CS 4400
Computer Systems

LECTURE 19

Dynamic memory allocation

Heap

- The heap begins immediately after the `.bss` and grows upward
  - the kernel maintains variable `brk` as a pointer to the top

`sbrk` Function

```
void* sbrk(int incr);
```

- The `sbrk` function grows or shrinks the heap by adding `incr` to the kernel's `brk` pointer
  - If successful, the old value of `brk` is returned
  - Else, -1 is returned and `errno` is set to `ENOMEM`.
- To get the current value of `brk`, call with `incr` = 0

`mmap` Function (newer, more powerful `sbrk`)

```
void* mmap(void *addr, size_t size,
           int prot, int flags,
           int fd, off_t offset);
```

- Allocates a new memory region
- Suggest a virtual address in `addr`
- Control other details via `prot` and `flags`
- Use `fd` and `offset` to connect the region to a file

Dynamic Memory Allocator

- The `sbrk` and `mmap` functions are too low-level for most purposes

- A ***dynamic memory allocator*** maintains the heap as a collection of various sized blocks

Dynamic Memory Allocator

- Each block is a contiguous piece of virtual memory
- Each block is designated as either ***allocated*** or ***free***
  - *allocated*: explicitly reserved for use by the application and remains so until explicitly freed (either by app or allocator)
  - *free*: available to be allocated and remains so until explicitly allocated by the application

Two Types of Allocators

- ***Explicit allocators***: require the application to explicitly free any allocated blocks
  - `malloc` in C, new in C++
- ***Implicit allocators***: allocator detects when an allocated block is no longer being used by the application and then free the block
  - AKA: garbage collectors
  - Java, JavaScript, Python, Perl, C#, Racket, ...
- Both require the application to explicitly allocate blocks

`malloc` Function

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

- Returns a pointer to a block of memory of at least `size` bytes, suitably aligned for any kind of data object.
  - typically, `size_t` is `unsigned int` and 8-byte alignment
- If `malloc` encounters a problem, it returns NULL and sets `errno` appropriately
  - e.g., requested block is larger than the available virtual memory

`realloc` Function

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

- To swap a previously allocated block with a block that is a different size, an application can use `realloc`.

`free` Function

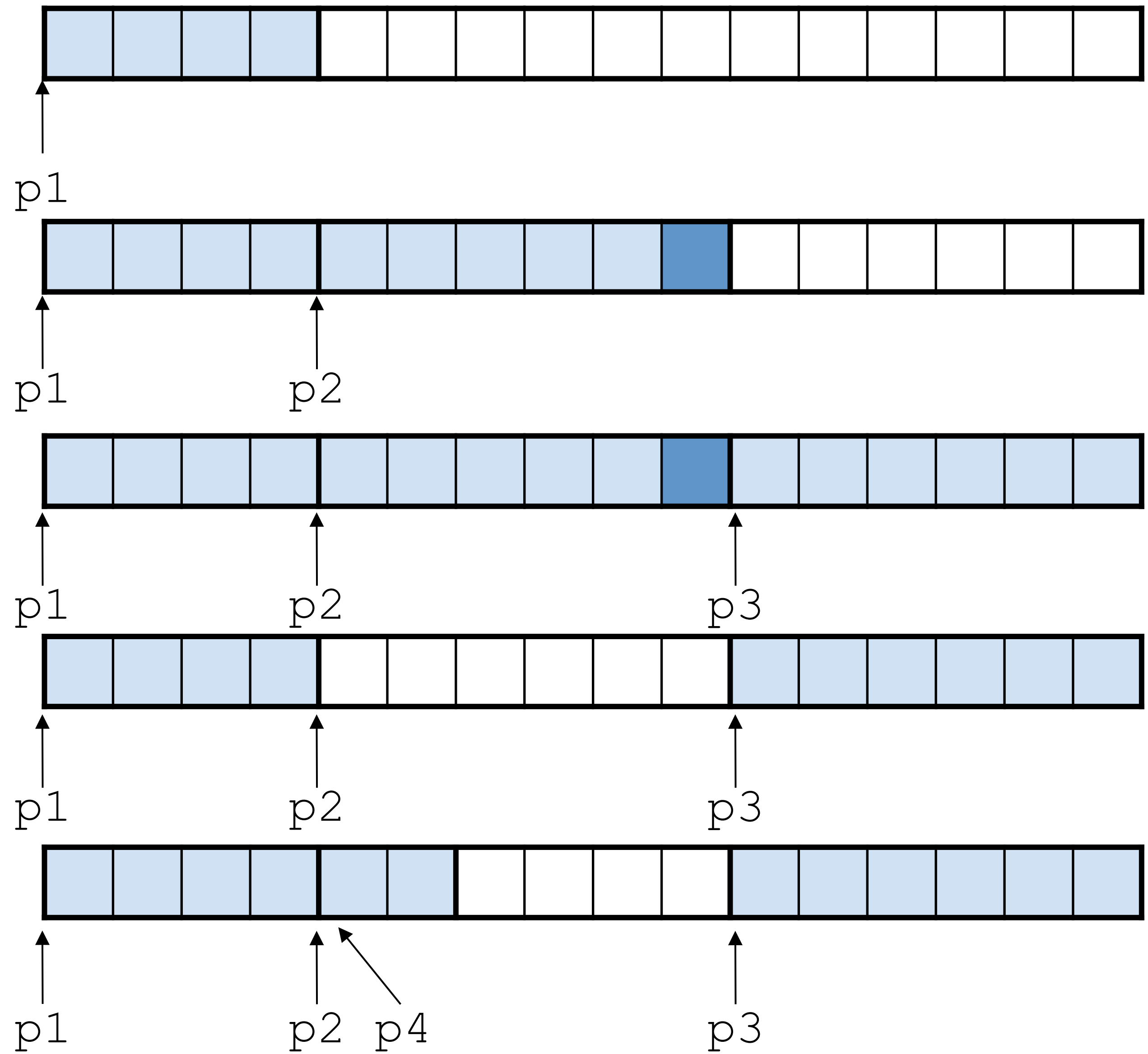
```
void free(void* ptr);
```

- Frees the allocated block indicated by `ptr`
- If `ptr` does not point to the beginning of an allocated block (obtained from `malloc`), the behavior of `free` is undefined
- Because `free` returns nothing, there is no indication to the application if something is wrong

Example: `malloc`

16-word heap (initially one free block), each box is a 4-byte word, double-word alignment

```
p1 = malloc(4*sizeof(int))

p2 = malloc(5*sizeof(int))

p3 = malloc(6*sizeof(int))

free(p2)

p4 = malloc(2*sizeof(int))
```



Example: Dynamic Mem Alloc

```
#define MAXN 15213

int main() {
  int i, n;
  int array[MAXN];

  scanf("%d", &n);
  if(n > MAXN) {
    printf("ERROR: too big\n");
     exit(0);
   }
  for(i = 0; i < n; i++)
    scanf("%d", &array[i]);

  exit(0);
}
```

```
int main() {
  int i, n, *array;

  scanf("%d", &n);
  array = malloc(n*sizeof(int));
  assert (array);
  for(i = 0; i < n; i++)
    scanf("%d", &array[i]);

  free(array);
  exit(0);
}
```

Explicit Allocator Requirements

- Must respond immediately to allocate requests
  - cannot reorder or buffer requests to improve performance
- Must use the heap
- Any allocated block must be aligned (typically 8-byte)

Explicit Allocator Requirements

- Cannot make any assumptions about the ordering of allocate and free requests.
  - cannot assume all allocate requests have matching free requests
- Cannot modify or move blocks once they are allocated

Explicit Allocator Goals

- Maximize throughput, i.e., the number of requests the allocator completes per unit of time.
  - 500 allocate and 500 free requests in 1 sec = 1000 ops per sec
  - minimize the average time to satisfy allocate and free requests
  - reasonable: linear-time allocate (worst case), constant-time free

Explicit Allocator Goals

- Maximize memory utilization
  - virtual memory is limited
  - it is a finite resource that must be used efficiently
  - especially true if asked to allocate and free large blocks

- Finding the appropriate balance between these two goals is a challenge

Fragmentation

- ***Internal fragmentation***—occurs when an allocated block is larger than the payload
  - because the allocator implementation imposes a minimum size
  - quantified as: sizes of allocated blocks – their payloads

Fragmentation

- ***External fragmentation***—occurs when there is enough free memory to satisfy an allocate request, but no single free block is large enough to handle the request.
  - depends on the pattern of previous request, as well as, the pattern of future requests (and allocator implementation)

Naïve Allocator Implementation

- Organize the heap as a large array of bytes and a pointer `p` that initially points to the first byte of the array.

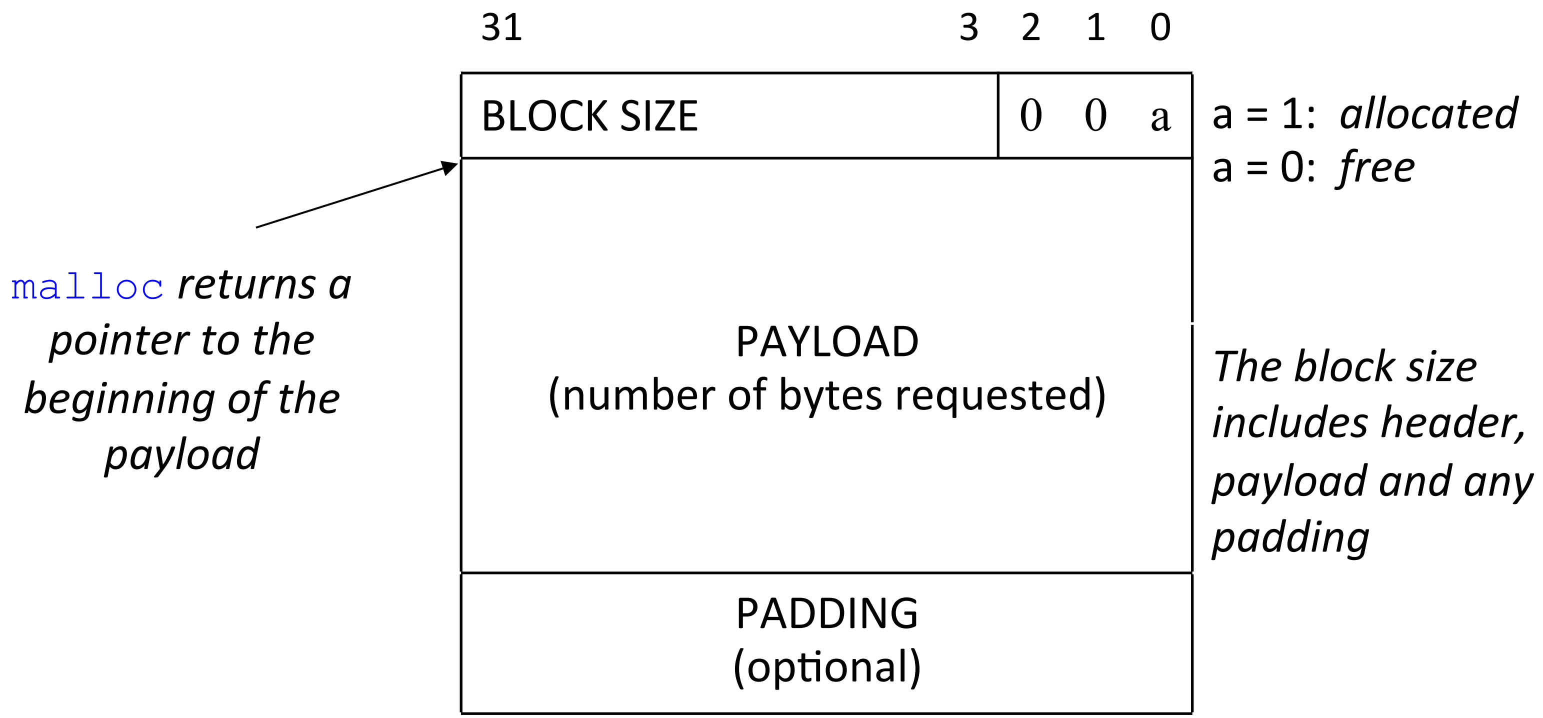
```
malloc(size):
    old_p = p
    p += size
    return old_p

free(ptr):
    do nothing
```

- Throughput is extremely good. Why?
- Memory utilization is extremely bad. Why?

Implementation Issues

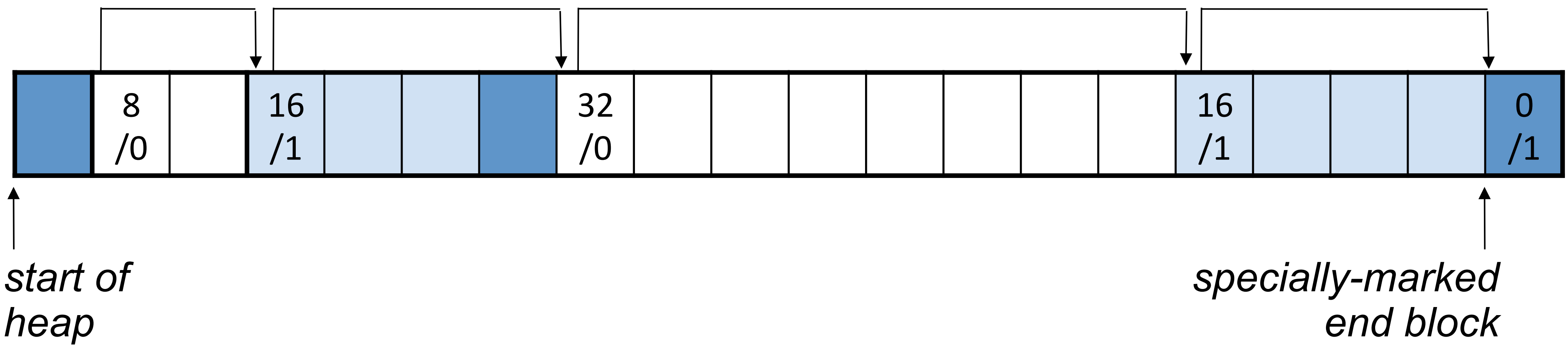
- ***Free block organization***—how do you keep track of free blocks?
- ***Placement***—how do you choose an appropriate free block in which to place a newly allocated block?
- ***Splitting***—after placing newly allocated block in some free block, what do you do with the remainder of the free block?
- ***Coalescing***—what do you do with a block that has just been freed?

Block Format



- Examples:
  - an allocated block with size 24 bytes has header `0x00000019`
  - a free block with size 40 byes has header `0x00000028`

Implicit Free List



- Free blocks are linked implicitly by the size fields in the headers.
- The allocator can indirectly traverse the entire set of free blocks by traversing all of the blocks in the heap.
- **Pro**: simplicity
- **Con**: cost of searching for a free block

Exercise: Block Format

- The minimum block size for an allocator is imposed by its alignment requirement and its block format.
- Determine the block sizes and header values the would result from the following `malloc` requests.
- *Assume*: double-word align, implicit free list, 4-byte headers
  - `malloc(1)`: 4 (header) + 1 (payload) + 3 (padding) = 8 bytes
    header = `0x8` | `0x1` = `0x9`
  - `malloc(5)`
  - `malloc(12)`
  - `malloc(13)`

Placing Allocated Blocks

- When a k-byte block is requested, the allocator searches the free list for a large enough block
  - the placement policy determines the manner of this search

Placement Policies

- ***First fit***
  - Start at the beginning of the free list and choose first free block that fits
  - **pro**: tends to retain large free blocks at the end of the list
  - **con**: tends to leave splinters of small free blocks at beginning of the list (increasing the search time for large blocks)

Placement Policies

- ***Next fit***
  - Start each search where previous search left off and choose the next free block that fits
  - If find fit in some block last time, good chance of finding fit in the remainder of the block next time
  - **pro**: can run significantly faster than first fit
  - **con**: studies suggest that memory utilization is worse

Placement Policies

- ***Best fit***
  - Examine every free block and choose the smallest size that fits
  - **pro**: studies show the memory utilization is the best
  - **con**: requires exhaustive search of the heap

Other Allocation Decisions

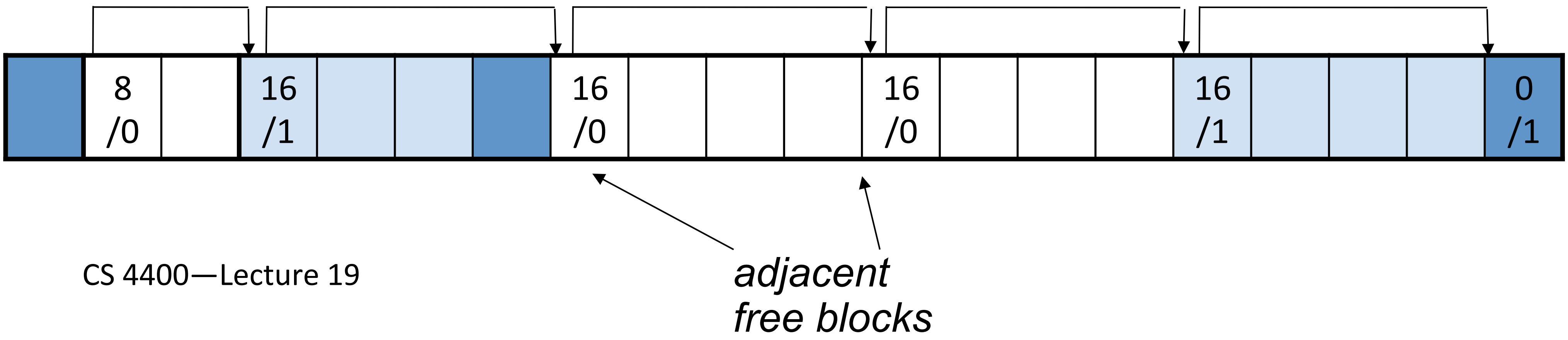
- Once a free block has been found that fits, how much of the free block should be allocated?
  - entire block—simple and fast, but introduces internal fragmentation
  - split the free block into two parts, allocated block and new free block

Other Allocation Decisions

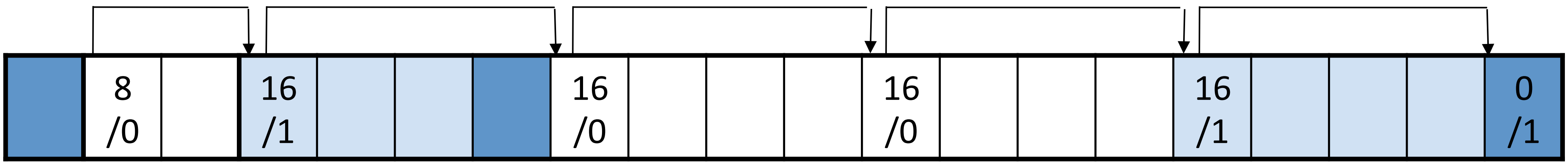
- What if the allocator is unable to find a fit?
  – create some larger free blocks by merging adjacent free blocks, if possible
  – ask the kernel for additional heap memory (`sbrk`), transform additional memory into one large free block in free list

Coalescing Free Blocks

- When an allocated block is freed, there might be other free blocks that are adjacent to the newly freed block
- ***False fragmentation***—a lot of available free memory chopped up into small, unusable free blocks.
- ***Coalescing***—merging adjacent free blocks.
  - immediate coalescing: performed each time a block is freed
  - deferred coalescing: waiting until some later time



Coalescing Free Blocks



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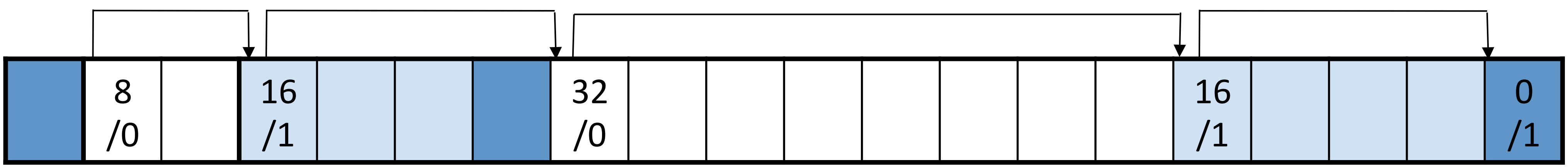
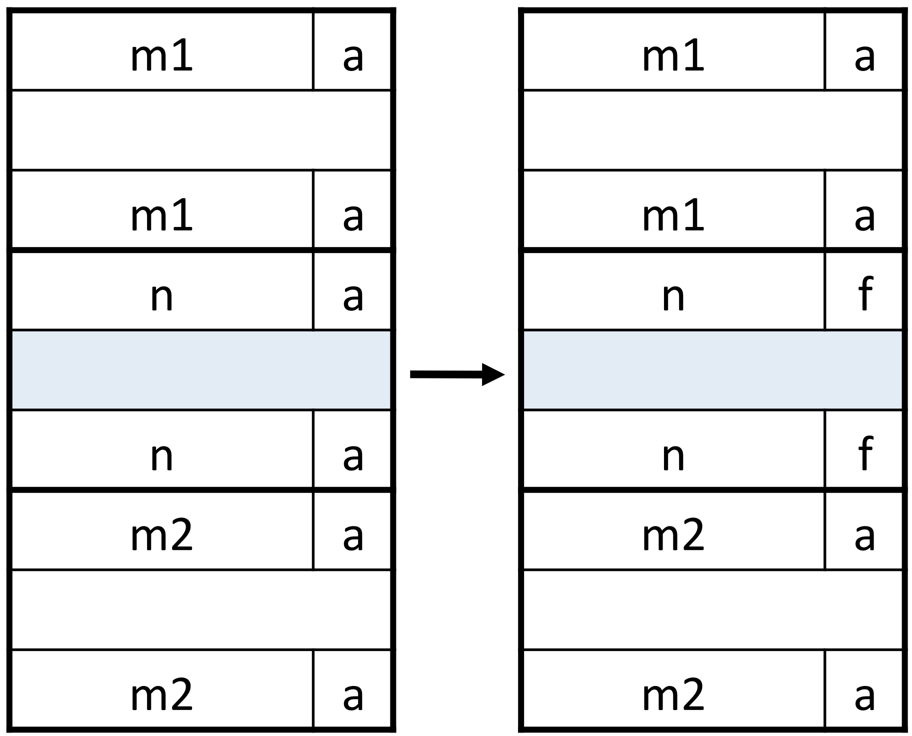
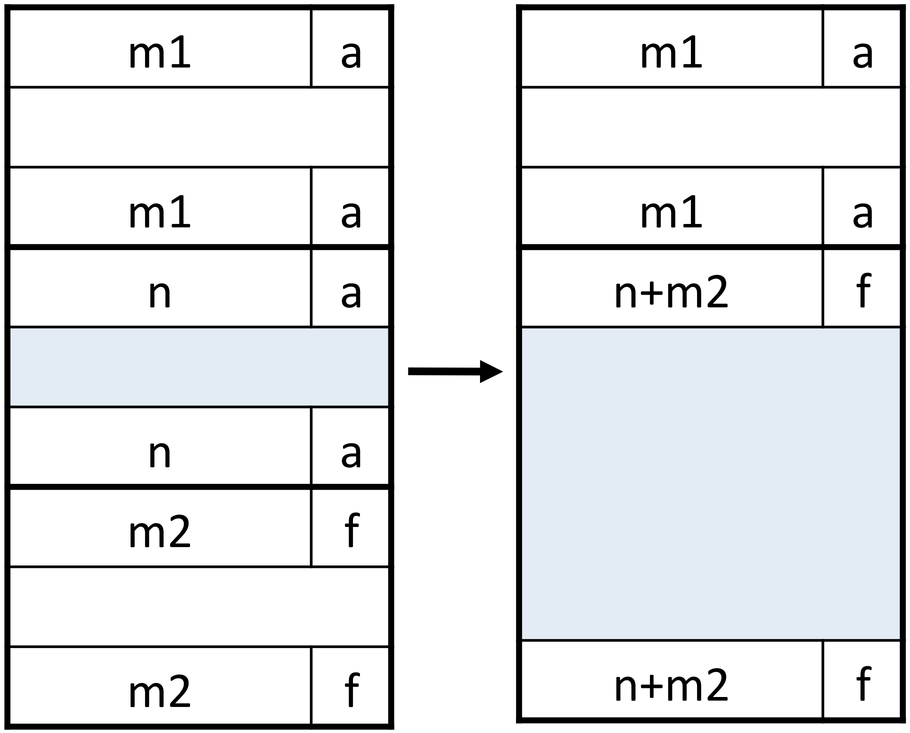


Boundary Tags

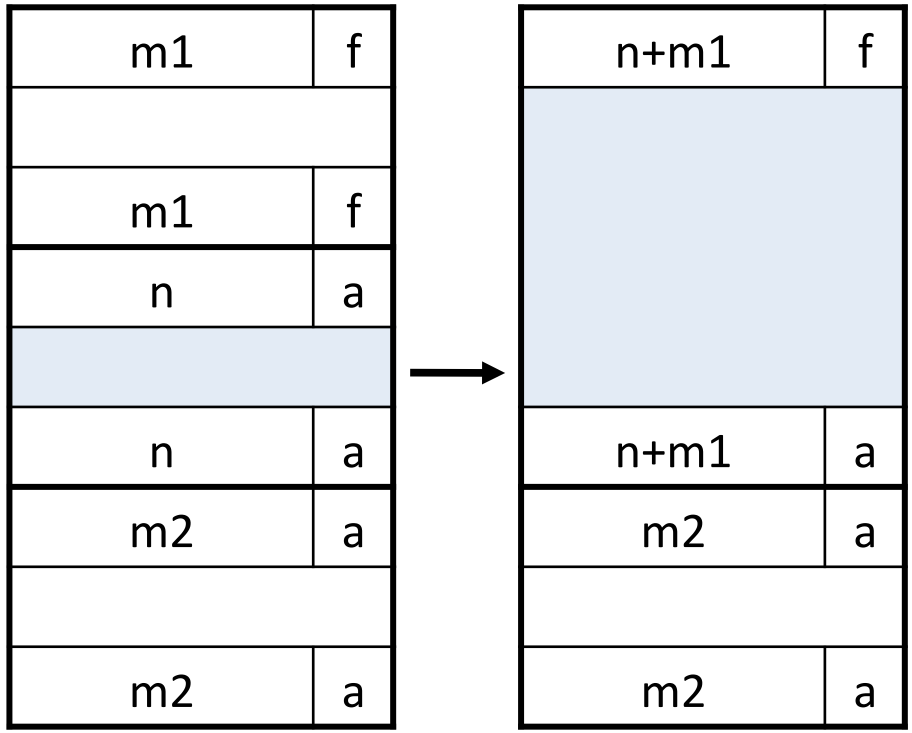
- Suppose we've just freed a block (the current block)
  - coalescing the next (free) block is straightforward
  - coalescing the previous (free) block requires a search
- Add a footer (the ***boundary tag***) at the end of each block
  - the footer is a replica of the header
  - The allocator can determine the starting location and status of the previous block by looking at its footer
- Is there a disadvantage to using boundary tags?
  - Do allocated blocks really need footers?



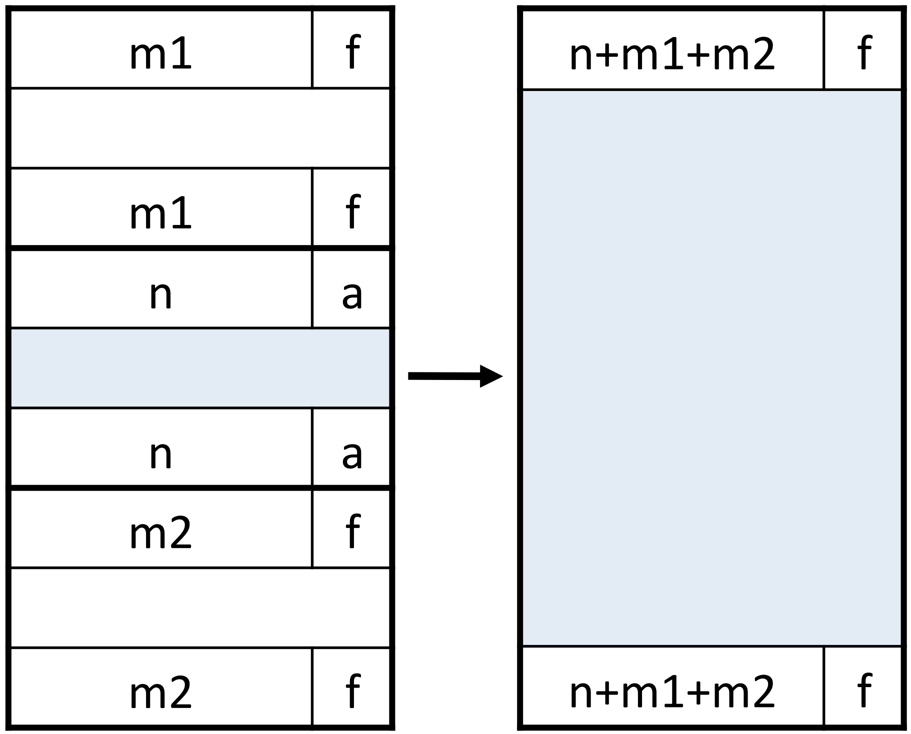
prev and next allocated



prev allocated, next free



prev free, next allocated



prev and next free

Exercise: Minimum Block Size

- Assume: implicit free list, headers/footers stored in 4-byte words, and every free block has a header and footer
- min block size = MAX(min allocated block size, min free block size)
- single-word alignment, allocated block has header and footer
  - alloc: 4-byte header, 1-byte payload, 4-byte footer – round up to 12
  - free: 4-byte header, 4-byte footer – 8
- single-word align, header only
- double-word align, header and footer
- double-word align, header only

Exercise: Minimum Block Size

- single-word align, header only
  - Alloc: 4 +1 + 3 = 8 Free: 4 + 4 = 8
- double-word align, header and footer
  - Alloc: 4 + 1 + 4 = 9, round to 16 Free: 4 + 4 = 8
- double-word align, header only
  - Alloc: 4 + 1 = 5, round to 8 Free: 4 + 4 = 8