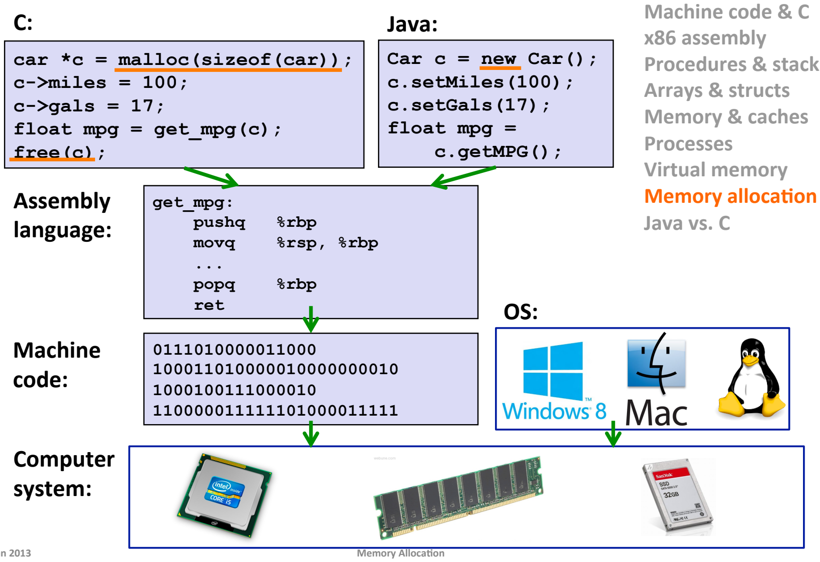
Roadmap



C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Computer system:

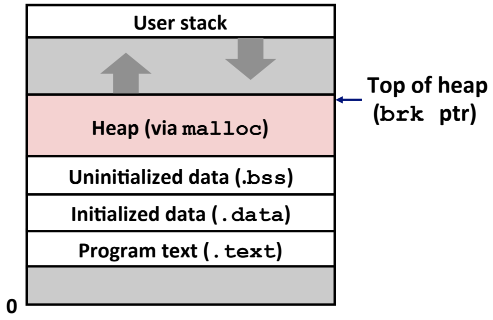
- Memory & data
- Integers & floats
- Machine code & C
- x86 assembly
- Procedures & stacks
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- **Memory allocation**
- Java vs. C

Memory Allocation Topics

- **Dynamic memory allocation**
  - Size/number of data structures may only be known at run time
  - Need to allocate space on the heap
  - Need to de-allocate (free) unused memory so it can be re-allocated
- **Implementation**
  - Implicit free lists
  - Explicit free lists – subject of next programming assignment
  - Segregated free lists
- **Garbage collection**
- **Common memory-related bugs in C programs**

Dynamic Memory Allocation

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



Dynamic Memory Allocation

- **Allocator maintains heap as collection of variable sized *blocks*, which are either *allocated* or *free***
  - Allocator requests pages in heap region; virtual memory hardware and OS kernel allocate these pages to the process.
  - Application objects are typically smaller than pages, so the allocator manages blocks *within* pages. (Sometimes larger)
- **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

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 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

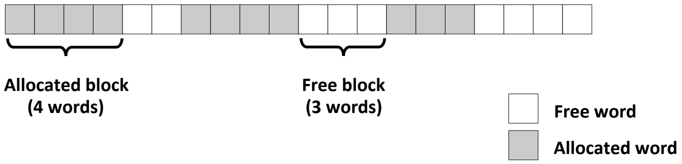
- **`calloc`**: Version of **`malloc`** that initializes allocated block to zero.
- **`realloc`**: Changes the size of a previously allocated block.
- **`sbrk`**: Used internally by allocators to grow or shrink the heap.
  - historical naming from before virtual memory was common…

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);
  }
  for (i=0; i<n; i++) p[i] = i;

  /* add space for m ints 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

- **Memory is word addressed (each word can hold a pointer)**
  - block size is a multiple of words



Allocated block (4 words)

Free block (3 words)

☐ **Free word**

▨ **Allocated word**

Allocation Example (32-bit)

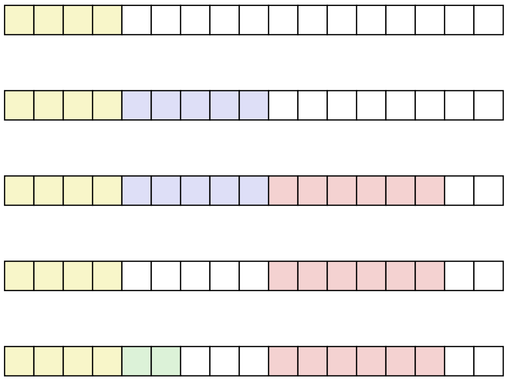
`p1 = malloc(16)`

`p2 = malloc(20)`

`p3 = malloc(12)`

`free(p2)`

`p4 = malloc(8)`



Constraints

- **Applications**
  - Can issue arbitrary sequence of malloc() and free() requests
  - free() requests must be made only for a previously 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.*, blocks can't overlap, *why not?*
  - Must align blocks so they satisfy all alignment requirements
    - 8 byte alignment for GNU malloc (`libc` malloc) on Linux
  - Can't move the allocated blocks once they are malloc()'d
    - *i.e.*, compaction is not allowed. *Why not?*

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

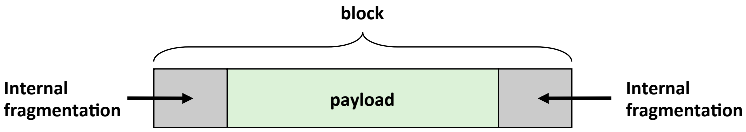
- **Given some sequence of `malloc` and `free` requests:**
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- ***Def: Aggregate payload*** P_k
  - `malloc(p)` results in a block with a ***payload*** of `p` bytes
  - After request R_k has completed, the ***aggregate payload*** P_k is the sum of currently allocated payloads
- ***Def: Current heap size =*** H_k
  - Assume H_k is monotonically nondecreasing
    - Allocator can increase size of heap using `sbrk()`
- ***Def: Peak memory utilization after k requests***
  - $U_k = (\max_{i \le k} P_i) \ / \ H_k$
  - Goal: maximize utilization for a sequence of requests.
  - *Why is this hard? And what happens to throughput?*

Fragmentation

- **Poor memory utilization is caused by *fragmentation.***
- **Sections of memory are not used to store anything useful, but cannot be allocated.**
- ***internal* fragmentation**
- ***external* fragmentation**

Internal Fragmentation

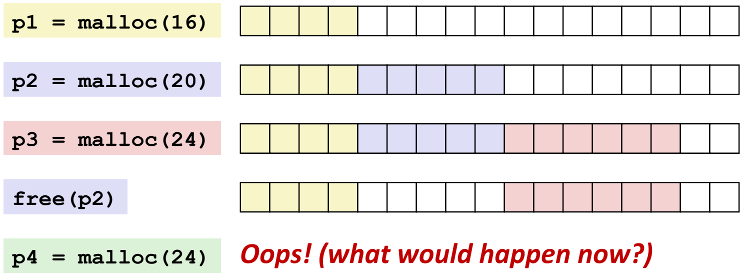
- For a given block, ***internal fragmentation*** occurs if payload is smaller than block size



- Caused by
  - overhead of maintaining heap data structures (inside block, outside payload)
  - padding for alignment purposes
  - explicit policy decisions (e.g., to return a big block to satisfy a small request)
    why would anyone do that?

External Fragmentation (32-bit)

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



`p1 = malloc(16)`

`p2 = malloc(20)`

`p3 = malloc(24)`

`free(p2)`

`p4 = malloc(24)`

Oops! (what would happen now?)

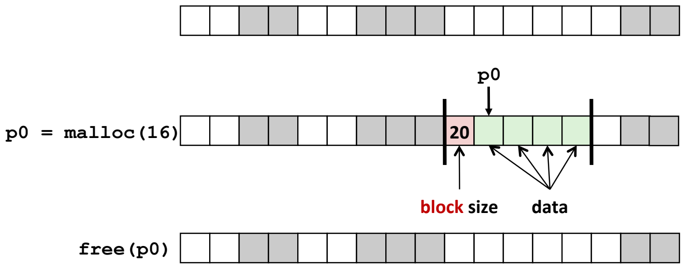
- Depends on the pattern of future requests
  - Thus, difficult to measure

Implementation Issues

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?
- How do we pick a block to use for allocation (when 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 into the heap?

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

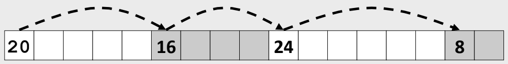


`p0 = malloc(16)`

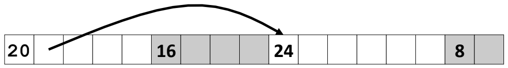
`free(p0)`

Keeping Track of Free Blocks

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



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



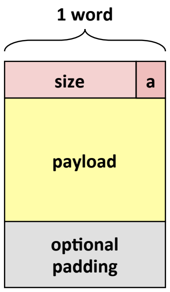
- **Method 3: *Segregated free list***
  - Different free lists for different size classes
- **Method 4: *Blocks sorted by size***
  - Can use a balanced binary tree (e.g. red-black tree) with pointers within each free block, and the length used as a key

---

Implicit Free Lists

e.g. with 8-byte alignment, sizes look like:
00000000
00001000
00010000
00011000
…

- **For each block we need: size, is-allocated?**
  - Could store this information in two words: wasteful!
- **Standard trick**
  - If blocks are aligned, some low-order size bits are always 0
  - Instead of storing an always-0 bit, use it as a allocated/free flag
  - When reading size, must remember to mask out this bit



Format of allocated and free blocks

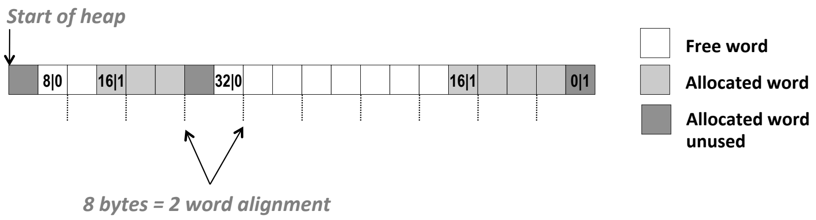
a = 1: allocated block
a = 0: free block

size: block size

payload: application data (allocated blocks only)

Implicit Free List Example (32-bit)

Sequence of blocks in heap (size|allocated): 8|0, 16|1, 32|0, 16|1



- **8-byte alignment**
  - May require initial unused word
  - Causes some internal fragmentation
- **Special one-word marker (0|1) marks end of list**
  - zero size is distinguishable from all real sizes

Implicit List: Finding a Free Block

*p gets the block *header*
*p & 1 extracts the allocated bit
*p & -2 masks the allocated bit, gets just the size

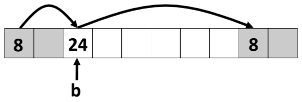
- ***First fit:***
  - Search list from beginning, choose ***first*** free block that fits:

```
p = heap_start;
while ((p < end) &&     // not past end
       ((*p & 1) ||     // already allocated
       (*p <= len))) {  // too small
  p = p + (*p & -2);    // go to next block (UNSCALED +)
}                       // p points to selected block or end
```

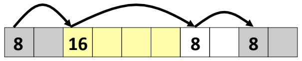
  - Can take time linear in total number of blocks (allocated and free)
  - In practice it can cause "splinters" at beginning of list
- ***Next fit:***
  - Like first-fit, but search list starting where previous search finished
  - Should often be faster than first-fit: avoids re-scanning unhelpful blocks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



`malloc(12)` → `split(b, 16)`



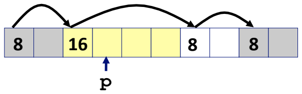
assume ptr points to word and has unscaled pointer arithmetic

```
void split(ptr b, int bytes) {          // bytes = desired block size
  int newsize = ((bytes + 7) >> 3) << 3;// round up to multiple of 8
  int oldsize = *b;                     // why not mask out low bit?
  *b = newsize;                         // initially unallocated
  if (newsize < oldsize)
    *(b+newsize) = oldsize - newsize;   // set length in remaining
}                                       // part of block (UNSCALED +)
```

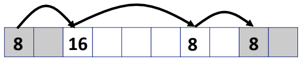
Implicit List: Freeing a Block

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

    `void free(ptr p) { ptr b = p – WORD; *b = *b & -2 }`
  - But can lead to "false fragmentation"



`free(p)`



`malloc(20)` ***Oops!***

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

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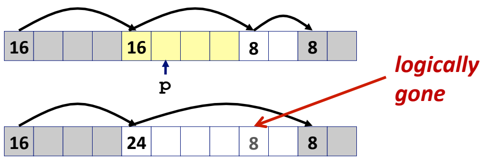
Implicit List: Coalescing

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

`free(p)`

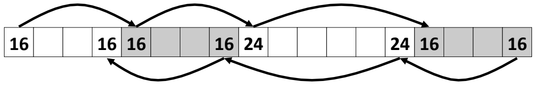


```
void free(ptr p) {          // p points to data
    ptr b = p – WORD;       // b points to block
    *b = *b & -2;           // clear allocated bit
    ptr next = b + *b;      // find next block (UNSCALED +)
    if ((*next & 1) == 0)
      *b = *b + *next;      // add to this block if
}                           //    not allocated
```

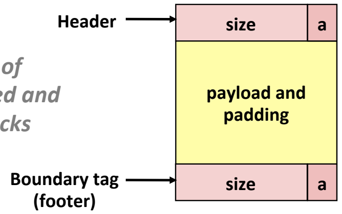
  - But how do we coalesce with the *previous* block?

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!



Format of allocated and free blocks



a = 1: allocated block
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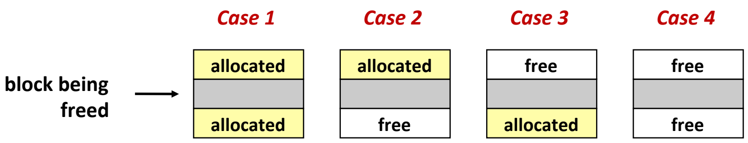
size: total block size

payload: application data (allocated blocks only)

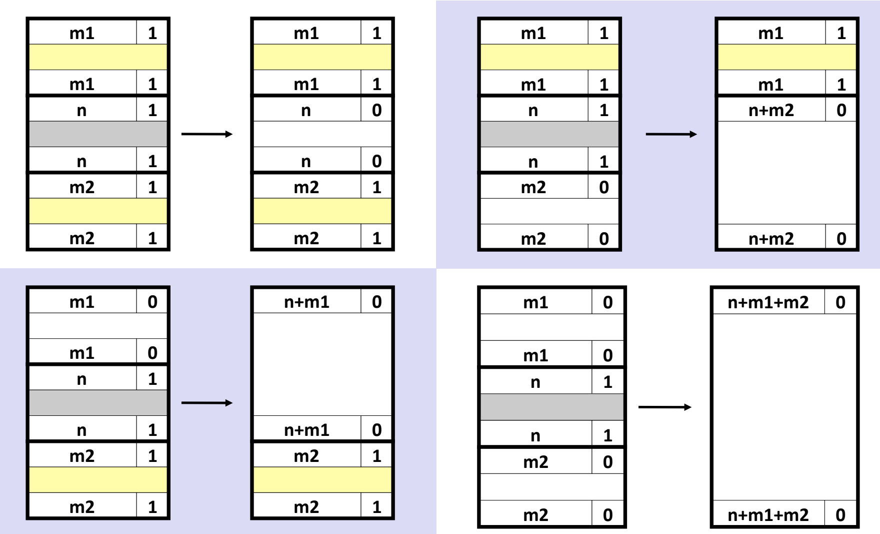
Constant Time Coalescing



block being freed

	Case 1	Case 2	Case 3	Case 4
	allocated	allocated	free	free
block being freed				
	allocated	free	allocated	free

Constant Time Coalescing



Implicit Free Lists: Summary

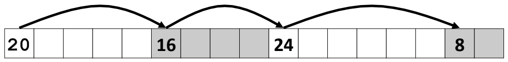
- **Implementation: very simple**
- **Allocate cost:**
  - linear time (in total number of heap blocks) worst case
- **Free cost:**
  - constant time worst case
  - even with coalescing
- **Memory utilization:**
  - will depend on placement policy
  - First-fit, next-fit or best-fit

- **Not used in practice for `malloc()`/`free()` because of linear-time allocation**
  - used in some special purpose applications

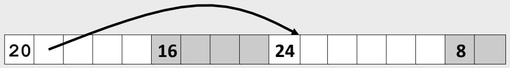
- **The concepts of splitting and boundary tag coalescing are general to *all* allocators**

Keeping Track of Free Blocks

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



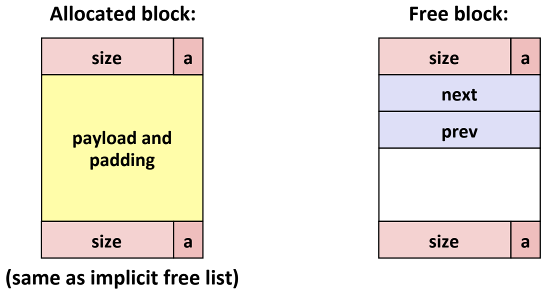
- **Method 2: *Explicit free list* among the free blocks using pointers**



- **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

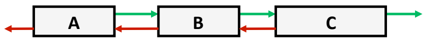
Explicit Free Lists



- **Maintain list(s) of *free* blocks, rather than implicit list of *all* blocks**
  - The "next" free block could be anywhere in the heap
    - So we need to store forward/back pointers, not just sizes
  - Luckily we track only free blocks, so we can use payload area for pointers
  - Still need boundary tags for coalescing

Explicit Free Lists

- **Logically (doubly-linked lists):**

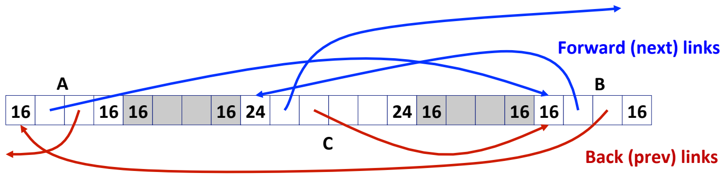


- **Physically?**

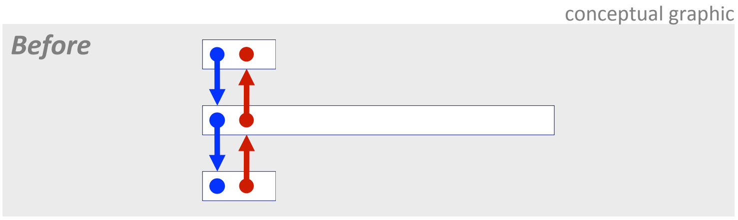
Explicit Free Lists

- **Logically (doubly-linked lists):**

- **Physically: blocks can be in any order**

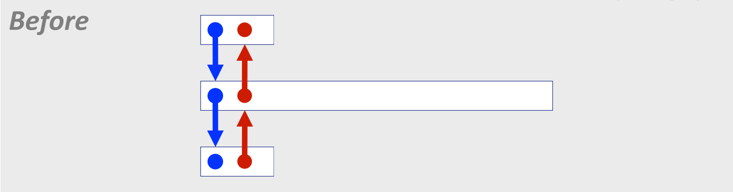


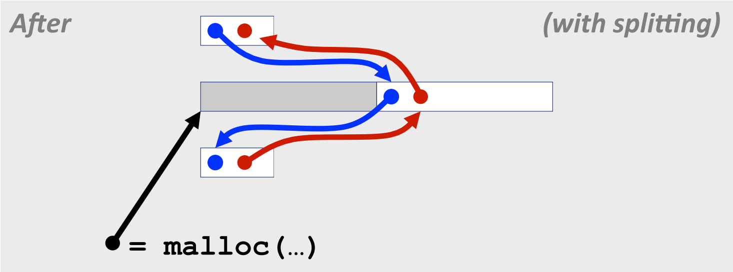
Allocating From Explicit Free Lists



Allocating From Explicit Free Lists

conceptual graphic





Freeing With Explicit Free Lists

- ***Insertion policy*: Where in the free list do you put a newly freed block?**

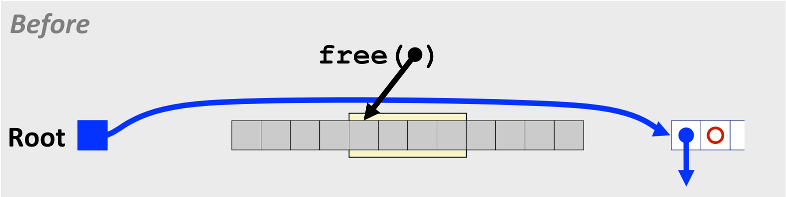
Freeing With Explicit Free Lists

- ***Insertion policy*: Where in the free list do you put a newly freed block?**
  - LIFO (last-in-first-out) policy
    - Insert freed block at the beginning of the free list
    - *Pro:* simple and constant time
    - *Con:* studies suggest fragmentation is worse than address ordered
  - Address-ordered policy
    - Insert freed blocks so that free list blocks are always in address order:

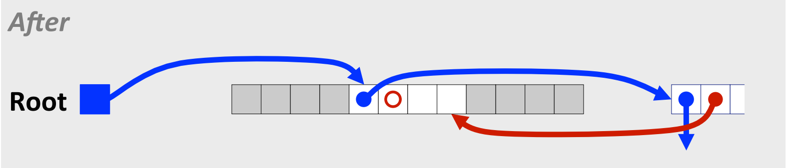
      addr(prev) < addr(curr) < addr(next)
    - *Con:* requires linear-time search when blocks are freed
    - *Pro:* studies suggest fragmentation is lower than LIFO
- **Cache effects?**

Freeing With a LIFO Policy (Case 1)

conceptual graphic

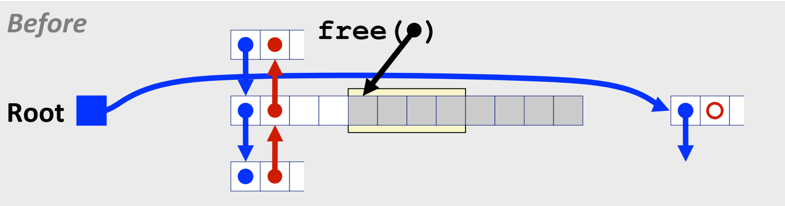


- **Insert the freed block at the root of the list**

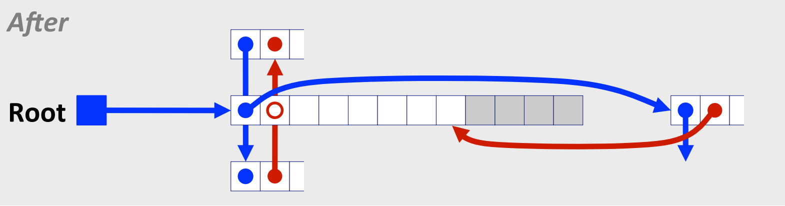


Freeing With a LIFO Policy (Case 2)

conceptual graphic

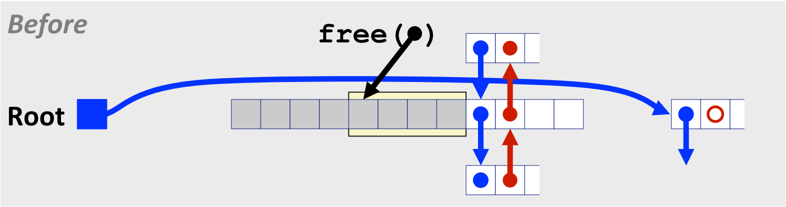


- Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list

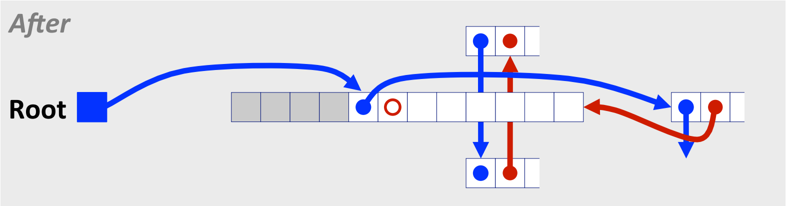


Freeing With a LIFO Policy (Case 3)

conceptual graphic

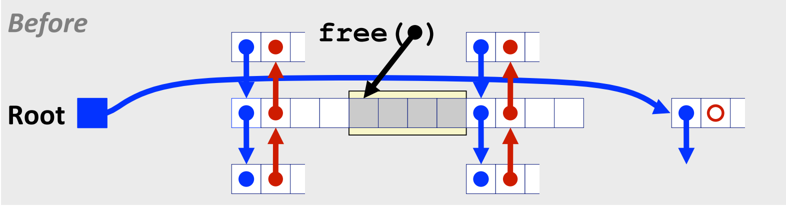


- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list

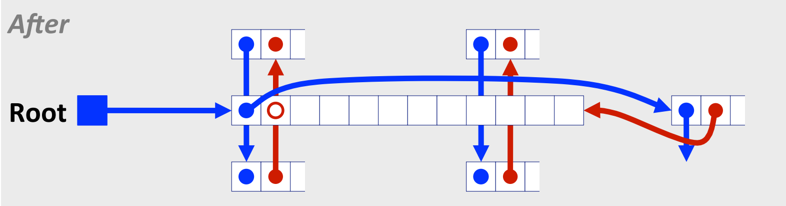


Freeing With a LIFO Policy (Case 4)

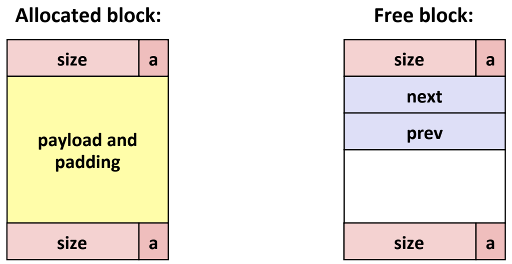
conceptual graphic



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



Do we always need the boundary tag?



- Lab 5 suggests no…

Explicit List Summary

- **Comparison to implicit list:**
  - Allocate is linear time in number of ***free*** blocks instead of ***all*** blocks
    - ***Much faster*** when most of the memory is full
  - Slightly more complicated allocate and free since needs to splice blocks in and out of the list
  - Some extra space for the links (2 extra words needed for each block)
    - Possibly increases minimum block size, leading to more internal fragmentation

- **Most common use of explicit lists is in conjunction with *segregated free lists***
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

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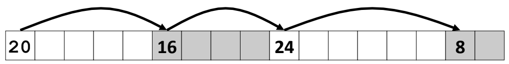
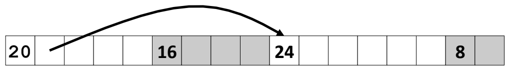
Keeping Track of Free Blocks

- **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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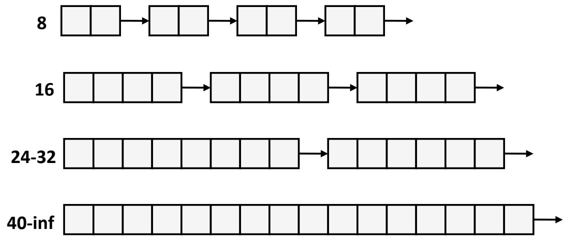
Segregated List (Seglist) Allocators

- **Each *size class* of blocks has its own free list**



- **Often have separate classes for each small size**
- **For larger sizes: One class for each two-power size**

Seglist Allocator

- **Given an array of free lists, each one for some size class**

- **To allocate a block of size *n*:**
  - Search appropriate free list for block of size *m* > *n*
  - If an appropriate block is found:
    - Split block and place fragment on appropriate list (optional)
  - If no block is found, try next larger class
  - Repeat until block is found

- **If no block is found:**
  - Request additional heap memory from OS (using `sbrk()`)
  - Allocate block of *n* bytes from this new memory
  - Place remainder as a single free block in largest size class

Seglist Allocator

- **To free a block:**
  - Coalesce and place on appropriate list (optional)

- **Advantages of seglist allocators**
  - Higher throughput
    - log time for power-of-two size classes
  - Better memory utilization
    - First-fit search of segregated free list approximates a best-fit search of entire heap.
    - Extreme case: Giving each block its own size class is equivalent to best-fit.

Summary of Key Allocator Policies

- **Placement policy:**
  - First-fit, next-fit, best-fit, etc.
  - Trades off lower throughput for less fragmentation
  - ***Observation***: segregated free lists 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

---

More Info on Allocators

- **D. Knuth, "*The Art of Computer Programming*", 2nd edition, Addison Wesley, 1973**
  - The classic reference on dynamic storage allocation

- **Wilson et al, "*Dynamic Storage Allocation: A Survey and Critical Review*", Proc. 1995 Int'l Workshop on Memory Management, Kinross, Scotland, Sept, 1995.**
  - Comprehensive survey
  - Available from CS:APP student site (csapp.cs.cmu.edu)

Wouldn't it be nice…

- **If we never had to free memory?**
- **Do you free objects in Java?**

Garbage Collection (GC)

(Automatic Memory Management / Implicit Memory Allocation)

- ***Garbage collection:*** **automatic reclamation of heap-allocated storage—application never explicitly frees memory.**

```
void foo() {
   int* p = (int *)malloc(128);
   return;  /* p block is now garbage */
}
```

- **Common in implementations of functional languages, scripting languages, and modern object oriented languages:**
  - Lisp, Racket, Erlang, ML, Haskell, Scala, Java, C#, Perl, Ruby, Python, Lua, JavaScript, Dart, Mathematica, MATLAB, many more…
- **Variants ("conservative" garbage collectors) exist for C and C++**
  - However, cannot necessarily collect all garbage

Garbage Collection

- **How does the memory allocator know when memory can be freed?**
  - In general, we cannot know what is going to be used in the future since it depends on conditionals (halting problem, etc.)

Garbage Collection

- **How does the memory allocator know when memory can be freed?**
  - In general, we cannot know what is going to be used in the future since it depends on conditionals (halting problem, etc.)
  - But, we can tell that certain blocks cannot be used if there are no pointers to them

- **So the memory allocator needs to know what is a pointer and what is not – how can it do this?**

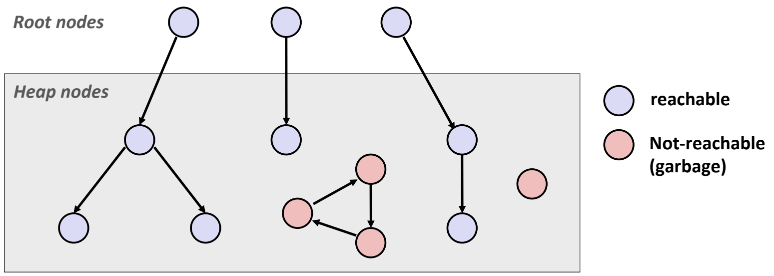
- **We'll make some assumptions about pointers:**
  - Memory allocator can distinguish pointers from non-pointers
  - All pointers point to the start of a block in the heap
  - Application cannot hide pointers
    (e.g., by coercing them to an `int`, and then back again)

Classical GC Algorithms

- **Mark-and-sweep collection (McCarthy, 1960)**
  - Does not move blocks (unless you also "compact")
- **Reference counting (Collins, 1960)**
  - Does not move blocks (not discussed)
- **Copying collection (Minsky, 1963)**
  - Moves blocks (not discussed)
- **Generational Collectors (Lieberman and Hewitt, 1983)**
  - Most allocations become garbage very soon, so
    focus reclamation work on zones of memory recently allocated.
- **For more information:**
  - Jones, Hosking, and Moss, *The Garbage Collection Handbook: The Art of Automatic Memory Management*, CRC Press, 2012.
  - Jones and Lin, *Garbage Collection: Algorithms for Automatic Dynamic Memory*, John Wiley & Sons, 1996.

Memory as a Graph

- **We view memory as a directed graph**
  - Each allocated heap block is a node in the graph
  - Each pointer is an edge in the graph
  - Locations not in the heap that contain pointers into the heap are called ***root*** nodes (e.g. registers, locations on the stack, global variables)

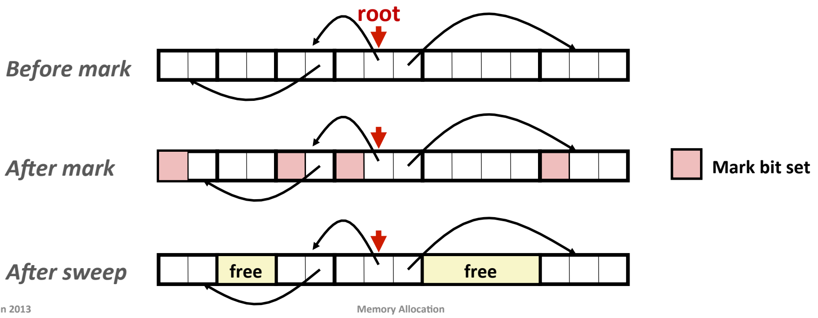


A node (block) is *reachable* if there is a path from any root to that node

Non-reachable nodes are *garbage* (cannot be needed by the application)

Mark and Sweep Collecting

- **Can build on top of malloc/free package**
  - Allocate using malloc until you "run out of space"
- **When out of space:**
  - Use extra ***mark bit*** in the head of each block
  - ***Mark:*** Start at roots and set mark bit on each reachable block
  - ***Sweep:*** Scan all blocks and free blocks that are not marked



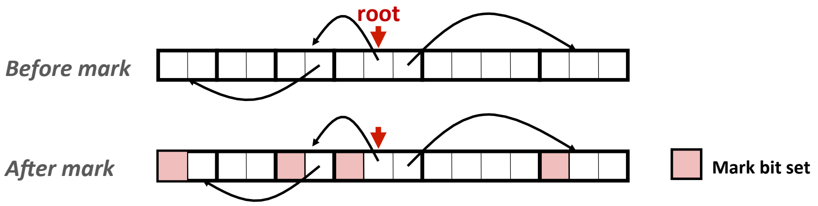
Assumptions For a Simple Implementation

- **Application can use functions to allocate memory:**
  - `b = new(n)` : returns pointer, b, to new block with all locations cleared
  - `b[i]` : read location i of block b into register
  - `b[i] = v` : write v into location i of block b
- **Each block will have a header word**
  - `b[-1]`
- **Functions used by the garbage collector:**
  - `is_ptr(p)`: determines whether p is a pointer to a block
  - `length(p)`: returns length of block pointed to by p, not including header
  - `get_roots()`: returns all the roots

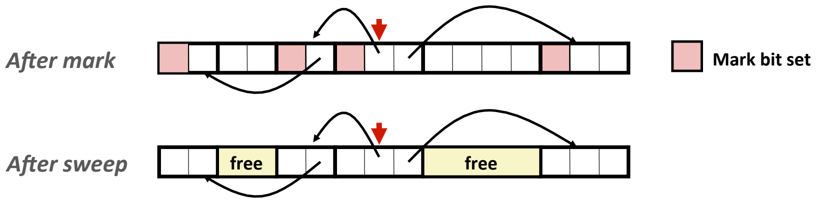
Mark

Mark using depth-first traversal of the memory graph

```
ptr mark(ptr p) {                 // p: some word in a heap block
   if (!is_ptr(p)) return;        // do nothing if not pointer
   if (markBitSet(p)) return;     // check if already marked
   setMarkBit(p);                 // set the mark bit
   for (i=0; i < length(p); i++)  // recursively call mark on
     mark(p[i]);                  //   all words in the block
   return;
}
```



Sweep

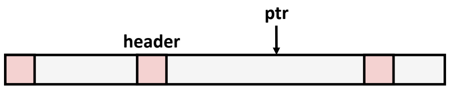


Sweep using lengths to find next block

```
ptr sweep(ptr p, ptr end) {         // ptrs to start & end of heap
   while (p < end) {                // while not at end of heap
      if markBitSet(p)              // check if block is marked
         clearMarkBit(p);           // if so, reset mark bit
      else if (allocateBitSet(p))   // if not marked, but allocated
         free(p);                   // free the block
      p += length(p);               // adjust pointer to next block
}
```

Conservative Mark & Sweep in C

- **Would mark & sweep work in C?**
  - `is_ptr()` (previous slide) determines if a word is a pointer by checking if it points to an allocated block of memory
  - But in C, pointers can point into the *middle* of allocated blocks (not so in Java)
    - Makes it tricky to find all allocated blocks in mark phase



  - There are ways to solve/avoid this problem in C, but the resulting garbage collector is *conservative:*
    - Every reachable node correctly identified as reachable, but some unreachable nodes might be incorrectly marked as reachable
  - In Java, all pointers (i.e., references) point to the starting address of an object structure – the start of an allocated block

---

Memory-Related Perils and Pitfalls in C !!!

- **Dereferencing bad pointers**
- **Reading uninitialized memory**
- **Overwriting memory**
- **Referencing nonexistent variables**
- **Freeing blocks multiple times**
- **Referencing freed blocks**
- **Failing to free blocks**

Dereferencing Bad Pointers

- **The classic `scanf` bug**

```
int val;

...

scanf("%d", val);
```

Dereferencing Bad Pointers

- **The classic `scanf` bug**

```
int val;

...

scanf(“%d”, val);
```

- **Will cause `scanf` to interpret contents of `val` as an address!**
  - Best case: program terminates immediately due to segmentation fault
  - Worst case: contents of `val` correspond to some valid read/write area of virtual memory, causing `scanf` to overwrite that memory, with disastrous and baffling consequences much later in program execution

---

Reading Uninitialized Memory

- **Assuming that heap data is initialized to zero**

```
/* return y = Ax */
int *matvec(int **A, int *x) {
   int *y = (int *)malloc( N * sizeof(int) );
   int i, j;

   for (i=0; i<N; i++) {
      for (j=0; j<N; j++) {
         y[i] += A[i][j] * x[j];
      }
   }
   return y;
}
```

Overwriting Memory

- **Allocating the (possibly) wrong sized object**

```
int **p;

p = (int **)malloc( N * sizeof(int) );

for (i=0; i<N; i++) {
   p[i] = (int *)malloc( M * sizeof(int) );
}
```

Overwriting Memory

- **Off-by-one error**

```
int **p;

p = (int **)malloc( N * sizeof(int *) );

for (i=0; i<=N; i++) {
   p[i] = (int *)malloc( M * sizeof(int) );
}
```

Overwriting Memory

- Not checking the max string size

```
char s[8];
int i;

gets(s);  /* reads “123456789” from stdin */
```

- Basis for classic buffer overflow attacks
  - Your lab assignment #3

Overwriting Memory

- Misunderstanding pointer arithmetic

```
int *search(int *p, int val) {

   while (p && *p != val)
      p += sizeof(int);

   return p;
}
```

Overwriting Memory

- Referencing a pointer instead of the object it points to

```
int *getPacket(int **packets, int *size) {
   int *packet;
   packet = packets[0];
   packets[0] = packets[*size - 1];
   *size--;   // what is happening here?
   reorderPackets(packets, *size);
   return(packet);
}
```

- ‘--’ and ‘*’ operators have same precedence and associate from right-to-left, so -- happens first!

Referencing Nonexistent Variables

- Forgetting that local variables disappear when a function returns

```
int *foo () {
   int val;

   return &val;
}
```

Freeing Blocks Multiple Times

- Nasty!

```
x = (int *)malloc( N * sizeof(int) );
        <manipulate x>
free(x);
...

y = (int *)malloc( M * sizeof(int) );
free(x);
        <manipulate y>
```

Freeing Blocks Multiple Times

- Nasty!

```
x = (int *)malloc( N * sizeof(int) );
        <manipulate x>
free(x);
...

y = (int *)malloc( M * sizeof(int) );
free(x);
        <manipulate y>
```

- What does the free list look like?

```
x = (int *)malloc( N * sizeof(int) );
        <manipulate x>
free(x);
free(x);
```

Referencing Freed Blocks

- Evil!

```
x = (int *)malloc( N * sizeof(int) );
  <manipulate x>
free(x);
   ...
y = (int *)malloc( M * sizeof(int) );
for (i=0; i<M; i++)
   y[i] = x[i]++;
```

Failing to Free Blocks (Memory Leaks)

- Slow, silent, long-term killer!

```
foo() {
   int *x = (int *)malloc(N*sizeof(int));
   ...
   return;
}
```

Failing to Free Blocks (Memory Leaks)

- **Freeing only part of a data structure**

```
struct list {
   int val;
   struct list *next;
};

foo() {
   struct list *head =
      (struct list *)malloc( sizeof(struct list) );
   head->val = 0;
   head->next = NULL;
   <create and manipulate the rest of the list>
    ...
   free(head);
   return;
}
```

Dealing With Memory Bugs

- **Conventional debugger (`gdb`)**
  - Good for finding bad pointer dereferences
  - Hard to detect the other memory bugs

- **Debugging `malloc` (UToronto CSRI `malloc`)**
  - Wrapper around conventional **`malloc`**
  - Detects memory bugs at **`malloc`** and **`free`** boundaries
    - Memory overwrites that corrupt heap structures
    - Some instances of freeing blocks multiple times
    - Memory leaks
  - Cannot detect all memory bugs
    - Overwrites into the middle of allocated blocks
    - Freeing block twice that has been reallocated in the interim
    - Referencing freed blocks

Dealing With Memory Bugs (cont.)

- **Some malloc implementations contain checking code**
  - Linux glibc malloc: **`setenv MALLOC_CHECK_ 2`**
  - FreeBSD: **`setenv MALLOC_OPTIONS AJR`**
- **Binary translator: valgrind (Linux), Purify**
  - Powerful debugging and analysis technique
  - Rewrites text section of executable object file
  - Can detect all errors as debugging **`malloc`**
  - Can also check each individual reference at runtime
    - Bad pointers
    - Overwriting
    - Referencing outside of allocated block

What about Java or ML or Python or …?

- **In *memory-safe languages*, most of these bugs are impossible**
  - Cannot perform arbitrary pointer manipulation
  - Cannot get around the type system
  - Array bounds checking, null pointer checking
  - Automatic memory management
- **But one of the bugs we saw earlier is possible. Which one?**

Memory Leaks with GC

- Not because of forgotten free() -- we have GC!
- Unneeded "leftover" roots keep objects reachable
- Sometimes nullifying a variable is not needed for correctness but is for performance
- Bigger issue with *reference counting* GC