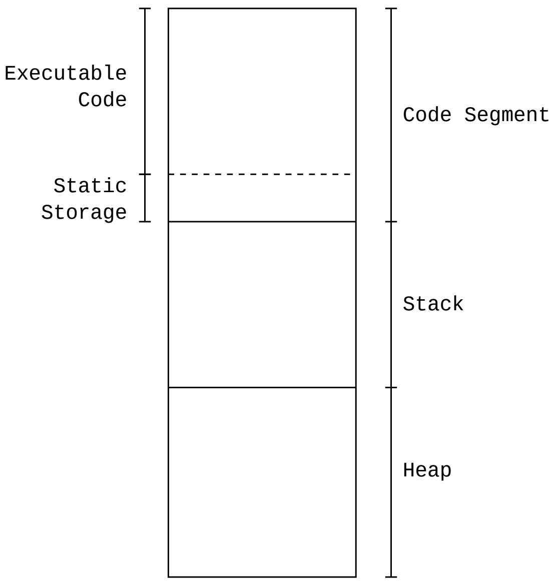
11-0: **Memory**

- Three places in memory that a program can store variables
  - Call stack
  - Heap
  - Code segment

11-1: **Memory**



11-2: **Memory**

- Three places in memory that a program can store variables
  - Call stack
    - Local Variables
  - Heap
    - Dynamically allocated variables
    - (Most of the variables in Java)
  - Code segment
    - Static variables

11-3: **Static Storage**

- If a variable is declared static, there is only one instance of the variable
- Variable is typically stored in the code segment, not the stack or the heap
  - Why?

11-4: **Static Storage**

- If a variable is declared static, there is only one instance of the variable

- Variable is typically stored in the code segment, not the stack or the heap
  - Stack storage is too transient
  - Using the code segment guarantees a single instance of the variable

11-5: **Static Storage**

```
class StaticVars {
   int x;
   static int y;
}
void main() {
   StaticVars SV1 = new StaticVars();
   StaticVars SV2 = new StaticVars();

   SV1.x = 1;
   SV1.y = 2;
   SV2.x = 3;
   SV2.y = 4;

   print(SV1.x);
   print(SV1.y);
   print(SV2.x);
   print(SV2.y);
}
```

11-6: **Static Storage**

```
class StaticVars {
   int x;
   static int y;
}
void main() {
   StaticVars SV1 = new StaticVars();
   StaticVars SV2 = new StaticVars();

   SV1.x = 1;
   SV1.y = 2;
   SV2.x = 3;
   SV2.y = 4;

   print(SV1.x);
   print(SV1.y);
   print(SV2.x);
   print(SV2.y);
}
```

Output: 1 4 3 4 11-7: **simpleJava Static Storage**

- What do we need to do to implement static storage in simpleJava?

11-8: **simpleJava Static Storage**

- What do we need to do to implement static storage in simpleJava?
- Looking at each portion of the compiler in turn:
  - Lexical Analysis – what needs to be done?

11-9: **simpleJava Static Storage**

- Lexical Analysis
  - Add a new keyword “static” to the language
  - – Add “static” token

11-10: **simpleJava Static Storage**

- Parsing & Building AST

11-11: **simpleJava Static Storage**

- Parsing & Building AST
    - Add a "static" tag to the AST for variable declarations (for both statements, and class instance variables)

11-12: **simpleJava Static Storage**

- Semantic Analysis

11-13: **simpleJava Static Storage**

- Semantic Analysis
    - No changes are necessary (apart form changes needed to implement building Abstract Assembly Tree)

11-14: **simpleJava Static Storage**

- Abstract Assembly Tree Generation

11-15: **simpleJava Static Storage**

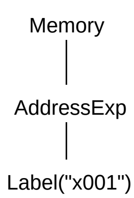
- Abstract Assembly Tree Generation
    - Add a new field to variable entries – "static" bit
    - Generate code for static variables
        - Need to access variables in the code segment
        - Need to be able to access a "direct address"

11-16: **simpleJava Static Storage**

- Need to access a "direct address"
    - Add an "AddressExp" node to our AAT
    - Single child – assembly language label
    - Represents the memory location at that address

11-17: **simpleJava Static Storage**

```
static int x;
```

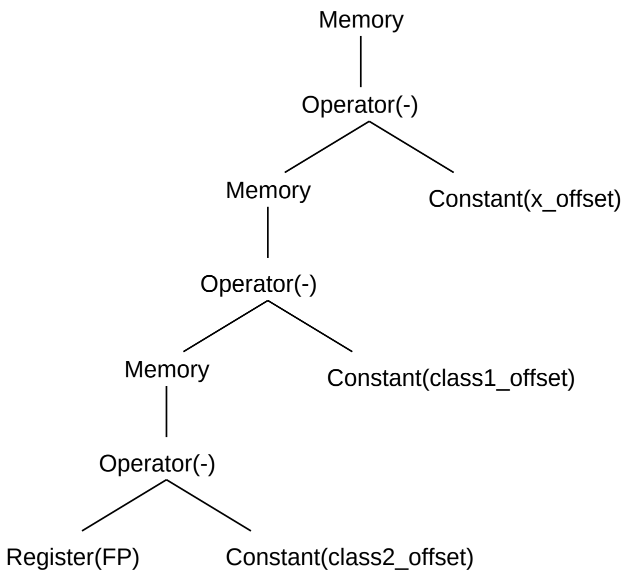


11-18: **simpleJava Static Storage**

```
class C1 {
   static int y;
   int x;
}
class C2 {
   int a;
   C1 class1;
}
...
C2 class2;
```

AAT for `class2.class1.x`?

11-19: **simpleJava Static Storage**

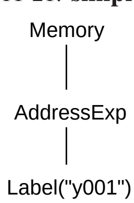


11-20: **simpleJava Static Storage**

```
class C1 {
   static int y;
   int x;
}
class C2 {
   int a;
   C1 class1;
}
...
C2 class2;
```

AAT for `class2.class1.y`?

11-21: **simpleJava Static Storage**



11-22: **simpleJava Static Storage**

- Code Generation

11-23: **simpleJava Static Storage**

- Code Generation
  - Add space to code segment to store static variables
  - Make sure the labels match!!

11-24: **Heap-based storage**

- There are 2 main memory-allocation dangers associated with heap-based storage
  - Dangling References
  - Memory leaks

11-25: **Dangling References**

```
int main() {
   int *a;
   int *b;
   a = (int *) malloc(sizeof(int));
   (*a) = 4;
   b = a;
   free b;
   ...
}
```

- What happens if we change `(*a)` `[(*a) = ...]`?

11-26: **Memory Leaks**

```
int main() {
   int *intPtr;
   intPtr = (int *) malloc(sizeof(int));
   intPtr = NULL;
   ...
}
```

- Allocated memory that we can't get to – *garbage*
- Eventually, use up heap memory

11-27: **Managing the Heap**

- Manage the heap to avoid memory leaks and dangling references
  - Give all decisions to the programmer
  - Automatic memory management

11-28: **Programmer Controlled**

- Advantages
  - Memory management system is less complicated
  - Lower run-time overhead for the memory manager
  - Can manage the memory needs for a specific program more efficiently than a general-purpose memory manager (at least in theory)

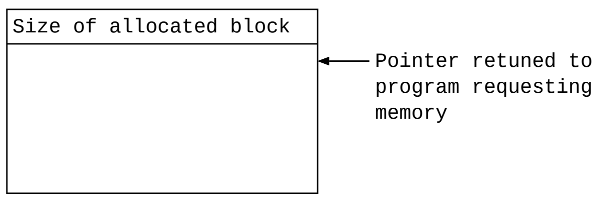
11-29: **Free List**

- List of all available blocks of memory

- When a request for a block of memory is made, it is removed from the free list
- Deallocated memory is returned to the free list

11-30: **Free List**

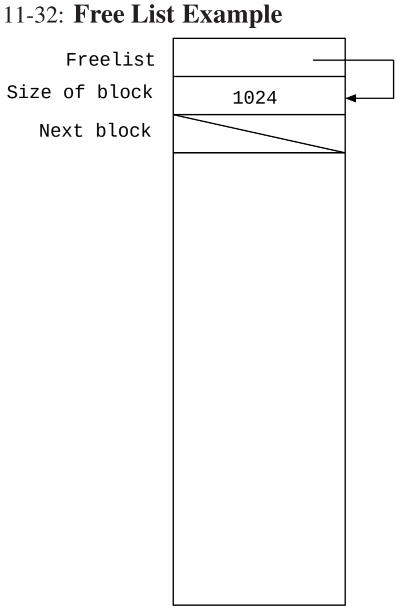
- Housekeeping
  - When a block is requested, allocated slightly more memory than requested.
  - Extra space is used to store header information (for now, just the size of the allocated block)
  - Return a pointer to just *after* the header information



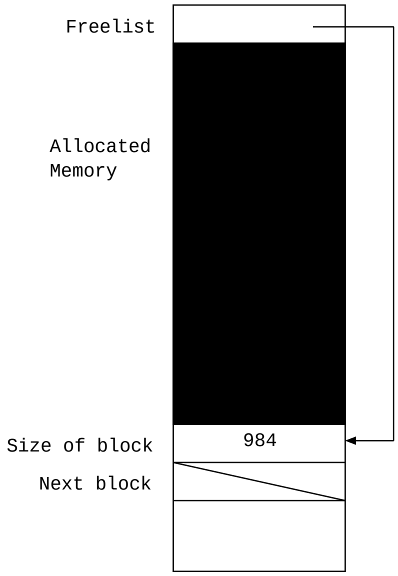
11-31: **Free List Example**

```
class oneElem {
   int x;
}
class twoElem {
   int x;
   int y;
}

oneElem A = new oneElem();
oneElem B = new oneElem();
twoElem C = new twoElem();
twoElem D = new twoElem();
```

11-32: **Free List Example**



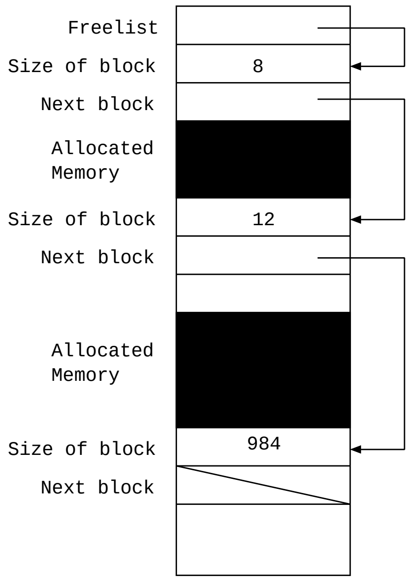
11-33: **Free List Example**



11-34: **Free List Example**

```
class oneElem {
   int x;
}
class twoElem {
   int x;
   int y;
}

oneElem A = new oneElem();
oneElem B = new oneElem();
twoElem C = new twoElem();
twoElem D = new twoElem();
delete A;
delete C;
```

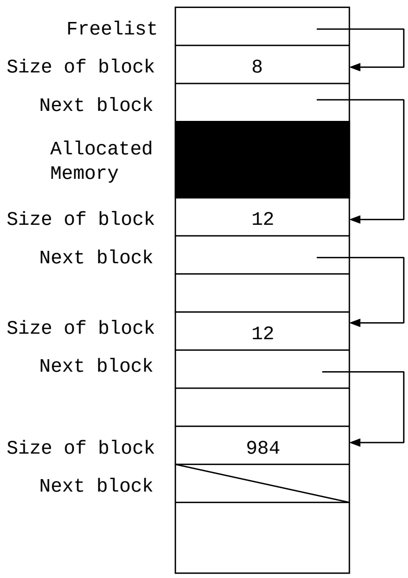
11-35: **Free List Example**



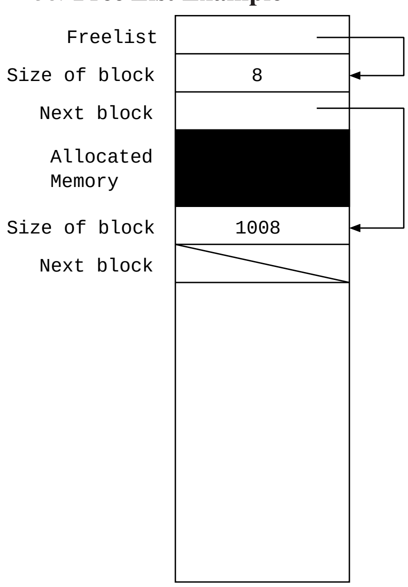
11-36: **Free List Example**

```
class oneElem {
   int x;
}
class twoElem {
   int x;
   int y;
}

oneElem A = new oneElem();
oneElem B = new oneElem();
twoElem C = new twoElem();
twoElem D = new twoElem();
delete A;
delete C;
delete D;
```

11-37: **Free List Example**



11-38: **Free List Example**



11-39: **First Fit**

- When there are several blocks to choose from on the free list, which do we use to fulfill a memory request?
  - First Fit
    - Return the first block that is large enough

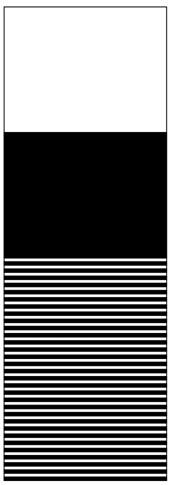
11-40: **First Fit**

```
class smallClass {
  int x;
}
void main() {
    int i;
    smallClass A[] = new smallClass[3000];
    smallClass B[] = new smallClass[3000];
    for (i=0; i<3000; i++)
        B[i] = new smallClass();
    for (i=0; i<3000; i = i + 2)
```

```
        delete B[i];
    delete A;

   /* Point A */

   for (i=0; i<3000; i = i + 2)
        B[i] = new smallClass();

  /* Point B */

}
```

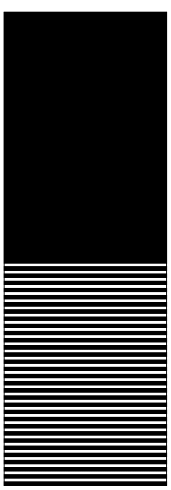
11-41: **First Fit**

- At Point A:



11-42: **First Fit**

- At Point B:



11-43: **First Fit**

- Plenty of space on the heap
- Divided into small blocks – can't service a request for a large block of memory
- Memory *fragmentation*

11-44: **Best Fit**

- When there are several blocks to choose from on the free list, which do we use to fulfill a memory request?
    - First Fit
        - Return the first block that is large enough
    - Best Fit
        - Return the *smallest* block that is large enough

11-45: **Best Fit**

- At Point B (using Best Fit):

11-46: **Best Fit**

- Best Fit will usually lead to less memory fragmentation than first fit
    - Don't "waste" large memory blocks on small requests
    - Large blocks should then be available when needed
- Will Best Fit *always* lead to less memory fragmentation?

11-47: **Best Fit vs First Fit**

```
for (i=0; i<100;i++)
  A[i] = malloc(4);
for (i=0;i<100;i++)
  B[i] = malloc(3);

for (i=0;i<100;i+=2)
  free(A[i]);
for (i=0;i<100;i+=2)
  free(B[i]);

for (i=0; i<100; i++)
  C[i] = malloc(2);
```

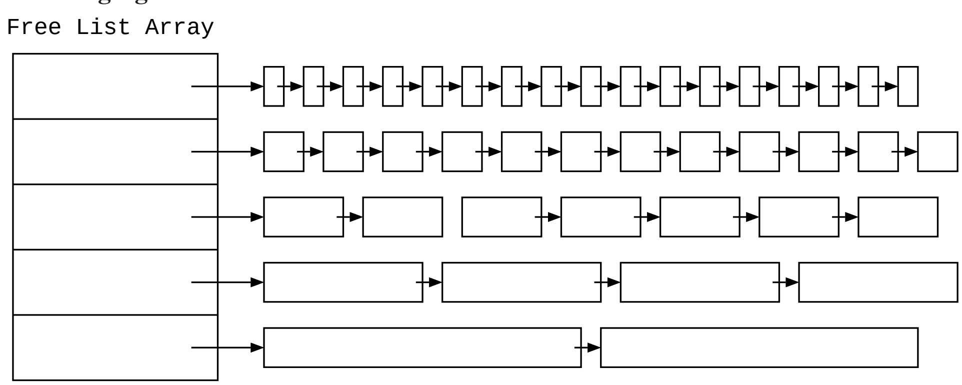
11-48: **Segregated Free List**

- Fragmentation problems caused by differing block sizes
- Remove the problem by having all blocks be the same size (like lisp)
  - Can't make all blocks the same size
  - Can use a limited # of standard block sizes

11-49: **Segregated Free List**

- Memory can only be allocated in set block sizes
  - Typically powers of 2 – 2 words, 4 words, 8 words, etc
- Separate free list maintained for each bock size
- When a request is made, the smallest block that can service the request is returned.

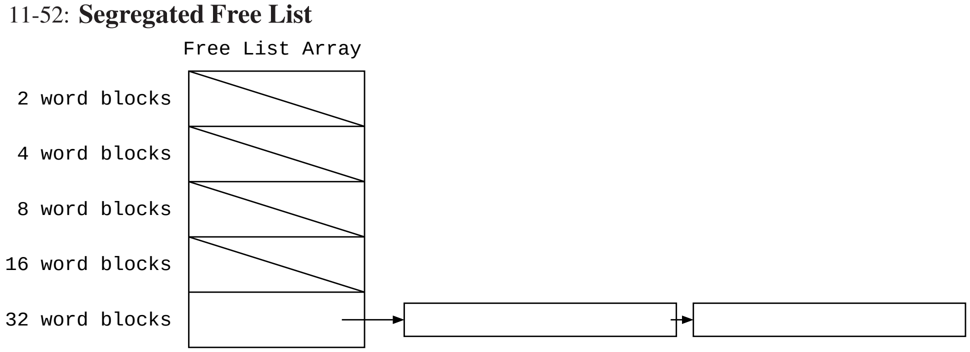
11-50: **Segregated Free List**



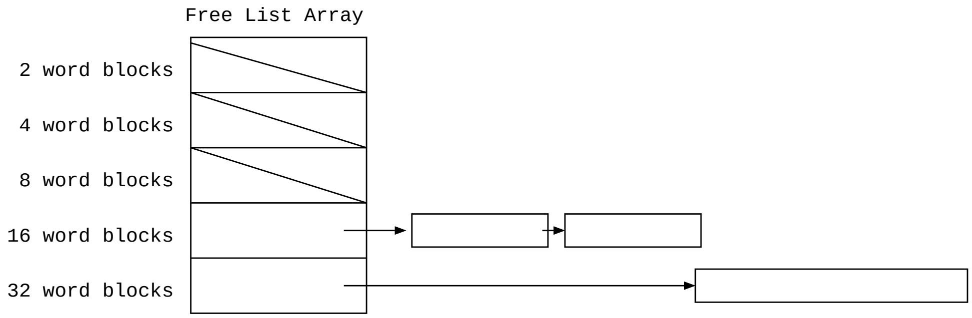
11-51: **Segregated Free List**

- Initially, all heap memory is placed in the largest block list
- If a request is made for a block of memory of size 2^k, and list k is empty:
  - Split a block from list $k+1$ into two blocks of size 2^k
  - Add these two blocks to list k
  - List k is no longer empty – can service the request

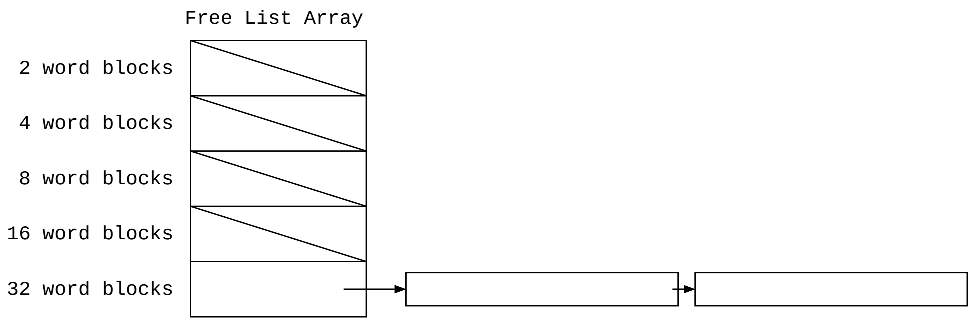
11-52: **Segregated Free List**



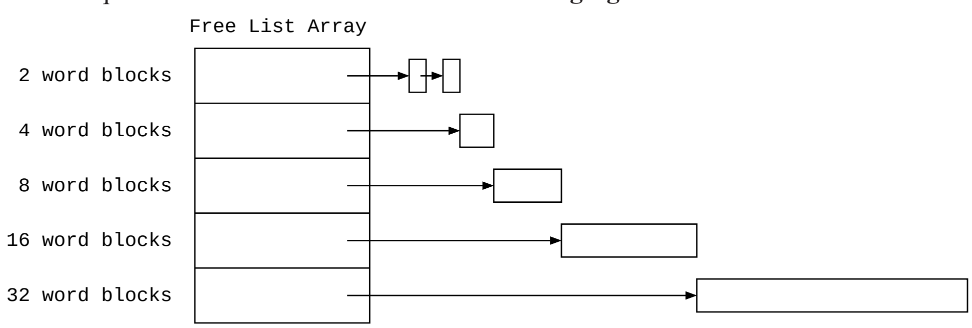
A request for a block of size 16 is made 11-53: **Segregated Free List**



11-54: **Segregated Free List**



A request for a block of size 2 is made 11-55: **Segregated Free List**



11-56: **Garbage Collection**

- Giving the user control of deallocation has problems:
  - Writing programs that properly deallocate memory is *hard*
  - Often, there are many pointers to the same block of memory (much like your current project!)
  - It can be difficult to determine when a block of memory should be freed
  - We don't want to be too aggressive in freeing memory (why not?)

11-57: **Garbage Collection**

- Giving the user control of deallocation has problems:
  - Writing programs that properly deallocate memory is *hard*
  - Often, there are many pointers to the same block of memory (much like your current project!)
  - It can be difficult to determine when a block of memory should be freed

- We don't want to be too aggressive in freeing memory (why not?)
- Solution – don't let programmer control deallocation!

11-58: **Garbage Collection**

- Don't allow programmer to deallocate any memory
- Garbage will collect
- Periodically collect the accumulated garbage, and return it to the free list

11-59: **Mark & Sweep**

- When Garbage Collection routine is invoked:
  - Mark all heap memory that is reachable by the program
    - Need to add a "mark" bit to each block of memory – can use the header
  - Sweep through the entire block of memory, moving unmarked blocks to the free list

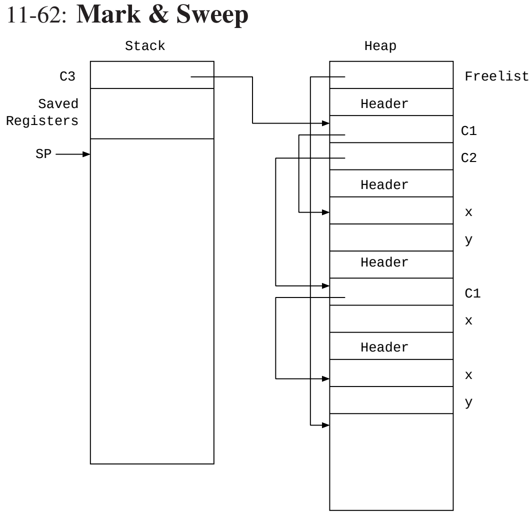
11-60: **Mark Phase**

```
for each pointer P on the stack
    mark(P)


mark(P) {
    if ((P is not null) and (mark bit of Mem[P] is not set))
       set mark bit of Mem[P]
       for each pointer Q in the block Mem[p]
           mark(Q)
}
```

11-61: **Mark & Sweep**

```
class Class1 {
   int x;
   int y;
}

class Class2 {
   Class1 C1
   int x;
}

class Class3 {
   Class1 C1;
   Class2 C2;
}

Class3 C3 = new Class3();
C3.C1 = new Class1();
C3.C2 = new Class2();
C3.C2.C1 = new Class1();
```

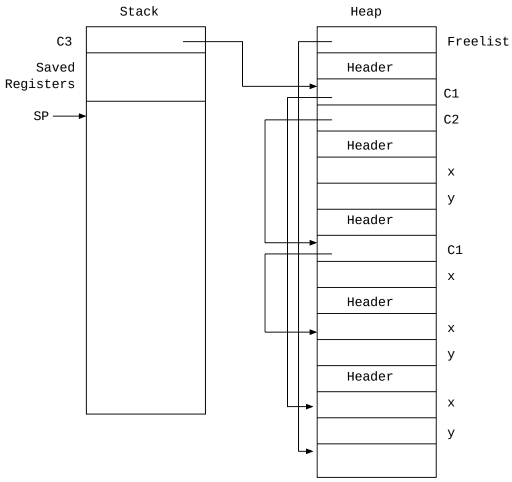
11-62: **Mark & Sweep**



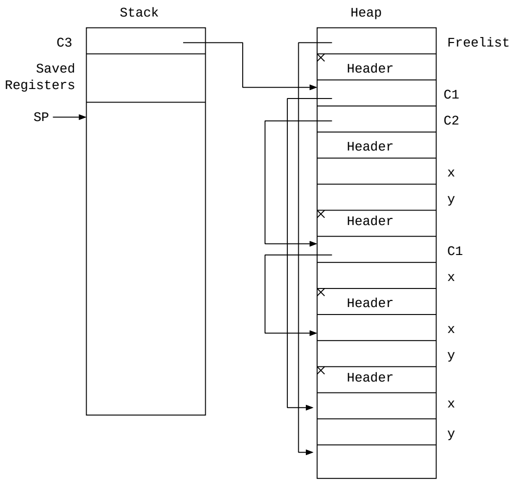
11-63: **Mark & Sweep**

```
class Class1 {
   int x;
   int y;
}

class Class2 {
   Class1 C1
   int x;
}

class Class3 {
   Class1 C1;
   Class2 C2;
}

Class3 C3 = new Class3();
C3.C1 = new Class1();
C3.C2 = new Class2();
C3.C2.C1 = new Class1();
C3.C1 = new Class1();
```

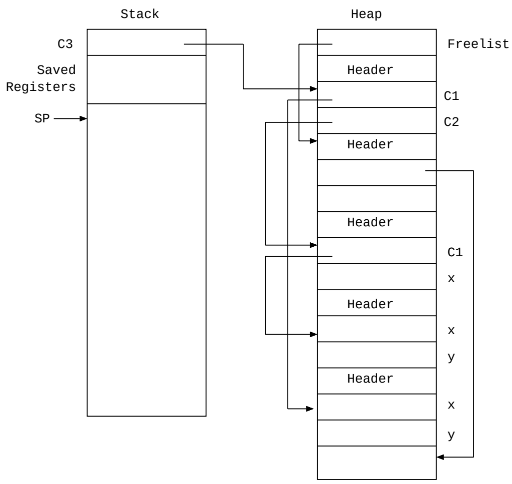
11-64: **Mark & Sweep**



11-65: **Mark & Sweep**



11-66: **Mark & Sweep**



11-67: **Whither Pointers?**

- In order for the Mark phase to work correctly, we need to know which memory locations are pointers, and which are not
  - Tag pointers
  - Assume that any value that *might* be a pointer *is* a pointer (*Conservative* garbage collection)
  - Create tables that store memory locations of all pointers

11-68: **Tagging Pointers**

- If we wish to tag pointers themselves, we have two options:
  - Tag the pointer itself (high order bits)
  - Store tag in preceding word

11-69: **Tagging Pointers**

- Tag the pointer itself (high order bits)
  - If the high order bits are 11, then the memory location represents a pointer
  - If the high oder bits are 00, 01, or 10, then the memory location represents an integer or boolean value
- Using 32-bit words, only 30 bits will be available for pointer values
  - Need to strip the tag before pointers can be dereferenced
- Using 32-bit words, slightly more than 31 bits are available for integer values (very large negative values prohibited)

11-70: **Tagging Pointers**

- Store tag in preceding word
  - Set aside a specific bit pattern as a sentinel value (something like -MAXINT)
  - Every pointer requires 2 words of storage – word for the sentinel, and a word for the pointer itself

11-71: **Tagging Pointers**

```
class Class1 {
   int x;
   Class2 C2;
   Class3 C3;
   boolean y;
}
```

Header	
	x
Sentinel	
	C2
Sentinel	
	C3
	y

11-72: **Conservative GC**

- Assume that every memory location that *could* be a pointer *is* a pointer
- The integer y will be considered a pointer if:
  - Heap addresses are in the range LOW .. HIGH, and LOW ¡= y ¡= HIGH
  - The memory location y is the beginning of an allocated block

11-73: **Conservative GC**

- Every memory block on the heap that is pointed to by something on the stack will be marked
  - No dangling references
- Some memory blocks on the heap that are *not* pointed to by something on the stack *may* be marked
  - May have some uncollected garbage
- Since no extra information (tagged pointers, etc.) is needed, Conservative Garbage Collectors can be run on languages not designed with garbage collection in mind (i.e., C)

11-74: **Pointer Tables**

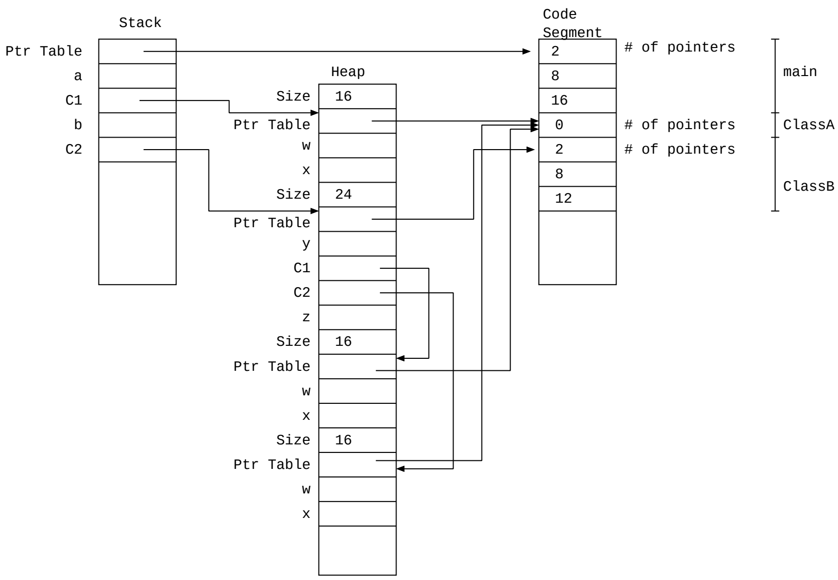
- Create a table for each function & class, which keeps track of where the pointers are in that function or class
  - This can be done at compile time
- Each function & class will need a "kind" field, to store what kind of function or class it is (classes will need a "kind" field anyway, if we want instanceof to work)

11-75: **Pointer Tables**

```
class ClassA {
   int w;
   int x;
}
class ClassB {
   int y;
   ClassA C1;
   ClassA C2;
   int z;
}
void main() {
   int a;
```

```
   ClassA C1;
   int b;
   ClassB C2;
   C1 = new ClassA();
   C2 = new ClassB();
   C2.C1 = new ClassA();
   C2.C2 = new ClassA();

   /* Body of main */
}
```

11-76: **Pointer Tables**



11-77: **Reference Counts**

- Each block of allocated memory contains a count of how many pointers point to it
- Each time a pointer appears on the LHS of an assignment:
  - Count of what the pointer *used* to point to is decremented
  - Count of what the pointer *now* points to is incremented
- When a count hits zero, add block back to free list

11-78: **Reference Count Problems**

From the *Jargon File:* (aka *Hacker's Dictionary*)

One day a student came to Moon and said: "I understand how to make a better garbage collector. We must keep a reference count of the pointers to each cons (block of memory)."

Moon patiently told the student the following story:

> "One day a student came to Moon and said:
> 'I understand how to make a better garbage
> collector...' "