# Dynamic Memory Allocation

Shuai Mu

based on slides from Jinyang Li and Tiger Wang

# 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?

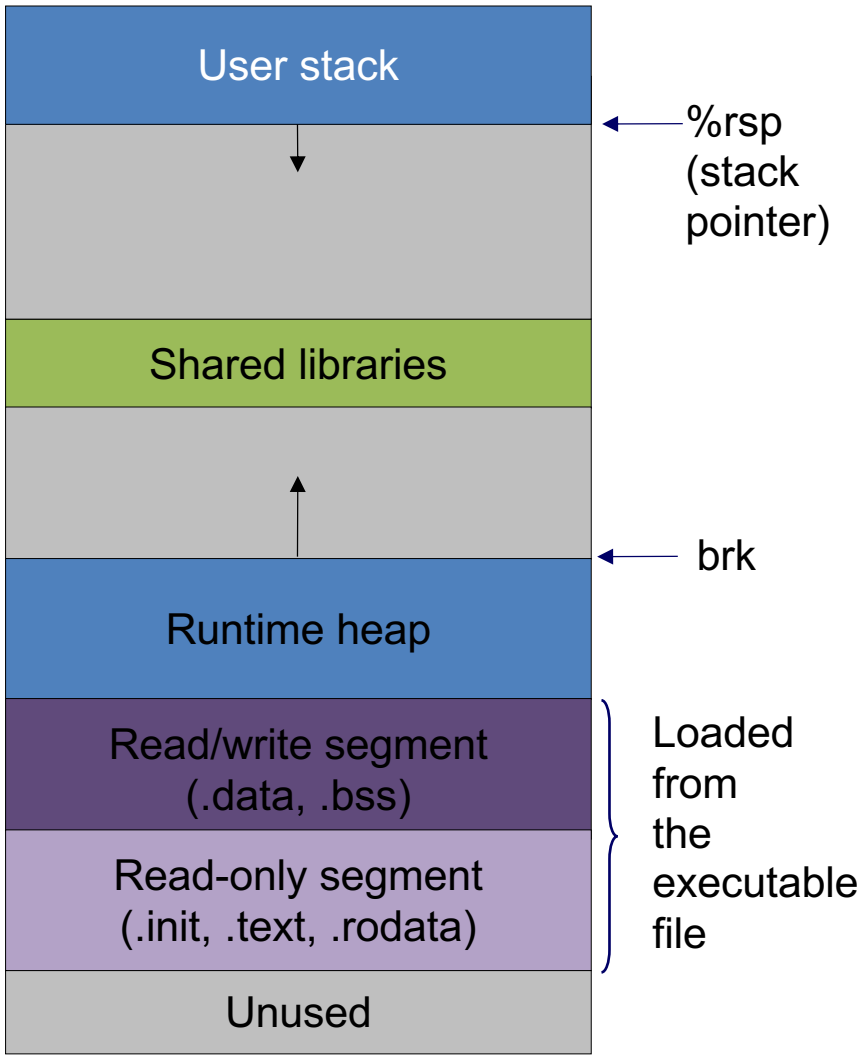
Allocation size is unknown until the program runs (at runtime).

```
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?



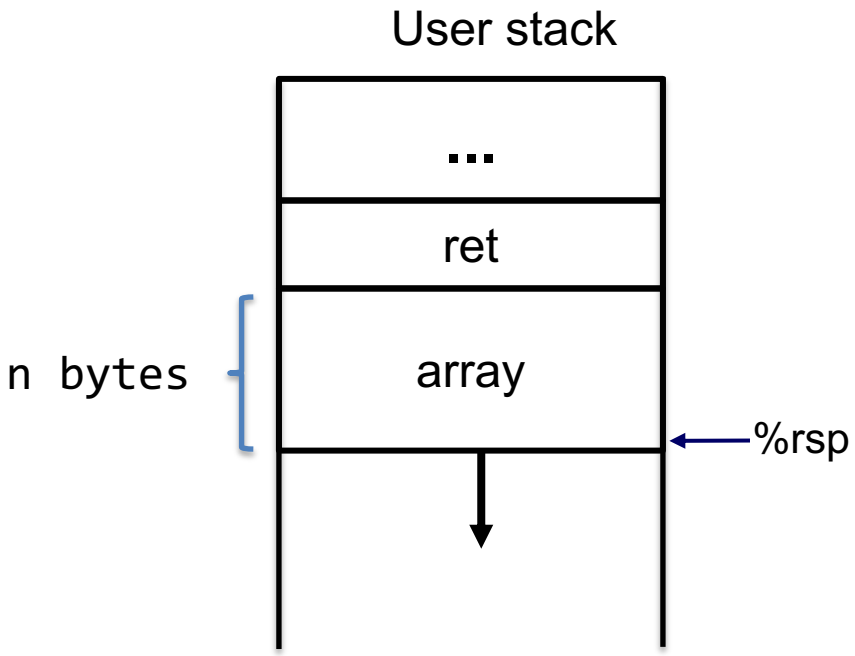
# Dynamic allocation on heap

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);
```

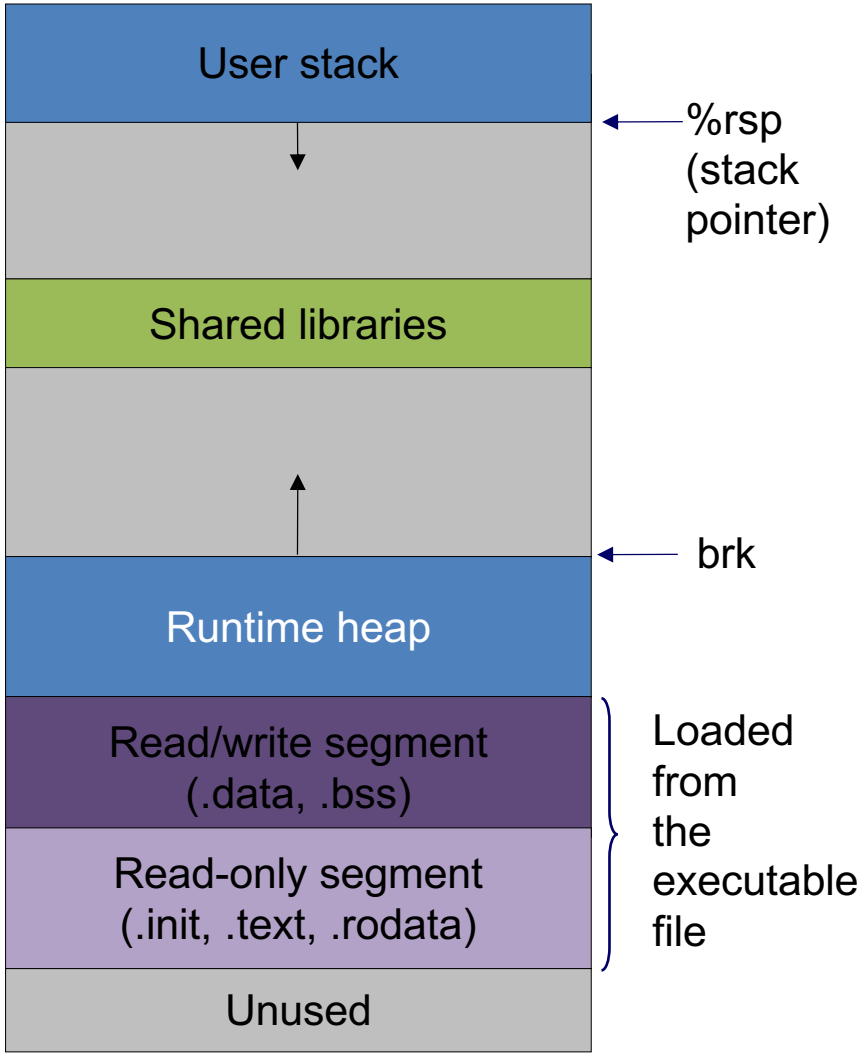
```
void func(int n) {
    array = alloca(n);
}
```




Not good practice!

# Dynamic allocation on heap

Question: How to allocate memory on heap?



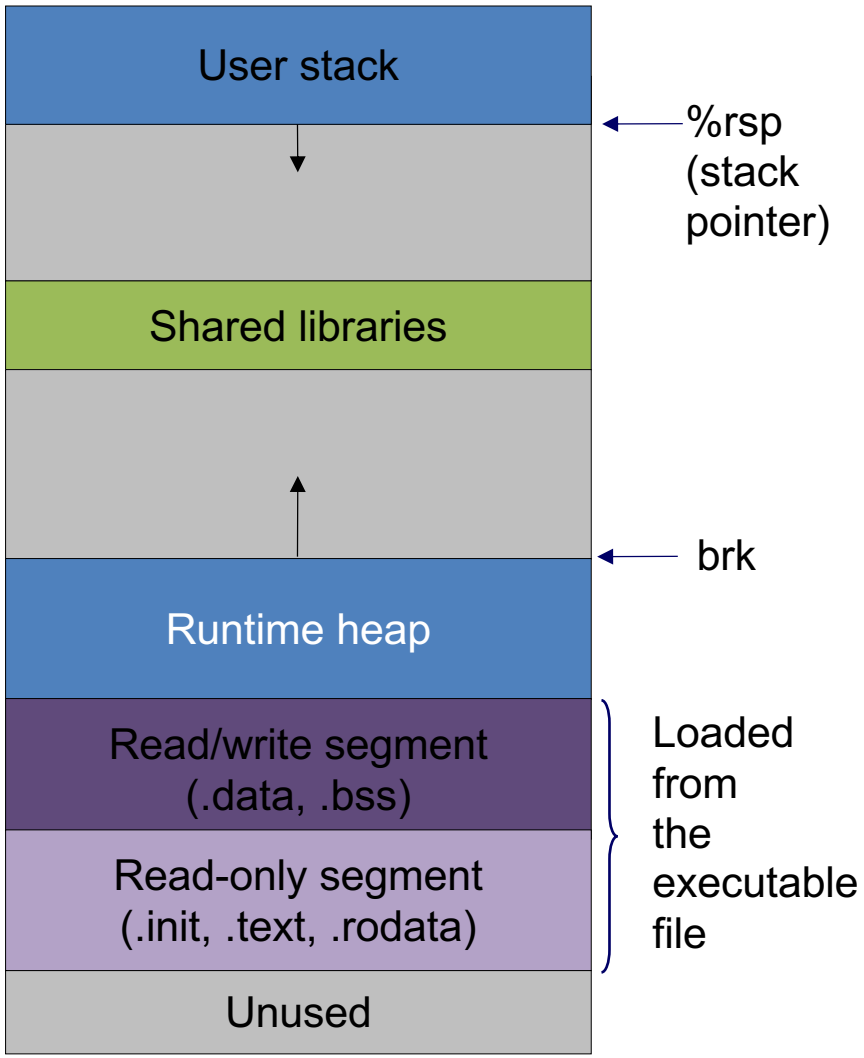
# Dynamic allocation on heap

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.



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void *sbrk(intptr_t size);
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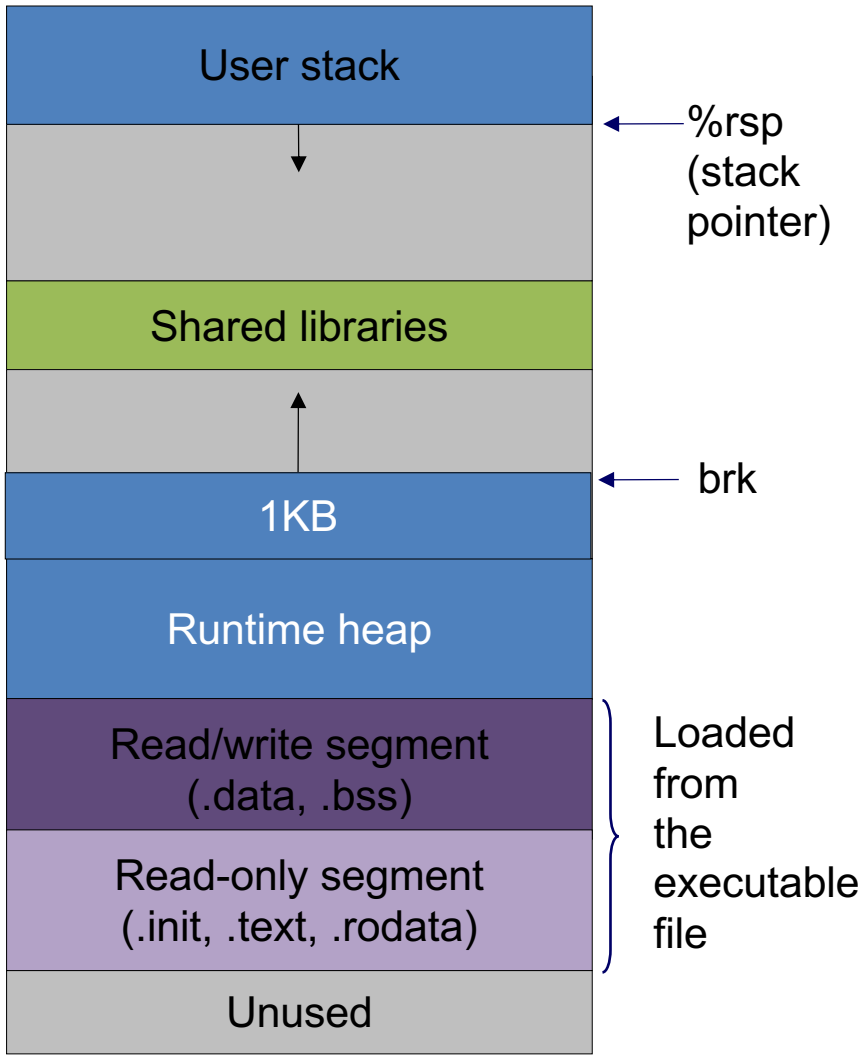
It increases the top of heap by “size” and returns a pointer to the base of new storage. The “size” can be a negative number.

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



# Dynamic allocation on heap

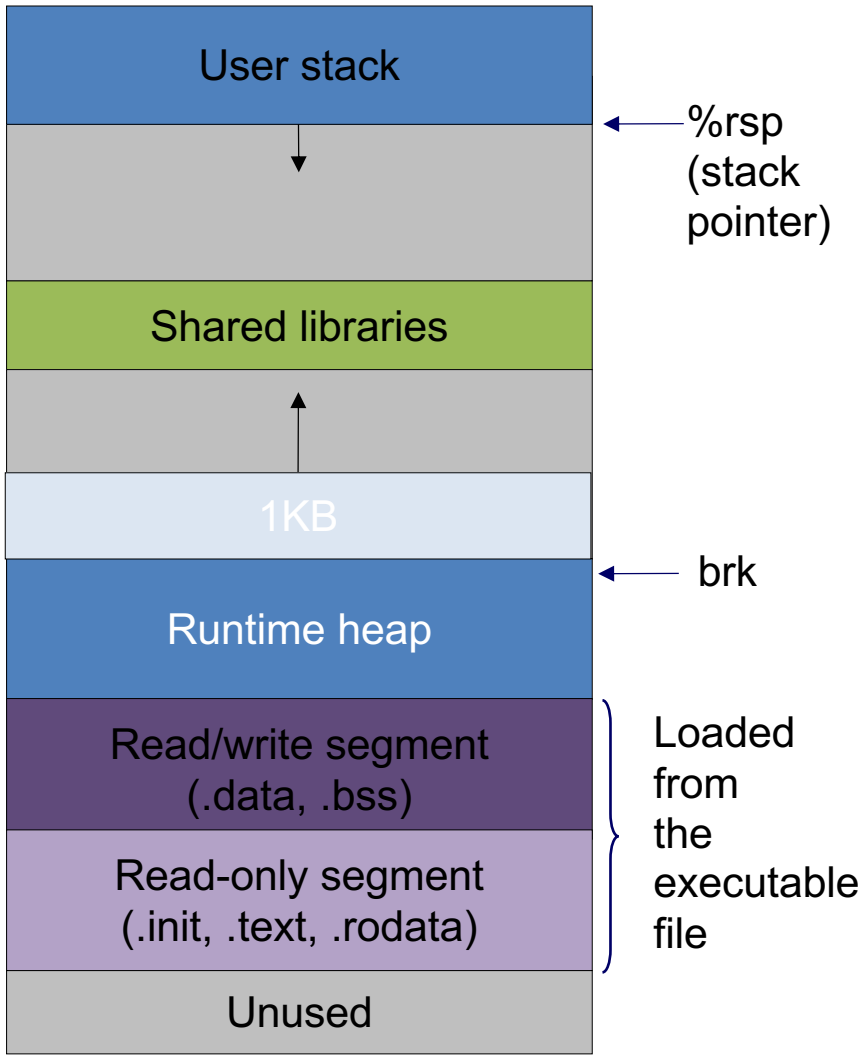
Question: How to allocate memory on heap?

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?

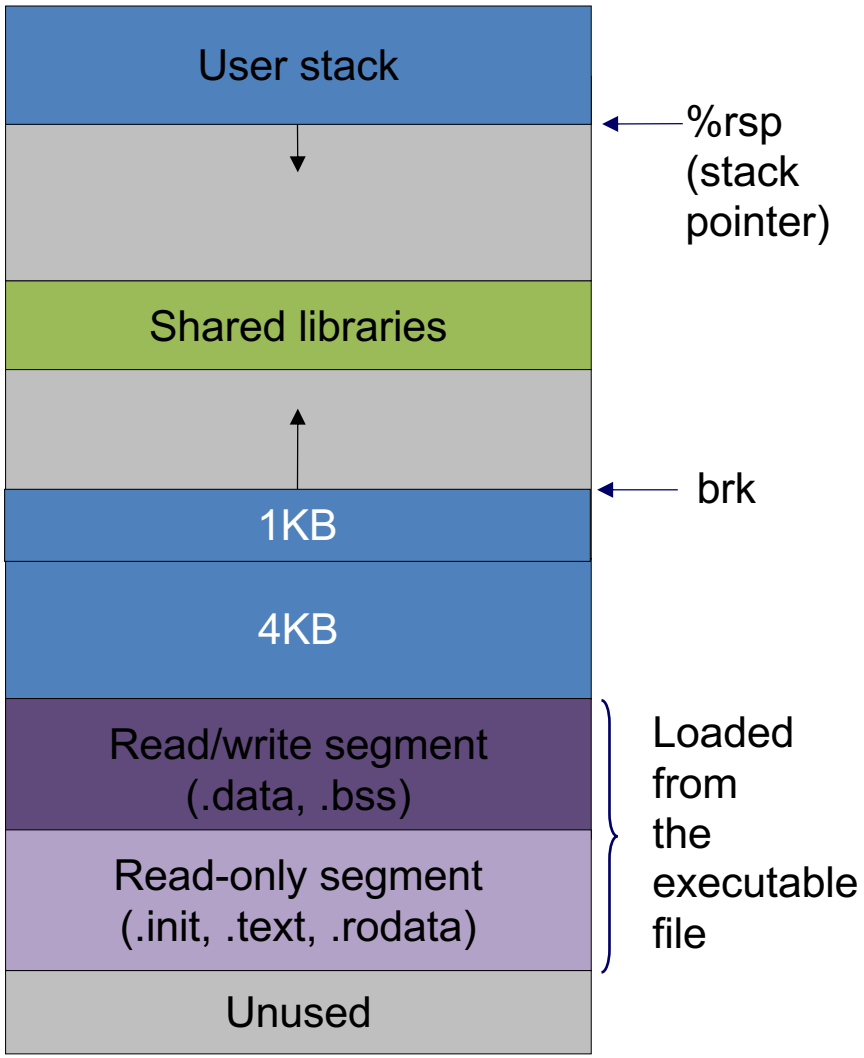
Ask OS for allocation on the heap via system calls

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

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

```
p1 = sbrk(1024) //allocate 1KB
p2 = sbrk(2048) //allocate 4KB
```

How to free p1?



# Dynamic allocation on heap

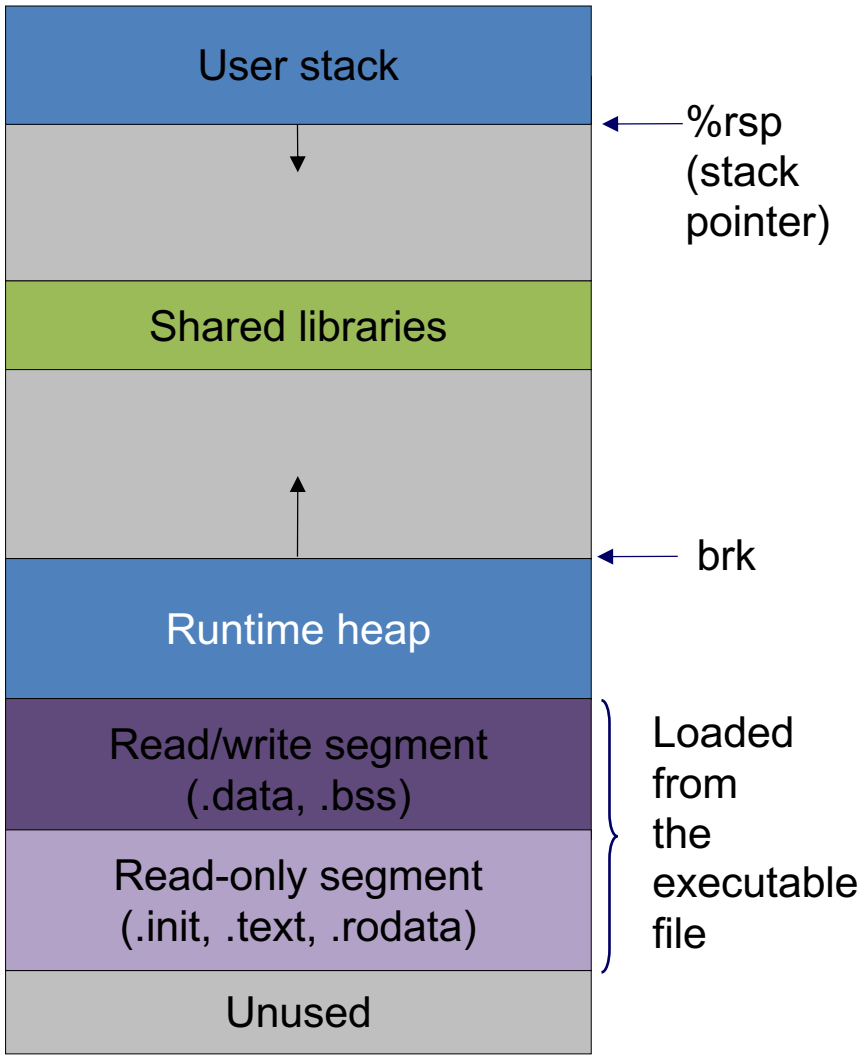
Question: How to allocate memory on heap?

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

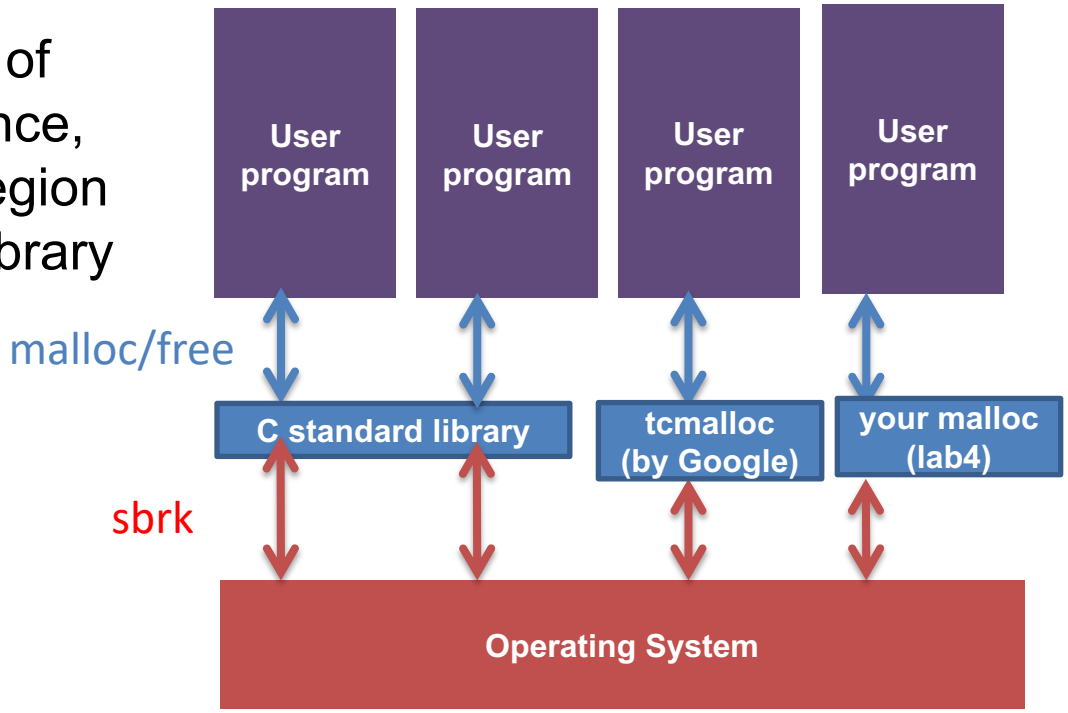
Issue II – system call has high performance cost > 10X



# 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

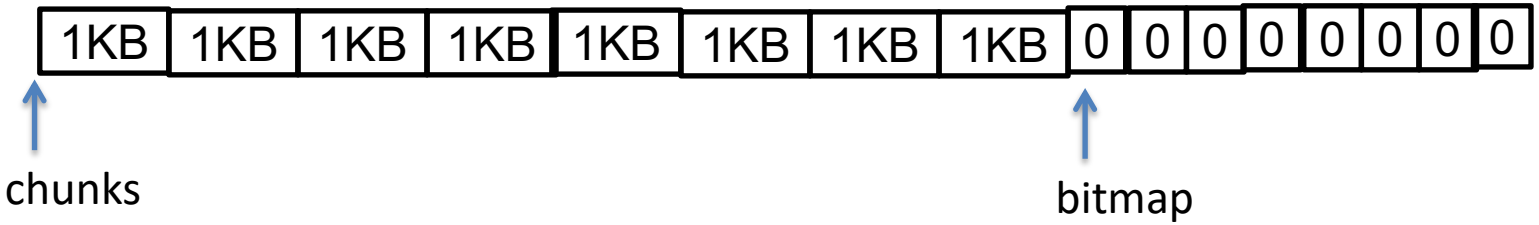
1. (Basic book-keeping) How to keep track which bytes are free and which are not?

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

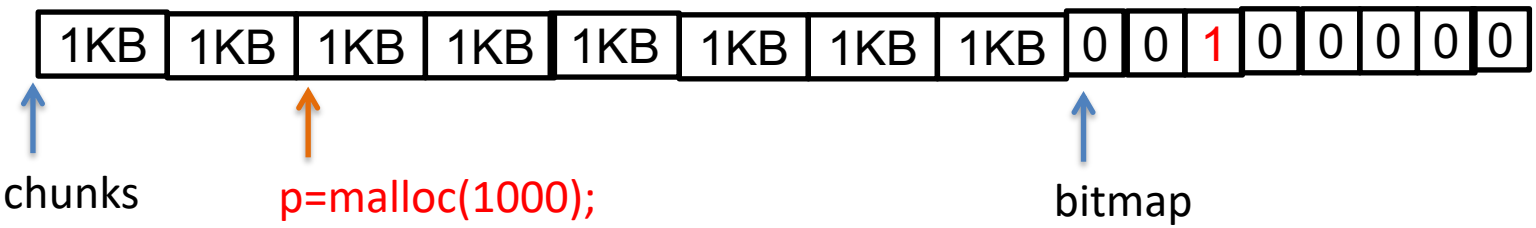
- Structure heap as n 1KB chunks + n metadata




```
#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

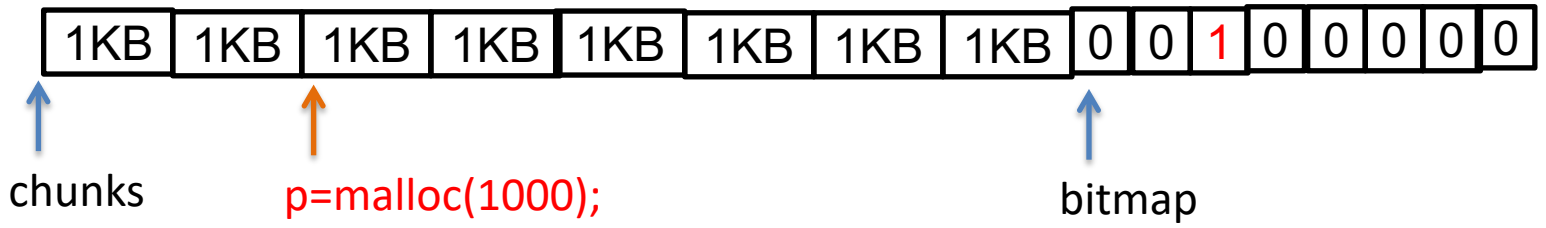



```
void *malloc(size_t sz) {
  assert(sz < CHUNKSIZE);
  size_t i = 0;
  for (; i < n_chunks; i++) {
    if !bitmap_get_pos(bitmap, i)
       break; //found a free chunk
  }

  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!

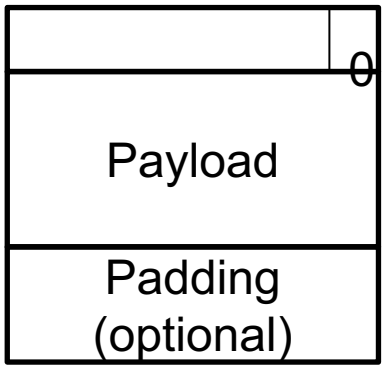
# How to implement a "linked list" without use of malloc

# Implicit list

Embed chunk metadata in the chunks

- Chunk meta-data has a 8-byte header
- Chunk data (payload) is 16-byte aligned

  → Chunk size (metadata+payload) is multiple of 16




header (8 bytes)

allocated: header & 0x1
size: header >> 1

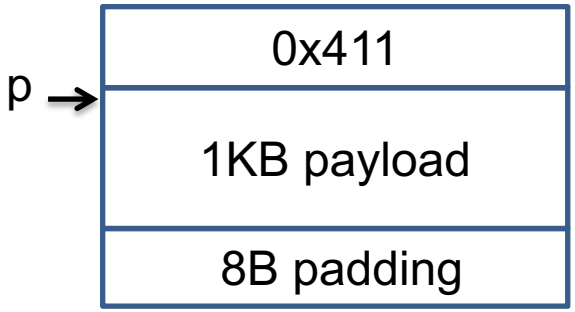
# Implicit list

Embed chunk metadata in the chunks

- Chunk meta-data has a 8-byte header
- Chunk data (payload) is 16-byte aligned

  → Chunk size (metadata+payload) is multiple of 16

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



# Implicit list

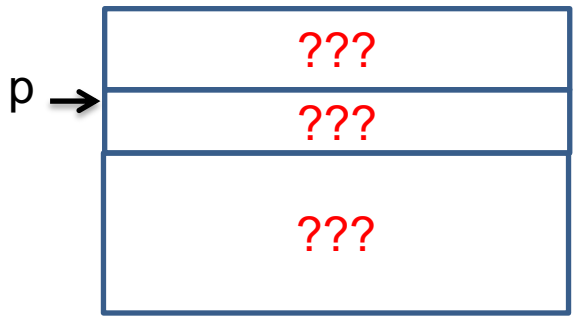
Embed the metadata in the chunks (blocks)

– Each block has a one-word (8 bytes) header

– Block is double-word (16 bytes) alignment

→ Size is multiple of 16

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



# Implicit list

Embed the metadata in the chunks (blocks)

- Each block has a one-word (8 bytes) header
- Block is double-word (16 bytes) alignment

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p  = malloc(1)
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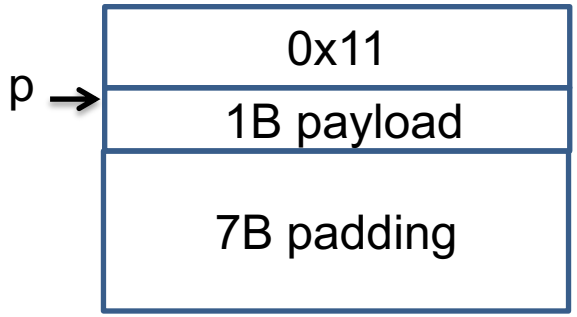


# Exercises

| Alignment | Request | Block size | Header (hex) |
|---|---|---|---|
| 8 bytes | malloc(5) | | |
| 4 bytes | malloc(13) | | |
| 16 bytes | malloc(20) | | |
| 8 bytes | malloc(3) | | |

# Exercises

| Alignment | Request | Block size | Header (hex) |
|---|---|---|---|
| 8 bytes | malloc(5) | 16 | 0x11 |
| 4 bytes | malloc(13) | 24 | 0x19 |
| 16 bytes | malloc(20) | 32 | 0x21 |
| 8 bytes | malloc(3) | 16 | 0x11 |

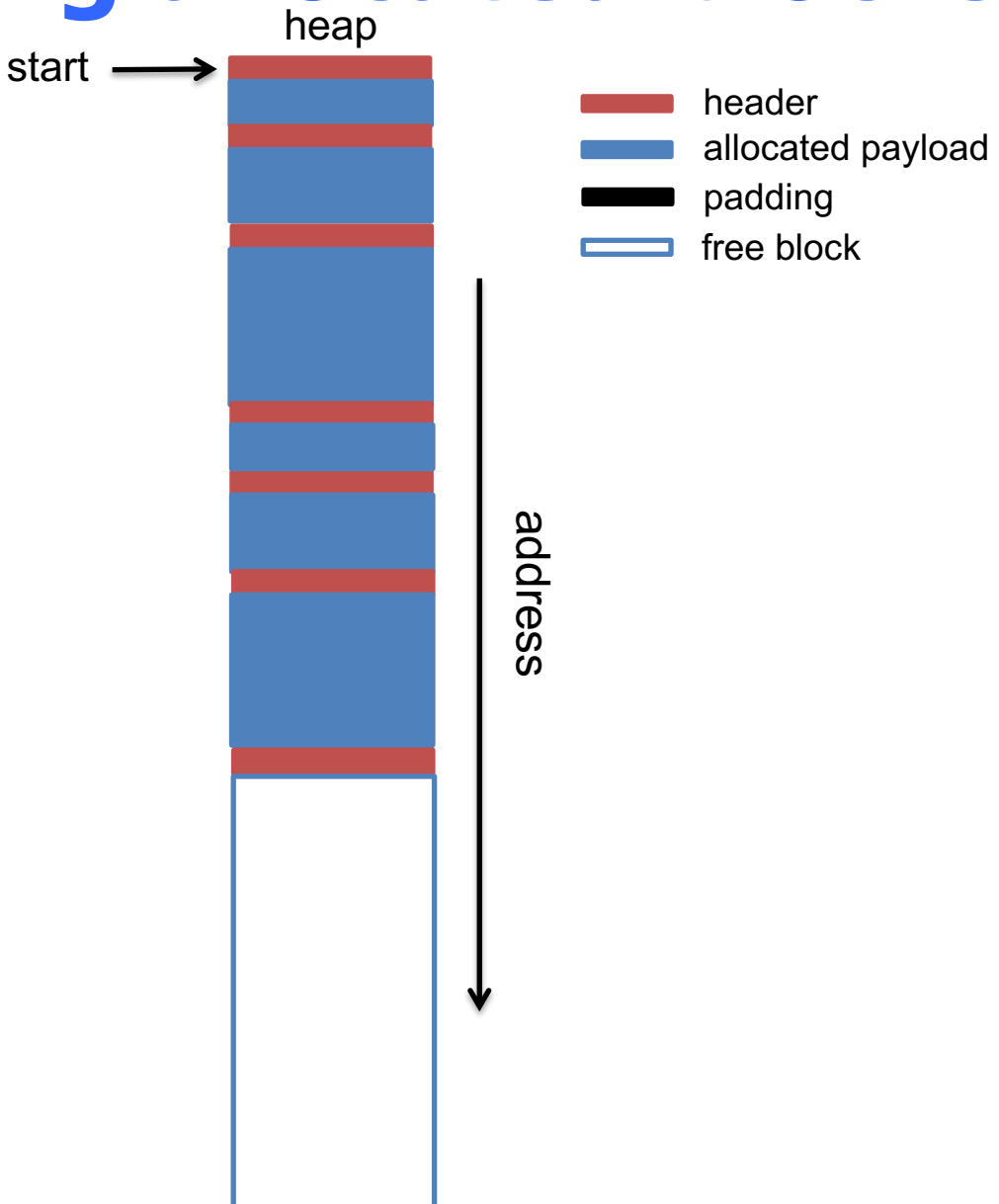
# How to traverse an implicit list

```
void traverse_implicit_list() {
   char *chunk = heap_lo();
   while (chunk < heap_high()) {
       bool allocated = get_status(*(unsigned long *)chunk);
       size_t csz = get_chunksz(*(unsigned long *)chunk);
       chunk += csz;
   }

}
bool get_status(unsigned long header) {
   return header & 0x1;
}
size_t get_chunksize(unsigned long header) {
   return header >> 1;
}
```

# 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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p1 = malloc(8)
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free(p2)
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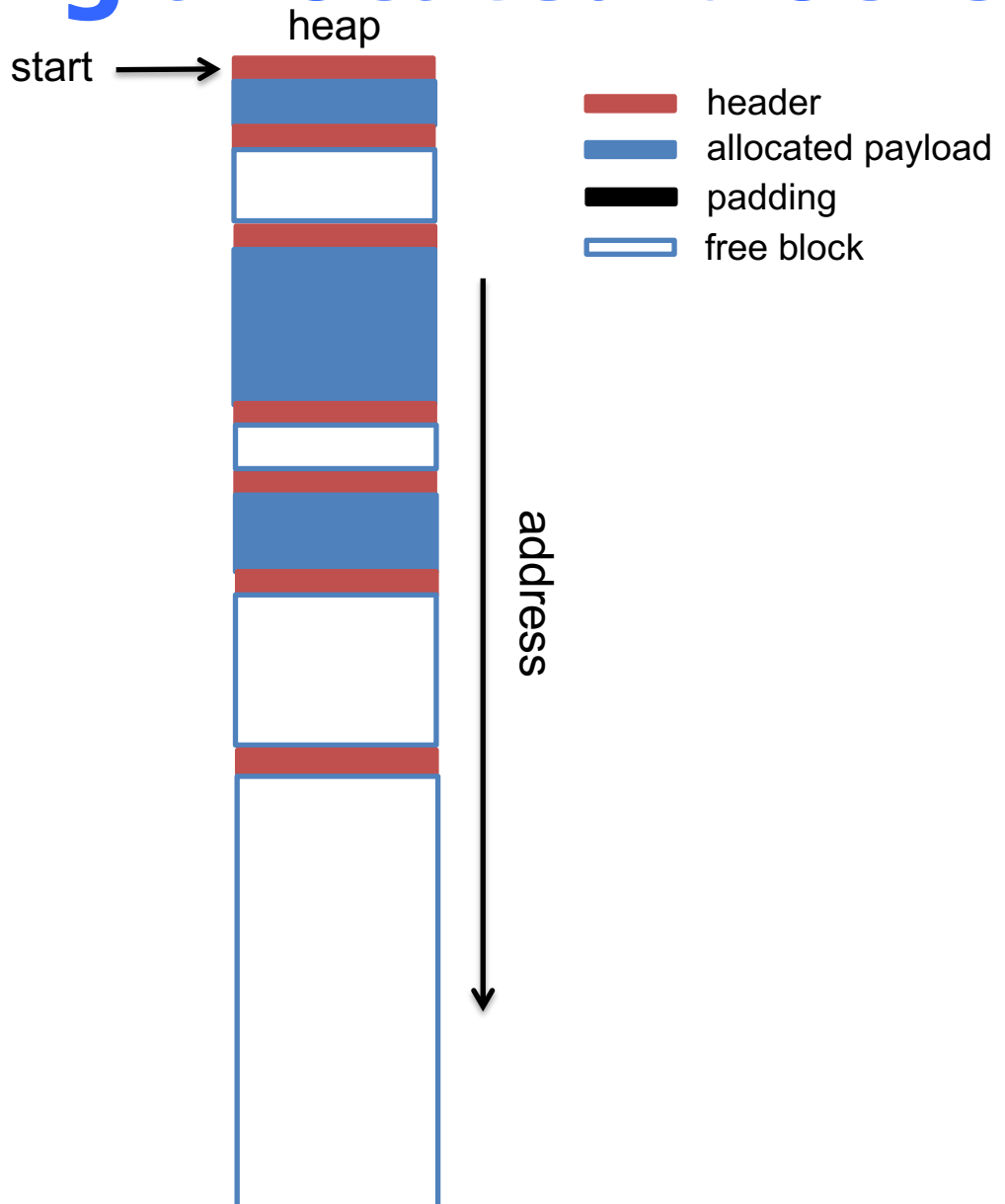
free(p6)
```



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p7 = malloc(8)
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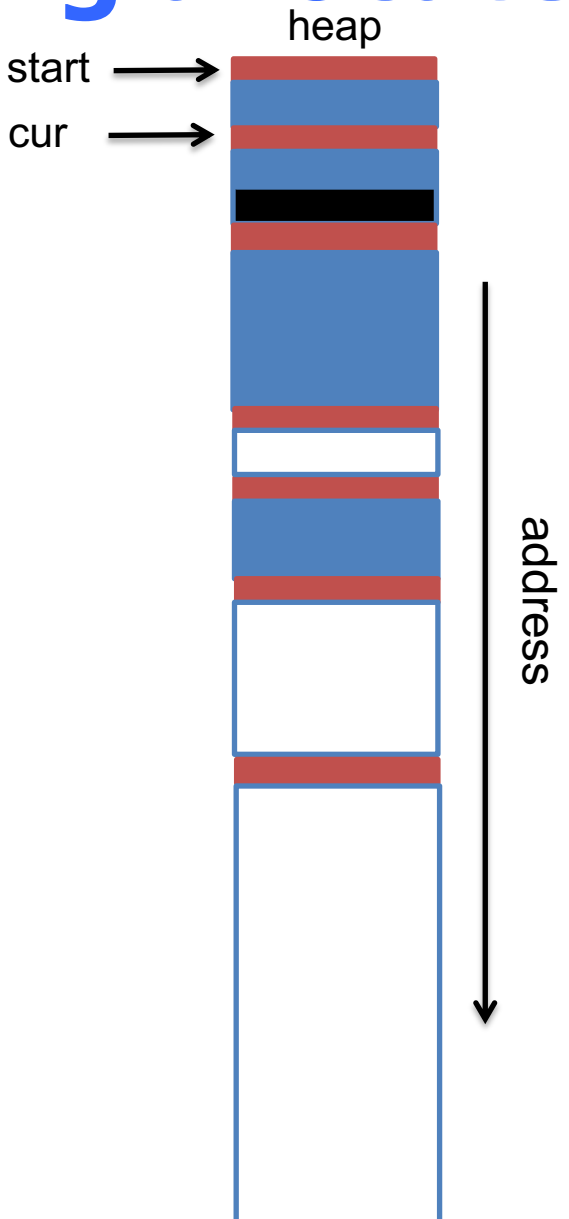


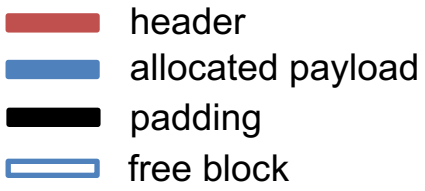


First fit – Search list from beginning, choose first free block that fits

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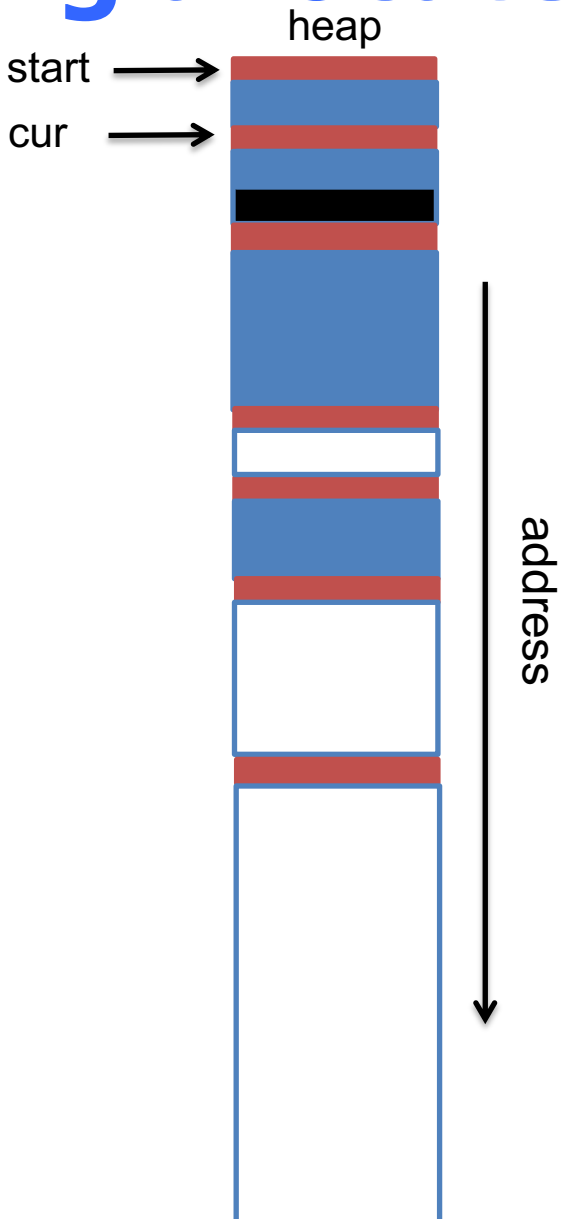


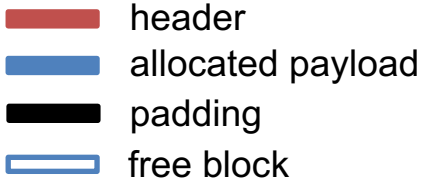


First fit – Search list from beginning, choose first free block that fits

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

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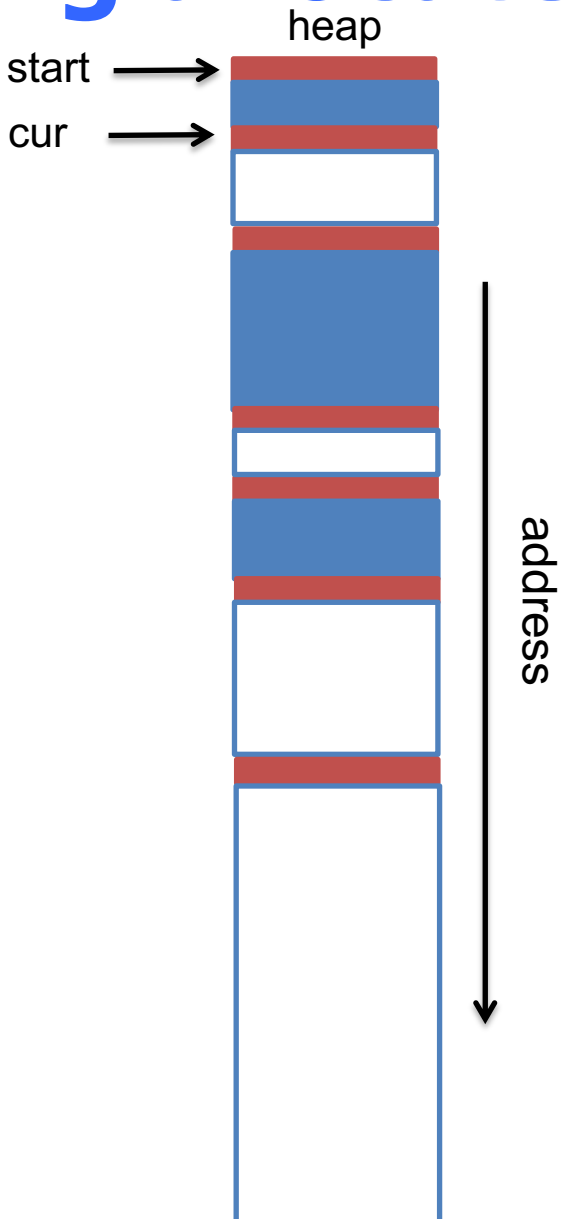


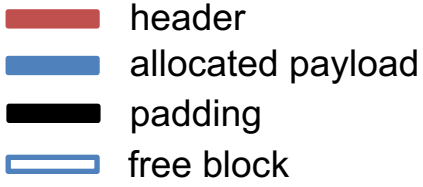


Best fit – choose the free block with the closest size that fits

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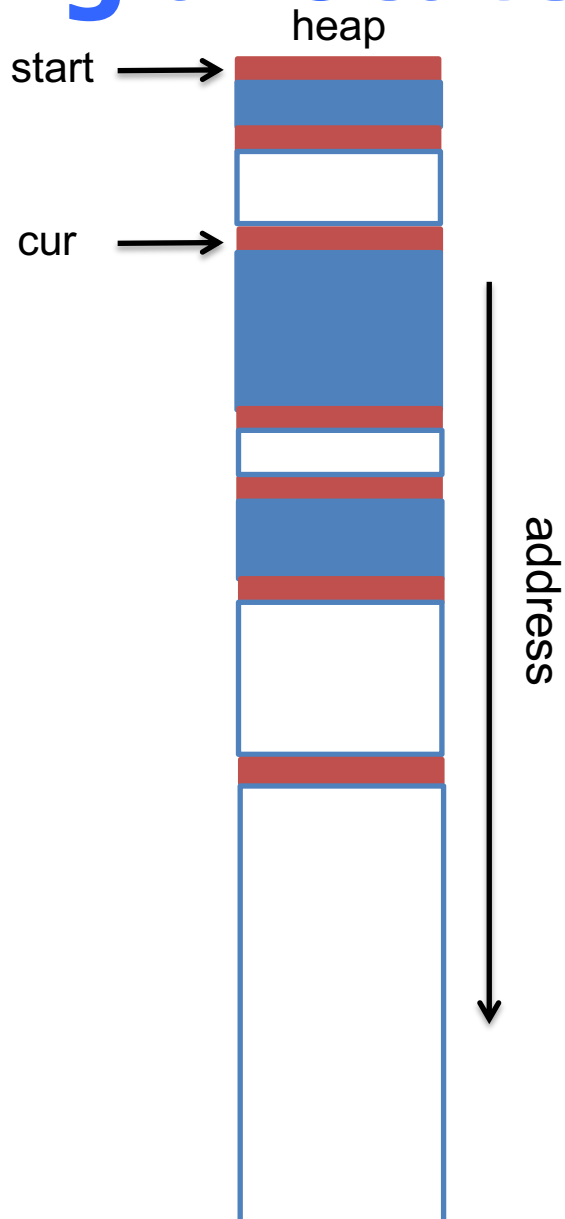


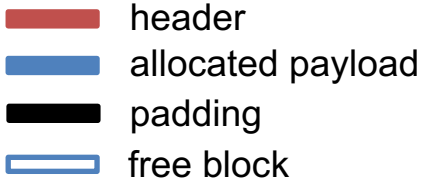


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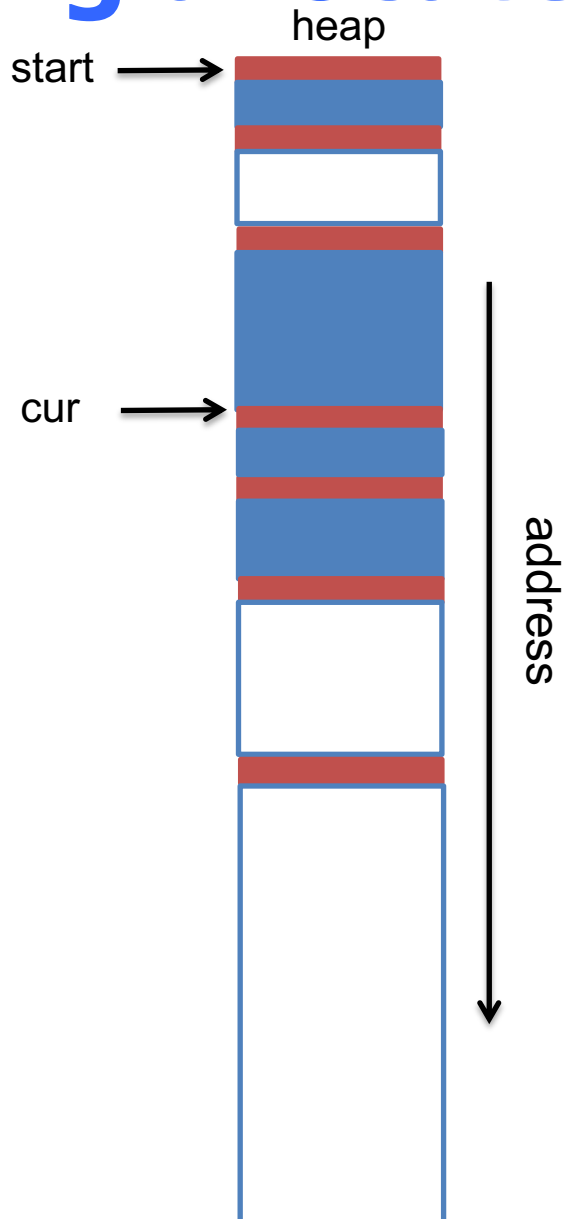


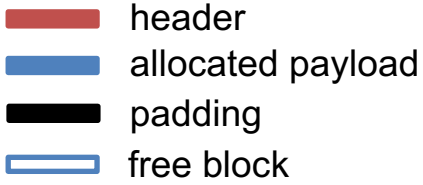


Best fit – Search list from beginning choose first free block that fits

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

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free(p6)
p7 = malloc(8)
p8 = malloc(56)
```

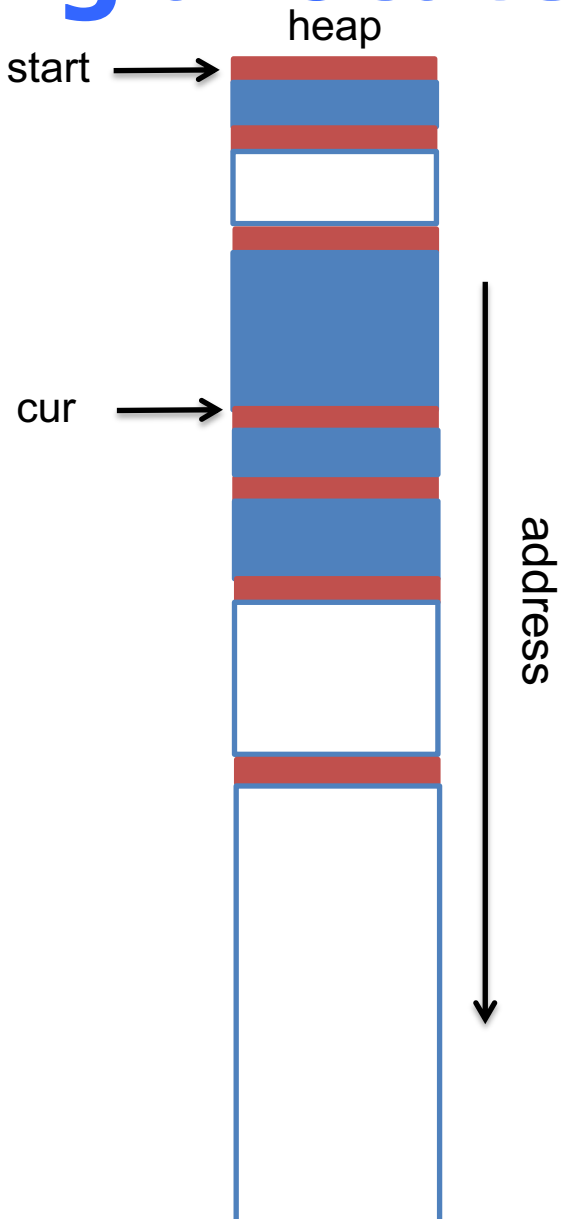


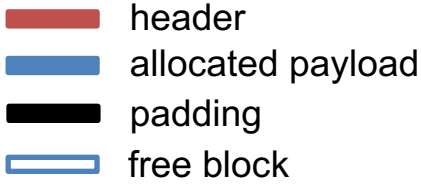


Next fit – like first-fit, but search list from the location where previous search left off.

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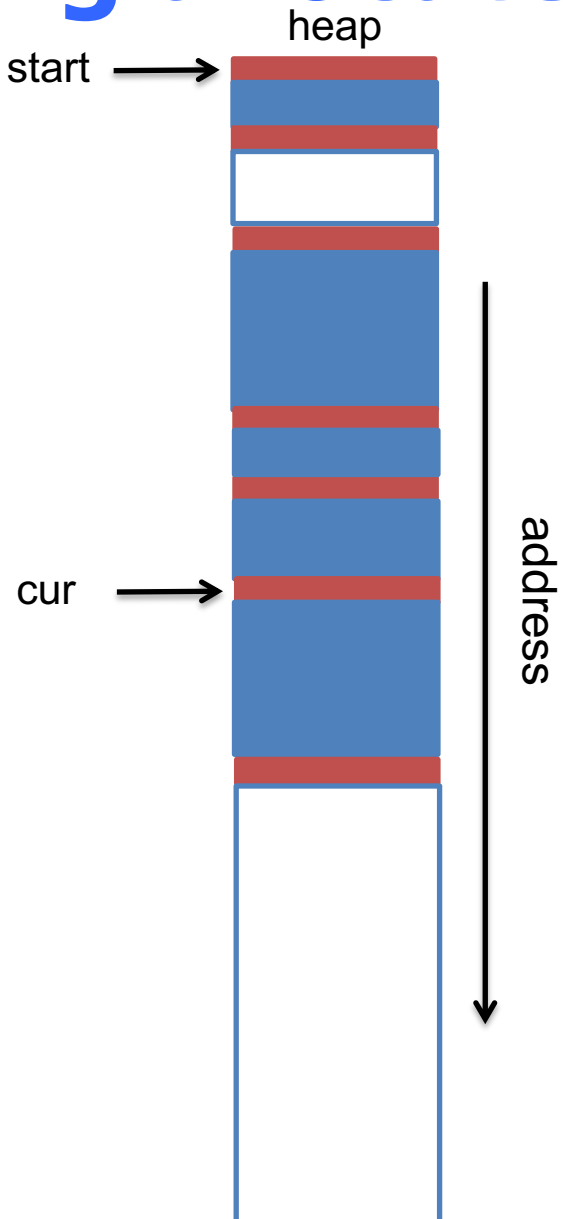


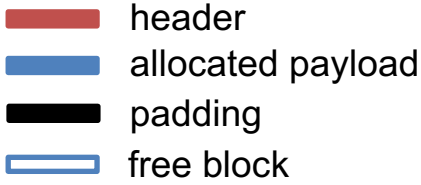


Next fit – like first-fit, but search list from from the location where previous search left off.

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

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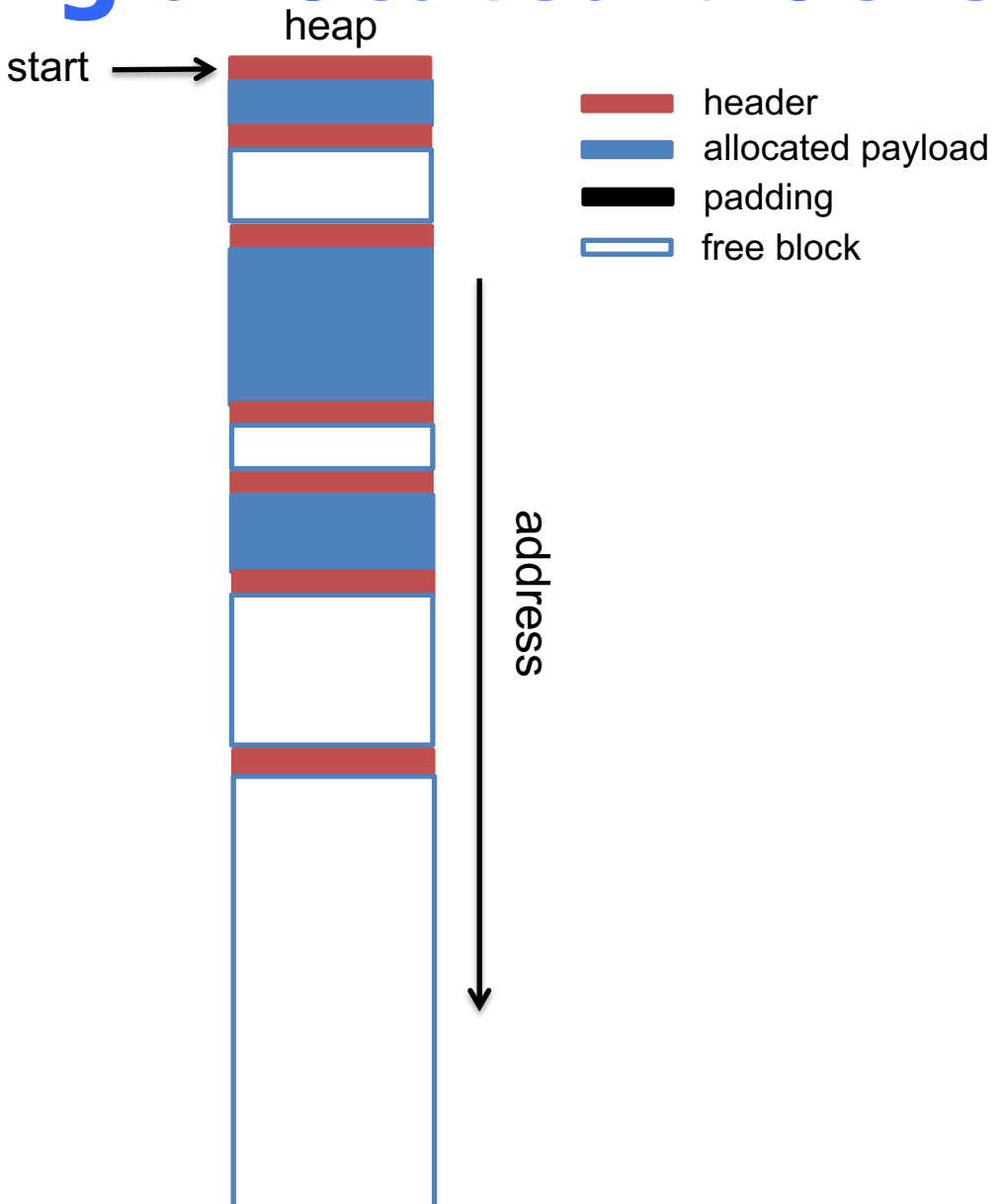

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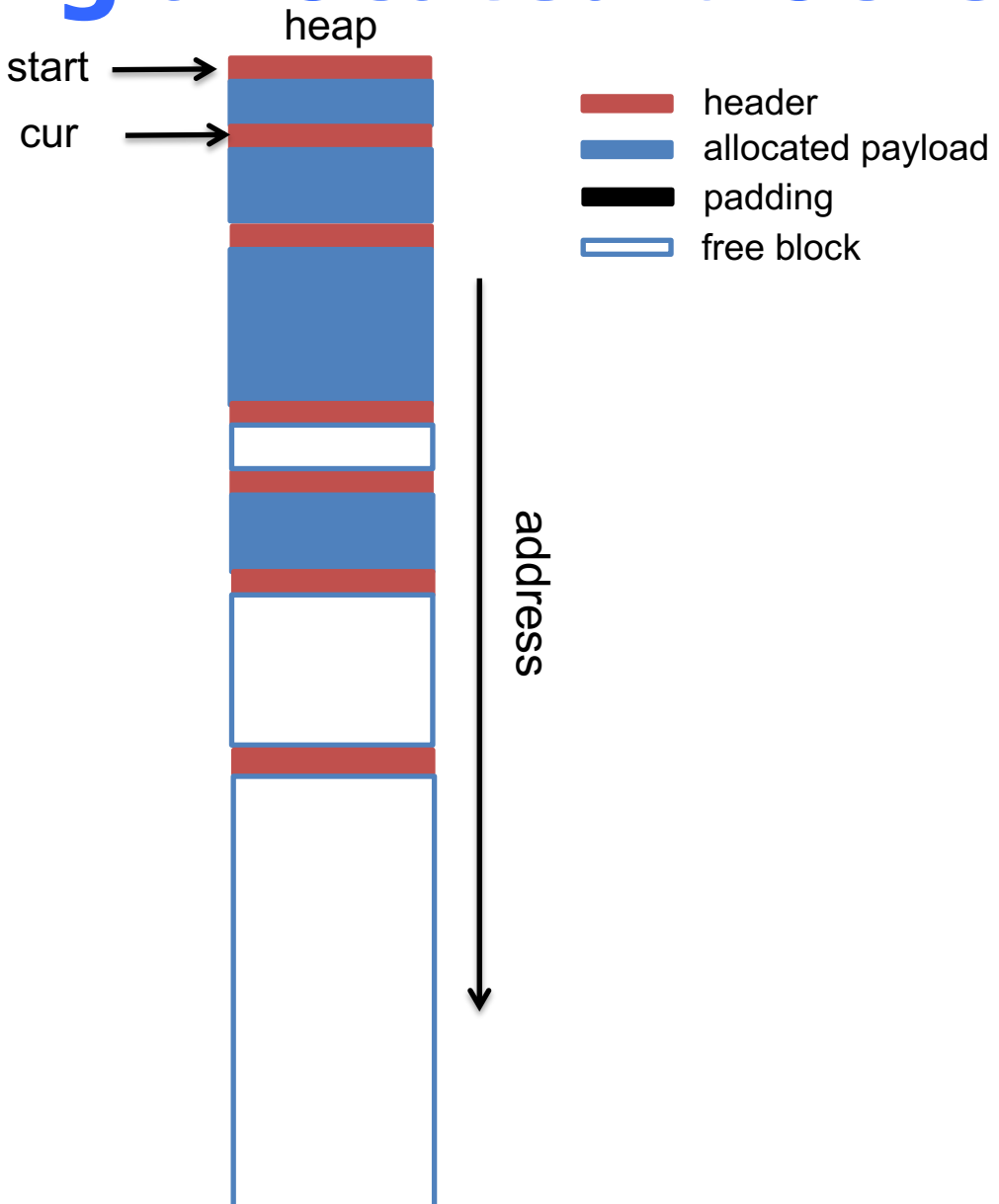

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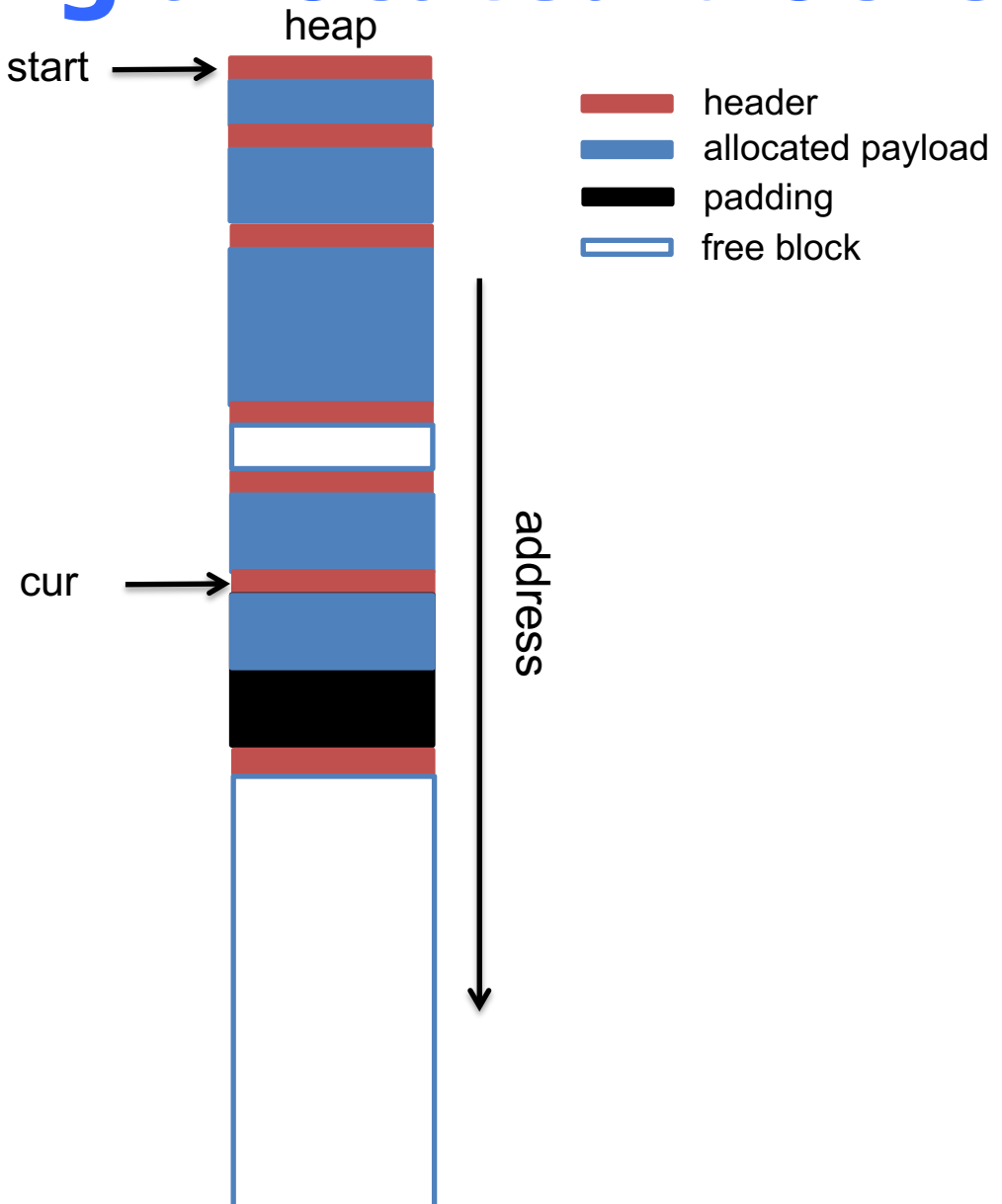
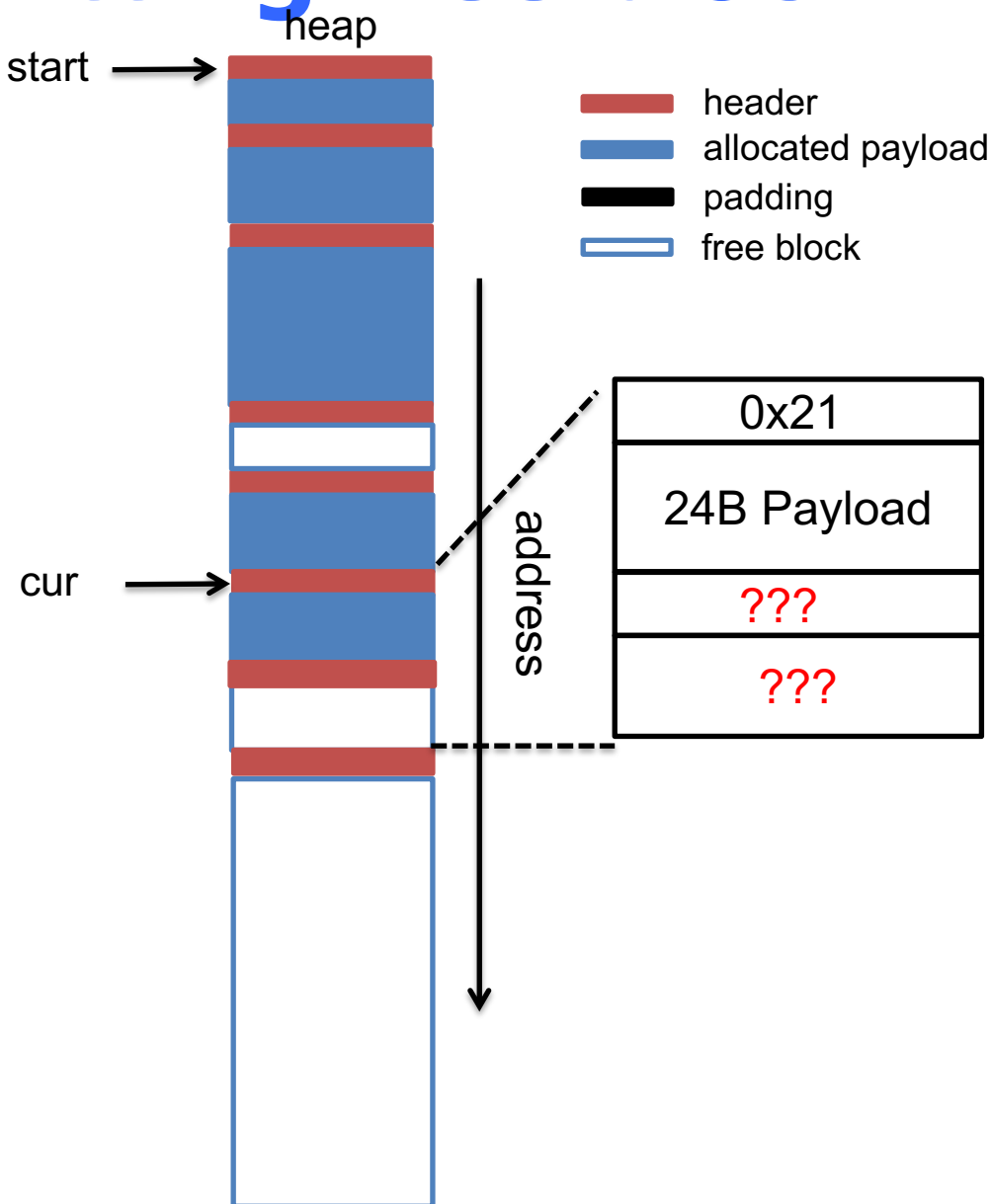


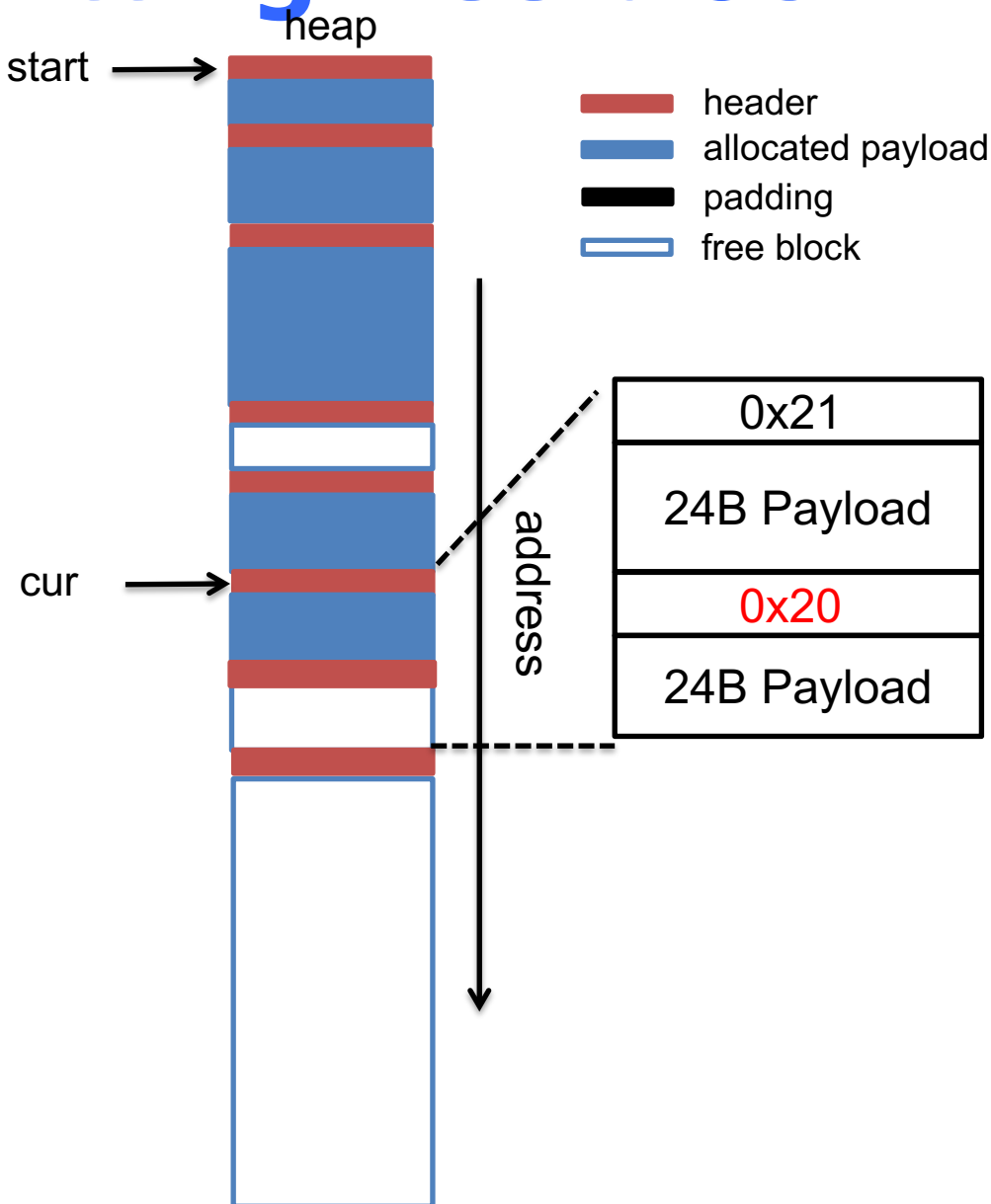
# Splitting free block

```
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(24)
p8 = malloc(24)
```



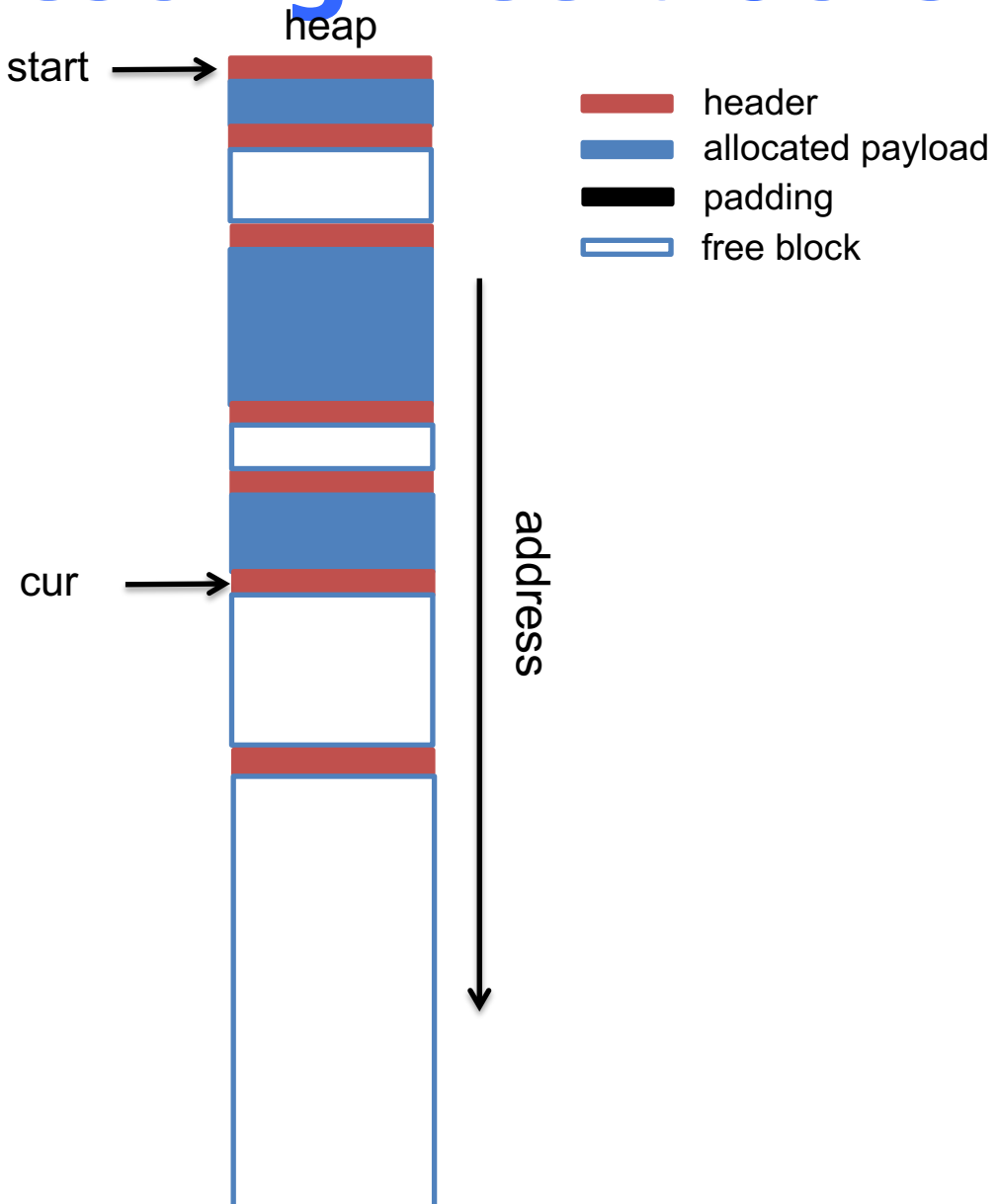
# Splitting free block

```
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(24)
p8 = malloc(24)
```



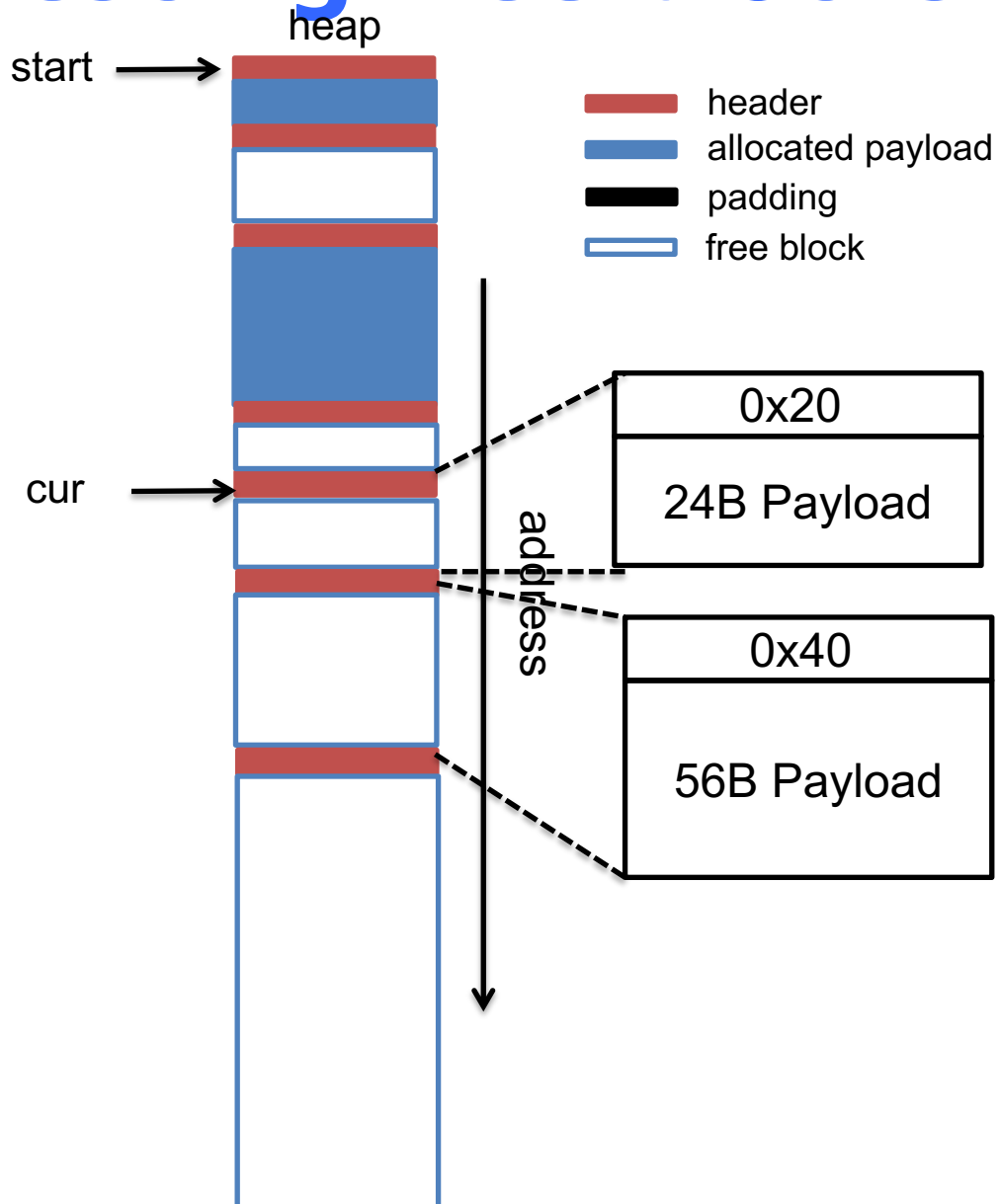
# Coalescing free blocks

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



# Coalescing free blocks

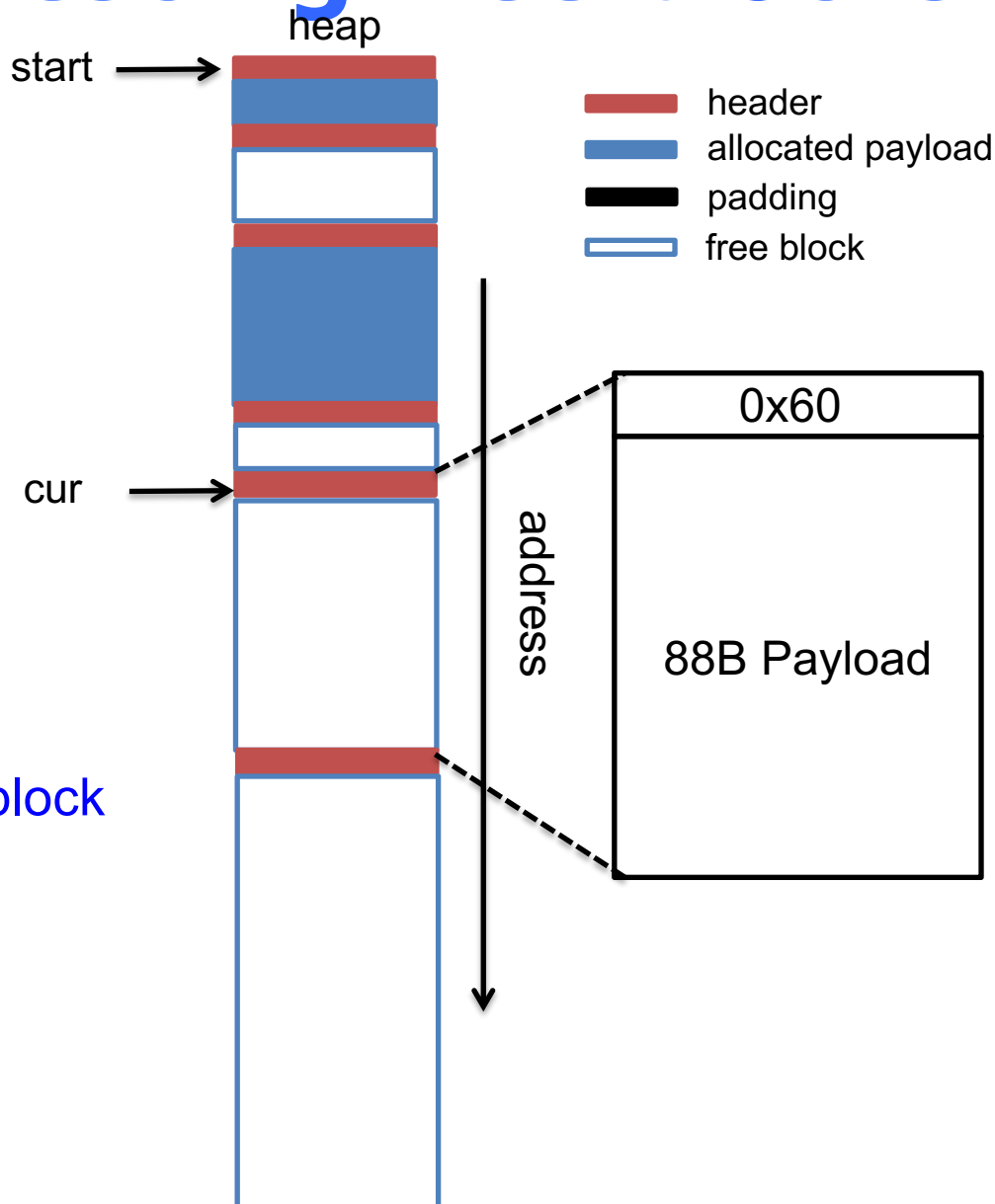
```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
free(p5)
```



# Coalescing free blocks

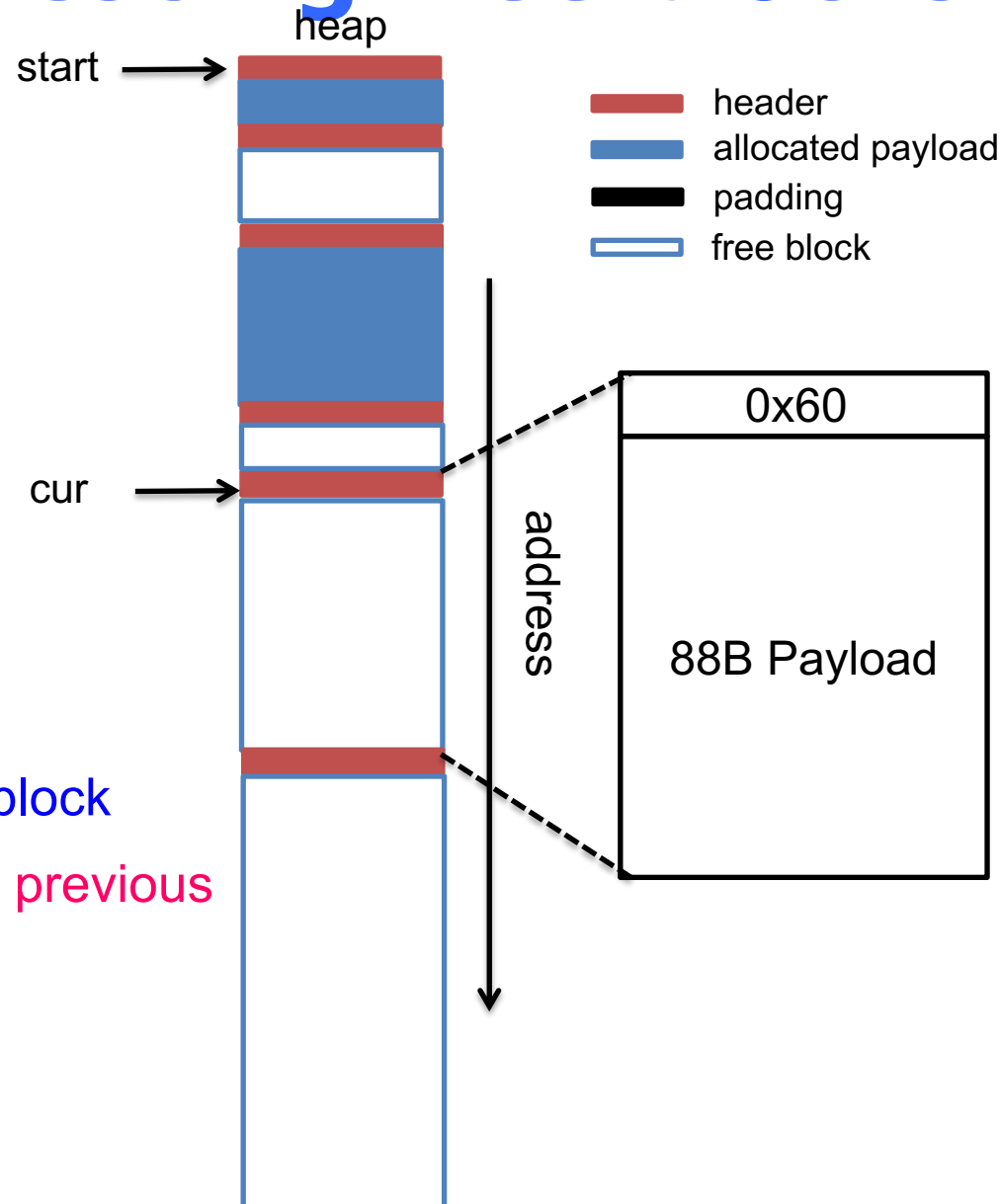
```
p1 = malloc(8)
p2 = malloc(24)
p3 = malloc(56)
p4 = malloc(8)
p5 = malloc(24)
p6 = malloc(56)
free(p2)
free(p4)
free(p6)
free(p5)
```

Coalescing with next block



# Coalescing free 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)
free(p5)
```

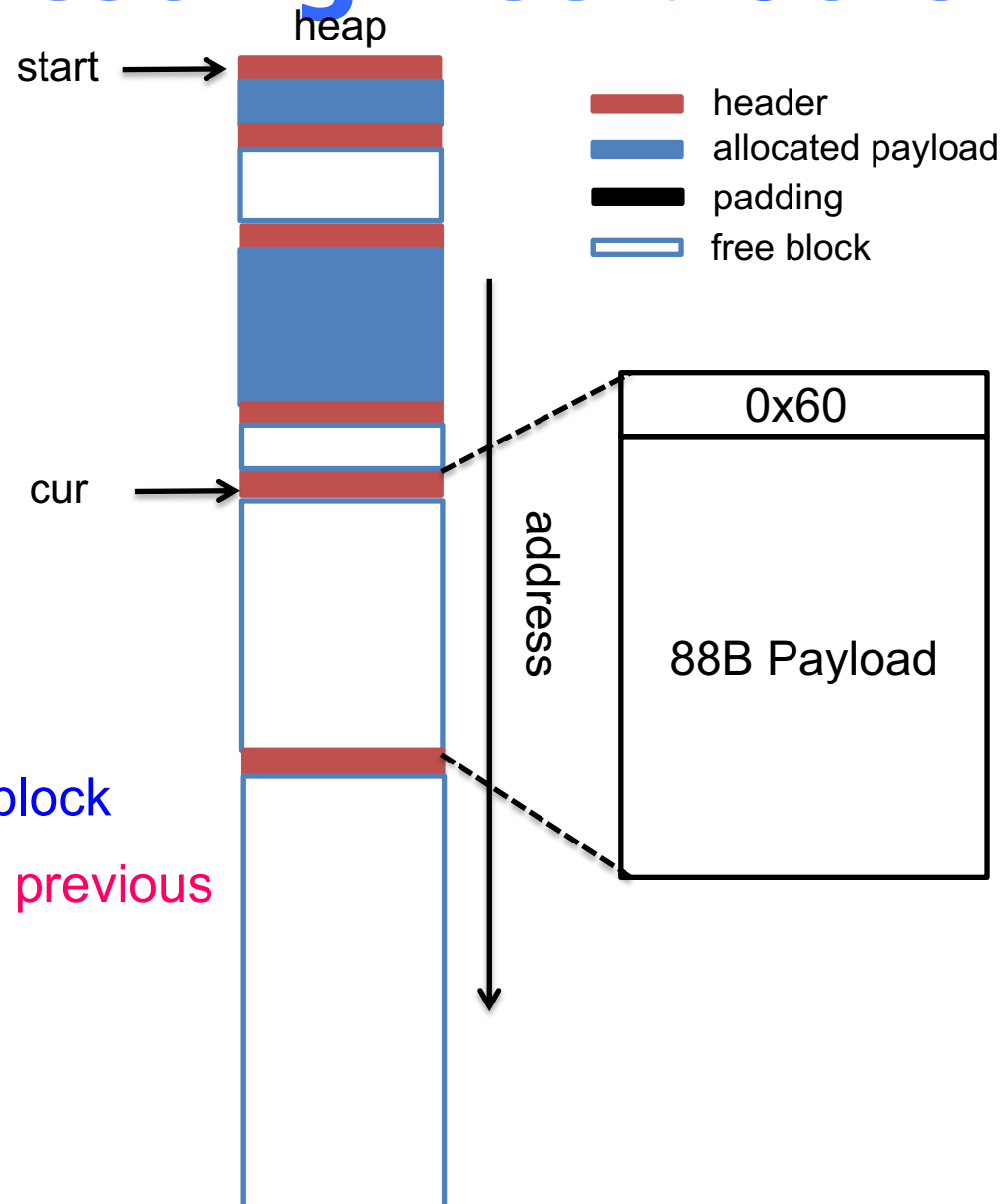



Coalescing with next block

How to coalesce with previous block?

# Coalescing free 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)
free(p5)
```




Coalescing with next block

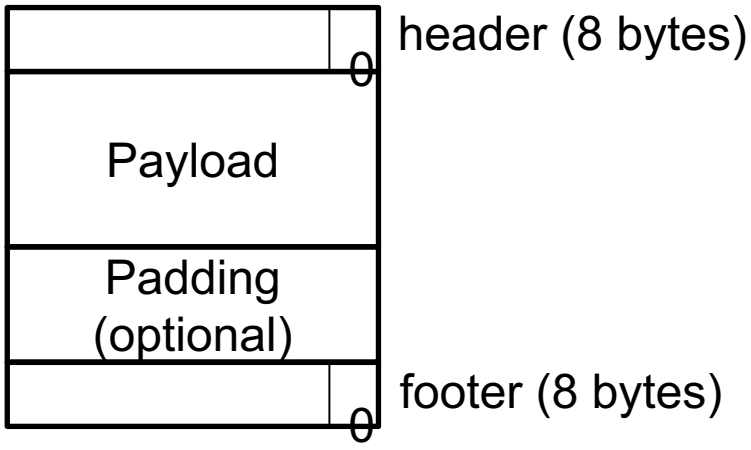
How to coalesce with previous block?

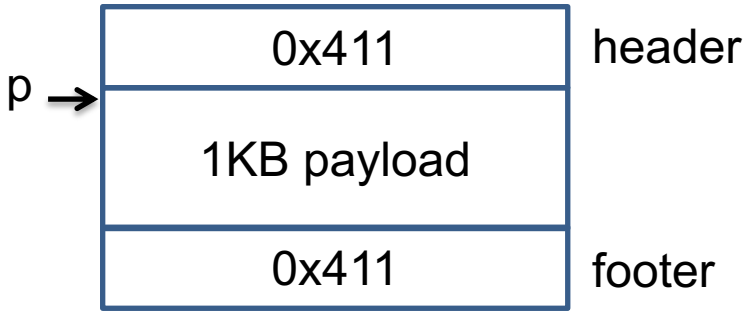
-- search from start?

# Coalescing free blocks

Embed the metadata in the chunks (blocks)

- Each block has a one-word (8 bytes) header and (8 bytes) footer
- Block is double-word (16 bytes) alignment
  → Size is multiple of 16

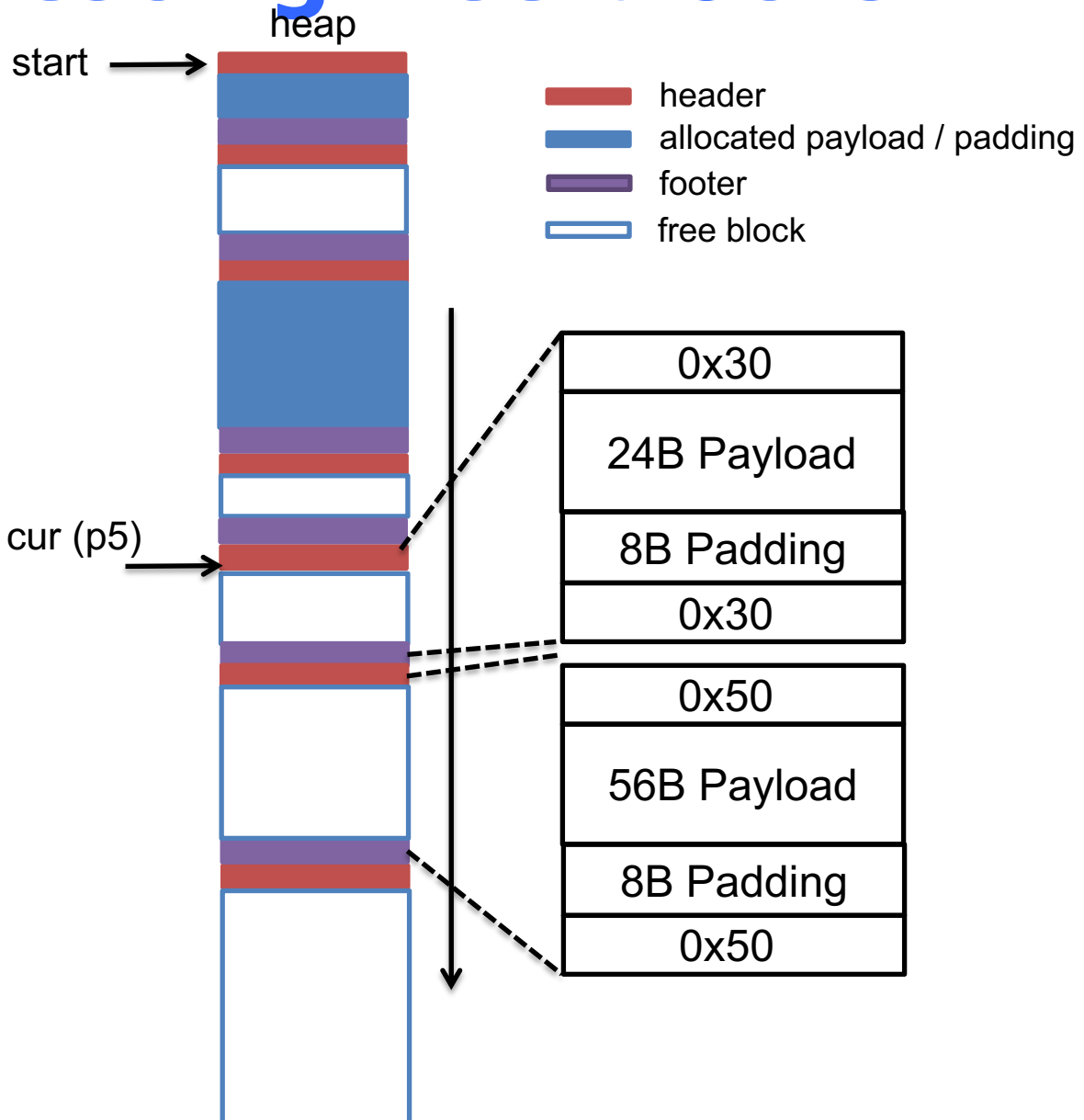



```
p  = malloc(1024)
```

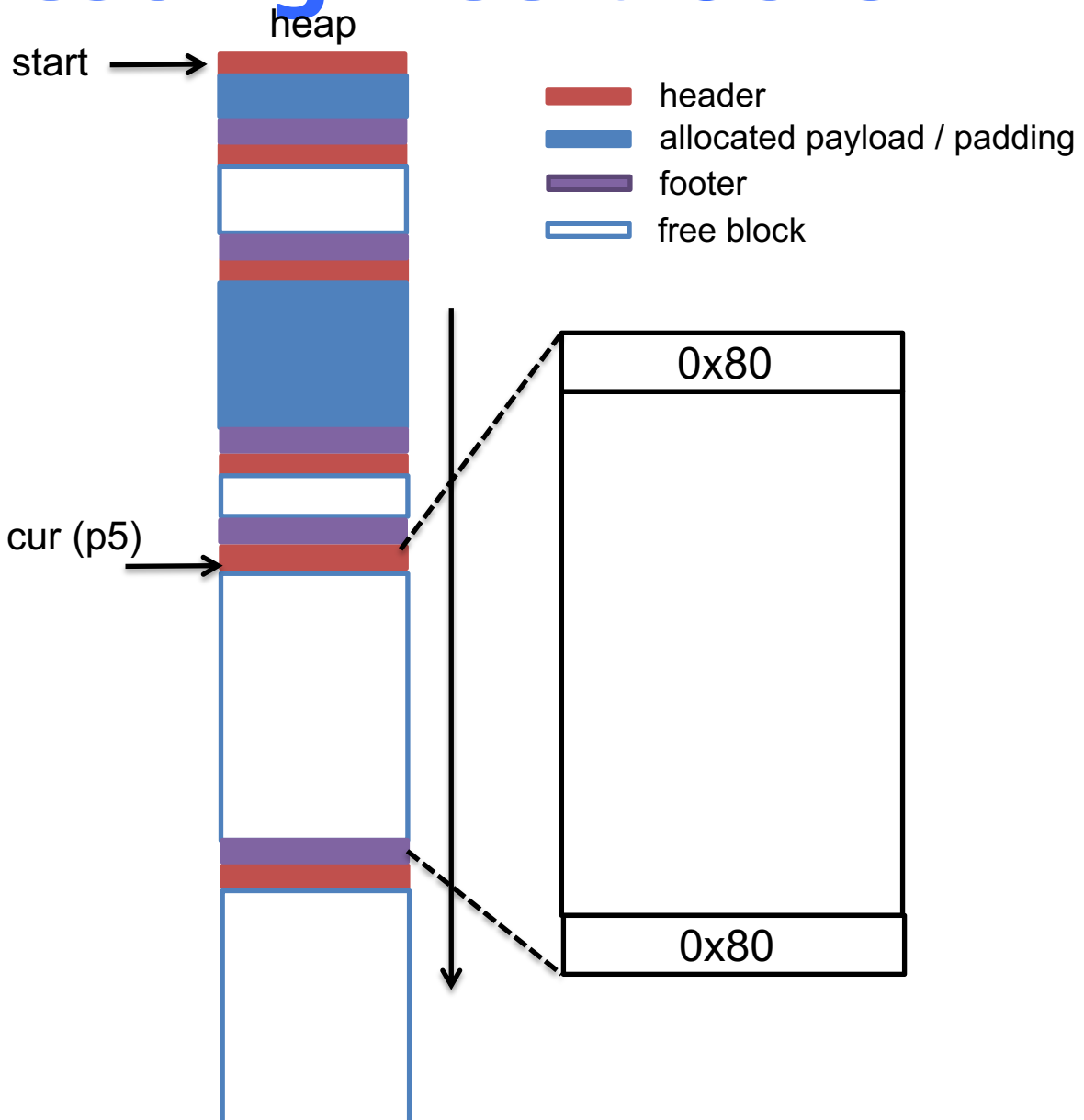
# Coalescing free blocks

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



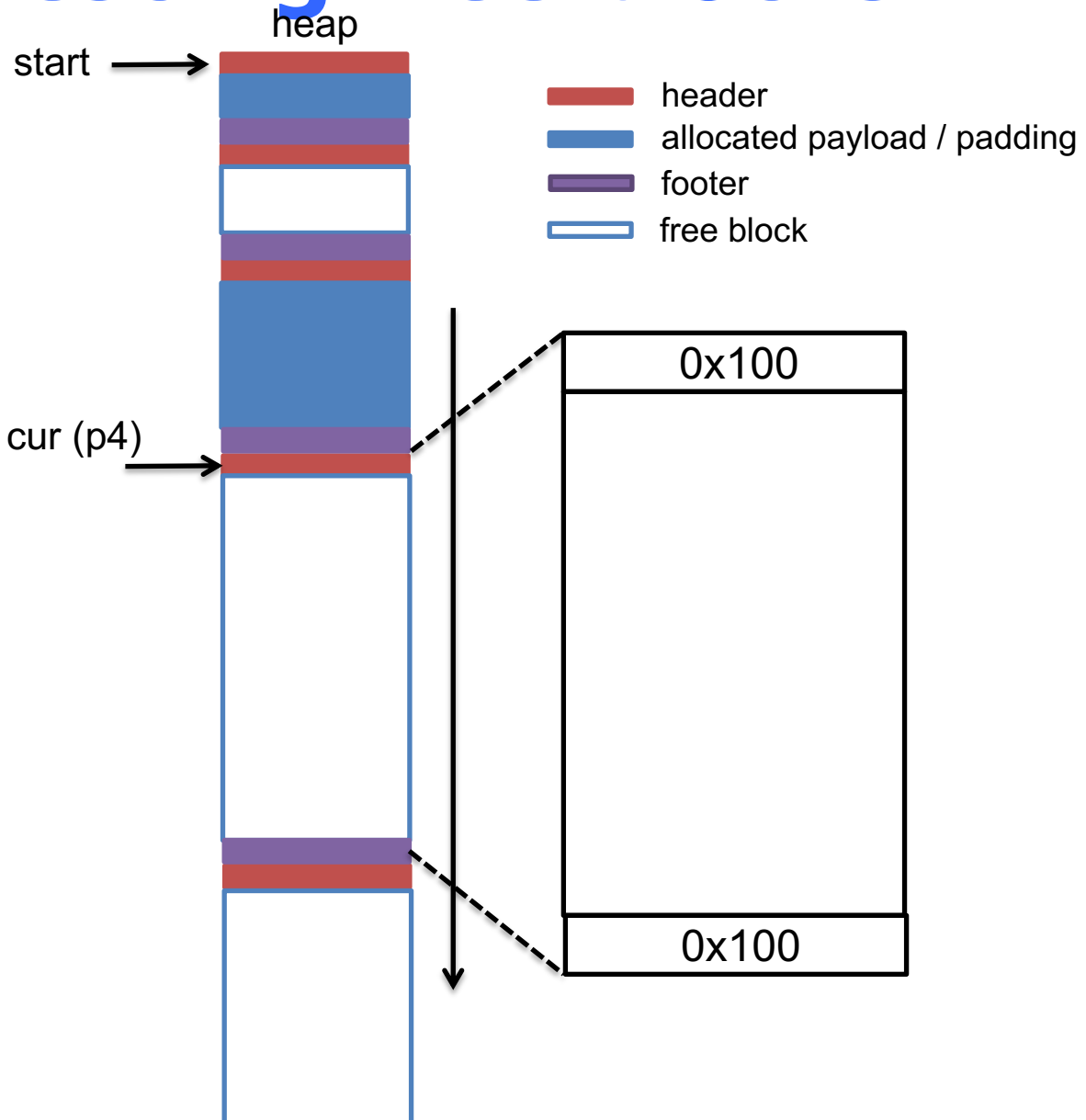
# Coalescing free blocks

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



# Coalescing free 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)
free(p5)
```



# Explicit free lists

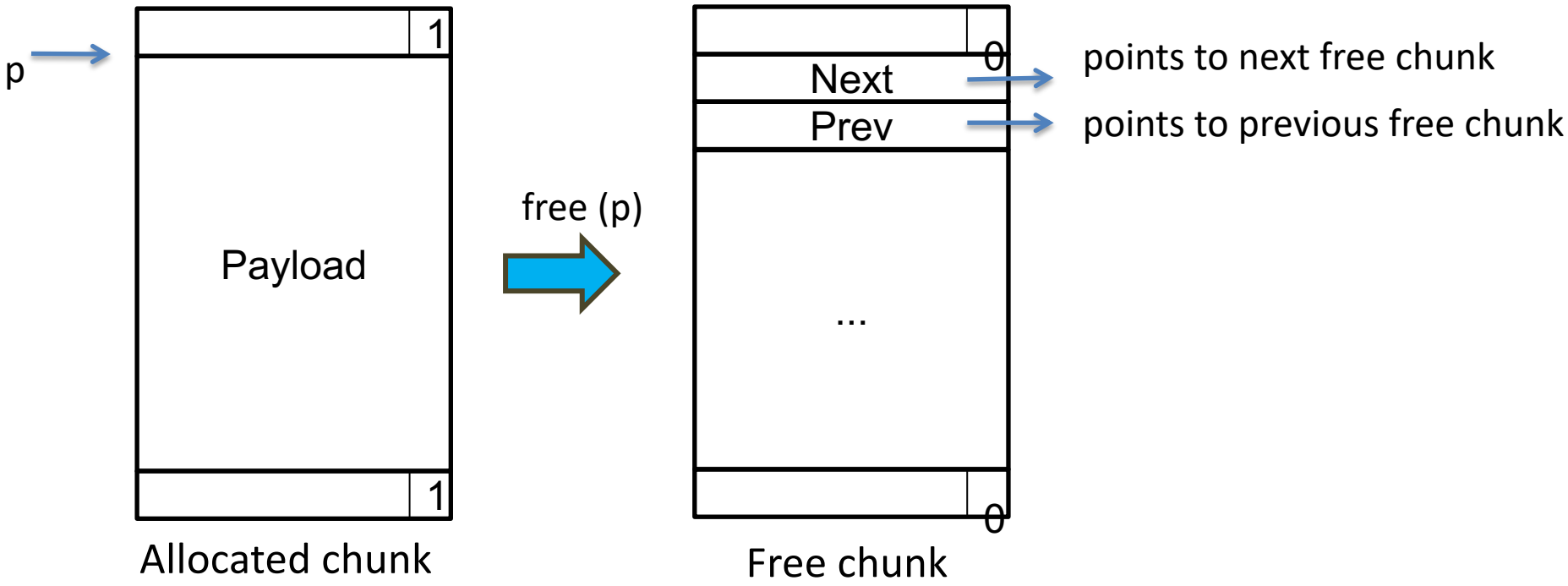
Problems of implicit list:

- 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 free chunk?

Answer: 32 bytes

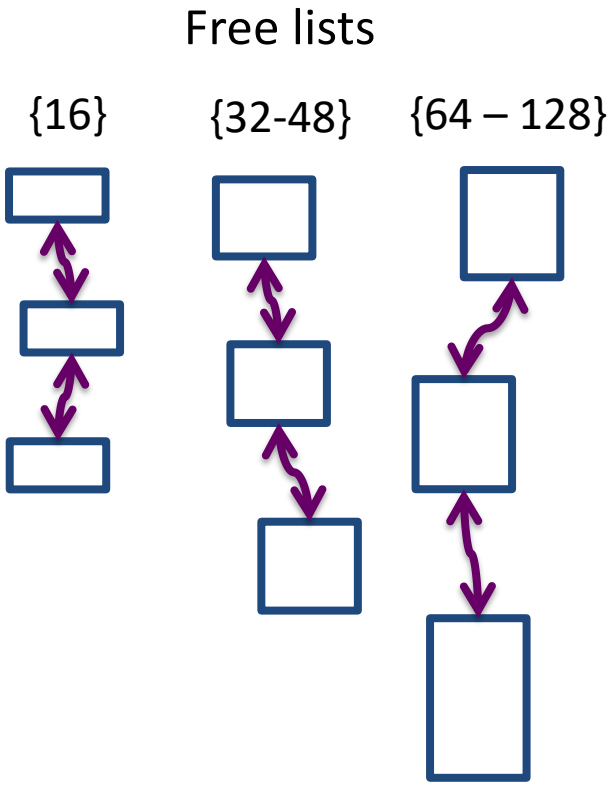
# How to traverse an explicit list

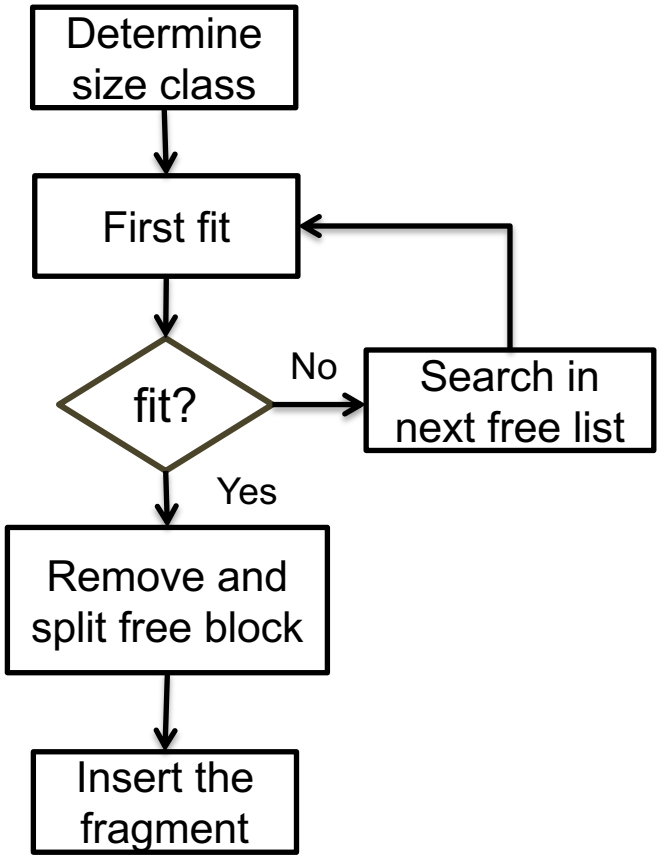
```
typedef struct free_header {
   unsigned long size_n_status;
   struct free_header *next;
   struct free_header *prev;
} free_hdr;

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->size_n_status);
       size_t csz = get_chunksz(f->size_n_status);
       f = f->next;
   }
}
```

# Segregated list

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

# Segregated list



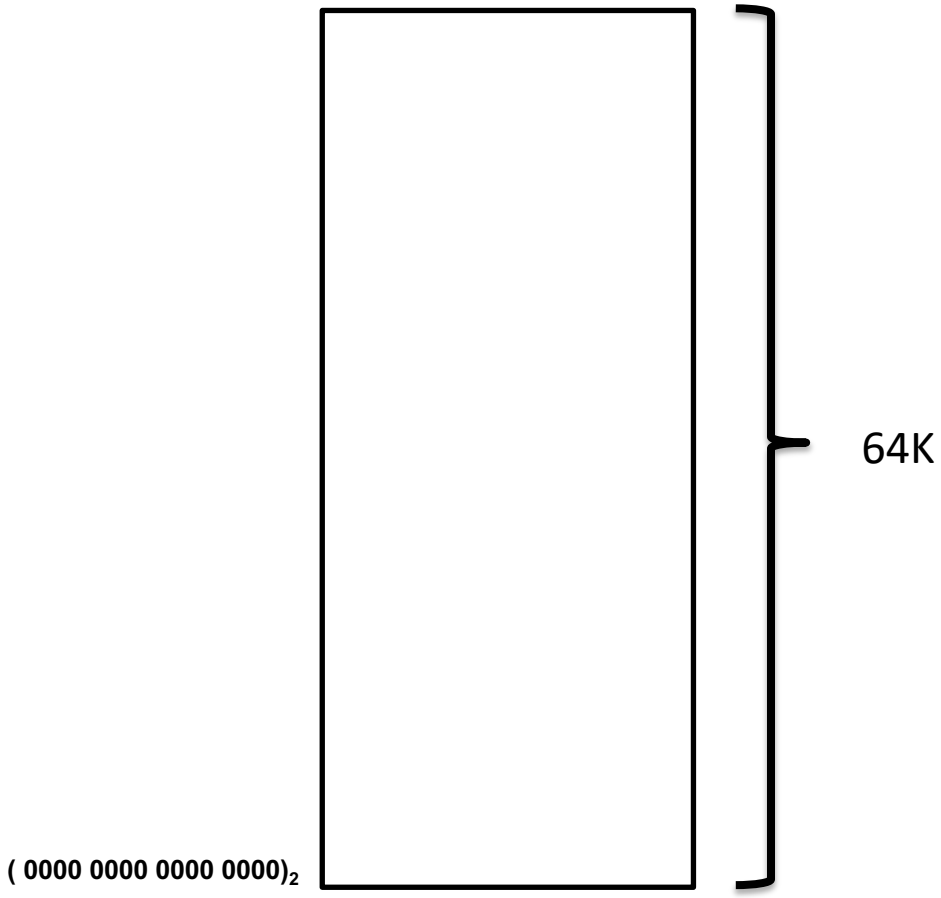
# Buddy System

Adopted by Linux kernel and jemalloc

This lecture

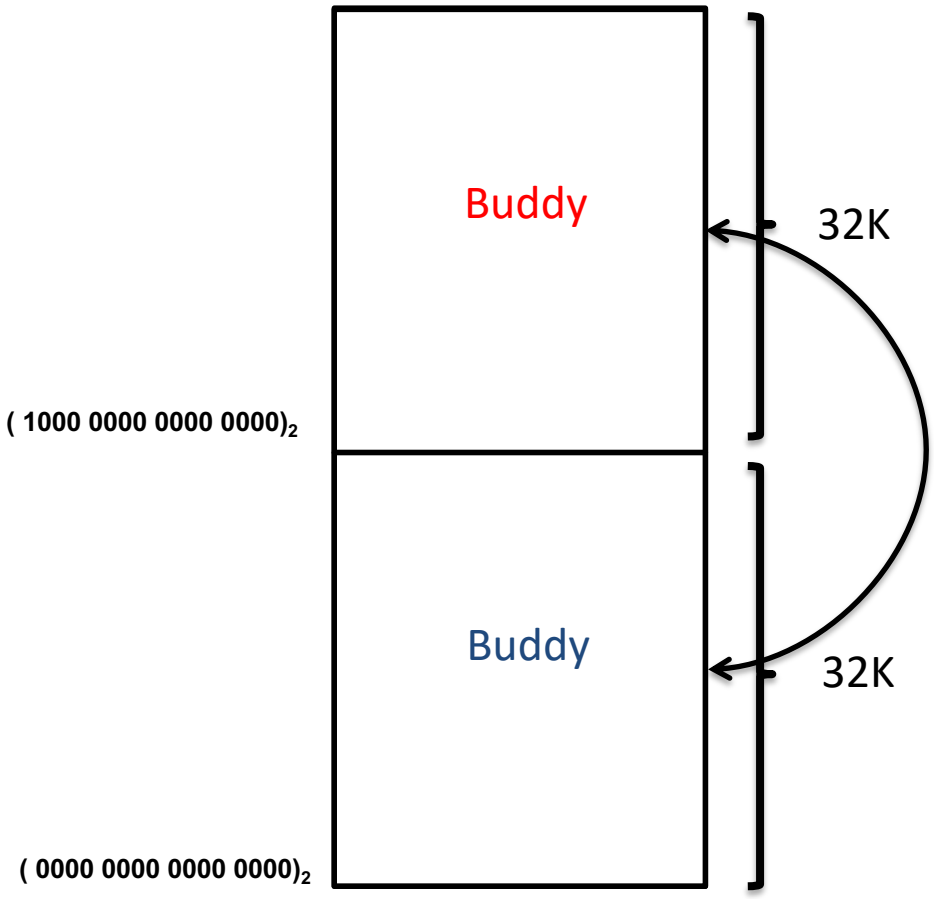
- A simplified binary buddy allocator

# Binary buddy system



# Binary buddy system

Split
- Split exactly in half

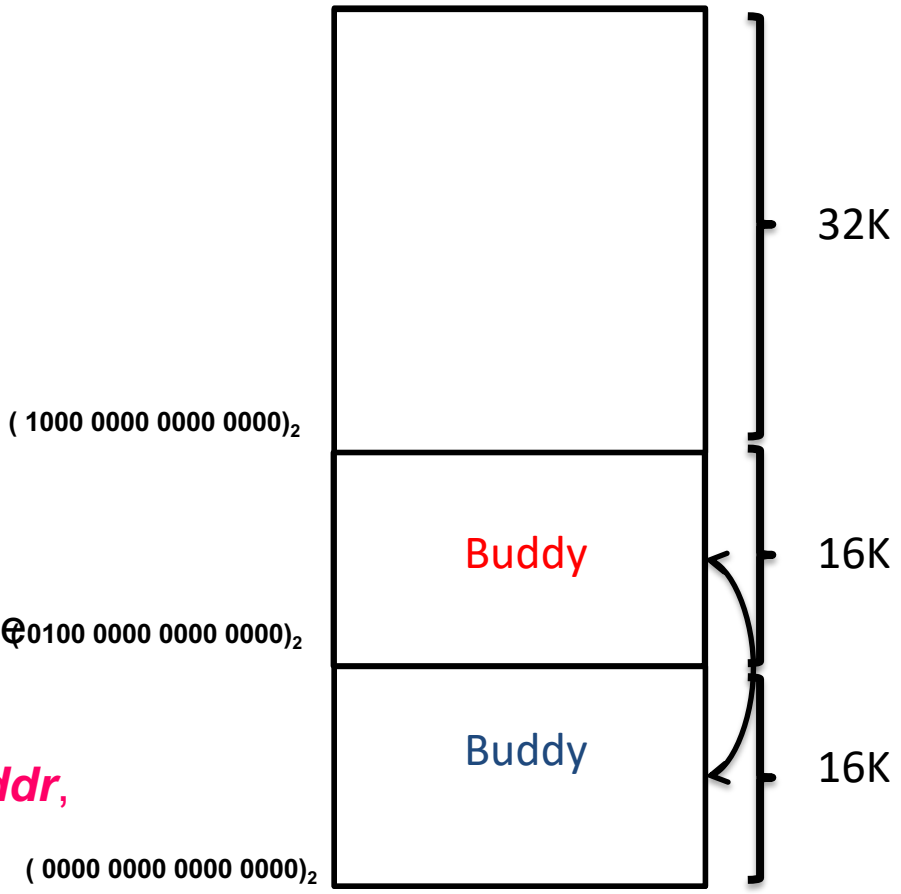


# Binary buddy system

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?

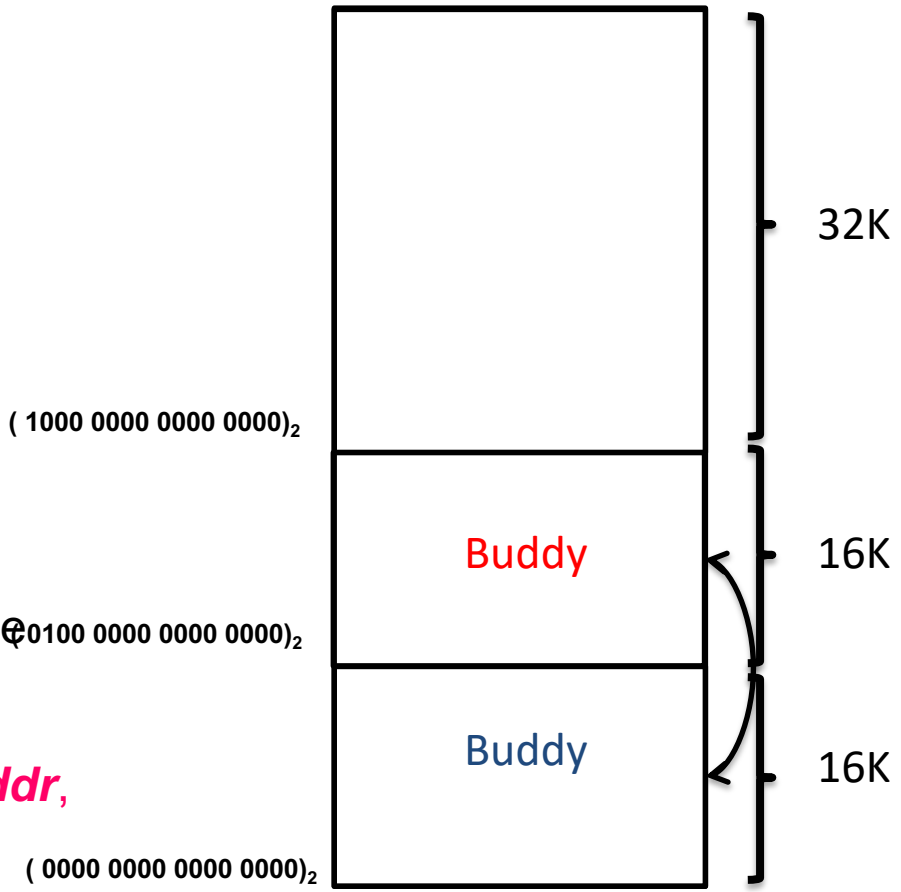


# Binary buddy system

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?
addr of buddy = addr ^ (1<<n)

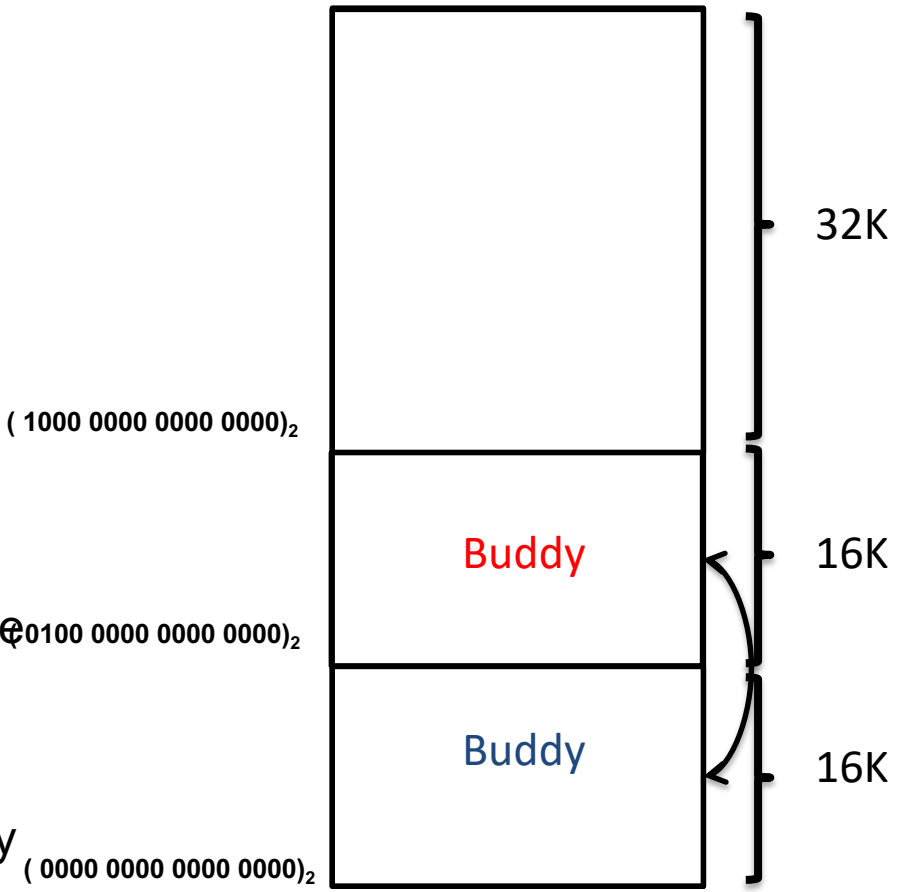


# Binary buddy system

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
- We assume only combine with its buddy block in our lecture

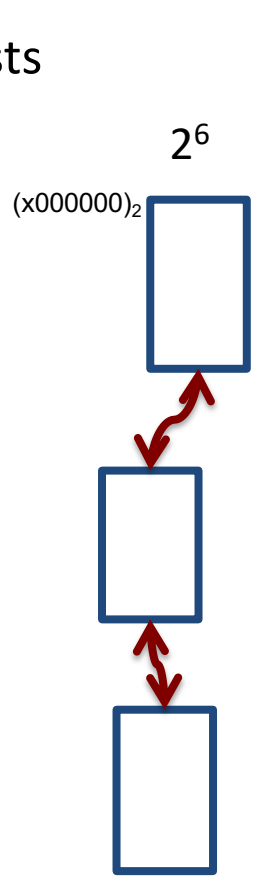


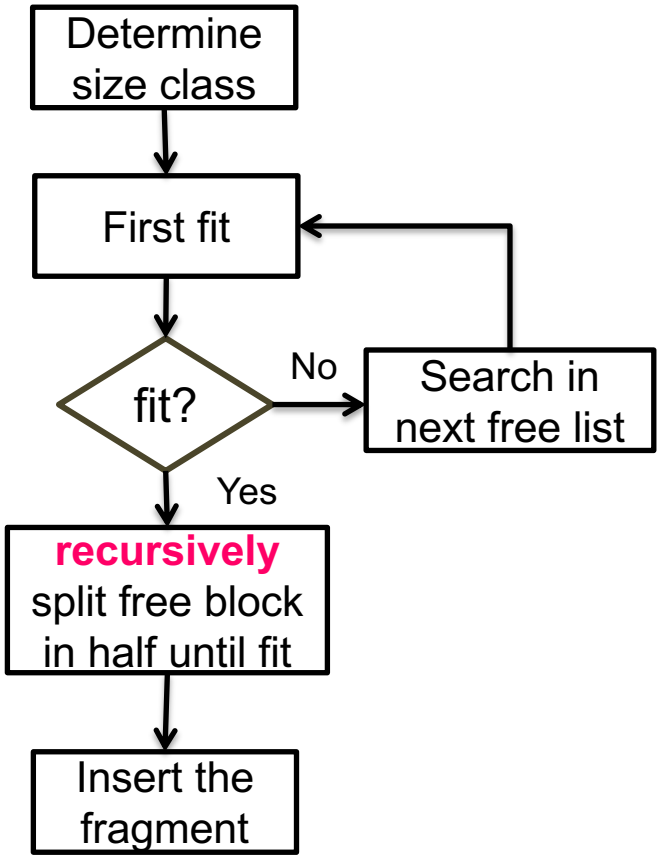
# Buddy system

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

Step 1. search in $2^6$ list

Step 2. recursive split



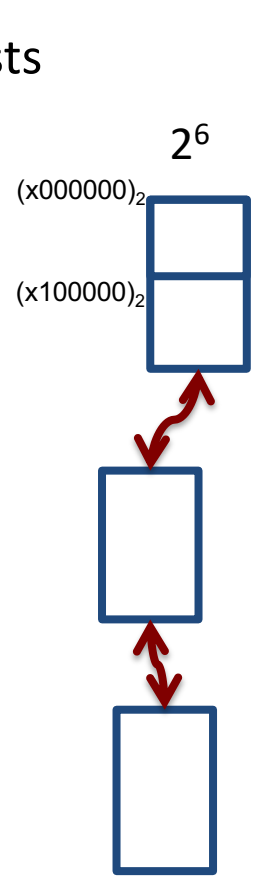

Each list has the same size of blocks which is a power of 2.

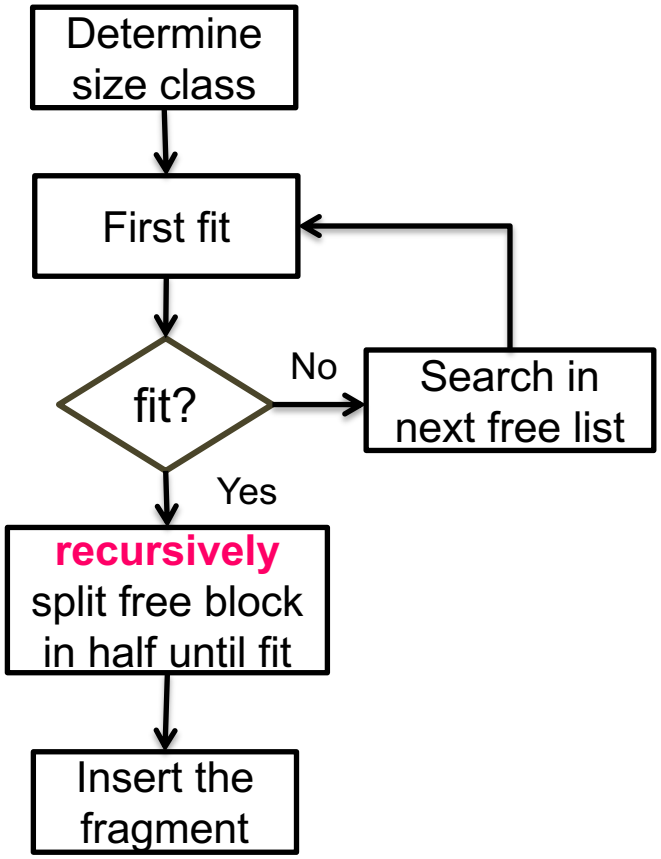
# Buddy system

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

Step 1. search in $2^6$ list

Step 2. recursive split



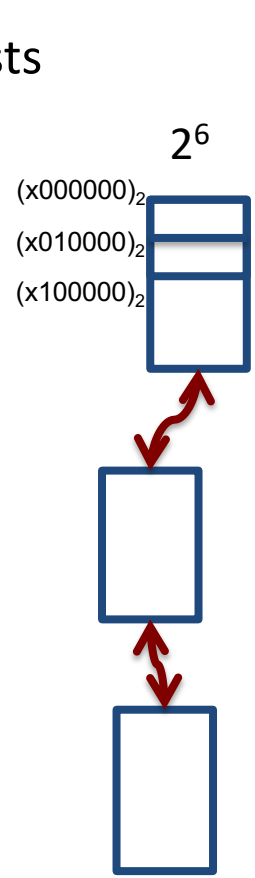



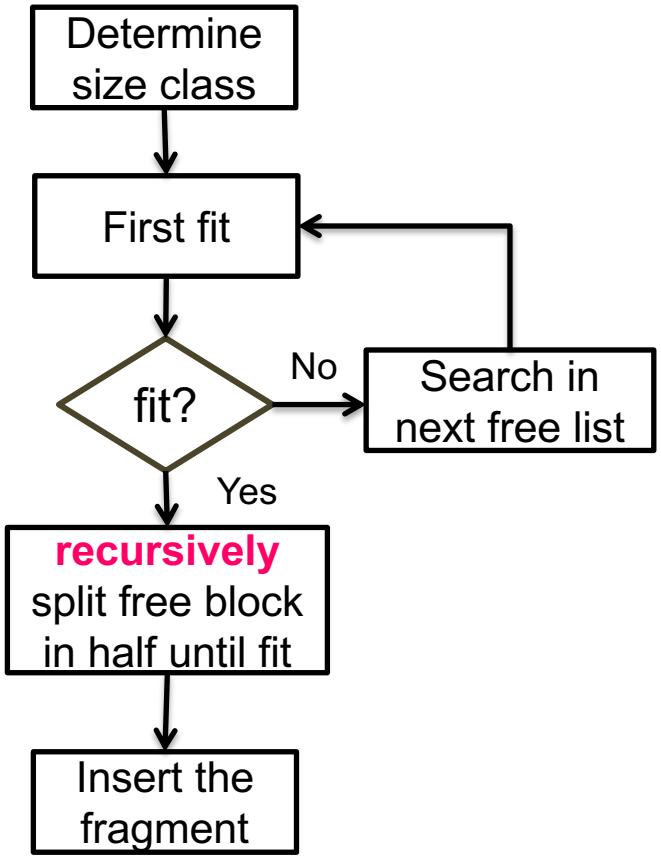
# Buddy system

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

Step 1. search in $2^6$ list

Step 2. recursive split



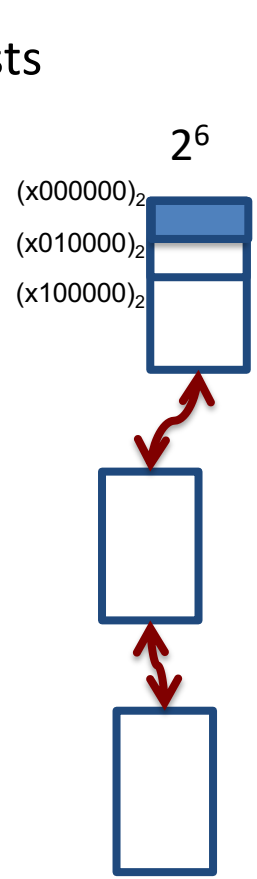



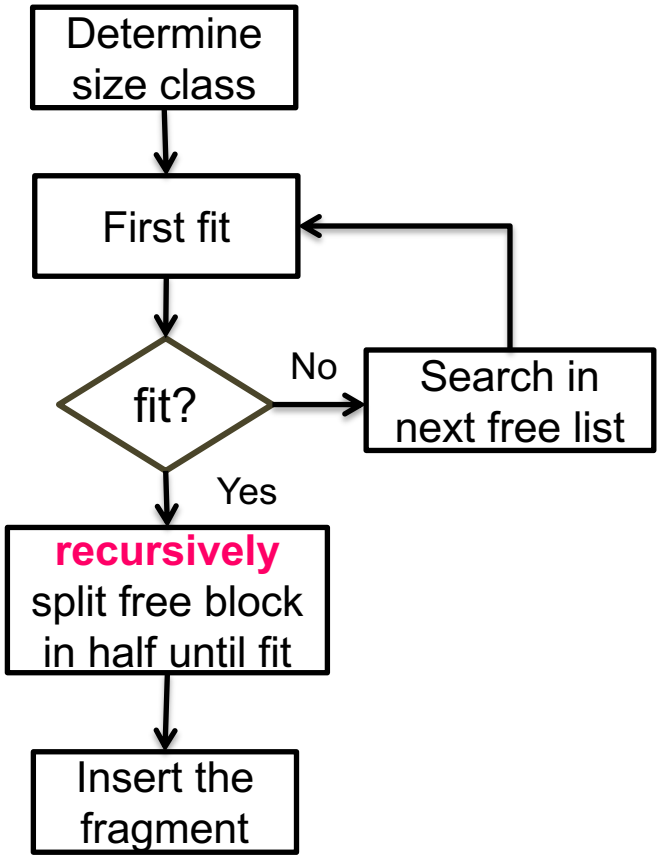
# Buddy system

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

Step 1. search in $2^6$ list

Step 2. recursive split



# Buddy system

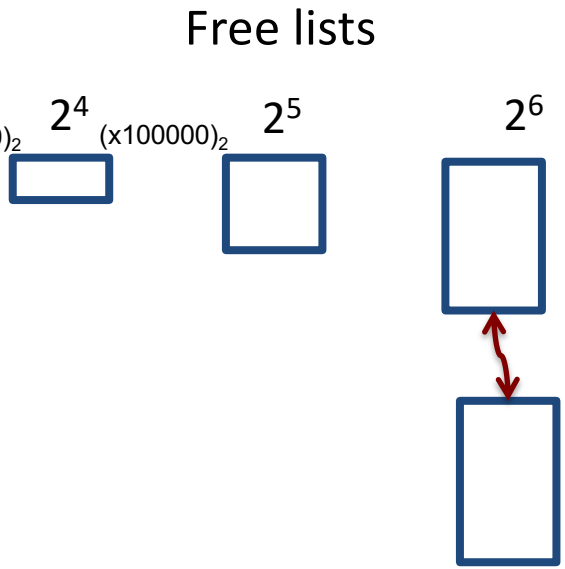
`p = malloc(1)`

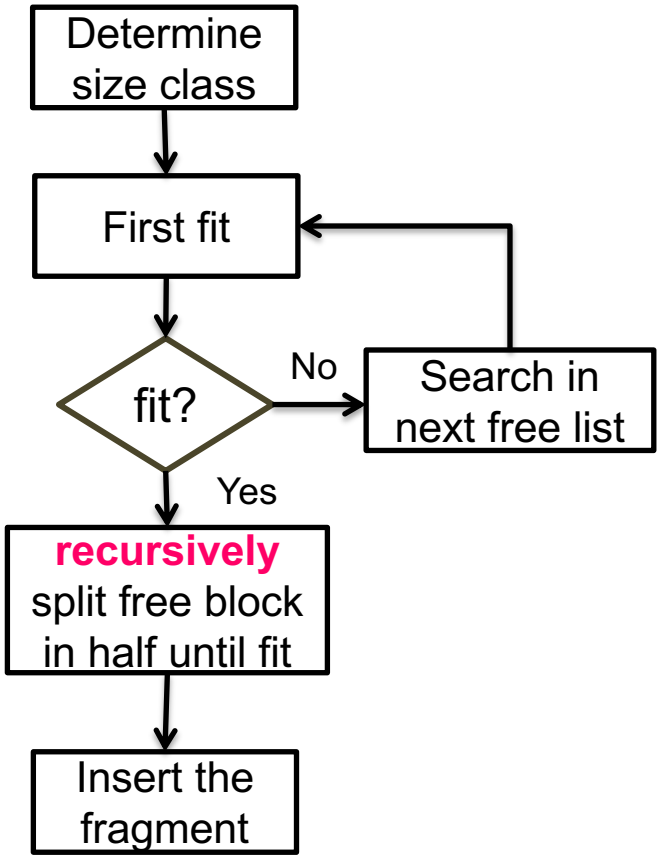
Step 1. search in $2^6$ list

Step 2. recursive split

Step 3. insert free blocks into the list

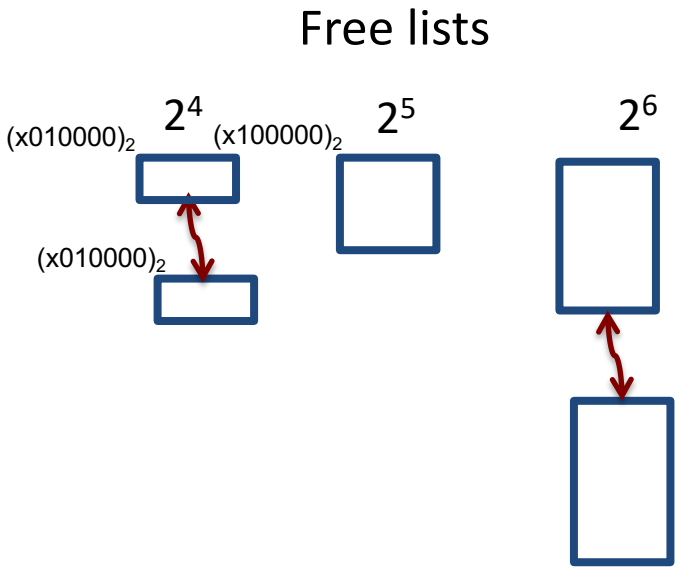
Step 4. return, p is $(x000000)_2$

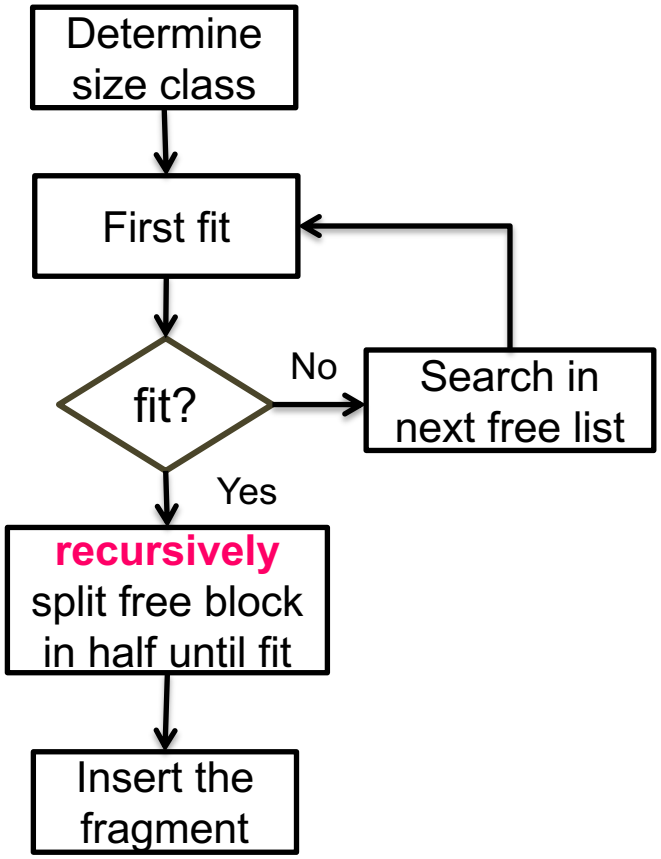


# Buddy system

```
p = malloc(1)

free(p)
```

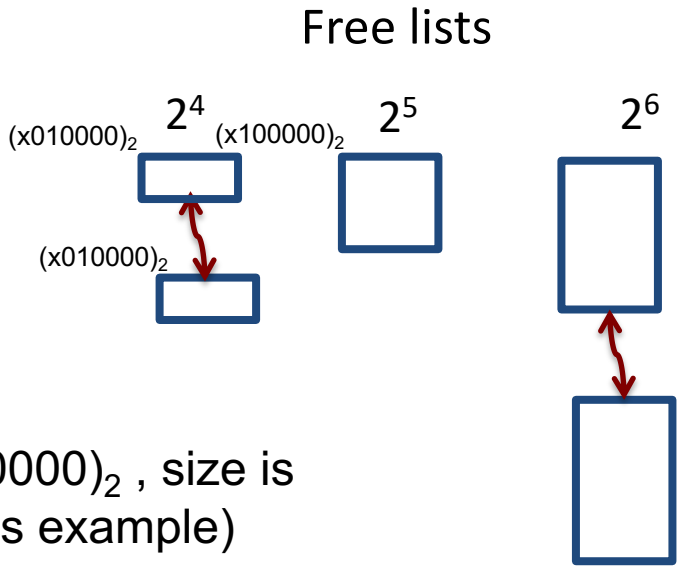


# Buddy system

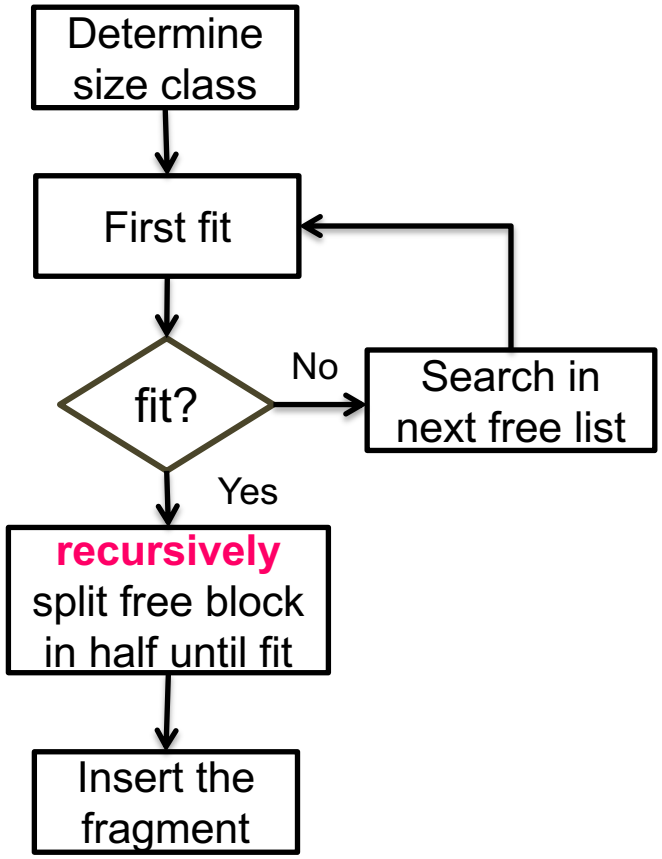
```
p = malloc(1)
```

free(p)




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

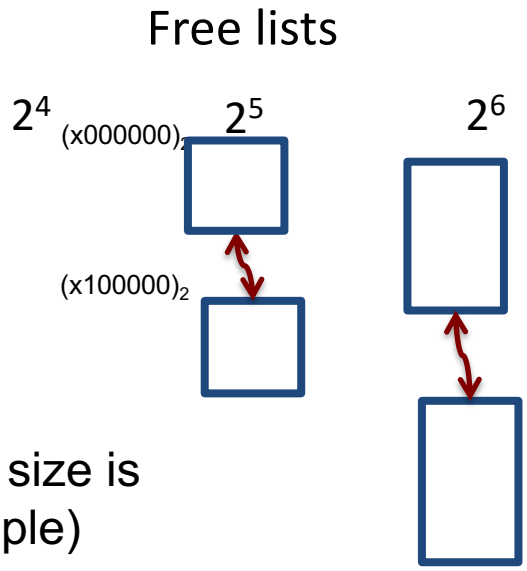
→ p's buddy is 16 B block begins at x000000 ^ (1<<4) which is $(x010000)_2$



# Buddy system

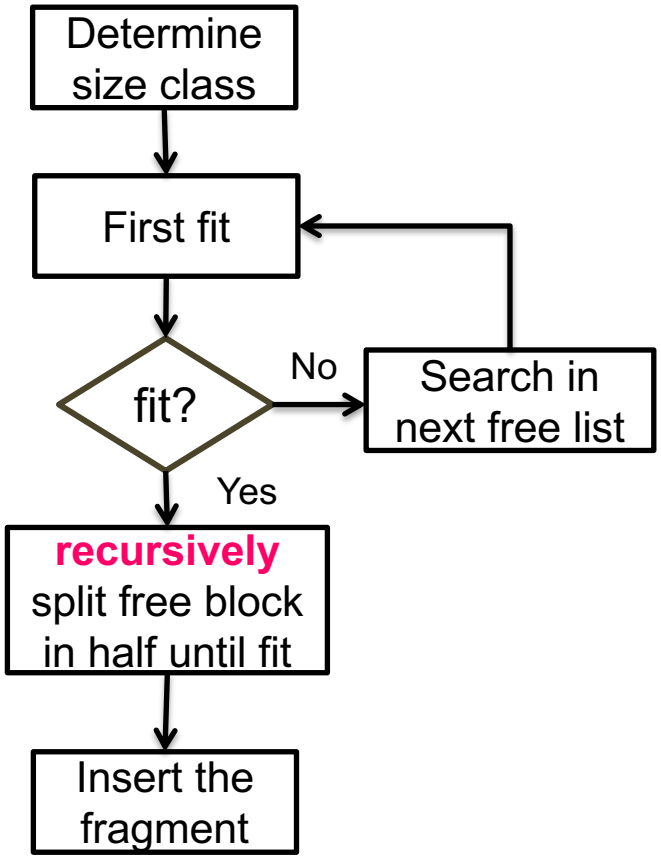
```
p = malloc(1)
```

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 $(x100000)_2$