15-213
“The course that gives CMU its Zip!”

Dynamic Memory Allocation I
November 2, 2004

Topics
- Simple explicit allocators
  - Data structures
  - Mechanisms
  - Policies
Harsh Reality

Memory Matters

Memory is not unbounded
- It must be allocated and managed
- Many applications are memory dominated
  - Especially those based on complex, graph algorithms

Memory referencing bugs especially pernicious
- Effects are distant in both time and space

Memory performance is not uniform
- Cache and virtual memory effects can greatly affect program performance
- Adapting program to characteristics of memory system can lead to major speed improvements
Dynamic Memory Allocation

<table>
<thead>
<tr>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Memory Allocator</td>
</tr>
<tr>
<td>Heap Memory</td>
</tr>
</tbody>
</table>

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

- In both cases the memory allocator provides an abstraction of memory as a set of blocks
- Doles out free memory blocks to application

Will discuss simple explicit memory allocation today
Allocators request additional heap memory from the operating system using the `sbrk` function.
# Malloc Package

```c
#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.
```
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 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 allocation and free requests
- Free requests must correspond to an allocated block

**Allocators**
- Can’t control number or size of allocated blocks
- Must respond immediately to all allocation 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 only manipulate and modify free memory
- Can’t move the allocated blocks once they are allocated
  - *i.e.*, compaction is not allowed
Goals of Good `malloc/free`

Primary goals

- **Good time performance for `malloc` and `free`**
  - Ideally should take constant time (not always possible)
  - Should certainly not take linear time in the number of blocks

- **Good space utilization**
  - User allocated structures should be large fraction of the heap.
  - Want to minimize “fragmentation”.

Some other goals

- **Good locality properties**
  - Structures allocated close in time should be close in space
  - “Similar” objects should be allocated close in space

- **Robust**
  - Can check that `free(p1)` is on a valid allocated object `p1`
  - Can check that memory references are to allocated space
Performance Goals: Throughput

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

- \( R_0, R_1, \ldots, R_k, \ldots, R_{n-1} \)

Want to 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:
- \( R_0, R_1, \ldots, R_k, \ldots, R_{n-1} \)

**Def: Aggregate payload \( P_k \):**
- `malloc()` 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 is denoted by \( H_k \)**
- Assume that \( H_k \) is monotonically nondecreasing

**Def: Peak memory utilization:**
- After \( k \) requests, peak memory utilization is:
  \[ U_k = \frac{\max_{i<k} P_i}{H_k} \]
**Internal Fragmentation**

Poor memory utilization caused by *fragmentation*.
- Comes in two forms: internal and external fragmentation

**Internal fragmentation**
- For some 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., not to split the block).
- Depends only on the pattern of *previous* requests, and thus is easy to measure.
External Fragmentation

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

\[
p1 = \text{malloc}(4)
\]

\[
p2 = \text{malloc}(5)
\]

\[
p3 = \text{malloc}(6)
\]

\[
\text{free}(p2)
\]

\[
p4 = \text{malloc}(6)
\]

oops!

External fragmentation depends on the pattern of future requests, and thus is difficult to measure.
Implementation Issues

- How do we know how much memory to free just given 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?

\[
\begin{array}{cccccccc}
\text{free(p0)} & & & & & & & \\
p1 = \text{malloc(1)}
\end{array}
\]
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

```
p0 = malloc(4)

free(p0)
```
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

Need to identify whether each block is free or allocated

- Can use extra bit
- Bit can be put in the same word as the size if block sizes are always multiples of two (mask out low order bit when reading size).

<table>
<thead>
<tr>
<th>size</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>payload</td>
<td></td>
</tr>
<tr>
<td>optional padding</td>
<td></td>
</tr>
</tbody>
</table>

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 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
```
- 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 from location of end of previous search
- Research suggests that fragmentation is worse

Best fit:
- Search the list, choose the free block with the closest size that fits
- Keeps fragments small --- usually helps fragmentation
- Will typically run slower than first-fit
Bitfields

How to represent the Header:

- Masks and bitwise operators
  
  ```c
  #define PACK(size, alloc)      ((size) | (alloc))
  #define getSize(x)            ((x)->size & SIZEMASK)
  ```

- bitfields

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

```c
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)
```

```c
4 4 6 2 2
```

```c
4 4 4 2 2
```
Implicit List: Freeing a Block

Simplest implementation:

- Only need to clear allocated flag
  
  ```c
  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 block if they are free

- Coalescing with next block

```c
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 of free blocks
- Allows us to traverse the “list” backwards, but requires extra space
- Important and general technique!

1 word

Format of allocated and free blocks

**Boundary tag** (footer)

<table>
<thead>
<tr>
<th>Header</th>
<th>size</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>payload and padding</td>
<td>size</td>
<td>a</td>
</tr>
</tbody>
</table>

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

- size: total block size
- payload: application data (allocated blocks only)

---

Table:

| 4 | 4 | 4 | 4 | 6 | 6 | 4 | 4 | 4 | 4 | 4 | 4 |

---

15-213, F'04
Constant Time Coalescing

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>allocated</td>
<td>allocated</td>
<td>free</td>
<td>free</td>
</tr>
<tr>
<td>allocated</td>
<td>free</td>
<td>allocated</td>
<td>free</td>
</tr>
</tbody>
</table>

block being freed
Constant Time Coalescing (Case 1)
Constant Time Coalescing (Case 2)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>1</td>
</tr>
<tr>
<td>n</td>
<td>1</td>
</tr>
<tr>
<td>m2</td>
<td>0</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>1</td>
</tr>
<tr>
<td>n+m2</td>
<td>0</td>
</tr>
</tbody>
</table>

Diagram showing coalescing of n and m2.
Constant Time Coalescing (Case 3)

```
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>0</td>
</tr>
<tr>
<td>n</td>
<td>1</td>
</tr>
<tr>
<td>m2</td>
<td>1</td>
</tr>
</tbody>
</table>
```

```
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>n+m1</td>
<td>0</td>
</tr>
<tr>
<td>m2</td>
<td>1</td>
</tr>
</tbody>
</table>
```
### Constant Time Coalescing (Case 4)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>m1</strong></td>
<td><strong>0</strong></td>
</tr>
<tr>
<td><strong>m1</strong></td>
<td><strong>0</strong></td>
</tr>
<tr>
<td><strong>n</strong></td>
<td><strong>1</strong></td>
</tr>
<tr>
<td><strong>n</strong></td>
<td><strong>1</strong></td>
</tr>
<tr>
<td><strong>m2</strong></td>
<td><strong>0</strong></td>
</tr>
<tr>
<td><strong>m2</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>n+m1+m2</strong></td>
<td><strong>0</strong></td>
</tr>
<tr>
<td><strong>n+m1+m2</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>
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 the 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 adjacent blocks 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: linear time worst case
- Free: 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 allocate. Used in many special purpose applications.

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