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;

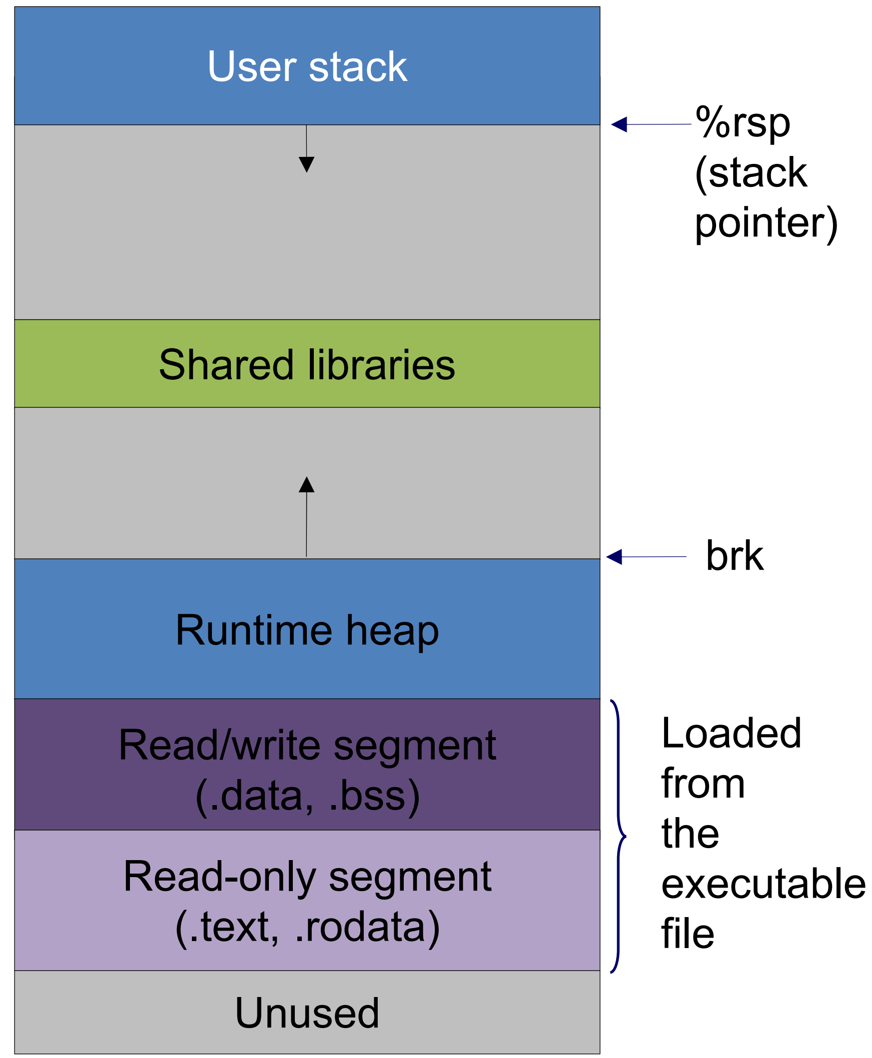
void list_insert(node *head, int v)
{
   node *np = malloc(sizeof(node));
   np->next = head;
   np->val = v;
   *head = np;
}

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?

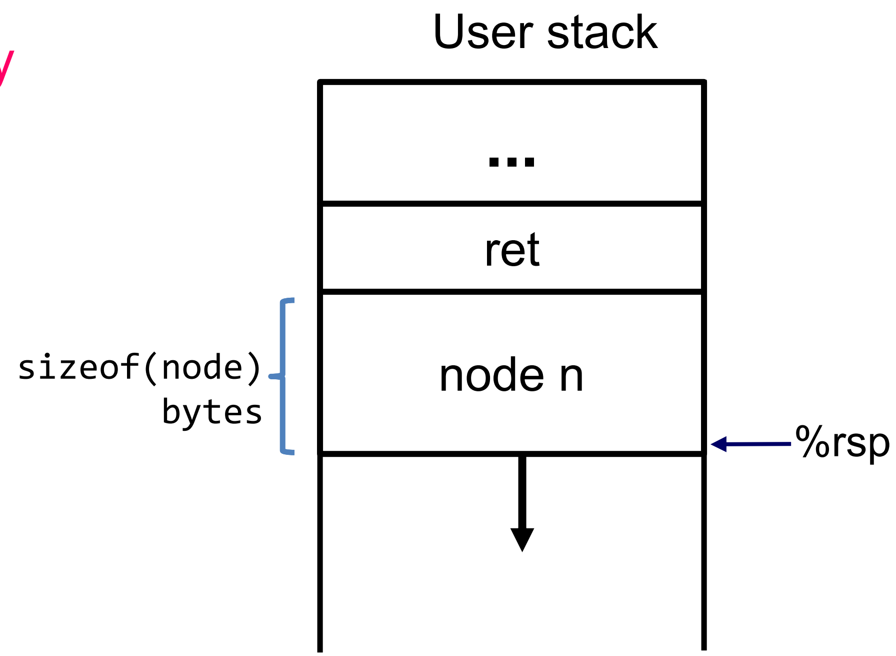


Dynamic allocation on heap

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

Answer: Yes, but space is freed upon function return

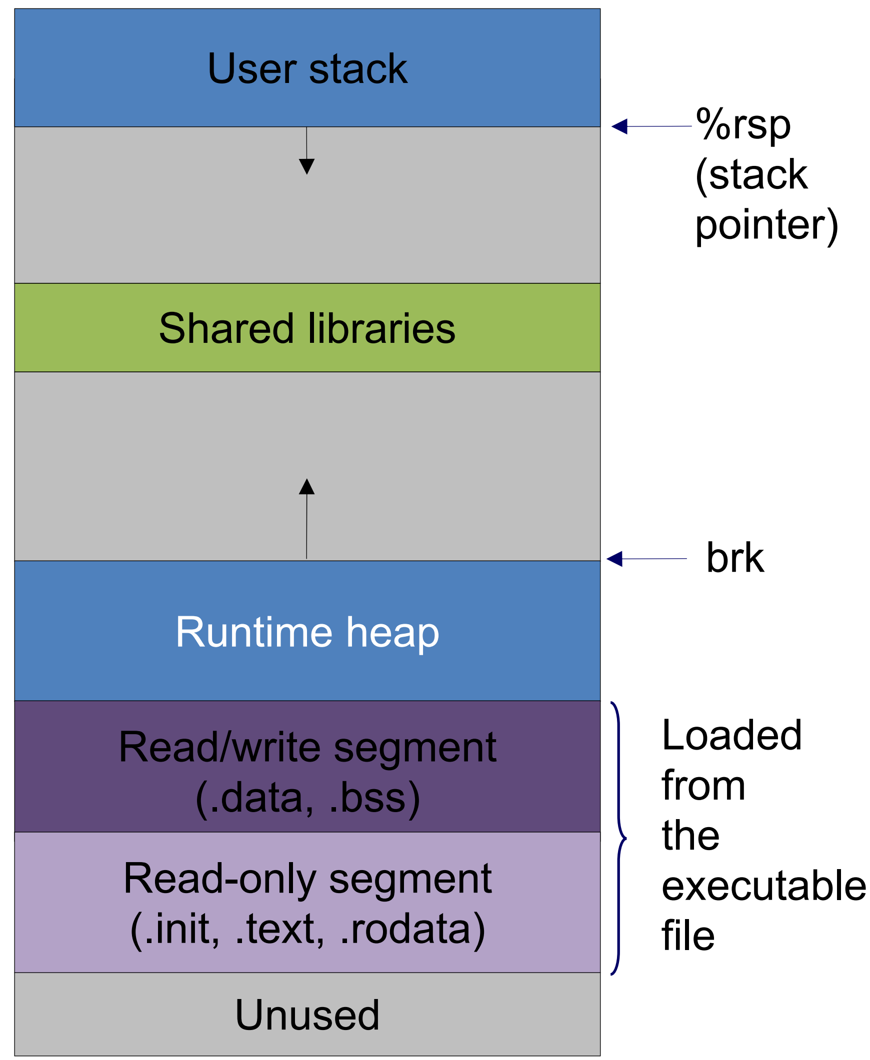
```
void
list_insert(node *head, int v) {
   node n;
   node *np = &n;
   np->next = head;
   np->val= v;
   *head = np;
}
```




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

Dynamic allocation on heap

Question: How to allocate memory on heap?



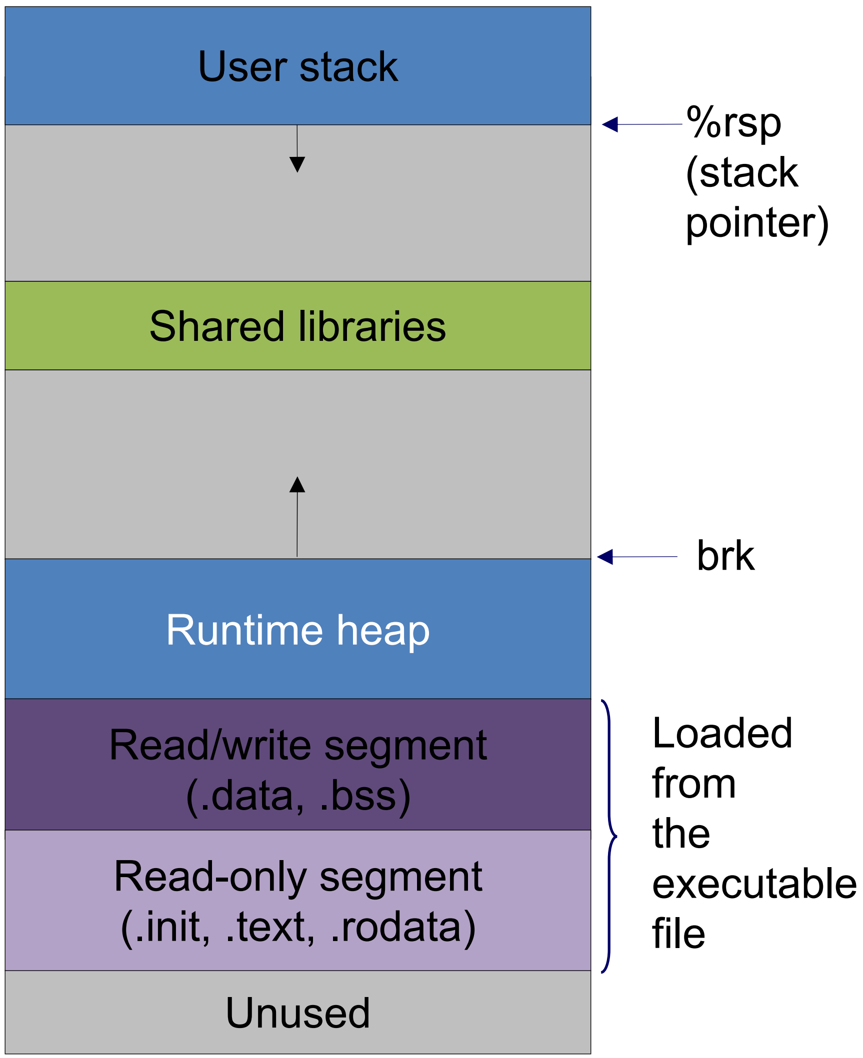
Dynamic allocation on heap

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

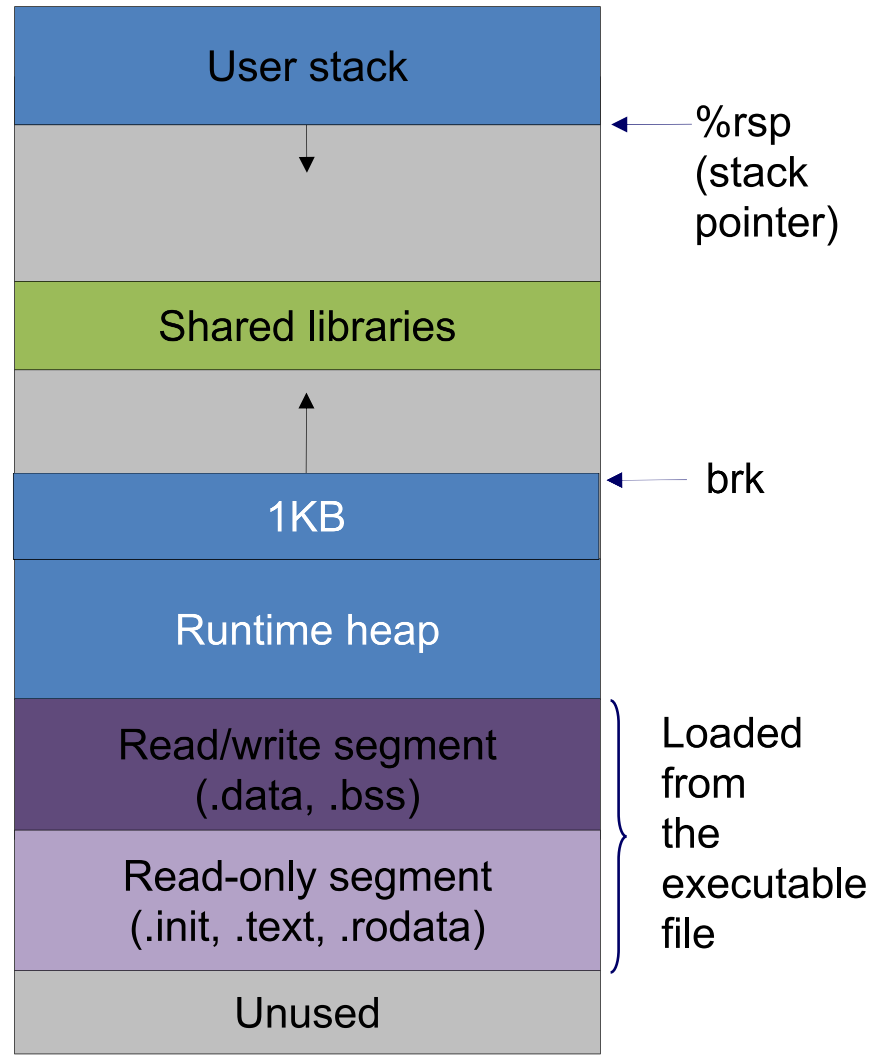
Question: How to allocate memory on heap?

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

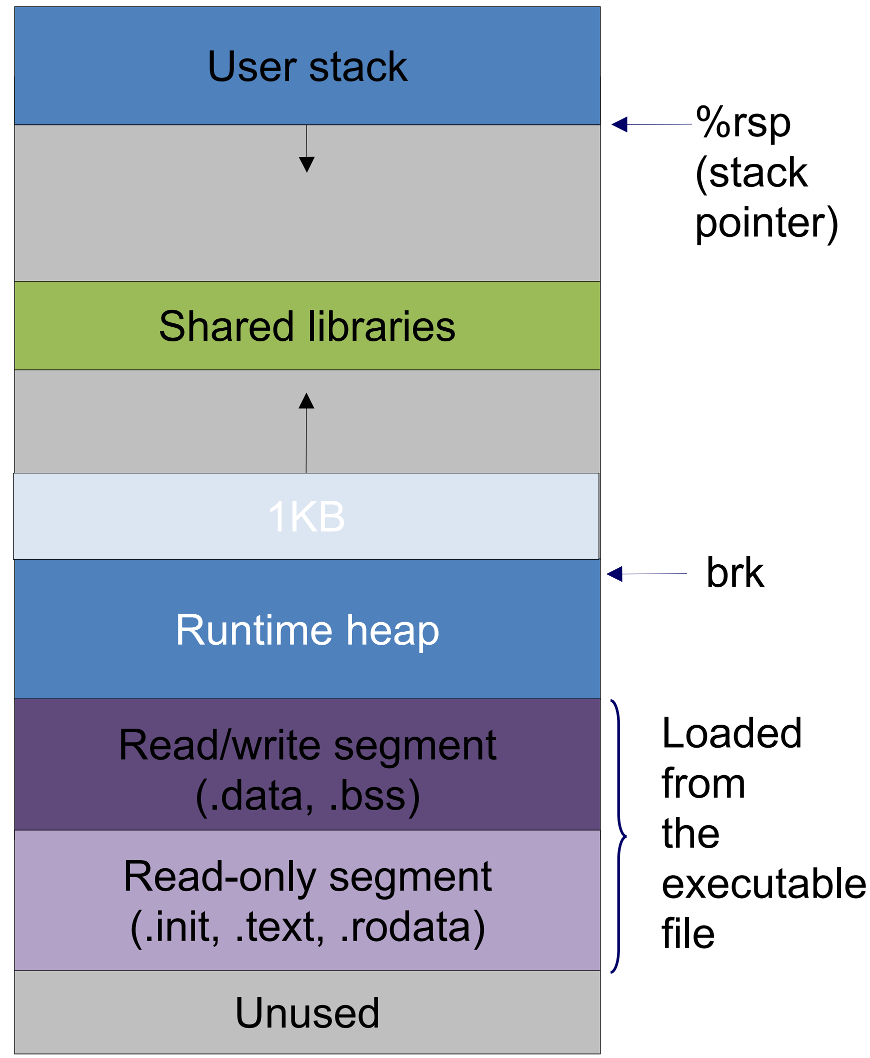
Question: How to allocate memory on heap?

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?

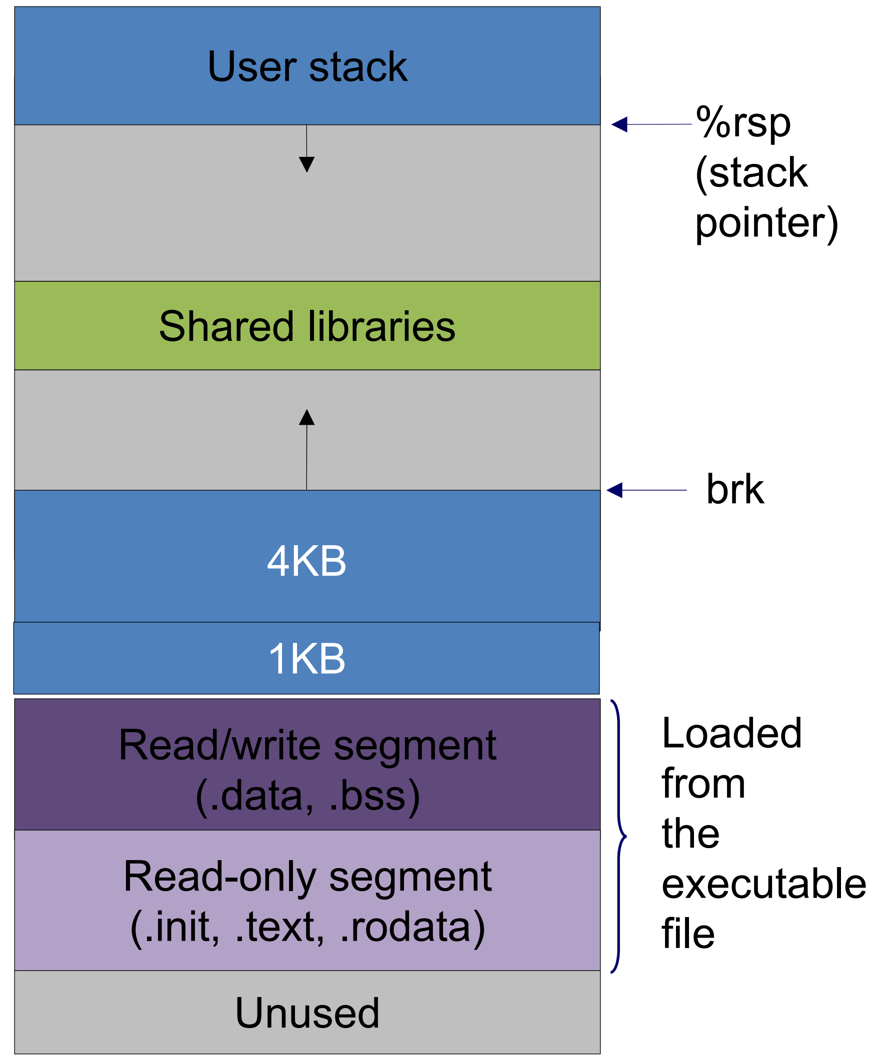
Ask OS for allocation on the heap via system calls

```
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

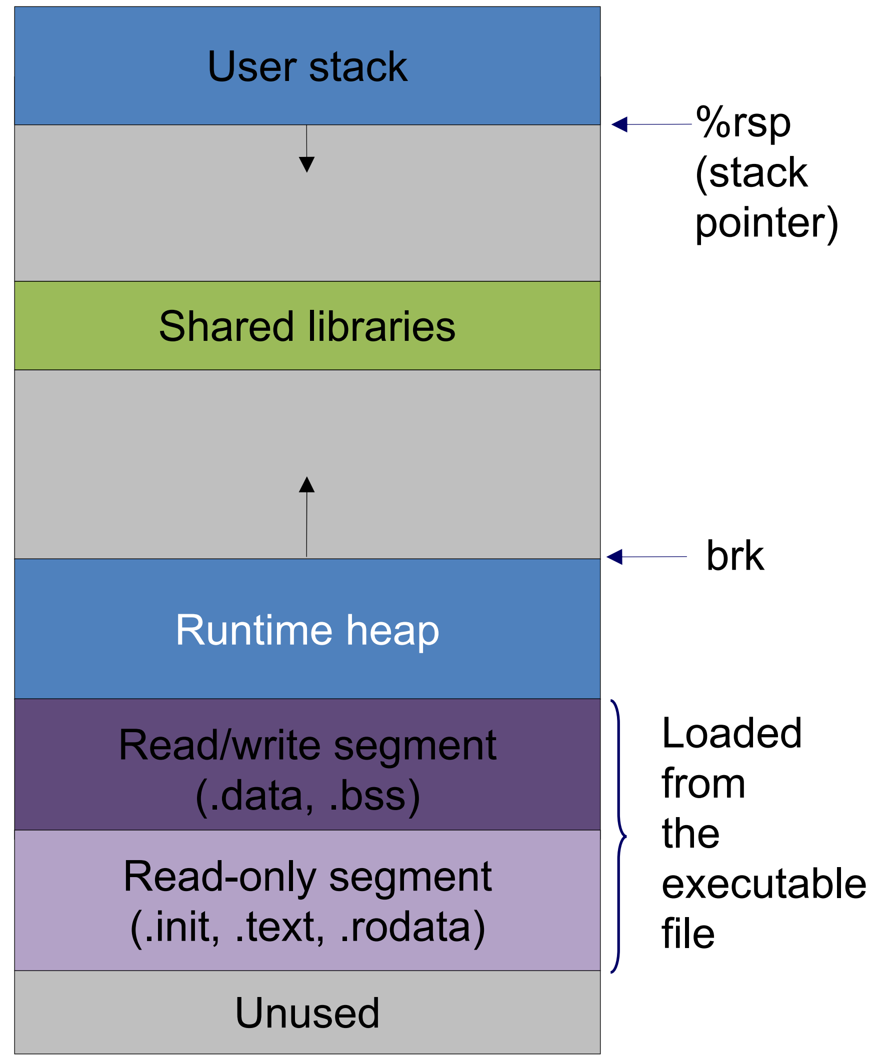
Question: How to allocate memory on heap?

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

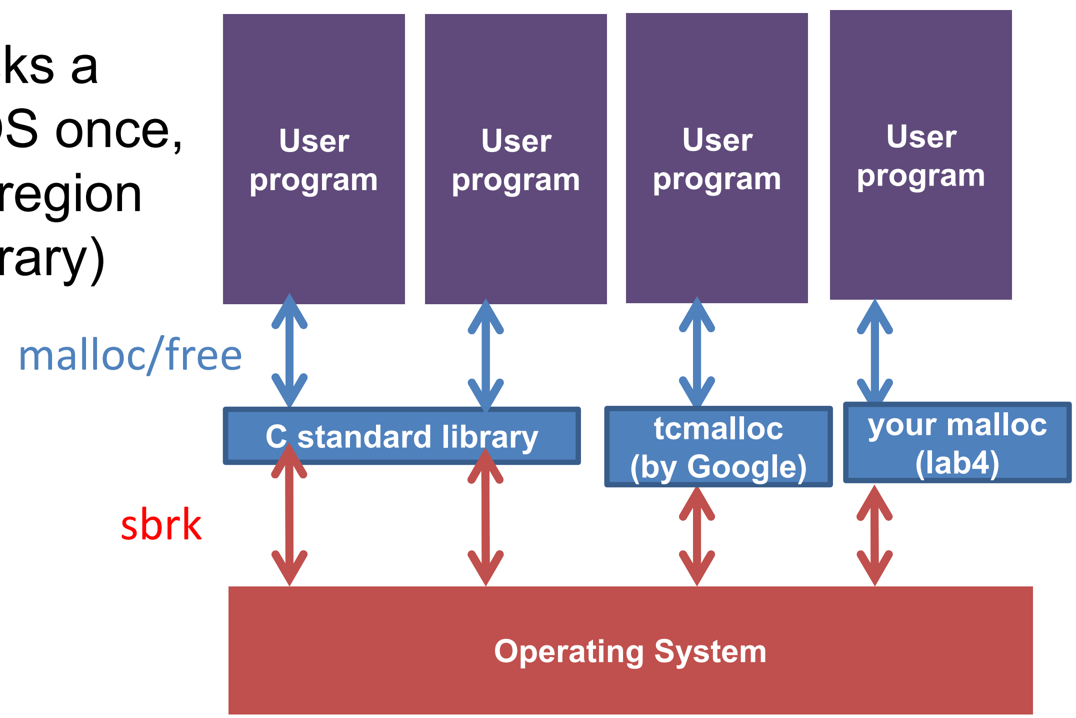
Issue II – system call has high performance cost > 10X



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?

- 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

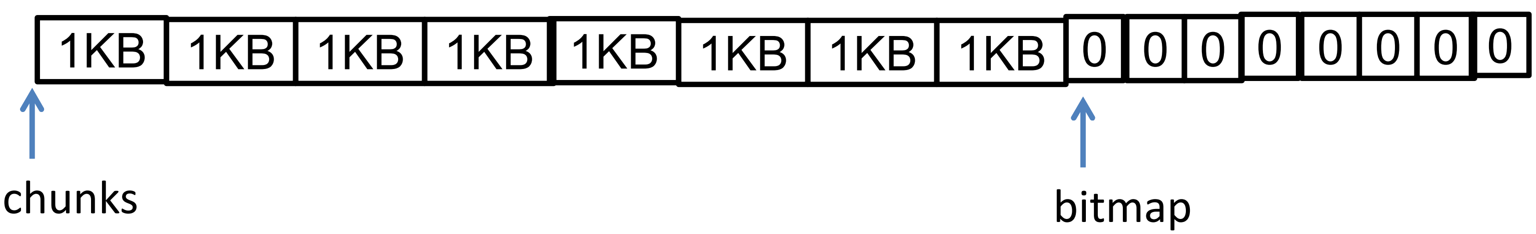
- (Basic book-keeping) How to keep track which bytes are free and which are not?

- (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

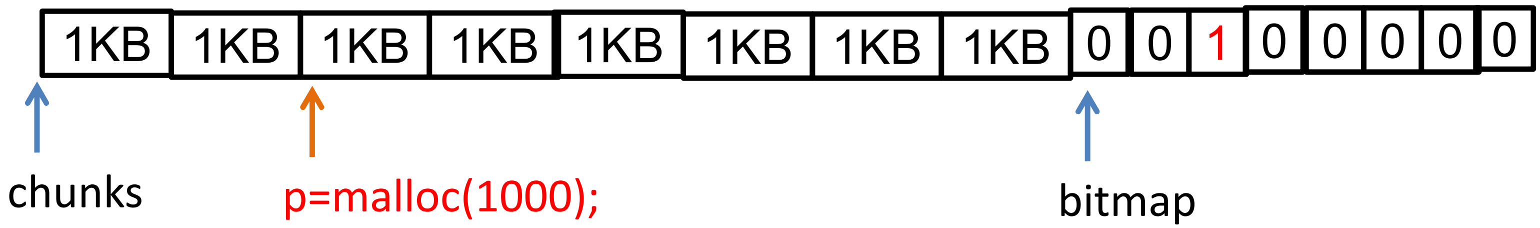



```
#define CHUNKSIZE 1<<10;
typedef char[CHUNKSIZE] chunk;
char *bitmap;
chunk *chunks;
size_t n_chunks;

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



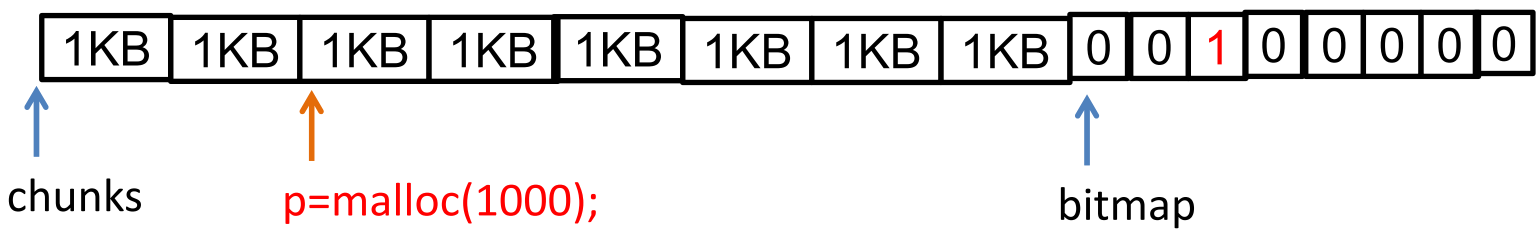

```
void* malloc(size_t sz) {
  // find out # of chunks needed to fit sz bytes
  csz = ...

  //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




```
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.

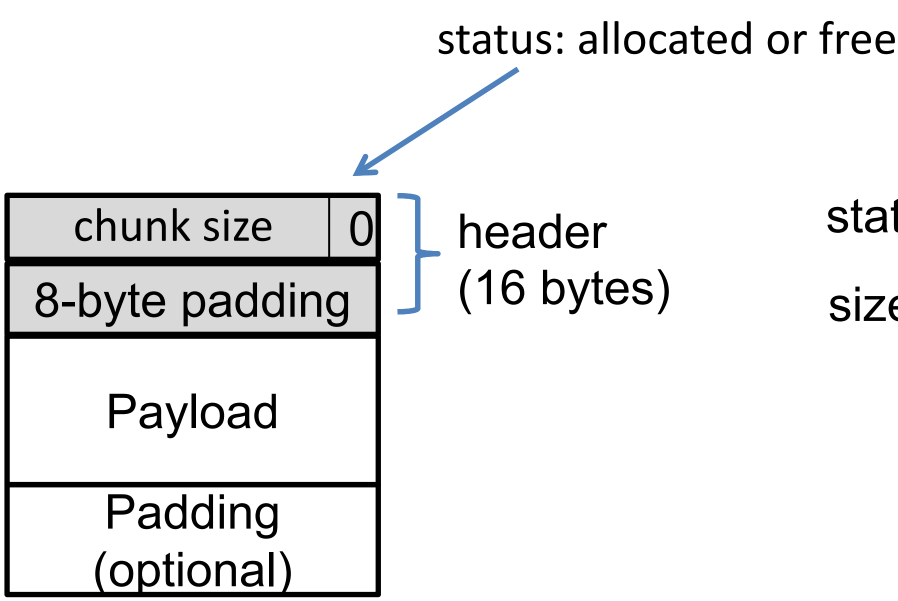
Problems of strawmans?

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



status: size_and_status & 0x1L

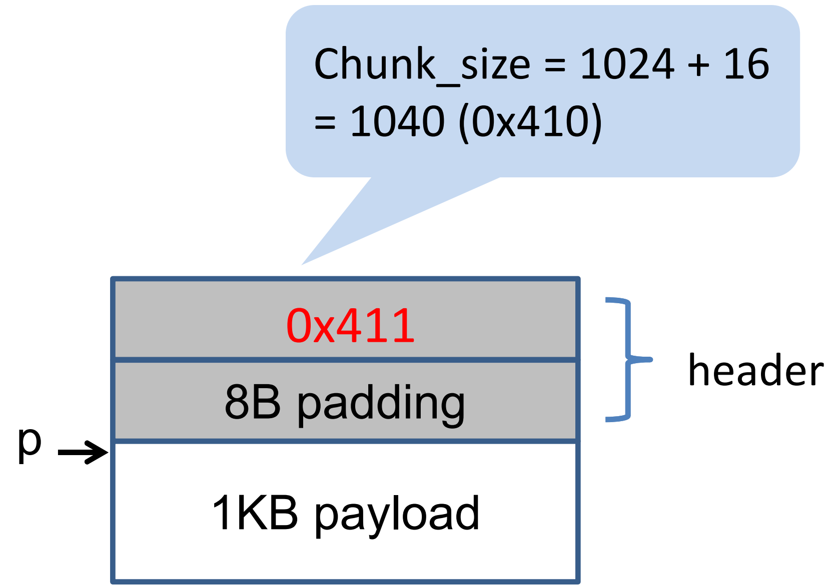
size: size_and_status & ~(0x1L)

Implicit list

Embed chunk metadata in the chunks

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

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

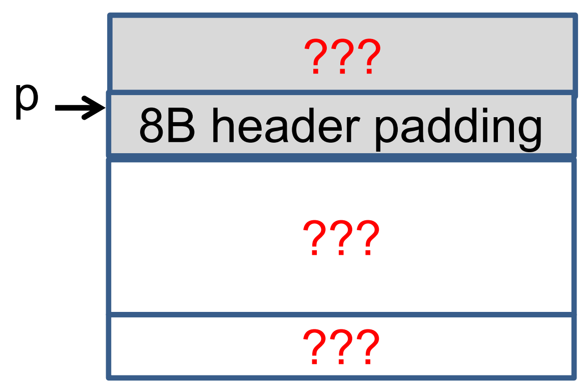


Implicit list

Embed chunk metadata in the chunks

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

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

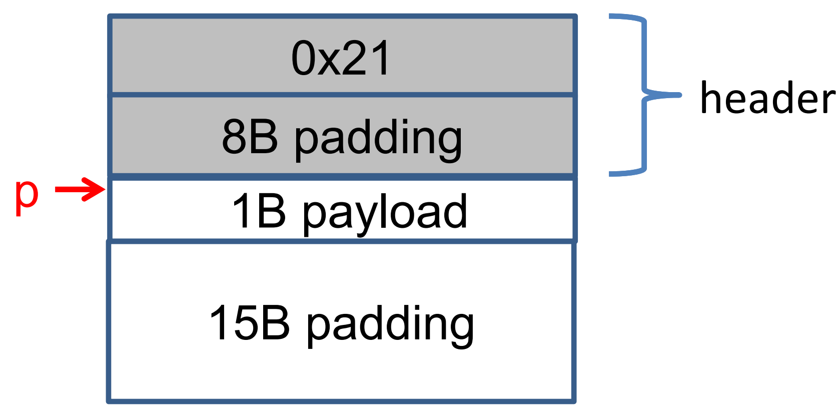


Implicit list

Embed chunk metadata in the chunks

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

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

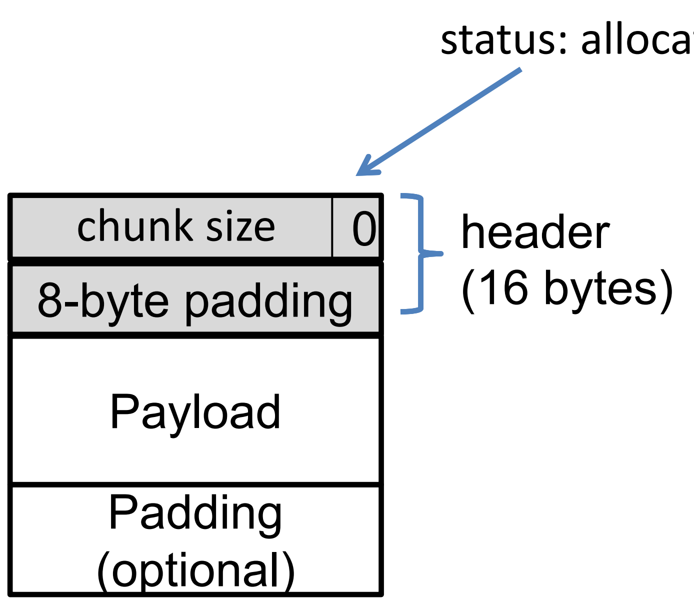


Today's lesson plan

- Previously:
  - Why dynamic memory allocation?
  - Design requirements and challenges
  - The basics of implicit list design.
- Today:
  - Implicit list
  - Explicit list

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, assume header size is 16 byte, payload size is x*16



status: size_and_status & 0x1L

size: size_and_status & ~(0x1L)

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

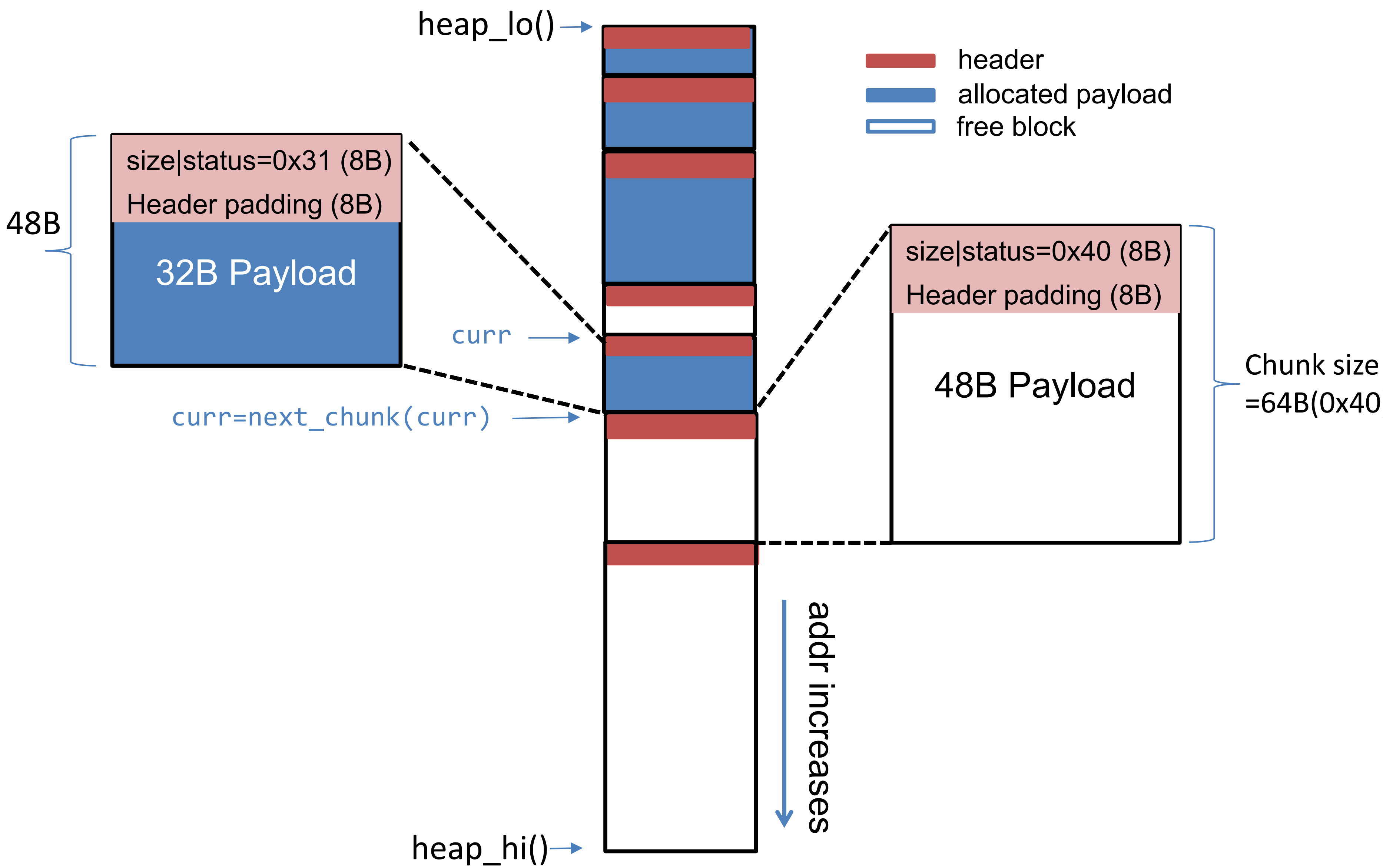
```
typedef struct {
  unsigned long size_and_status;
  unsigned long padding;
} header;
```

```
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

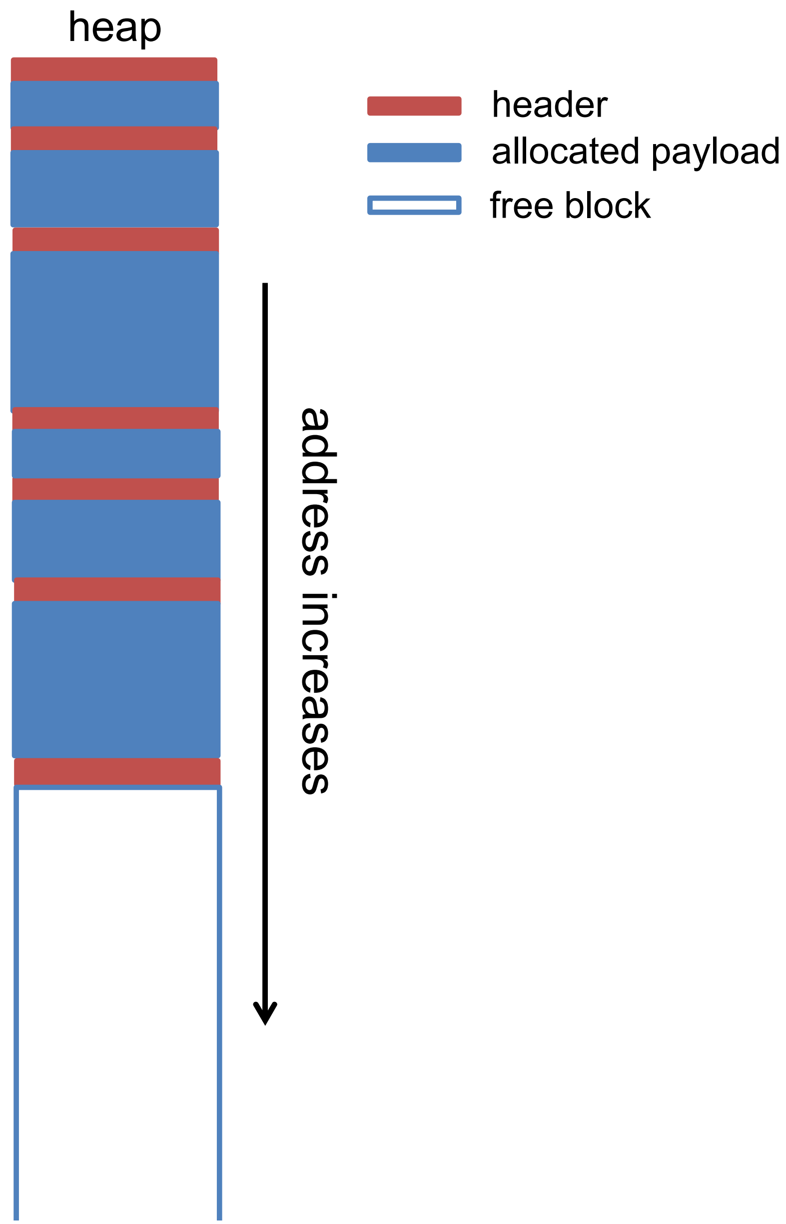


malloc() in an implicit list

```
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);
}
```

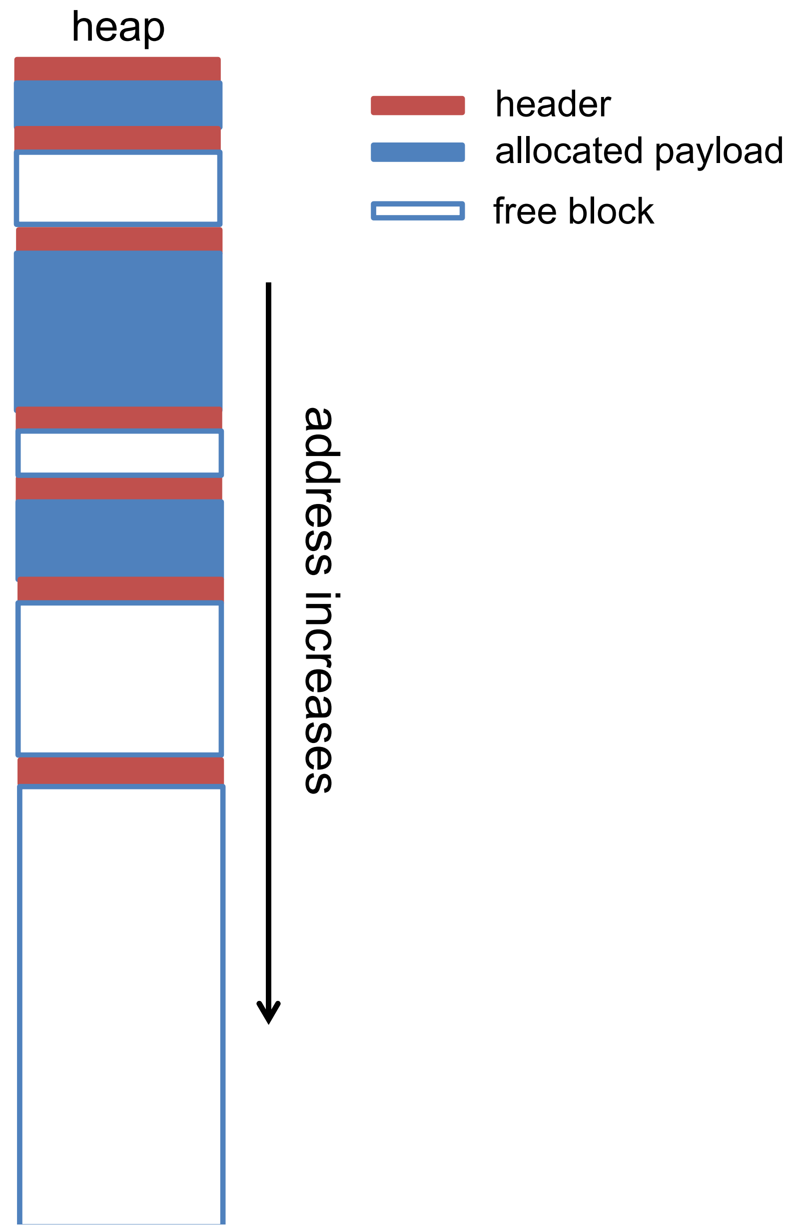
Where to place an allocation?

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



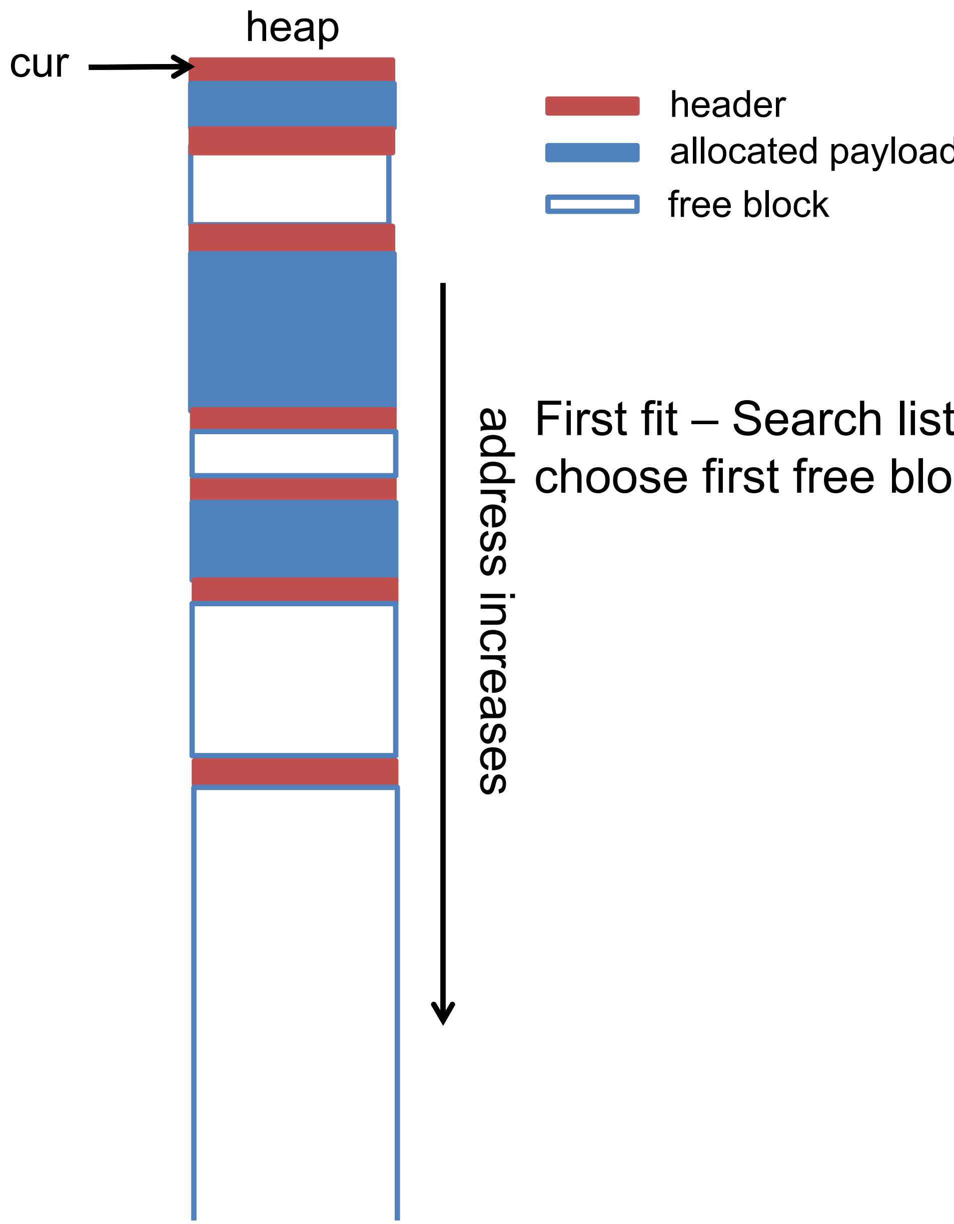
Where to place an allocation?

```
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

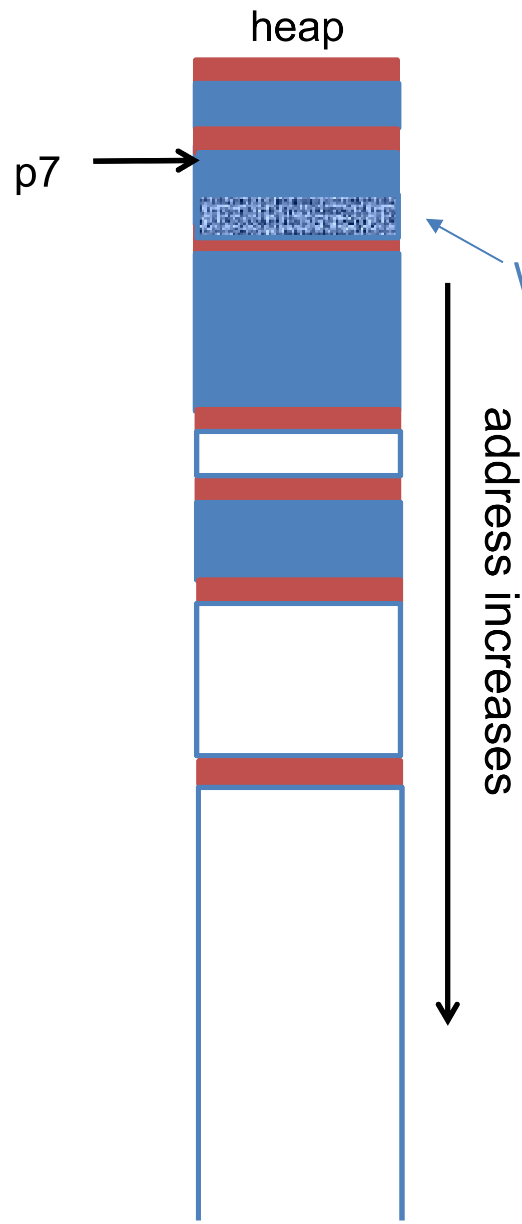
```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
```



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)
```



header
allocated payload
free block

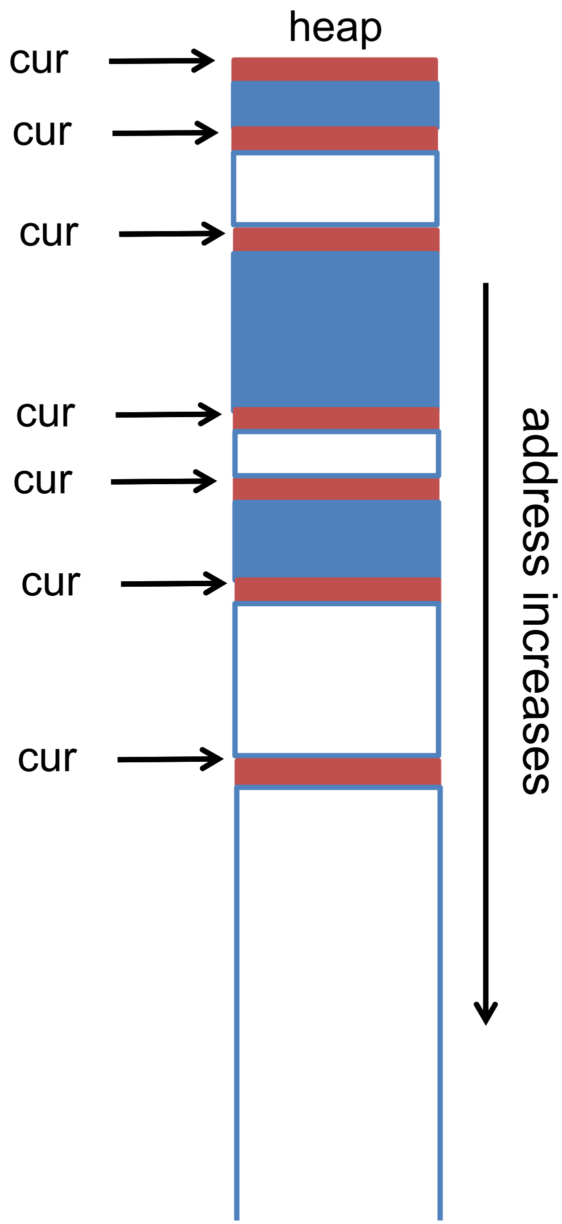
Wasted space as padding

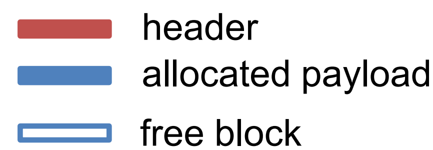
First fit – Search list from beginning, choose first free block that fits

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)
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free(p2)
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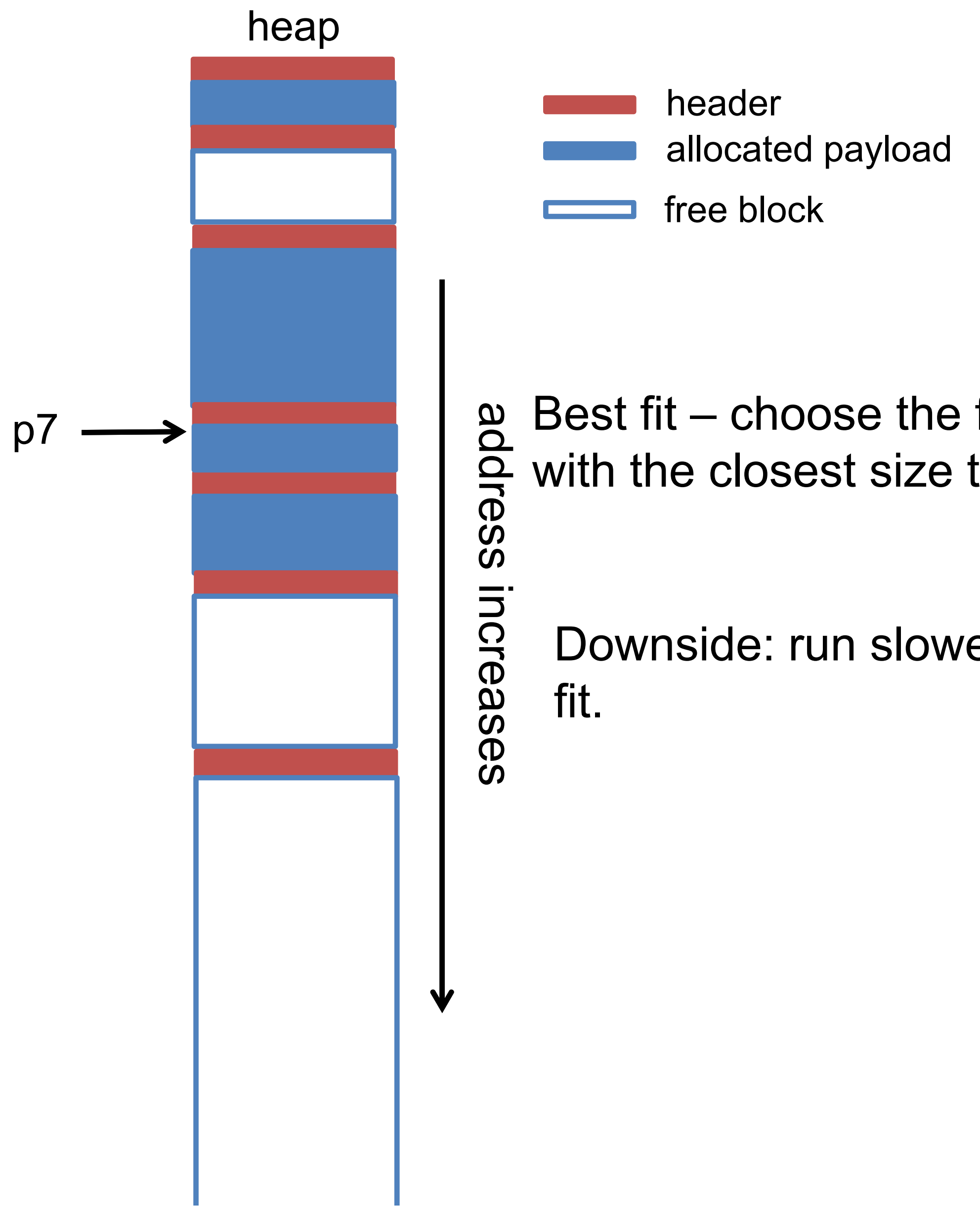
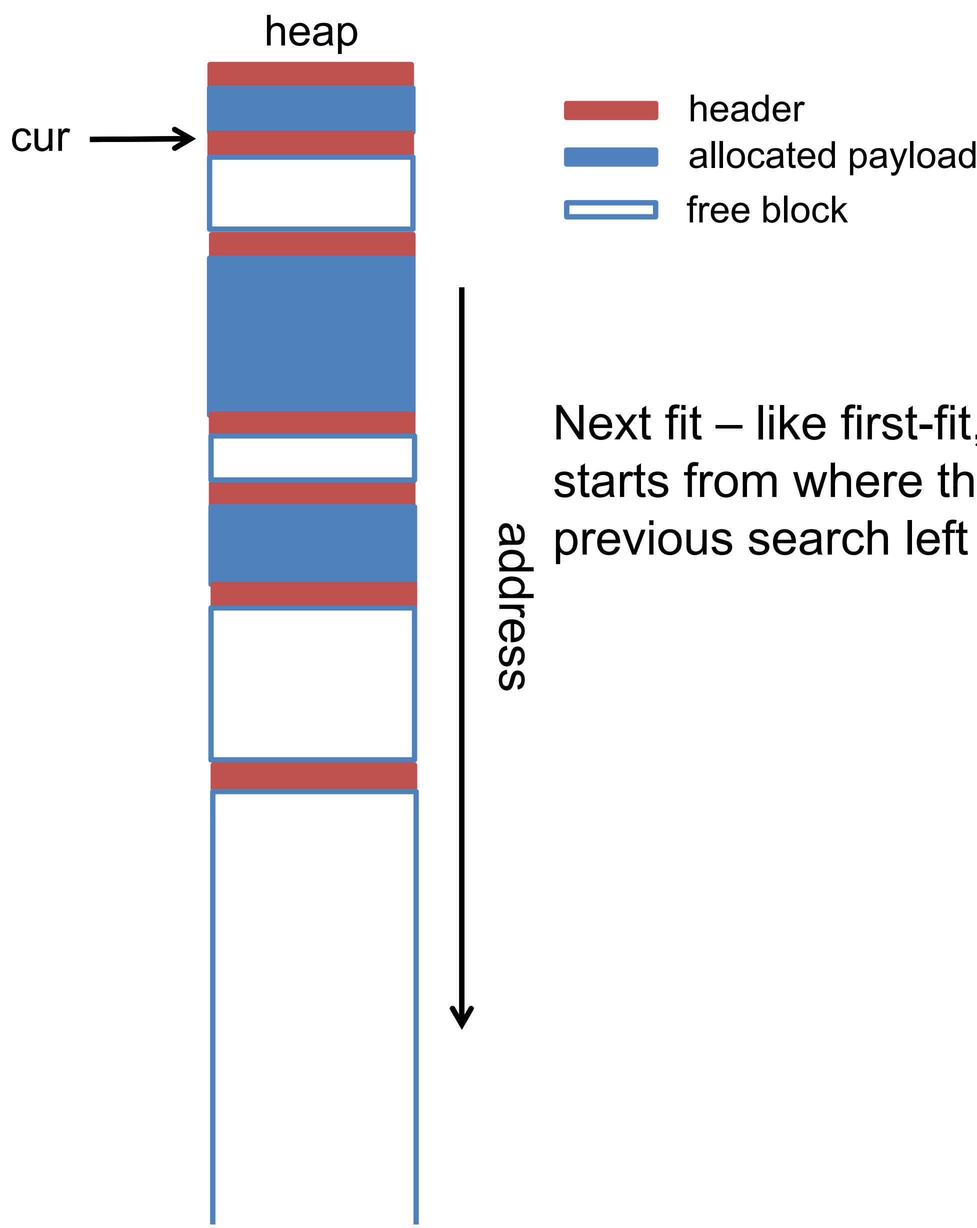


Best fit – choose the free block with the closest size that fits

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

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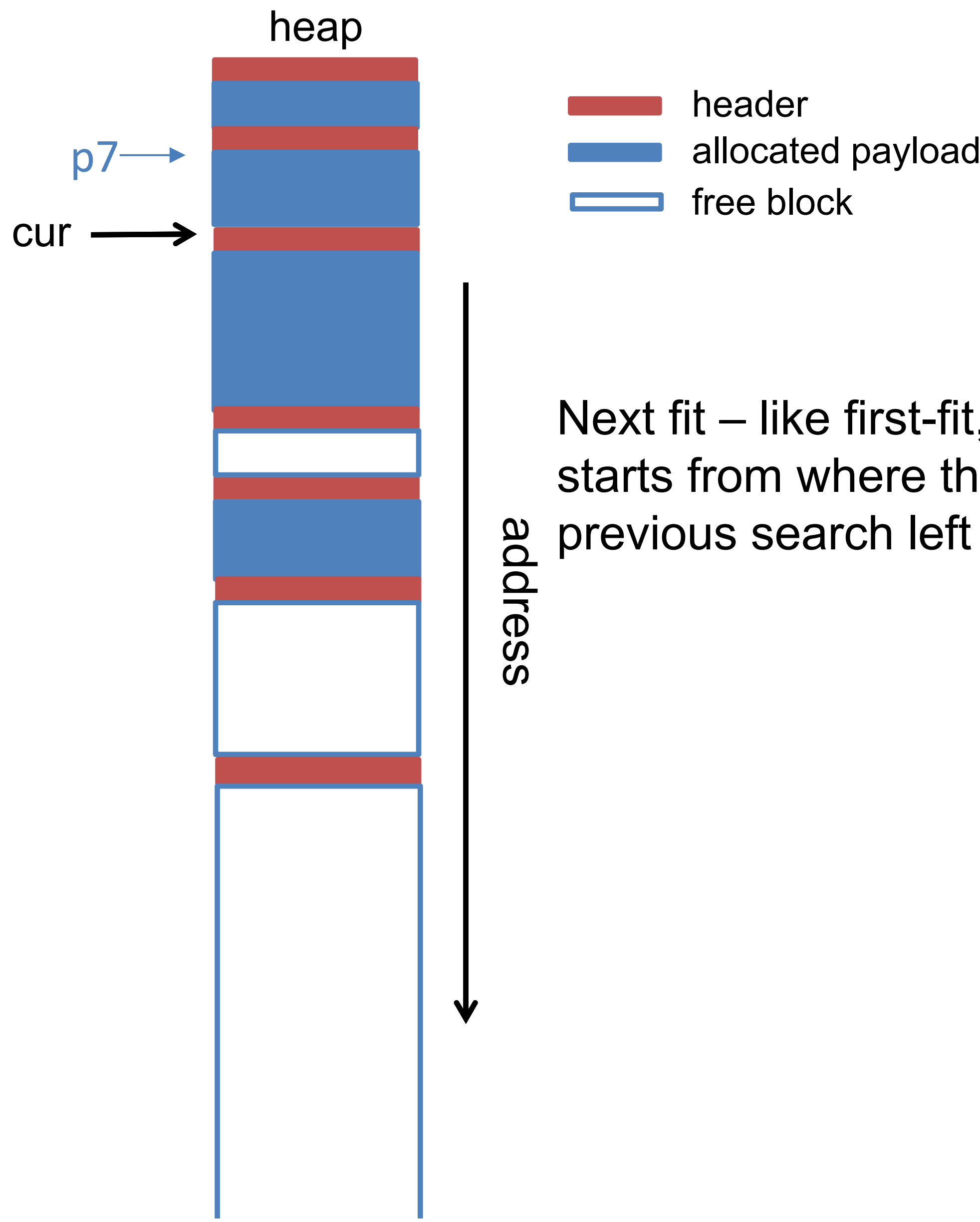

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Next fit

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p7 = malloc(8)
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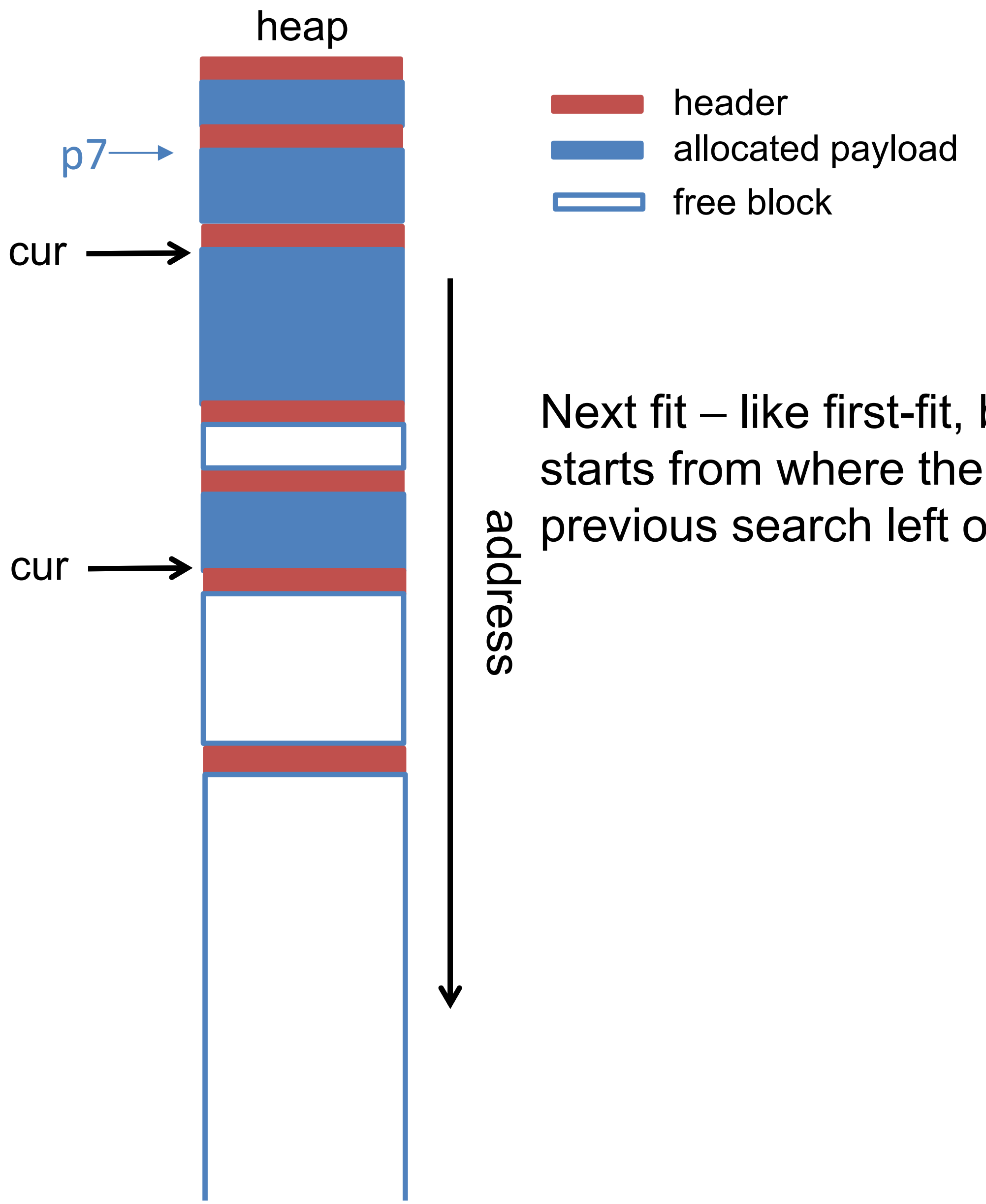

Next fit – like first-fit, but search starts from where the previous search left off.

Next fit

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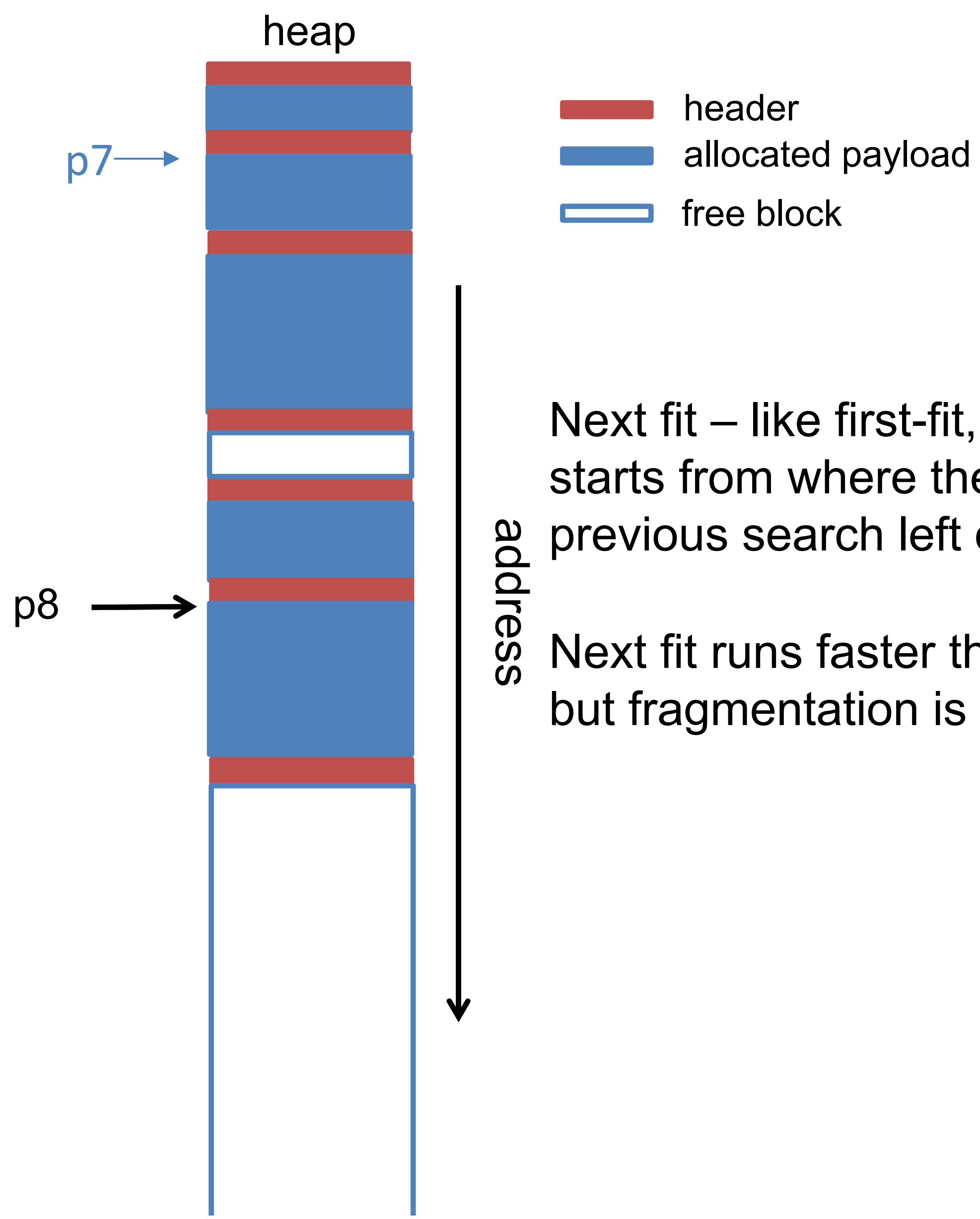
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
p8 = malloc(56)
```



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

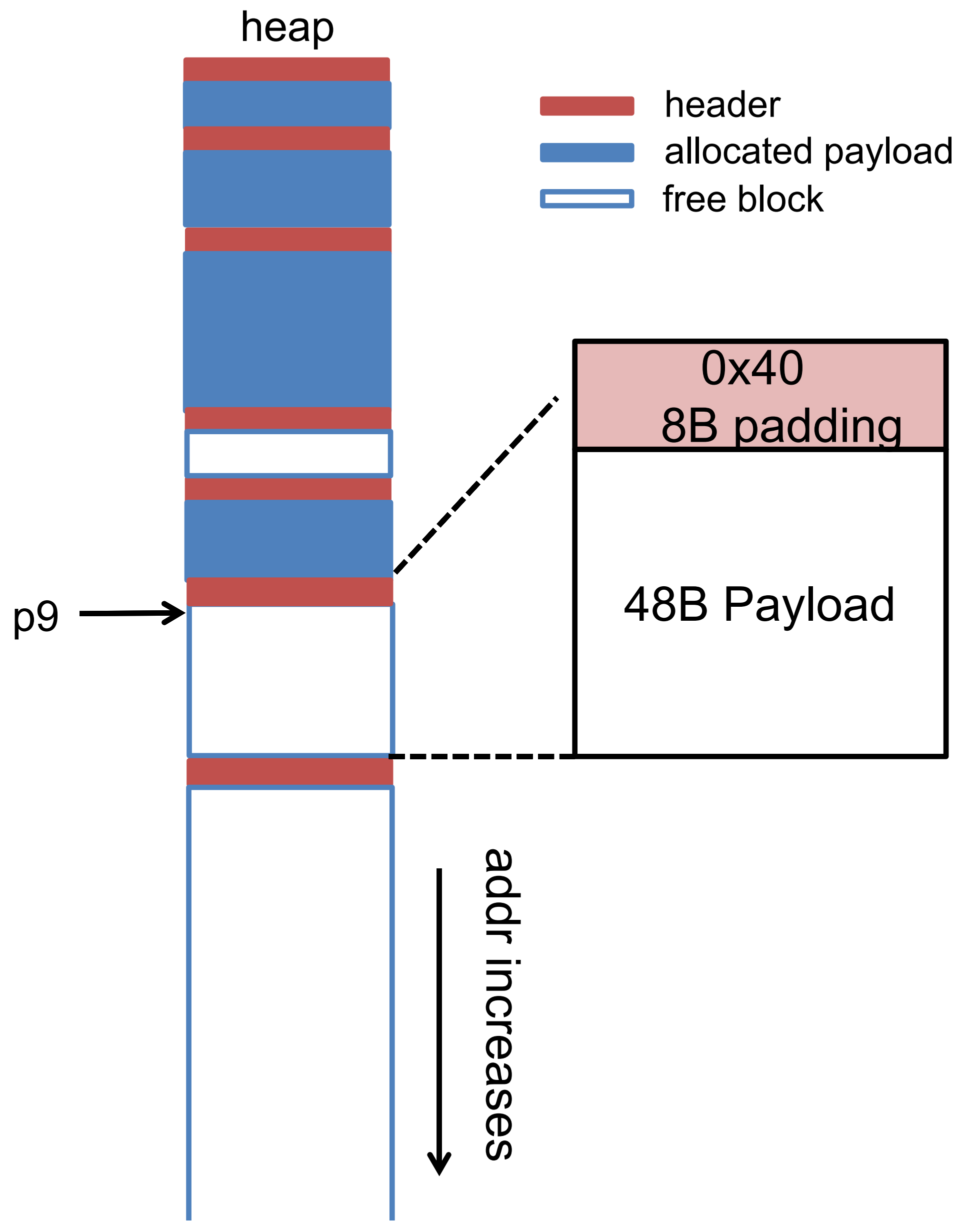
Next fit runs faster than first fit, but fragmentation is worse.

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);
}
```

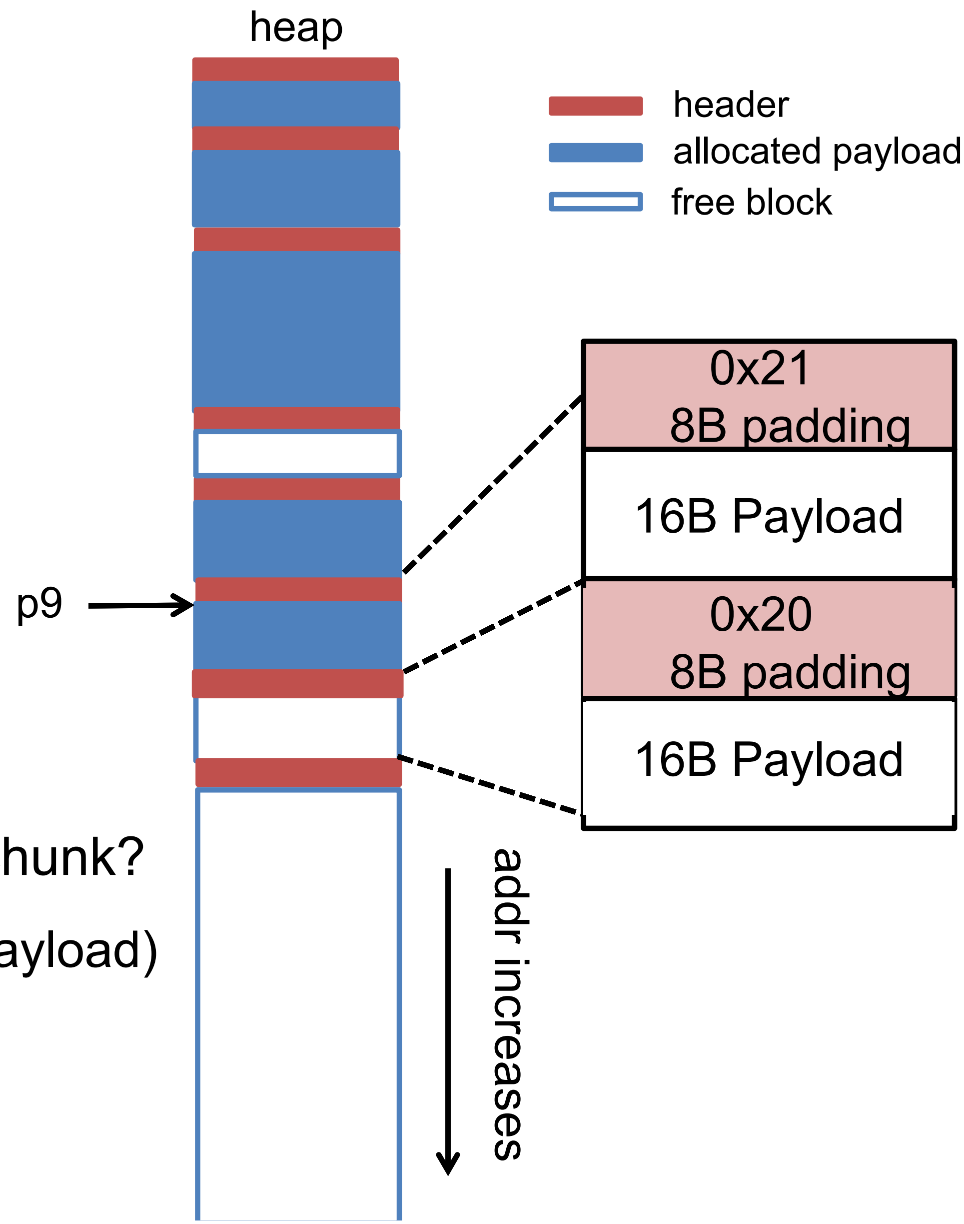
Splitting a free block

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



Splitting a free block

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

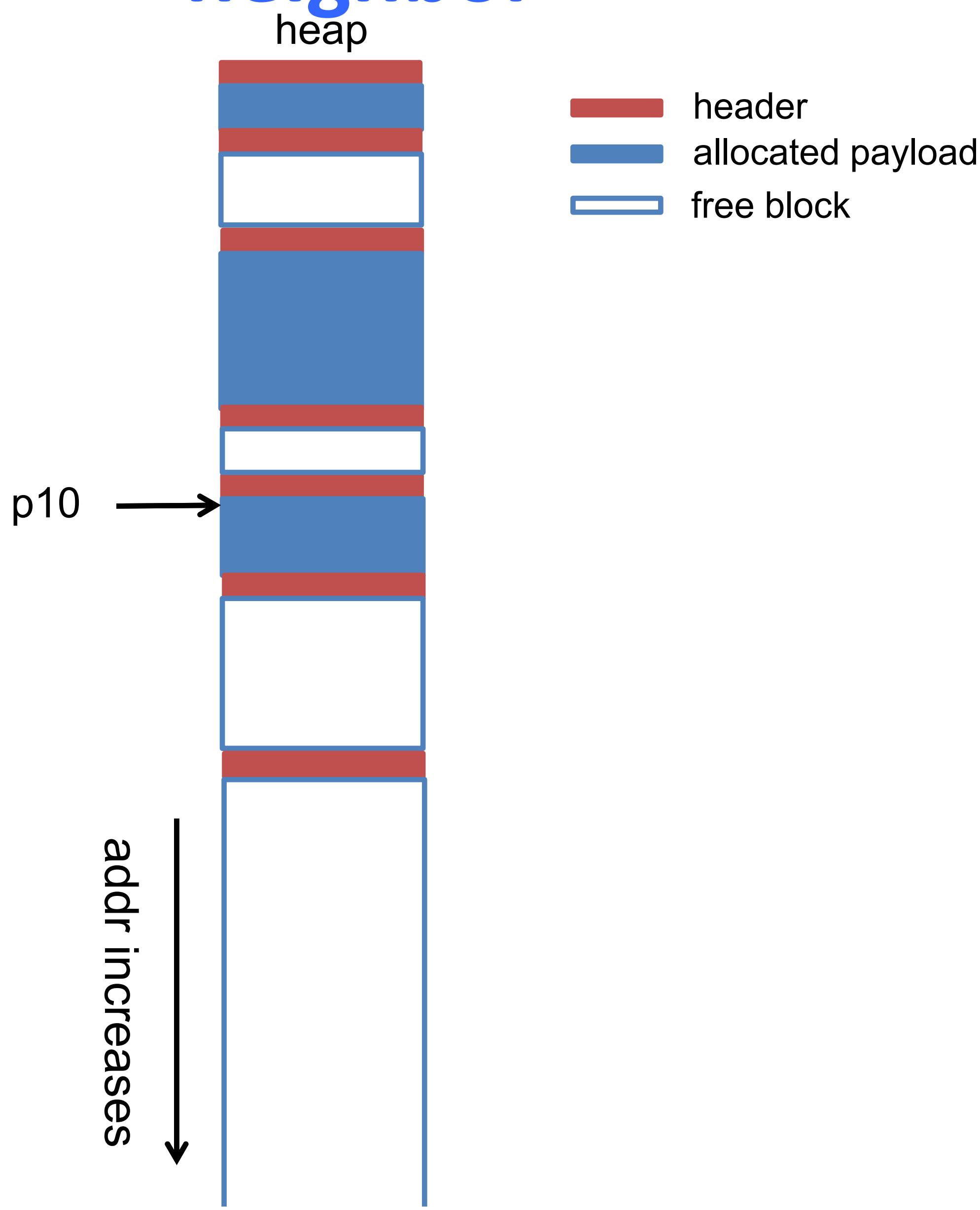


Q: what's the smallest chunk?

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

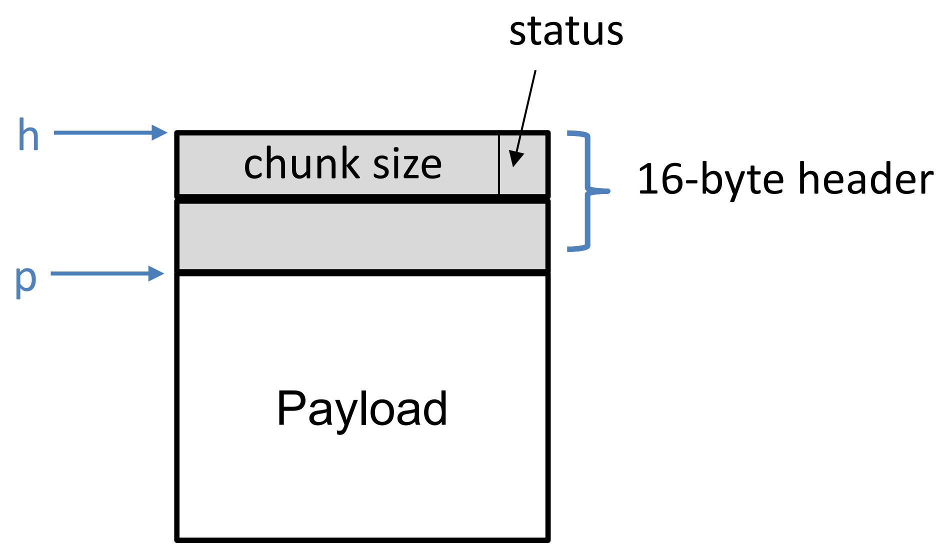
Coalescing a free block with its next free neighbor

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



free() in an implicit list

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

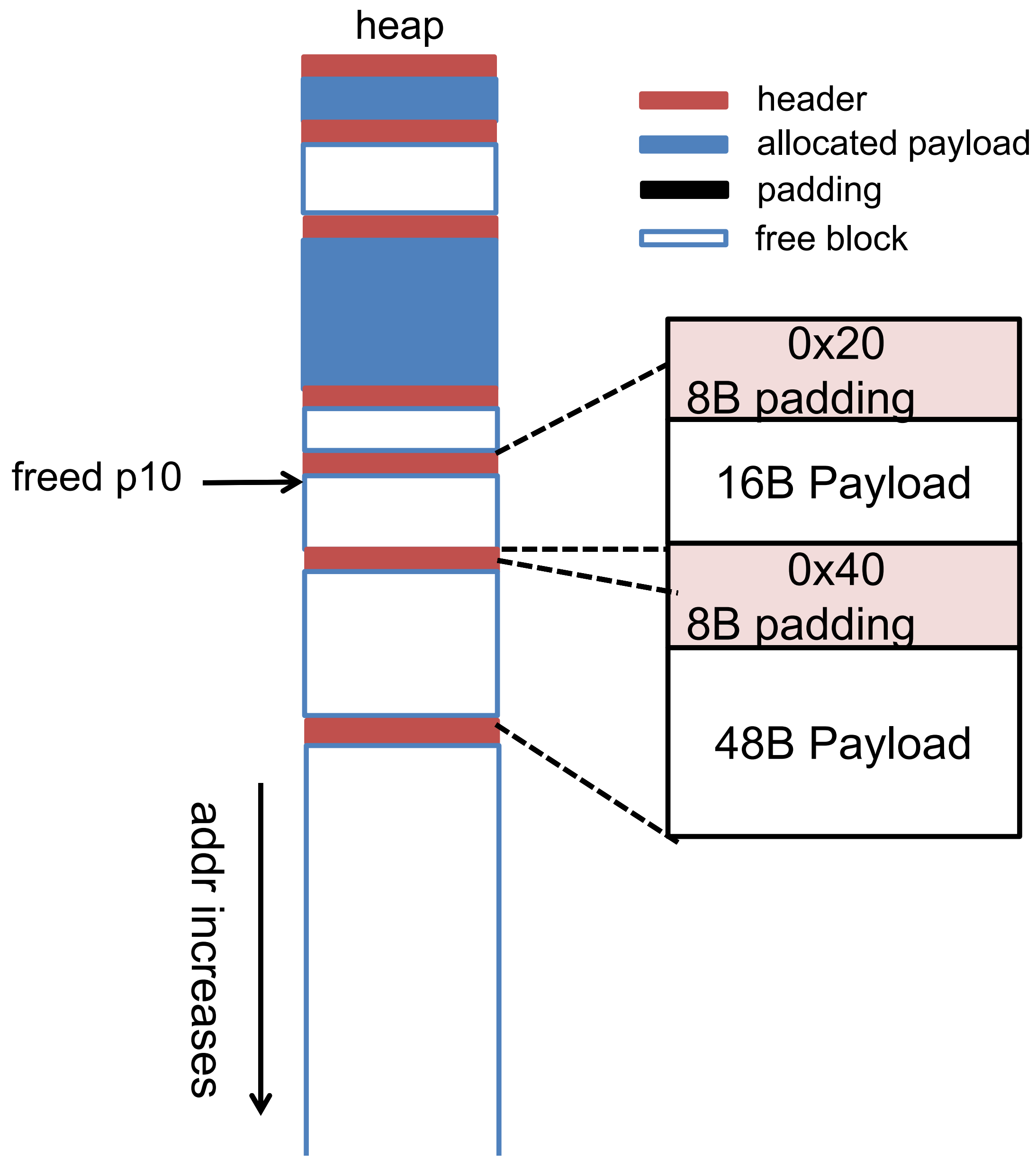



```
header *payload2header(void *p)
{


}
```

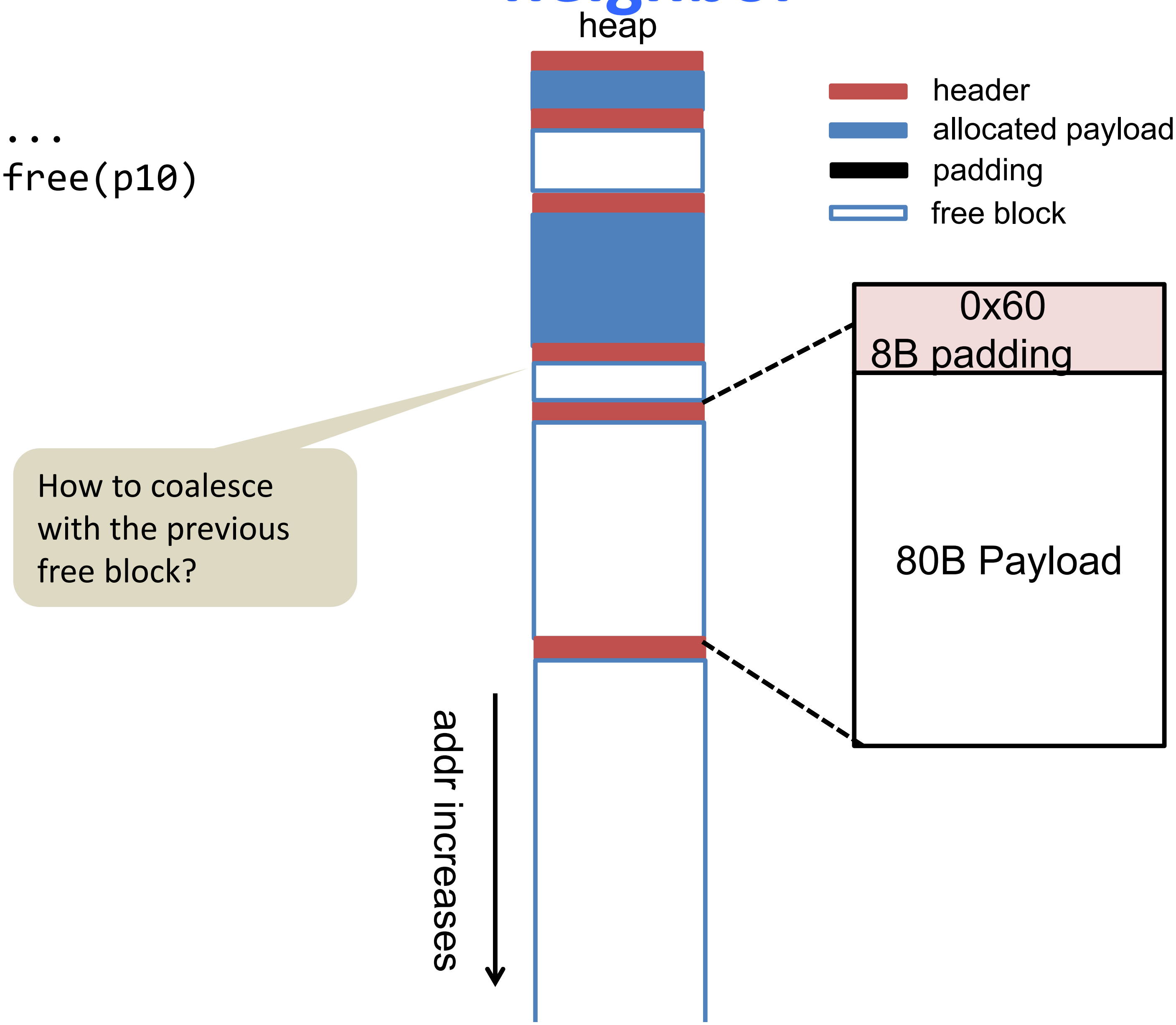
Coalescing a free block with next free neighbor

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



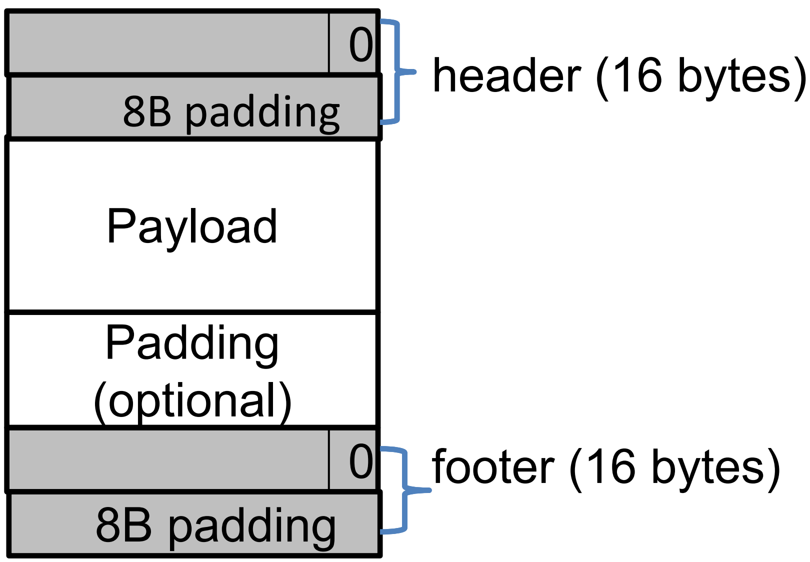
Coalescing a free block with its next free neighbor

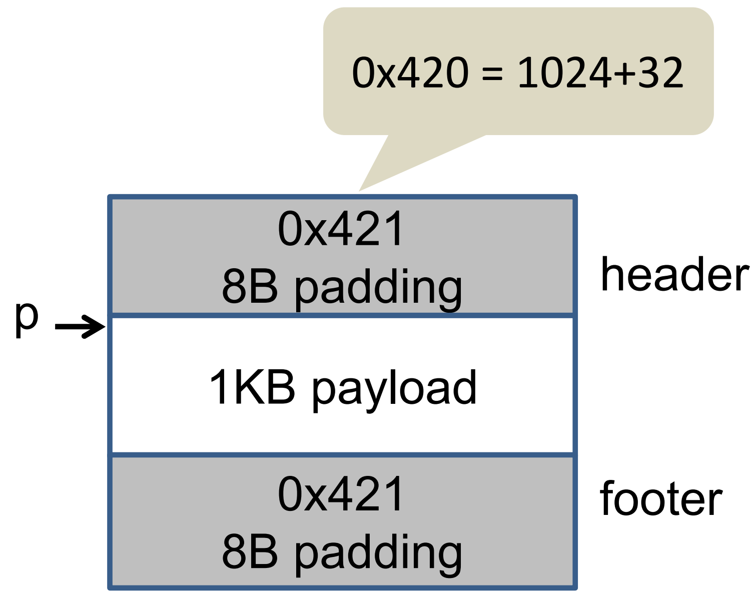
```
...
free(p10)
```



Use footer to coalesce with previous block

- Duplicate header information into the footer

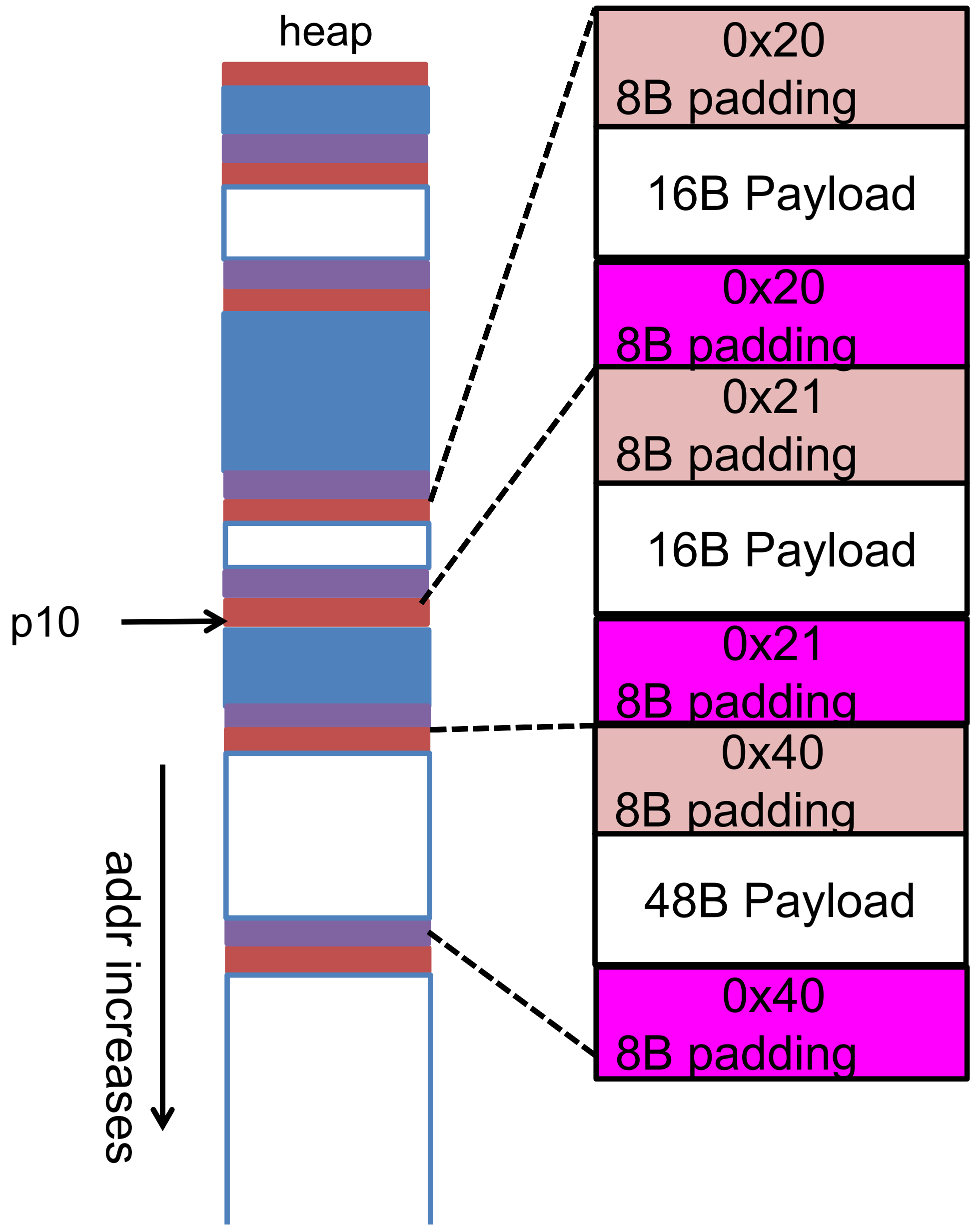





```
p  = malloc(1024)
```

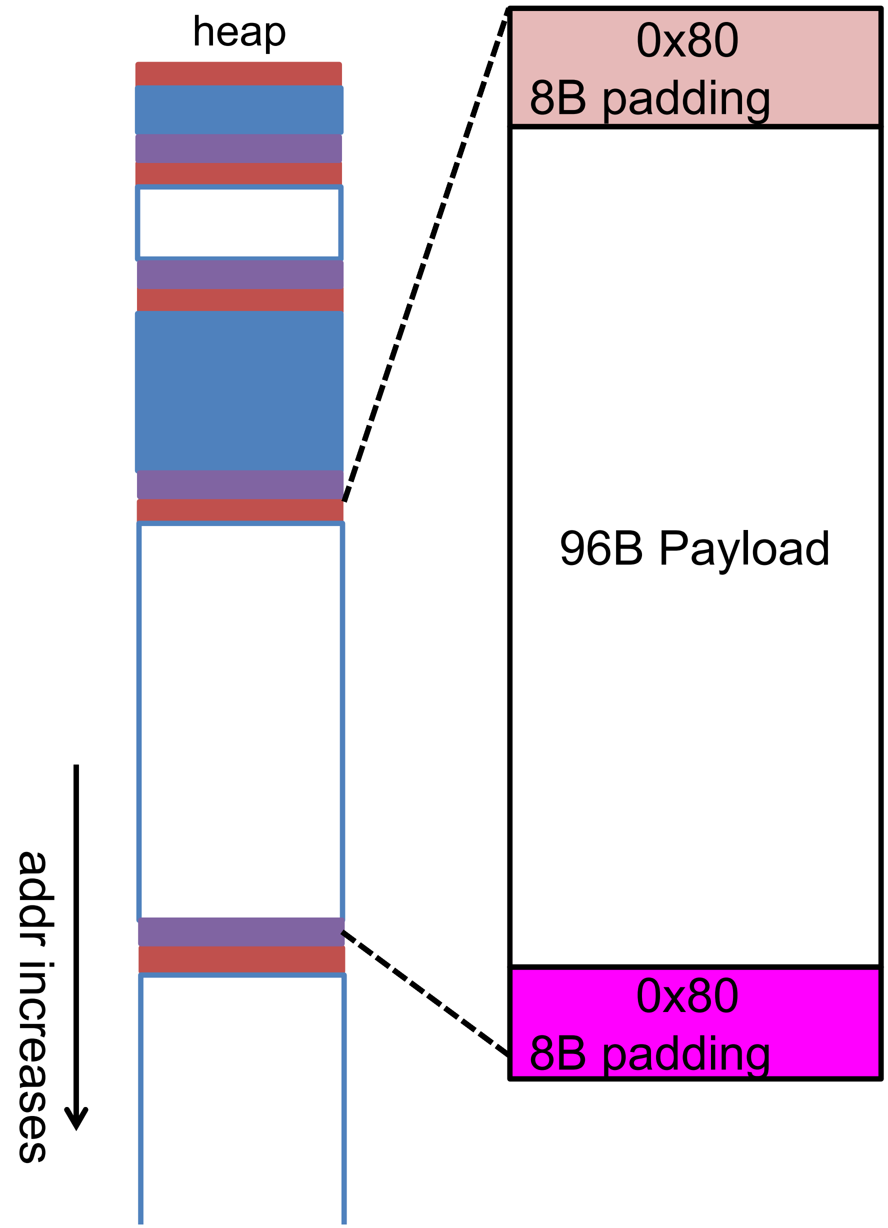
Coalescing prev and next blocks

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



Coalescing prev and next blocks

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



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.

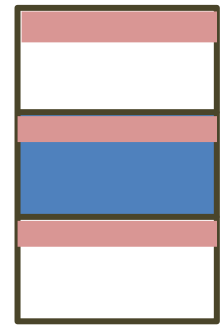
Today’s lesson plan

- Explicit list
- Segregated list
- Buddy system

Review: implicit → explict

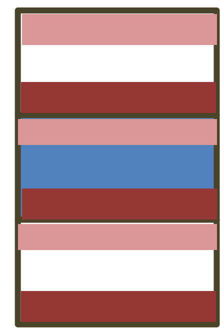
Implicit list (header-only)

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



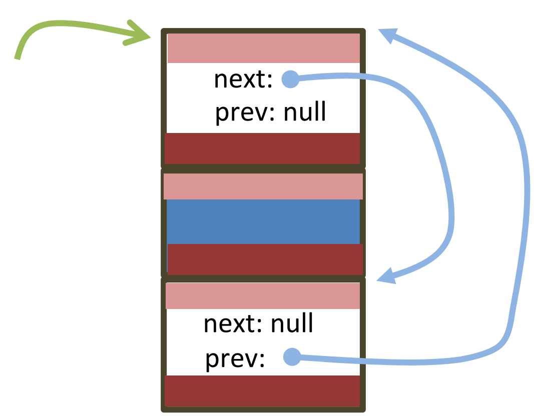
Implicit list (header+footer)

Problem: search for free block scans over allocated blocks



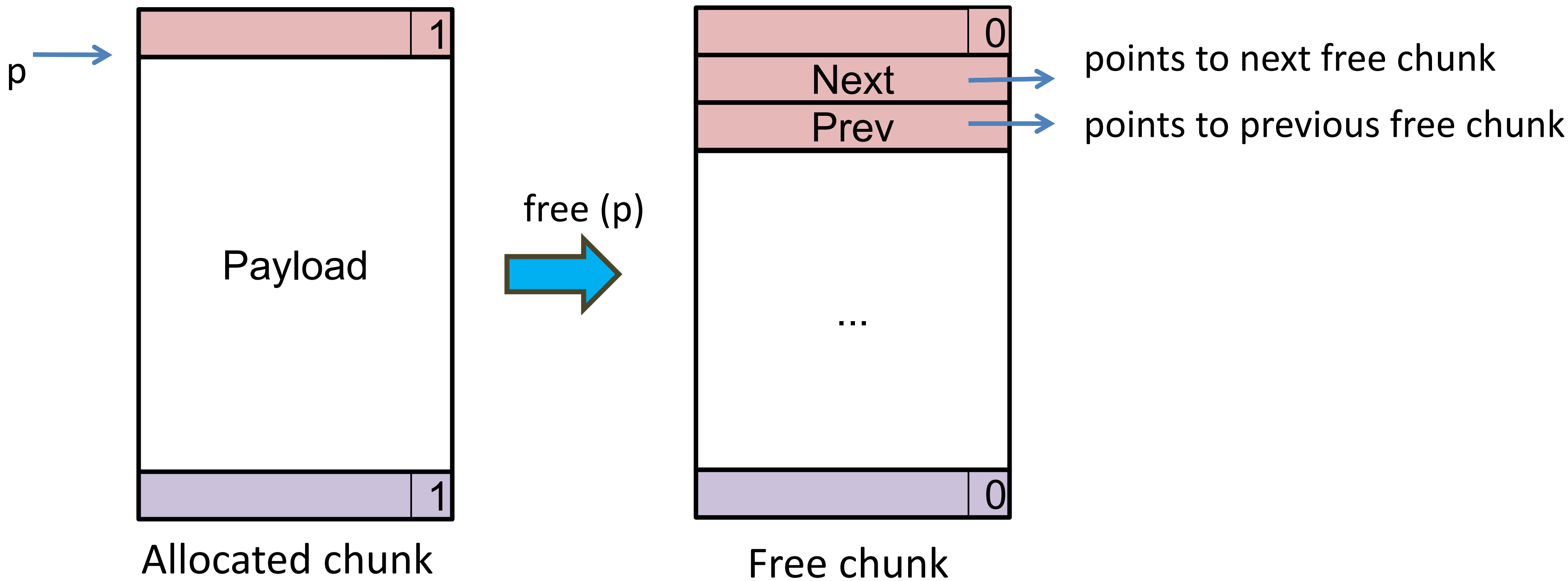
explicit list (header+footer)

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.

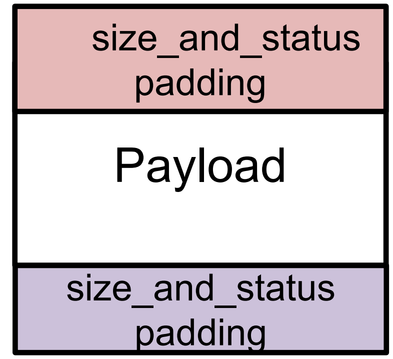
- Question: what's the minimal size of a chunk?

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

Explicit list: implementation

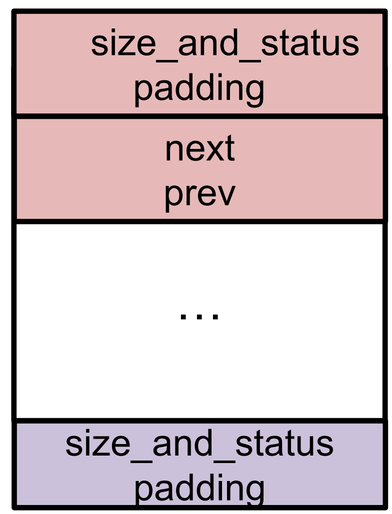
```
typedef struct {
  unsigned long size_and_status;
  unsigned long padding;
} header;
```

Allocated chunk:




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

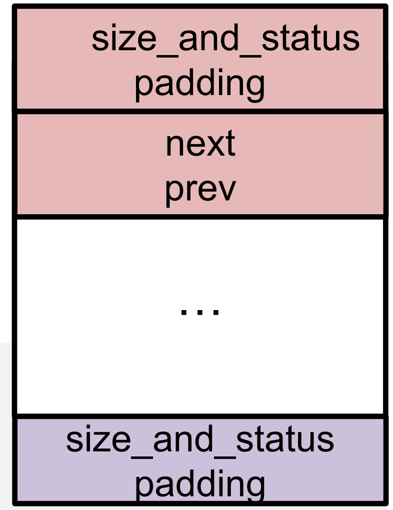
Free chunk:



Explicit list: initialization

```
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;
   set_size(&h->common_header, csz);
   set_size(header2footer(&h->common_header), csz);
   free_hdr *newchunk = (free_hdr *)((char *)n+csz);
   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))
       h = coalesce((free_hdr *)h, (free_hdr *)next);
    header *prev = prev_chunk(h);
    if (!get_status(prev))
       h = coalesce((free_hdr *)h, (free_hdr *)prev);

    insert(&freelist, (free_hdr *)h);
}
```

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(header2footer(&h->common_header), sum, false);
   h->next = h->prev = NULL;
   return h;
}
```

Segregated list

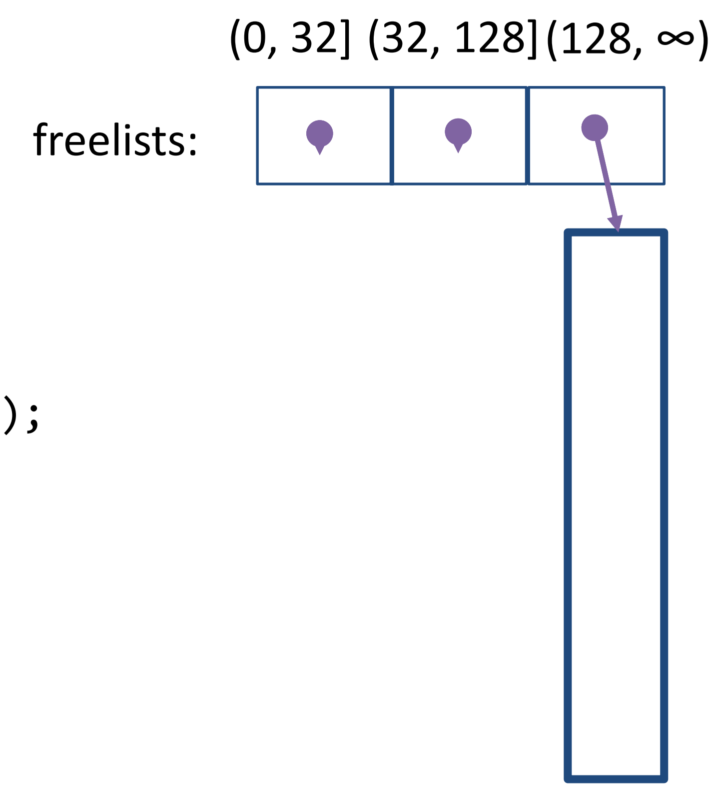
- Idea: keep multiple freelists
  - each freelist contains chunks of similar sizes

Segregated list: initialize

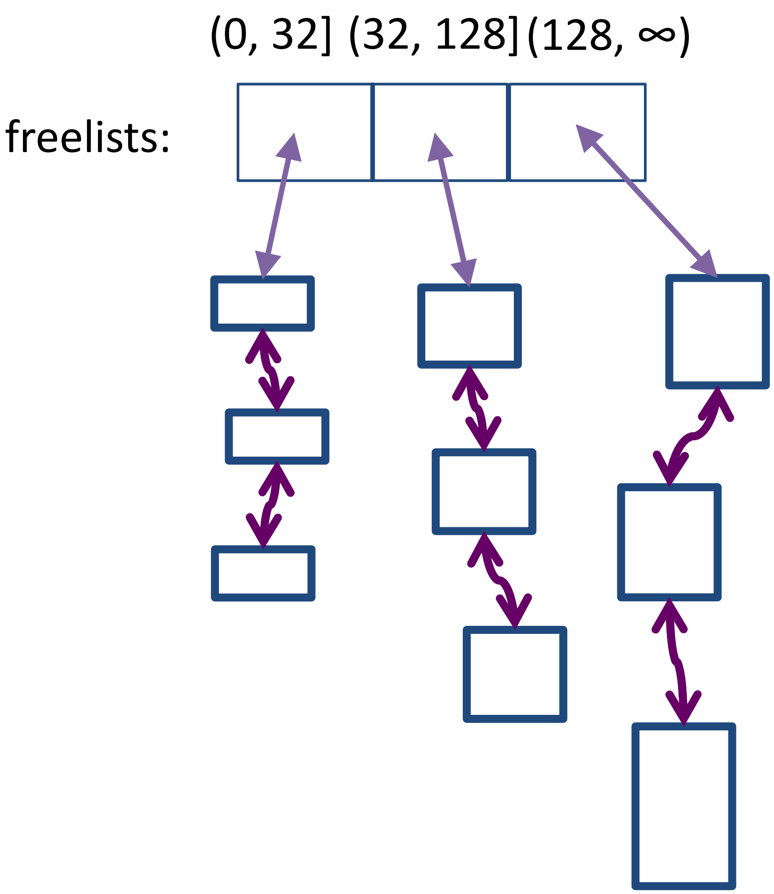
```
#define NLISTS 3
free_hdr* freelists[NLISTS];
size_t size_classes[NLISTS] = {32, 128, (size_t)-1};

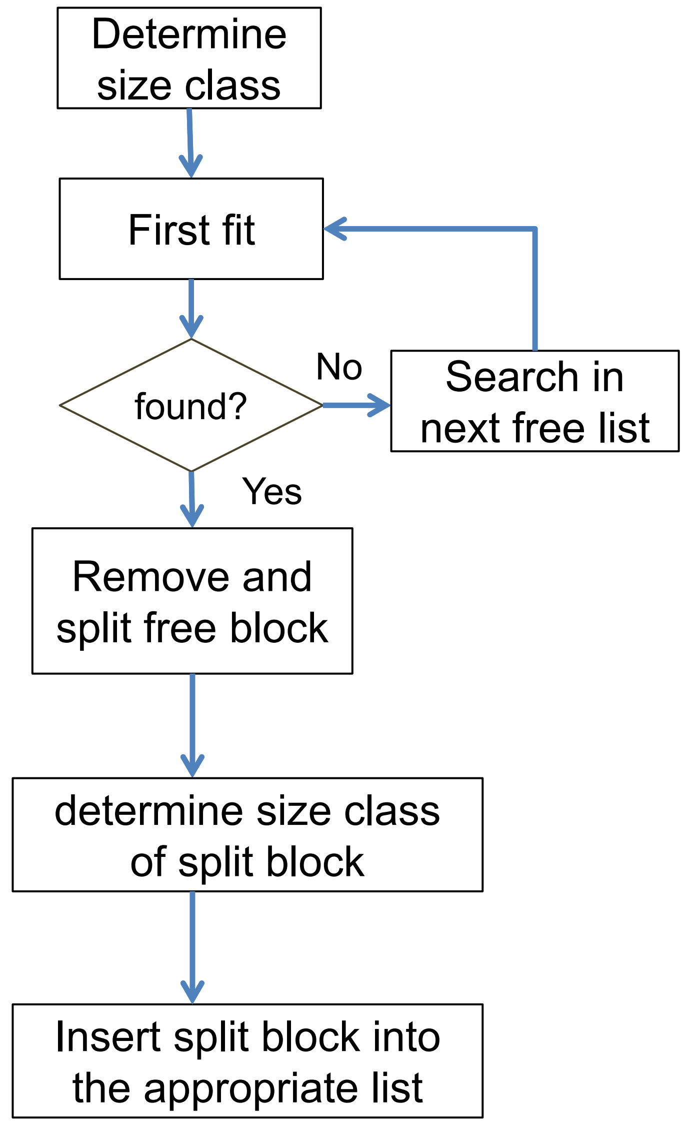
int which_freelist(size_t s) {
   int ind = 0;
   while (s > size_classes[ind])
      ind++;
   return ind;
}


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

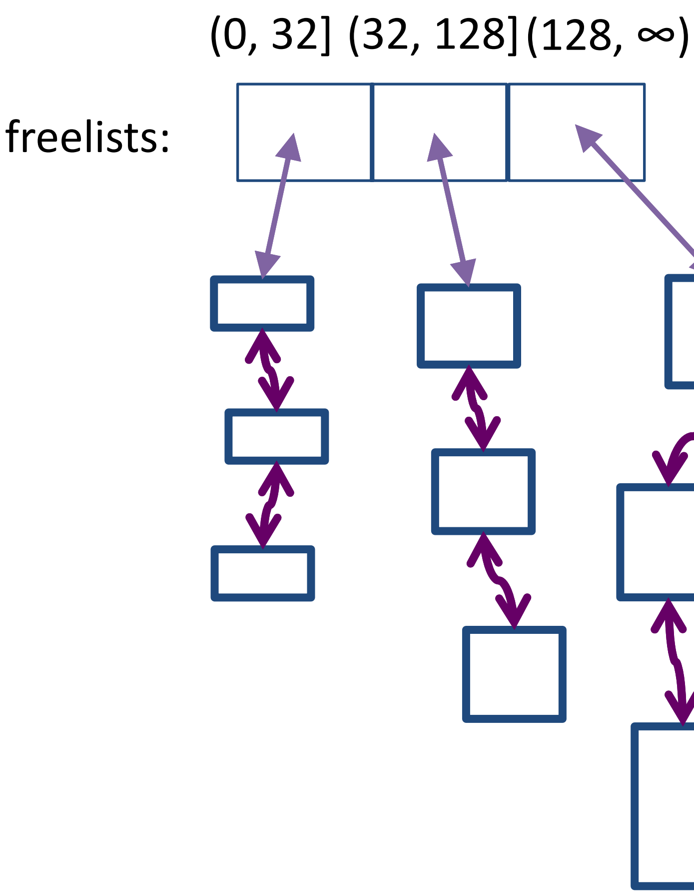


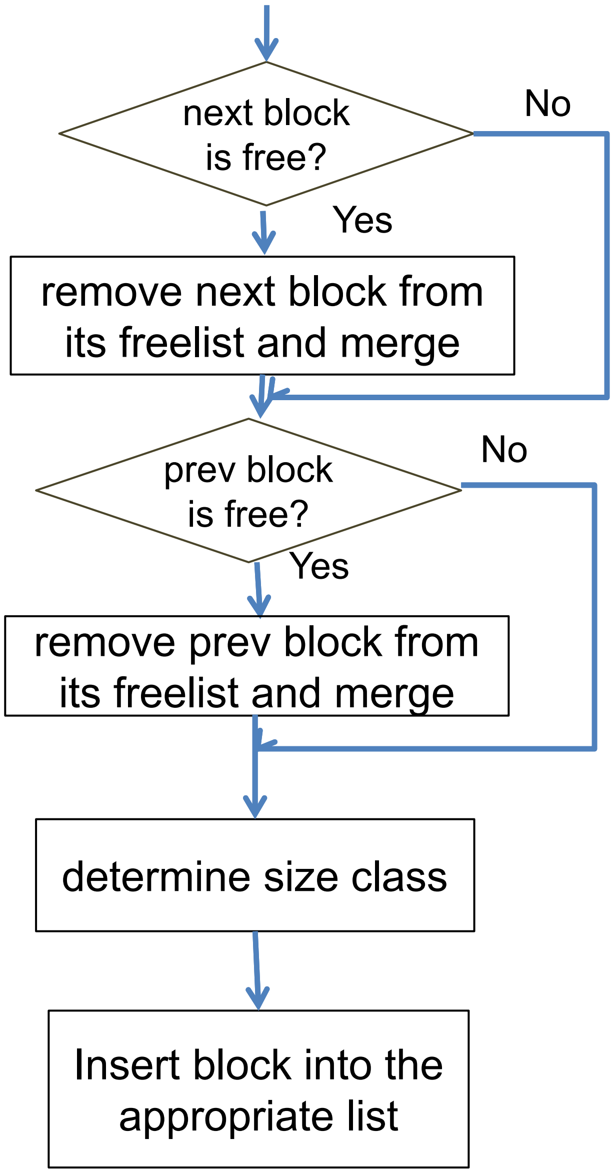
Segregated list: allocation





Segregated list: free





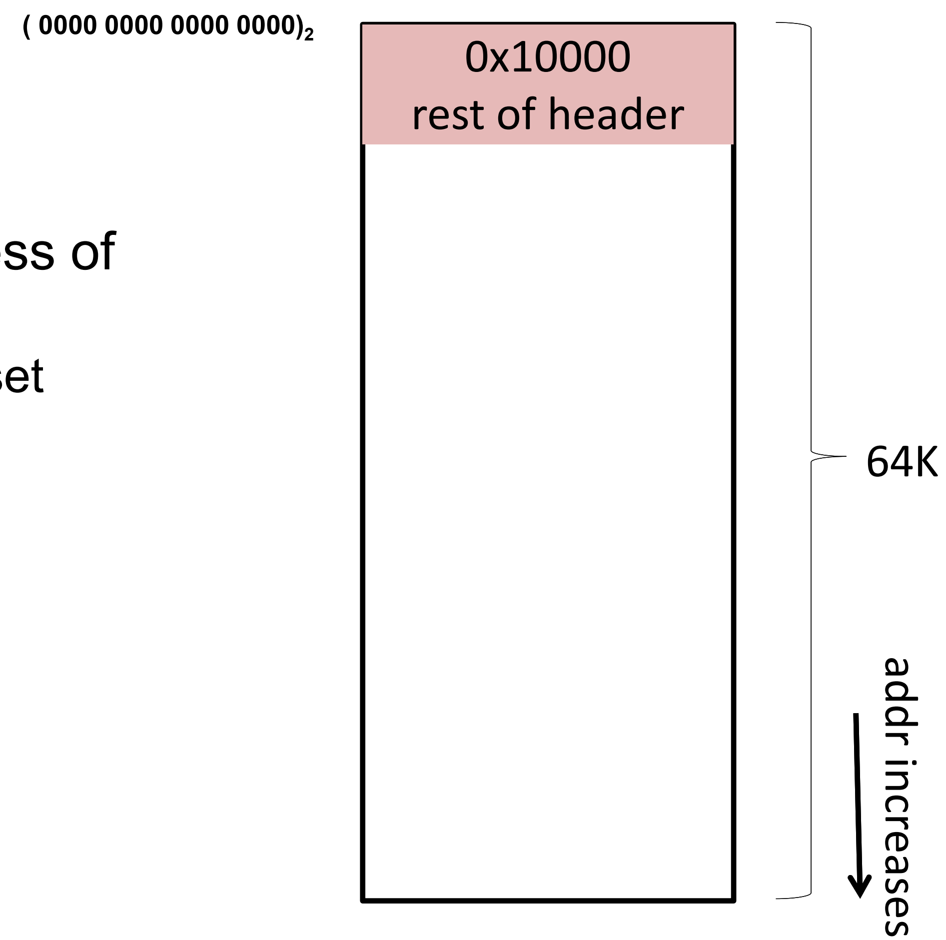
Buddy System

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

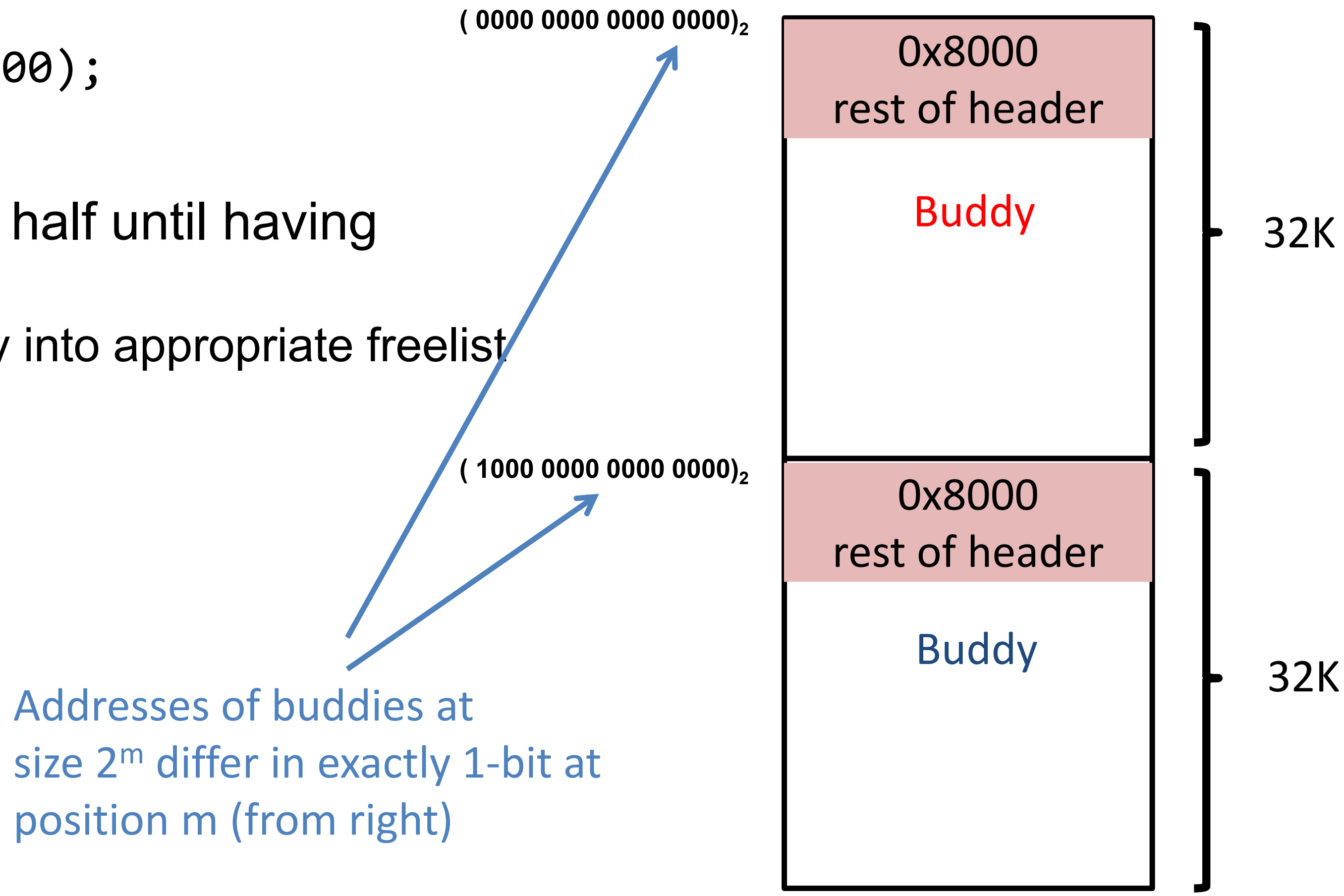


Binary buddy system: allocate

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

Recursive split in half until having the right size

– insert free buddy into appropriate freelist

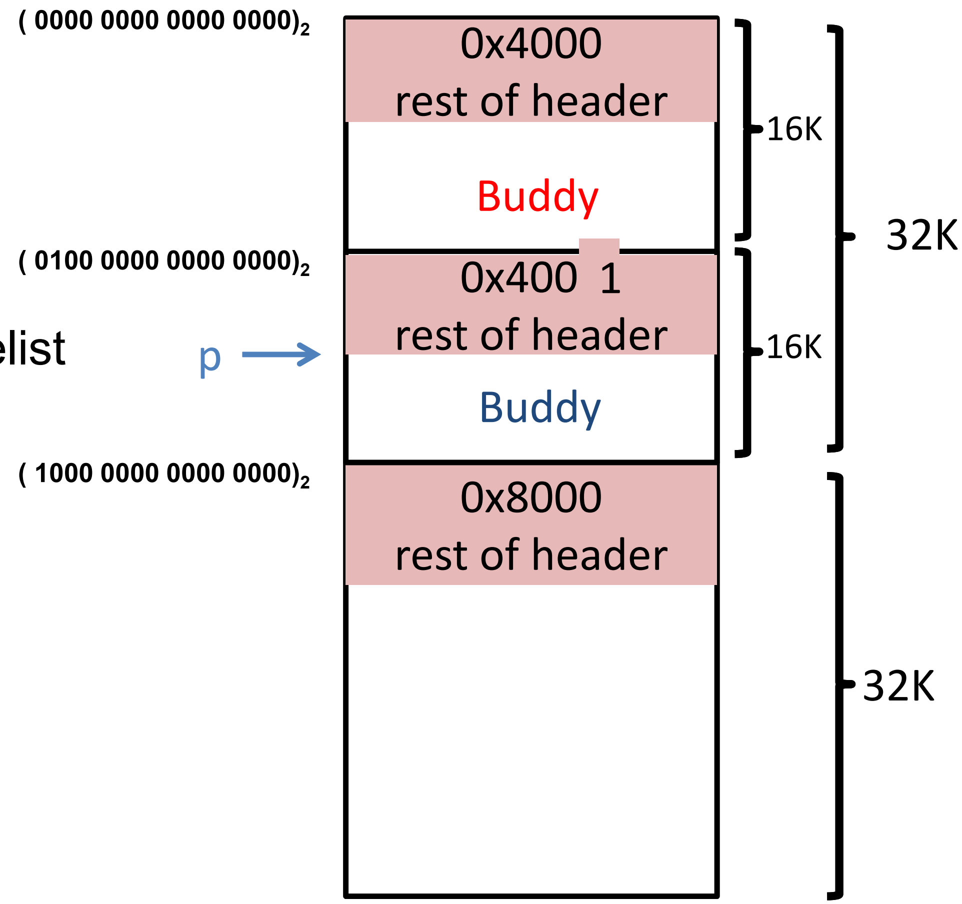


Binary buddy system: allocate

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

Recursive split in half until having the right size

– insert free buddy into appropriate freelist

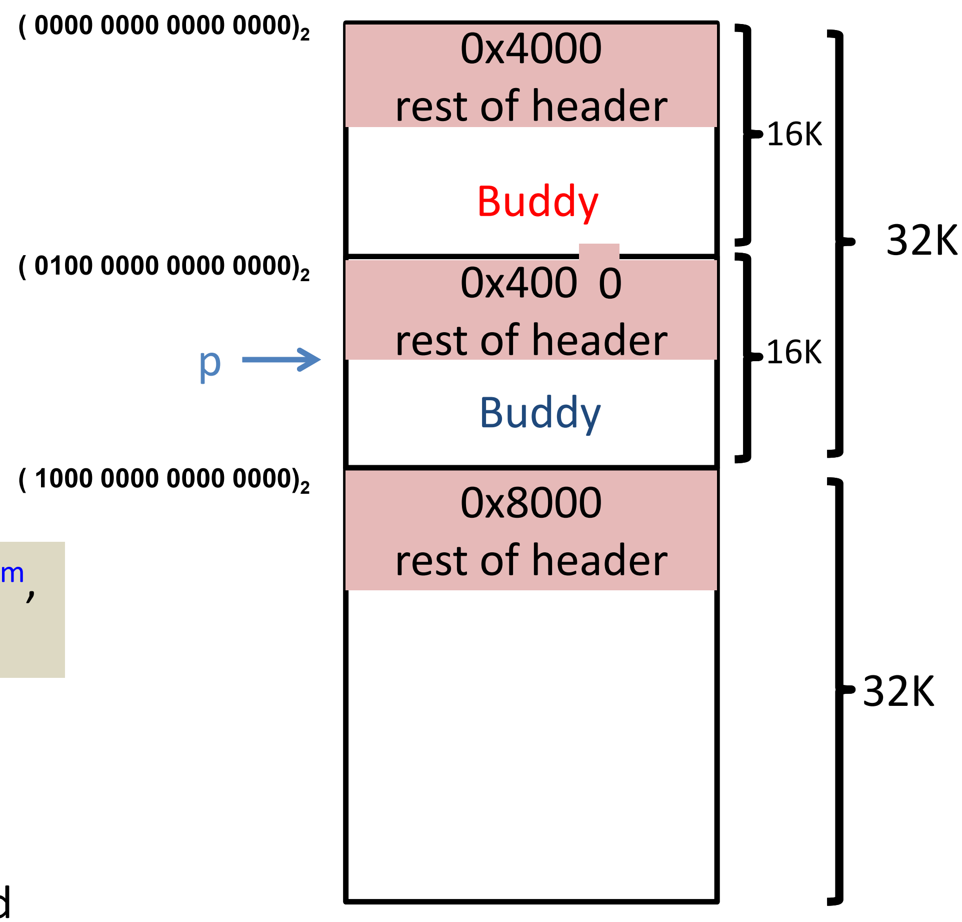


Binary buddy system: free

```
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)

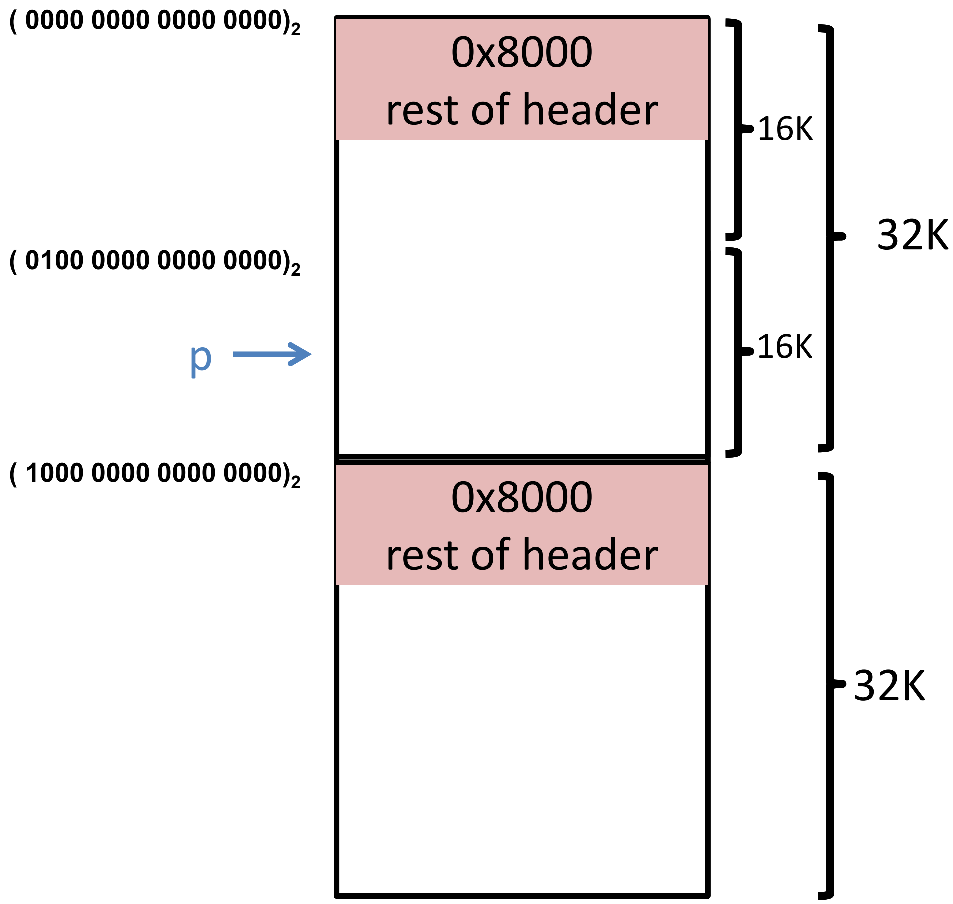
any bit XOR 0 = unchanged
any bit XOR 1 = flipped

Binary buddy system: free

```
free(p);
```

If buddy is free:

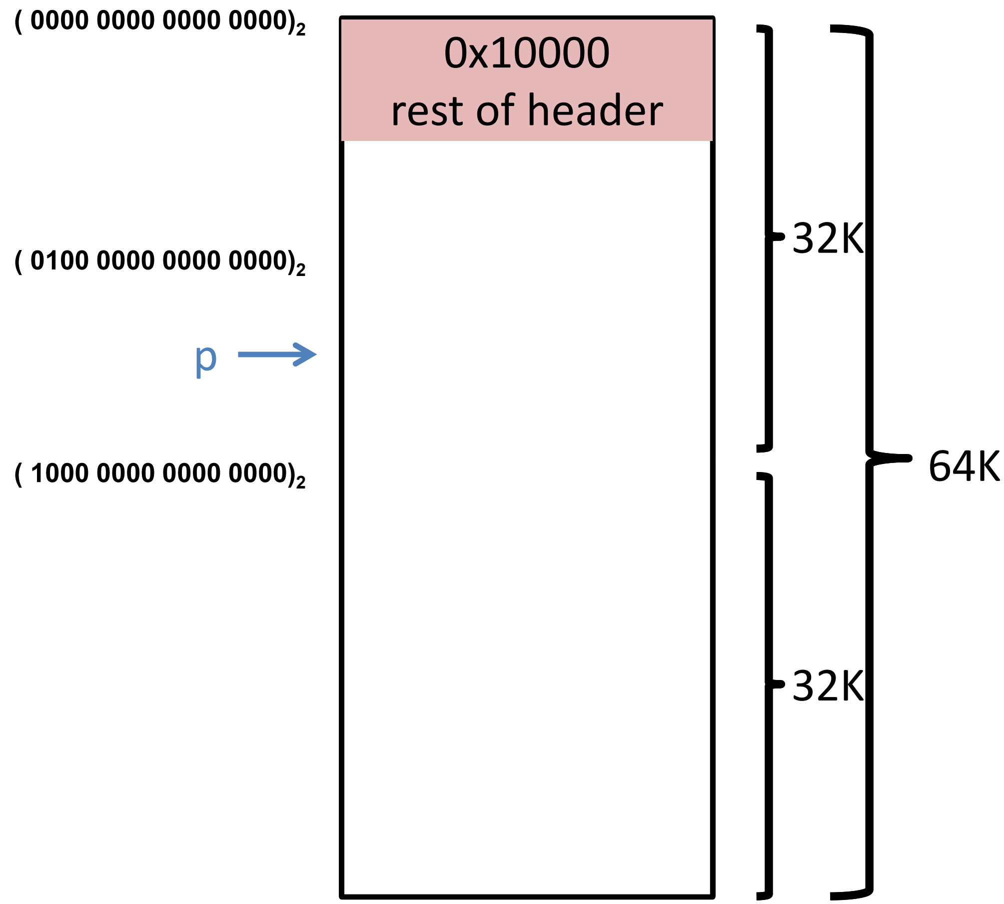
2. Detach free buddy from its list
3. Combine with current block



Binary buddy system: free

```
free(p);
```

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



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