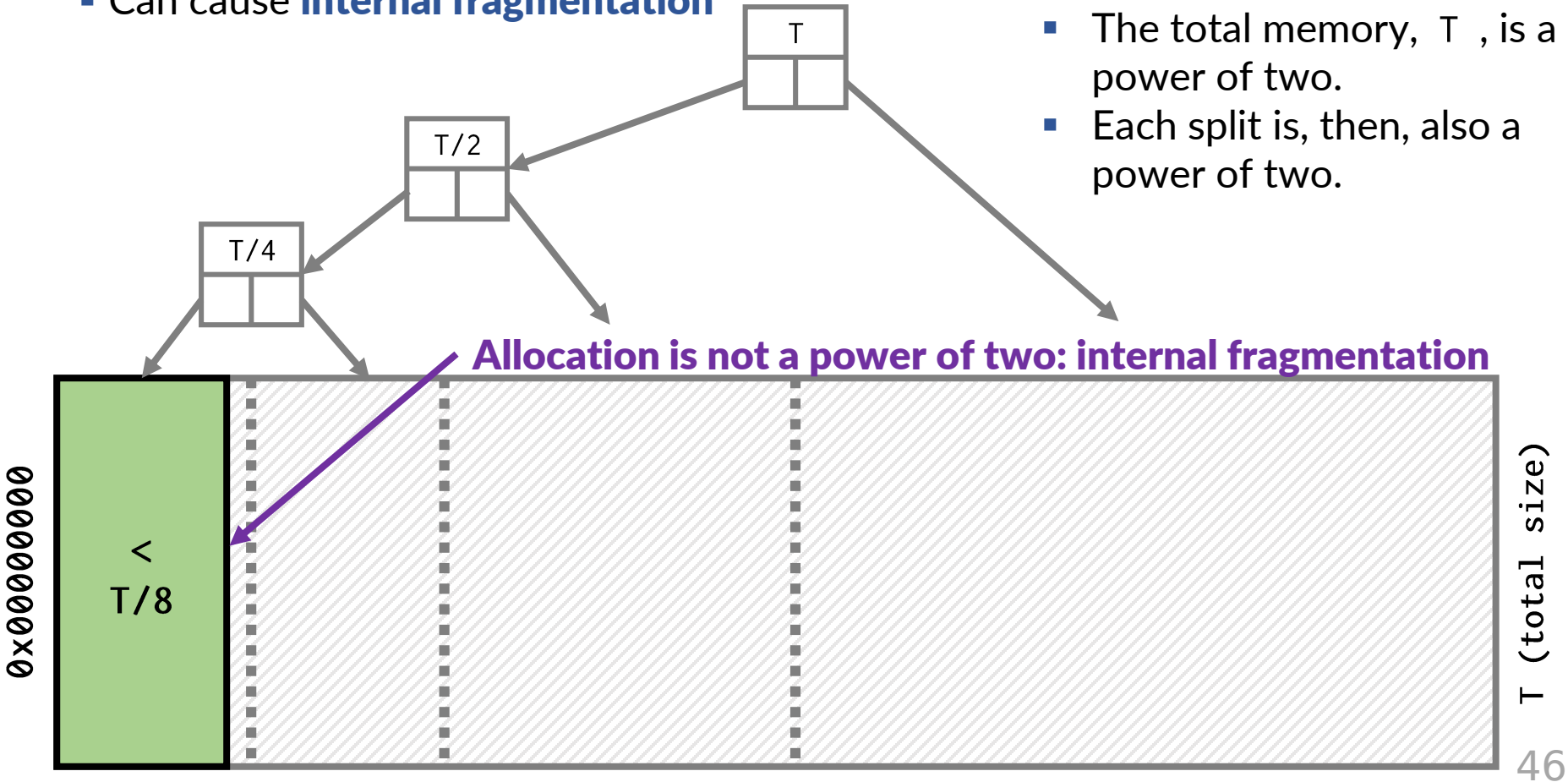
Trees are your buddy

- Recall that we easily took the ideas around linked lists and made binary trees.
- You can manage memory with a binary tree as well.
- This is called a **buddy allocator**.



Divide and conquer

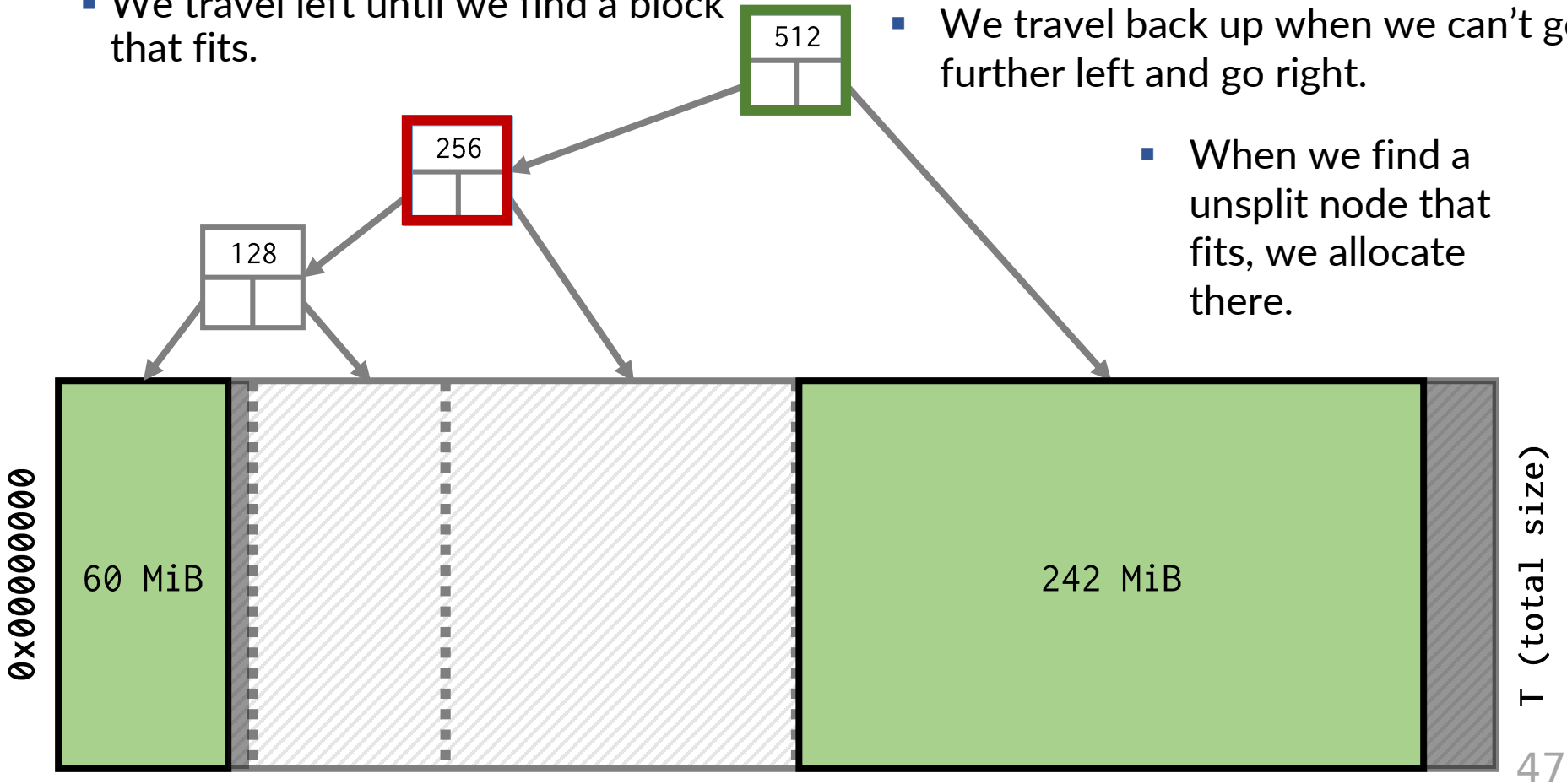
- Buddy allocators divide memory into halves that are powers of two.
  - Can cause **internal fragmentation**



- The total memory, `T`, is a power of two.
- Each split is, then, also a power of two.

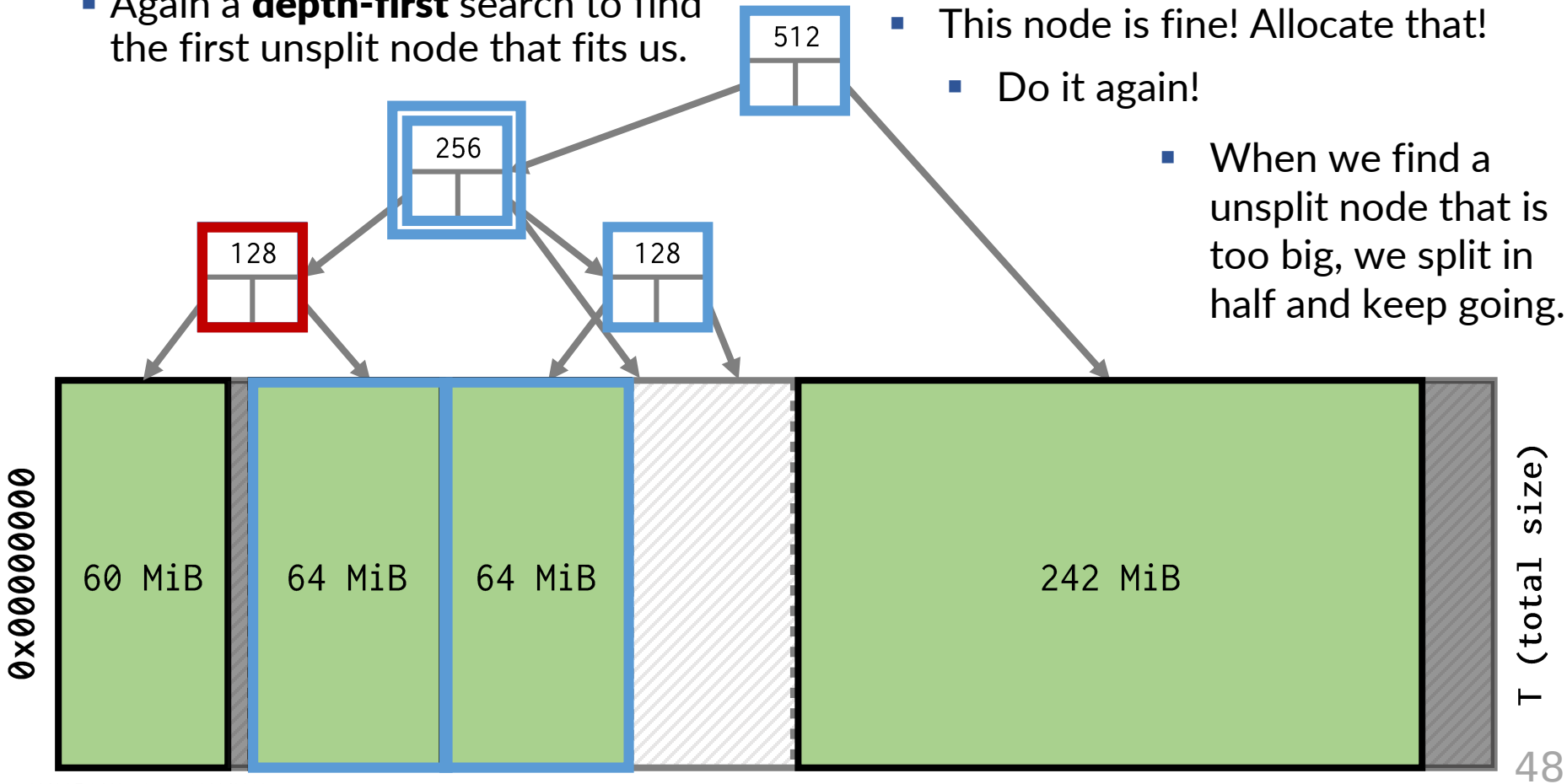
Allocating with trees

- Assuming `T` is `512`, and we allocate 242MiB: `malloc(242*1024*1024)`
  - We travel left until we find a block that fits.
  - We travel back up when we can't go further left and go right.
  - When we find a unsplit node that fits, we allocate there.



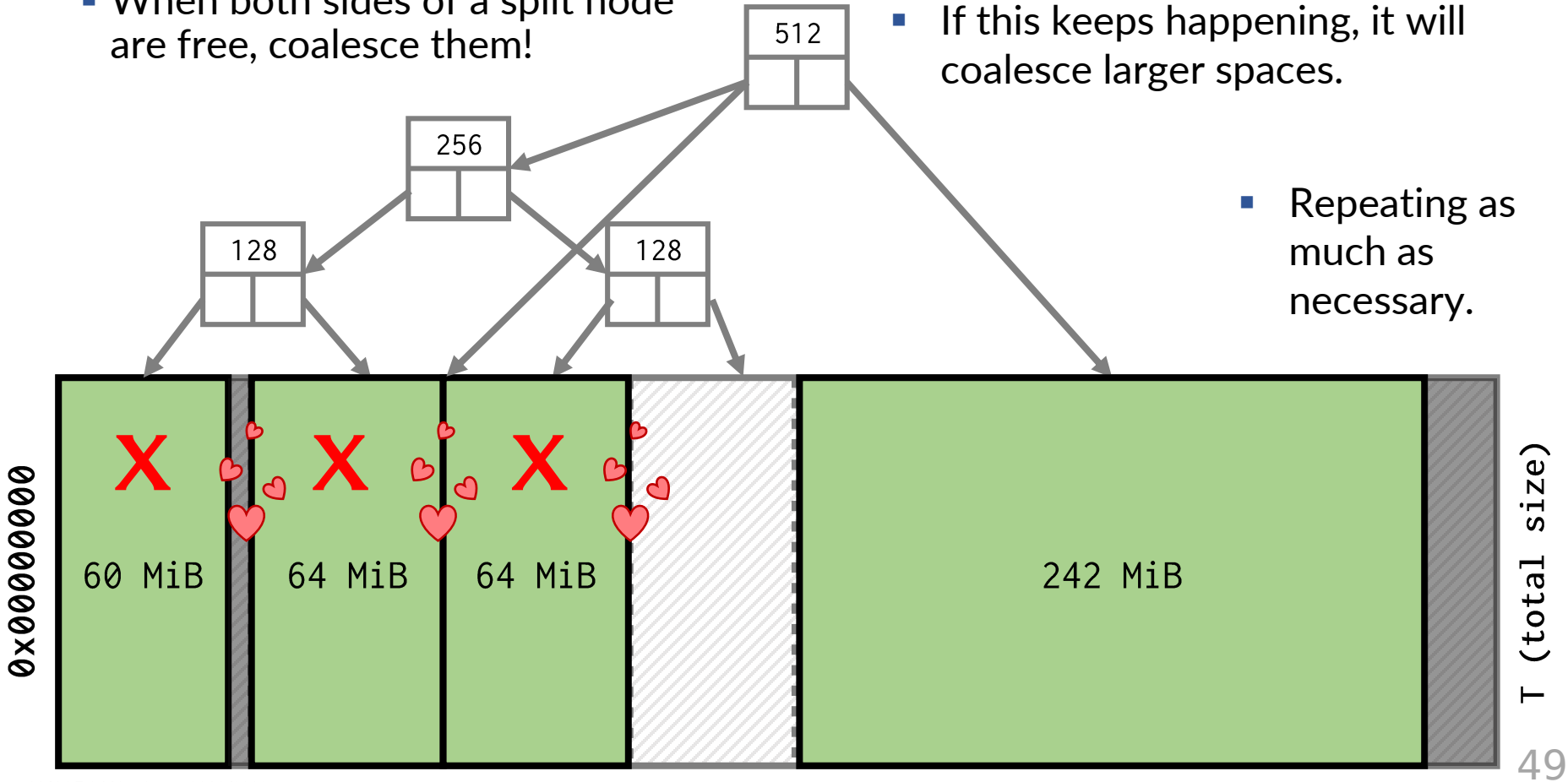
Burying the hatchet: Chopping the trees

- Let's allocate 64MiB. So nice, we will allocate it twice.
  - Again a **depth-first** search to find the first unsplit node that fits us.
  - This node is fine! Allocate that!
    - Do it again!
      - When we find a unsplit node that is too big, we split in half and keep going.



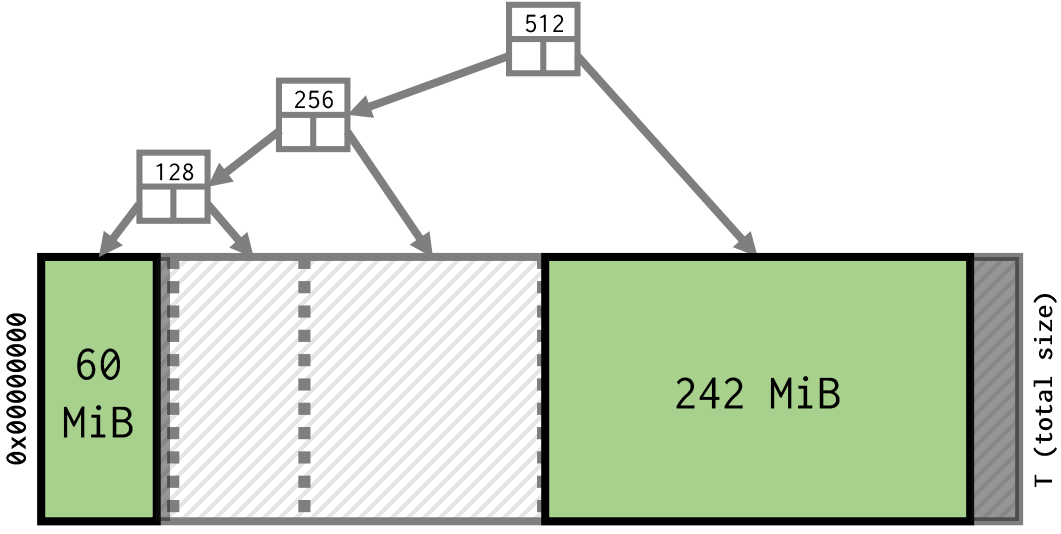
Coalescing friendships (animated)

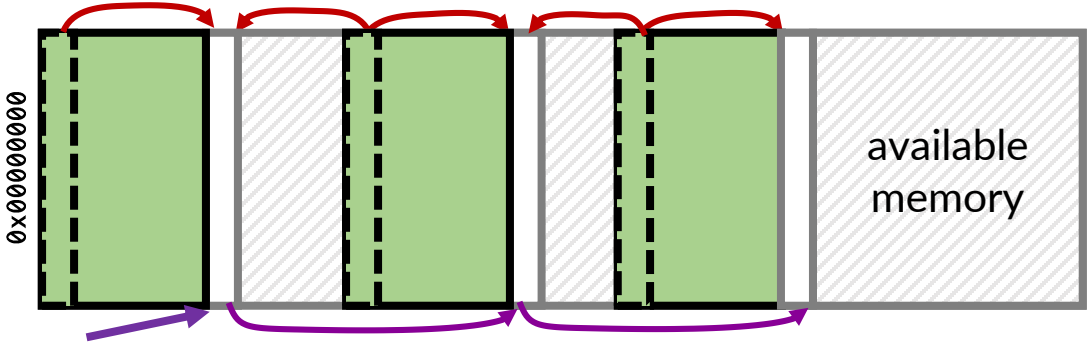
- Coalescing happens because every block has a buddy!
  - When both sides of a split node are free, coalesce them!
  - If this keeps happening, it will coalesce larger spaces.
  - Repeating as much as necessary.



Thinking like an arborist (but only if you are feeling listless)

- How does a tree-based allocation system deal with fragmentation?
- What are some immediate drawbacks from using a tree scheme?





- Can you imagine a possibility of using a hybrid approach?

Lies and Damned Lies!

- **Does your program actually own all of memory?**
  - On modern systems, absolutely heckin not.
- **Your program still has to request memory allocations from the OS.**
  - Generally, `malloc` takes on this responsibility behind the scenes.
  - In Linux, you request pages in the normal heap in LIFO order with `sbrk`.
  - Or, you request specific virtual memory pages with `mmap`.
- **What is a segmentation fault.**
  - Segments are the “code”, “data”, “heap” separation. You fault by doing something the segment does not allow. (write to read-only memory)
  - A historic misnomer since we actually have paging, not segmented memory.
- **What is a “page”? Virtual memory??**
  - It replaced segments and is part of the much grander lie about sharing memory with multiple applications at the same time. More on this later!

I want to know MORE

- If you find this topic interesting, it is a WIDE area of research.
- Malloc is generally more complex or specialized these days than the options here.
  - Or some kind of hybrid, as the need arises.
- The Linux kernel makes use of a Slab Allocator
  - https://en.wikipedia.org/wiki/Slab_allocation
- Modern C (glibc) uses a hybrid malloc:
  - https://www.gnu.org/software/libc/manual/html_node/The-GNU-Allocator.html
- Professor Knuth has written about several classic algorithms.
  - Buddy Allocation comes from the 60s. Groovy.