Dynamic Memory Allocation: Basic Concepts

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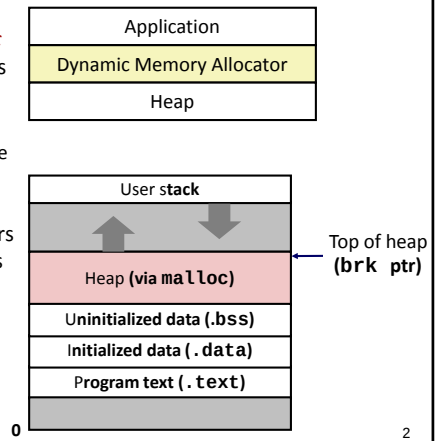
Dynamic Memory Allocation

- Programmers use *dynamic memory allocators* (such as **`malloc`**) to acquire memory 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*.



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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
- We discuss explicit memory allocation today

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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`**

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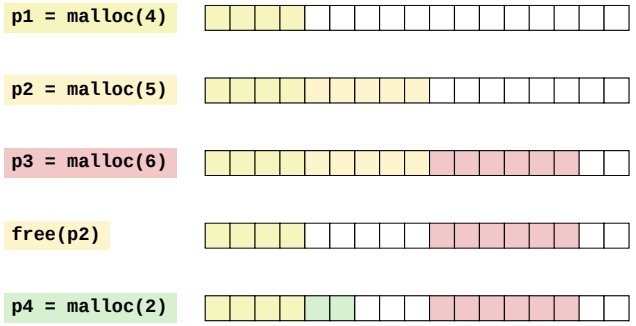
Allocation Example



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Constraints

- Applications
  - Can issue arbitrary sequence of **`malloc`** and **`free`** requests
  - **`free`** request must be to a **`malloc`**'d block
- Allocators
  - Must respond immediately to **`malloc`** requests
  - Can manipulate and modify only free memory
  - Must allocate blocks from free memory
  - Must align blocks so they satisfy all alignment requirements
    - 8 byte alignment for GNU **`malloc`** (**`libc malloc`**) on Linux boxes
  - Can't move the allocated blocks once they are **`malloc`**'d
    - *i.e.*, compaction is not allowed

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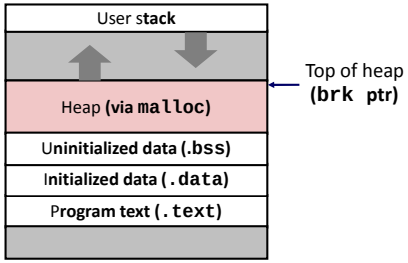
Interaction with OS

- Change heap size
  - **`brk`** system call



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Performance Goal: Runtime Speed

- Given some sequence of **`malloc`** and **`free`** requests:
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- Speed – 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

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Performance Goal: 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
- *Def:* *Heap size* H_k
  - Maximum heap size so far
- *Def:* *Peak memory utilization after k requests*
  - $U_k = (max_{i<k} P_i) \ / \ H_k$
- Goals: maximize runtime speed and memory utilization
  - Somewhat conflicting

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Fragmentation

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

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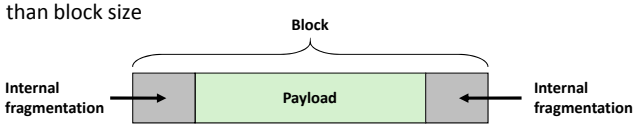
Internal Fragmentation

- 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)

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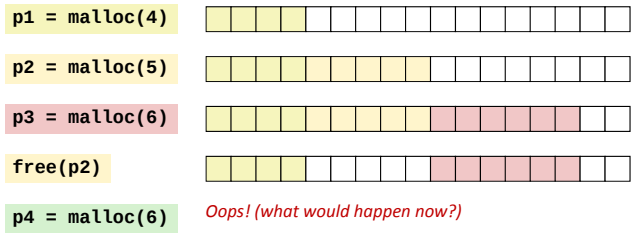
External Fragmentation

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



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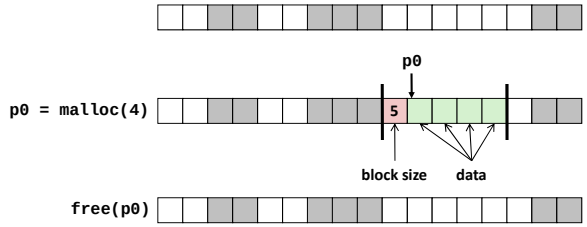
Structure of Allocated Block

- 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



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Free Block Management

- How to keep track of free blocks?
- Allocate from free blocks:
  - How do we pick a block to use for allocation – many might fit?
  - 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 reinsert freed block?

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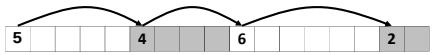
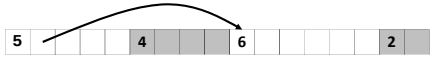
Keeping Track of Free Blocks

- 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

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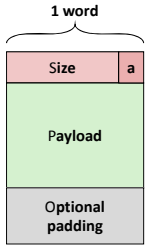
Method 1: Implicit Free Block List

- 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)

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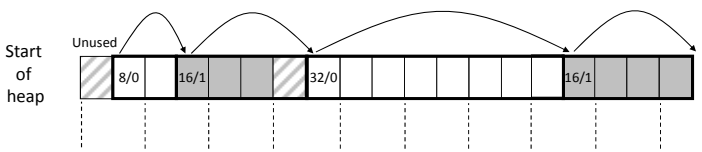
Detailed Implicit Free List Example



Double-word aligned

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

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Implicit List: Finding a Free Block

- *First fit:*
  - Search list from beginning, choose ***first*** free block that fits:
  - Can take linear time in total number of blocks (allocated and free)
  - It may 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

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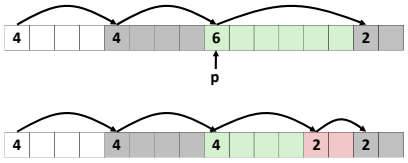
Implicit List: Allocating in Free Block

- Allocating in a free block: *splitting*
  - Since allocated space might be smaller than free space, we might want to split the block



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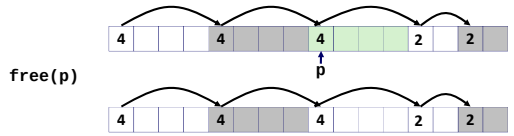
Implicit List: Freeing a Block

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

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

  - But can lead to "false fragmentation"



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

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

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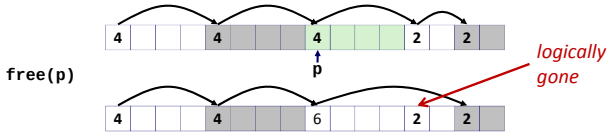
Implicit List: Coalescing

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



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

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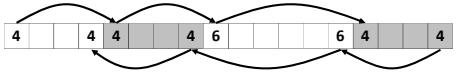
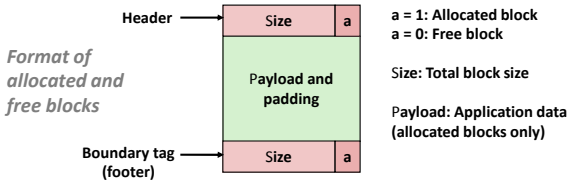
Implicit List: Bidirectional Coalescing

- *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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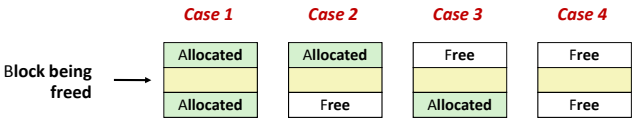
Constant Time Coalescing



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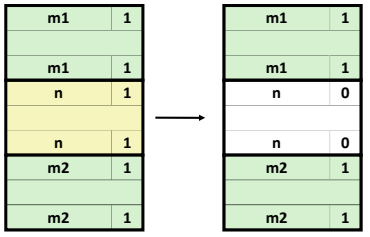
Constant Time Coalescing (Case 1)



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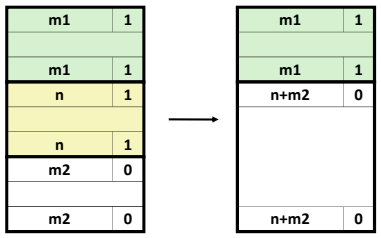
Constant Time Coalescing (Case 2)



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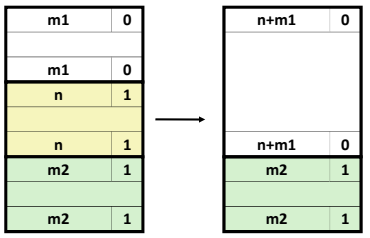
Constant Time Coalescing (Case 3)



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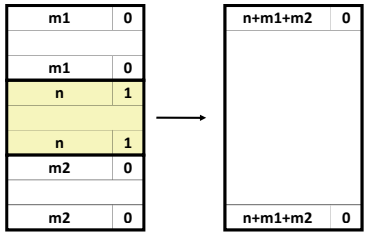
Constant Time Coalescing (Case 4)



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Space use of footers

- Additional space consumption
- Can it be optimized?
  - Footer tag is free in free blocks
  - No need to coalesce in allocated blocks

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Implicit Free Block Lists: Summary

- Implementation: very simple
- Allocate cost:
  - linear time worst case
- Free cost:
  - constant time worst case
  - even with coalescing
- Memory usage:
  - Depend on placement policy: first-fit, next-fit or best-fit
- Not used in general allocator because of linear-time allocation
- Segregated free lists (next lecture) approximate a best fit placement policy without having to search entire free list

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Disclaimer

These slides were adapted from the CMU course slides provided along with the textbook of "Computer Systems: A programmer's Perspective" by Bryant and O'Hallaron. The slides are intended for the sole purpose of teaching the computer organization course at the University of Rochester.

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