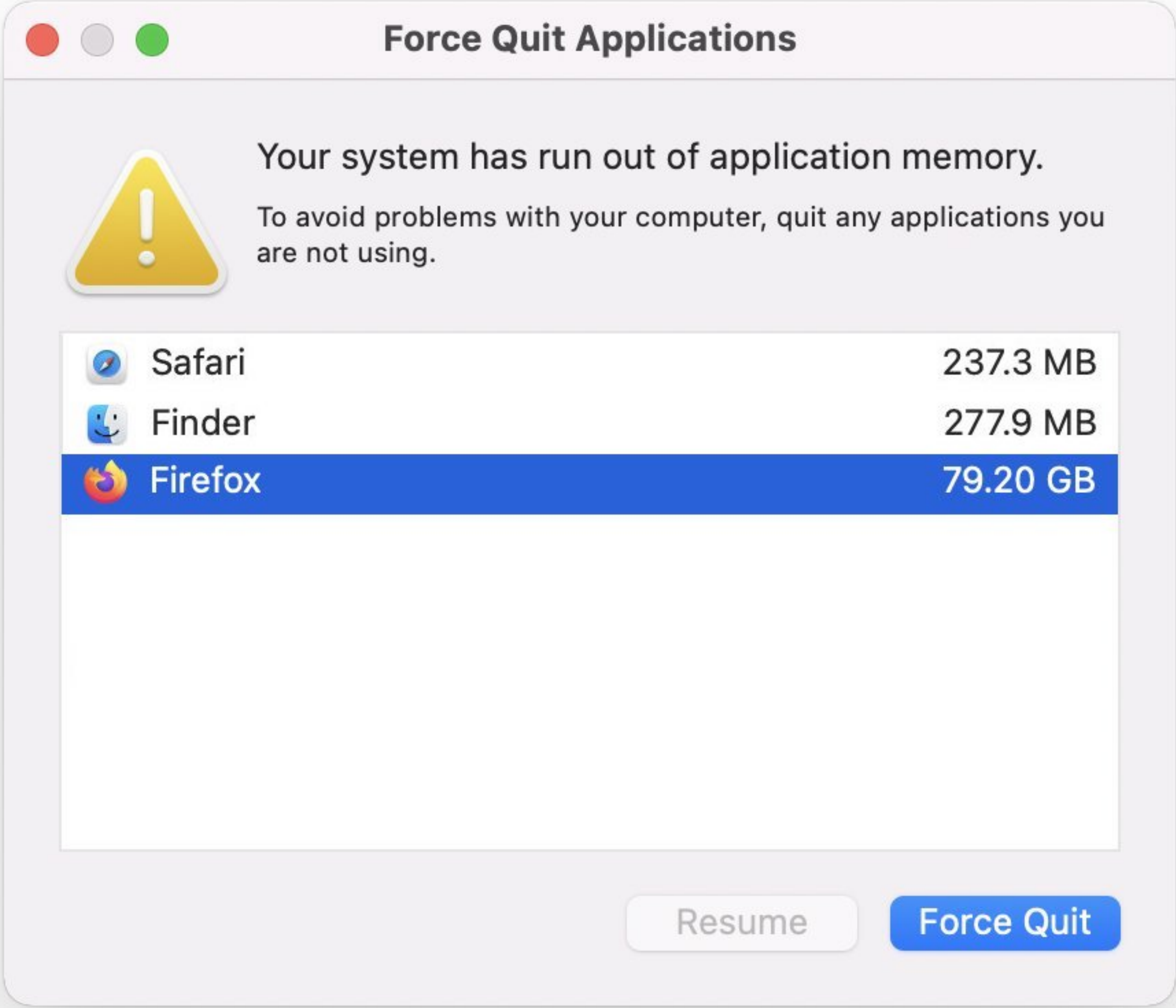
Dynamic Memory Allocation in the Heap

Explicit allocators

Manual memory management

C: implementing malloc and free



Force Quit Applications

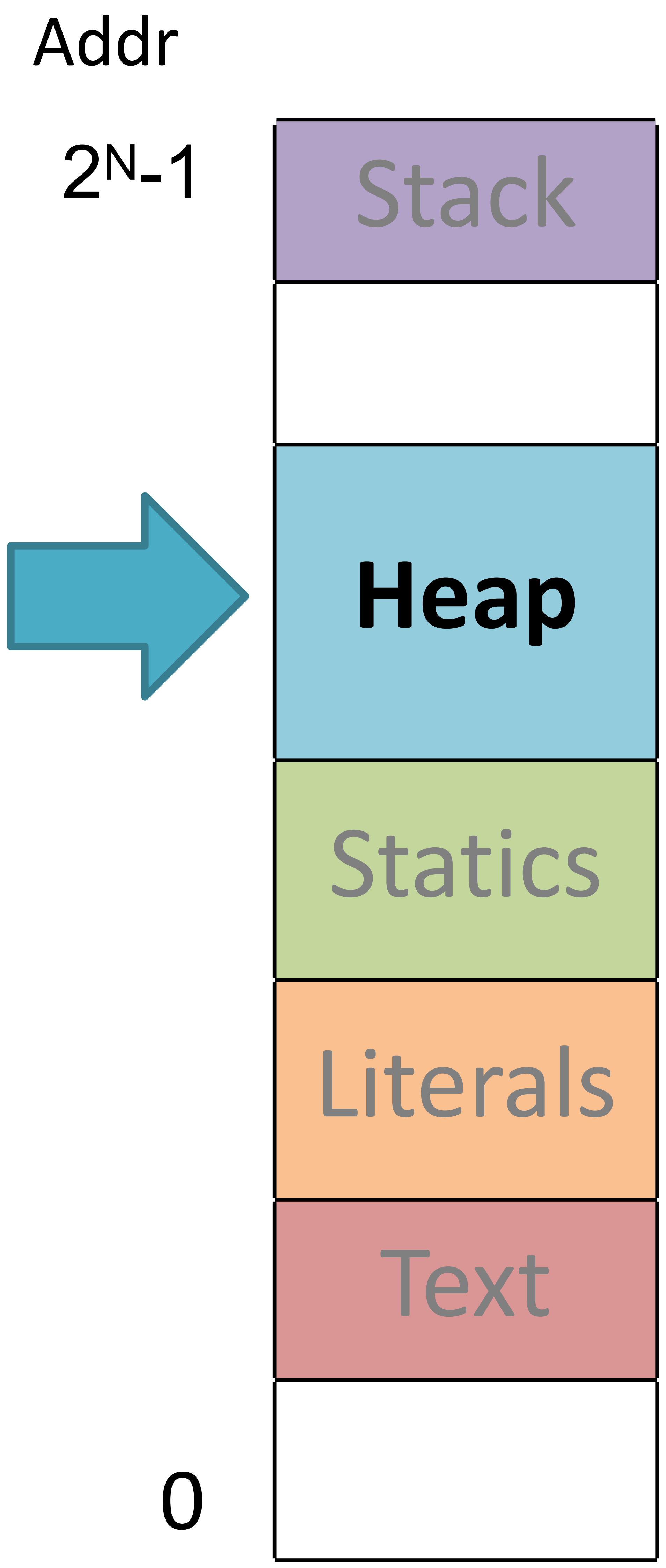
Your system has run out of application memory.

To avoid problems with your computer, quit any applications you are not using.

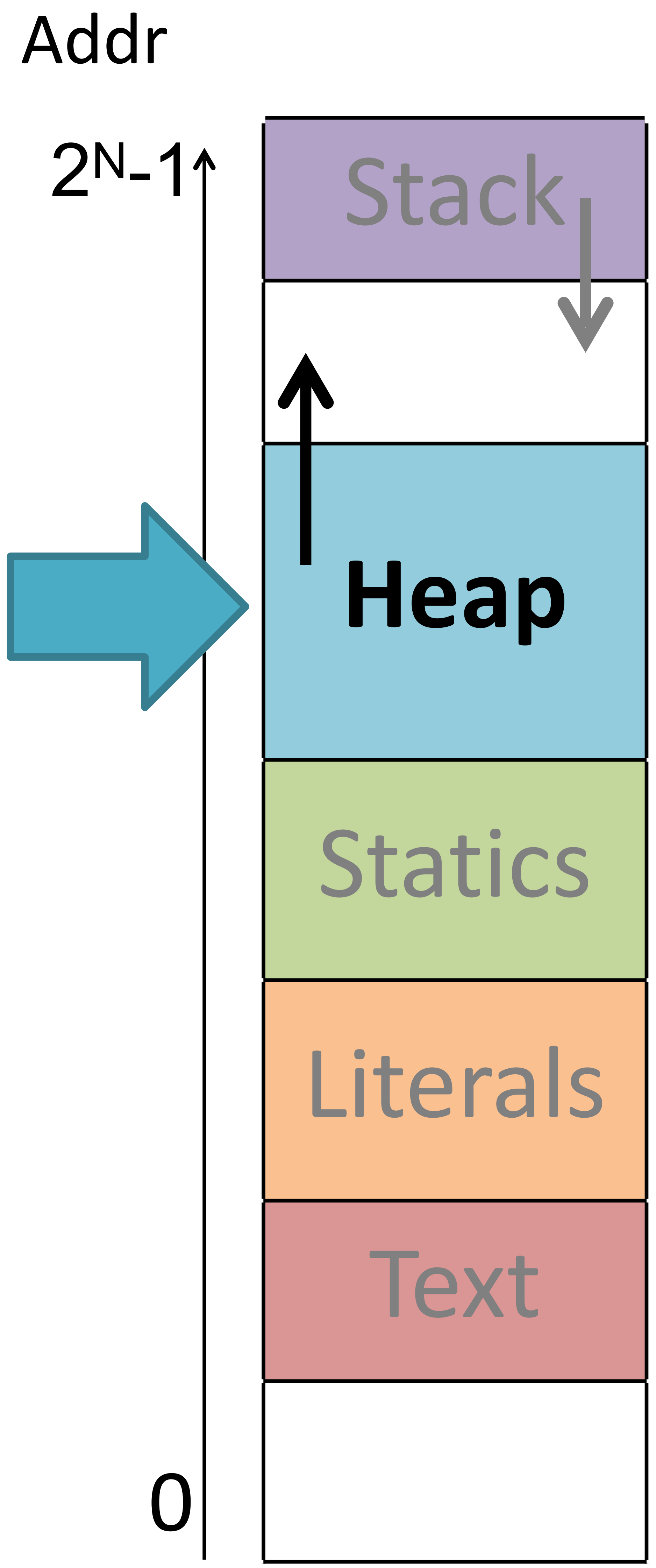
Safari	237.3 MB
Finder	277.9 MB
Firefox	79.20 GB

Outline

- Motivation/alternatives
- Design goals for a memory allocator
  - Utilization/fragmentation
- Implicit free list allocator
  - Tracking sizes
  - Allocating blocks
  - Coalescing blocks
- Explicit free lists
  - List vs. memory order
  - Freeing/coalescing

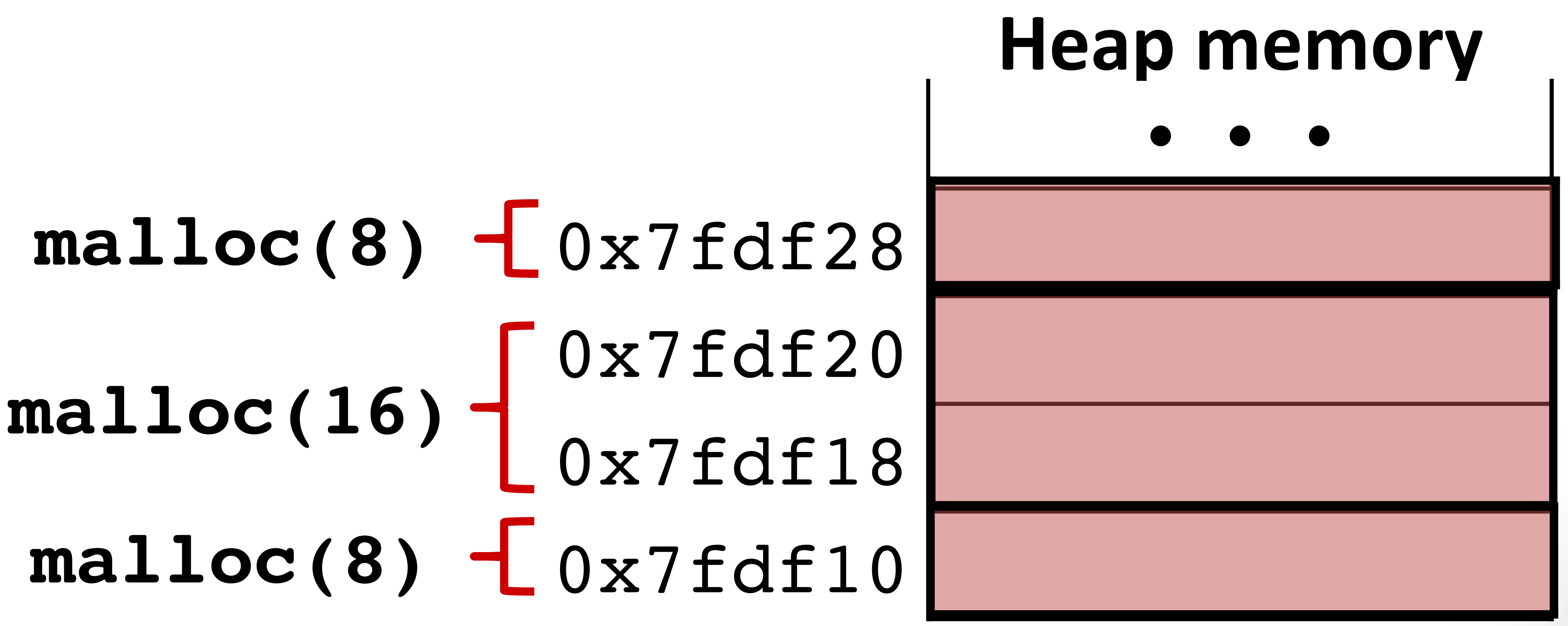


Heap Allocation

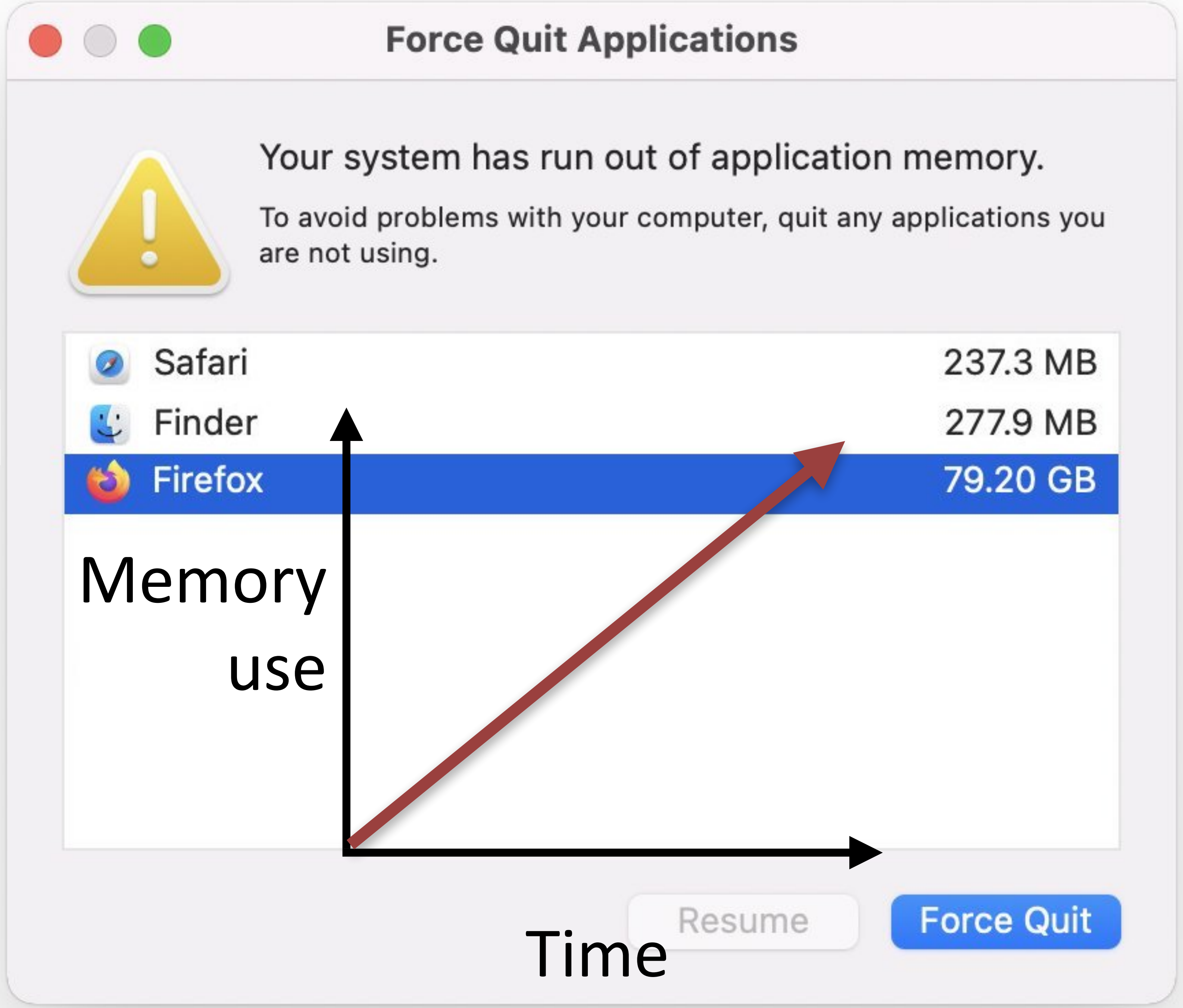


Perm	Contents	Managed by	Initialized
RW	Procedure context	Compiler	Run-time
RW	**Dynamic data structures**	Programmer, **malloc/free,** new/ GC	**Run-time**
RW	Global variables/ static data structures	Compiler/ Assembler/Linker	Startup
R	String literals	Compiler/ Assembler/Linker	Startup
X	Instructions	Compiler/ Assembler/Linker	Startup

Motivation: why not just allocate in memory order?



```
void process_incoming_data(int data[]) {
  // Build complicated data structures
  // ...
  print("%d", result);
  // Don't need data or backing work!
}
```



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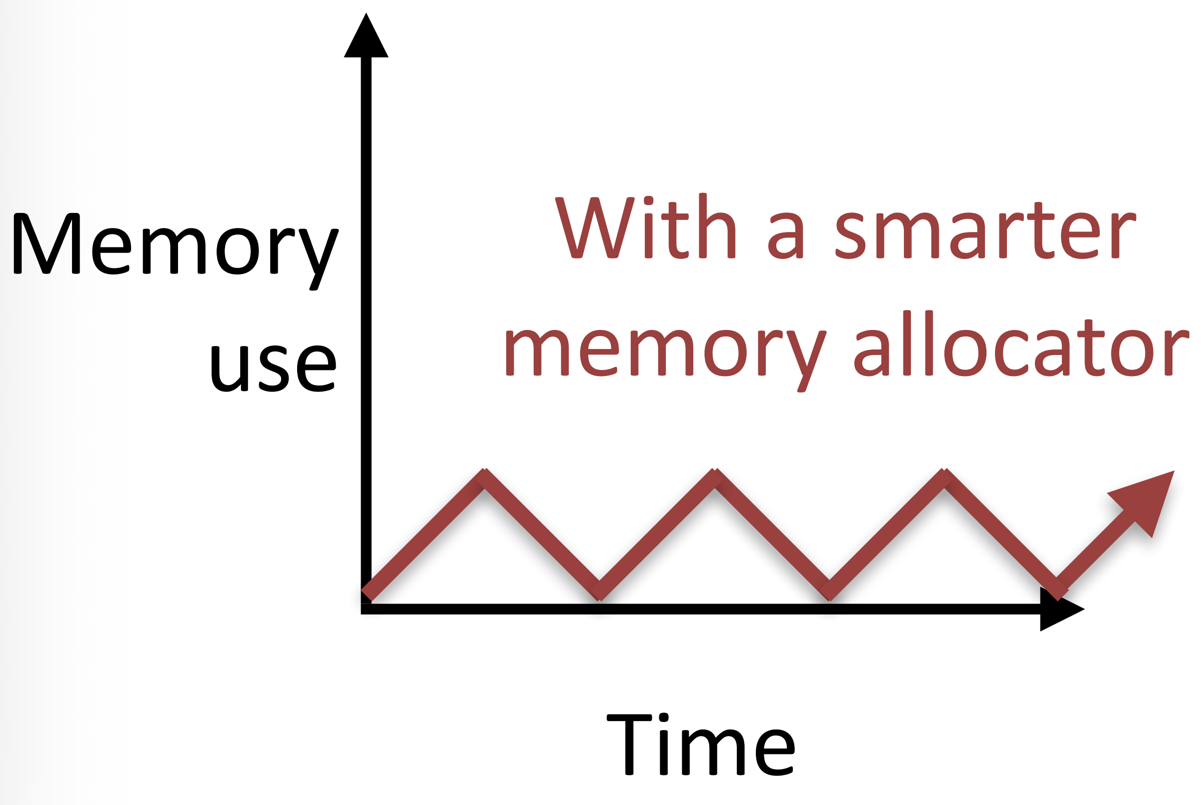


Motivation: what data do we need to track?

ex

Idea: given a page (4096 bytes), support these two functions

pointer to newly allocated block of at least that size

number of contiguous bytes required

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

pointer to allocated block to free

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

What data structures could we use to track this?

Actual dynamic memory allocator design

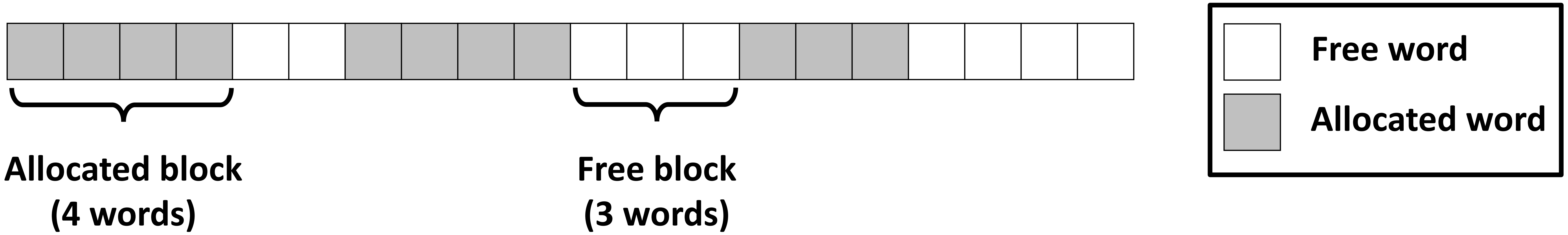
Design the allocator to store data “inline” within the heap memory itself

- Space efficient: no need for much data “on the side”
- Use pointer arithmetic to calculate results
- Good use of caches/locality (we’ll cover more later)

Allocator basics

Pages (OS-provided) too coarse-grained for allocating individual objects.

Instead: flexible-sized, word-aligned blocks.



pointer to newly allocated block of at least that size

number of contiguous bytes required

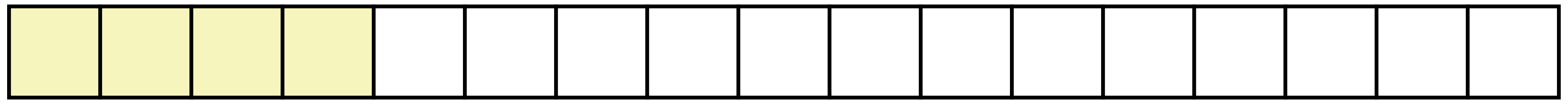
```
void* malloc(size_t size);
```

pointer to allocated block to free

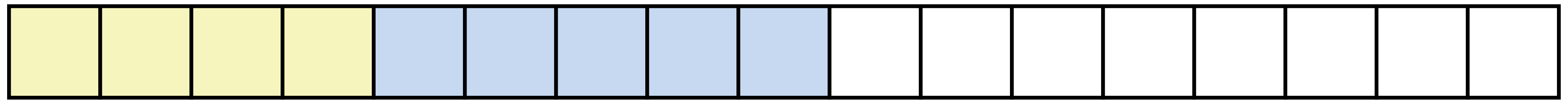
```
void free(void* ptr);
```

Example (64-bit words)

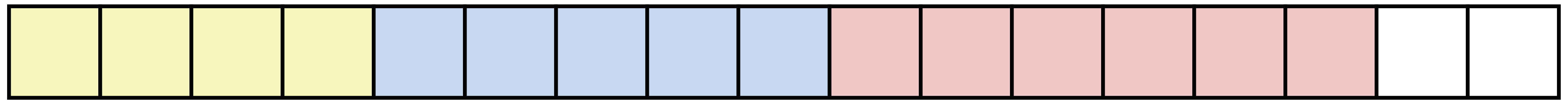
```
p1 = malloc(32);
```



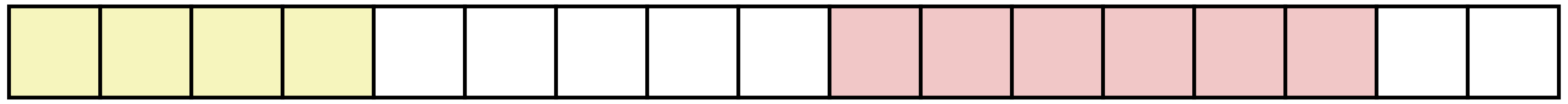
```
p2 = malloc(40);
```



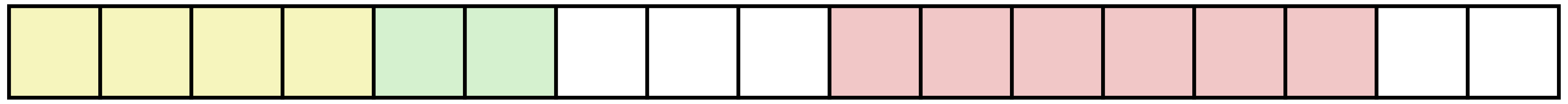
```
p3 = malloc(48);
```



```
free(p2);
```



```
p4 = malloc(16);
```



Allocator goals: malloc/free

1. Programmer does not decide locations of distinct objects.

Programmer decides: what size, when needed, when no longer needed

```
p = malloc(32);
// ...
free(p)
```

2. Fast allocation.

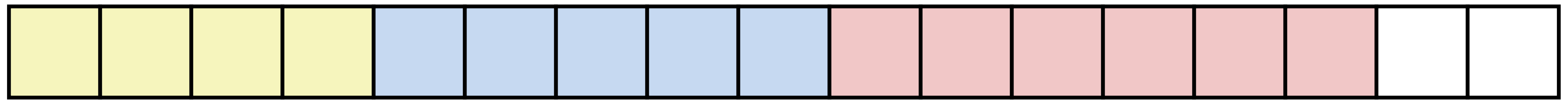
mallocs/second or bytes malloc'd/second

$O(\ldots)$

3. High memory utilization.

Most of heap contains necessary program data.

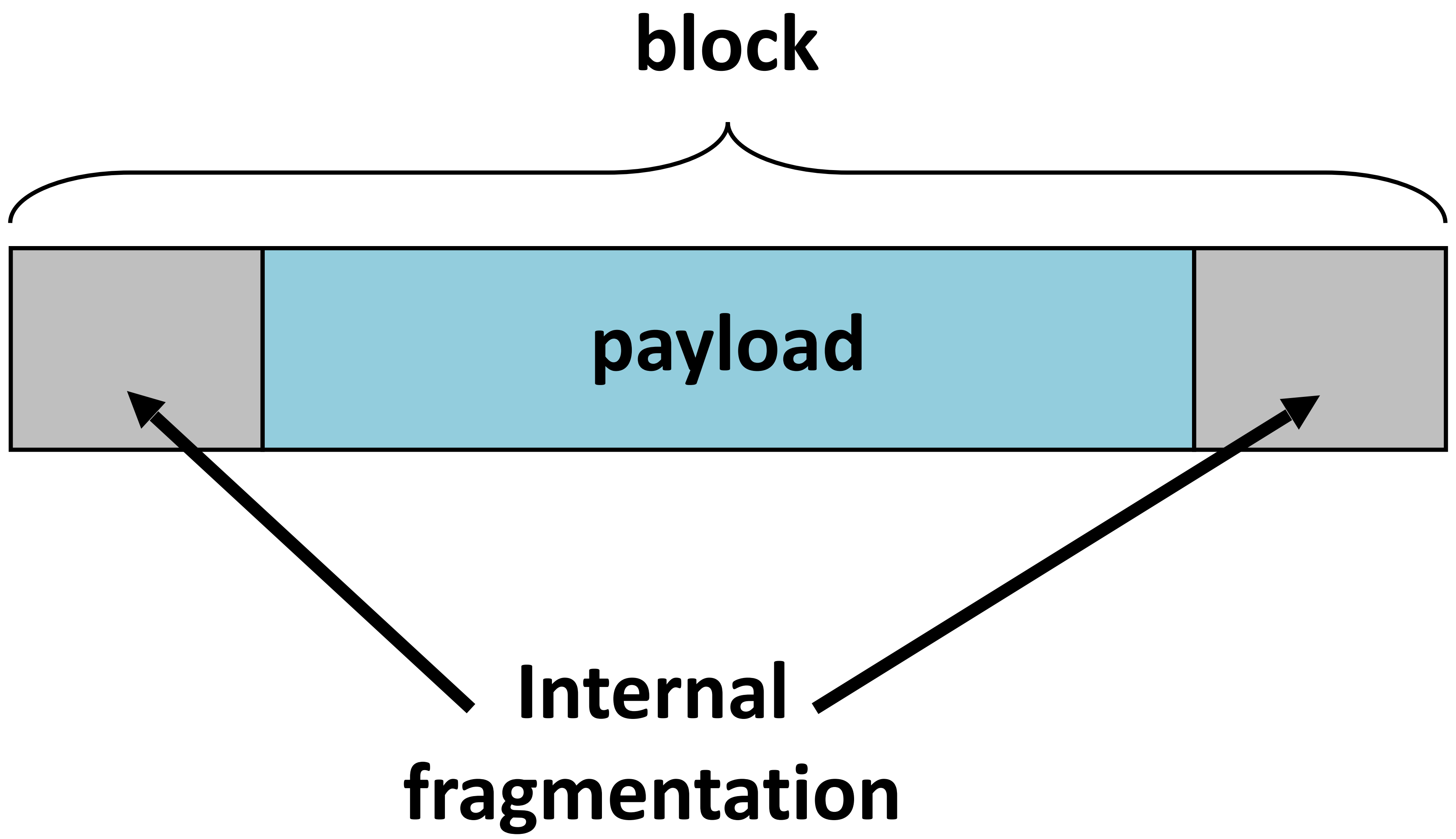
Little wasted space.



Enemy: **fragmentation** – unused memory that cannot be allocated.

Internal fragmentation

Payload smaller than block

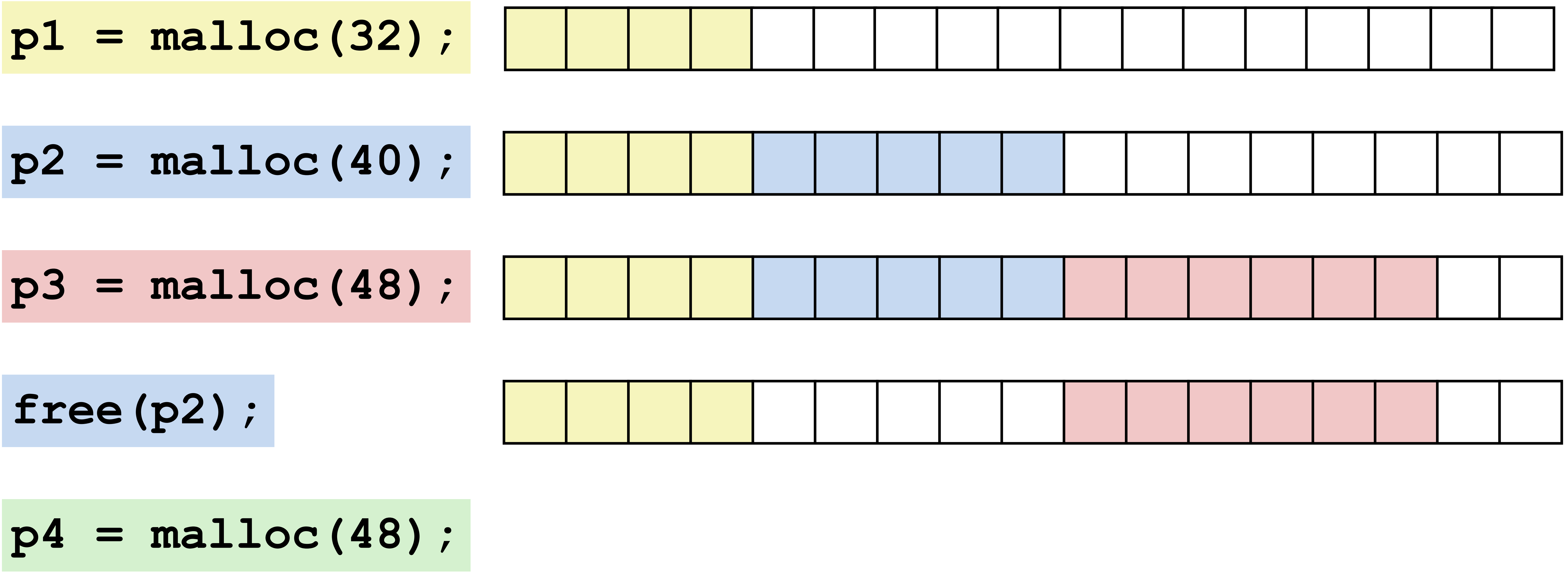


Causes

- Metadata (bookkeeping)
- Alignment (8, 16, …)
- Policy decisions

External fragmentation (64-bit words)

Total free space large enough, but no contiguous free block large enough!



```
p1 = malloc(32);
p2 = malloc(40);
p3 = malloc(48);
free(p2);
p4 = malloc(48);
```

Depends on the pattern of future requests.

Implementation issues

1. Determine **how much** to free given just a pointer.

2. Keep track of **free blocks**.

3. **Pick** a block to allocate.

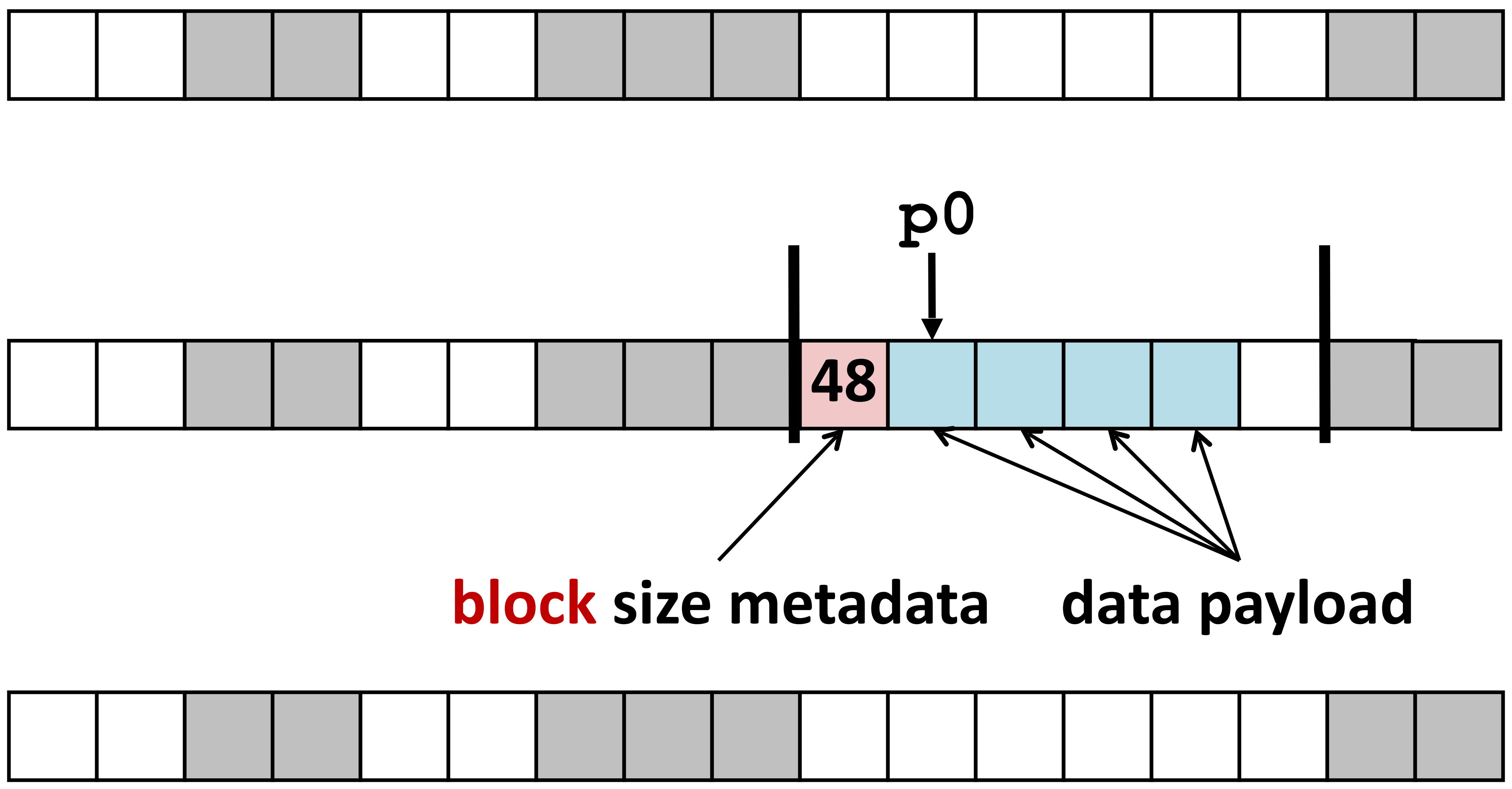
4. Choose what do with **extra space** when allocating a structure that is smaller than the free block used.

5. Make a **freed block available** for future reuse.

Knowing how much to free

Keep length of block in *header* word preceding block

Takes extra space!



`p0 = malloc(32);`

`free(p0);`

p0

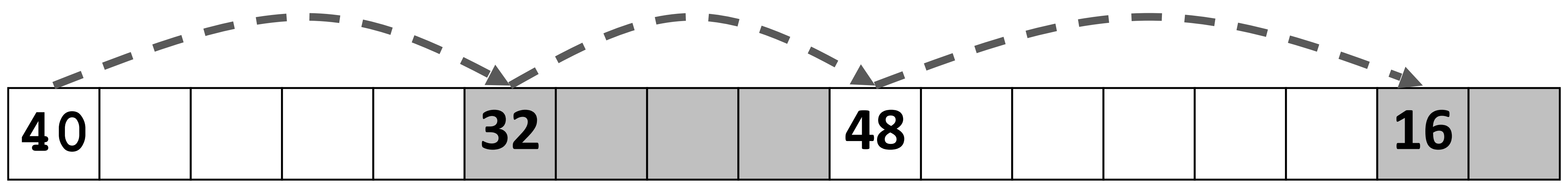
48

block size metadata

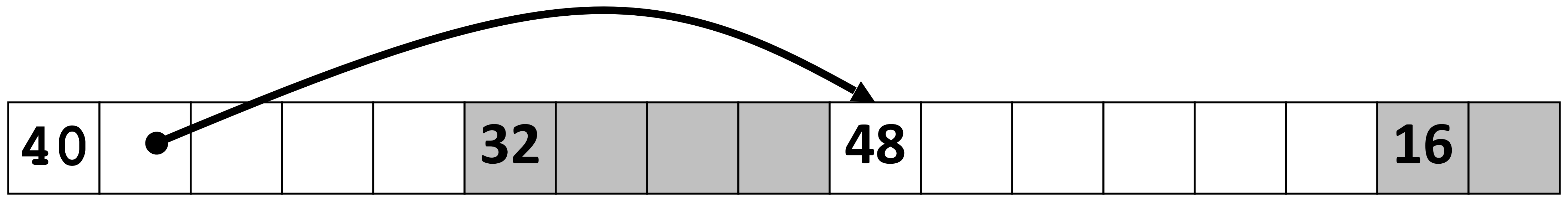
data payload

Keeping track of free blocks

Method 1: *Implicit free list* of all blocks using length



Method 2: *Explicit free list* of free blocks using pointers



Method 3: *Seglist*

Different free lists for different size blocks

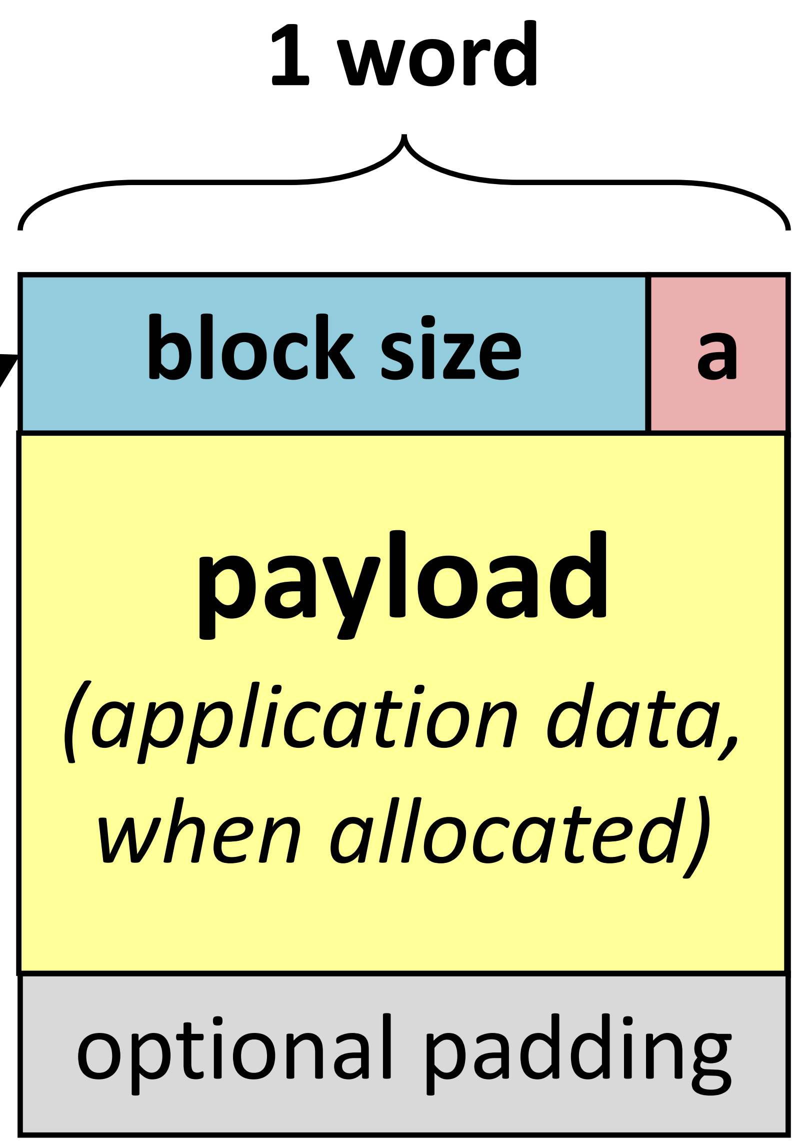
More methods that we will skip…

Implicit free list: block format

Block metadata:

1. Block size
2. Allocation status

Store in one header word.



1 word

block size | **a**

payload

(application data, when allocated)

optional padding

Steal LSB for status flag.

LSB = 1: allocated

LSB = 0: free

16-byte aligned sizes have
4 zeroes in low-order bits

0000**0000**

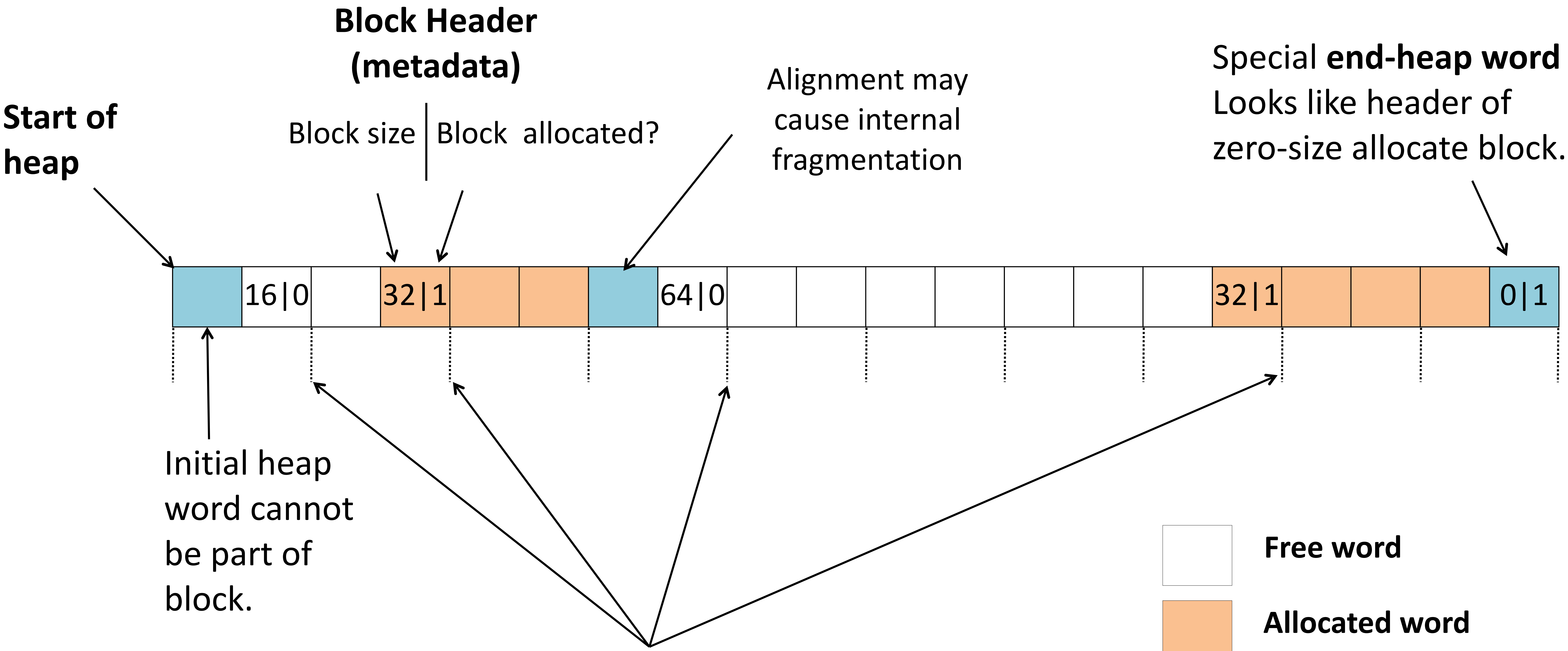
0001**0000**

0010**0000**

0011**0000**

...

Implicit free list: **heap layout**



Start of heap

Block Header (metadata)

Block size | Block allocated?

Alignment may cause internal fragmentation

Special **end-heap word**
Looks like header of zero-size allocate block.

Initial heap word cannot be part of block.

Payloads start at 16-byte (2-word) alignment.
Pointers returned by malloc are to payloads, not headers
Block sizes are multiples of 16 bytes.

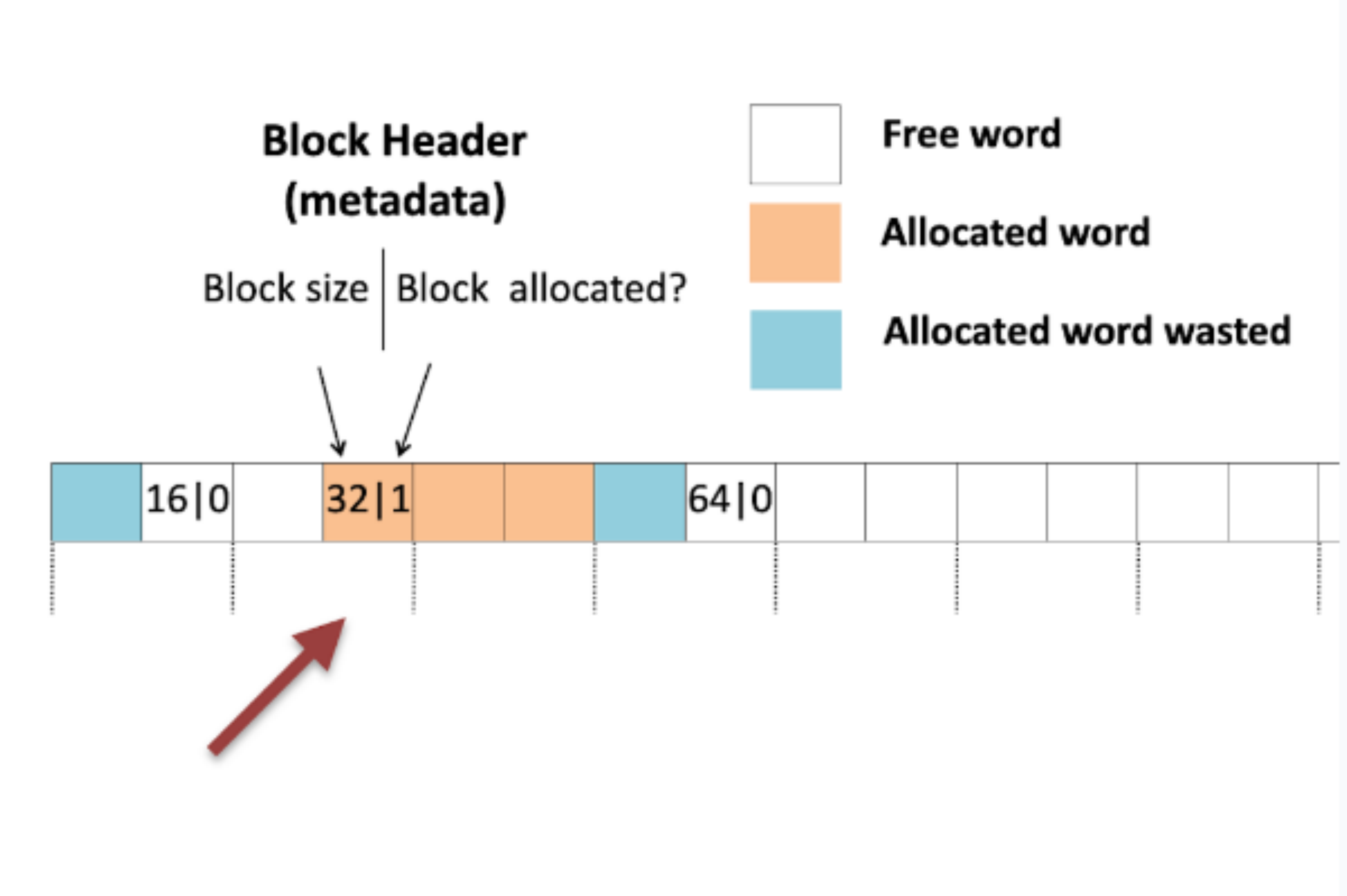
⬜ **Free word**

🟧 **Allocated word**

🟦 **Allocated word wasted**

Recall: in this implicit free list heap, why does the block pointed to by the red arrow have size 32?

0



payload is 2 words, 2*16=32 **(A)**

payload is 2 words, header 2, 4*8=32 **(B)**

payload is 3 words, header 1, 4*8=32 **(C)**

payload 2 words, header 1, 1 wasted (alig… **(D)**

None of the above **(E)**

Implicit free list: **finding a free block**

First fit:

Search list from beginning, choose ***first*** free block that fits

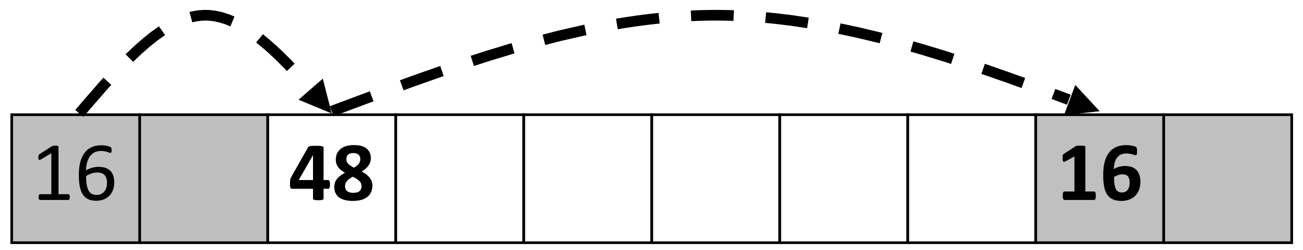
Next fit:

Do first-fit starting where previous search finished

Best fit:

Search the list, choose the ***best*** free block: fits, with fewest bytes left over

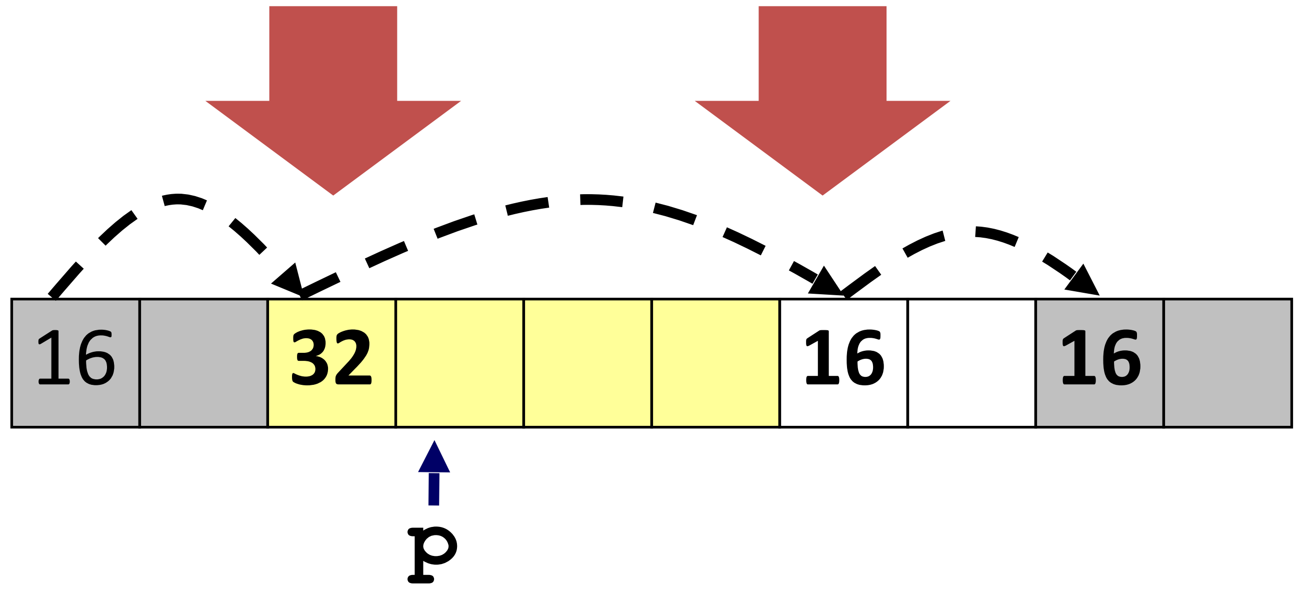
Implicit free list: **allocating a free block**



```
p = malloc(24);
```

Allocated space ≤ free space.

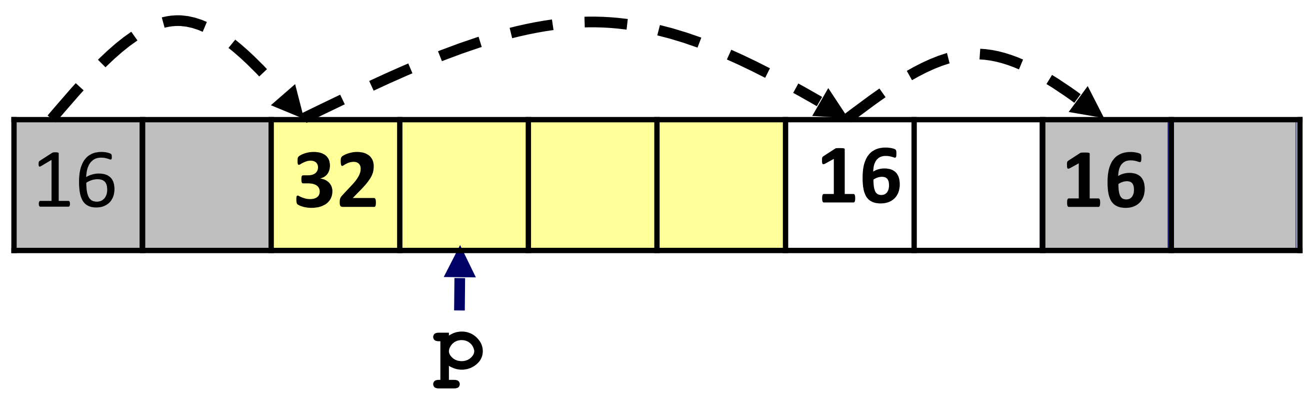
Use it all? Split it up?



Block **Splitting**

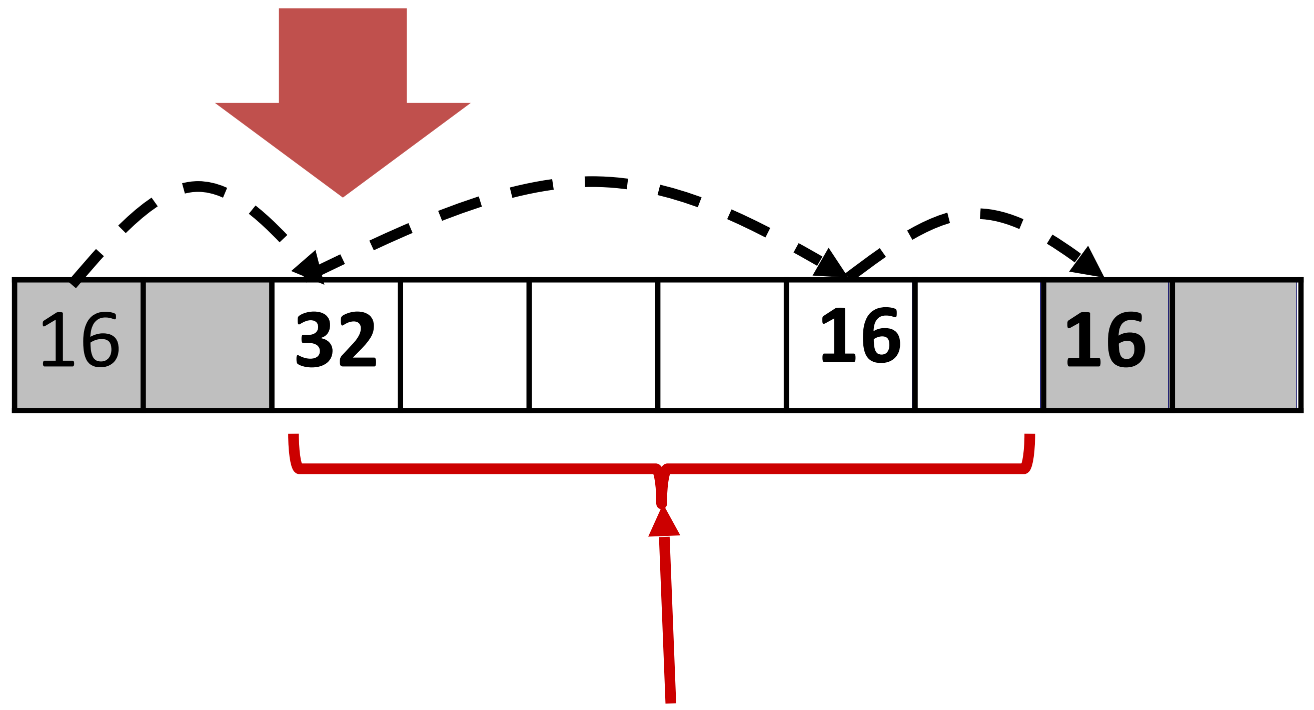
Now showing allocation status flag implicitly with shading.

Implicit free list: **freeing an allocated block**



```
free(p);
```

Clear *allocated* flag.



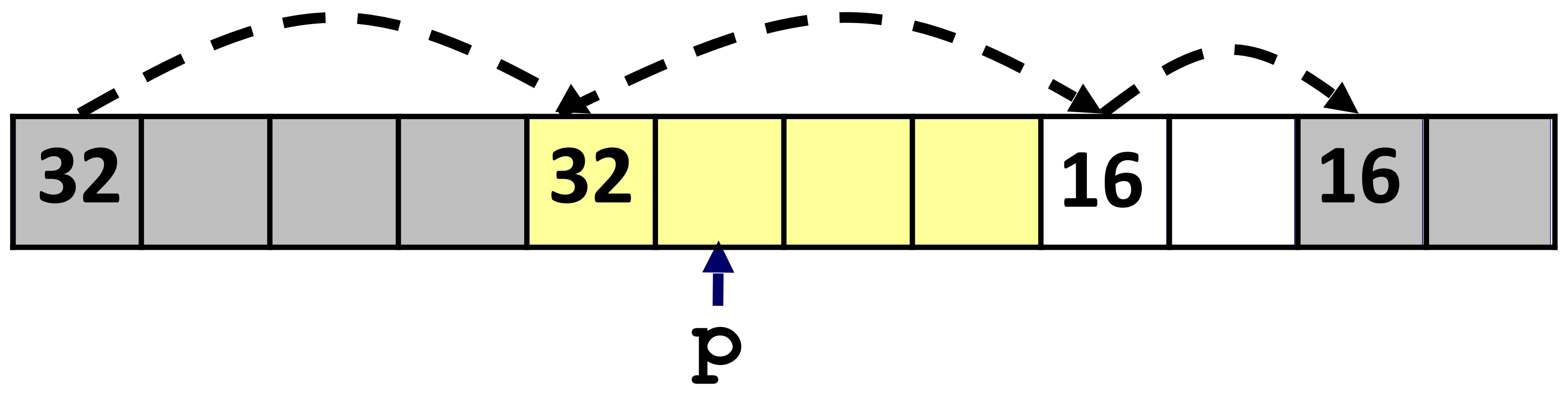
```
malloc(40);
```

✗

External fragmentation!

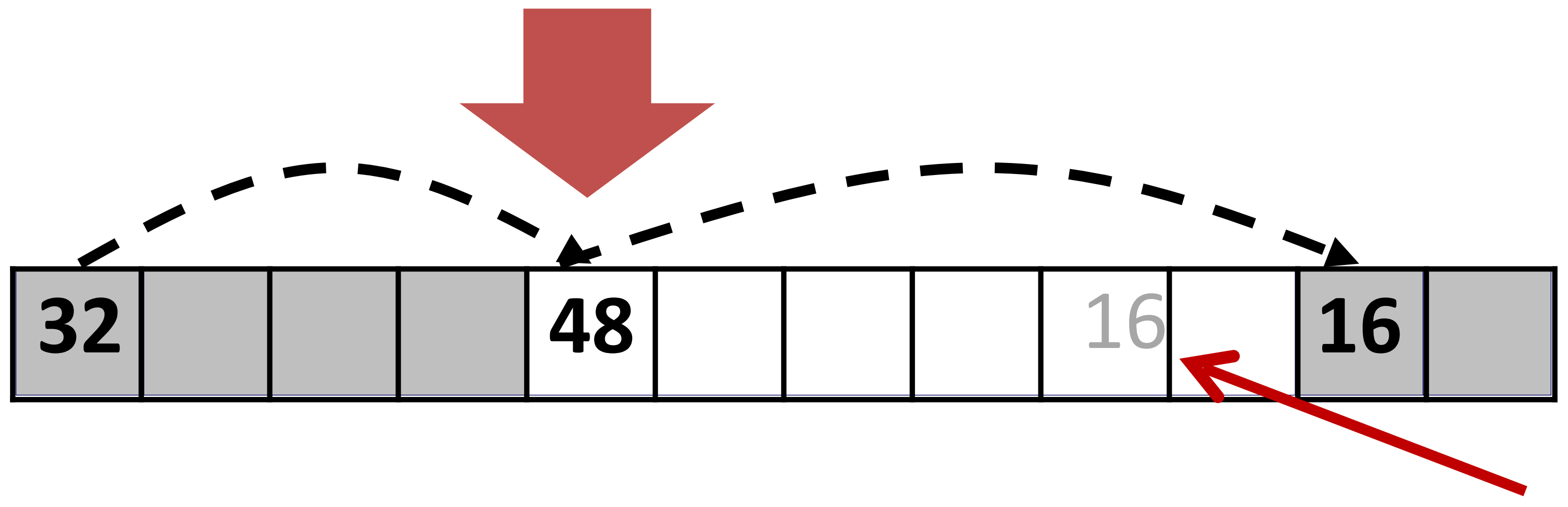
Enough space, not one block.

Coalescing free blocks



`free(p)`

Coalesce with following *free* block.



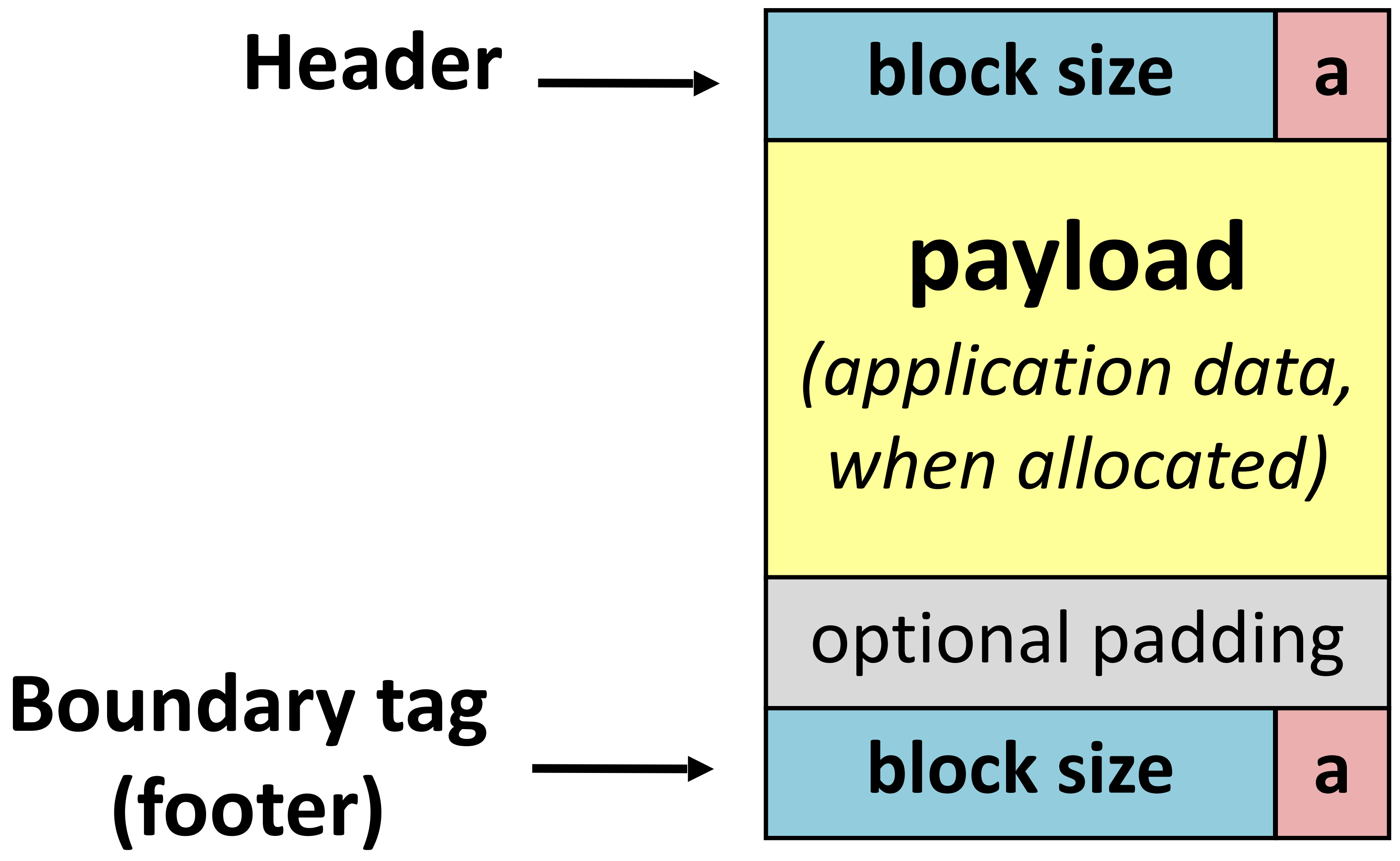
logically gone

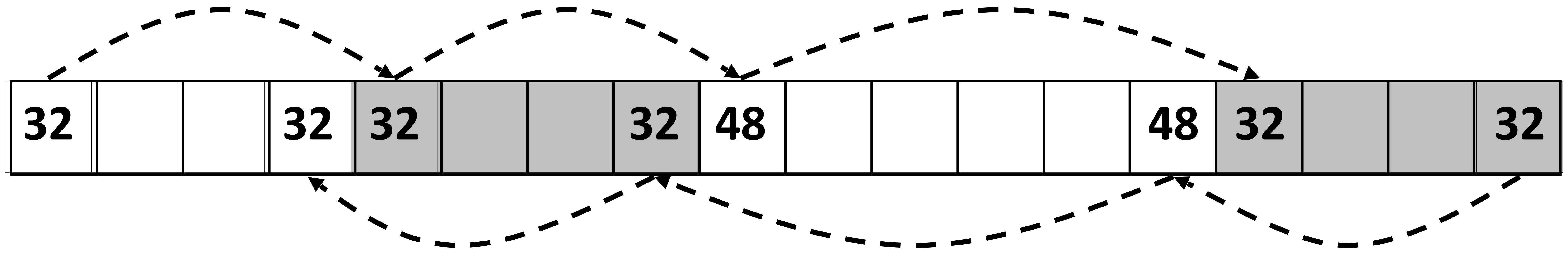
Coalesce with **preceding** *free* block?

Bidirectional coalescing: boundary tags

[Knuth73]

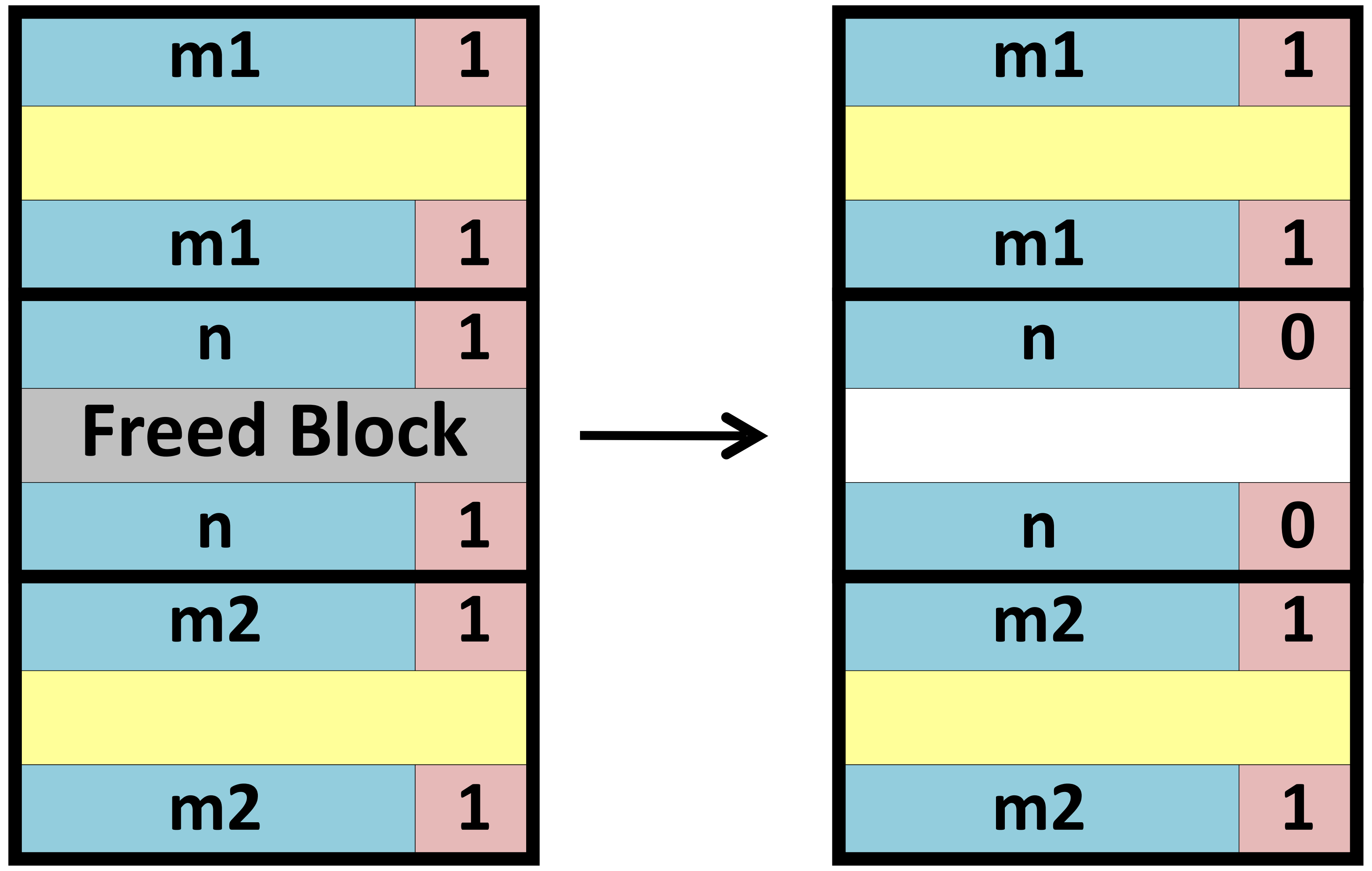
Conceptually: more like a doubly-linked list

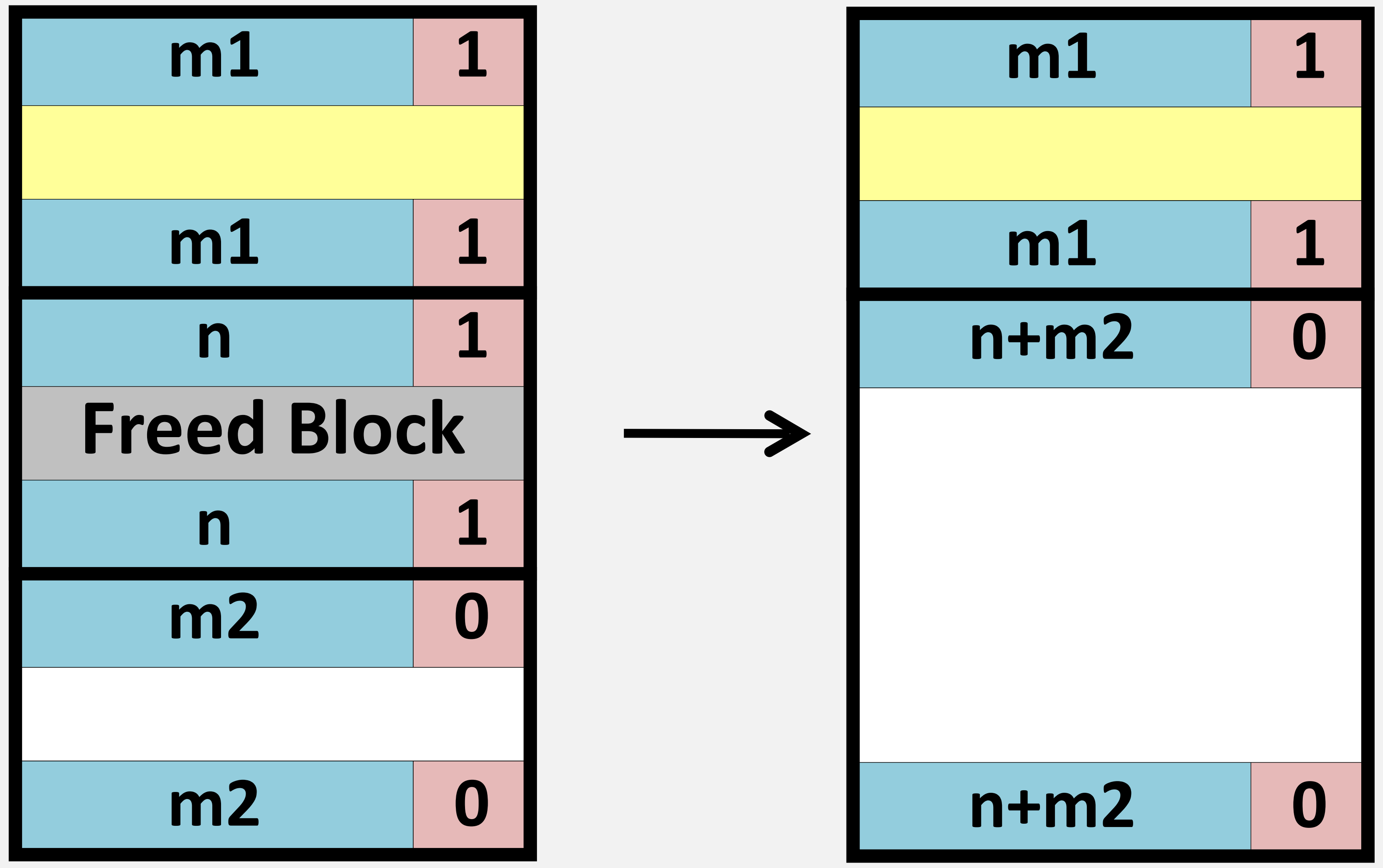




Constant-time O(1) coalescing: 4 cases

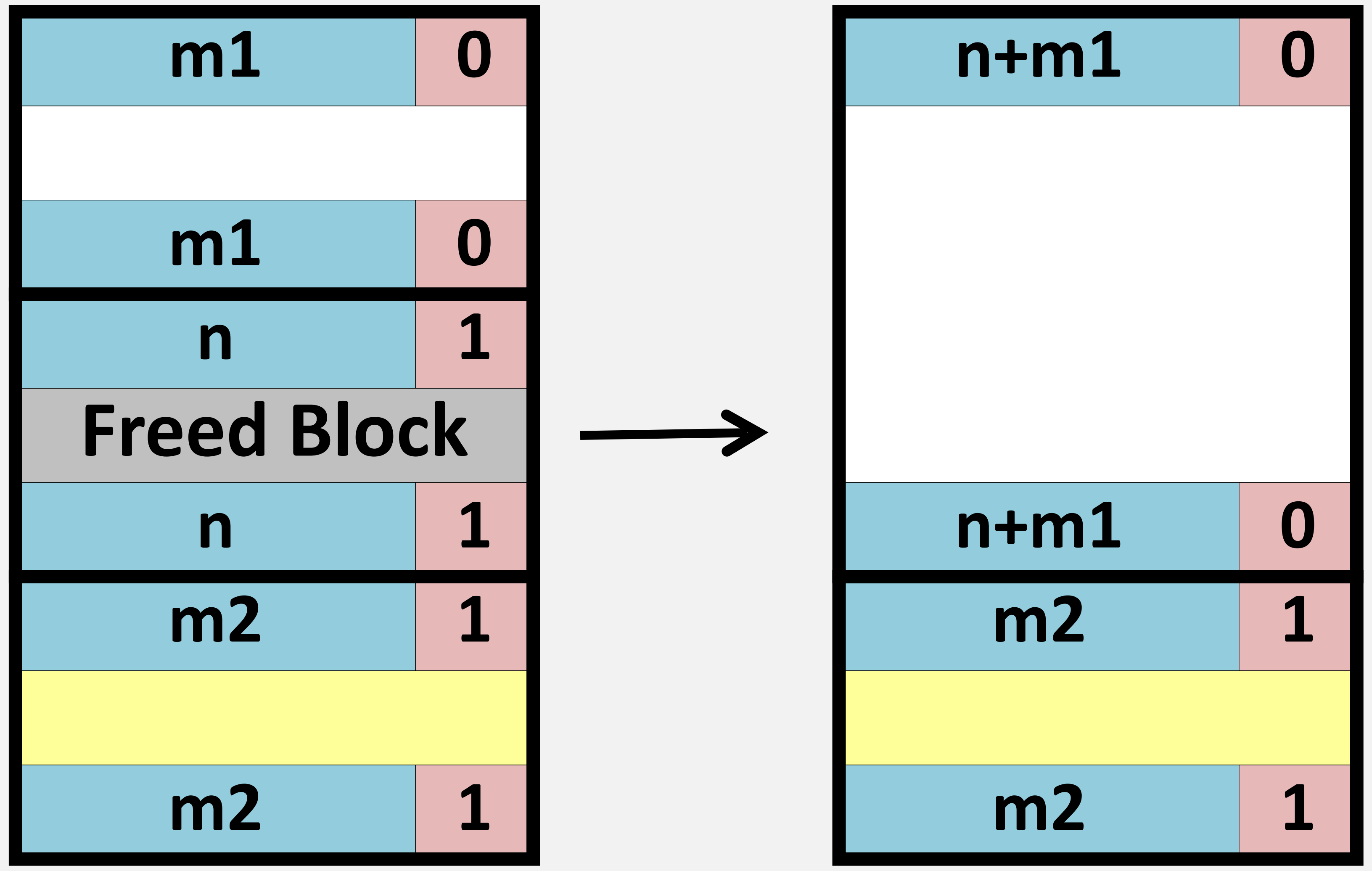
before: alloced
after: alloced

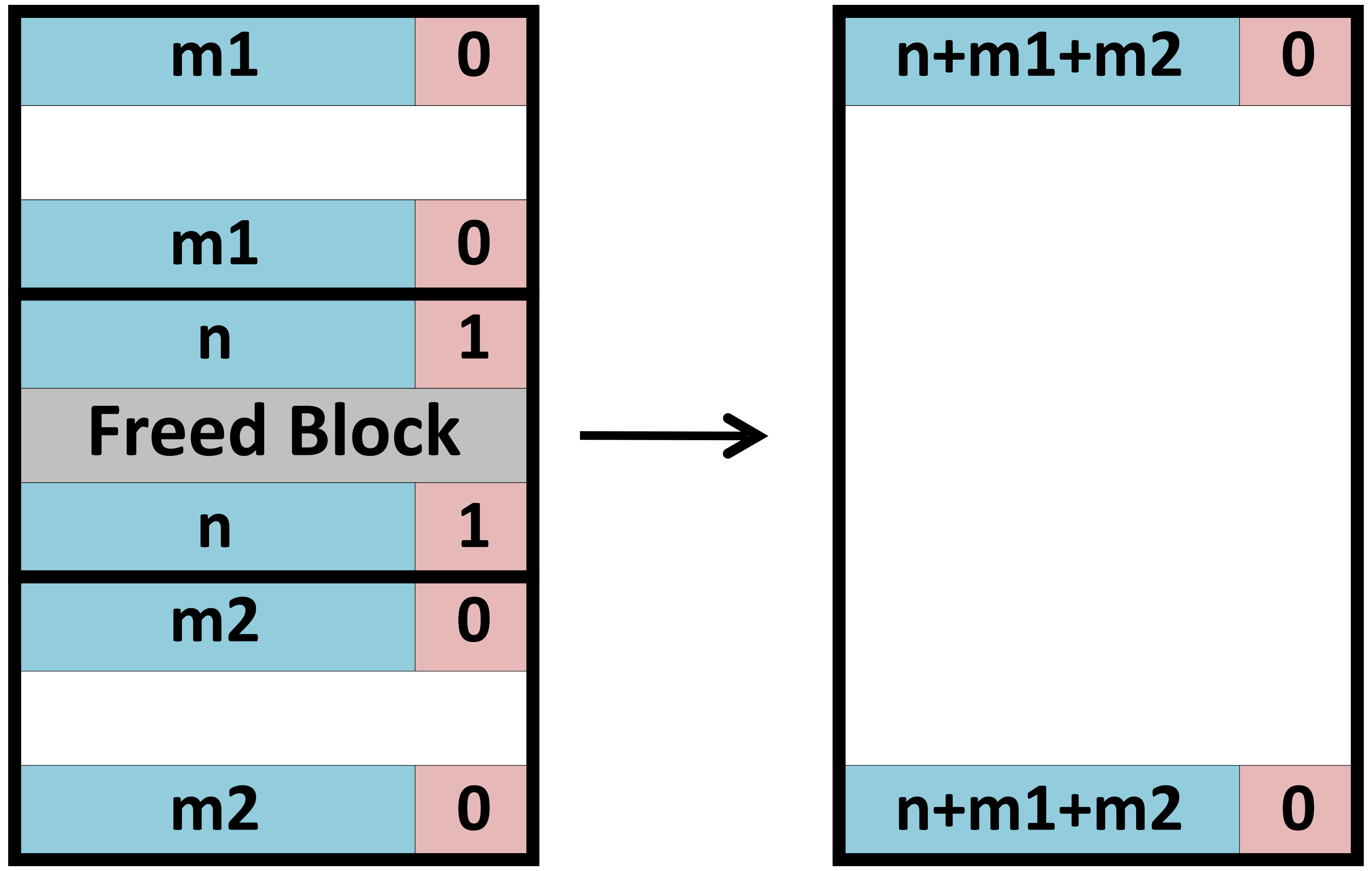




before: alloced
after: free

before: free
after: alloced



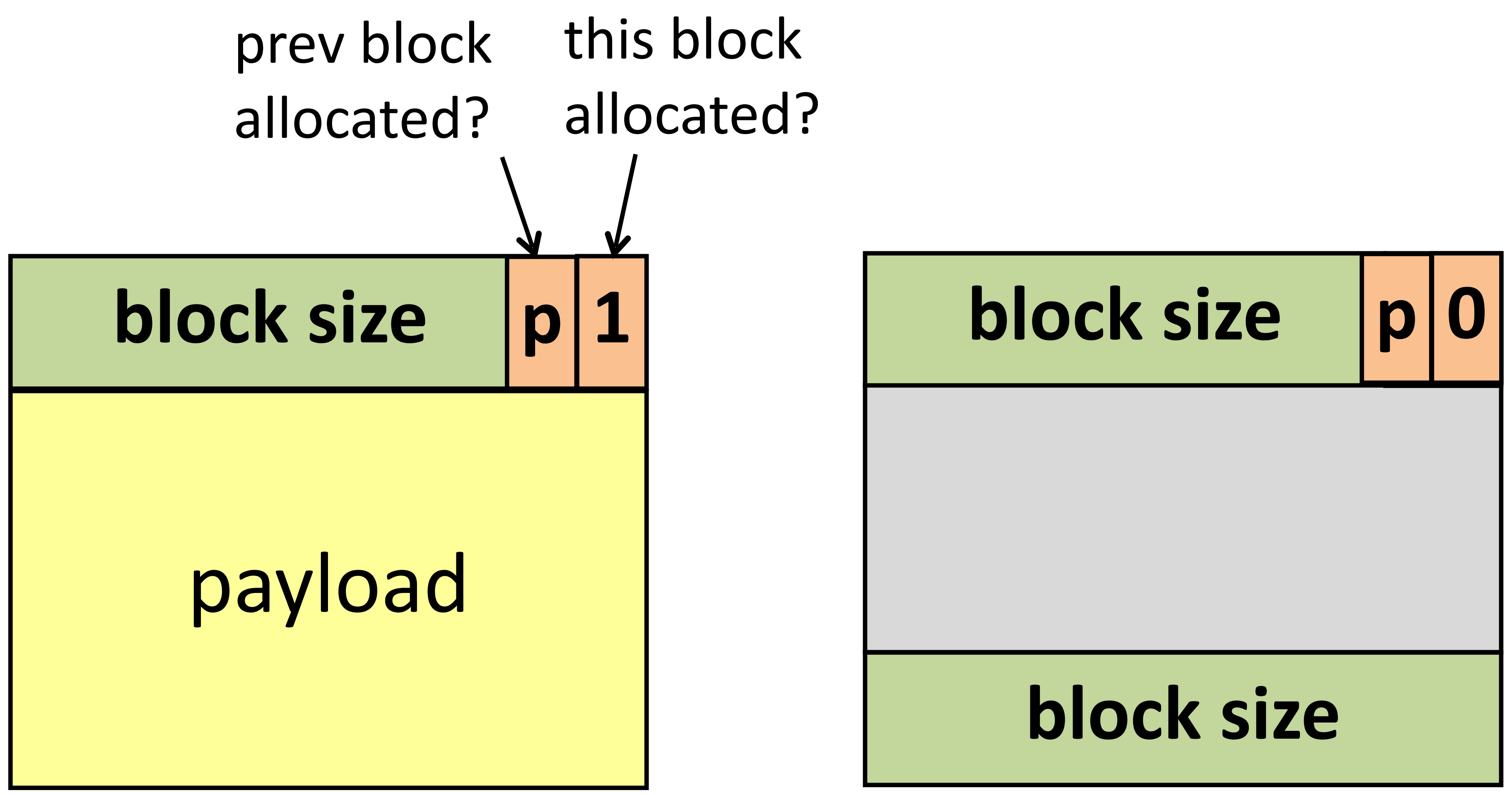


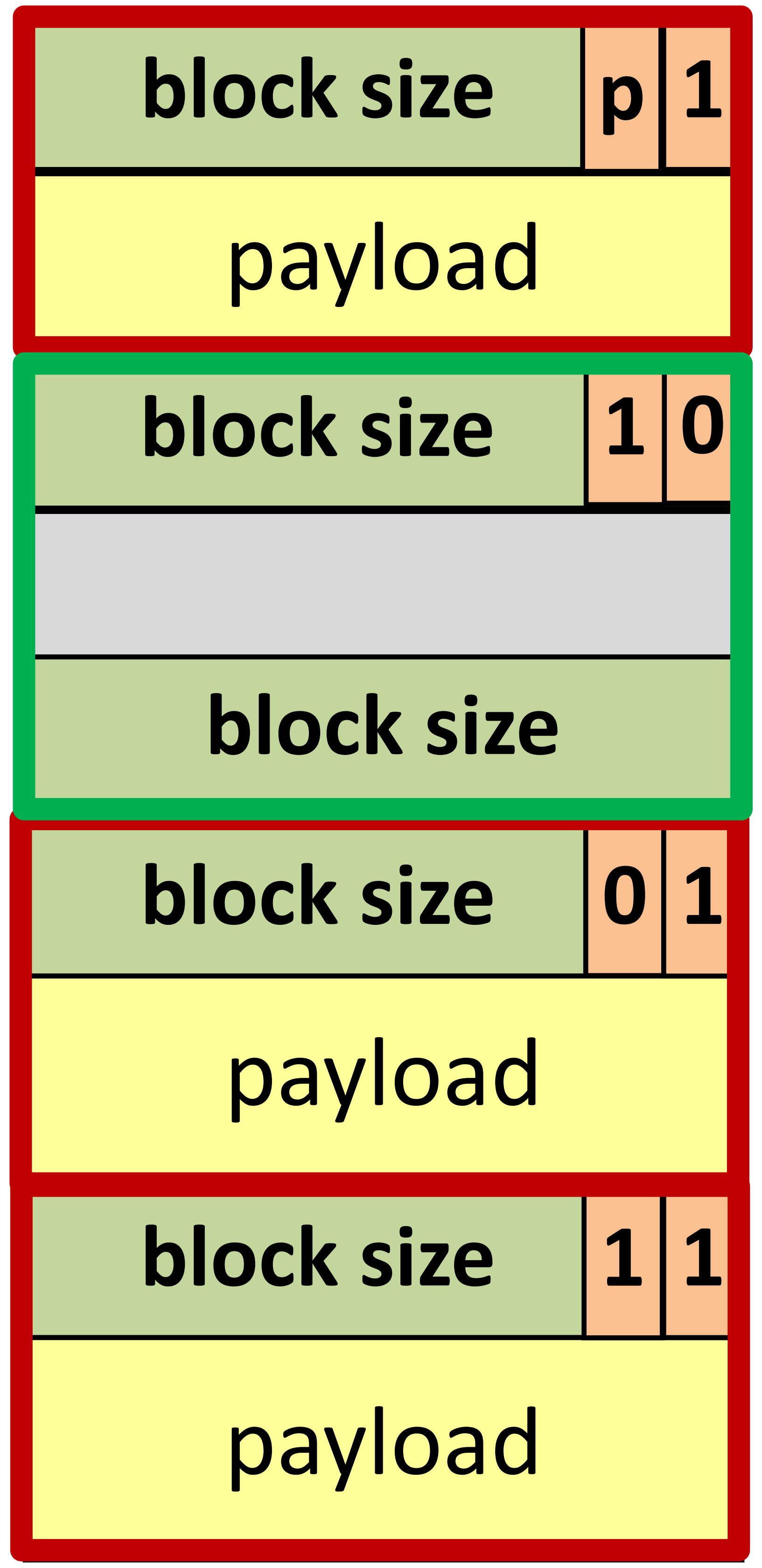
before: free
after: free

Improved block format
for implicit free lists

Allocated block:

Free block:

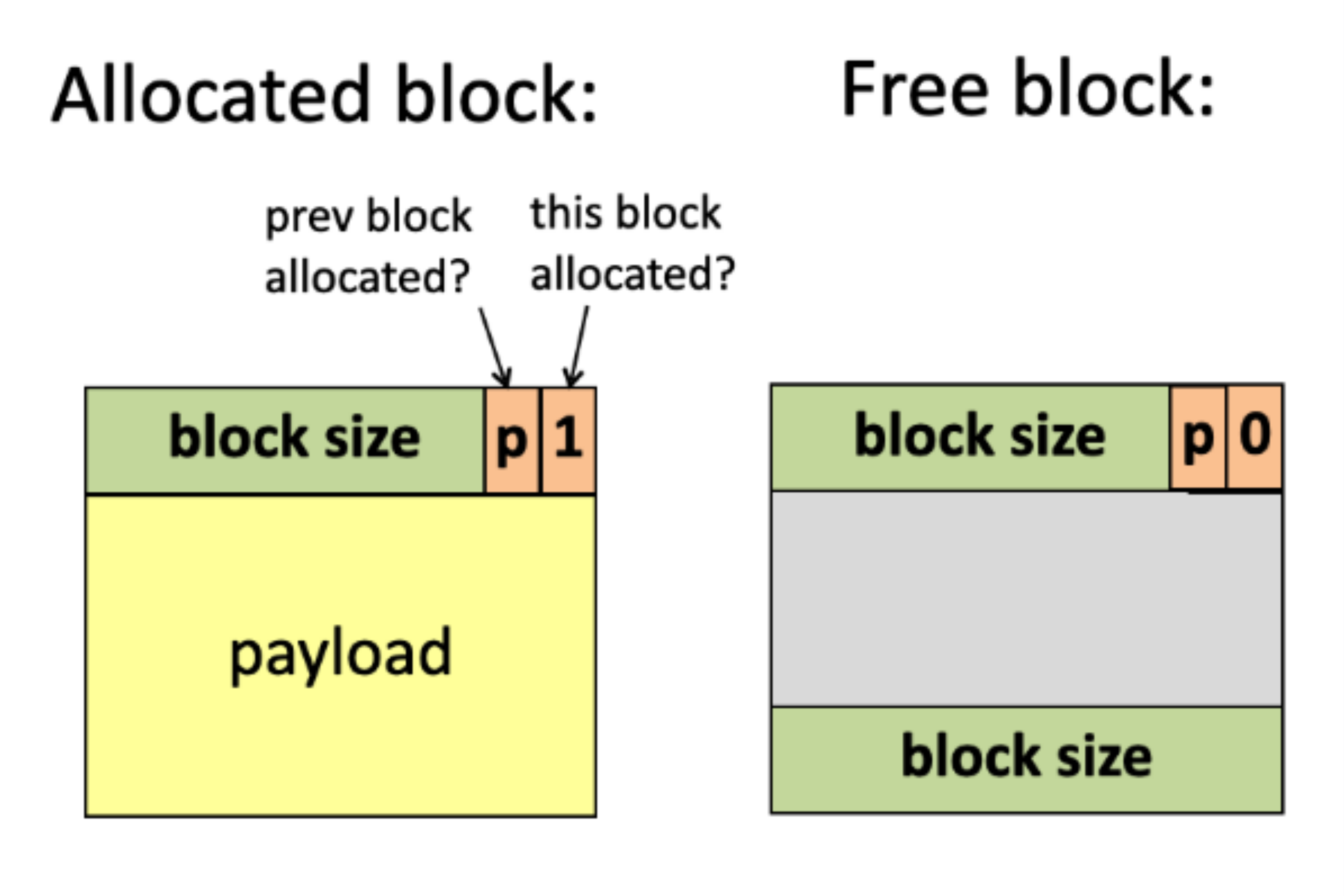




Update headers of 2 blocks on each malloc/free.

Minimum block size for implicit free list?

What is the minimum block size for an implicit free block (in bytes)?



8

16

24

32

None of the above

Summary: **implicit free lists**

Implementation: simple

O(…) for allocate and free?

Allocate: O(blocks in heap)

Free: O(1)

Memory utilization: depends on placement policy

Not widely used in practice

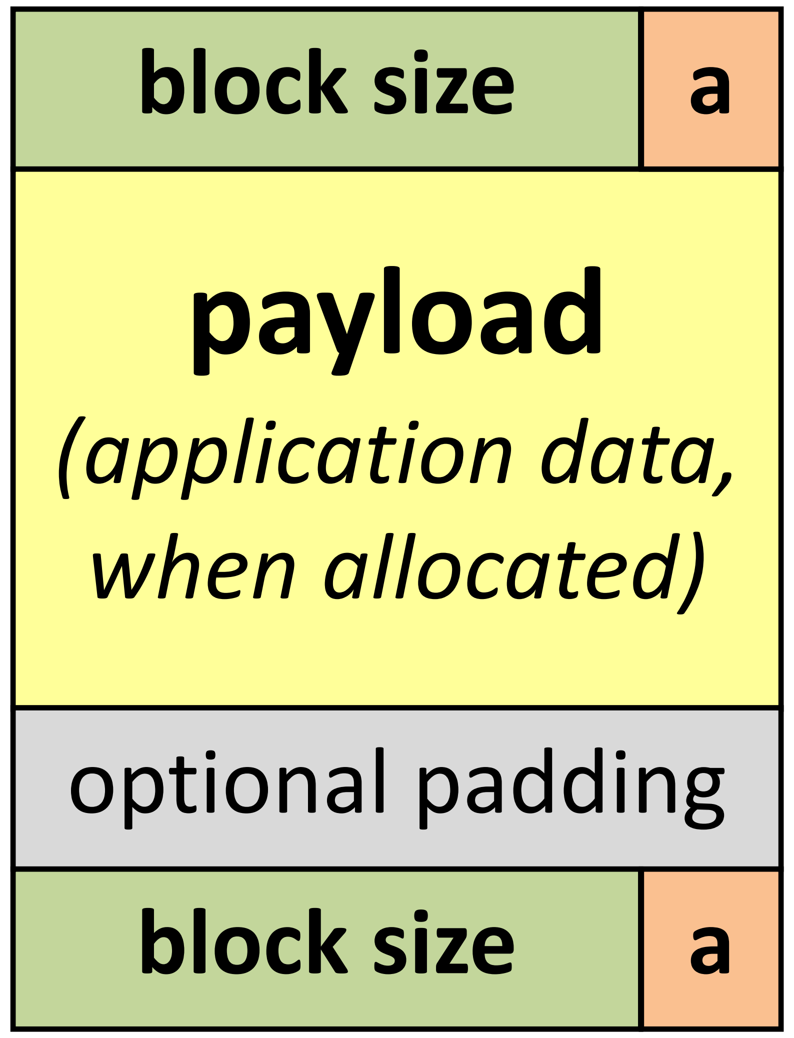
some special purpose applications

Splitting, boundary tags, coalescing are **general** to *all* allocators.

Explicit free list: block format

Explicit list of ***free*** blocks rather than implicit list of ***all*** blocks.

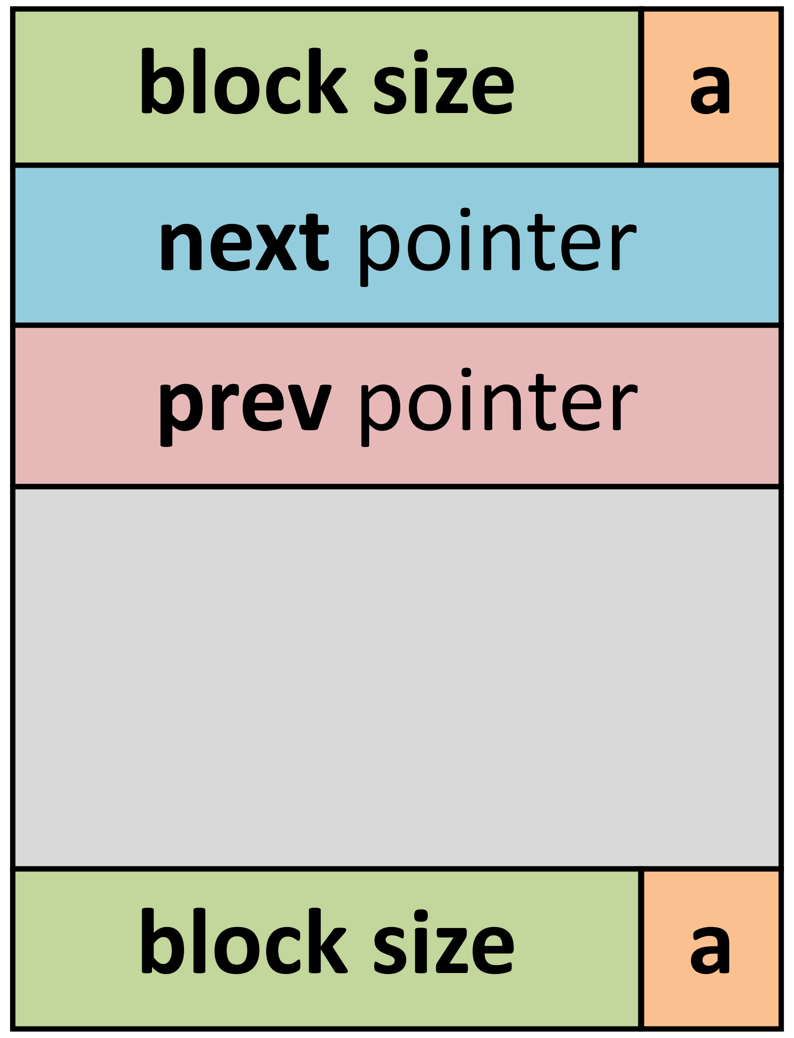
Allocated block:



Possible to omit footer

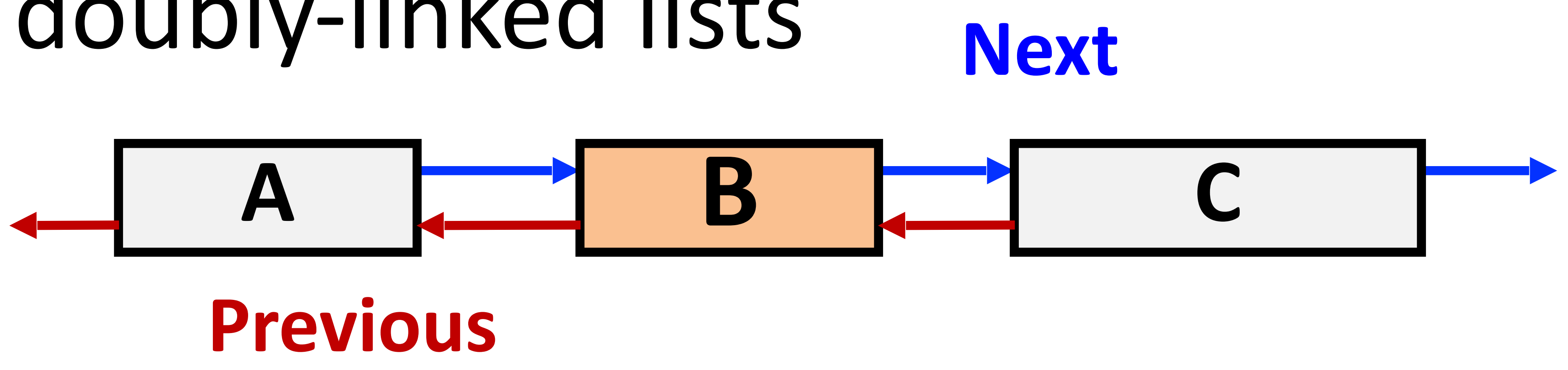
(same as implicit free list)

Free block:

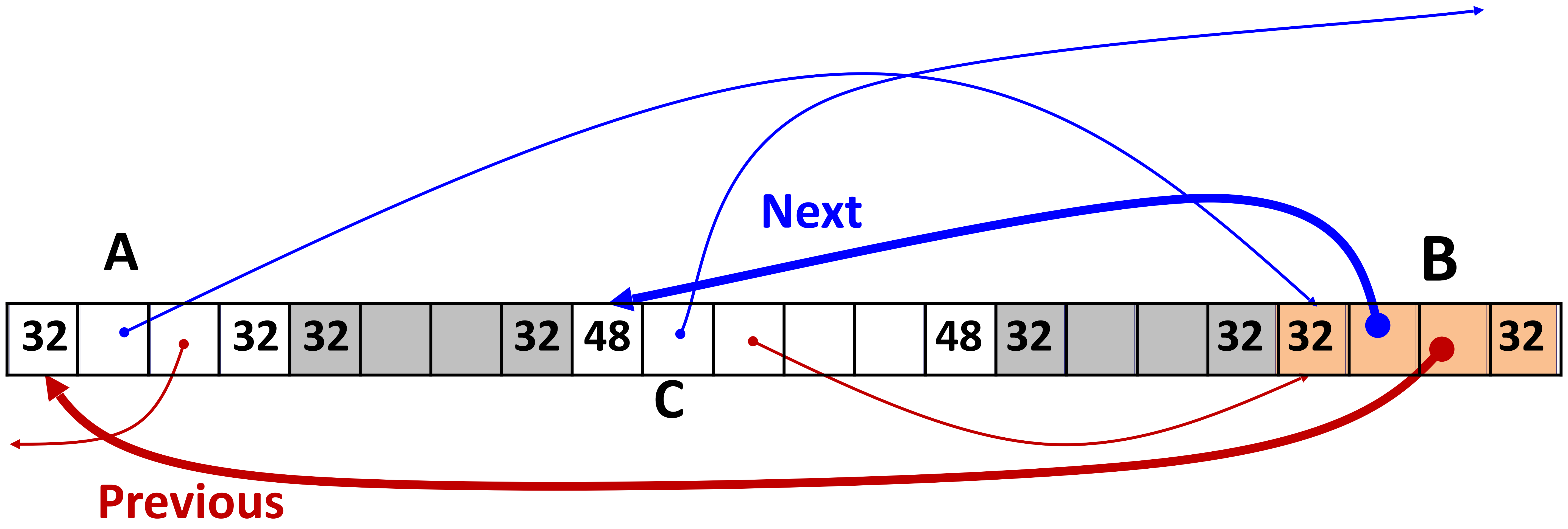


Explicit free list: **list vs. memory order**

Abstractly: doubly-linked lists

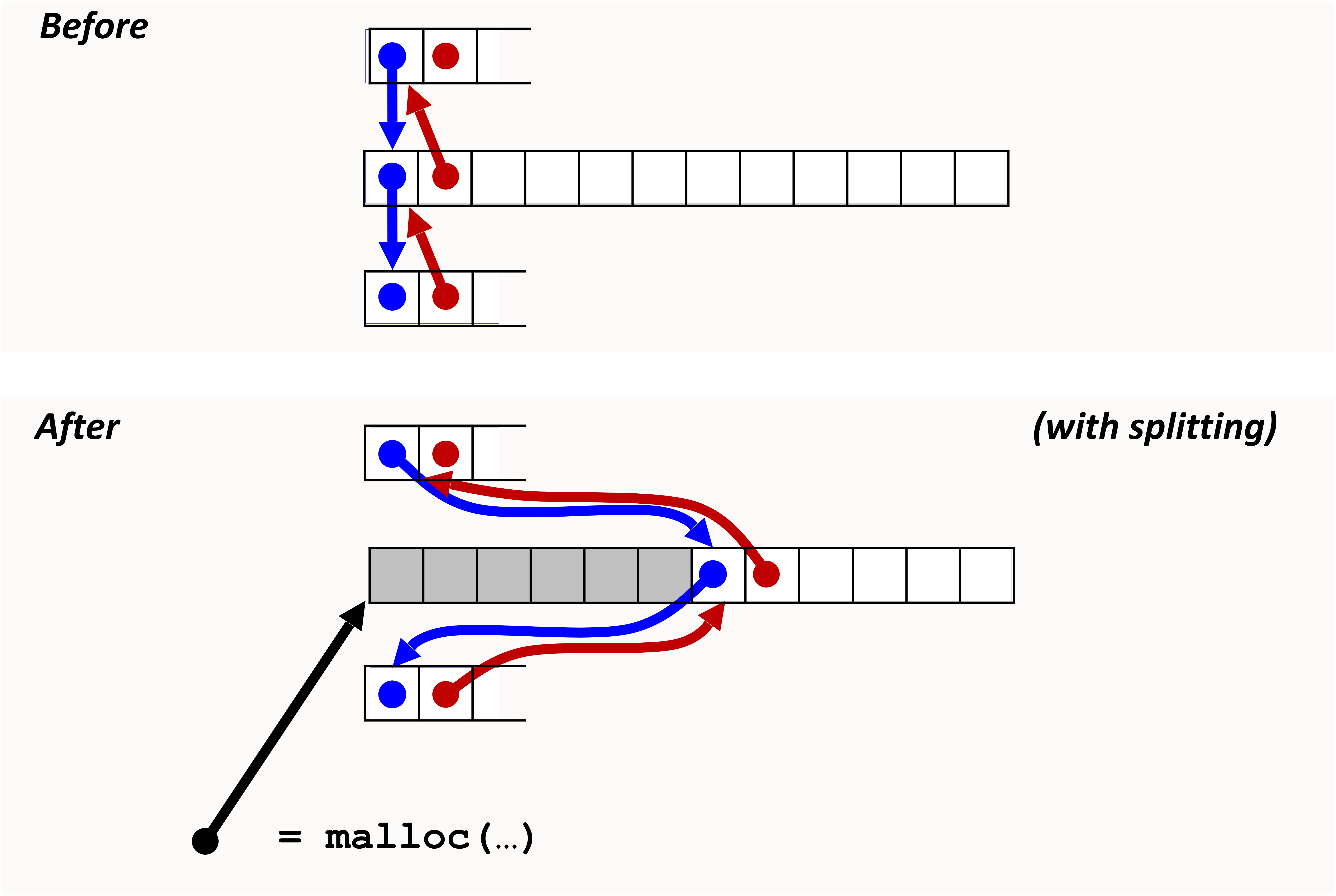


Concretely: free list blocks in any memory order



List Order ≠ Memory Order

Explicit free list: **allocating a free block**



Explicit free list: **freeing a block**

Insertion policy**:** Where in the free list do you add a freed block?

LIFO (last-in-first-out) policy

Pro: simple and constant time

Con: studies suggest fragmentation is worse than address ordered

Address-ordered policy

Con: linear-time search to insert freed blocks

Pro: studies suggest fragmentation is lower than LIFO

LIFO Example: 4 cases of freed block neighbor status.

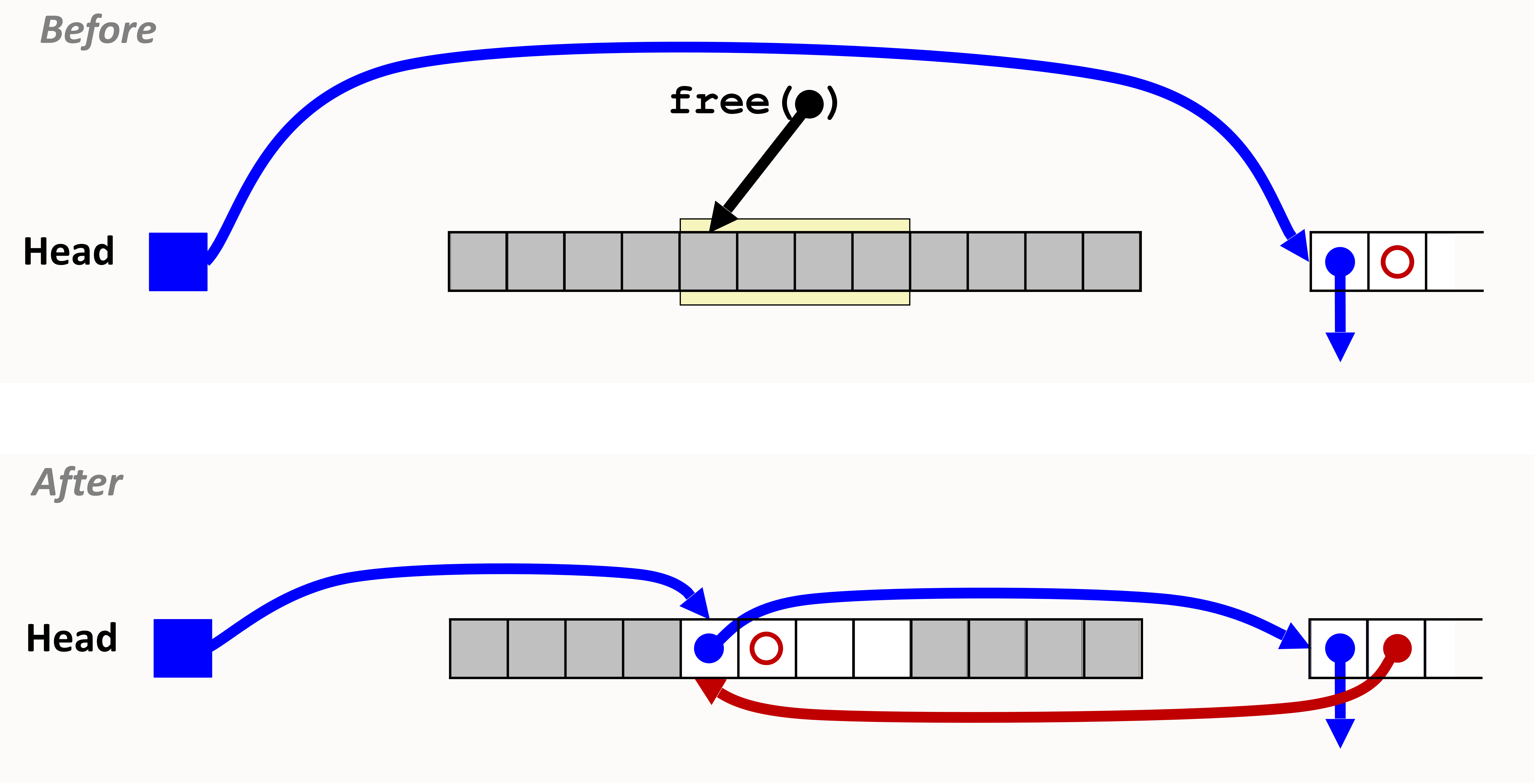
Freeing with LIFO policy: **between allocated blocks**

ex

Insert the freed block at head of free list.

blue: next
red: prev

open: NULL



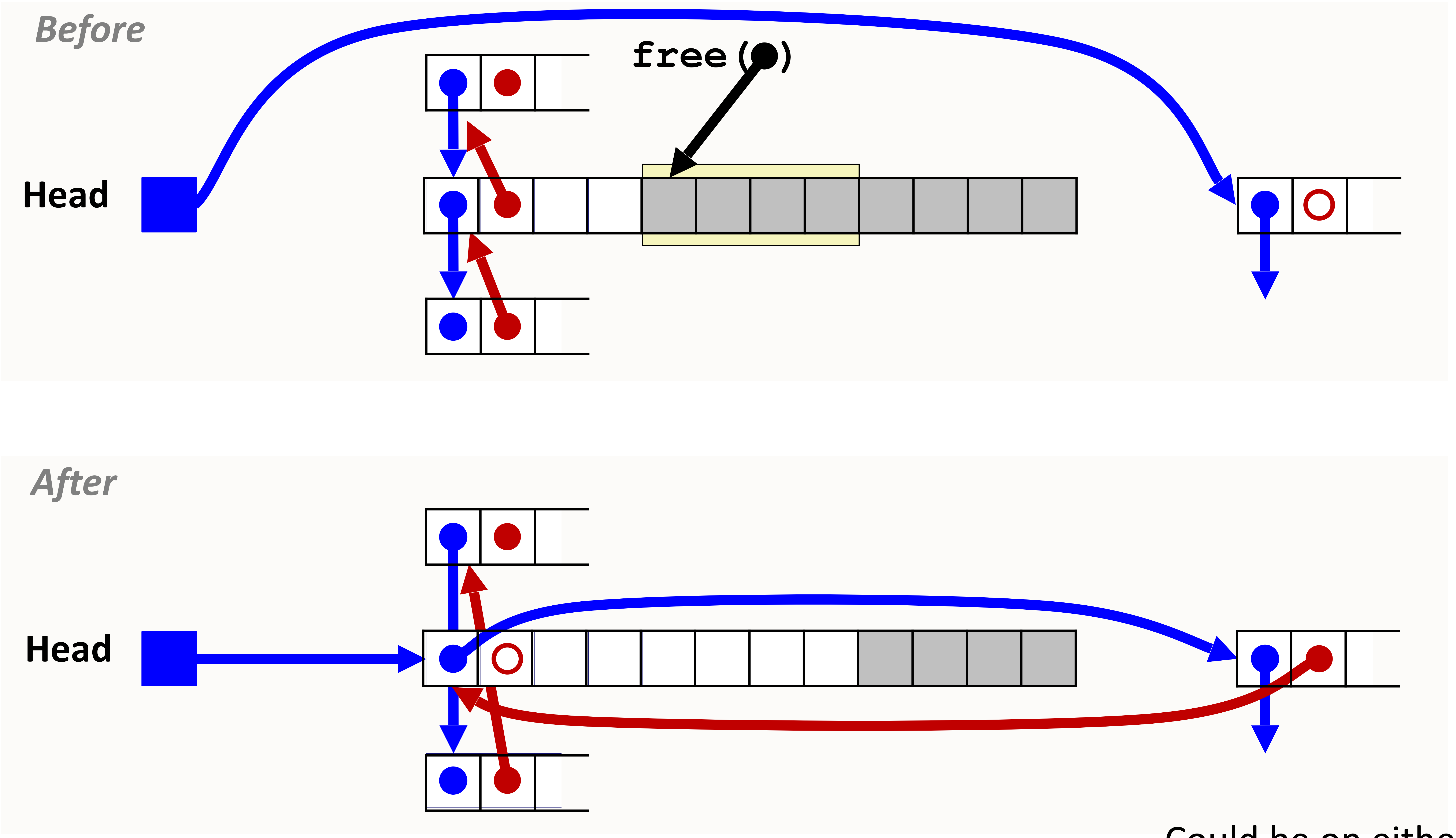
Freeing with LIFO policy:
between free and allocated

ex

Splice out predecessor block, coalesce both memory blocks, and insert the new block at the head of the free list.

blue: next
red: prev

open: NULL



Could be on either or both sides...

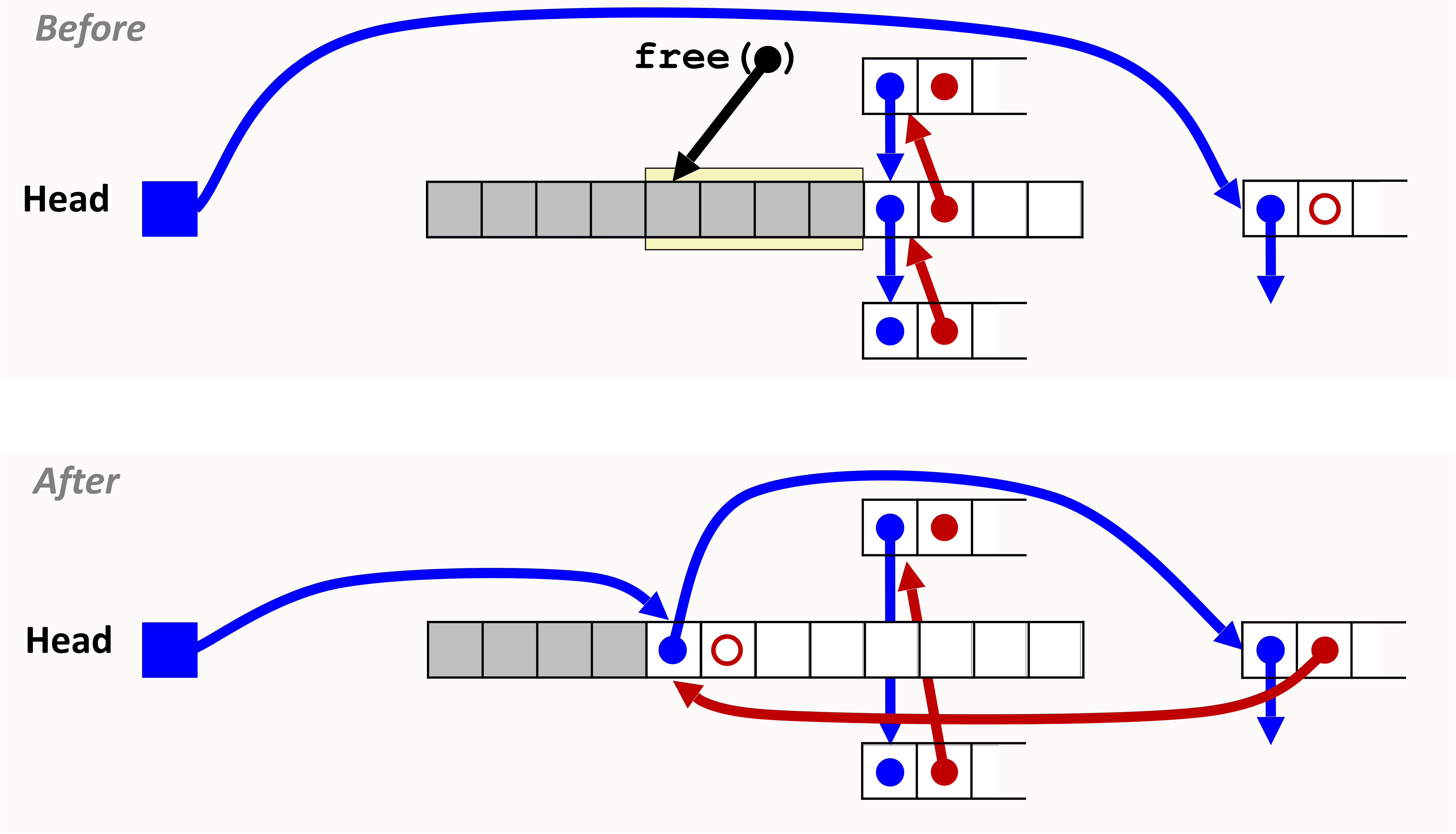
Freeing with LIFO policy:
between allocated and free

ex

Splice out successor block, coalesce both memory blocks and insert the new block at the head of the free list.

blue: next
red: prev

open: NULL



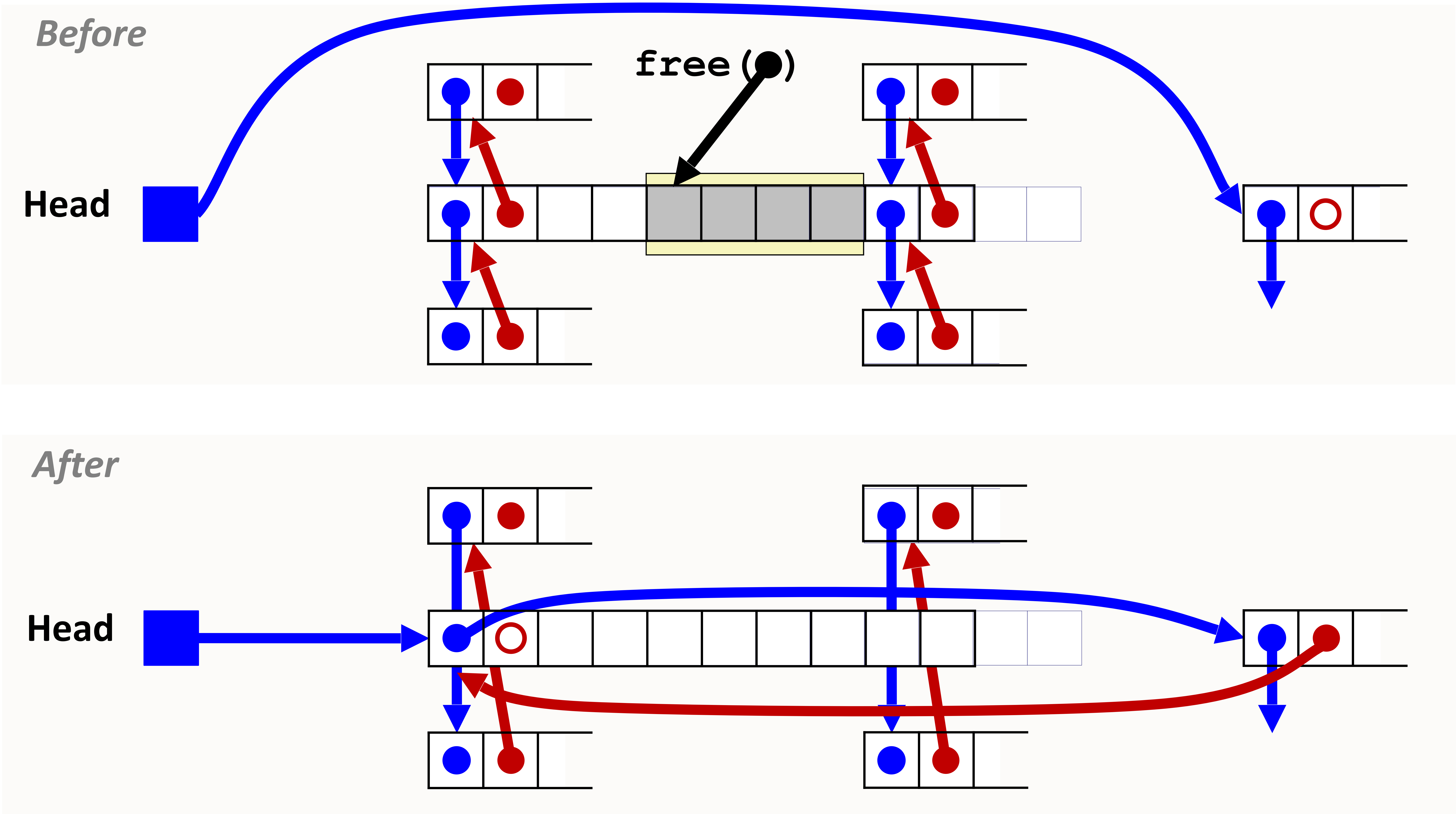
Freeing with LIFO policy: **between free blocks**

ex

Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the head of the list.

blue: next
red: prev

open: `NULL`



Summary: **Explicit Free Lists**

Implementation: fairly simple

Allocate:	O(*free* blocks)	vs. O(*all* blocks)
Free:	O(1)	vs. O(1)

Memory utilization:

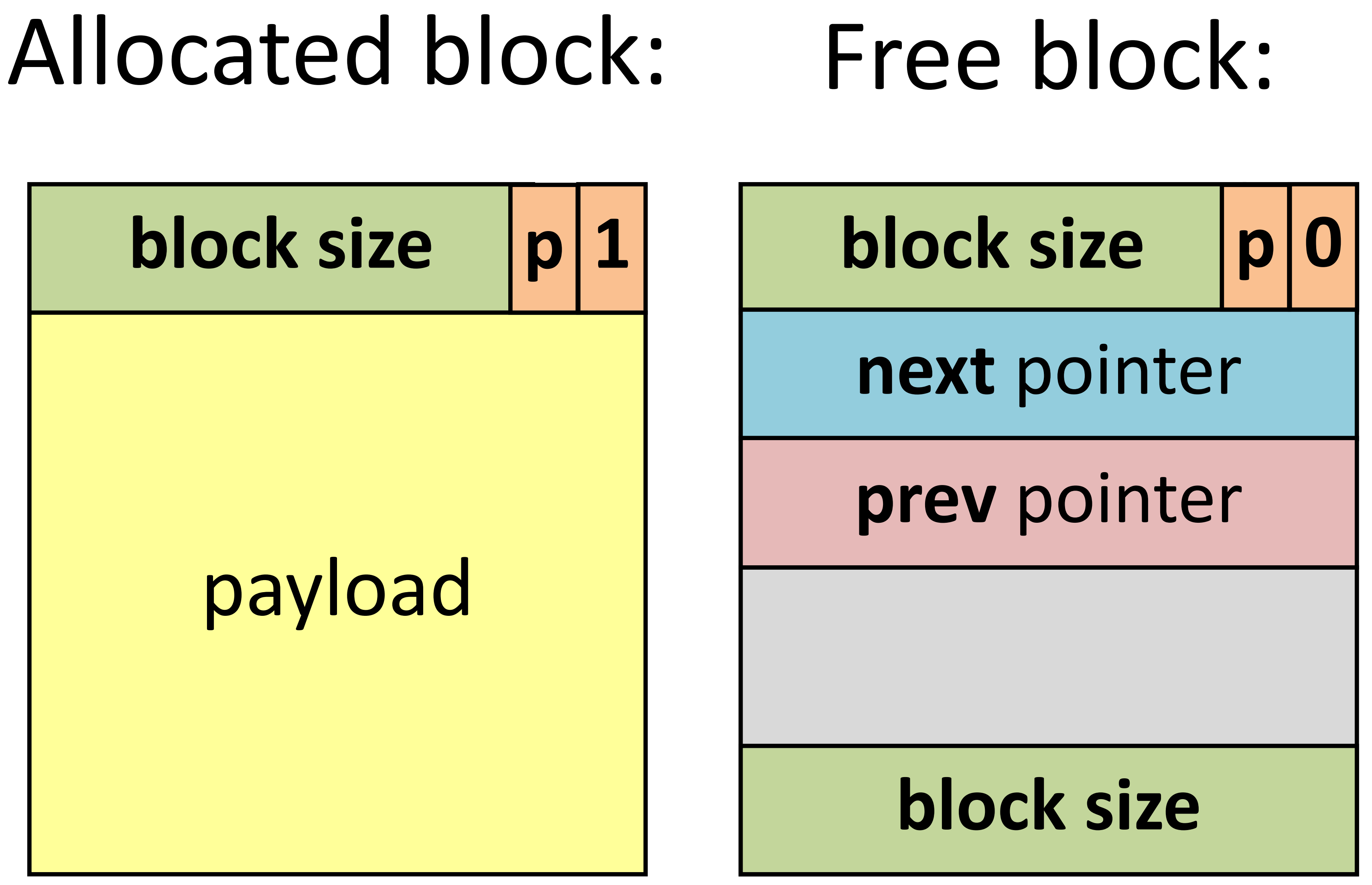
depends on placement policy

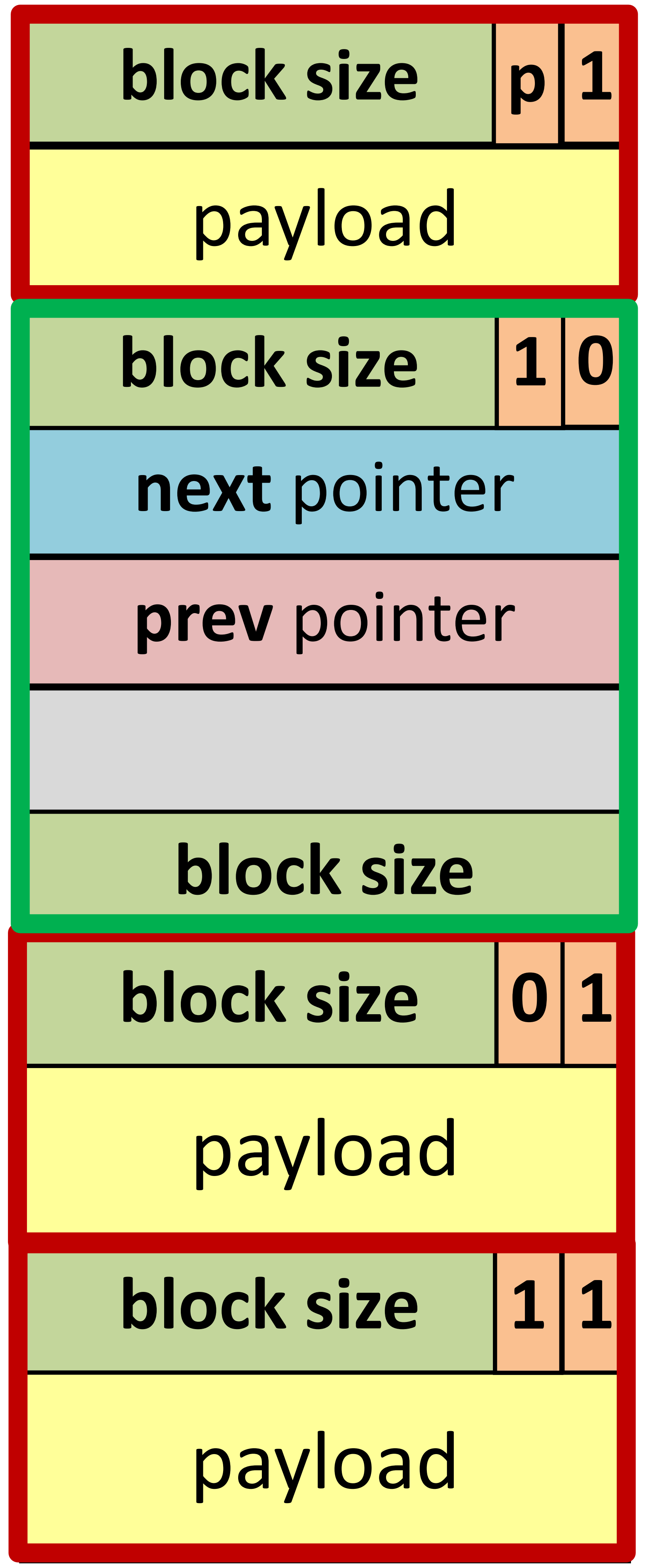
larger minimum block size (next/prev) vs. implicit list

Used widely in practice, often with more optimizations.

Splitting, boundary tags, coalescing are general to *all* allocators.

Improved block format for explicit free lists

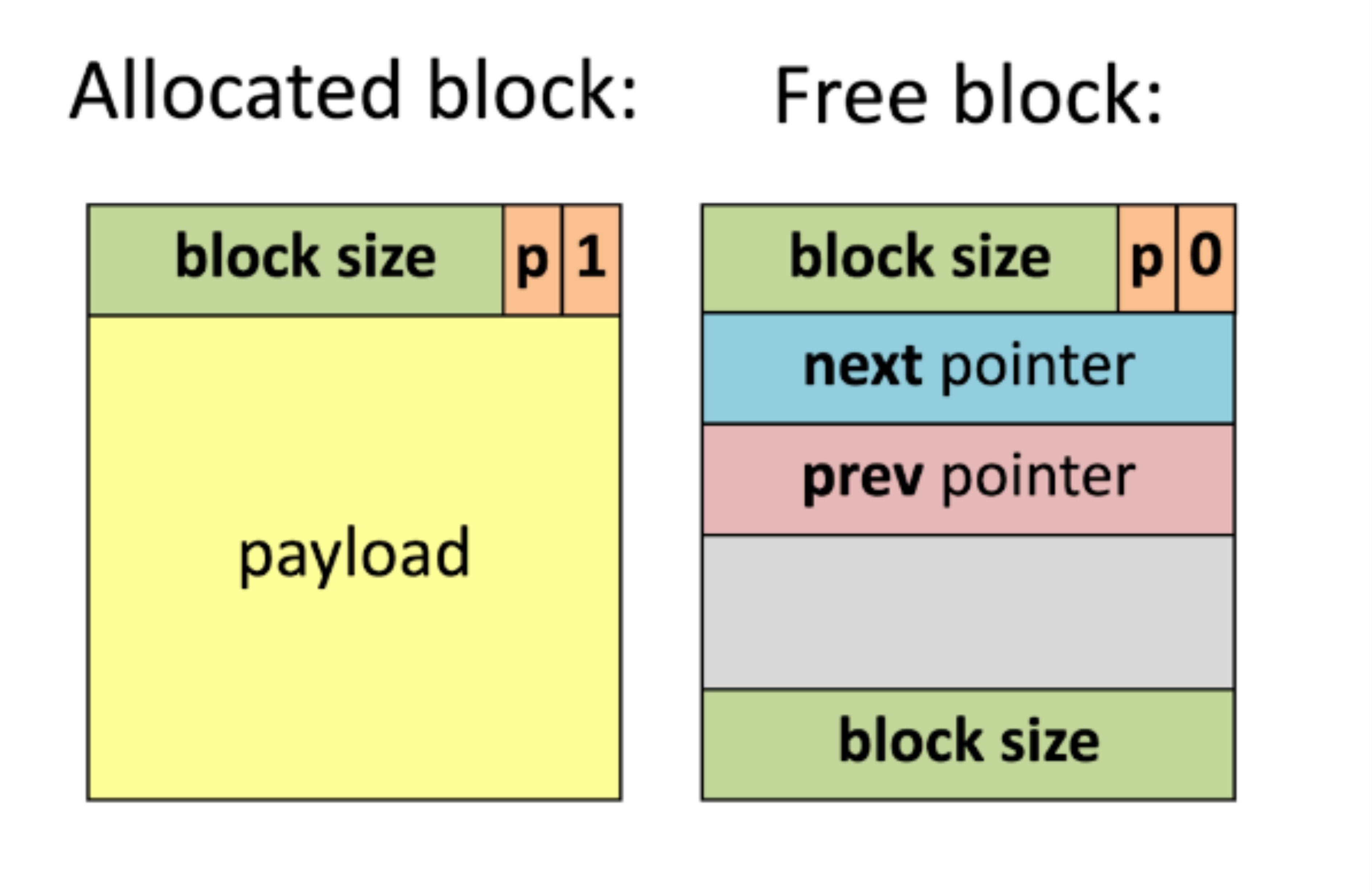




Update headers of 2 blocks on each malloc/free.

Minimum block size for explicit free list?

What is the minimum block size for an explicit free block (in bytes)?



8

16

24

32

None of the above

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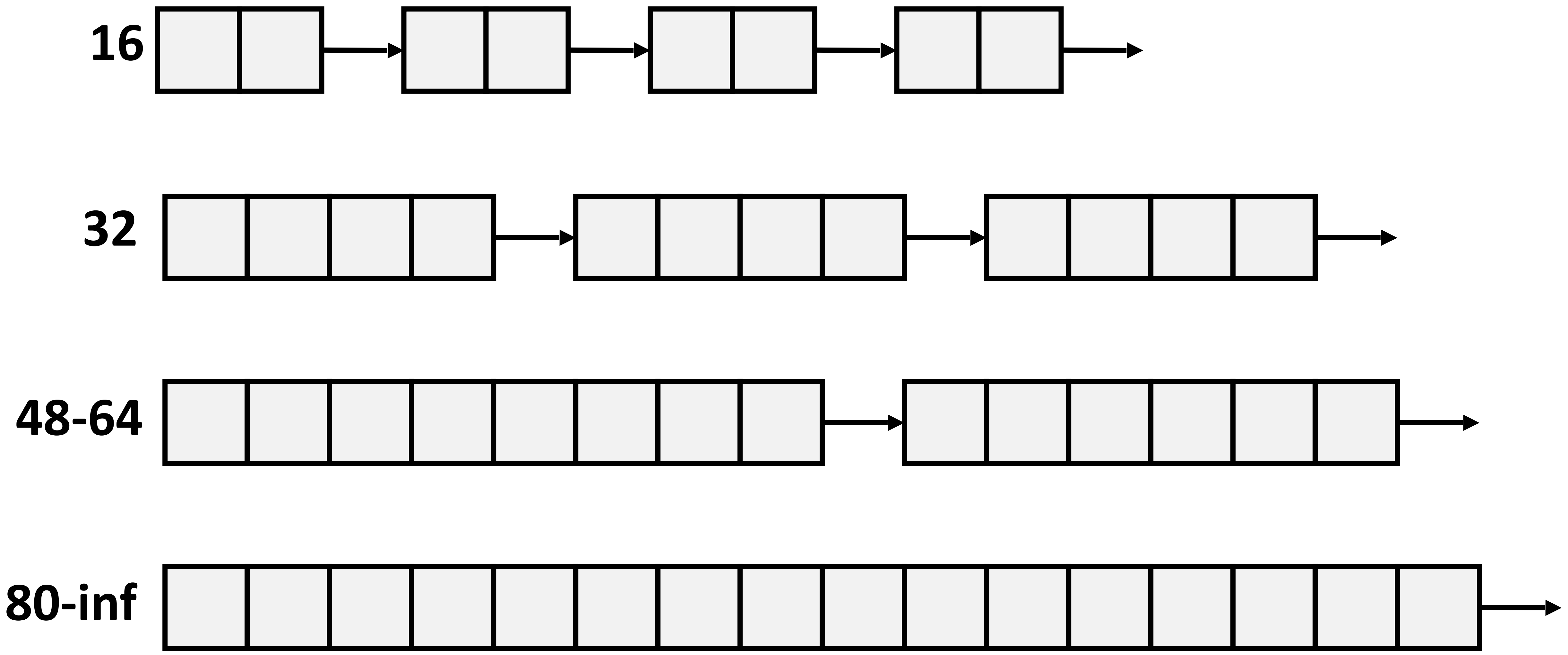
Seglist allocators

Each ***size bracket*** has its own free list



Faster best-fit allocation...

Summary: **allocator policies**

All policies offer **trade-offs** in fragmentation and throughput.

Placement policy:

First-fit, next-fit, best-fit, etc.

Seglists approximate best-fit in low time

Splitting policy:

Always? Sometimes? Size bound?

Coalescing policy:

Immediate vs. deferred