Dynamic Memory Allocation: Basic Concepts

15-213: Introduction to Computer Systems
17th Lecture, Oct. 21, 2010

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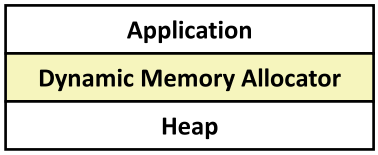
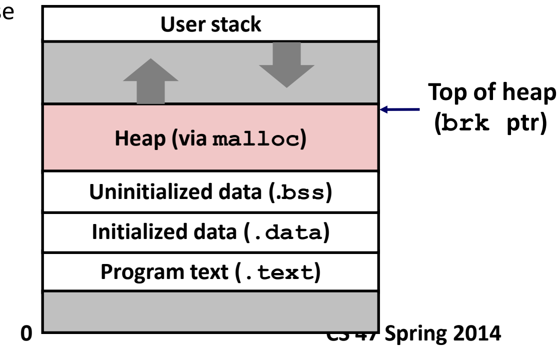
Today

- **Basic concepts**
- Implicit free lists

Dynamic Memory Allocation

- Programmers use ***dynamic memory allocators*** (such as `malloc`) to acquire VM at run time.
  - For data structures whose size is only known at runtime.
- Dynamic memory allocators manage an area of process virtual memory known as the ***heap***.





Dynamic Memory Allocation

- Allocator maintains heap as collection of variable sized ***blocks***, which are either ***allocated*** or ***free***
- Types of allocators
  - ***Explicit allocator***: application allocates and frees space
    - E.g., `malloc` and `free` in C
  - ***Implicit allocator:*** application allocates, but does not free space
    - E.g. garbage collection in Java, ML, and Lisp

- Will discuss simple explicit memory allocation today

The `malloc` Package

`#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`**

Other functions

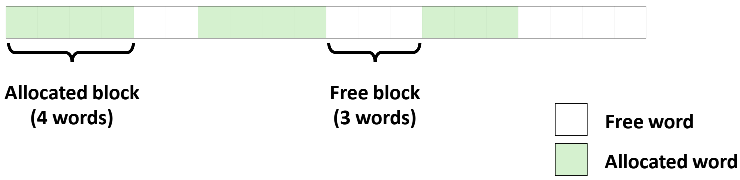
- **`calloc`:** Version of **`malloc`** that initializes allocated block to zero.
- **`realloc`:** Changes the size of a previously allocated block.
- **`sbrk`:** Used internally by allocators to grow or shrink the heap

`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);
    }

    /* Initialize allocated block */
    for (i=0; i<n; i++)
        p[i] = i;


    /* Return p to the heap */
    free(p);
}
```

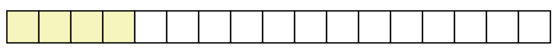
Assumptions Made in This Lecture

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

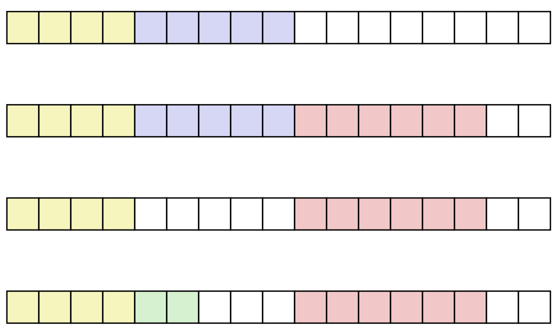


Allocation Example

```
p1 = malloc(4)
```



```
p2 = malloc(5)
p3 = malloc(6)
free(p2)
p4 = malloc(2)
```



Constraints

- **Applications**
  - Can issue arbitrary sequence of **`malloc`** and **`free`** requests
  - **`free`** request 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

Performance Goal: Peak Memory Utilization

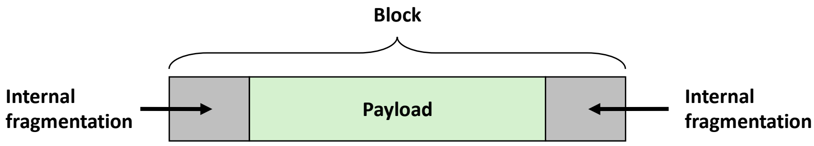
- **Given some sequence of `malloc` and `free` requests:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- ***Def:* Aggregate payload P_k**
  - `malloc(p)` results in a block with a ***payload*** of `p` bytes
  - After request R_k has completed, the ***aggregate payload*** P_k is the sum of currently allocated payloads
- ***Def:* Current heap size H_k**
  - Assume H_k is monotonically nondecreasing
    - i.e., heap only 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

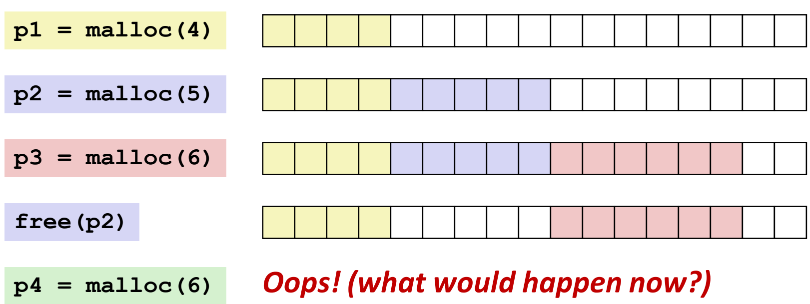
- **For a given block, *internal fragmentation* occurs if payload is smaller than block size**



- **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

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



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

Implementation Issues

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?
- What do we do with the extra space when allocating a structure 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 freed block?

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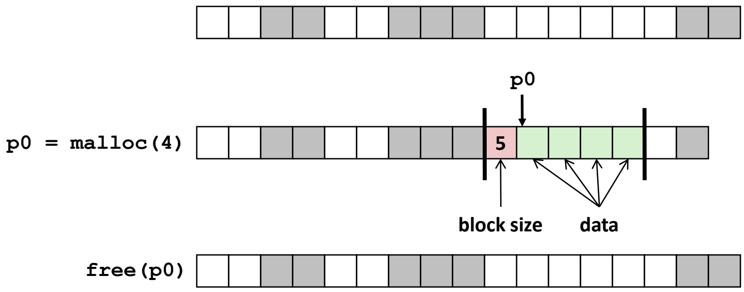
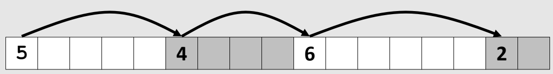
Knowing How Much to Free

- **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

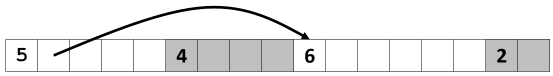


Keeping Track of Free Blocks

- **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

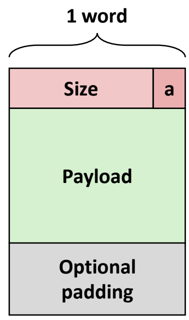
Today

- Basic concepts
- **Implicit free lists**

Method 1: Implicit List

- **For each block we need both size and allocation status**
  - 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



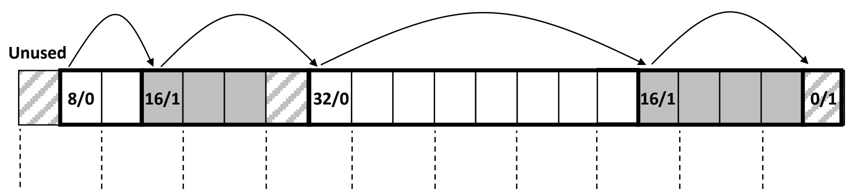
a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data (allocated blocks only)

Detailed Implicit Free List Example

Start of heap



Double-word aligned

Allocated blocks: shaded
Free blocks: unshaded
Headers: labeled with size in bytes/allocated bit

Implicit List: Finding a Free Block

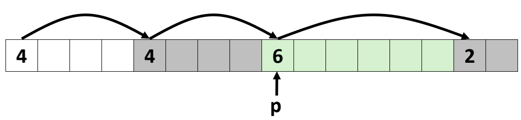
- ***First fit:***
  - Search list from beginning, choose ***first*** free block that fits:

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

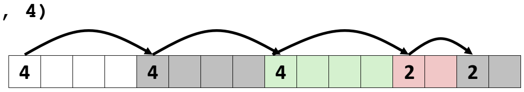
  - Can take linear time in total number of blocks (allocated and free)
  - In practice it can cause "splinters" at beginning of list
- ***Next fit:***
  - Like first fit, but search list starting where previous search finished
  - Should often be faster than first fit: avoids re-scanning unhelpful blocks
  - 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




```
addblock(p, 4)
```



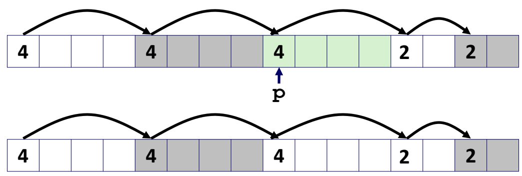

```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining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

Implicit List: Freeing a Block

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

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

  - But can lead to "false fragmentation"



`free(p)`

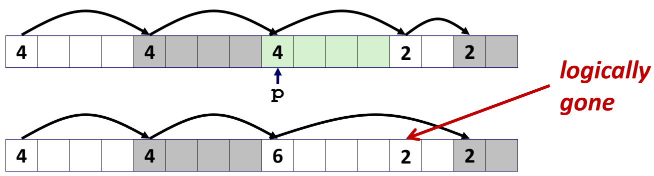
`malloc(5)` ***Oops!***

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

`free(p)`

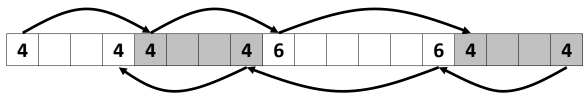



```
void free_block(ptr p) {
    *p = *p & -2;          // clear allocated flag
    next = p + *p;         // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;     // add to this block if
}                          //    not allocated
```

  - 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!



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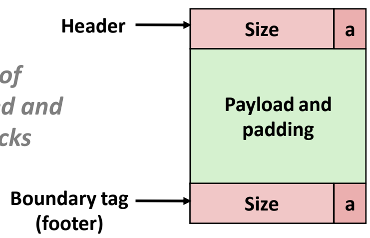

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Size: Total block size

Payload: Application data (allocated blocks only)

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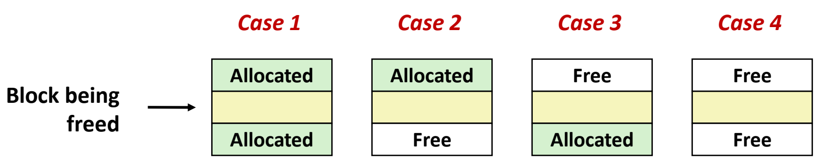
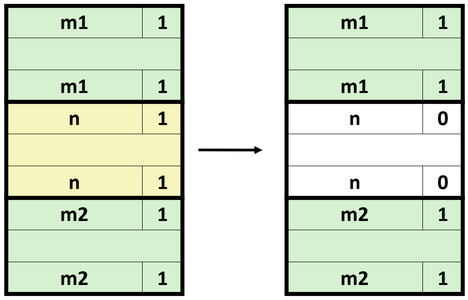
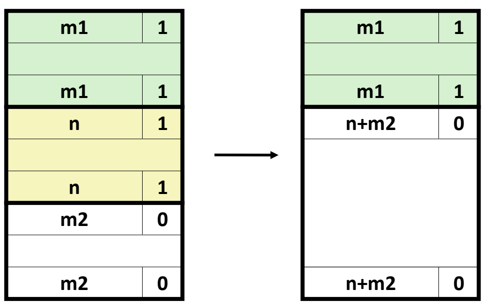
Constant Time Coalescing



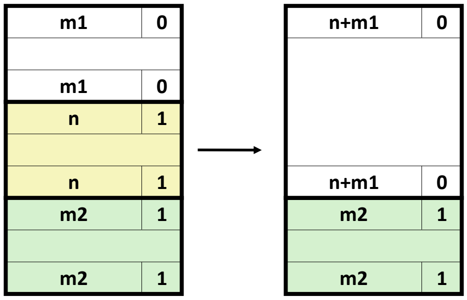
Constant Time Coalescing (Case 1)



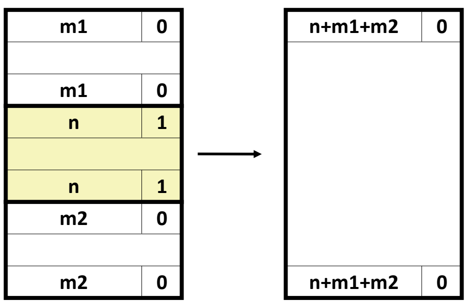
Constant Time Coalescing (Case 2)



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

- **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**