Dynamic Memory Allocation

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based on Tiger Wang's slides

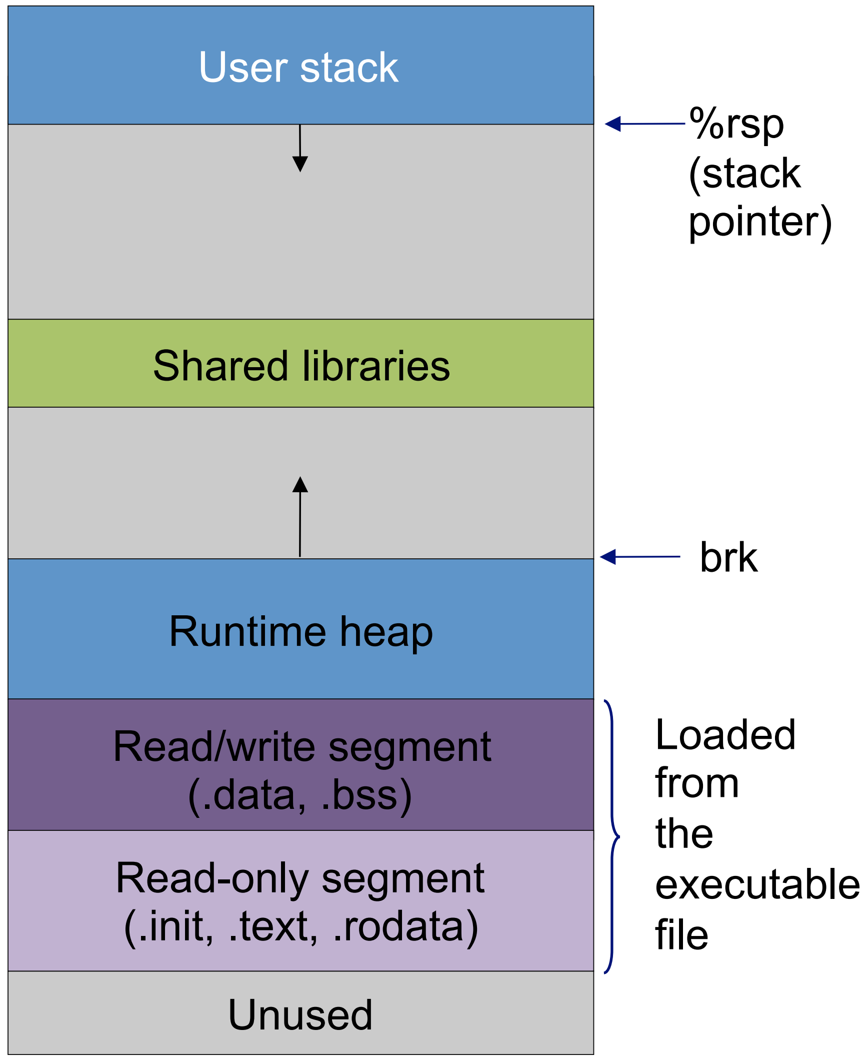
Why dynamic memory allocation?

```
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) {
   char buf[100];
   node *head = NULL;
   while (fgets(buf, 100, stdin)) {
      list_insert(&head, atoi(buf));
   }
}
```

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?

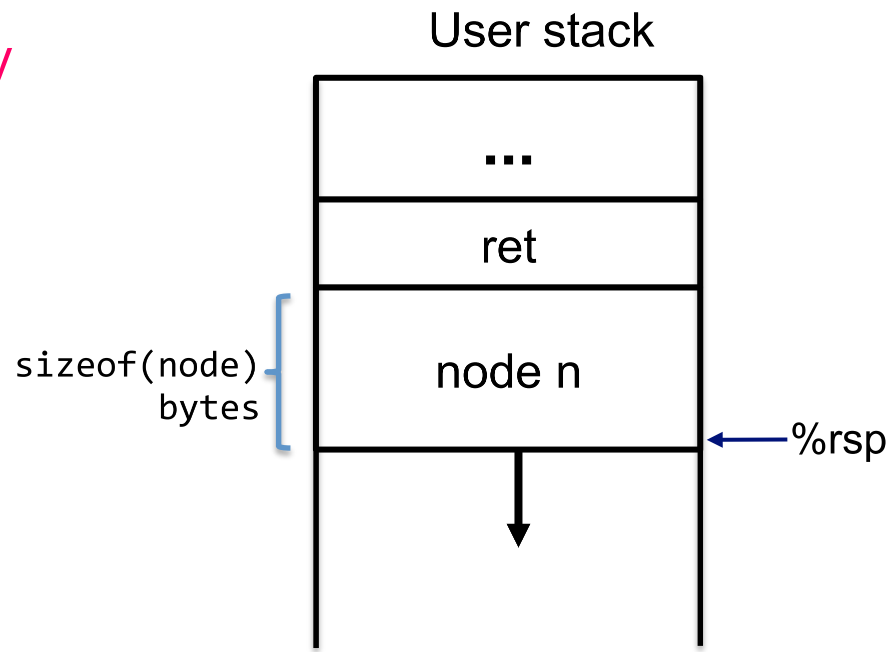


Dynamic allocation on heap

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

Answer: Yes, but space is freed upon function return

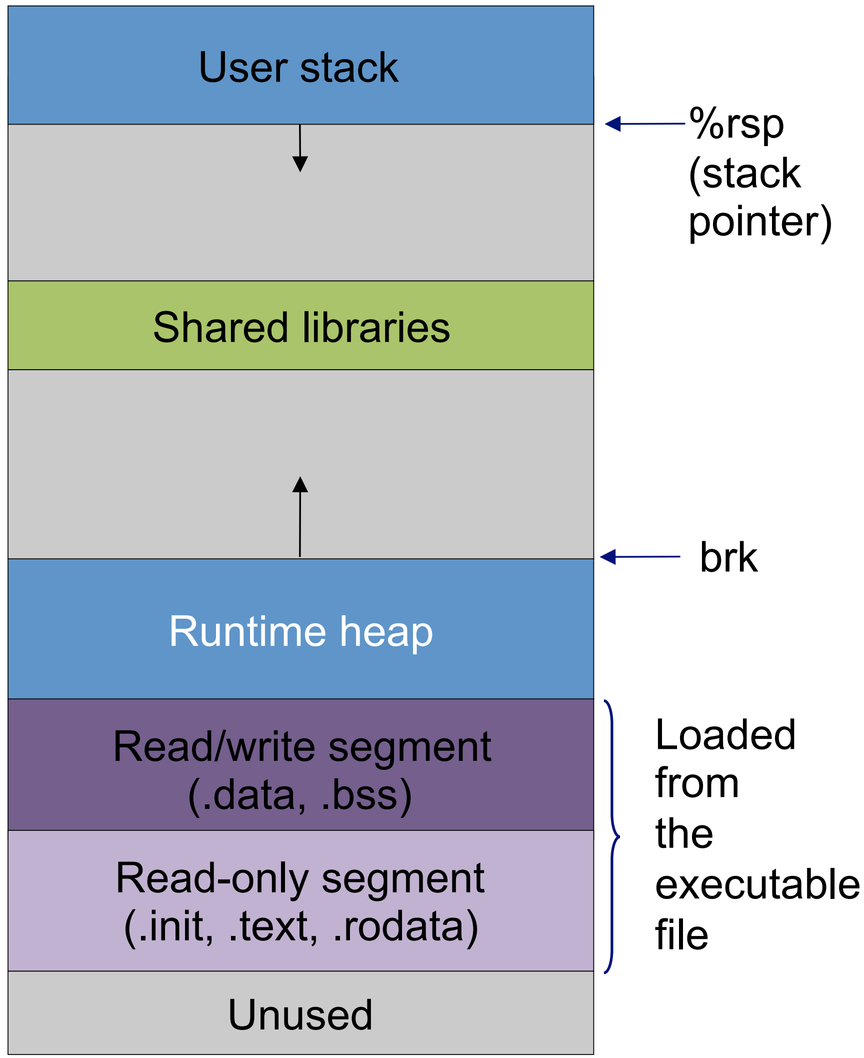
```
void
list_insert(node *head, int v) {
   node n;
   node *np = &n;
   np->next = head;
   np->val= v;
   *head = np;
}
```




```
subq $16,%rsp
```

Dynamic allocation on heap

Question: How to allocate memory on heap?



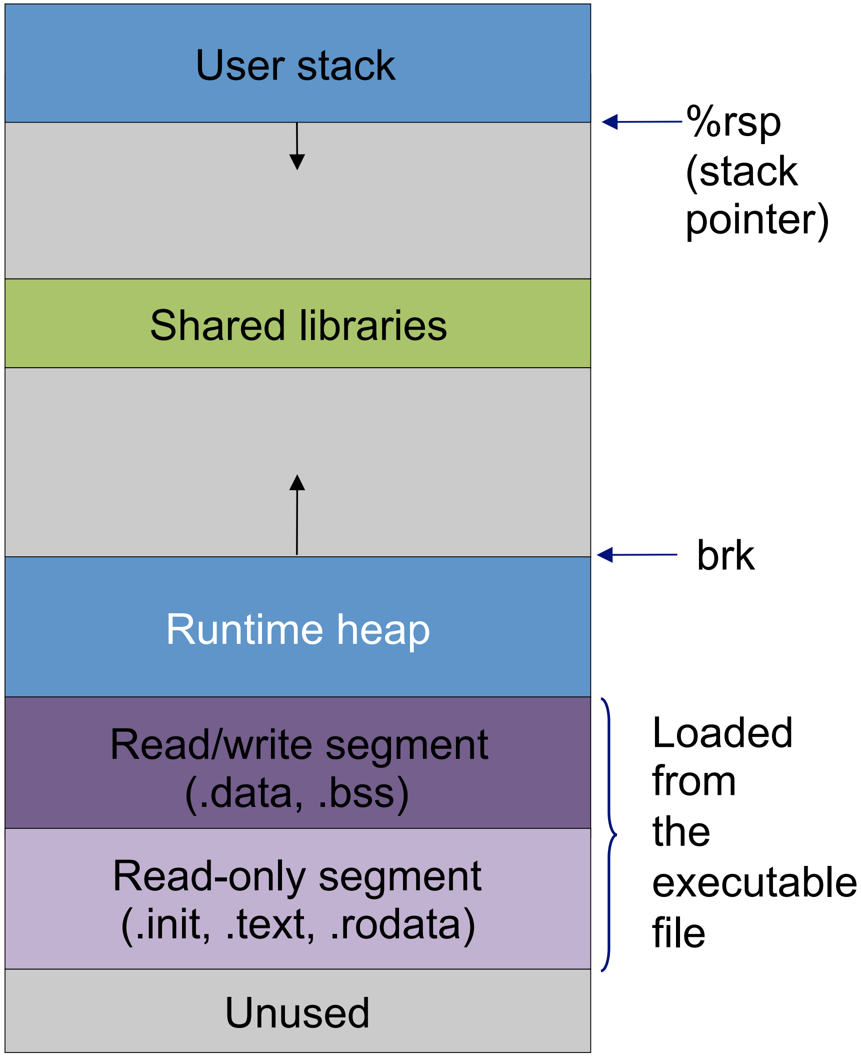
Dynamic allocation on heap

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

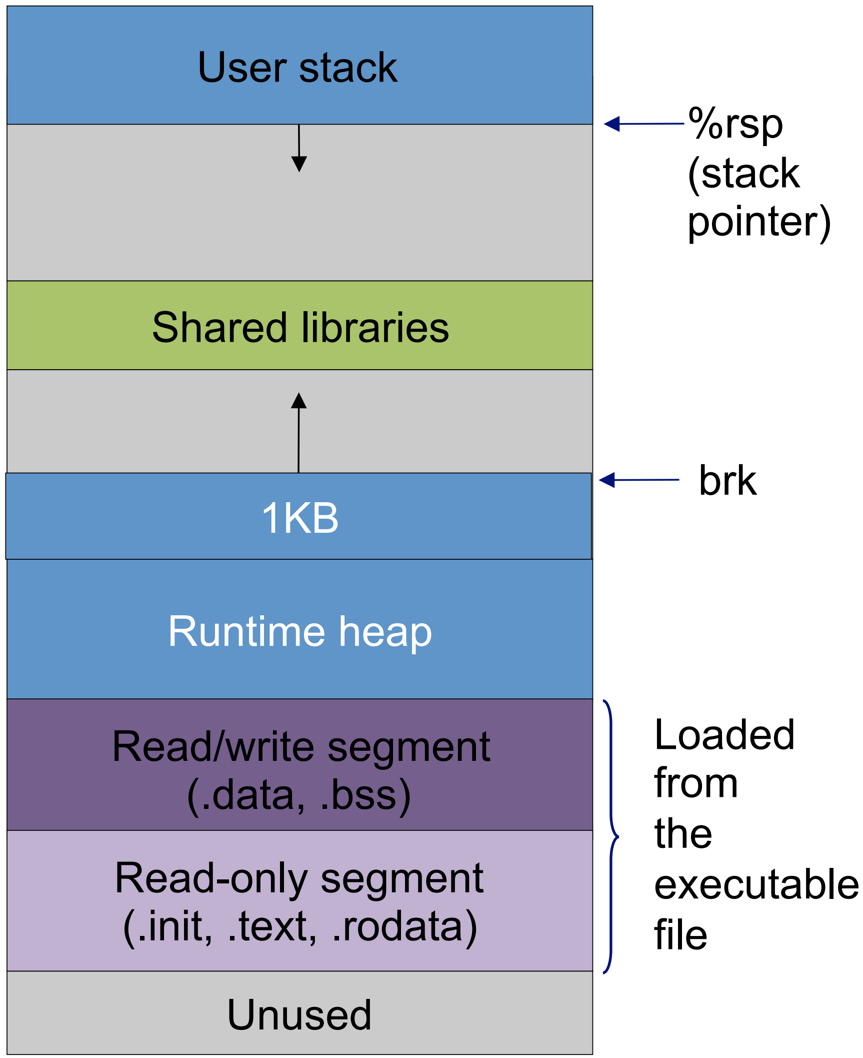
Question: How to allocate memory on heap?

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

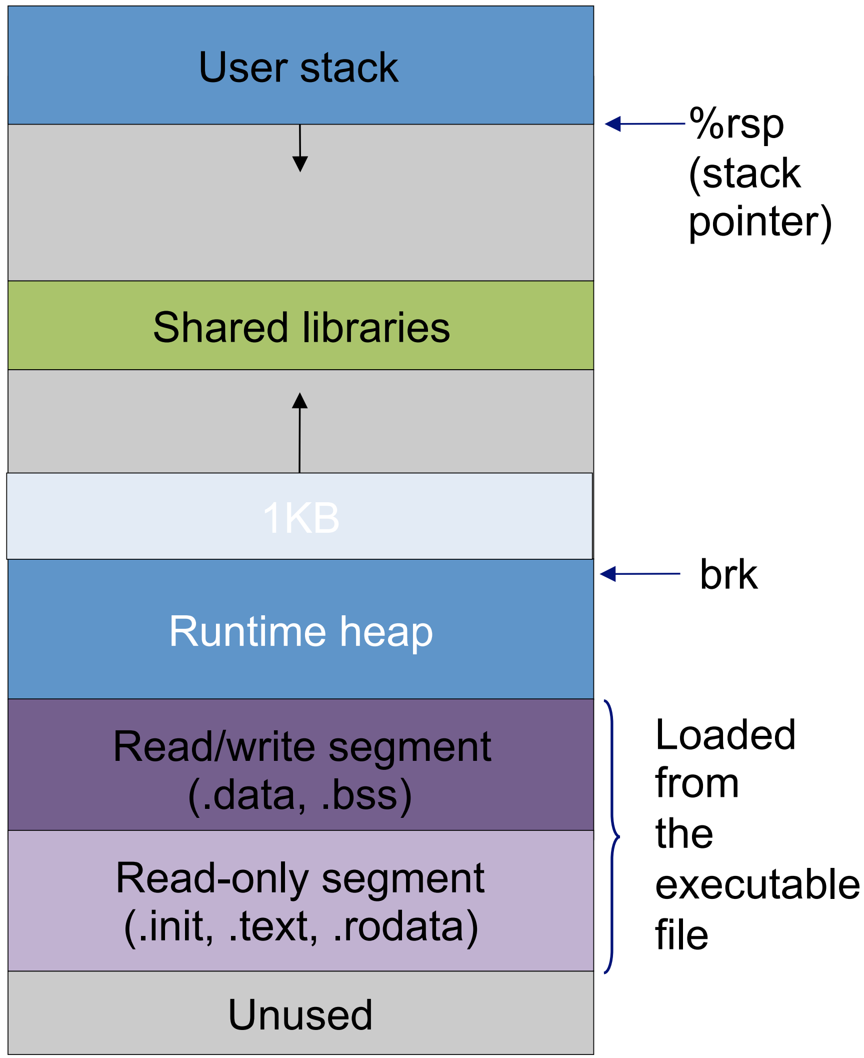
Question: How to allocate memory on heap?

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?

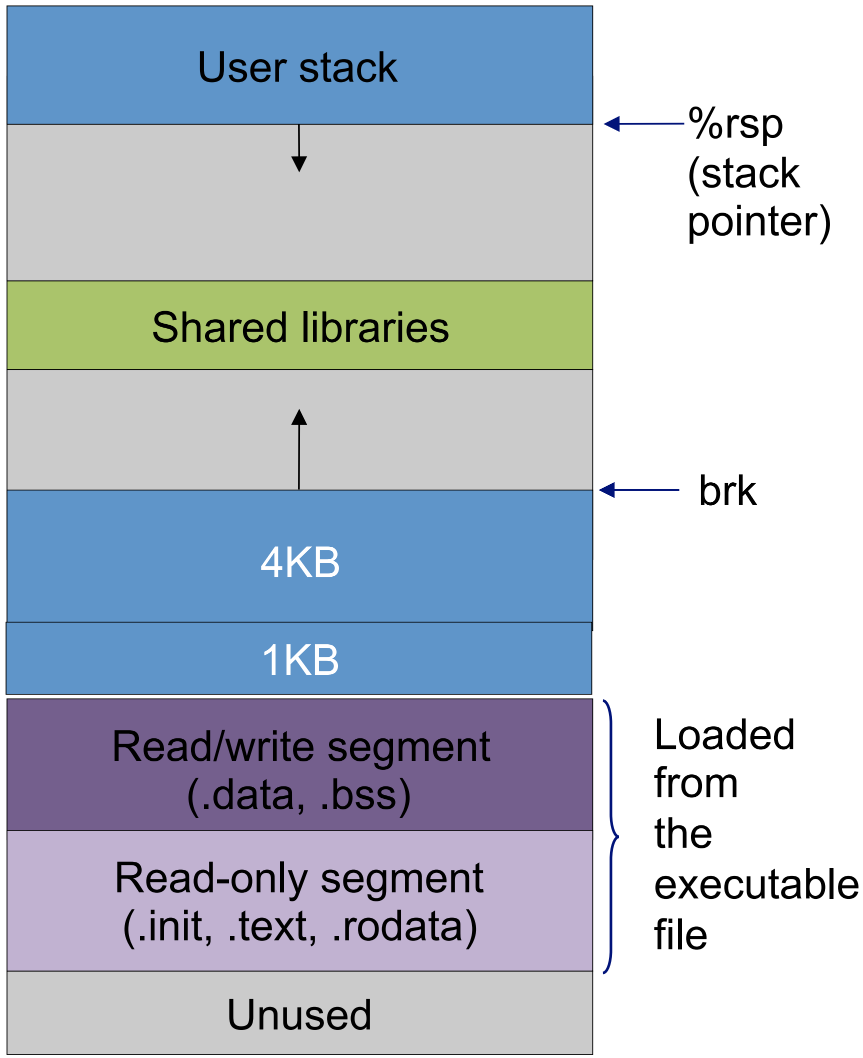
Ask OS for allocation on the heap via system calls

```
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

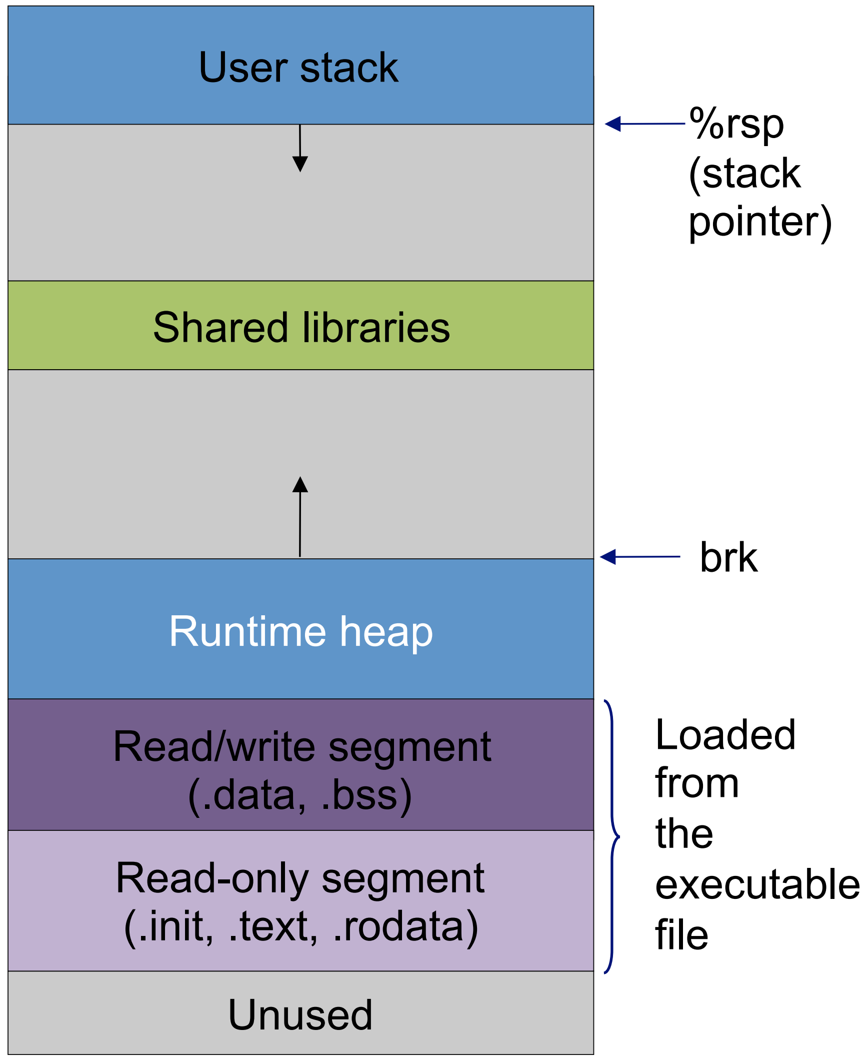
Question: How to allocate memory on heap?

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

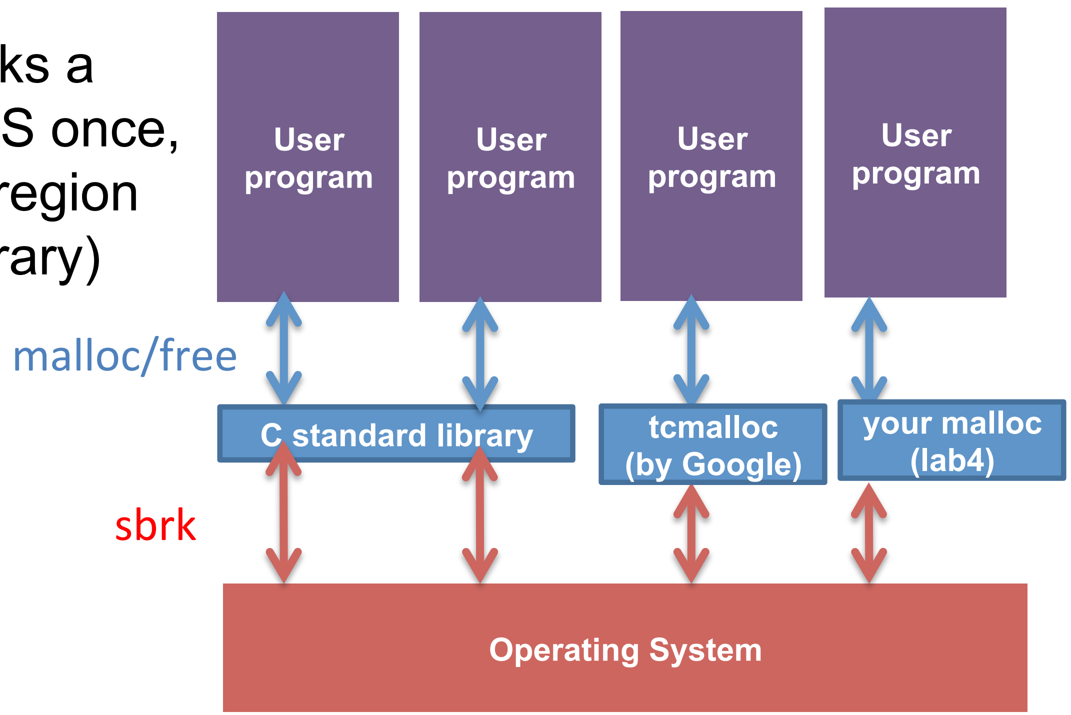
Issue II – system call has high performance cost > 10X



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

Questions

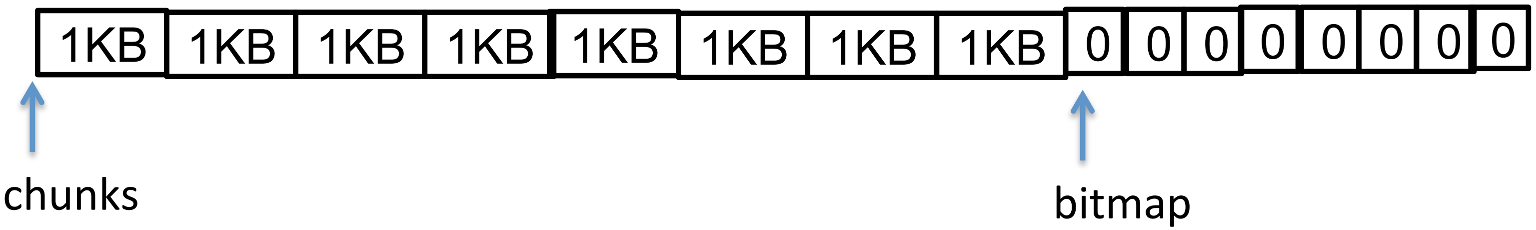
1. (Basic book-keeping) How to keep track which bytes are free and which are not?

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

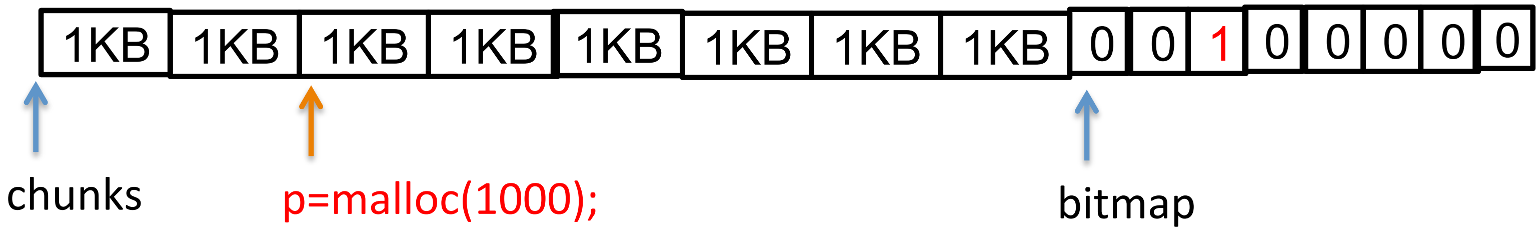
- Structure heap as n 1KB chunks + n metadata




```
#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;
}
```

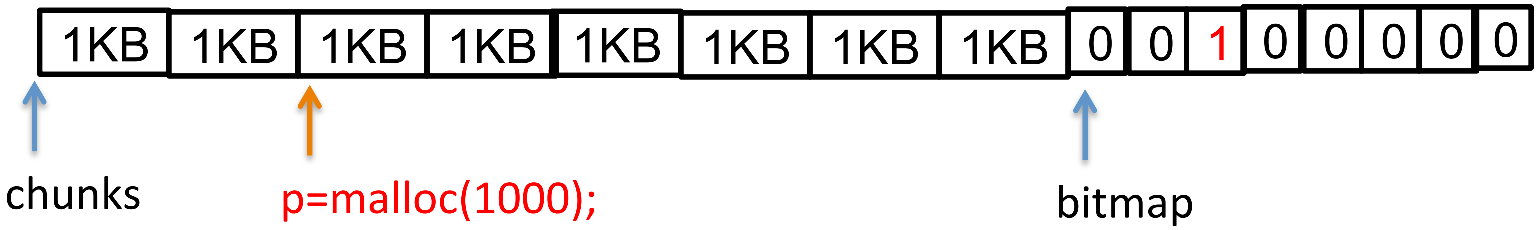
> Assume allocator asks for enough memory from OS in the beginning

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?

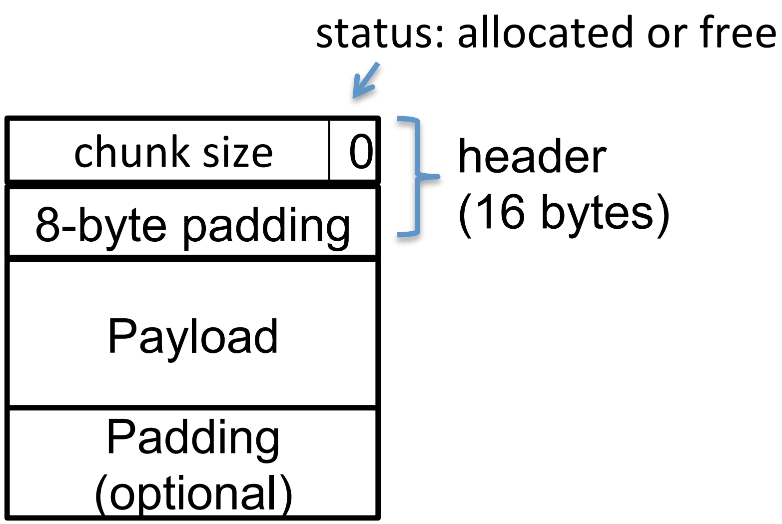
Implementing a hash table and linked list requires use of a dynamic memory allocator!

How to implement a
“linked list” without use of malloc

Implicit list

Embed chunk metadata in the chunks

- Chunk has a header storing size and status
- 16-byte aligned
  - → Chunk size (metadata+payload) is multiple of 16
  - → Header must be also aligned to 16 bytes



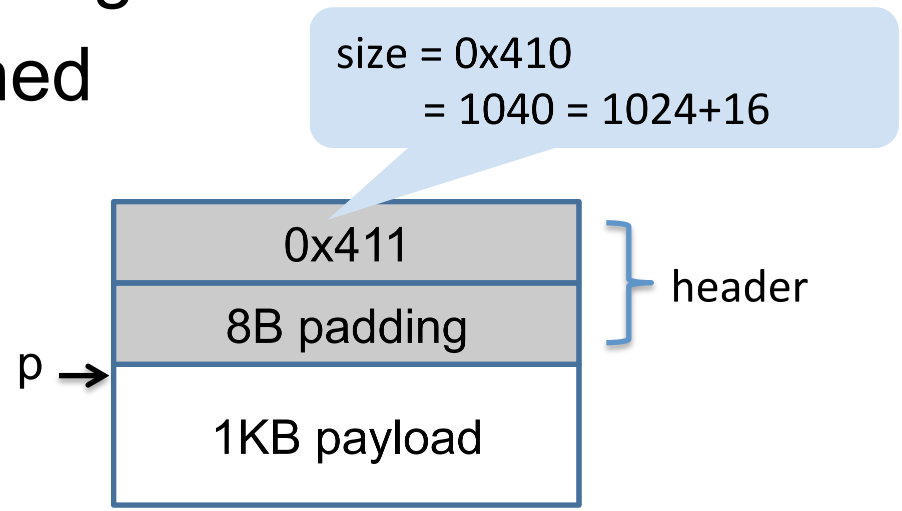
allocated: size_and_status & 0x1L
size: size_and_status & ~(0x1L)

Implicit list

Embed chunk metadata in the chunks

- Chunk has a header storing size and status
- Payload is 16-byte aligned

```
p  = malloc(1024)
```

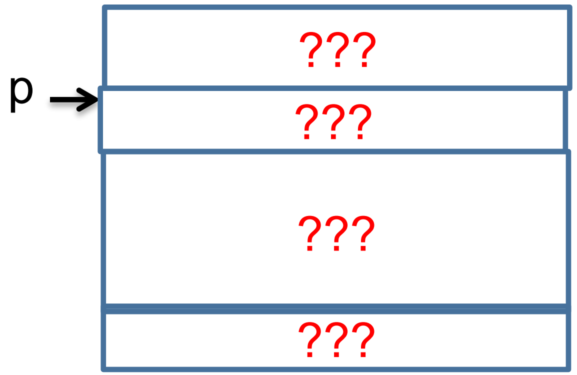


Implicit list

Embed chunk metadata in the chunks

- Chunk has a header storing size and status
- Payload is 16-byte aligned

```
p  = malloc(1)
```

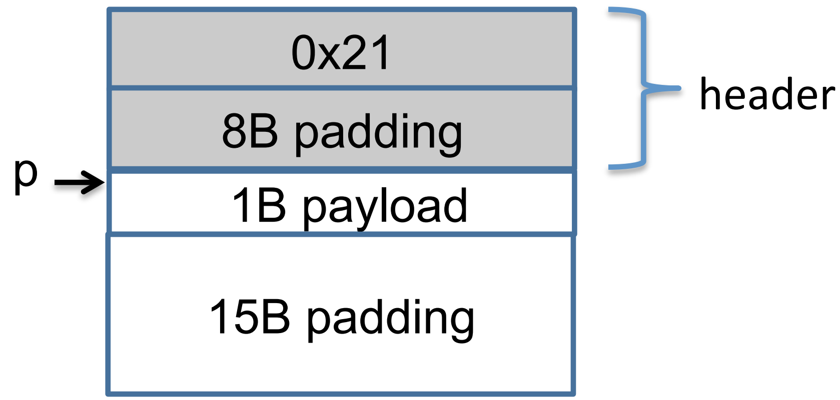


Implicit list

Embed chunk metadata in the chunks

- Chunk has a header storing size and status
- Payload is 16-byte aligned

```
p  = malloc(1)
```

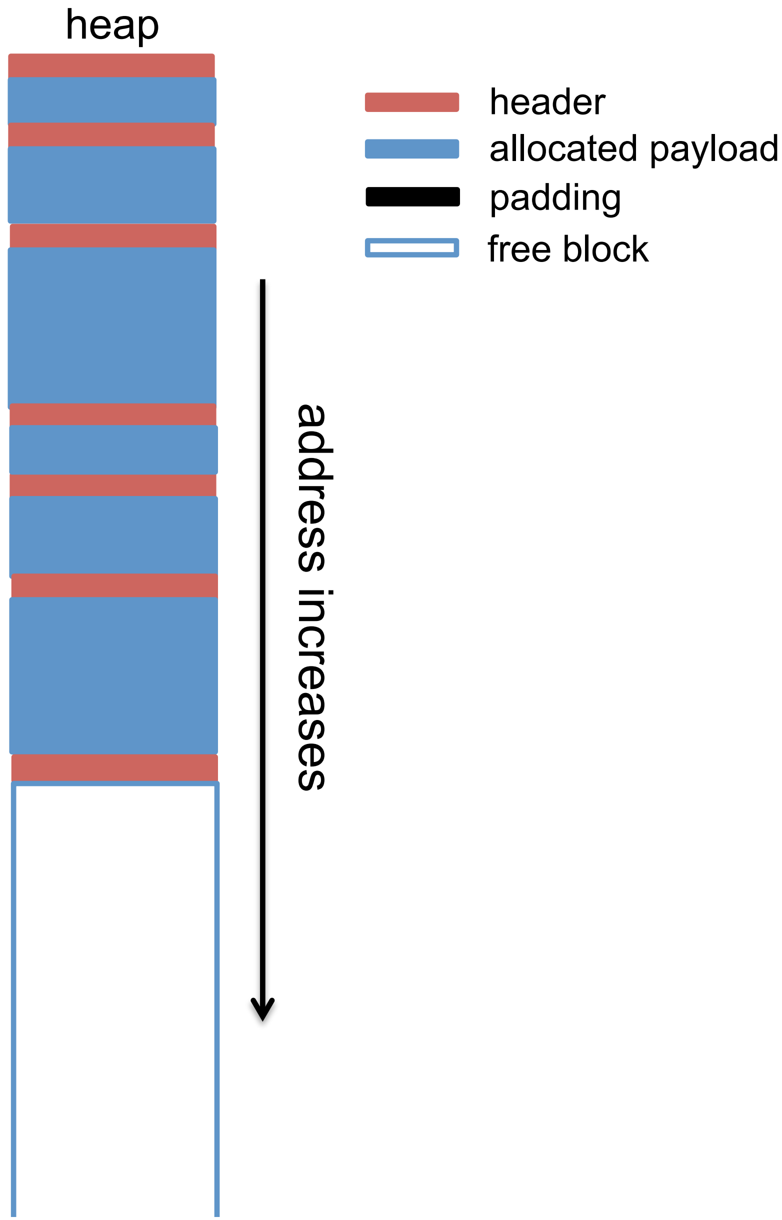


How to traverse an implicit list

```
typedef struct {
  unsigned long size_and_status;
  unsigned long padding;
} header;

void traverse_implicit_list() {
   header *curr = (header *)heap_lo();
   while ((char *)curr < heap_high()) {
       bool allocated = get_status(curr);
       size_t csz = get_chunksz(curr);
       curr = (header *)((char *)curr + csz);
   }
}
bool get_status(header *h) {
   return h->size_and_status & 0x1L;
}
size_t get_size(header *h) {
   return h->size_and_status & ~(0x1L);
}
```

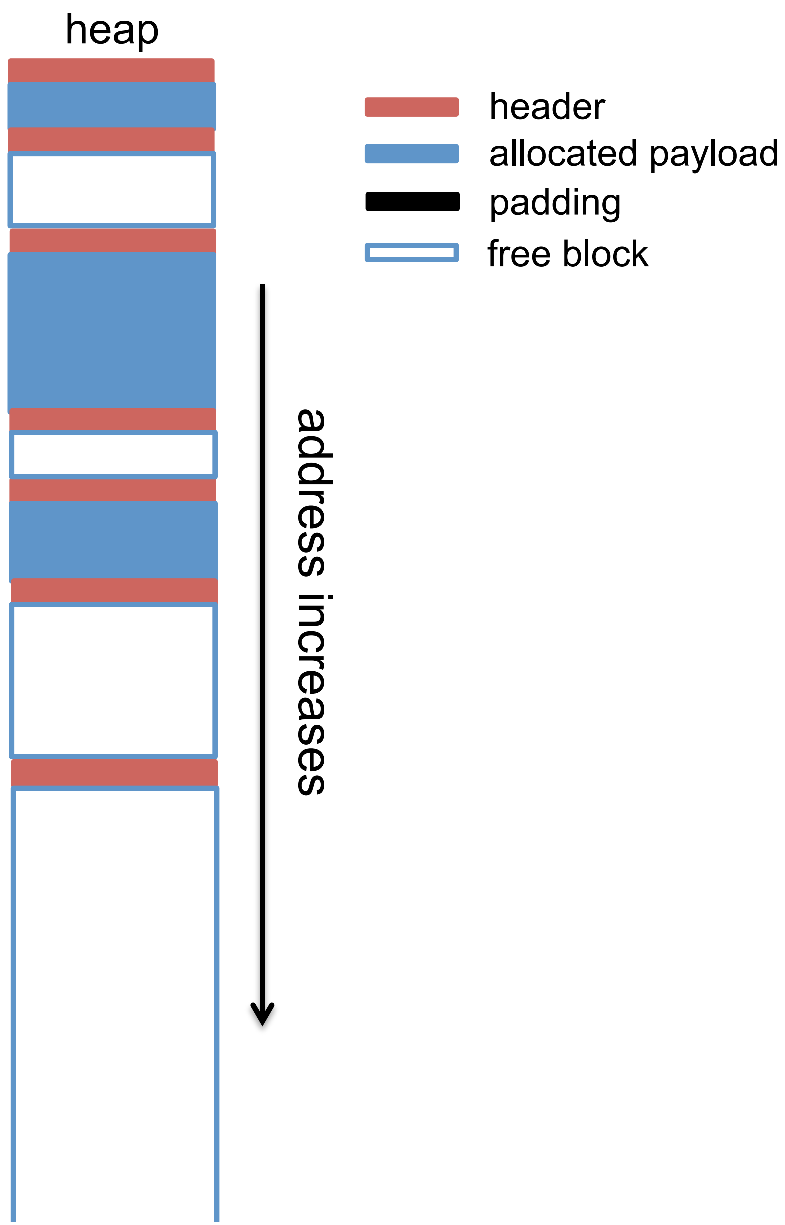
Placing allocated blocks

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



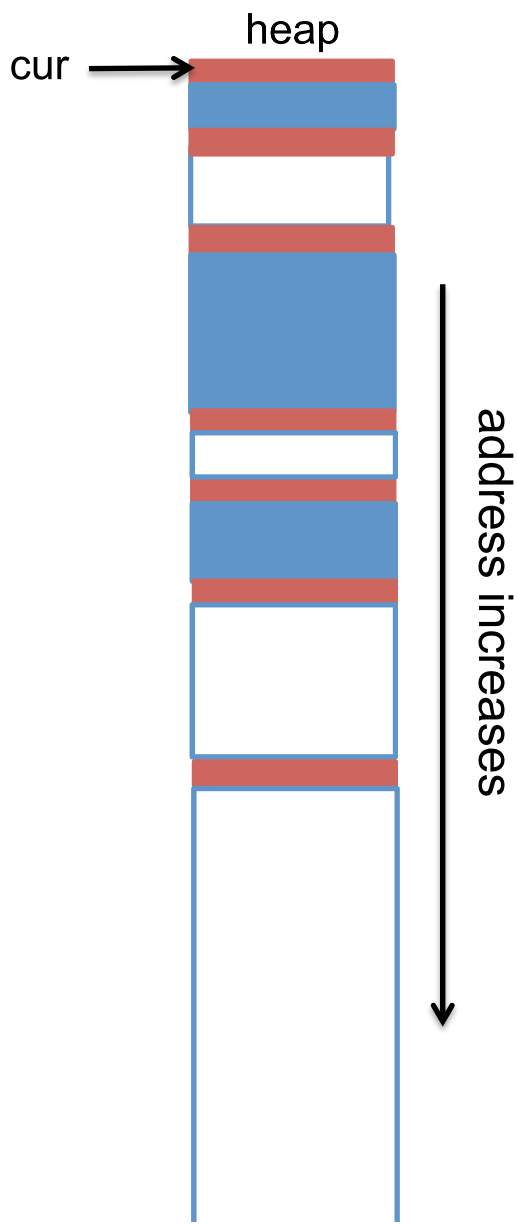
Where to place an allocation?

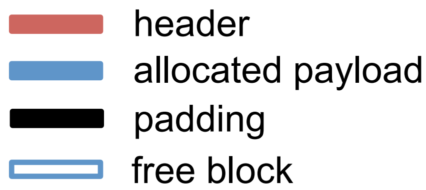
```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
```



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)
```

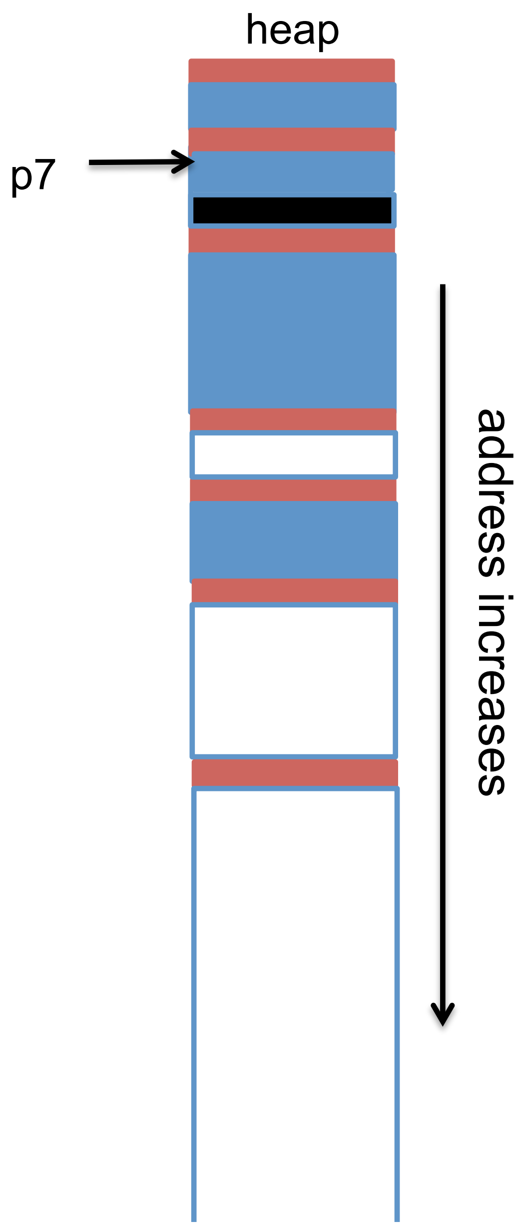


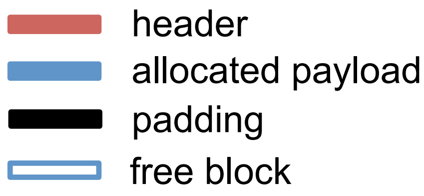


First fit – Search list from beginning, choose first free block that fits

First fit

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



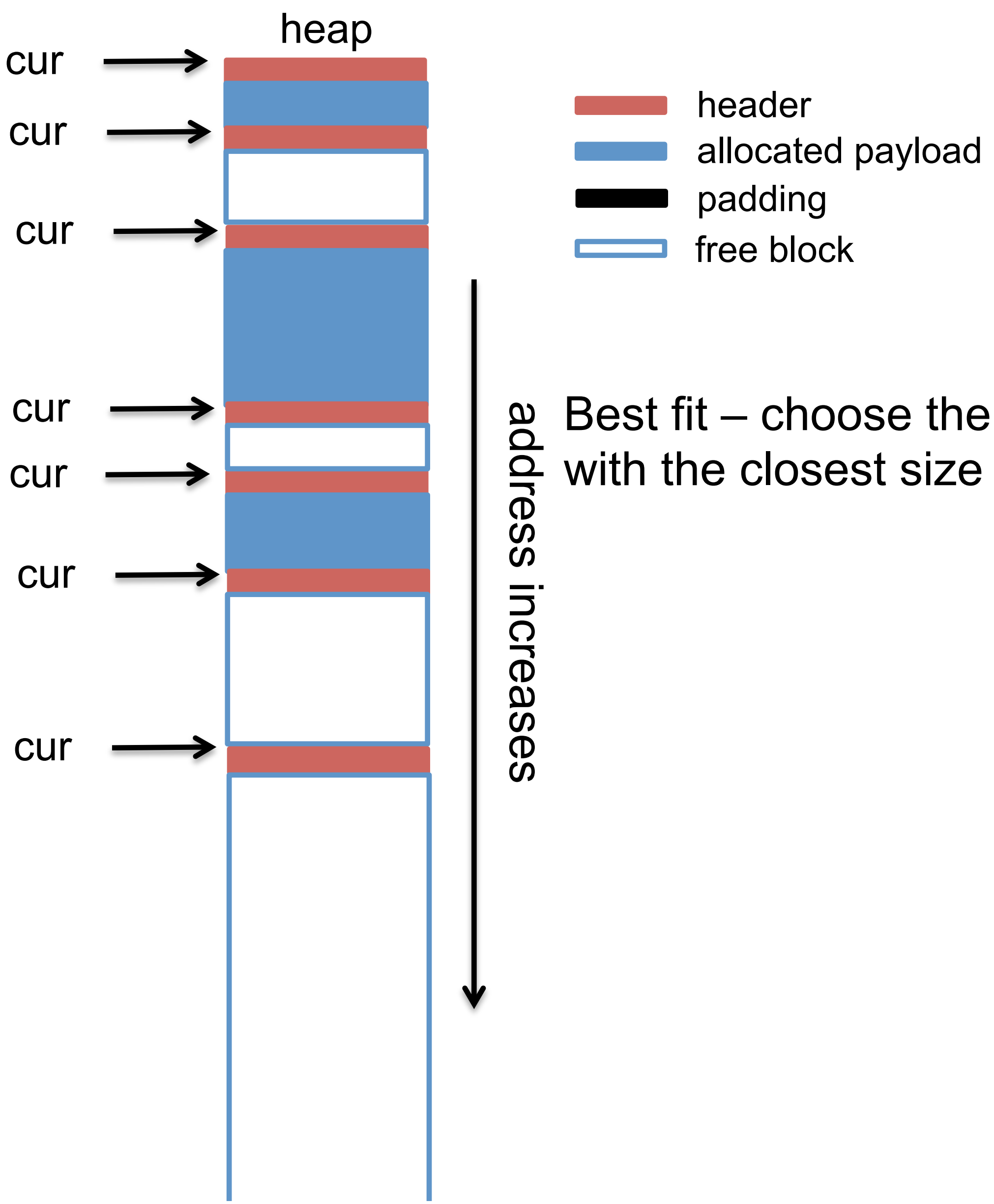


First fit – Search list from beginning, choose first free block that fits

Downside: cause fragmentation at beginning of the heap

Best fit

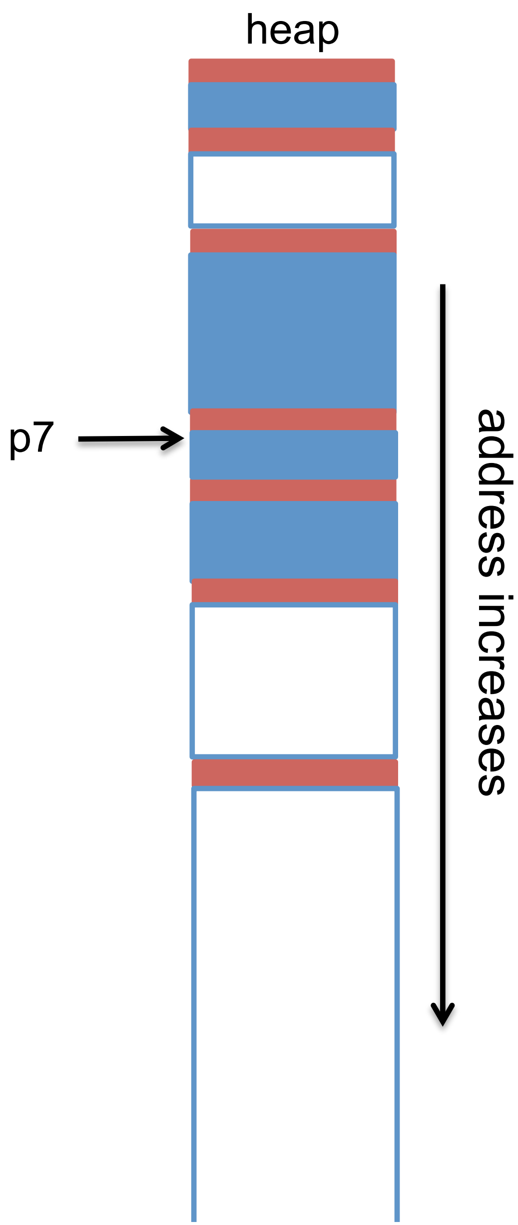
```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
```

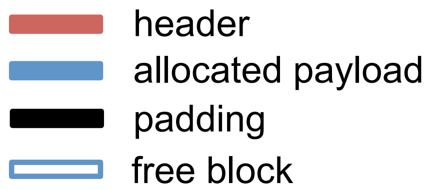


Best fit – choose the free block with the closest size that fits

Best fit

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



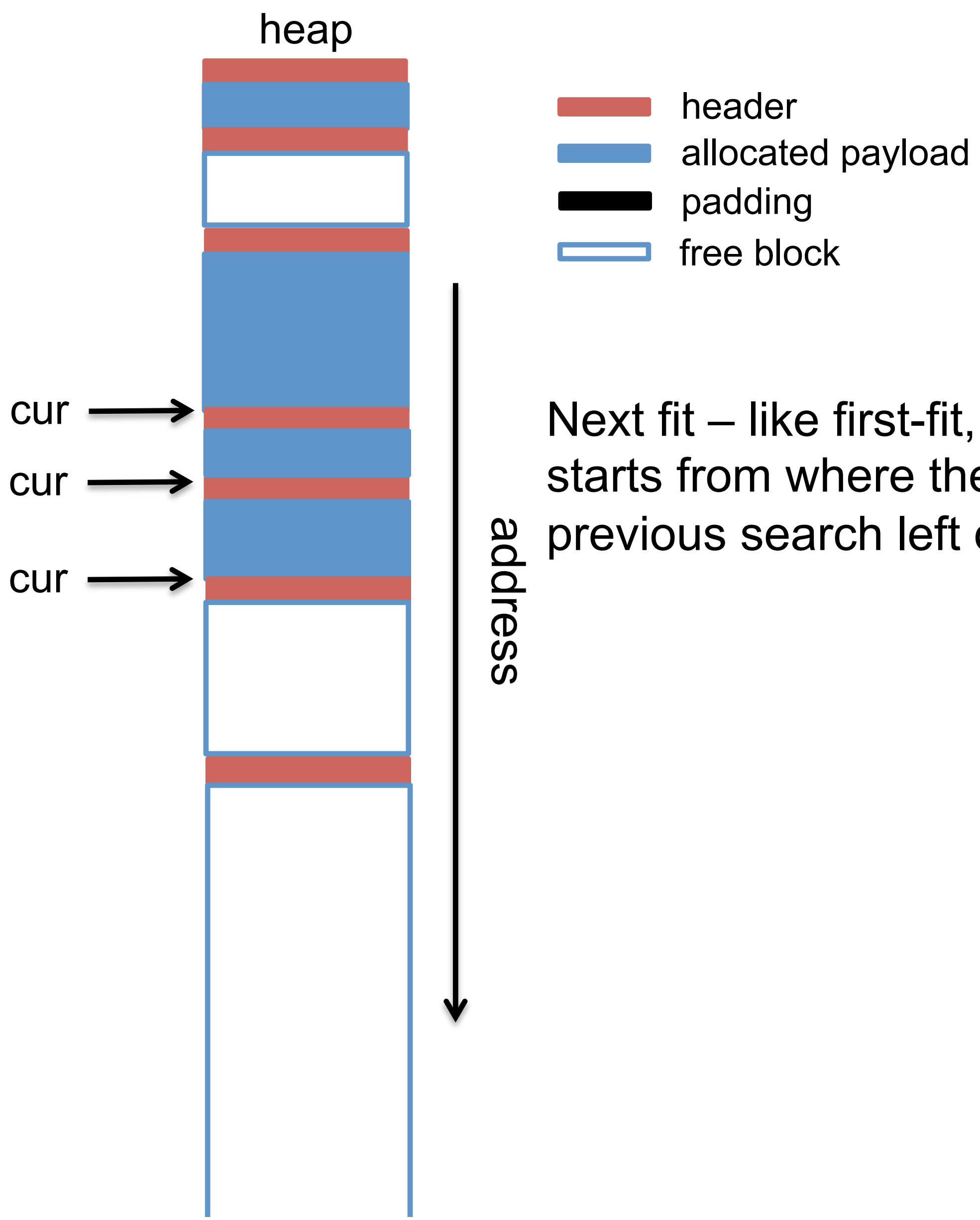


Best fit – choose the free block with the closest size that fits

Downside: run slower than first fit.

Next fit

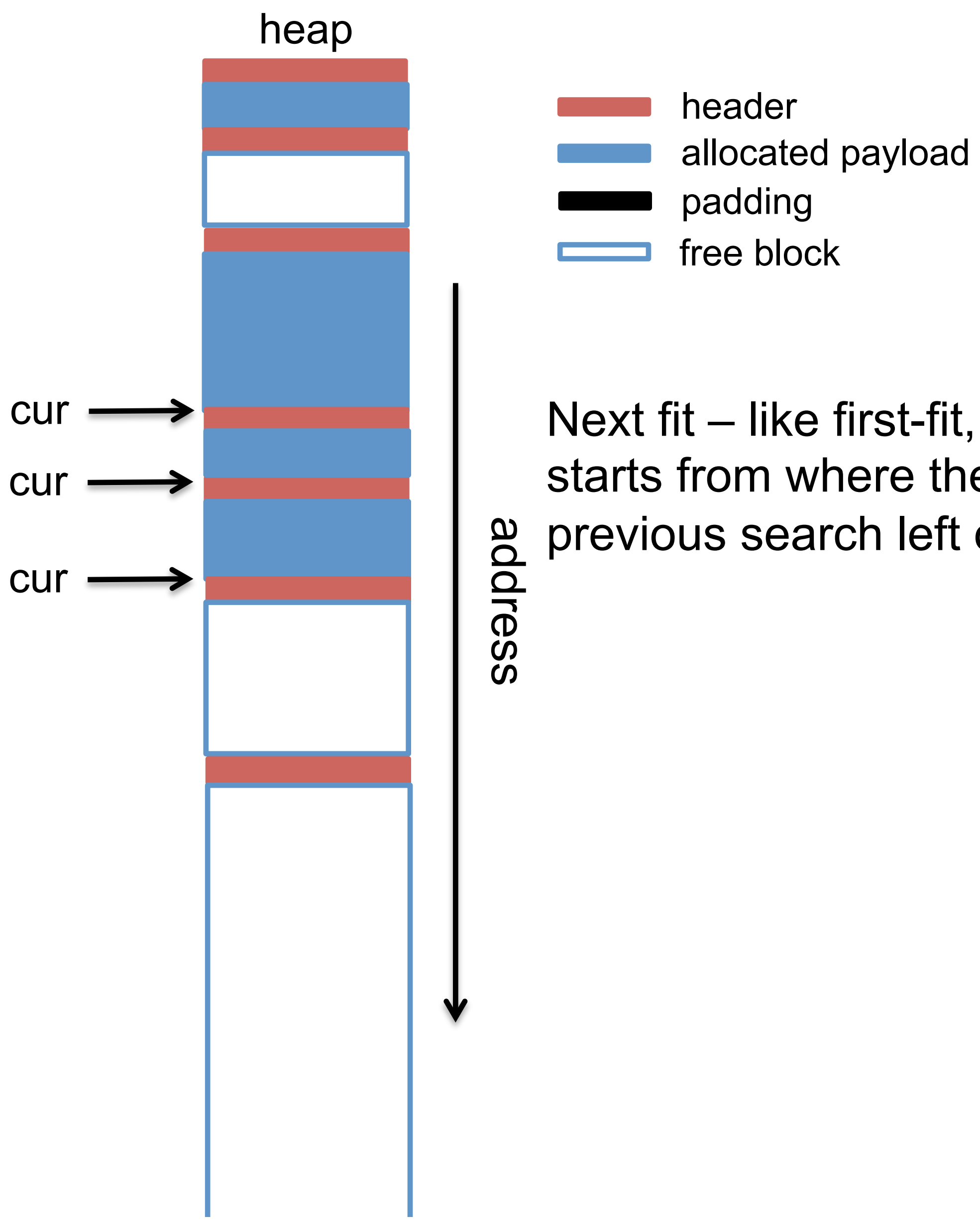
```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
p8 = malloc(56)
```



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

Next fit

```
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

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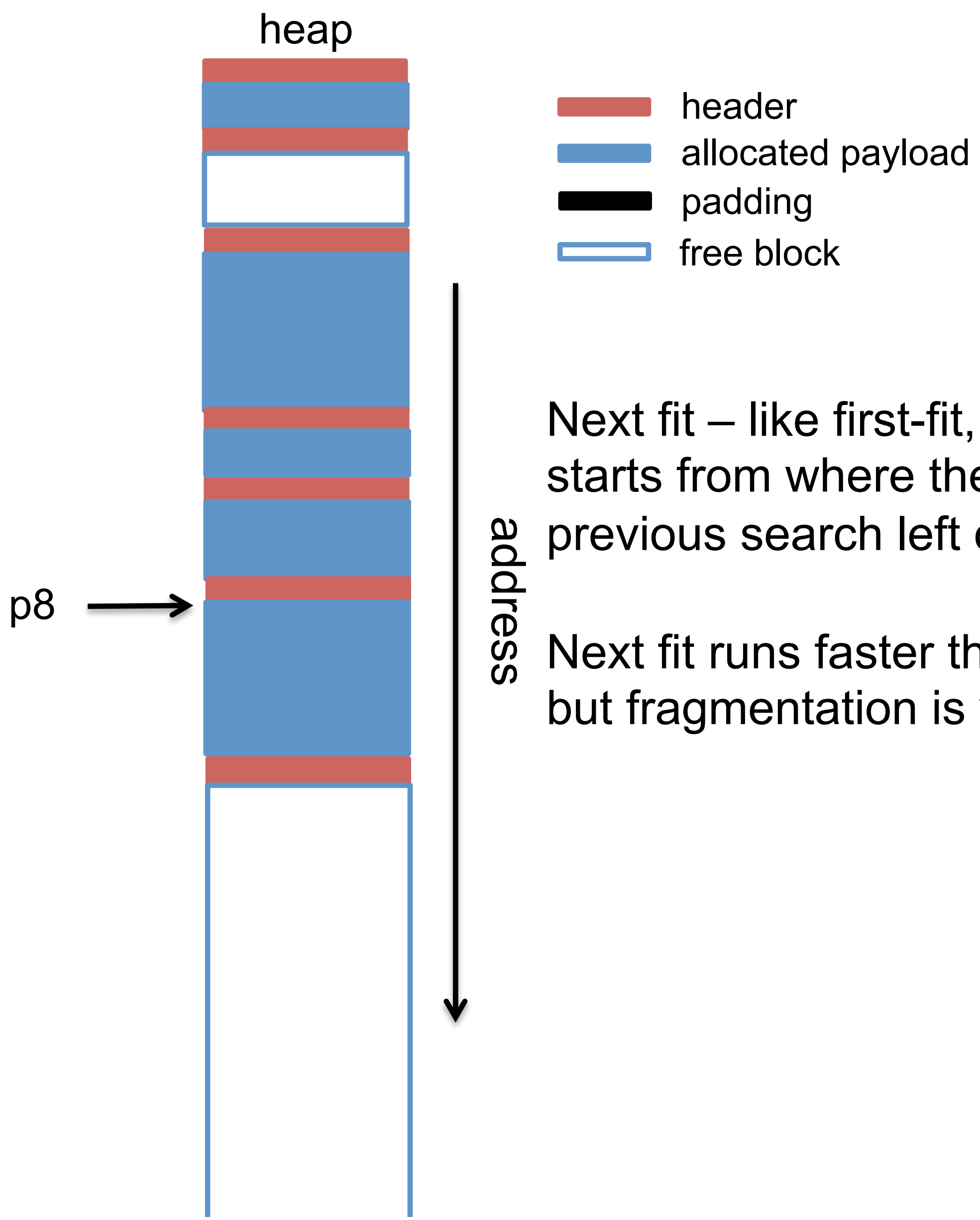
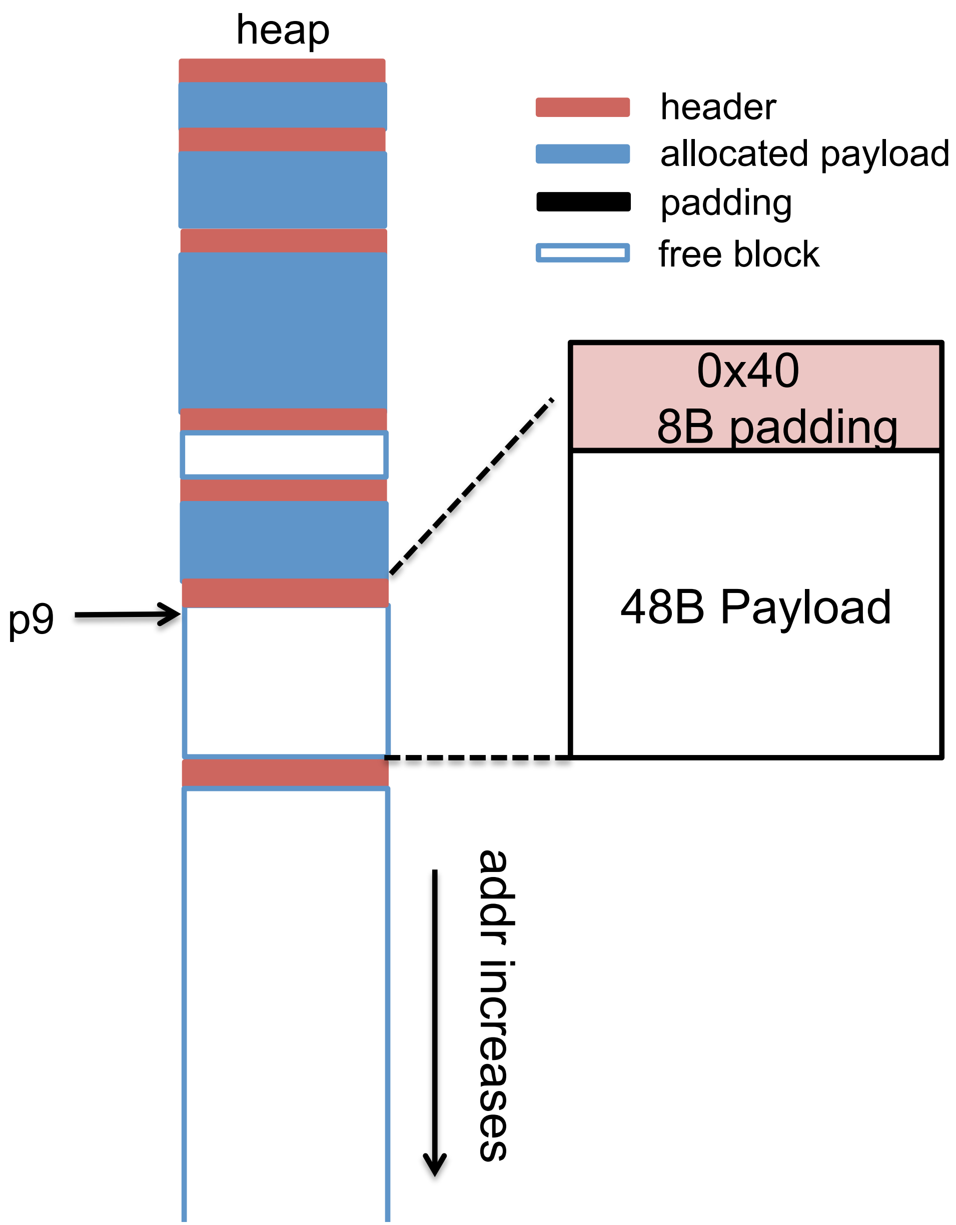



Next fit – like first-fit, but search starts from where the previous search left off.

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

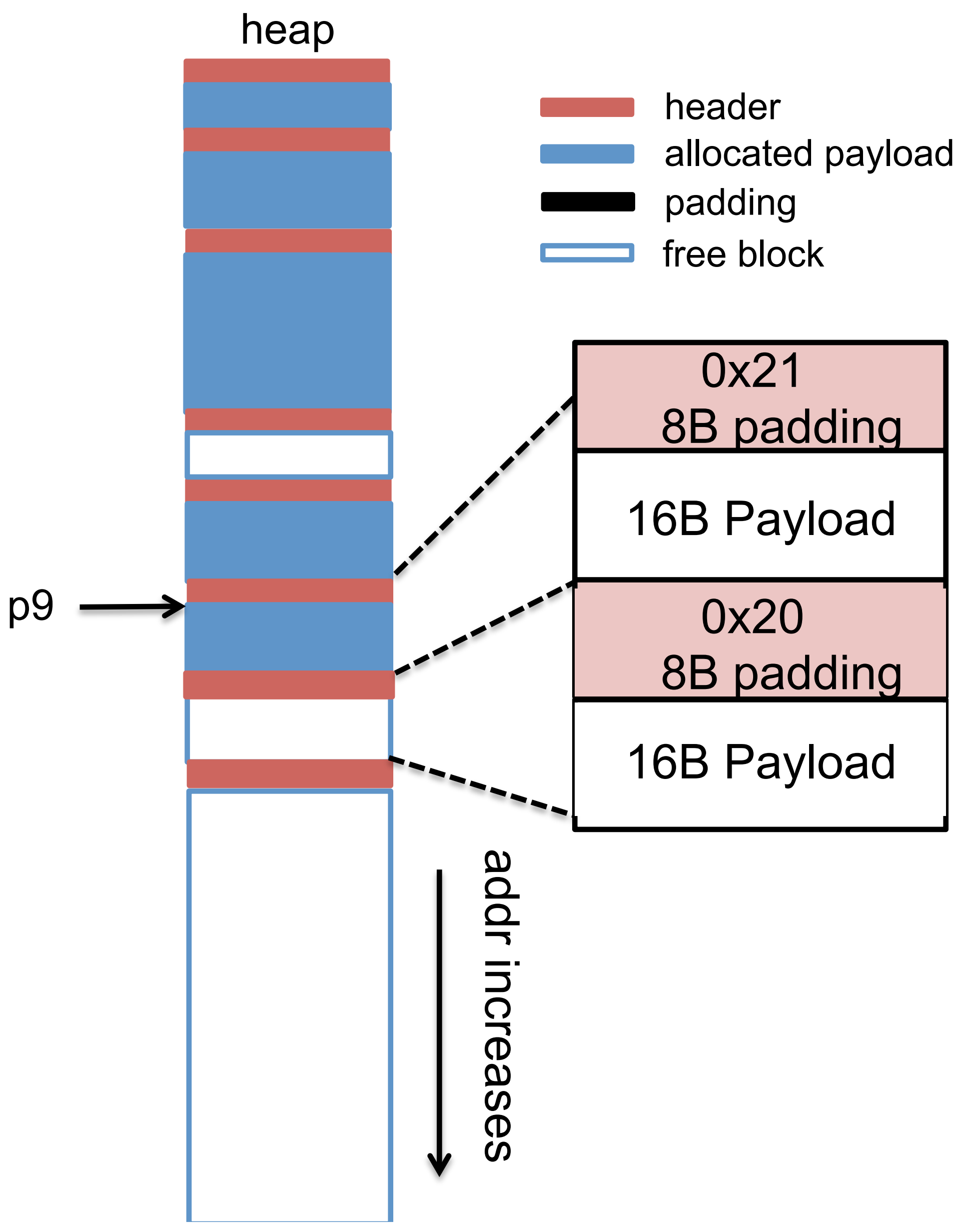
Splitting a free block

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



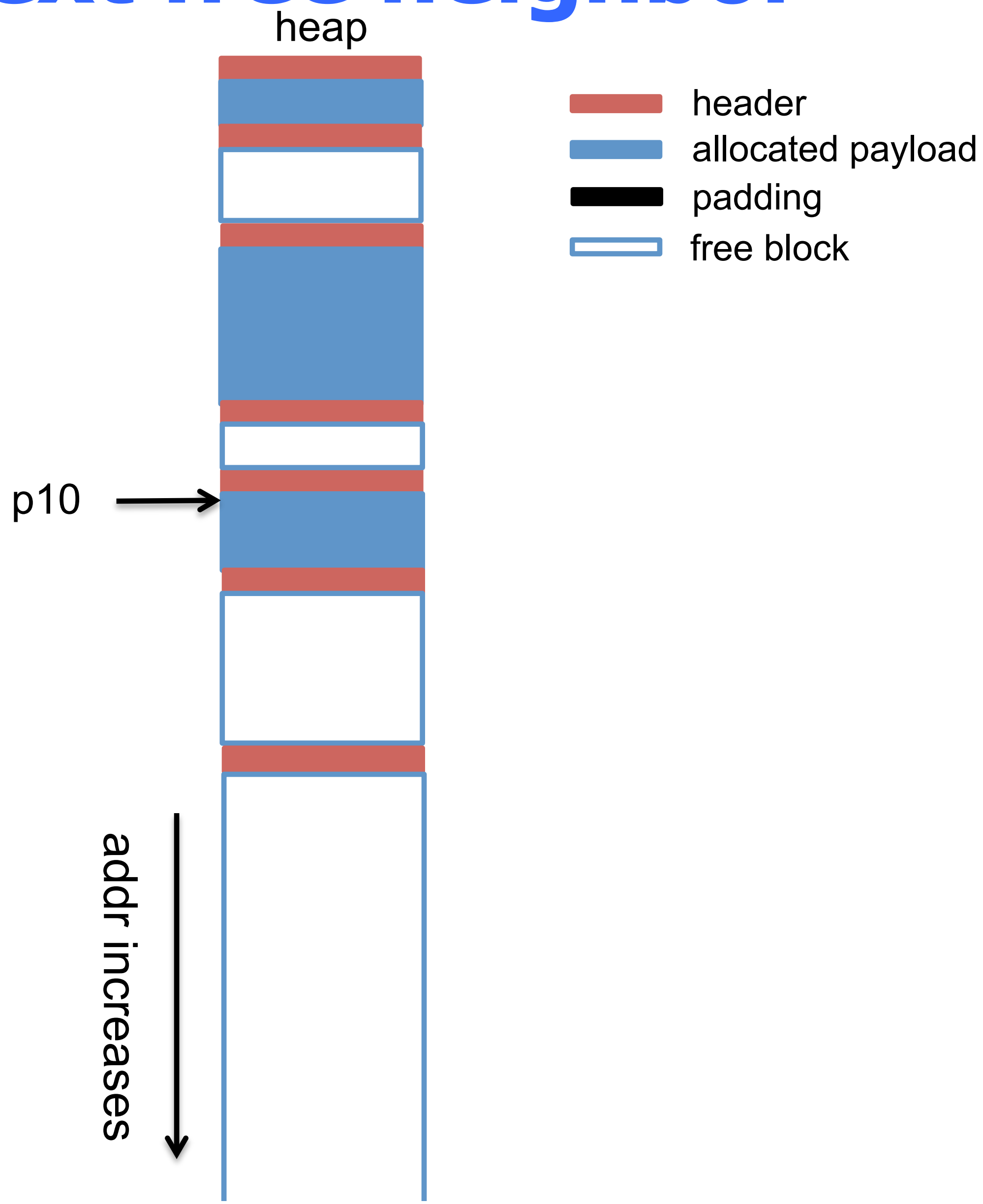
Splitting a free block

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



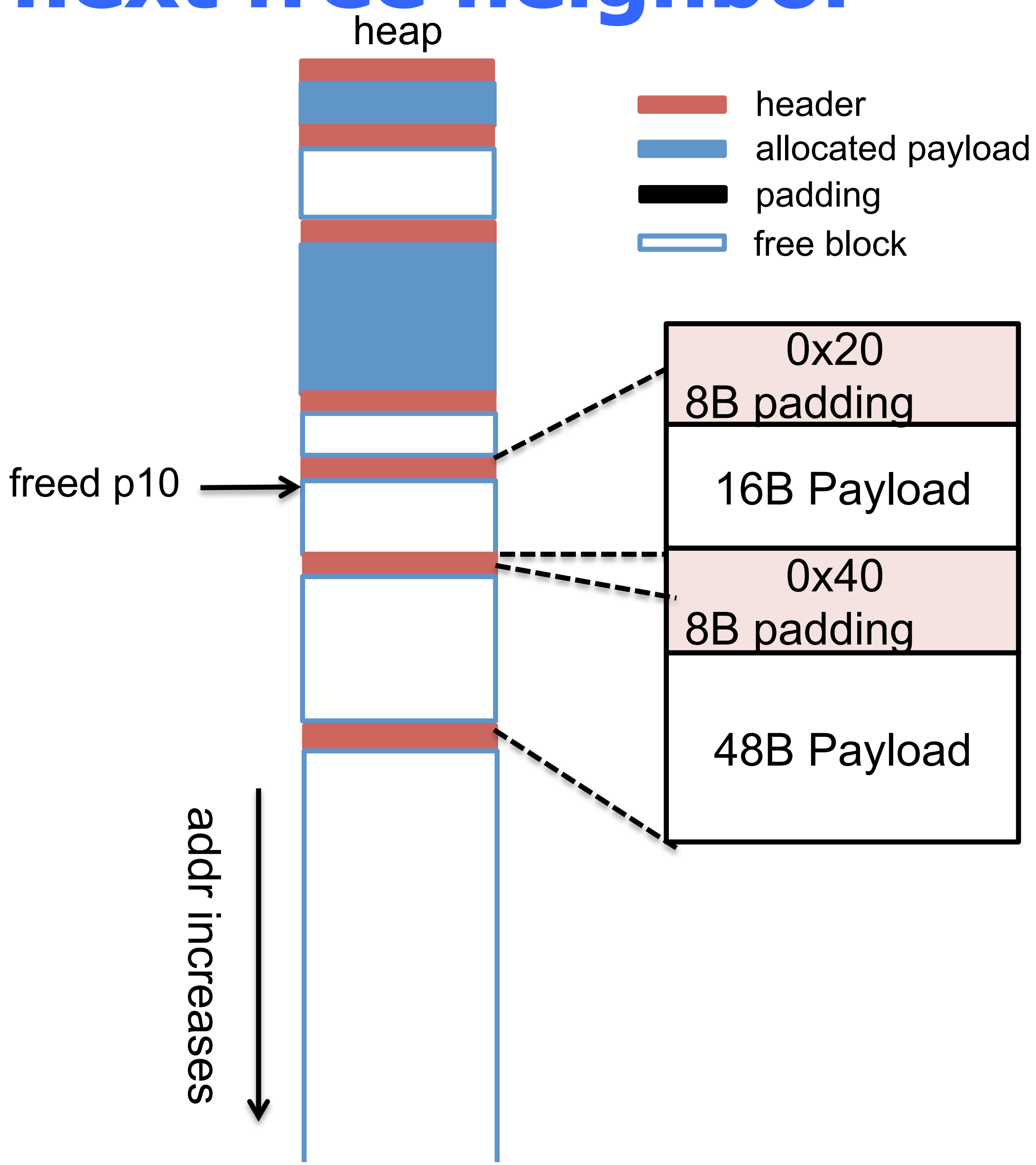
Coalescing a free block with its next free neighbor

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



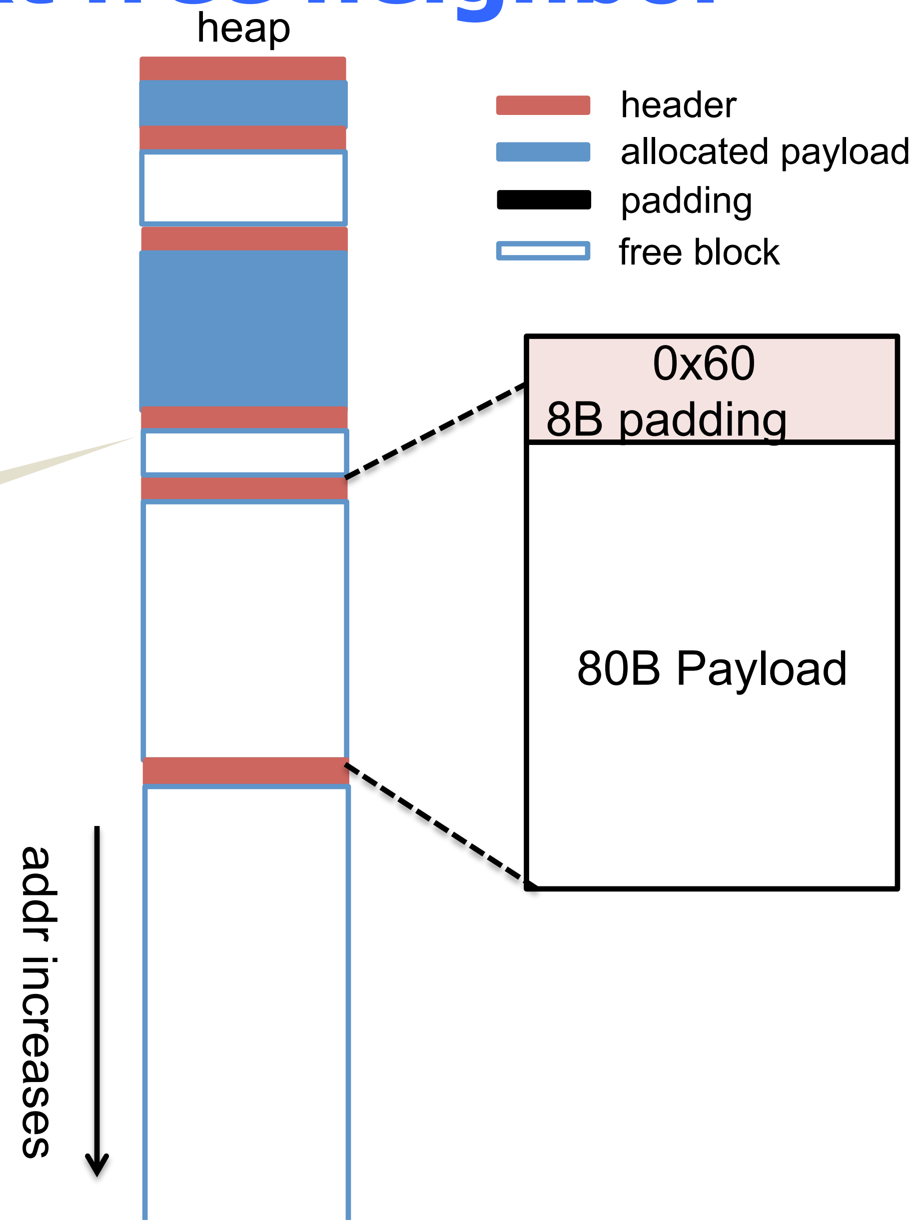
Coalescing a free block with its next free neighbor

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



Coalescing a free block with its next free neighbor

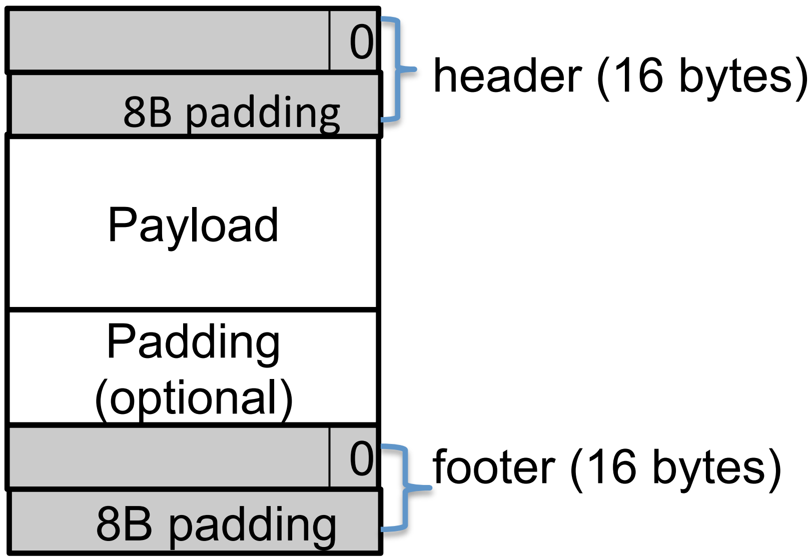
```
...
free(p10)
```

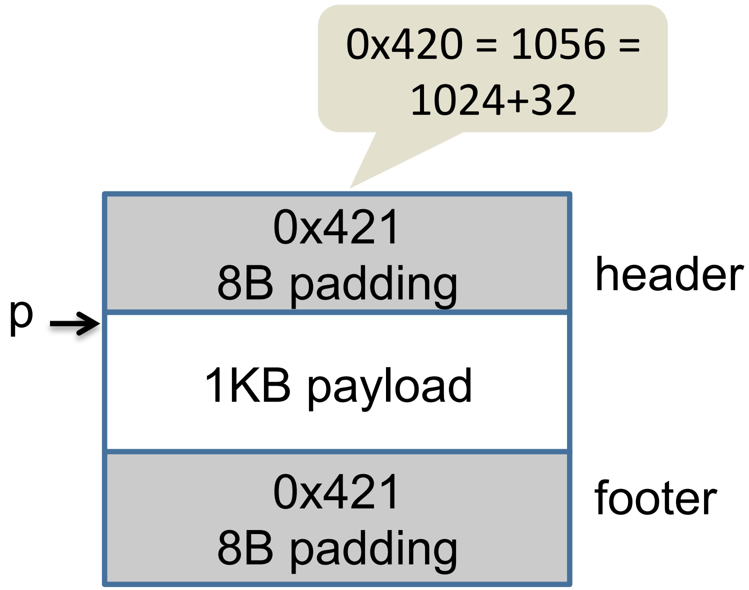


How to coalesce with the previous free block

Use footer to coalesce with previous block

- Duplicate header information into the footer

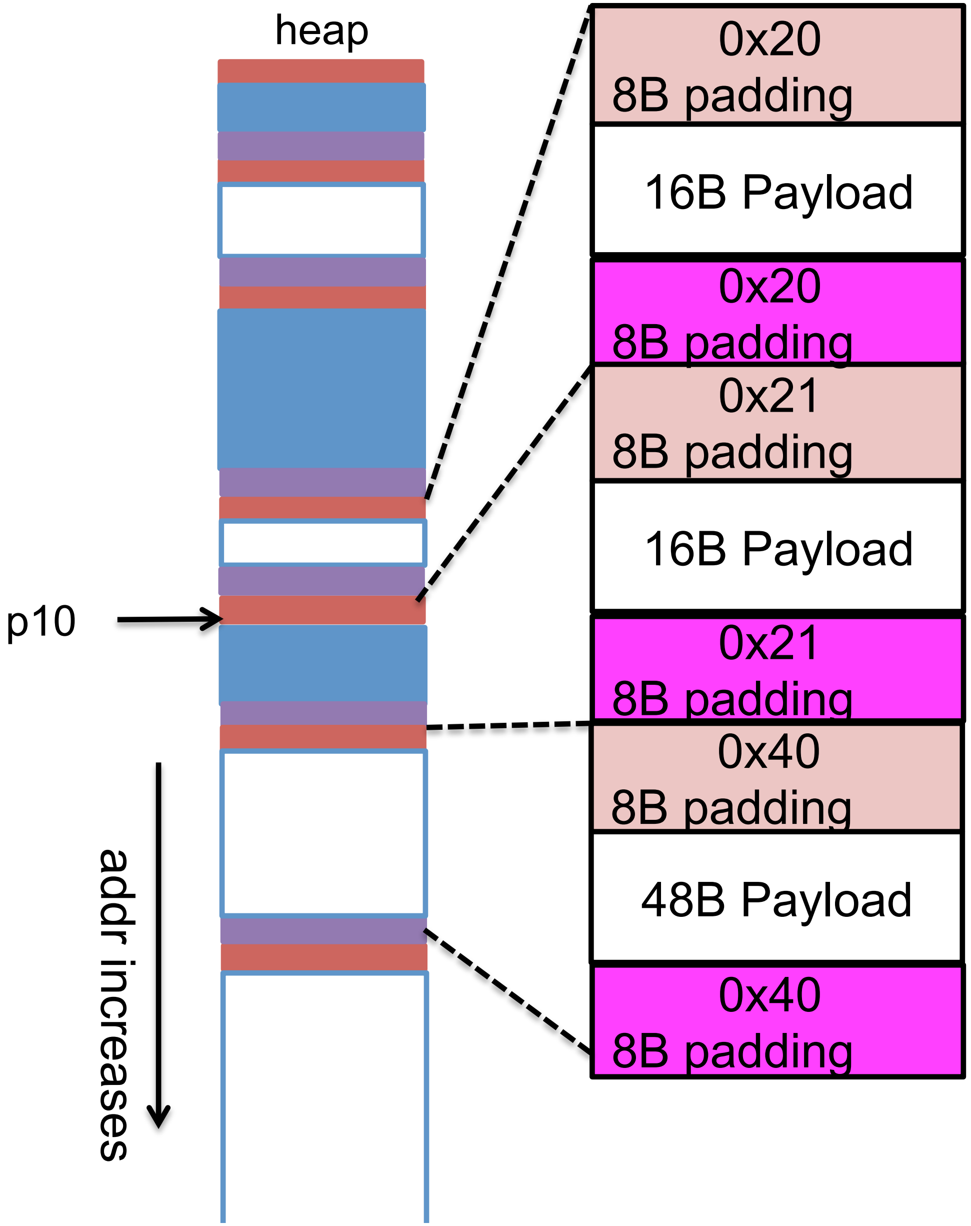





```
p = malloc(1024)
```

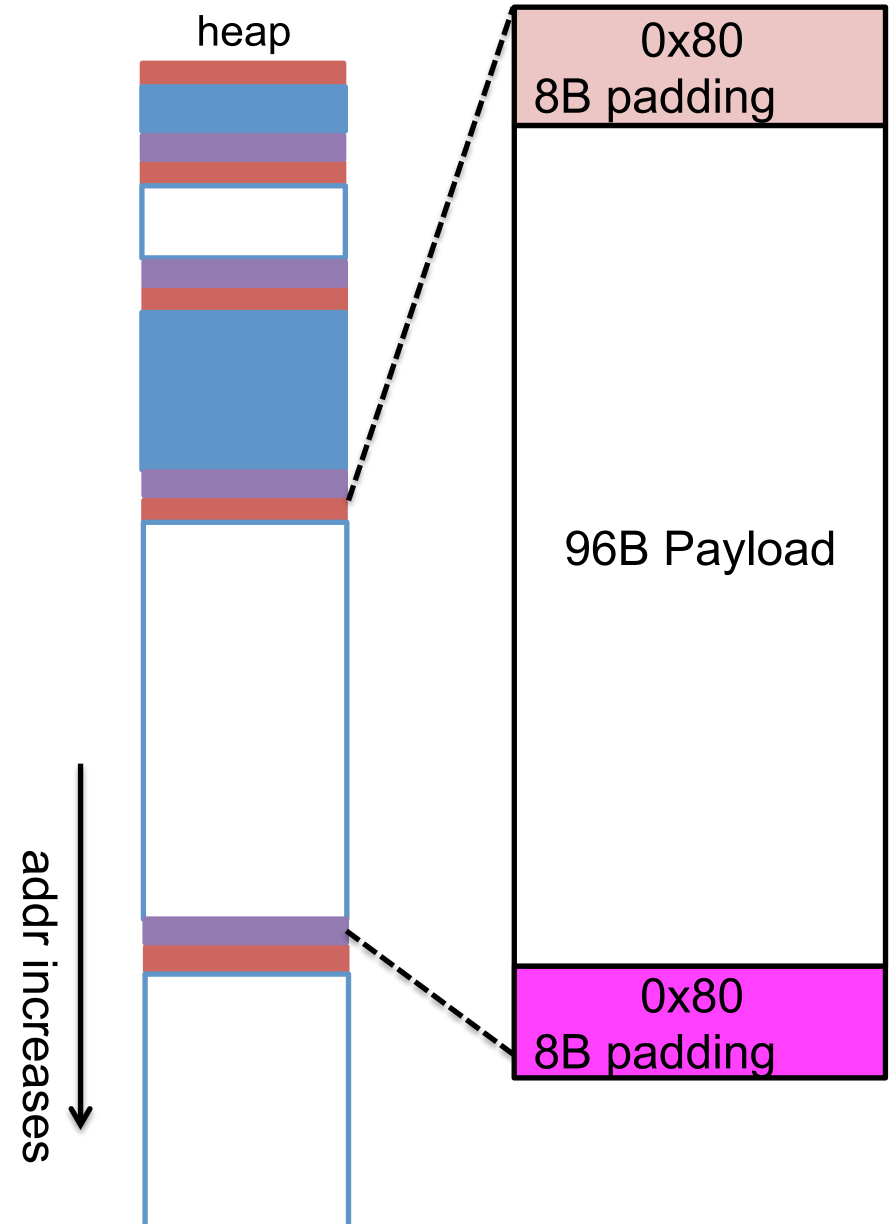
Coalescing prev and next blocks

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

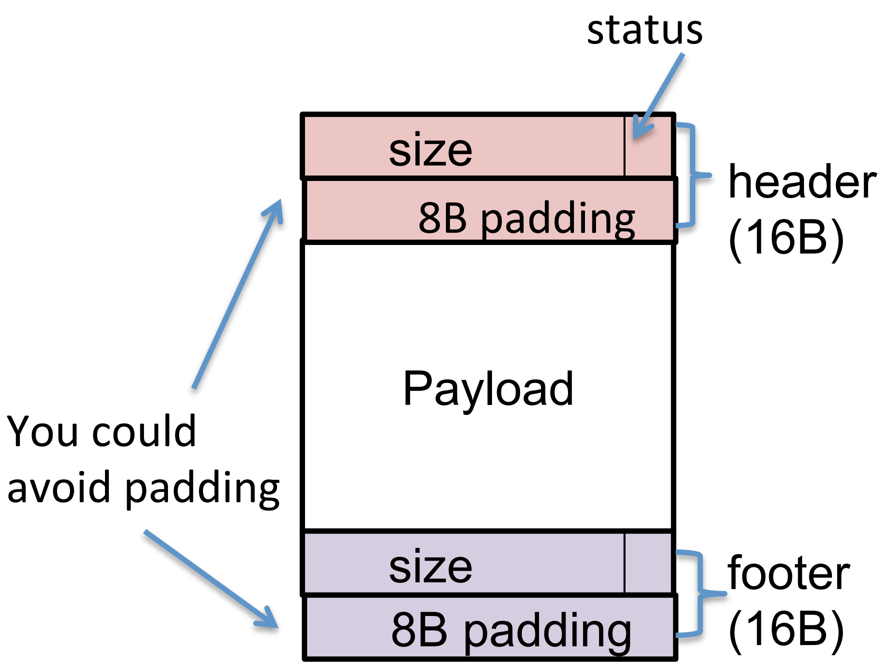


Coalescing prev and next blocks

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



Recap: malloc using implicit list



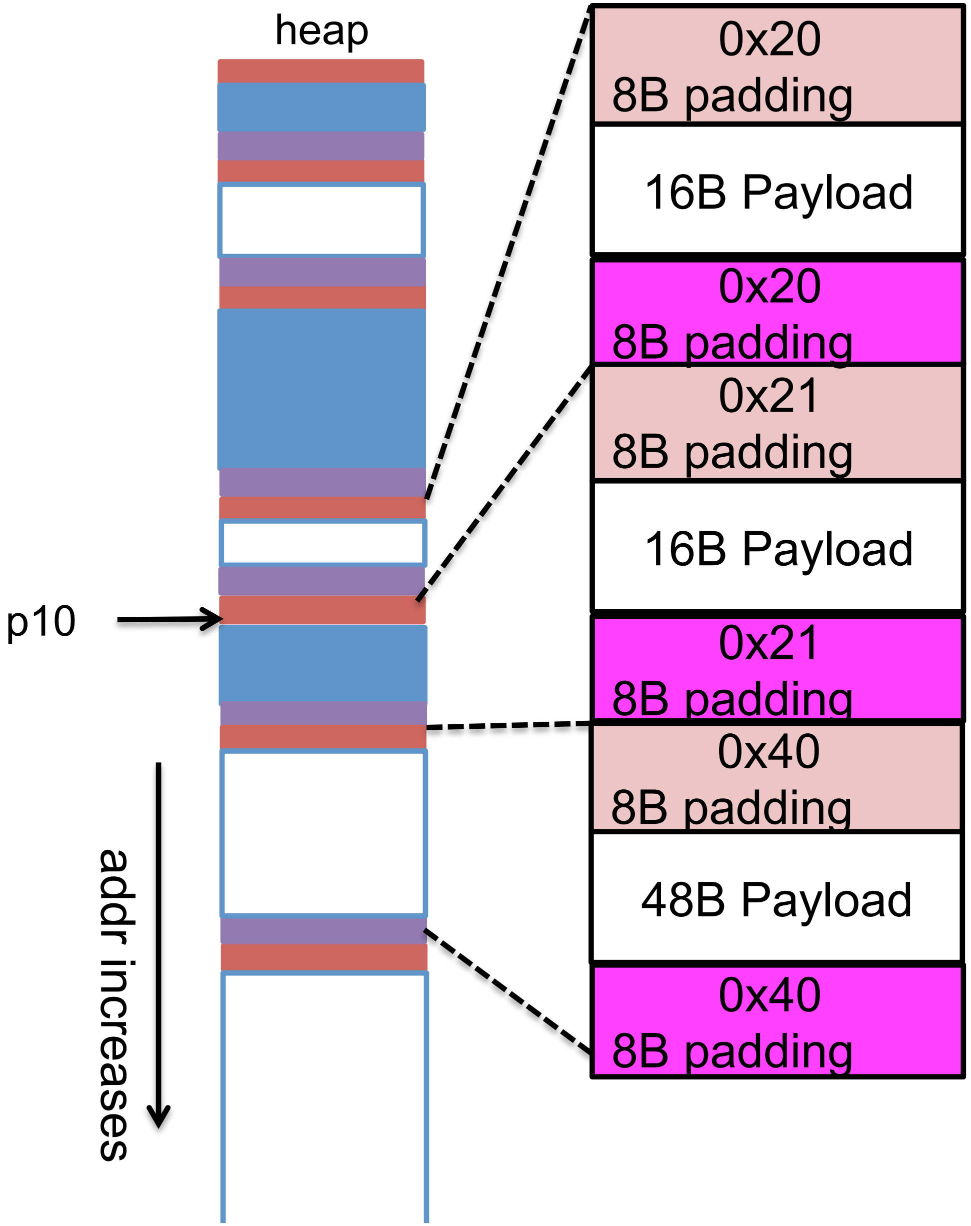
- We can traverse the entire list of chunks on heap by incrementing pointer with chunk sizes,
- To allocate, find a block that fits, split if necessary

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

Answer: > 16 (header) + 16 (footer) + 16 (min payload) = 48 bytes

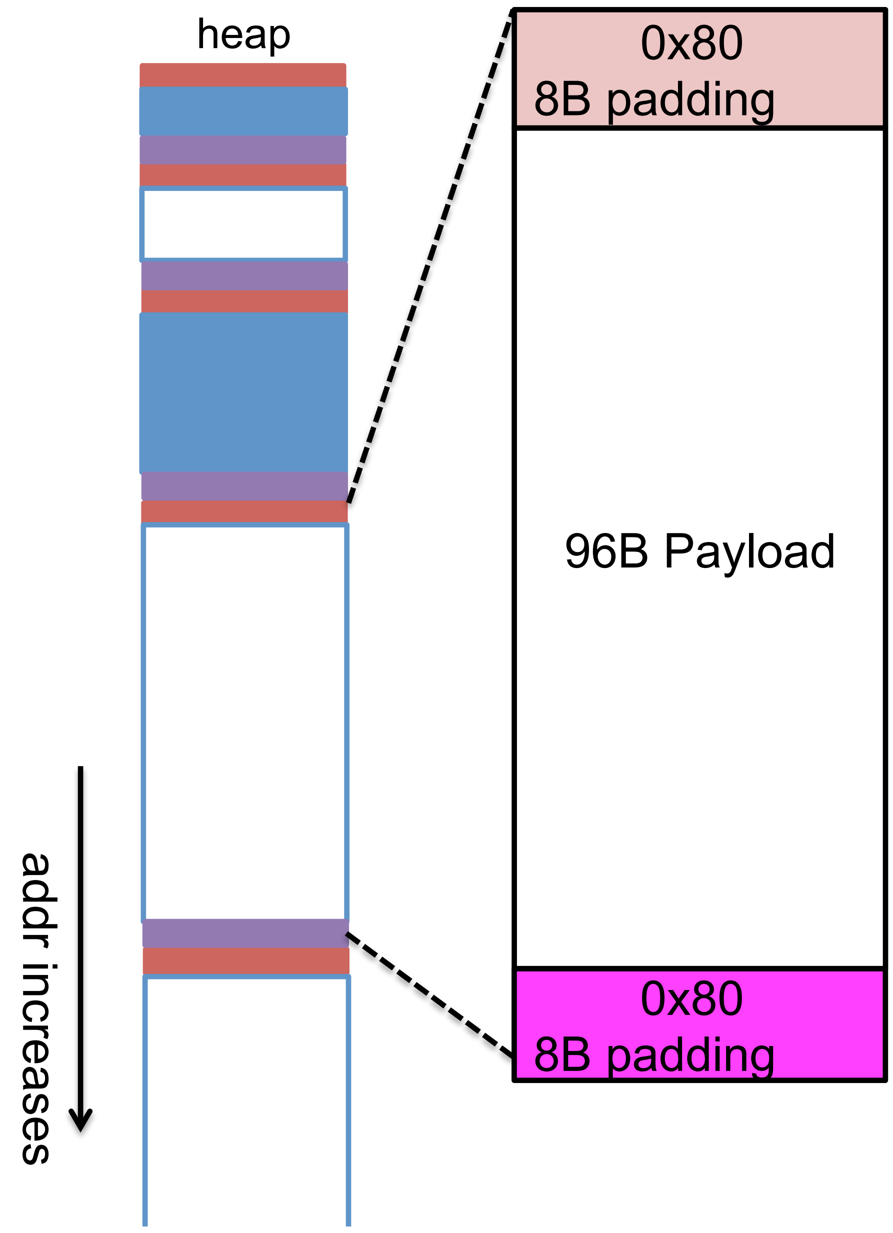
Coalescing prev and next blocks

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



Coalescing prev and next blocks

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



Explicit free lists

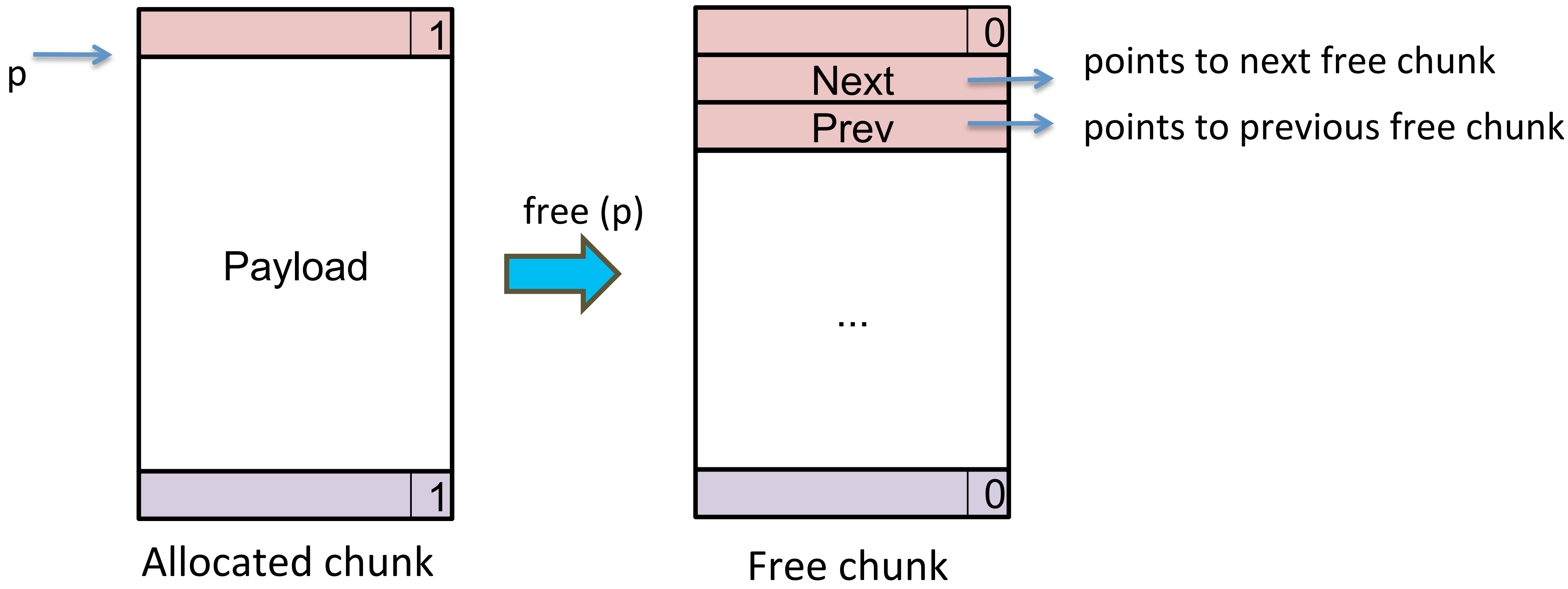
Problems of implicit list:

– 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



- 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: 16 (header) + 16 (footer) + 8 (next pointer) + 8 (previous pointer) = 48 bytes

Explicit list: types, basic helpers

```
typedef struct {
  unsigned long size_and_status;
  unsigned long padding;
} header;

typedef struct free_hdr {
   header common_header;
   struct free_hdr *next;
   struct free_hdr *prev;
} free_hdr;

bool
get_status(header *h) {
  return h->size_and_status & 0x1L;
}

size_t
get_size(header *h) {
  return h->size_and_status & ~(0x1L);
}
```

```
void
set_size_status(header *h,
  size_t sz, bool status) {

  h->size_and_status = sz | status;
}

void
set_status(header *h, bool status){
   size_t sz = get_size(h);
   set_size_status(h, sz, status);
}

void
set_size(header *h, size_t sz) {
   status = get_status(h);
   set_size_status(h, sz, status);
}
```

Explicit list: globals, initialization

```
free_hdr *freelist;

header*
get_footer_from_header(header *h) {
    return (header *)((char *)h + get_size(h) – sizeof(header));
}

init_free_chunk(free_hdr *h, size_t sz) {
   set_size_status(&h->common_header, sz, false);
   h->prev = h->next = NULL;
   set_size_status(get_footer_from_header(h->common_header), sz, false);
}

free_hdr *
get_block_from_OS(size_t sz) {
   free_hdr *h = sbrk(sz);
   init_free_chunk(h, sz); //init header and footer
   return h;
}
#define MIN_OS_ALLOC_SZ 1024
void init() {
   freelist = get_block_from_OS(MIN_OS_ALLOC_SZ);
}
```

Explicit list: helpers to insert and detach from freelist

```
void insert(free_hdr **head, free_hdr *node) {
     if (*head)
           (*head)->prev = node;
     node->next = *head;
     *head = node;  //node becomes the new head
}

void delete(free_hdr **head, free_hdr *node) {
     if (node->prev) { //node is not the first node in the list
         node->prev->next = node->next;
         if (node->next)
             node->next->prev = node->prev;
     } else { //delete the first node in the list
         *head = node->next;
         if (node->next)
             node->next->prev = NULL;
     }
}
```

Explicit list: allocate

assume s>=16 and is 16-byte aligned

```
void *
malloc(size_t s) {
   size_t csz = s + 2*sizeof(header); //min chunk size required
   free_hdr *n = first_fit(csz);
   if (!n)
       n = get_block_from_OS(csz>MIN_OS_ALLOC_SIZE?csz:MIN_OS_ALLOC_SIZE);

   free_hdr *newchunk = split(n, csz);
   insert(&freelist, newchunk);
   set_status(n, true);
   return (char *)n+sizeof(header);
}

free_hdr *
first_fit(size_t sz) {
   free_hdr *n = freelist;
   while (n) {
      if (get_size(n->common_header)>= sz) {
          delete(&freelist, n);
          break;
      }
      n = n->next;
   }
   return n;
}
```

Explicit list: free

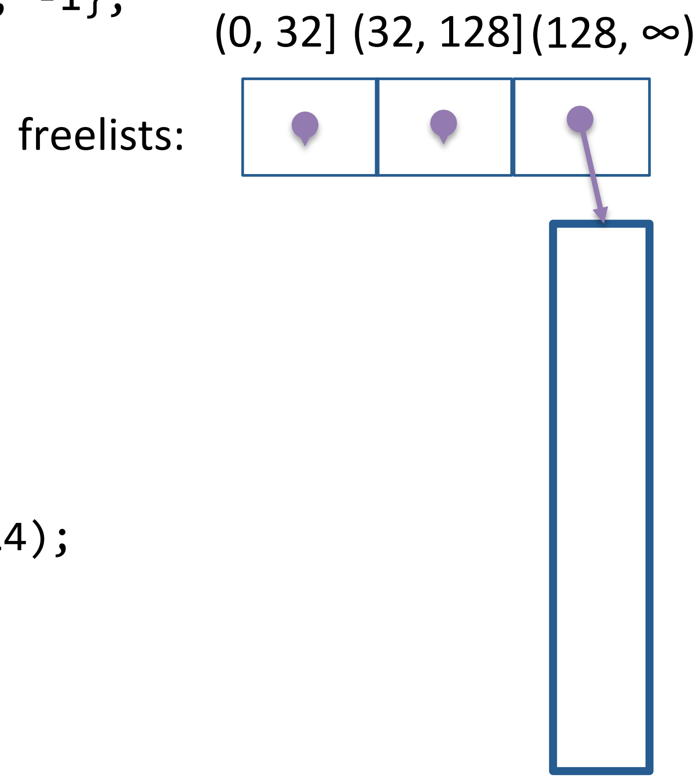
```
void free(void *p) {
     header *h = get_header_from_payload(p);
     init_free_chunk((free_hdr *)h, get_size(h));

     header *next = get_next_header(h);
     if (!get_status(next))
        h = coalesce((free_hdr *)h, (free_hdr *)next);
     header *prev = get_prev_header(h);
     if (!get_status(prev))
        h = coalesce((free_hdr *)h, (free_hdr *)prev);

     insert(&freelist, (free_hdr *)h);
}
free_hdr *
coalesce(free_hdr *me, free_hdr *other) {
   delete(&freelist, other);
   int sum = get_size(me->common_header)+get_size(other->common_header));
   free_hdr *h = me<other? me:other;
   set_size_status(h->common_header, sum, false);
   set_size_status(get_footer_from_header((header *)h, sum, false);
   h->next = h->prev = NULL;
   return h;
}
```

Segregated list

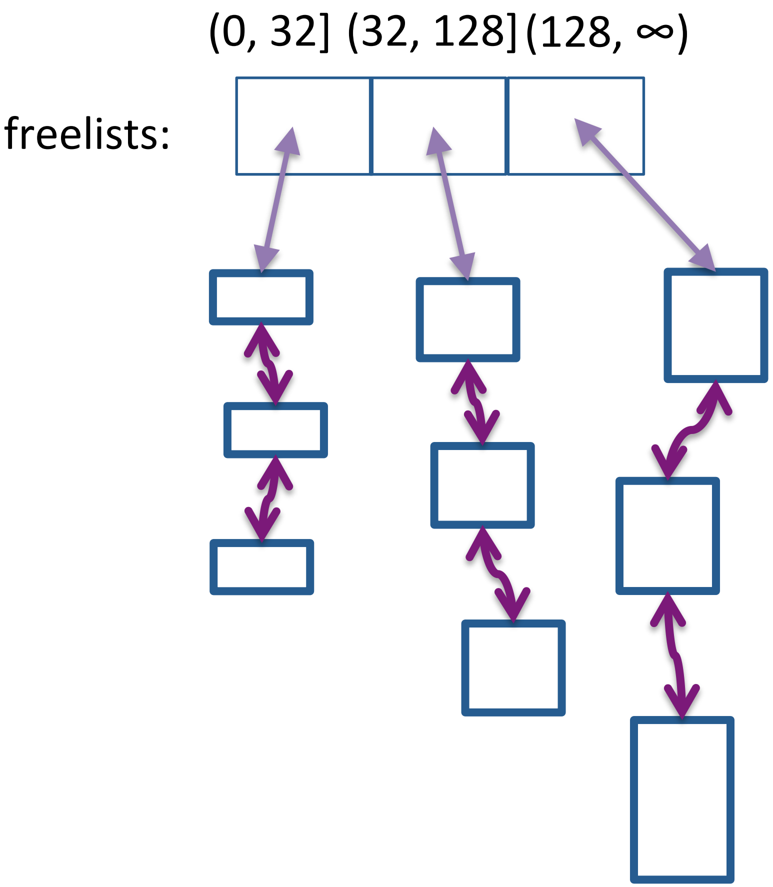
- Idea: keep multiple freelists
  - each freelist contains chunks of similar sizes

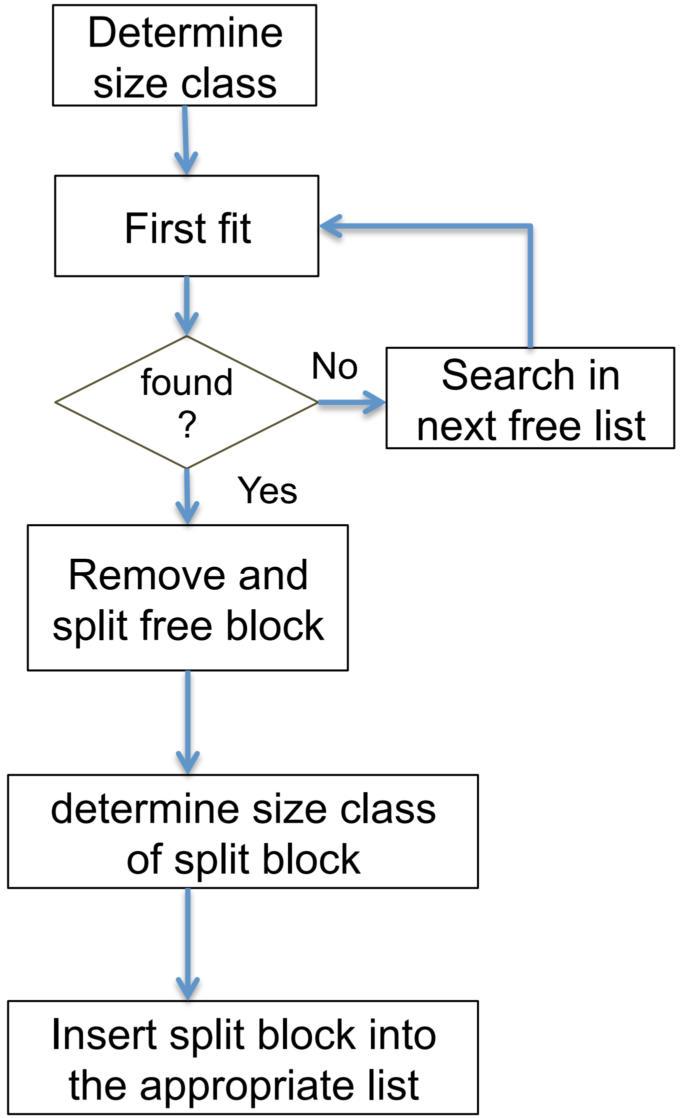
Segregated list: initialize

```
#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() {
    free_hdr *h = get_block_from_OS(1024);
    freelist[which_freelist(1024)] = h;
 }
```

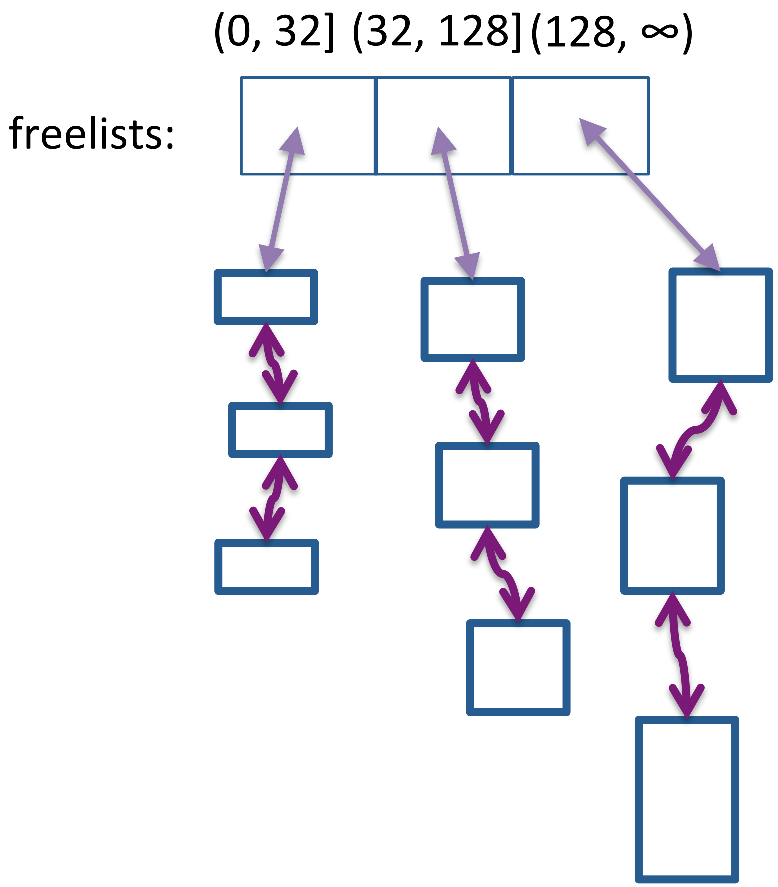


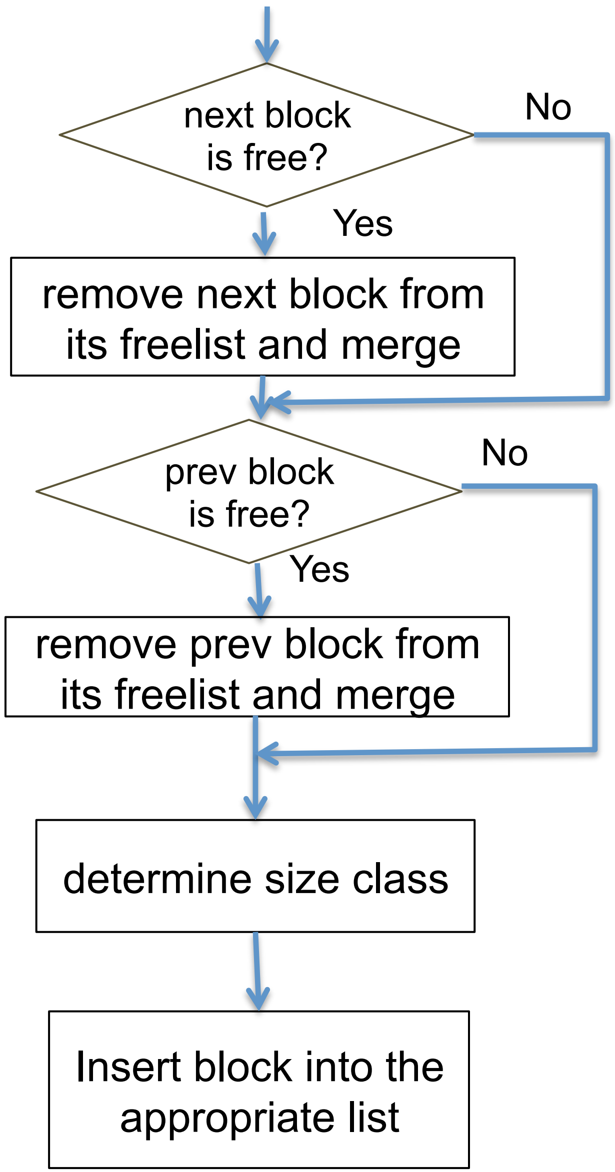
Segregated list: allocation





Segregated list: free





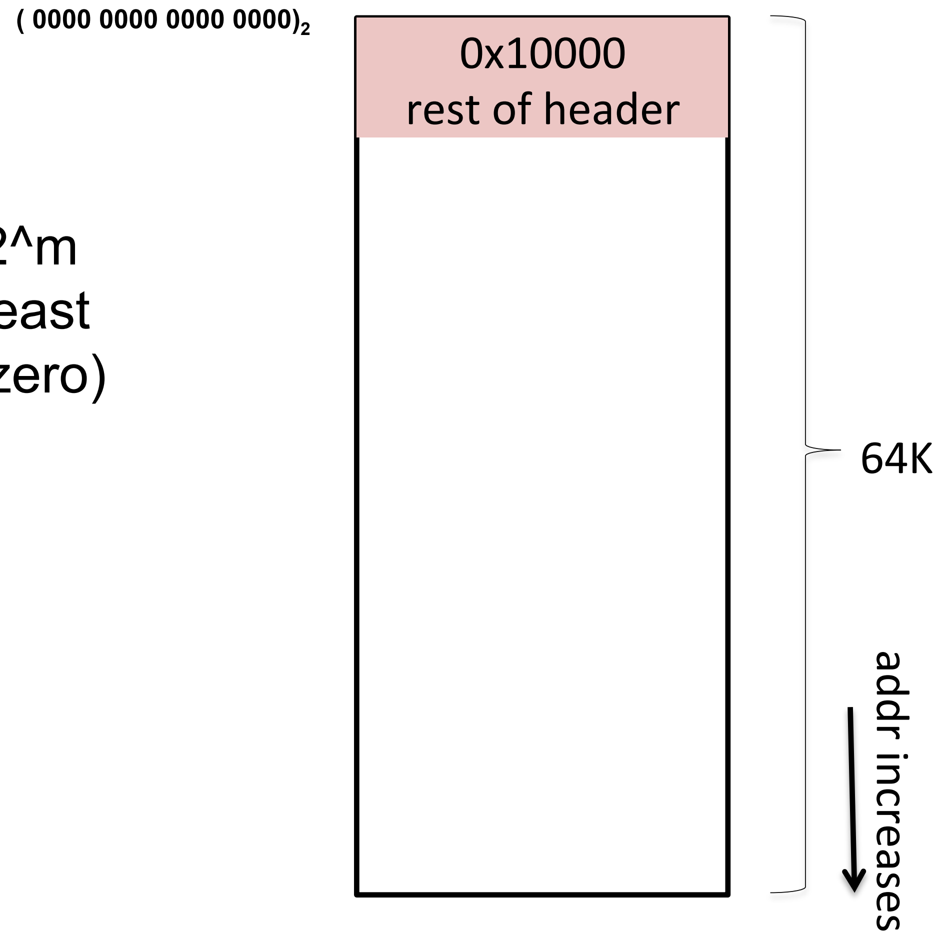
Buddy System

- 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:

- for simplicity, assume the initial 2^m block is aligned at 2^m (i.e. the least significant m-bits of its addr are zero)

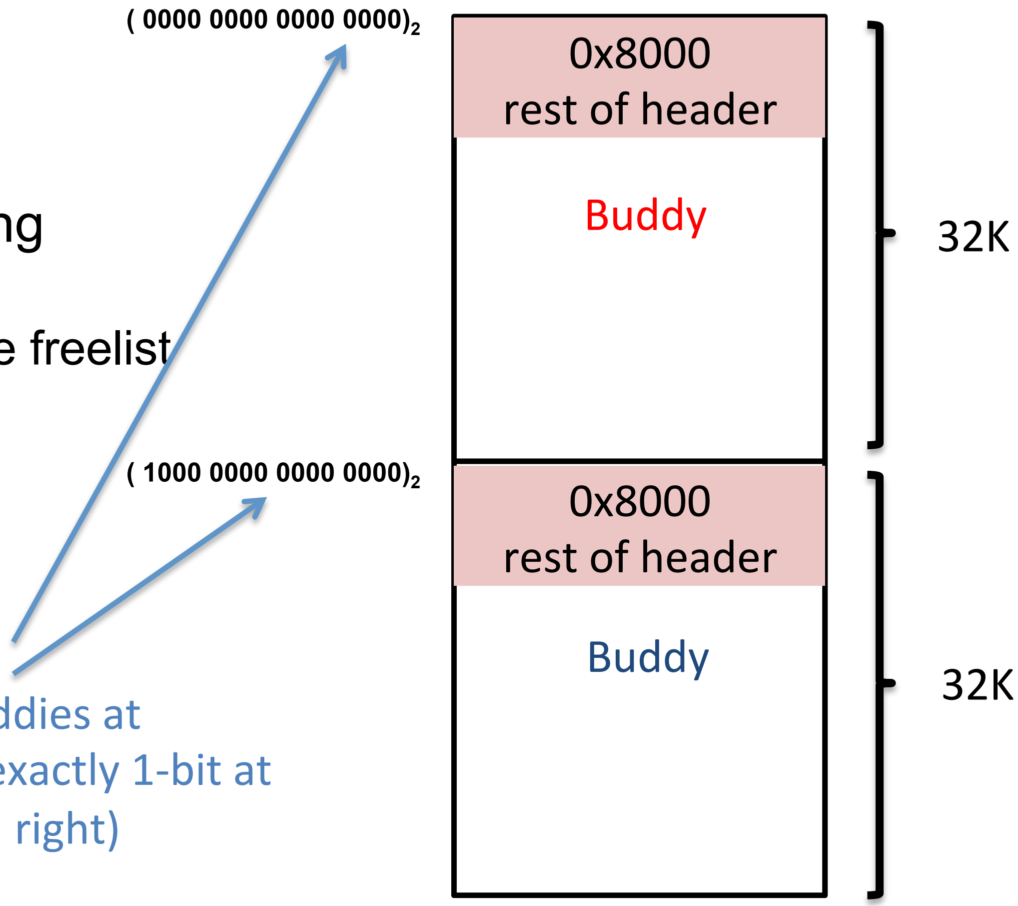


Binary buddy system: allocate

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

Recursive split in half until having the right size

- insert free buddy into appropriate freelist



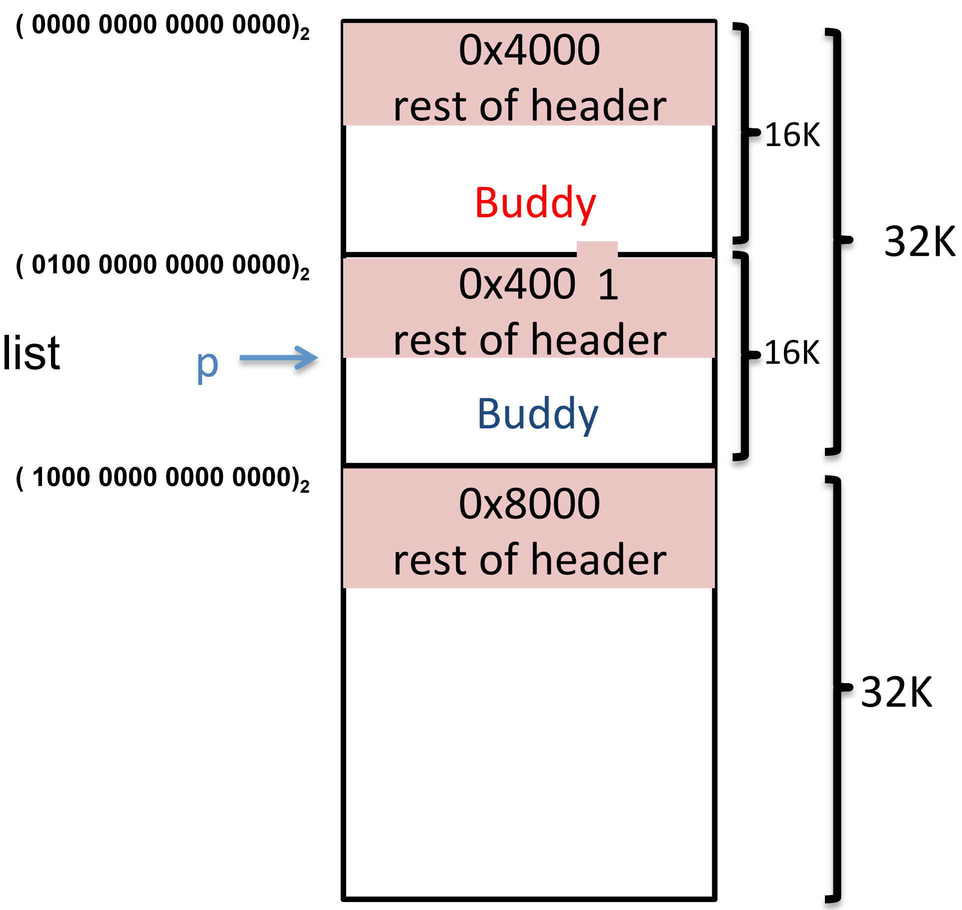
Addresses of buddies at size 2^m differ in exactly 1-bit at position m (from right)

Binary buddy system: allocate

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

Recursive split in half until having the right size

- insert free buddy into appropriate freelist

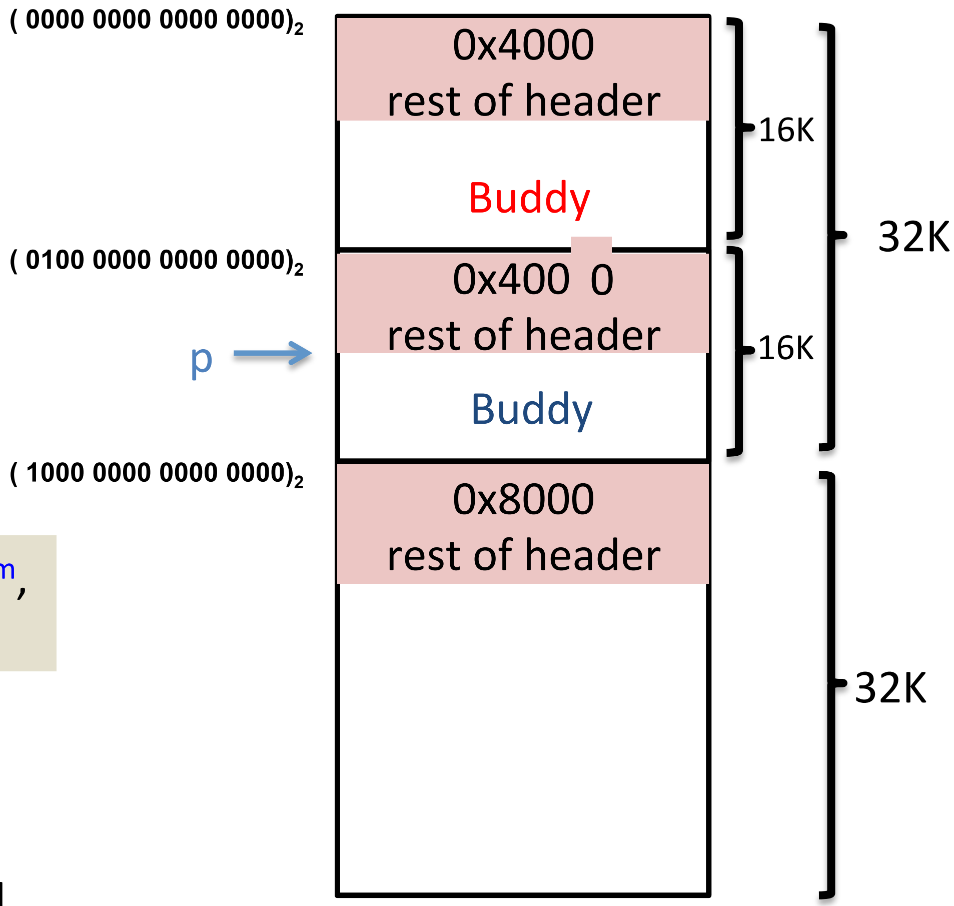


Binary buddy system: free

```
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)

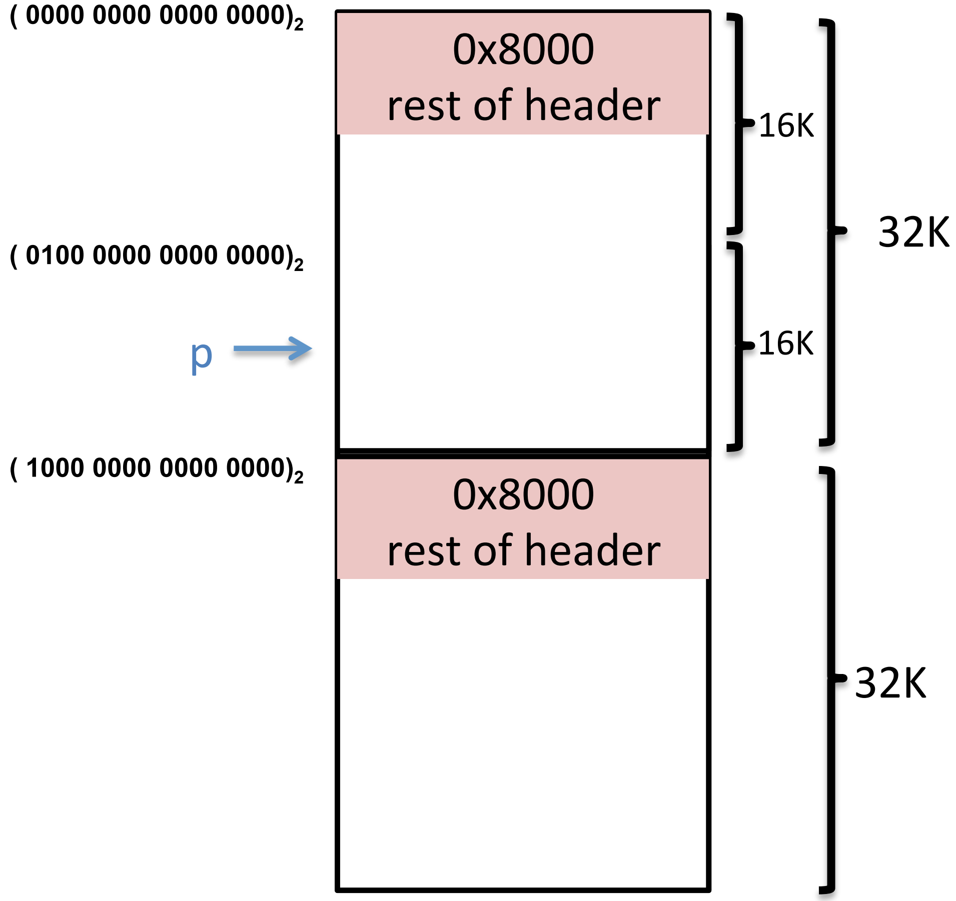
any bit XOR 0 = unchanged
any bit XOR 1 = flipped

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