Lecture 15

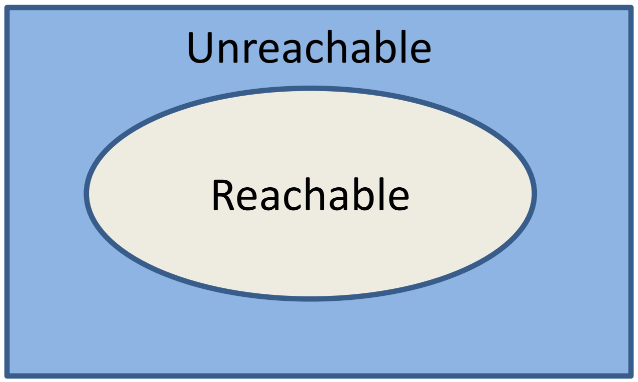
Garbage Collection

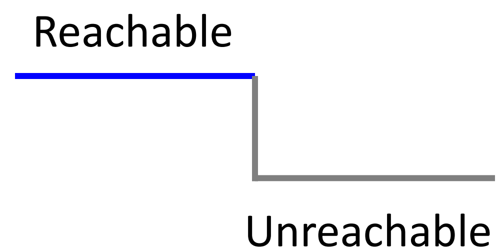
I. Introduction to GC
   -- Reference Counting
   -- Basic Trace-Based GC
II. Copying Collectors
III. Break Up GC in Time (Incremental)
IV. Break Up GC in Space (Partial)

Readings: Ch. 7.4 - 7.7.4

I. What is Garbage?

Two Approaches to Garbage Collection





What is not reachable, cannot be found!
Needs to find the complement
of reachable objects.
Cannot collect a single object
until all reachable objects are found!
Stop-the-world garbage collection!

Catch the transition
from reachable to unreachable.
Reference counting

When is an Object not Reachable?

- **Mutator (the program)**
  - New / malloc: (creates objects)
  - Store: q = p; p->o1, q->o2
    - \+ q->o1
    - − If q is the only ptr to o2, o2 loses reachability

More?

  - Load
  - Procedure calls
    - on entry: + formal args -> actual params
    - on exit: + actual arg -> returned object

More?

- **Important property**
  - once an object becomes unreachable, stays unreachable

Reference Counting

- **Free objects as they transition from "reachable" to "unreachable"**
- **Keep a count of pointers to each object**
- **Zero reference -> not reachable**
  - When the reference count of an object = 0
    - delete object
    - subtract reference counts of objects it points to
    - recurse if necessary
- **Not reachable -> zero reference?**

answer?

- **Cost**
  - overhead for each statement that changes ref. counts (needs to be atomic)

Why is Trace-Based GC Hard?

- **Reasons**
  - Requires complementing the reachability set - that's a large set
  - Interacts with resource management: memory

Trace-based GC Basics

- **Assumption: Type-safe languages**
  - C, C++ can turn any numbers into a memory location
- **Reachable objects**
  - Root set: (directly accessible by prog. without deref'ing pointers)
    - objects on the stack, globals, static field members
  - \+ objects reached transitively from ptrs in the root set.

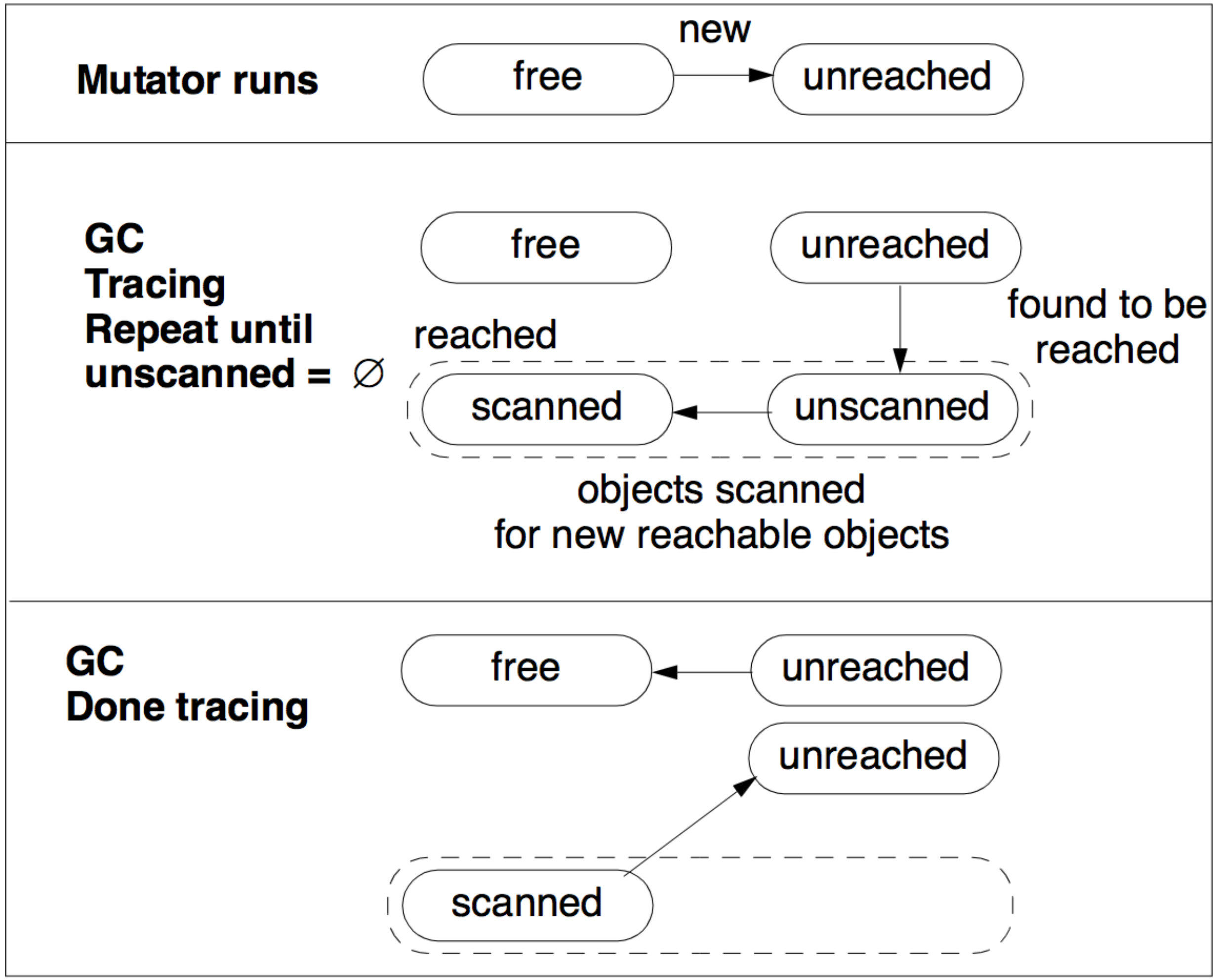
Complications Due to Compiler Optimizations

- **Registers may hold pointers**
- **Optimizations (e.g. strength reduction, common subexpressions) may generate pointers to the middle of an object**
- **Solution**
  - Ensure that a "base pointer" is available in the root set
  - Compiler writes out a GC map
    to decipher registers and compiler-generated variables
  - Too costly to write out map at every program point
    - Restrict program points where GC is allowed
    - Need a GC point in every loop or recursive cycle

Basic GC Algorithm: Baker's Algorithm

- **Data structures (Linked Lists)**
  - **Free**: a list of free space
  - **Unreached**: a list of allocated objects, not Reached, not Scanned
  - **Unscanned**: a work list: Reached, but not Scanned
  - **Scanned**: a list of scanned objects: Reached and Scanned
- **Algorithm**
  - Scanned = $\emptyset$
  - Move objects in root set from Unreached to Unscanned
  - While Unscanned $\neq \emptyset$
    - move object o from Unscanned to Scanned
    - scan o, move newly reached objects from Unreached to Unscanned
  - Free = Free $\cup$ Unreached
  - Unreached = Scanned

Trace-Based GC: Memory Life-Cycle



When Should We GC?

Frequency of GC

- **How many objects?**
  - Language dependent, for example, Java:
    - all non-primitive objects are allocated on the heap
    - all elements in an array are individually allocated
    - “Escape” analysis is useful
      -- object escapes if it is visible to caller
      -- allocate object on the stack if it does not escape

- **How long do objects live?**
  - Objects die young

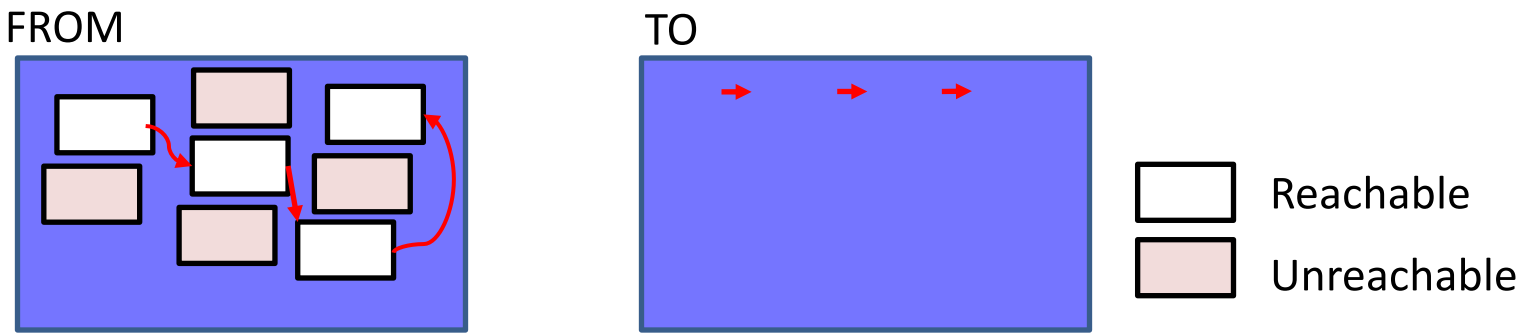
- **Cost of reachability analysis:** depends on the # of **reachable** objects
  - Less frequent: faster overall, requires more memory

Performance Metric

	Reference Counting	Trace-Based
Space reclaimed		
Overall execution time		
Pause time		
Space usage		
Data locality		

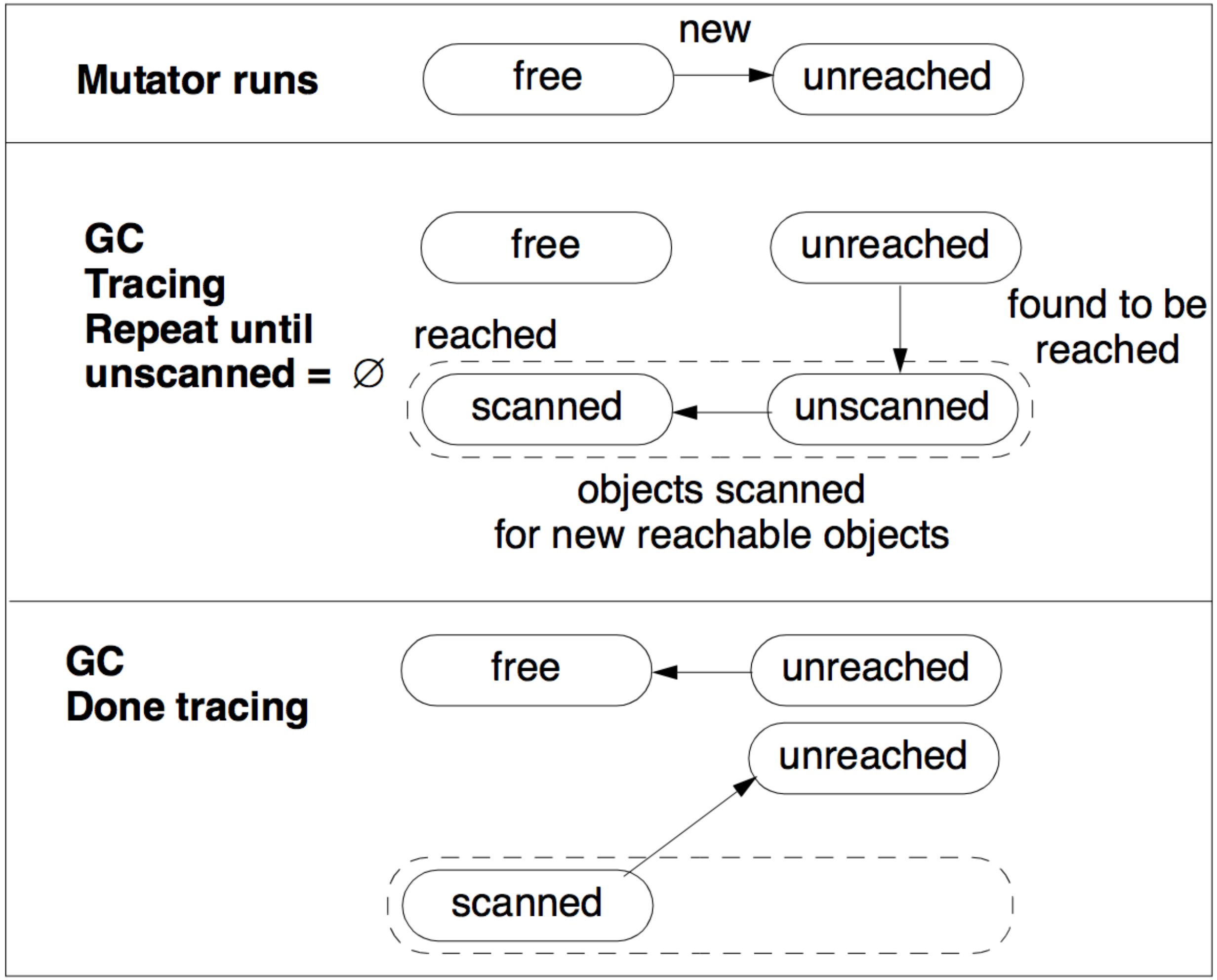
II. Copying Collector

- **To improve data locality**
  - place all live objects in contiguous locations as we trace -- cheap
- **Memory separated into 2 (semi-)spaces: From and To**

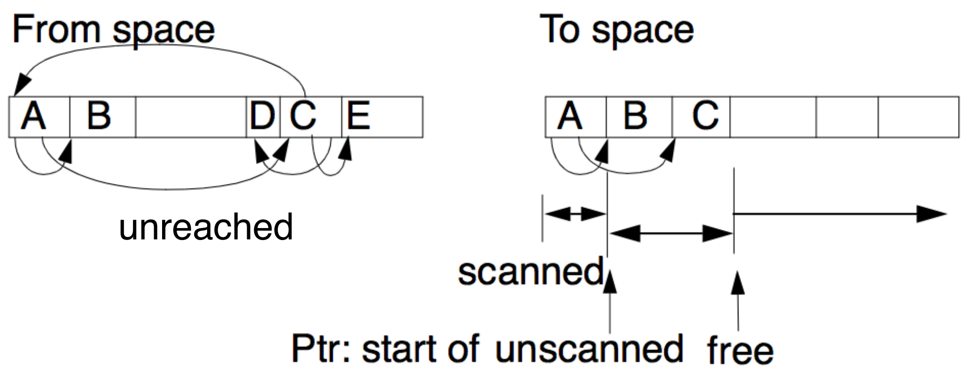


  - Allocate objects in one
  - When (nearly) full, invoke GC,
    which copies reachable objects to the other space.
  - Swap the roles of semi-spaces and repeat

Trace-Based GC: Memory Life-Cycle



Copying Collector Algorithm



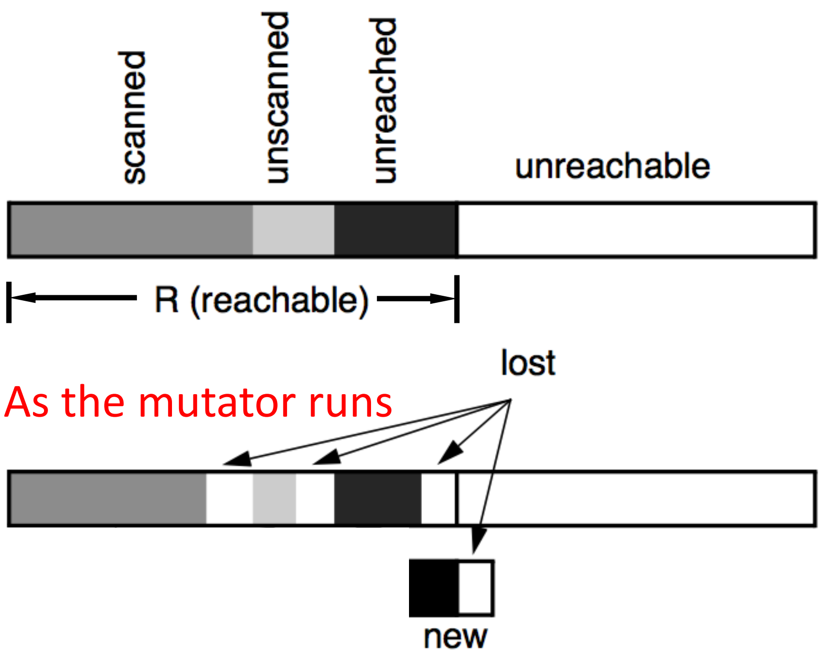
- UnScanned = Free = Start of To space
- Copy root set of objects space after Free, update Free;
- While UnScanned ≠ Free
  - scan o, object at UnScanned
  - copy all newly reached objects to space after Free, update Free
  - update pointers in o
  - update UnScanned

III. Incremental GC

- **Break up GC to reduce pause time: interleave GC with mutator**
  - Trace reachability in multiple rounds: GC-mutator-GC-…
  - Collect identified garbage in the last round

Kinds of Objects **(not memory placement)**

After the first GC round



As the mutator runs

R: Reachable objects before the first round of GC
New: Objects created since the first round of GC
Lost: Objects that lose reachability since the first round of GC

Ideal = (R ∪ New) - Lost

Ideal ⊆ Answer ⊆ (R ∪ New)

Forward progress guaranteed

Effects of Mutation

Ideal = (R $\cup$ New) - Lost $\subseteq$ Answer $\subseteq$ (R $\cup$ New)

- **Ideal: Very expensive**
- **Conservative Incremental GC:**

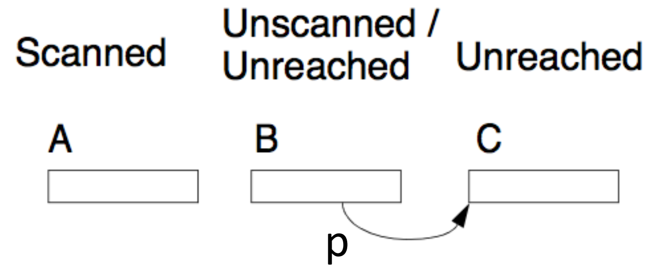
  May misclassify some unreachable as reachable
  - should not include objects unreachable before GC starts
  - guarantees that garbage will be eliminated in the next round
- **Forward progress guaranteed**

Algorithm Proposal 1

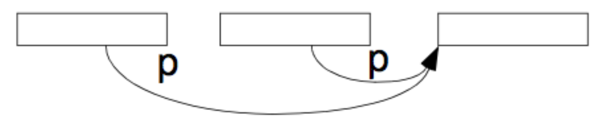
- **Initial condition**
  - Scanned, Unscanned lists from before
- **To resume GC**
  - Find root sets
  - Place newly reached objects in “unscanned list”
  - Continue to trace reachability without redoing “scanned” objects
- **Did we find all reachable objects?**

Error: A reachable object classified as unreachable

- **When GC runs again:** A previously unreached, but reachable, object (C) is pointed to only in scanned objects (A)
- **How it can happen:**
  - Before the mutator runs
    - p in an unscanned or unreached object (B) points to an unreached object in C.



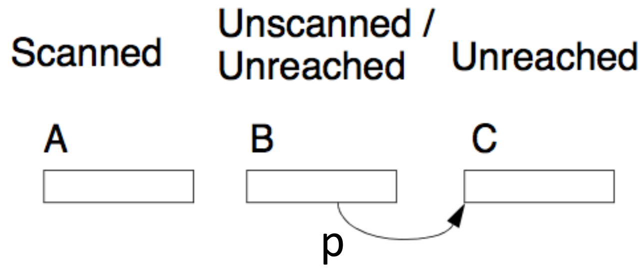
  - When the mutator runs
    - p copied to a scanned object (A)



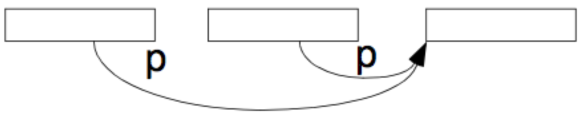
    - p is overwritten in the unscanned/unreached set (B)

Solution

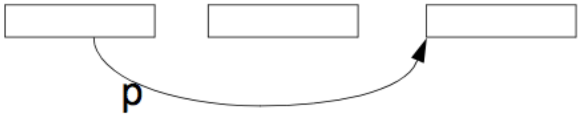
- **Intercept p in any of the three steps**
- **Treat pointee of p as "unscanned"**
- **How it can happen:**
  - Before the mutator runs
    - p in an unscanned or unreached object (B) points to an unreached object in C.
      Read Barrier:
      remember loads of pointers from B objects pointing at C objects



  - When the mutator runs
    - p copied to a scanned object (A)
      Write Barrier:
      remember stores of pointers into A objects pointing at C objects



    - p is overwritten in the unscanned/unreached set (B)
      Overwrite Barrier:
      remember values overwritten in B objects pointing to C objects

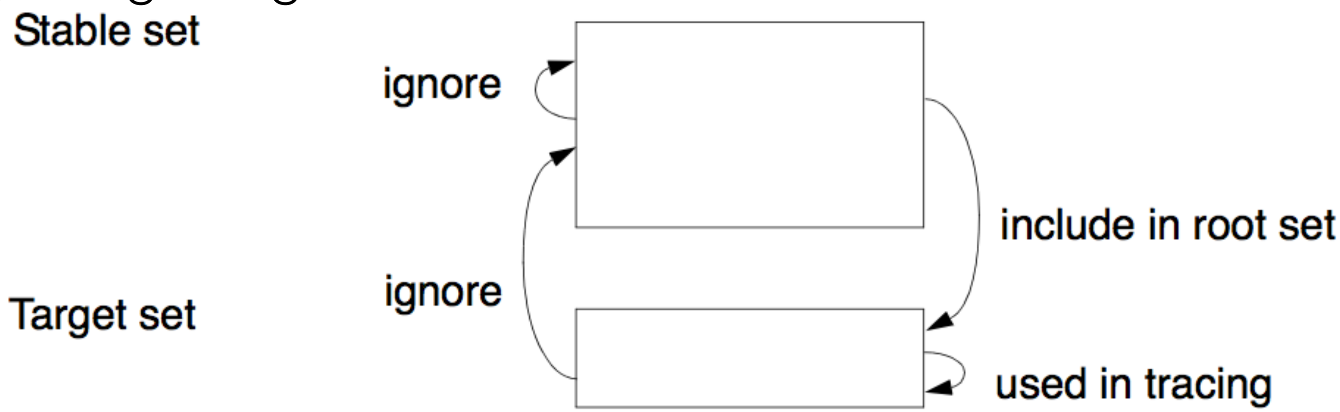


Efficiency of Different Barriers

- **Most efficient: Write barrier**
  - less instances than read barrier
  - includes less unreachable objects than over-write barriers

IV. Partial GC: Incremental in Space

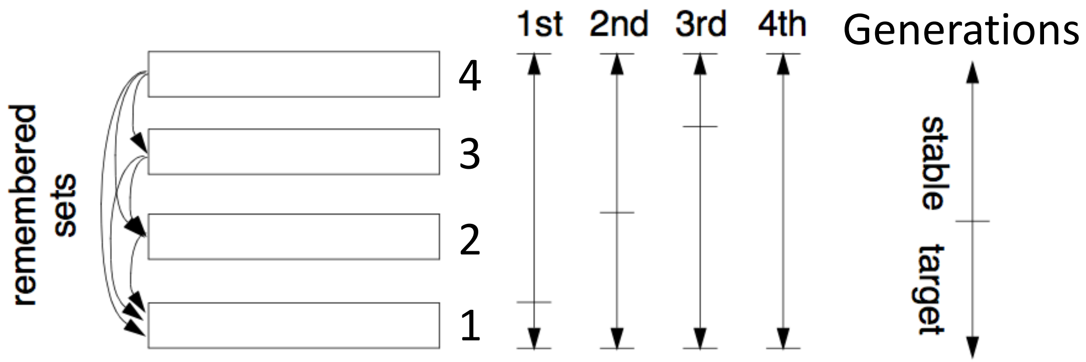
- **Reduces pause time by collecting a subset of garbage in target area:**
  - Ignore garbage in stable set



- **Algorithm**
  - New "root set"
    = original root set + pointers from Stable to Target set
  - Change program to intercept all writes to Stable set
- **Never misclassify reachable as unreachable**
- **May misclassify unreachable as reachable**

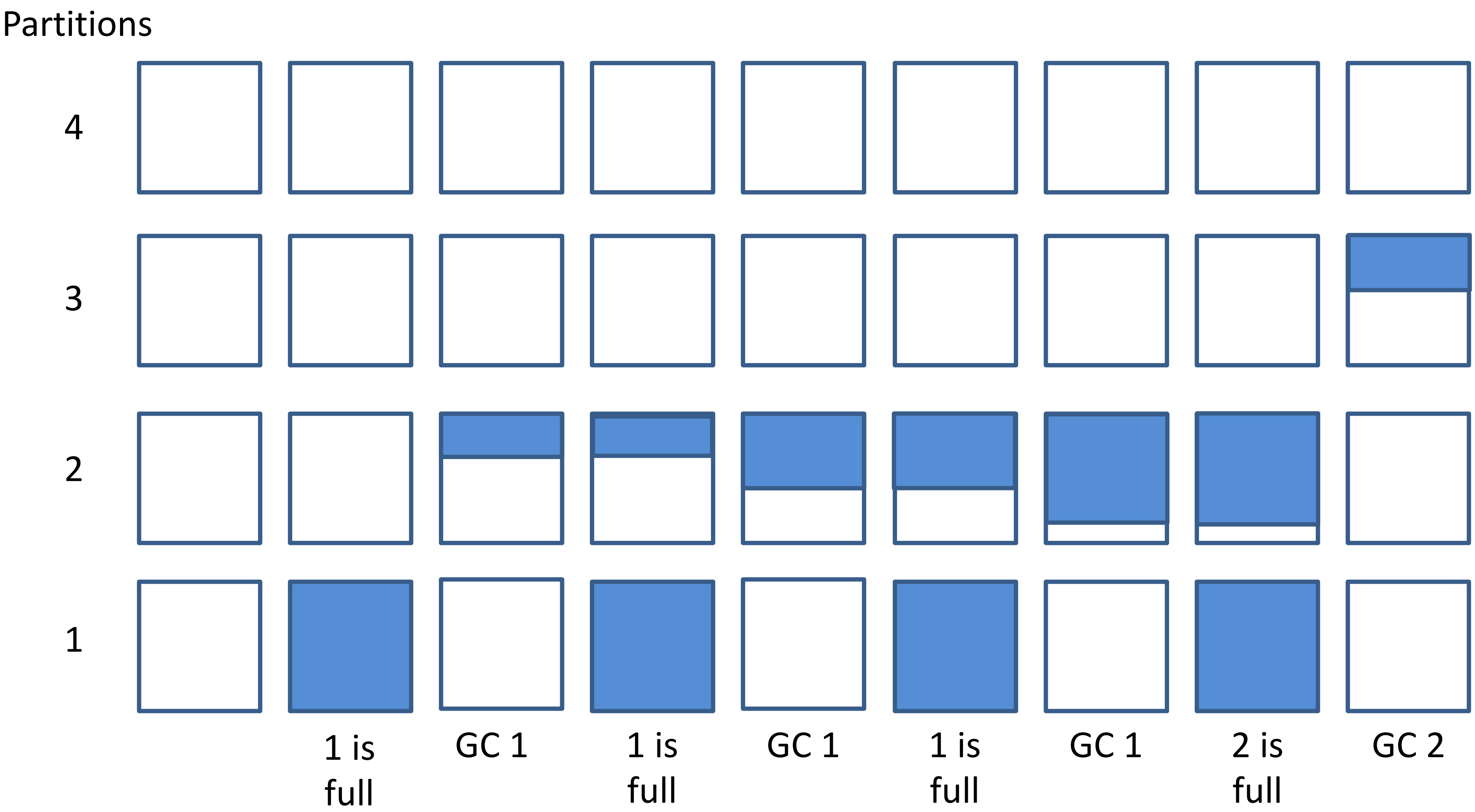
Generational GC

- **Observation: objects die young**
  - 80-98% die within a few million instructions or before 1 MB has been allocated
- **Generational GC: collect newly allocated objects more often**



- **ith generation**
  - Stable set: Partitions # > i
  - Target set: Partitions # <= i
  - new root set = original root set + all pointers from the stable set to the target set
  - Ignore pointers from target back to stable

Generational Garbage Collection



Generational GC

- **Algorithm**
  - Always allocates in partition 1
    - Good locality for newly created objects
  - Copy to ith generation only when 1,…, (i-1) fills up
  - GC of mature objects takes longer
    - Size of target set increases
    - Eventually a full GC is performed (need incremental GC)
- **Effectiveness**
  - Objects die young:
    GC time is spent on partitions that are mostly garbage
- **Correctness and precision**
  - Conservative: Never misclassify reachable as unreachable
  - May misclassify unreachable as reachable
    - when pointers in earlier generations are overwritten
    - eventually collect all garbage as generations get larger

Conclusions

- **Reference counting:**
  - Cannot reclaim circular data structures
  - Expensive
- **Trace-based GC:**
  find all reachable objects, complement to get unreachable
  - 4 states: free, unreached, unscanned, scanned
  - break up reachability analysis
    - in time (incremental)
    - in space (partial: generational)

General Lessons

- **Understanding the program behavior**
  - is key to improve the efficiency of garbage collection
- **GC addresses a universal problem: memory management**
  - Time is spent on GC research saves a lot of time for developers!
- **The importance of compilers + runtime systems!**