CS 240
Foundations of Computer Systems

WELLESLEY

Dynamic Memory Allocation in the Heap

Explicit allocators

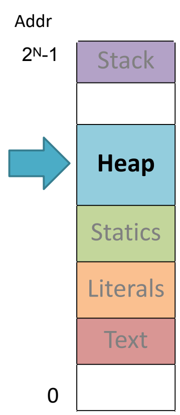
Manual memory management

C: implementing malloc and free

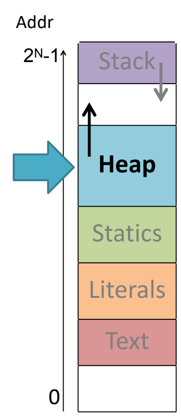
Big picture: how is dynamic memory implemented in C?

Outline

- Motivation/alternatives
- Design goals for a memory allocator
  - Utilization/fragmentation
- Implicit free list allocator
  - Tracking sizes
  - Allocating blocks
  - Coalescing blocks
- Explicit free lists
  - List vs. memory order
  - Freeing/coalescing

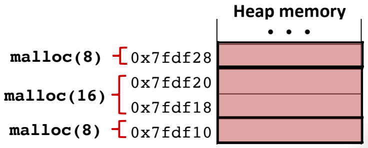


Heap Allocation

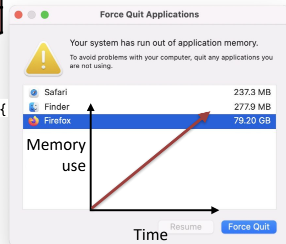


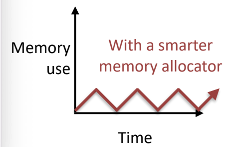
	Perm	Contents	Managed by	Initialized
Stack	RW	Procedure context	Compiler	Run-time
Heap	RW	**Dynamic data structures**	Programmer, **malloc/free,** new/GC	**Run-time**
Statics	RW	Global variables/ static data structures	Compiler/ Assembler/Linker	Startup
Literals	R	String literals	Compiler/ Assembler/Linker	Startup
Text	X	Instructions	Compiler/ Assembler/Linker	Startup

Motivation: why not just allocate in memory order?




```
void process_incoming_data(int data[]) {
  // Build complicated data structures
  // ...
  print("%d", result);
  // Don't need data or backing work!
}
```





Motivation: what data do we need to track?

ex

Idea: given a page (4096 bytes), support these two functions

pointer to newly allocated block of at least that size

number of contiguous bytes required

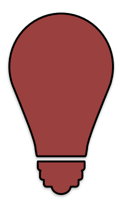
```
void* malloc(size_t size);
```

pointer to allocated block to free

```
void free(void* ptr);
```

What data structures could we use to track this?

Actual dynamic memory allocator design

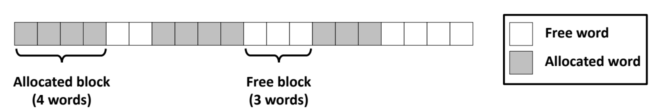


Design the allocator to store data "inline" within the heap memory itself

- Space efficient: no need for much data "on the side"
- Use pointer arithmetic to calculate results
- Good use of caches/locality (we'll cover more later)

Allocator basics

Pages (OS-provided) too coarse-grained for allocating individual objects.
Instead: flexible-sized, word-aligned blocks.



pointer to newly allocated block of at least that size

number of contiguous bytes required

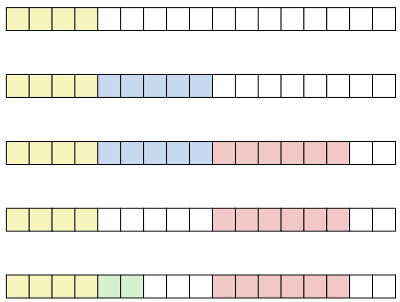
```
void* malloc(size_t size);
```

pointer to allocated block to free

```
void free(void* ptr);
```

Example (64-bit words)

```
p1 = malloc(32);
p2 = malloc(40);
p3 = malloc(48);
free(p2);
p4 = malloc(16);
```



Allocator goals: malloc/free

1. **Programmer does not decide locations of distinct objects.**
   Programmer decides: what size, when needed, when no longer needed

```
p = malloc(32);
// ...
free(p)
```

2. **Fast allocation.**
   mallocs/second or bytes malloc'd/second

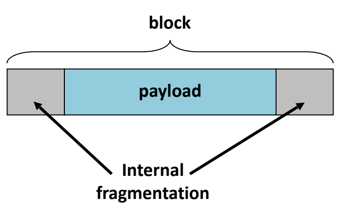
$O(\ldots)$

3. **High memory utilization.**
   Most of heap contains necessary program data.
   Little wasted space.

Enemy: **fragmentation** – unused memory that cannot be allocated.

Internal fragmentation

Payload smaller than block

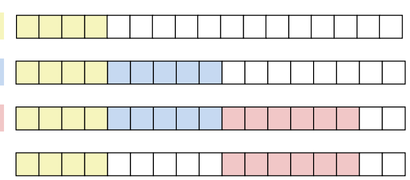


Causes
- Metadata (bookkeeping)
- Alignment (8, 16, ...)
- Policy decisions

External fragmentation (64-bit words)

Total free space large enough, but no contiguous free block large enough!

```
p1 = malloc(32);
p2 = malloc(40);
p3 = malloc(48);
free(p2);
p4 = malloc(48);
```



Depends on the pattern of future requests.

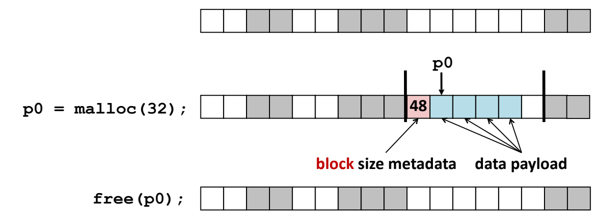
Implementation issues

1. Determine **how much** to free given just a pointer.
2. Keep track of **free blocks**.
3. **Pick** a block to allocate.
4. Choose what do with **extra space** when allocating a structure that is smaller than the free block used.
5. Make a **freed block available** for future reuse.

Knowing how much to free

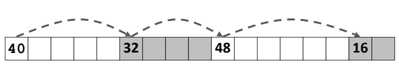
Keep length of block in *header* word preceding block

Takes extra space!

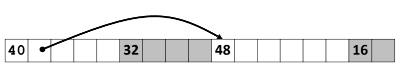


Keeping track of free blocks

Method 1: *Implicit free list* of all blocks using length



Method 2: *Explicit free list* of free blocks using pointers



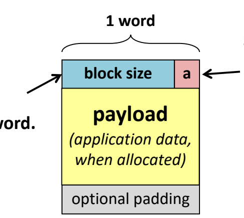
Method 3: *Seglist*
Different free lists for different size blocks

More methods that we will skip…

Implicit free list: block format

Block metadata:
1. Block size
2. Allocation status

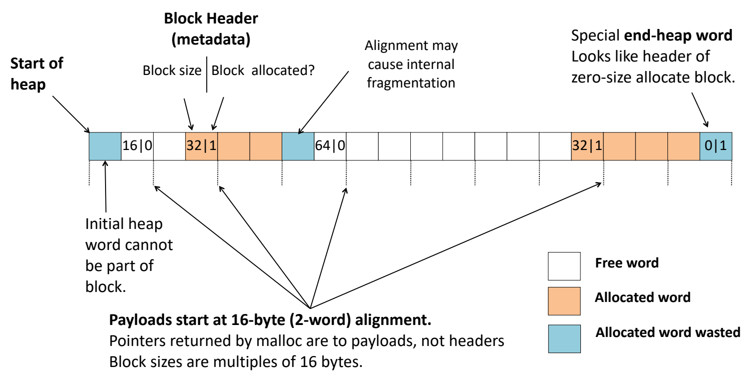
Store in one header word.



Steal LSB for status flag.
LSB = 1: allocated
LSB = 0: free

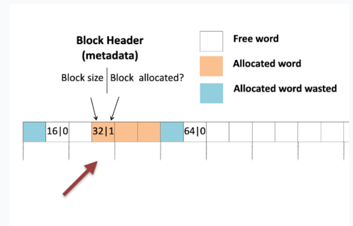
16-byte aligned sizes have
4 zeroes in low-order bits
0000**0000**
0001**0000**
0010**0000**
0011**0000**
…

Implicit free list: **heap layout**



Recall: in this implicit free list heap, why does the block pointed to by the red arrow have size 32?

0



- payload is 2 words, 2*16=32 **(A)**
- payload is 2 words, header 2, 4*8=32 **(B)**
- payload is 3 words, header 1, 4*8=32 **(C)**
- payload 2 words, header 1, 1 wasted (alig… **(D)**
- None of the above **(E)**

Implicit free list: **finding a free block**

First fit:

Search list from beginning, choose ***first*** free block that fits

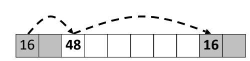
Next fit:

Do first-fit starting where previous search finished

Best fit:

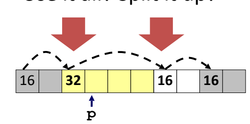
Search the list, choose the ***best*** free block: fits, with fewest bytes left over

Implicit free list: **allocating a free block**




```
p = malloc(24);
```

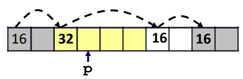
Allocated space ≤ free space.
Use it all? Split it up?



Block **Splitting**

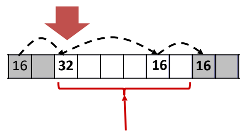
Now showing allocation status flag implicitly with shading.

Implicit free list: **freeing an allocated block**



`free(p);`

Clear *allocated* flag.

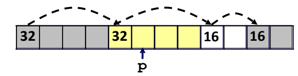


`malloc(40);`

External fragmentation!

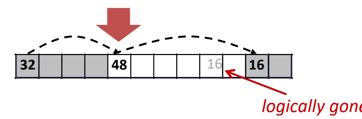
Enough space, not one block.

Coalescing free blocks



`free(p)`

Coalesce with following *free* block.

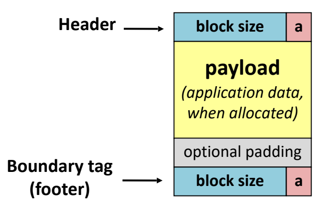


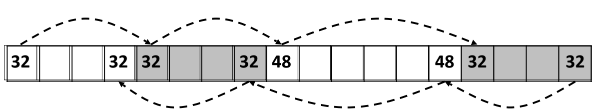
Coalesce with **preceding** *free* block?

Bidirectional coalescing: boundary tags

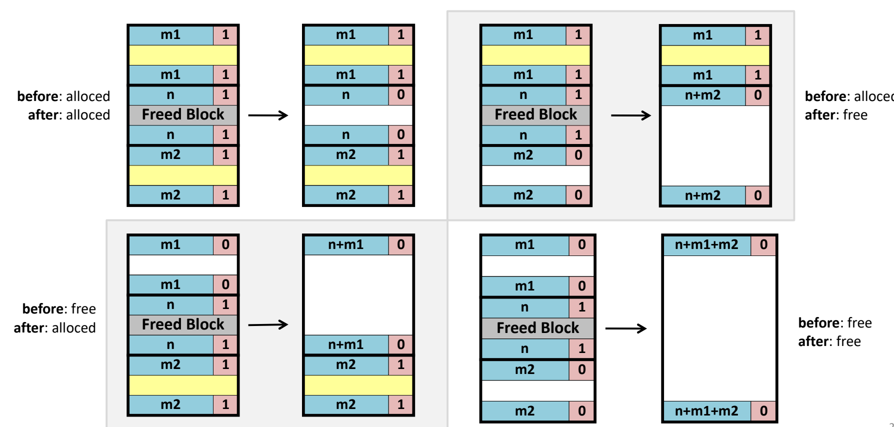
[Knuth73]

Conceptually: more like a doubly-linked list

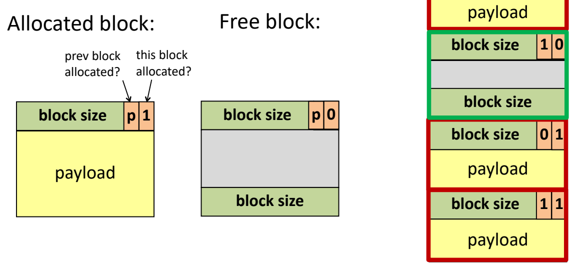




Constant-time O(1) coalescing: 4 cases



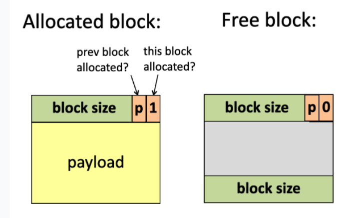
Improved block format for implicit free lists



Update headers of 2 blocks on each malloc/free.

Minimum block size for implicit free list?

What is the minimum block size for an implicit free block (in bytes)?



- 8
- 16
- 24
- 32
- None of the above

Summary: **implicit free lists**

Implementation: simple

O(…) for allocate and free?
Allocate: O(blocks in heap)
Free: O(1)

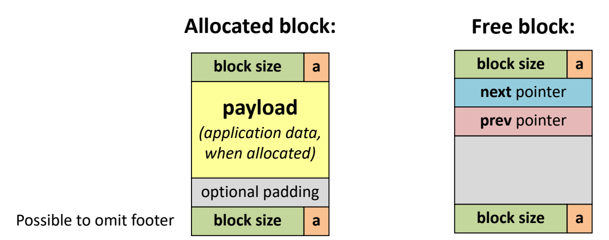
Memory utilization: depends on placement policy

Not as widely used in practice
some special purpose applications

Splitting, boundary tags, coalescing are **general** to *all* allocators.

Explicit free list: block format

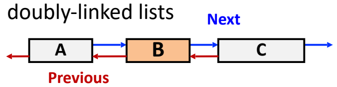
Explicit list of ***free*** blocks rather than implicit list of ***all*** blocks.



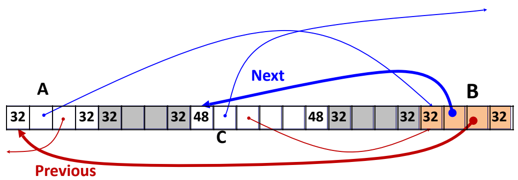
(same as implicit free list)

Explicit free list: **list vs. memory order**

Abstractly: doubly-linked lists

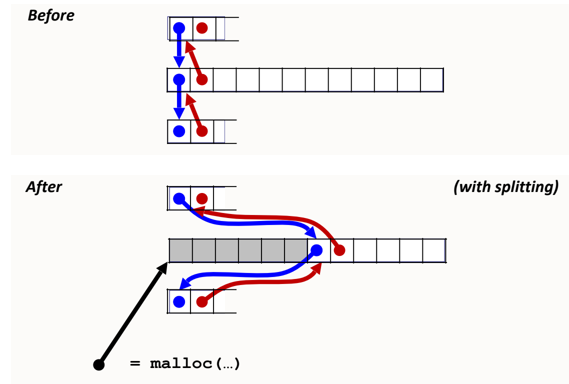


Concretely: free list blocks in any memory order



List Order ≠ Memory Order

Explicit free list: **allocating a free block**



Explicit free list: **freeing a block**

Insertion policy: Where in the free list do you add a freed block?

LIFO (last-in-first-out) policy

Pro: simple and constant time

Con: studies suggest fragmentation is worse than address ordered

Address-ordered policy

Con: linear-time search to insert freed blocks

Pro: studies suggest fragmentation is lower than LIFO

LIFO Example: 4 cases of freed block neighbor status.

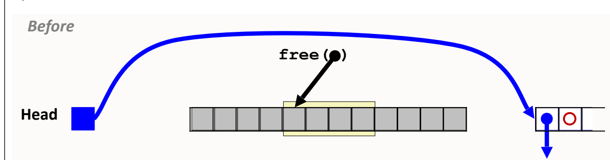
Freeing with LIFO policy: **between allocated blocks**

ex

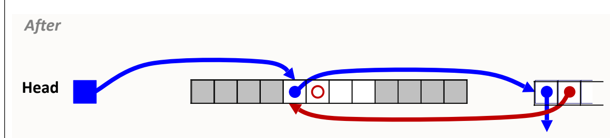
blue: next
red: prev
open: NULL

Imagine we used this struct for each block header:

```
typedef struct Block {
    struct Block* next;
    struct Block* prev;
} Block;
```



Write code to insert the freed block at head of free list.

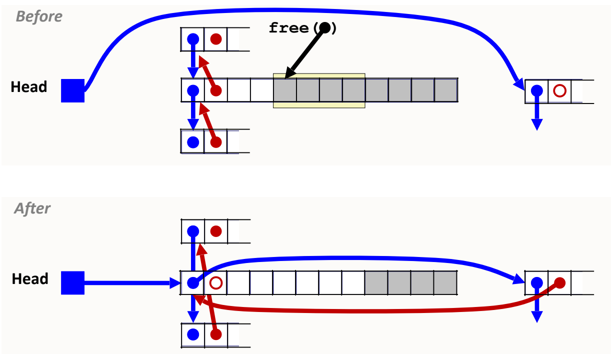



```
Block *head;

void insert1(Block* freed){
    // ... fill in

}
```

Freeing with LIFO policy: **between free and allocated**

blue: next
red: prev
open: `NULL`

Splice out predecessor block, coalesce both memory blocks, and insert the new block at the head of the free list.



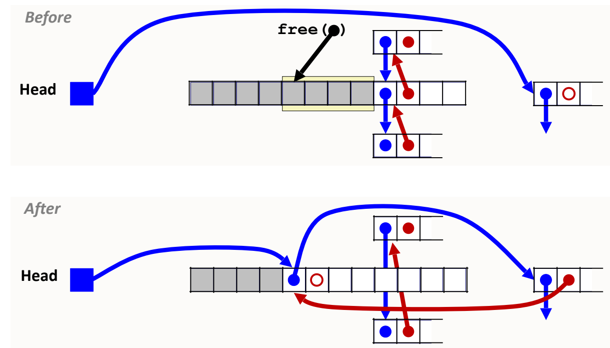

```
typedef struct Block {
    struct Block* next;
    struct Block* prev;
} Block;

Block *head;

void insert2(Block* freed){
    // ... fill in

}
```

Could be on either or both sides...

Freeing with LIFO policy: **between allocated and free**

blue: next
red: prev
open: `NULL`

Splice out successor block, coalesce both memory blocks and insert the new block at the head of the free list.

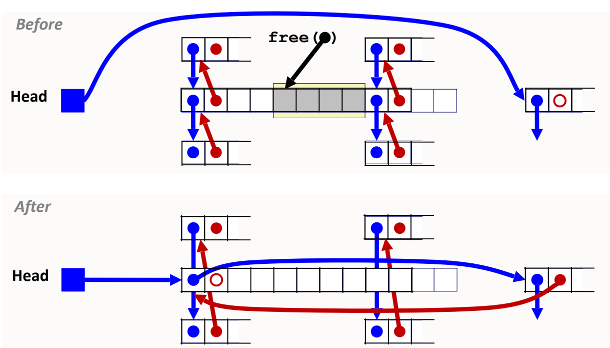



```
typedef struct Block {
    struct Block* next;
    struct Block* prev;
} Block;

Block *head;

void insert3(Block* freed){
    // ... fill in

}
```


Freeing with LIFO policy: **between free blocks**

blue: next
red: prev
open: `NULL`

Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the head of the list.




```
typedef struct Block {
    struct Block* next;
    struct Block* prev;
} Block;

Block *head;

void insert4(Block* freed){
    // ... fill in

}
```


Summary: **Explicit Free Lists**

Implementation: fairly simple

Allocate:	O(*free* blocks)	vs. O(*all* blocks)
Free:	O(1)	vs. O(1)

Memory utilization:

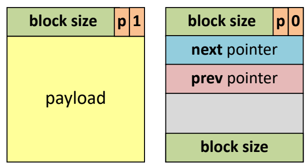
depends on placement policy
larger minimum block size (next/prev) vs. implicit list

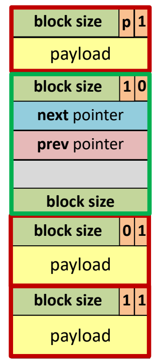
Used widely in practice, often with more optimizations.

Splitting, boundary tags, coalescing are general to *all* allocators.

Improved block format for explicit free lists

Allocated block: Free block:





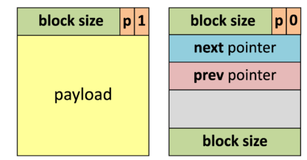
Update headers of 2 blocks on each malloc/free.

Minimum block size for explicit free list?

What is the minimum block size for an explicit free block (in bytes)?

0

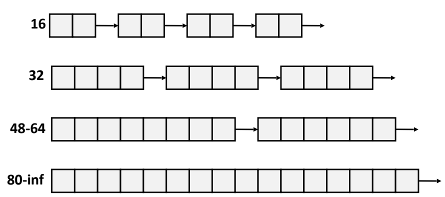
Allocated block: Free block:



- 8
- 16
- 24
- 32
- None of the above

Seglist allocators

Each ***size bracket*** has its own free list



Faster best-fit allocation...

Summary: **allocator policies**

All policies offer **trade-offs** in fragmentation and throughput.

Placement policy:
First-fit, next-fit, best-fit, etc.
Seglists approximate best-fit in low time

Splitting policy:
Always? Sometimes? Size bound?

Coalescing policy:
Immediate vs. deferred