CS356 Unit 10

Memory Allocation &
Heap Management

BASIC OS CONCEPTS & TERMINOLOGY

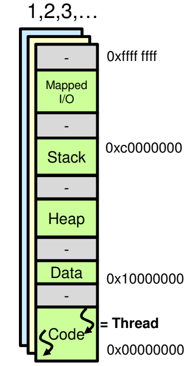
User vs. Kernel Mode

- Kernel mode is a special mode of the processor for executing __________ code
  - Certain _________________ (such as I/O access) are only allowed to code running in kernel mode
  - OS and other system software should run in kernel mode
- User mode is where user applications are designed to run to limit what they can do on their own
  - Provides _______________ by forcing them to use the OS for many services
- User vs. kernel mode determined by some bit(s) in some processor control register
  - x86 Architecture uses lower 2-bits in the CS segment register (referred to as the Current Privilege Level bits [CPL])
  - 0=Most privileged (_________ mode) and 3=Least privileged (_____ mode)
    - Levels 1 and 2 may also be used but are not by Linux

Processes

- **Process**
  - **(def 1.)** **Address Space + Threads**
    - 1 or more threads
  - **(def 2.) : Running instance of a program that has limited rights**
    - Memory is protected: Address translation (VM) ensures no access to any other processes' memory
    - I/O is protected: Processes execute in user-mode (not kernel mode) which generally means direct I/O access is disallowed instead requiring **system calls** into the kernel
- Kernel is not considered a "process"
  - Has access to all resources and much of its code is invoked under the execution of a user process thread (i.e. during a system call)
- User process invokes the OS (kernel code) via system calls (see next slide)

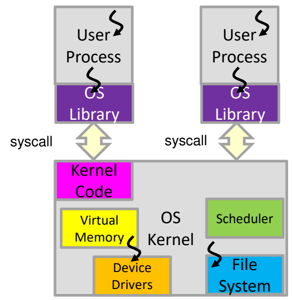
Program/Process
1,2,3,…



Address Spaces

System Calls and Mode Switches

- What causes user to kernel mode switch?
  - An exception: interrupt, error, or **system call**
- System Calls: Provide a controlled method for user mode applications to _______ kernel mode (OS) code
  - OS will define all possible system calls available to user apps.




```
enum
 {
  /* Projects 2 and later. */
  SYS_HALT,     /* 0 = Halt the operating system. */
  SYS_EXIT,     /* 1 = Terminate this process. */
  SYS_EXEC,     /* 2 = Start another process. */
  SYS_WAIT,     /* 3 = Wait for a child process */
  SYS_CREATE,   /* 4 = Create a file. */
  SYS_REMOVE,   /* 5 = Delete a file. */
  SYS_OPEN,     /* 6 = Open a file. */
  SYS_FILESIZE, /* 7 = Obtain a file's size. */
  SYS_READ,     /* 8 = Read from a file. */
  SYS_WRITE,    /* 9 = Write to a file. */
  ...
 };
```

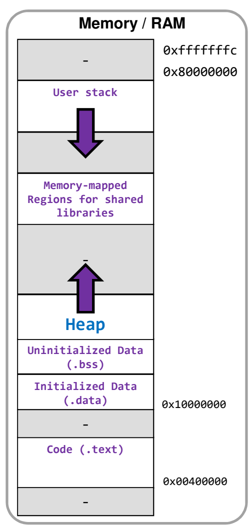
Syscalls from Pintos OS

HEAP MANAGEMENT

Overview

CS:APP 9.9.1

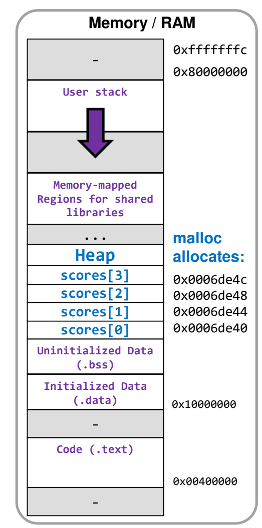
- Heap management is an important component that affects program performance
- Need to balance:
  - __________ & performance of allocation/deallocation
  - Memory utilization (reduce ________________ areas)
  - Ease of usage by the programmer



C Dynamic Memory Allocation

- `void* malloc(int num_bytes)` function in stdlib.h
  - Allocates the number of bytes requested and returns a pointer to the block of memory
- `free(void * ptr)` function
  - Given the pointer to the (starting location of the) block of memory, free returns it to the system for re-use by subsequent malloc calls
- C++ uses the familiar new/delete

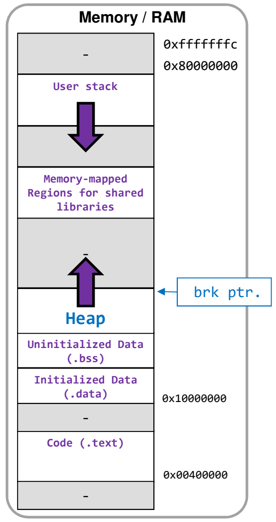
```
int main()
{
  int num;
  printf("How many students?\n");
  scanf("%d", &num);

  int *scores = (int*) malloc(num * sizeof(int));
  // can now access scores[0] .. scores[num-1];

  free(scores); // deallocate
  return 0;
}
```



OS & the Heap

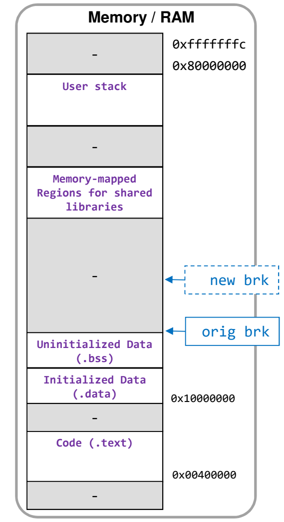
- The OS kernel maintains the brk pointer
  – Virtual address of the ______________
  – ______ process
- brk pointer is updated via a ________ _______ (see Linux example below)
  – #include <unistd.h>
  – _________ sbrk(intptr_t increment);
    - Increments the brk pointer (up or down) and returns the _______ pointer on success
  – Newly allocated memory is _____________
- Malloc/new provide the common interface to use this

intptr_t is a signed integer type that will match the size of pointers (32- or 64-bits)



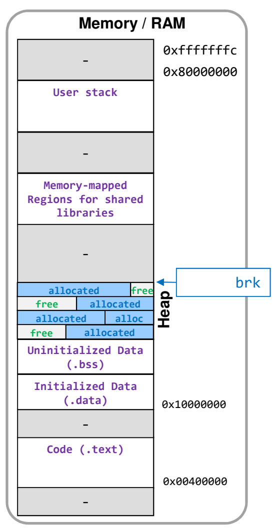
A First Look at Malloc/New (1)

- The C-library implementation will provide an implementation to manage the heap
- At startup, the C-Library will allocate an initialize size of the heap via sbrk
  – `void* heap_init;`
  – `heap_init = sbrk(________); // 1 MB`



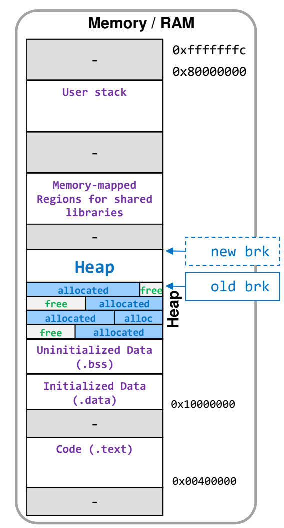
A First Look at Malloc/New (2)

- The C-library implementation will provide an implementation to manage the heap
- At startup, the C-Library will allocate an initialize size of the heap via sbrk
- Subsequent requests by malloc or new will give out portions of the heap
- Calls to free or delete will reclaim those memory areas
- If there is not enough free heap memory to satisfy a call to malloc/new then the library will use sbrk to increase the size of the heap
  – When no memory exists, an ______________________ will be returned and the program may fail



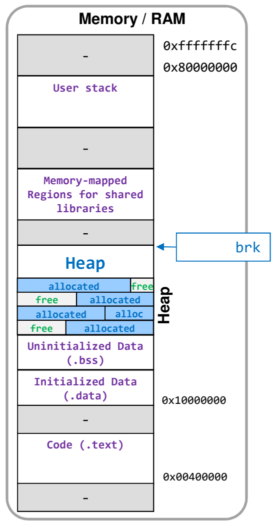
A First Look at Malloc/New (3)

- The C-library implementation will provide an implementation to manage the heap
- At startup, the C-Library will allocate an initialize size of the heap via sbrk
- Subsequent requests by malloc or new will give out portions of the heap
- Calls to free or delete will reclaim those memory areas
- If there is not enough free heap memory to satisfy a call to malloc/new then the library will use sbrk to increase the size of the heap
  – When no memory exists, an exception or NULL pointer will be returned and the program may fail



Allocators and Garbage Collection

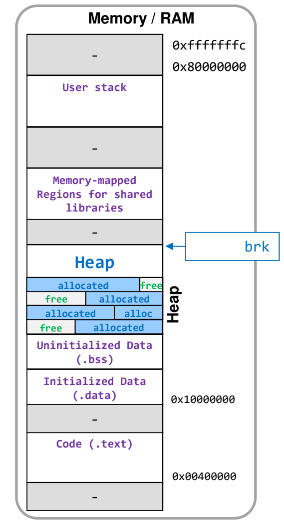
- An allocator will manage the free space of the heap
- Types:
  - Explicit Allocator: Requires the programmer to explicitly _______ memory when it is no longer used
    - Exemplified by malloc/new in C/C++
  - Implicit Allocator: Requires the allocator to determine when memory can be _______________ and freed (i.e. known as garbage collection)
    - Used by Java, Python, etc.



Allocator Requirements

CS:APP 9.9.3

- Arbitrary request sequences:
  - No correlation to when ____________ and ______ requests will be made
- Immediate response required
  - Cannot _________ a request to ___________ allocation strategy
- Use only the heap
  - Any heap management data must exist on the heap or be scalar (single & not arrays) variables
- ___________ blocks
  - Allocated blocks must be __________ to any type of data
- Allocated blocks may not be ____________ or modified
  - Once allocated the block cannot be altered by the allocator until it is freed

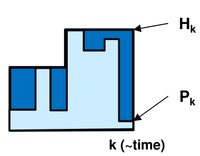


Allocator Goals

- Maximize throughput
  - Make the allocation and deallocation time fast
- Maximize memory utilization (i.e. don't waste memory)
  - Need a way to formally define utilization
    - Let H_k be the _____ size of the heap (both allocated and free) after the *k*-th request
      - Note H_k is montonically nondecreasing (we never shrink the heap)
    - Let P_k be the total _____________ (aka "payload") memory after the *k*-th request
    - Define peak utilization as:

$$U_k = \frac{max_{i \le k} P_i}{H_k}$$

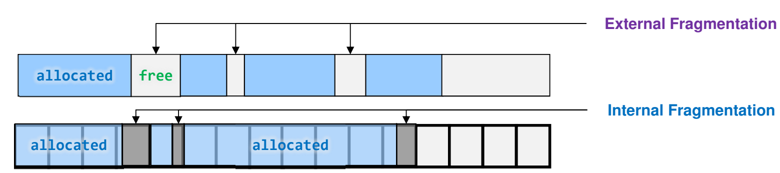
- These goals can be at odds with one another
  - Consider the allocation strategy of always allocating memory from the current top of the heap, never reusing freed memory. Fast!
  - Tension between speed and planning for the future



Fragmentation

CS:APP 9.9.4

- The enemy of high _________________ is **fragmentation**
- Two kinds
  - _____________: Many small fragments of free space between allocated blocks
  - _____________: When payload of is smaller than the block size allocated
    - Often used when fixed size "chunks" are allocated
- Notice: There may be enough total free memory for a request but not contiguous free memory



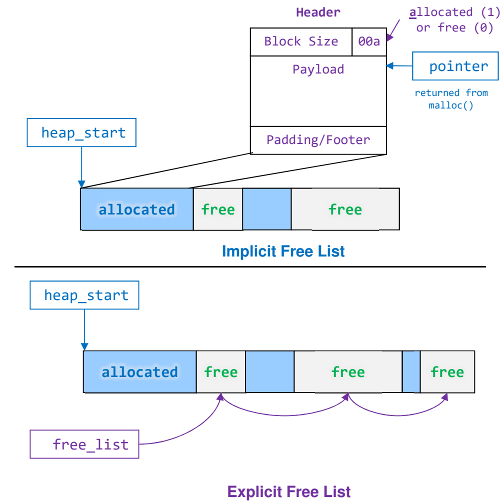
Implementation Issues

CS:APP 9.9.5

- Free block management
  - Tracking free areas on the heap
- Placement Algorithm
  - ______-fit, _____-fit, _____-fit, ____________, …
- Splitting/______________
  - What overhead info do we keep when we split a block or need to coalesce (__________ contiguous free) blocks

Free Block Management

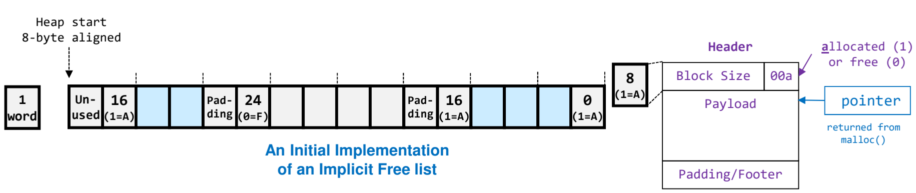
- Allocated blocks are the programmer's to manage and need not be _________ explicitly
- We must manage free lists to make new allocations
- Implicit free lists:
  - Scan through ________ allocated and free blocks to find an appropriate free block to allocate
- Explicit free lists:
  - Maintain explicit list of free blocks with each storing information to find the __________ free block(s)



Implicit Free List Implementation

CS:APP 9.9.6

- A block must be aligned to largest type (`double` or pointer type) which is an 8-byte boundary for 64-bit systems
  - Book uses "word" to refer to an `int` size chunk (i.e. 4-bytes); thus "double word" refers to an 8-byte chunk
- Use headers so we can traverse the list to find free blocks

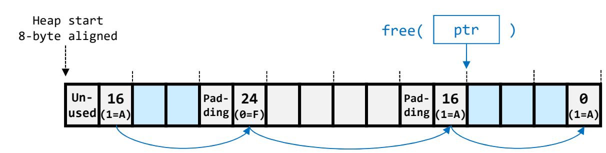


An Initial Implementation of an Implicit Free list

Coalescing

CS:APP 9.9.10

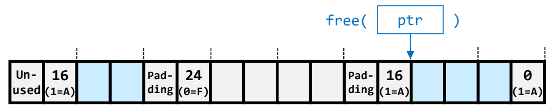
- How would we coalesce the free blocks when the 12-byte chunk at the end is freed?
  - Nothing in the block being freed would help us find the _________ block to see if we should coalesce the two?
  - Would need to scan from the beginning…____________
  - Could consider alternate organizations beyond just a linear list but there is still cost associated with finding the previous block
  - Instead, consider storing additional data to help find the previous block



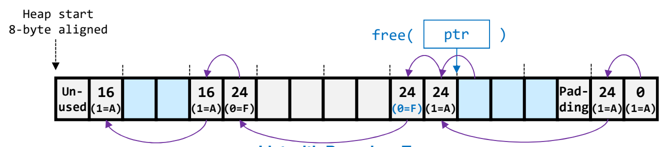
An Initial Implementation of an Implicit Free List

Coalescing w/ Boundary Tags

- Store a _________ (boundary tag) on each block that is really a __________________________ and indicates the size of the block
  - Each footer is always just before a header
  - When a block is freed, we can look at the footer before the header to determine ____ we should coalesce and _________ the previous header is
- Allows constant time O(1) coalescing (free) operation



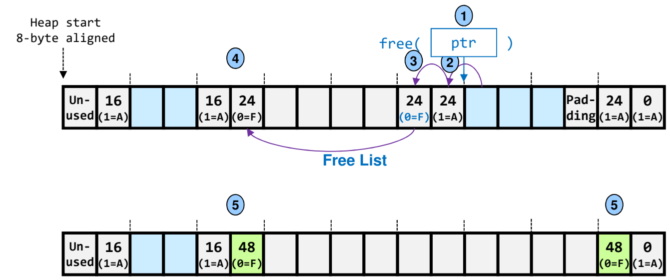
Original List



List with Boundary Tags

Coalescing Example

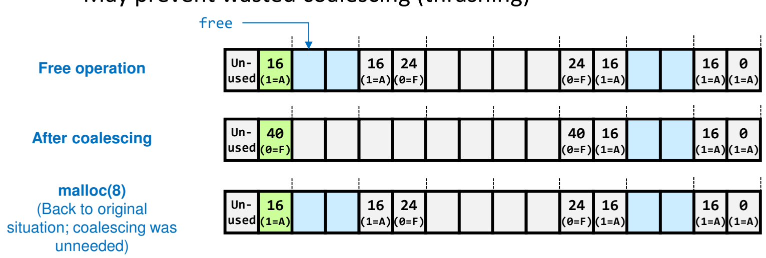
- When we free the block given by ptr we would:
  1. Start with the address provided by free
  2. Walk ________________ to find the header (and size) of this block
  3. Walk ___________________ to find the footer (boundary tag) of the previous block from which we can determine if the block is free and needs to be coalesced
  4. Walk to the header of the previous block (&footer_block - (footer_size-4))
  5. Update the size to be the ______________________ and update the footer as well



Updated Free List

When To Coalesce

- We can coalesce:
  - _________________ when we free the block
    - Generally easier to implement
  - At some _______________ time when we scan through and coalesce any contiguous free blocks
    - Likely when we can't find a large enough free block
    - May prevent wasted coalescing (thrashing)



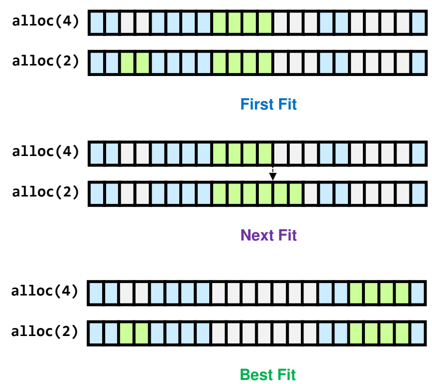
Coalescing Cases

- If we coalesce immediately then only 4 cases need be considered to ensure the list remains in an appropriate state

Placement Algorithms

CS:APP 9.9.7

- First Fit: Scan from the ________ of the heap on each request and use the first free block that is ______ ________
- Next Fit: Scan starting from where the ________ allocation was made
- Best Fit: Find the ________ free block that is large enough for the request

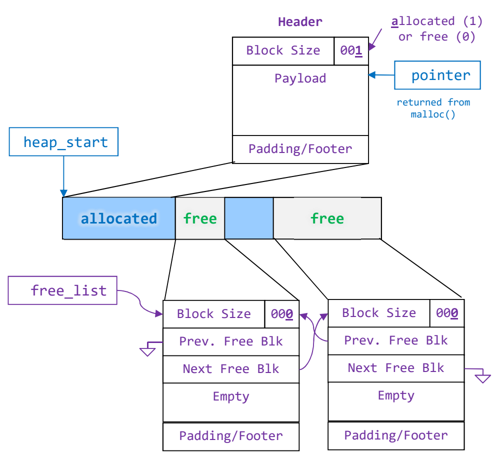


EXPLICIT FREE LISTS

Explicit Free Lists

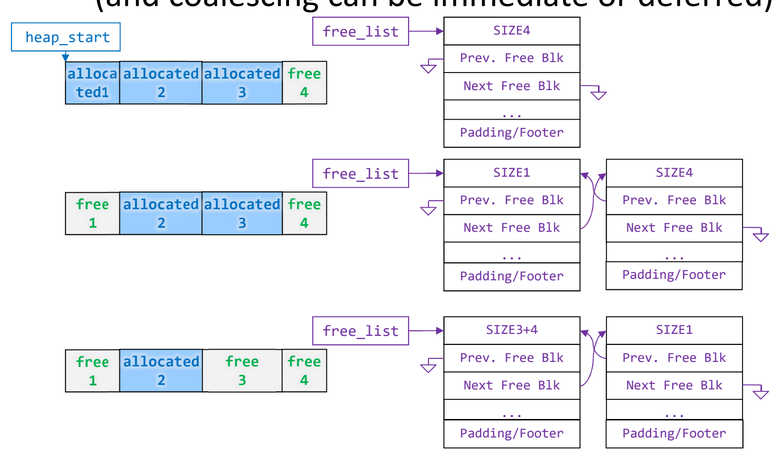
CS:APP 9.9.13

- When a block is free we can use some portion of the block to store explicit __________ to "other" free blocks
  - Could use a simple _______ ______ list or some other data structure
- Increases minimum size block (and potential internal fragmentation for small allocations)
- We can return the blocks in ____ order (more on the next slide)



Explicit Free Lists

- Freed blocks can be placed at the front of the list (and coalescing can be immediate or deferred)



If coalescing is deferred, we can have 3 free blocks in the list in the order: 3, 1, 4

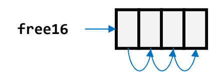
Segregated Free Lists

CS:APP 9.9.14

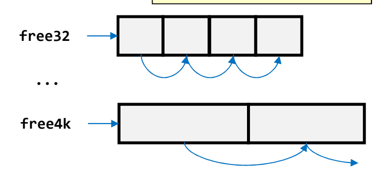
- Idea:
  - Keep separate free lists based on ______ of the free block
  - Based on the __________, pick the appropriate list
- Variations:
  - Segregated Storage
  - Segregated Fit

Segregated Storage

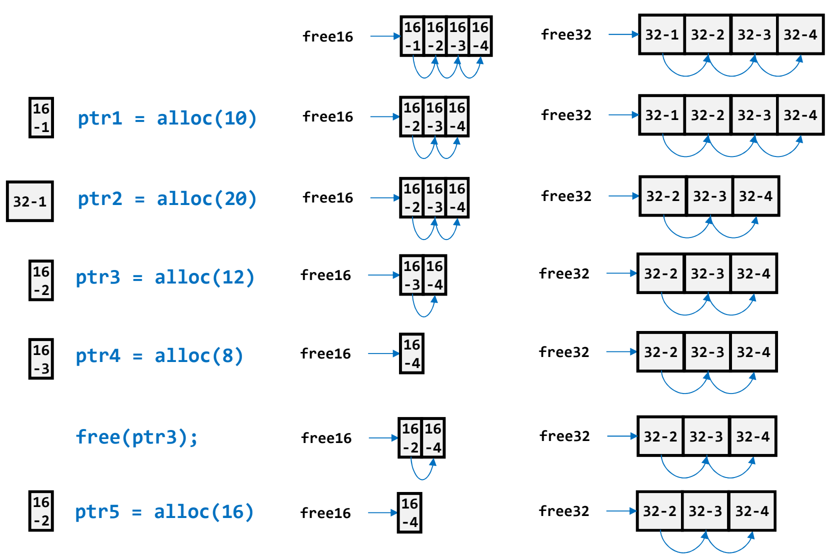
- One (common) implementation:
  - Maintain lists for fixed size chunks
  - Based on request, allocate smallest fixed size chunk that is free
- Fixed sized blocks allow:
  - No header size or allocated/free flag
  - No coalescing (thus no footer and only singly-linked list)
    - Allows small minimum block size
- If no free blocks in a specific list, allocate more heap space and break it into that size chunks
- Suffers from
  - Internal fragmentation (due to fixed size)
  - Can degenerate to pathological case in some circumstances (ascending order of requests)




```
struct free16
{
  struct free16* next;
  char padding[8];
};

union block16
{
  struct free16 empty;
  char payload[16];
};

union block16* free16;
...
```

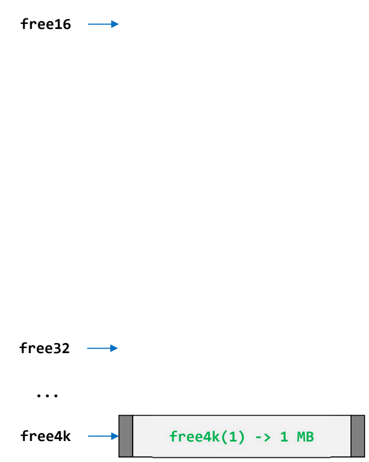


Segregated Storage Example



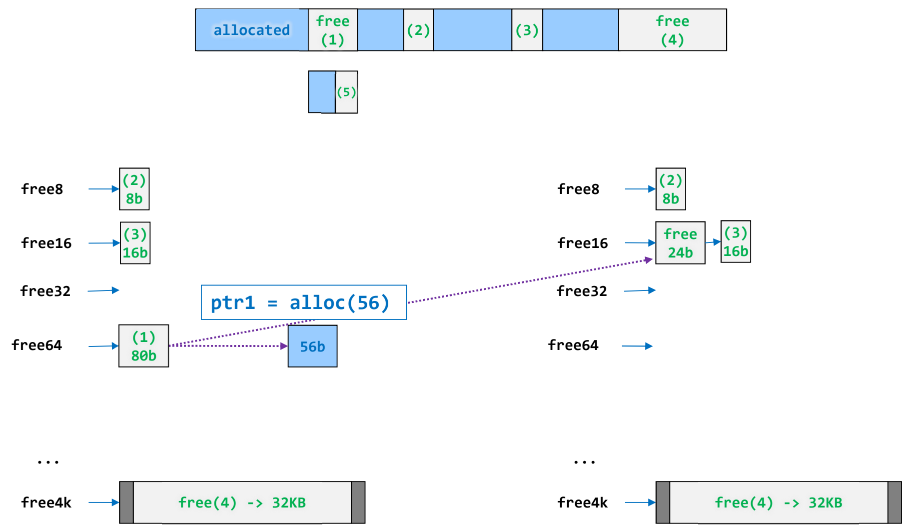
Segregated Fit

- Separate lists for various size free chunks
  - Chunks in list size N are at least size N but no more than the lower limit of the next list size
- On allocation, ______ a chunk of appropriate size and put the fragment back in the appropriate list (based on its size)
- If no free chunk of desired size, keep moving __________ sized lists
  - If largest list size has no free chunks allocated more heap spaces
- Can coalesce upon freeing a block



At start only largest size may exist

Segregated Fit

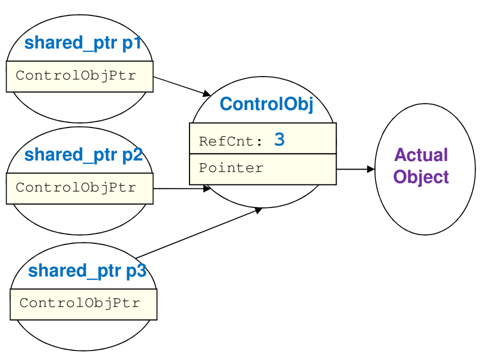


GARBAGE COLLECTION

Managed Pointers

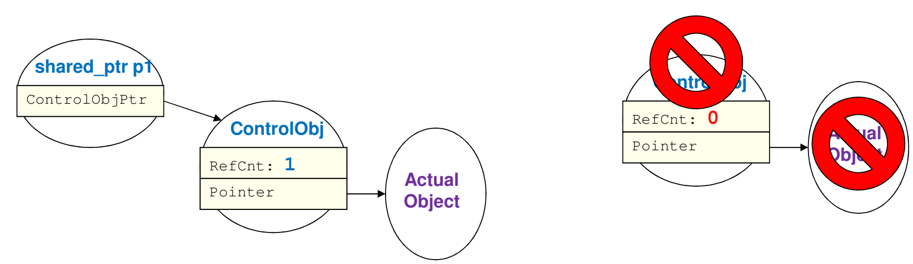
CS:APP 9.10

- Reference count how many items are pointing at the object and deallocate it when the count reaches 0
  - Some languages will perform this automatically, behind the scenes (i.e. Python)



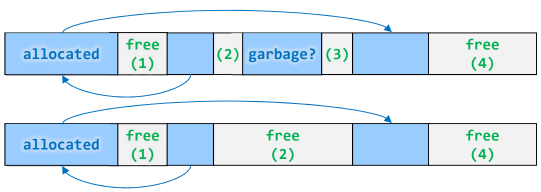
Managed Pointers (2)

- When the last managed pointer dies or changes to point at another object, the reference count will be decremented to 0 and trigger deallocation



Implicit Garbage Collection

- Can potentially perform an ____________ search of allocated blocks (and the stack and globals) to see if any word (dword) is a pointer to another piece of memory in an allocated block
- Any allocated block that is not reachable through some pointer can be garbage collected and marked free
- Requires some intricate book keeping and can be expensive to compute



Allocation Worksheet

- Consider an 80-byte heap starting at address 0 with the use of implicit free lists with boundary tags.
- Given the sequence of allocations and frees update the state of the heap.

Op	Return	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76
Start (t=0)		4,1	72,0																	72,0	4,1
1/A(8)																					
2/A(18)																					
3/A(12)																					
F(8)																					
4/A(10)																					
F(24)																					
5/A(10)																					
6/A(4)																					
F(8)																					
F(56)																					
F(32)																					