Garbage Collection Algorithms

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Announcement

- MP4 posted
- Term paper posted

Introduction

- Garbage : discarded or useless material
- Collection : the act or process of collecting
- Garbage collection is the reclamation of chunks of storage holding objects that can no longer be accessed by a program.

Why GC?

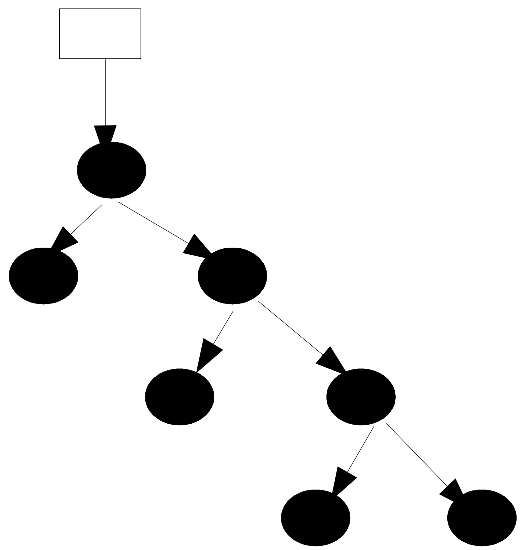
- Manual deallocation is tedious and error-prone
  - memory leaks
  - dangling pointer dereference
- GC also offers other advantages
  - memory compaction
  - improving locality (temporal and spatial)

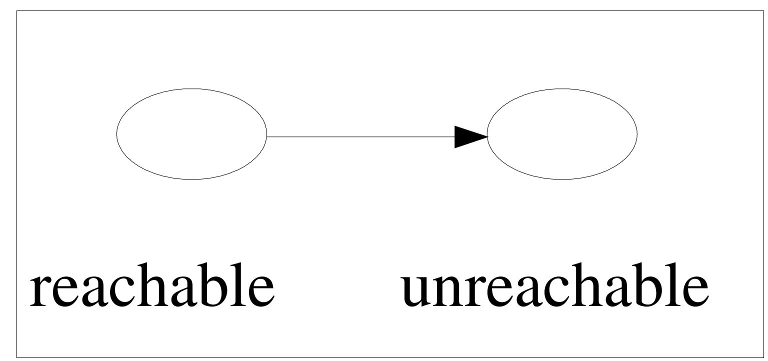
Definitions

- Mutator : the program that modifies the objects in heap (simply, the user program)
- Root set :
  - data accessed directly **without pointer dereference**
  - e.g. set of static field variables & all local variables (JAVA)

Reachability Analysis

- Transitive closure of all the object references





Reachability

- Compiler might complicate reachability analysis
  - store references in registers
  - pointers to middle of an array

Basic Requirement

- Type safety
  - ML – statically typed
  - JAVA – dynamically typed
- C and C++ are type unsafe
  - pointer arithmetic
  - integer casts (any memory is reachable)

Essential characteristics

- minimal **overall execution time**
- optimal **space usage** (no fragmentation)
- minimal **pause time** (esp. real time tasks)
- improved **locality** for mutator

Reachable object set

- Object Allocations (+)
- Parameter passing (;)
- Return values (;)
- Reference assignments (-)
- Procedure returns (-)

Garbage Collection Schemes

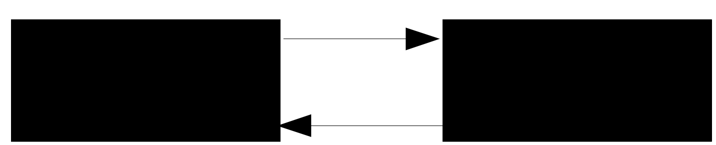
- Reference counting
- Trace based collection
  - mark & sweep
  - Baker's
  - mark & compact
  - copying collectors
- Short-Pause Garbage Collection
  - incremental
  - partial

Reference Counting

- Add a count to each heap object
- Update on :
  - object allocation (+) : c(A) = 1
  - parameter passing (+) : c(A)++;
  - reference assignments (+/-) : c(u)--; c(v)++;
  - returns (-) : c(A)--;
  - **transitively** decrement the count upon zero
    - c(A) = 0 ==> c(B)--; for all B pointed to by A.

Reference Counting

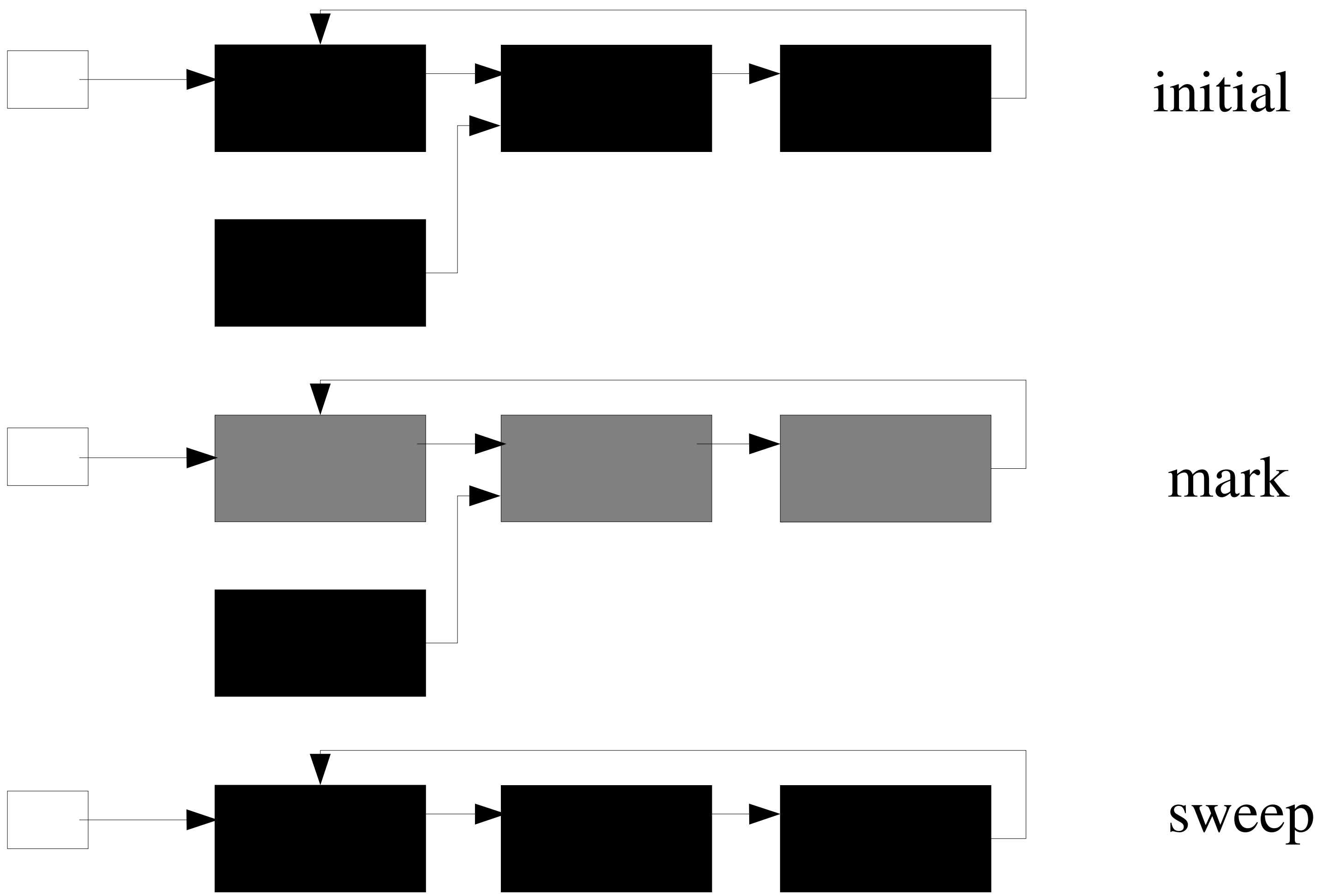
- Advantages
  - Simple
  - Immediate garbage collection
  - Short pause times
  - Low space usage
- Disadvantages



Trace-Based Collection

- Run the garbage collection periodically
  - for ex, when the free space is exhausted
  - or a cut-off is reached
- Sweep all the **allocated objects**

Mark-and-Sweep collector



Basic Mark-and-Sweep Algorithm

```
/* marking phase */
Unscanned = all the objects referenced by root set
while (unscanned != 0) {
      remove some object o from Unscanned;
       for (each object o' reference in o) {
          if (o' is Unreached) {
              set the reached bit of o' to 1;
           put o' in Unscanned;
          }
      }
}
/* sweeping phase */
Free = 0;
for (each chunk of memory o in the heap) {
   if (the reached bit of o is 0) add o to Free;
   else set the reached bit of o to 0;
}
```

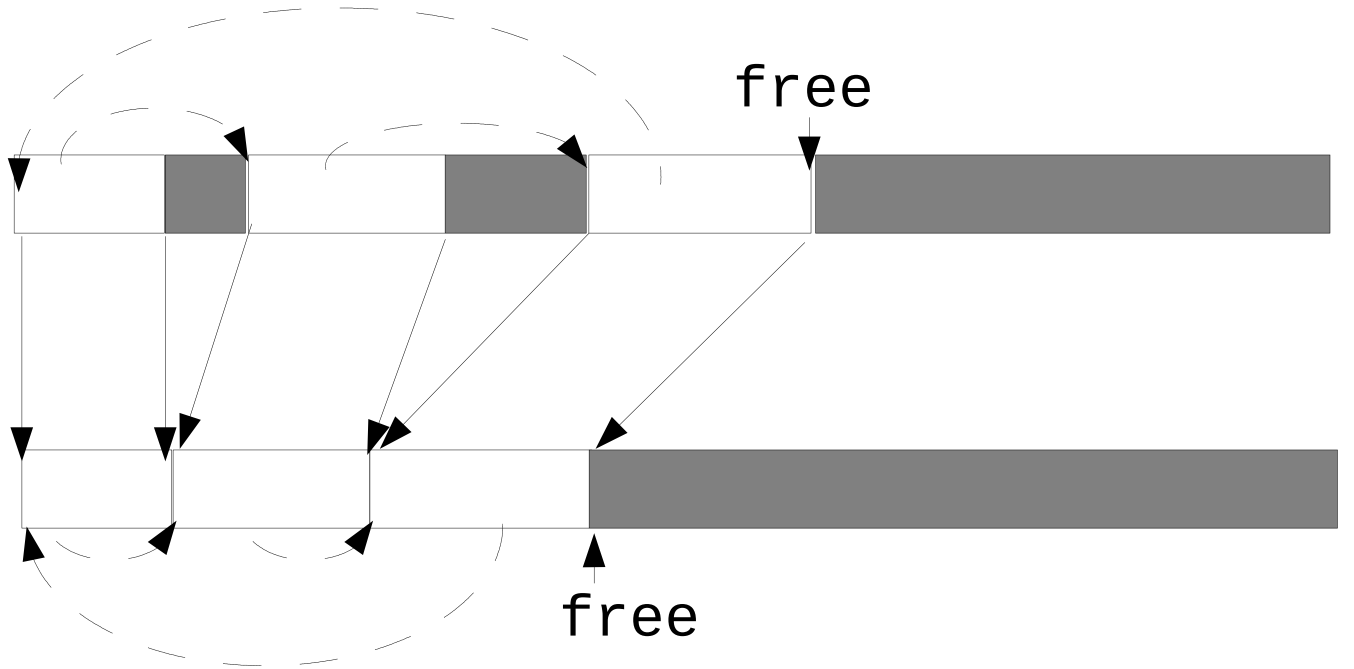
Baker's Mark-and-Sweep Algorithm

```
/* marking phase */
Unscanned = all the objects referenced by root set
Unreached = set of all the allocated objects
while (Unscanned != 0) {
      remove some object o from Unscanned;
       for (each object o' reference in o) {
          if (o' is in Unreached) {
             move o' from Unreached to Unscanned;
         }
      }
}
/* sweeping phase */
Free = Free U Unreached;
Unreached = Scanned;
```

Relocating Collectors

- Relocates the reachable objects to end of heap
- Improves locality
- Reduces fragmentation
- Catch: update the references contained in all the reachable objects

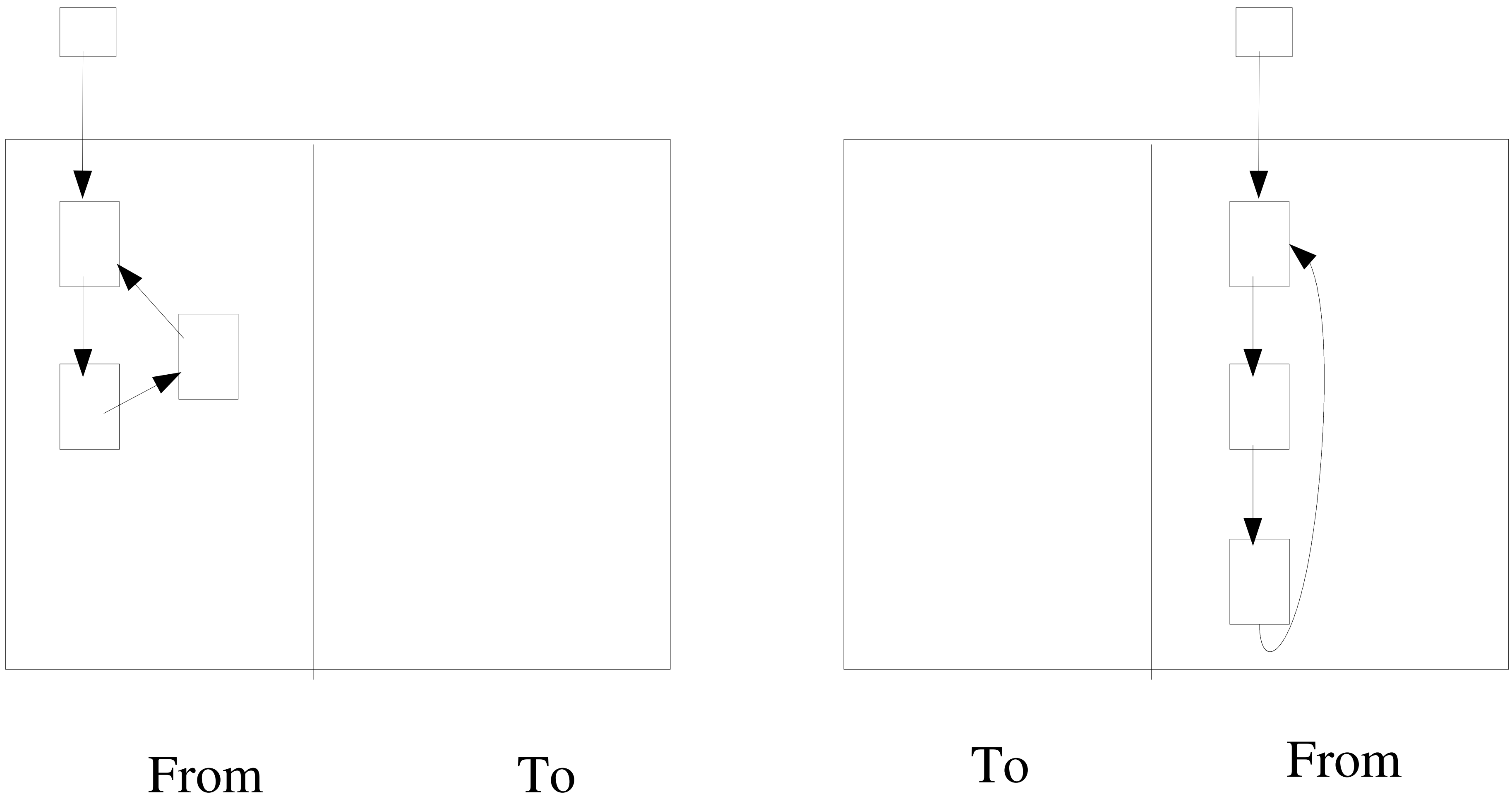
Mark-and-Compact



Mark-and-Compact

- Mark all the reachable objects
- Find the new location for each reachable object
- move each reachable object to new location
  - modify its references
- modify the references in the root set

Copying collector



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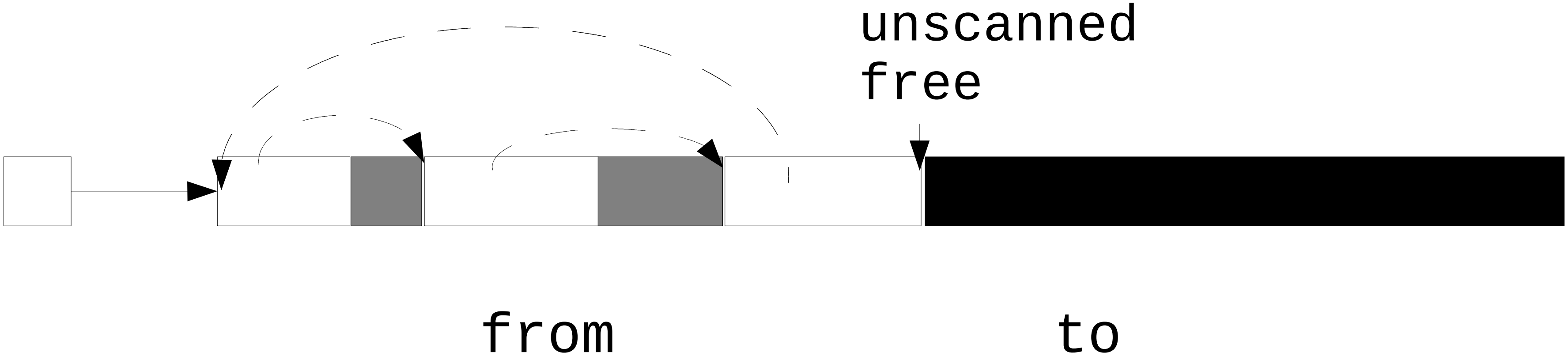

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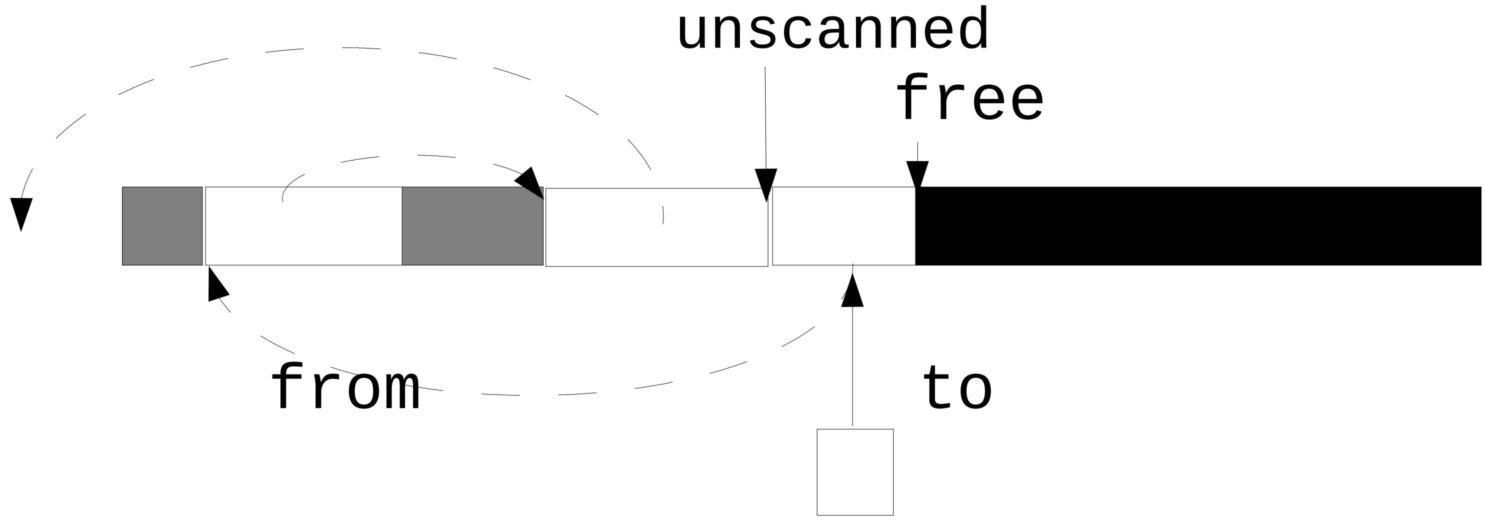

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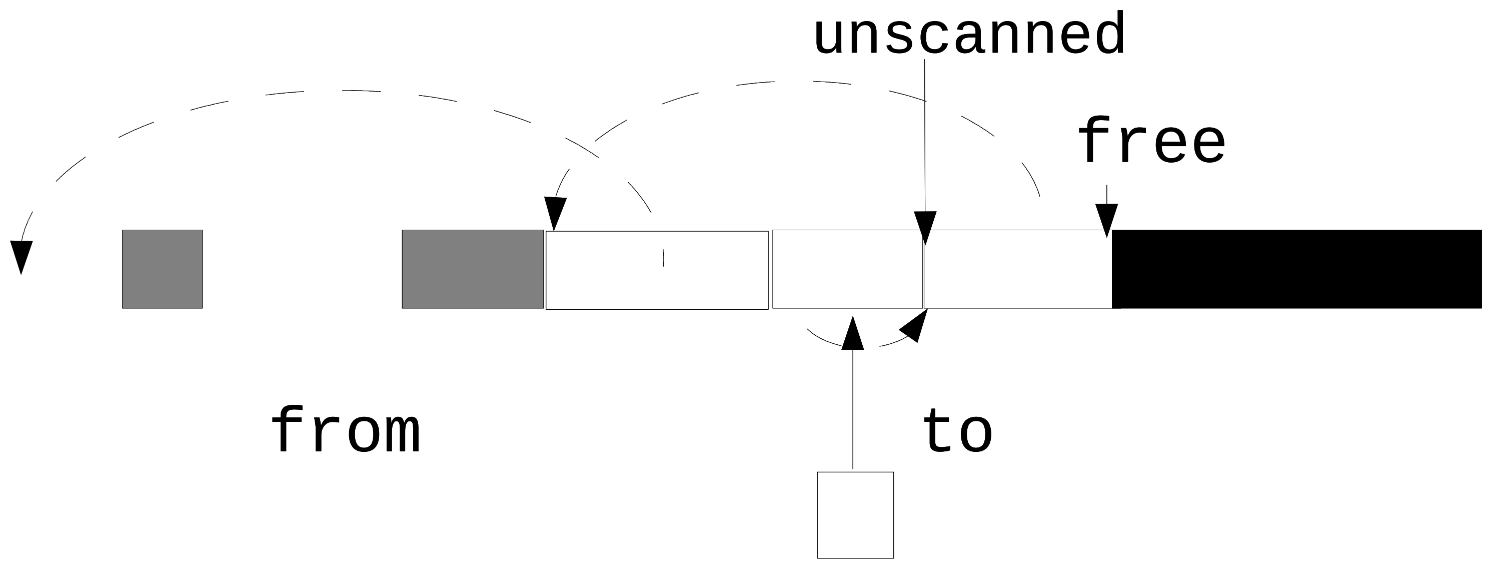

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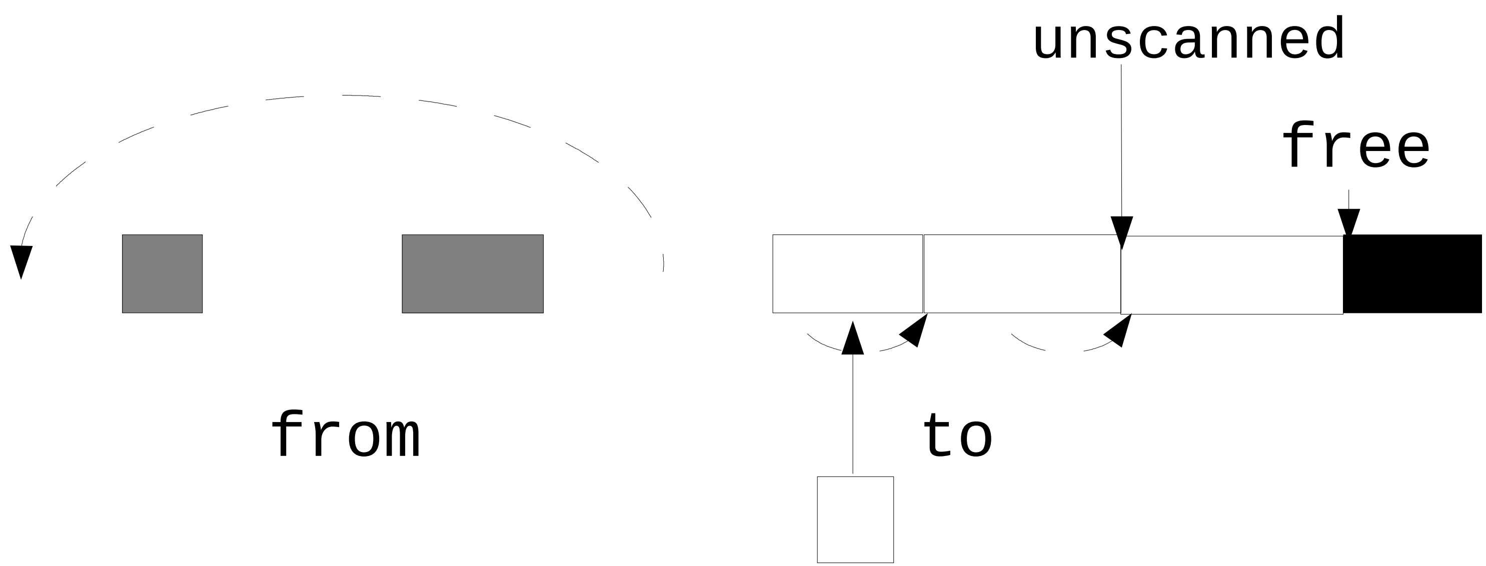

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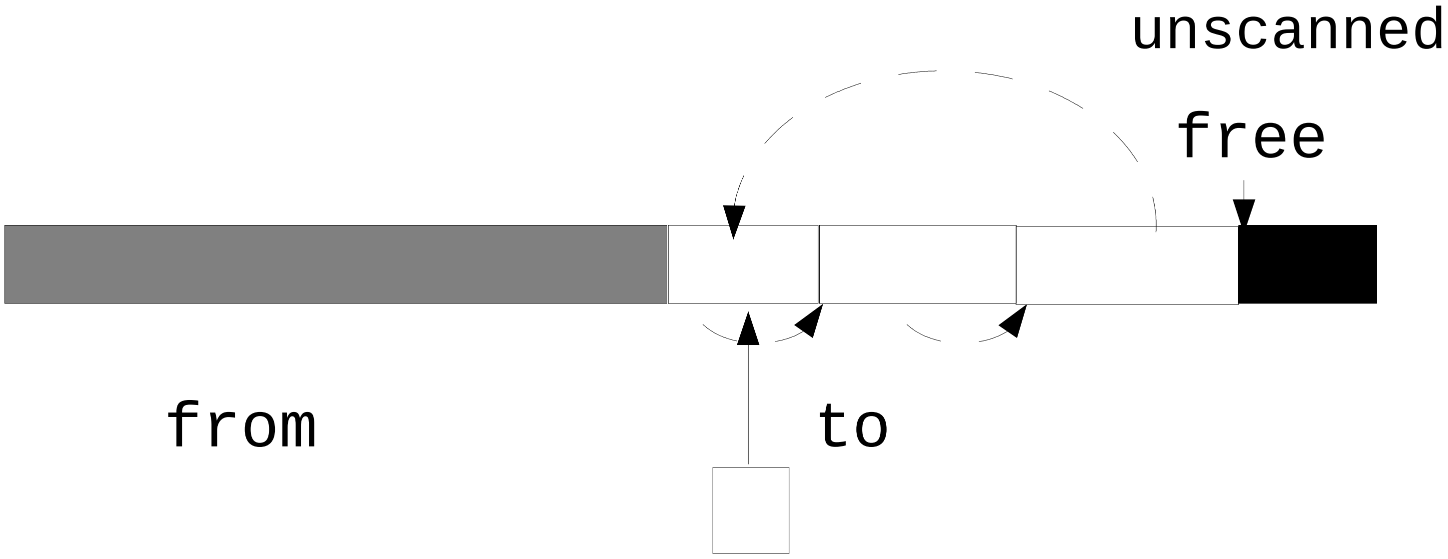


Summary

- Mark-and-Sweep : O(h)
- Baker's : O(r)
- Mark-and-Compact : O(h + s(r))
- Copying : O(s(r))
- h = size of heap, r = # of reach objects s(r) : total size of reached objects

Short-Pause Garbage Collection

- GC in part
  - incremental = by time
  - partial or generational = by space

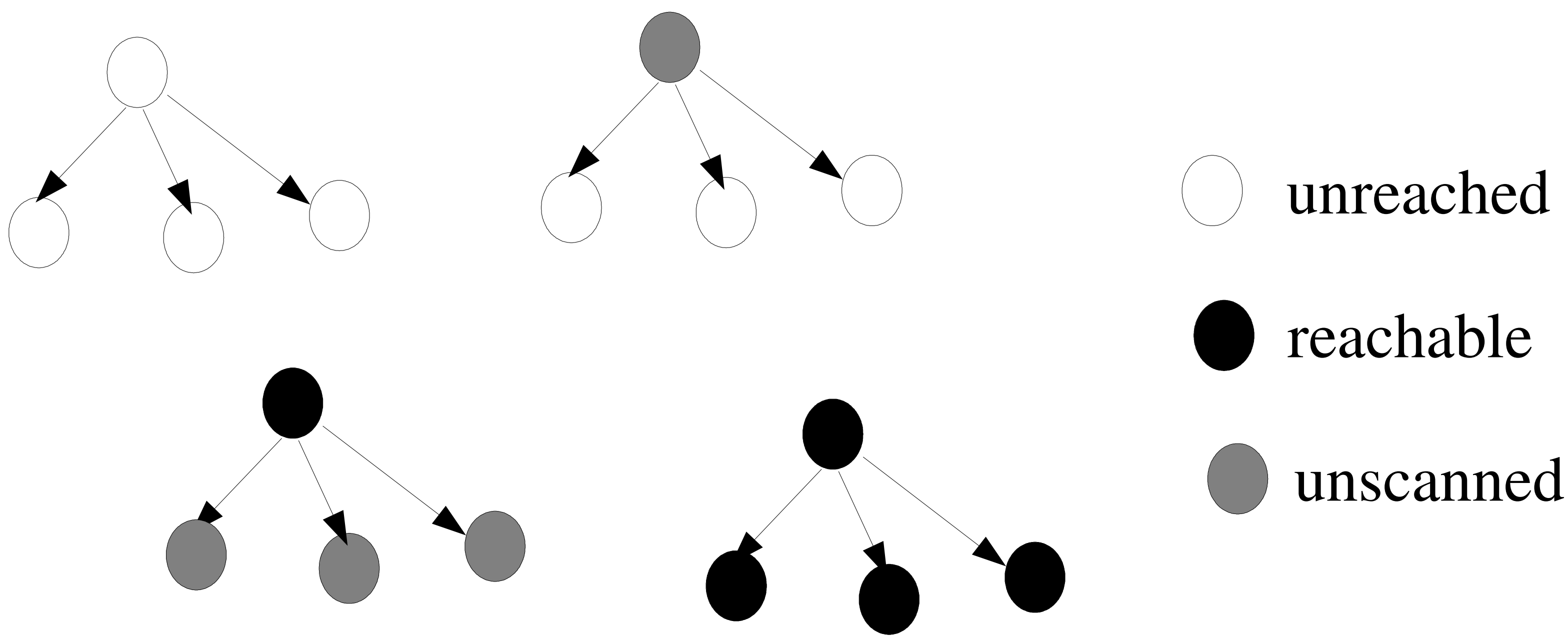
Incremental Garbage Collector

- Breaks the reachability analysis into smaller units
- mutator is executed between these units

Problem (I)

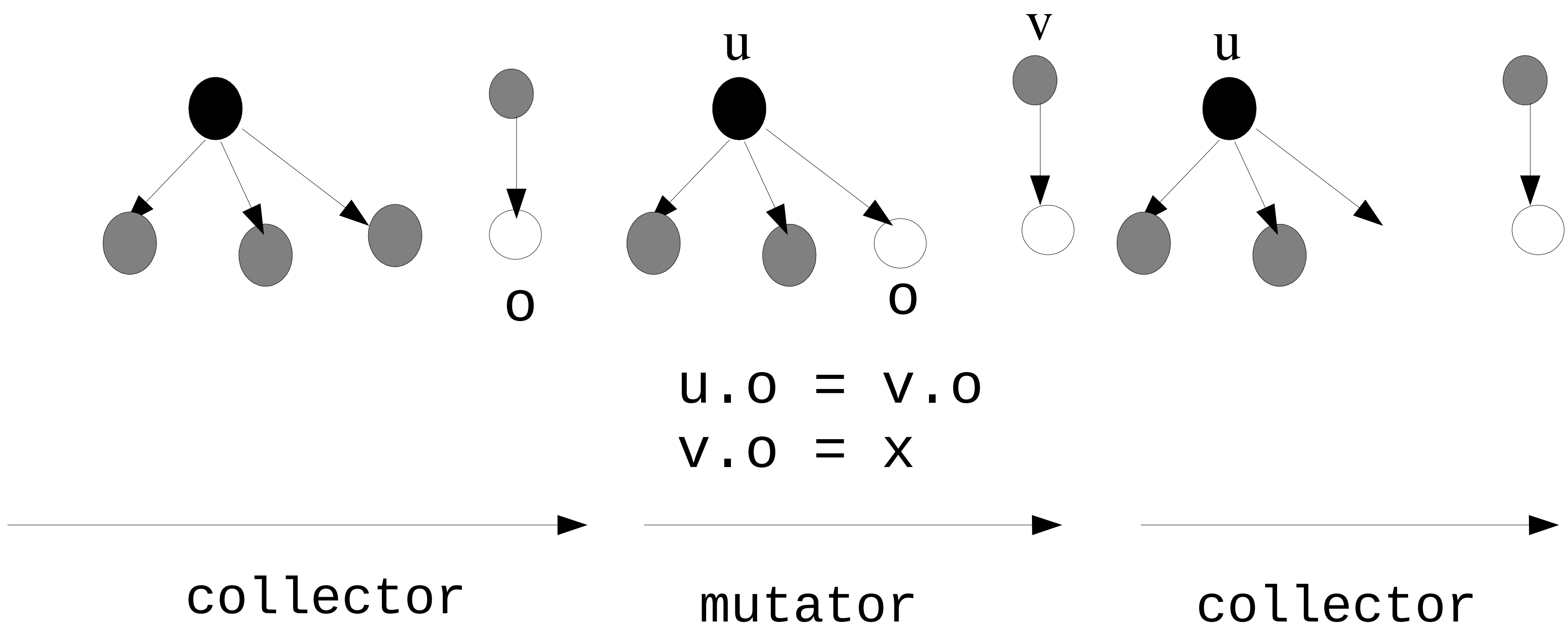
- Mutator changes the reachable set
- Solution:
  - Preserve all the references that existed before GC and mark them unscanned
    - intercept all the write operations
  - All the new objects are placed in the unscanned state

Problem (II)



black always points to blacks or grays

Problem (II)



Solutions

- Write Barriers
  - intercept writes of references to blacks, mark the reference gray or change the black to gray
- Read Barriers
  - intercept the reads of references in whites or grays, mark the reference gray

Partial-Collection

- Objects die young
  - 80% - 98% die within a few million instructions or before another MB is allocated
- Objects that survive a collection once are likely to survive more

Generational Garbage Collection

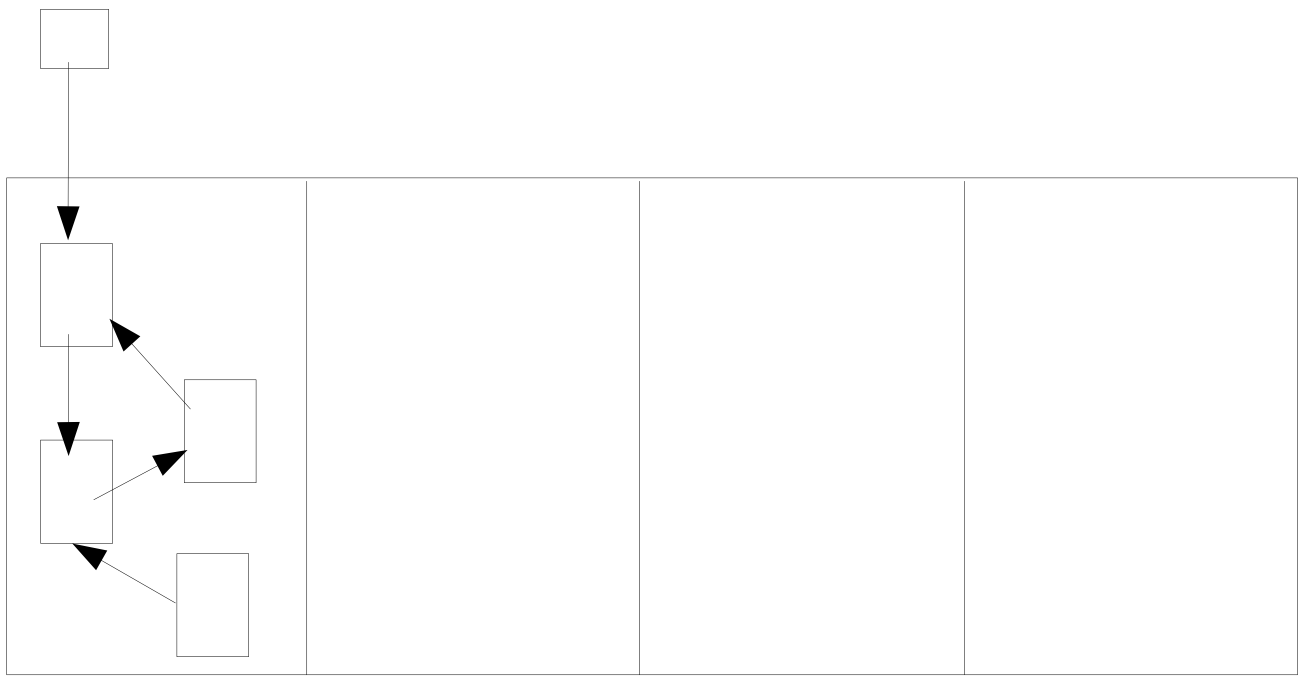
- Splits the heap in to generations
- Younger objects in the recent generation
- Mature objects in the older generations

Generational Garbage Collection

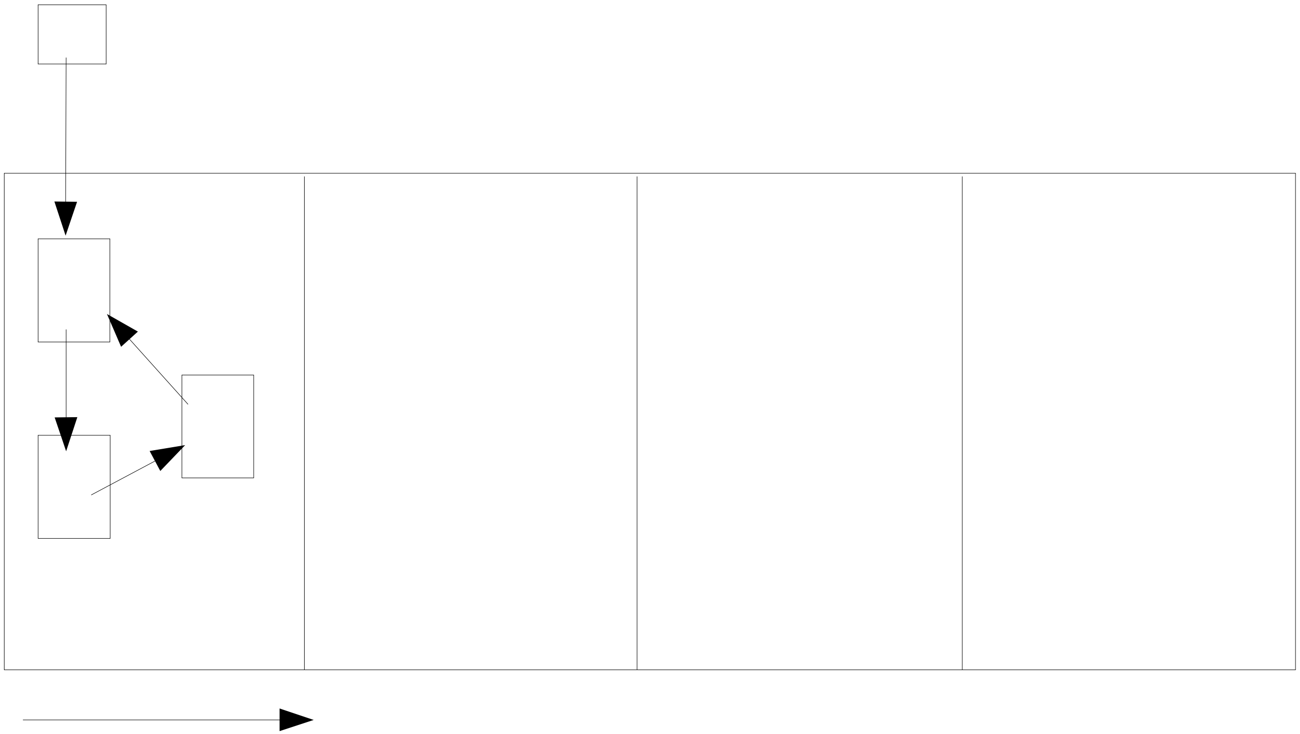
young
(target)

mature
(stable)

Generational Garbage Collection



Generational Garbage Collection



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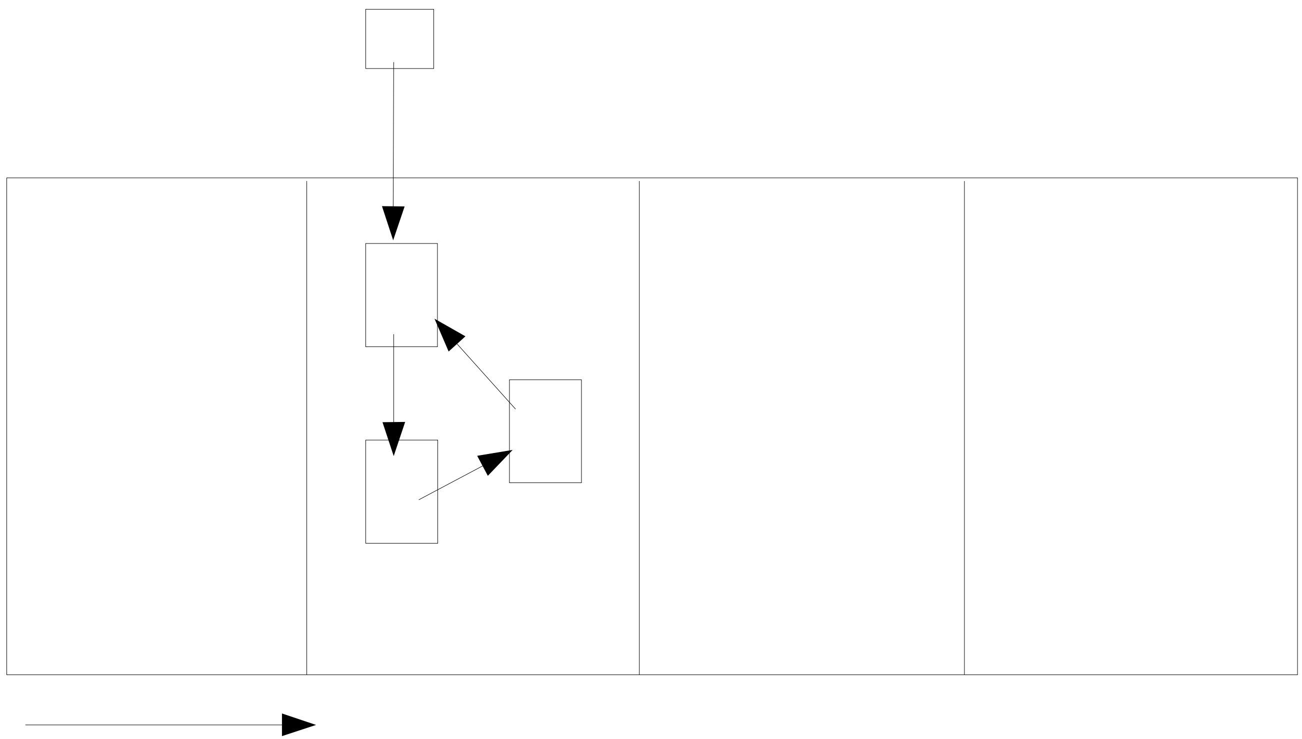

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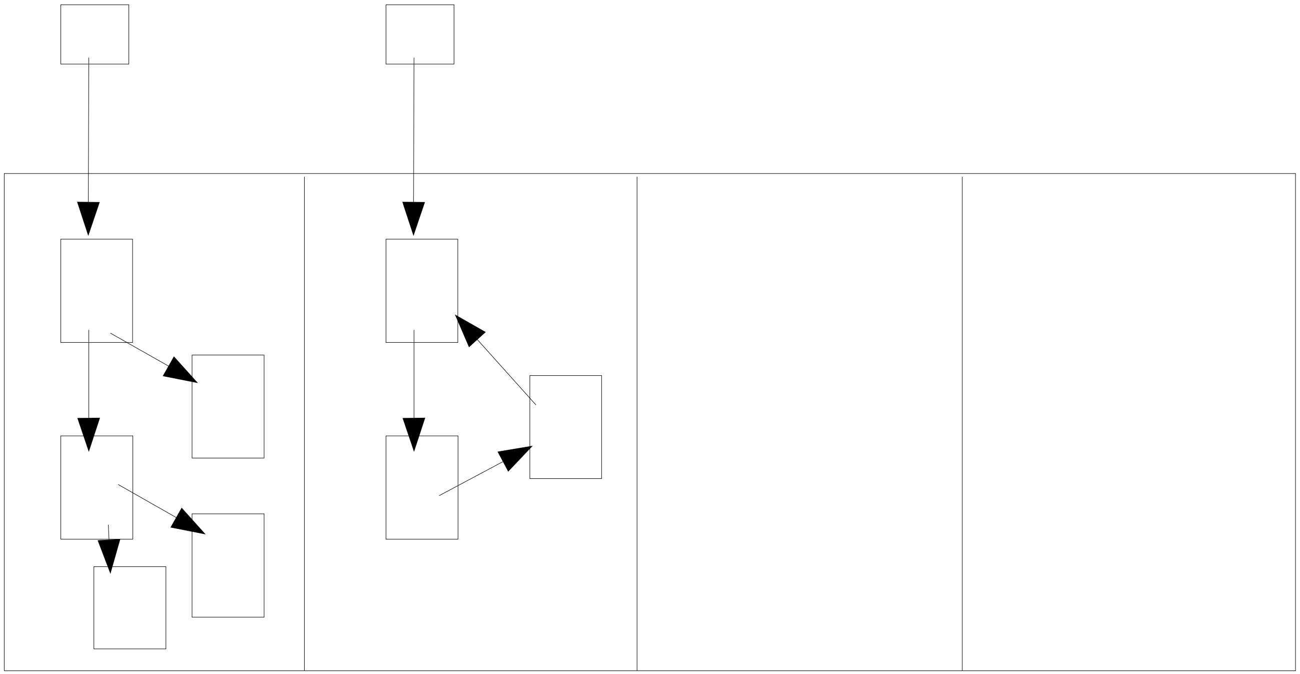

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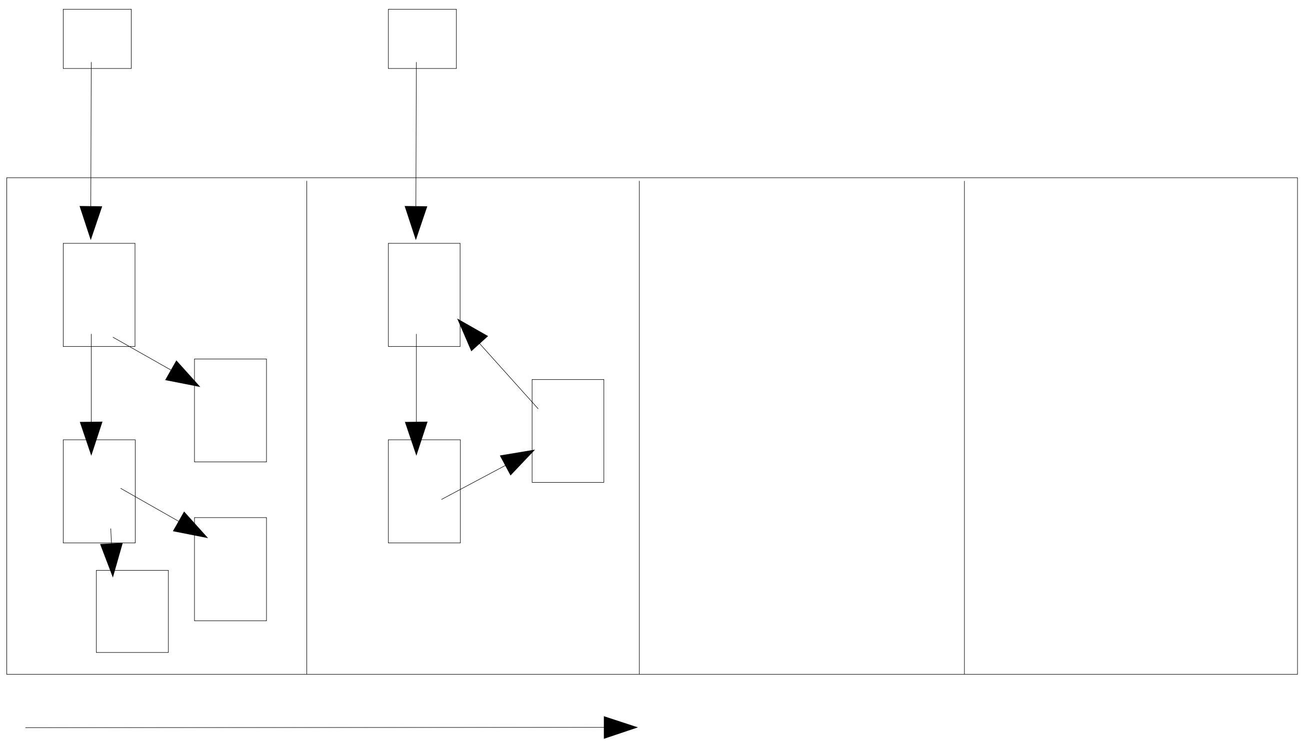
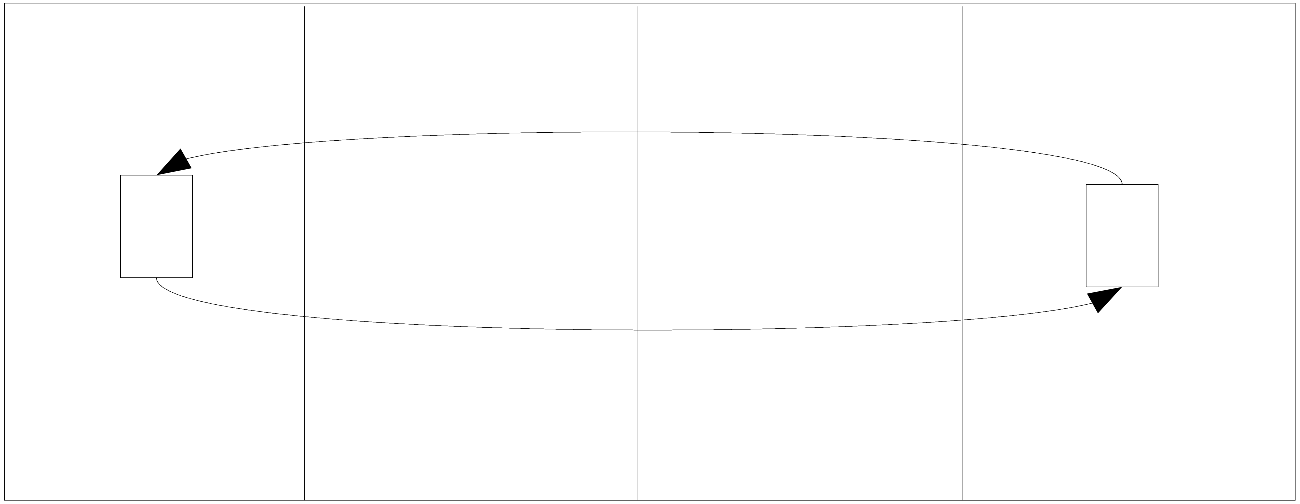


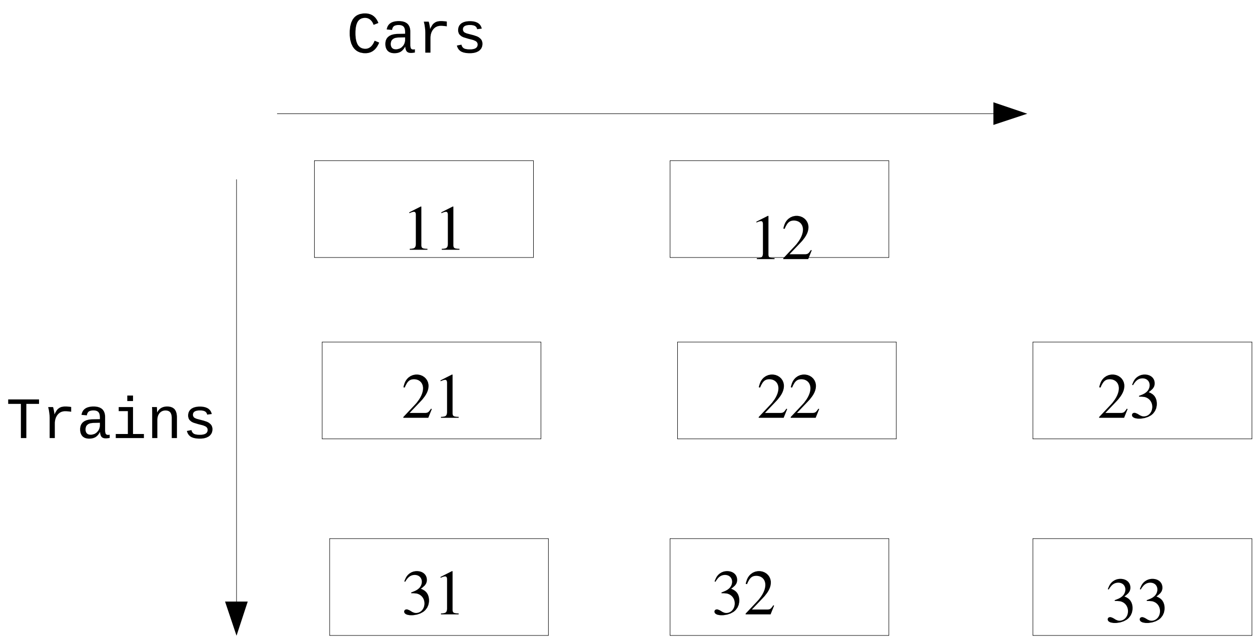
Generational Garbage Collection

- root Set + = remembered set
- remembered set (i) = all the objects from partition > i that point to the objects in set i

Train Algorithm



Train Algorithm



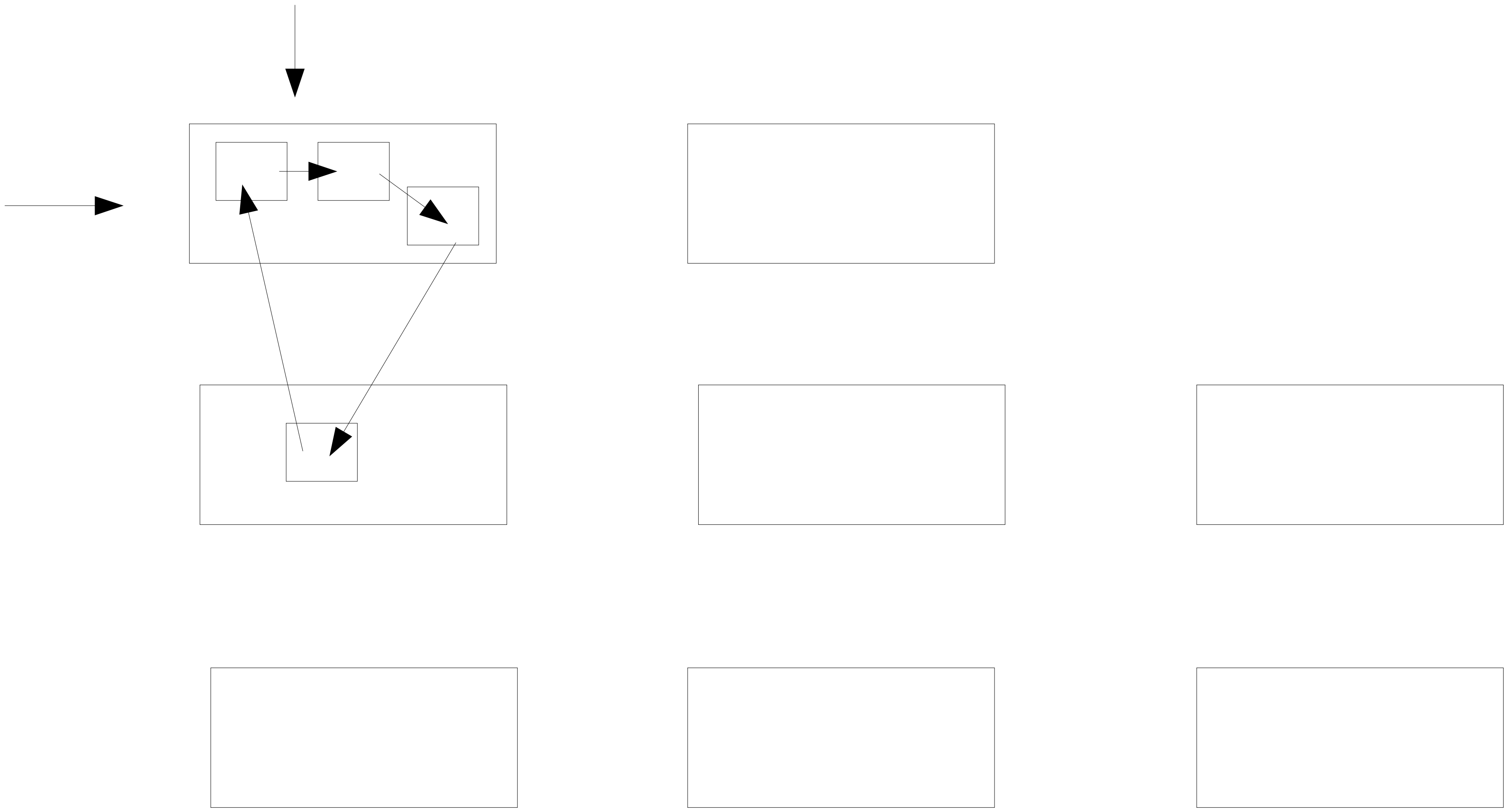
Train Algorithm

- Remembered Sets for each train
  - internal (within the cars of the train)
  - external (other trains)
  - only higher numbered cars & trains
- Root set **+=** remembered set

Train Algorithm

- Start with (1)
- If the **entire train** has **no reference** fully collect
- Step 1:
  - Move objects with **references from** other trains to those trains
- Step 2:
  - Move object with references from root set or other cars to those cars
- Collect (1,1)

Train Algorithm



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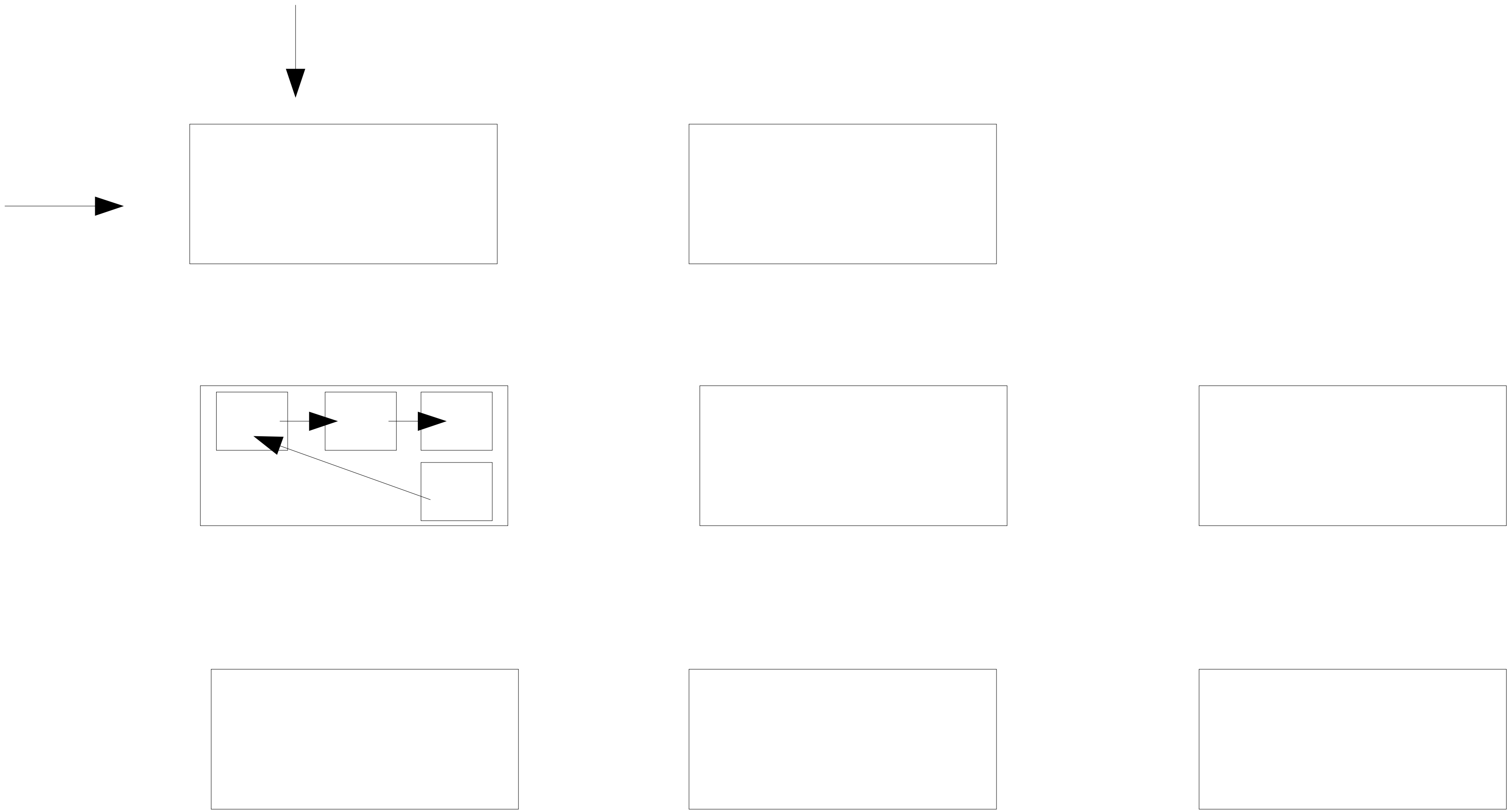

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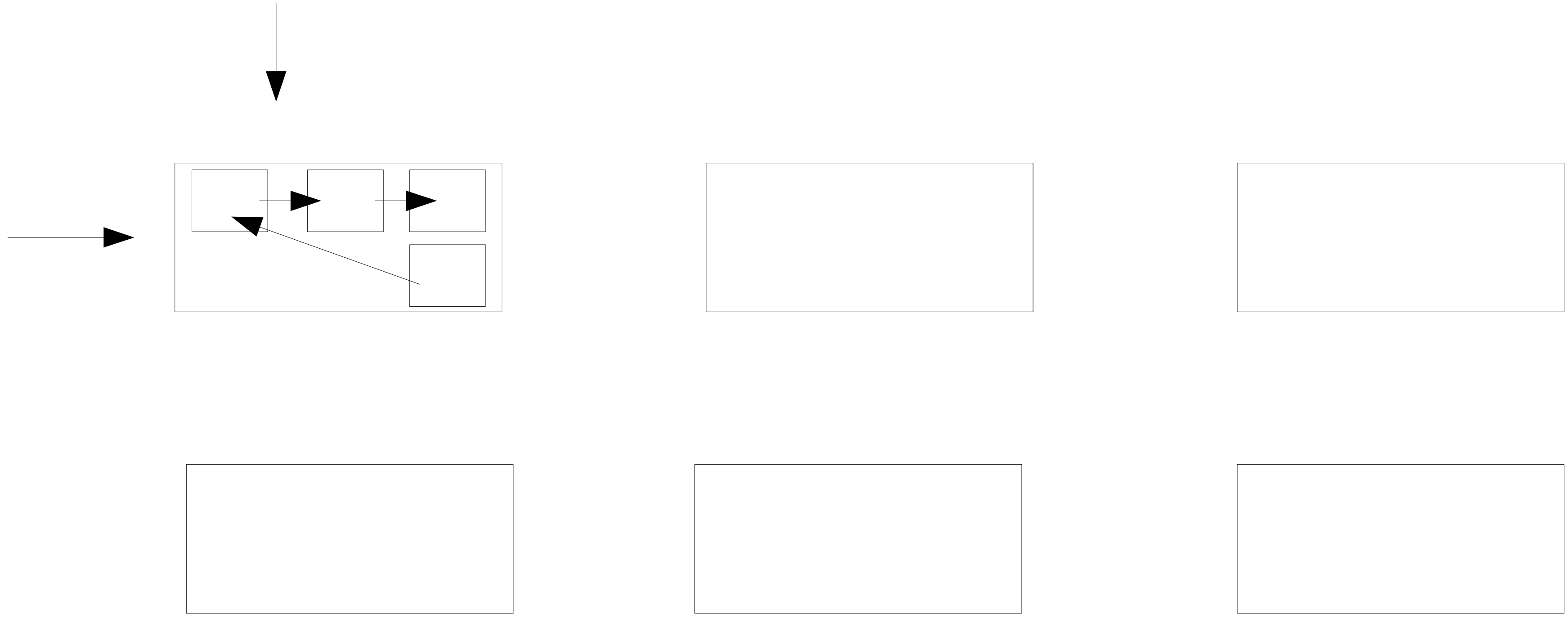

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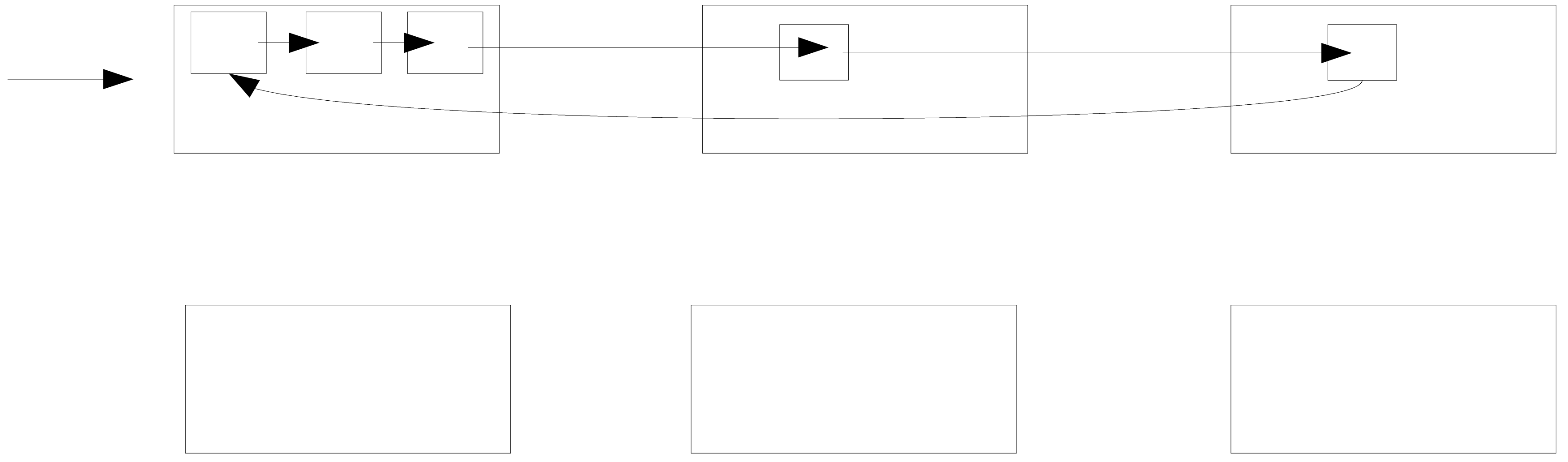


Train Algorithm

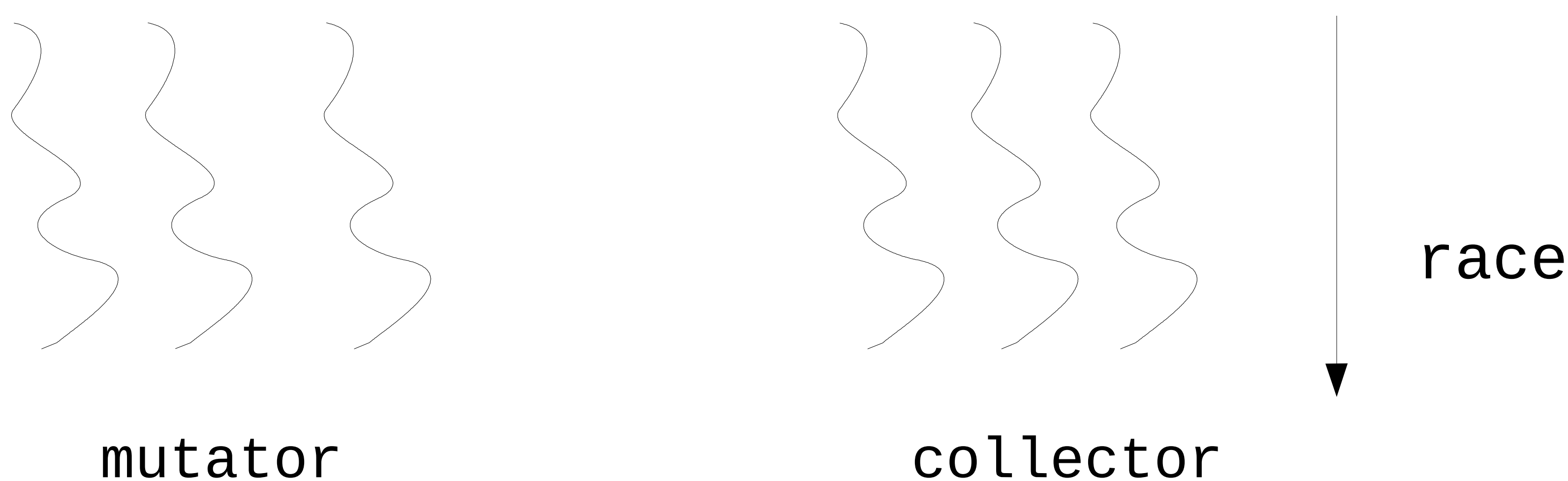
- Ensures that related structures in same train
  - that is why, we can detect cycles
- Useful for mature objects
- Two phase scheme
  - Generational for young objects
  - Train for mature objects

Issues

- How are trains managed?
  - for eg. after every k new objecs a new train is created
- What if we are stuck in (1)?
  - step 2 just keeps on producing cars in same train
  - panic mode
- Why this happens?
  - Mutator changes the references from higher numbered trains during collection

Parallel & Concurrent GC

- Extension of incremental GC
- parallel = uses multiple gc threads
- concurrent = runs simultaneously with mutator



Parallel & concurrent GC

- Tracing phase (parallel & concurrent)
- Stop-the-world phase (atomic)
- Scale of the problem is huge
  - Root set = union of root set of all the threads

Parallel & concurrent GC

- Recall the incremental GC:
  - Find the root set atomically
  - Interleave the **tracing** with mutator
    - remember dirty cards
  - Stop the mutator(s) again to rescan all dirty cards

Parallel & Concurrent GC

- Scan the root set for each **thread** (p)
- Scan the objects in Unscanned state (p & c)
  - In parallel using a **queue**
- **Rescan** for dirty objects (p & c)
  - once or for a fixed number of times
- Stop the mutator & collect the garbage (p)

Conclusion

- Garbage collection is extremely important
- Various types of garbage collection schemes
- Minimizing the **pause time** is the key