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Lecture 21: Dynamic memory allocation

Computer Architecture and
Systems Programming
(252-0061-00)

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Last time

What is a device?

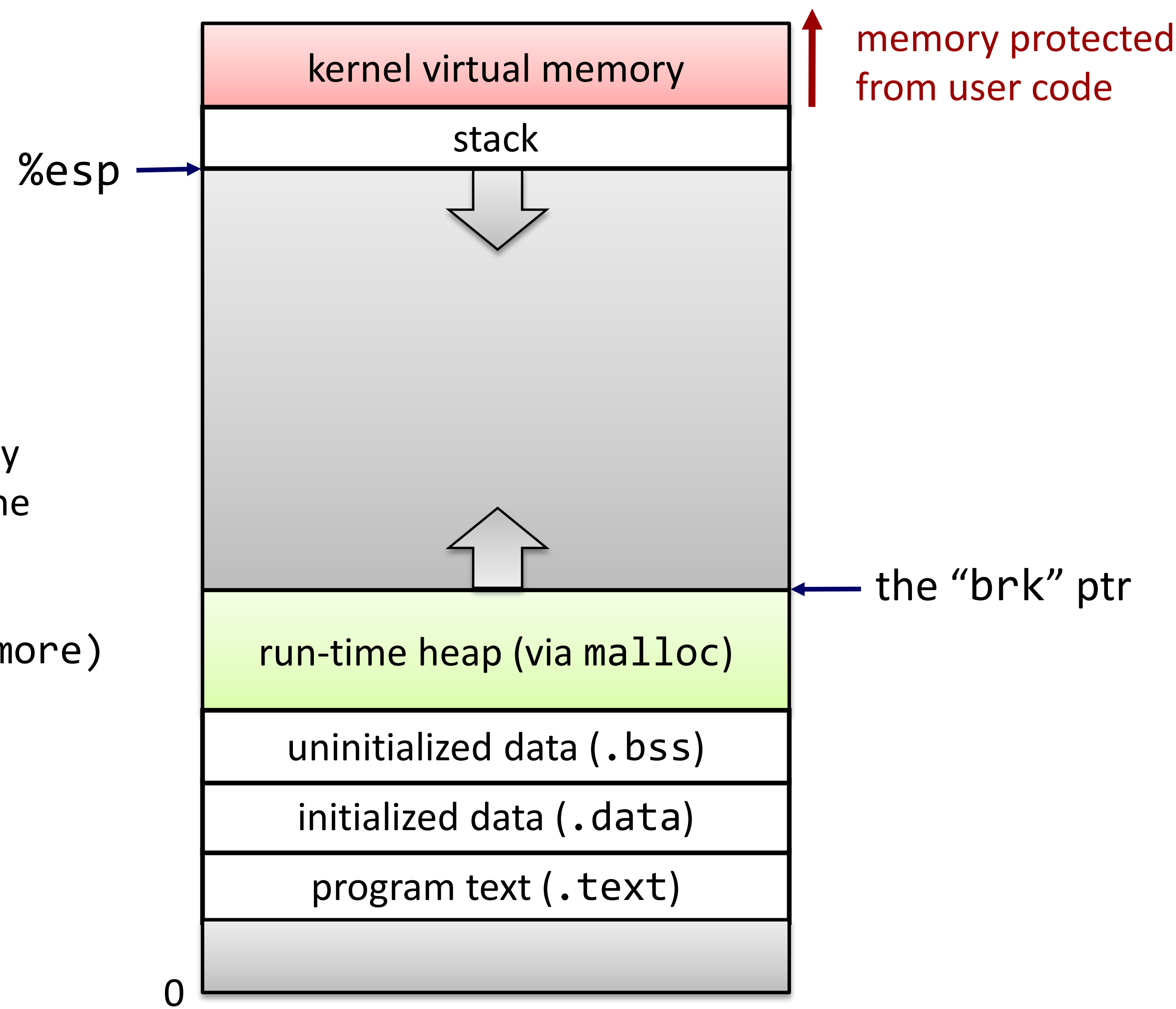
- Registers, Interrupts, DMA
  - Example: NS16550 UART
- PCI (Peripheral Component Interconnect)

We'll return to this next week, and look at more complex devices.

Today:
Dynamic memory allocation

- How does `malloc()` work?
  - Principles apply to many other allocators
- Problem definition
  - What are we trying to achieve?
  - The issue of fragmentation
- Implementation 1: Implicit lists
  - How it works
  - Constant-time coalescing
  - Boundary tags
- Next time: better implementations

Process Memory Image



Allocators request additional heap memory from the kernel using the `sbrk()` function:

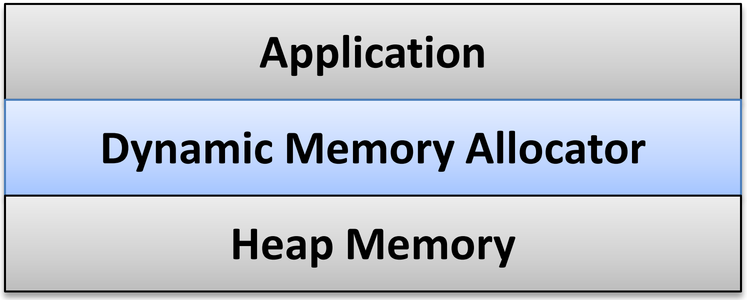
```
error = sbrk(amt_more)
```

Why Dynamic memory allocation?

- It's very simple:

Sizes of needed data structures may only be known at runtime

Dynamic Memory Allocation



- Memory allocator?
  - VM hardware and kernel allocate pages
  - Application objects are typically smaller
  - Allocator manages objects within pages

- Explicit vs. Implicit Memory Allocator
  - ***Explicit:*** application allocates and frees space
    - In C: `malloc()` and `free()`
  - ***Implicit:*** application allocates, but does not free space
    - In Java, ML, Lisp: garbage collection
- Allocation
  - A memory allocator doles out memory blocks to application
  - A “block” is a contiguous range of bytes
    - of any size, in this context
- *Today:* simple explicit memory allocation

Malloc Package

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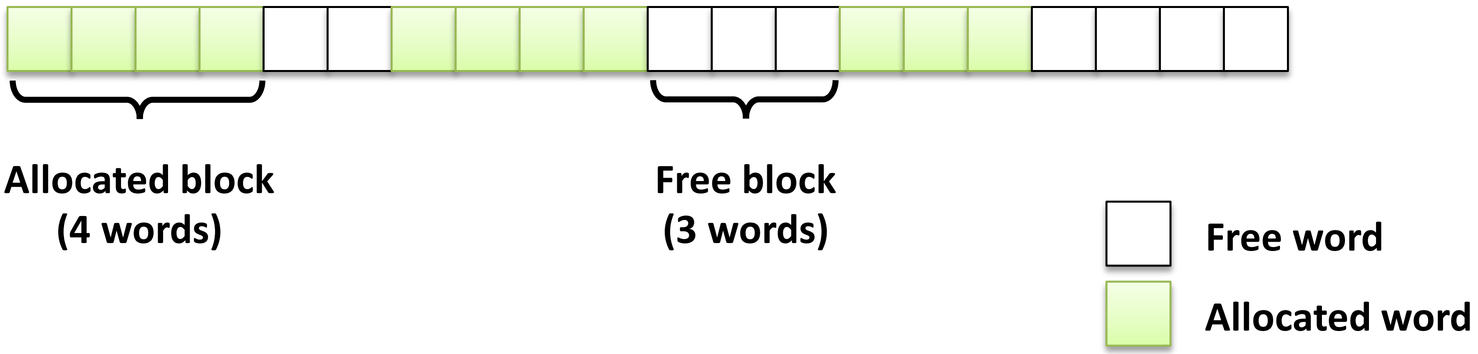
- `#include <stdlib.h>`
- `void *malloc(size_t size)`
  - Successful:
    - Returns a pointer to a memory block of at least `size` bytes (typically) aligned to 8-byte boundary
    - If `size == 0`, returns NULL
  - Unsuccessful: returns NULL (0) and sets `errno`
- `void free(void *p)`
  - Returns the 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 */
}
```

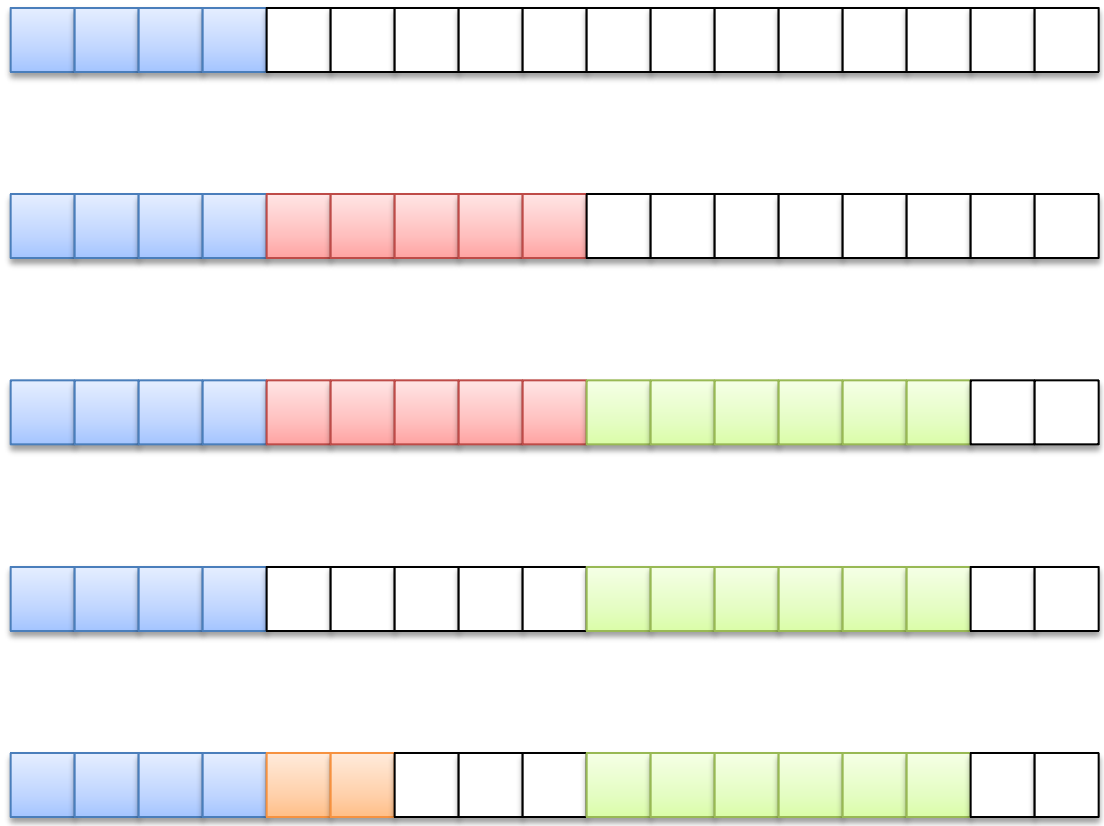
Assumptions we make (in this lecture)

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



Allocation Example

```
p1 = malloc(4)

p2 = malloc(5)

p3 = malloc(6)

free(p2)

p4 = malloc(2)
```



Constraints

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- Applications
  - Can issue arbitrary sequence of `malloc()` and `free()` requests
  - `free()` requests must be 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 Goal: Throughput

- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- 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
  - ***How to do `malloc()` and `free()` in O(1)? What's the problem?***

Performance Goal: Peak Memory Utilization

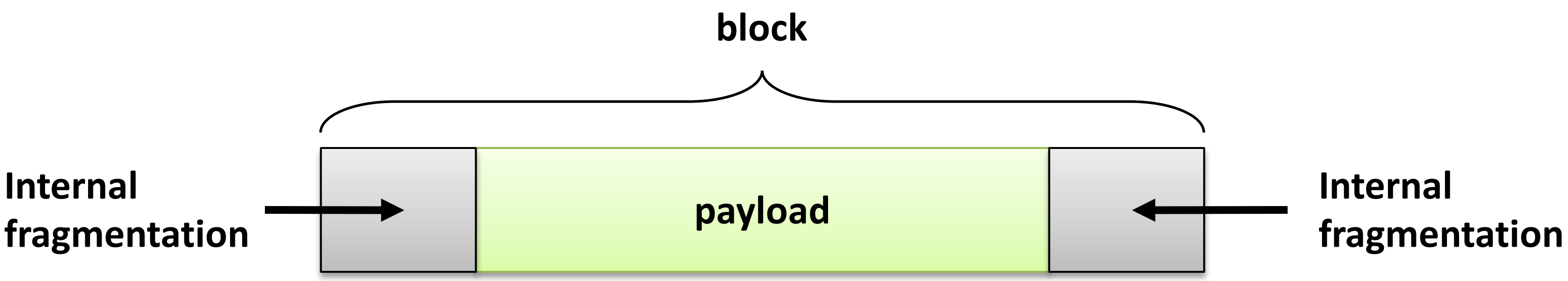
- Given some sequence of `malloc` and `free` requests:
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- *Def: Aggregate payload P_k*
  - `malloc(p)` results in a block with a ***payload*** of p bytes
  - After request R_k has completed, the ***aggregate payload*** P_k is the sum of currently allocated payloads
    - all `malloc()`'d stuff minus all `free()`'d stuff
- *Def: Current heap size = H_k*
  - Assume H_k is monotonically nondecreasing
    - reminder: it grows when allocator uses `sbrk()`
- *Def: Peak memory utilization after k requests*
  - $U_k = (\max_{i<k} P_i) \; / \; H_k$

Fragmentation

- Poor memory utilization caused by *fragmentation*
  - ***internal*** fragmentation
  - ***external*** fragmentation

Internal Fragmentation

- For a given block, *internal fragmentation* occurs if payload is smaller than block size



- Caused by
  - overhead of maintaining heap data structures
  - padding for alignment purposes
  - 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

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

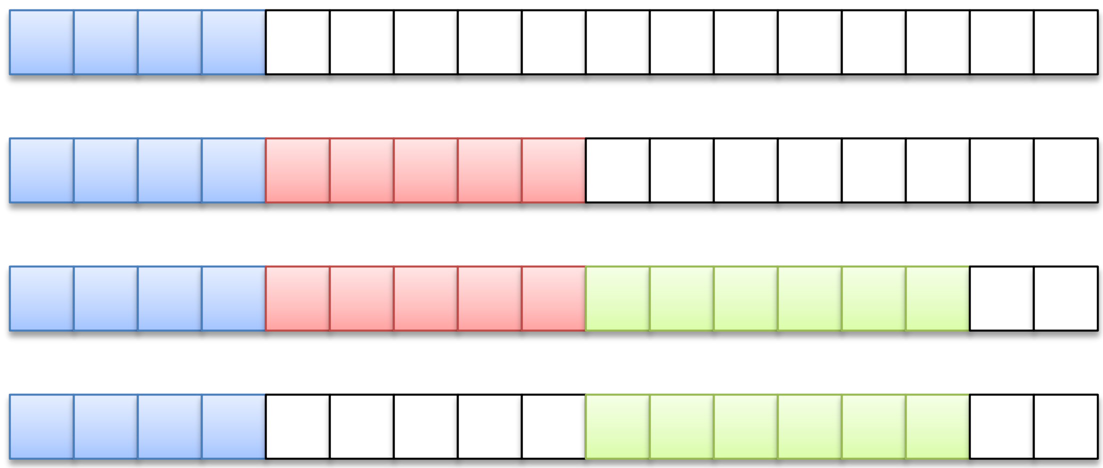
```
p1 = malloc(4)

p2 = malloc(5)

p3 = malloc(6)

free(p2)

p4 = malloc(6)
```



Oops! (what would happen now?)

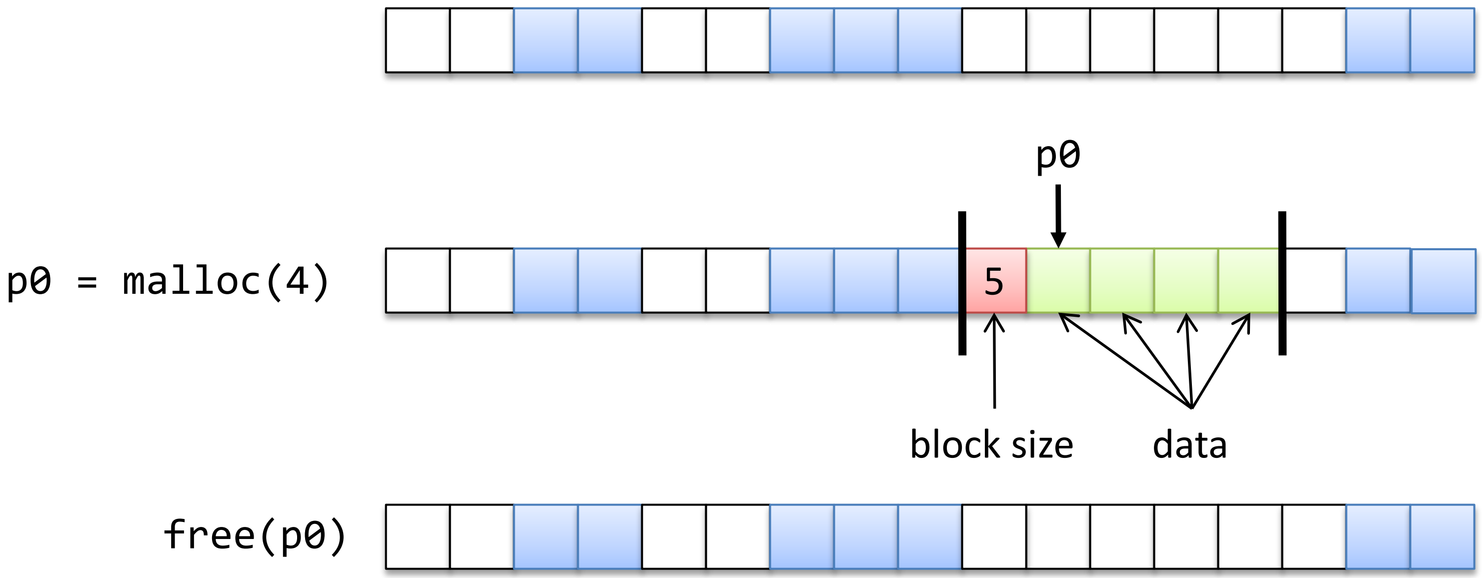
- Depends on the pattern of future requests
  - Thus, difficult to measure

Implementation Issues

- How to know how much memory is being `free()`'d when it is given only a pointer (and no length)?
- How to keep track of the free blocks?
- What to do with extra space when allocating a block that is smaller than the free block it is placed in?
- How to pick a block to use for allocation—many might fit?
- How to reinsert a freed block into the heap?

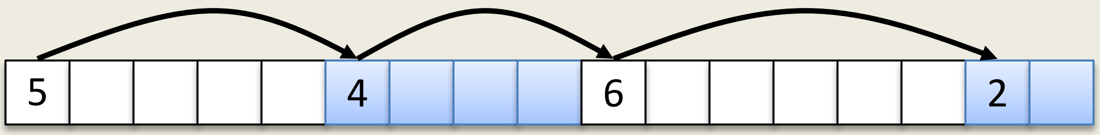
Knowing How Much to Free

- 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

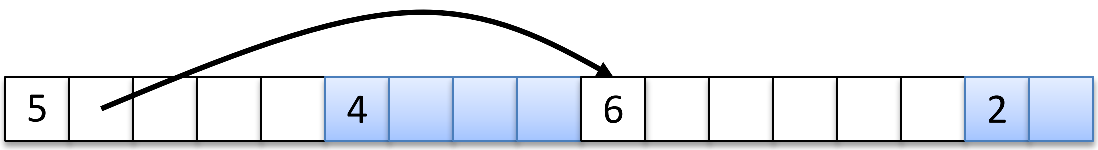


Keeping Track of Free Blocks

- Method 1: *Implicit list* using length—links all blocks



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

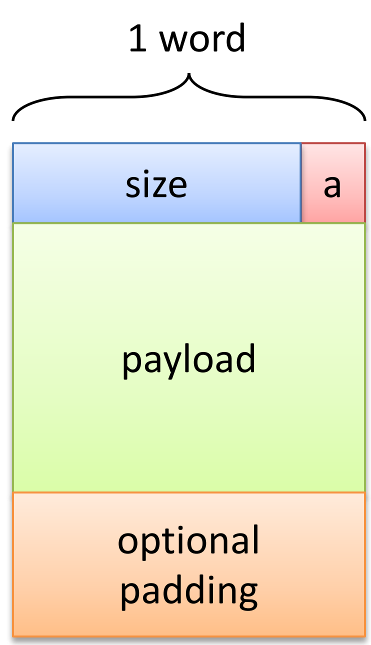


- Method 3: *Segregated free list*
  - Different free lists for different size classes
- Method 4: *Blocks sorted by size*
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

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



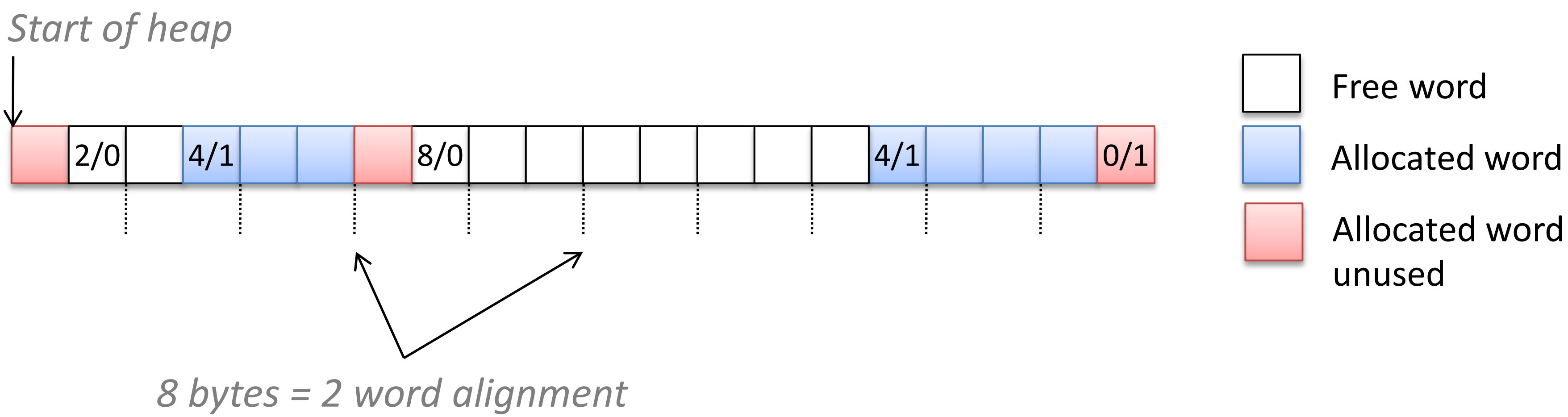
a = 1: allocated block
a = 0: free block

size: block size

payload: application data
(allocated blocks only)

Example

Sequence of blocks in heap: 2/0, 4/1, 8/0, 4/1



- 8-byte alignment
  - May require initial unused word
  - Causes some internal fragmentation
- One word (0/1) to mark end of list
- Here: block size in words for simplicity

Implicit List: Finding a Free Block

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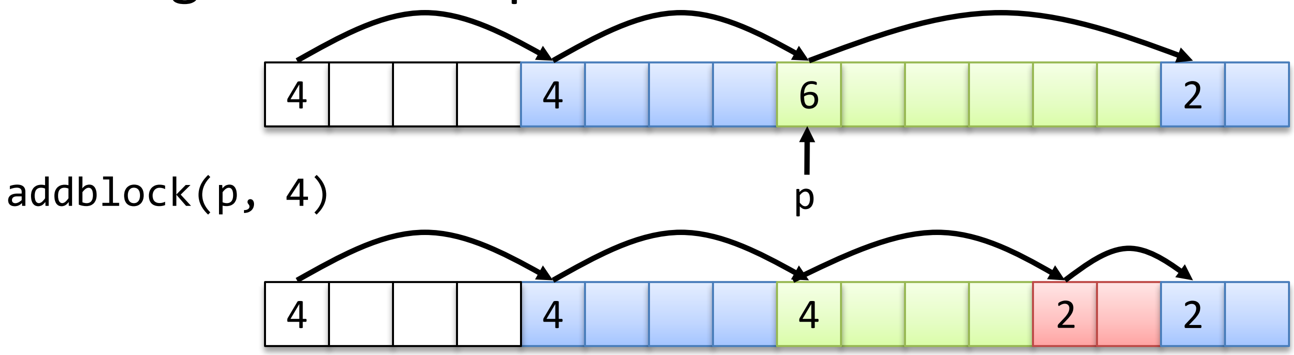
- *First fit:*
  - Search list from beginning, choose *first* free block that fits: *(Cost?)*

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

  - 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 *best* free block: fits, with fewest bytes left over
  - Keeps fragments small—usually helps fragmentation
  - Will typically run slower than first-fit

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;  // round up to even
  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
```

Implicit List: Freeing a Block

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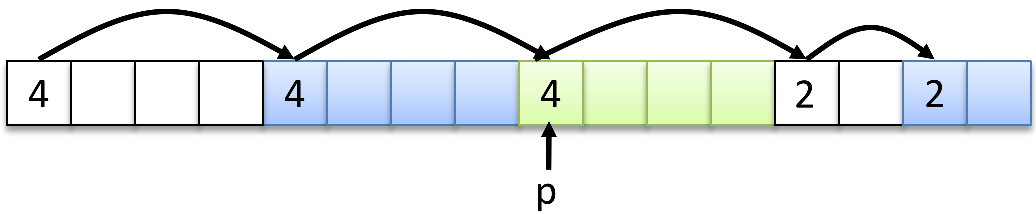
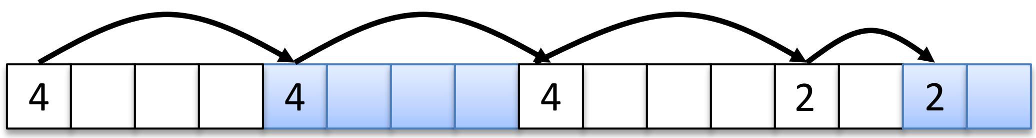
- Simplest implementation:
  - Need only clear the "allocated" flag

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

  - But can lead to "false fragmentation"



`free(p)`

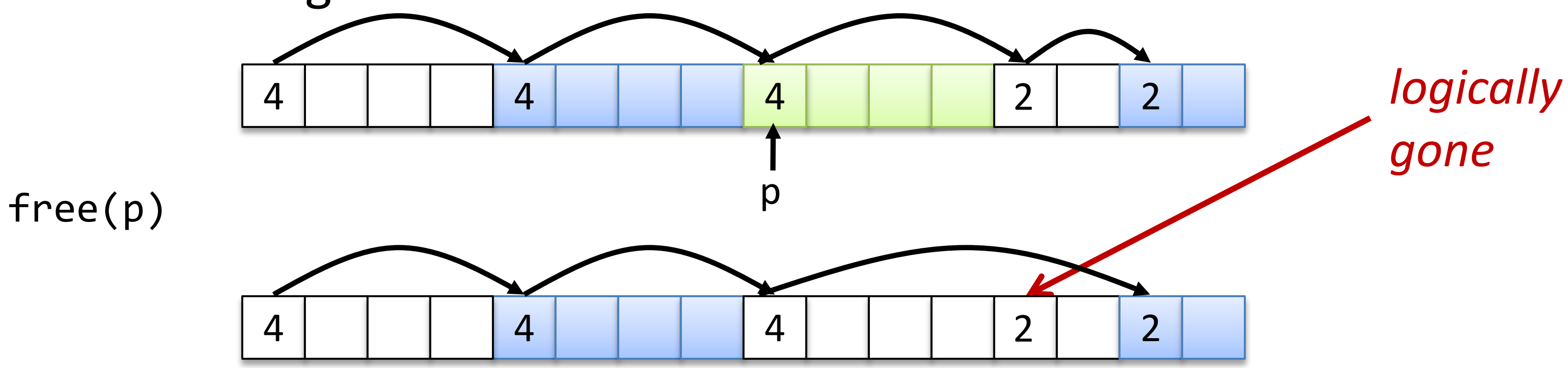


`malloc(5)` *Oops!*

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

Implicit List: Coalescing

- Join *(coalesce)* with next/previous blocks, if they are free
  - Coalescing with next block:

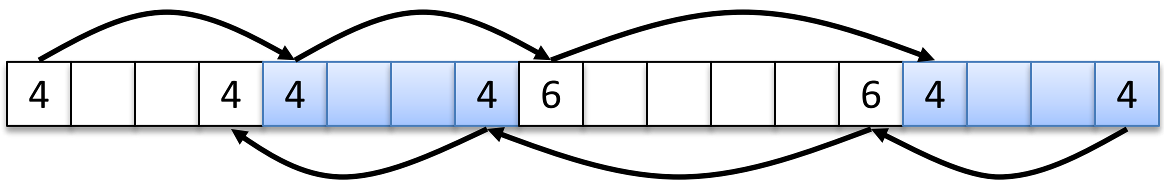



```
void free_block(ptr p) {
    *p = *p & -2;           // clear allocated flag
    next = p + *p;          // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;      // add to this block if
}                           //    not allocated
```

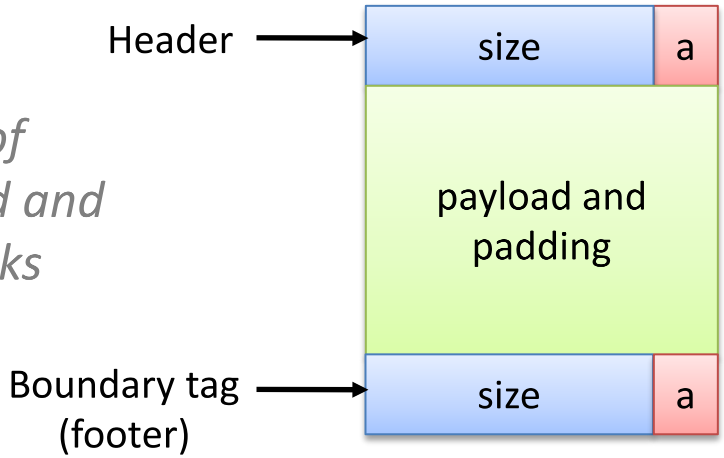
  - But how do we coalesce with *previous* block?

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!



Format of allocated and free blocks

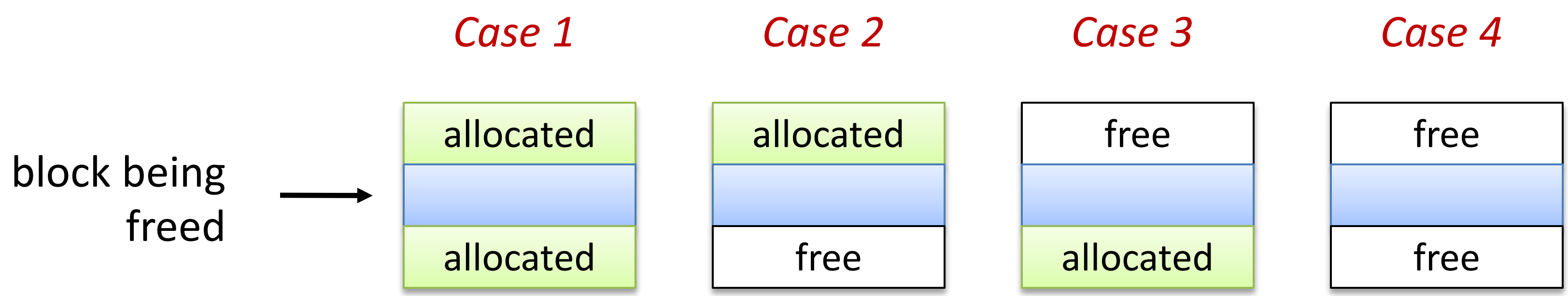


a = 1: allocated block
a = 0: free block

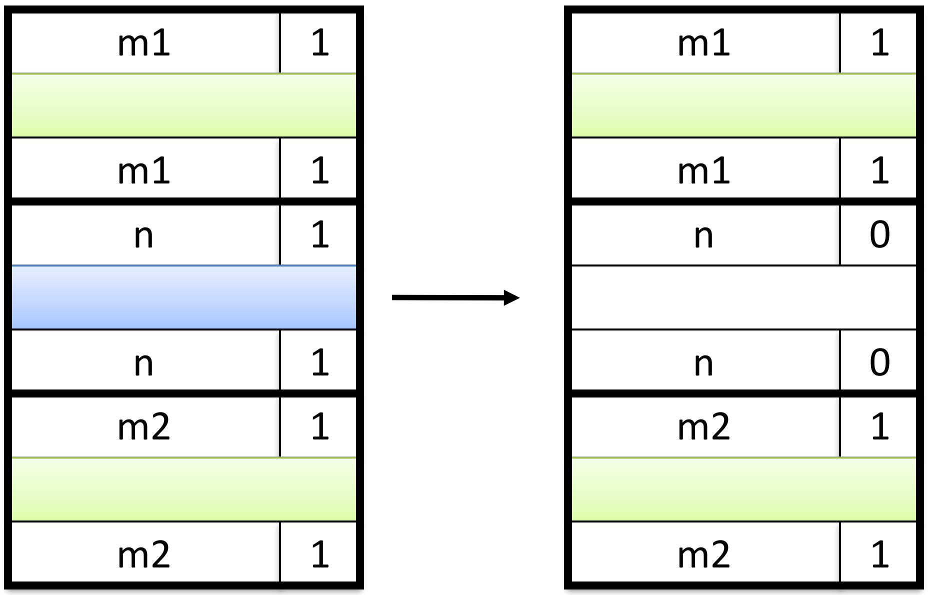
size: total block size

payload: application data (allocated blocks only)

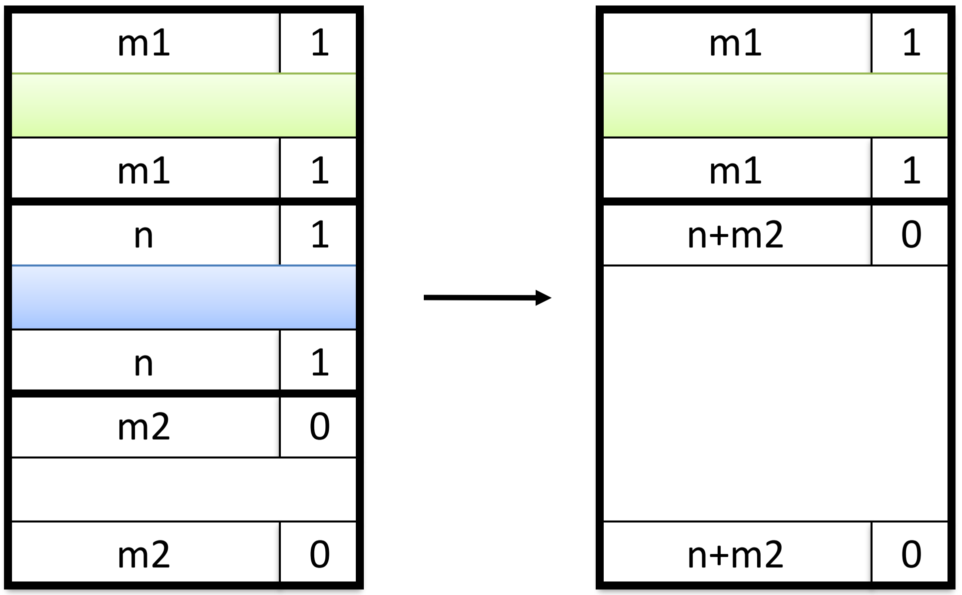
Constant Time Coalescing



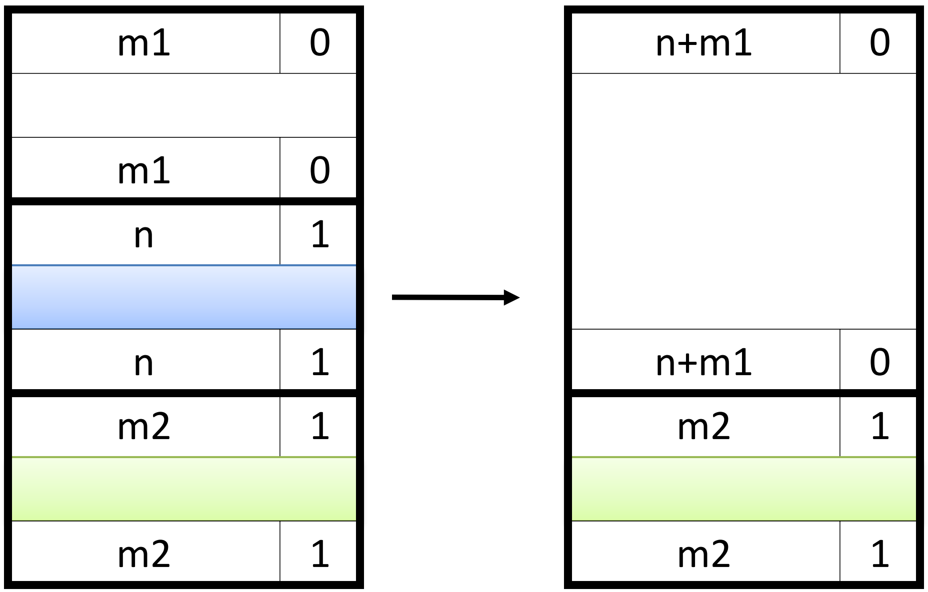
Constant Time Coalescing
Case 1



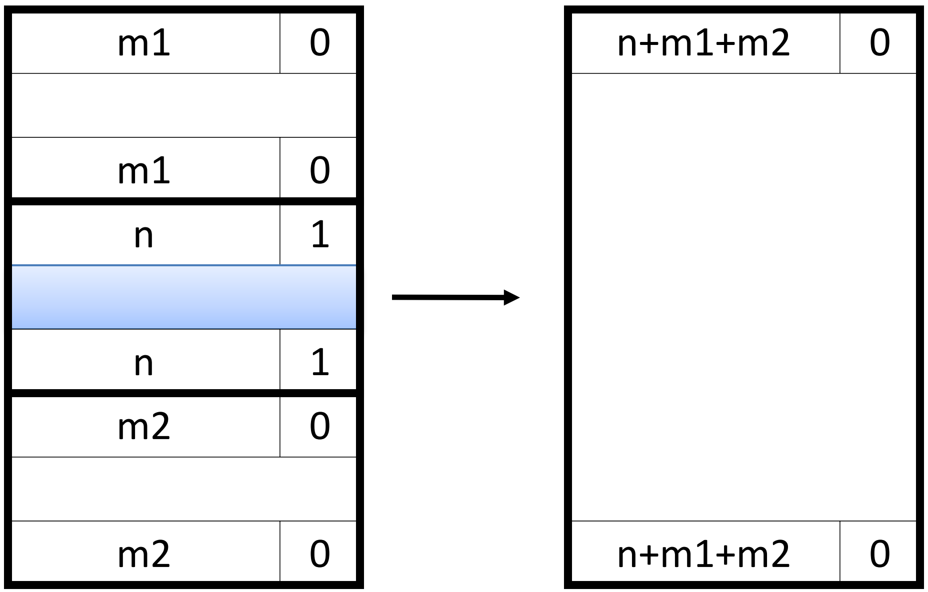
Constant Time Coalescing
Case 2



Constant Time Coalescing
Case 3



Constant Time Coalescing
Case 4



Disadvantages of Boundary Tags

- Internal fragmentation

- Can it be optimized?
  - Which blocks need the footer tag?
  - What does that mean?

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. Examples:
    - Coalesce as you scan the free list for `malloc()`
    - Coalesce when the amount of external fragmentation reaches some threshold

Implicit Lists: Summary

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- 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