Garbage Collection

Reference Counting

Mark-and-Sweep

Short-Pause Methods

The Essence

- Programming is easier if the run-time system "garbage-collects" --- makes space belonging to unusable data available for reuse.
  - Java does it; C does not.
  - But stack allocation in C gets some of the advantage.

Desiderata

1. Speed --- low overhead for garbage collector.
2. Little program interruption.
   - Many collectors shut down the program to hunt for garbage.
3. *Locality* --- data that is used together is placed together on pages, cache-lines.

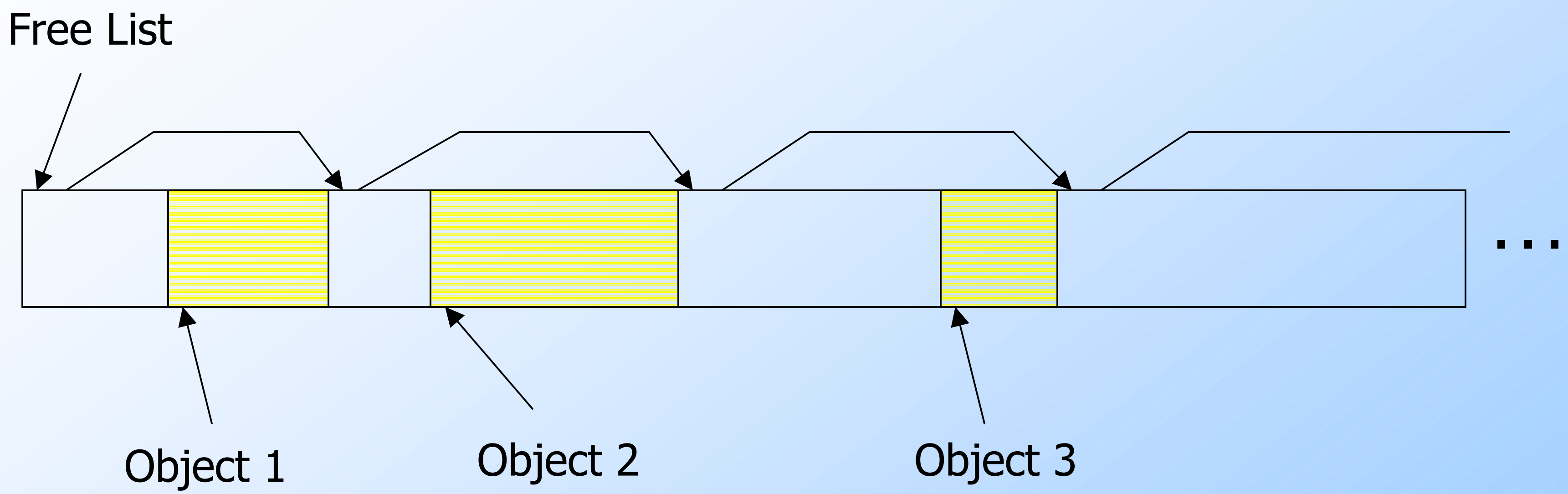
The Model --- (1)

- There is a *root set* of data that is a-priori reachable.
  - Example: In Java, root set = static class variables plus variables on run-time stack.
- *Reachable data* : root set plus anything referenced by something reachable.
- Question: Why doesn't this make sense for C? Why is it OK for Java?

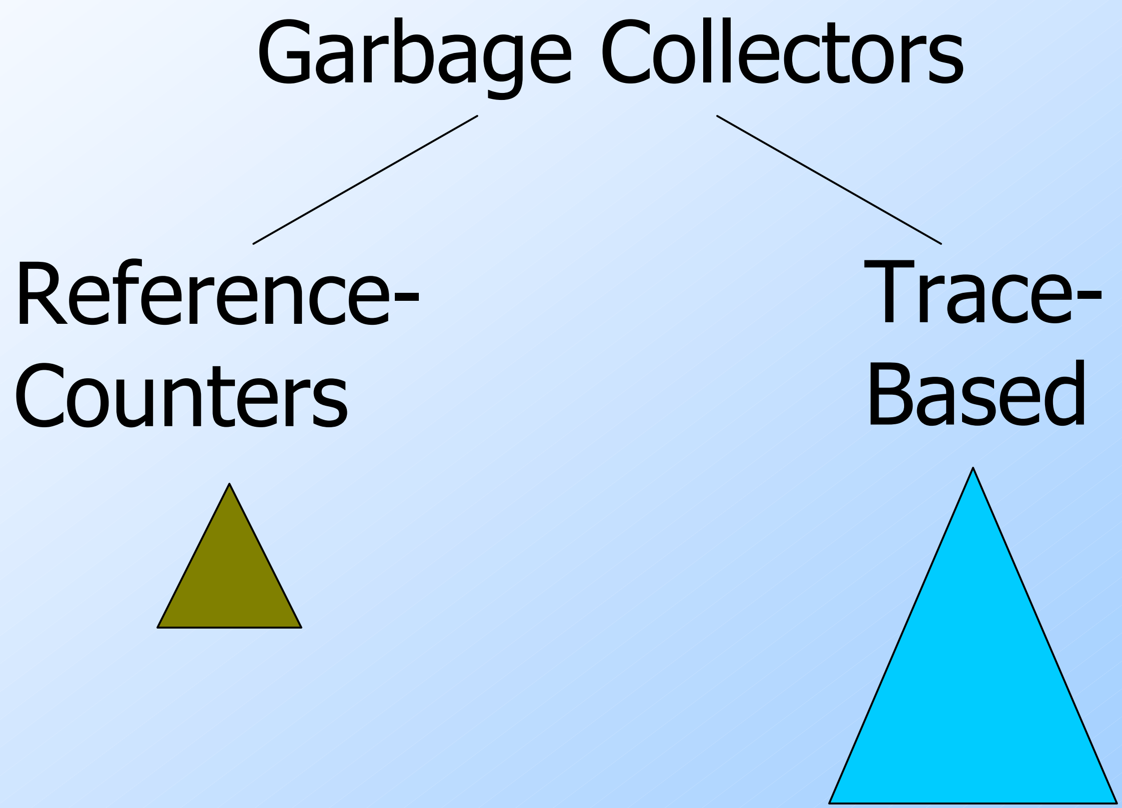
The Model --- (2)

- Things requiring space are "objects."
- Available space is in a *heap* --- large area managed by the run-time system.
  - *Allocator* finds space for new objects.
    - Space for an object is a *chunk*.
  - *Garbage collector* finds unusable objects, returns their space to the heap, and maybe moves objects around in the heap.

A Heap



Taxonomy



Reference Counting

- The simplest (but imperfect) method is to give each object a *reference count* = number of references to this object.
  - OK if objects have no internal references.
- Initially, object has one reference.
- If reference count becomes 0, object is garbage and its space becomes available.

Examples

`Integer i = new Integer(10);`

- Integer object is created with RC = 1.

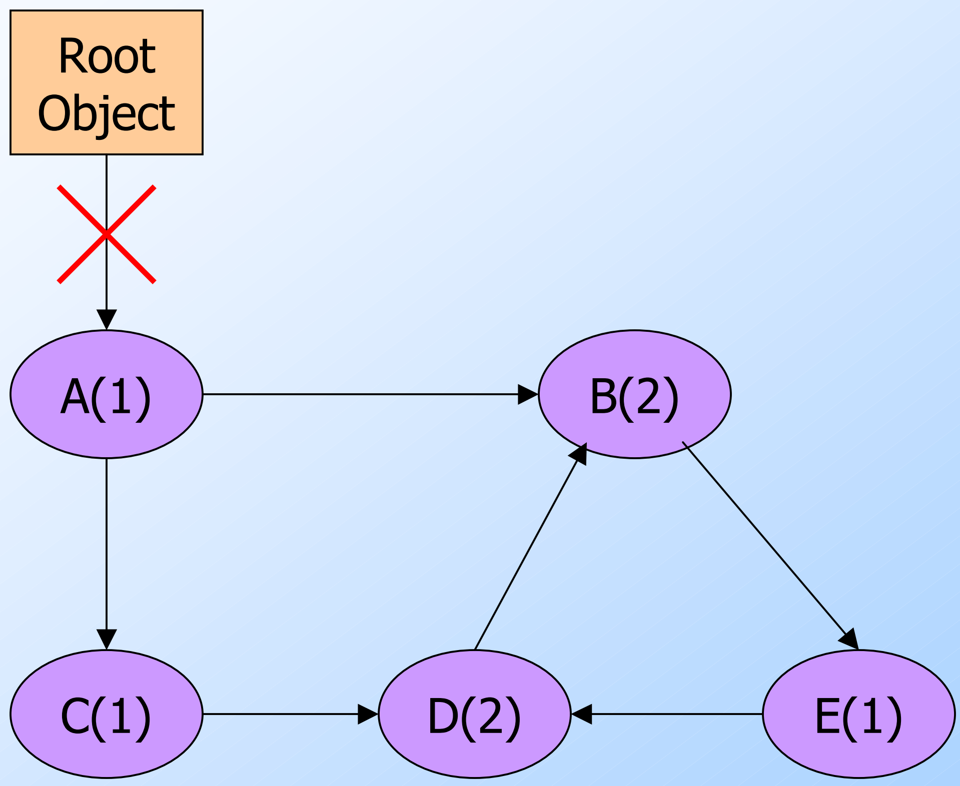
`j = k;` (j, k are Integer references.)

- Object referenced by j has RC--.
- Object referenced by k has RC++.

Transitive Effects

- If an object reaches RC=0 and is collected, the references within that object disappear.
- Follow these references and decrement RC in the objects reached.
- That may result in more objects with RC=0, leading to recursive collection.

Example: Reference Counting



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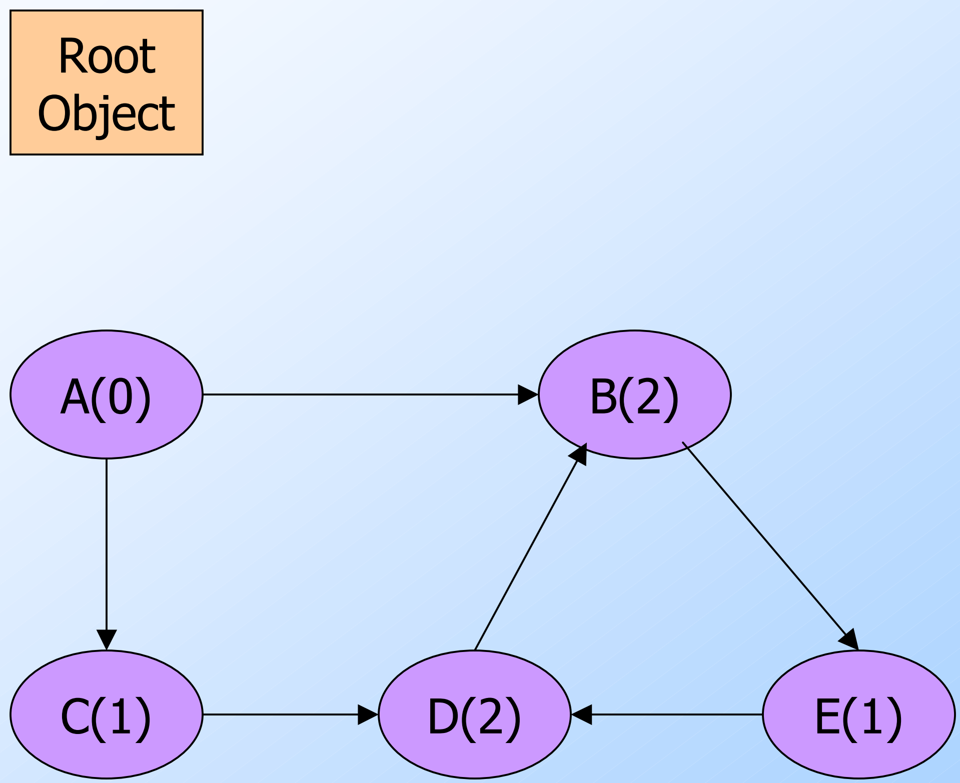

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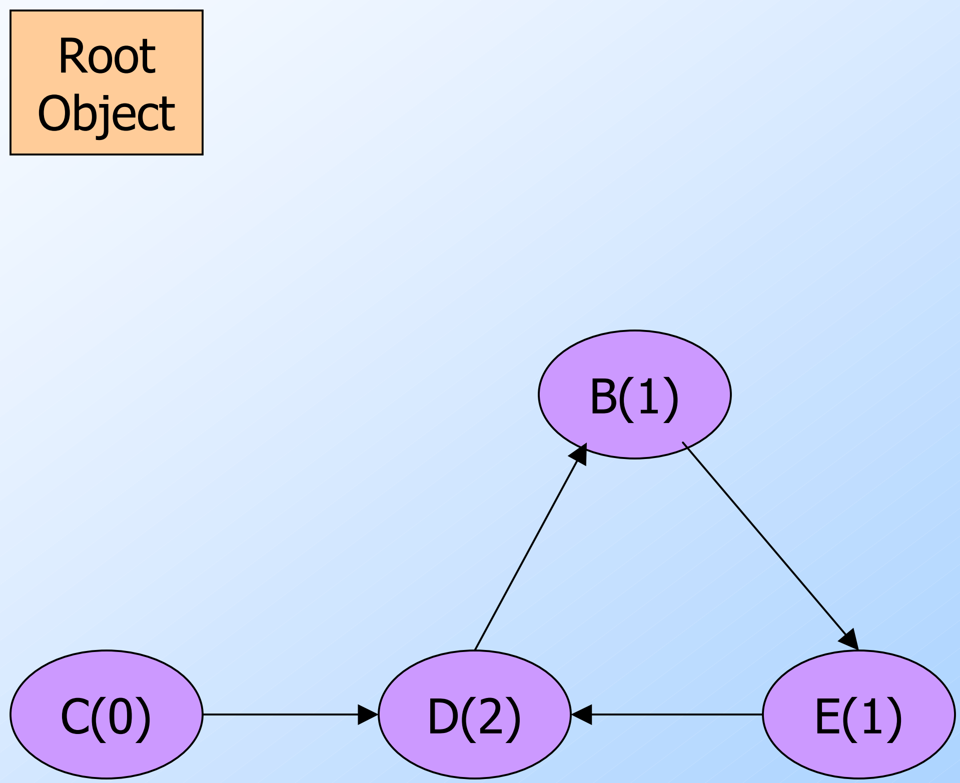

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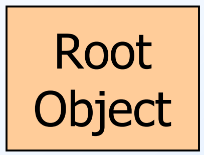
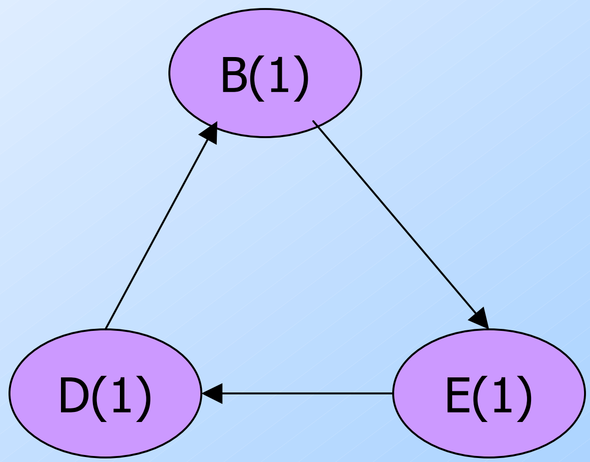


B, D, and E are garbage, but their reference counts are all > 0. They never get collected.



Taxonomy

- Garbage Collectors
  - Reference-Counters
  - Trace-Based
    - Stop-the-World
      - Mark-and-Sweep
        - Basic
      - Mark-and-Compact
    - Short-Pause

Four States of Memory Chunks

1. *Free* = not holding an object; available for allocation.
2. *Unreached* = Holds an object, but has not yet been reached from the root set.
3. *Unscanned* = Reached from the root set, but its references not yet followed.
4. *Scanned* = Reached and references followed.

Marking

1. Assume all objects in Unreached state.
2. Start with the root set. Put them in state Unscanned.
3. **while** Unscanned objects remain **do**

    examine one of these objects;

    make its state be Scanned;

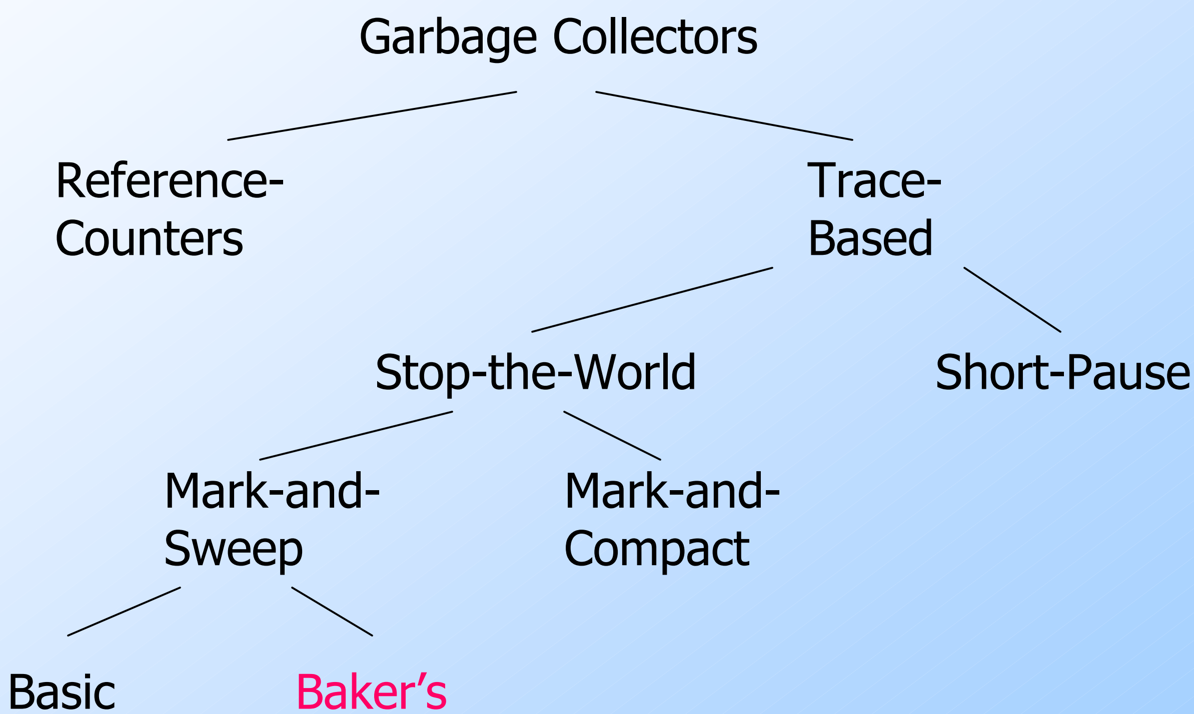
    add all referenced objects to Unscanned if they have not been there;

   end;

Sweeping

- Place all objects still in the Unreached state into the Free state.
- Place all objects in Scanned state into the Unreached state.
  - To prepare for the next mark-and-sweep.

Taxonomy


Garbage Collectors
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Basic
Baker's

Baker's Algorithm --- (1)

- Problem: The basic algorithm takes time proportional to the heap size.
  - Because you must visit all objects to see if they are Unreached.
- Baker's algorithm keeps a list of all allocated chucks of memory, as well as the Free list.

Baker's Algorithm --- (2)

- Key change: In the sweep, look only at the list of allocated chunks.
- Those that are not marked as Scanned are garbage and are moved to the Free list.
- Those in the Scanned state are put in the Unreached state.
  - For the next collection.

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Issue: Why Compact?

- *Compact* = move reachable objects to contiguous memory.
- *Locality* --- fewer pages or cache-lines needed to hold the active data.
- *Fragmentation* --- available space must be managed so there is space to store large objects.

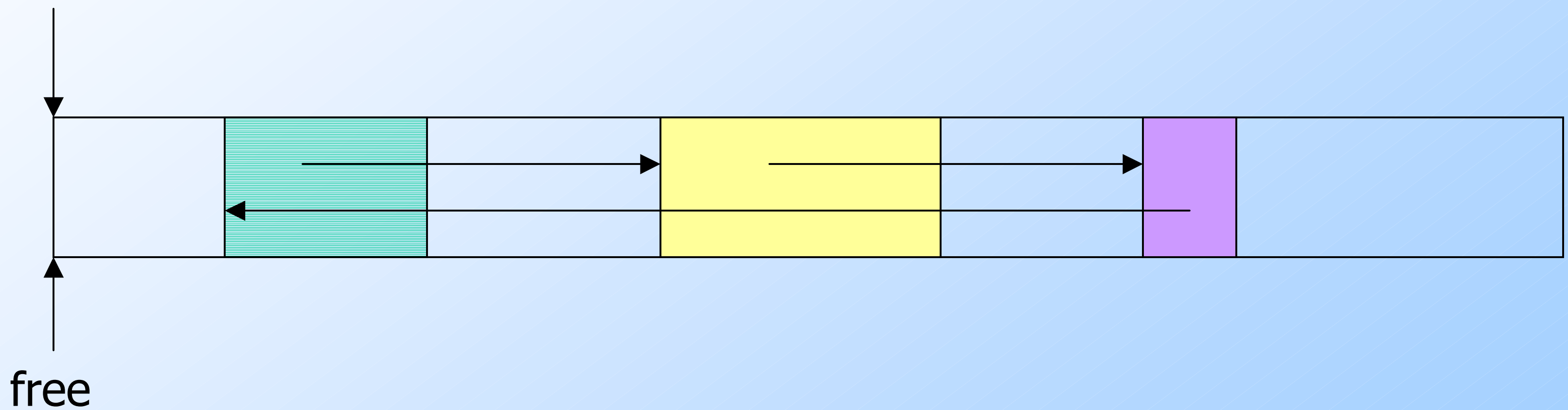
Mark-and-Compact

1. Mark reachable objects as before.
2. Maintain a table (hash?) from reached chunks to new locations for the objects in those chunks.
   - Scan chunks from low end of heap.
   - Maintain pointer *free* that counts how much space is used by reached objects so far.

Mark-and-Compact --- (2)

3. Move all reached objects to their new locations, and also retarget all references in those objects to the new locations.
   - Use the table of new locations.
4. Retarget root references.

Example: Mark-and-Compact



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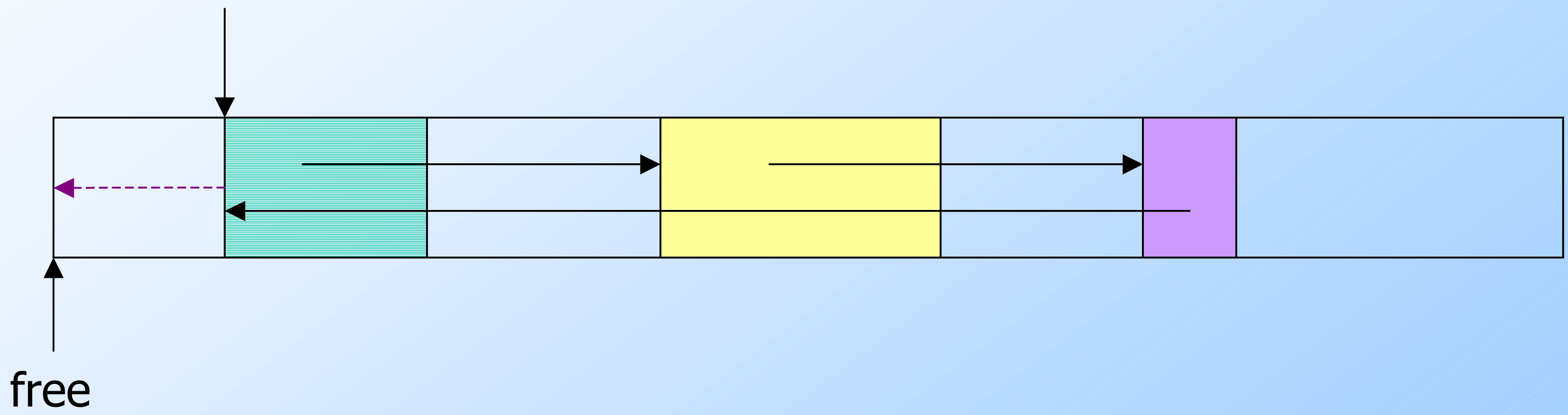

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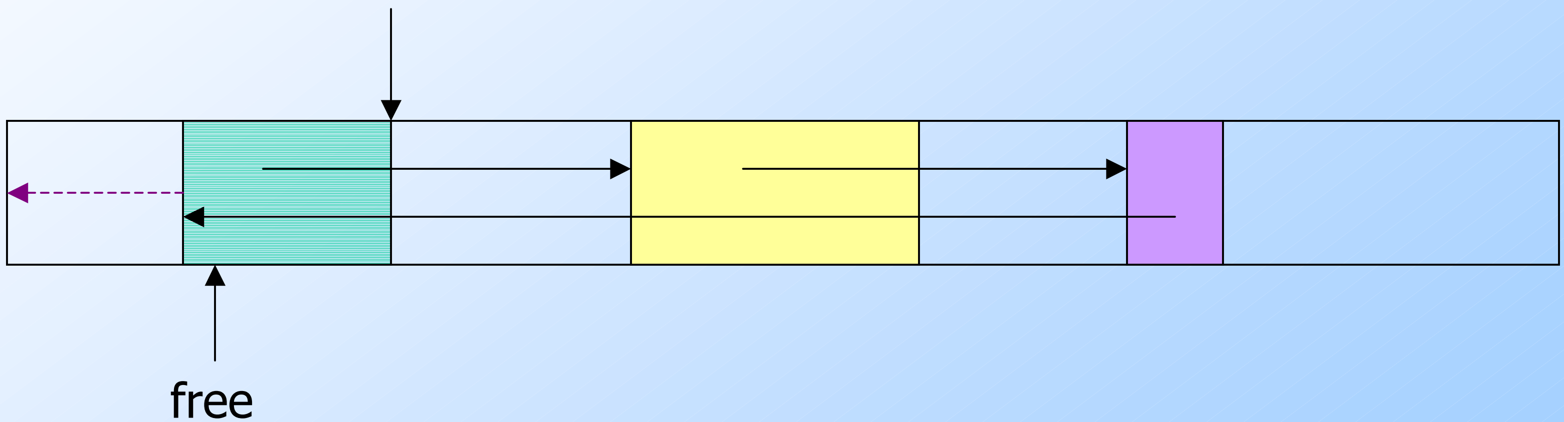

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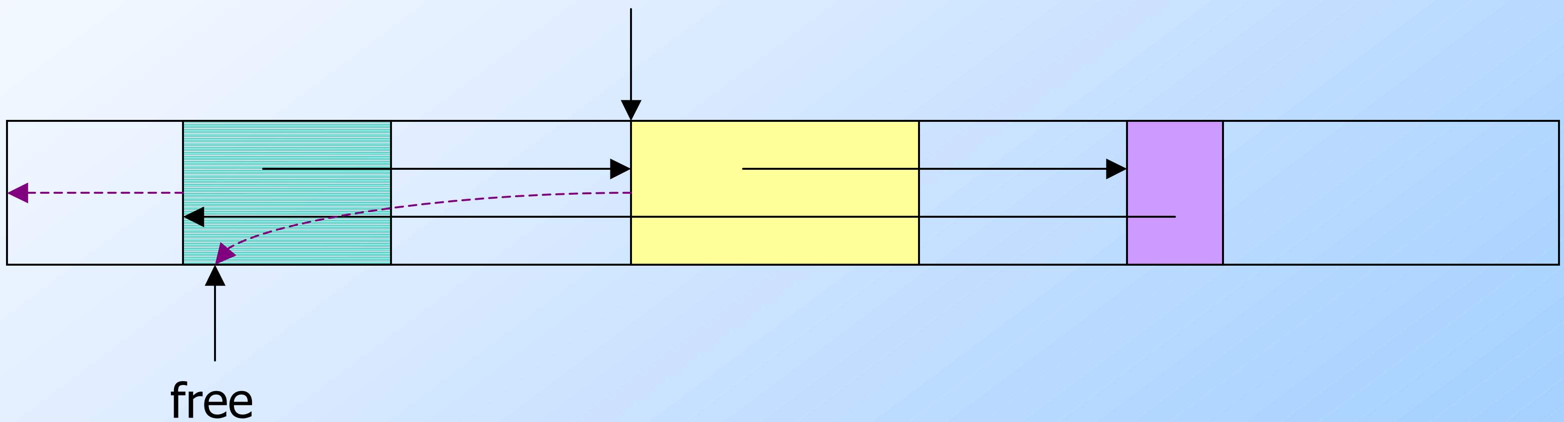

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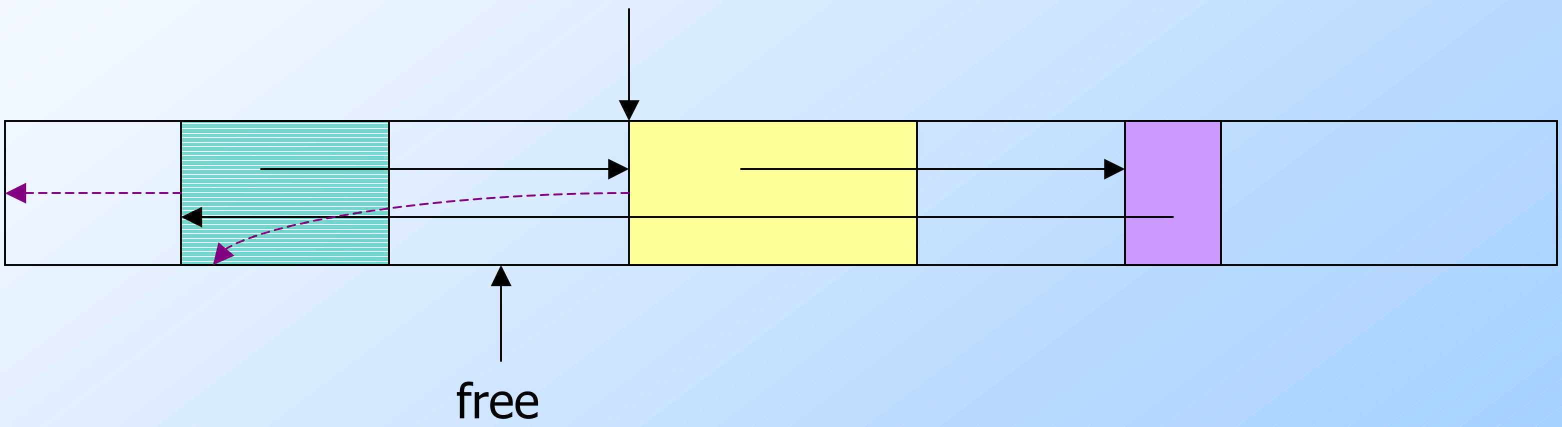

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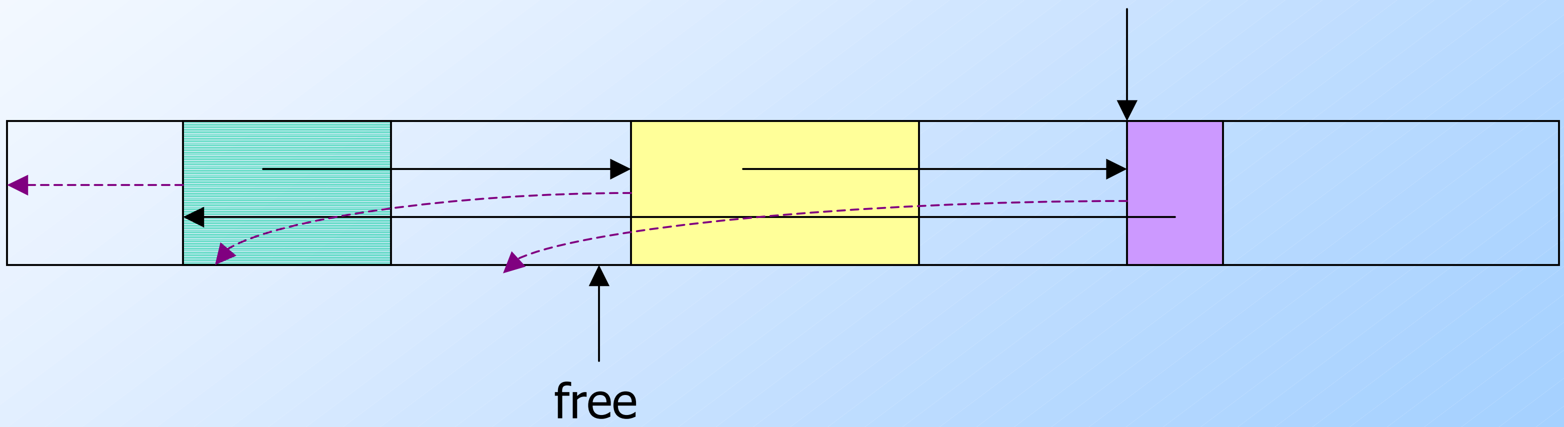

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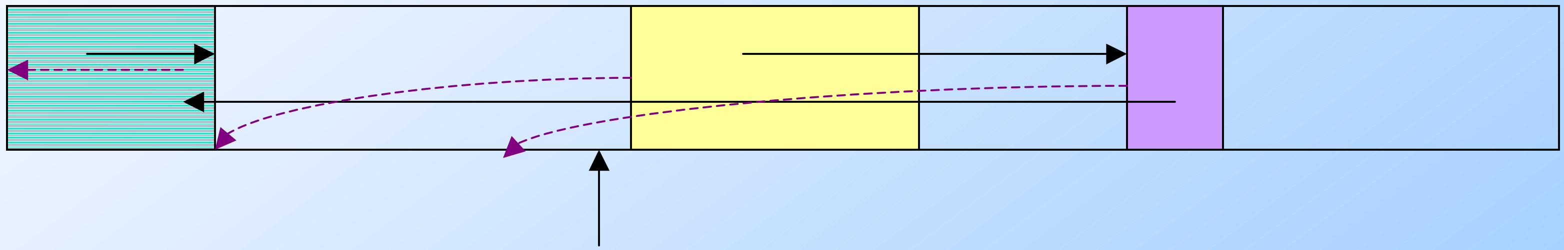

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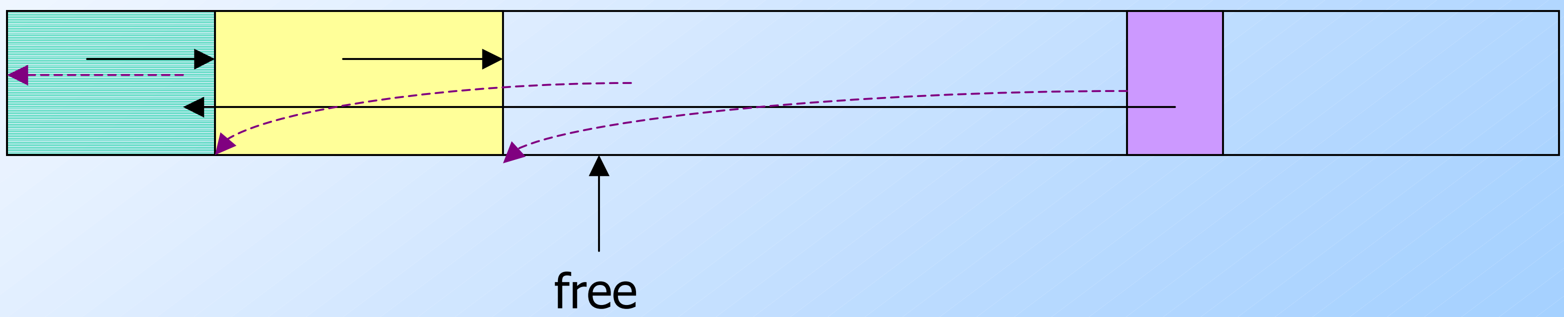

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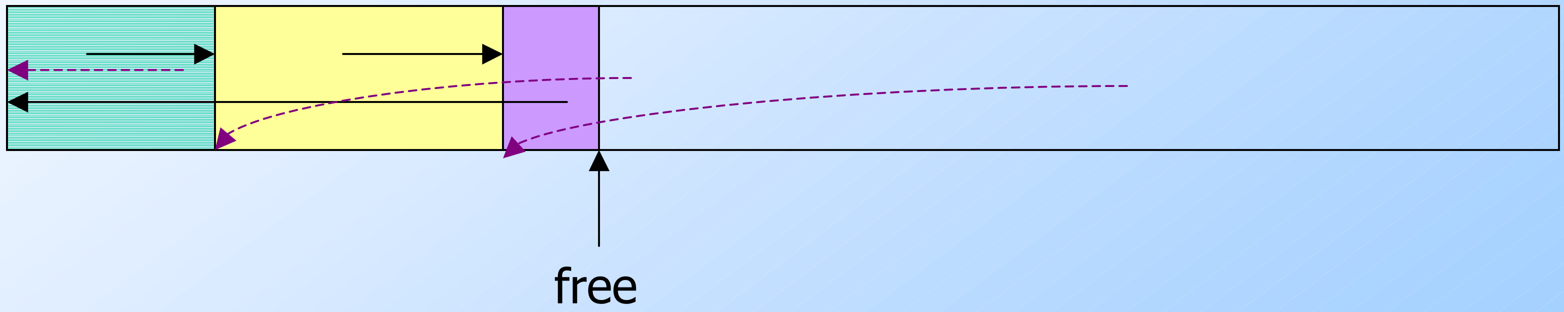

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A different Cheney, BTW, so no jokes, please.

Cheney's Copying Collector

- A shotgun approach to GC.
- 2 heaps: Allocate space in one, copy to second when first is full, then swap roles.
- Maintain table of new locations.
- As soon as an object is reached, give it the next free chunk in the second heap.
- As you scan objects, adjust their references to point to second heap.

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      - Incremental
      - Partial

Short-Pause Garbage-Collection

1. *Incremental* --- run garbage collection in parallel with *mutation* (operation of the program).
2. *Partial* --- stop the mutation, but only briefly, to garbage collect a part of the heap.

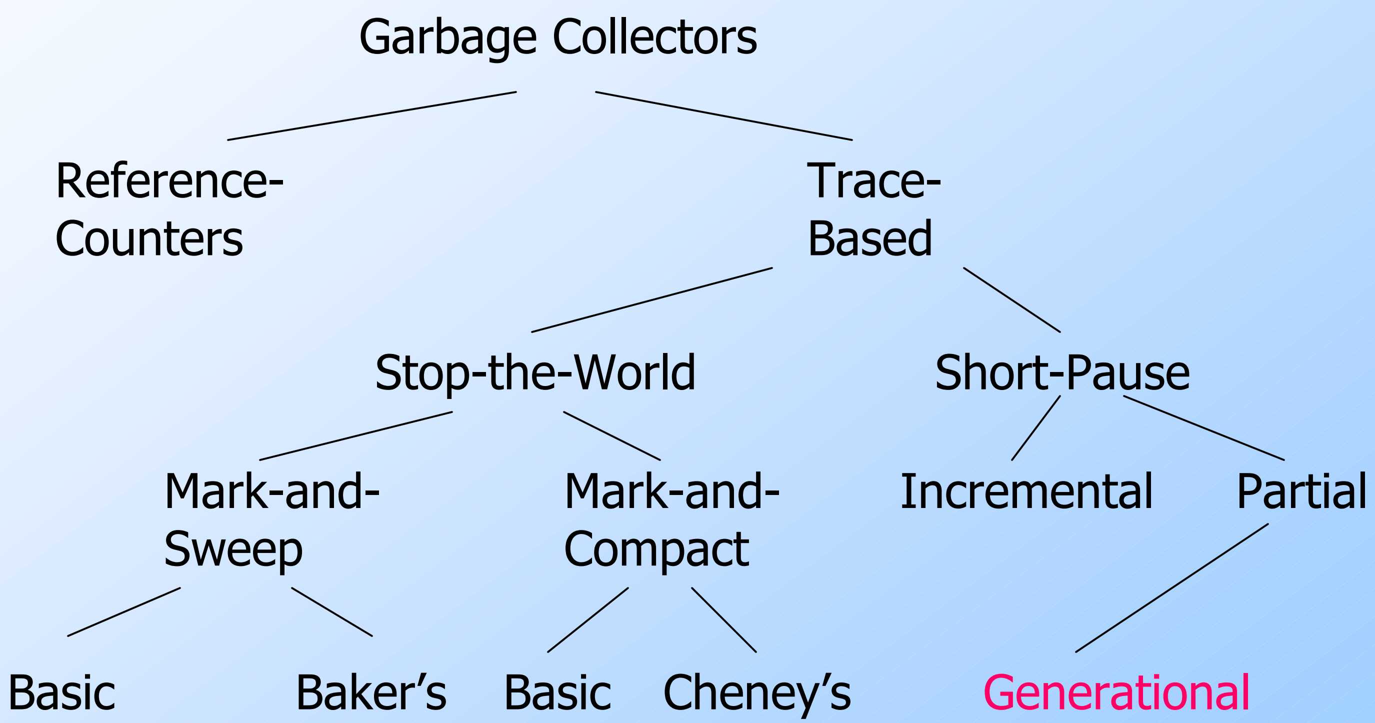
Problem With Incremental GC

- OK to mark garbage as reachable.
- Not OK to GC a reachable object.
- If a reference r within a Scanned object is mutated to point to an Unreached object, the latter may be garbage-collected anyway.
  - Subtle point: How do you point to an Unreached object?

One Solution: *Write Barriers*

- Intercept every write of a reference in a scanned object.
- Place the new object referred to on the Unscanned list.
- A trick: protect all pages containing Scanned objects.
  - A hardware interrupt will invoke the fixup.

Taxonomy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Generational

The Object Life-Cycle

- "Most objects die young."
  - But those that survive one GC are likely to survive many.
- Tailor GC to spend more time on regions of the heap where objects have just been created.
  - Gives a better ratio of reclaimed space per unit time.

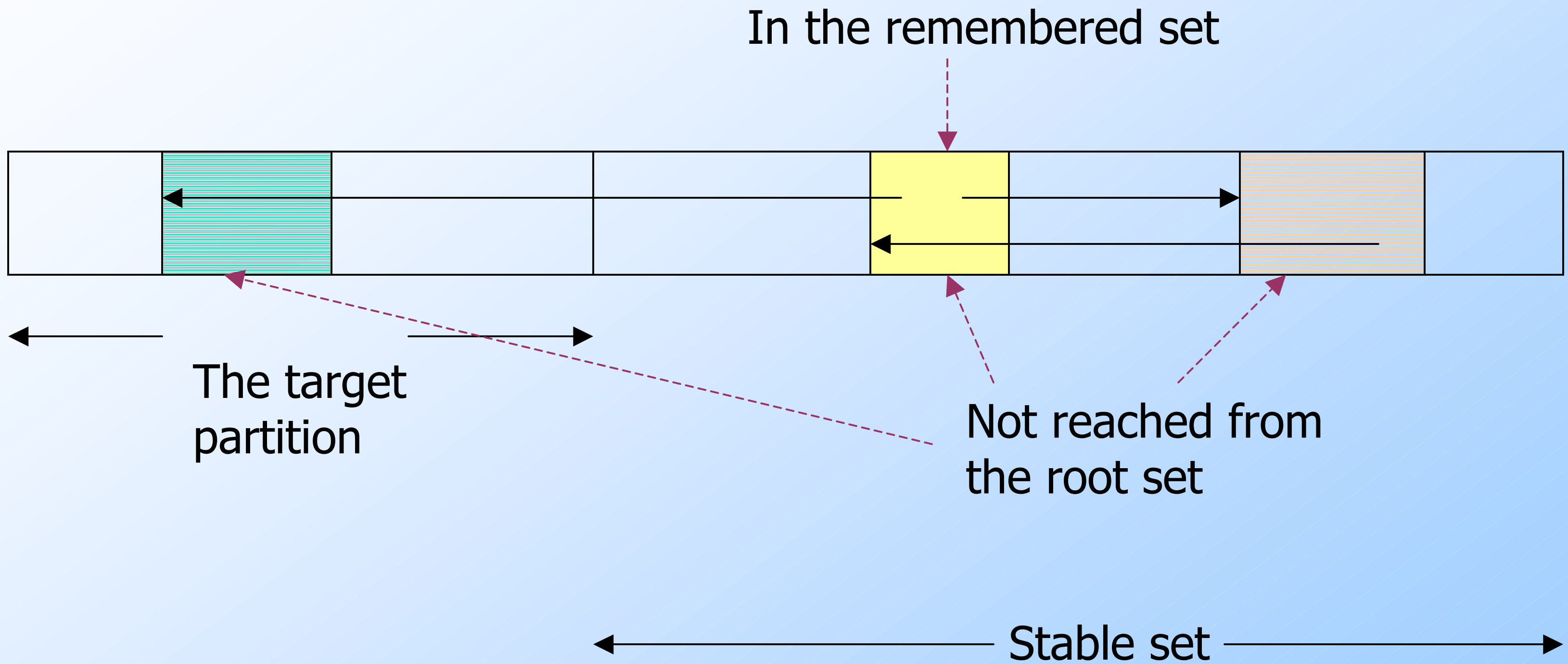
Partial Garbage Collection

- We collect one part(ition) of the heap.
  - The *target* set.
- We maintain for each partition a *remembered* set of those objects outside the partition (the *stable* set) that refer to objects in the target set.
  - Write barriers can be used to maintain the remembered set.

Collecting a Partition

- To collect a part of the heap:
  1. Add the remembered set for that partition to the root set.
  2. Do a reachability analysis as before.
- Note the resulting Scanned set may include garbage.

Example: “Reachable” Garbage



Generational Garbage Collection

- Divide the heap into partitions P0, P1,…
  - Each partition holds older objects than the one before it.
- Create new objects in P0, until it fills up.
- Garbage collect P0 only, and move the reachable objects to P1.

Generational GC --- (2)

- When P1 fills, garbage collect P0 and P1, and put the reachable objects in P2.
- In general: When P*i* fills, collect P0, P1,…,P*i* and put the reachable objects in P(*i*+1).

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      - Incremental
      - Partial
        - Generational
        - Train

The Train Algorithm

- Problem with generational GC:
  1. Occasional total collection (last partition).
  2. Long-lived objects move many times.
- Train algorithm useful for long-lived objects.
  - Replaces the higher-numbered partitions in generational GC.

Partitions = “Cars”

Train 1	Car 11	Car 12	Car 13	
Train 2	Car 21	Car 22	. . .	Car 2k
.				
.				
.				
Train n	Car n1	Car n2		

Organization of Heap

- There can be any number of trains, and each train can have any number of cars.
  - You need to decide on a policy that gives a reasonable number of each.
- New objects can be placed in last car of last train, or start a new car or even a new train.

Garbage-Collection Steps

1. Collect the first car of the first train.
2. Collect the entire first train if there are no references from the root set or other trains.
   - Important: this is how we find and eliminate large, cyclic garbage structures.

Remembered Sets

- Each car has a remembered set of references from later trains and later cars of the same train.
- Important: since we only collect first cars and trains, we never need to worry about “forward” references (to later trains or later cars of the same train).

Collecting the First Car of the First Train

- Do a partial collection as before, using every other car/train as the stable set.
- Move all Reachable objects of the first car somewhere else.
- Get rid of the car.

Moving Reachable Objects

- If object o has a reference from another train, pick one such train and move o to that train.
  - Same car as reference, if possible, else make new car.
- If references only from root set or first train, move o to another car of first train, or create new car.

Panic Mode

- The problem: it is possible that when collecting the first car, nothing is garbage.
- We then have to create a new car of the first train that is essentially the same as the old first car.

Panic Mode --- (2)

- If that happens, we go into *panic mode*, which requires that:
  1. If a reference to any object in the first train is rewritten, we make the new reference a "dummy" member of the root set.
  2. During GC, if we encounter a reference from the "root set," we move the referenced object to another train.

Panic Mode --- (3)

- Subtle point: If references to the first train never mutate, eventually all reachable objects will be sucked out of the first train, leaving cyclic garbage.
- But perversely, the last reference to a first-train object could move around so it is never to the first car.