CMSC 330: Organization of Programming Languages

Memory Management and Garbage Collection

Memory Attributes

- Memory to store data in programming languages has the following lifecycle
  - Allocation
    - When the memory is allocated to the program
  - Lifetime
    - How long allocated memory is used by the program
  - Recovery
    - When the system recovers the memory for reuse
- The allocator is the system feature that performs allocation and recovery

Memory Attributes (cont.)

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

Memory Classes

- Static memory – Usually at a fixed address
  - Lifetime – The execution of program
  - Allocation – For entire execution
  - Recovery – By system when program terminates
  - Allocator – Compiler
- Automatic memory – Usually on a stack
  - Lifetime – Activation of method using that data
  - Allocation – When method is invoked
  - Recovery – When method terminates
  - Allocator – Typically compiler, sometimes programmer

Memory Classes (cont.)

- Dynamic memory – Addresses allocated on demand in an area called the heap
  - Lifetime – As long as memory is needed
  - Allocation – Explicitly by programmer, or implicitly by compiler
  - Recovery – Either by programmer or automatically (when possible and depends upon language)
  - Allocator – Manages free/available space in heap

Memory Classes (cont.)

- Persistent memory – Usually the file system
  - Lifetime – Multiple executions of a program
    - E.g., files or databases
  - Allocation – By program or user
    - Often outside of program execution
  - Recovery – When data no longer needed
  - 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 Errors

- 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

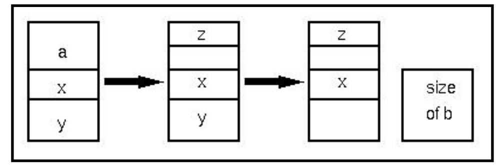
Ways to Avoid Mistakes in C

- Don't allocate memory on the heap
  - Could lead to confusing code
- Never free memory
  - OS will reclaim process's memory anyway at exit
  - Memory is cheap; who cares about a little leak?
- But: Both of the above two may be impractical
- Can avoid all three problems by using automatic memory management
  - Though it does not prevent all leaks, as we will see

Fragmentation

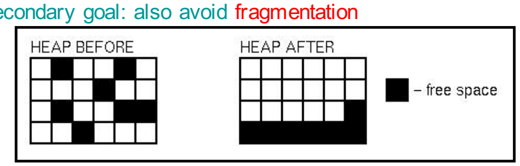
- Another memory management problem
- Example sequence of calls

  allocate(a);
  allocate(x);
  allocate(y);
  free(a);
  allocate(z);
  free(y);
  allocate(b);
  - Not enough contiguous space for b



Automatic memory management

- Primary goal: automatically reclaim dynamic memory
  - Secondary goal: also avoid fragmentation



- Insight: You can do reclamation and avoid fragmentation if you can identify every pointer in a program
  - You can move the allocated storage, then redirect pointers to it
    - Compact it, to avoid fragmentation
  - Compiler ensures perfect knowledge LISP, OCAML, Java, Prolog (with caveats), but not in C, C++, Pascal, Ada

Strategy

- 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"
- Thus we need garbage collection (GC) algorithms that can
  1. Distinguish live from dead objects
  2. Reclaim the dead objects and retain the live ones

Determining Liveness

- 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 a safe 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

Liveness by Reachability

- An object is reachable if it can be accessed by dereferencing ("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

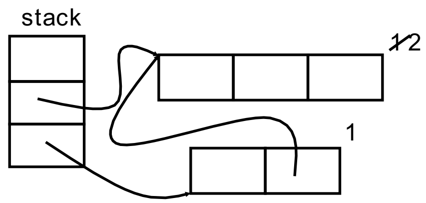
Roots

- 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 determining reachability

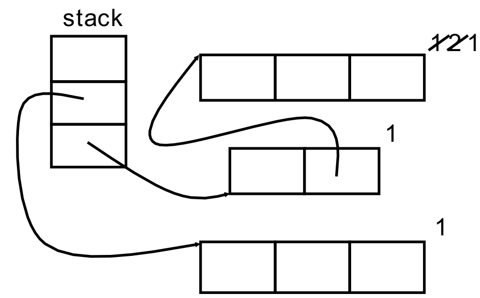
Reference Counting

- Idea: Each object has count of number of pointers to it from the roots or other objects
  - When count reaches 0, object is unreachable
- Count tracking code may be manual or automatic
- In regular use
  - C++ (smart pointer library), Cocoa (manual), Python
- Method doesn't address fragmentation problem
- Invented by Collins in 1960
  - A method for overlapping and erasure of lists. *Communications of the ACM*, December 1960

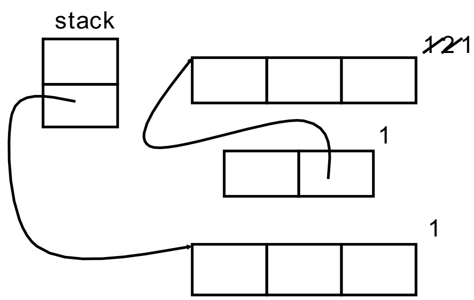
Reference Counting Example



Reference Counting Example (cont.)



Reference Counting Example (cont.)



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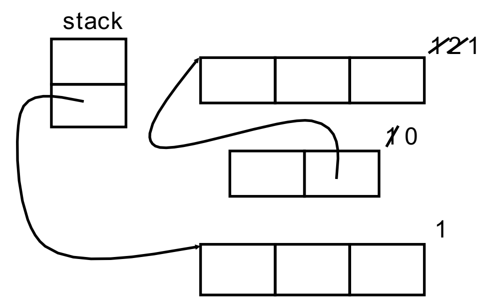

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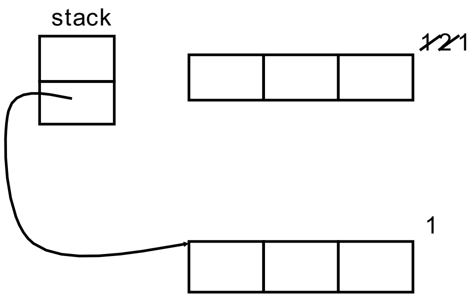

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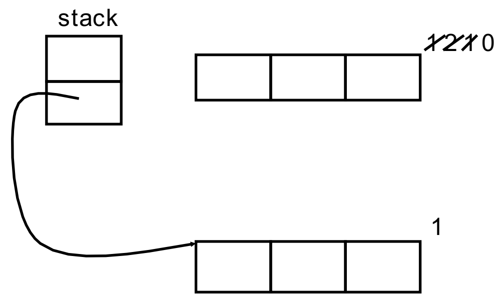

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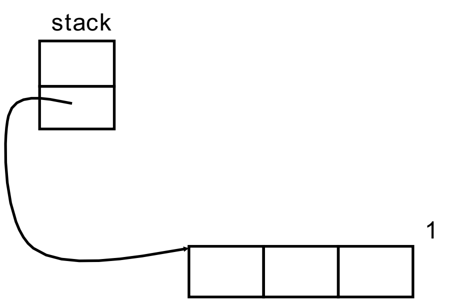
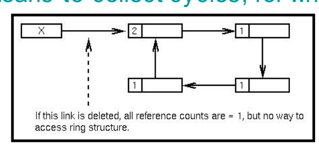


Reference Counting Tradeoffs

- 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
  - Need other means to collect cycles, for which counts never go to 0



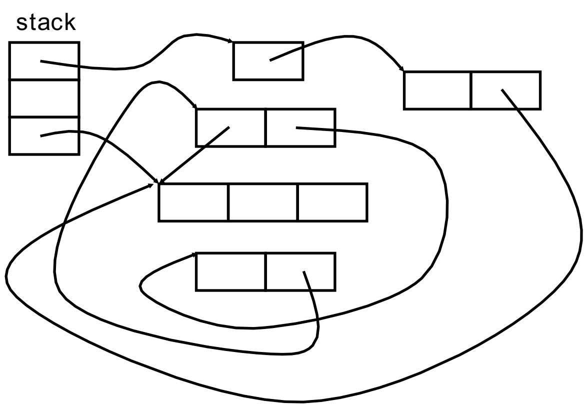
Tracing Garbage Collection

- Idea: Determine reachability as needed, rather than by stored counts
- Every so often, stop the world and
  - Follow pointers from live objects (starting at roots) to expand the live object set
    - Repeat until no more reachable objects
  - Deallocate any non-reachable objects
- Two main variants of tracing GC
  - Mark/sweep (McCarthy 1960) and stop-and-copy (Cheney 1970)

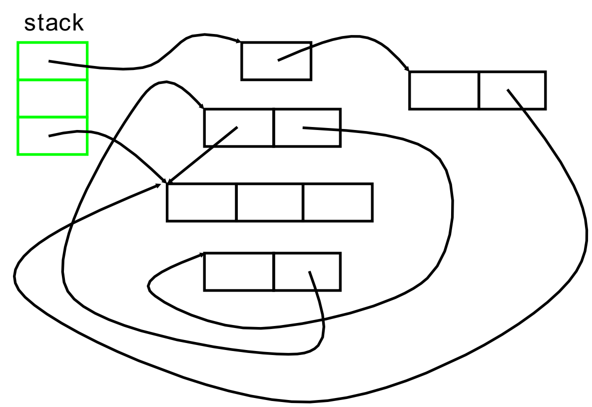
Mark and Sweep GC

- Two phases
  - Mark phase: trace the heap and mark all reachable objects
  - Sweep phase: go through the entire heap and reclaim all unmarked objects

Mark and Sweep Example



Mark and Sweep Example (cont.)



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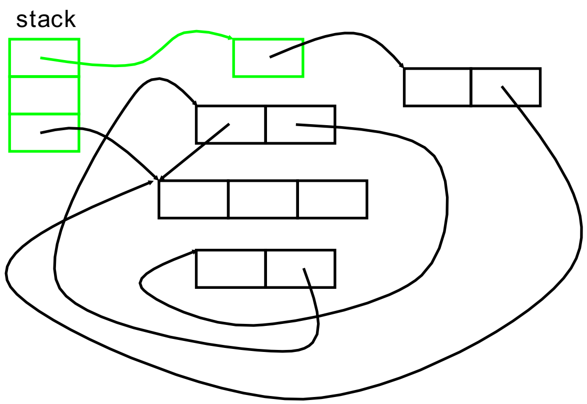

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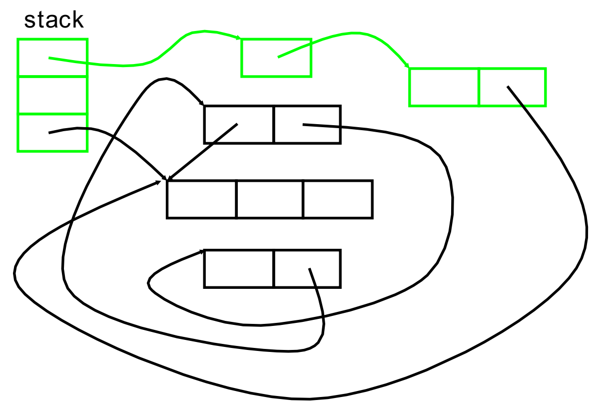
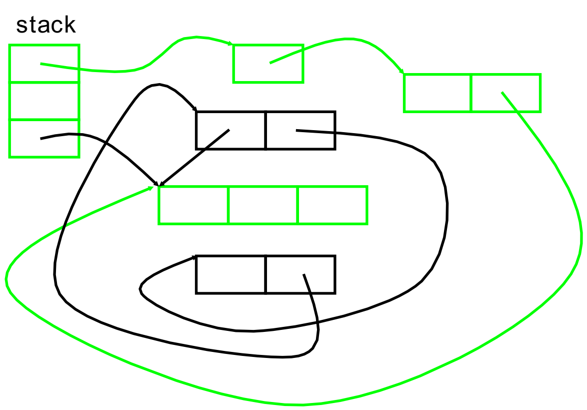


Mark and Sweep Example (cont.)



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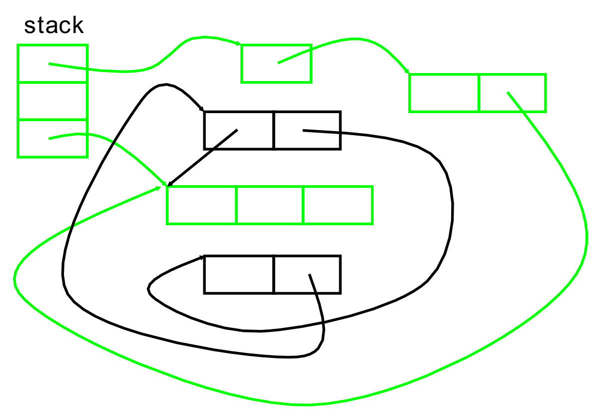

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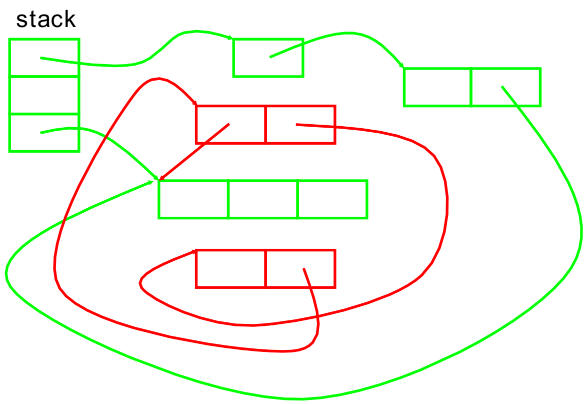

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Mark and Sweep Advantages

- No problem with cycles
- Memory writes have no cost
- Non-moving
  - Live objects stay where they are
  - Makes conservative GC possible
    - Used when identification of pointer vs. non-pointer uncertain
    - More later

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Mark and Sweep 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

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Copying 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 roots
    2. Copy live data into other semispace
    3. Declare everything in current semispace dead
    4. Switch to other semispace

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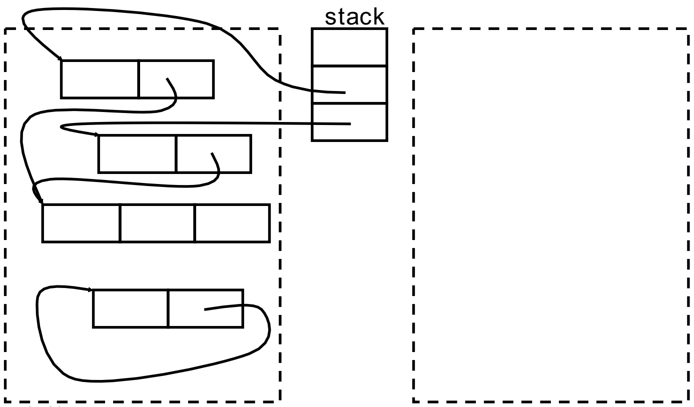
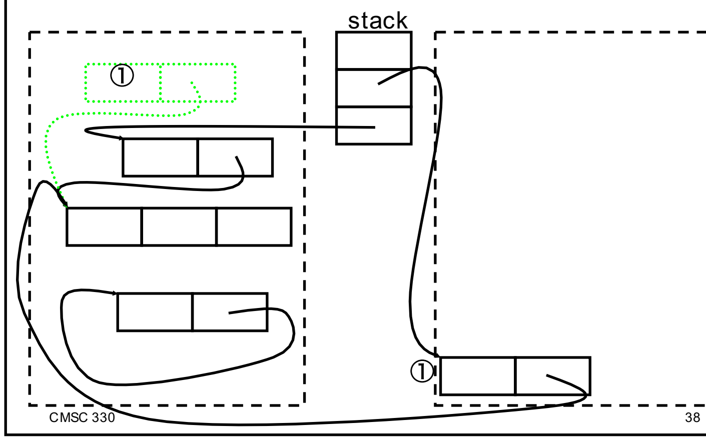
Copying GC Example



Copying GC Example (cont.)



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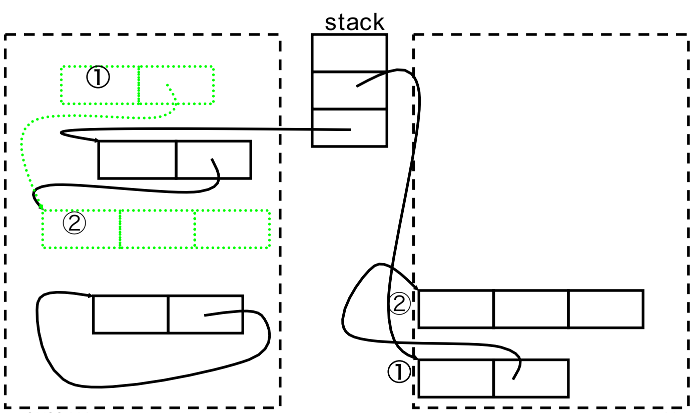

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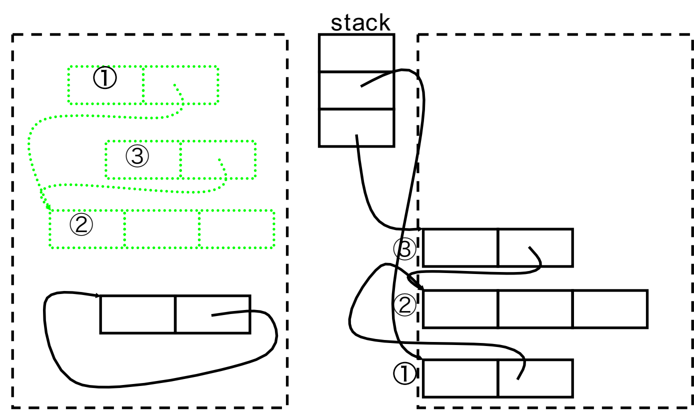


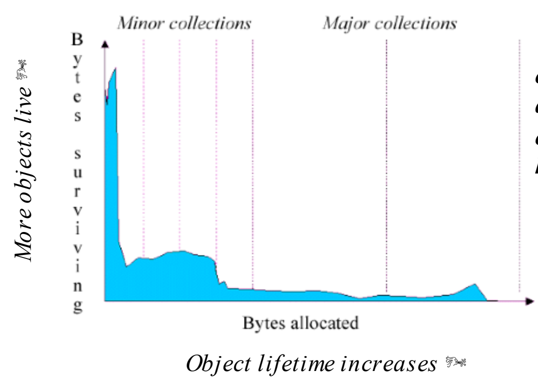
Copying GC Tradeoffs

- Advantages
  - Only touches live data
  - No fragmentation (automatically compacts)
    - Will probably increase locality
- Disadvantages
  - Requires twice the memory space

Stop the World: Potentially Long Pause

- Both of the previous algorithms "stop the world" by prohibiting program execution during GC
  - Ensures that previously processed memory is not changed or accessed, creating inconsistency
- But the execution pause could be too long
  - Bad if your car's braking system performs GC while you are trying to stop at a busy intersection!
- How can we reduce the pause time of GC?
  - Don't collect the whole heap at once (incremental)

The Generational Principle



"Young objects die quickly; old objects keep living"

Generational Collection

- Long lived objects visited multiple times
  - Idea: Have more than one heap region, divide into generations
    - Older generations collected less often
    - Objects that survive many collections get promoted into older generations
    - Need to track pointers from old to young generations to use as roots for young generation collection
      - Tracking one in the remembered set
- One popular setup: Generational, copying GC

Conservative Garbage Collection (for C)

- For C, we cannot be sure which elements of an object are pointers
  - Because of incomplete type information, the use of unsafe casts, etc.
- Idea: suppose it is a pointer if it looks like one
  - Most pointers are within a certain address range, they are word aligned, etc.
  - May retain memory spuriously
- Different styles of conservative collector
  - Mark-sweep: important that objects not moved
  - Mostly-copying: can move objects you are sure of

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

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

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

More Issues in GC (cont.)

- Stopping the 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