Dynamic Memory Allocation

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based on Tiger Wang's slides

What we’ve learnt: how C program is executed by hardware

- Compiler translates C programs to machine code
  - Basic execution:
    - Load instruction from memory, decode + execute, advance %rip
  - Control flow
    - Arithmetic instructions, cmp/test set RFLAGS
    - jge (…) changes %rip depending on RFLAGS
  - Procedure call
    - return address is stored on stack
    - %rsp points to top of stack (stack grows down)
    - call/ret
- Linking:
  - Combine multiple compiled object files together
  - Resolve and relocate symbols (functions, global variables)

Today's lesson plan

- dynamic memory allocation (malloc/free)

Why dynamic memory allocation?

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

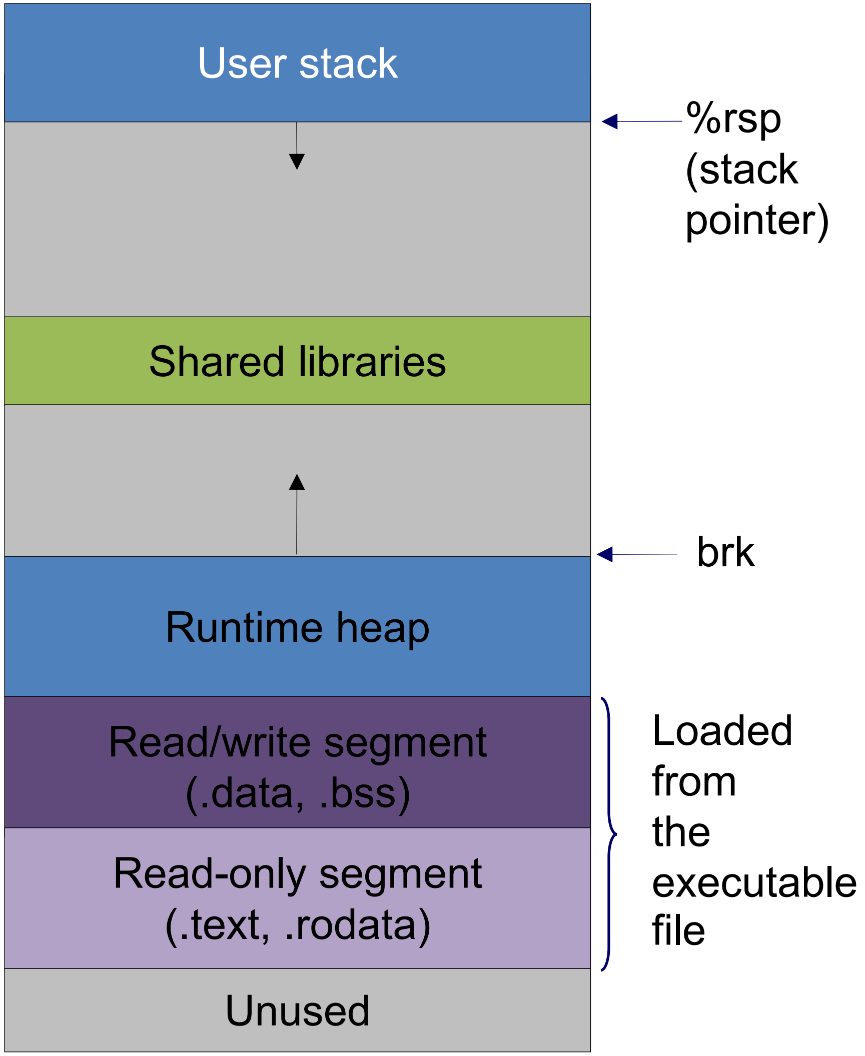
void list_insert(node *head, int v)
{
   node *np = malloc(sizeof(node));
   np->next = head;
   np->val = v;
   *head = np;
}

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?

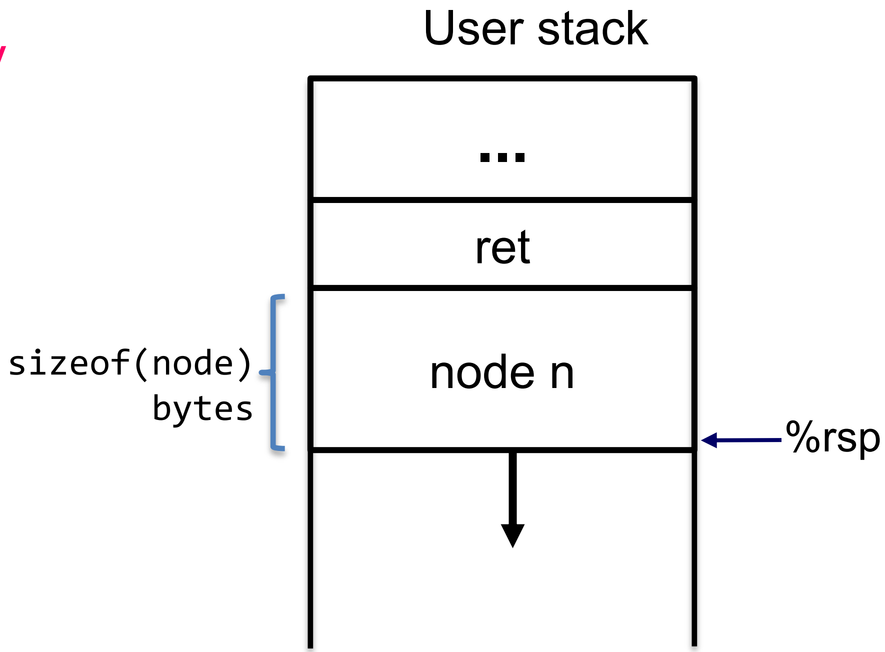

User stack
%rsp (stack pointer)
Shared libraries
brk
Runtime heap
Read/write segment (.data, .bss)
Read-only segment (.text, .rodata)
Loaded from the executable file
Unused

Dynamic allocation on heap

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

Answer: Yes, but space is freed upon function return

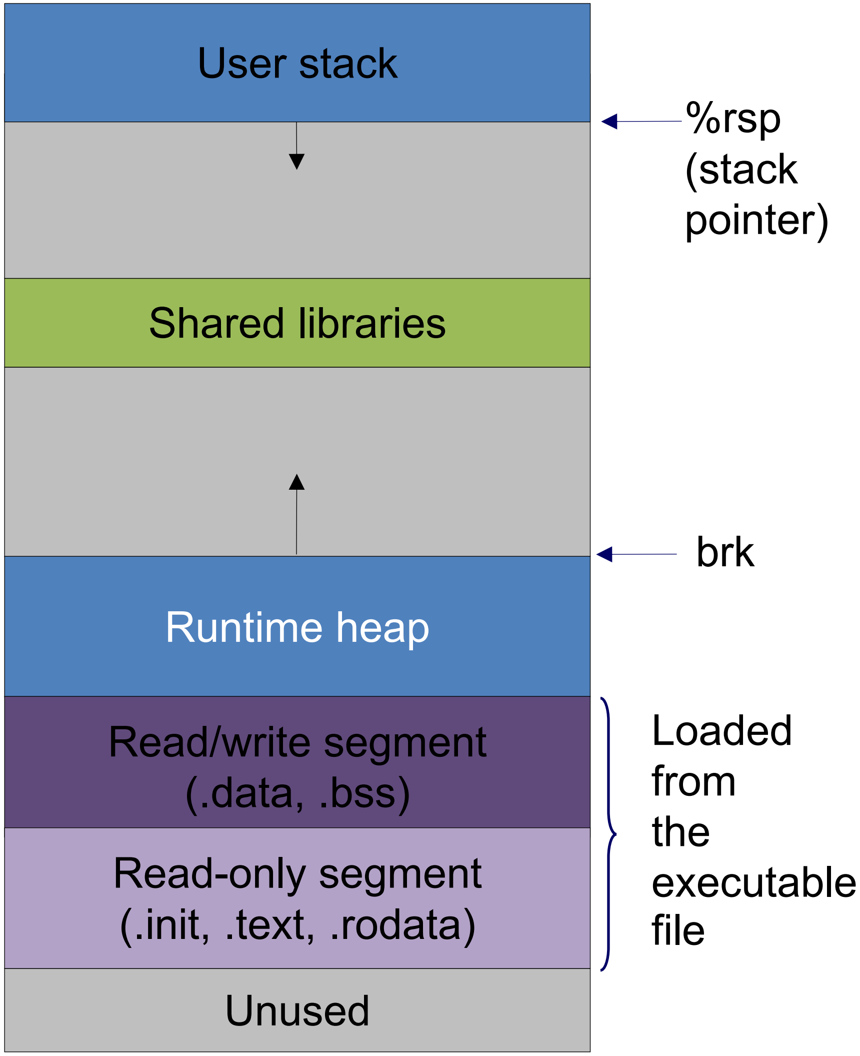
```
void
list_insert(node *head, int v) {
   node n;
   node *np = &n;
   np->next = head;
   np->val= v;
   *head = np;
}
```



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

Dynamic allocation on heap

Question: How to allocate memory on heap?


User stack
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Shared libraries
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Runtime heap
Read/write segment (.data, .bss)
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Unused

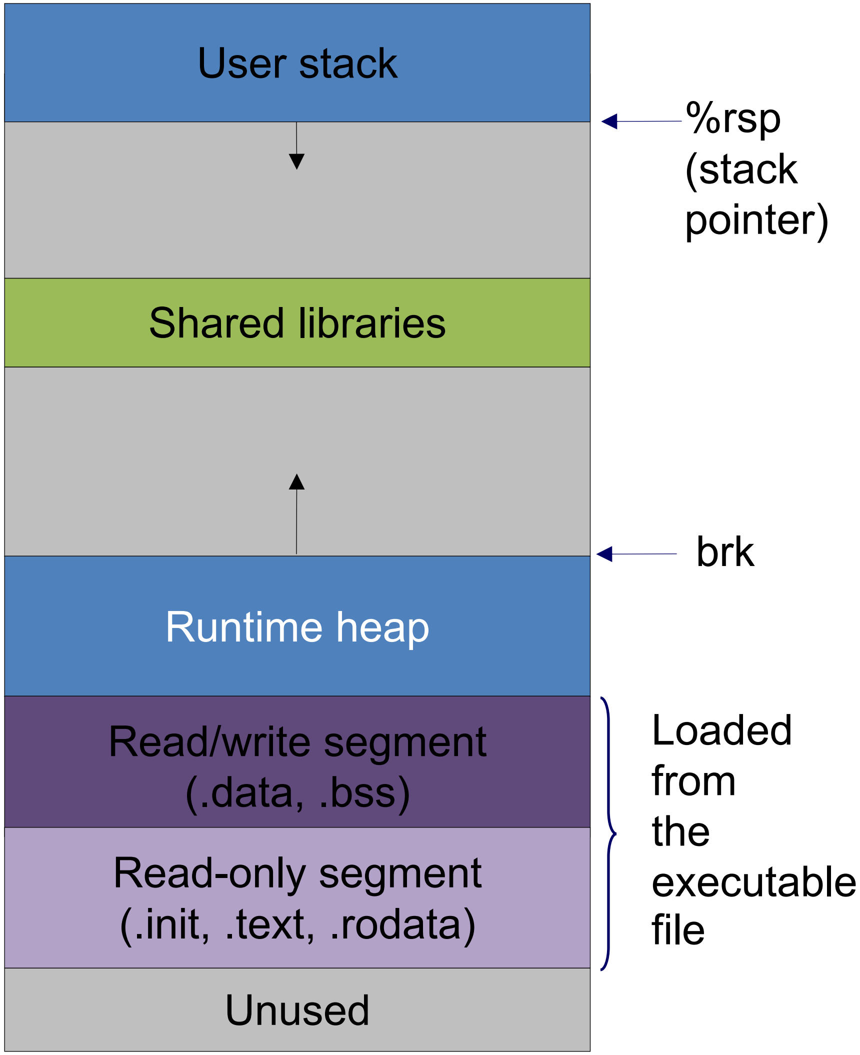
Dynamic allocation on heap

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.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Runtime heap
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Dynamic allocation on heap

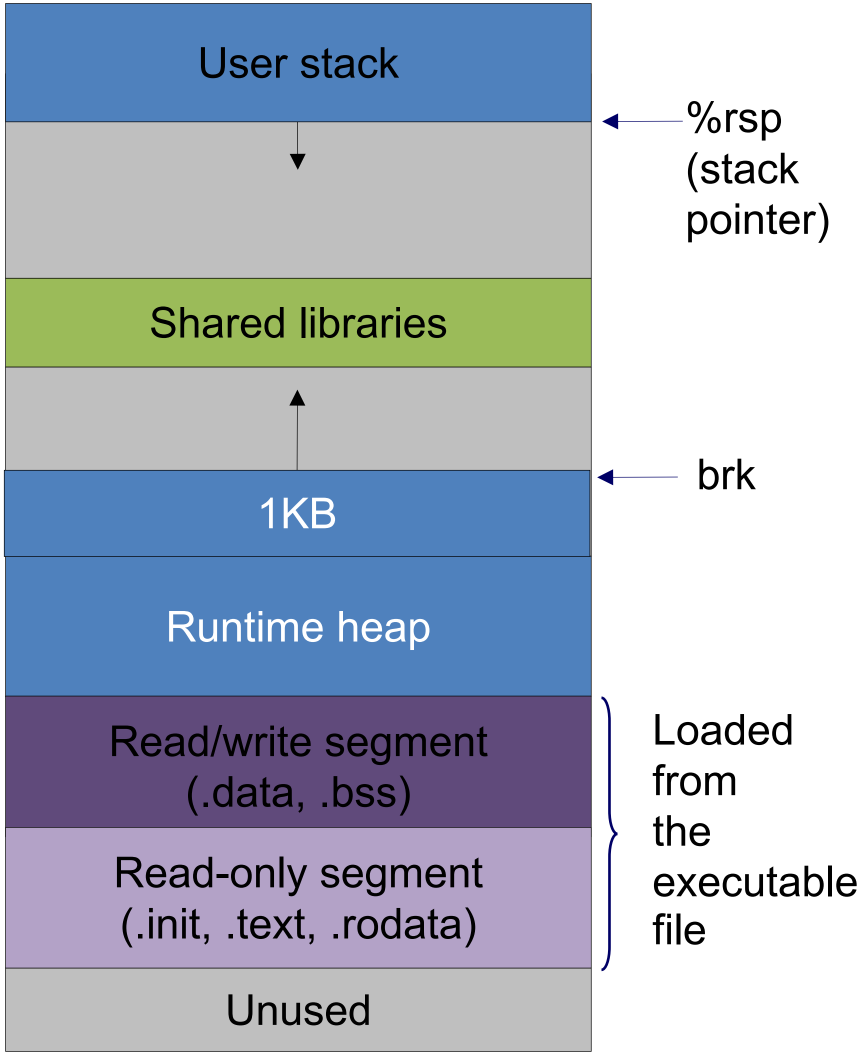
Question: How to allocate memory on heap?

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
```


User stack
%rsp (stack pointer)
Shared libraries
brk
1KB
Runtime heap
Read/write segment (.data, .bss)
Read-only segment (.init, .text, .rodata)
Loaded from the executable file
Unused

Dynamic allocation on heap

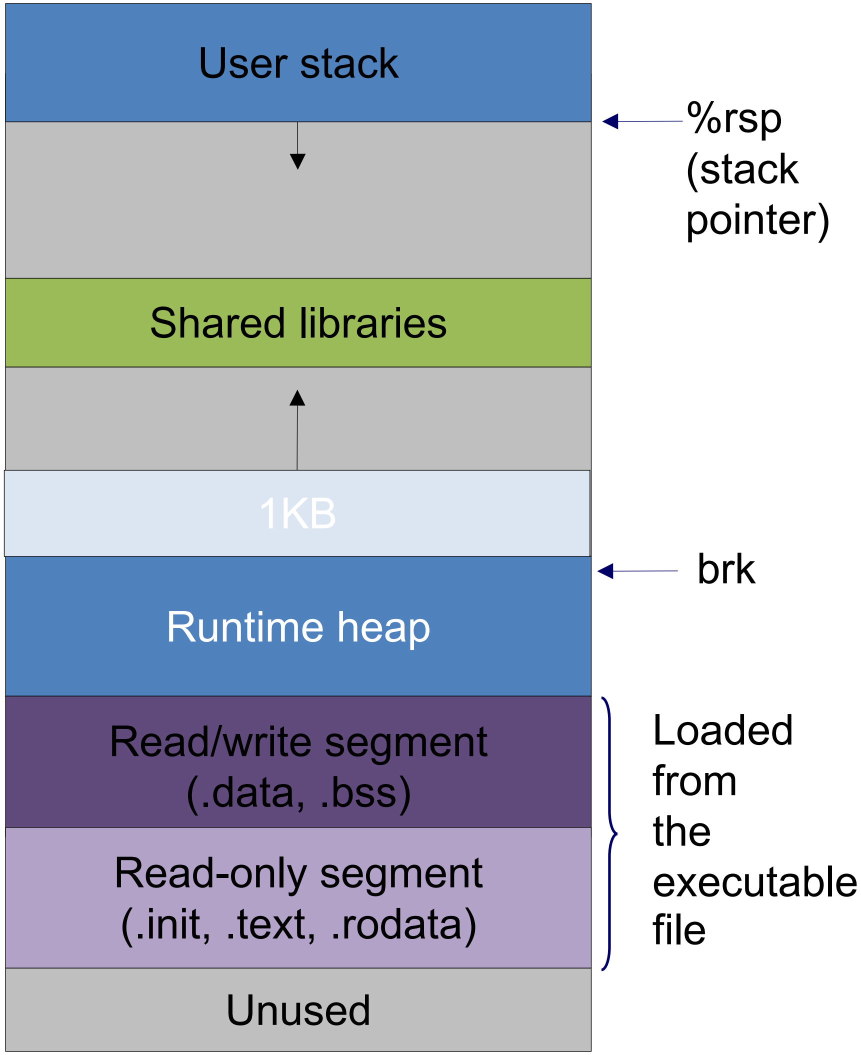
Question: How to allocate memory on heap?

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
```


User stack
%rsp (stack pointer)
Shared libraries
1KB
brk
Runtime heap
Read/write segment (.data, .bss)
Read-only segment (.init, .text, .rodata)
Loaded from the executable file
Unused

Dynamic allocation on heap

Question: How to allocate memory on heap?

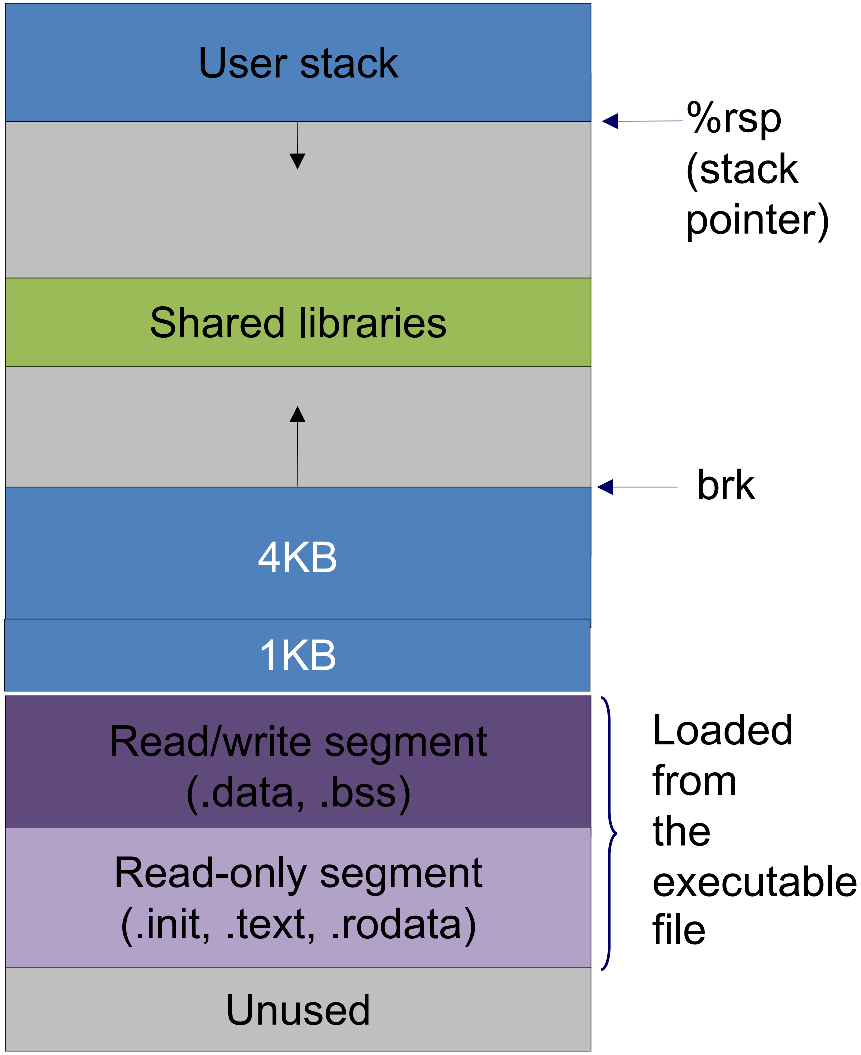
Ask OS for allocation on the heap via system calls

```
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?


User stack
%rsp (stack pointer)
Shared libraries
brk
4KB
1KB
Read/write segment (.data, .bss)
Read-only segment (.init, .text, .rodata)
Loaded from the executable file
Unused

Dynamic allocation on heap

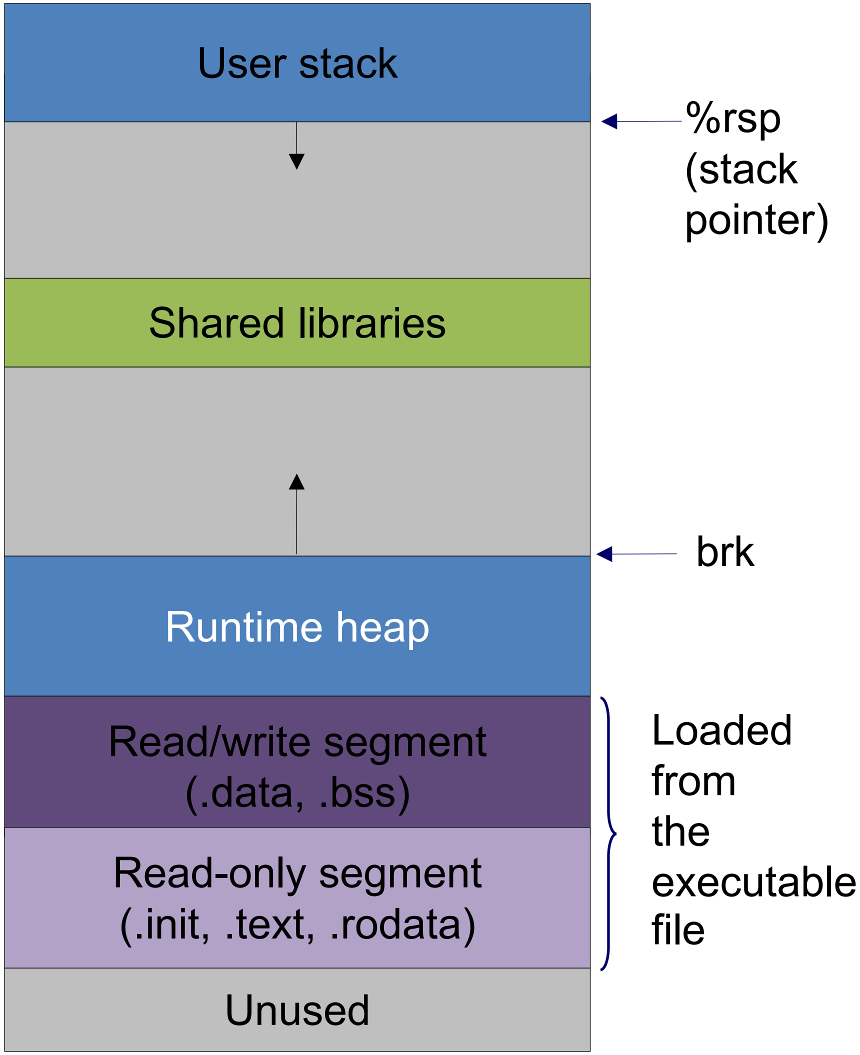
Question: How to allocate memory on heap?

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

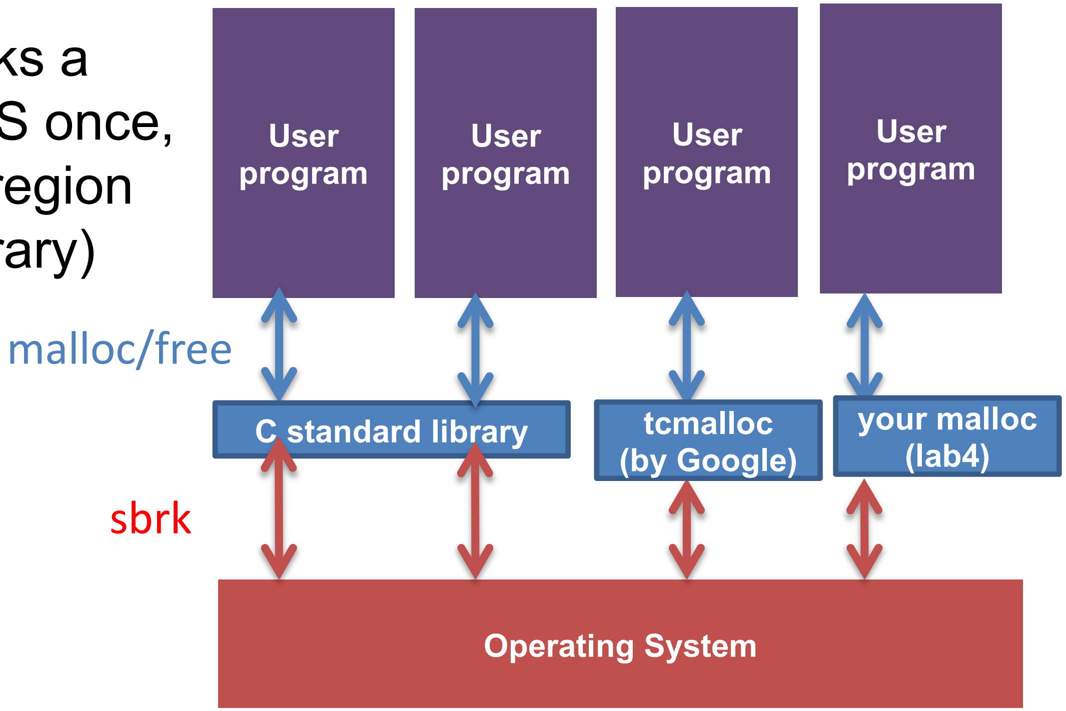
Issue II – system call has high performance cost > 10X


User stack
%rsp (stack pointer)
Shared libraries
brk
Runtime heap
Read/write segment (.data, .bss)
Read-only segment (.init, .text, .rodata)
Loaded from the executable file
Unused

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?

- Assumptions on application behavior:
  - Use APIs correctly
    - Argument of free must be the return value of a previous malloc
    - No double free
  - Use APIs freely
    - Can issue an arbitrary sequence of malloc/free

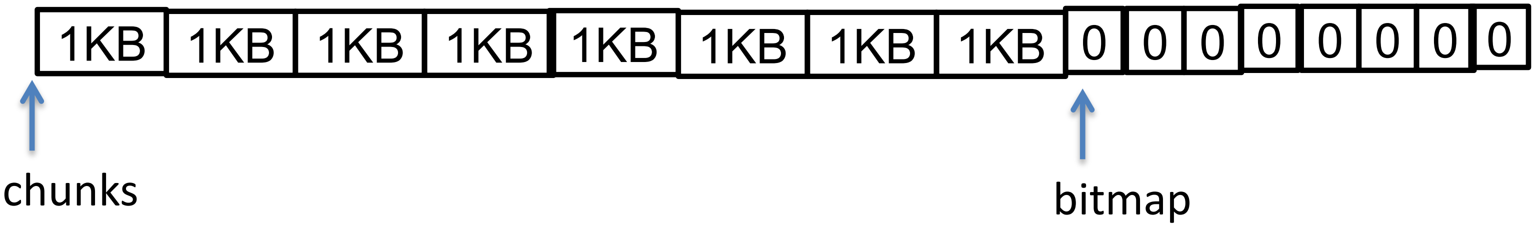
- Restrictions on the allocator:
  - Once allocated, space cannot be moved around

Questions

- (Basic book-keeping) How to keep track which bytes are free and which are not?
- (Allocation decision) Which free chunk to allocate?
- (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

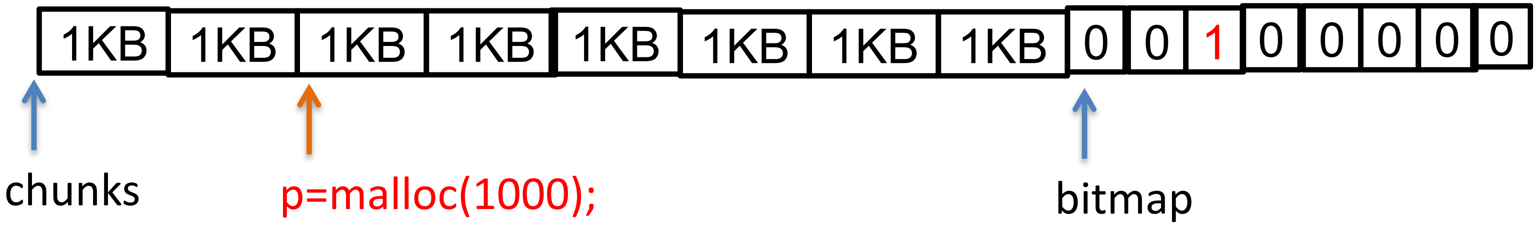


```
#define CHUNKSIZE 1<<10;
typedef char[CHUNKSIZE] chunk;
char *bitmap;
chunk *chunks;
size_t n_chunks;

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



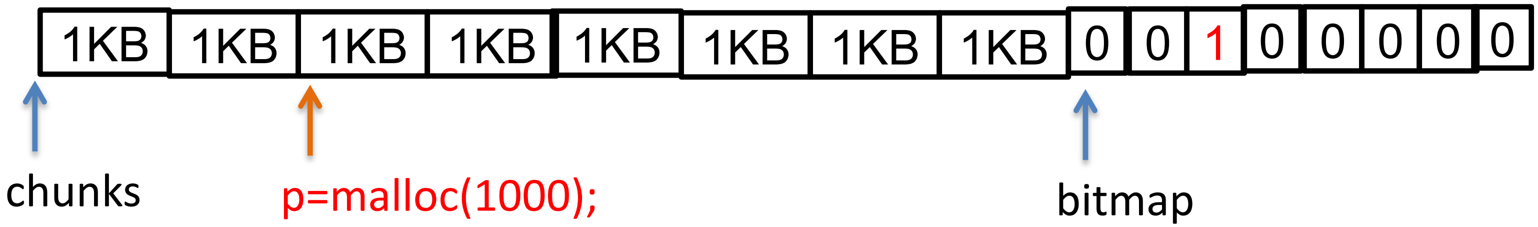
```
void* malloc(size_t sz) {
  // find out # of chunks needed to fit sz bytes
  csz = ...

  //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



chunks

p=malloc(1000);

bitmap

```
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!

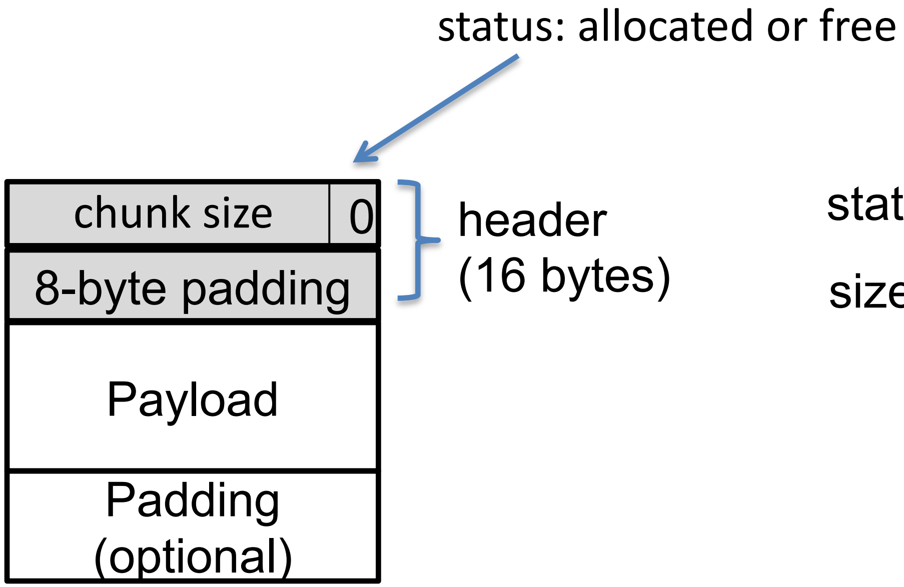
Today’s lesson plan

- Previously:
  - Why dynamic memory allocation?
  - Design requirements and challenges
- Today:
  - Implicit list
  - Explicit list

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
    - Payload starting address must be some multiple of 16
    - To simplify design, make header size 16 byte, payload size x*16 bytes



status: allocated or free

chunk size | 0

8-byte padding

Payload

Padding (optional)

header (16 bytes)

status: size_and_status & 0x1L

size: size_and_status & ~(0x1L)

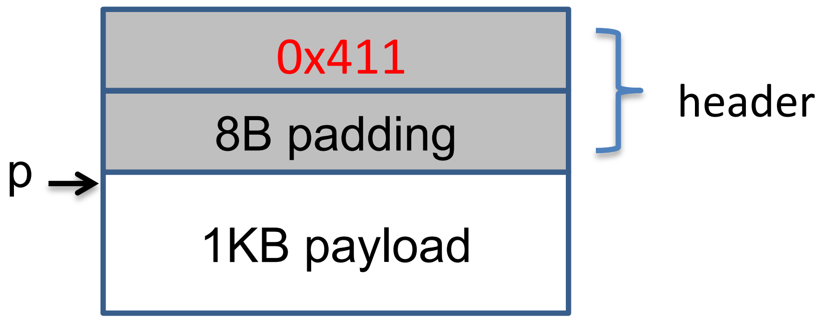
Implicit list

Embed chunk metadata in the chunks

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

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

Chunk_size = 1024 + 16 = 1040 (0x410)

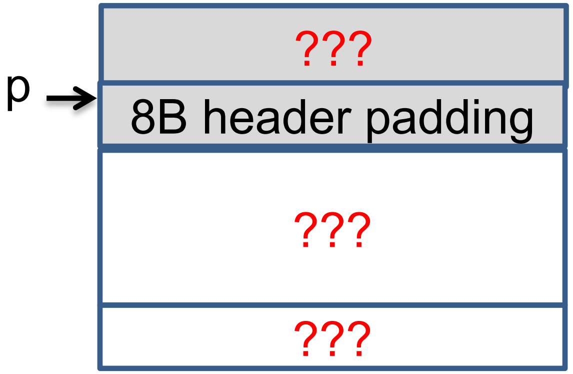


Implicit list

Embed chunk metadata in the chunks

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

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

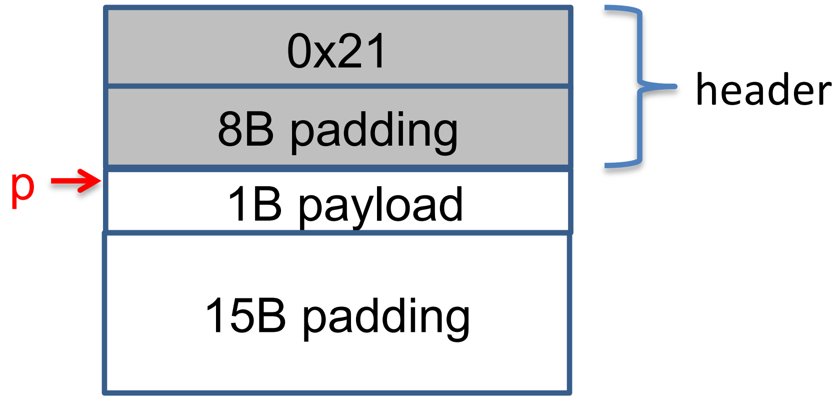


Implicit list

Embed chunk metadata in the chunks

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

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



How to initialize an implicit list

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

void init_chunk(header *p, unsigned long sz, bool status)
{
    p->size_and_status = sz | (unsigned long) status;
}

void init()
{
    header *p;
    p = ask_os_for_chunk(INITIAL_CSZ);
    init_chunk(p, INITIAL_CSZ, status);
}
```

How to traverse an implicit list

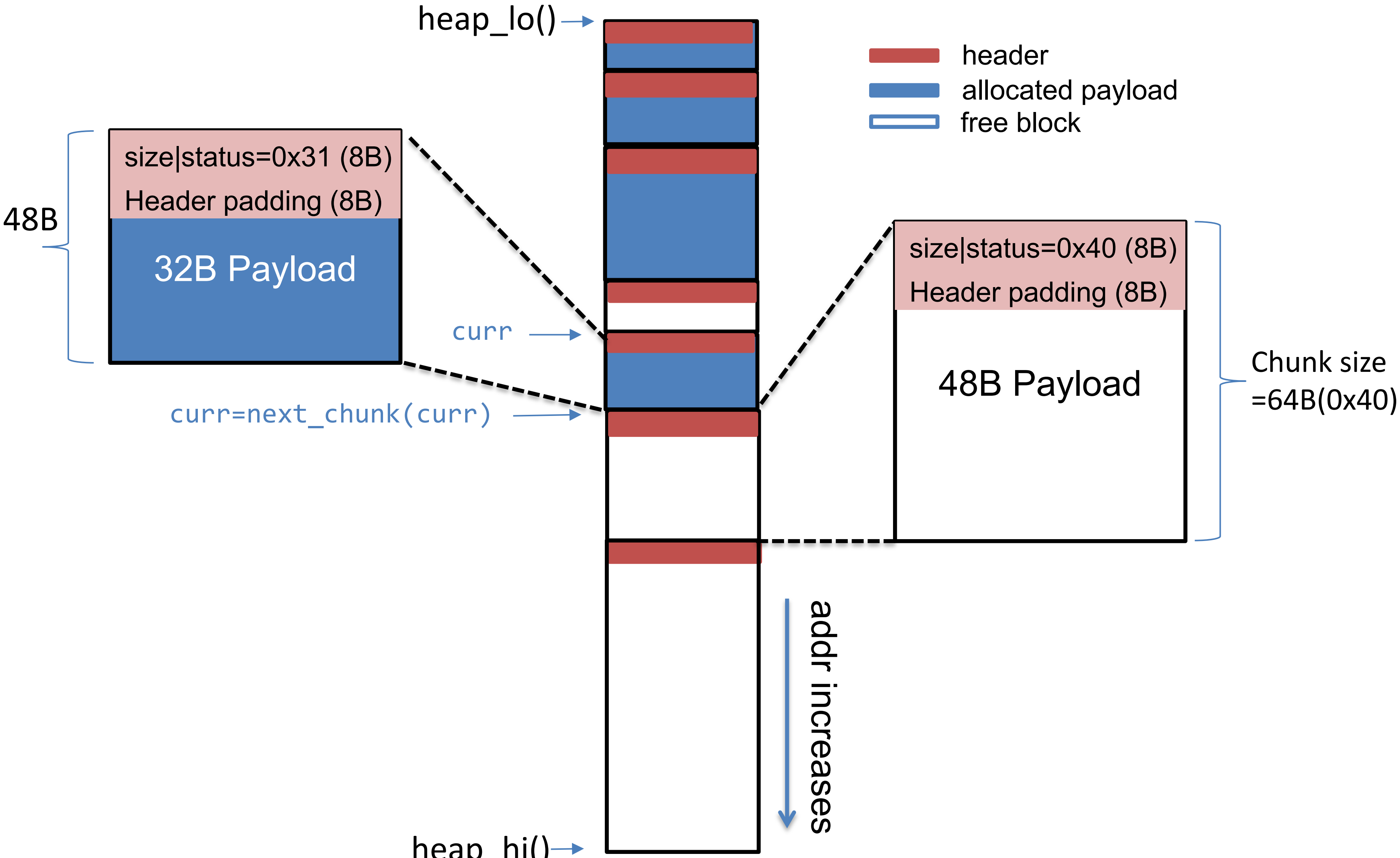
```
typedef struct {
  unsigned long size_and_status;
  unsigned long padding;
} header;
```

```
bool get_status(header *h) {
 // return status of the chunk
}
size_t get_size(header *h) {
 // return size of the chunk
}

header *next_chunk(header *curr) {
 // How to set curr to point to next chunk?
}
```

```
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);
    printf(“chunk size=%d status=%d\n”,csz,allocated);
    curr = next_chunk(curr);
  }
}
```

How to traverse an implicit list

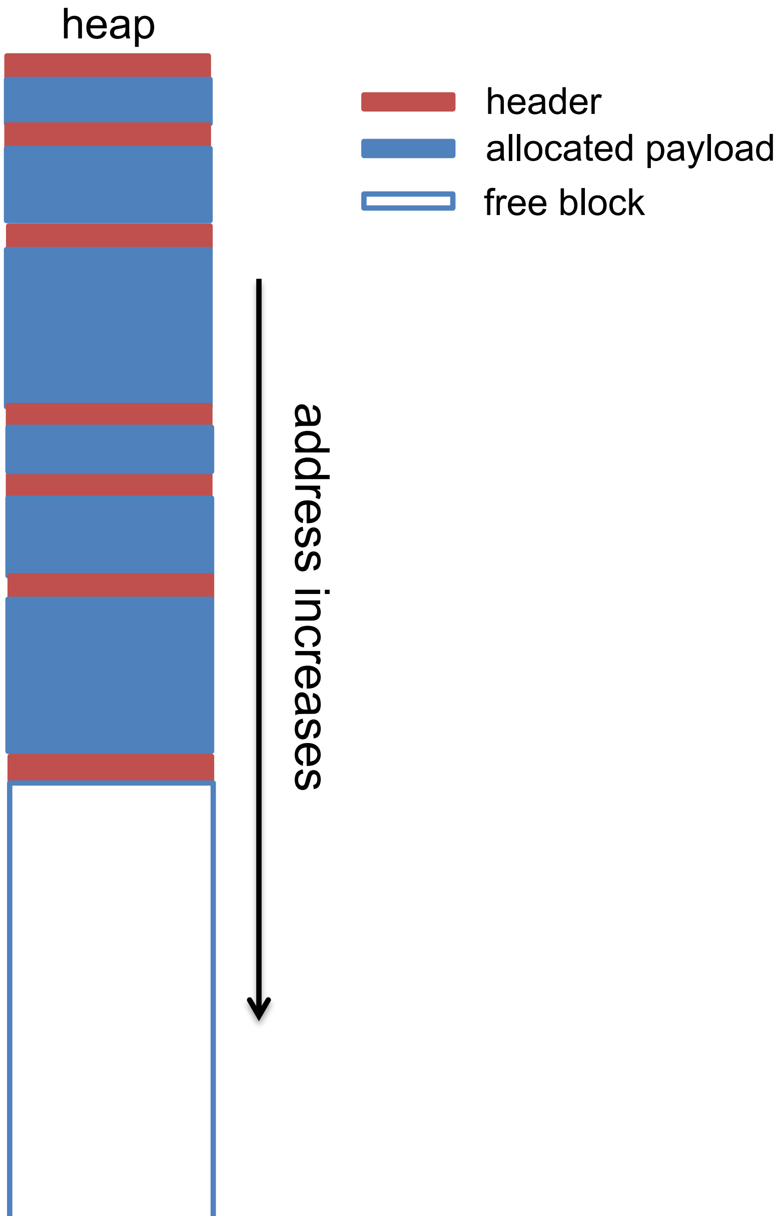


malloc() in an implicit list

```
void malloc(unsigned long size) {
  unsigned long chunk_sz = align(size) + sizeof(header);
  header *h = find_fit(chunk_sz);
  //split if chunk is larger than necessary
  split(h, chunk_sz);
  set_status(h, true);
}
```

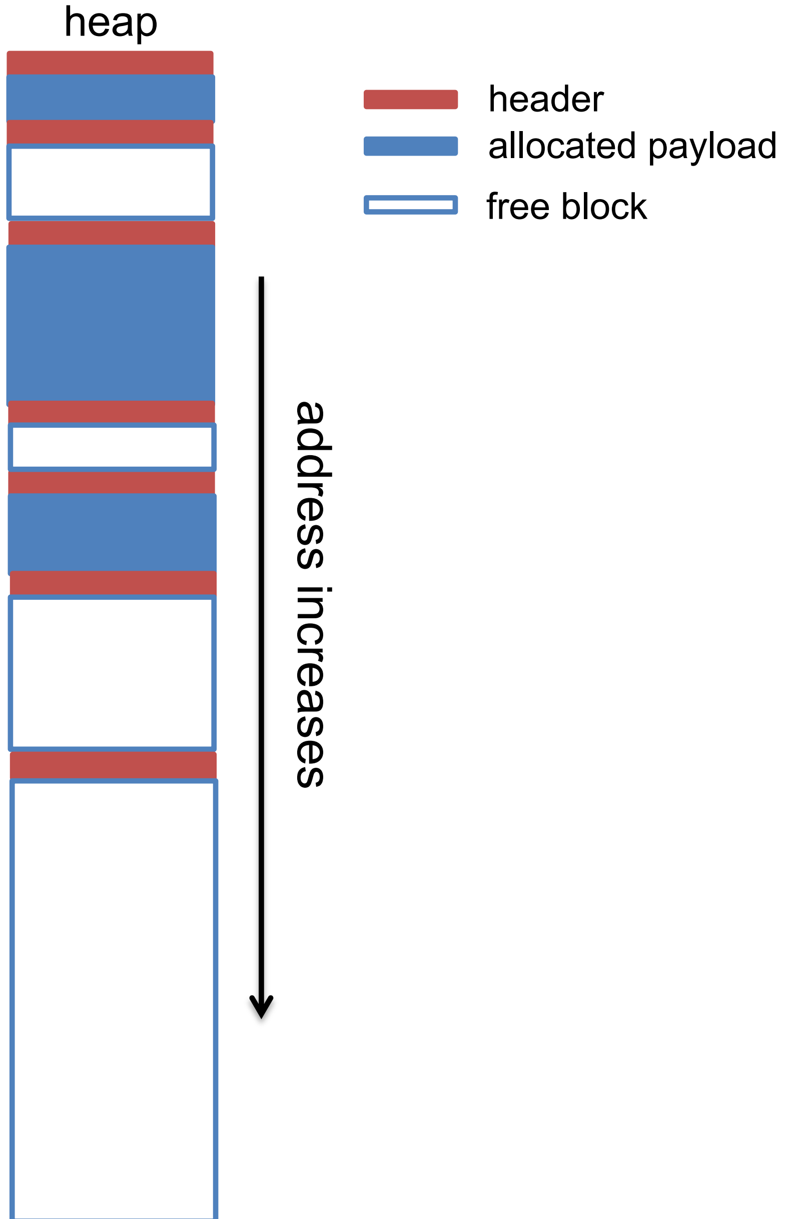
Where to place an allocation?

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



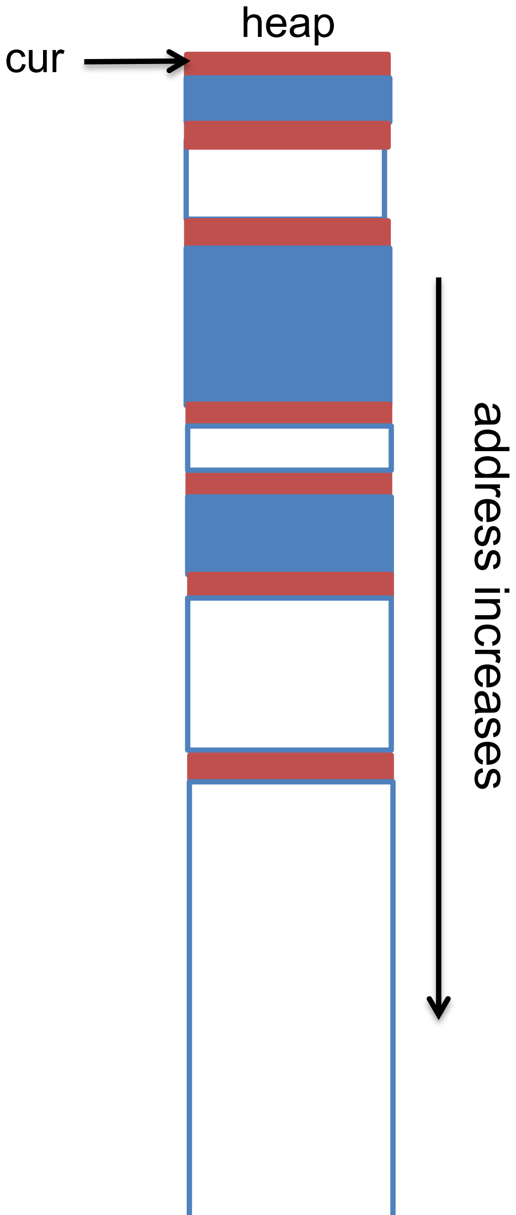
Where to place an allocation?

```
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)
```

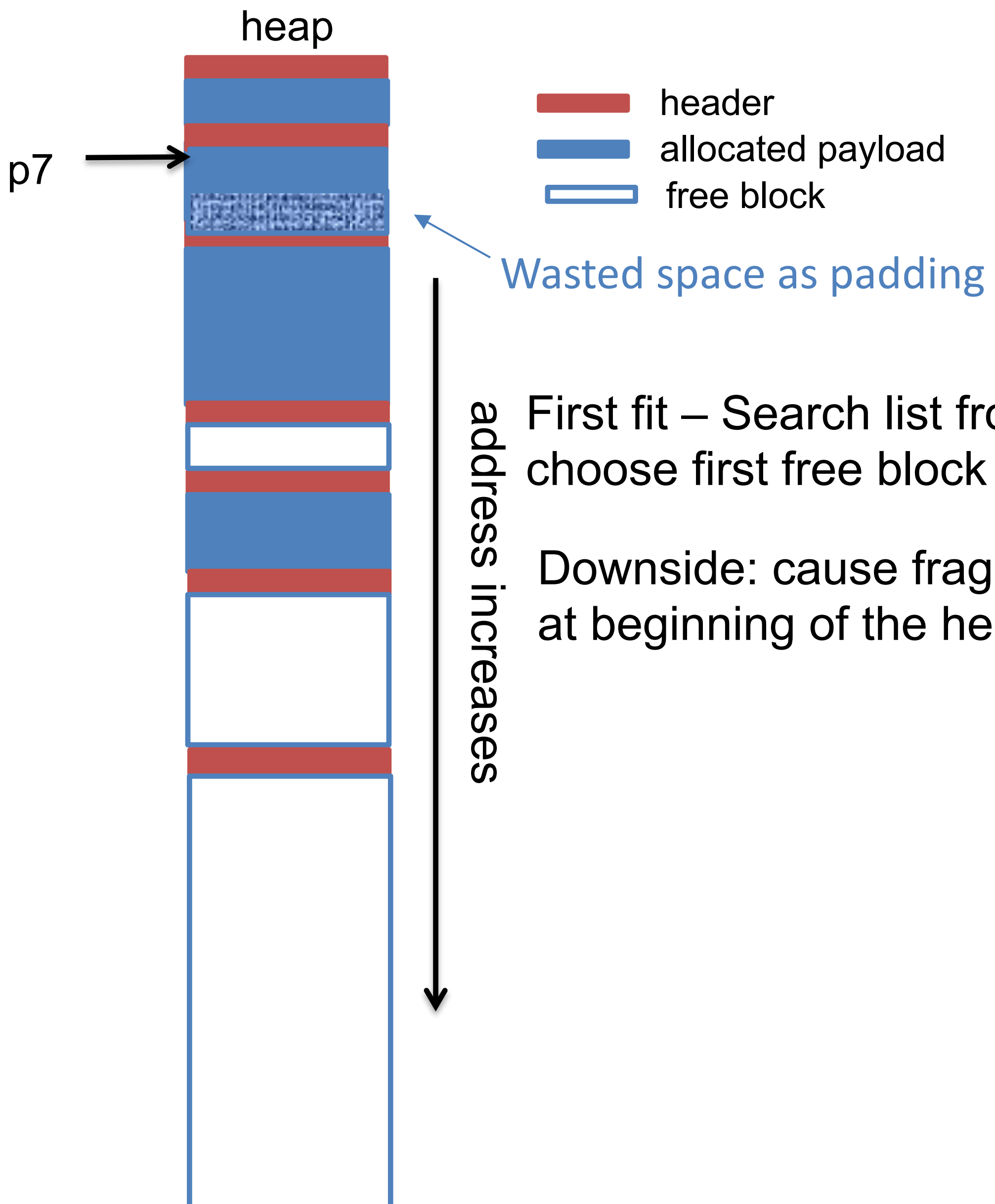


🟥 header
🟦 allocated payload
□ free block

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)
```

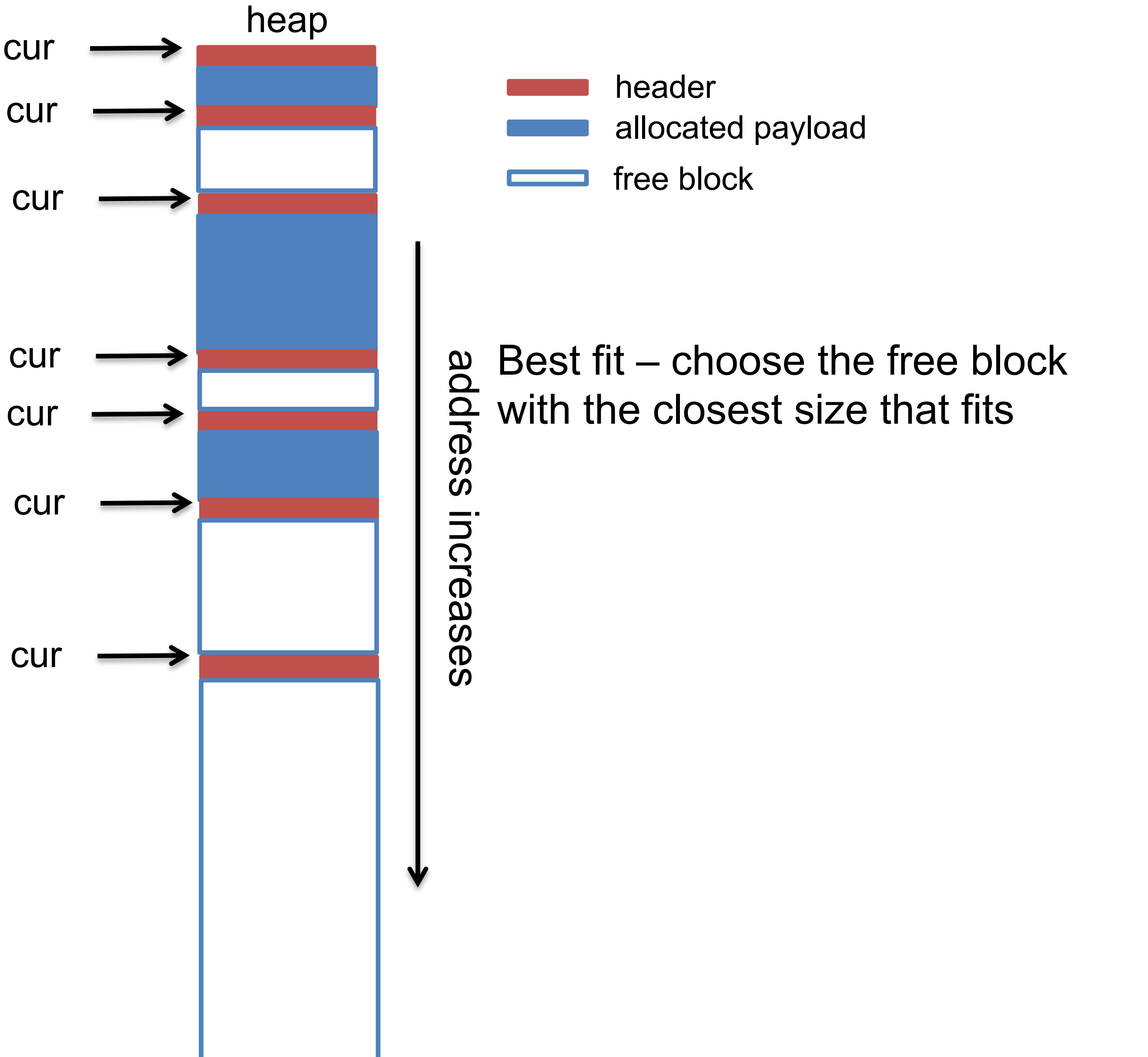


First fit – Search list from beginning, choose first free block that fits

Downside: cause fragmentation at beginning of the heap

Best fit

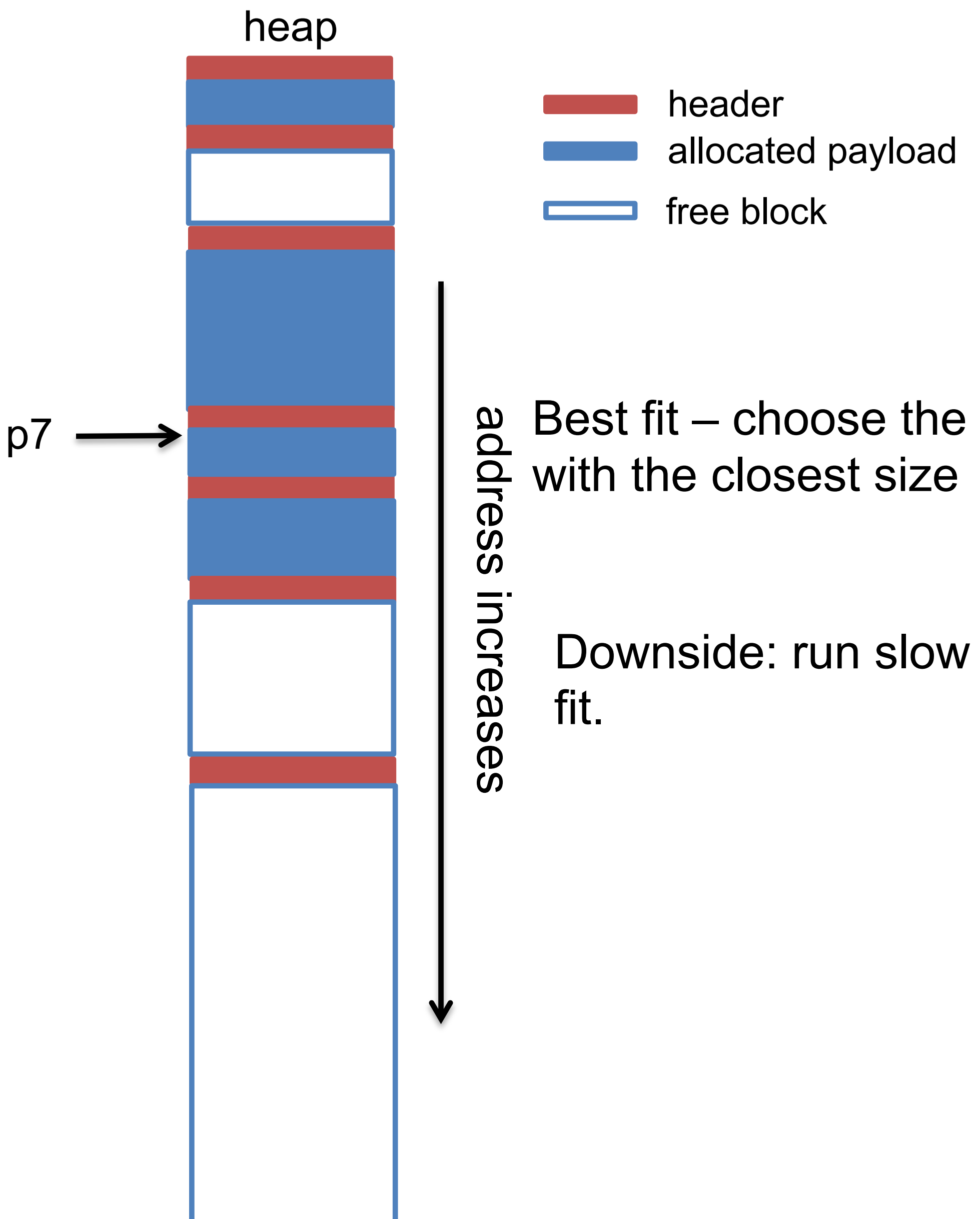
```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
```



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)
```

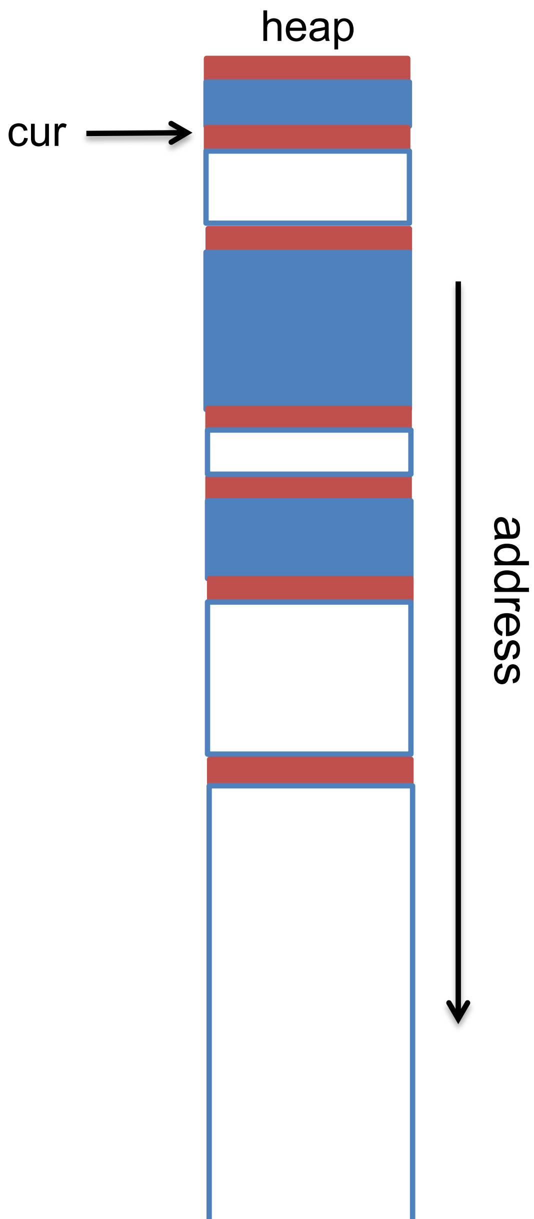


Best fit – choose the free block with the closest size that fits

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)
```



🟥 header

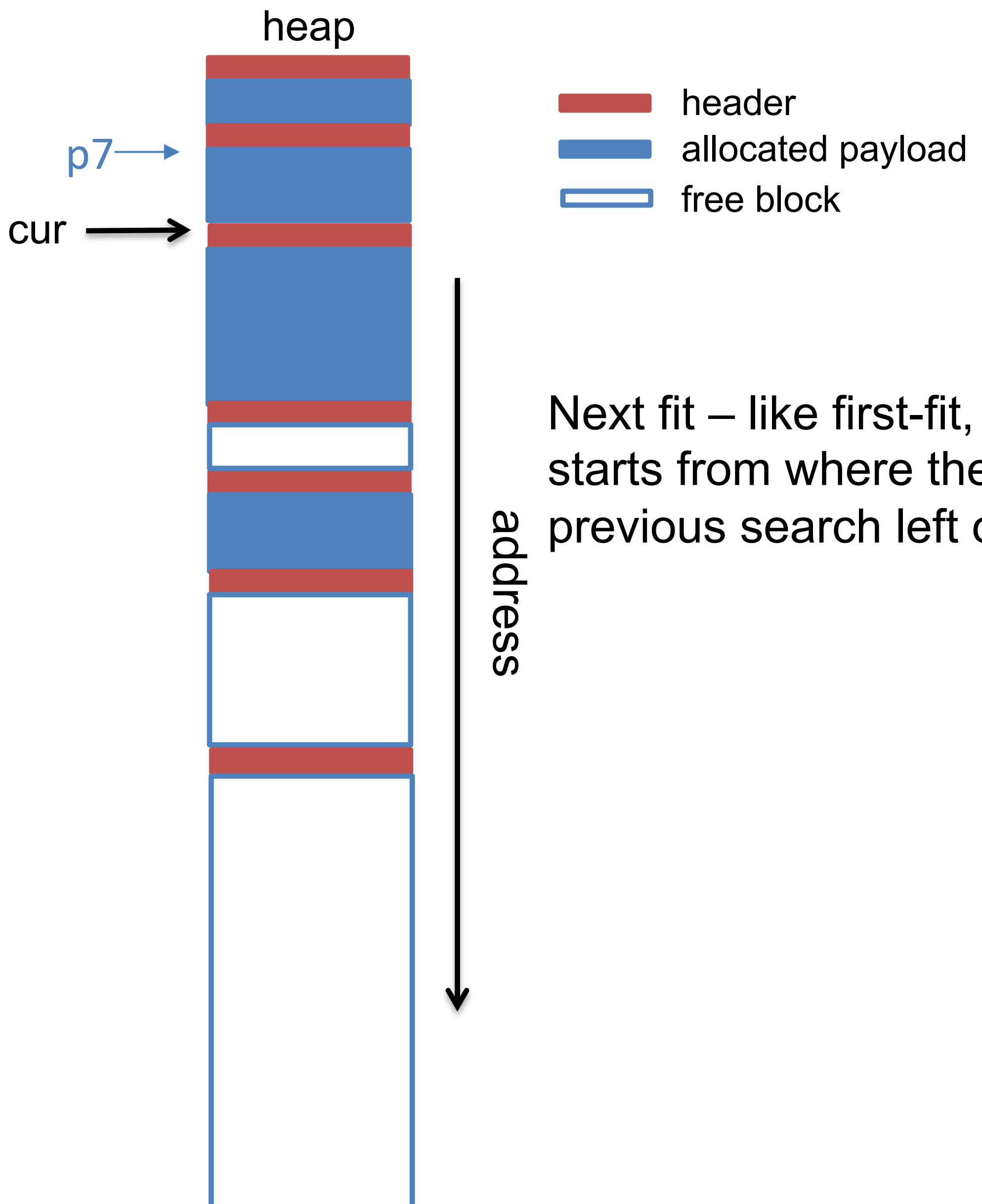
🟦 allocated payload

□ free block

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

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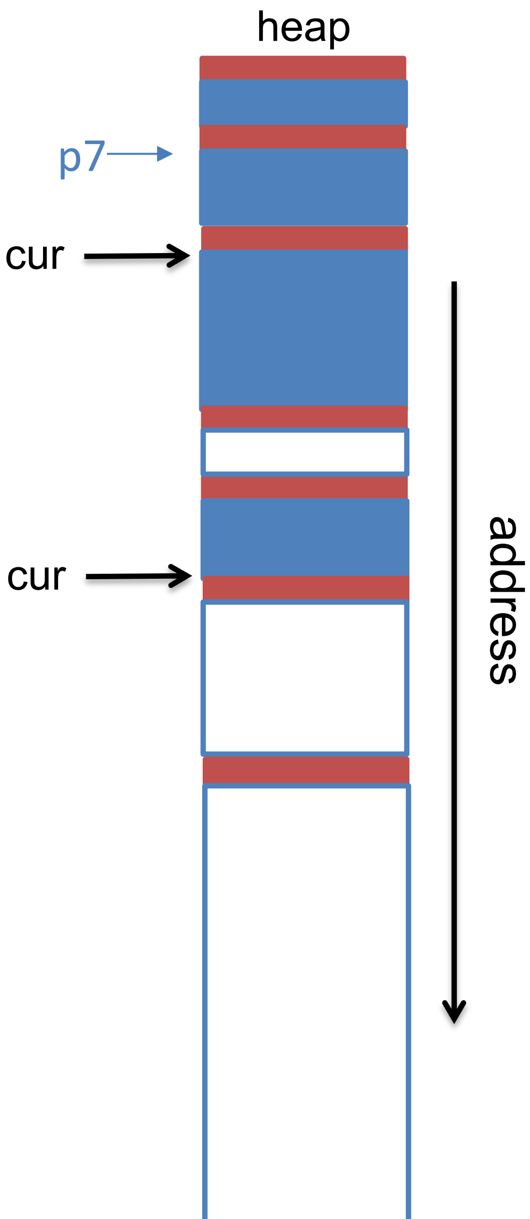
p8 = malloc(56)
```



🟥 header

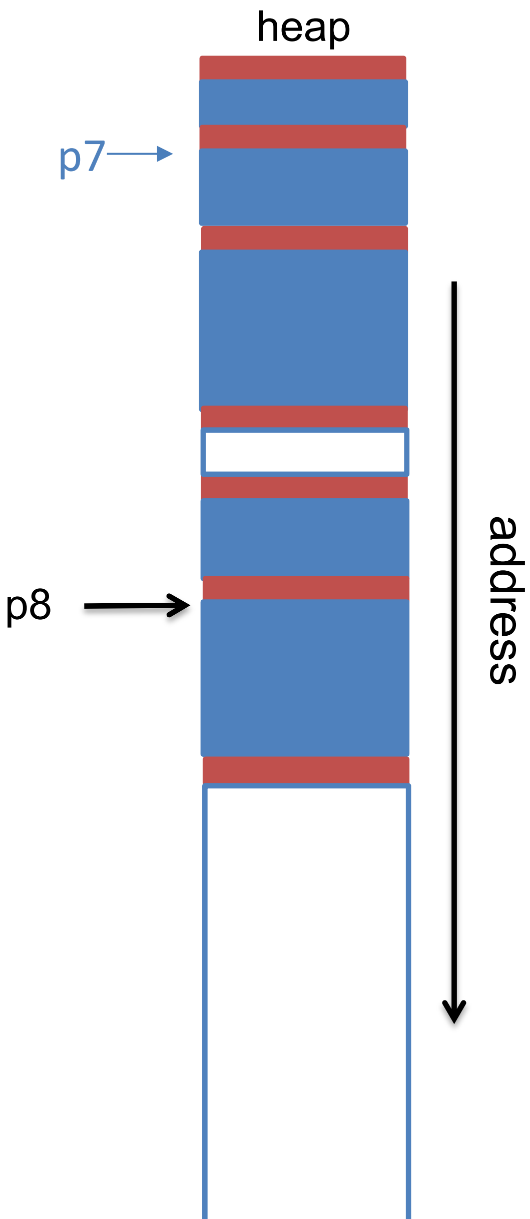
🟦 allocated payload

▭ free block

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)
```



🟥 header

🟦 allocated payload

▭ free block

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

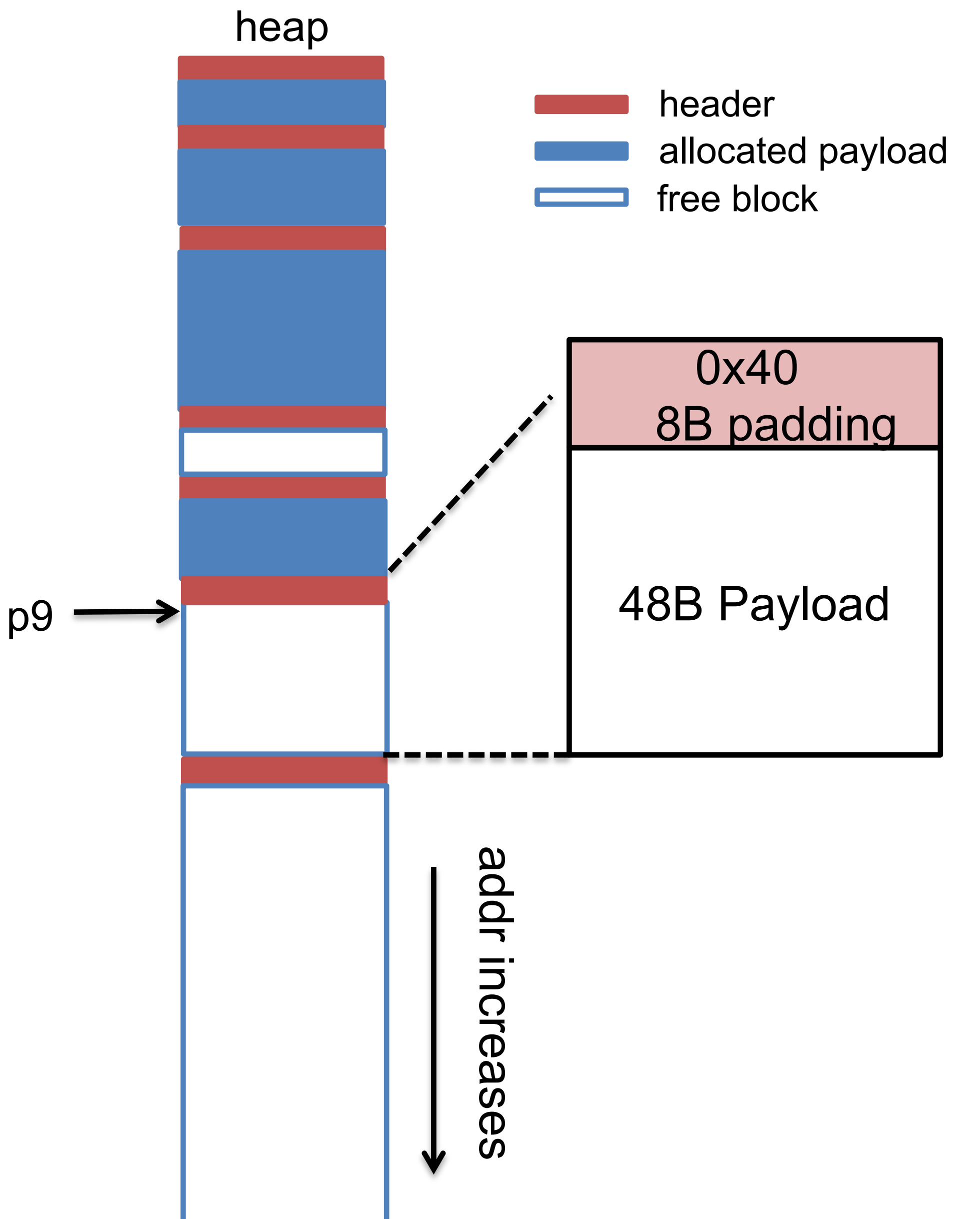
Next fit runs faster than first fit, but fragmentation is worse.

malloc() in an implicit list

```
void* malloc(unsigned long size) {
  unsigned long chunk_sz = align(size) + sizeof(header);
  header *h = find_fit(chunk_sz);
  //split if chunk is larger than necessary
  split(h, chunk_sz);
  set_status(h, true);
  return header2payload(h);
}
```

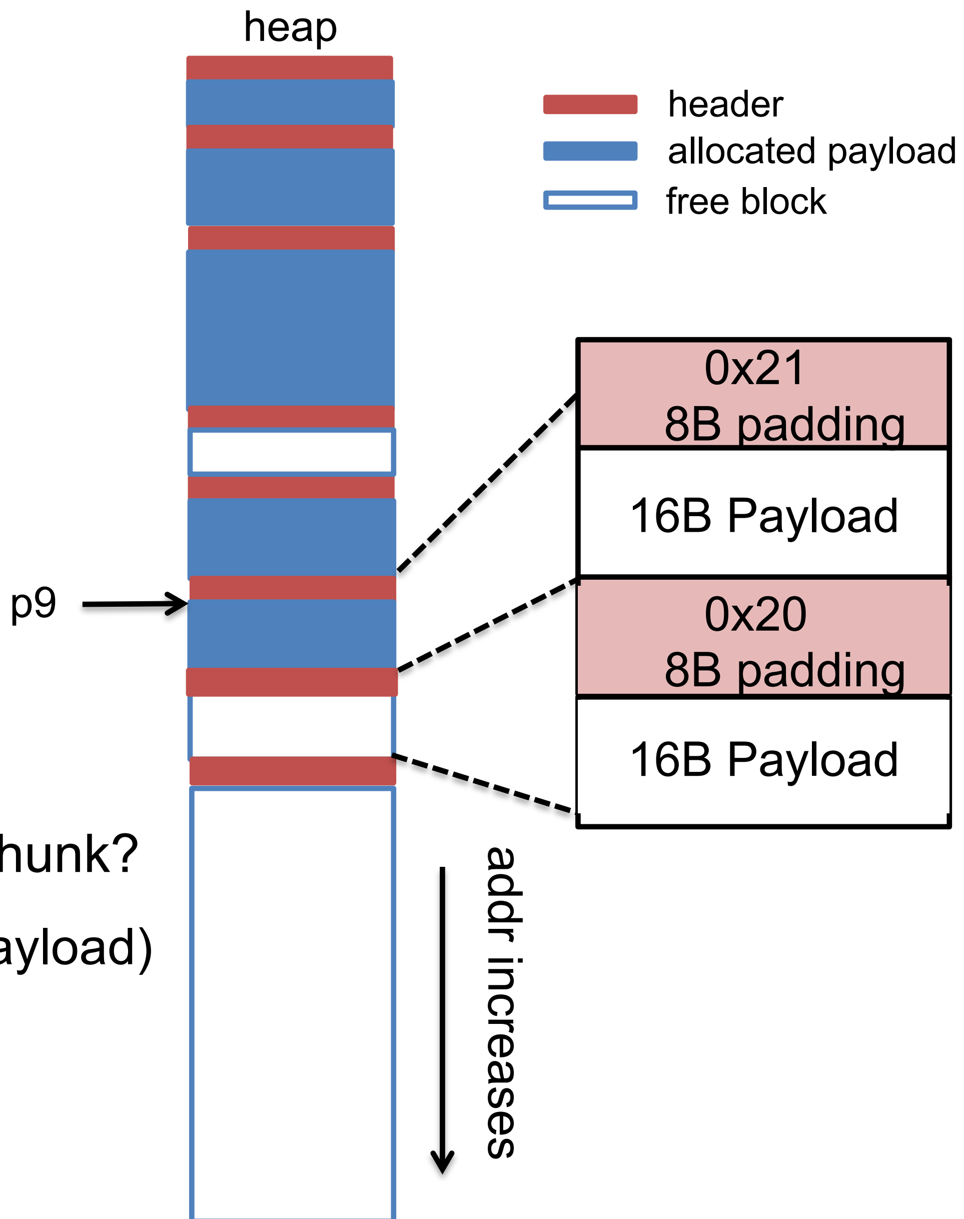
Splitting a free block

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



Splitting a free block

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

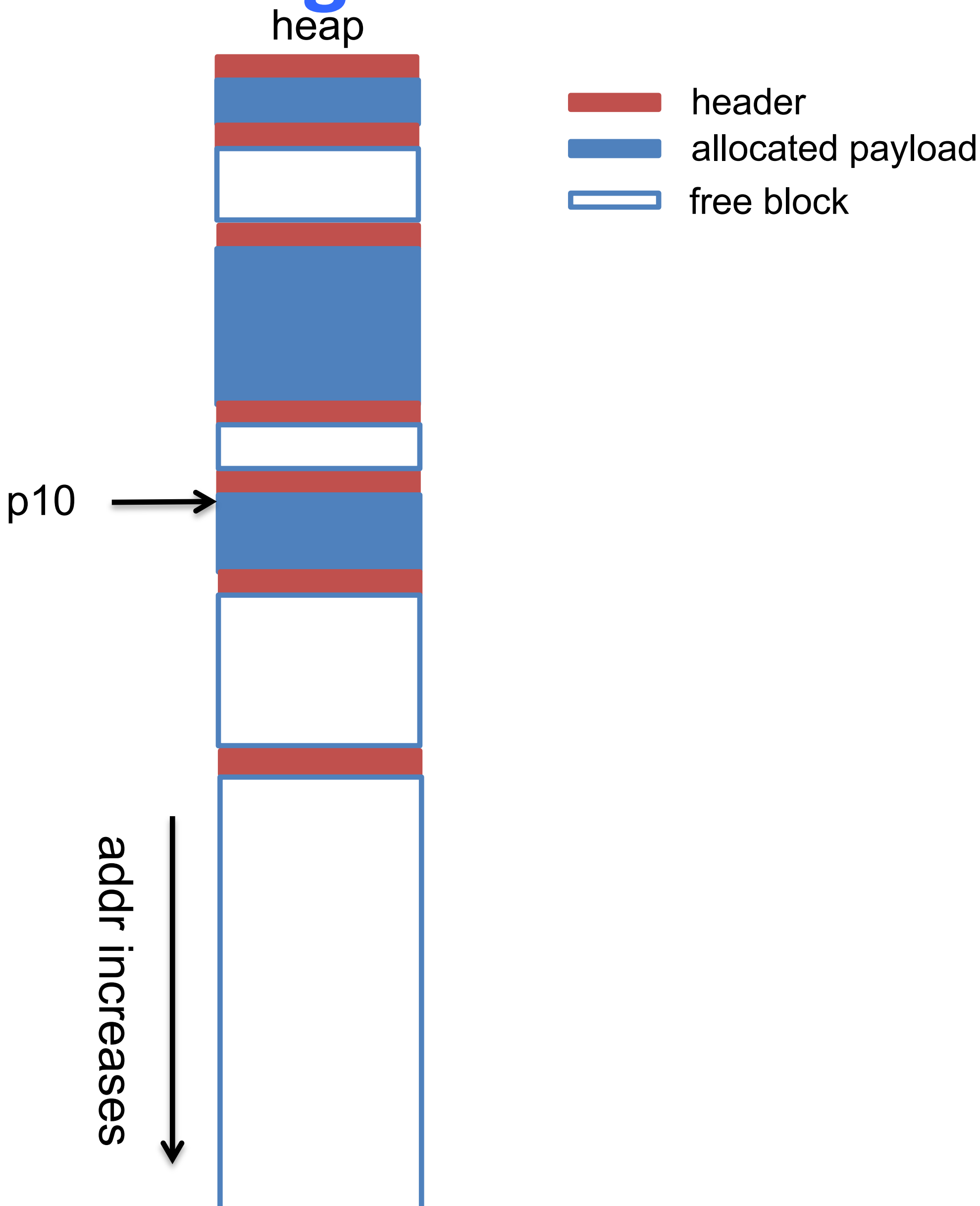


Q: what's the smallest chunk?

A: 16 (header)+16(min payload) = 32B

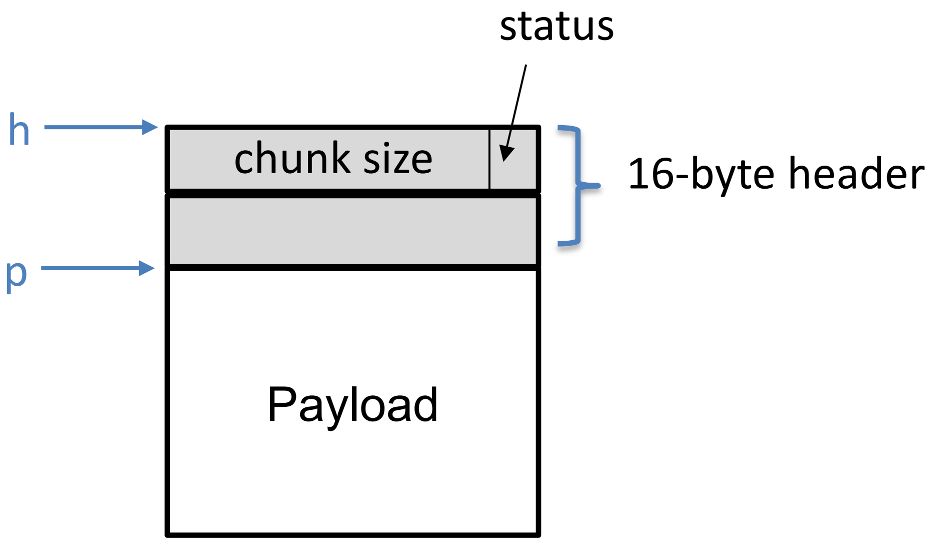
Coalescing a free block with its next free neighbor

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



free() in an implicit list

```
void free(void *p) {
  header *h = payload2header(p);
  set_status(h, false);
  coalesce(h);
}
```

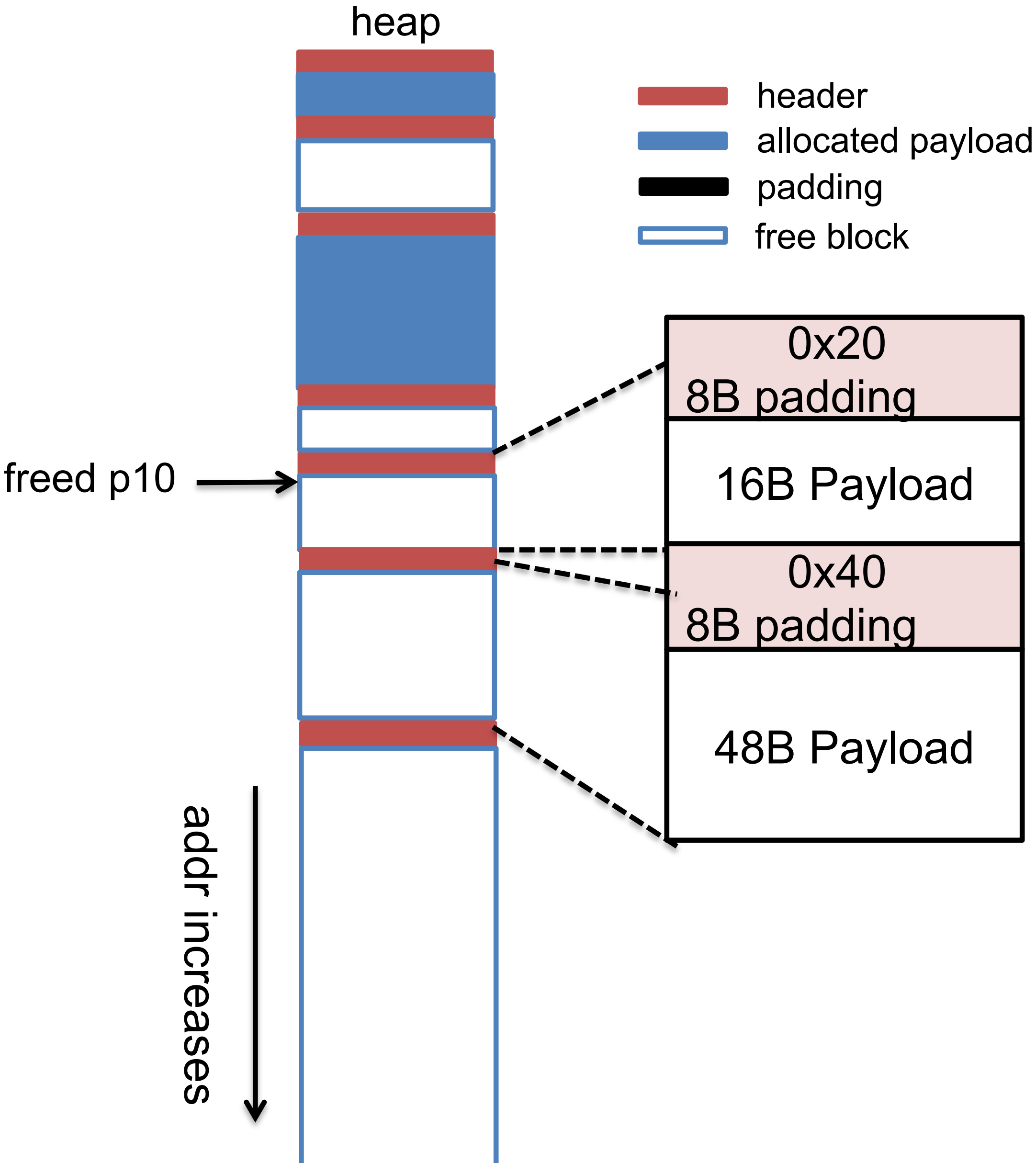


```
header *payload2header(void *p)
{


}
```

Coalescing a free block with next free neighbor

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



heap

freed p10

addr increases

🟥 header

🟦 allocated payload

⬛ padding

□ free block

0x20
8B padding

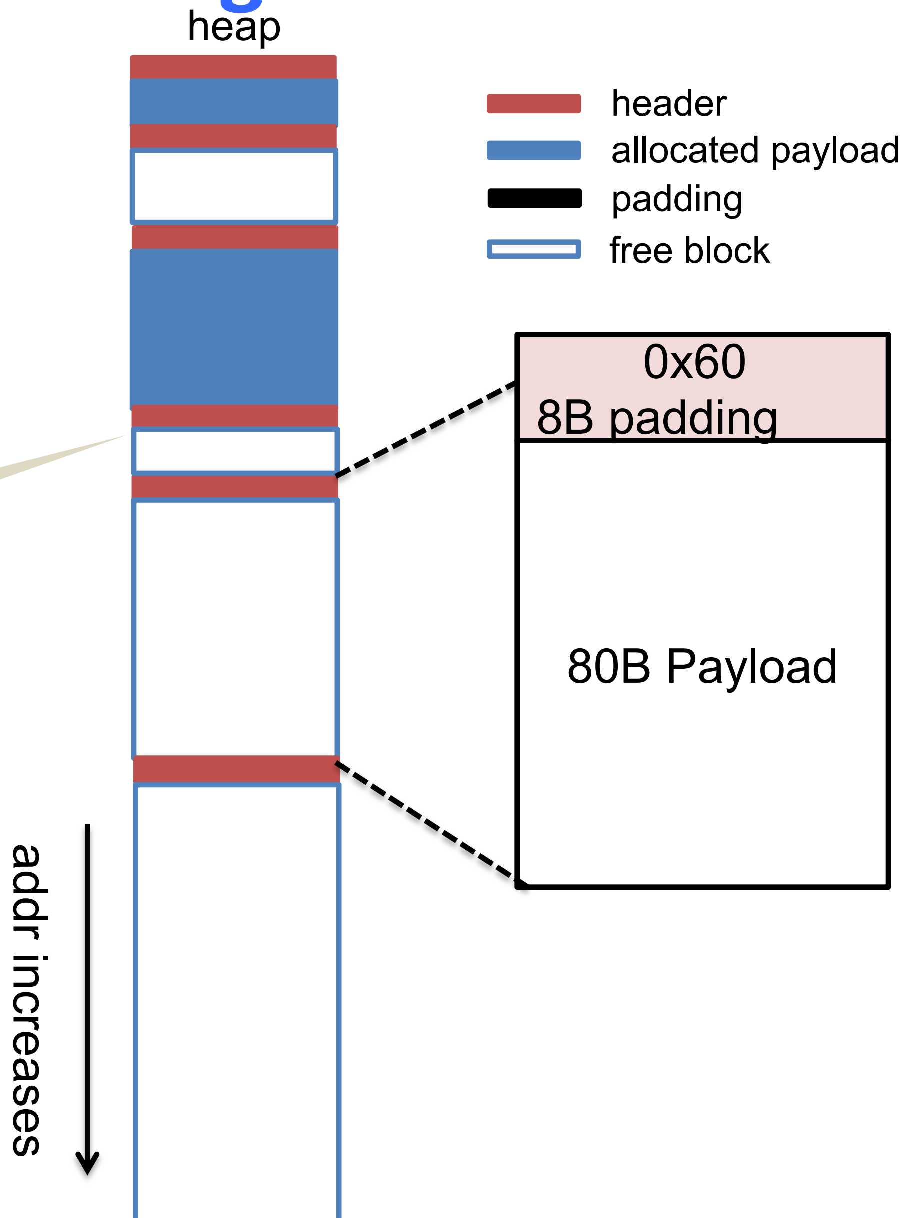
16B Payload

0x40
8B padding

48B Payload

Coalescing a free block with its next free neighbor

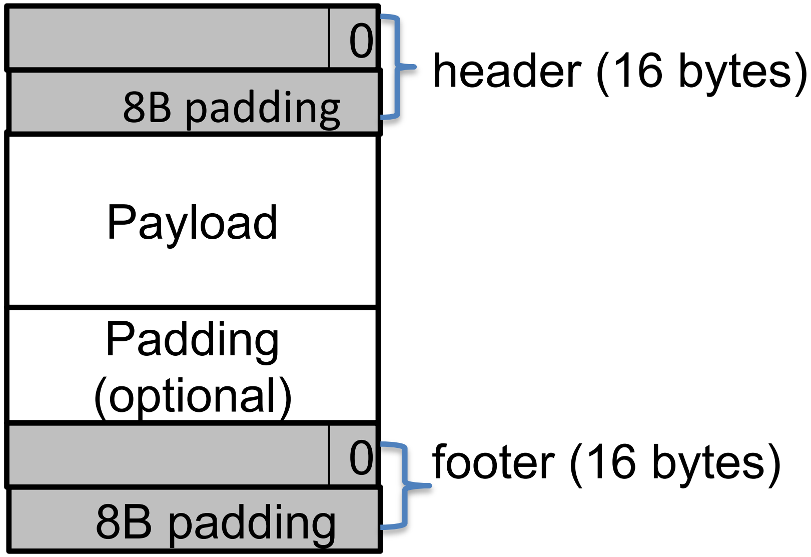
```
...
free(p10)
```

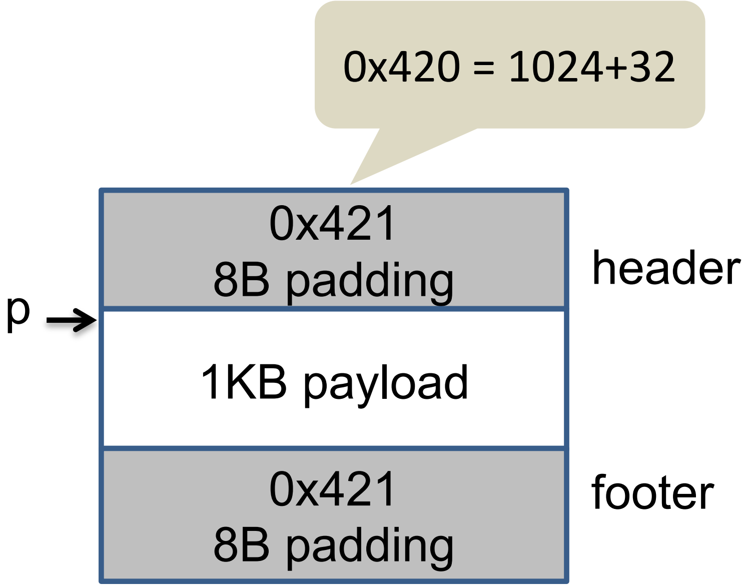


How to coalesce with the previous free block?

Use footer to coalesce with previous block

- Duplicate header information into the footer

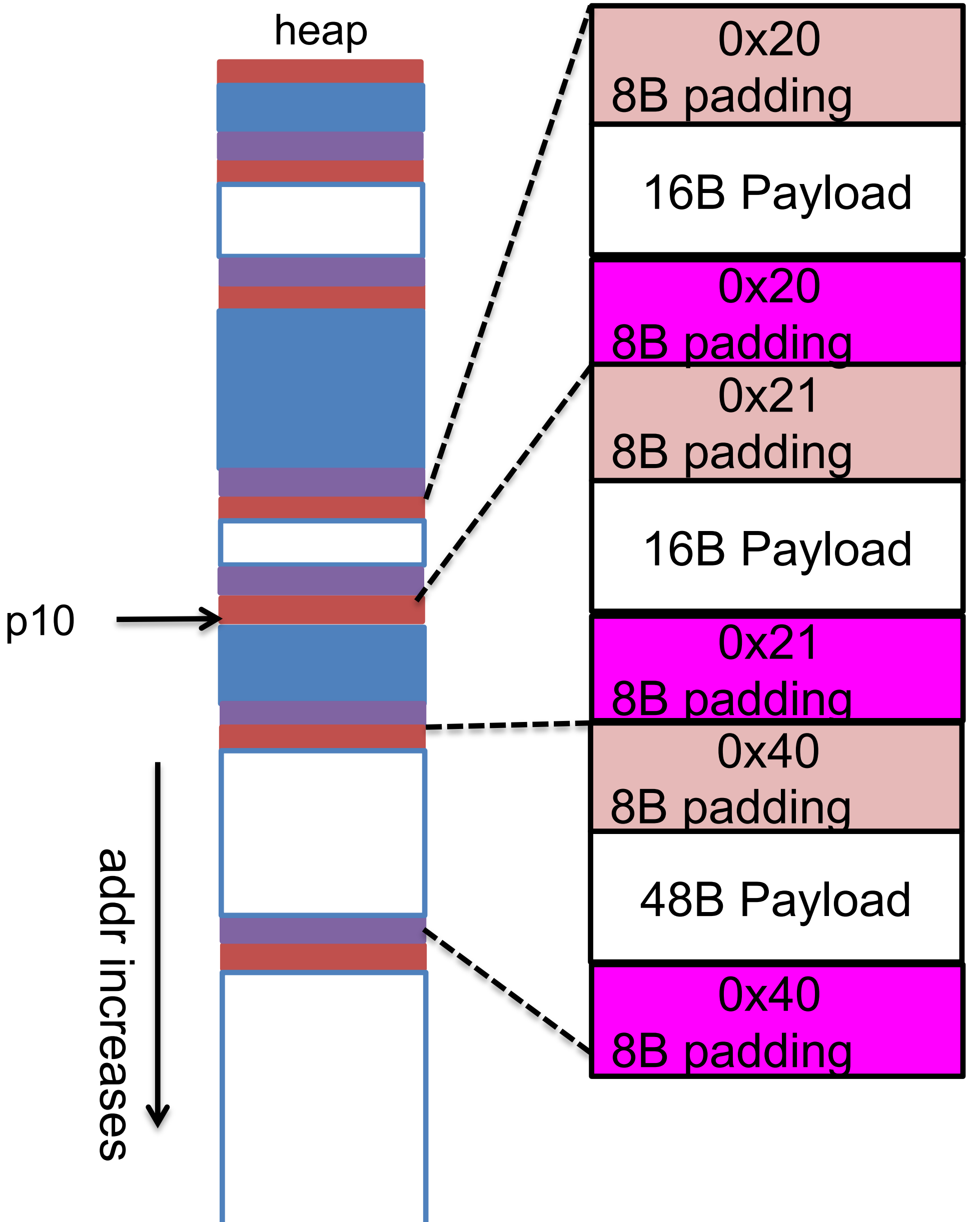




```
p  = malloc(1024)
```

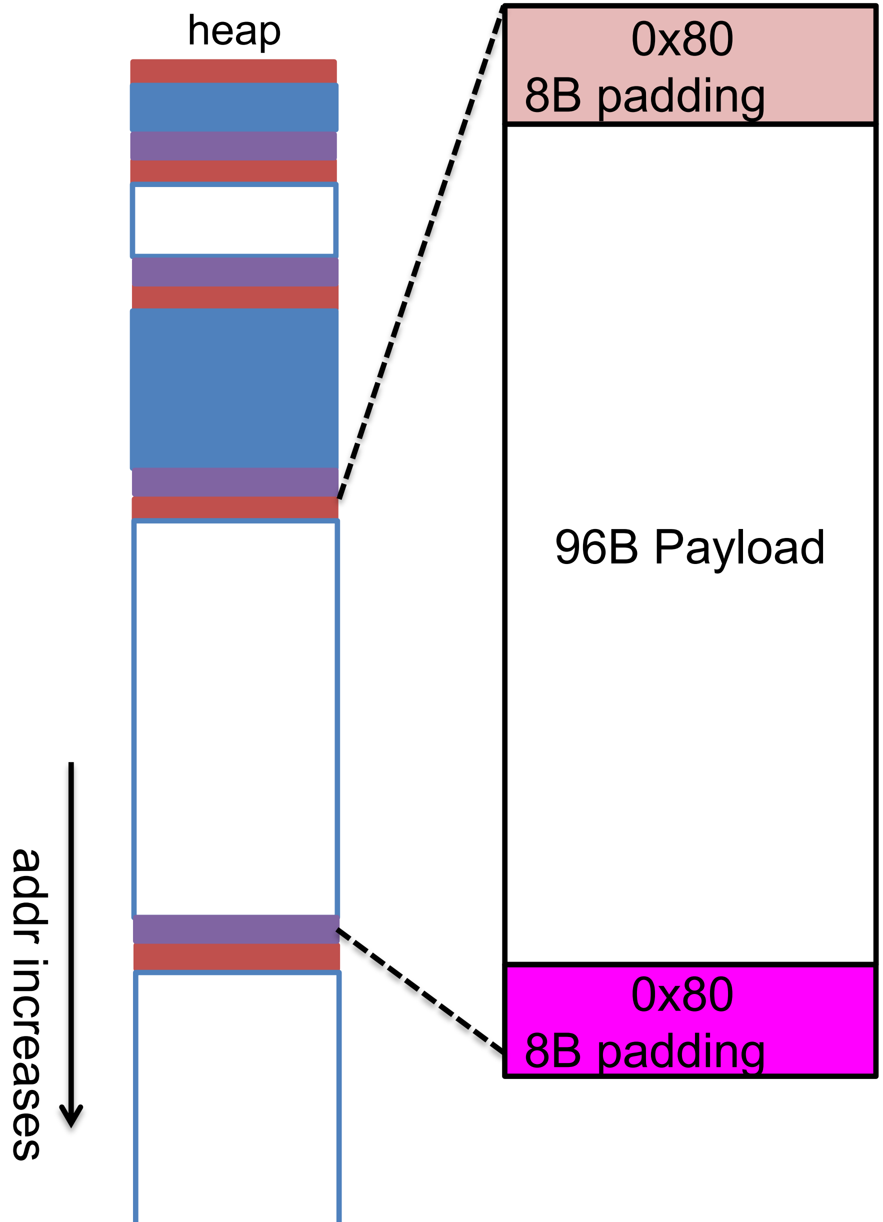
Coalescing prev and next blocks

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

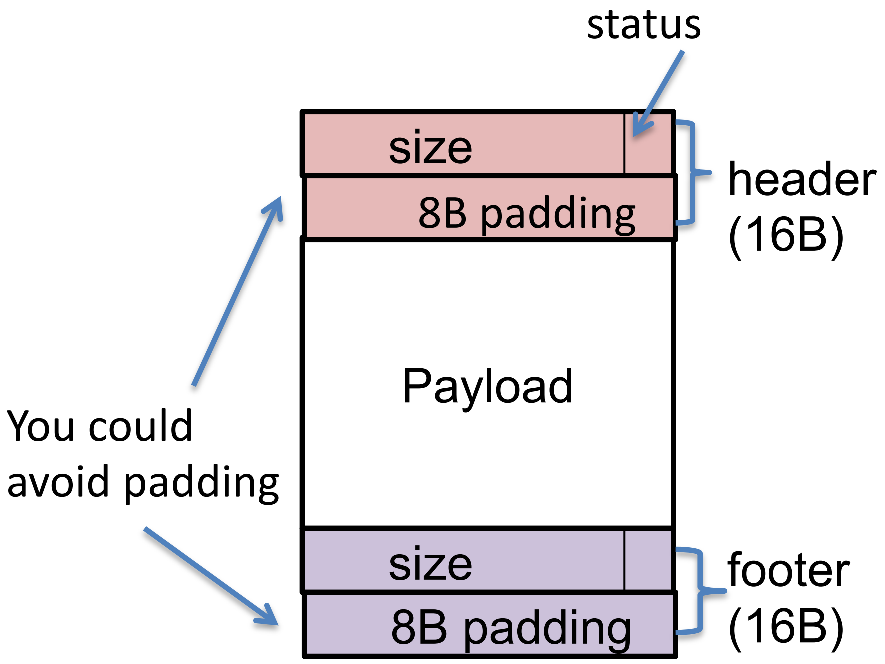


Coalescing prev and next blocks

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



Summary: 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
- To de-allocate, merge with predecessor and/or successor free blocks

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

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

Today’s lesson plan

- Explicit list
- Segregated list
- Buddy system

Explicit free lists

Problems of implicit list:

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

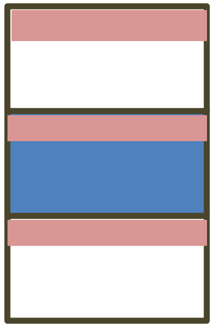
Explicit free list:

- Maintain a linked list of free chunks only.

Review: implicit → explict

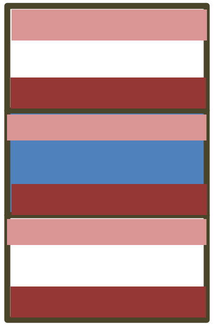
Implicit list (header-only)

Problem: cannot coalesce with previous free block
→ contiguous free blocks



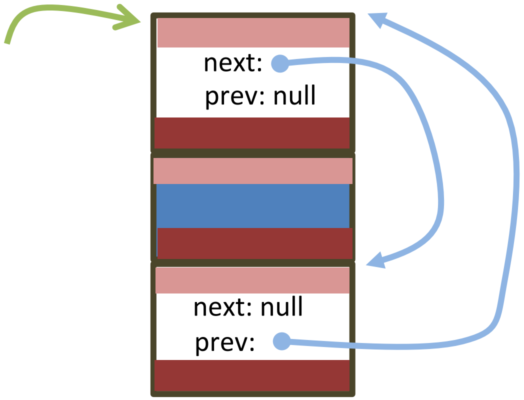
Implicit list (header+footer)

Problem: search for free block scans over allocated blocks



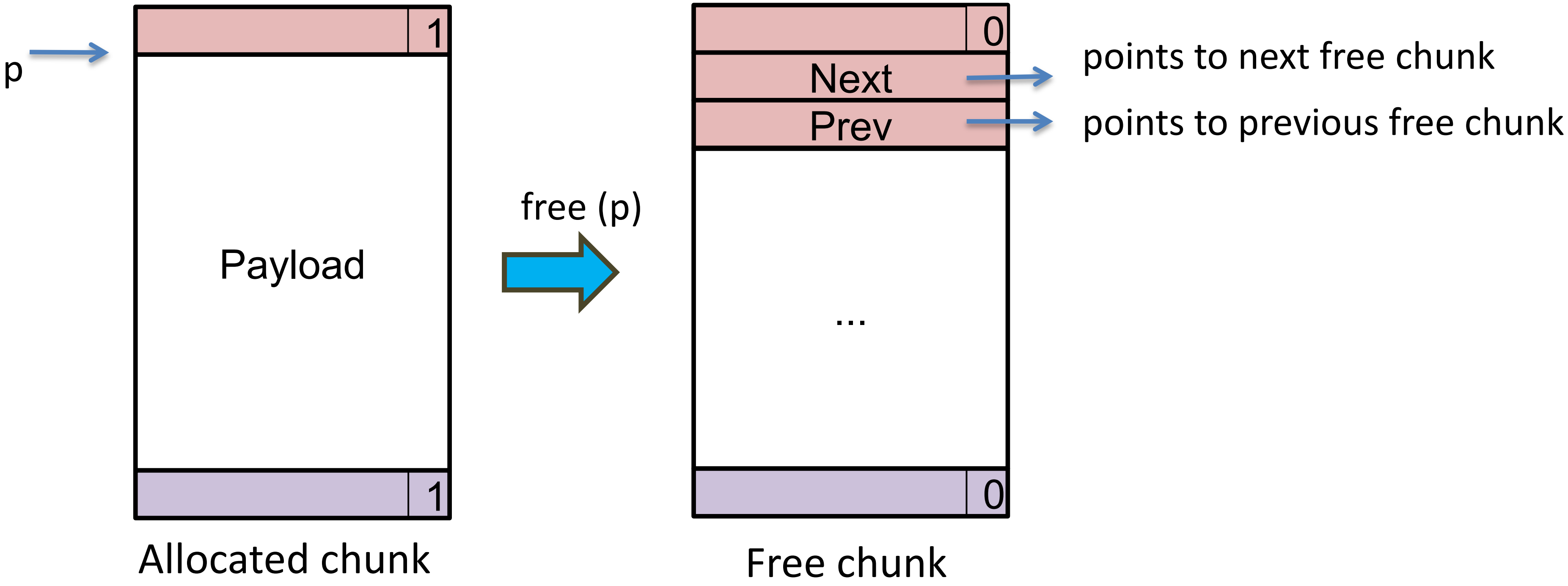
explicit list (header+footer)

head of freelist:



Q: Why use a doubly linked list?

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.

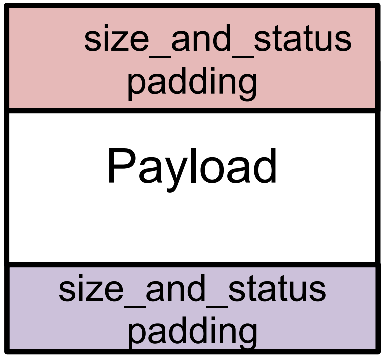
- Question: what's the minimal size of a chunk?

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

Explicit list: implementation

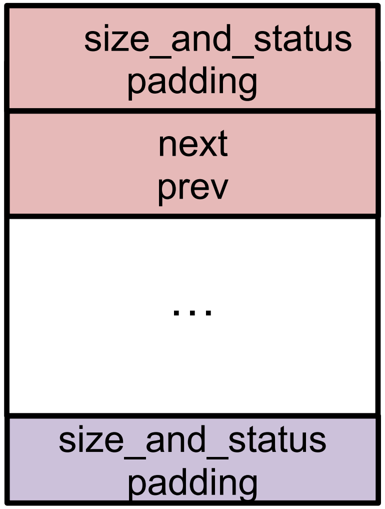
```
typedef struct {
  unsigned long size_and_status;
  unsigned long padding;
} header;
```

Allocated chunk:

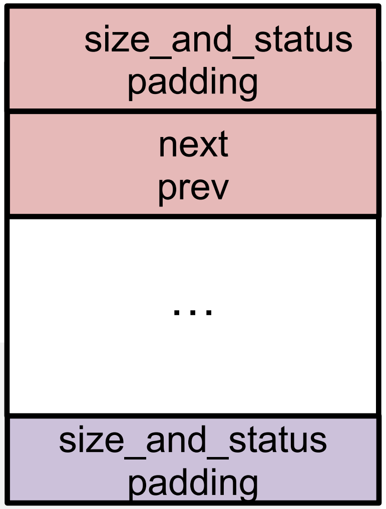


```
typedef struct free_hdr {
   header common_header;
   struct free_hdr *next;
   struct free_hdr *prev;
} free_hdr;
```

Free chunk:



Explicit list: initialization



size_and_status
padding

next
prev

…

size_and_status
padding

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

```
free_hdr *freelist = NULL;
```

```
//initialize a region of memory of size ‘sz’
//with start address ‘h’ as a free chunk
void 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);
}
```

```
void init() {
   free_hdr *h = get_block_from_OS(INIT_ALLOC_SZ);
   init_free_chunk(h, sz);
   insert(&freelist, h);
}
```

Explicit list: allocate

```
void *malloc(size_t s) {
   size_t csz = align(s) + 2*sizeof(header); //min chunk size required
   free_hdr *h = first_fit(csz);
   //if h=NULL (not enough space), ask OS to enlarge heap
   free_hdr *newchunk = split(h, csz);
   if (newchunk)
      insert(&freelist, newchunk);
   set_status(h, true);
   return header2payload(h);
}
free_hdr *first_fit(size_t sz) {









}
```

Explicit list: allocate

```
void *malloc(size_t s) {
    size_t csz = align(s) + 2*sizeof(header); //min chunk size required
    free_hdr *h = first_fit(csz);
    //if h=NULL (not enough space), ask OS to enlarge heap
    free_hdr *newchunk = split(h, csz);
    if (newchunk)
        insert(&freelist, newchunk);
    set_status(h, true);
    return header2payload(h);
}
free_hdr *first_fit(size_t sz) {
    free_hdr *h = freelist;
    while (h) {
        if (get_size(&h->common_header)>= sz) {
            delete(&freelist, h);
            break;
        }
        h = h->next;
    }
    return h;
}
```

Explicit list: allocate

```
void *malloc(size_t s) {
   size_t csz = align(s) + 2*sizeof(header); //min chunk size required
   free_hdr *h = first_fit(csz);
   //if h=NULL (not enough space), ask OS to enlarge heap
   free_hdr *newchunk = split(h, csz);
   if (newchunk)
      insert(&freelist, newchunk);
   set_status(h, true);
   return header2payload(h);
}

free_hdr *split(free_hdr *h, size_t csz)
{









}
```

Explicit list: allocate

```
void *malloc(size_t s) {
   size_t csz = align(s) + 2*sizeof(header); //min chunk size required
   free_hdr *h = first_fit(csz);
   //if h=NULL (not enough space), ask OS to enlarge heap
   free_hdr *newchunk = split(h, csz);
   if (newchunk)
      insert(&freelist, newchunk);
   set_status(h, true);
   return header2payload(h);
}

free_hdr *split(free_hdr *h, size_t csz)
{
   size_t remain_sz = get_size(&h->common_header) – csz;
   if (remain_sz < MIN_CHUNK_SZ)
       return NULL;
   init_free_chunk(h, csz);
   free_hdr *newchunk = next_chunk(h);
   init_free_chunk(newchunk, remain_sz);
   return newchunk;
}
```

Explicit list: free

```
void free(void *p) {
    header *h = payload2header(p);
    init_free_chunk((free_hdr *)h, get_size(h));

    header *next = next_chunk(h);
    if (!get_status(next)) {
       delete(&freelist, next);
       h = coalesce((free_hdr *)h, (free_hdr *)next);
    }
    header *prev = prev_chunk(h);
    if (!get_status(prev)) {
       delete(&freelist, prev);
       h = coalesce((free_hdr *)prev, (free_hdr *)h);
    }
    insert(&freelist, (free_hdr *)h);
}

free_hdr *coalesce(free_hdr *h, free_hdr *other) {
   //merge h and other into a single free chunk
}
```

Segregated list

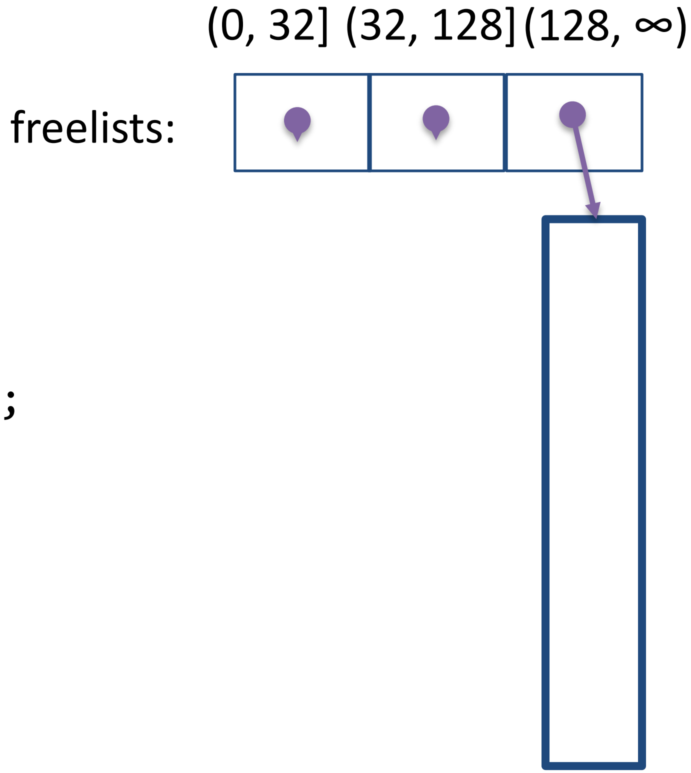
- Idea: keep multiple freelists
  - each freelist contains chunks of similar sizes

Segregated list: initialize

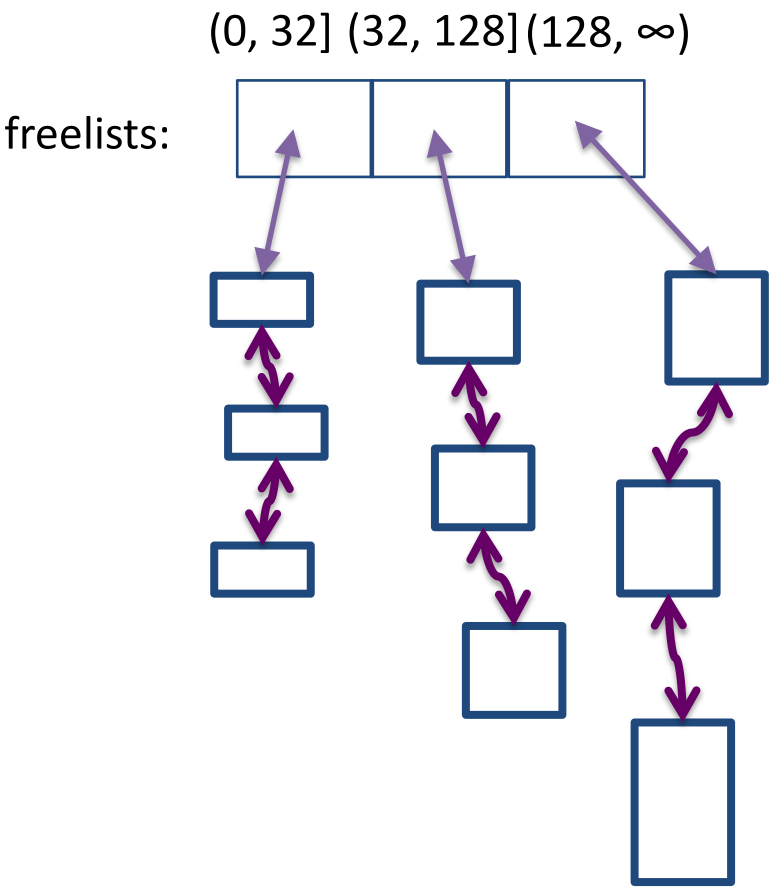
```
#define NLISTS 3
free_hdr* freelists[NLISTS];
size_t size_classes[NLISTS] = {32, 128, (size_t)-1};

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

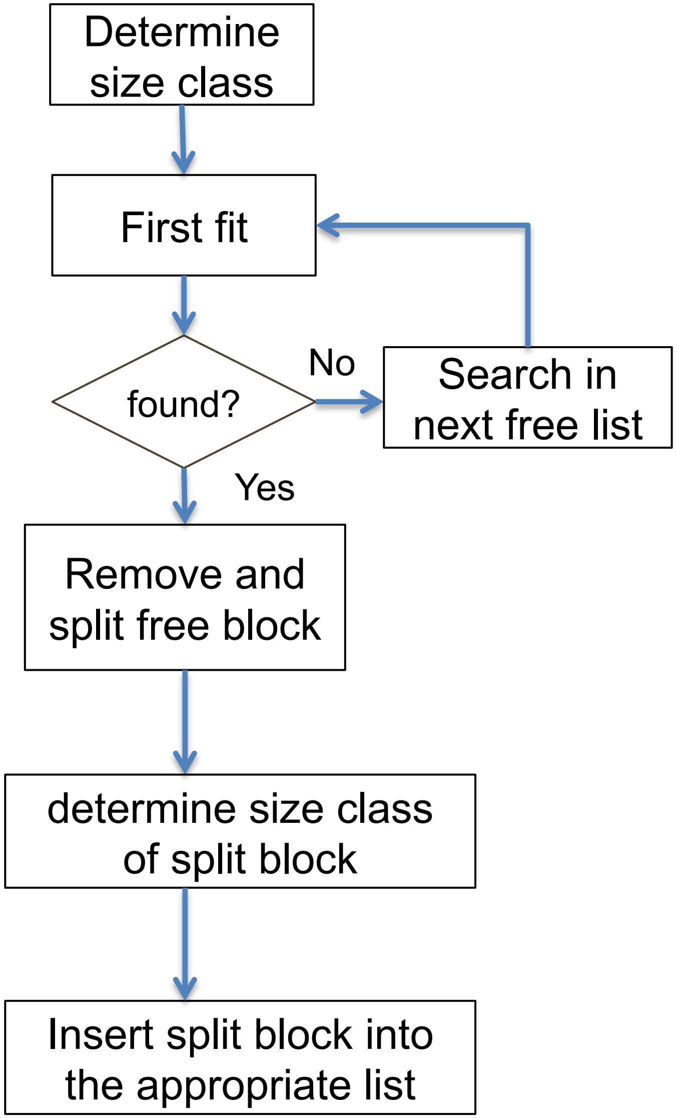

 void init() {
    free_hdr *h = get_block_from_OS(1024);
    freelist[which_freelist(1024)] = h;
 }
```



Segregated list: allocation


(0, 32] (32, 128](128, ∞)

freelists:


Determine size class

First fit

found?

No

Yes

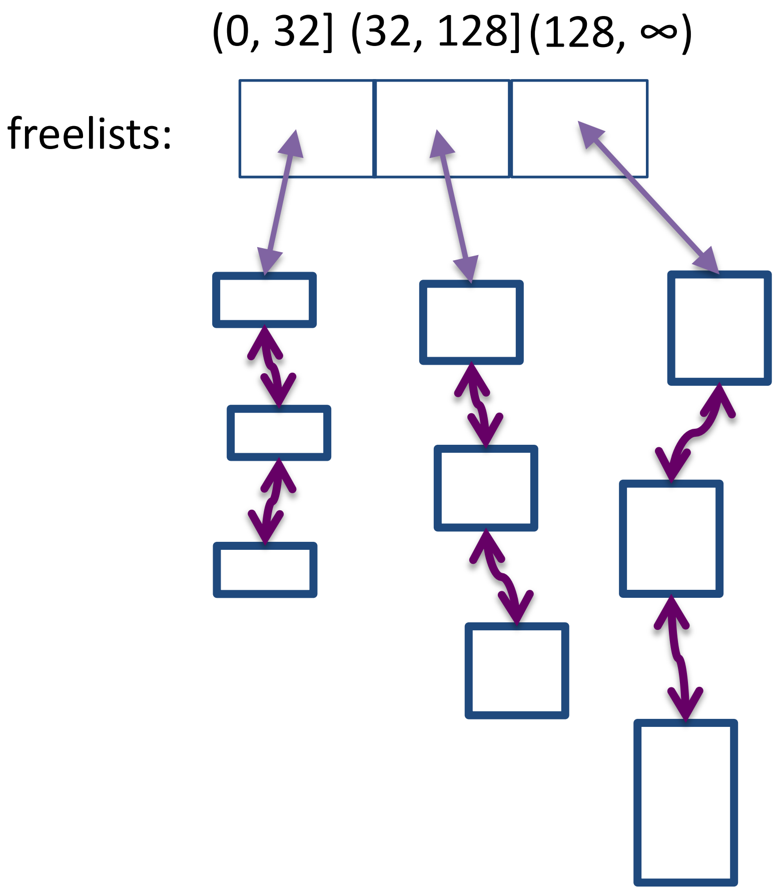
Search in next free list

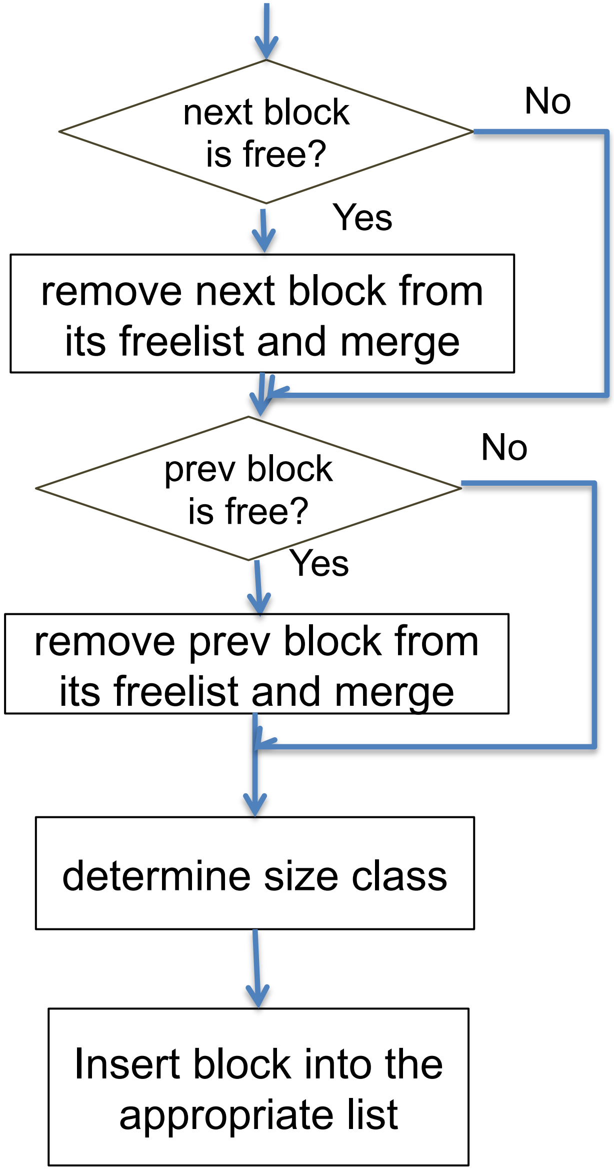
Remove and split free block

determine size class of split block

Insert split block into the appropriate list

Segregated list: free





next block is free?

No

Yes

remove next block from its freelist and merge

prev block is free?

No

Yes

remove prev block from its freelist and merge

determine size class

Insert block into the appropriate list

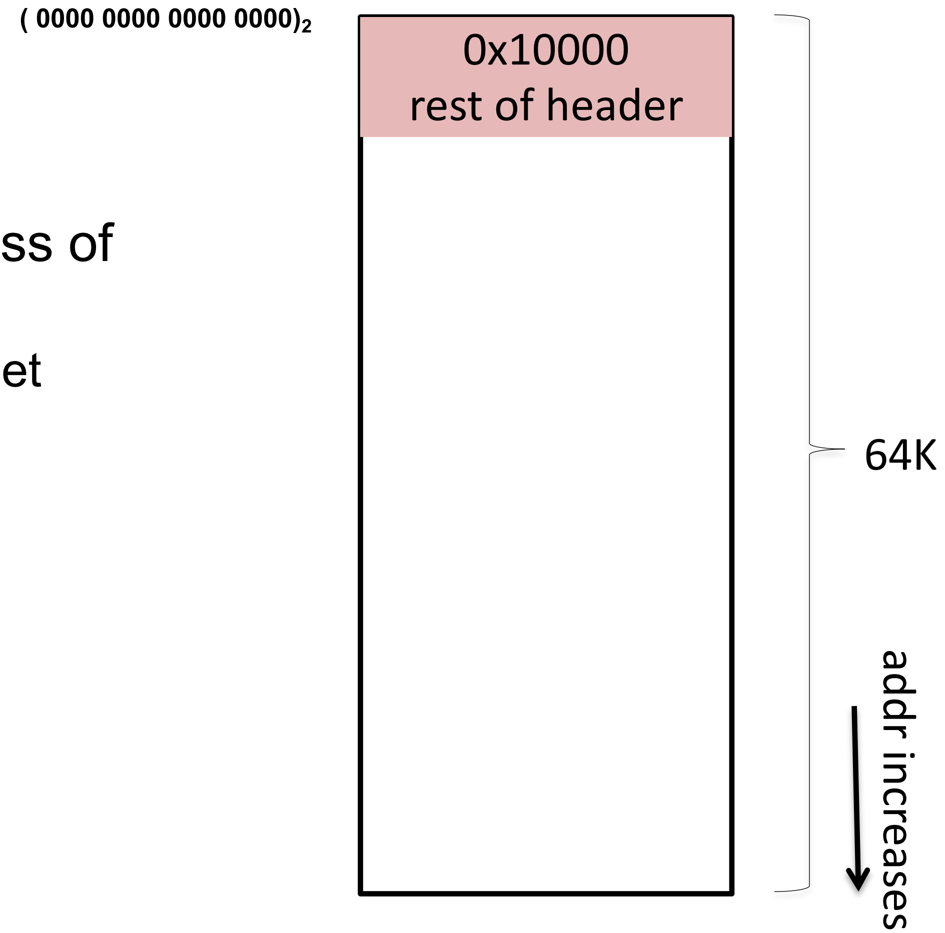
Buddy System

- 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 the address of all zeros
  - Implementation can add an offset

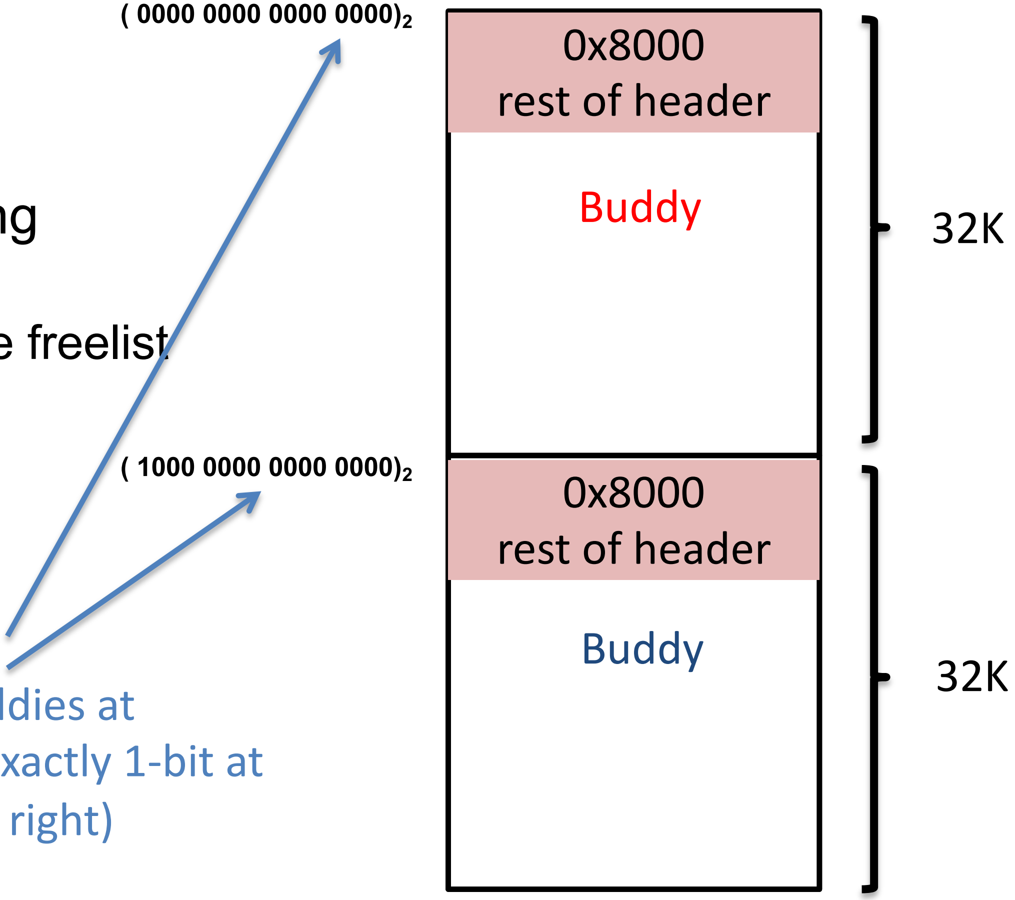


Binary buddy system: allocate

```
p = malloc(15000);
```

Recursive split in half until having the right size

- insert free buddy into appropriate freelist



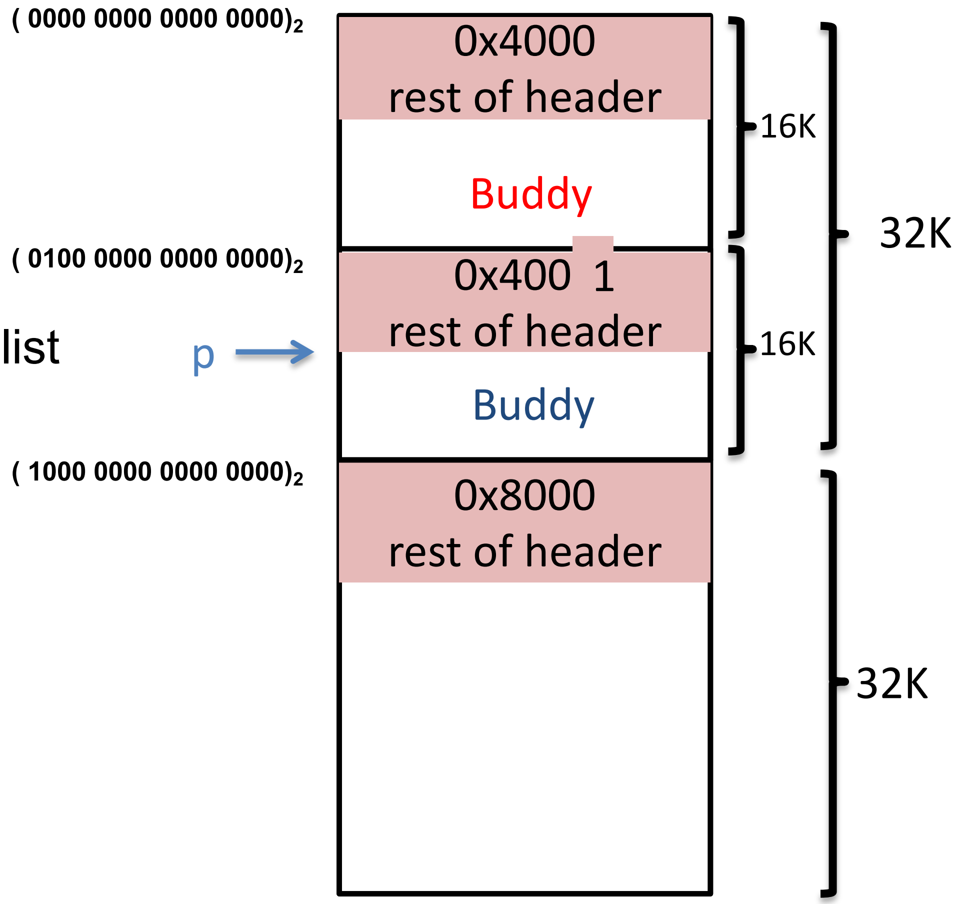
Addresses of buddies at size 2^m differ in exactly 1-bit at position m (from right)

Binary buddy system: allocate

```
p = malloc(15000);
```

Recursive split in half until having the right size

- insert free buddy into appropriate freelist



Binary buddy system: free

```
free(p);
```

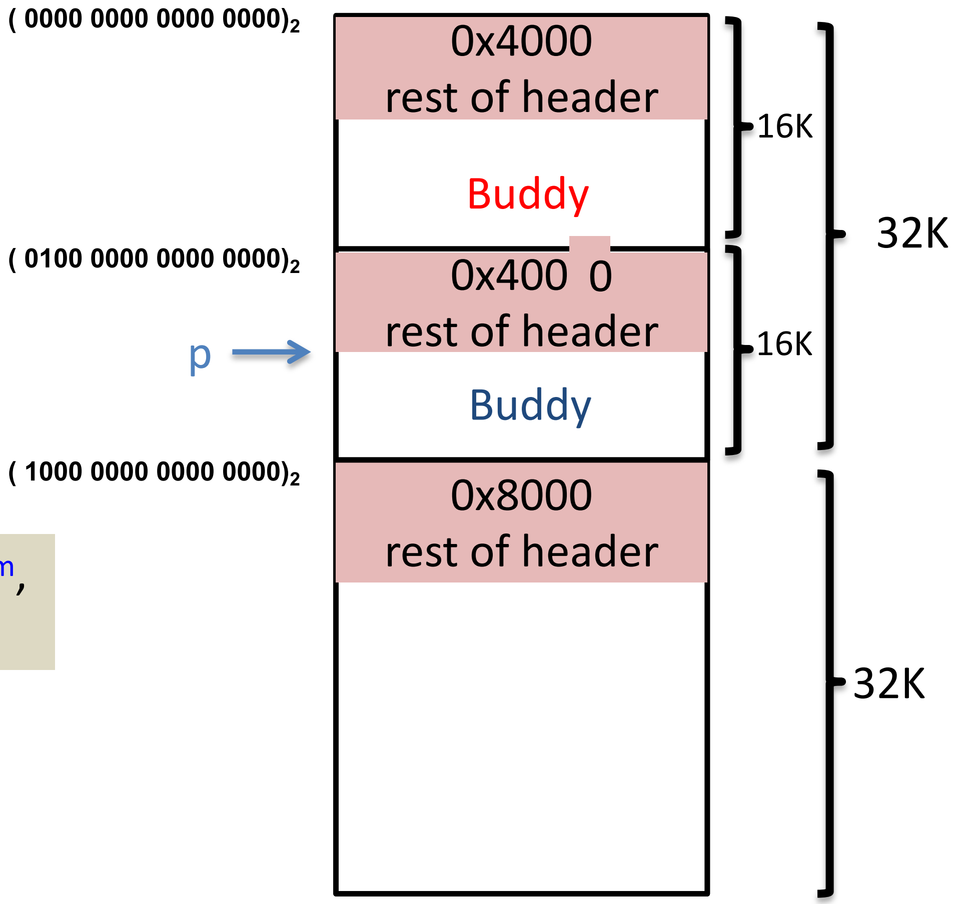
Recursively merge block with buddy

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

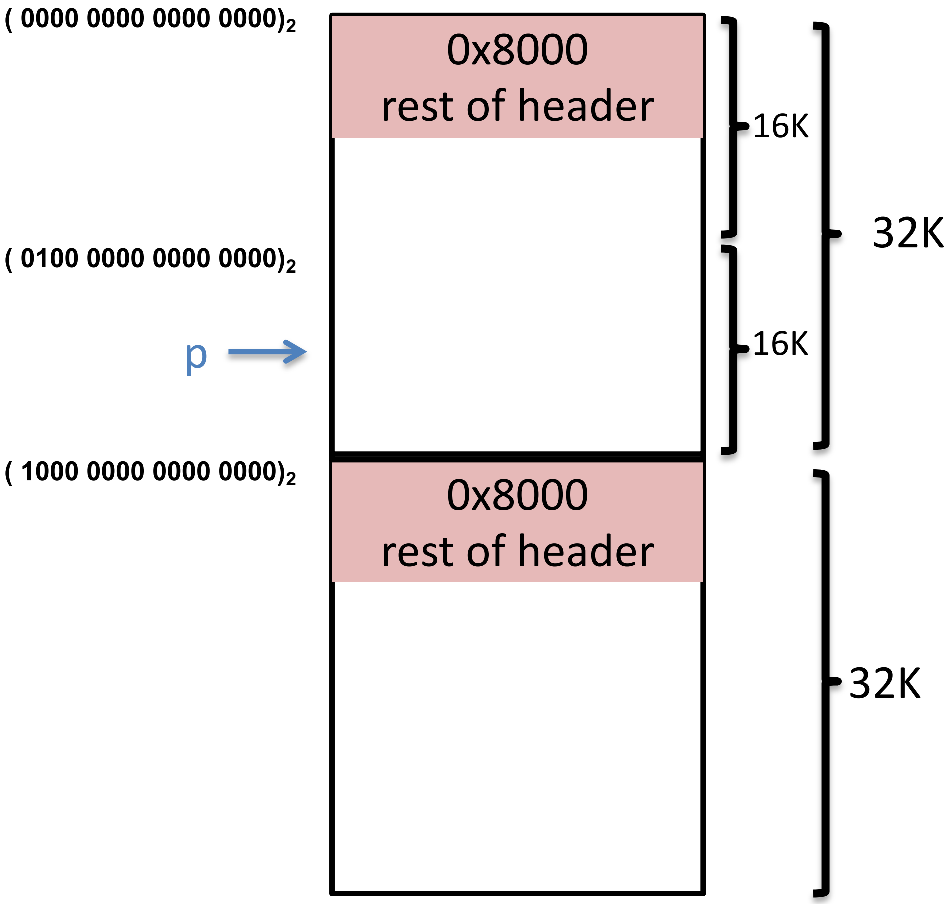


Binary buddy system: free

```
free(p);
```

If buddy is free:

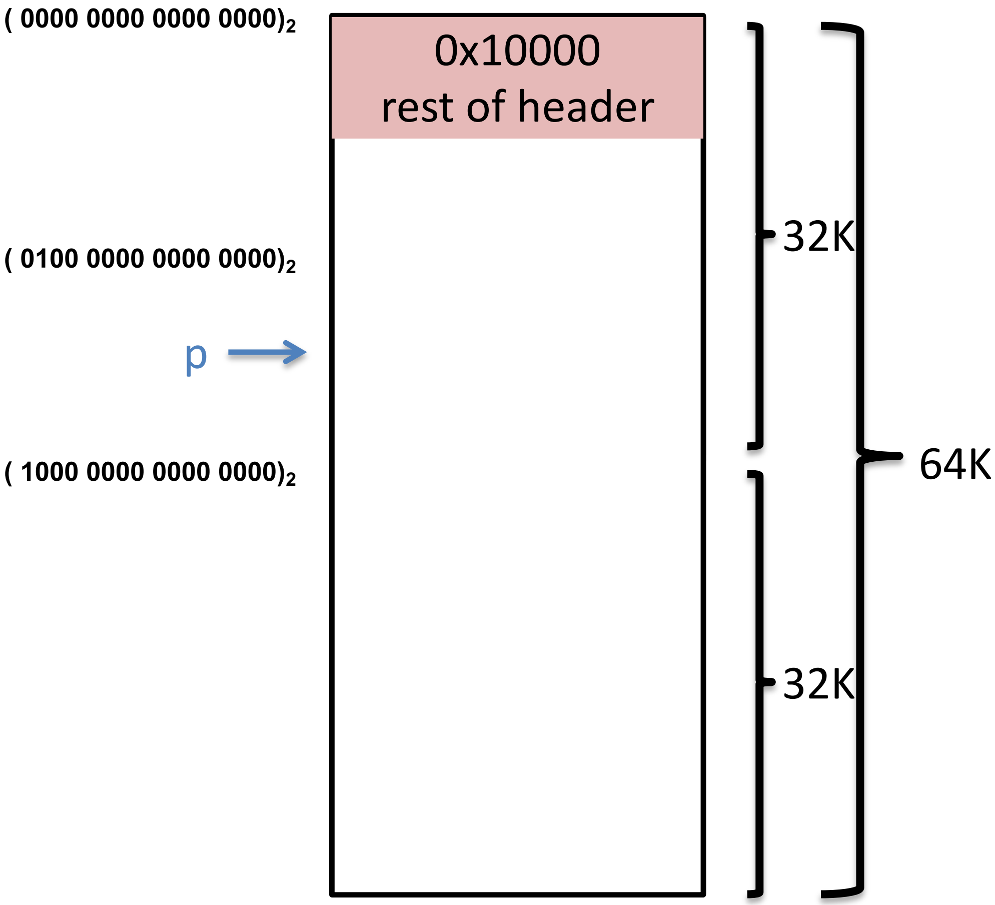
2. Detach free buddy from its list
3. Combine with current block



Binary buddy system: free

```
free(p);
```

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



Summary

- Dynamic memory allocation
- Design constraints:
  - Free API does not include size
  - Space cannot be moved around
- Evolution of designs
  - Implicit list
  - Explicit list
  - Segragated list
  - Buddy system