Dynamic Memory Allocation

Jinyang Li

based on Tiger Wang's slides

Why dynamic memory allocation?

Allocation size is unknown until the program runs (at runtime).

```
#define MAXN 15213
int array[MAXN];

int main(void)
{
      int i, n;
      scanf("%d", &n);
      if (n > MAXN)
           app_error("Input file too big");
      for (i = 0; i < n; i++)
           scanf("%d", &array[i]);
      exit(0);
}
```

Why dynamic memory allocation?

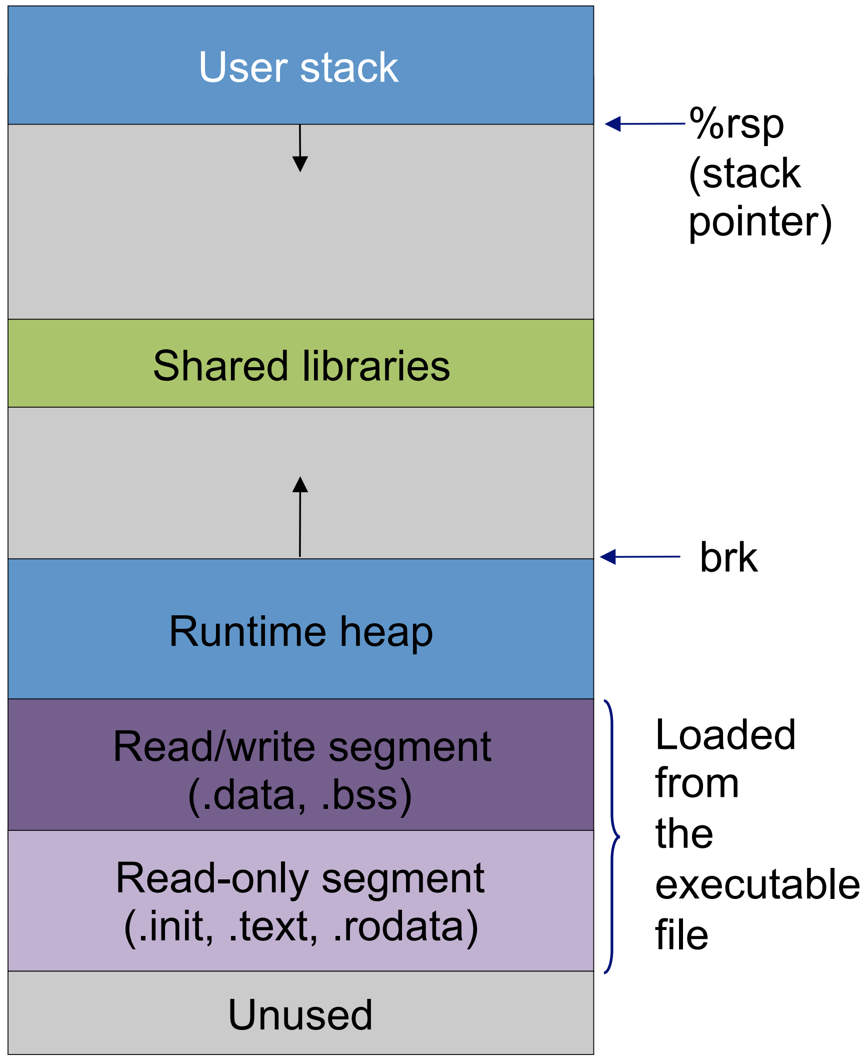
Allocation size is unknown until the program runs (at runtime).

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

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

Dynamic allocation on heap

Question: can one dynamically allocate memory on stack?



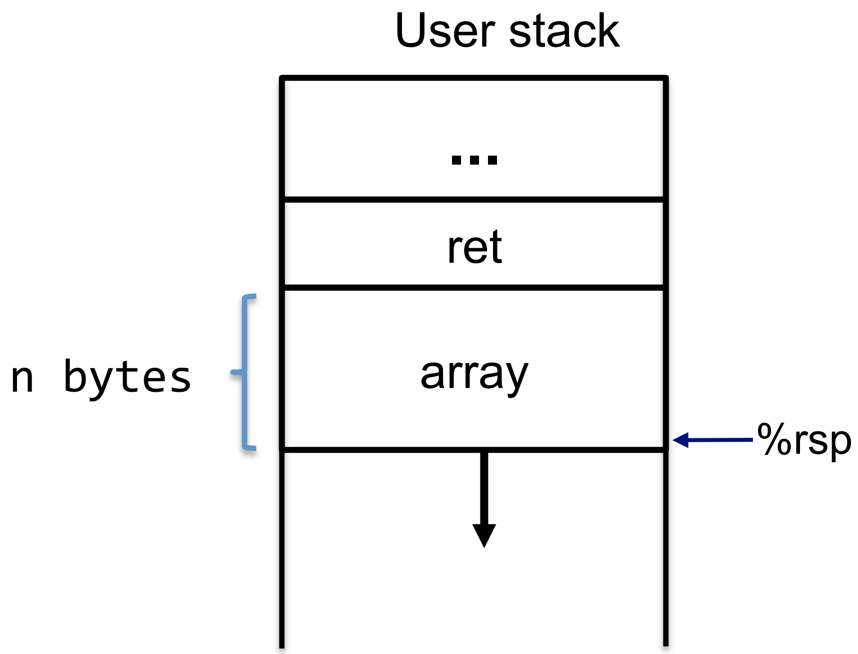
Dynamic allocation on heap

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

Answer: Yes, but space is freed upon function return

```
#include <stdlib.h>
void *alloca(size_t size);


void func(int n) {
    array = alloca(n);
}
```

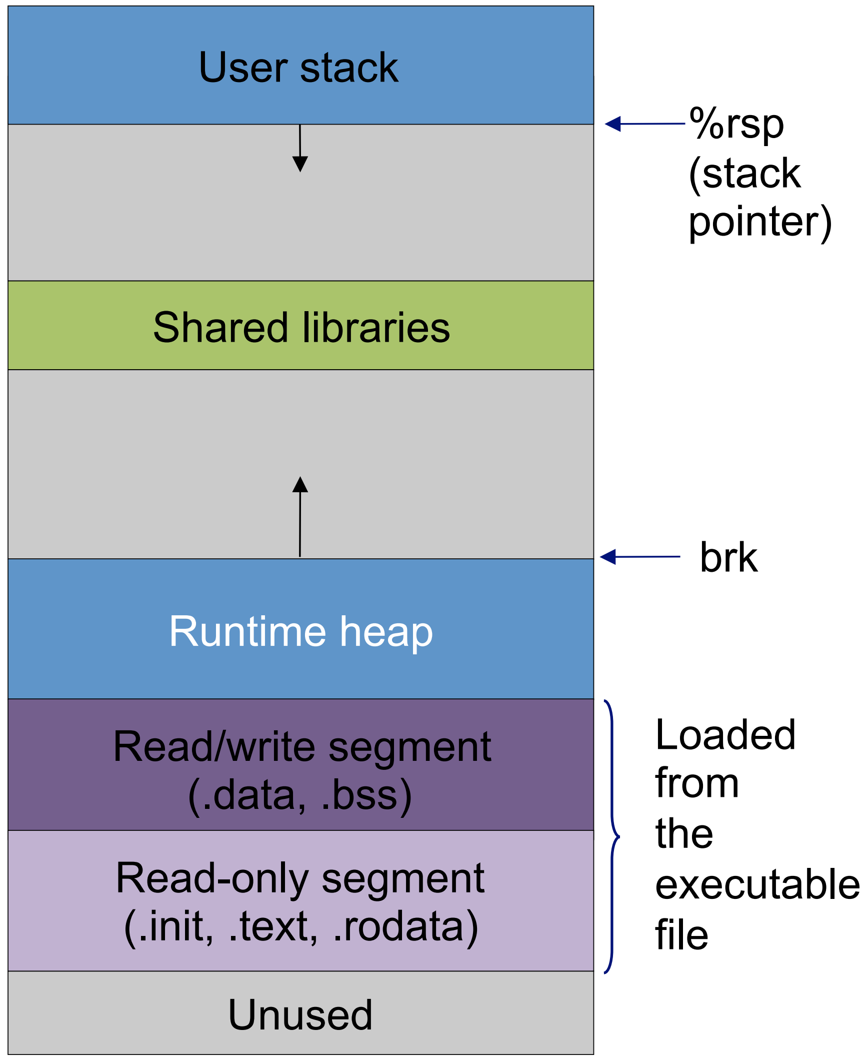



```
subq $n,%rsp
```

Not good practice!

Dynamic allocation on heap

Question: How to allocate memory on heap?



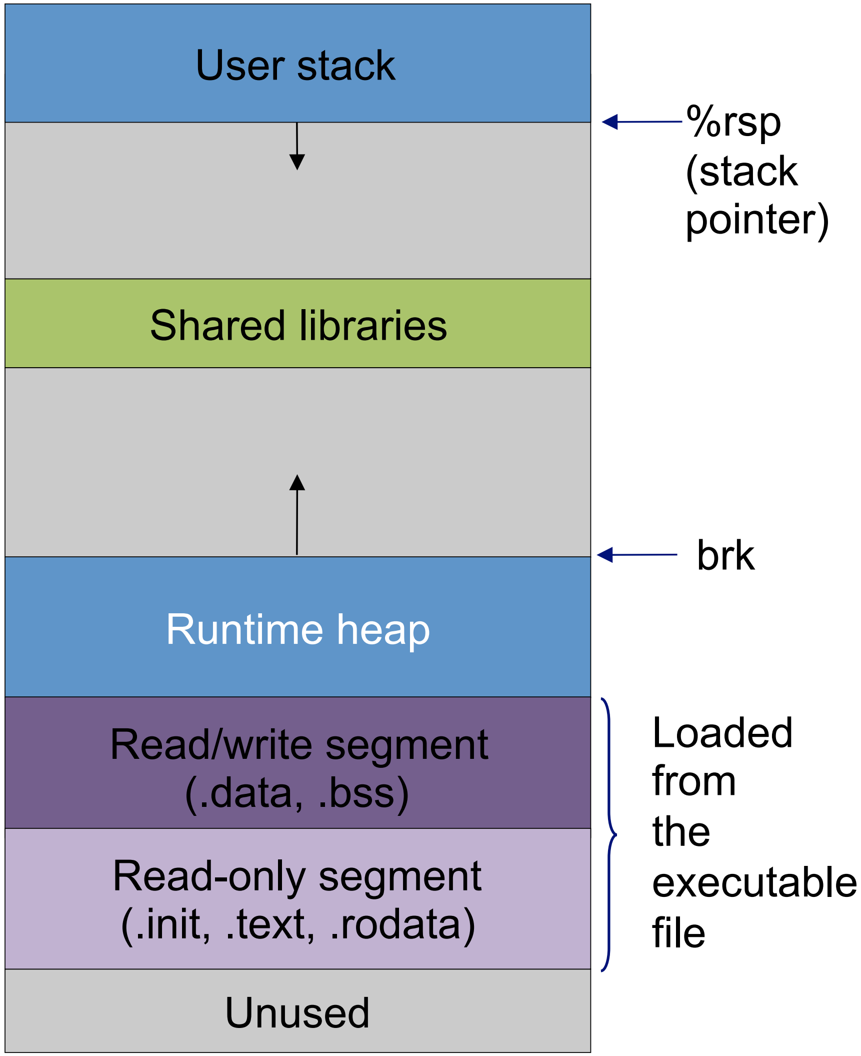
Dynamic allocation on heap

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

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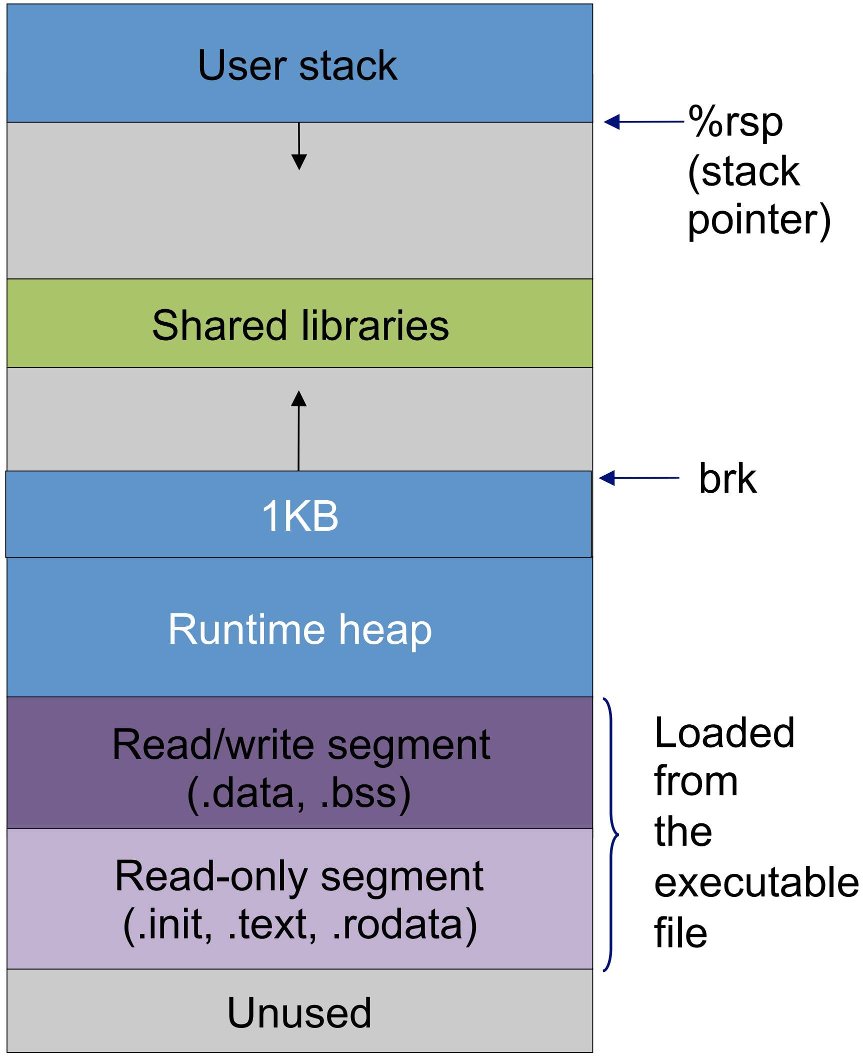
Ask OS for allocation on the heap via system calls

```
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

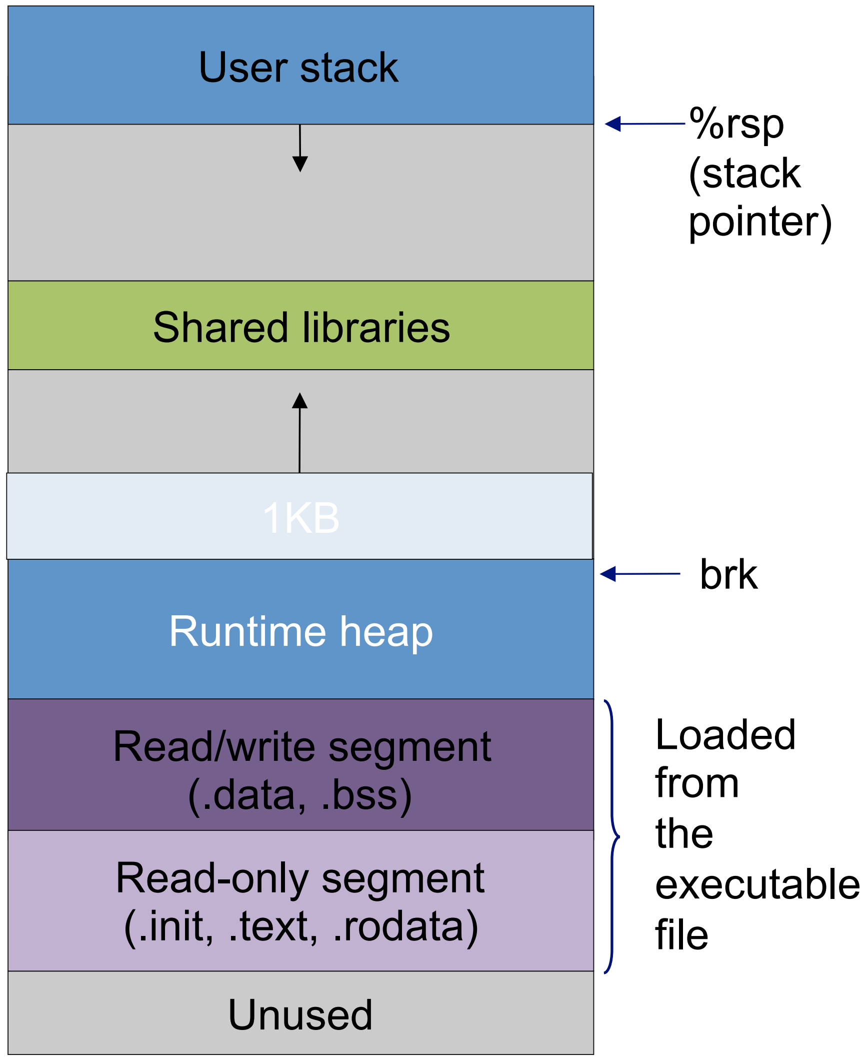
Question: How to allocate memory on heap?

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?

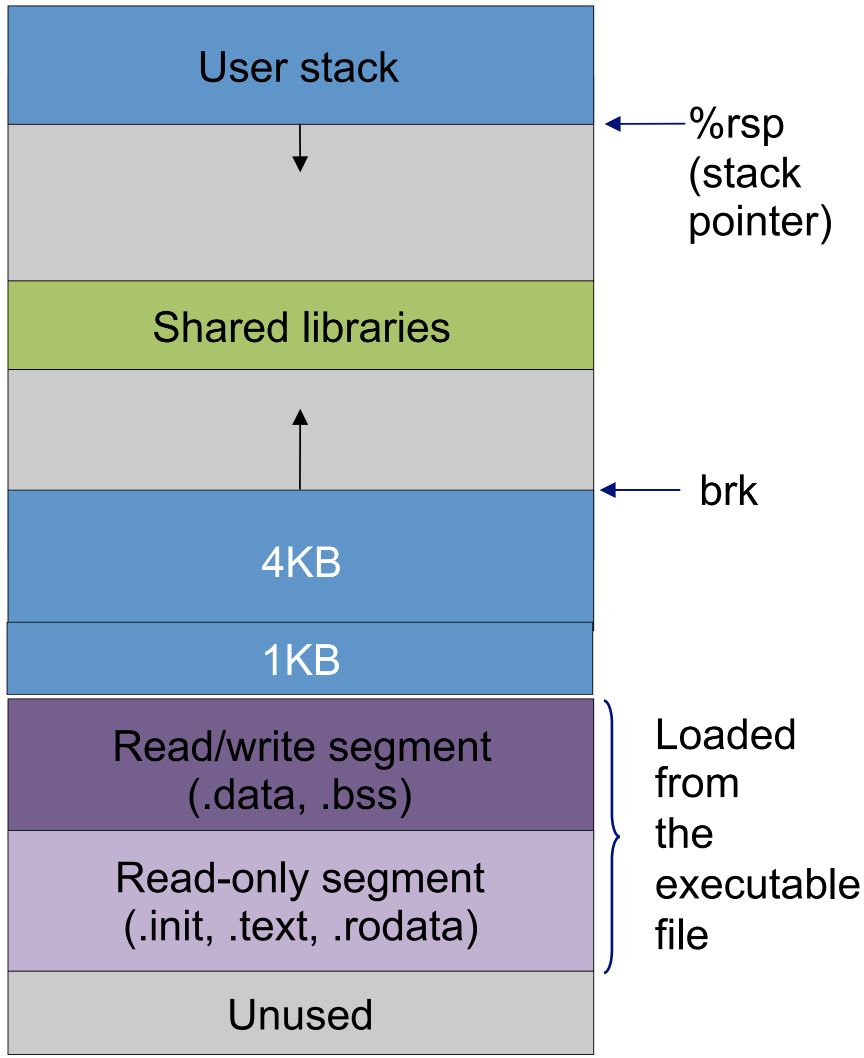
Ask OS for allocation on the heap via system calls

```
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

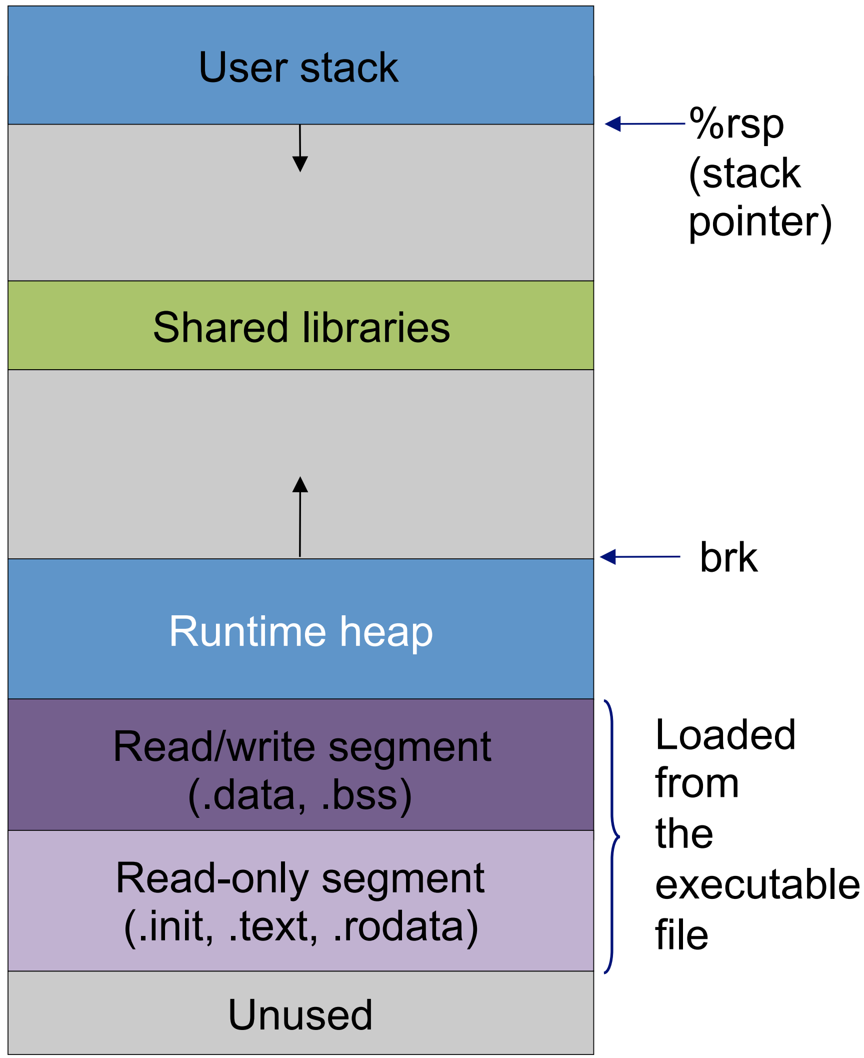
Question: How to allocate memory on heap?

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

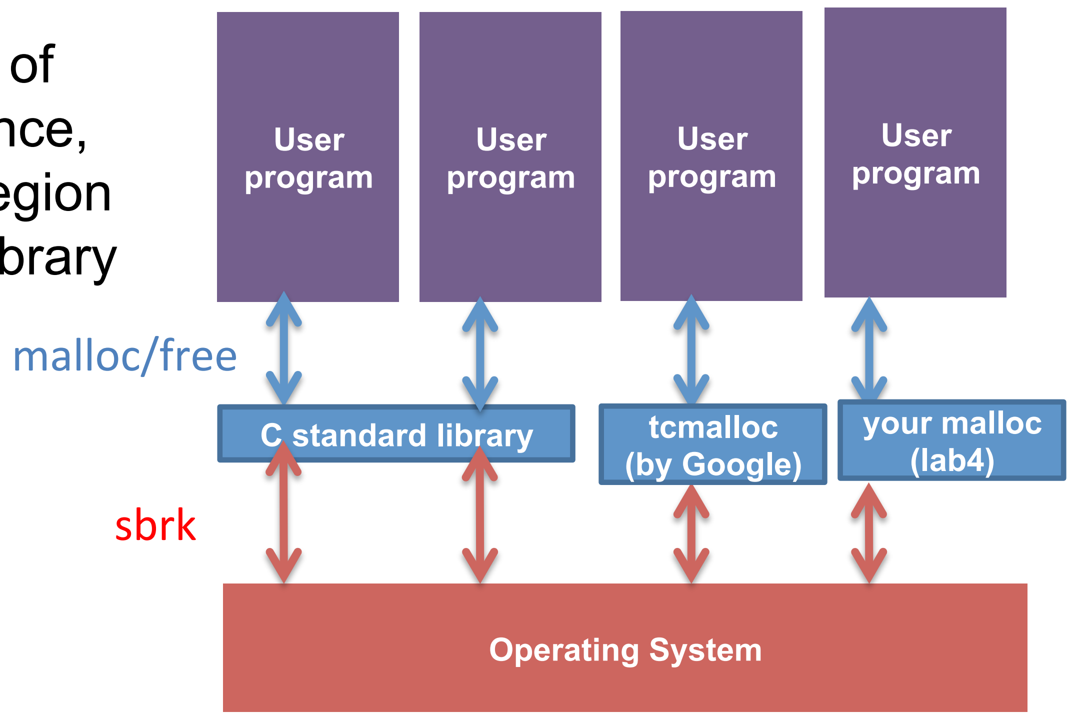
Issue II – system call has high performance cost > 10X



Dynamic allocation on heap

Question: How to effciently allocate memory on heap?

Basic idea – request a large of memory region from heap once, then manage this memory region by itself. → allocator in the library



Memory Allocator

Assumption in this lecture

- At the beginning, the allocator requests enough memory with `sbrk`

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

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, cannot be moved

Questions

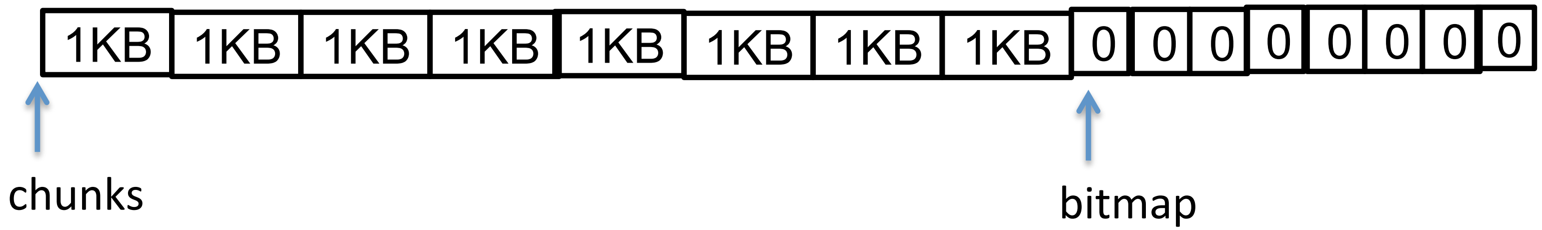
1. (Basic book-keeping) How to keep track which bytes are free and which are not?

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

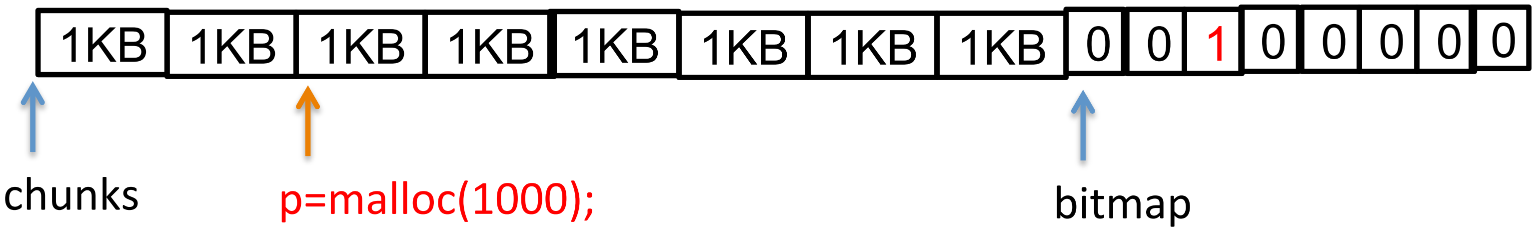
- Structure heap as n 1KB chunks + n metadata




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

void init() {
  n_chunks = 1<<10;
  sbrk(n_chunks*CHUNKSIZE + n_chunks/8);
  bitmap = heap_hi()+1 - n_chunks/8;
  chunks = (chunk *)heap_lo();
}
```

How to bookkeep? Strawman #1

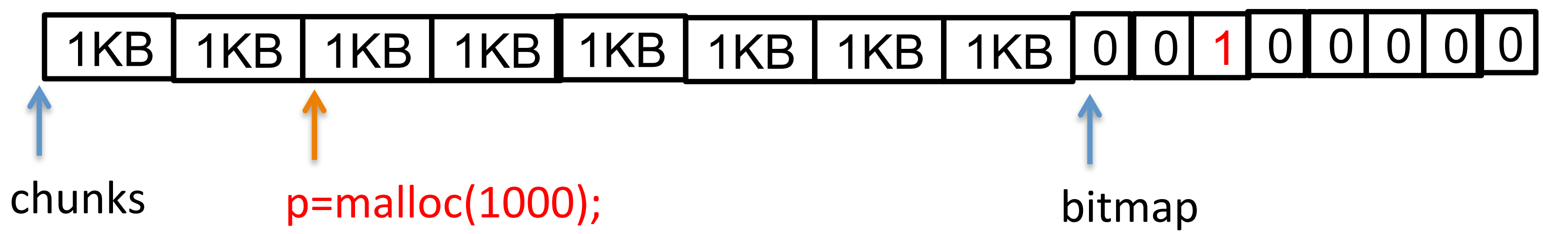



```
void *malloc(size_t sz) {
  assert(sz < CHUNKSIZE);
  size_t i = 0;
  for (; i < n_chunks; i++) {
    if !bitmap_get_pos(bitmap, i)
       break; //found a free chunk
  }

  if (i == n_chunks) //did not find a free chunk
     return NULL;

  bitmap_set_pos(bitmap, i);
  return (void *)&chunk[i];
}
```

How to bookkeep? Strawman #1




```
void free(void *p) {
  i = ((char *)p - (char *)chunks)/CHUNKSIZE;
  bitmap_unset_pos(bitmap, i);
}
```

- Problem with strawman?
  - cannot malloc more than a chunk at a time
  - cannot malloc less than a chunk

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?

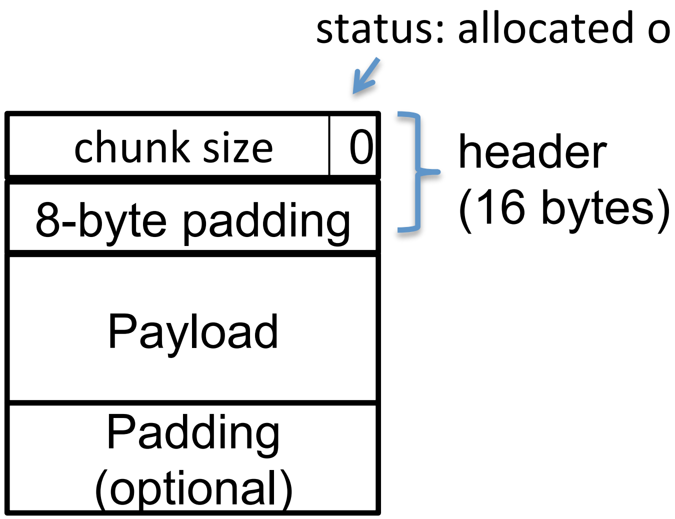
Implementing a hash table and linked list requires use of a dynamic memory allocator!

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
- Payload is 16-byte aligned
  - → Chunk size (metadata+payload) is multiple of 16
  - → Header must be also aligned to 16 bytes



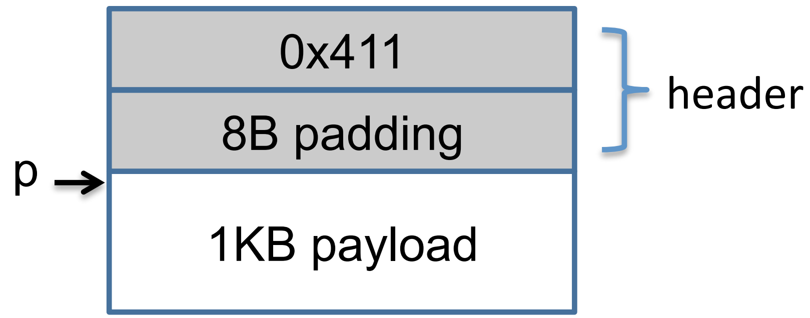
allocated: size_and_status & 0x1L
size: size_and_status & ~(0x1L)

Implicit list

Embed chunk metadata in the chunks

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

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

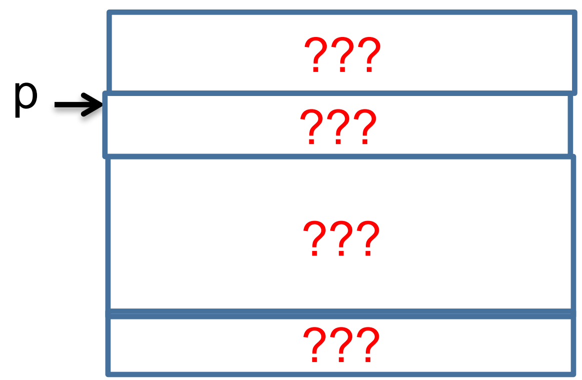


Implicit list

Embed chunk metadata in the chunks

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

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

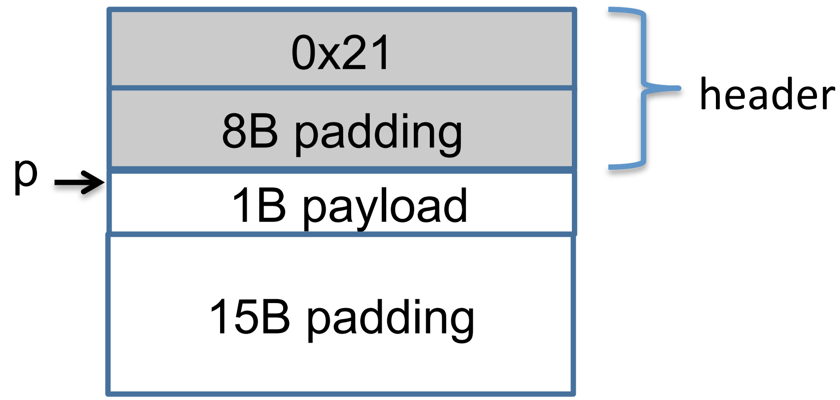


Implicit list

Embed chunk metadata in the chunks

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

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



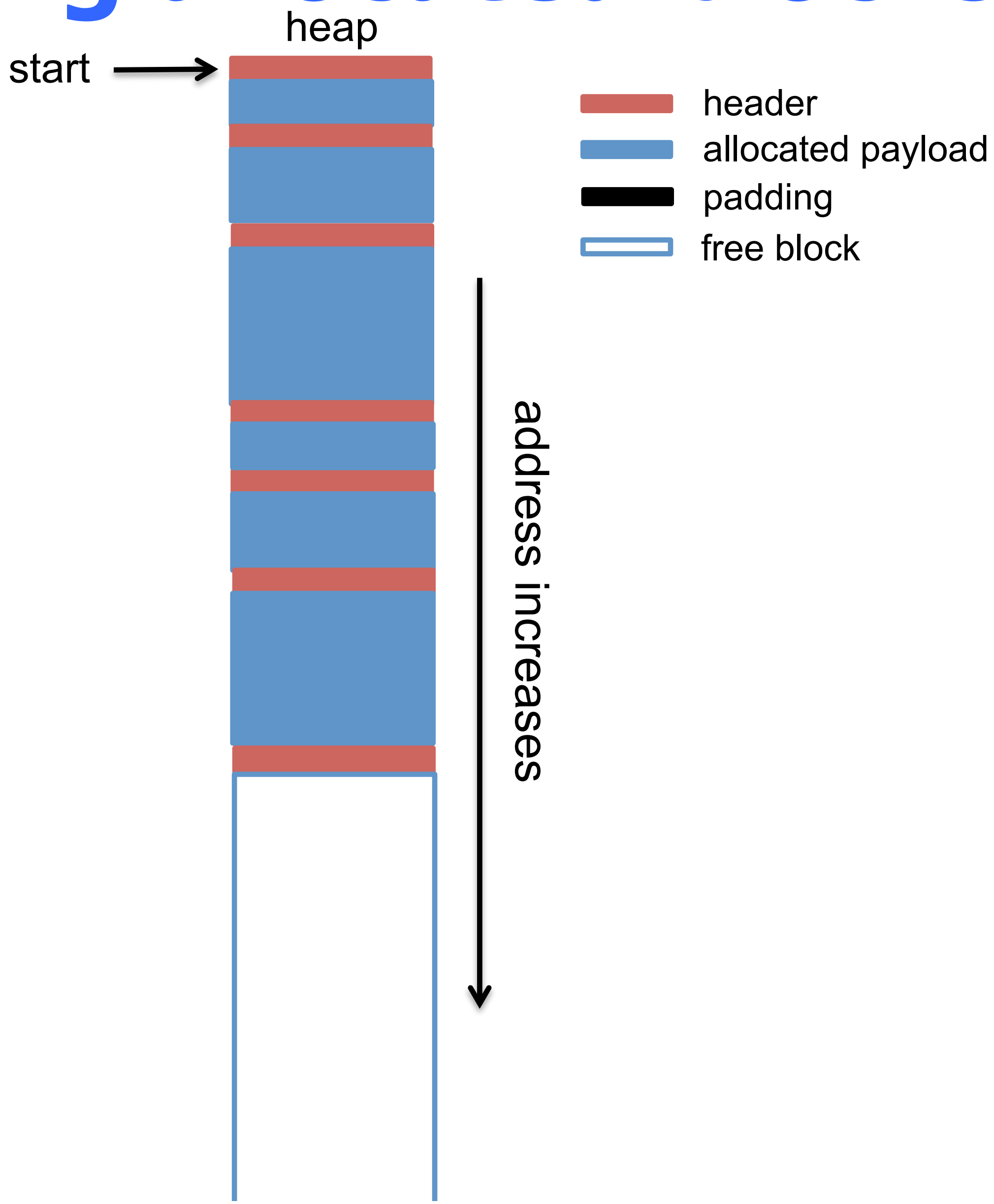
How to traverse an implicit list

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

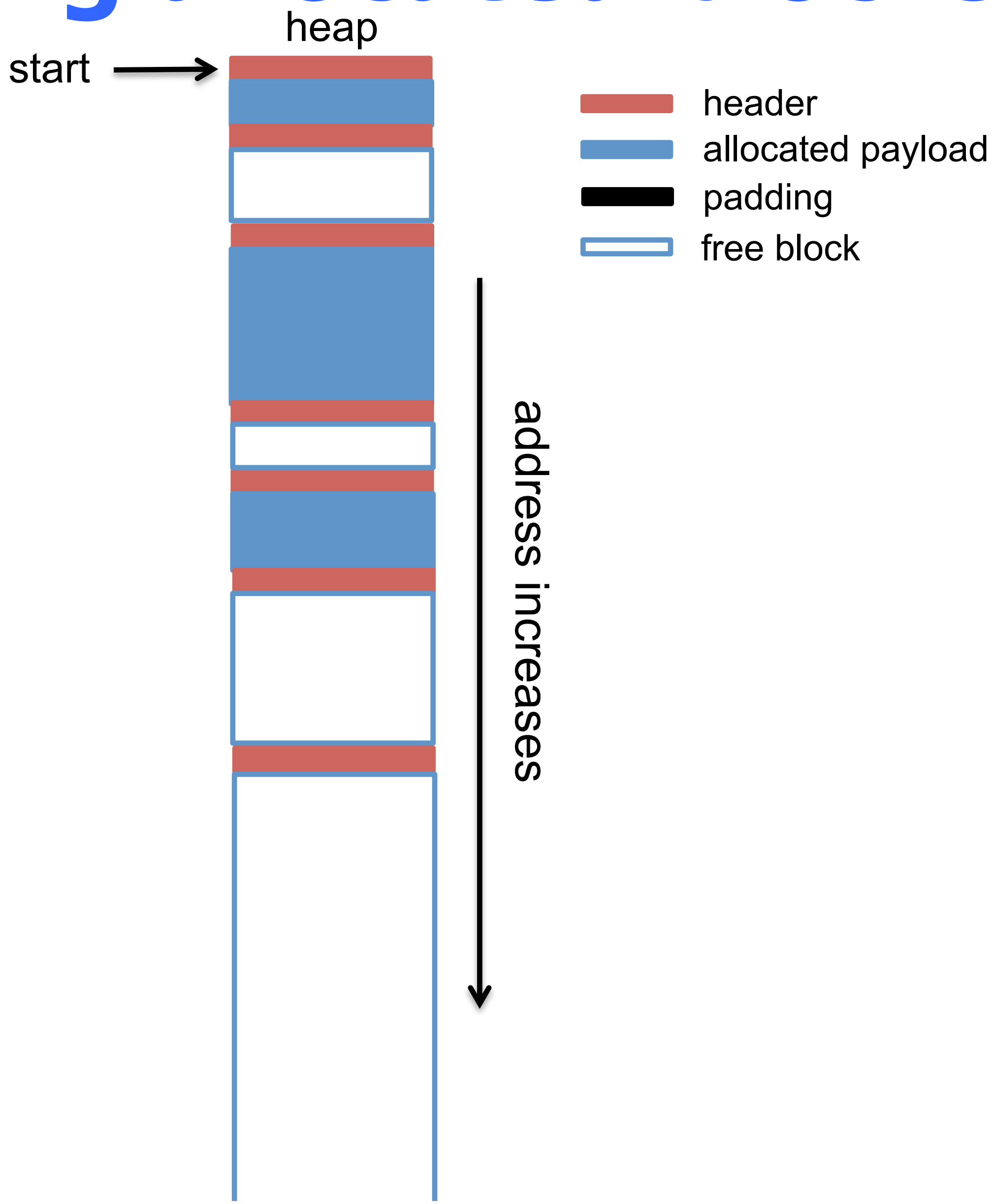
Placing allocated blocks

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



Placing allocated blocks

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



Placing allocated blocks

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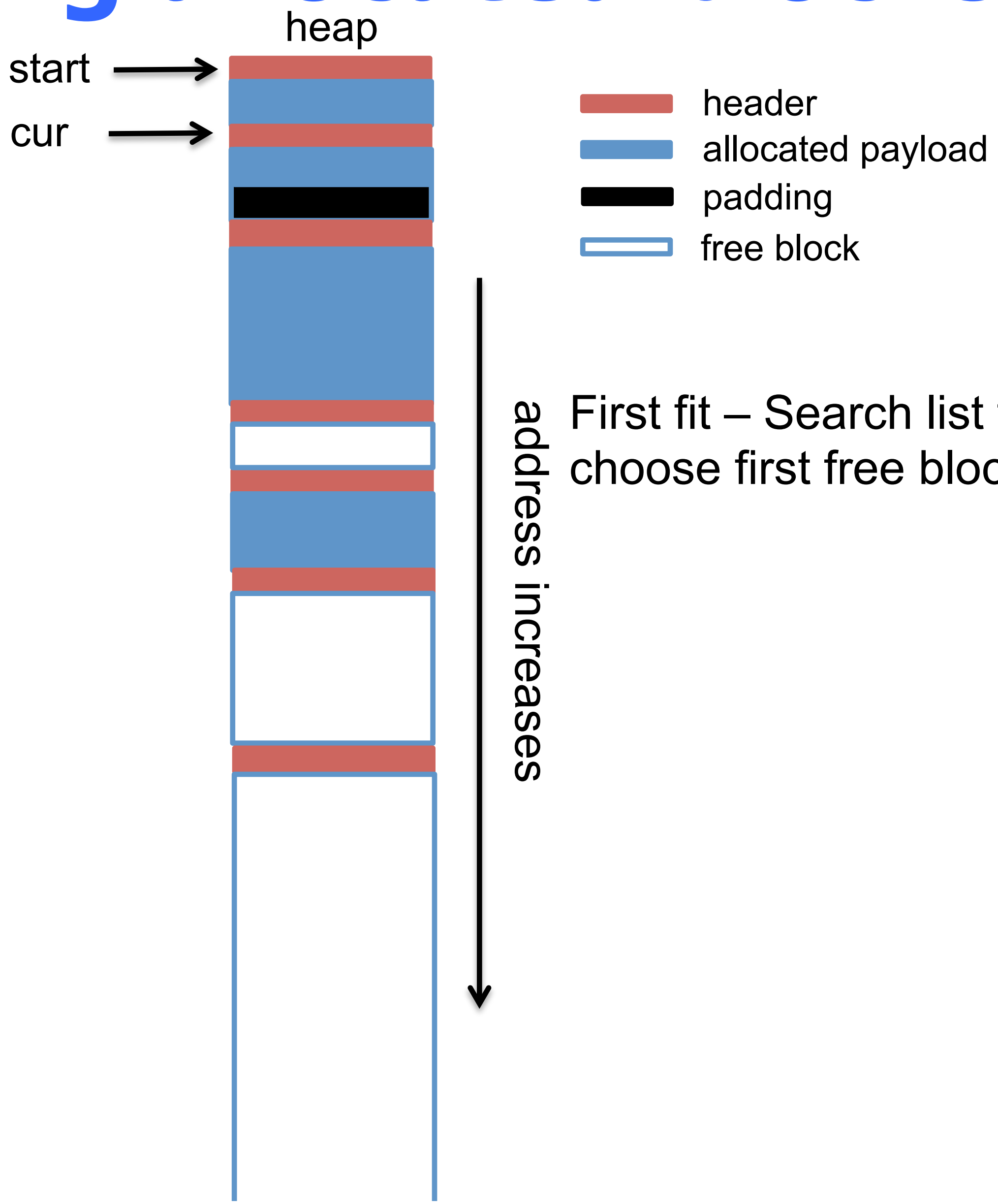
free(p2)
free(p4)
free(p6)
p7 = malloc(8)
```



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

Placing allocated blocks

```
p1 = malloc(8)
p2 = malloc(24)
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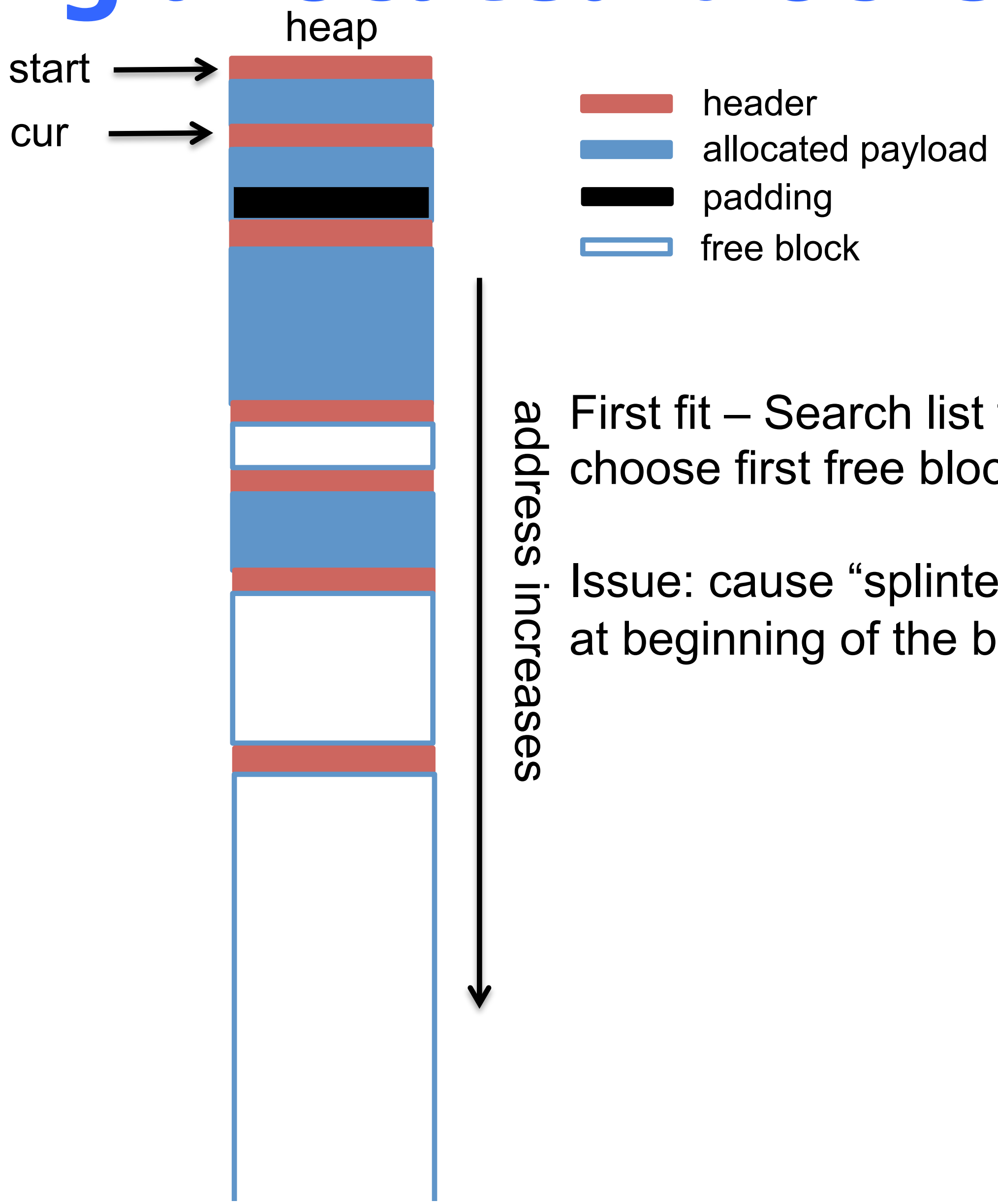
p7 = malloc(8)
```



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

Issue: cause “splinters/fragments” at beginning of the buffer

Placing allocated blocks

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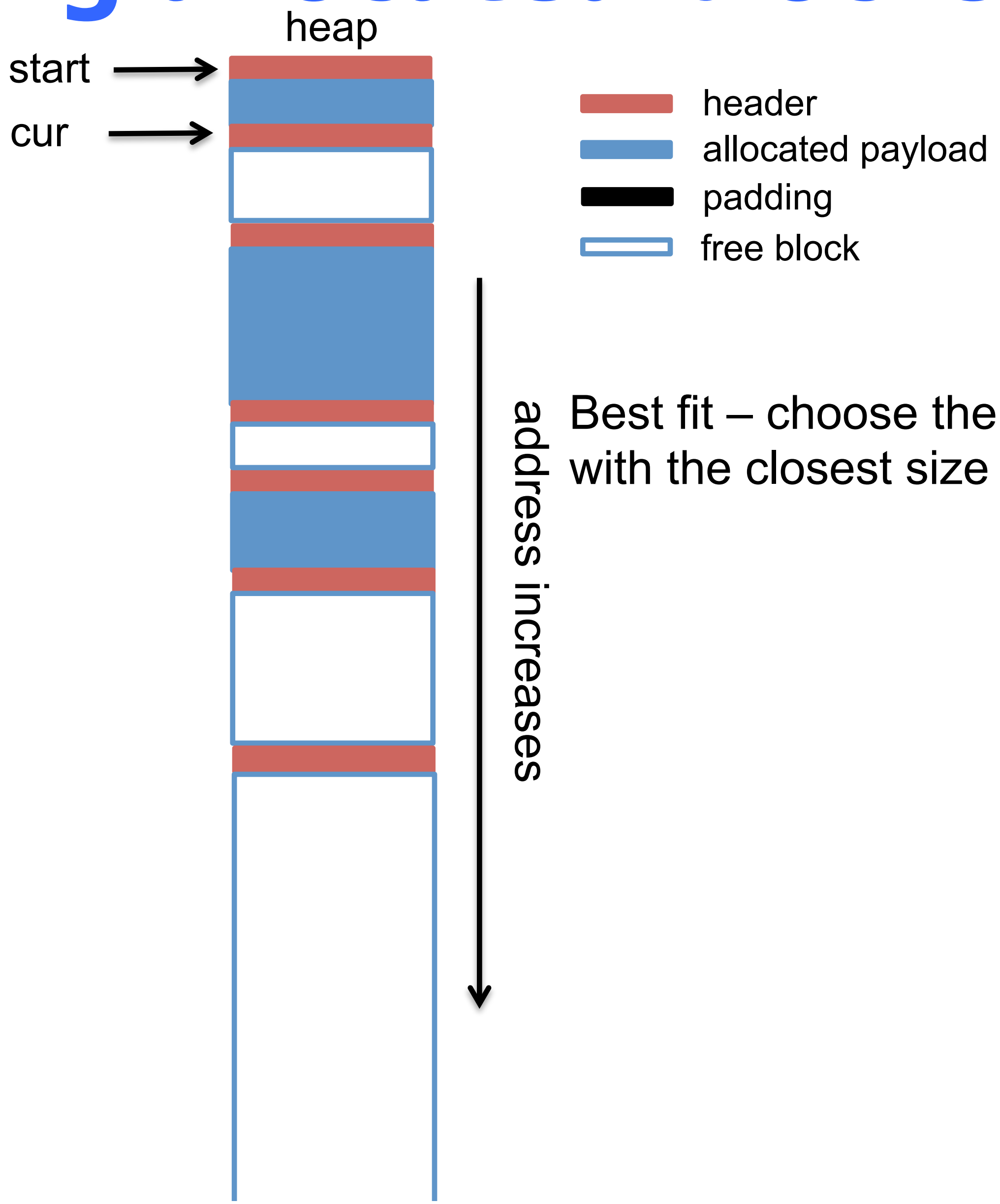
free(p6)
p7 = malloc(8)
```



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

Placing allocated blocks

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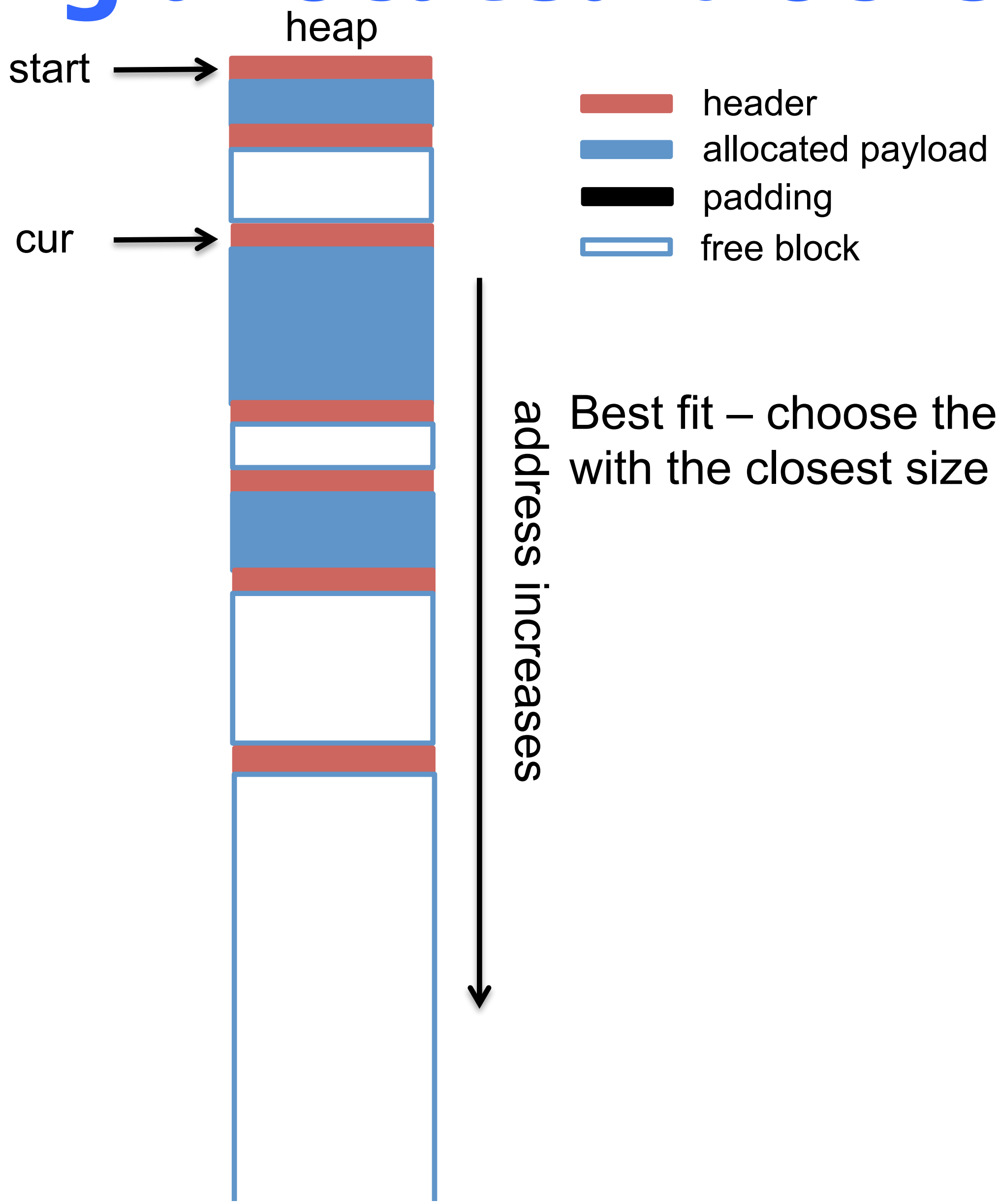

Best fit – choose the free block with the closest size that fits

Placing allocated blocks

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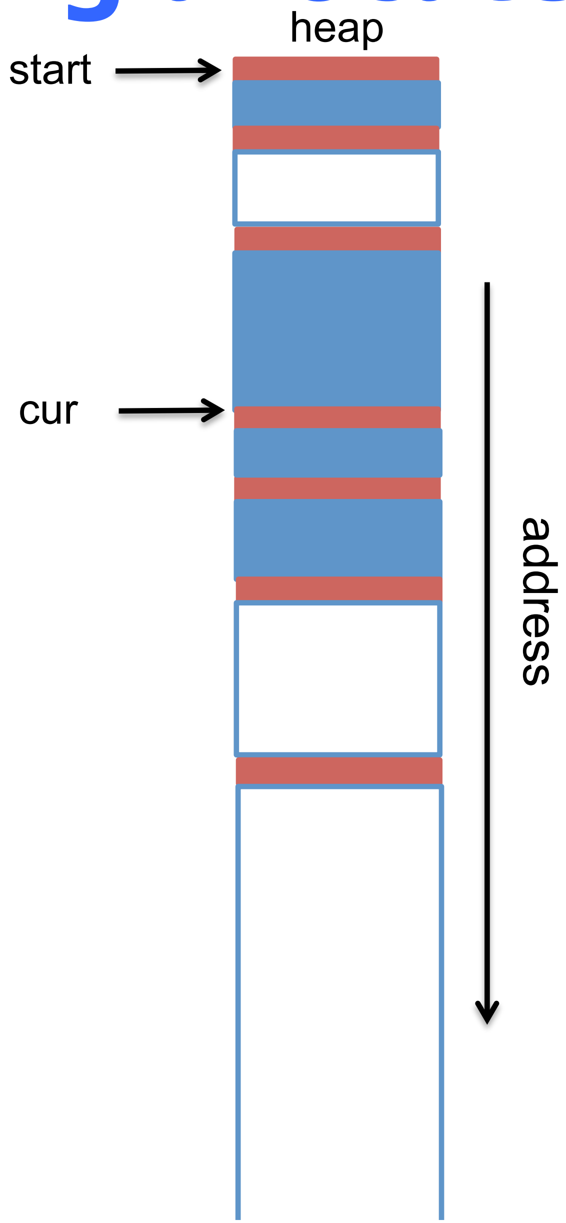
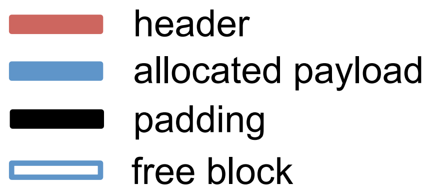


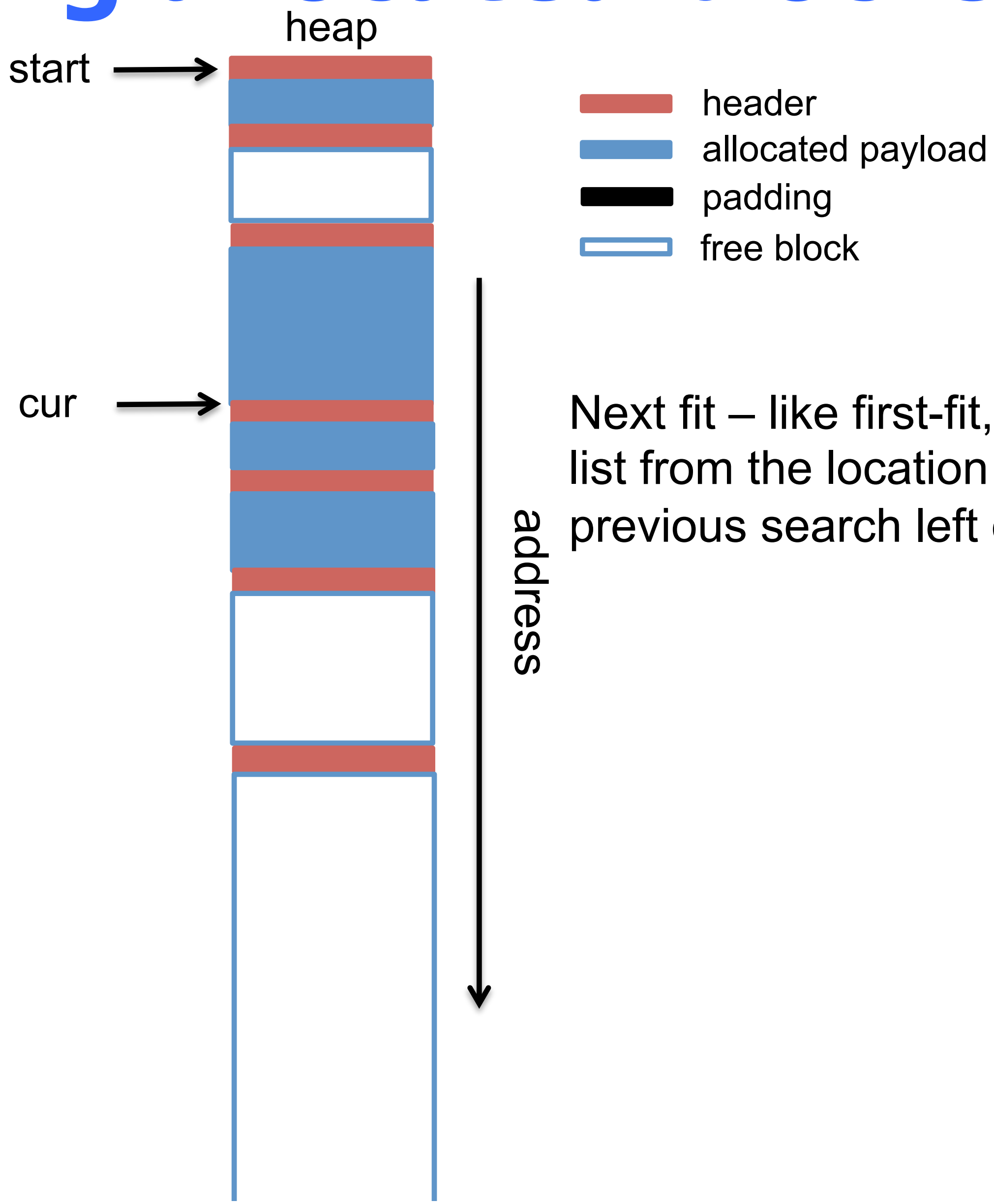


Best fit – Search list from beginning choose first free block that fits

Best fit keeps fragments small, but typically run slower than first fit.

Placing allocated blocks

```
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 list from the location where previous search left off.

Placing allocated blocks

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p1 = malloc(8)
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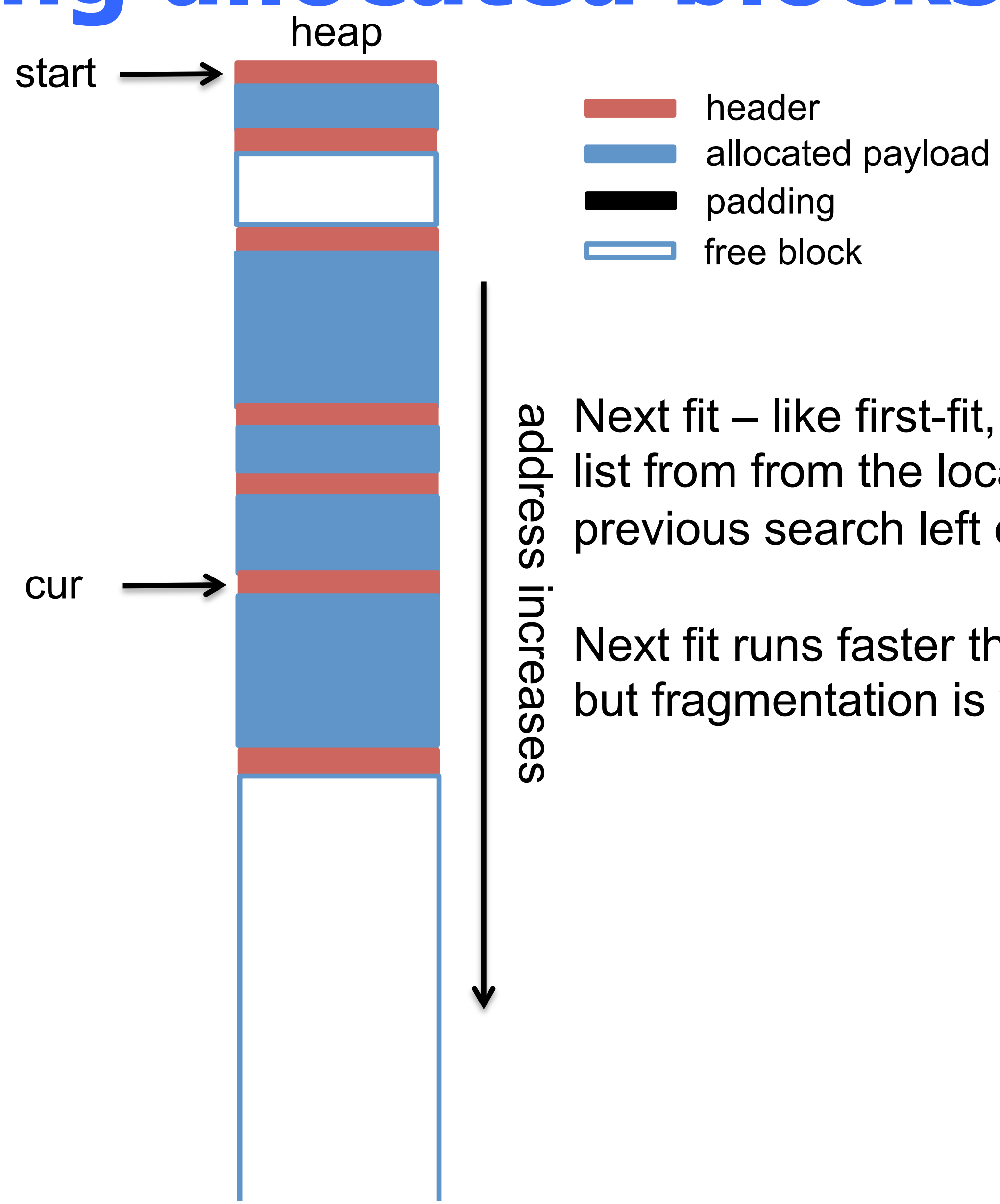

Next fit – like first-fit, but search list from from the location where previous search left off.

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

Placing allocated blocks

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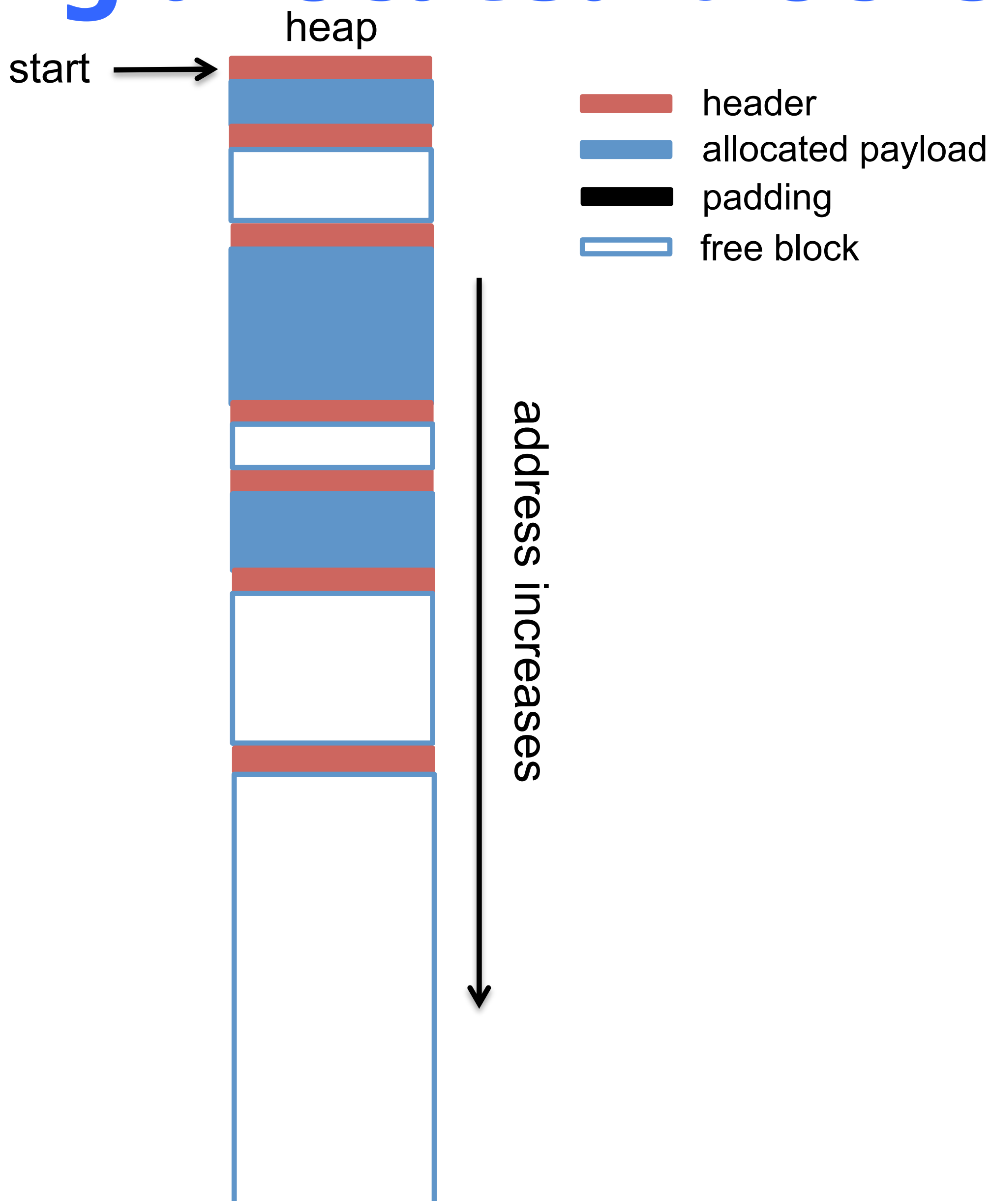
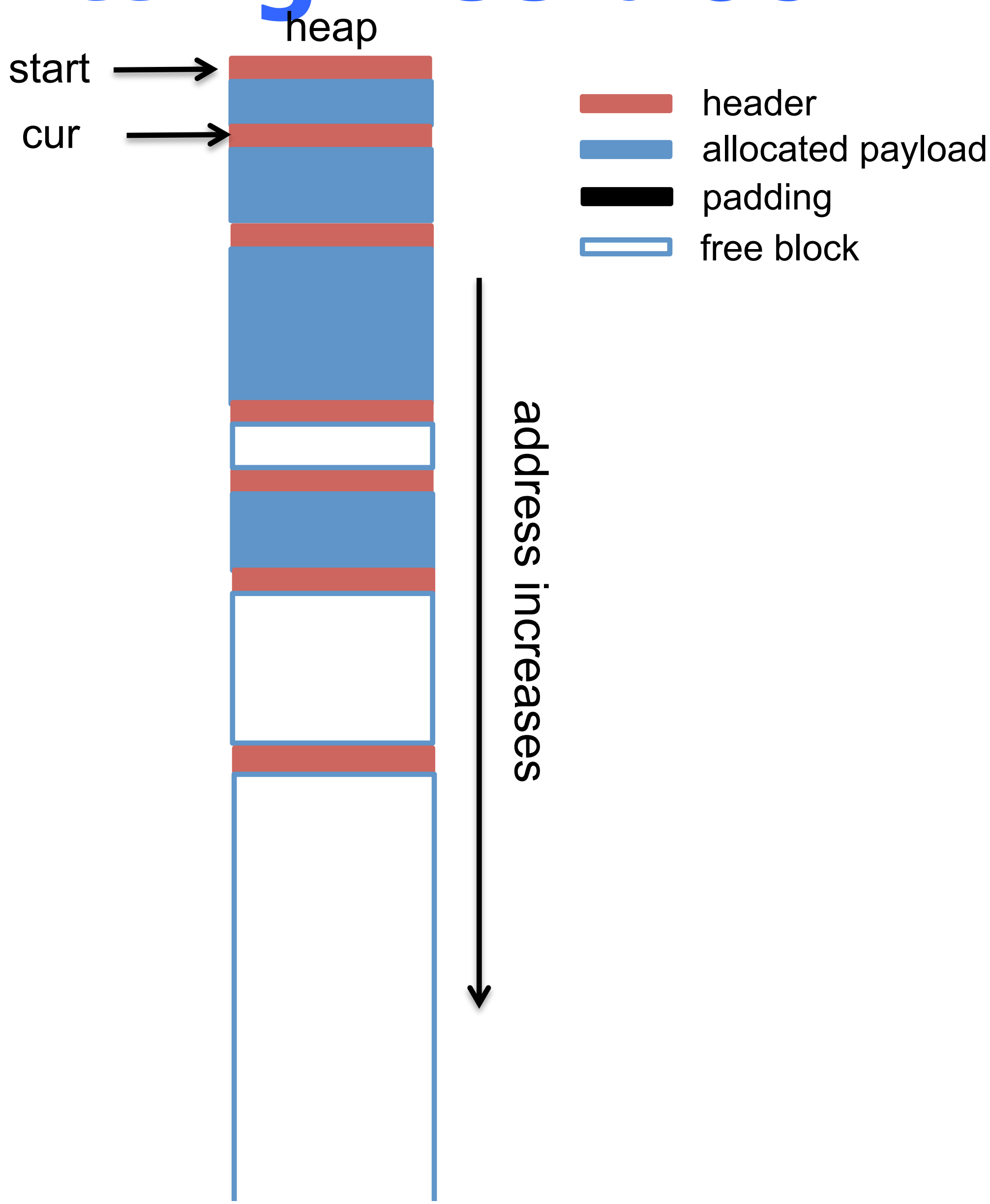
free(p6)
p7 = malloc(24)
p8 = malloc(24)
```



Splitting free block

```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(16)
p6 = malloc(48)
free(p2)
free(p4)
free(p6)
p7 = malloc(16)
p8 = malloc(16)
```



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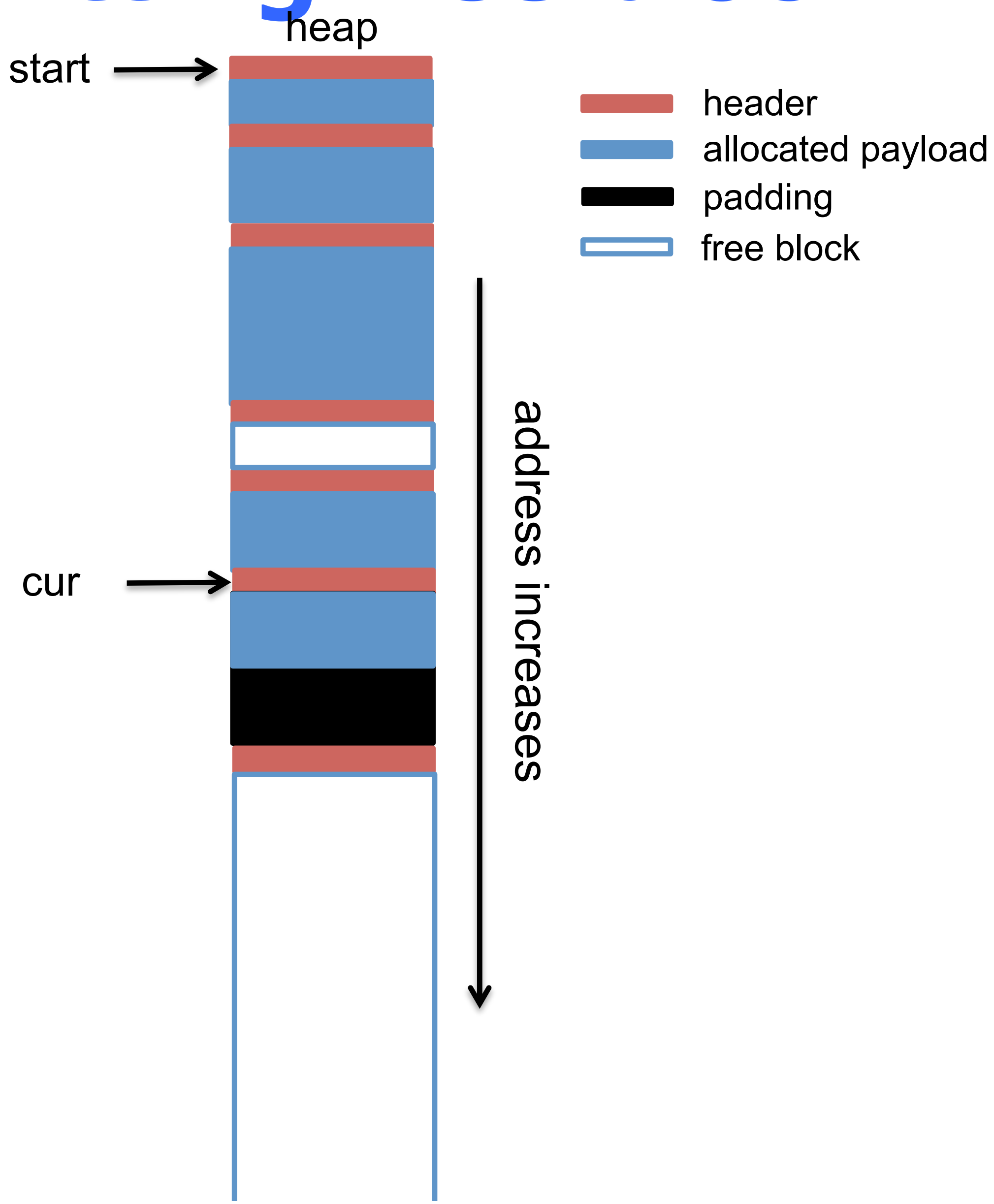

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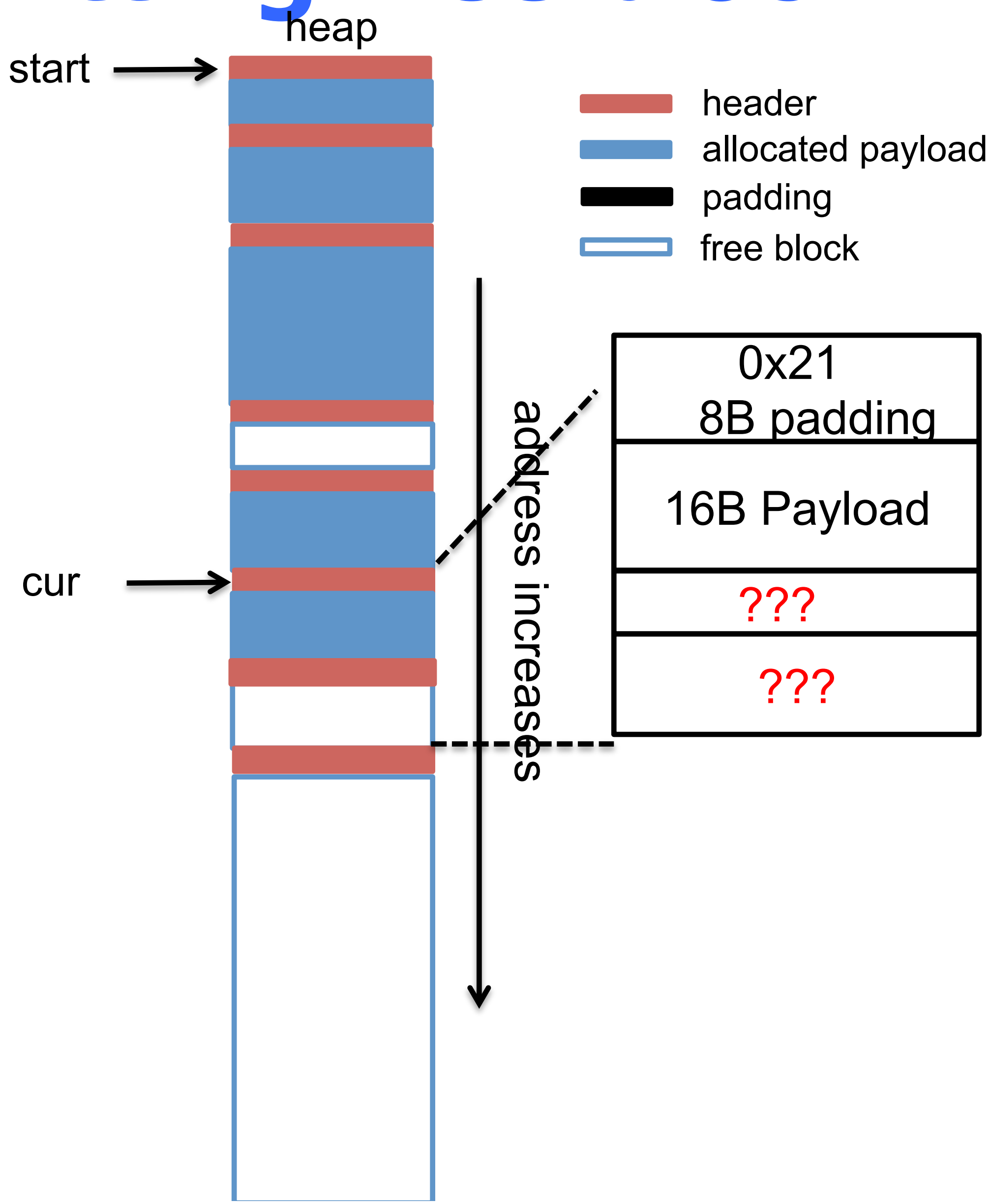

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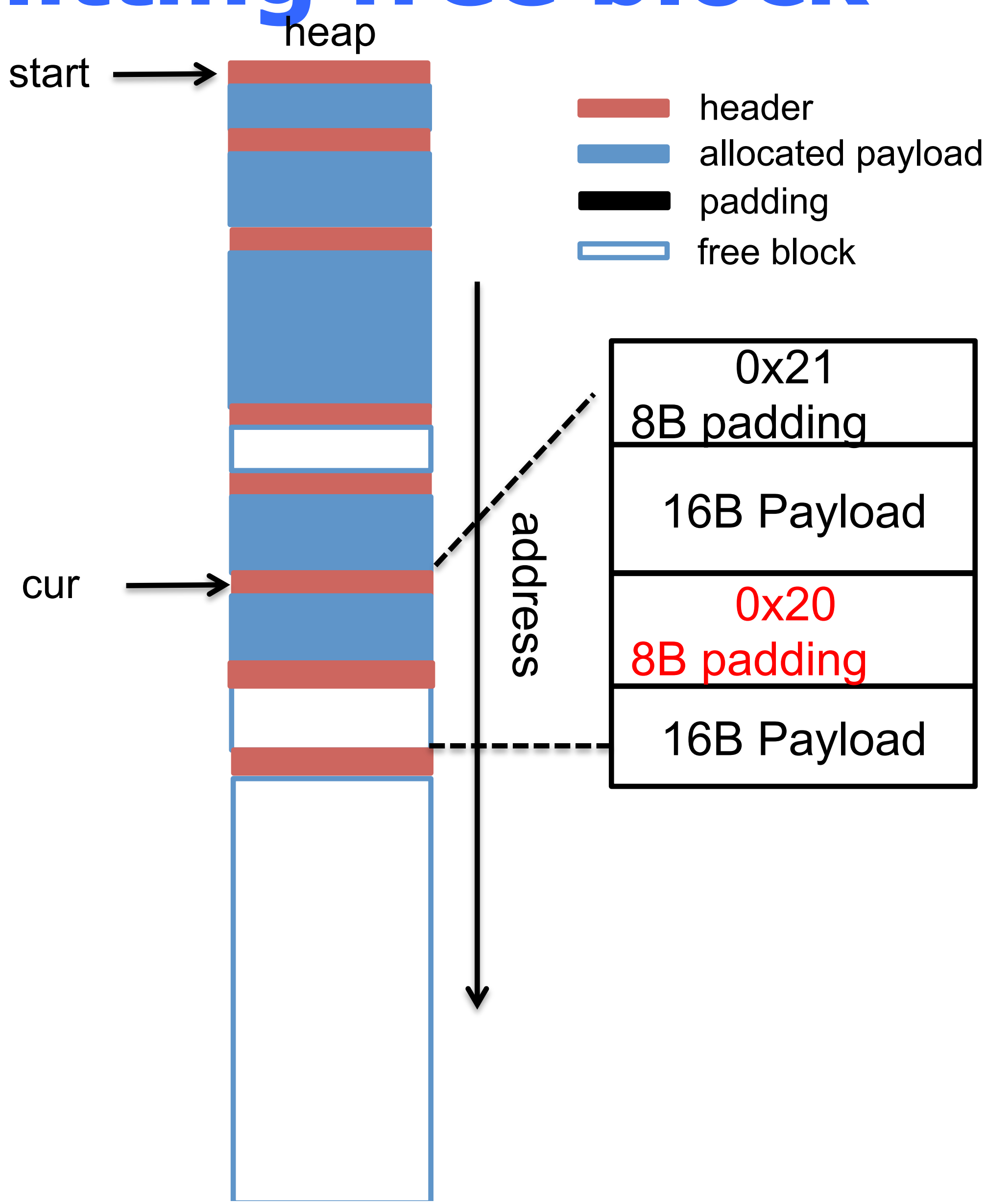

Coalescing free blocks

```
p1 = malloc(8)
p2 = malloc(24)
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p4 = malloc(8)
p5 = malloc(16)
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free(p2)
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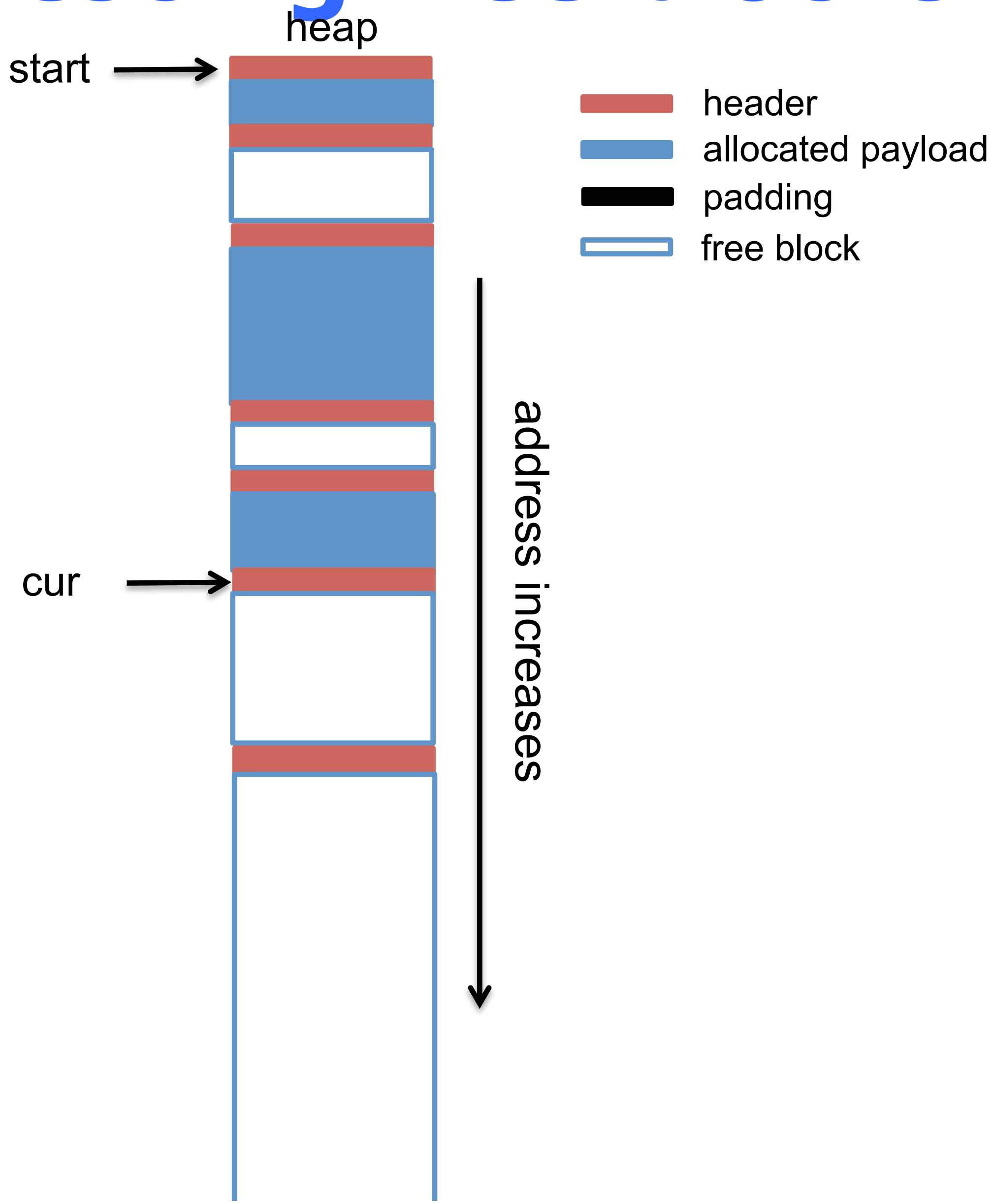
free(p6)
free(p5)
```



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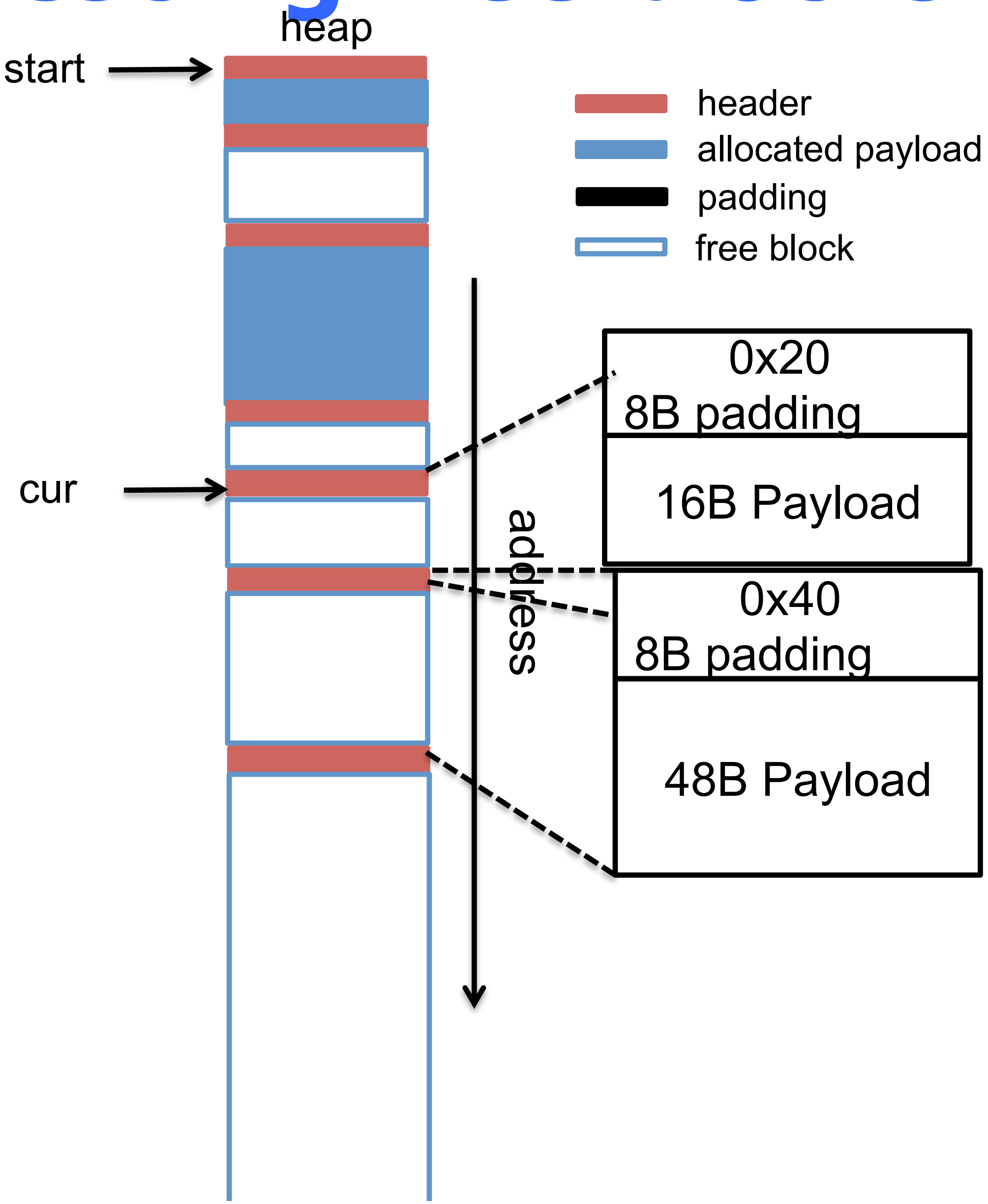

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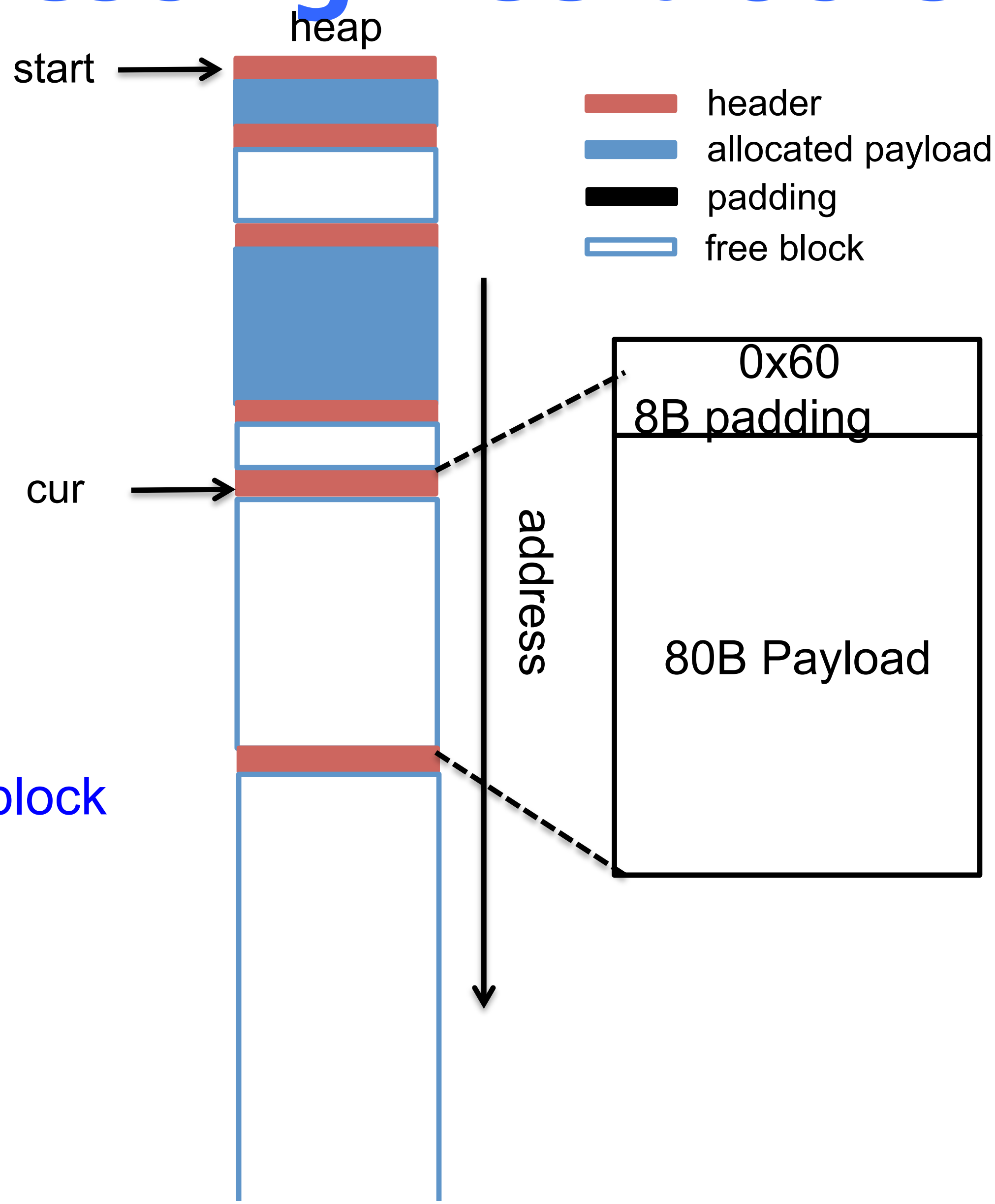

Coalescing with next block

Coalescing free blocks

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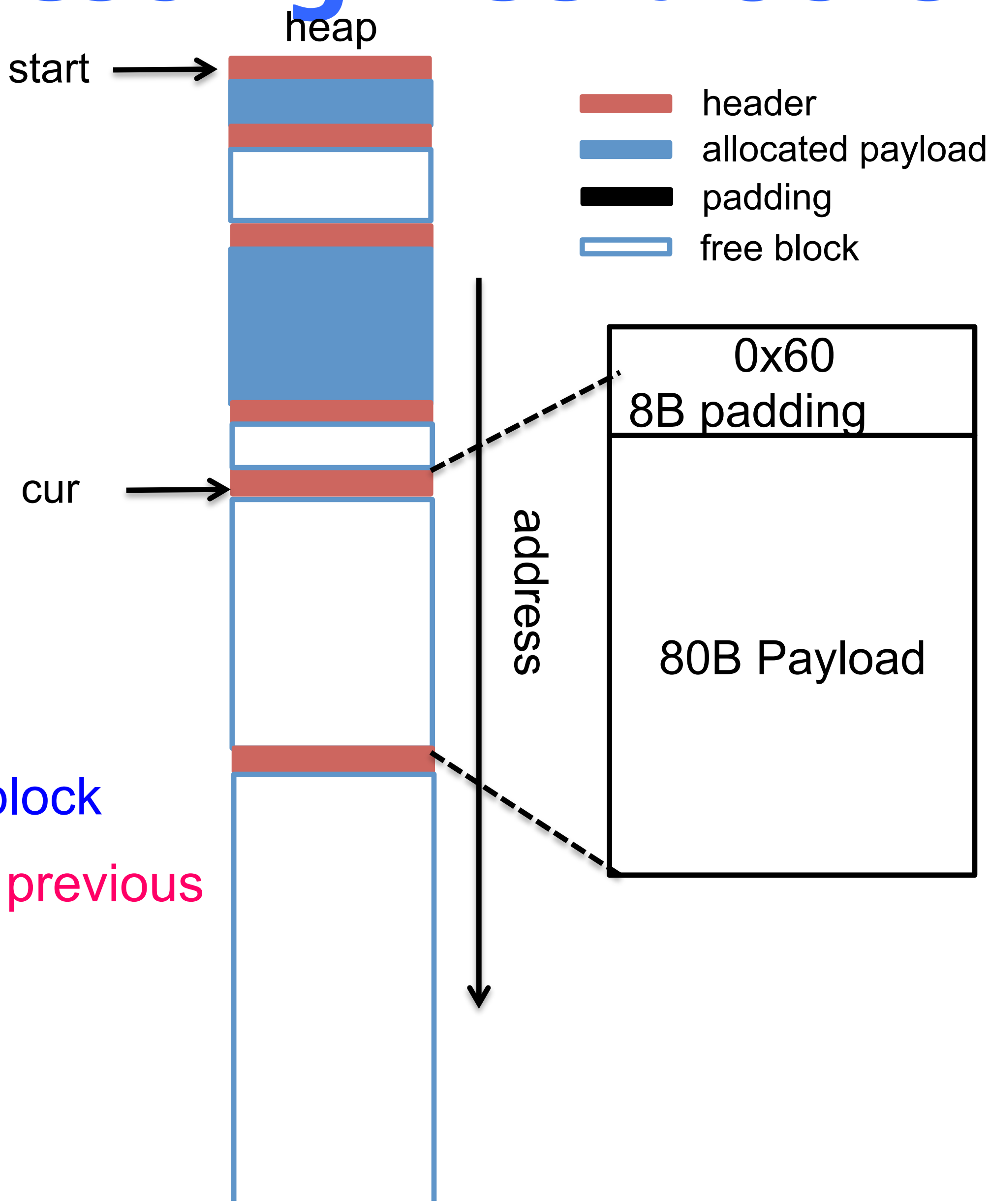
```



Coalescing with next block

How to coalesce with previous block?

Coalescing free blocks

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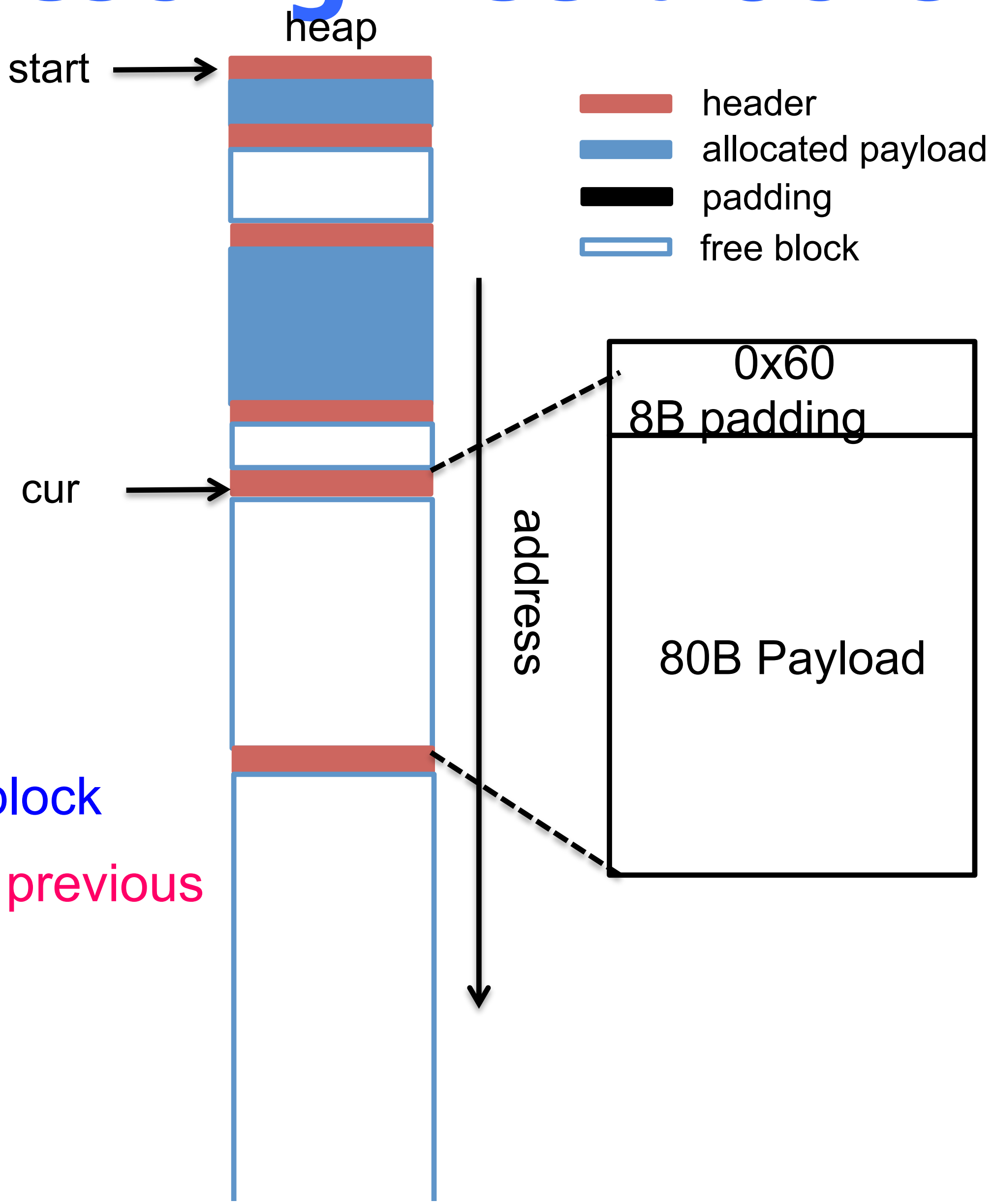
p4 = malloc(8)
p5 = malloc(16)
p6 = malloc(48)
free(p2)
free(p4)
free(p6)
free(p5)
```



Coalescing with next block

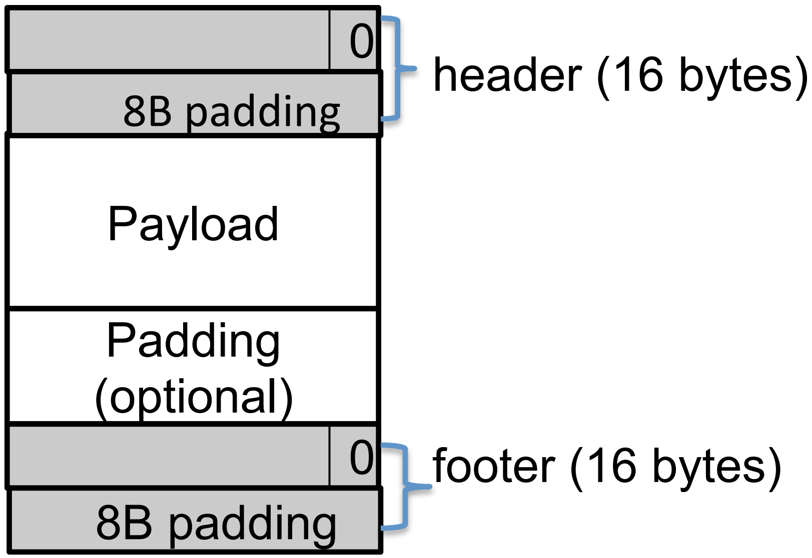
How to coalesce with previous block?

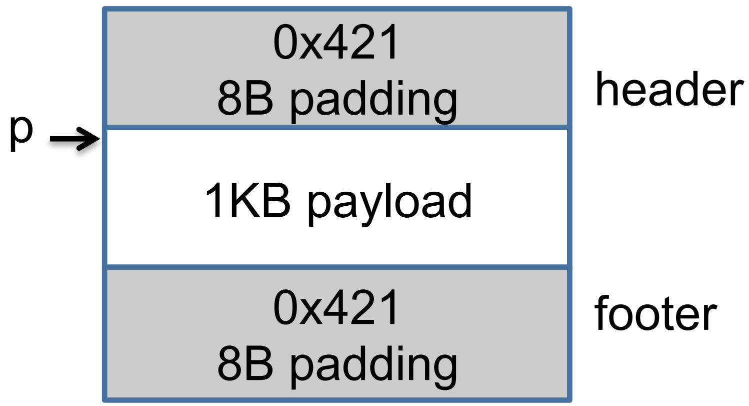
-- search from start?

Coalescing free blocks

Embed chunk metadata in the chunks

- Chunk has a header storing size and status
- Payload is 16-byte aligned
  - Easiest way to align is to make chunk size, header and footer all 16-byte aligned.

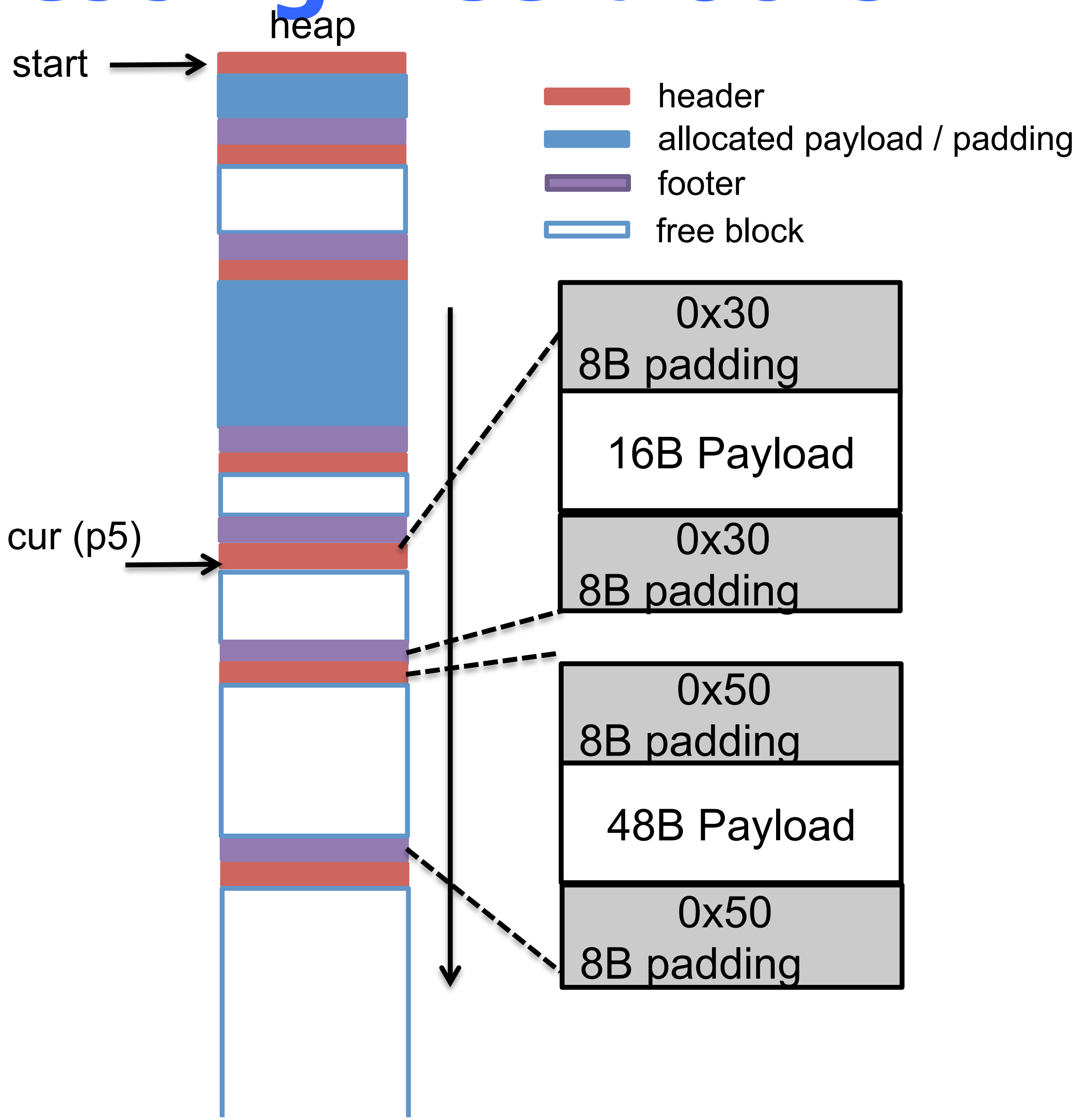





```
p   = malloc(1024)
```

Coalescing free blocks

```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(16)
p6 = malloc(48)
free(p2)
free(p4)
free(p6)
free(p5)
```



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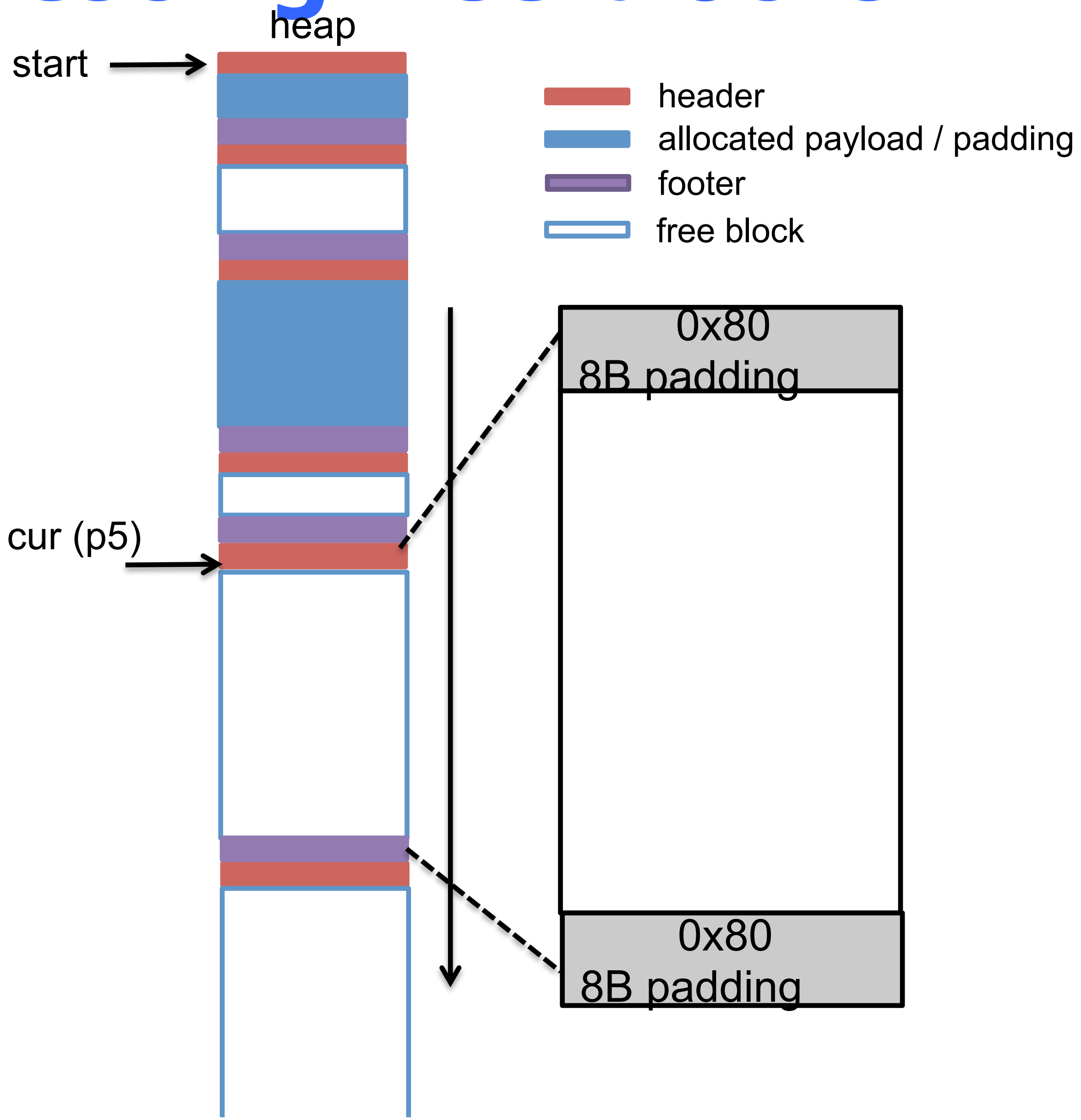


Explicit free lists

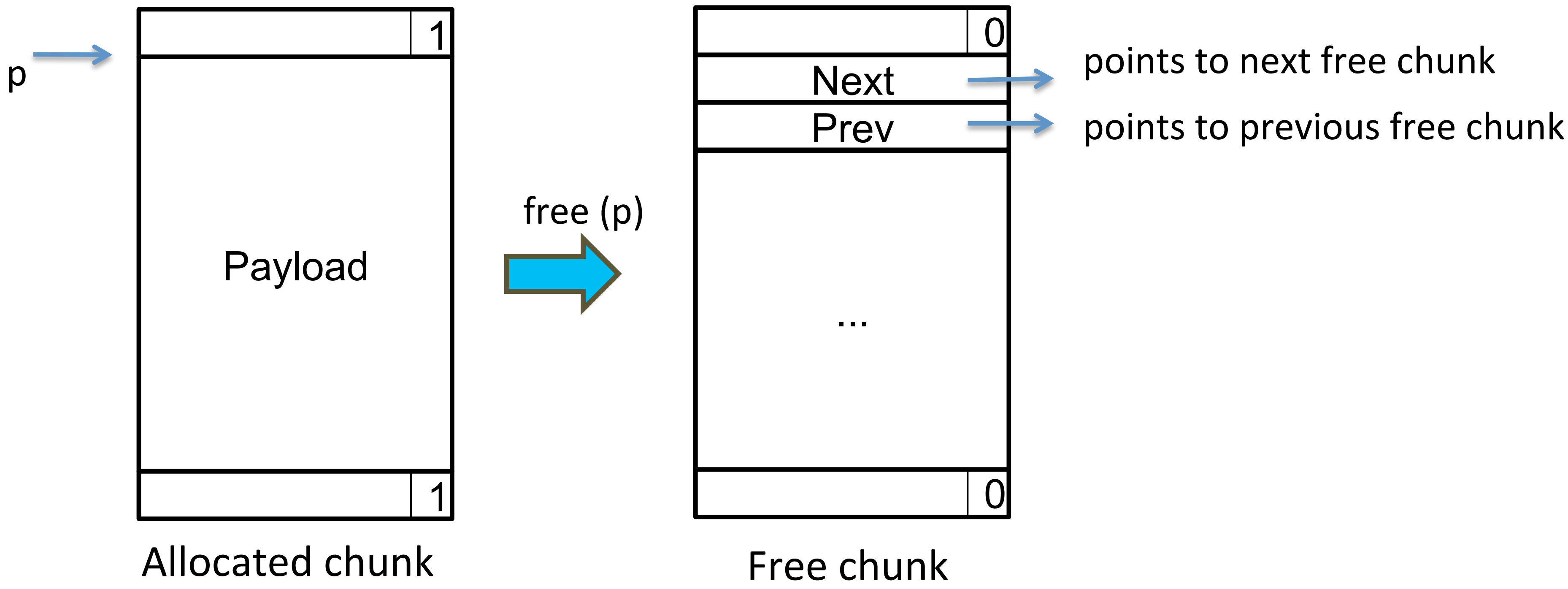
Problems of implicit list:

– 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 traverse allocated blocks only. 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

How to traverse an explicit list

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

free_header *freelist;
void init() {
  //starts with a list of one free chunk
}
void traverse_explicit_list() {
   free_hdr *f = freelist;
   while (f!=NULL) {
       bool allocated = get_status(f->common_header.size_n_status);
       size_t csz = get_chunksz(f->common_header.size_n_status);
       f = f->next;
   }
}
```

Allocation from an explicit list

```
void *malloc(size_t size) {
    free_header *f;
    f = get_freechunk(freelist, size);

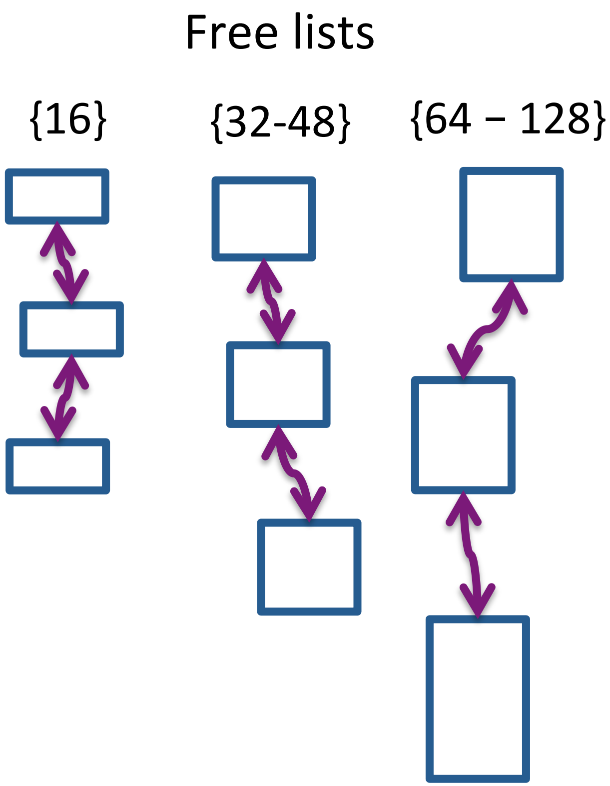
    delete_from_linked_list(freelist, f);
    set_status(f->header.size_n_status); //set footer too if there’s one

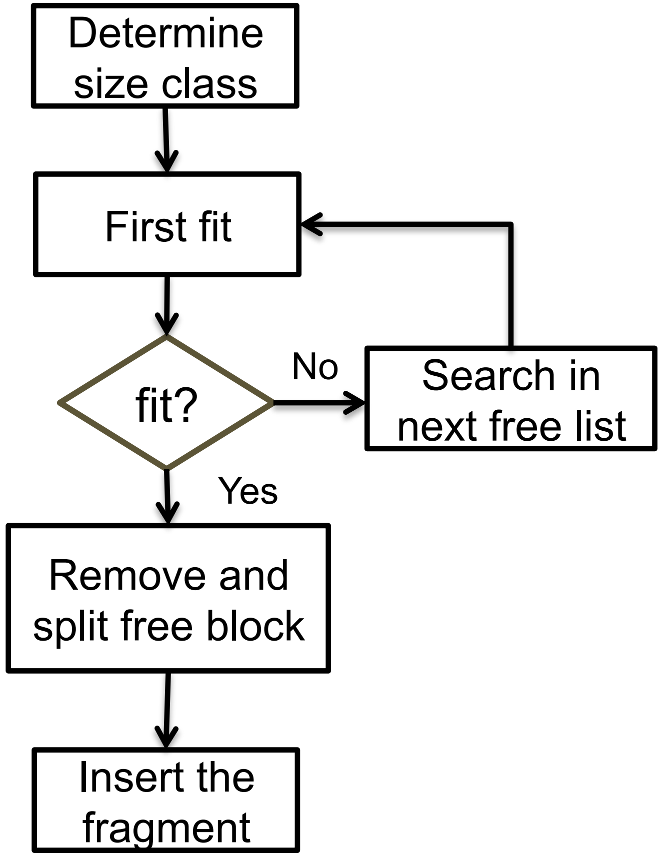
    return (void *)(((char *)f)+sizeof(f->header));
}
```

Segregated list

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

Segregated list





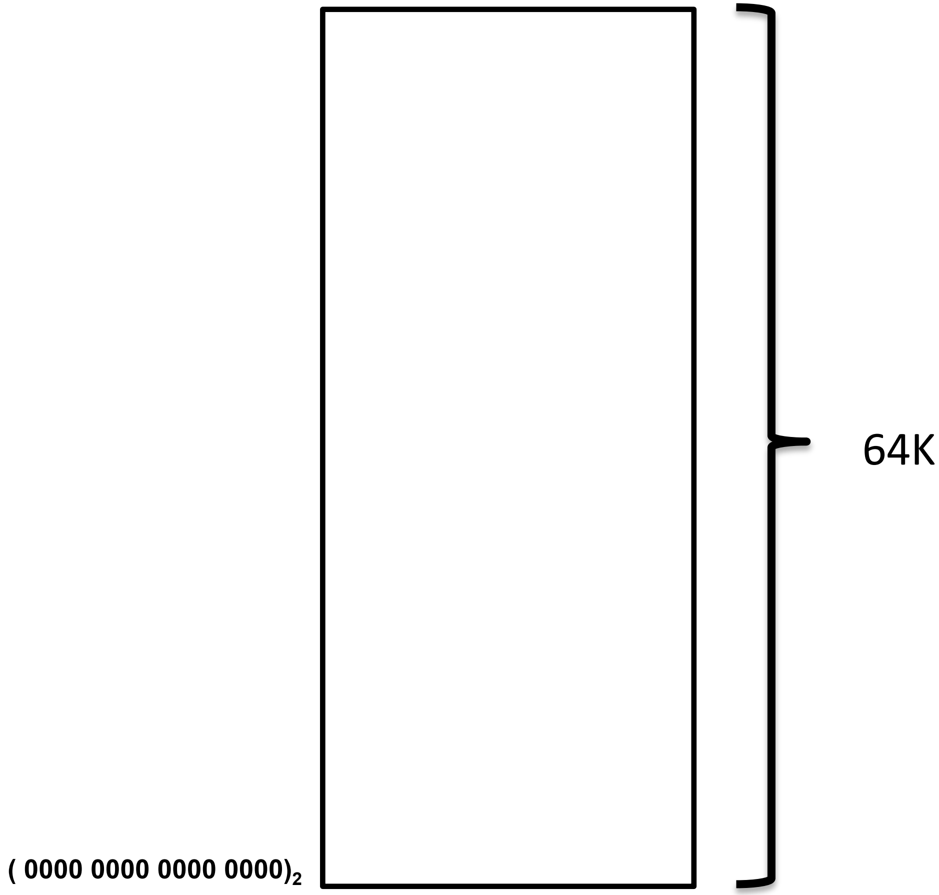
Buddy System

Adopted by Linux kernel and jemalloc

This lecture

- A simplified binary buddy allocator

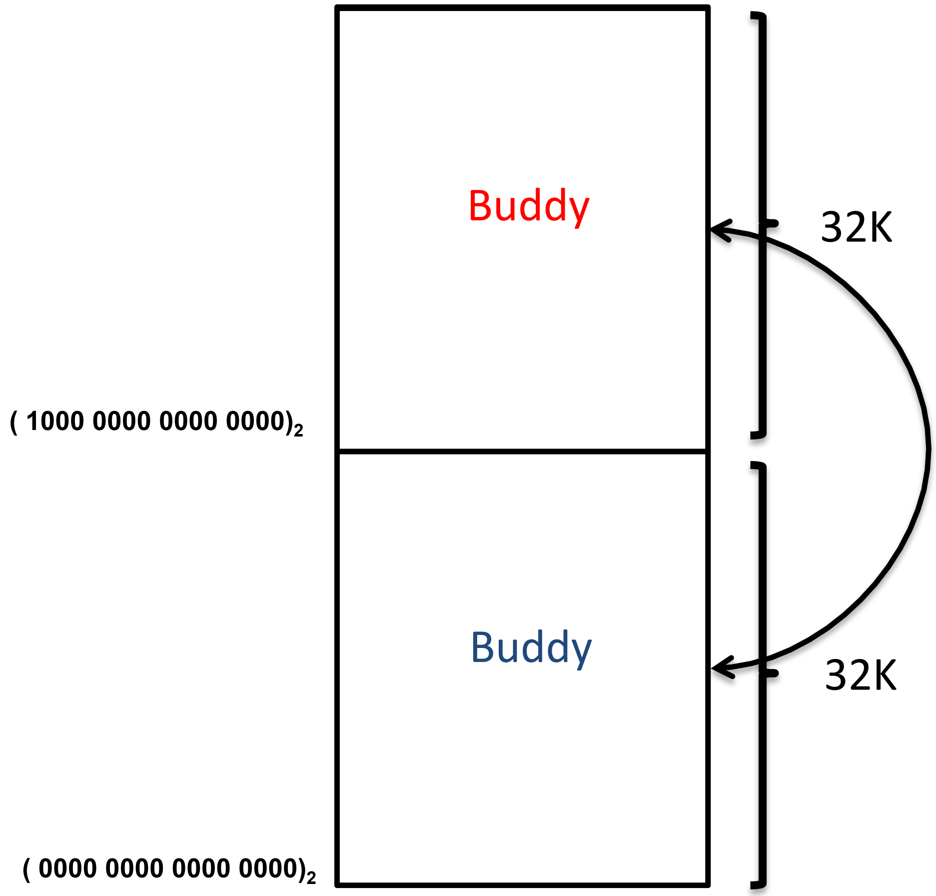
Binary buddy system



Binary buddy system

Split

- Split exactly in half



Binary buddy system

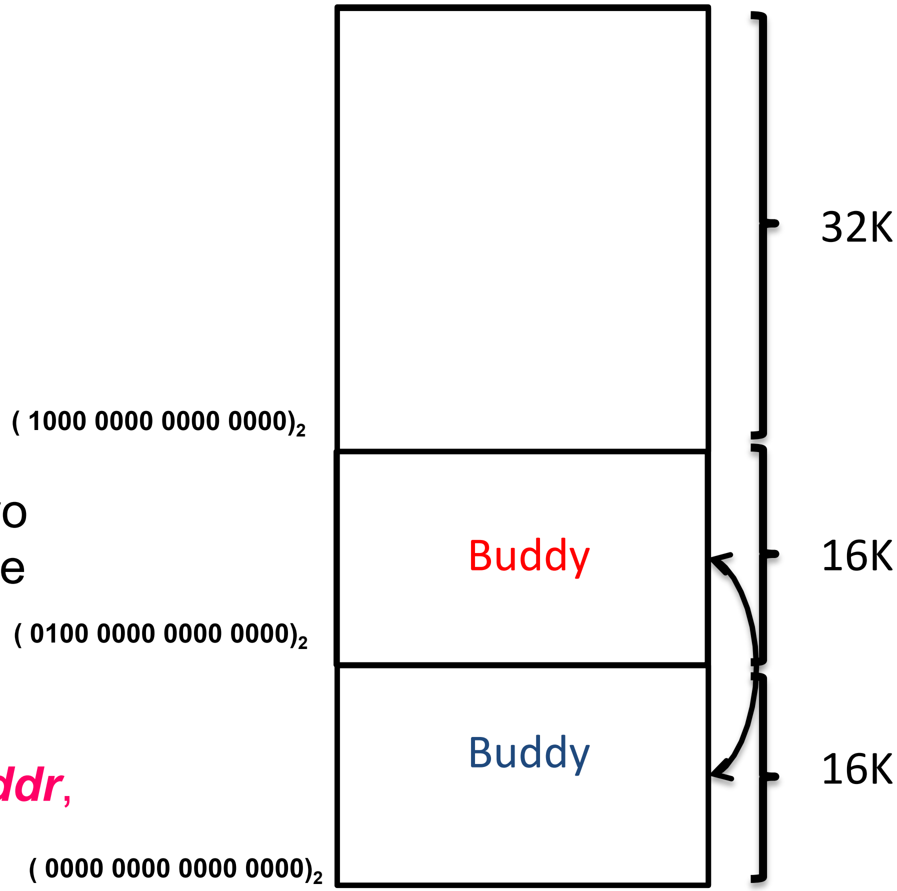
Split

- Split exactly in half
- Each half is the buddy of the other

Address

- Block of size 2^n begin at memory addresses where the ***n*** least significant bits are zero
- When a block of size 2^{n+1} is split into two blocks of size 2^n, the addresses of these two blocks will differ in exactly one bit, bit **n**.

If a block of size 2^n begins at address ***addr***, what is its buddy address and size?



Binary buddy system

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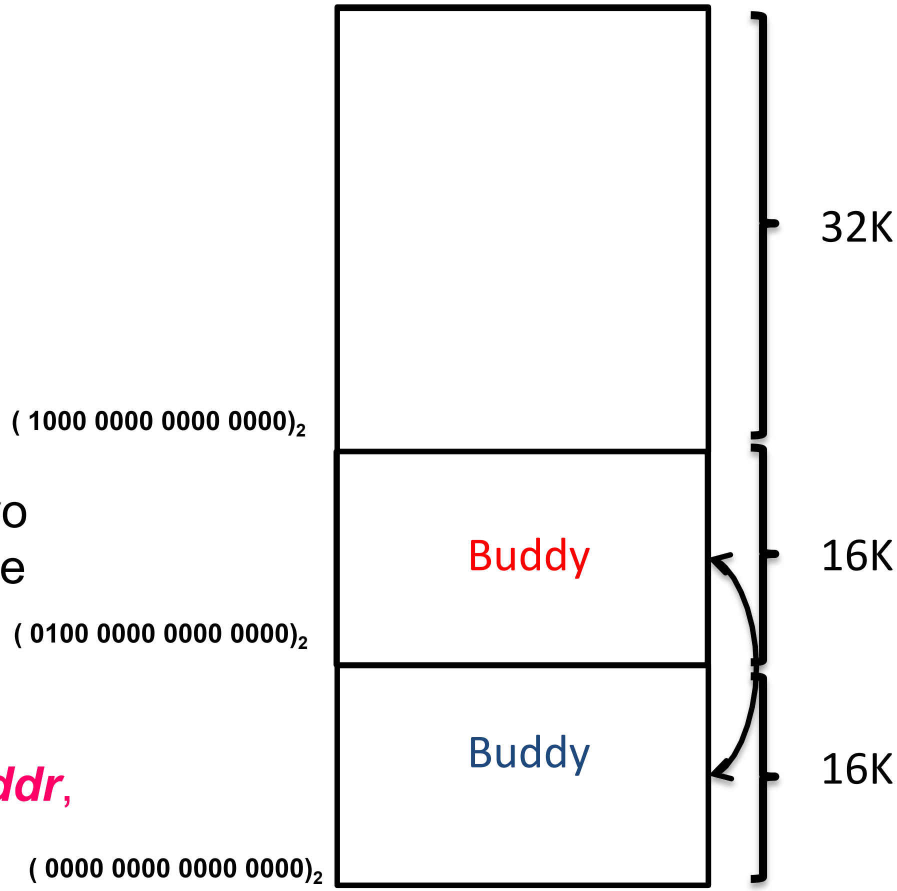
- Block of size 2^{n} begin at memory addresses where the ***n*** least significant bits are zero
- When a block of size 2^{n+1} is split into two blocks of size 2^{n}, the addresses of these two blocks will differ in exactly one bit, bit **n**.

If a block of size 2^{n} begins at address ***addr***, what is its buddy address and size?
addr of buddy = addr ^ (1<<n)

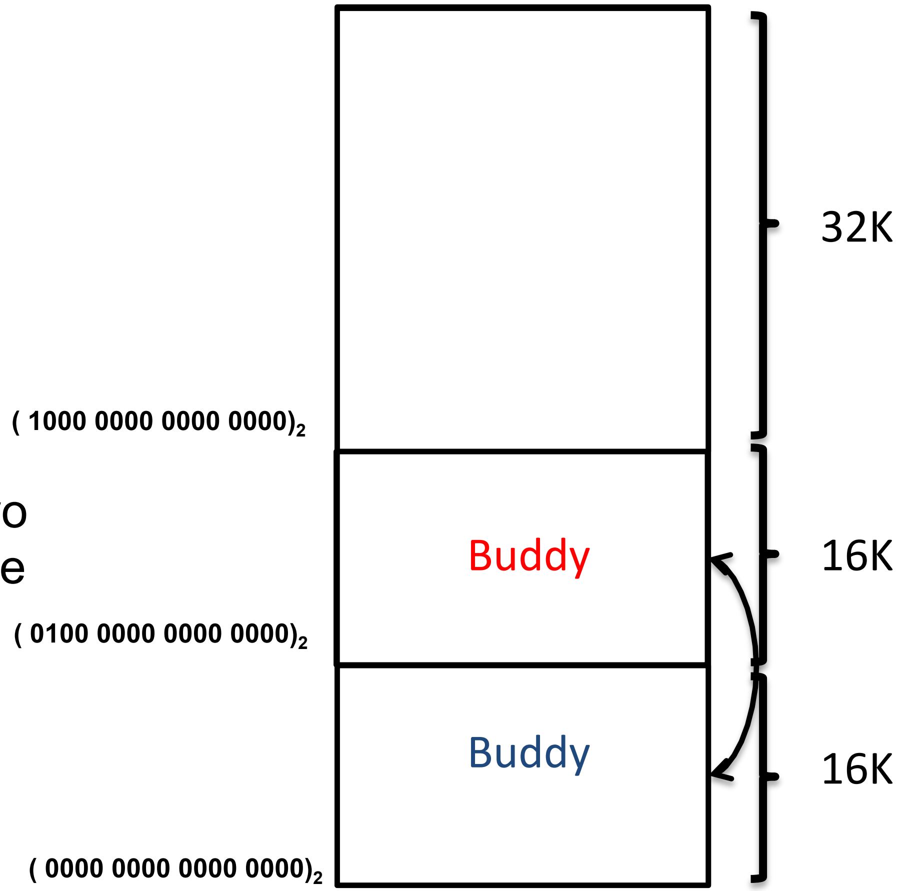


Binary buddy system

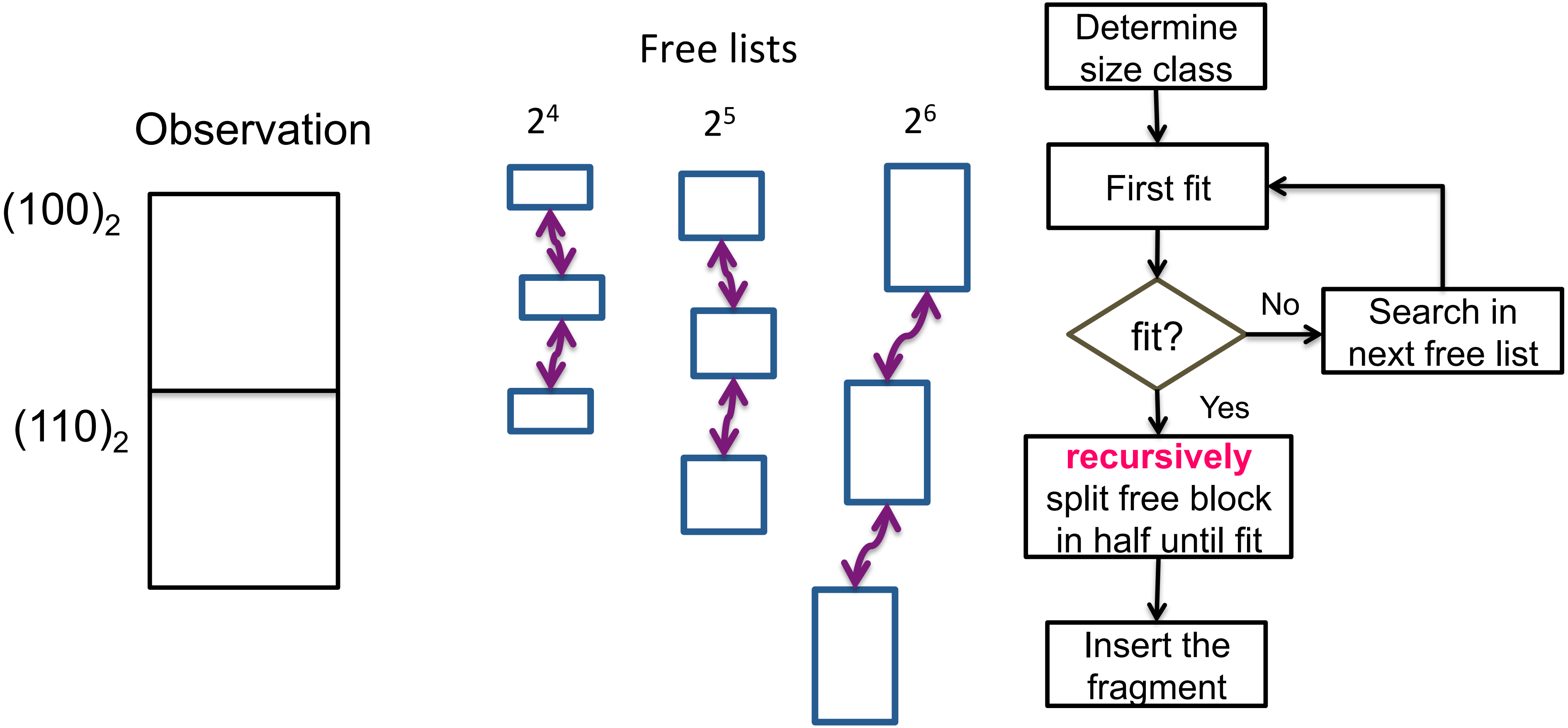
Split
- Split exactly in half
- Each half is the buddy of the other

Address
- Block of size 2^n begin at memory addresses where the n least significant bits are zero
- When a block of size 2^{n+1} is split into two blocks of size 2^n, the addresses of these two blocks will differ in exactly one bit, bit **n**.

Combine
- only combine a block with its buddy



Buddy system



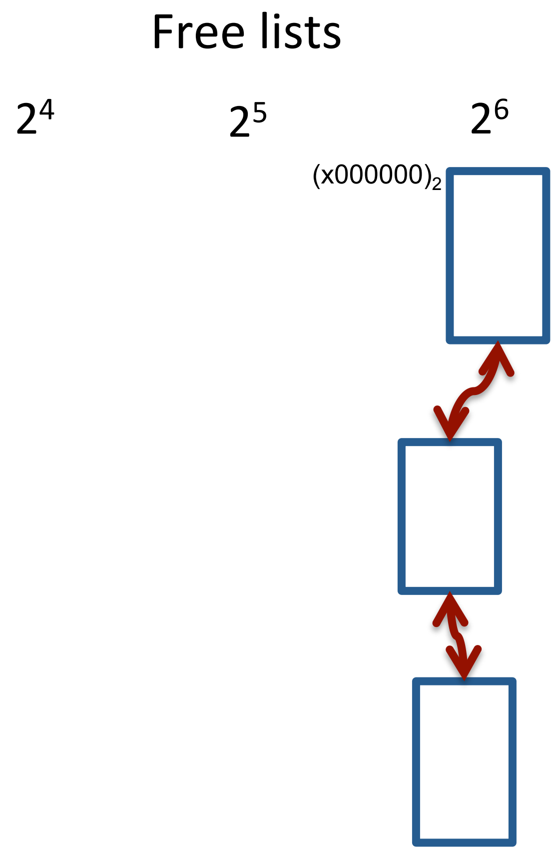
Each list has the same size of blocks which is a power of 2.

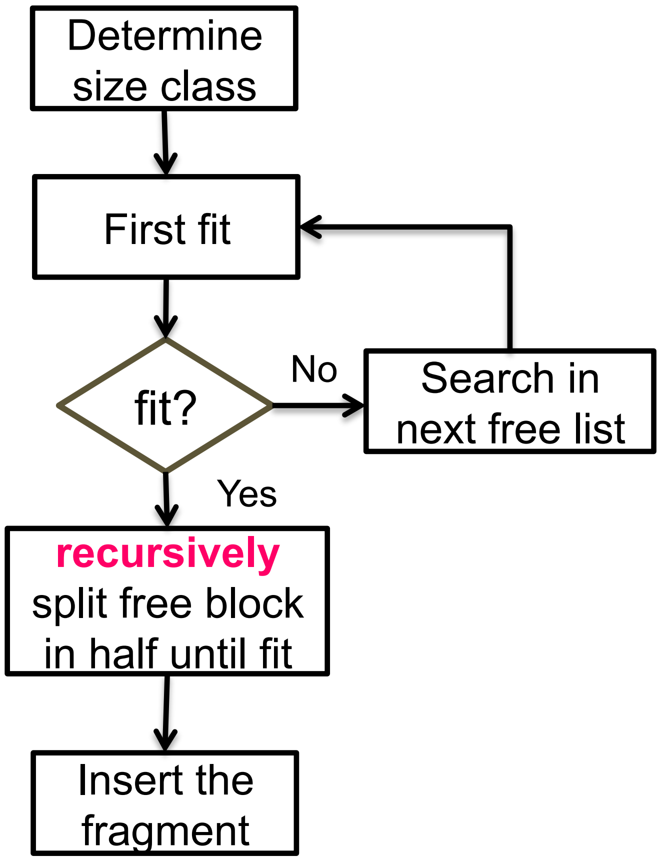
Buddy system

`p = malloc(1)`

Step 1. search in 2^6 list

Step 2. recursive split





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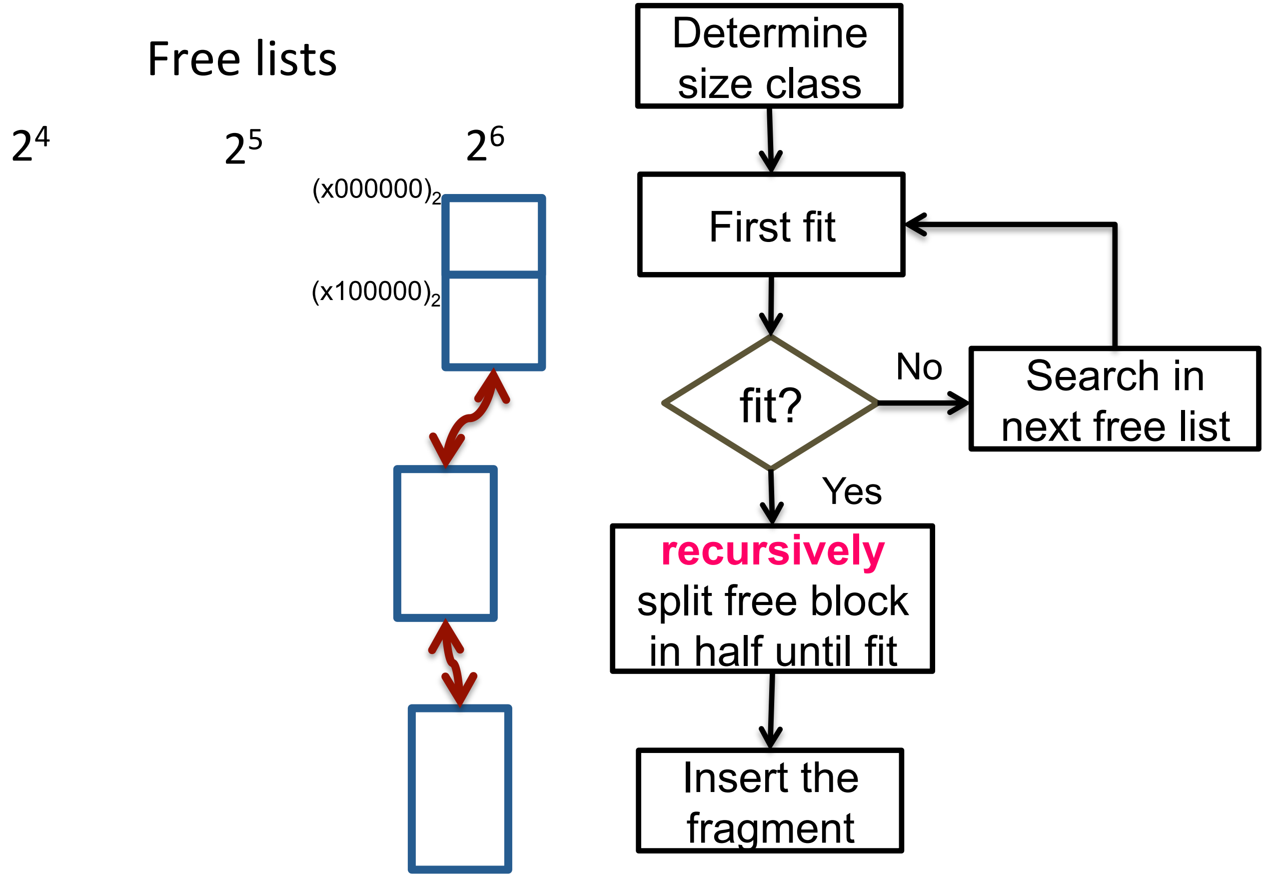

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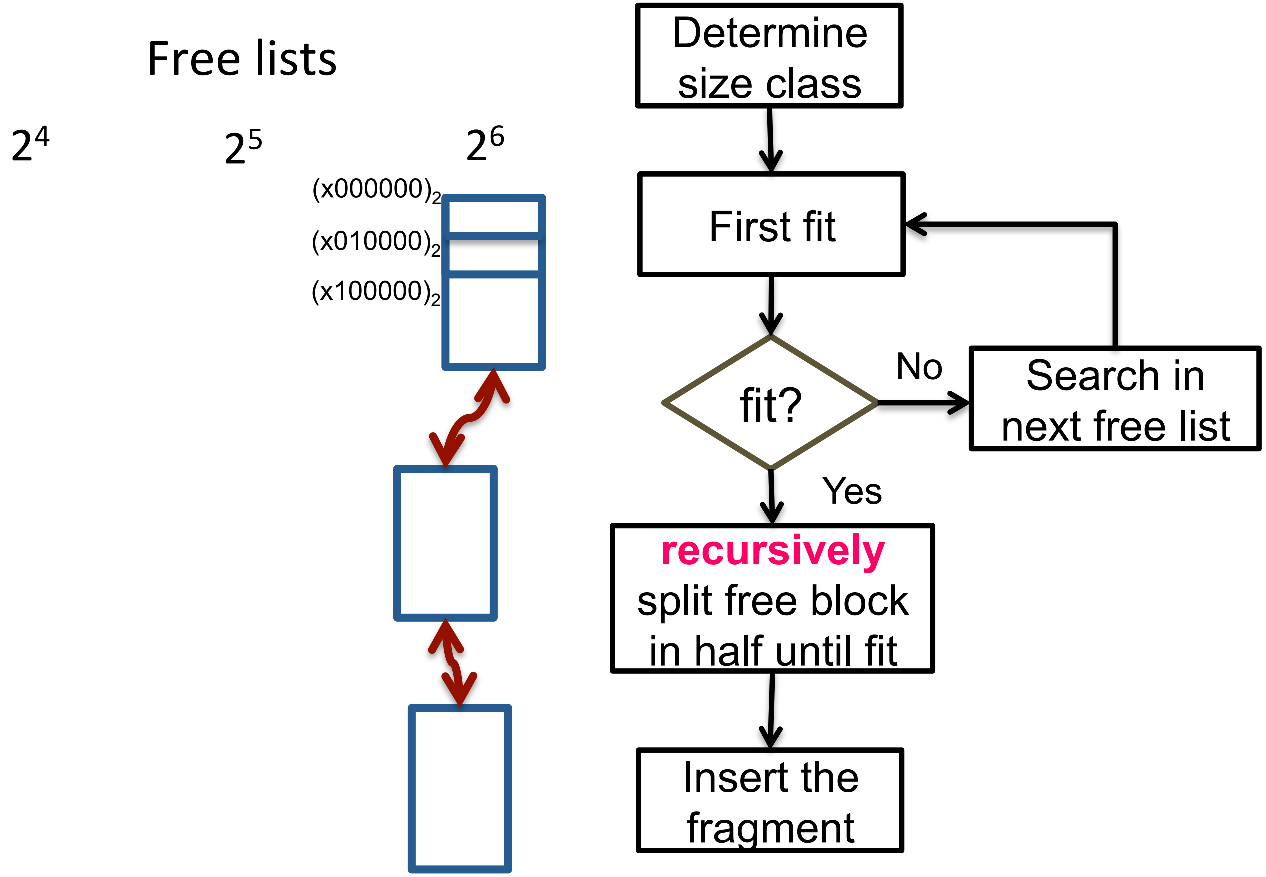

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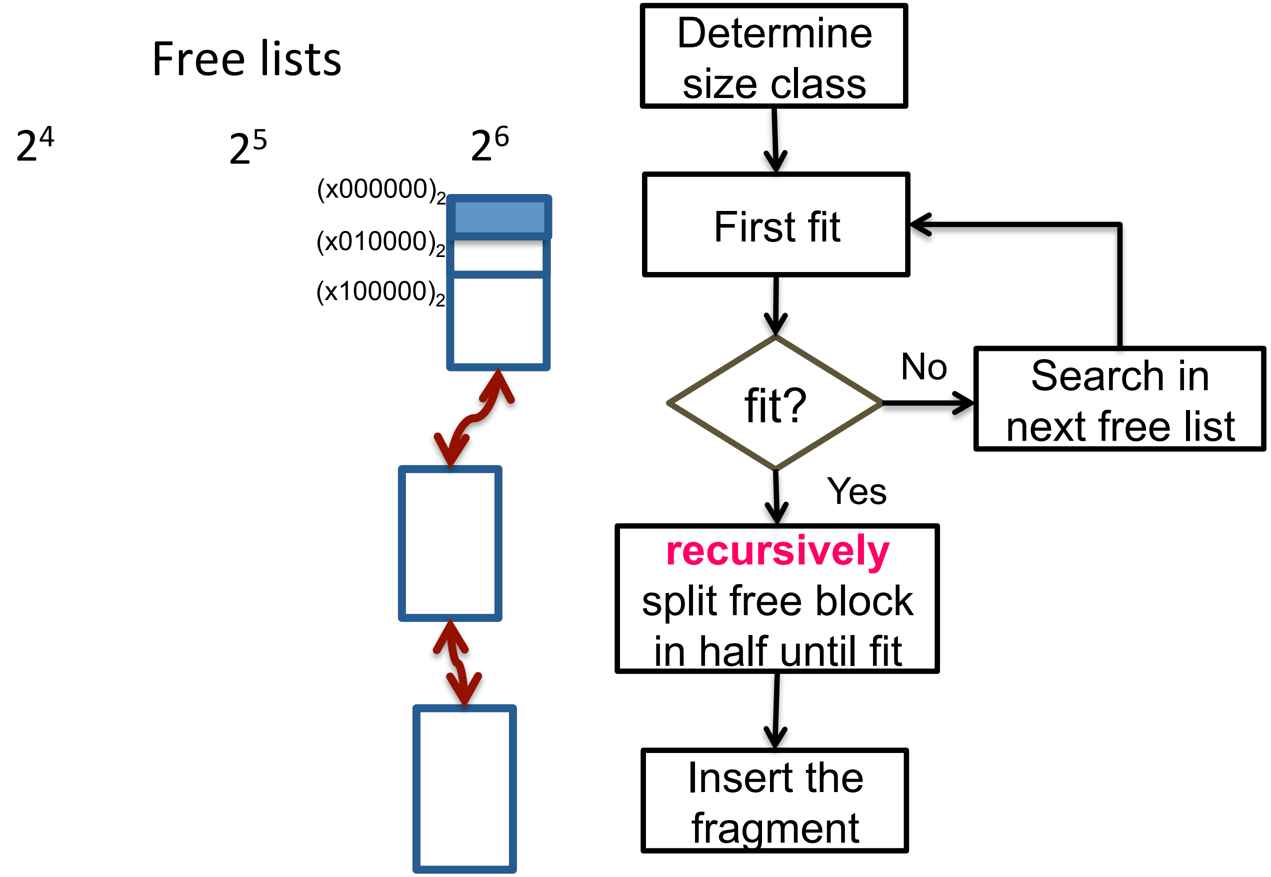


Buddy system

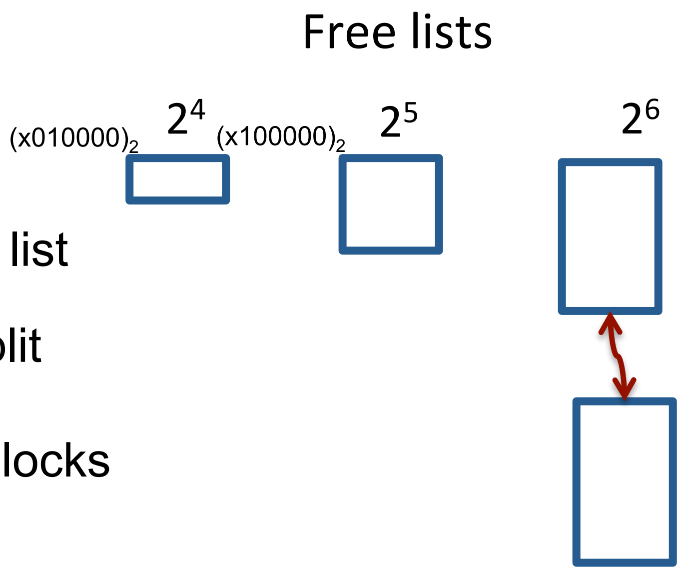
```
p = malloc(1)
```

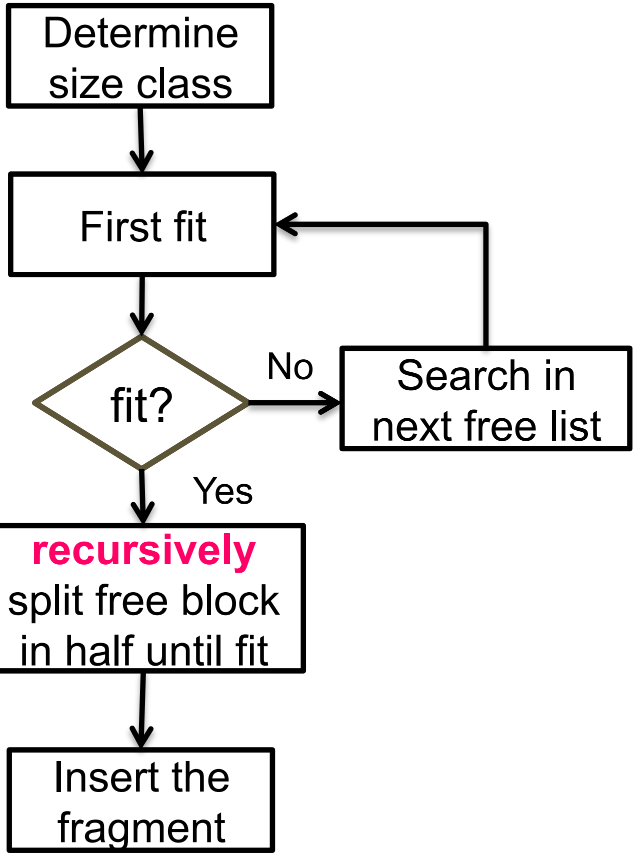
Step 1. search in 2^6 list

Step 2. recursive split

Step 3. insert free blocks
into the list

Step 4. return, p is $(x000000)_2$

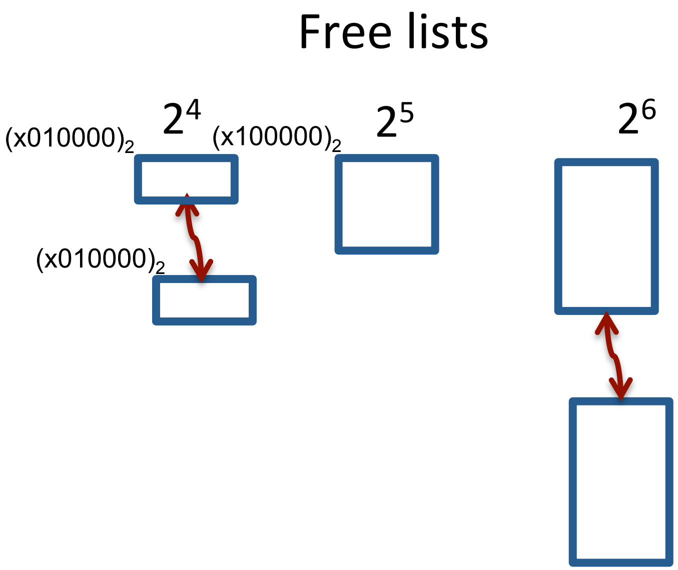


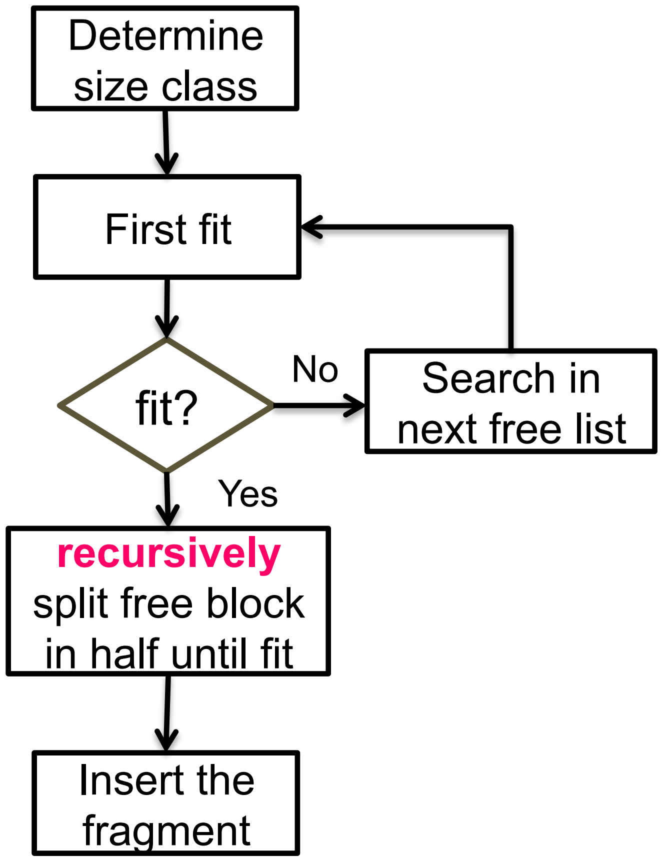


Buddy system

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

free(p)





Buddy system

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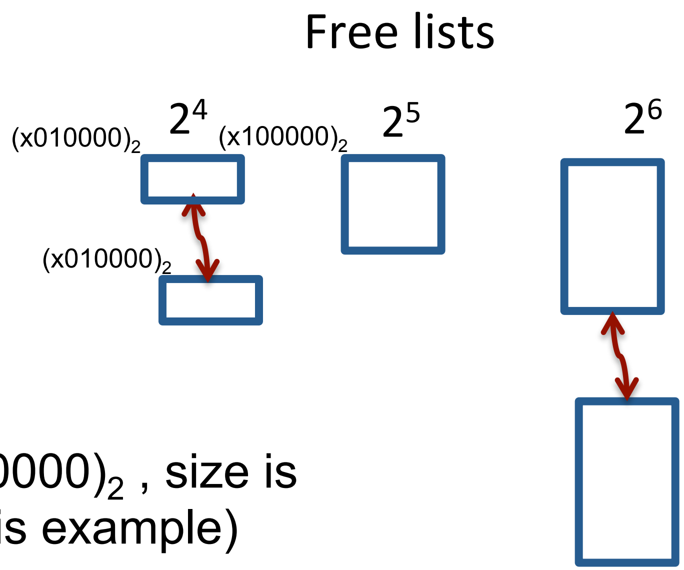
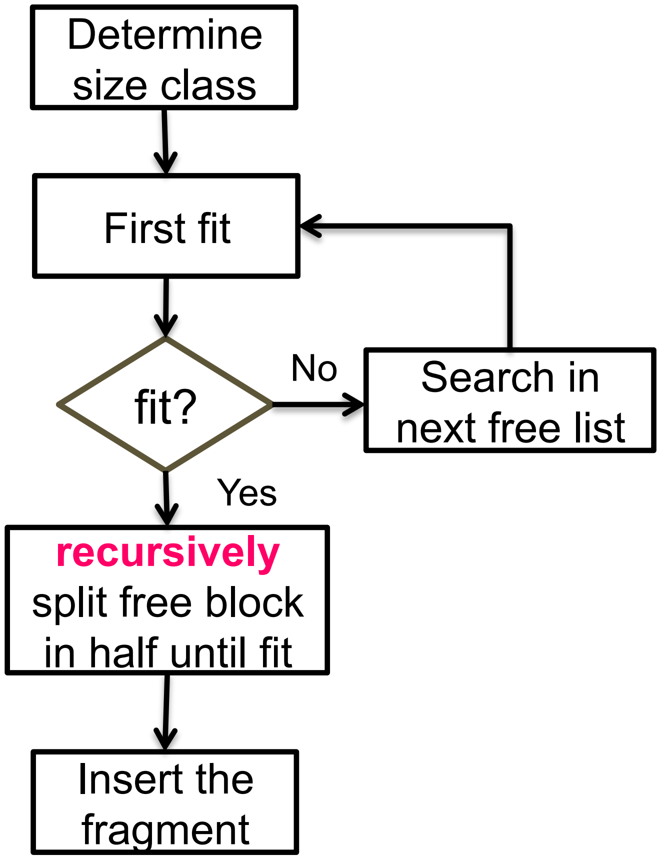


p's address is $(x000000)_2$, size is 16B (no footer in this example)

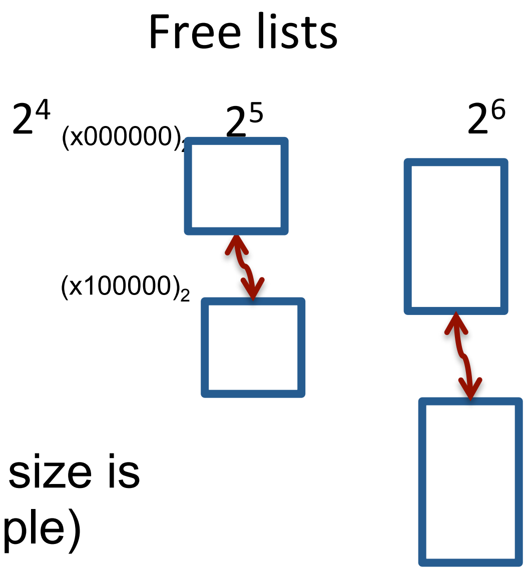
→ p's buddy is 16 B block begins at x000000 ^ (1<<4) which is $(x010000)_2$

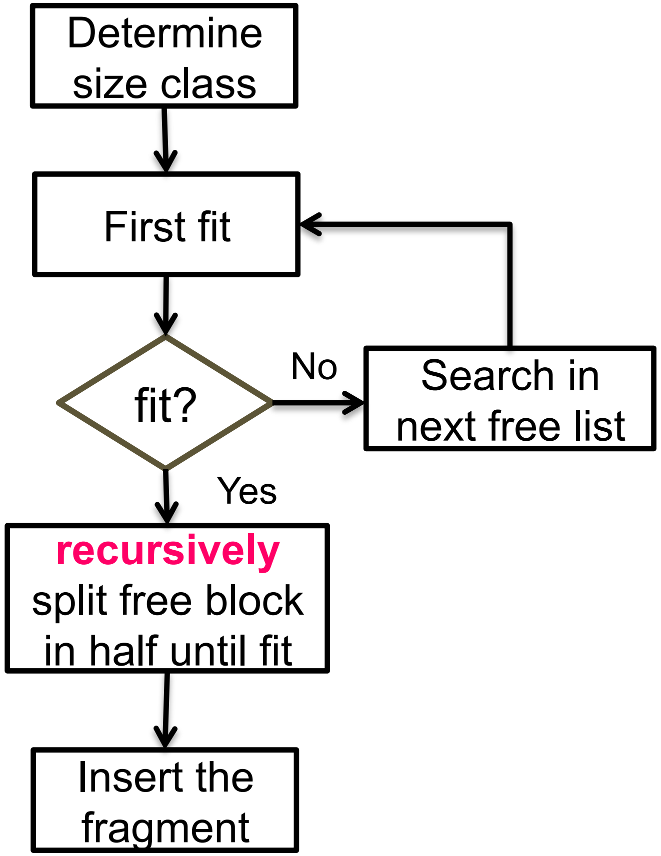


Buddy system

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

free(p)





p's address is (x000000)$_2$, size is 32B (no footer in this example)

→ p's buddy is 32 B block begins at x000000 ^ (1<<5) which is (x100000)$_2$

Buddy system

p = malloc(1)

free(p)

p's address is $(x000000)_2$, size is 32B

→ p's next block address is p + 32B which is $(x100000)_2$

Free lists