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
  - Persistence (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
  - Persistence – The execution of program
  - Allocation – For entire execution
  - Recovery – By system when program terminates
  - Allocator – Compiler
- Automatic memory – Usually on a stack
  - Persistence – Lifetime 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
  - Persistence – 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
  - Persistence – 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 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

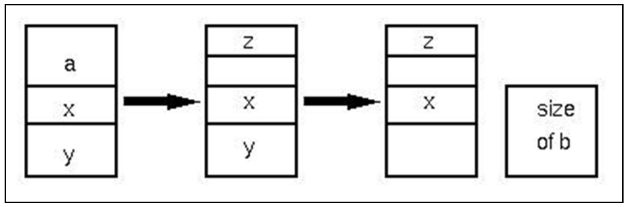
```
{ int *x = ...malloc(); free(x); free(x); }
```

  - 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

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

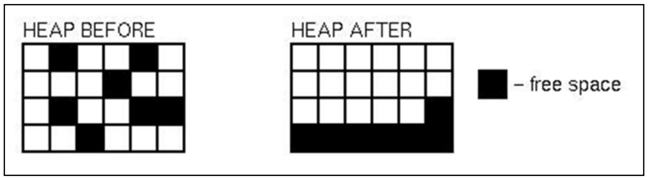
Ways to Avoid Mistakes in C

- 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

Automatic memory management

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



- Insight: You can do reclamation and memory compaction if you can identify every pointer in a program
  - You can move the allocated storage, then redirect pointers to it
  - 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 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

Liveness by 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

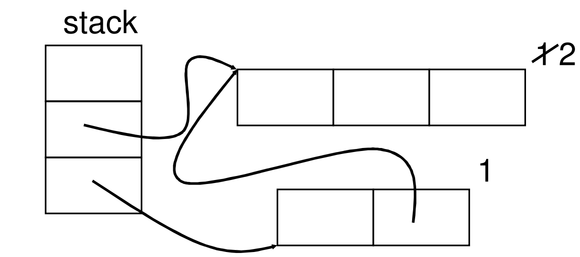
Roots

- 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

- 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



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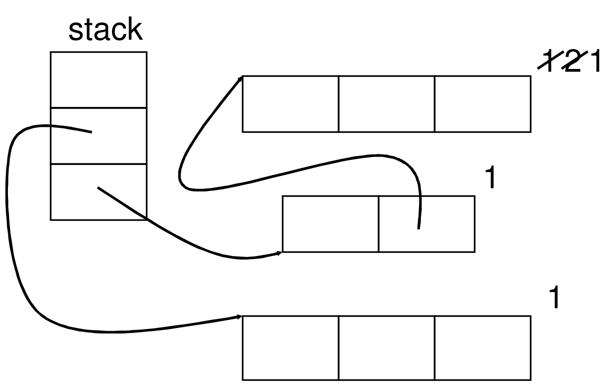
Reference Counting Example (cont.)



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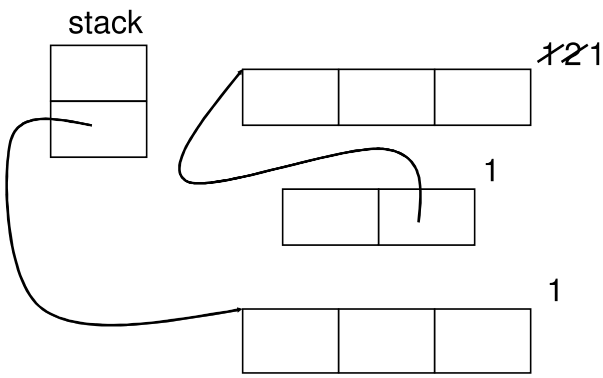
Reference Counting Example (cont.)



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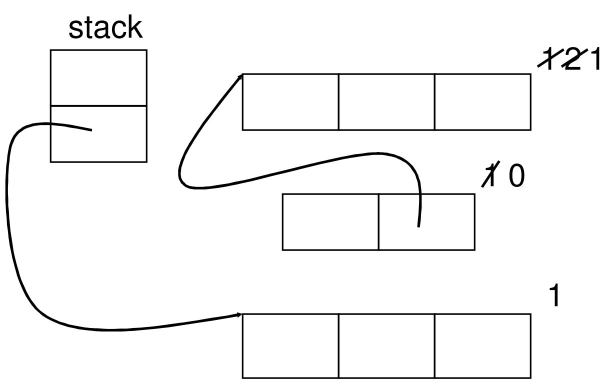

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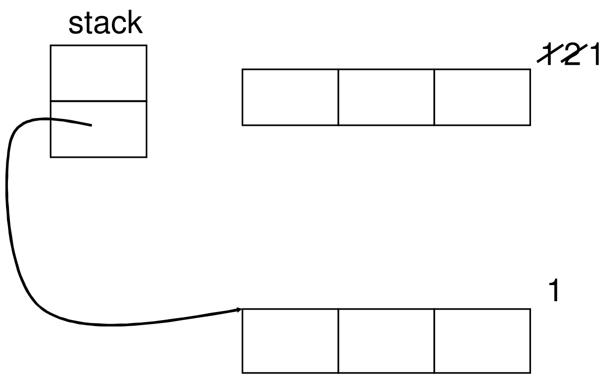

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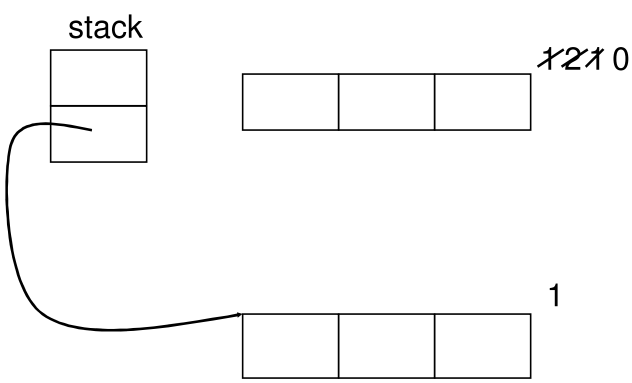

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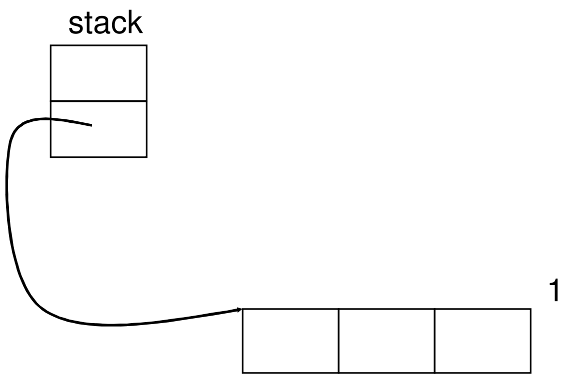
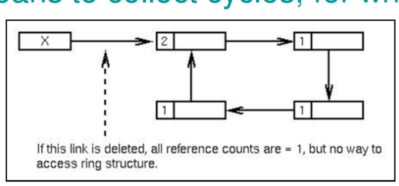


Reference Counting Tradeoffs

- 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



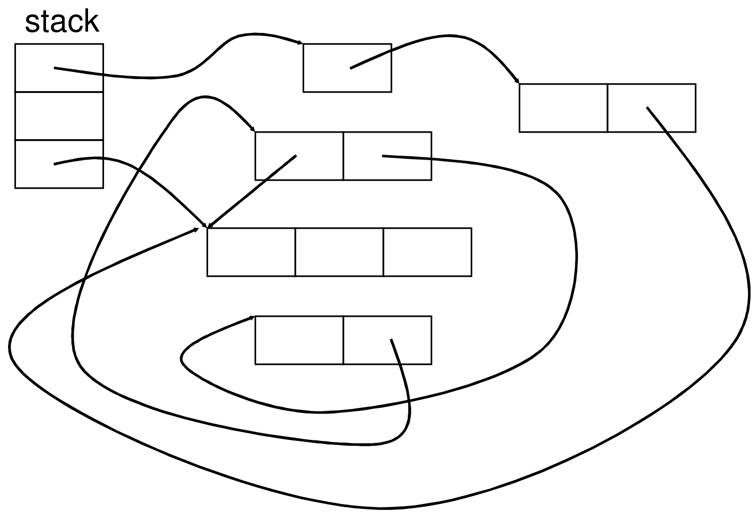
Tracing Garbage Collection

- Idea: Determine reachability as needed, rather than by stored counts
- Every so often, stop the world and
  - Deem all objects on stack as live
  - Follow pointers from live objects 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)

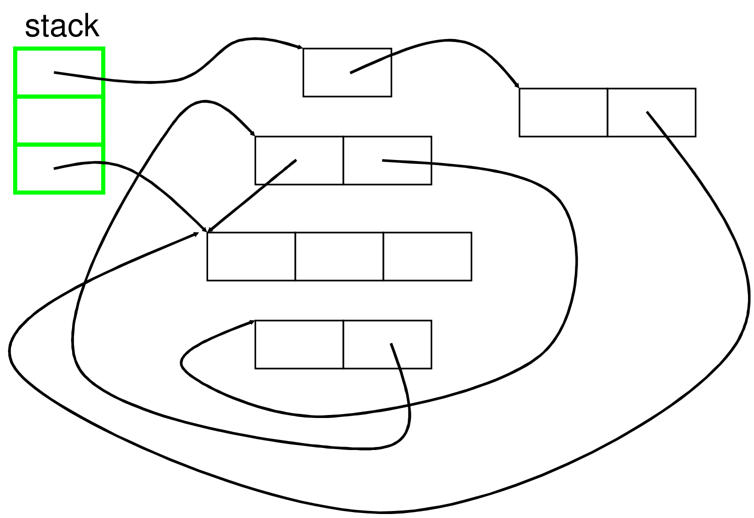
Mark and Sweep GC

- 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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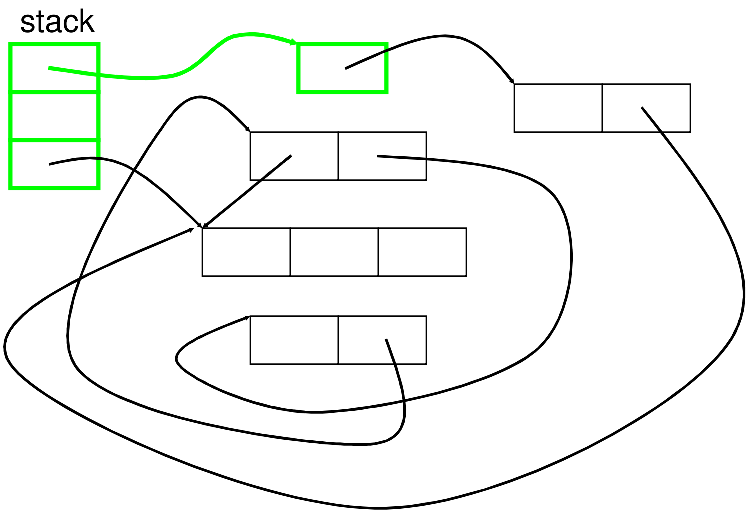
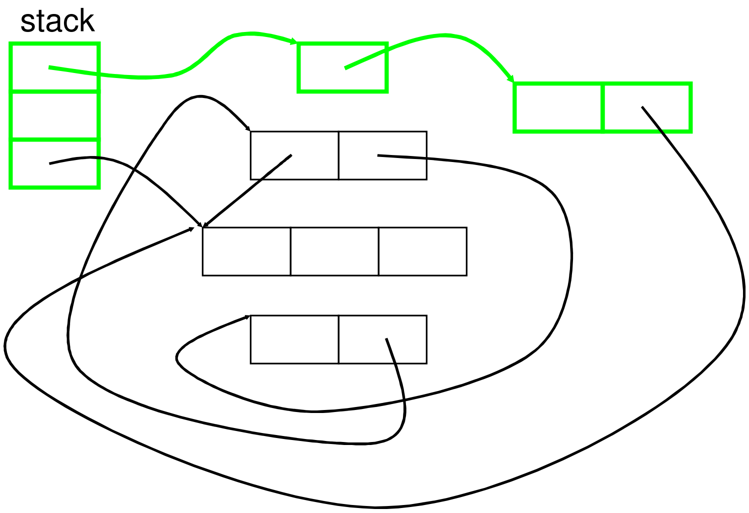


Mark and Sweep Example (cont.)



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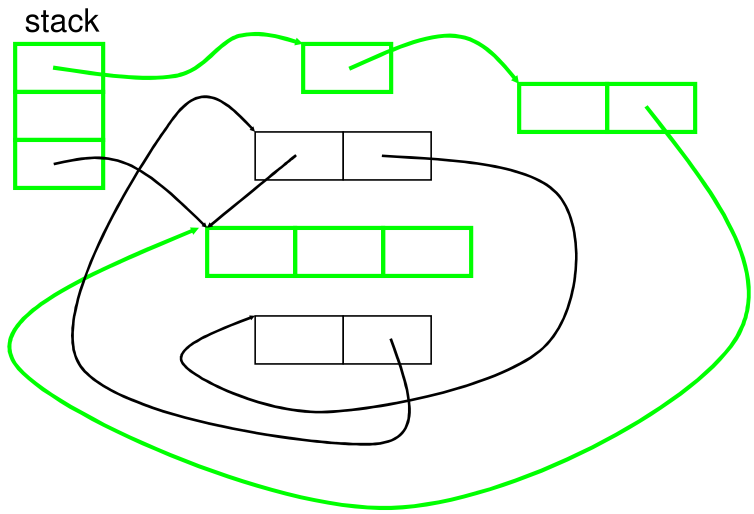

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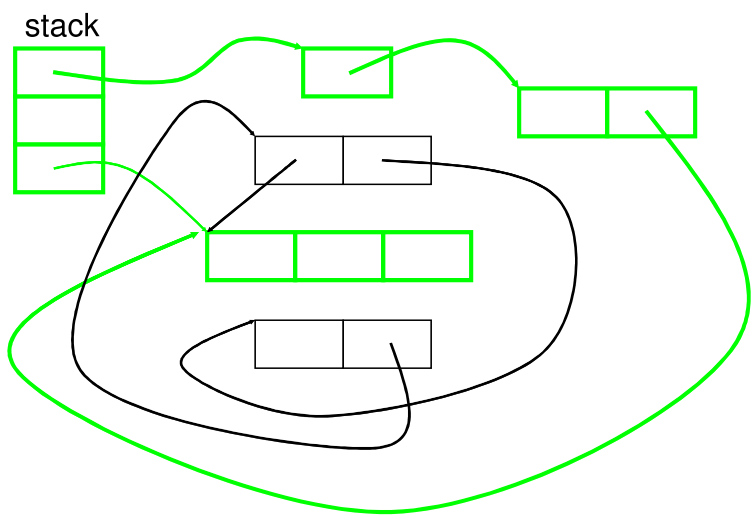

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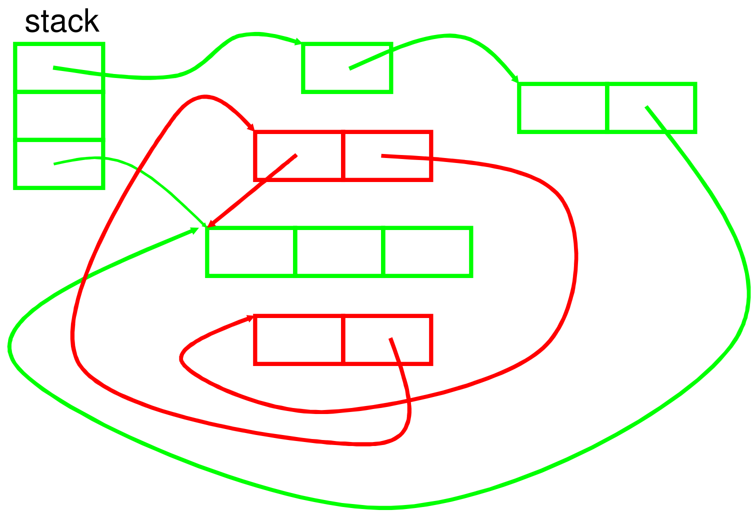


Mark and Sweep Advantages

- 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. int uncertain

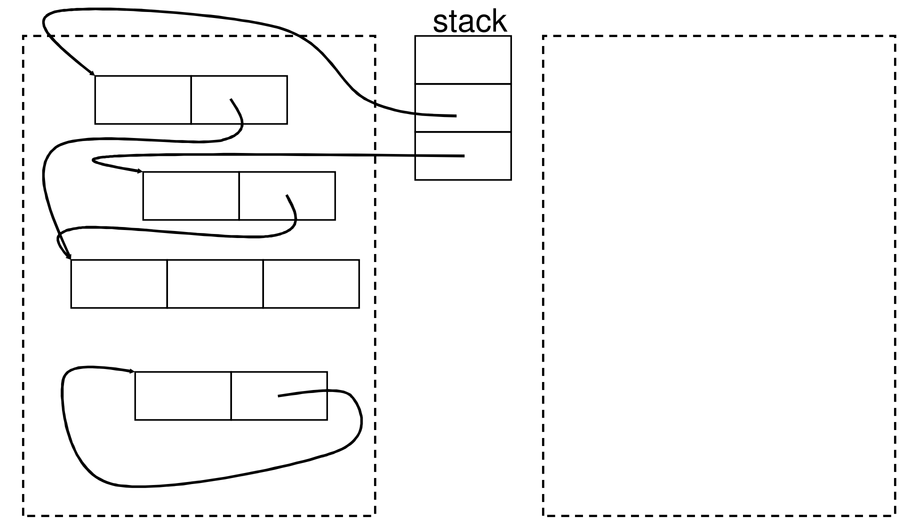
Mark and Sweep Disadvantages

- 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
- "Stop-the-world" variant not real-time
  - Bad if your car's braking system performs GC while you are trying to stop at a busy intersection
    - Can make the marking/sweeping concurrent/incremental

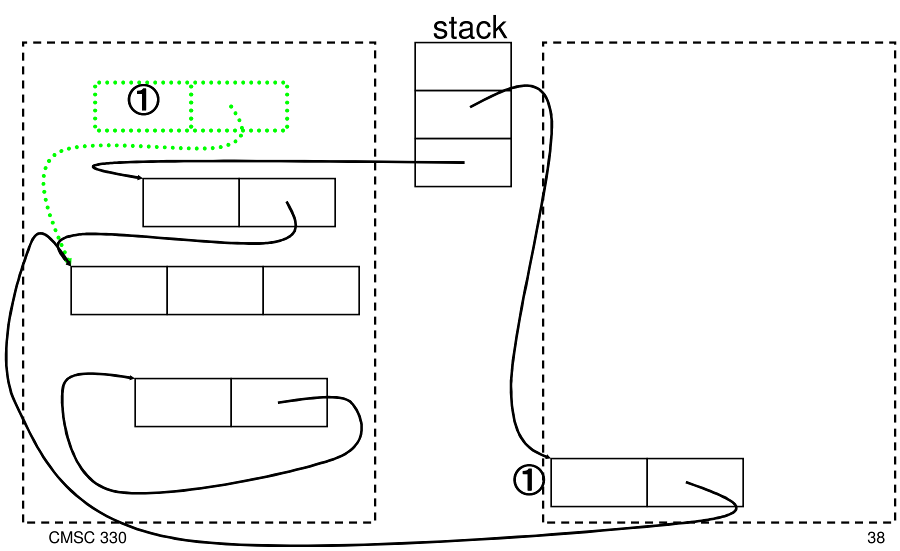
Stop and Copy GC

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

Stop and Copy Example



Stop and Copy Example (cont.)



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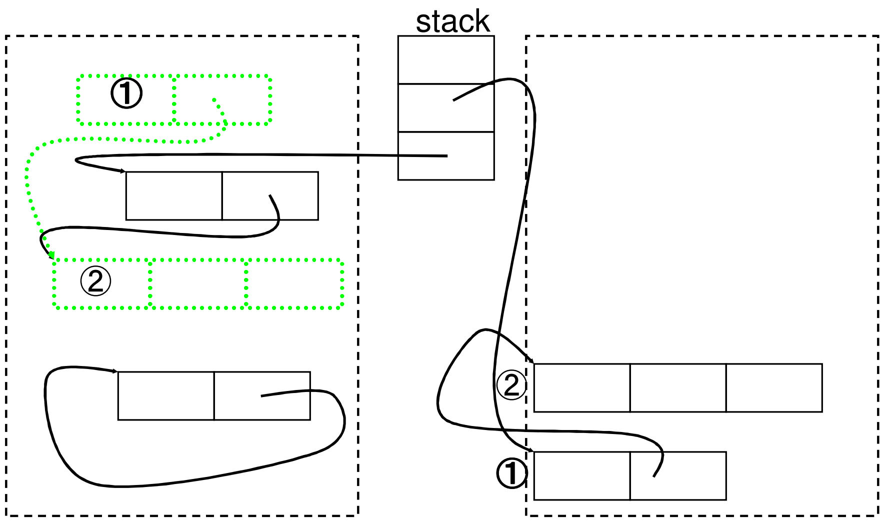

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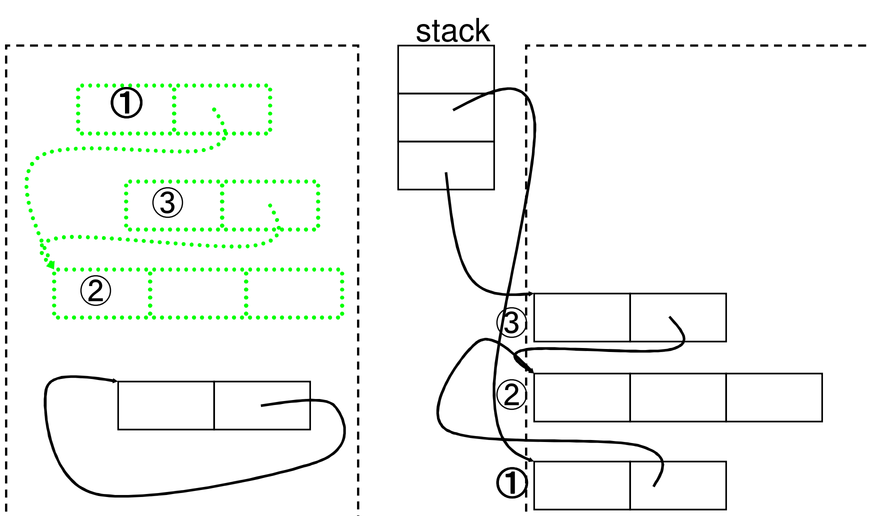
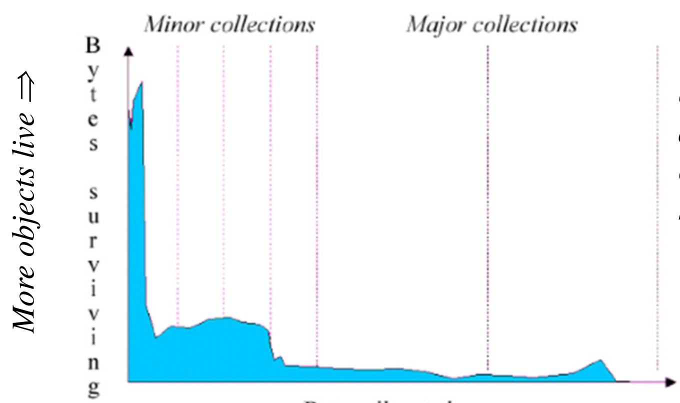


Stop and Copy Tradeoffs

- 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
- Idea: We reduce collection pause time by not traversing the whole heap at once

The Generational Principle



"Young objects die quickly; old objects keep living"

Object lifetime increases ⇒

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 stop and copy

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
    - 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

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 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