15-213

“The course that gives CMU its Zip!”

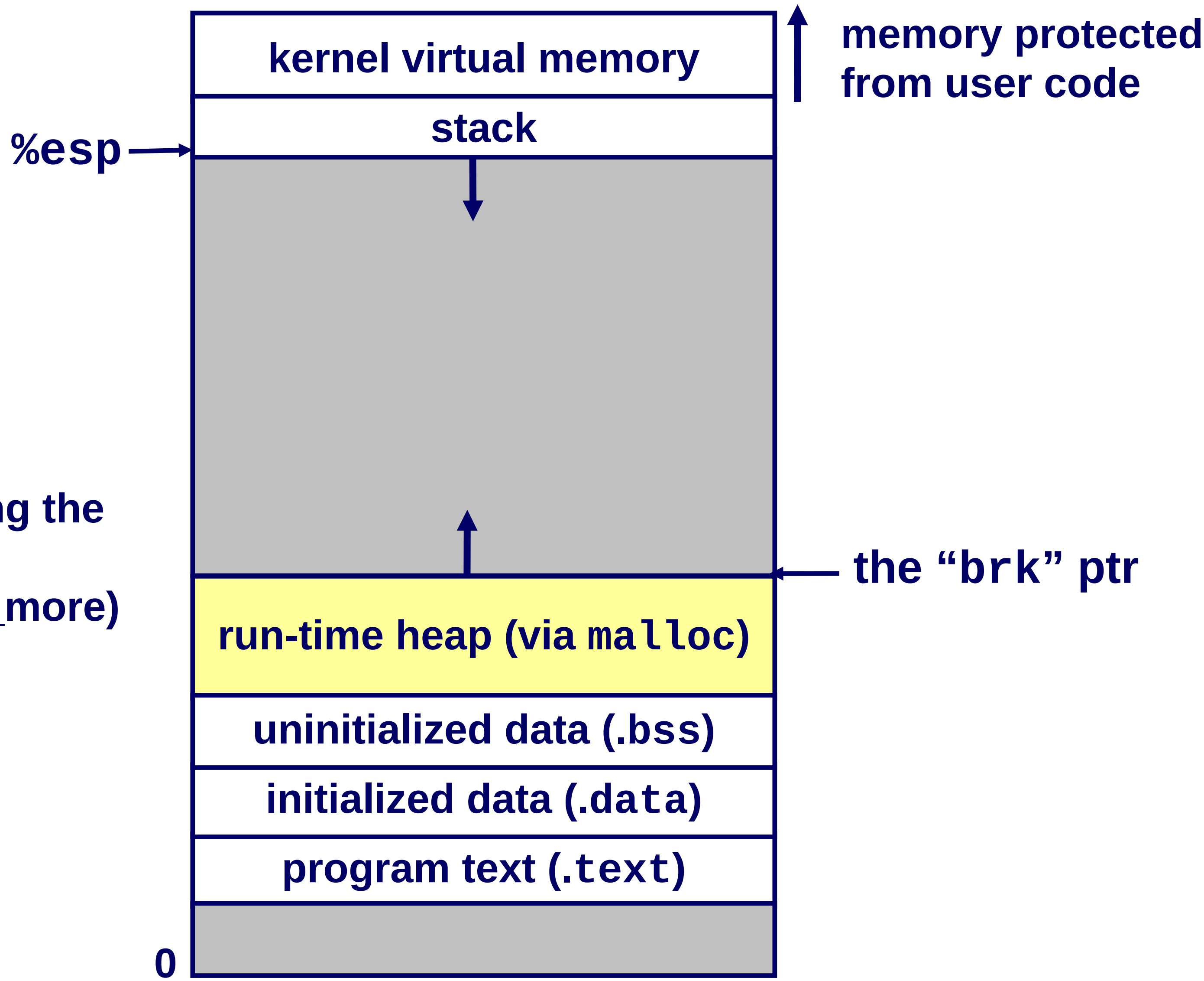
Dynamic Memory Allocation I
October 16, 2008

Topics

- **Simple explicit allocators**
  - **Data structures**
  - **Mechanisms**
  - **Policies**

`lecture-15.ppt`

Process Memory Image



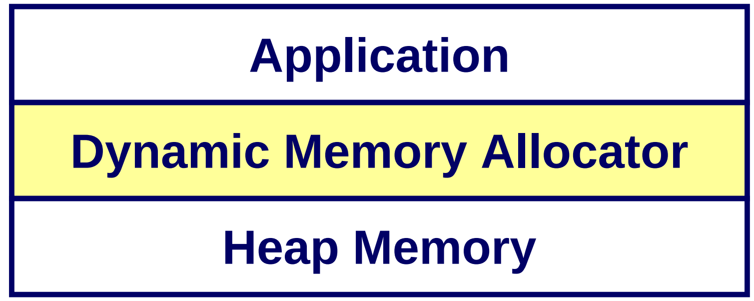
Allocators request
Add'l heap memory
from the kernel using the
`sbrk()` function:

error = sbrk (&amt_more)

Dynamic Memory Allocation

Memory Allocator?

- VM hardware and kernel allocate *pages*
- Application objects are typically smaller
- Allocator manages objects within pages
  - 4K page can hold ~64 64-byte objects



Explicit vs. Implicit Memory Allocator

- Explicit: application allocates and frees space
  - E.g., `malloc()` and `free()` in C
- Implicit: application allocates, but does not free space
  - E.g. garbage collection in Java, ML or Lisp

Allocation

- A memory allocator doles out memory blocks to application
- A “block” is a contiguous range of bytes
  - of any size, in this context

Will discuss simple explicit memory allocation today

Malloc Package

```
#include <stdlib.h>
```

```
void *malloc(size_t size)
```

- If successful:
  - Returns a pointer to a memory block of at least size bytes, (typically) aligned to 8-byte boundary
  - If size == 0, returns NULL
- If unsuccessful: returns NULL (0) and sets errno

```
void free(void *p)
```

- Returns the block pointed at by p to pool of available memory
- p must come from a previous call to `malloc()` or `realloc()`

```
void *realloc(void *p, size_t size)
```

- Changes size of block p and returns pointer to new block
- Contents of new block unchanged up to min of old and new size
- Old block has been `free()`'d (logically, if new != old)

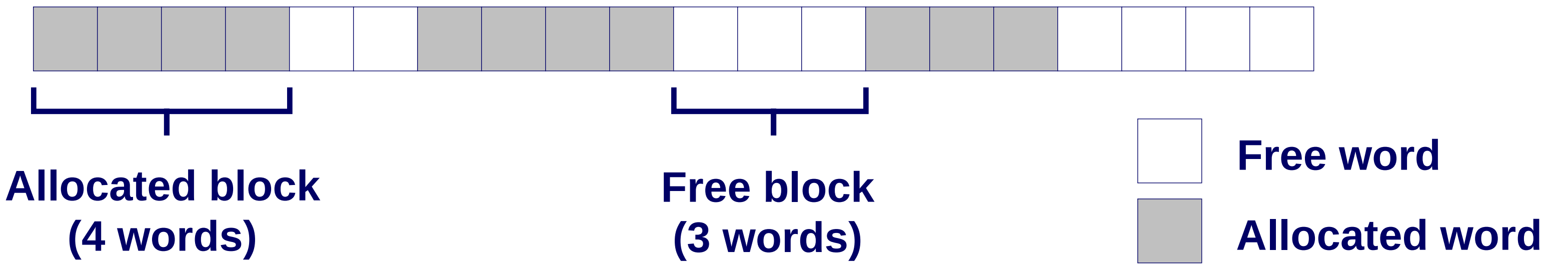
Malloc Example

```
void foo(int n, int m) {
  int i, *p;

  /* allocate a block of n ints */
  p = (int *)malloc(n * sizeof(int));
  if (p == NULL) {
    perror("malloc");
    exit(0);
  }
  for (i=0; i<n; i++) p[i] = i;

  /* add m bytes to end of p block */
  if ((p = (int *) realloc(p, (n+m) * sizeof(int))) == NULL) {
    perror("realloc");
    exit(0);
  }
  for (i=n; i < n+m; i++) p[i] = i;

  /* print new array */
  for (i=0; i<n+m; i++)
    printf("%d\n", p[i]);

  free(p); /* return p to available memory pool */
}
```

Assumptions

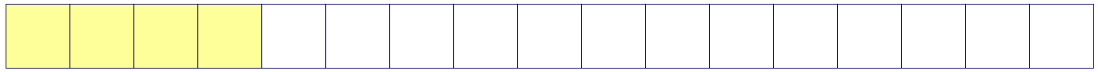
Assumptions made in this lecture

- Memory is word addressed (each word can hold a pointer)

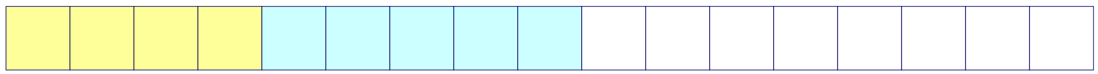


Allocation Examples

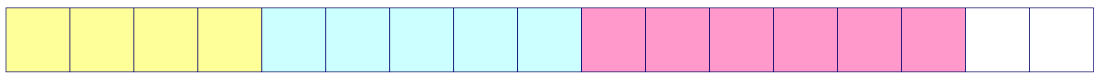
`p1 = malloc(4)`



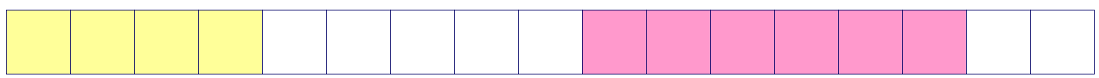
`p2 = malloc(5)`



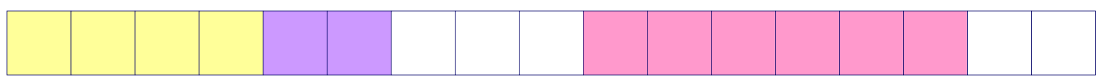
`p3 = malloc(6)`



`free(p2)`



`p4 = malloc(2)`



Constraints

Applications:

- Can issue arbitrary sequence of malloc() and free() requests
- Free() requests must correspond to a malloc()'d block

Allocators

- Can't control number or size of allocated blocks
- Must respond immediately to malloc() requests
  - *i.e.*, can't reorder or buffer requests
- Must allocate blocks from free memory
  - *i.e.*, can only place allocated blocks in free memory
- Must align blocks so they satisfy all alignment requirements
  - 8 byte alignment for GNU malloc (`libc` malloc) on Linux boxes
- Can manipulate and modify only free memory
- Can't move the allocated blocks once they are malloc()'d
  - *i.e.*, compaction is not allowed

Performance Goals: Throughput

Given some sequence of `malloc` and `free` requests:

- $R_0, R_1, ..., R_k, ... , R_{n-1}$

Goals: maximize throughput and peak memory utilization

- **These goals are often conflicting**

Throughput:

- **Number of completed requests per unit time**
- **Example:**
  - **5,000 `malloc()` calls and 5,000 `free()` calls in 10 seconds**
  - **Throughput is 1,000 operations/second**

Performance Goals: Peak Memory Utilization

Given some sequence of `malloc` and `free` requests:

- ***$R_0, R_1, ..., R_k, ... , R_{n-1}$***

Def: Aggregate payload P_k:

- **`malloc(p)` results in a block with a *payload* of p bytes**
- **After request R_k has completed, the *aggregate payload* P_k is the sum of currently allocated payloads**
  - **all `malloc()`'d stuff minus all `free()`'d stuff**

Def: Current heap size is denoted by H_k

- **Assume that H_k is monotonically nondecreasing**
  - **reminder: it grows when allocator uses `sbrk()`**

Def: Peak memory utilization:

- **After *k* requests, *peak memory utilization* is:**
  - $U_k = (\max_{i<k} P_i) \;/\; H_k$

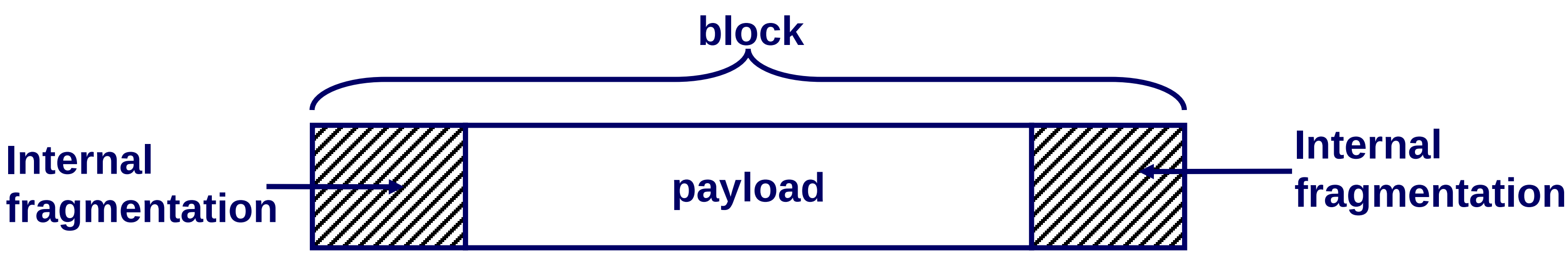
Internal Fragmentation

Poor memory utilization caused by *fragmentation*.

- **Comes in two forms: *internal* and *external* fragmentation**

Internal fragmentation

- **For a given block, *internal fragmentation* is the difference between the block size and the payload size**

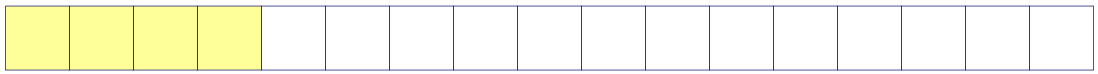


- **Caused by overhead of maintaining heap data structures, padding for alignment purposes, or explicit policy decisions (e.g., to return a big block to satisfy a small request)**
- **Depends only on the pattern of *previous* requests**
  - **thus, easy to measure**

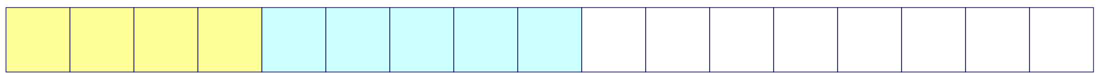
External Fragmentation

Occurs when there is enough aggregate heap memory, but no single free block is large enough

`p1 = malloc(4)`



`p2 = malloc(5)`



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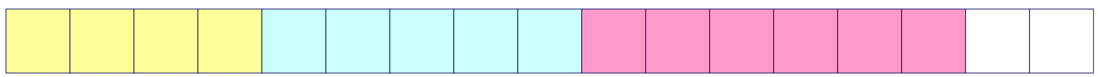
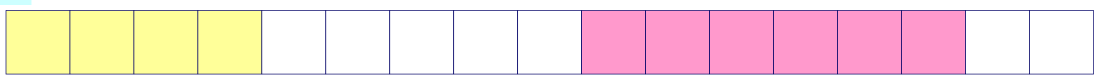


`free(p2)`



`p4 = malloc(6)`

Oops!

External fragmentation depends on the pattern of *future* requests

- thus, difficult to measure

Implementation Issues

How do we know how much memory is being `free()`'d when we are given only a pointer (no length)?

How do we keep track of the free blocks?

What do we do with extra space when allocating a block that is smaller than the free block it is placed in?

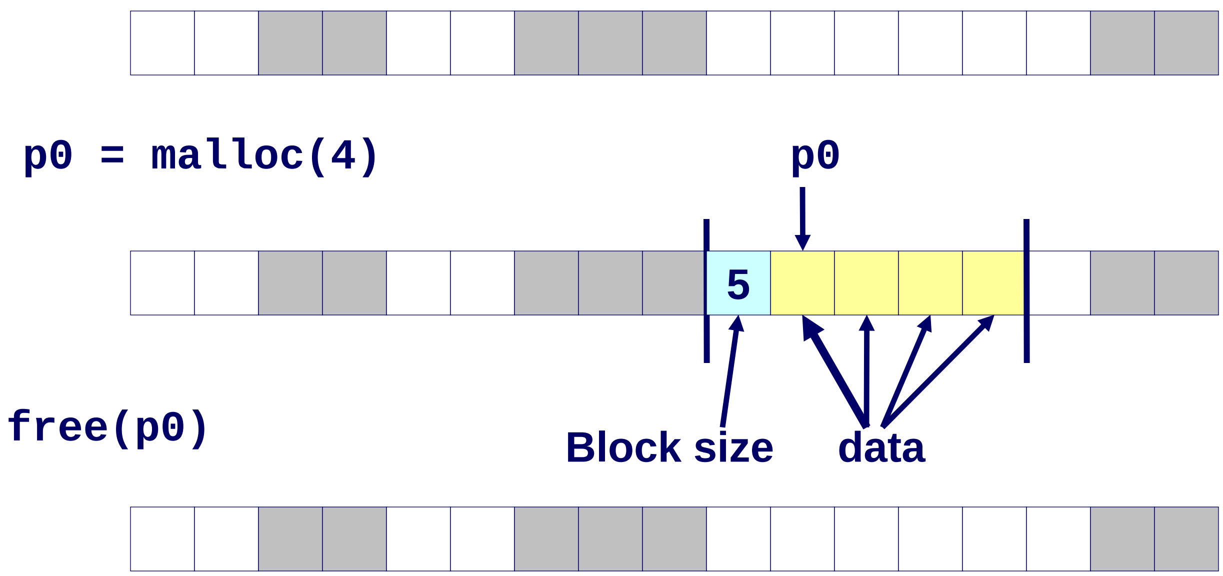
How do we pick a block to use for allocation -- many might fit?

How do we reinsert a freed block into the heap?

Knowing How Much to Free

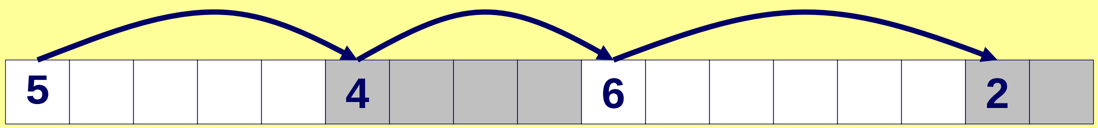
Standard method

- **Keep the length of a block in the word preceding the block.**
  - **This word is often called the *header field* or *header***
- **Requires an extra word for every allocated block**

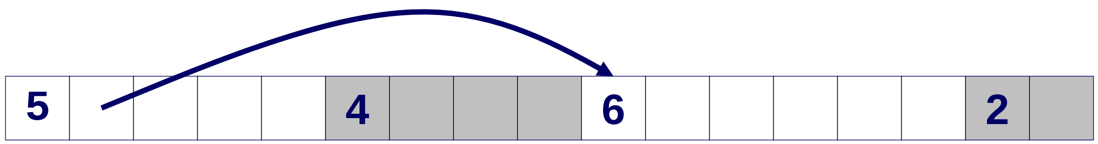


Keeping Track of Free Blocks

Method 1: *Implicit list* using lengths -- links all blocks



Method 2: *Explicit list* among the free blocks using pointers within the free blocks



Method 3: *Segregated free list*

- Different free lists for different size classes

Method 4: Blocks sorted by size

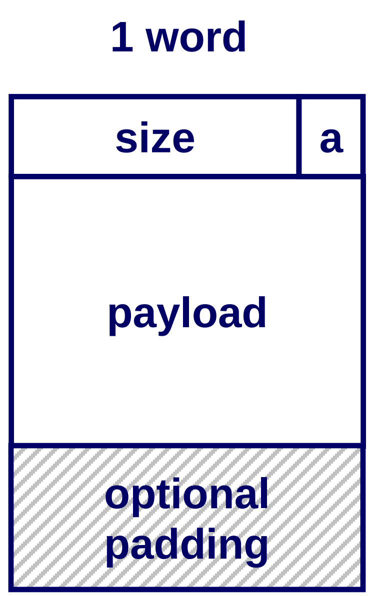
- Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Method 1: Implicit List

For each block we need (length, is-allocated?)

- Could store this information in two words - wasteful!
- Standard trick
  - If blocks are aligned, some low-order address bits are always 0
  - Instead of storing an always-0 bit, use it as a allocated/free flag
    - When reading size word, must mask out this bit

Format of allocated and free blocks



a = 1: allocated block
a = 0: free block

size: block size

payload: application data
(allocated blocks only)

Implicit List: Finding a Free Block

First fit:

- Search list from beginning, choose <u>first</u> free block that fits

```
p = start;
while ((p < end) &&       \\ not passed end
       ((*p & 1) ||       \\ already allocated
       (*p <= len)))      \\ too small
  p = p + (*p & -2);      \\ goto next block
```

- Can take linear time in total number of blocks (allocated and free)
- In practice it can cause “splinters” at beginning of list

Next fit:

- Like first-fit, but search list starting where previous search finished
  - Should often be faster than first-fit – avoids re-scanning unhelpful blocks
  - Some research suggests that fragmentation is worse

Best fit:

- Search the list, choose the <u>best</u> free block: fits, with fewest bytes left over
- Keeps fragments small --- usually helps fragmentation
- Will typically run slower than first-fit

Bit Fields

How to represent the Header:

Masks and bitwise operators

```
#define SIZEMASK                (~0x7)
#define PACK(size, alloc)  ((size) | (alloc))
#define GET_SIZE(p)       ((p)->size & SIZEMASK)
```

Bit Fields

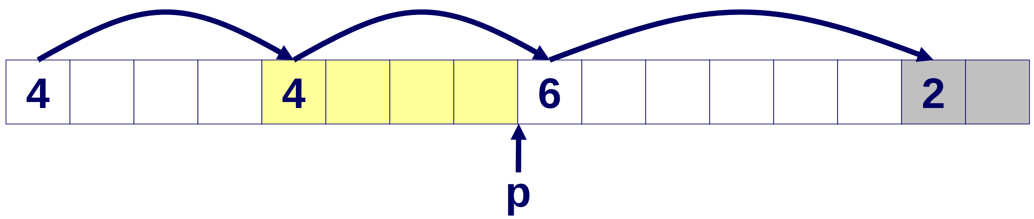
```
struct {
    unsigned allocated:1;
    unsigned size:31;
} Header;
```

Check your K&R: structures are not necessarily packed

Implicit List: Allocating in Free Block

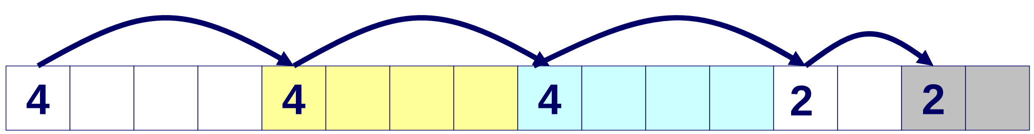
Allocating in a free block - *splitting*

- Since allocated space might be smaller than free space, we might want to split the block




```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // add 1 and round up
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   part of block
```

`addblock(p, 2)`



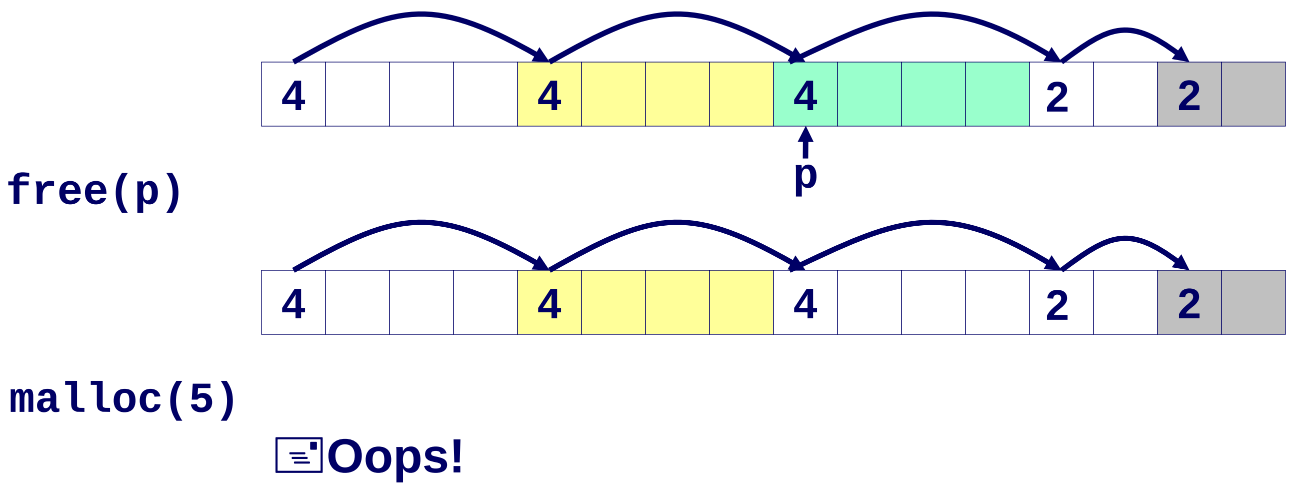
Implicit List: Freeing a Block

Simplest implementation:

- Need only clear the "allocated" flag

```
void free_block(ptr p) { *p = *p & -2}
```

- But can lead to "false fragmentation"



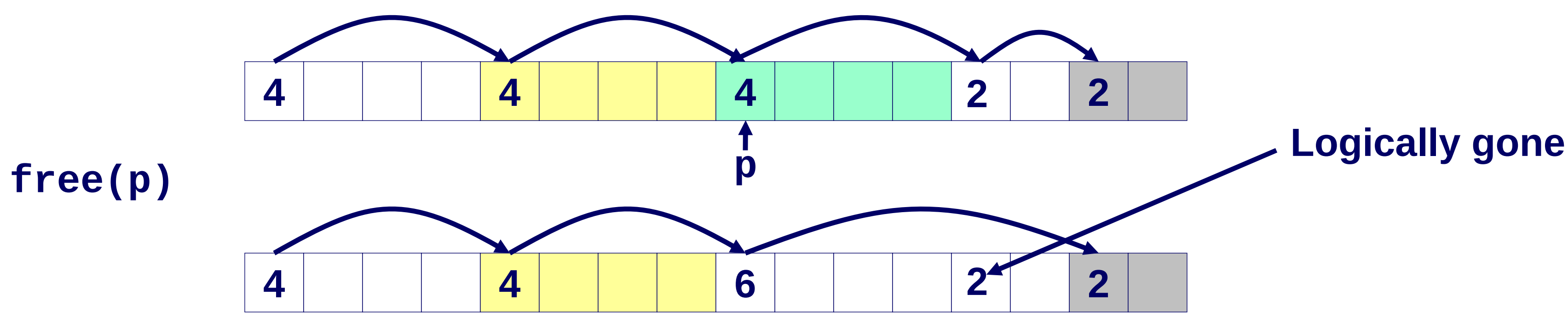
There is enough free space, but the allocator won't be able to find it

Implicit List: Coalescing

Join (*coalesce*) with next and/or previous blocks, if they are free

- Coalescing with next block

```
void free_block(ptr p) {
    *p = *p & -2;            // clear allocated flag
    next = p + *p;           // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;      // add to this block if
}                           //    not allocated
```

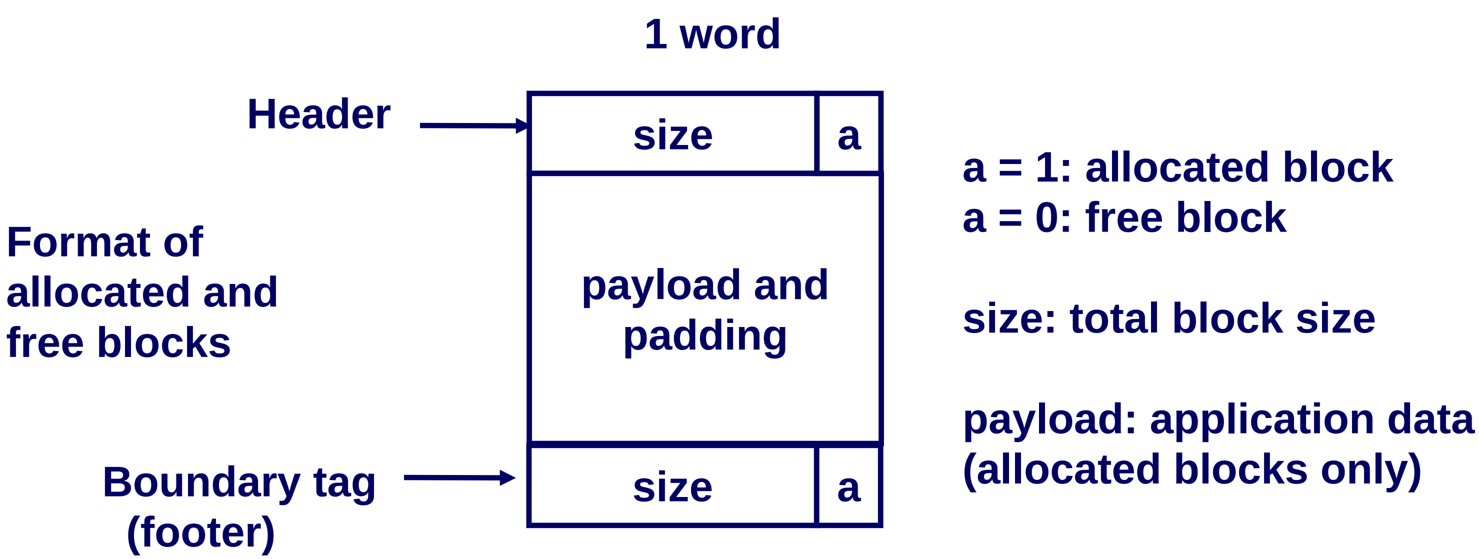


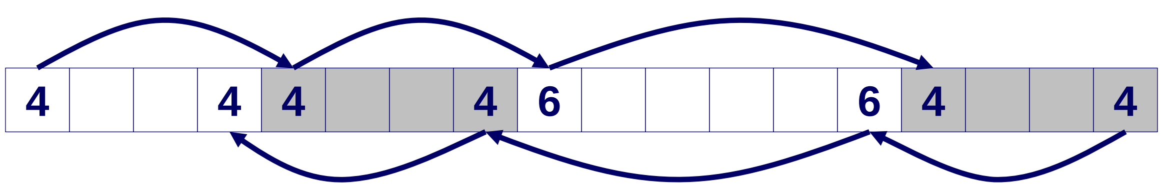
- But how do we coalesce with *previous* block?

Implicit List: Bidirectional Coalescing

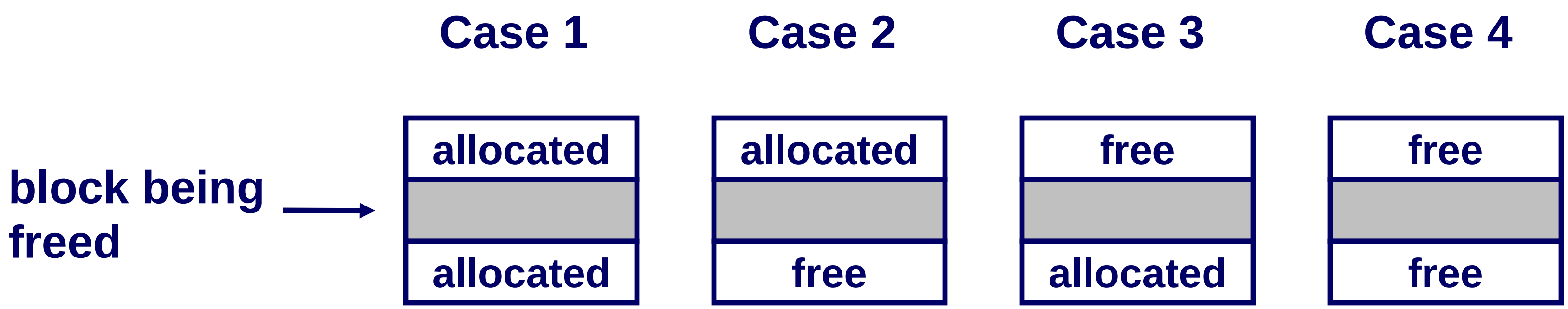
Boundary tags **[Knuth73]**

- **Replicate size/allocated word at "bottom" (end) of free blocks**
- **Allows us to traverse the "list" backwards, but requires extra space**
- **Important and general technique!**

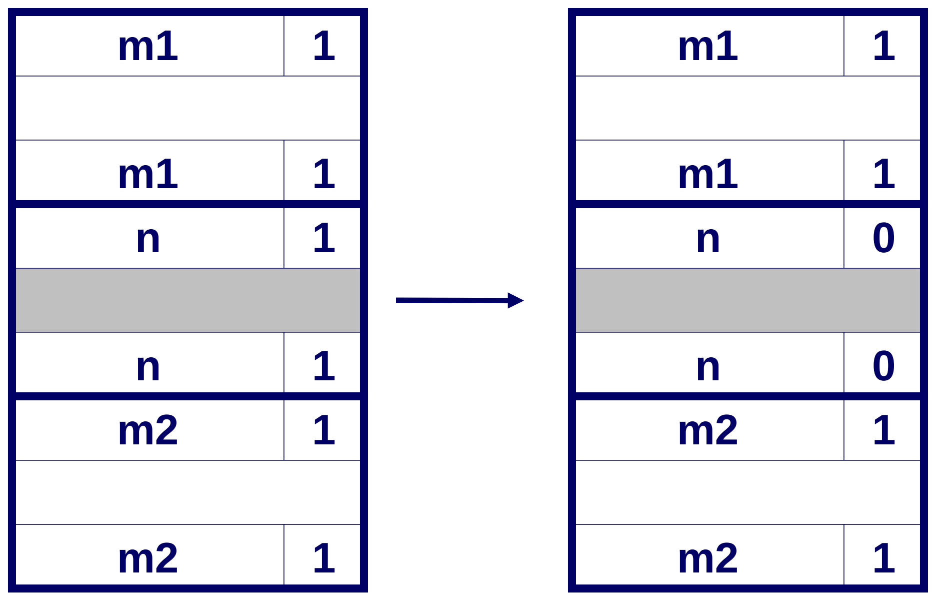




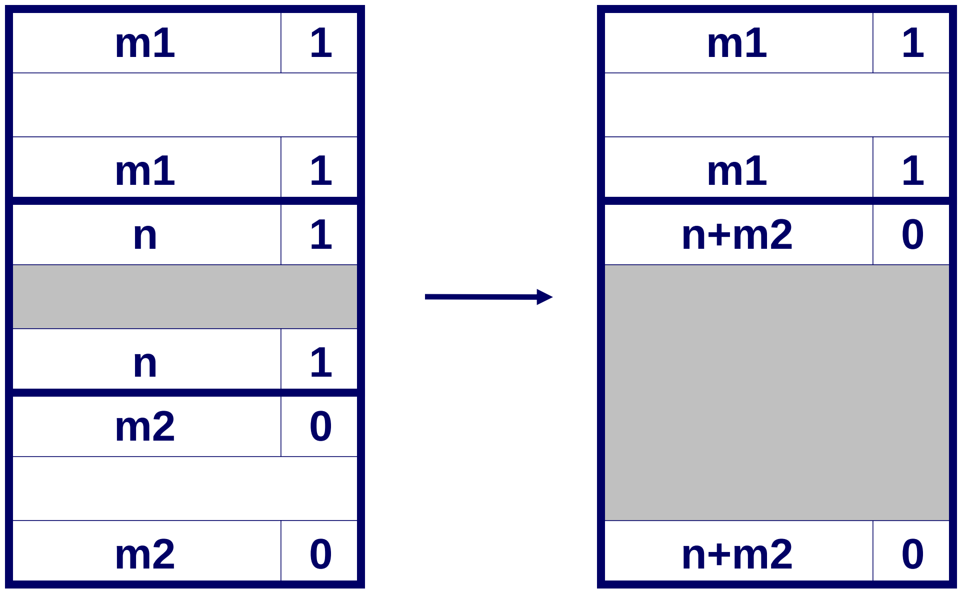
Constant Time Coalescing



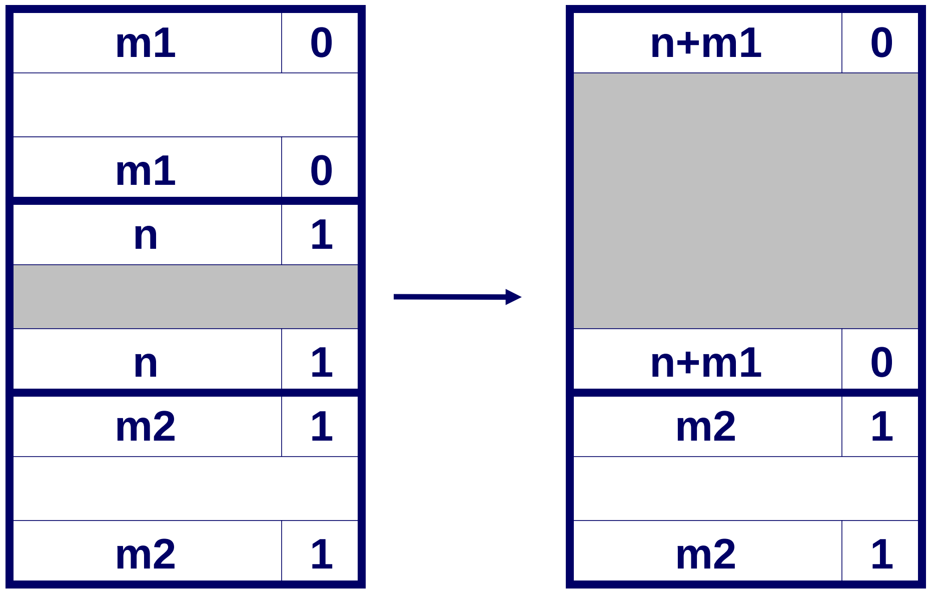
Constant Time Coalescing (Case 1)



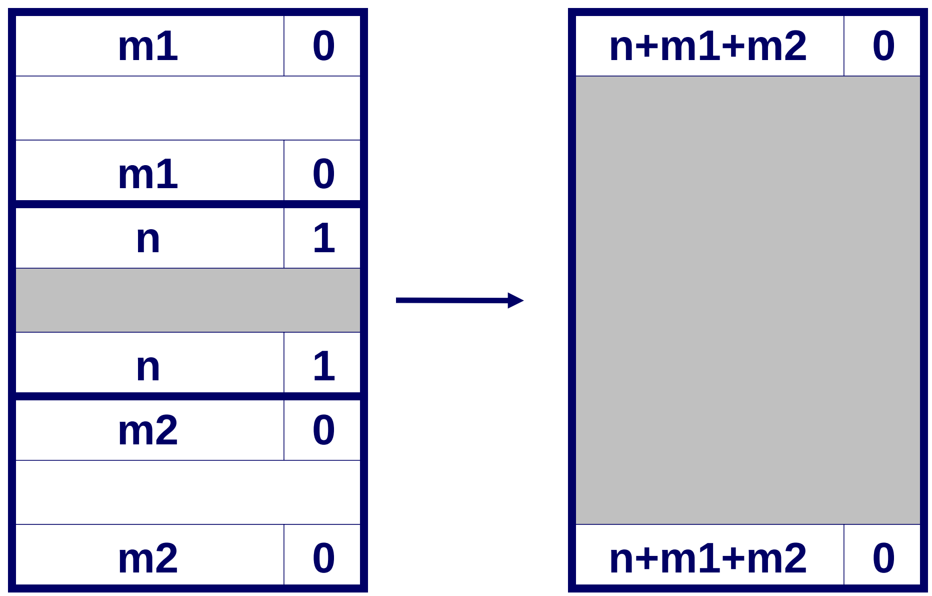
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



Summary of Key Allocator Policies

Placement policy:

- First-fit, next-fit, best-fit, etc.
- Trades off lower throughput for less fragmentation
  - *Interesting observation*: segregated free lists (next lecture) approximate a best fit placement policy without having to search entire free list

Splitting policy:

- When do we go ahead and split free blocks?
- How much internal fragmentation are we willing to tolerate?

Coalescing policy:

- *Immediate coalescing:* coalesce each time `free()` is called
- *Deferred coalescing:* try to improve performance of `free()` by deferring coalescing until needed. e.g.,
  - Coalesce as you scan the free list for `malloc()`
  - Coalesce when the amount of external fragmentation reaches some threshold

Implicit Lists: Summary

Implementation: very simple

Allocate cost: linear time worst case

Free cost: constant time worst case

- even with coalescing

Memory usage: will depend on placement policy

- First-fit, next-fit or best-fit

Not used in practice for `malloc()/free()` because of linear-time allocation

- used in many special purpose applications

However, the concepts of splitting and boundary tag coalescing are general to *all* allocators