# CMSC 330: Organization of Programming Languages

## Garbage Collection

## Memory Attributes

- Memory to store data in programming languages has several attributes
  - Persistence (or lifetime)
    - How long the memory exists
  - Allocation
    - When the memory is available for use
  - Recovery
    - When the system recovers the memory for reuse



## Memory Attributes (cont.)

- Most programming languages are concerned with some subset of the following 4 memory classes
  1. Fixed (or static) memory
  2. Automatic memory
  3. Programmer allocated memory
  4. Persistent memory



## Memory Classes

- Static memory – Usually a fixed address in memory
  - Persistence – Lifetime of execution of program
  - Allocation – By compiler for entire execution
  - Recovery – By system when program terminates
- Automatic memory – Usually on a stack
  - Persistence – Lifetime of method using that data
  - Allocation – When method is invoked
  - Recovery – When method terminates



## Memory Classes (cont.)

- Allocated memory – Usually memory on a heap
  - Persistence – As long as memory is needed
  - Allocation – Explicitly by programmer
  - Recovery – Either by programmer or automatically (when possible and depends upon language)



## Memory Classes (cont.)

- Persistent memory – Usually the file system
  - Persistence – Multiple execution of a program (e.g., files or databases)
  - Allocation – By program or user, often outside of program execution
  - Recovery – When data no longer needed
  - Note
    - Dealing with persistent memory → databases (CMSC 424)

## Memory Management in C

- Local variables live on the stack
  - Allocated at function invocation time
  - Deallocated when function returns
  - Storage space reused after function returns
- Space on the heap allocated with malloc()
  - Must be explicitly freed with free()
  - Called explicit or manual memory management
    - Deletions must be done by the user



## Memory Management Mistakes

- May forget to free memory (memory leak)

```
{ int *x = (int *) malloc(sizeof(int)); }
```

- May retain ptr to freed memory (dangling pointer)

```
{ int *x = ...malloc();
  free(x);
  *x = 5; /* oops! */
}
```

- May try to free something twice

```
{ int *x = ...malloc(); free(x); free(x); }
```

  - This may corrupt the memory management data structures
    - E.g., the memory allocator maintains a free list of space on the heap that's available



## Ways to Avoid Mistakes

- Don't allocate memory on the heap
  - Often impractical
  - Leads to confusing code (e.g., alloca() )
- Never free memory
  - OS will reclaim process's memory anyway at exit
  - Memory is cheap; who cares about a little leak?
  - LISP model – System halts program and reclaims unused memory when there is no more available
- Use a garbage collector
  - E.g., conservative Boehm-Weiser collector for C



## Memory Management in Ruby

- Local variables live on the stack
  - Storage reclaimed when method returns
- Objects live on the heap
  - Created with calls to Class.new
- Objects never explicitly freed
  - Ruby uses automatic memory management
    - Uses a garbage collector to reclaim memory



## Memory Management in OCaml

- Local variables live on the stack
- Tuples, closures, and constructed types live on the heap
  - `let x = (3, 4)` (* heap-allocated *)
  - `let f x y = x + y in f 3` (* result heap-allocated *)
  - `type 'a t = None | Some of 'a`
  - `None` (* not on the heap–just a primitive *)
  - `Some 37` (* heap-allocated *)
- Garbage collection reclaims memory

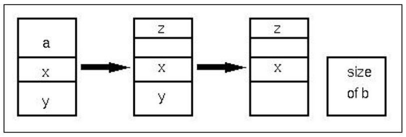


## Memory Management in Java

- Local variables live on the stack
  - Allocated at method invocation time
  - Deallocated when method returns
- Other data lives on the heap
  - Memory is allocated with new
  - But never explicitly deallocated
    - Java uses automatic memory management

# Fragmentation

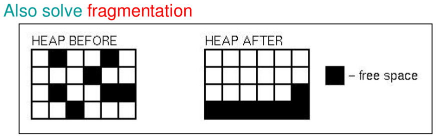
- Another memory management problem
- Example sequence of calls
  - allocate(a);
  - allocate(x);
  - allocate(y);
  - free(a);
  - allocate(z);
  - free(y);
  - allocate(b);
  - ⇒ Not enough contiguous space for b






# Garbage Collection Goal

- Process to reclaim memory
  - Also solve fragmentation




- Algorithm: You can do garbage collection and memory compaction if you know where every pointer is in a program. If you move the allocated storage, simply change the pointer to it.
- This is true in LISP, OCAML, Java, Prolog
- Not true in C, C++, Pascal, Ada



# Garbage Collection (GC)

- At any point during execution, can divide the objects in the heap into two classes
  - Live objects will be used later
  - Dead objects will never be used again
    - They are "garbage"
- Idea
  - Can reuse memory from dead objects (recycling!)
- Goals
  - Reduce memory leaks
  - Make dangling pointers impossible



# Many GC Techniques

- In most languages we can't know for sure which objects are really live or dead
  - Undecidable, like solving the halting problem
- Thus we need to make an approximation
  - OK if we decide something is live when it's not
  - But we'd better not deallocate an object that will be used later on



# Reachability

- An object is reachable if it can be accessed by chasing pointers from live data
- Safe policy: delete unreachable objects
  - An unreachable object can never be accessed again by the program
    - The object is definitely garbage
  - A reachable object may be accessed in the future
    - The object could be garbage but will be retained anyway
    - Could lead to memory leaks



# Roots

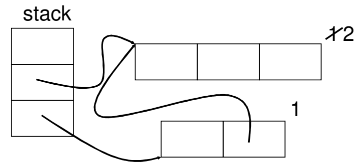
- At a given program point, we define liveness as being data reachable from the root set
  - Global variables
    - What are these in Java? Ruby? OCaml?
  - Local variables of all live method activations
    - I.e., the stack
- At the machine level
  - Also consider the register set
    - Usually stores local or global variables
- Next
  - Techniques for pointer chasing

## Reference Counting

- Old technique (1960)
- Each object has count of number of pointers to it from other objects and from the stack
  - When count reaches 0, object can be deallocated
- Counts tracked by either compiler or manually
- To find pointers, need to know layout of objects
  - In particular, need to distinguish pointers from ints
- Method works mostly for reclaiming memory
  - Doesn't handle fragmentation problem

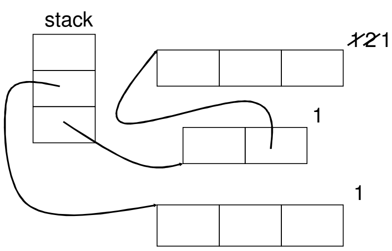


## Reference Counting Example






## Reference Counting Example (cont.)



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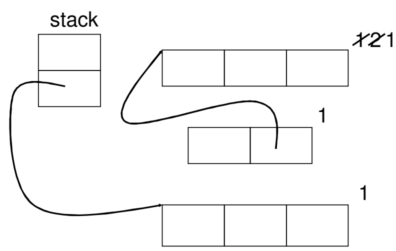




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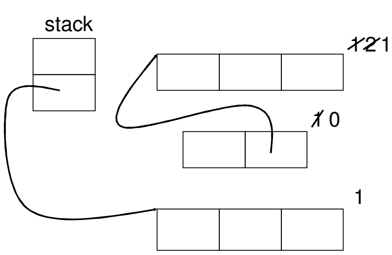




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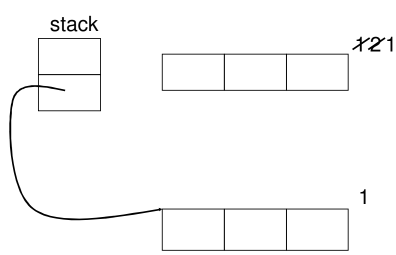

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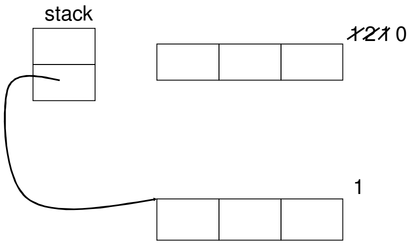




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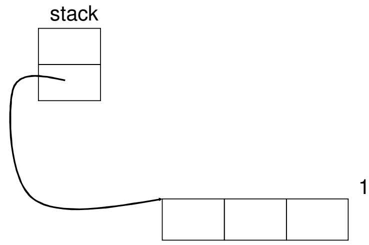
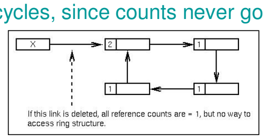





## Reference Counting Tradeoffs

- Advantage
  - Incremental technique
    - Generally small, constant amount of work per memory write
    - With more effort, can even bound running time
- Disadvantages
  - Cascading decrements can be expensive
  - Requires extra storage for reference counts
  - Can't collect cycles, since counts never go to 0



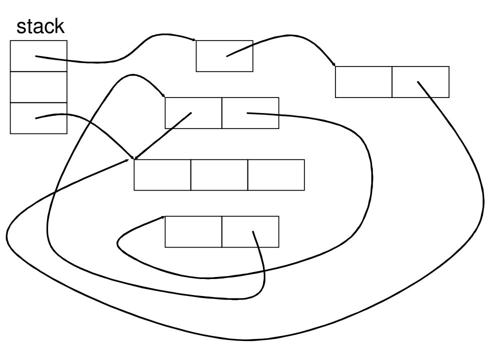



## Mark and Sweep GC

- Idea
  - Only objects reachable from stack can be live
- Every so often, stop the world and do GC
  - Mark all objects on stack as live
  - Mark object reachable from live object as live
    - Repeat until no more reachable objects
  - Deallocate any non-reachable objects
- This is a tracing garbage collector
  - Does not handle fragmentation problem



## Mark and Sweep Example



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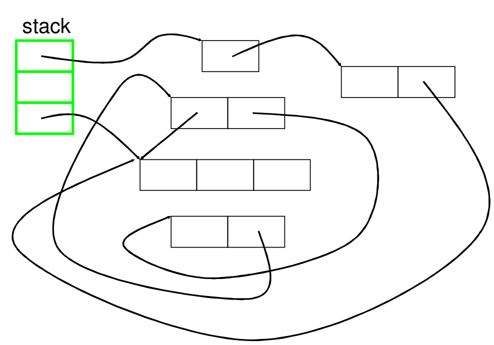

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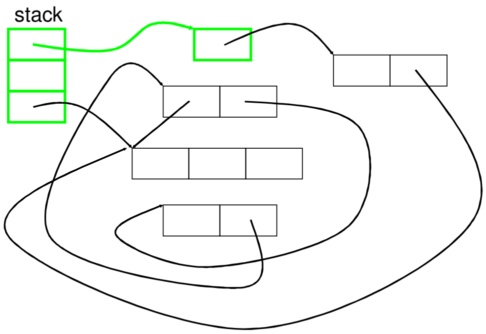




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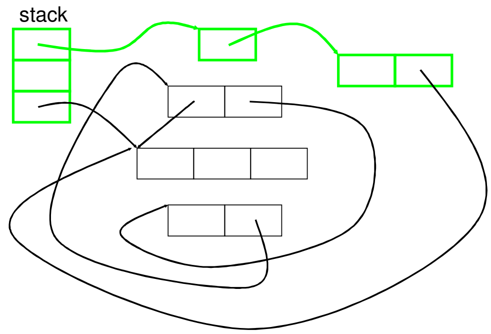




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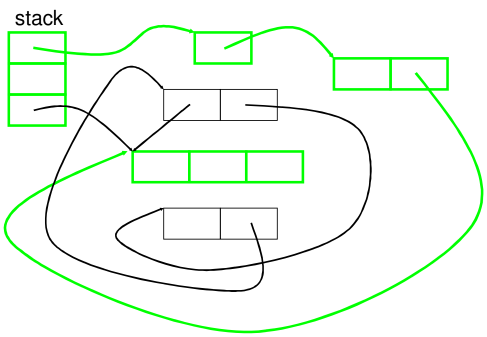




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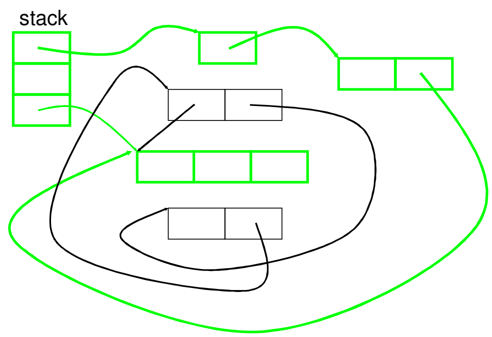




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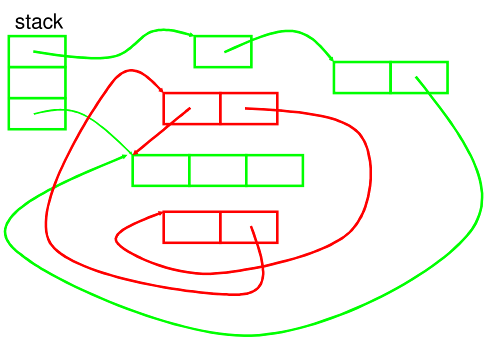





## Mark and Sweep Tradeoffs

- Advantages
  - No problem with cycles
  - Memory writes have no cost

## Mark and Sweep Tradeoffs (cont.)

- Disadvantages
  - Fragmentation
    - Available space broken up into many small pieces
      - Thus many mark-and-sweep systems may also have a compaction phase (like defragmenting your disk)
  - Cost proportional to heap size
    - Sweep phase needs to traverse whole heap – it touches dead memory to put it back on to the free list
  - Not appropriate for real-time applications
    - Bad if your car's braking system performs GC while you are trying to stop at a busy intersection

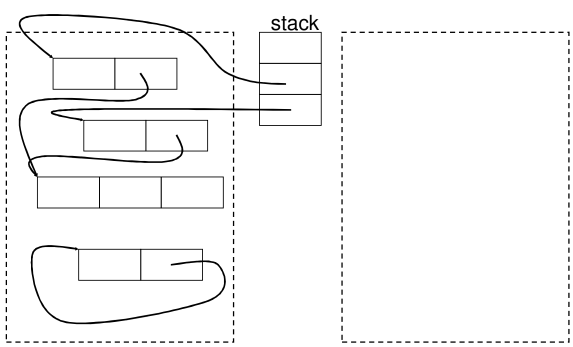


## Stop and Copy GC

- Like mark and sweep, but only touches live objects
  - Divide heap into two equal parts (semispaces)
  - Only one semispace active at a time
  - At GC time, flip semispaces
    1. Trace the live data starting from the stack
    2. Copy live data into other semispace
    3. Declare everything in current semispace dead
    4. Switch to other semispace



## Stop and Copy Example



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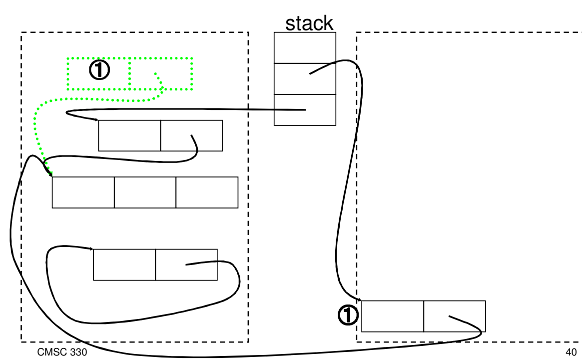




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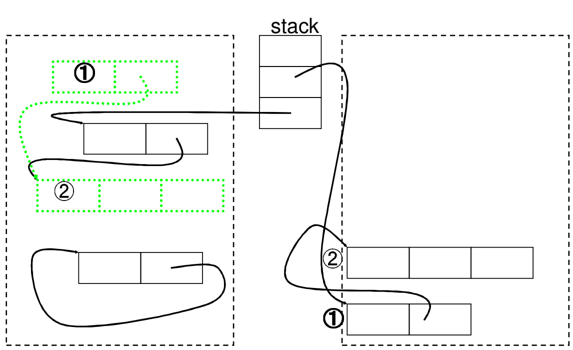




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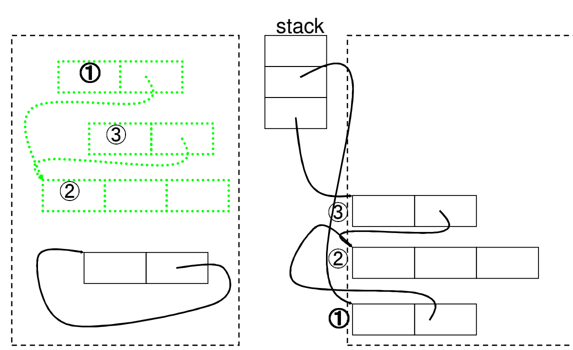
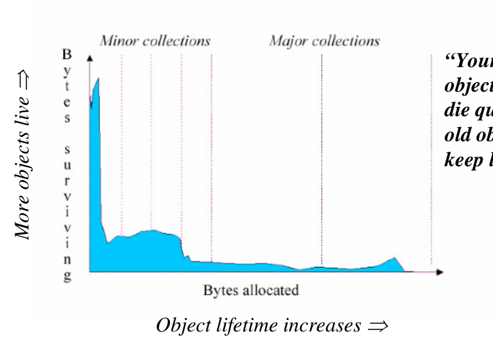


## Stop and Copy Tradeoffs

- Advantages
  - Only touches live data
  - No fragmentation (automatically compacts)
    - Will probably increase locality
- Disadvantages
  - Requires twice the memory space
  - Like mark and sweep, need to “stop the world”
    - Program must stop running to let garbage collector move around data in the heap



## The Generational Principle




***“Young objects die quickly; old objects keep living”***



## Generational Collection

- Long lived objects get copied over and over
  - Idea: Have more than one semispace, divide into generations
    - Older generations collected less often
    - Objects that survive many collections get pushed into older generations
    - Need to track pointers from old to young generations to use as roots for young generation collection
- One popular setup
  - Generational stop and copy



## Java HotSpot SDK 1.4.2 Collector

- Multi-generational, hybrid collector
  - Young generation
    - Stop and copy collector
  - Tenured generation
    - Mark and sweep collector
  - Permanent generation
    - No collection
- Questions
  - Why does using a copy collector for the youngest generation make sense?
  - What apps will be penalized by this setup?



## More Issues in GC (cont.)

- Stopping is world is a big hit
  - Unpredictable performance
    - Bad for real-time systems
  - Need to stop all threads
    - Without a much more sophisticated GC
- One-size fits all solution
  - Sometimes, GC just gets in the way
  - But correctness comes first



## What Does GC Mean to You?

- Ideally, nothing
  - GC should make programming easier
  - GC should not affect performance (much)
- Usually bad idea to manage memory yourself
  - Using object pools, free lists, object recycling, etc…
  - GC implementations have been heavily tuned
    - May be more efficient than explicit deallocation
- If GC becomes a problem, hard to solve
  - You can set parameters of the GC
  - You can modify your program

## Increasing Memory Performance

- Don't allocate as much memory
  - Less work for your application
  - Less work for the garbage collector
- Don't hold on to references
  - Null out pointers in data structures
  - Example

```
Object a = new Object;
…use a…
a = null;          // when a is no longer needed
```



## Find the Memory Leak

```
class Stack {
  private Object[] stack;
  private int index;
  public Stack(int size) {
    stack = new Object[size];
  }
  public void push(Object o) {
    stack[index++] = o;
  }
  public void pop() {
    stack[index] = null;  // null out ptr
    return stack[index--];
  }
}
```

From Haggar, Garbage Collection and the Java Platform Memory Model

Answer: pop() leaves item on stack array; storage not reclaimed