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
  - Dealing with persistent memory → databases
    - CMSC 424

Memory Management in C

- Local variables live on the stack
  - Storage space for them reused after function returns
- Space on the heap allocated with malloc()
  - Must be explicitly freed with free()
  - This is 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?
- 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 gabage 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

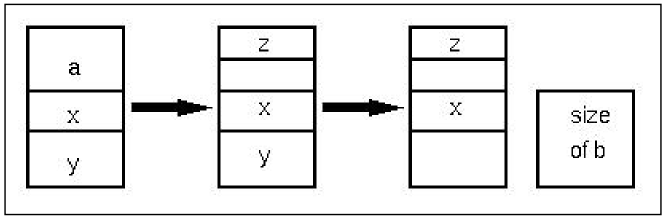
Memory Management in Java

- 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

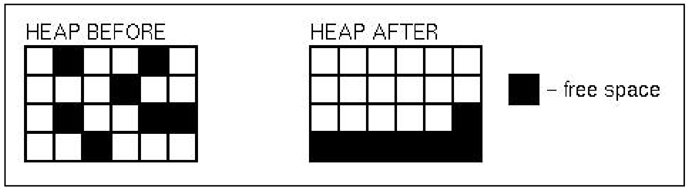
- Another memory management problem
- Example sequence of calls

  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
- Goals: Reduce memory leaks, and make dangling pointers impossible

Many GC Techniques

- 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

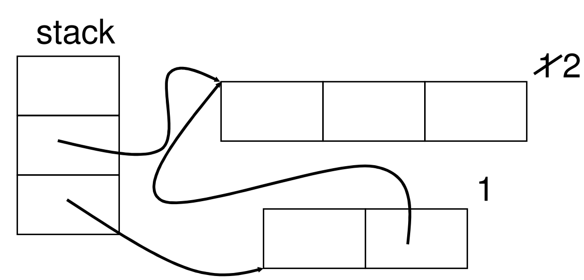
Roots

- 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

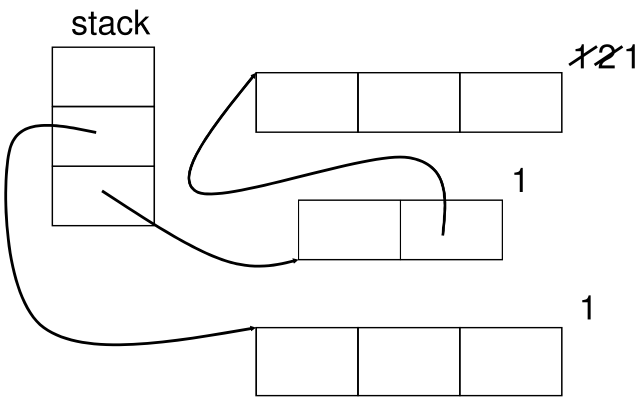
Reference Counting

- 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
- Note: in order 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



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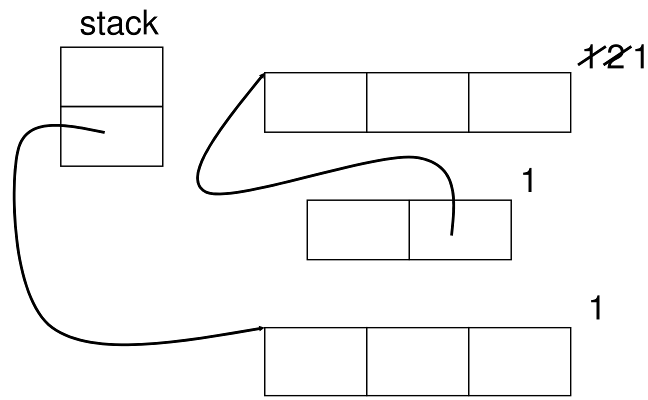

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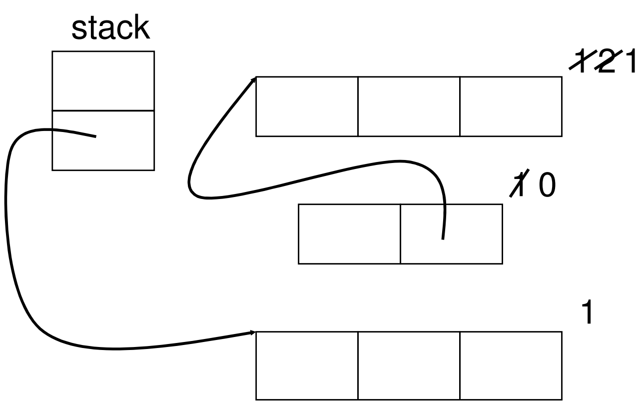

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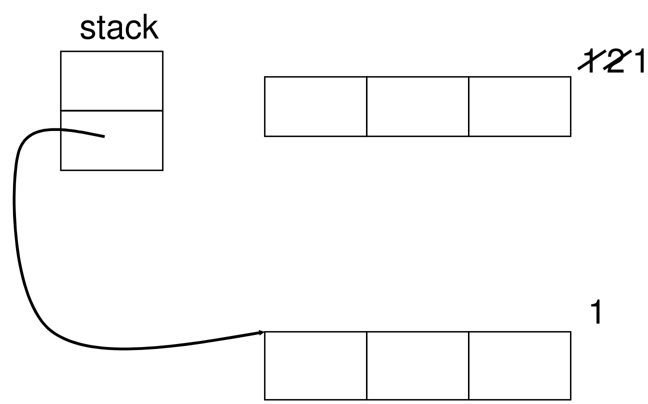

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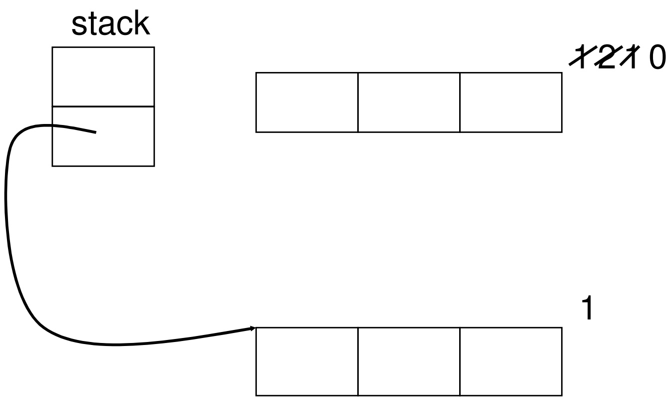

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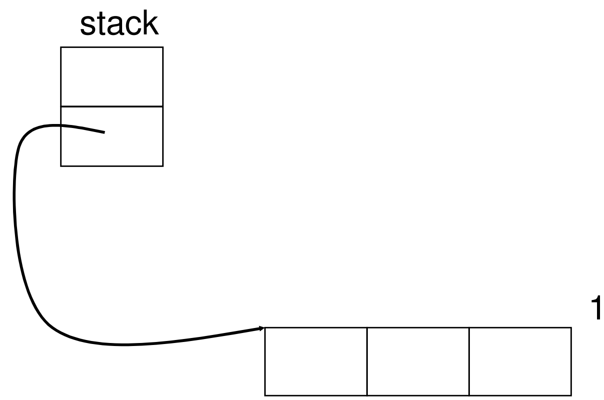


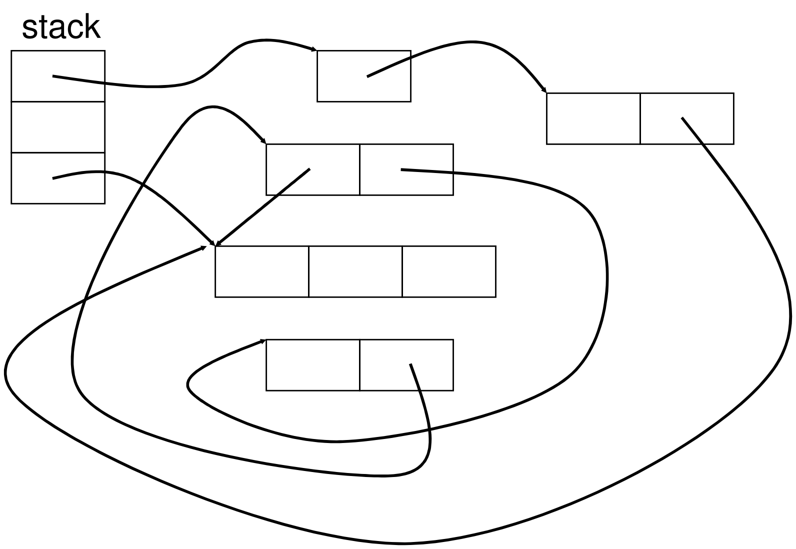
Tradeoffs

- Advantage: incremental technique
  - Generally small, constant amount of work per memory write
  - With more effort, can even bound running time
- Disadvantage: Can’t collect cycles
  - Data structures with a cycle in them will always have non-zero reference counts
    - But can be used if cycles not possible, or can use modified techniques that can handle cycles
  - Also requires extra storage for reference counts

Mark and Sweep GC

- Idea: Only objects reachable from stack could possibly be live
  - Every so often, stop the world and do GC:
    - Mark all objects on stack as live
    - Until no more reachable objects,
      - Mark object reachable from live object as live
    - Deallocate any non-reachable objects
- This is a *tracing* garbage collector

Mark and Sweep Example



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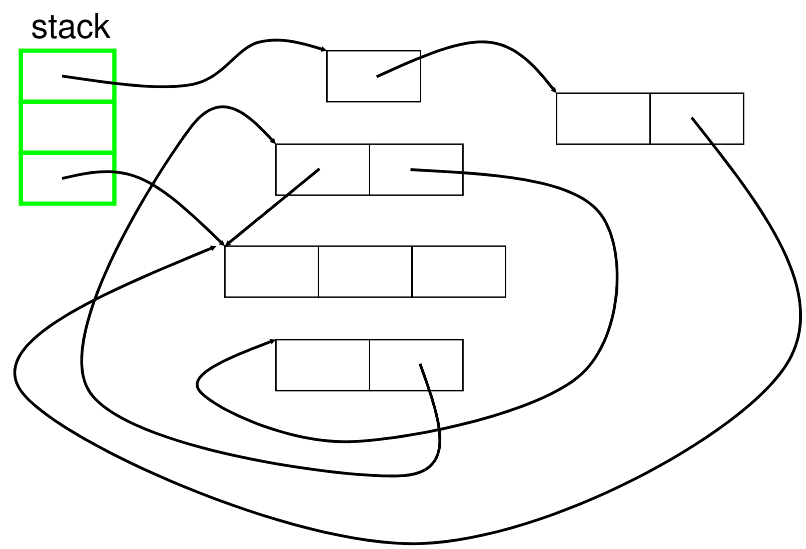

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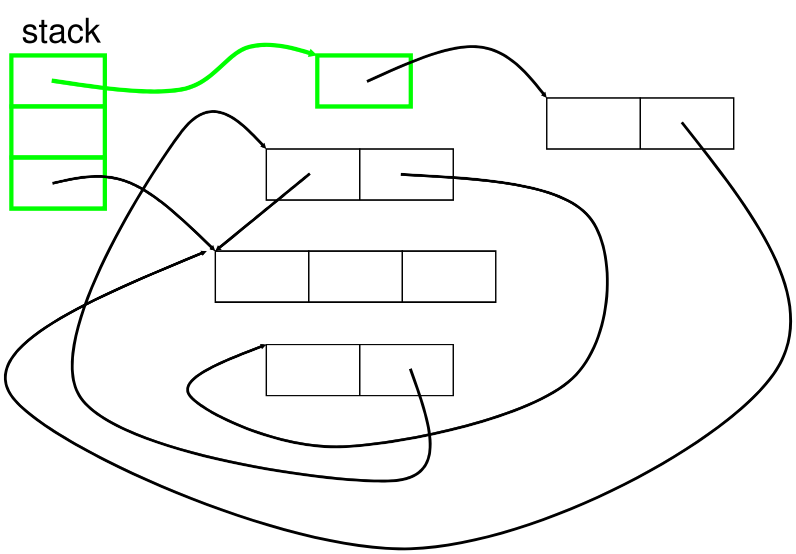

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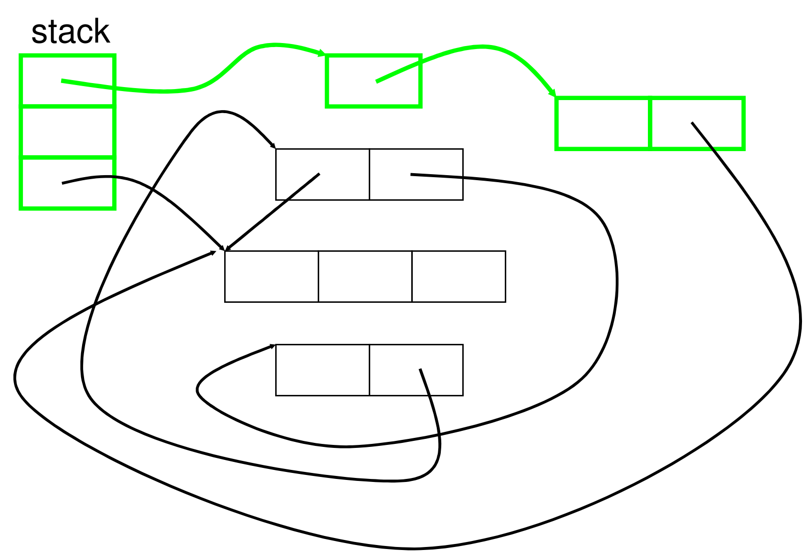

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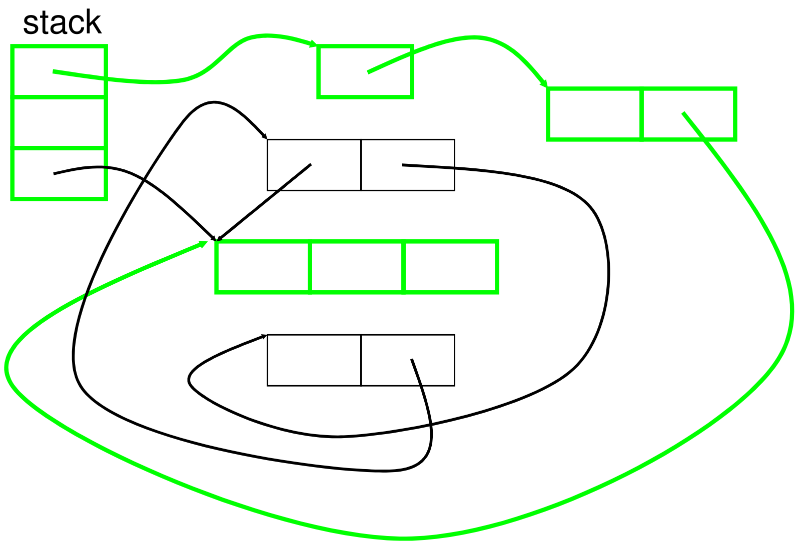

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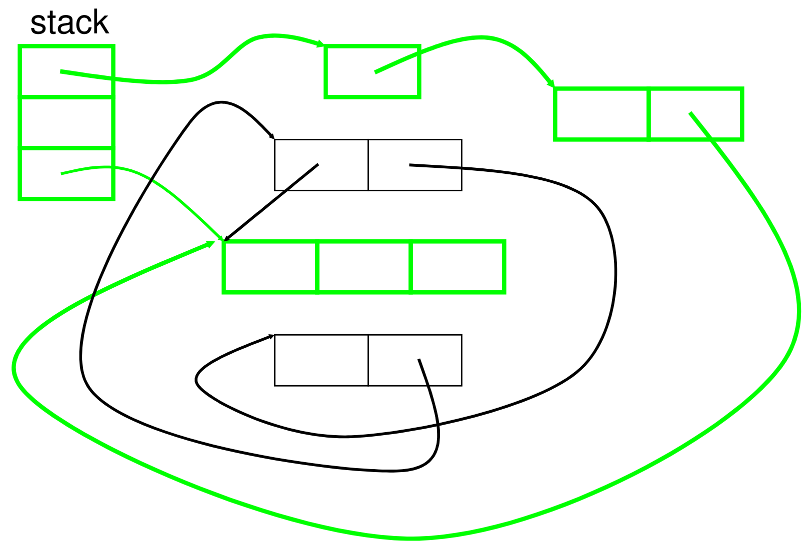

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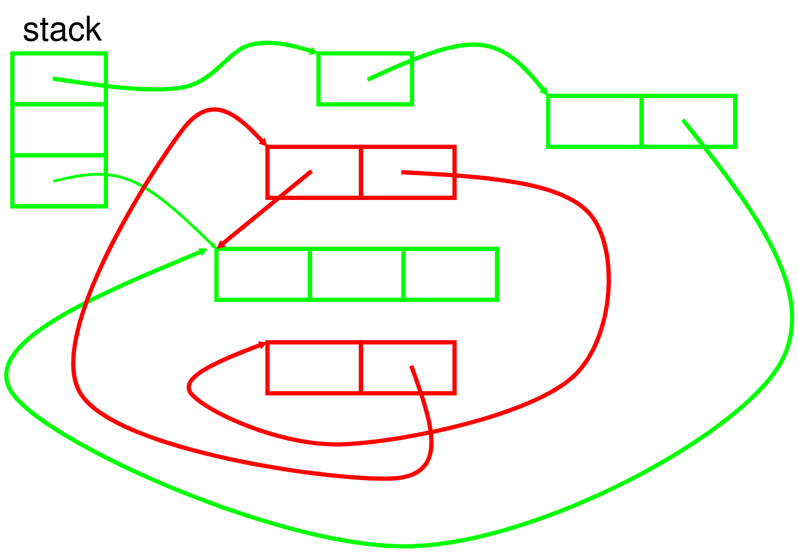


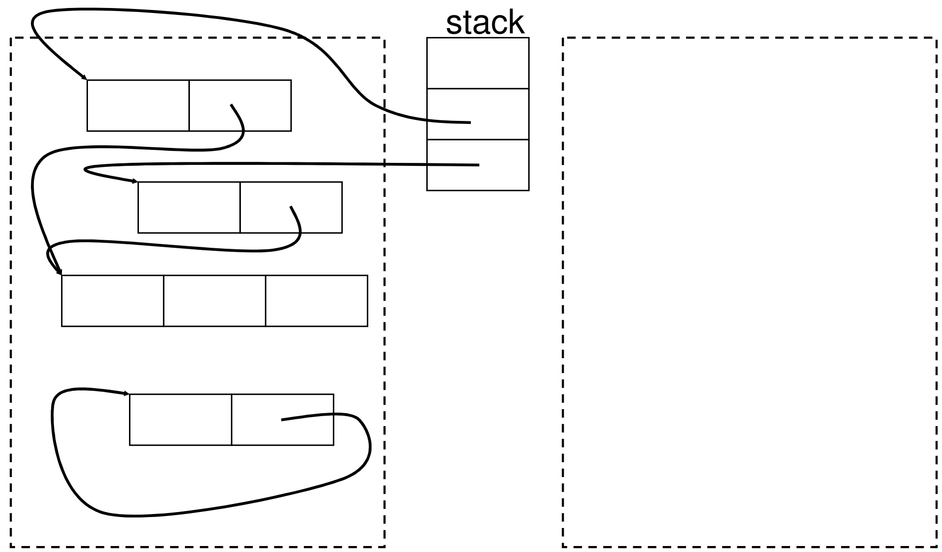
Tradeoffs with Mark and Sweep

- Pros:
  - No problem with cycles
  - Memory writes have no cost
- Cons:
  - 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
    - Trace the live data starting from the stack
    - Copy live data into other semispace
    - Declare everything in current semispace dead; switch to other semispace

Stop and Copy Example



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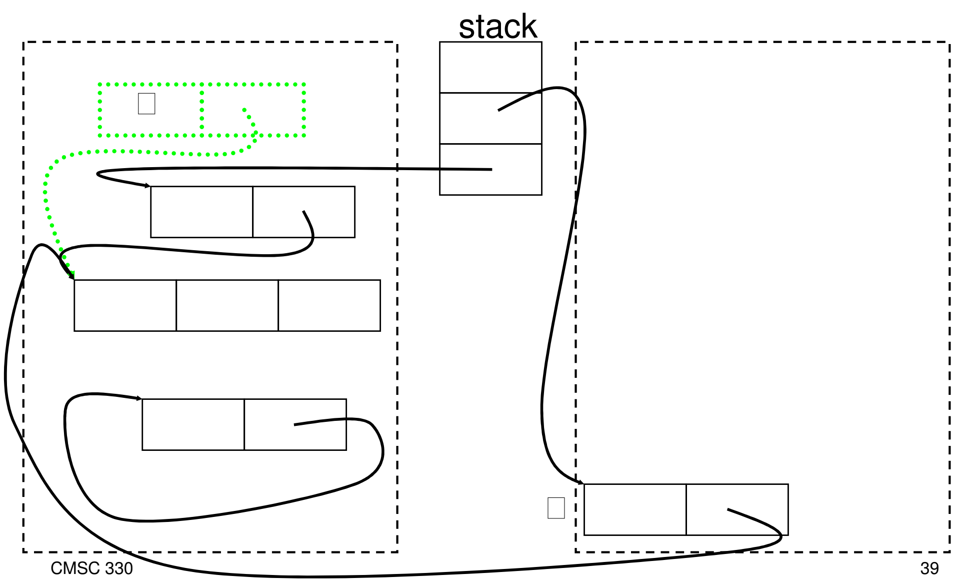

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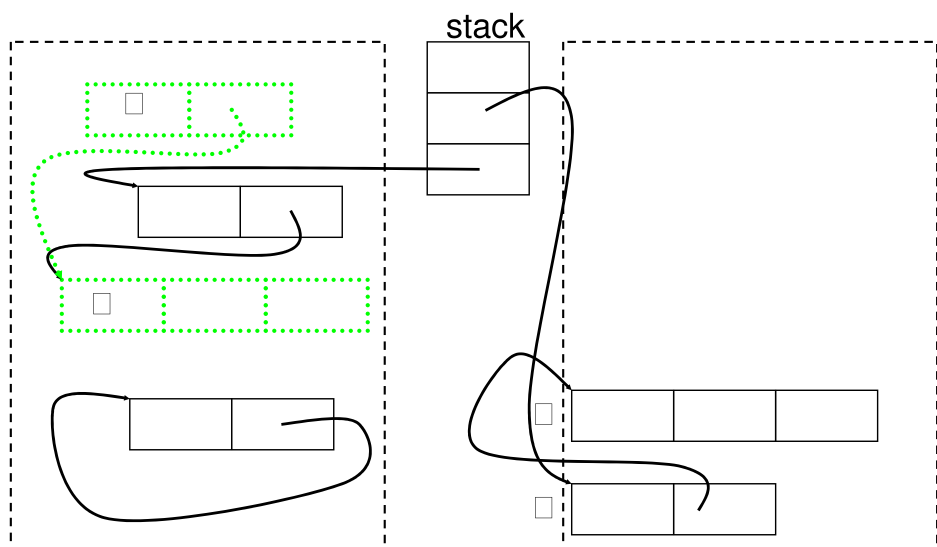

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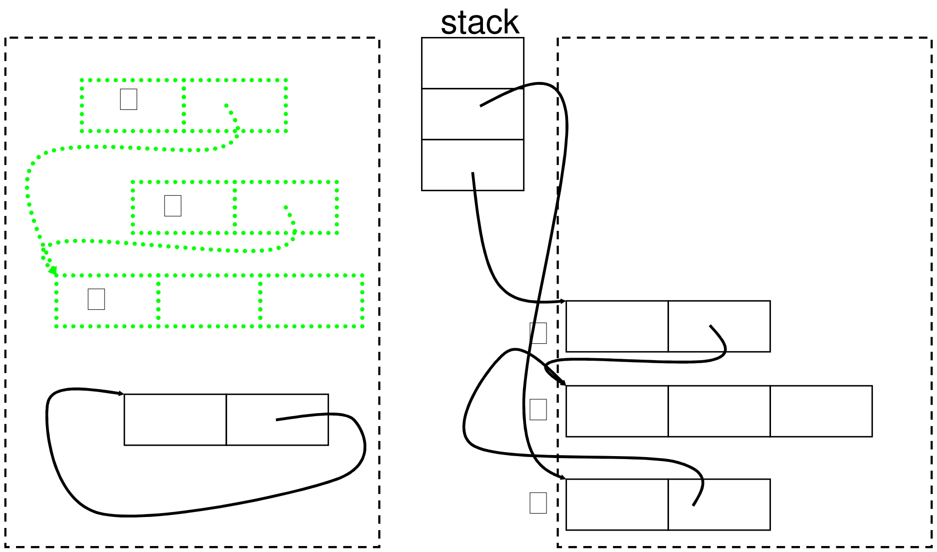


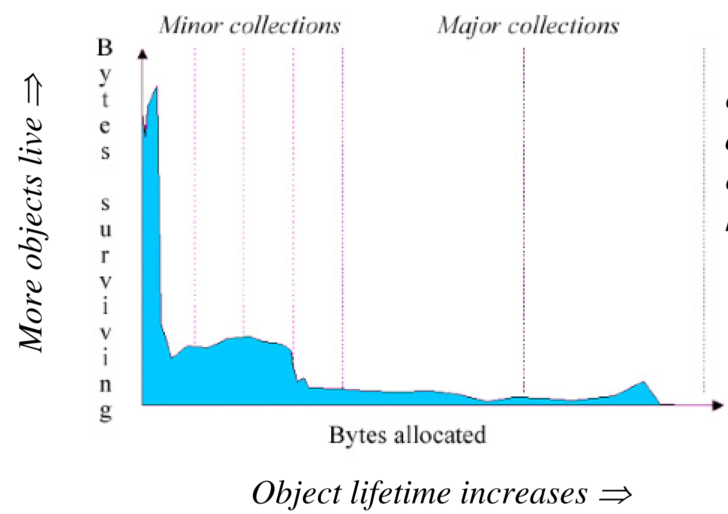
Stop and Copy Tradeoffs

- Pros:
  - Only touches live data
  - No fragmentation; automatically compacts
    - Will probably increase locality
- Cons:
  - 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

Improving Stop and Copy

- Long lived objects get copied over and over
  - Idea: Have more than one semispace, divide into generations
    - Objects that survive copying passes get pushed into older generations
    - Older generations collected less often
- One popular setup is *generational stop and copy*

The Generational Principle



“Young objects die quickly; old objects keep living”

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'd)

- 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
  - It should make your life easier
  - And shouldn't affect performance too much
    - May even give better performance than you'd have with 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
  - Should improve performance
- Don't hold on to references- null out pointers in data structures

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() {
    return stack[index--];
  }
 }
```

– From Haggar, Garbage Collection and the Java Platform Memory Model

Bad Ideas (Usually)

- Calling System.gc() in Java
  - This is probably a bad idea
  - You have no idea what the GC will do
  - And it will take a while
- Managing memory yourself
  - Object pools, free lists, object recycling
  - GC's have been heavily tuned to be efficient

Dealing with GC Problems

- Best idea: measure where your problems are coming from
  - Find a language implementation that has lots of heap profiling information
  - Understand thoroughly what's happening
  - Find solution
- No easy solution
  - But don't try to optimize too early