# 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

# Memory Management in C

```
int g = 5;
int *foo(int y) {
  int *z = malloc(sizeof(int));
  *z = y+g;
  return z;
}
int main() {
  int *p = foo(3);
  free(p);
}
```

**Static memory** – (global variable g) at a fixed address, never freed

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**Static memory** – (global variable g) at a fixed address, never freed

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**Heap memory** – allocated *when needed* (by malloc), and freed (by free) when *no longer needed*

# Memory Management in Ruby, Java, OCaml

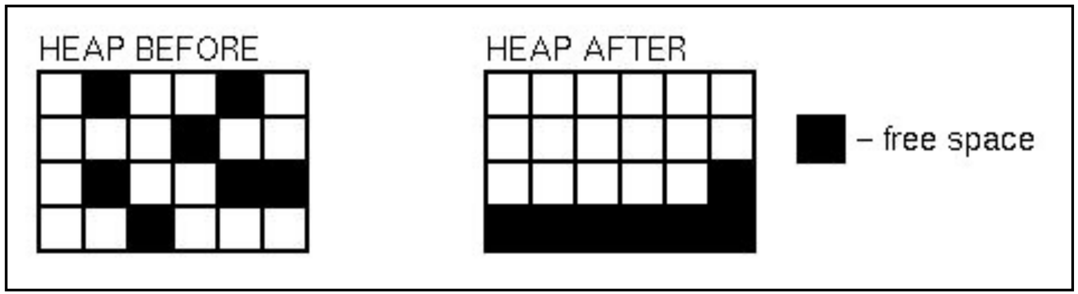
- Local variables live on the stack
  - Storage reclaimed when method returns
- Objects, closures, tuples, etc. live on the heap
  - Ruby, Java: Created with calls to Class.new
  - OCaml: Allocation happens implicitly
- Heap objects never explicitly freed: *automatic* memory management (garbage collection)

# Manual vs. Automatic Recovery

- Manual memory management is
  - Efficient – requires less storage overall
  - Error prone – programmers can easily make mistakes, leading to leaks and use-after-free errors, which have security ramifications
- Automatic memory management is
  - Less efficient – in space usage and latency – than manual management
  - Easy to use, more compositional – no worries about when an object is truly dead
    - Avoids security problems

# Automatic memory management

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




- Insight: You can do reclamation and avoid fragmentation (next slide) 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 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

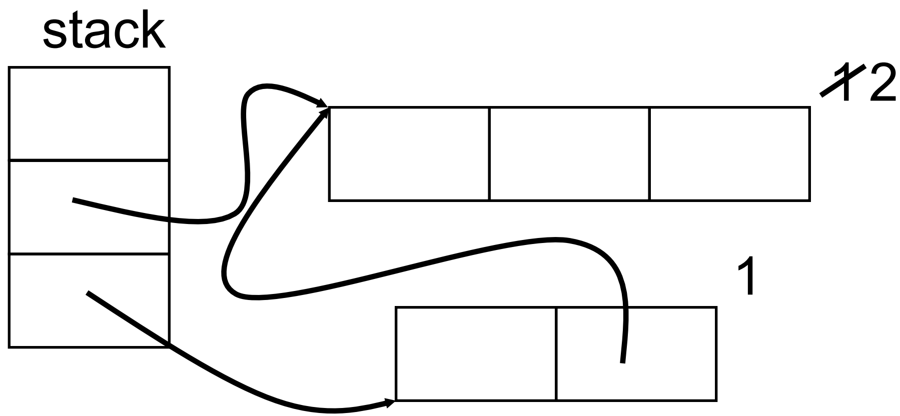
# Roots

- 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

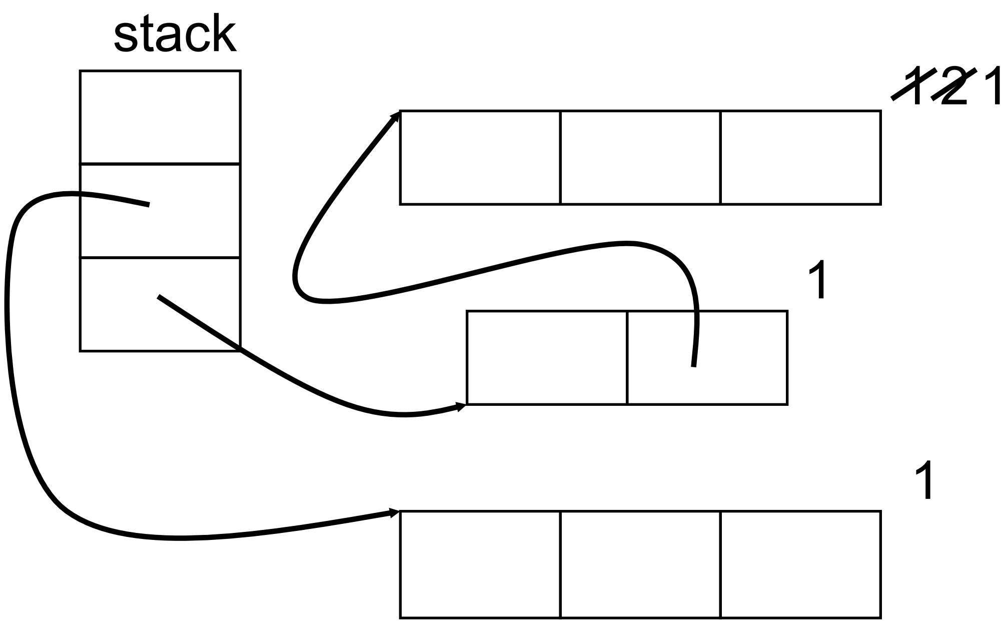
# Reference Counting

- 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++ and **Rust** (manual: smart pointers), Cocoa (manual), Python (automatic)
- 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.)



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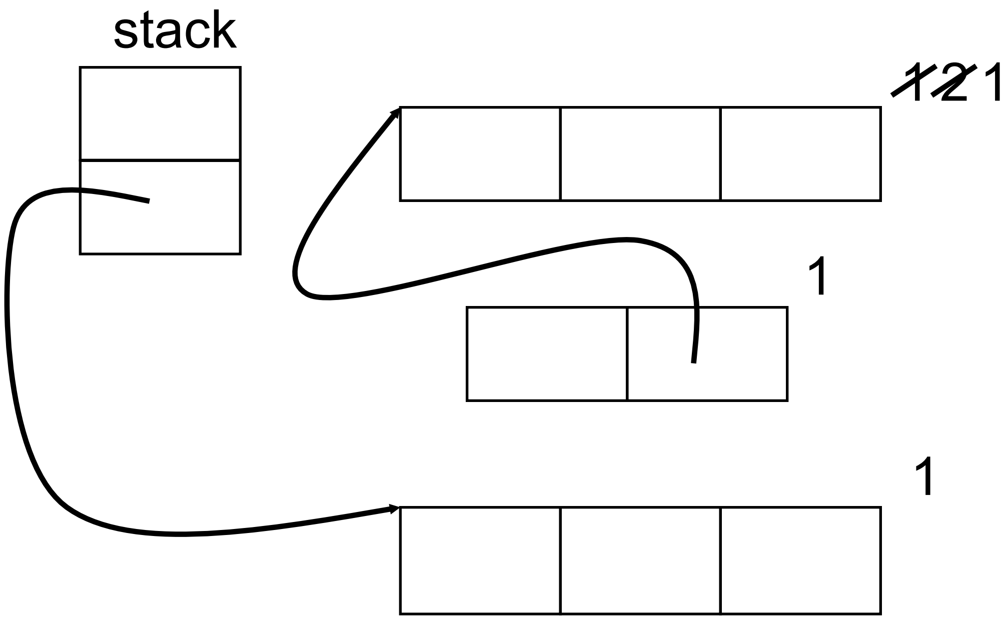

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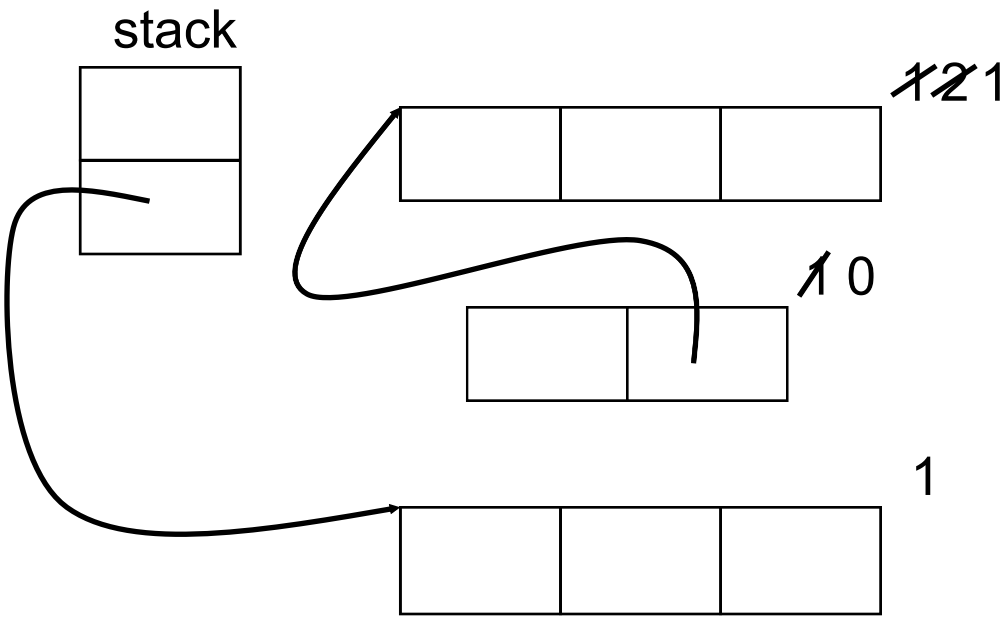

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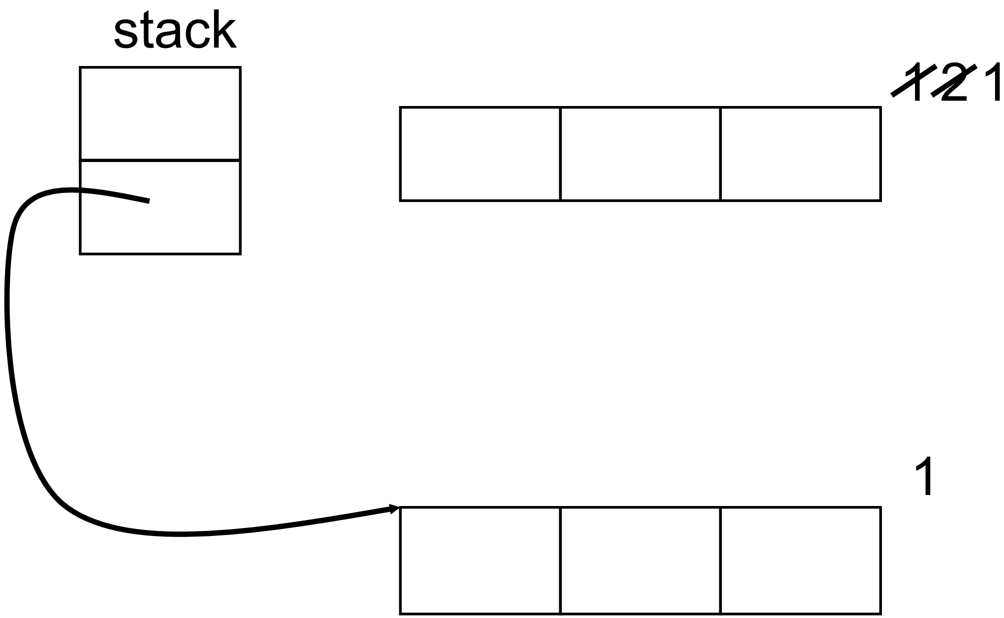

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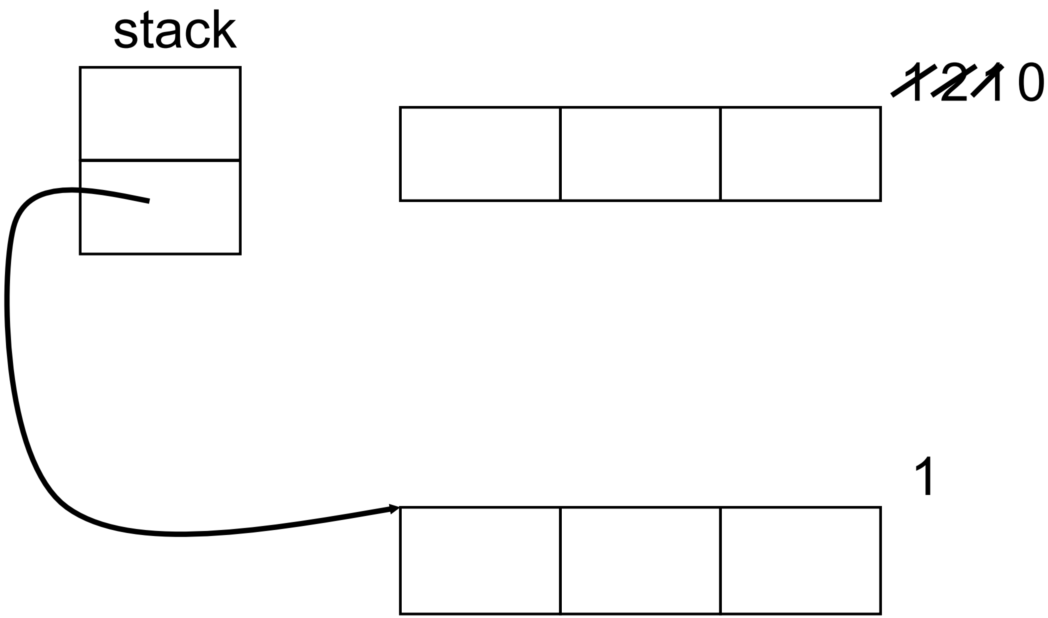

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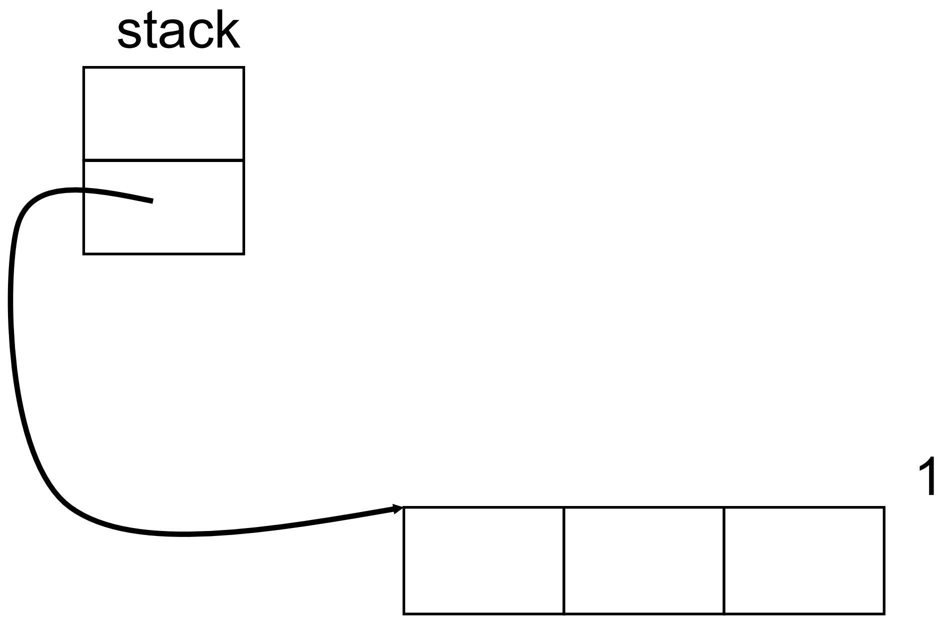


# Rust Rc Example

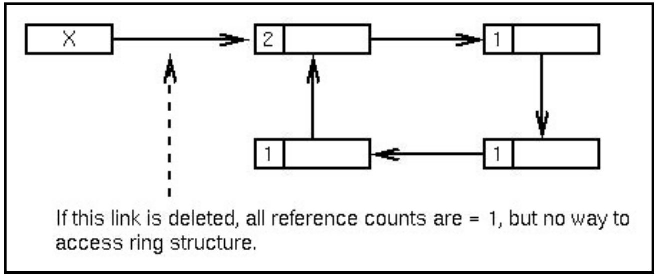
```
use std::rc::Rc;
fn main() {
    let s = String::from("hello");
    let r1 = Rc::new(&s);
    {
        let r2 = Rc::clone(&r1);
        println!("r1 = {}",Rc::strong_count(&r1));
        println!("r2 = {}",Rc::strong_count(&r2));
    }
    // r2 is out of scope
    println!("r1 = {}",Rc::strong_count(&r1));
}
```

Output:

```
r1 = 2
r2 = 2
r1 = 1
```

# 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



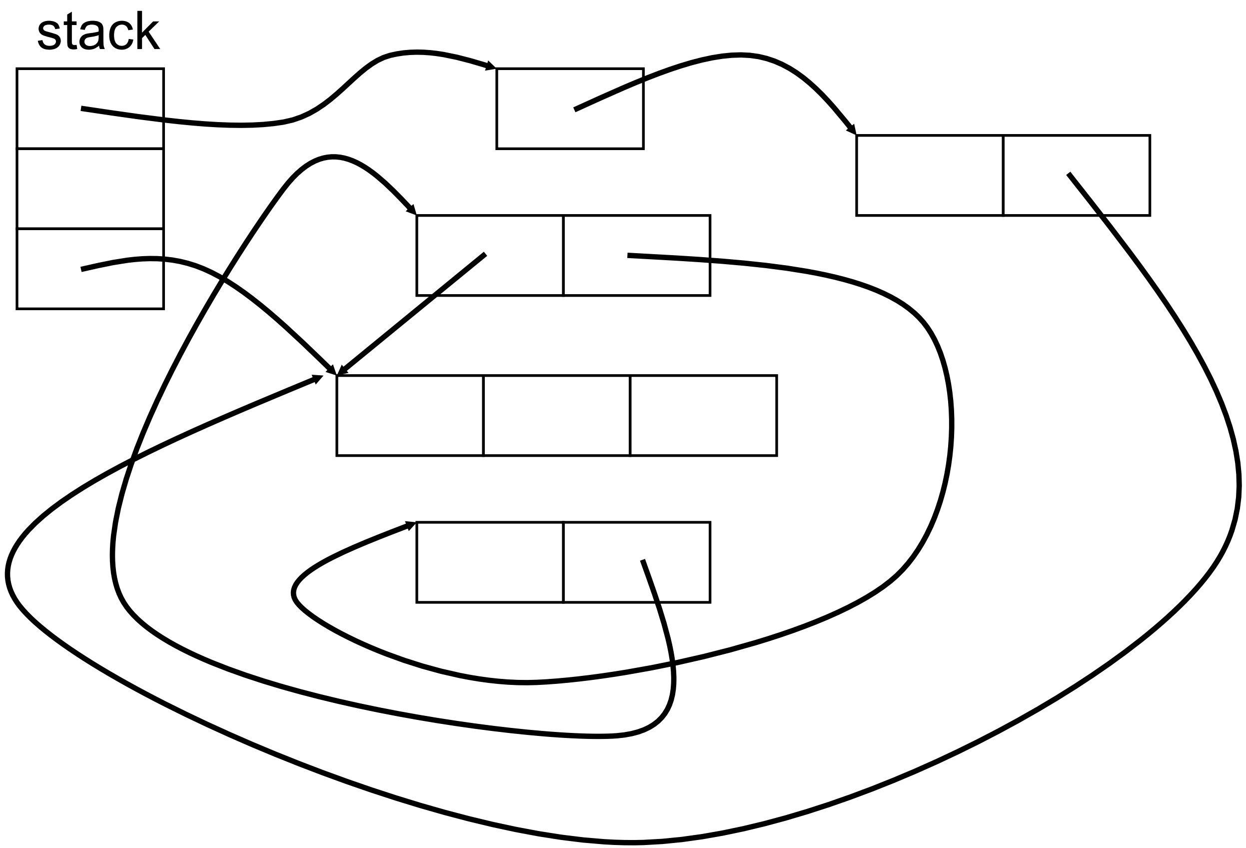
# Tracing Garbage Collection

- Idea: Determine reachability as needed, rather than by stored counts, incrementally
- 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)

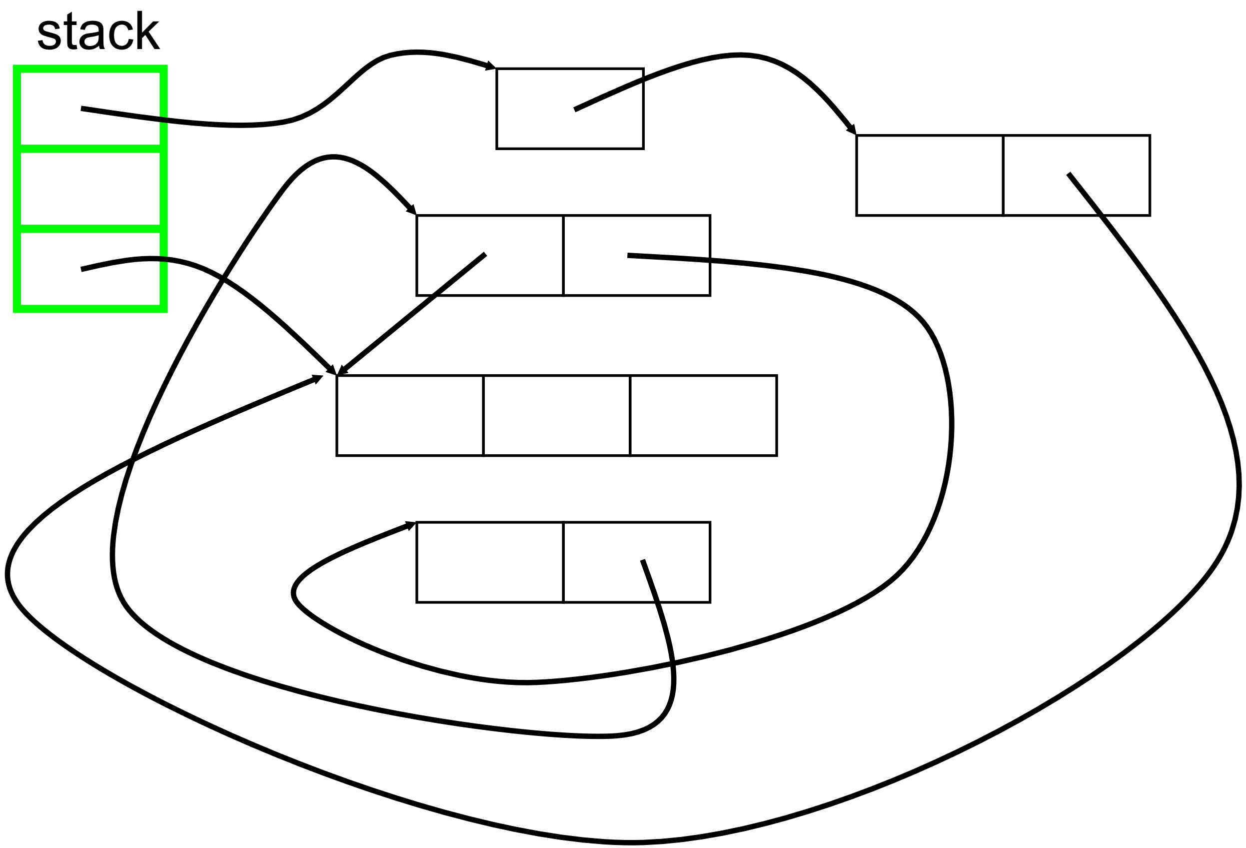
# Mark and Sweep GC

- 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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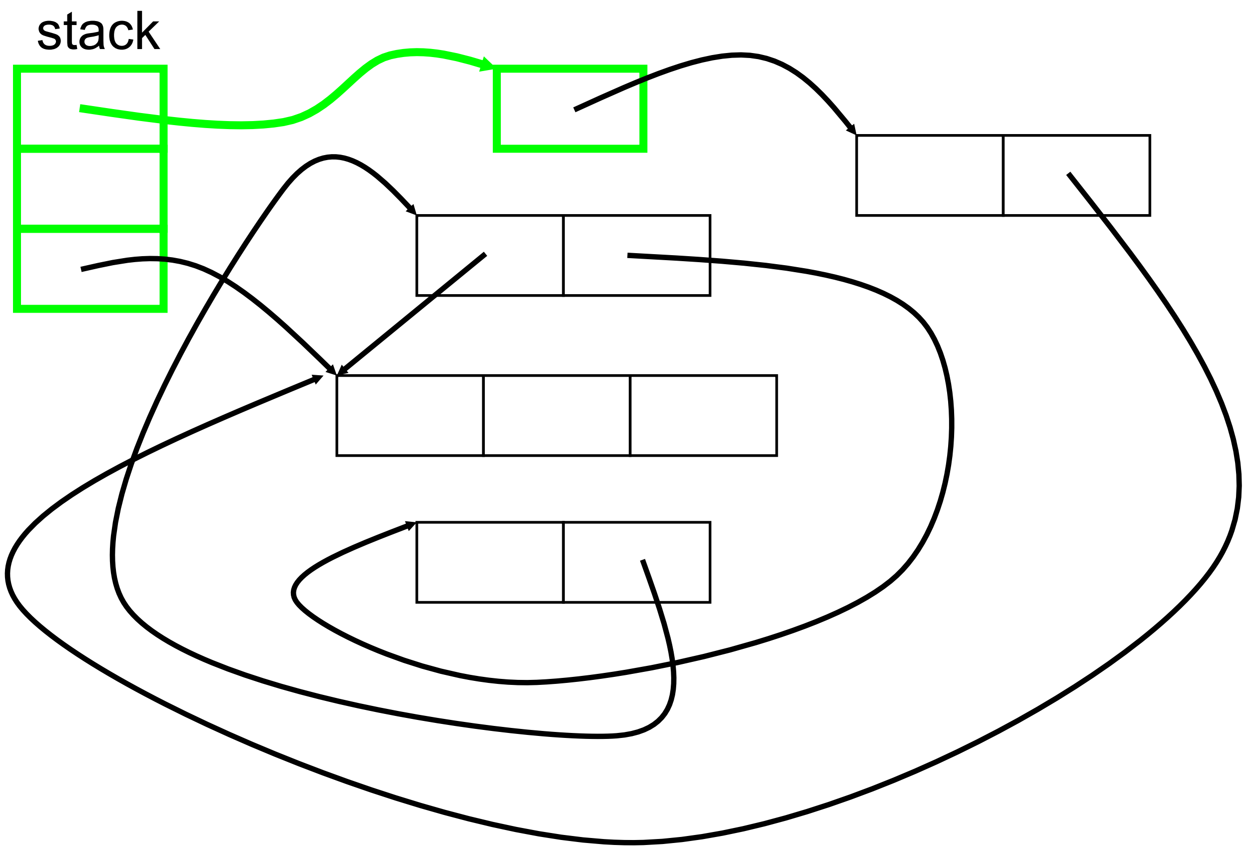

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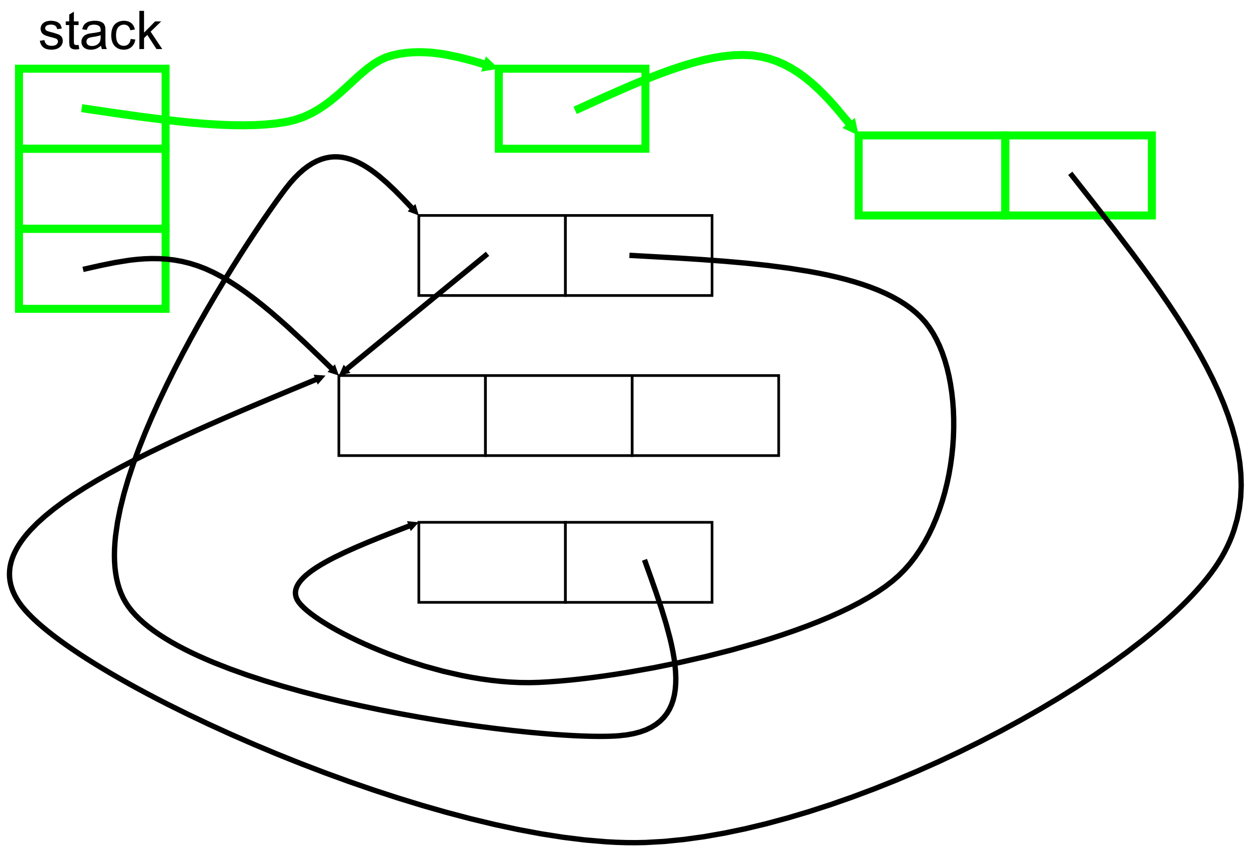

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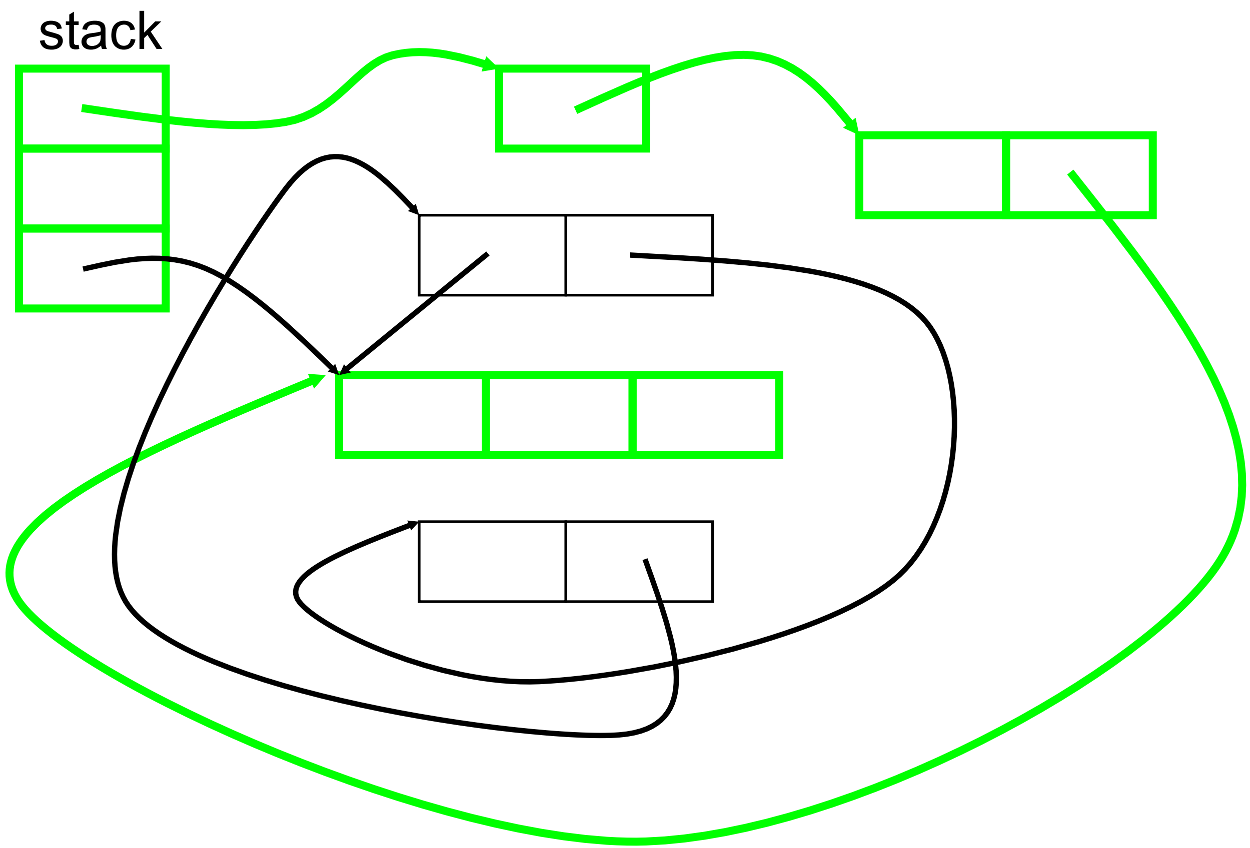

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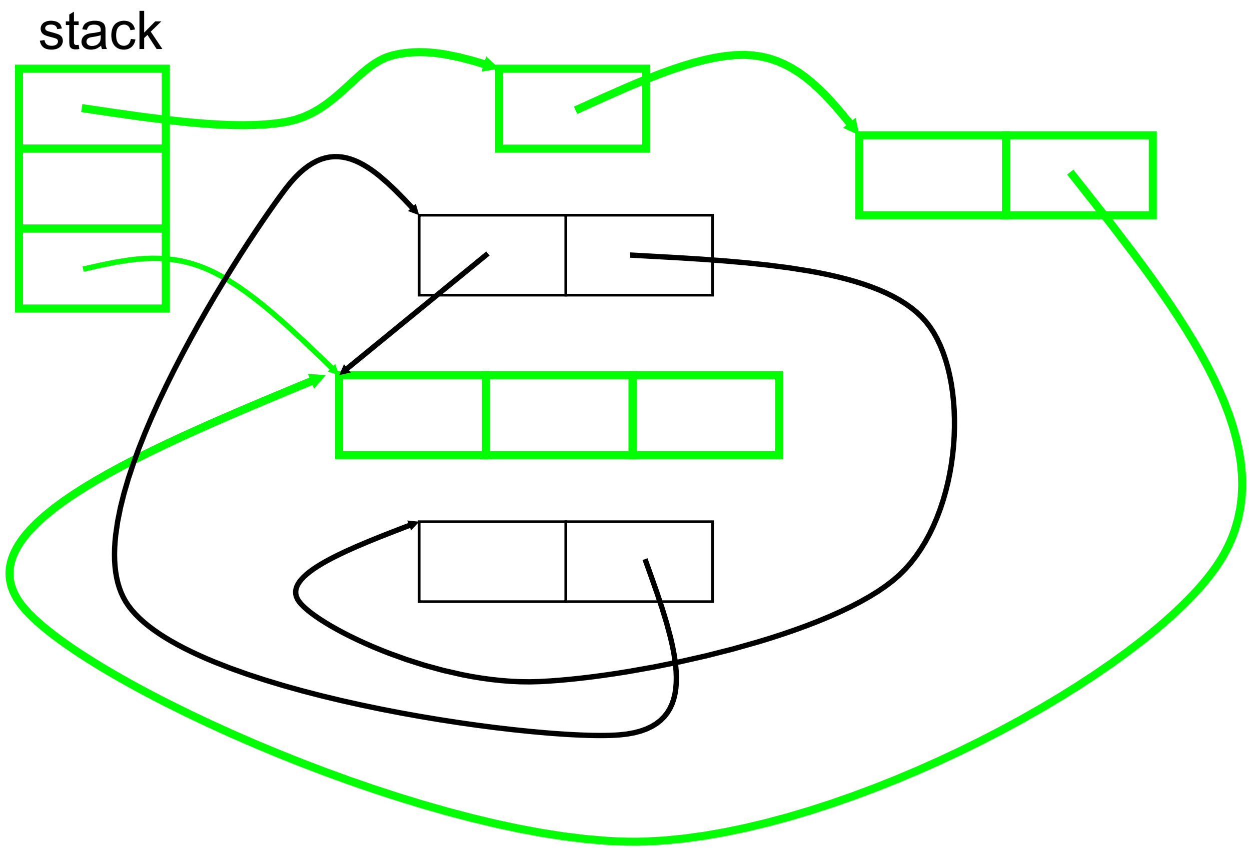

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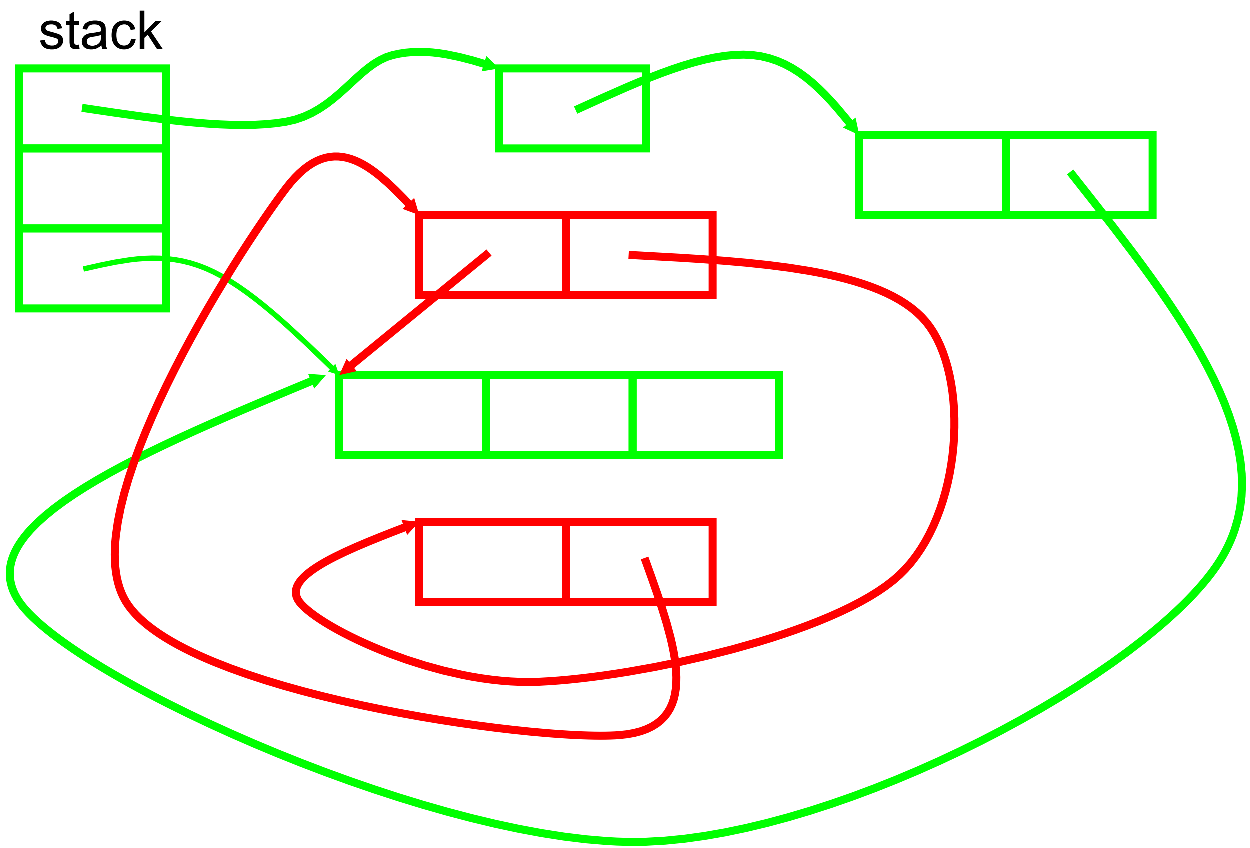
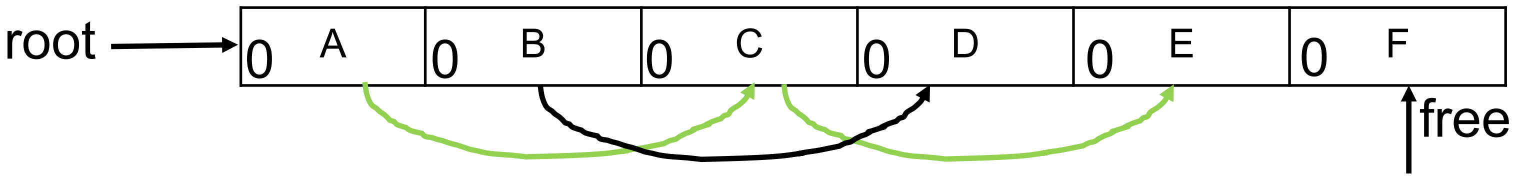
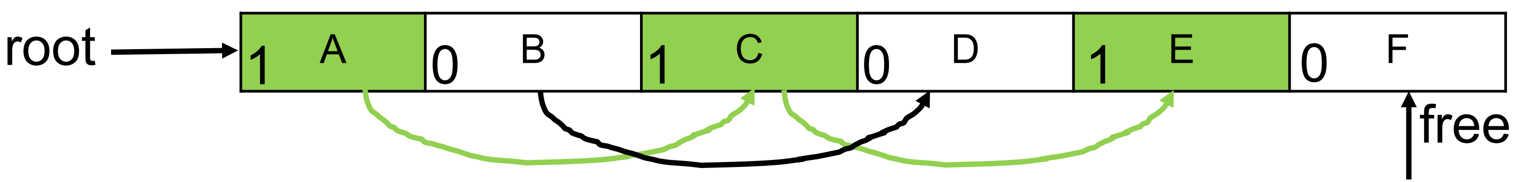


# Mark and Sweep Example 2




**After Mark**



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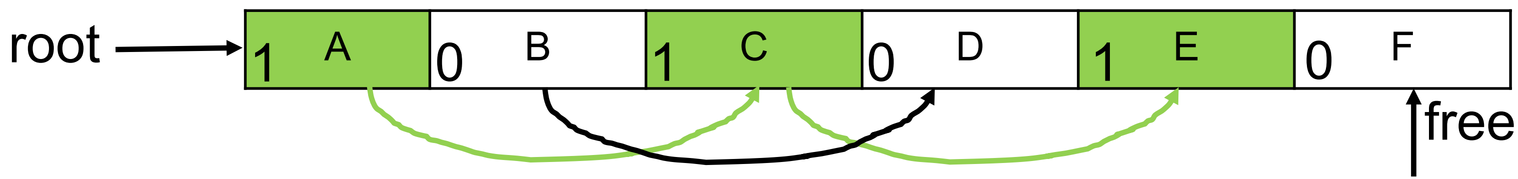
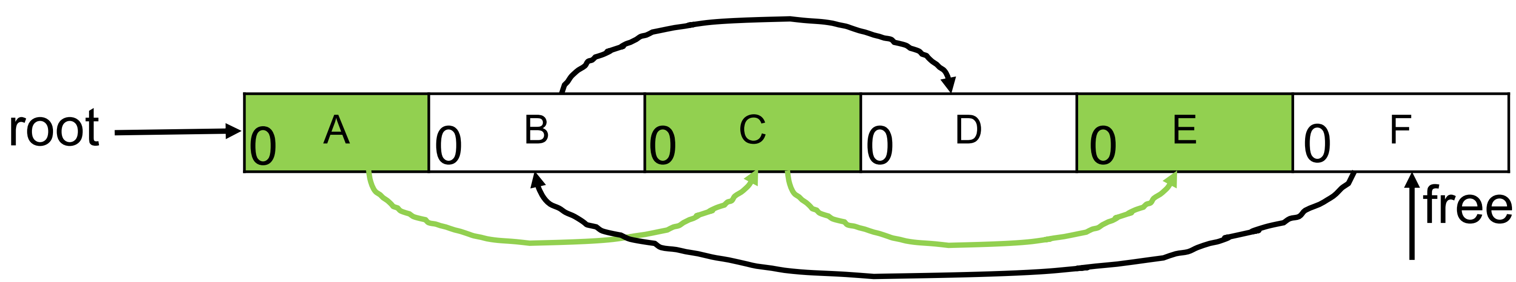



**After Sweep**




Free list: F->B->D

# Mark and Sweep Advantages

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

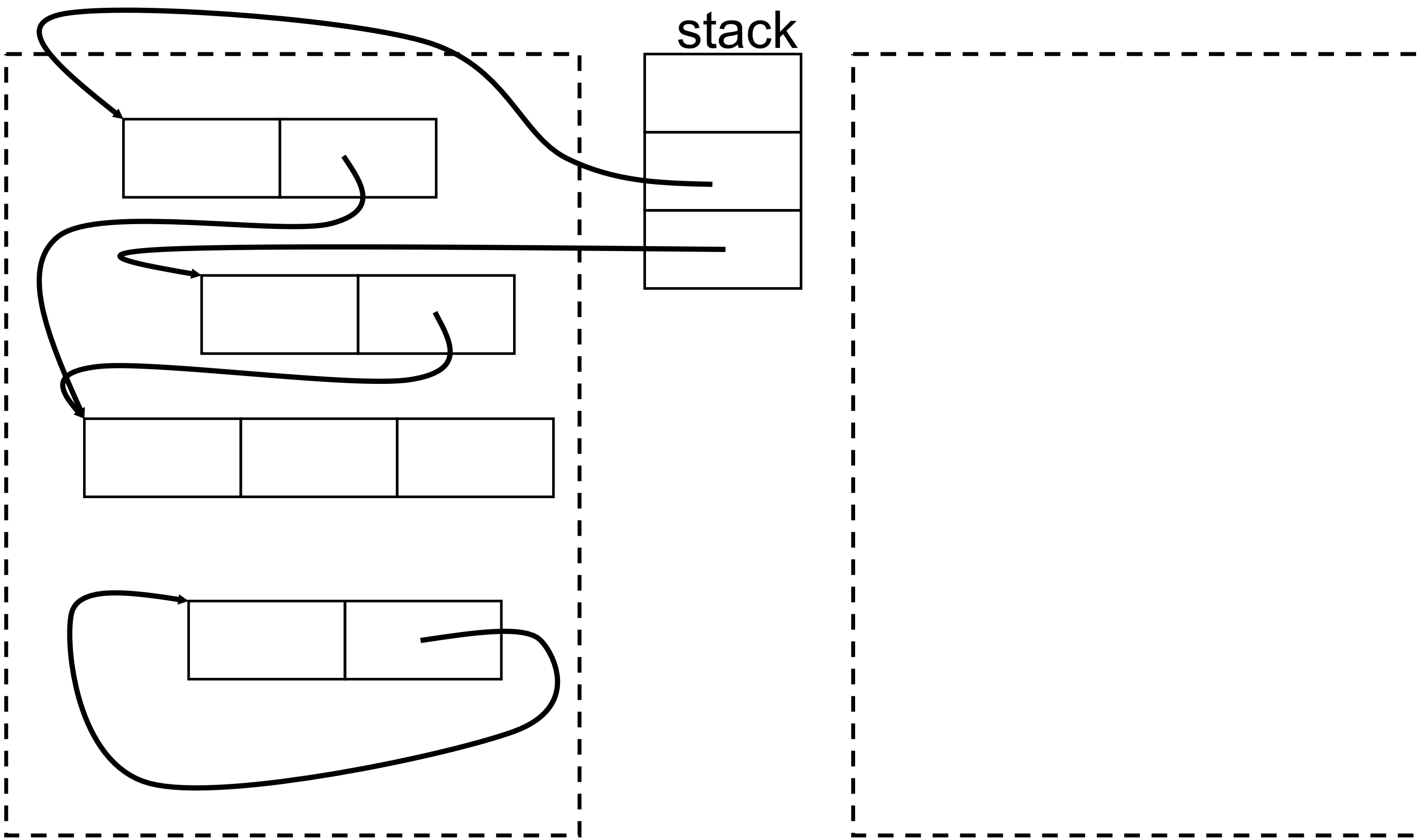
# Mark and Sweep Disadvantages

- 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

# 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

# Copying GC Example



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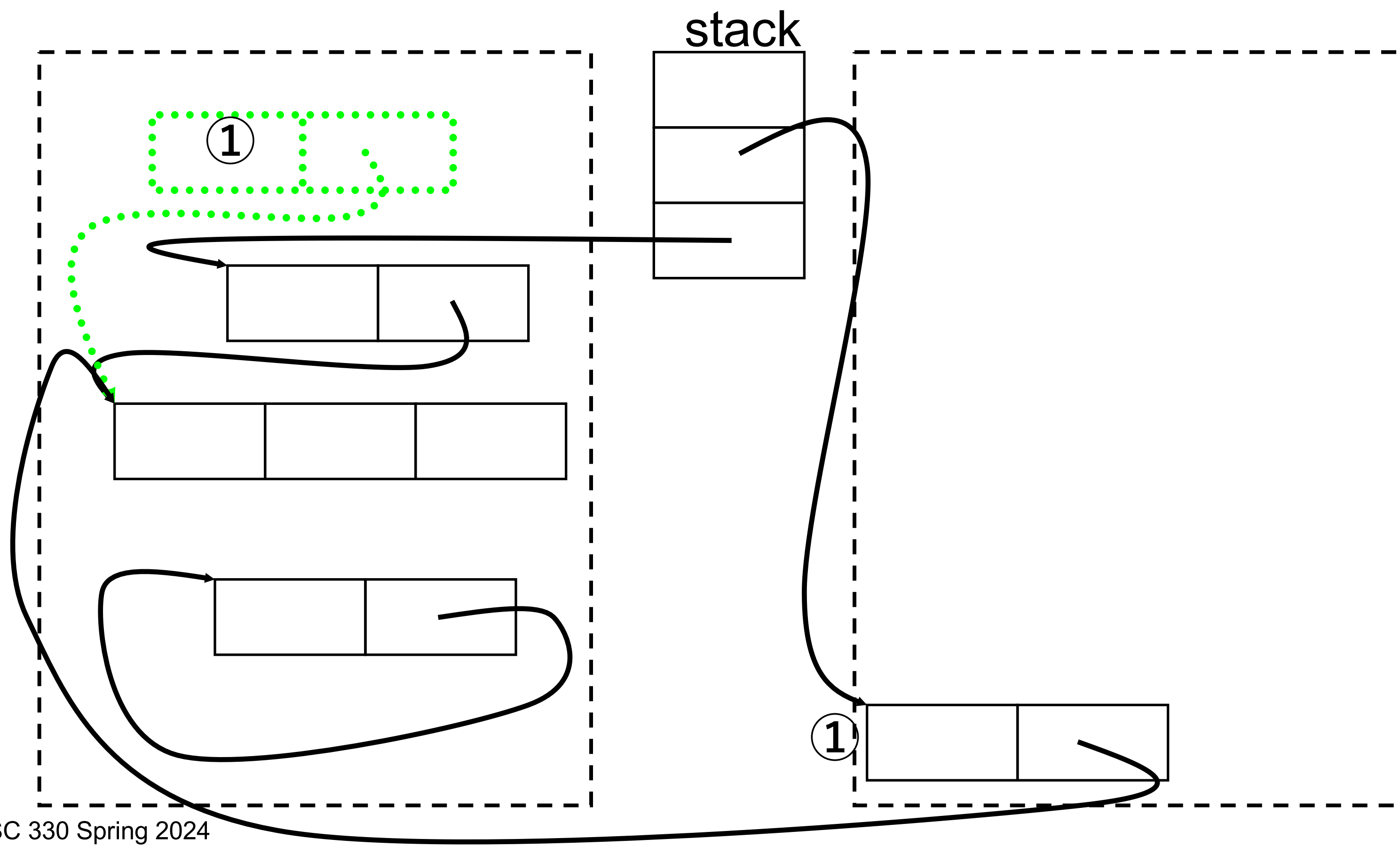

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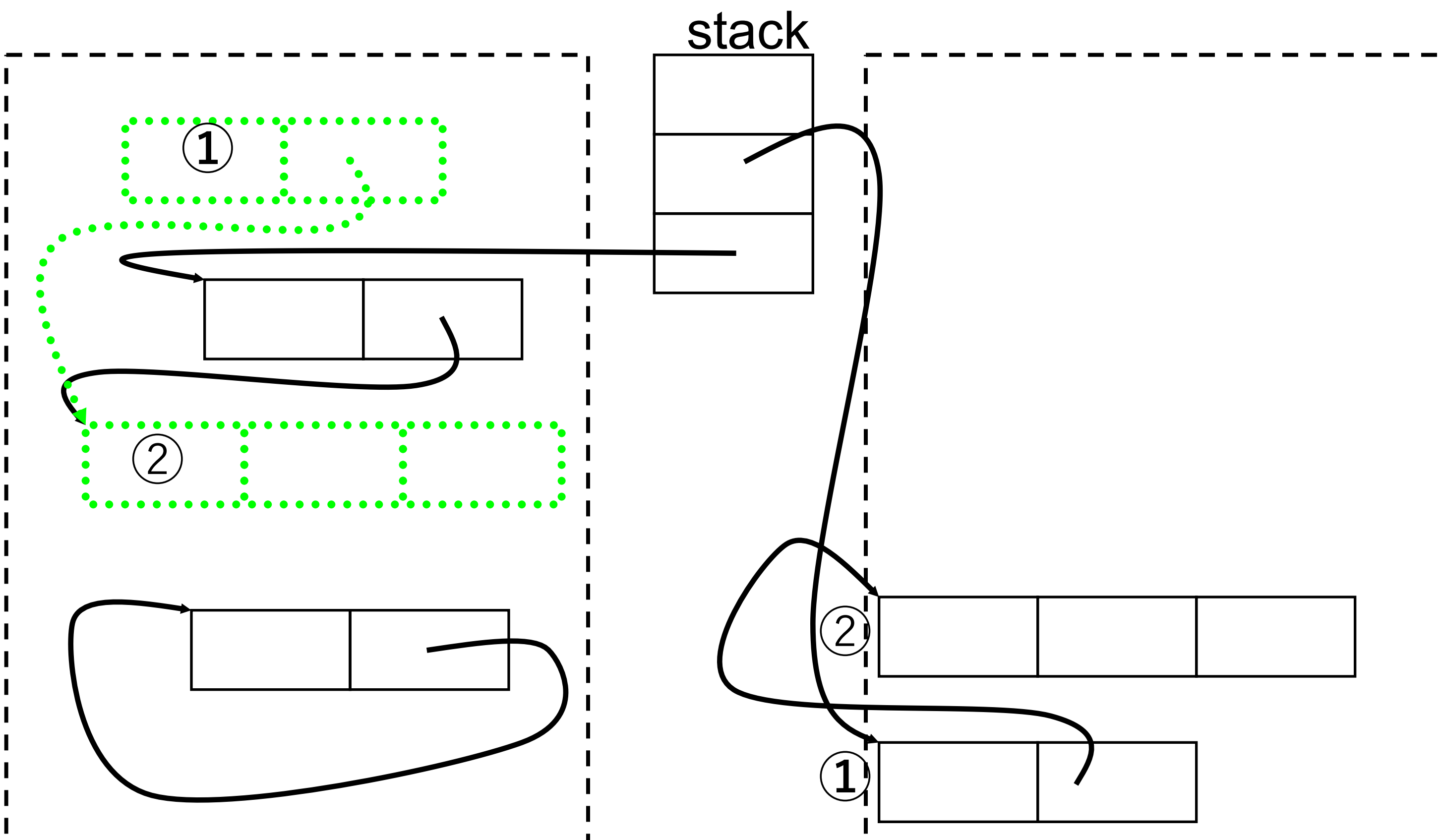

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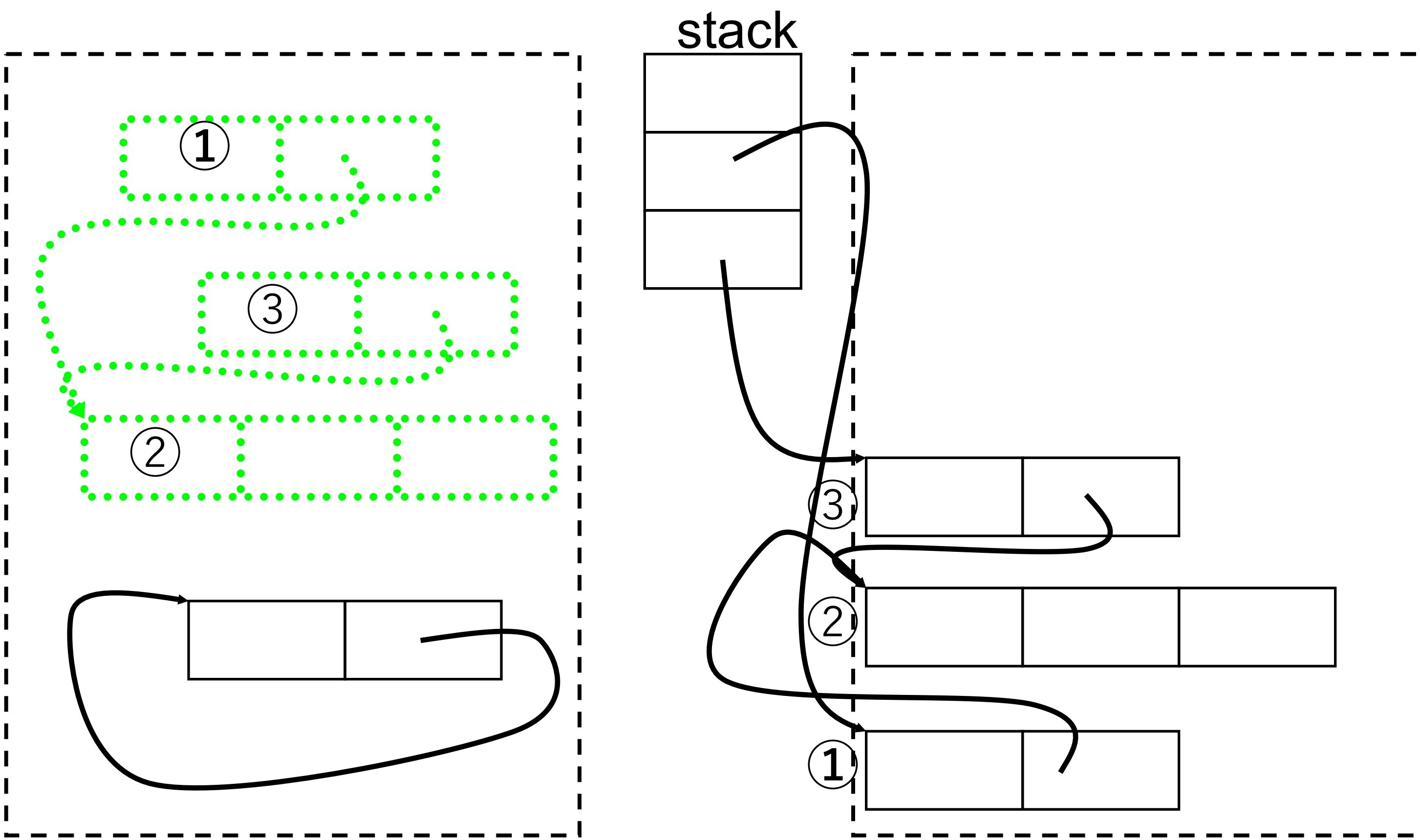

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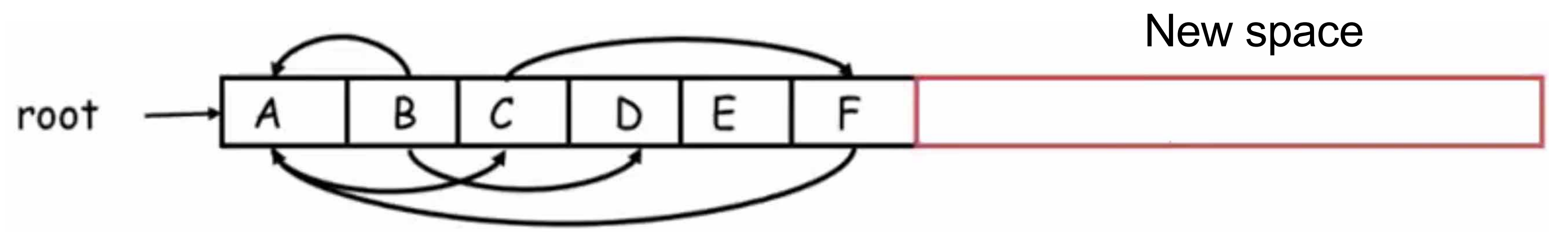

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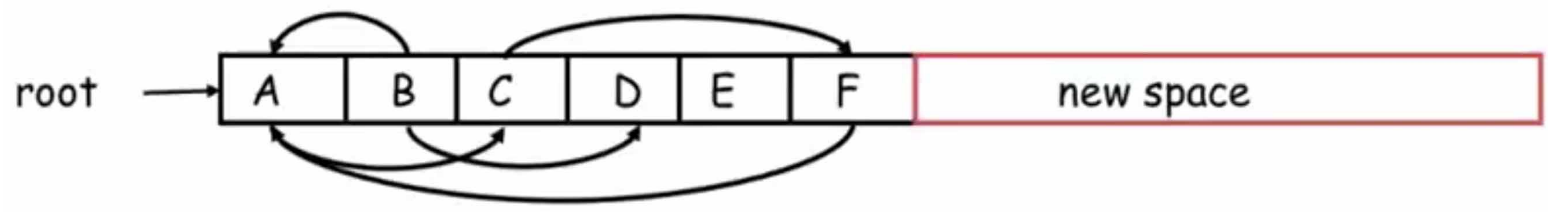
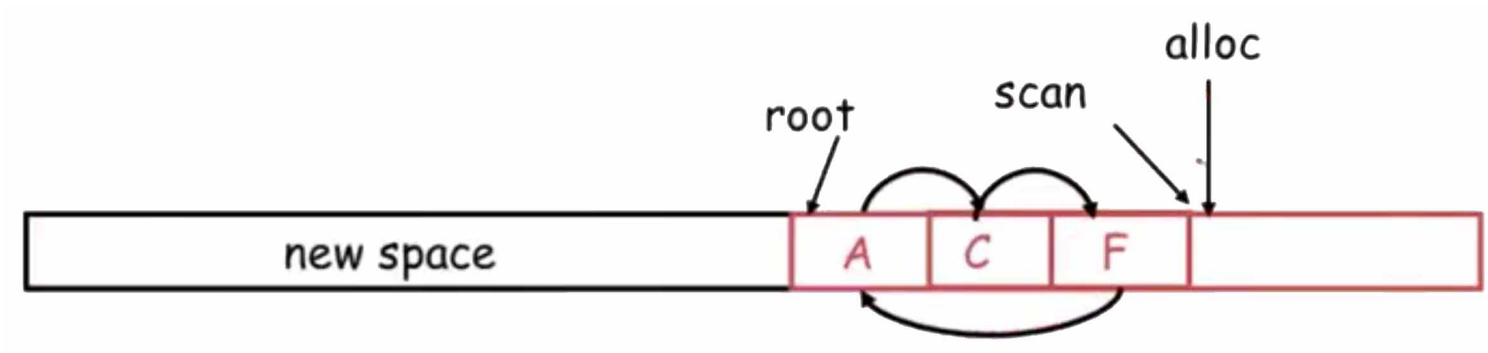


# Copying GC Tradeoffs

- Advantages
  - Only touches live data
  - No fragmentation (automatically compacts)
    - Will probably increase locality

- Disadvantages
  - Requires twice the memory space

# Conservative Garbage Collection (for C)

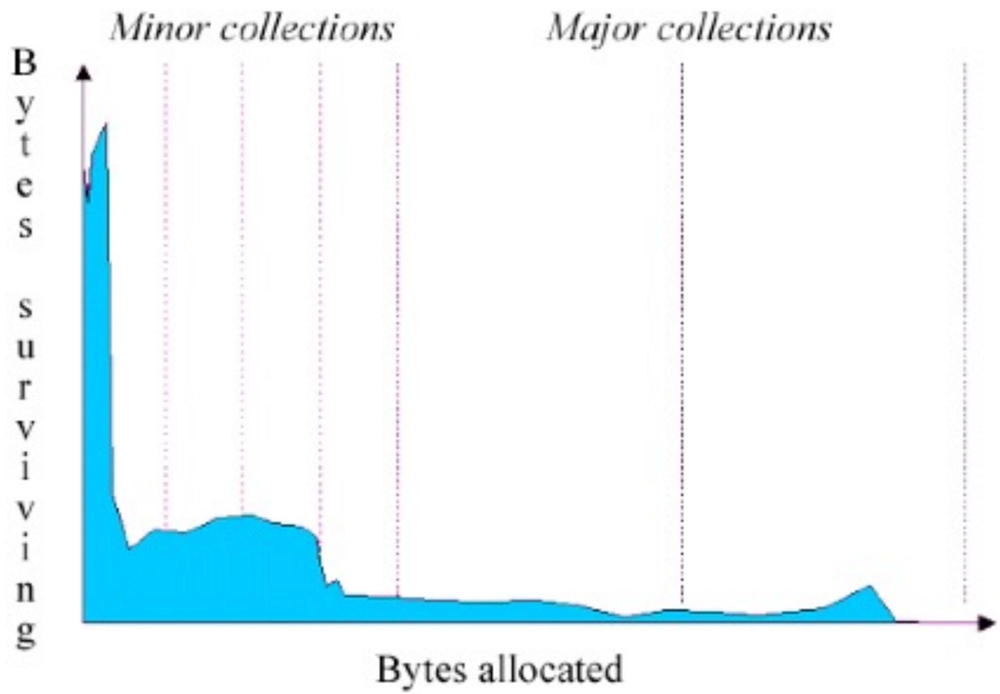
- For C, we can't be sure which words are pointers
  - Due to incomplete type information, the use of unsafe casts, etc.
- Idea: suppose it is a pointer if it looks like one
  - Most pointers are within a certain address range, they are word aligned, etc.
  - May retain dead memory (floating point # looks like a pointer)
- Different styles of conservative collector
  - Mark-sweep: important that objects not moved
  - Mostly-copying: can move objects you are sure of

# 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**

- How can we reduce the pause time of GC? Ideas:
  - Incremental: Collect a little at a time
  - Parallel: Do GC in multiple threads at once
  - Concurrent: Do GC while main program is running

# The Generational Principle




*More objects live* ⇑

*Object lifetime increases* ⇒

***"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

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

From Haggar, Garbage Collection and the Java Platform Memory Model

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     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