Dynamic Memory Allocation

CSCI 237: Computer Organization
33rd Lecture, Monday, November 25, 2024

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Administrative Details

- Read CSAPP 9.9
- Lab #6 due 12/6 at 5pm
- No quiz this week
- Meet in Ward lab (TBL 301) on Monday 12/2 at 10am

Last Time

- Address translation (Ch 9.6)
- End-to-end example of a simple memory system
- Dynamic Memory Allocation (Ch 9.9)

Today: Dynamic Memory Allocation

- Dynamic Memory Allocation (Ch 9.9)
  - Basic concepts
    - Fragmentation
      - Internal (fragmentation)
      - External (free space fragmentation)
  - Performance
    - How to Measures "allocator" performance?
      - Throughput
      - (Peak) Utilization

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*
- **Performance Goals:**
  - **1) Maximize throughput**
  - **2) Maximize peak memory utilization**
- **These goals are often conflicting!**
  - i.e., heap only grows when allocator uses **`sbrk`**
- *Def: Peak memory utilization after k+1 requests*
  - $U_k = (max_{i \le k} P_i) \ / \ H_k$

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Fragmentation

- Poor memory utilization often caused by *fragmentation*
- Two classes:
  - ***internal*** fragmentation
  - ***external*** fragmentation

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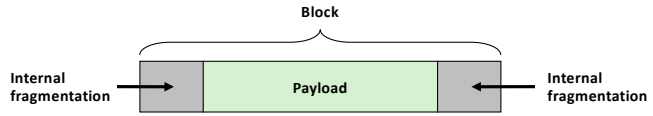
Internal Fragmentation

- 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

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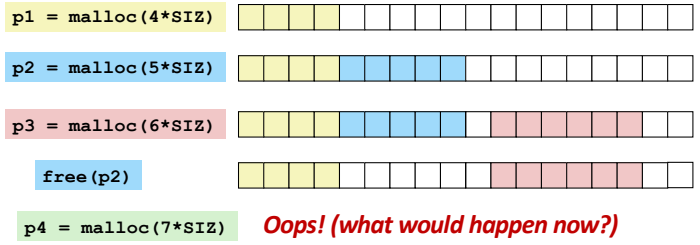
External Fragmentation

```
#define SIZ sizeof(int)
```

- 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

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Implementation Issues

- How do we know how much memory to **free(void *)** 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 blocks to our pool of available data?

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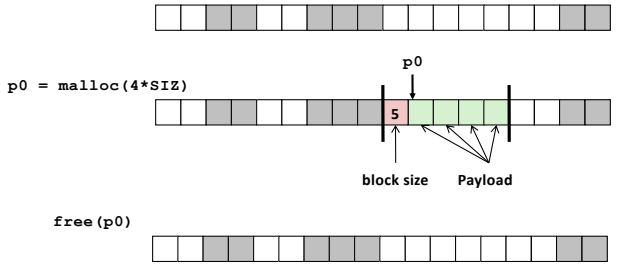
Knowing How Much to Free

- Standard method
  - Keep the length of a block in the word preceding the block.
    - This word is often called the ***header field*** or ***header***
  - Downside: this method requires an extra word for every allocated ***block***



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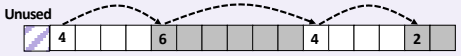
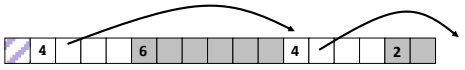
Keeping Track of Free Blocks

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



Need to tag each block as allocated/free

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



Need space for 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

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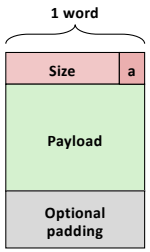
Method 1: Implicit Free List (Ch 9.9.6)

- For each block we need both size and allocation status
  - We could store this information in two words, but that is wasteful!
- Standard trick
  - When blocks are aligned, some (3) low-order address bits are always 0
  - Instead of storing an always-0 bit, repurpose it as an allocated/free flag
  - When reading the `Size` word, we just 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)

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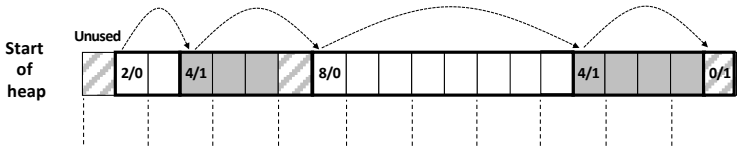
Detailed Implicit Free List Example



Double-word aligned

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

Note: both allocated and free blocks are all in the same implicit list

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Implicit List: Finding a Free Block (9.9.7)

- *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 – fragmentation!
- *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 (i.e., fits with the fewest bytes left over)
  - Keeps fragments small—usually improves memory utilization
  - Will typically run slower than first fit

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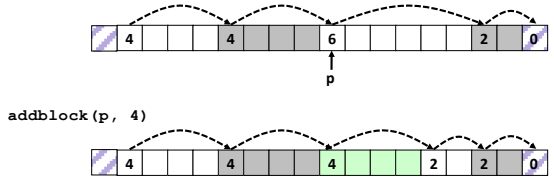
Implicit List: Allocating in Free Block

- 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 (zero) out lowest bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   part of block
```

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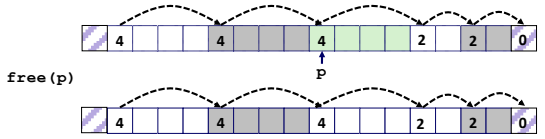
Implicit List: Freeing a Block

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

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

  - But can lead to "false fragmentation"




```
malloc(5*SIZ)
```

Oops!

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

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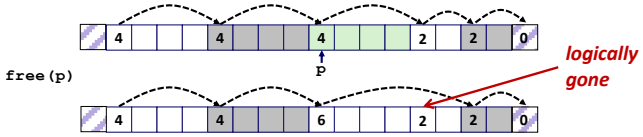
Implicit List: Coalescing

- 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?

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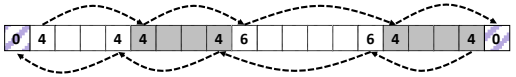
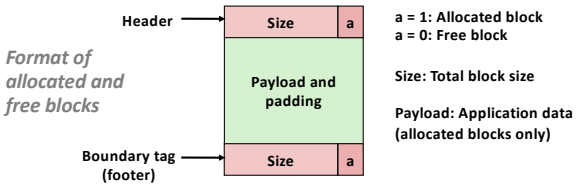
Implicit List: Bidirectional Coalescing

- *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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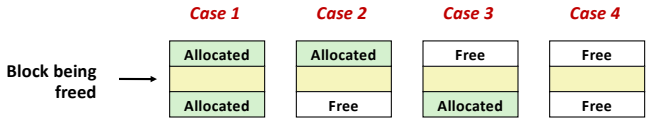
Constant Time Coalescing with Boundary Tags



Given a block to free and its two neighbors, there are 4 unique combinations of free/allocated to consider. Let's look at each case individually

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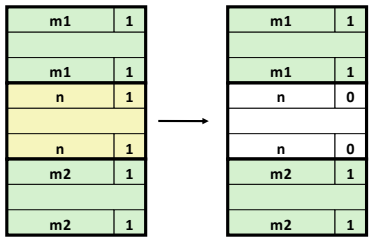
Constant Time Coalescing (Case 1)

The block's immediate neighbors are both allocated.



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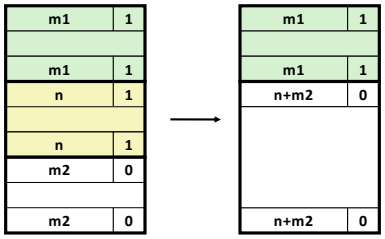
Constant Time Coalescing (Case 2)

The block's predecessor is allocated, but its successor is free.



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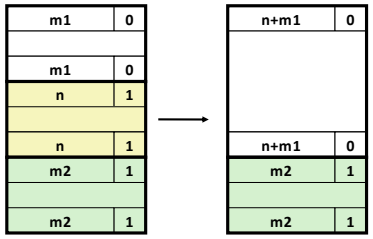
Constant Time Coalescing (Case 3)

The block's predecessor is free, but it's successor is allocated.



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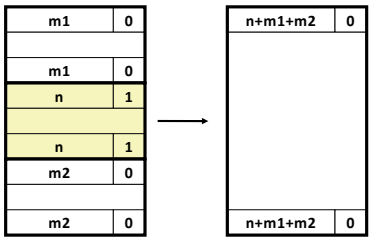
Constant Time Coalescing (Case 4)

The block's immediate neighbors are both free.



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Disadvantages of Boundary Tags

- Internal fragmentation
  - Extra non-payload bytes needed for boundary tag/footer
- Can it be optimized?
  - Which blocks need the footer tag?
  - What does that mean?

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Disadvantages of Boundary Tags

- Internal fragmentation
  - Extra non-payload bytes needed for boundary tag/footer
- Can it be optimized?
  - Which blocks need the footer tag? Only free blocks!
  - What does that mean? Can save space!

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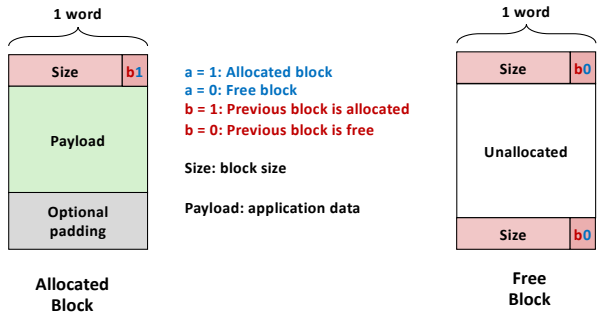
Optimization: No Boundary Tag for Allocated Blocks

- Boundary tag is only needed for free blocks
- Insight: when sizes are multiples of 4 or more, have 2+ spare bits



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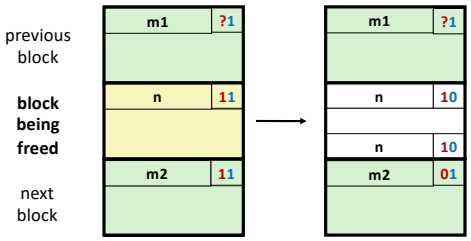
No Boundary Tag for Allocated Blocks (Case 1)



Header: **Use 2 bits (always zero due to alignment):**
(previous block allocated)<<1 | (current block allocated)

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