CMSC 433 – Programming Language Technologies and Paradigms
Fall 2006

Memory Management

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

Memory Mgmt and the JVM

- The JVM Specification doesn't say how to manage the heap
- Simplest valid memory management strategy: never delete any objects
  - Not such a bad idea in some circumstances (when?)
  - Need to consider relevant performance criteria

Performance Criteria

- Throughput
  - How much work does my application complete?
- Latency (promptness)
  - How long might my application pause (due to a memory management)?
- Memory footprint
  - How much memory is required by the application above what's needed for its work?

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

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
- How to implement reachability?
  - What data is live?
  - How to perform pointer chasing?

Roots

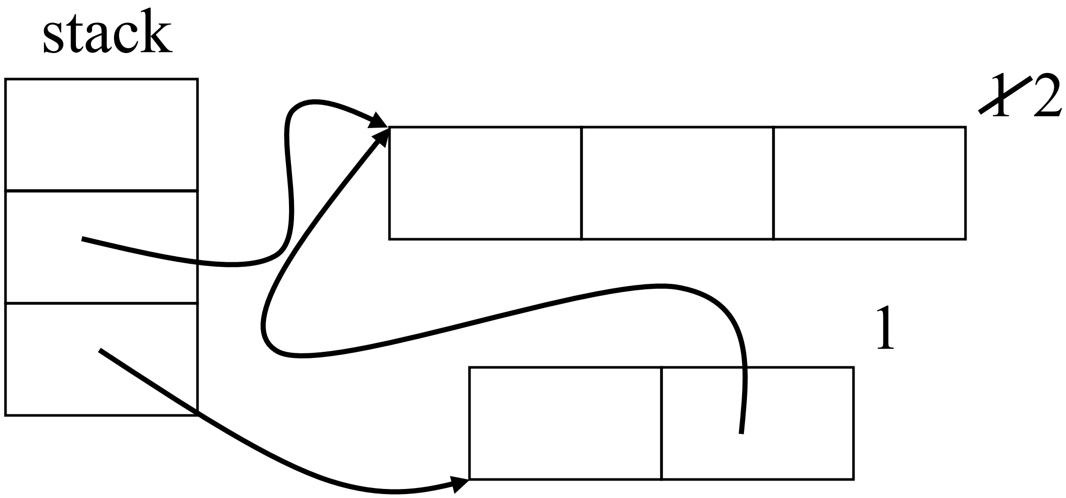
- At a given program point, we define liveness as being data reachable from the root set:
  - Global variables (i.e., static fields)
  - Local variables of all live method activations (i.e., the stack)
- At the machine level, we also consider the register set (usually stores local or global variables)

- Next: techniques for pointer chasing

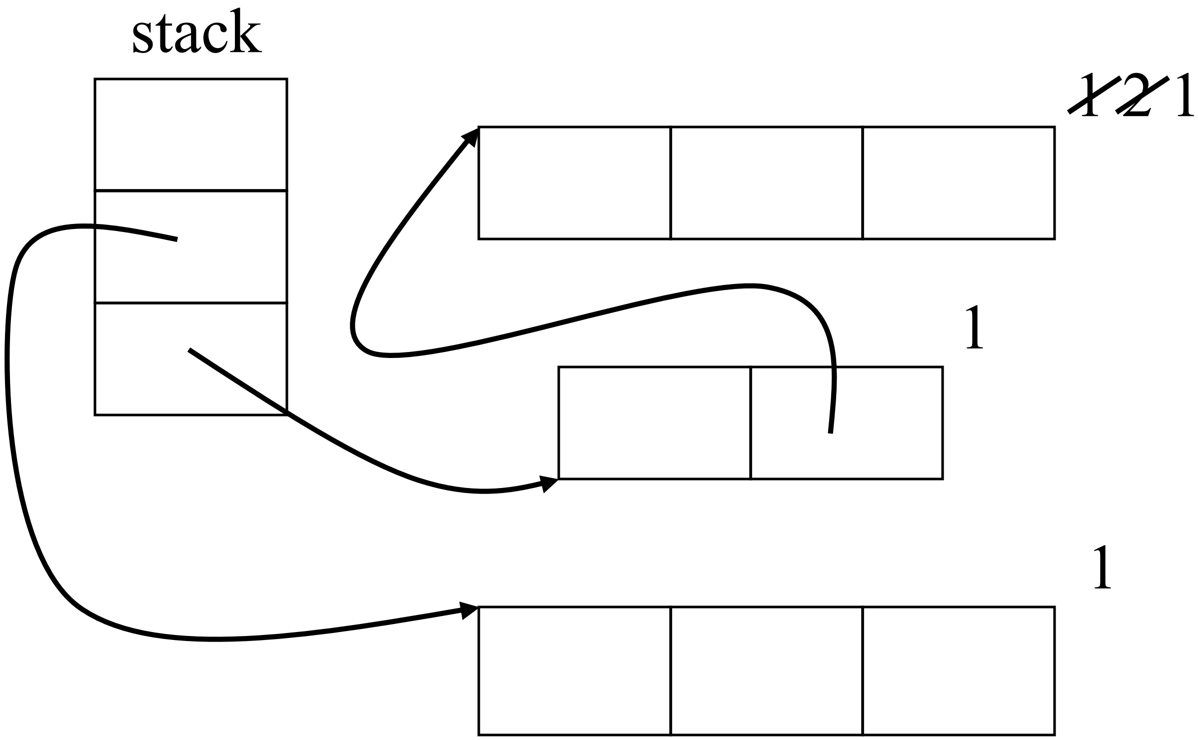
Reference Counting

- Old technique (1960)
- Each object tracks the number of pointers to it from other objects and from the roots.
  - When count reaches 0, object can be deallocated
- Counts incremented/decremented by the compiler (auto) or by hand (manual) when program statements create or remove aliases.

Reference Counting Example



Reference Counting Example



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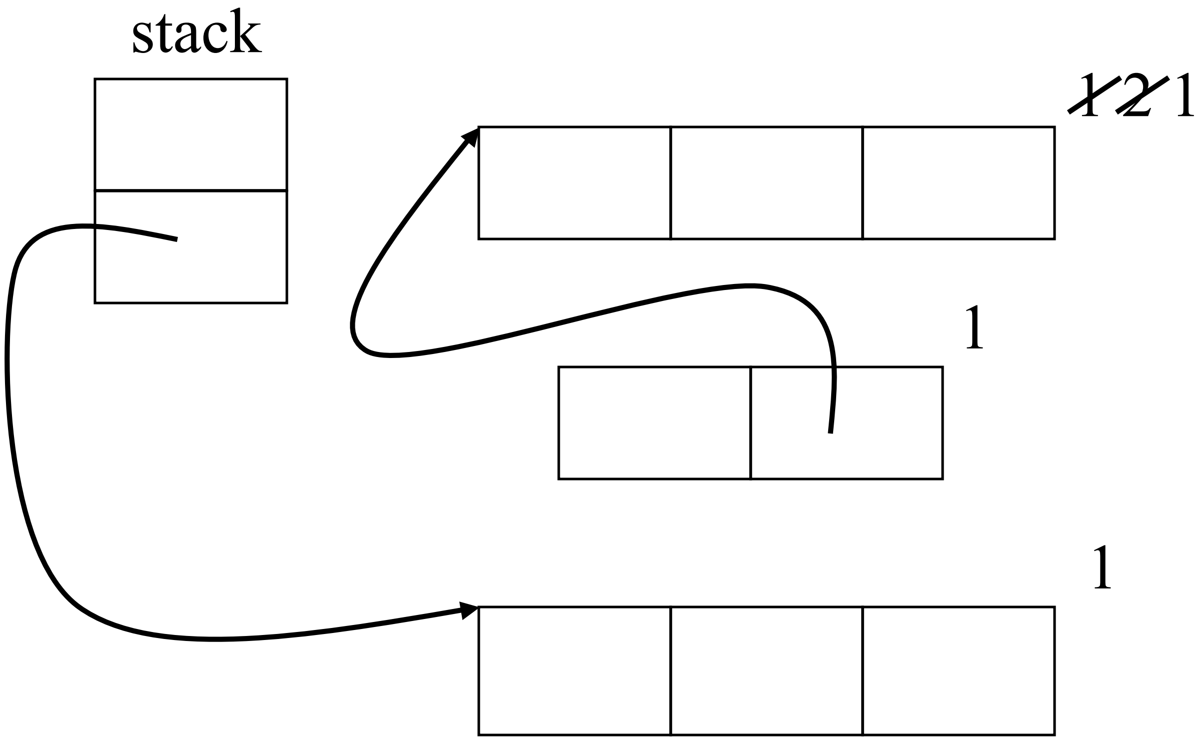

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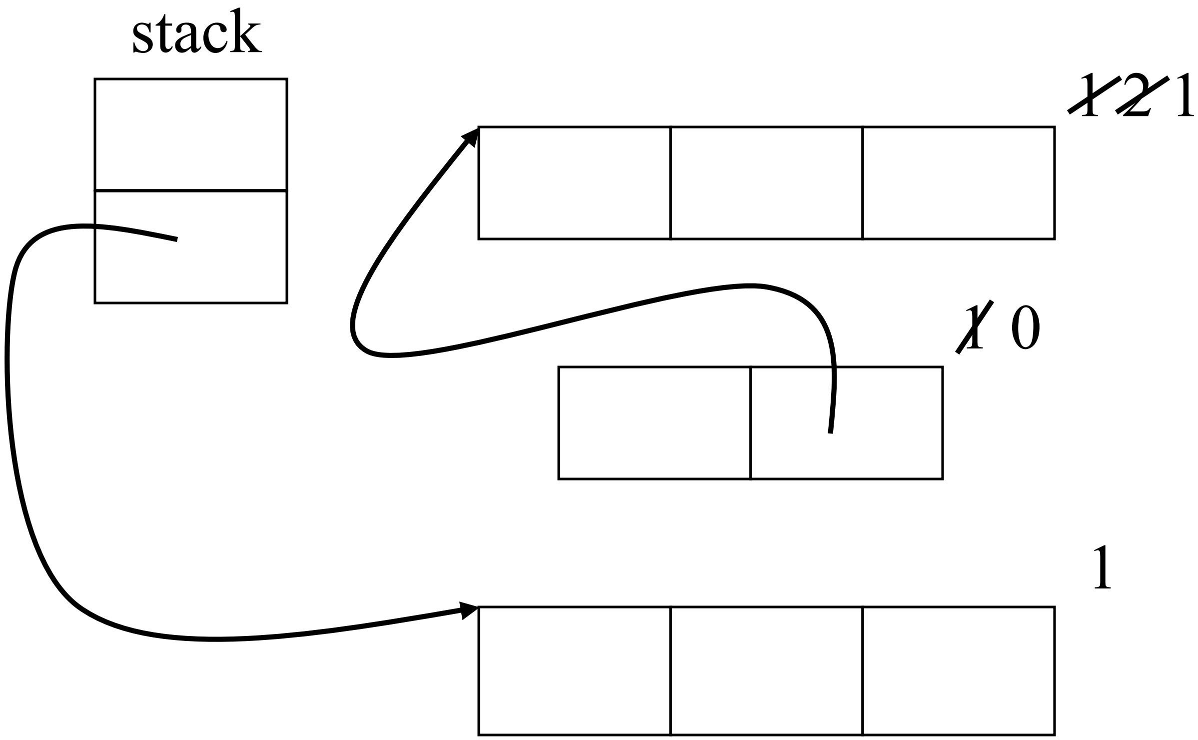

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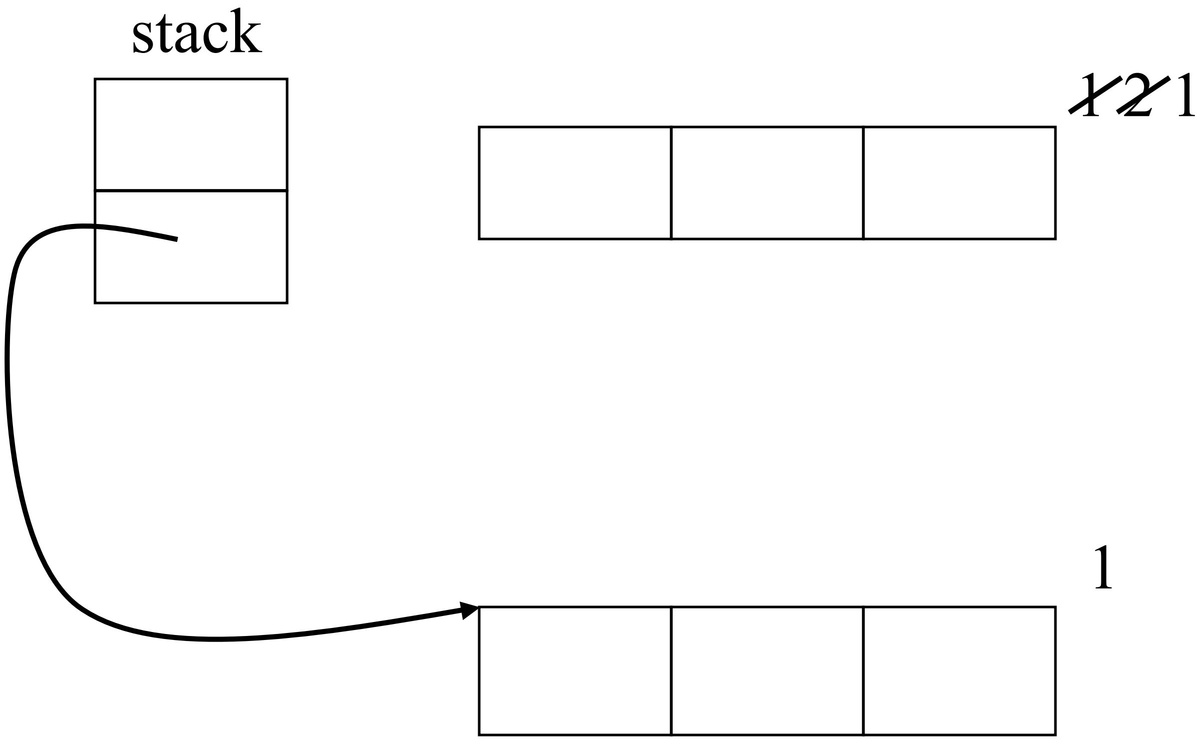

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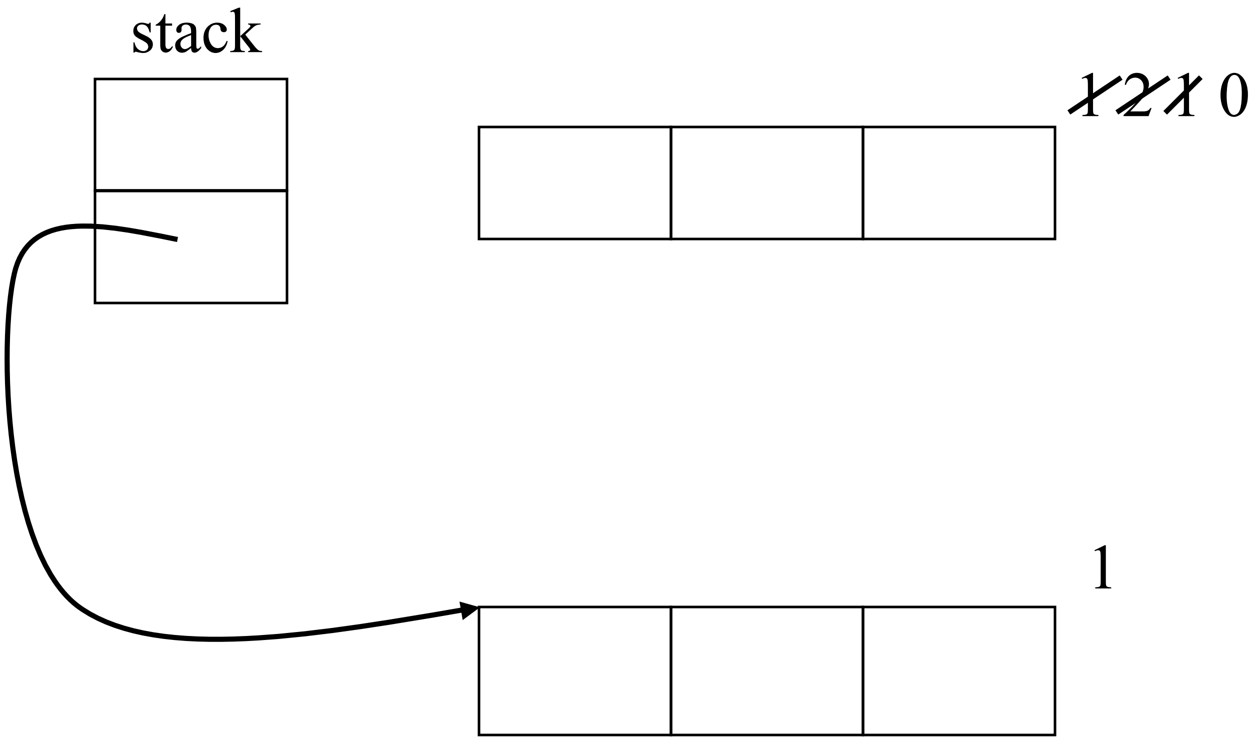

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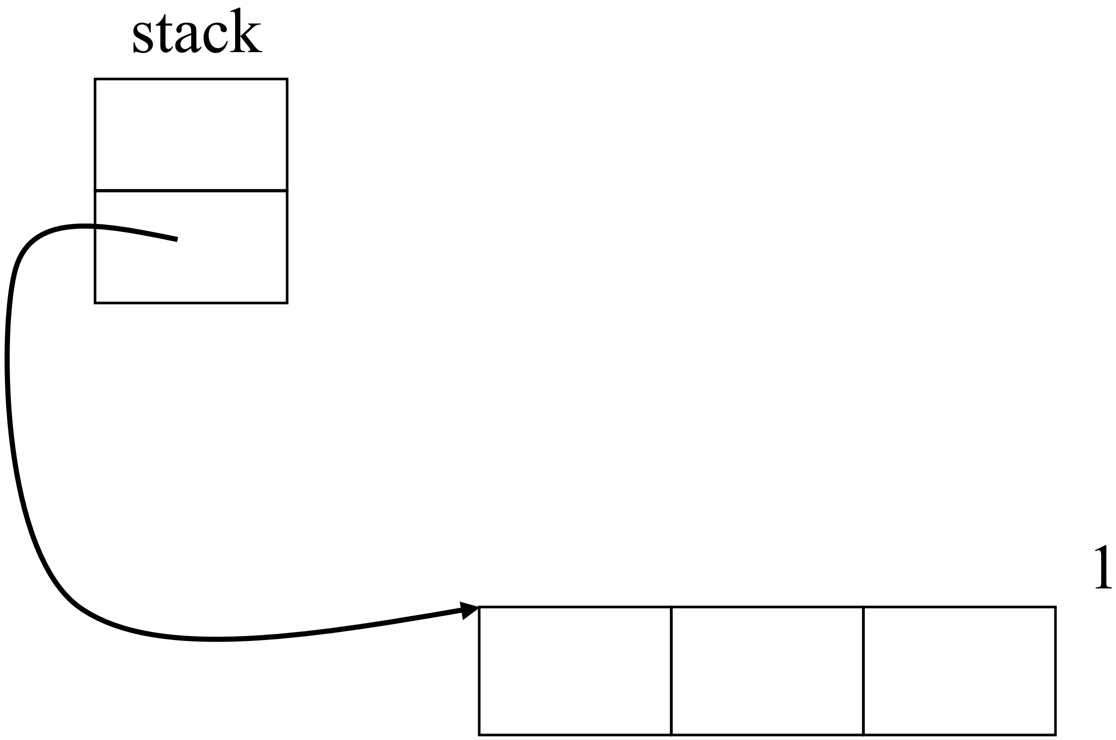


Tradeoffs with Ref Counting

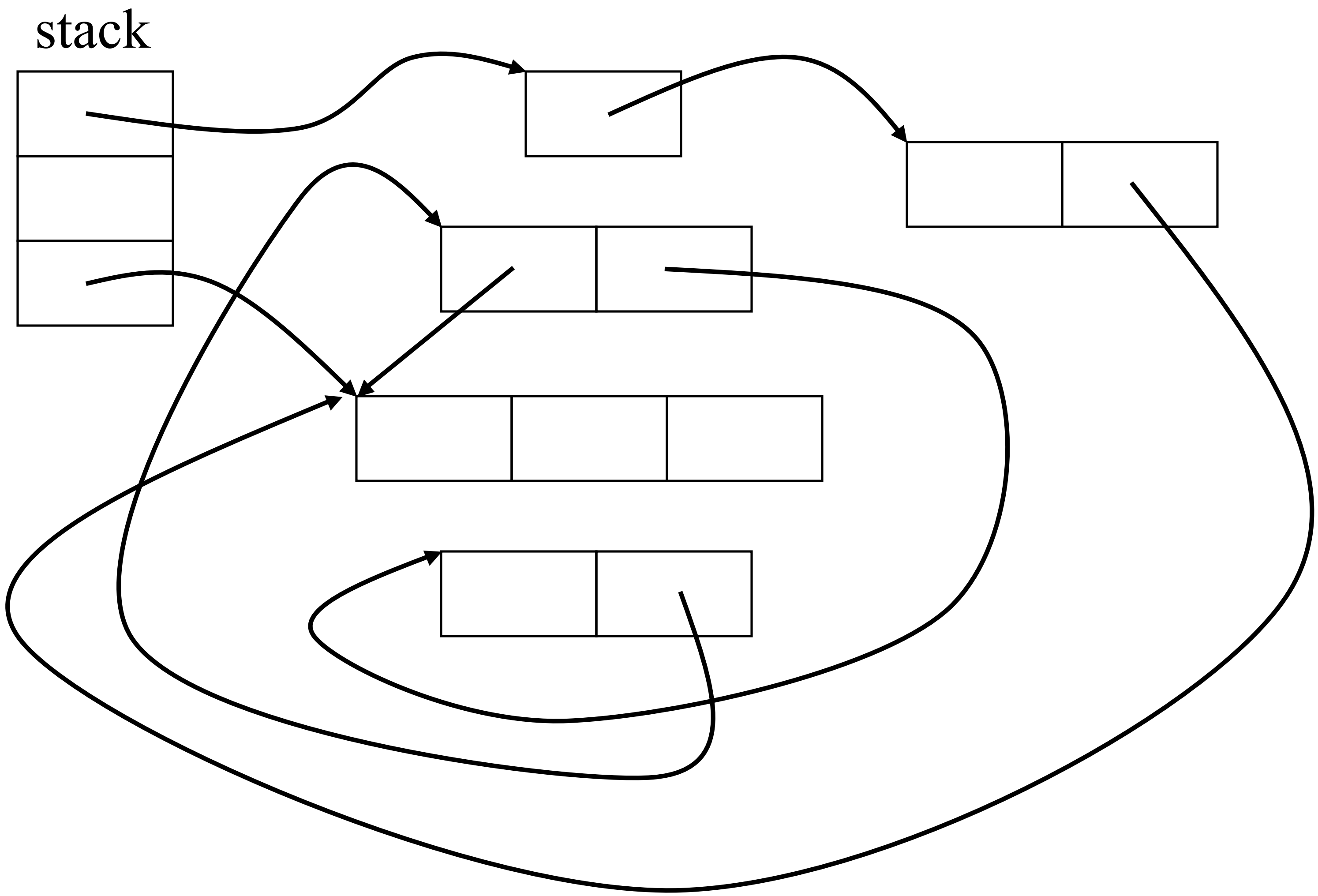
- Advantage: Incremental technique
  - Small amount of work per memory write
  - With more effort, can bound running time
    - Useful for real-time systems
- Problems:
  - Data on cycles can't be collected; counts never go to 0
  - Cascading decrements can be expensive
    - E.g., when an aggregate data structure that is dropped

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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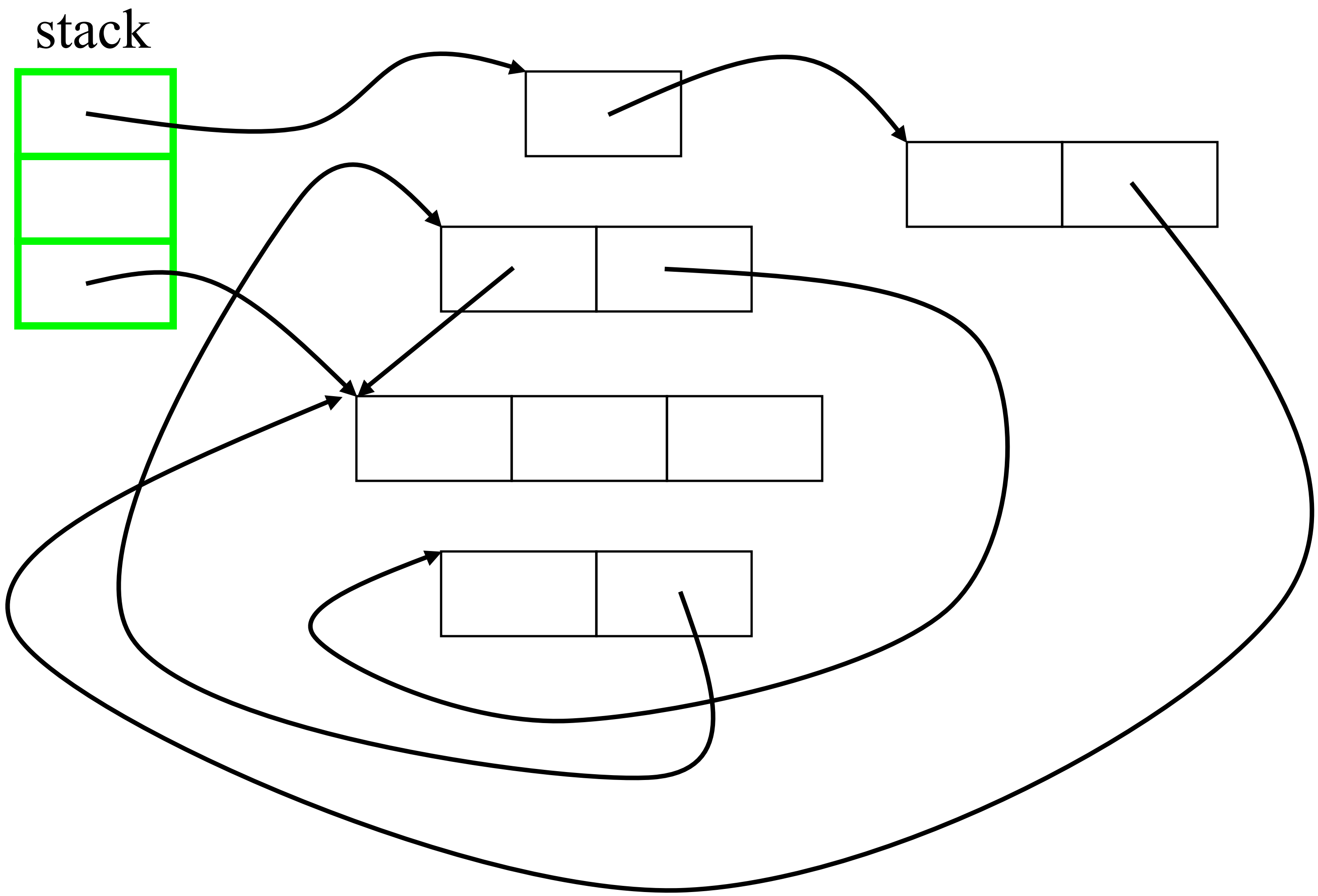

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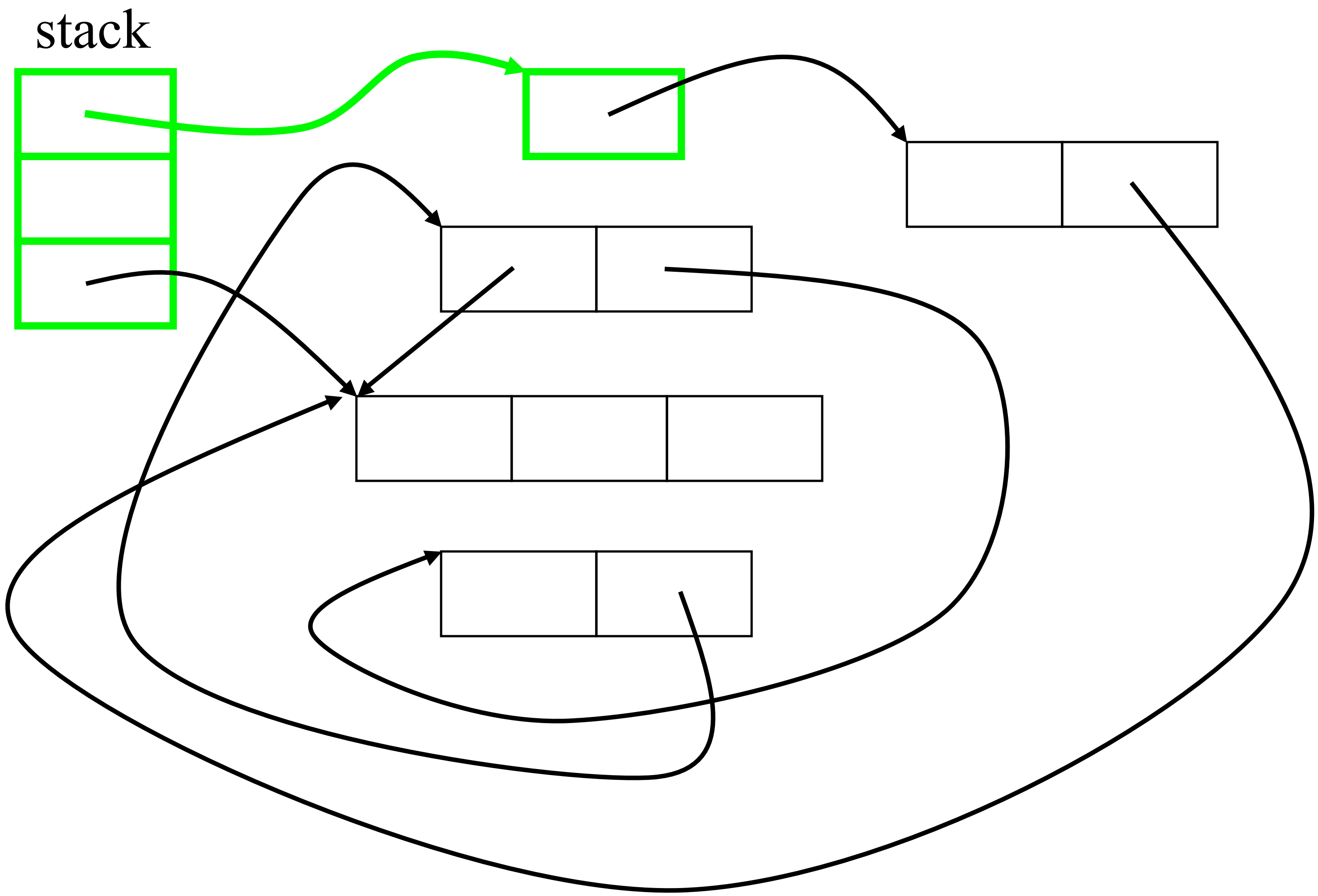

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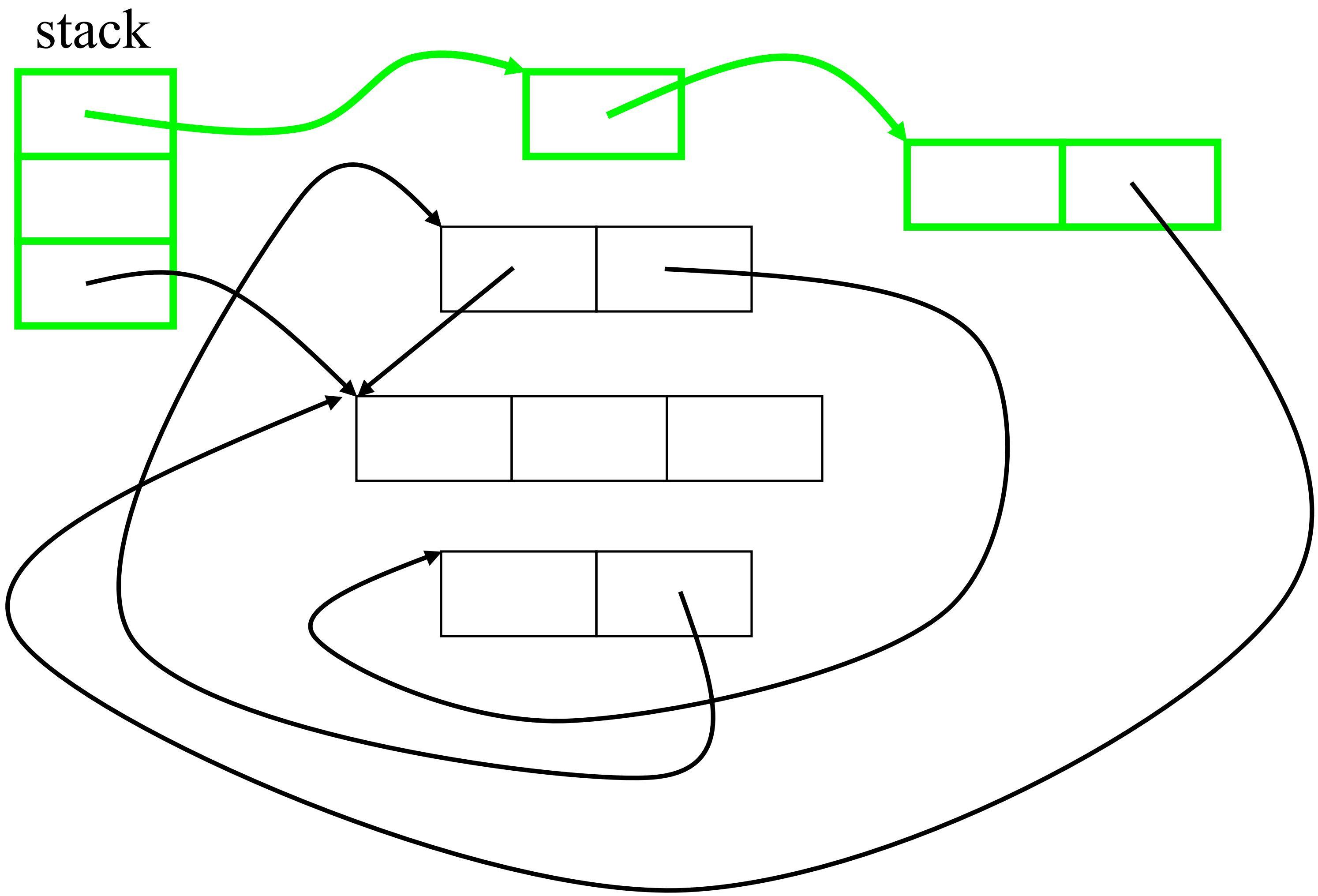

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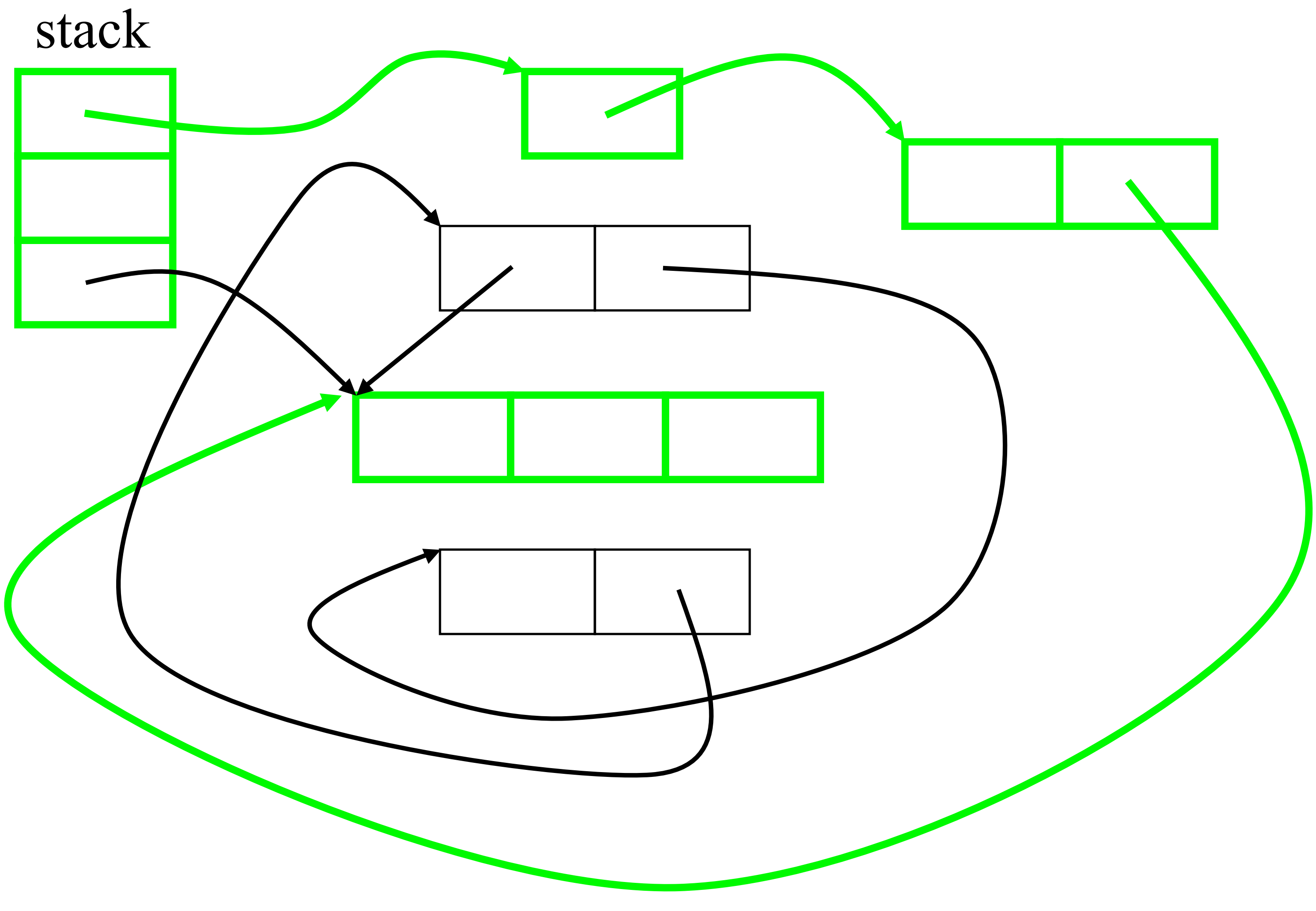

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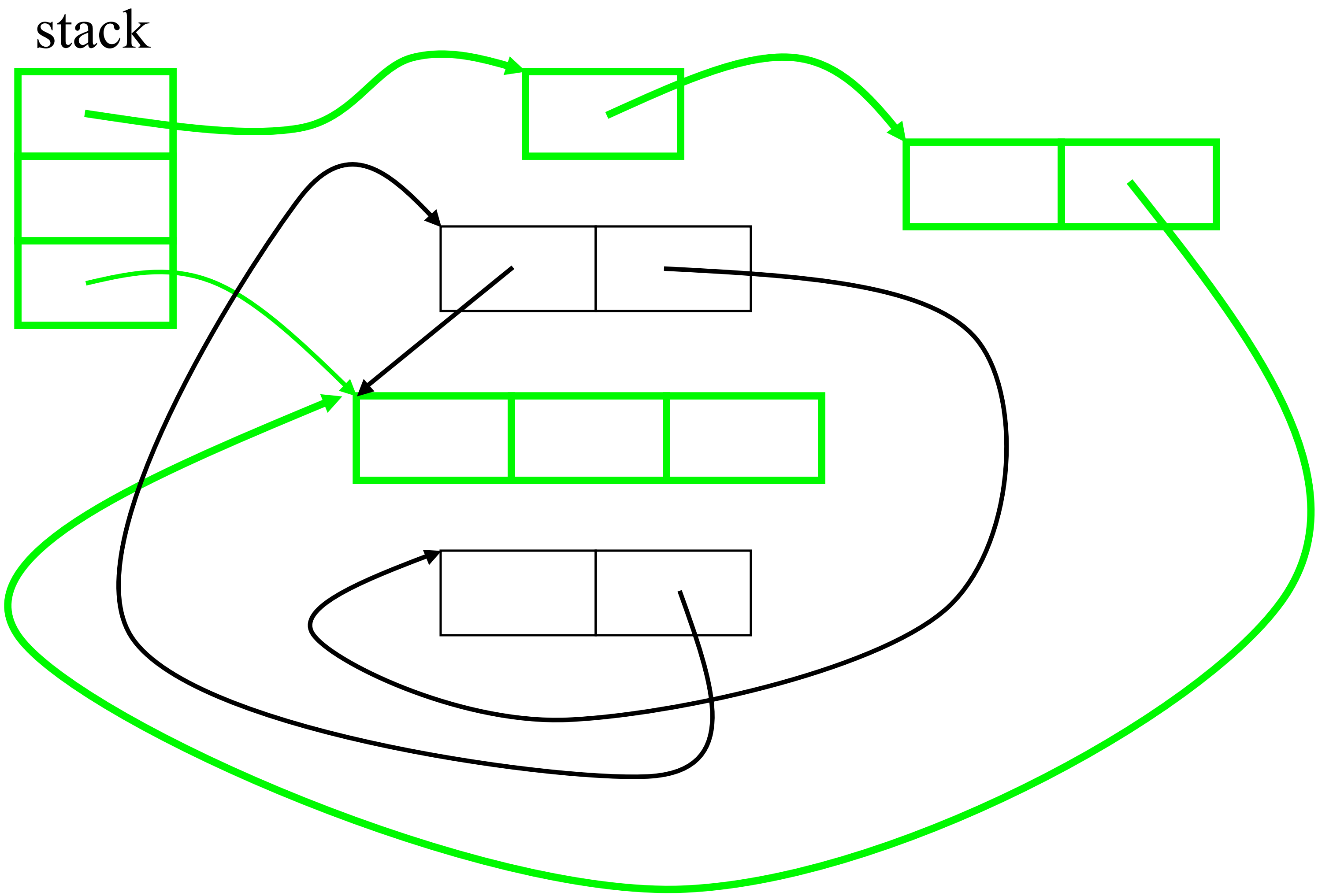

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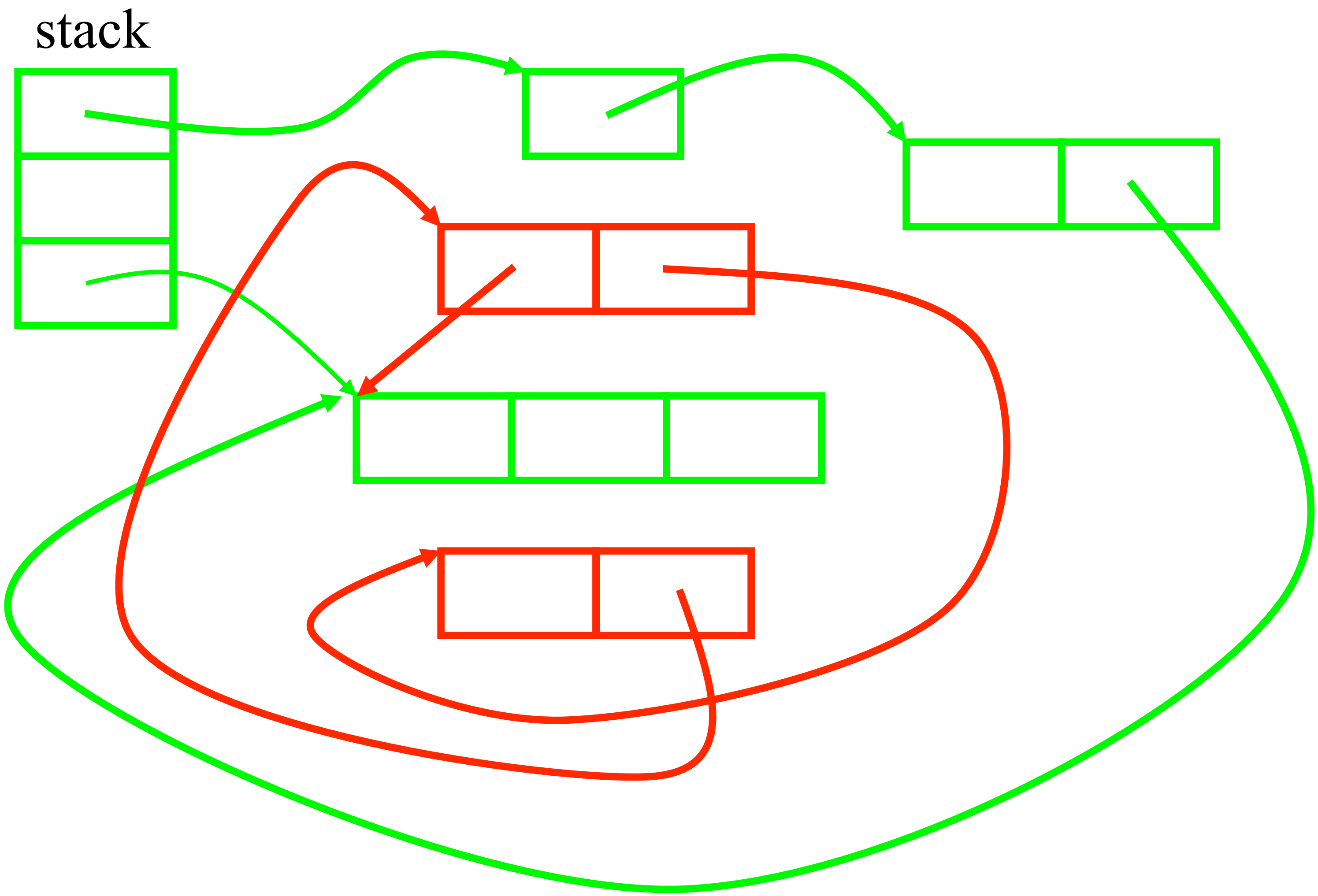


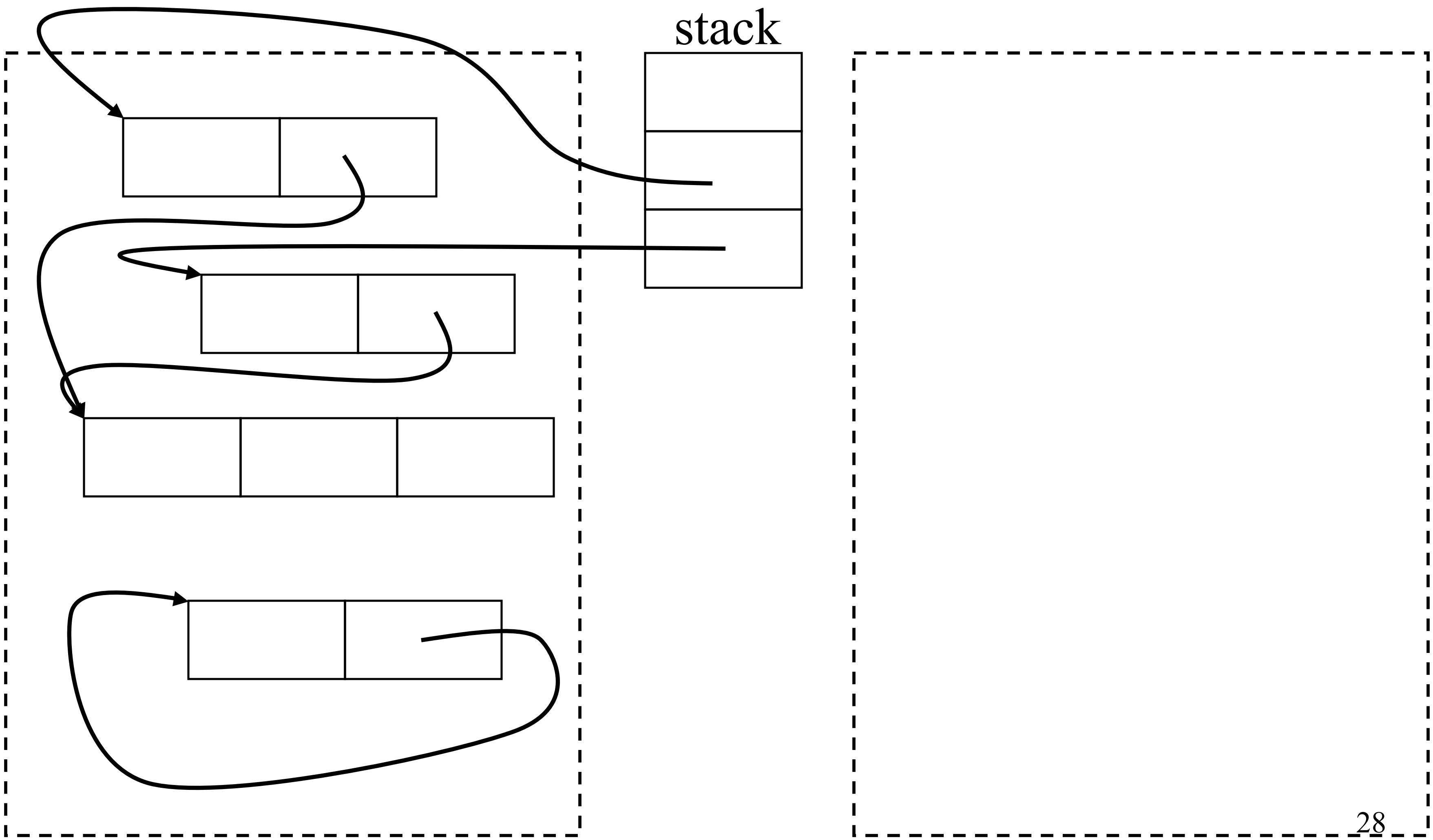
Tradeoffs with Mark and Sweep

- Pros:
  - No problem with cycles
  - Memory writes/dropped aliases have no cost
- Cons:
  - Fragmentation
  - Cost proportional to heap size
    - Sweep phase needs to traverse whole heap

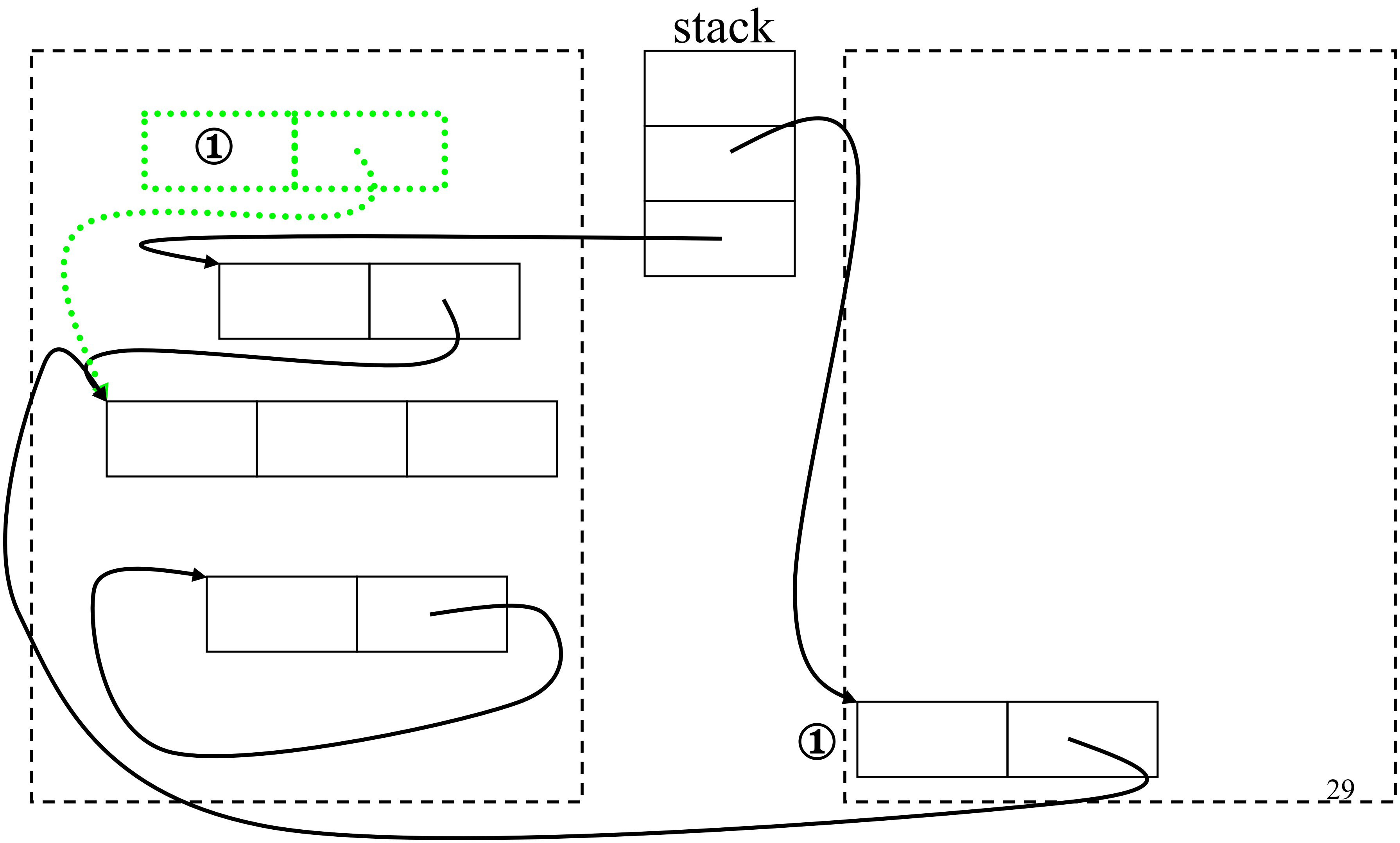
Copying GC

- Like mark and sweep, but only touches live objects
  - Divide heap into two equal parts (semispaces)
  - Only one semispace active at a time
  - GC copies data from one to the other
    - Trace the live data starting from the stack
    - Copy live data into other semispace
    - Declare everything in current semispace dead; switch to other semispace

Copying GC Example



Copying GC Example



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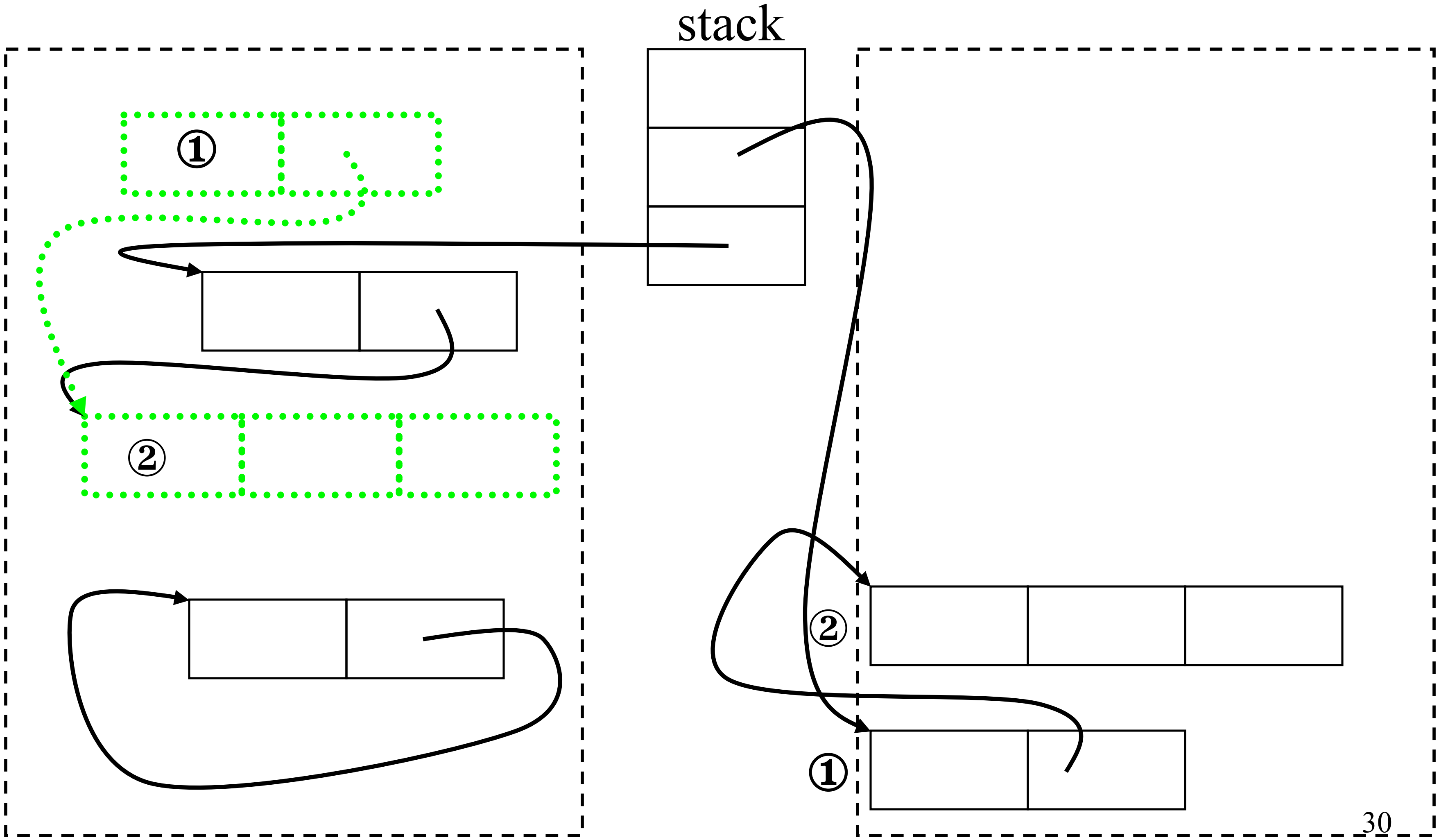
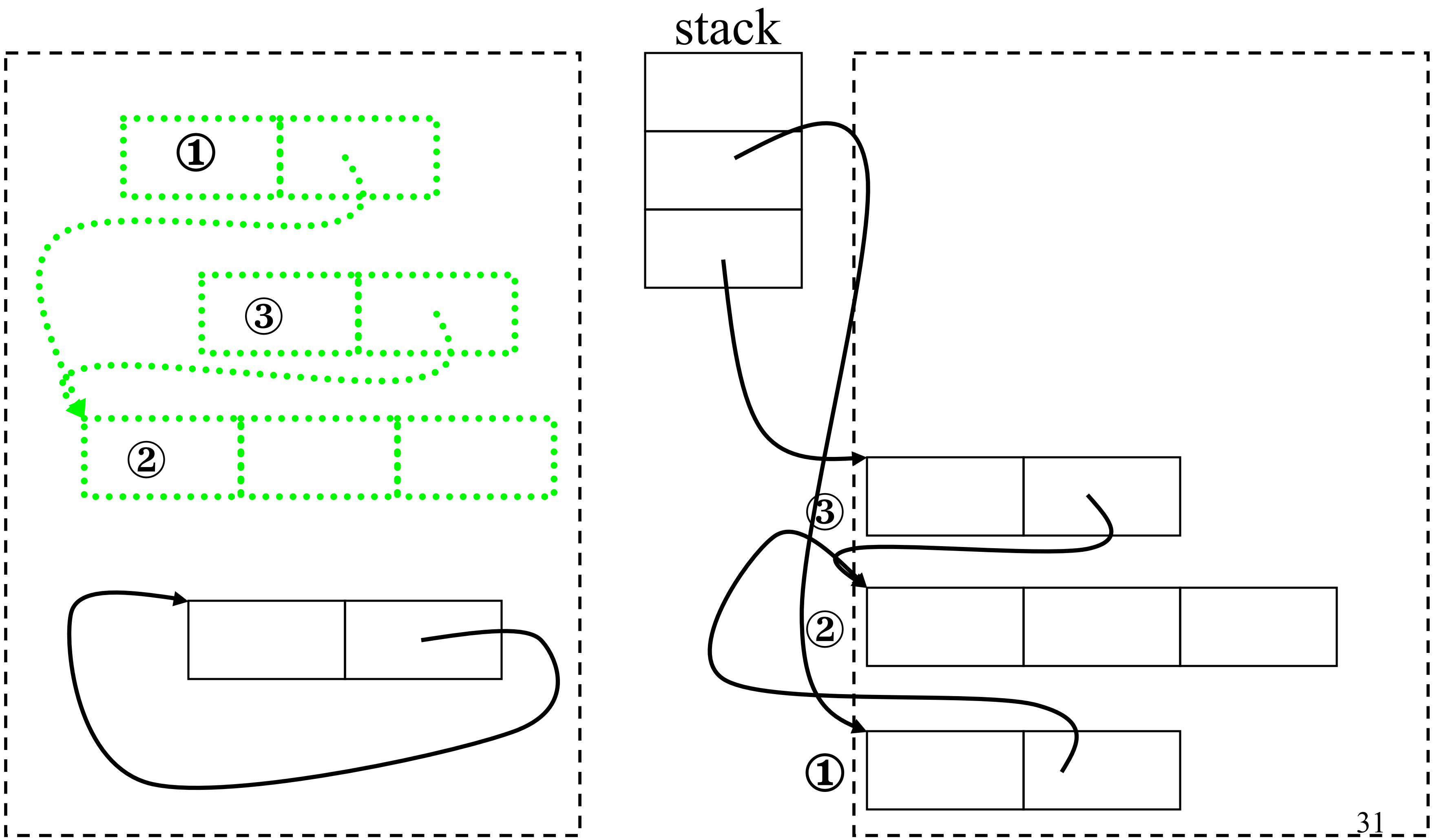


Copying GC Example



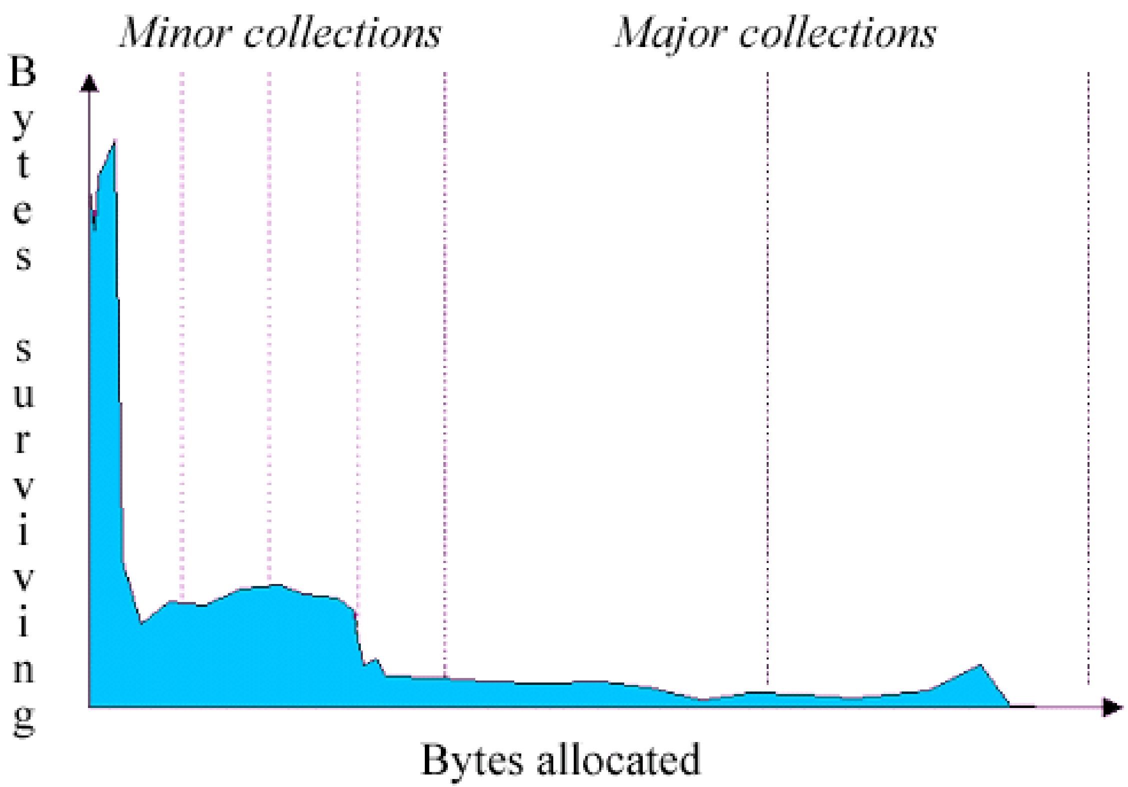
Copying GC Tradeoffs

- 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

The Generational Principle

More objects live ⇑



Object lifetime increases ⇒

"Young objects die quickly; old objects keep living"

Generational Collection

- Divide heap into *generations*
- Objects that survive many collections get pushed into older generations
  - Older generations collected less often
  - Need to track pointers from old to young generations to use as roots for young generation collection
    - Usually implemented with a "write barrier"

HotSpot SDK 1.4.2 Collector

- Multi-generational, hybrid collector
  - Young gen : stop and copy collector
  - Tenured gen : mark and sweep collector
  - Permanent gen : no collection
- Why does using a copy collector for the youngest generation make sense?
- What apps will be penalized by this setup?

Stopping the World

- What if the program (the "mutator") is modifying the heap while the GC is running?
- Simplest thing: stop the world during a GC
- Problem: big performance impact for parallel programs.

Scaling up GC

- Incremental collection
  - GC runs in mutator thread, but runs only for a short time and then resumes
- Concurrent collection
  - GC thread runs in parallel with the mutator
- Parallel collection
  - Many GC threads, all running in parallel

- All techniques require read/write barriers, which can be expensive

HotSpot VM

- Parallel collection of young space
  - Easy: each thread has its own young generation
- Concurrent collection of tenured space
- Incremental collection of tenured space
  - Does a little work with each minor collection

- All enabled by separate flags

Metronome

- GC developed by IBM research, targetting real-time systems.
- Uses parallel, concurrent collection
- Can provide strong guarantees of pause time and throughput.

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

Dealing with GC Problems

- Best idea: Measure where your problems are coming from
- For HotSpot VM, try running with
  - **-verbose:gc**
  - Prints out messages with statistics when a GC occurs

```
[GC 325407K->83000K(776768K), 0.2300771 secs]
[GC 325816K->83372K(776768K), 0.2454258 secs]
[Full GC 267628K->83769K(776768K), 1.8479984 secs]
```

GC Parameters

- Can resize the generations
  - How much to use initially, plus max growth
- Change the total heap size
  - In terms of an absolute measure
  - In terms of ratio of free/allocated data
- For server applications, two common tweaks:
  - Make the total heap as big as possible
  - Make the young generation half the total heap

Increasing Memory Performance

- Don’t allocate as much memory
  - Less work for your application
  - Less work for the garbage collector
  - Should improve performance
    - (Why only “should”?)
- Don’t hold on to references
  - Null out pointers in data structures
  - Or use weak references

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()
  - 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

java.lang.ref

- Package that lets you interact with GC
  - If there's a *strong* (normal) reference to an object, GC will consider it live
  - Can use java.lang.ref to make references to object that "don't count"

```
public abstract class Reference {
        void clear();
        public Object get();
        ...
}
```

SoftReference

- Constructor SoftReference(Object o)
  - Make a soft reference to object o
  - Access using get() method
- GC *may* free object if
  - Only soft, weak, or phantom refs to it
    - No strong refs
- GC invokes clear() on SoftRef if freed
  - Like a finalizer

WeakReference

- Constructor WeakReference(Object o)
- GC *will* free object if
  - Only weak or phantom refs to it
    - No strong or soft refs
- GC invokes clear() on WeakRef if freed

PhantomReference

- Can't ever get a reference from a phantom reference
  - only useful to get notification when an object is GC'd

ReferenceQueue

- When you create a reference, you can specify a reference queue
  - when the reference is cleared, it is enqueued in the reference queue

WeakHashMap

- Uses weak references to hold keys
- If the only reference to an object is as the key of a weak hash map
  - the object is GC'd and removed from the WeakHashMap
- Particularly useful for objects that use the default equals
  - If the only reference to an object is from a map, you are unlikely to use it as a key

Uses of Soft and Weak Refs

- Use soft references for caches
  - Data can be recomputed/reconstructed
  - GC flushes cache (clears soft refs) if memory full
- Use weak references for mappings
  - E.g., object reuse (if you're going to do it...)
  - GC frees object once strong refs are gone

Caveat for Weak References

- Which is correct?

```
WeakReference wr = …;
obj = wr.get();
if (obj == null) {
  obj = new A();
  wr = new WeakRef(obj);
}
```

```
WeakReference wr = …;
obj = wr.get();
if (obj == null) {
  wr = new WeakRef(new A());
  obj = wr.get();
}
```

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

Caveat for Weak Refs (cont'd)

- Left side is correct
  - Consider `new WeakRef(new A())`
  - Object A allocated
  - Put into WeakReference
  - Suppose GC happens right after
  - Then A may be deallocated before `wr.get()`