Dynamic Memory Allocation

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Some are based on Tiger Wang’s slides

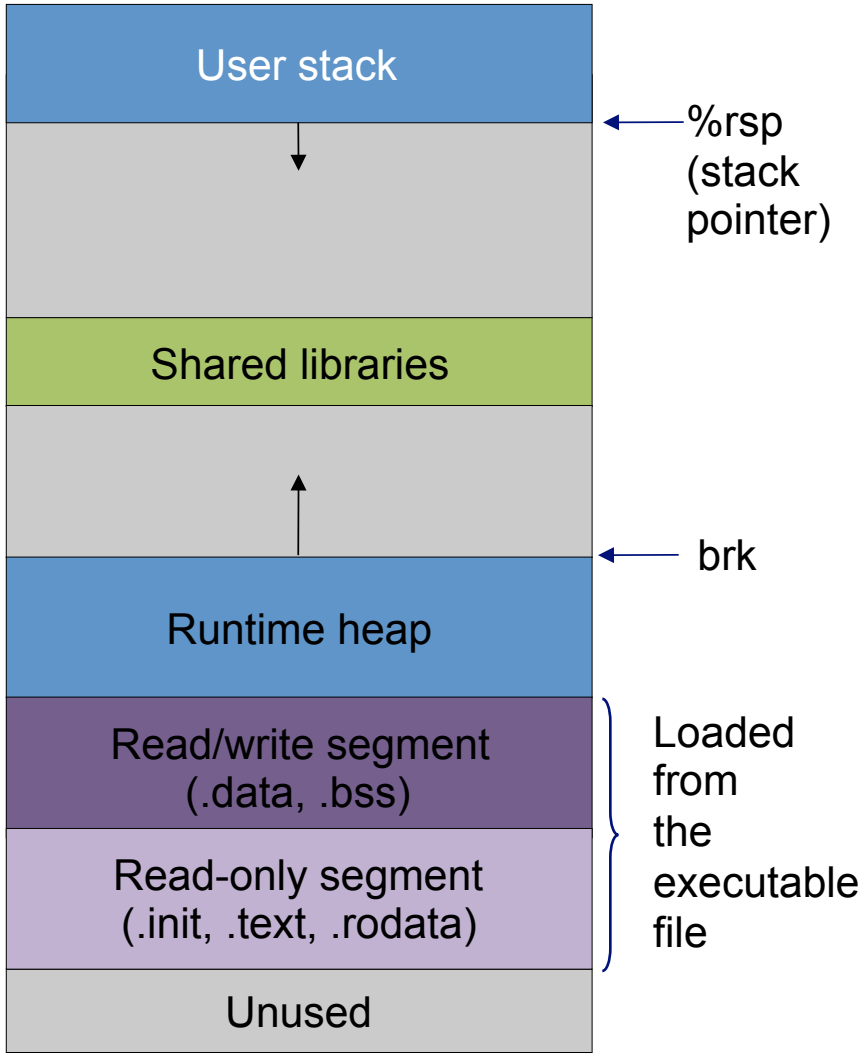
Why dynamic memory allocation?

```
typedef struct node {
   int val;
   struct node *next;
} node;

void
list_insert(node **head, int v) {
   node *np = malloc(sizeof(node));
   np->next = head;
   np->val = v;
   *head = np;
}

int
main(void) {
   node *head = NULL;
   int n = atoi(argv[1]);
   for (int i = 0; i < n; i++) {
      list_insert(&head, i);
   }
}
```

How many nodes to allocate is only known at runtime (when the program executes)

Dynamic allocation on heap

Question: can one dynamically allocate memory on stack?

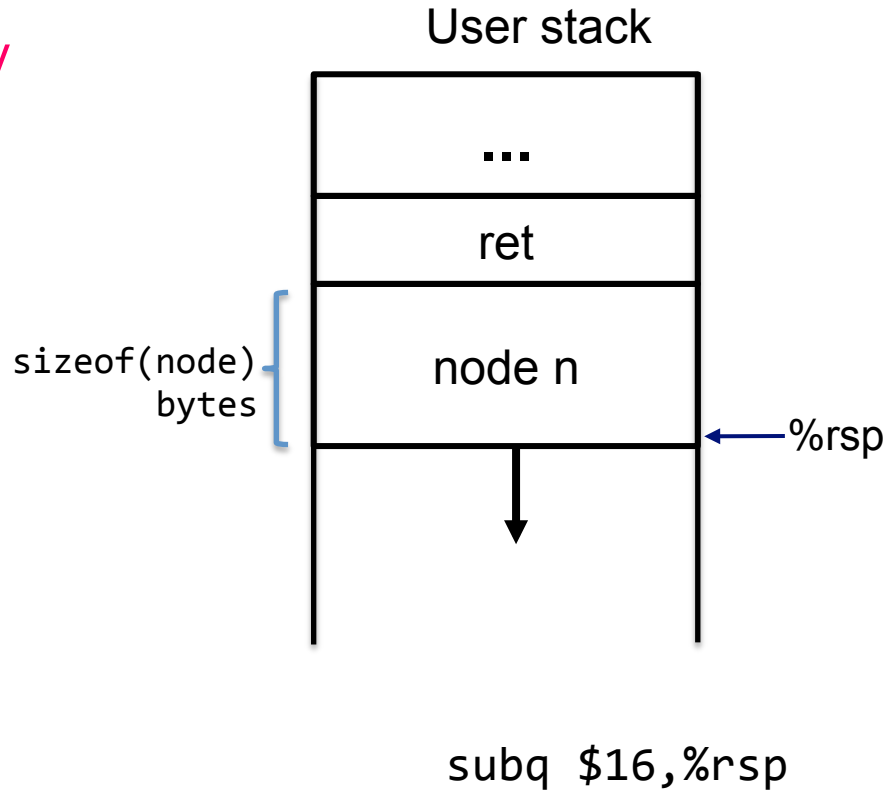


Dynamic allocation on heap

Question: Is it possible to dynamically allocate memory on stack?

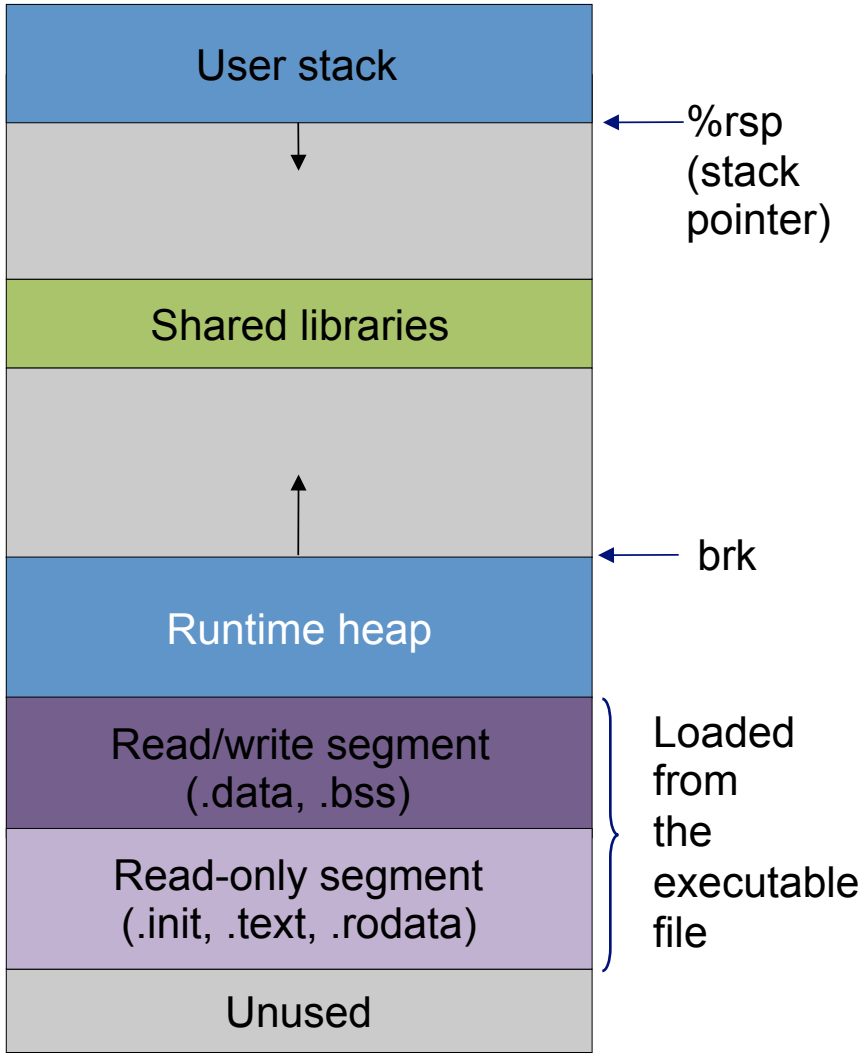
Answer: Yes, but space is freed upon function return

```
void
list_insert(node *head, int v) {
   node n;
   node *np = &n;
   np->next = head;
   np->val= v;
   *head = np;
}
```



Dynamic allocation on heap

Question: How to allocate memory on heap?



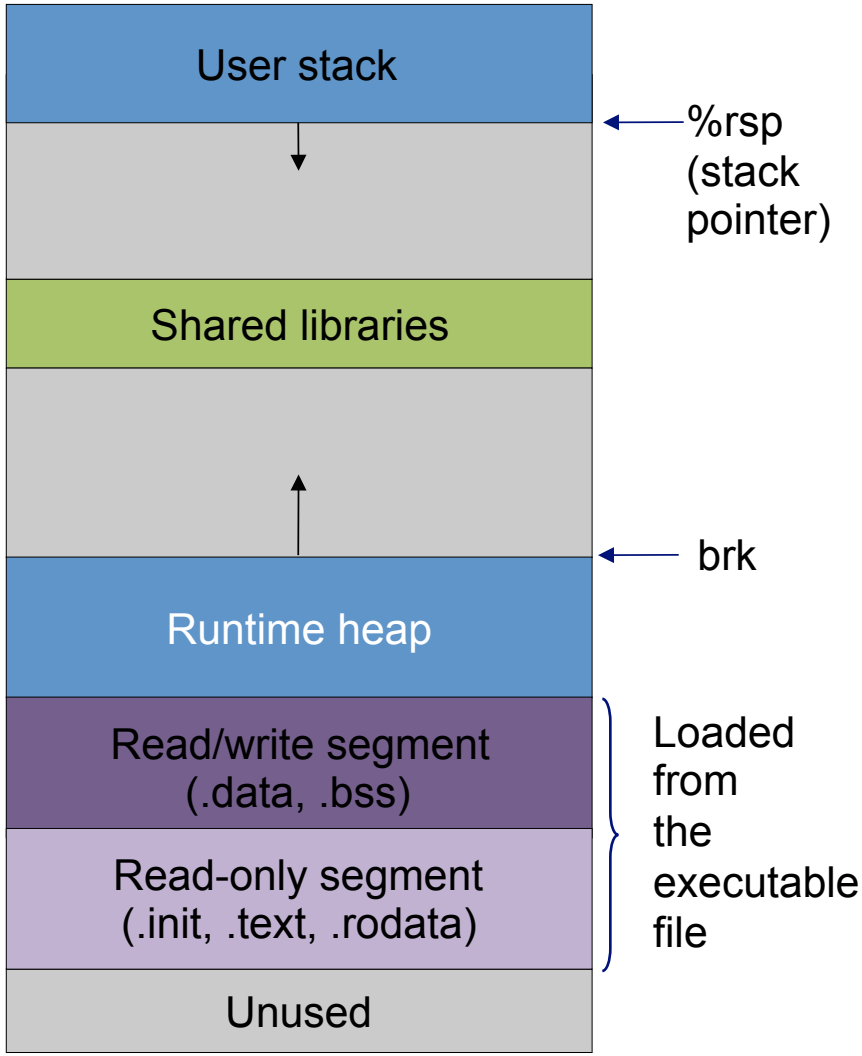
Dynamic allocation on heap

Question: How to allocate memory on heap?

Ask OS for allocation on the heap via system calls

```
void *sbrk(intptr_t size);
```

It increases the top of heap by “size” and returns a pointer to the base of new storage. The “size” can be a negative number.



Dynamic allocation on heap

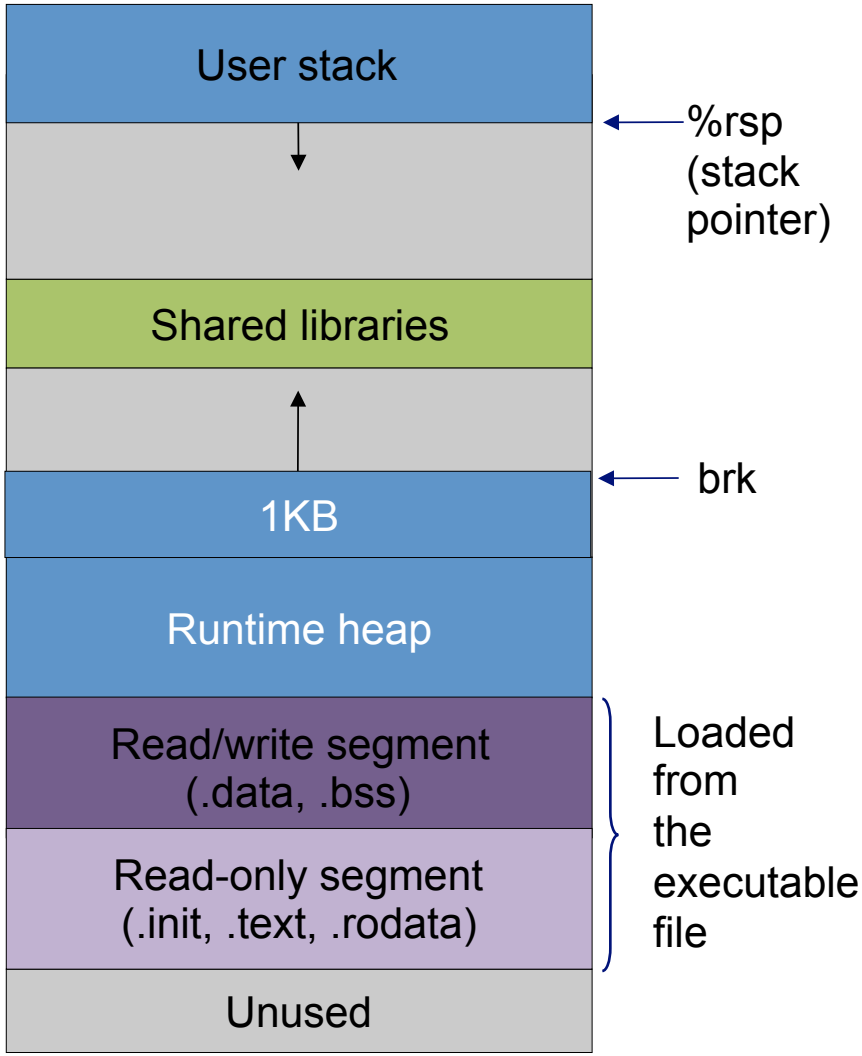
Question: How to allocate memory on heap?

Ask OS for allocation on the heap via system calls

```
void *sbrk(intptr_t size);
```

It increases the top of heap by “size” and returns a pointer to the base of new storage. The “size” can be a negative number.

```
p = sbrk(1024) //allocate 1KB
```



Dynamic allocation on heap

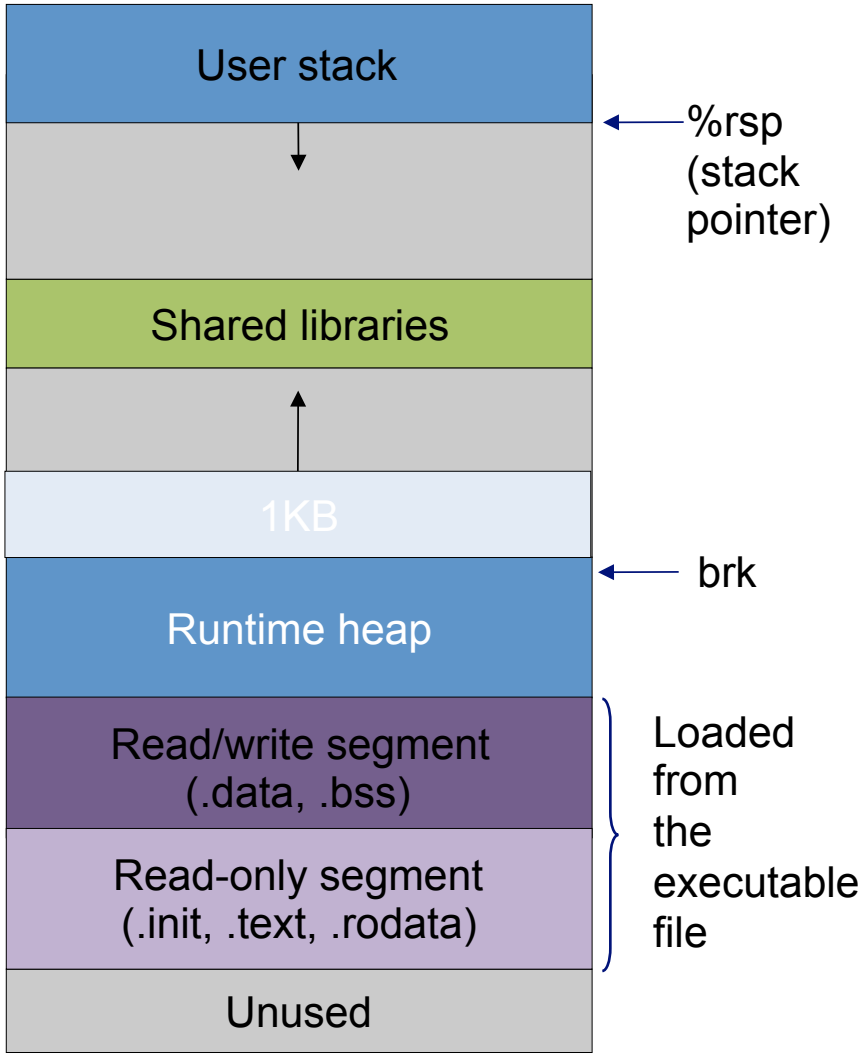
Question: How to allocate memory on heap?

Ask OS for allocation on the heap via system calls

```
void *sbrk(intptr_t size);
```

It increases the top of heap by “size” and returns a pointer to the base of new storage. The “size” can be a negative number.

```
p = sbrk(1024) //allocate 1KB
sbrk(-1024) //free p
```



Dynamic allocation on heap

Question: How to allocate memory on heap?

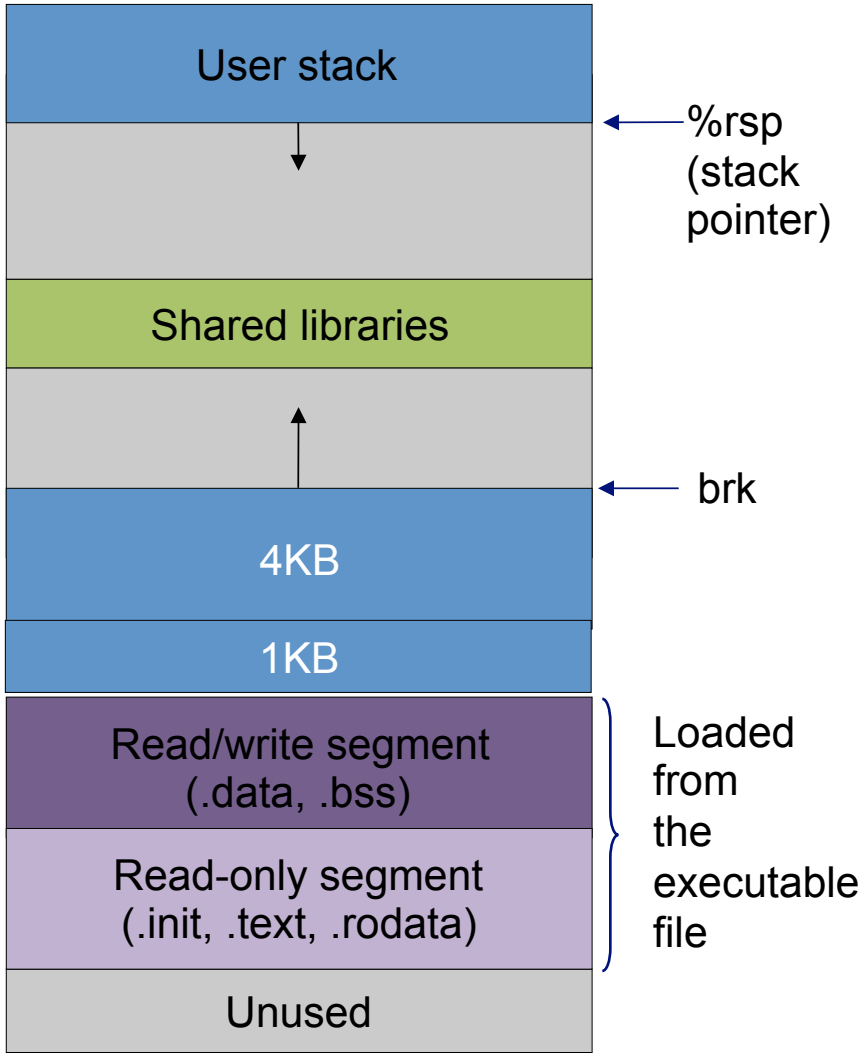
Ask OS for allocation on the heap via system calls

```
void *sbrk(intptr_t size);
```

Issue I – can only free the memory on the top of heap

```
p1 = sbrk(1024) //allocate 1KB
p2 = sbrk(4096) //allocate 4KB
```

How to free p1?



Dynamic allocation on heap

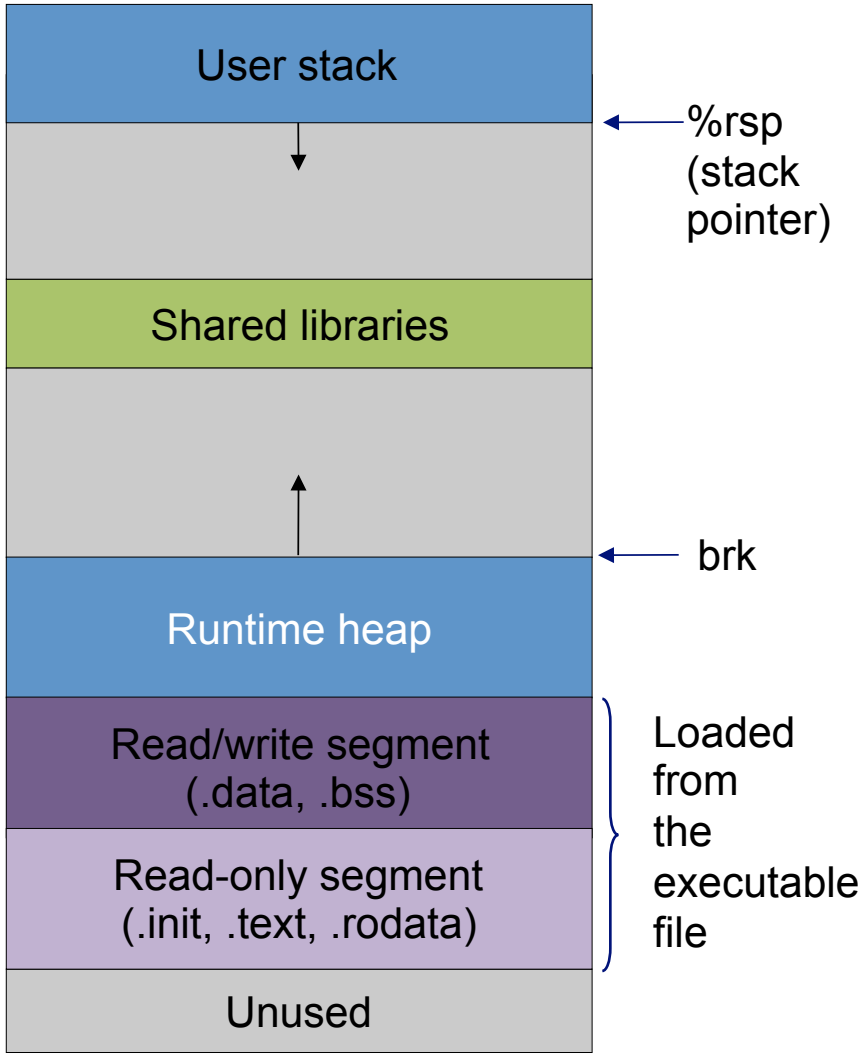
Question: How to allocate memory on heap?

Ask OS for allocation on the heap via system calls

```
void *sbrk(intptr_t size);
```

Issue I – can only free the memory on the top of heap

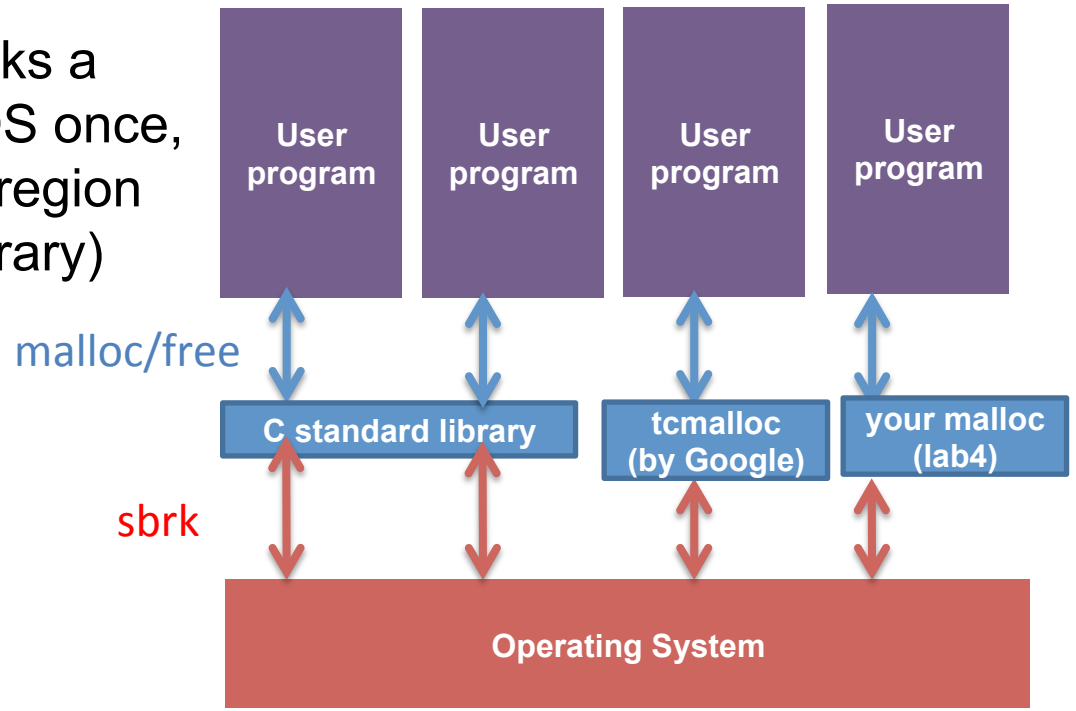
Issue II – system call has high performance cost > 10X



Dynamic allocation on heap

Question: How to effciently allocate memory on heap?

Basic idea: user program asks a large memory region from OS once, then manages this memory region by itself (using a “malloc” library)



How to implement a memory allocator?

API:

- void* malloc(size_t size);
- void free(void *ptr);

Goal:

- Efficiently utilize acquired memory with high throughput
  - high throughput – how many mallocs / frees can be done per second
  - high utilization – fraction of allocated size / total heap size

How to implement a memory allocator?

Assumed behavior of applications:

- Issue an arbitrary sequence of malloc/free
- Argument of free must be the return value of a previous malloc
- No double free

Restrictions on the allocator:

- Once allocated, space cannot be moved around

Malloc design challenges

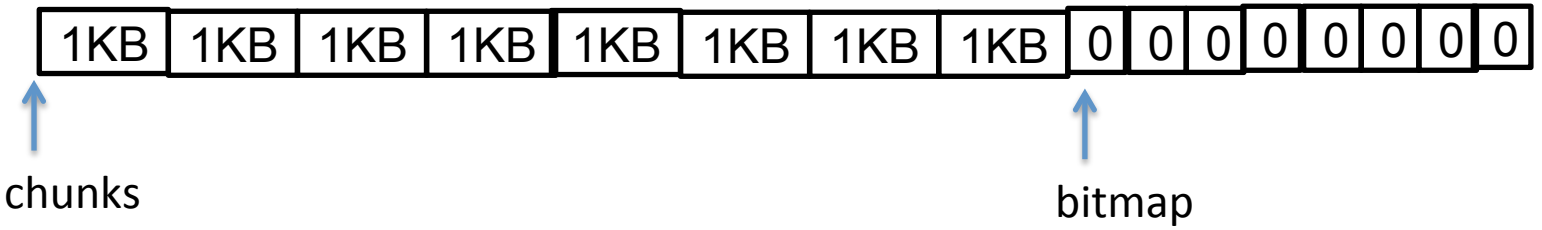
1. (Basic book-keeping) How to keep track which bytes are free and which are not?

2. (Allocation decision) Which free chunk to allocate?

3. (API restriction) free is only given a pointer, how to find out the allocated chunk size?

How to bookkeep? Strawman #1

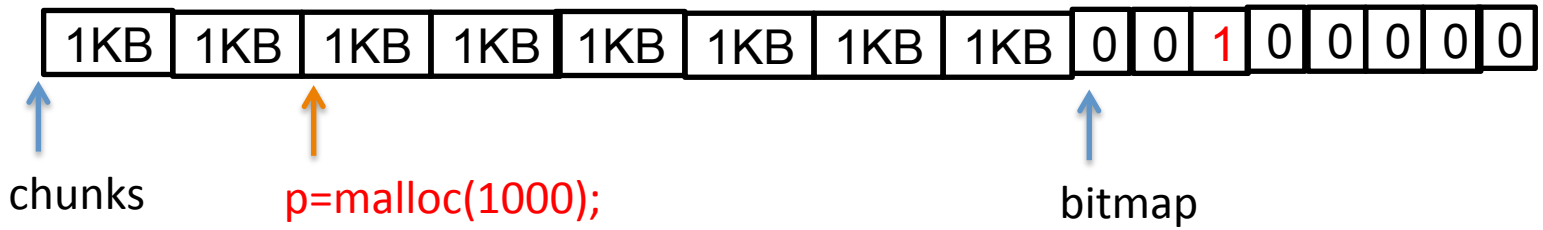
- Structure heap as n 1KB chunks + n metadata




```
#define CHUNKSIZE 1<<10;
typedef char[CHUNKSIZE] chunk;
char *bitmap;
chunk *chunks;
size_t n_chunks;

void init() {
  n_chunks = 128;
  sbrk(n_chunks*sizeof(chunk)+ n_chunks/8);
  chunks = (chunk *)heap_lo();
  bitmap = heap_lo() + n_chunks *CHUNKSIZE;
}
```

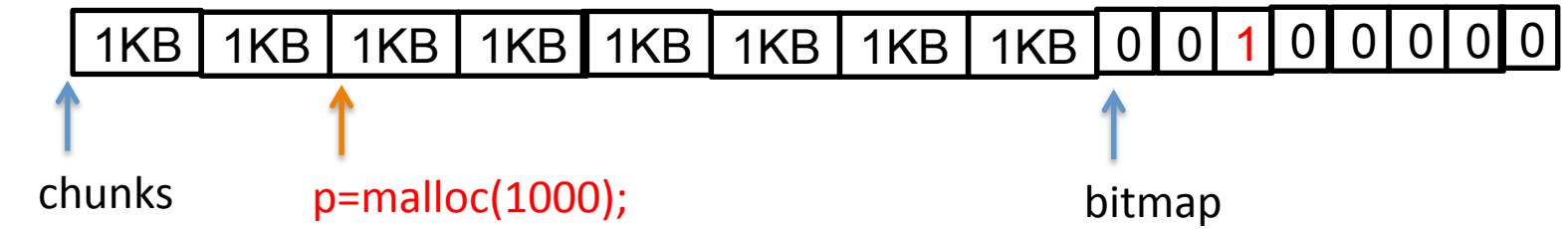
Assume allocator asks for enough memory from OS in the beginning

How to bookkeep? Strawman #1




```
void* malloc(size_t sz) {
  // find out # of chunks needed to fit sz bytes
  csz = ...

  //find csz consecutive free chunks according to bitmap
  int i = find_consecutive_chunks(bitmap);

  // return NULL if did not find csz free consecutive chunks
  if (i < 0)
    return NULL;

  // set bitmap at positions i, i+1, ... i+csz-1
  bitmap_set_pos(bitmap, i, csz);
  return (void *)&chunks[i];
}
```

How to bookkeep? Strawman #1




```
void free(void *p) {
  i = ((char *)p - (char *)chunks)/sizeof(chunk);
  bitmap_clear_pos(bitmap, i); //how many bits to clear??
}
```

- Problem with strawman?
  - free does not know how many chunks allocated
  - wasted space within a chunk (internal fragmentation)
  - wasted space for non-consecutive chunks (external fragmentation)

How to bookkeep? Other Strawmans

- How to support a variable number of variable-sized chunks?
  - Idea #1: use a hash table to map address → [chunk size, status]
  - Idea #2: use a linked list in which each node stores [address, chunk size, status] information.

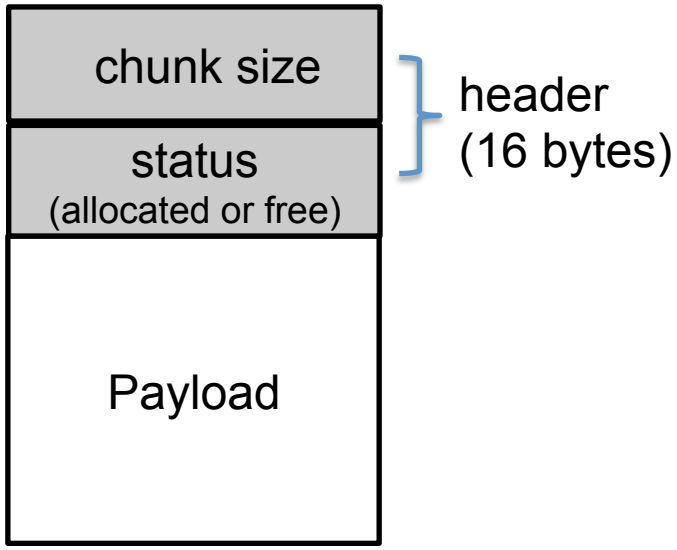
Problems of strawmans?

Implementing a hash table and linked list requires use of a dynamic memory allocator!

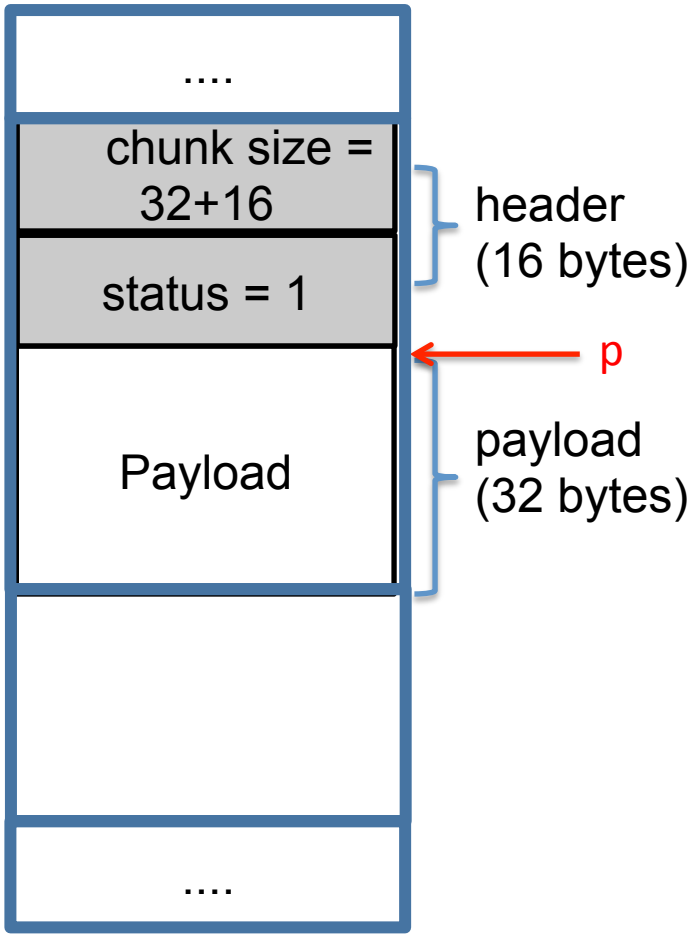
How to implement a "list" without use of malloc

Implicit list

- Each chunk contains metadata + payload
  - Metadata (chunk header) stores chunk size and status
- Alignment requirement: 16-byte (aka the starting address of payload must be multiples of 16).
  - Make header 16-byte in size
  - Make chunk multiples of 16 in size.



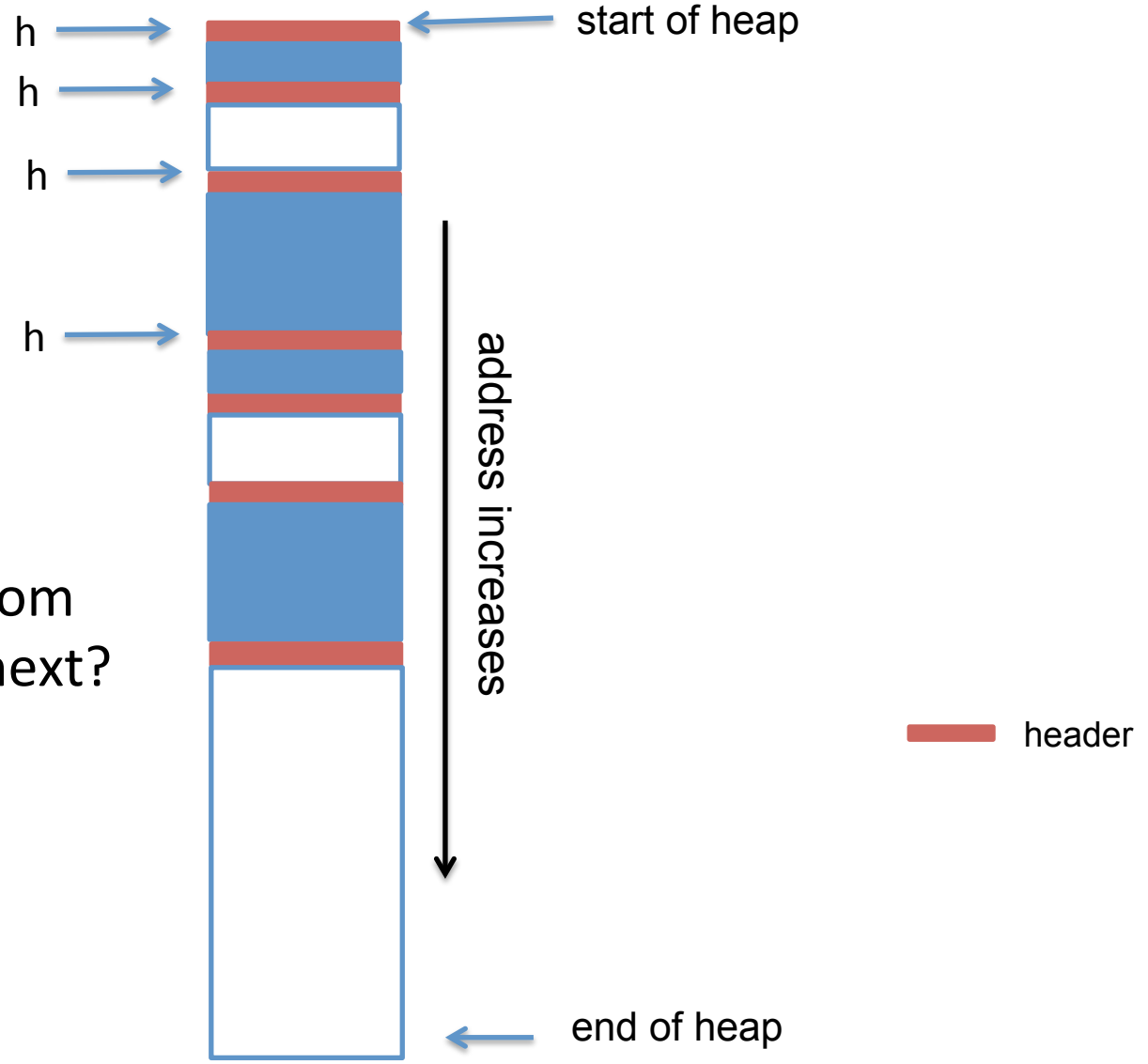
Implicit list: chunk format




```
p  = malloc(20)
```

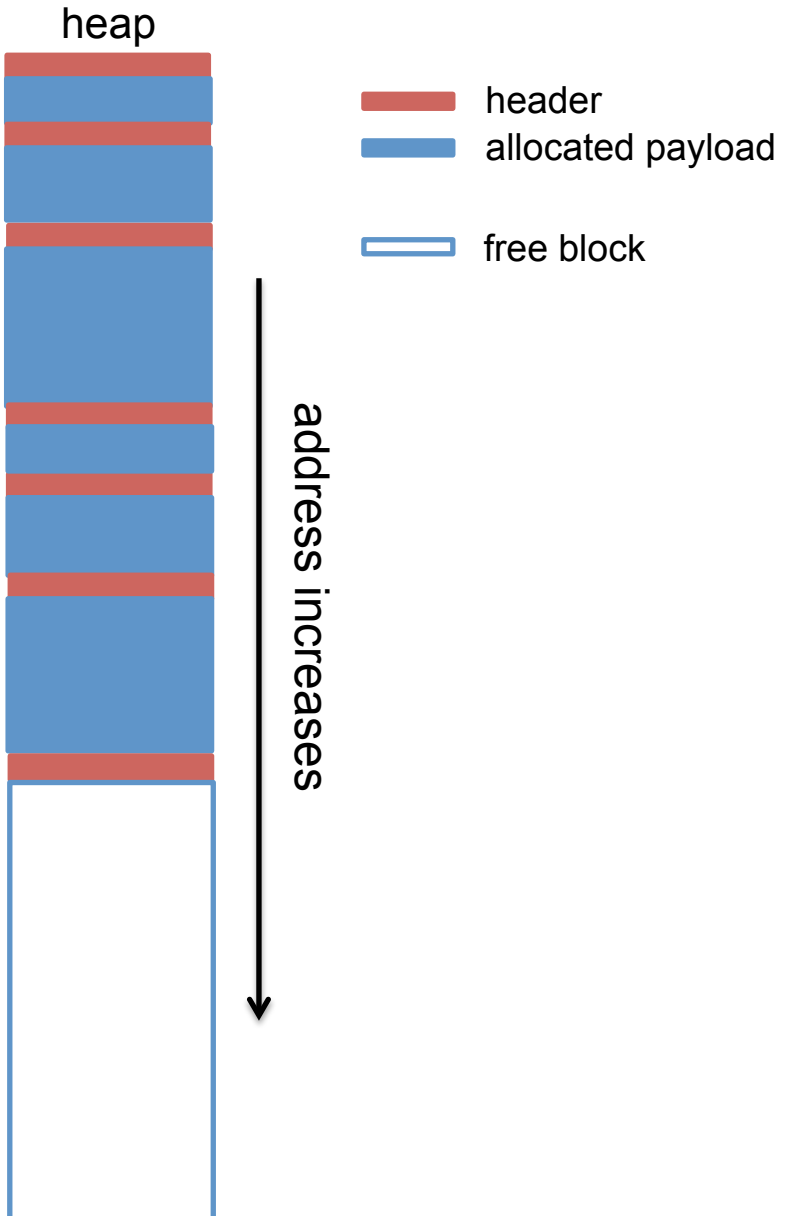
Implicit list: heap traversal

How to advance from one chunk to the next?



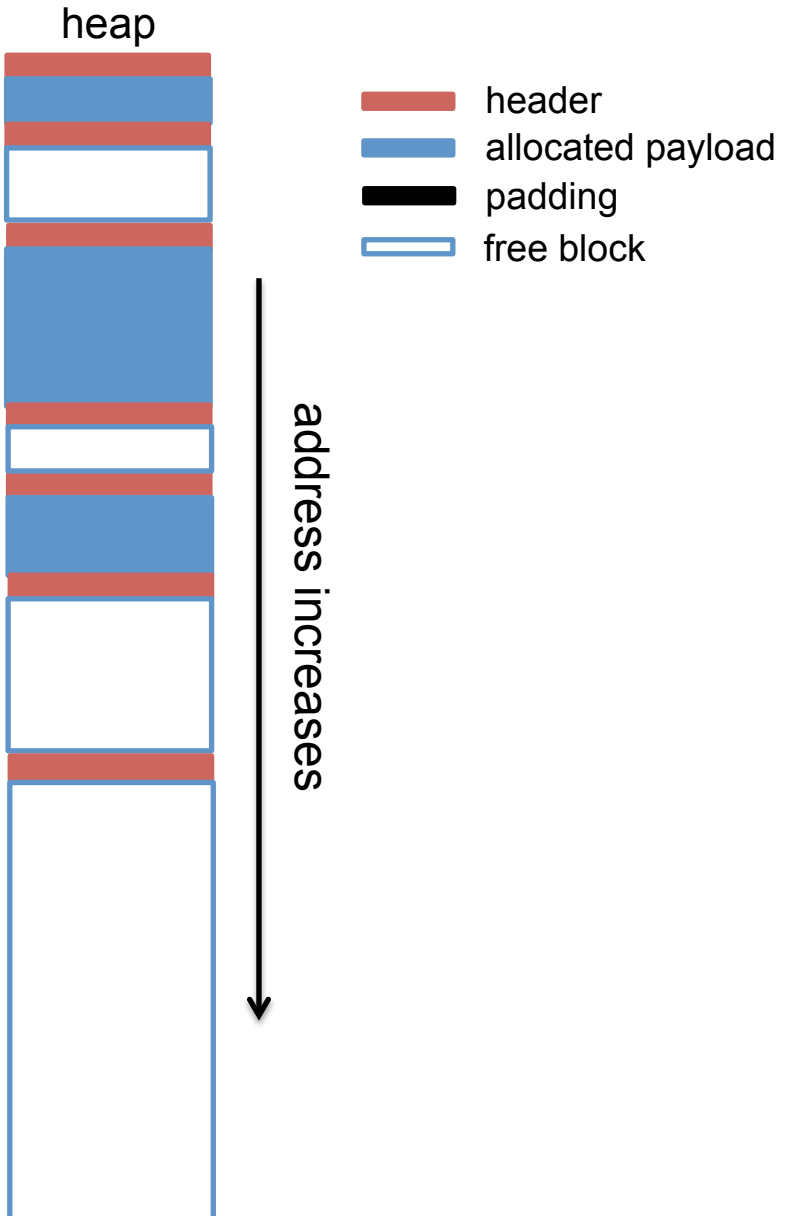
Which chunk to allocate?

```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
```



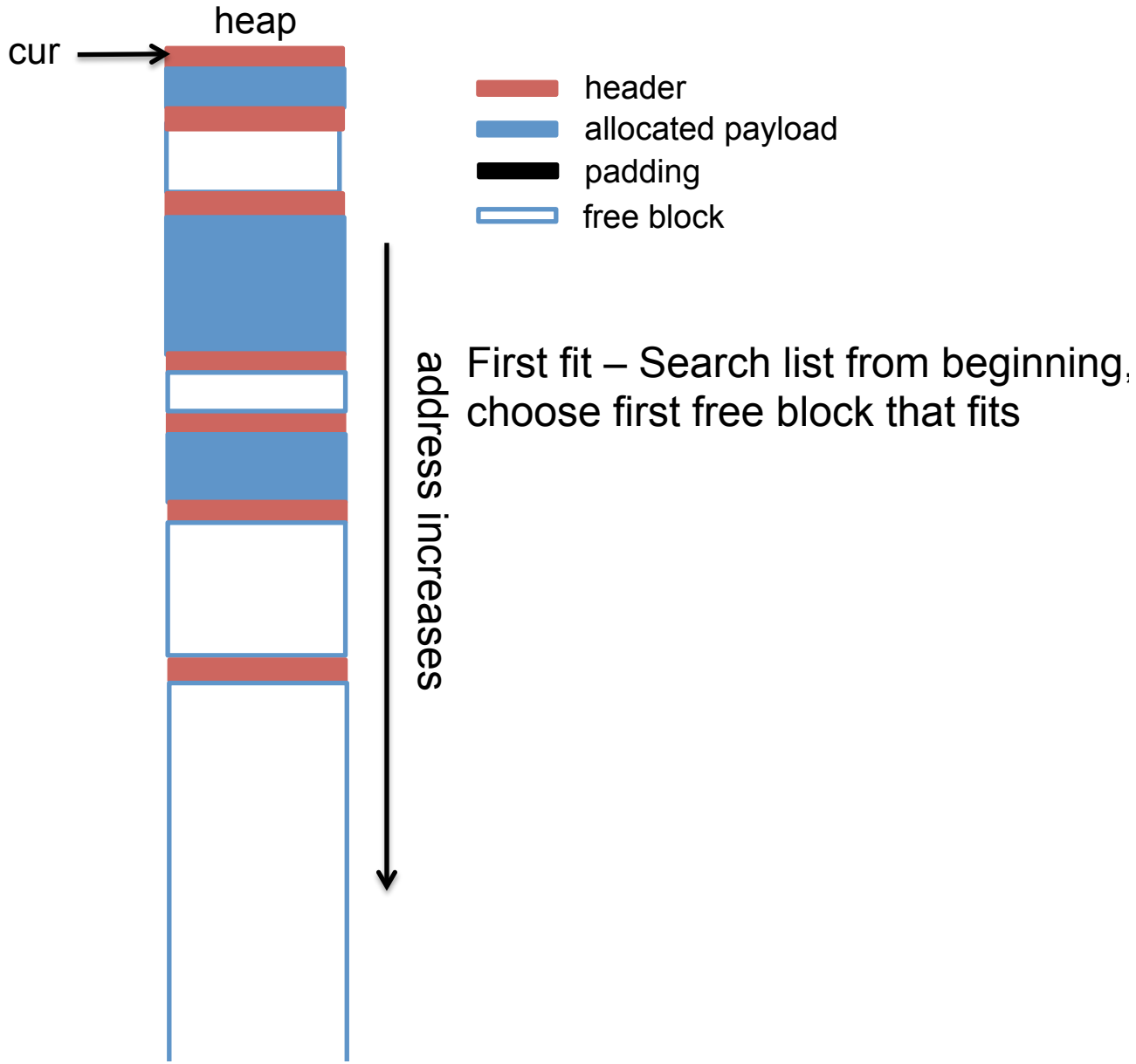
Where to place an allocation?

```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
```



First fit

```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
```



First fit – Search list from beginning, choose first free block that fits

First fit

```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
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```
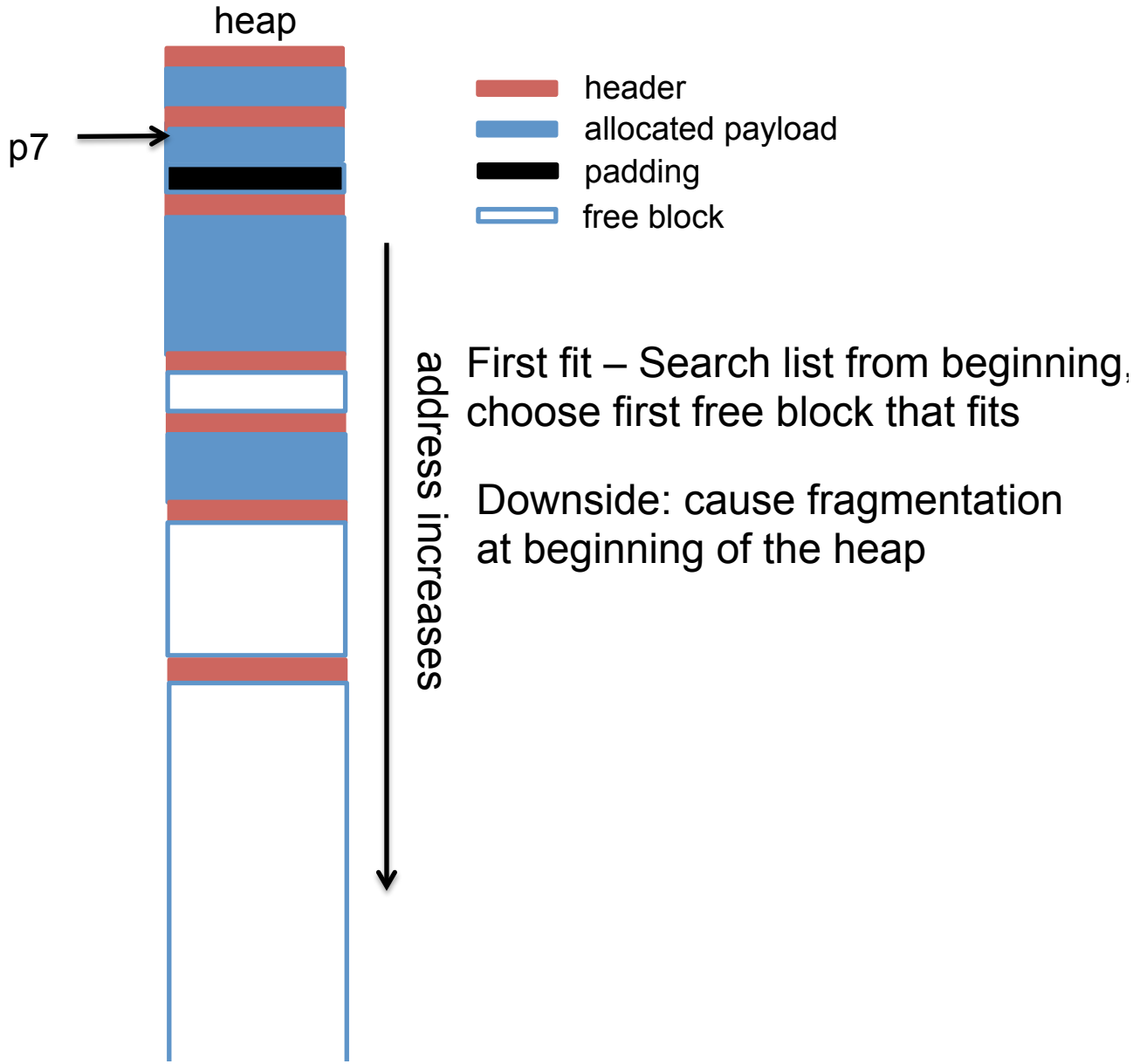
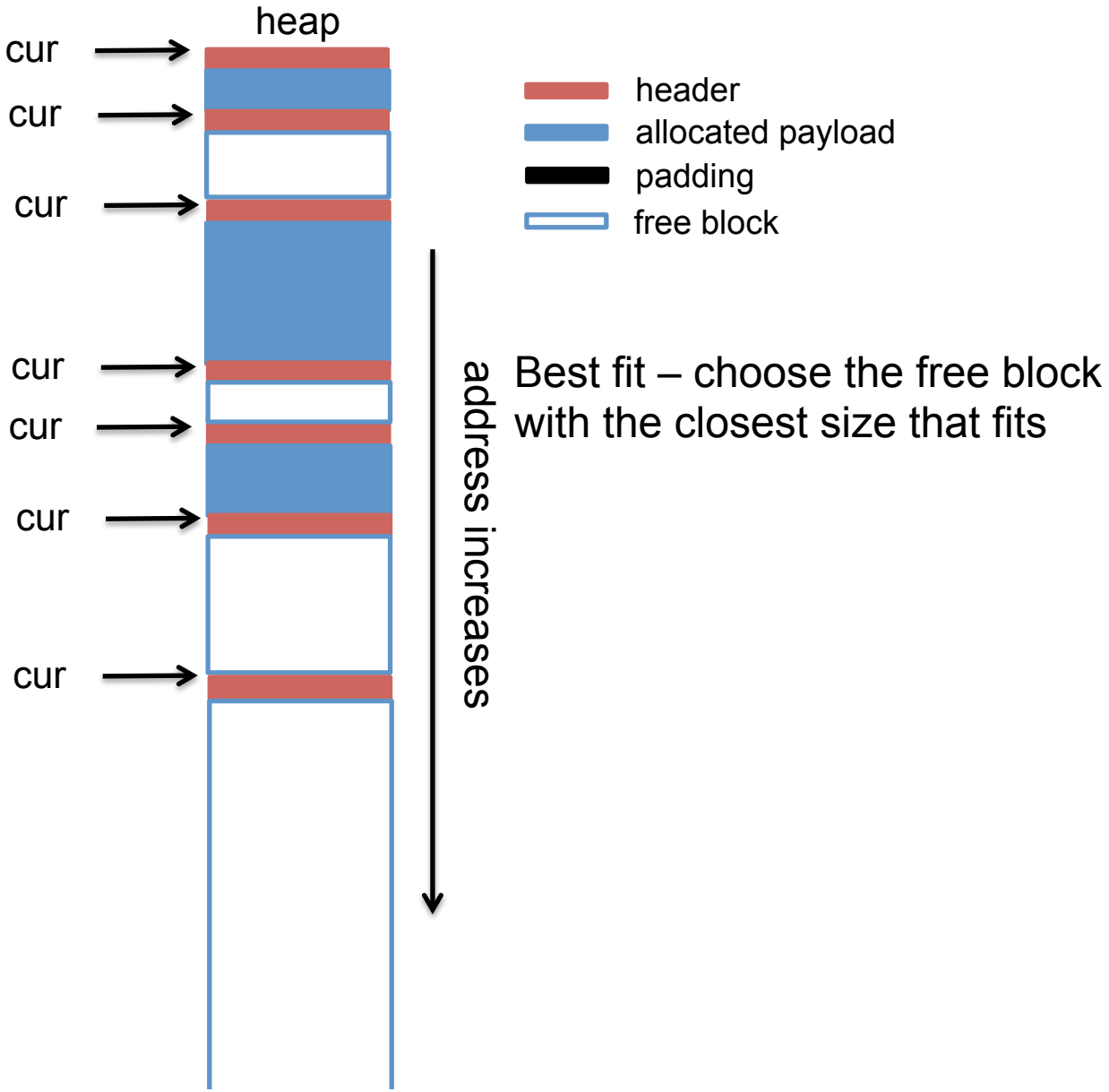



First fit – Search list from beginning, choose first free block that fits

Downside: cause fragmentation at beginning of the heap

Best fit

```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
```



Best fit – choose the free block with the closest size that fits

Best fit

```
p1 = malloc(8)
p2 = malloc(24)
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p4 = malloc(8)
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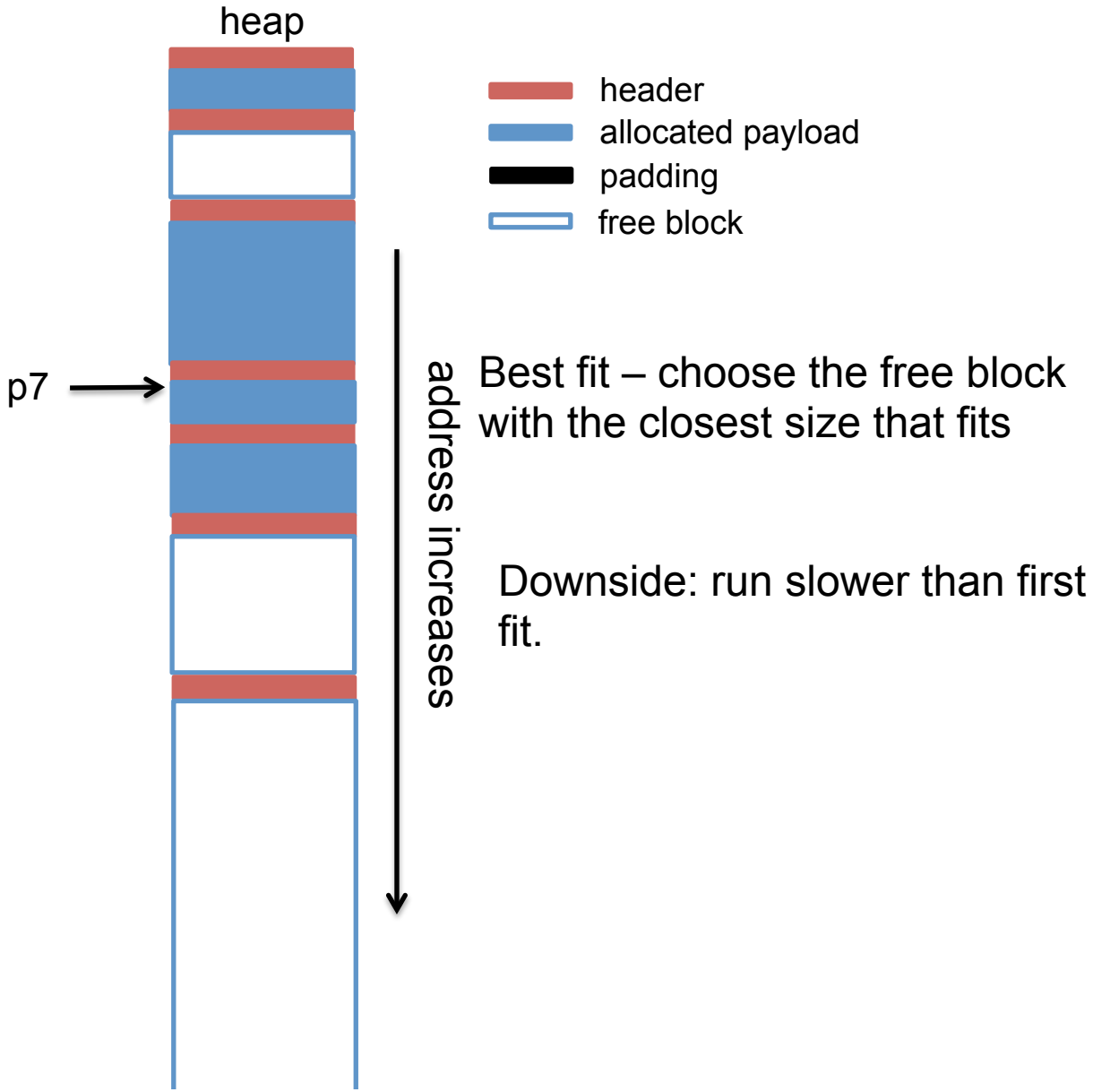
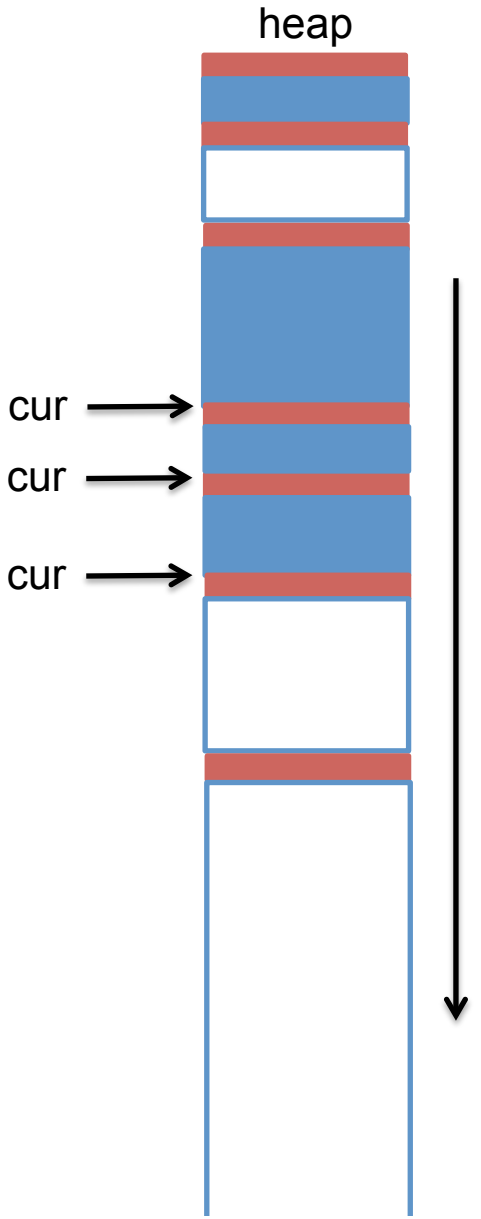


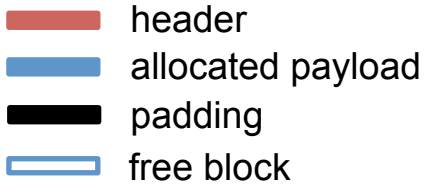
Best fit – choose the free block with the closest size that fits

Downside: run slower than first fit.

Next fit

```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
p8 = malloc(56)
```





Next fit – like first-fit, but search starts from where the previous search left off.

Next fit

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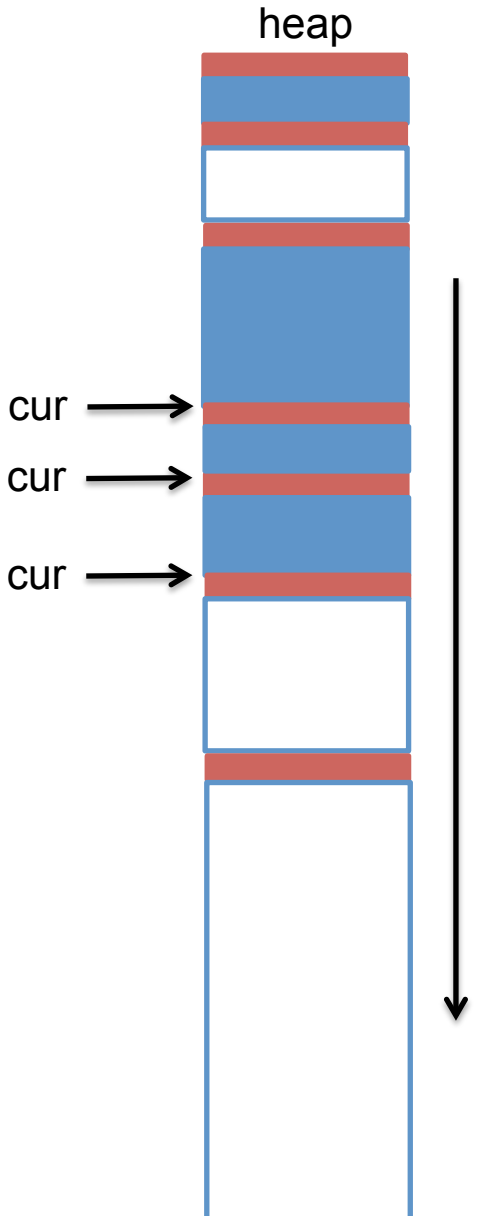

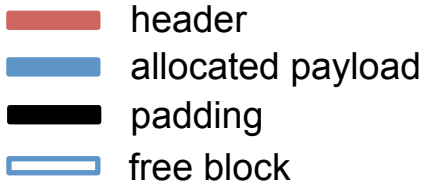

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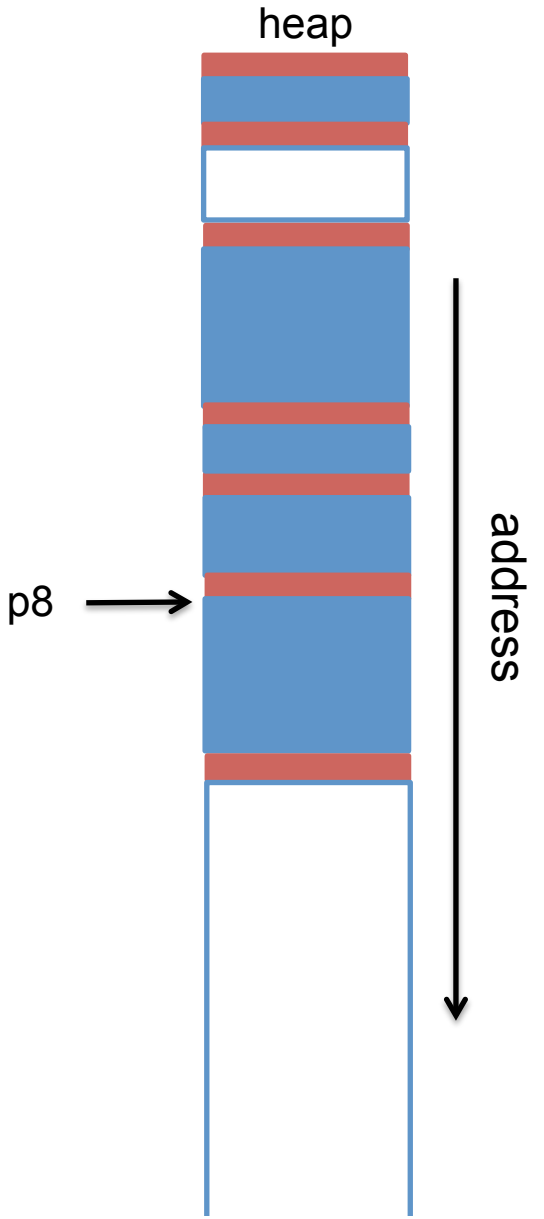
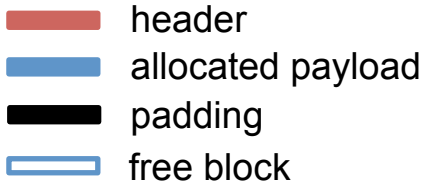


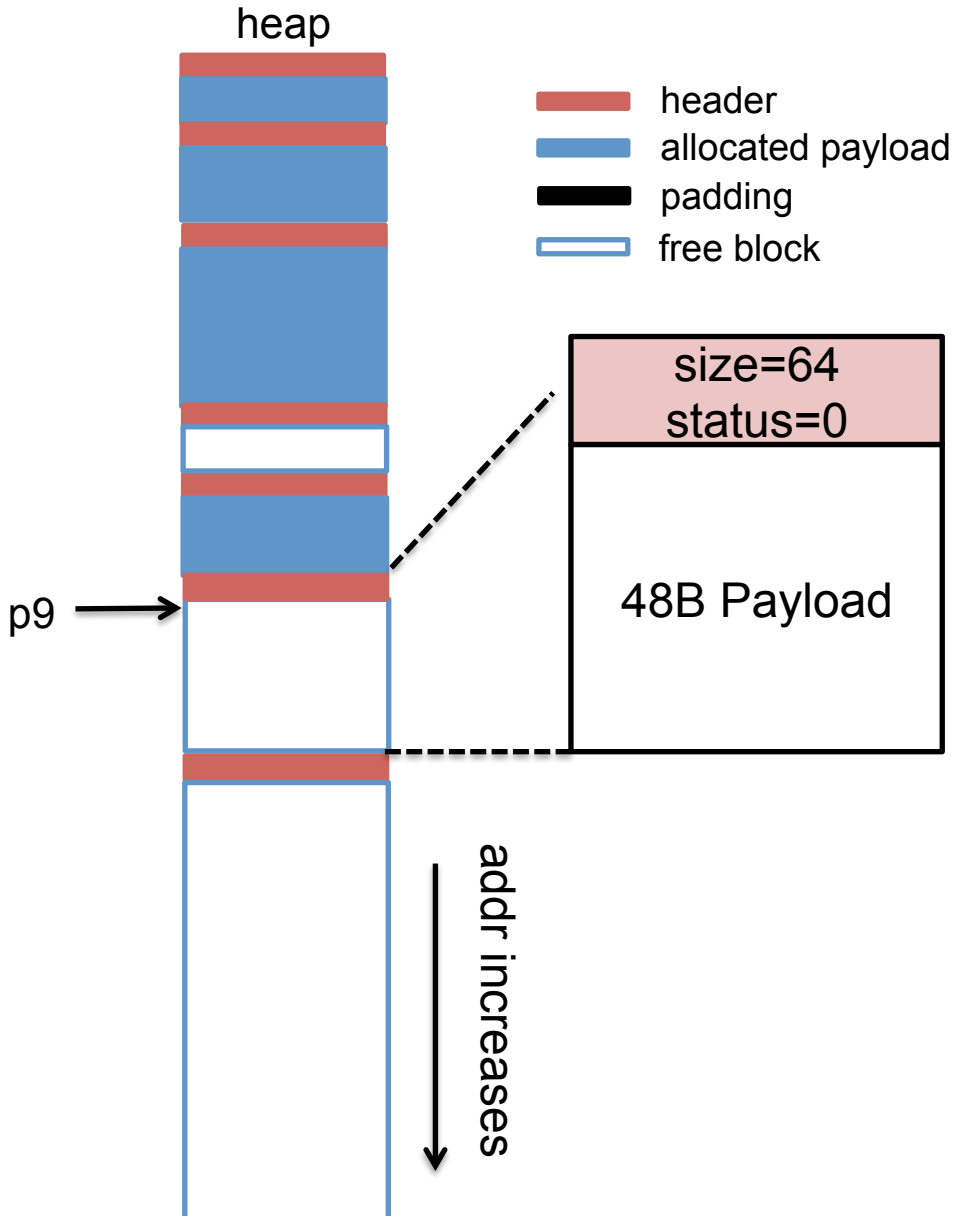


Next fit – like first-fit, but search starts from where the previous search left off.

Next fit runs faster than first fit, but fragmentation is worse.

Splitting a free block

```
...
p9 = malloc(16)
```



Splitting a free block

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...
p9 = malloc(16)
```
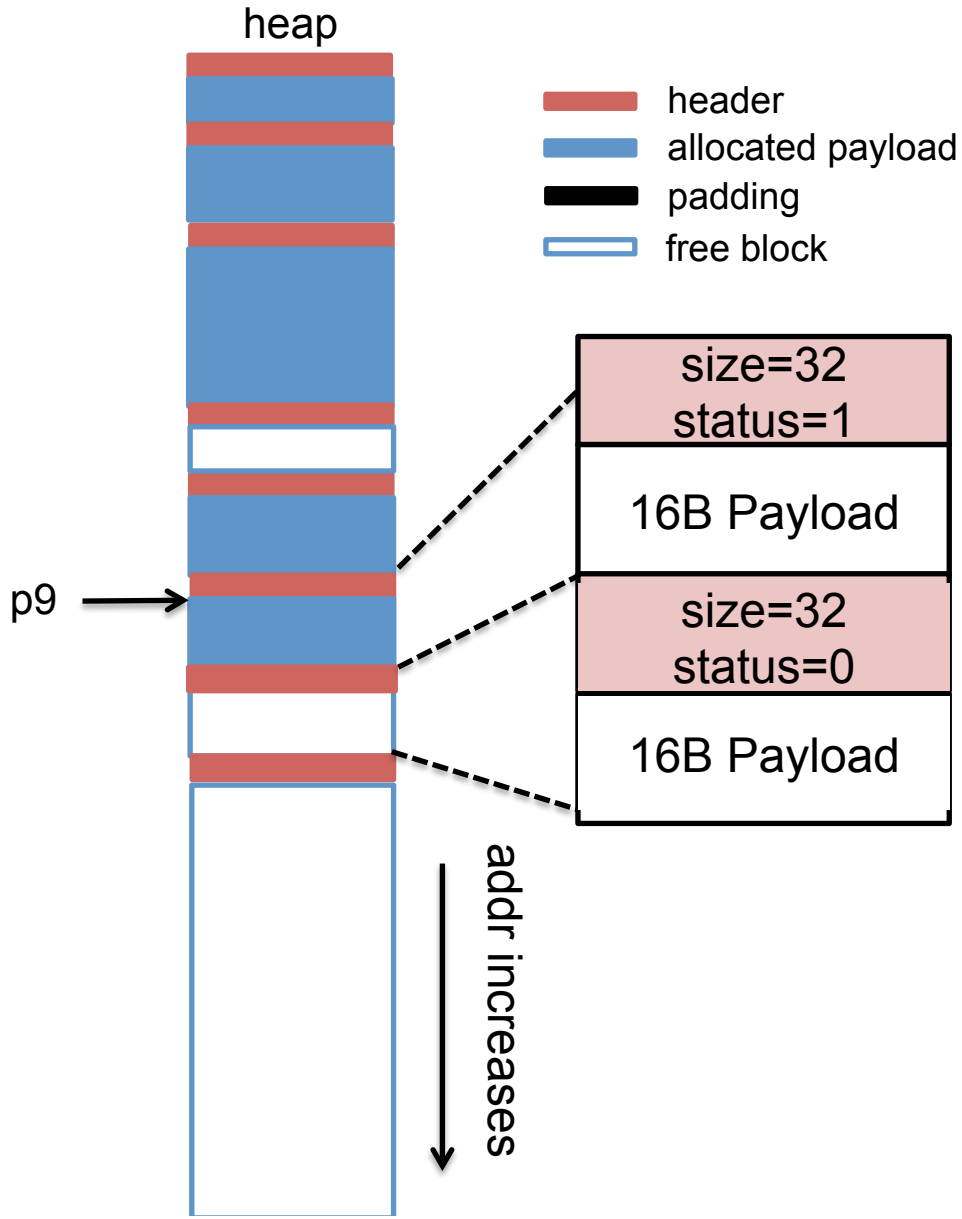
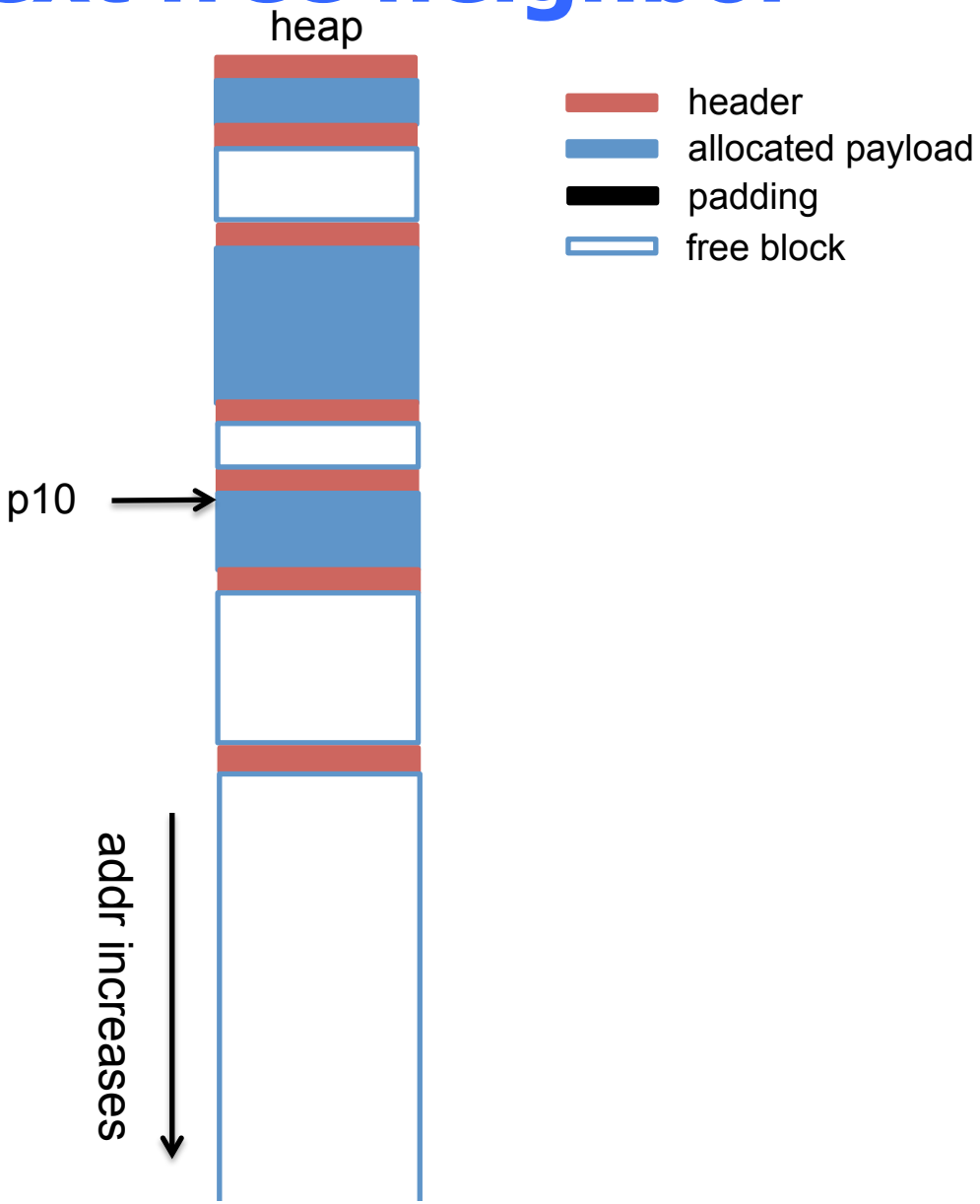



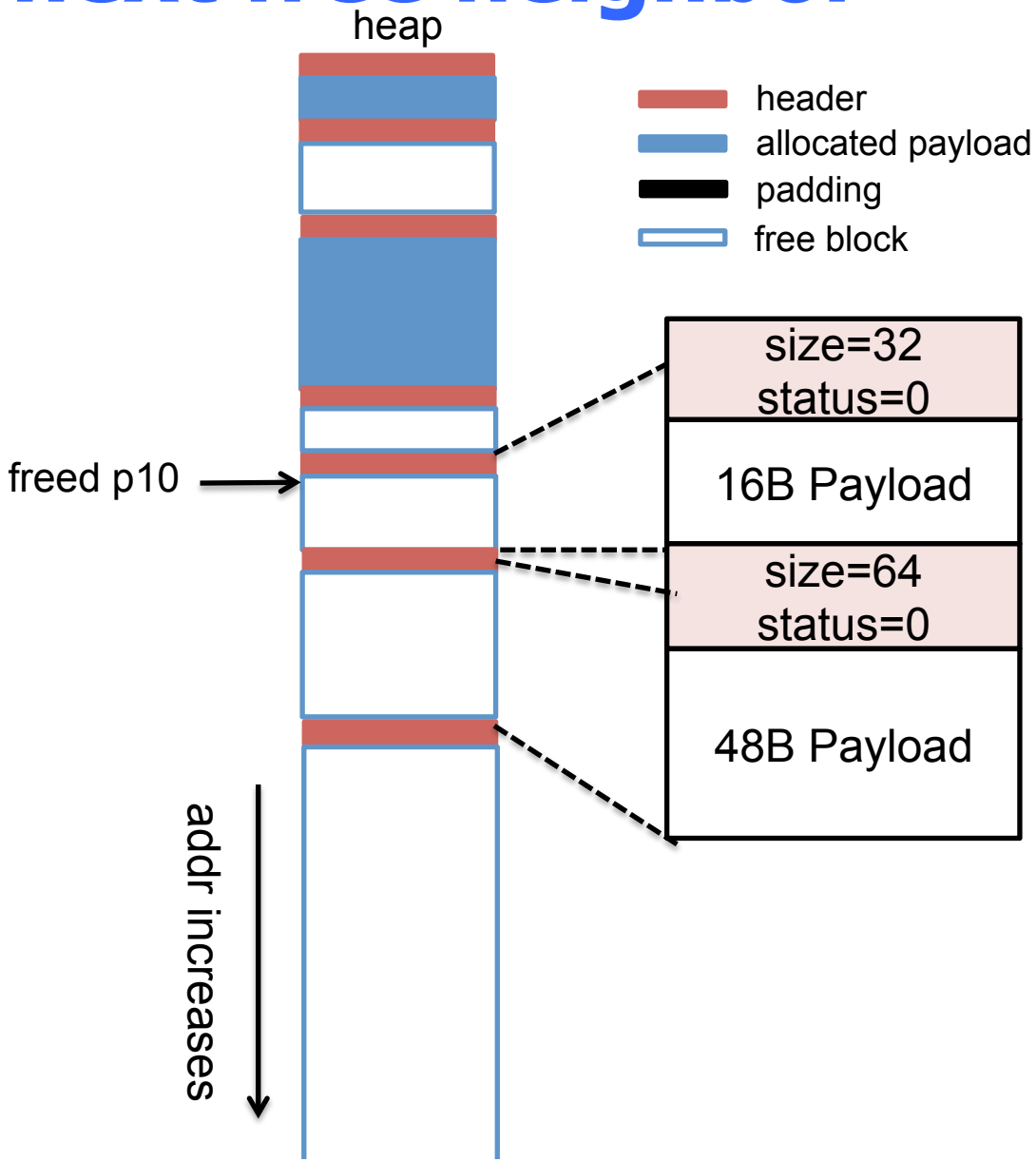
Coalescing a free block with its next free neighbor

```
...
free(p10)
```

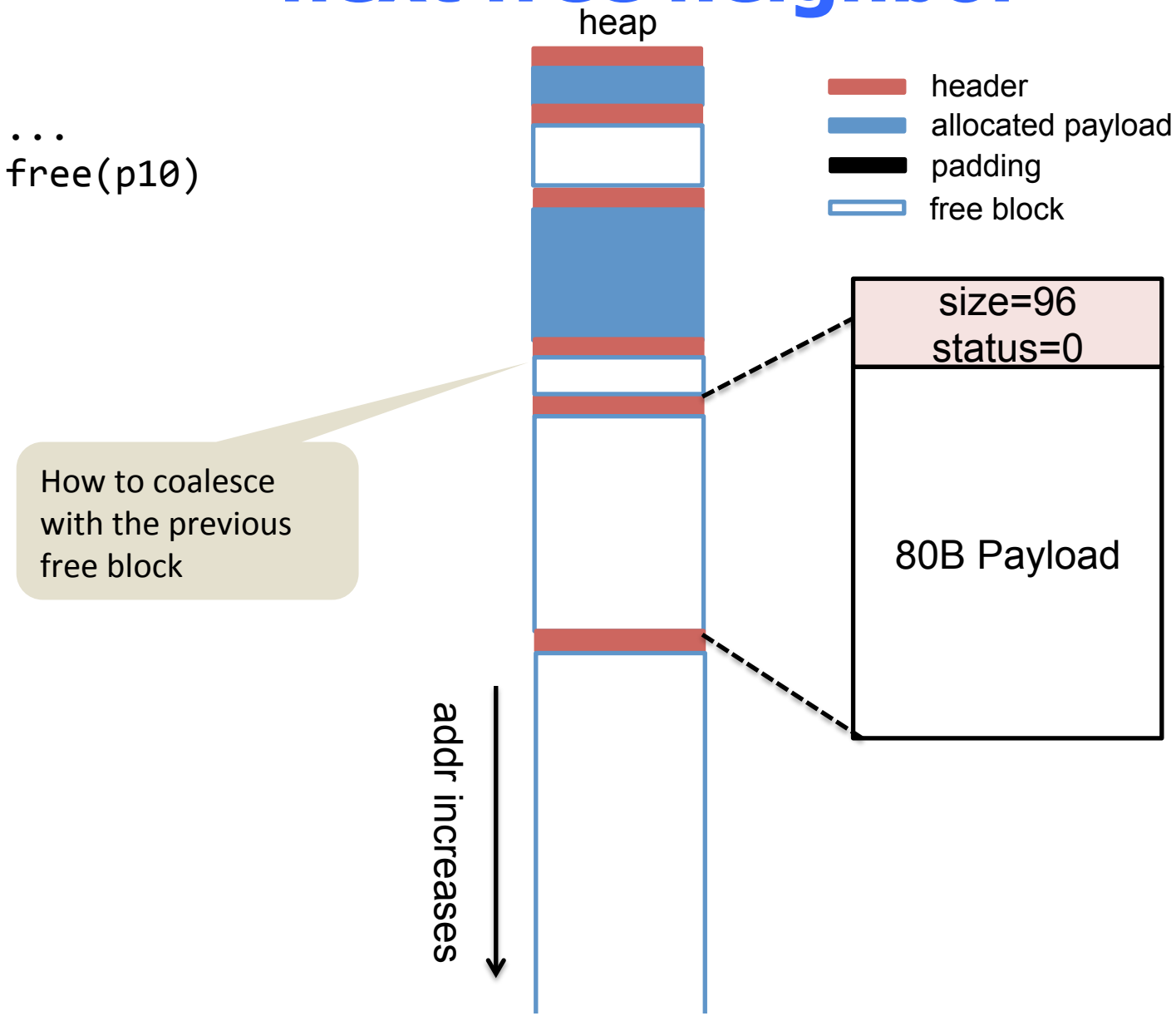


Coalescing a free block with its next free neighbor

```
...
free(p10)
```



Coalescing a free block with its next free neighbor



implicit list impl (lab 4)

unsigned long

```
typedef struct {
  size_t size;
  size_t allocated;
} header_t;
```

```
int mm_init();
void *mm_malloc(size_t size);
void mm_free(void *p);
```

implicit list implementation

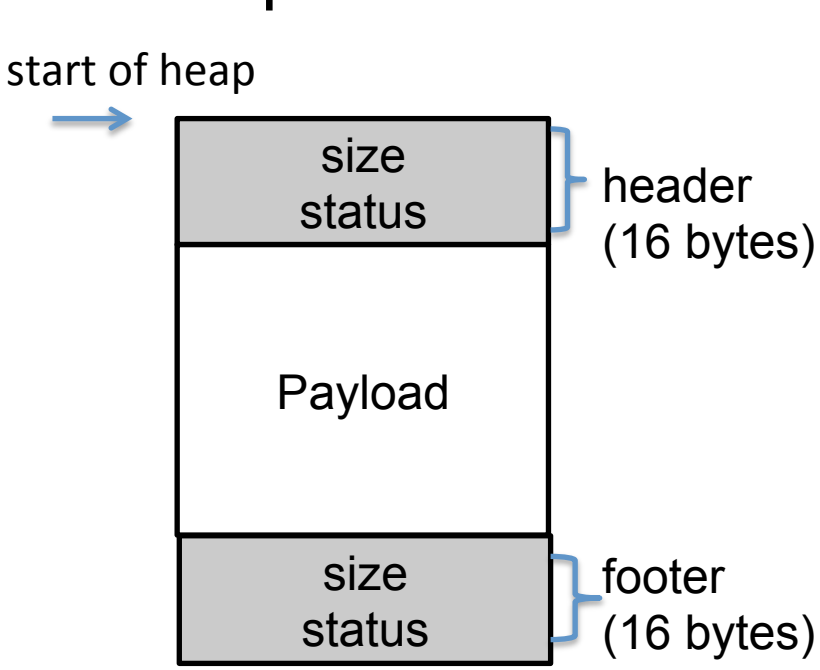
```
size_t hdr_size = sizeof(header_t);

int init() {
   return 0; //start with empty heap
}


void *mm_malloc(size_t size) {

   size = align(size);
   size_t csz = size + hdr_size;
   header_t *h = first_fit(csz); //find a free chunk
   if (!h) {
       h = ask_os_for_chunk(csz);
   } else {
       split(h, csz); //split if necessary
   }
   ... // set chunk status to be allocated
}
```

implicit list implementation

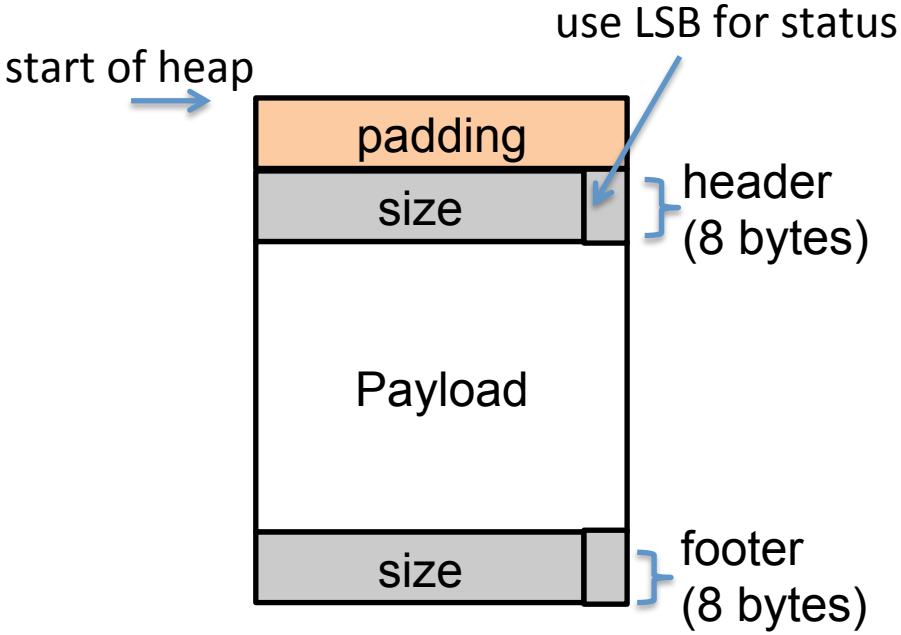
```
header_t *payload2header(void *p) {


}


void *mm_free(void *p) {
   header_t *h = payload2header(p);
   ... //set chunk status to be free
   coalesce(h);
}
```

Use footer to coalesce with previous block

- Duplicate header information into the footer



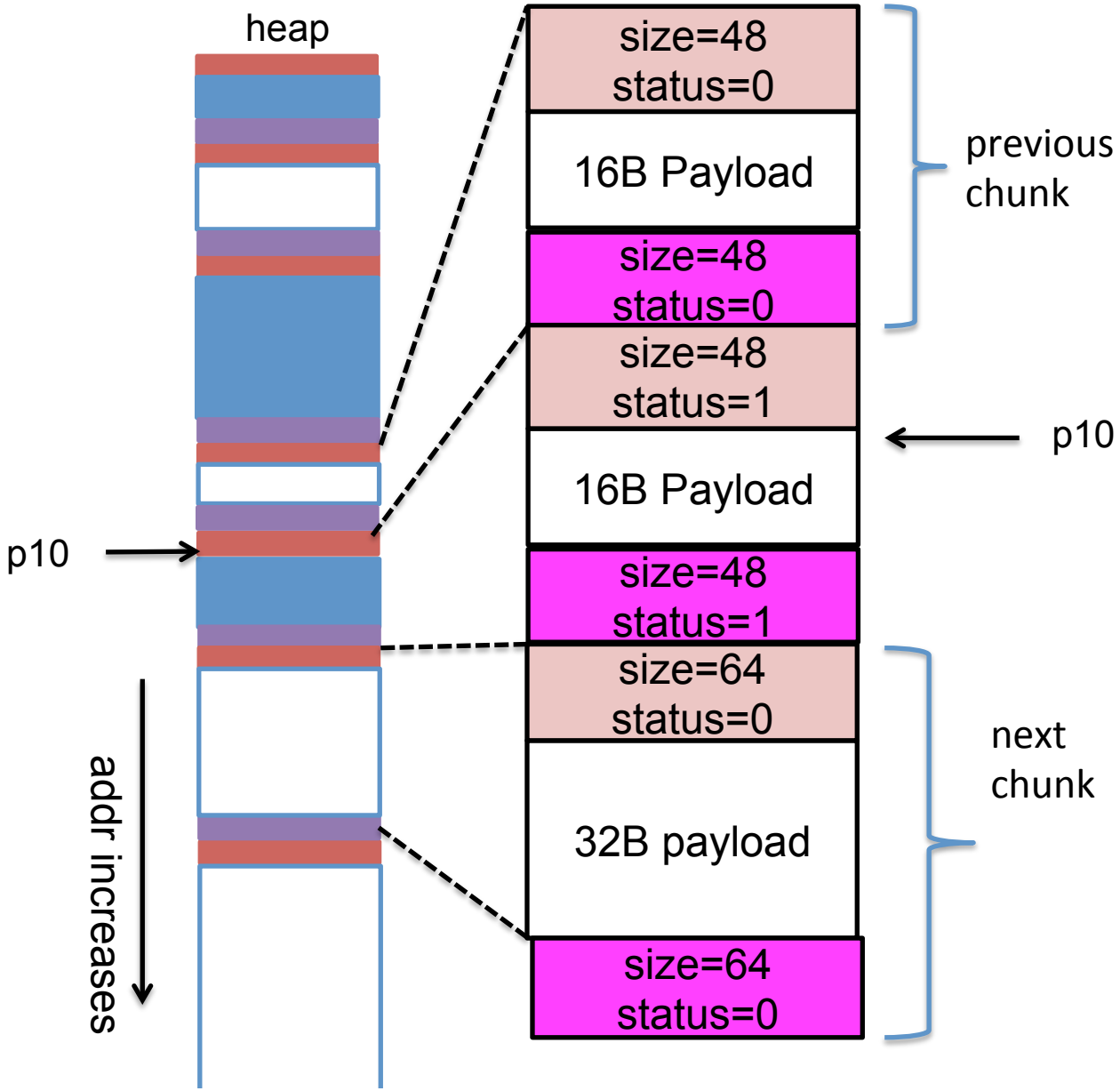
design 1: super easy



design 2: less header overhead

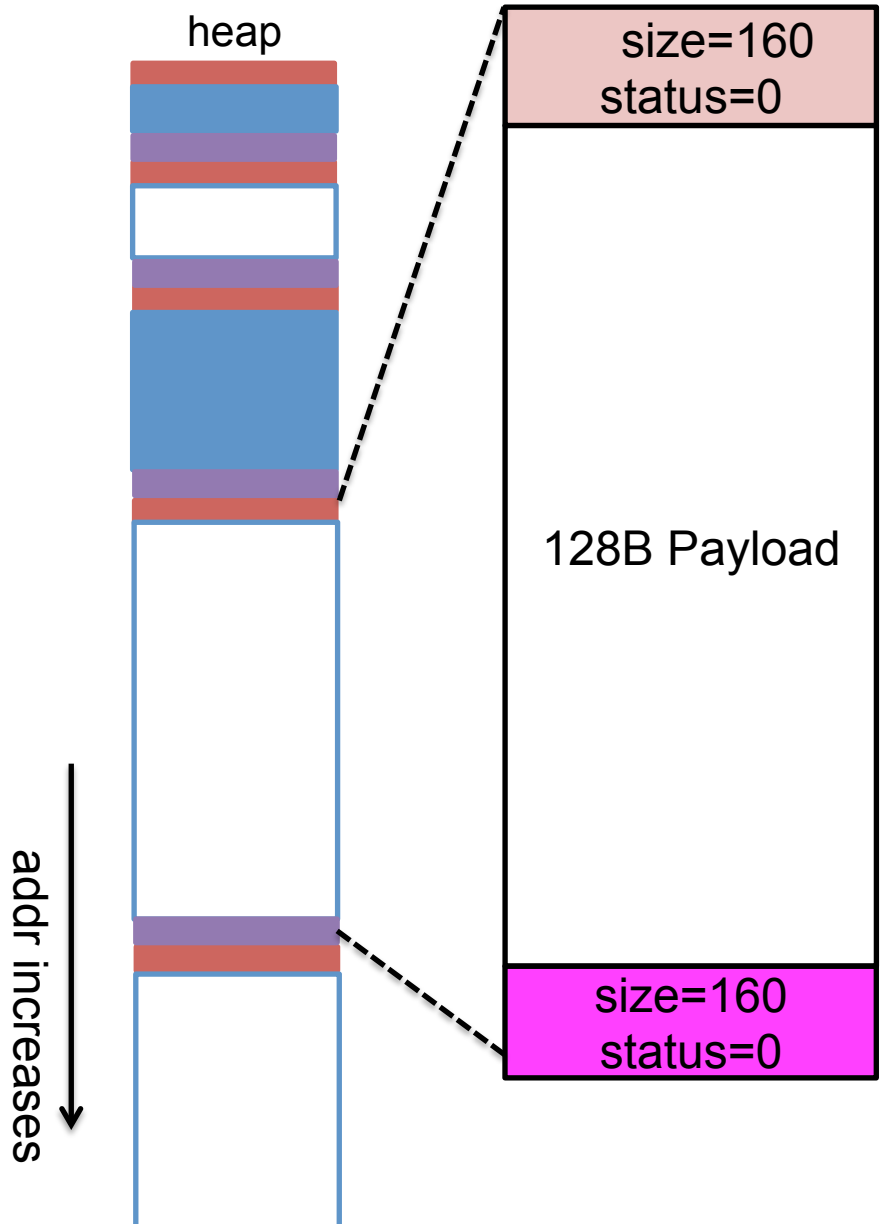
Coalescing prev and next blocks

```
...
free(p10)
```

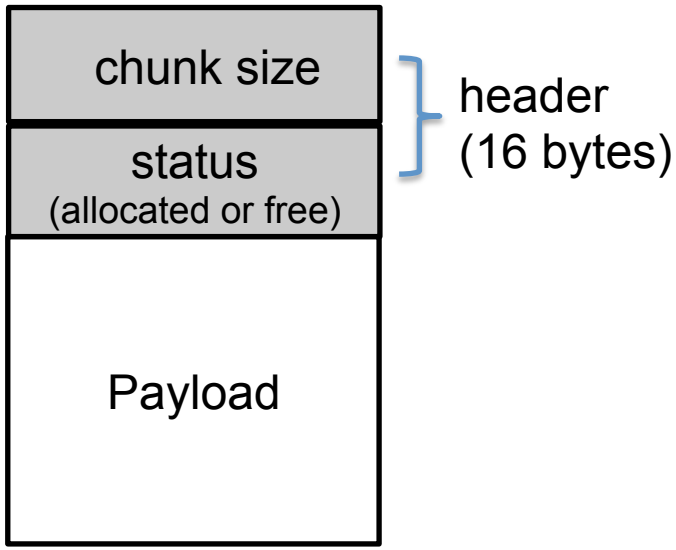


Coalescing prev and next blocks

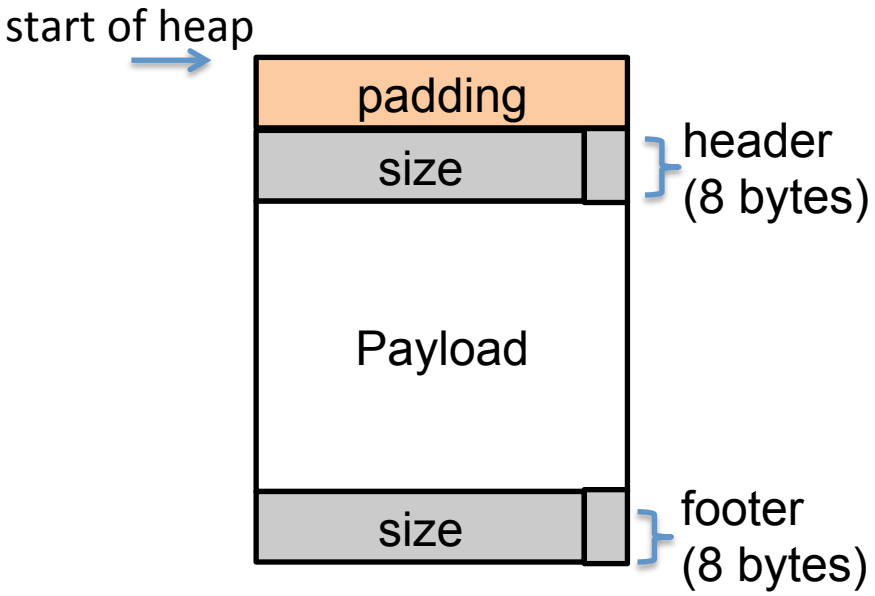
```
...
free(p10)
```



Recap: malloc using implicit list



Design without footer



Design with footer

Explicit free lists

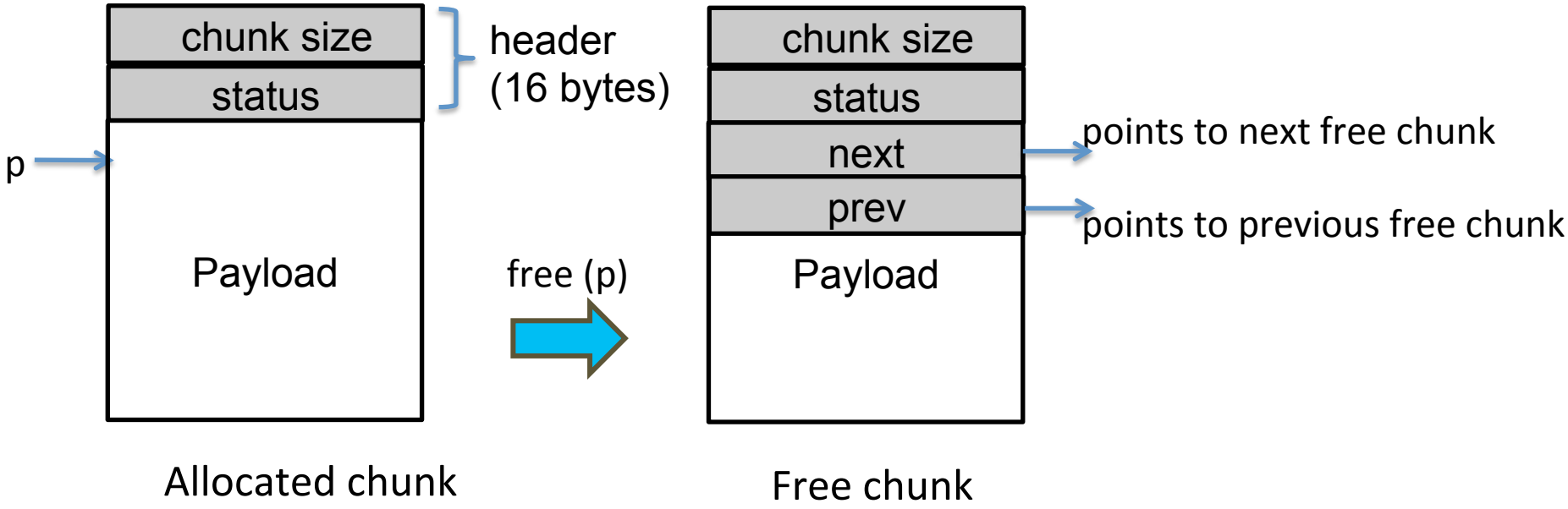
Problems of implicit list:

- Allocation time is linear in # of total (free and allocated) chunks

Explicit free list:

- Maintain a linked list of free chunks only.

Explicit free list



Add footer to coalesce with previous chunk during free

- Question: do we need next/prev fields for allocated blocks?

Answer: No. We do not need to chain together allocated blocks. We can still traverse all blocks (free and allocated) as in the case of implicit list.

- Question: what's the minimal size of a chunk?

Answer: 8 (header) + 8 (footer) + 8 (next pointer) + 8 (previous pointer) = 32 bytes

Explicit list: types, globals, initialization

```
typedef struct {
   size_t size;
   size_t status;
}hdr_t;

typedef struct free_hdr_t {
   hdr_t header;
   struct free_hdr *next;
   struct free_hdr *prev;
} free_hdr_t;
```

```
free_hdr_t *freelist;
```

```
void init() {
   freelist = NULL;
}
```

Explicit list: globals, initialization

```
void *malloc(size_t size) {
   size = align(size);
   size_t csz = sizeof(hdr_t) + size;        //size of chunk to allocate

   free_hdr_t *h = first_fit(csz);
   if (!h) {
      h = ask_os_for_chunk(csz);
   } else {
      split(h);                              //split if necessary
   }
   return  (char *)h + sizeof(hdr_t);        //return pointer to payload
}
```

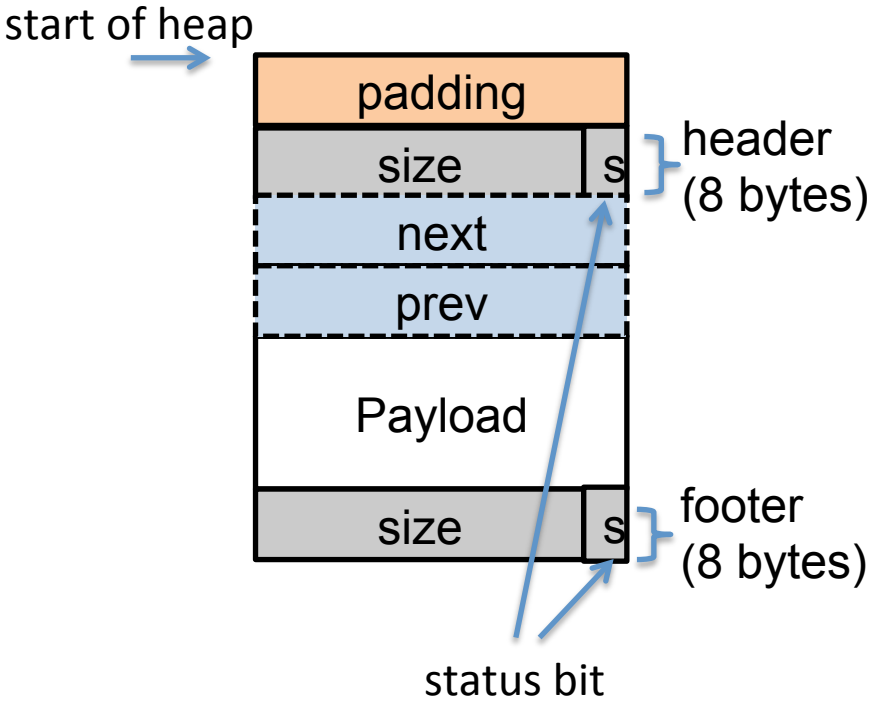
Explicit list: find a chunk

```
void list_insert(free_hdr_t **head, free_hdr_t *node) {
   ...
}

void list_delete(free_hdr_t **head, free_hdr_t *node) {
   ...
}

//find a chunk in freelist whose size is >= csz
//detach the found chunk from freelist
free_hdr_t *
first_fit(size_t csz) {
    free_hdr_t *curr = freelist;

    while (curr) {
       if (curr->header.size) >= sz) {
          list_delete(&freelist, curr);
          return curr;
       }
       curr = curr->next;
    }
    return NULL;

}
```

Explicit list: free

```
void free(void *p) {
    header *h = payload2header(p);
    init_free_chunk((free_hdr_t *)h, h->size);

    coalesce(h);
    list_insert(&freelist, h);
}


void init_free_chunk(free_hdr_t *h, size_t sz) {
   h->next = h->prev = NULL;
   h->status = 0;
   h->size = size;
}

void coalesce(free_hdr_t *h) {

   header_t *next = next_chunk((header_t)h);
   if (!next->status) {
      list_delete(&freelist, (free_hdr_t *)next);
      h->size += next->size;
   }
}
```

Explicit list with footer




```
typedef size_t hdr_t;

typedef struct free_hdr_t {
   hdr_t header;
   struct free_hdr *next;
   struct free_hdr *prev;
} free_hdr_t;
```

```
bool get_status(hdr_t *h) {
    return (*h) & 0x1L;
}

size_t get_size(hdr_t *h) {
    return (*h) & ~0x1L;
}
```

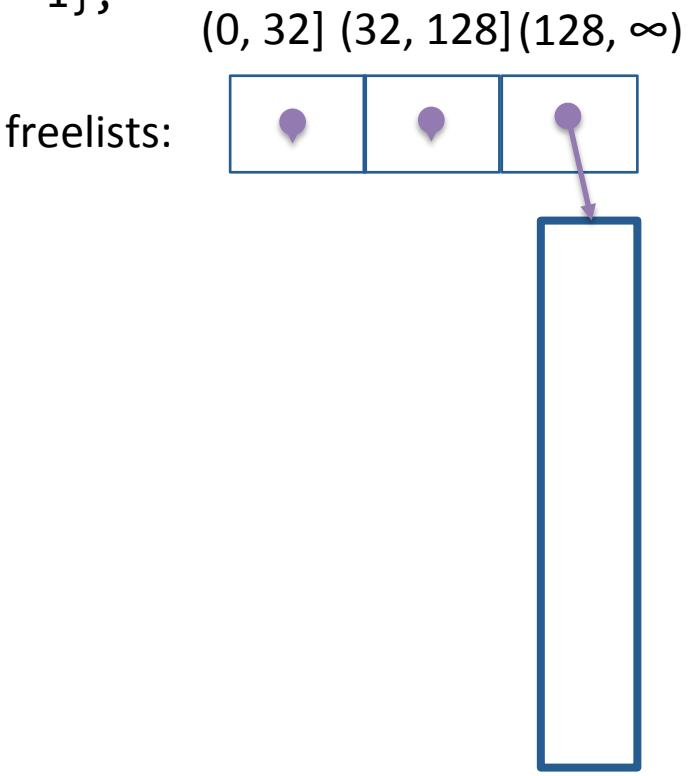
```
void set_size_status(hdr_t *h,
  size_t sz, bool status) {
  *h = sz | status;
}

void set_status(header *h, bool status){
   ...
}

void set_size(header *h, size_t sz) {
   ...
}
```

Segregated list

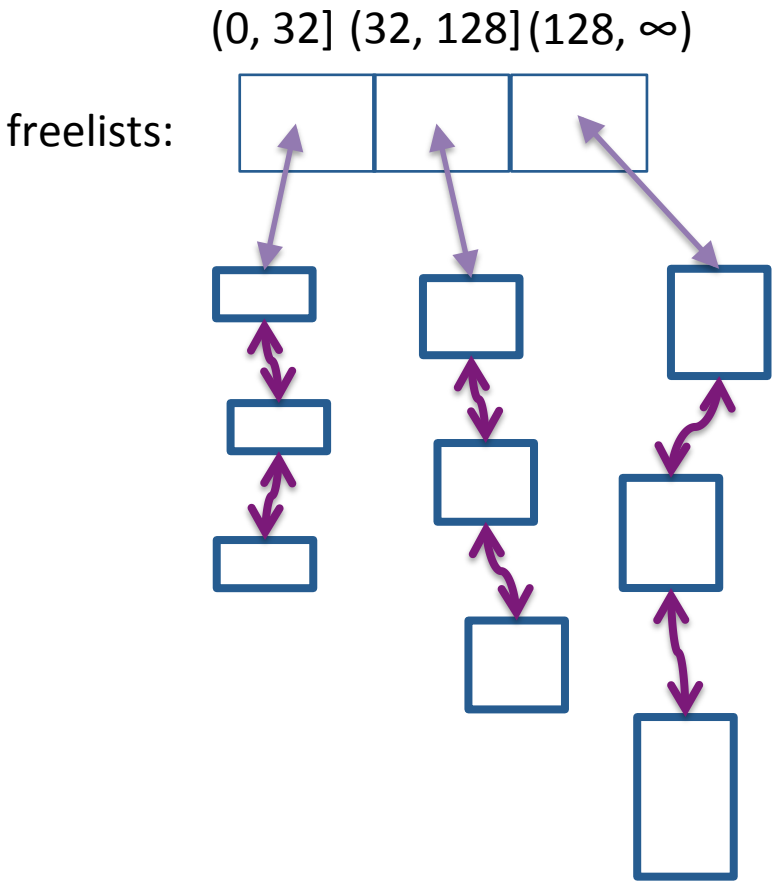
- Idea: keep multiple freelists
  - each freelist contains chunks of similar sizes

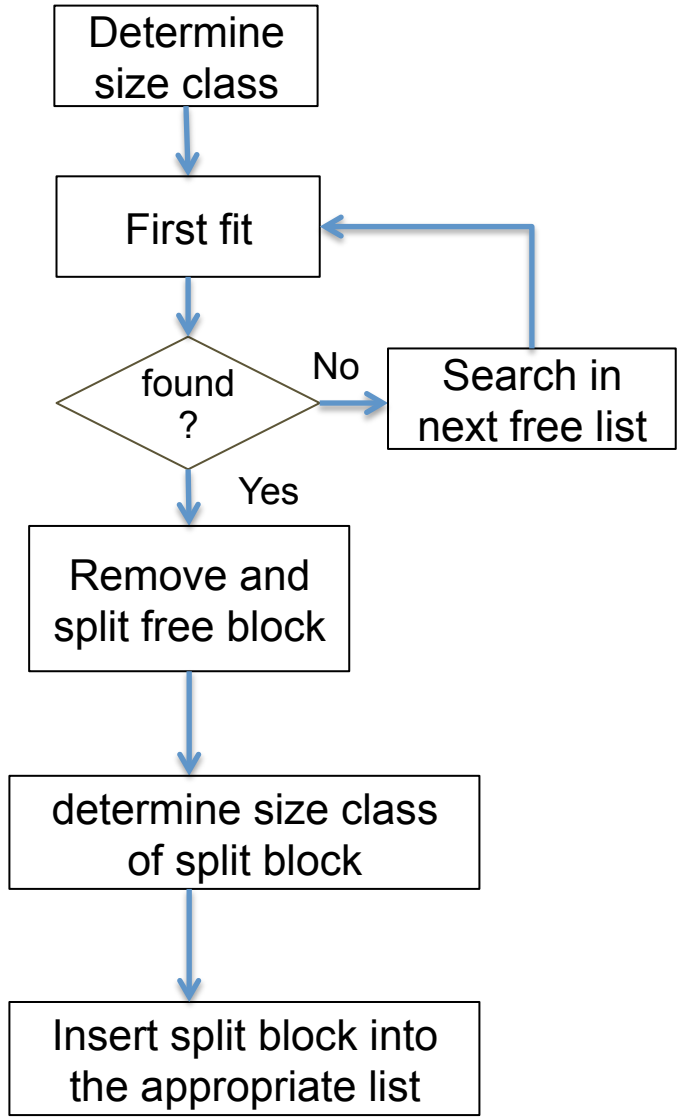
Segregated list: initialize

```
#define NLISTS 3
free_hdr* freelists[NLISTS];
size_t size_classes[NLISTS] = {32, 128, -1};

int which_freelist(size_t s) {
   int ind = 0;
   while (s > size_classes[ind])
      ind++;
   return ind;
}


 void init() {
   for (int i = 0; i < NLISTS; i++) {
      freelists[i] = NULL;
   }
 }
```

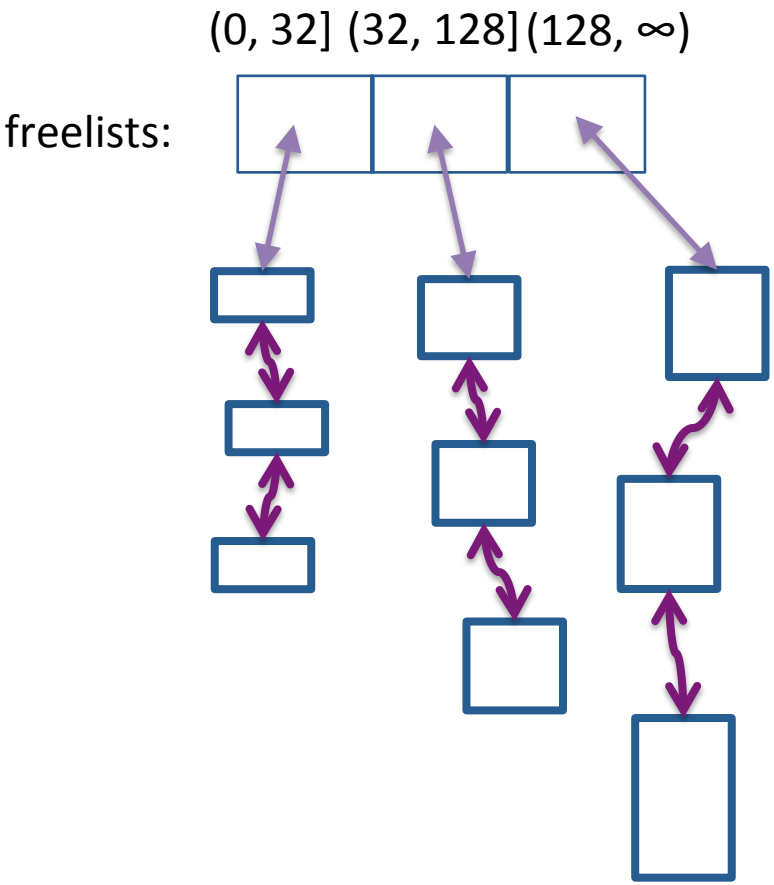


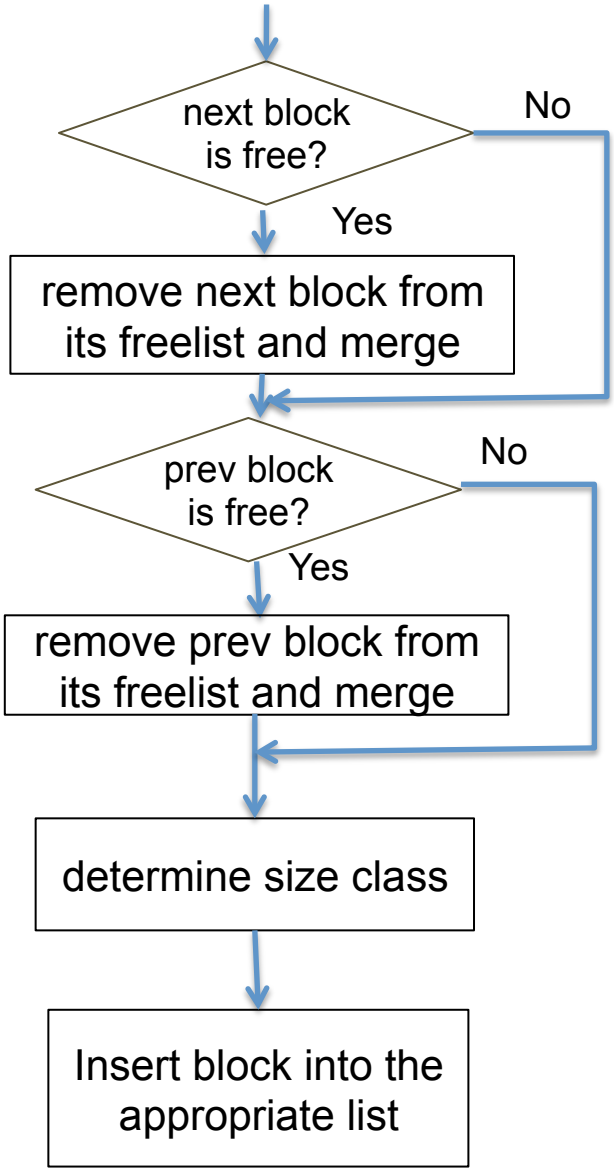
Segregated list: allocation





Segregated list: free





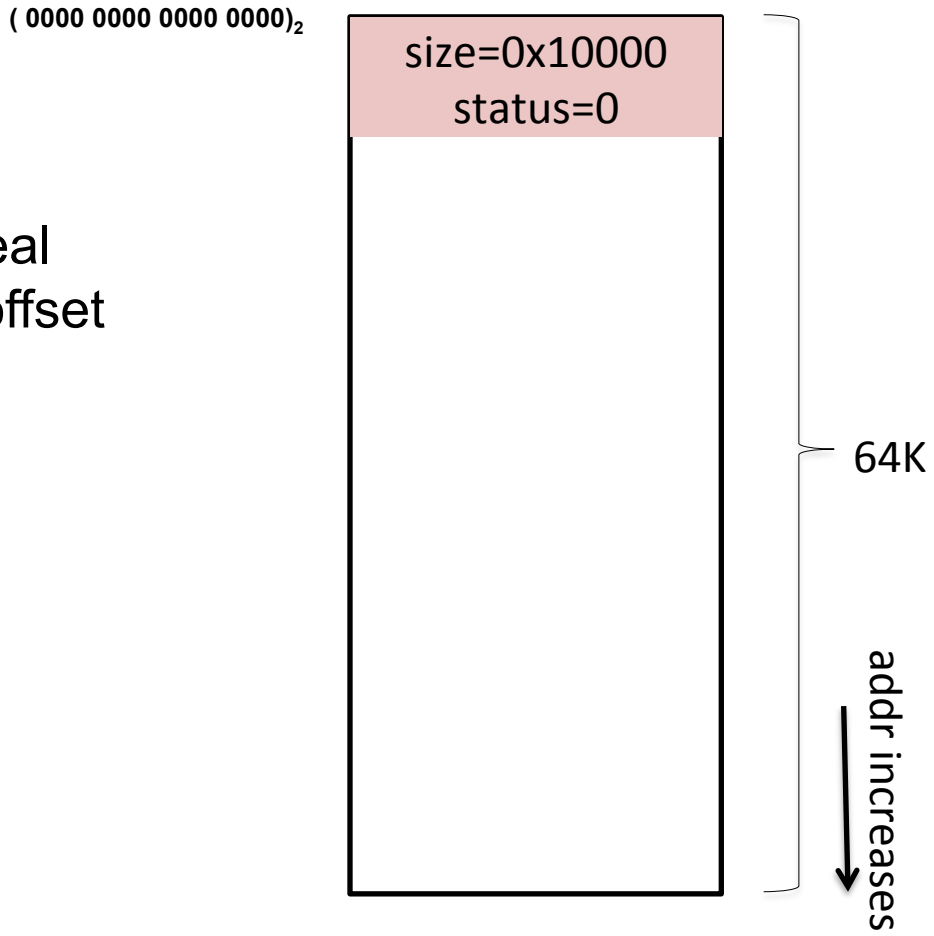
Buddy System

- A special case of segregated list
  - each freelist has *identically-sized* blocks
  - block sizes are powers of 2
- Advantage over a normal segregated list?
  - Less search time (no need to search within a freelist)
  - Less coalescing time
- Adopted by Linux kernel and jemalloc

Simple binary buddy system

Initialize:

- assume heap starts at 00...00 (real heap address is just a constant offset from 00...00)

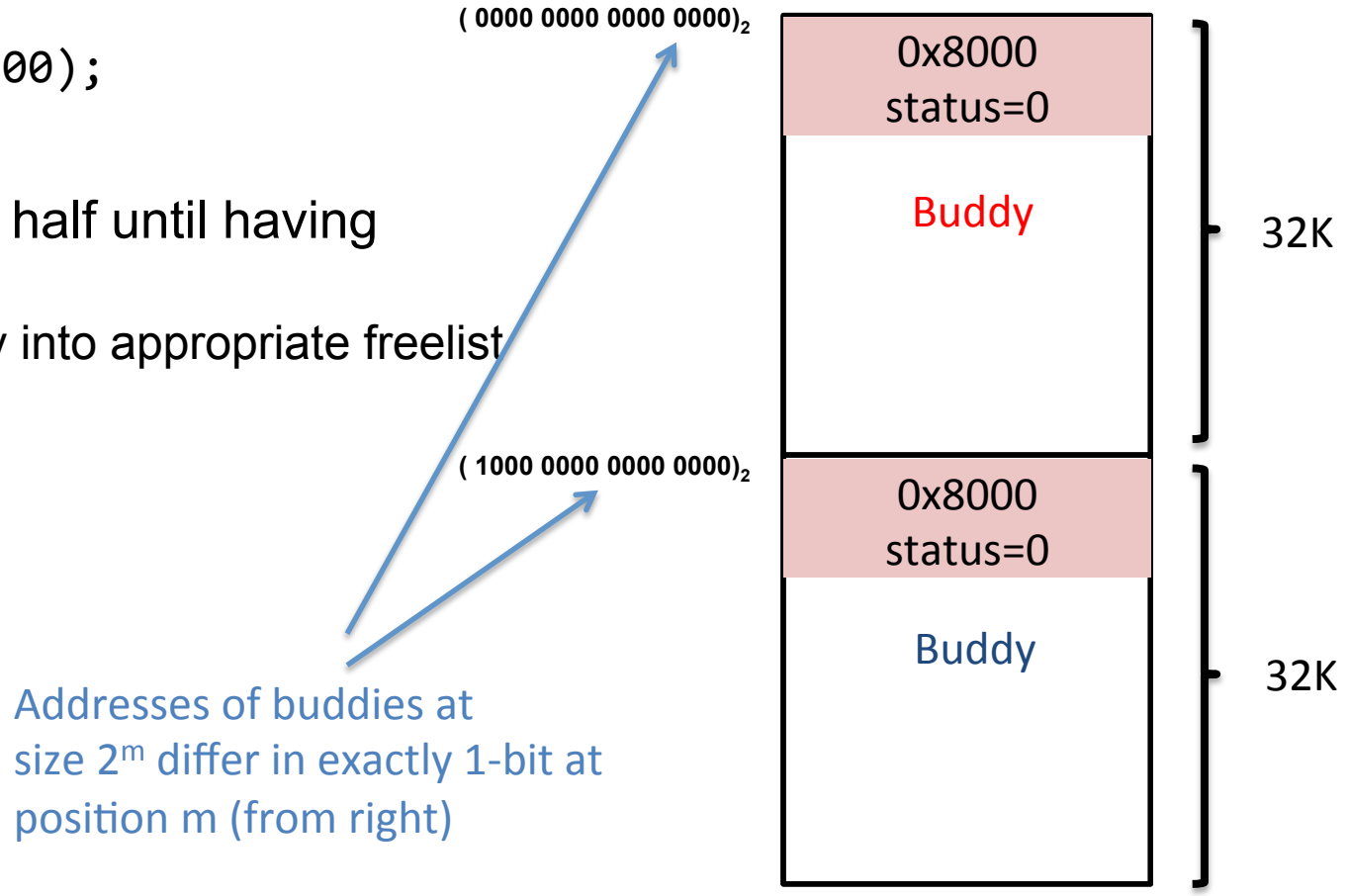


Binary buddy system: allocate

```
p = malloc(16000);
```

Recursive split in half until having the right size

- insert free buddy into appropriate freelist



Binary buddy system: allocate

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Recursive split in half until having the right size

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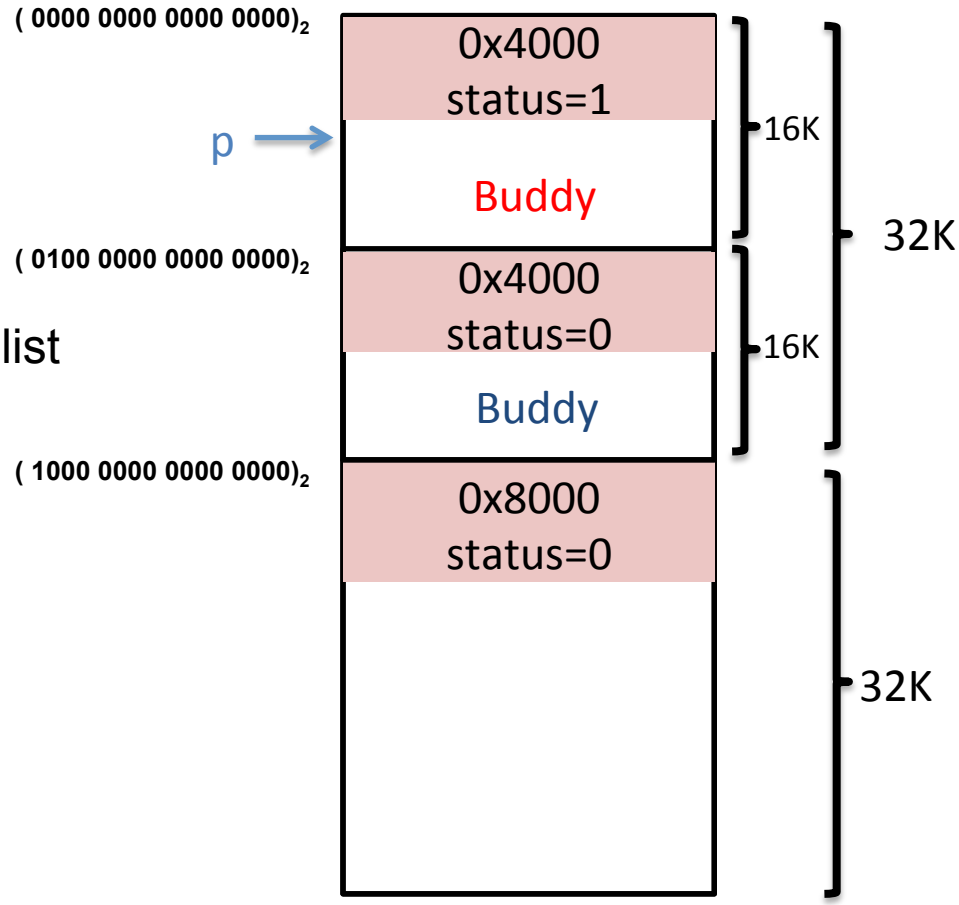


Binary buddy system: free

```
free(p);
```

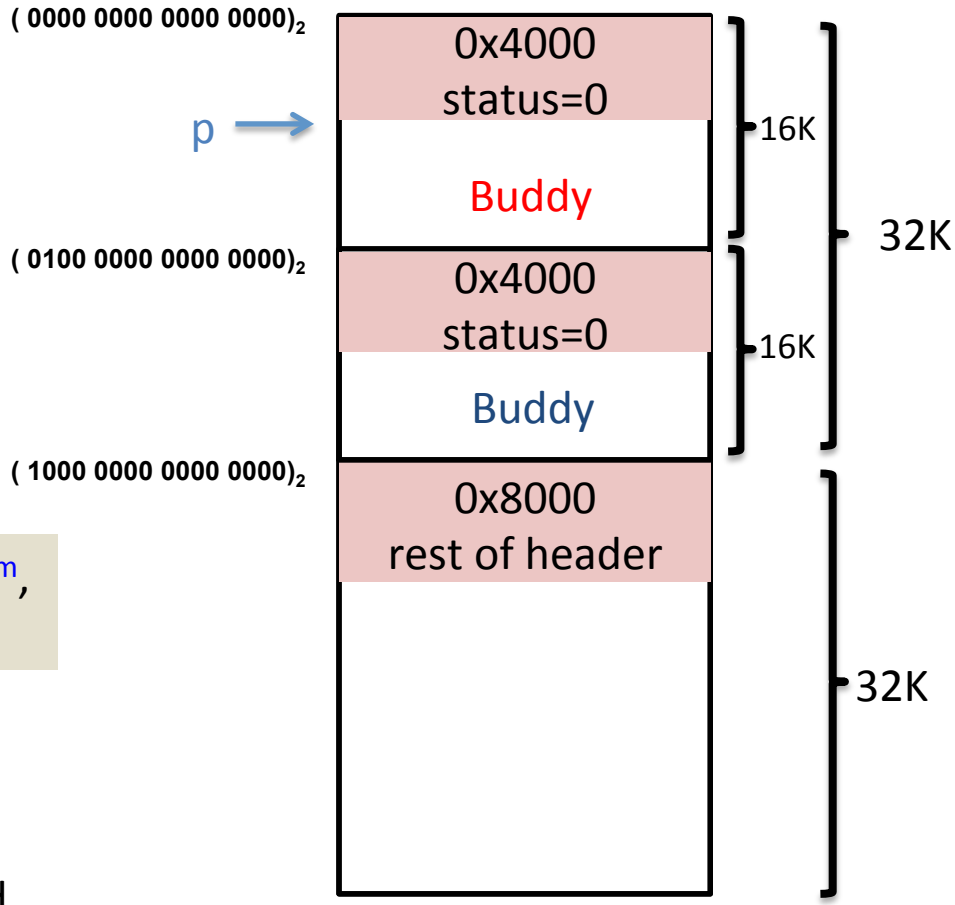
Recursively merge block with buddy

1. Calculate addr of buddy block, determine buddy status

Question: given addr a of block with size 2^m, how to calculate its buddy's address?

a ^ (1<<m)

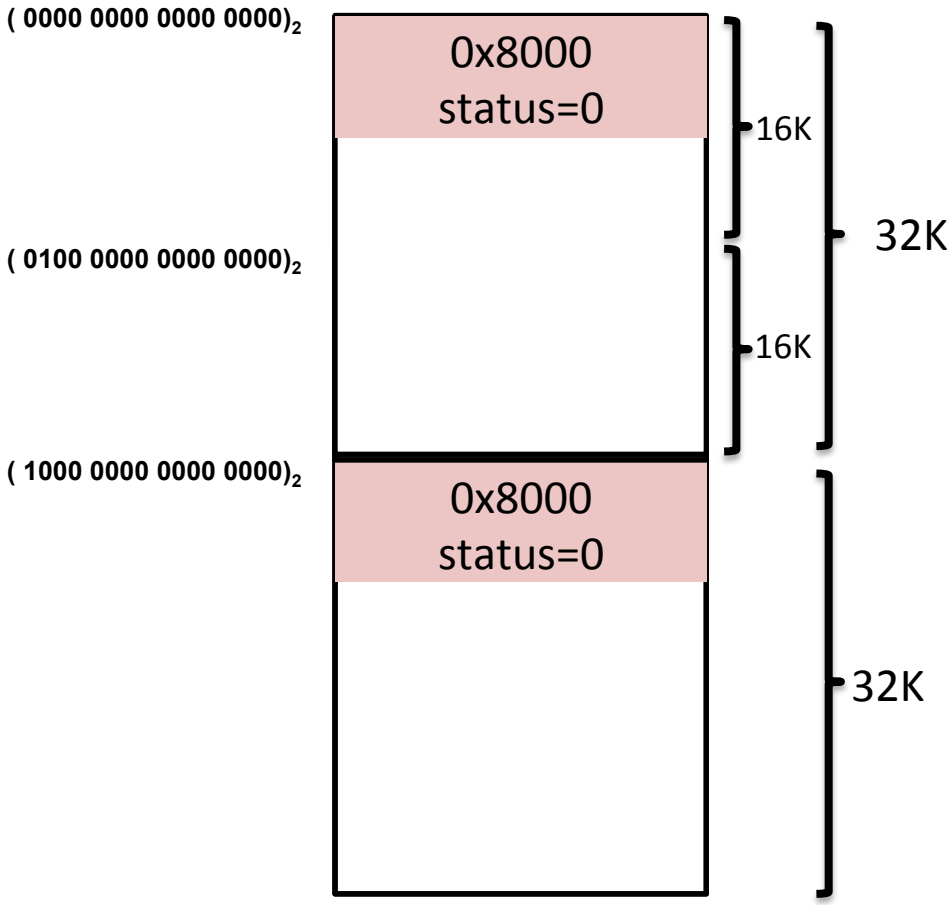
any bit XOR 0 = unchanged
any bit XOR 1 = flipped



Binary buddy system: free

```
free(p);
```

If buddy is free:
2. Detach free buddy from its list
3. Combine with current block



Binary buddy system: free

```
free(p);
```

Repeat to merge with larger buddy
Insert final block into appropriate freelist