Mostly Concurrent Garbage Collection

Ausgewählte Kapitel der Systemsoftware

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TECHNISCHE FAKULTÄT

A Simple Server Program...

```c
int socket = ...;

// Accept and handle connection after connection
while (true) {
    int connection = accept(socket, NULL, NULL);
    // do stuff
    struct task *currentTask
        = malloc(sizeof(struct task));
    // do more stuff
    if (someError)
        continue;
    // do even more stuff
    // we have done ALL the stuff and can clean up
    free(currentTask);
    close(connection);
}
```

…May Not Be So Simple after All

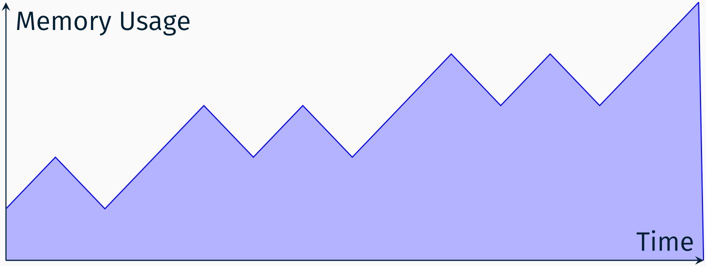

Figure 1: Memory Usage over Time

...May Not Be So Simple after All

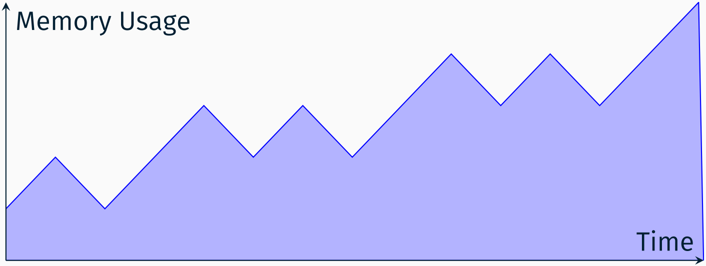

Figure 1: Memory Usage over Time

Problem: Out of Memory

forgotten `free()` call → memory leak

More Memory Management, More Problems

```c
struct list *list = ... // [1, 2, -3, 0, 1]
struct list *min = list;
for (struct list *curr = list; curr->next != NULL;
 ↪  curr = curr->next) {
    if (curr->value < min->value) min = curr;
    free(curr); // We only traverse the list once,
     ↪  so let's get rid of unused objects
}
// Add an element to another list
struct list *list2 = malloc(sizeof(struct list));
list2->value = 3;
// Everything is still alright. Right? Right?!
assert(min->value == -3);
```

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Problem: *Maybe* Corrupted Data

`free()` call on in-use object → subsequent allocation may re-use heap space

Manual memory management is *hard!*

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Better automatic, but needs to be *correct* and *fast*

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Automatic Memory Management with Tracing Garbage Collectors

Tracing Garbage Collection

Idea

- known set of in-use objects and references (*root set*)
- recursively follow pointers and remember visited objects
- only unreachable objects remain unvisited

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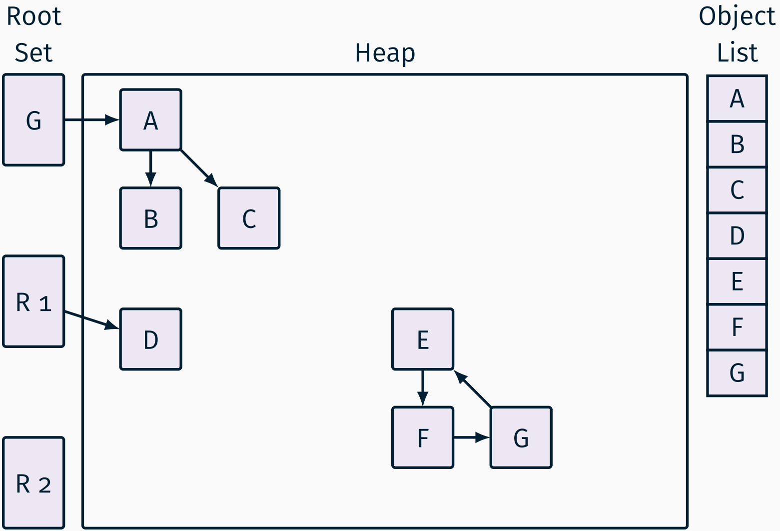
Requirements

- determination of root set
- pointer identification
- integration with memory allocator

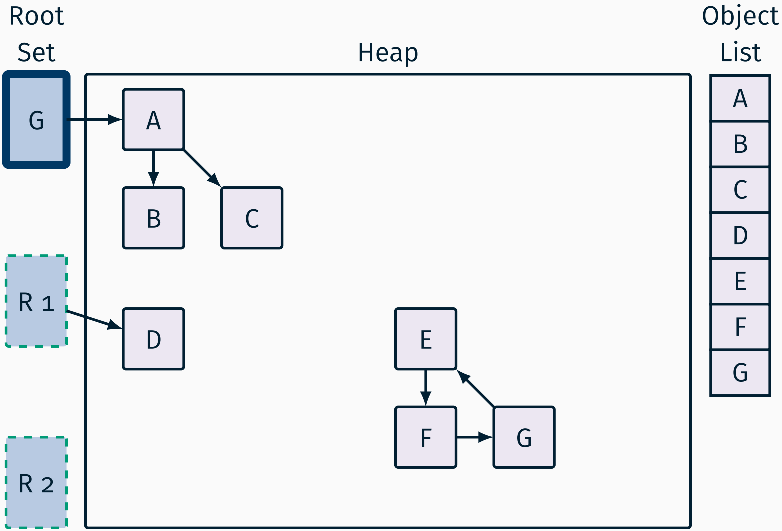
Simple Idea: Mark-and-Sweep Garbage Collection

1. Stop the application (“stop the world” [STW])
2. Trace from root set (*mark* phase)
3. Collect unmarked objects (*sweep* phase)
4. Reset all marks
5. Resume the application

Mark-and-Sweep GC by Example: Heap State at GC Invocation



Mark-and-Sweep GC by Example: Mark Phase



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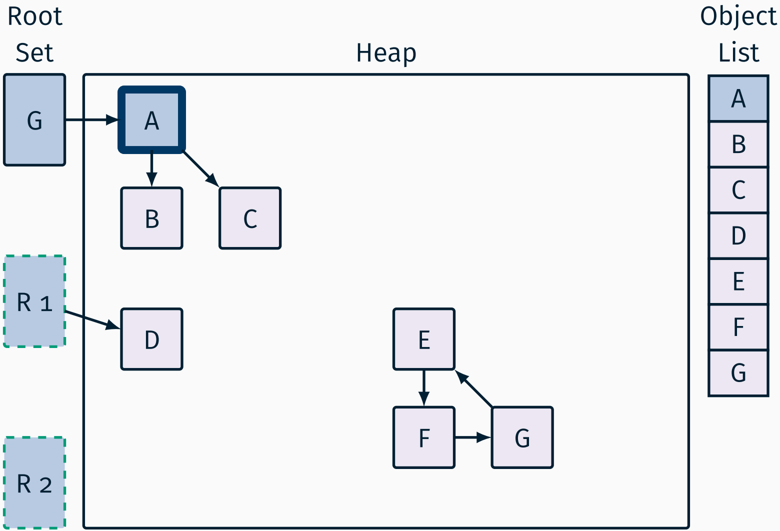

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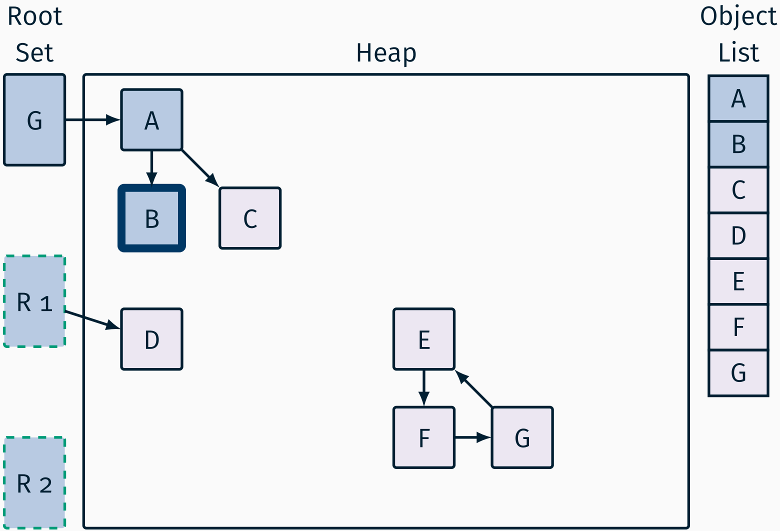

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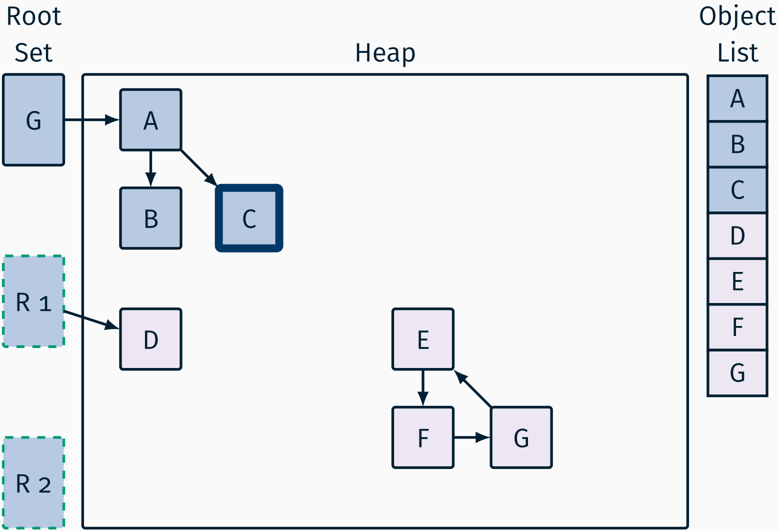

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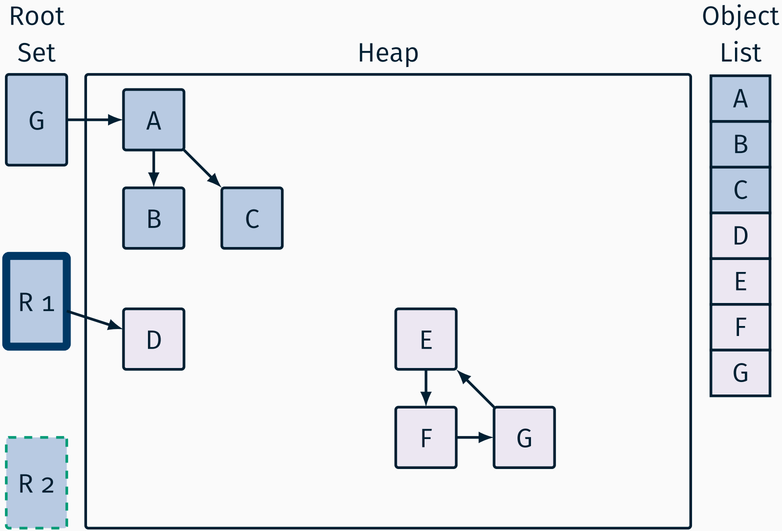

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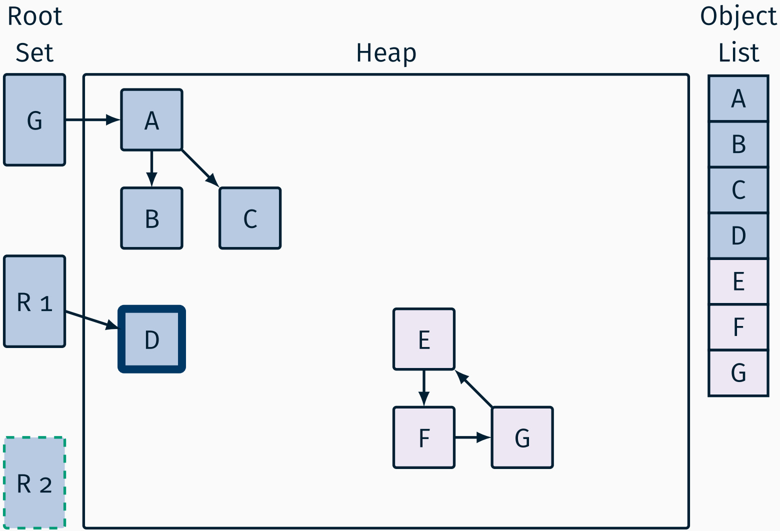

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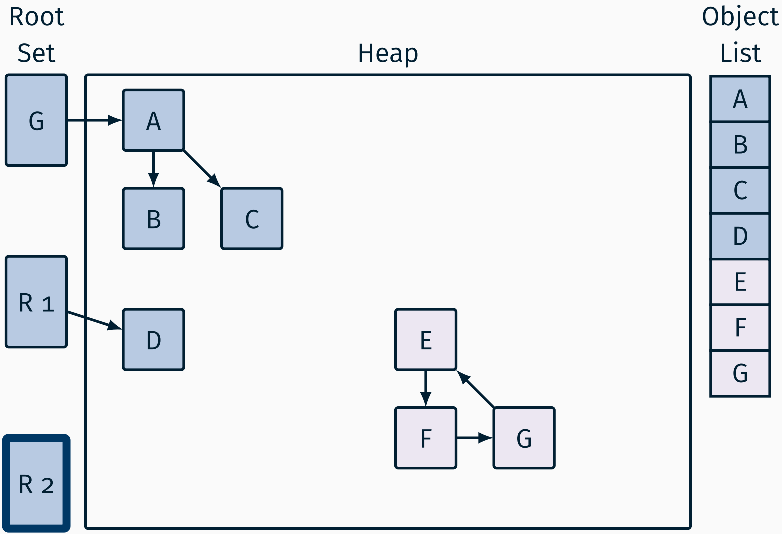
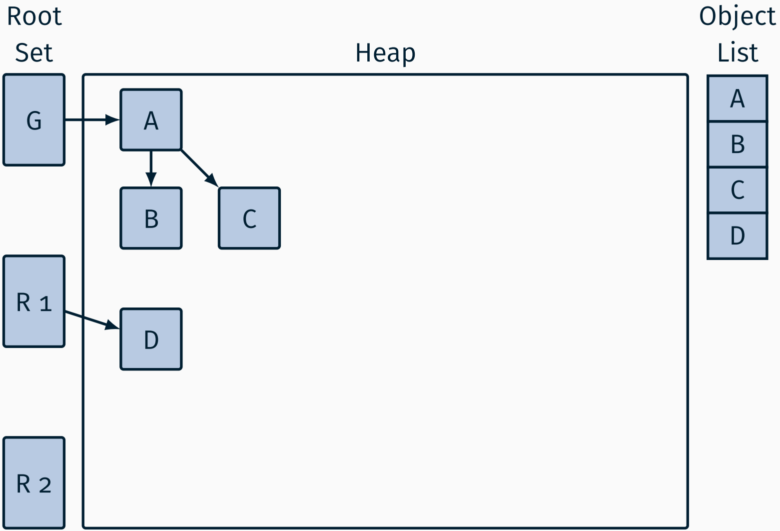
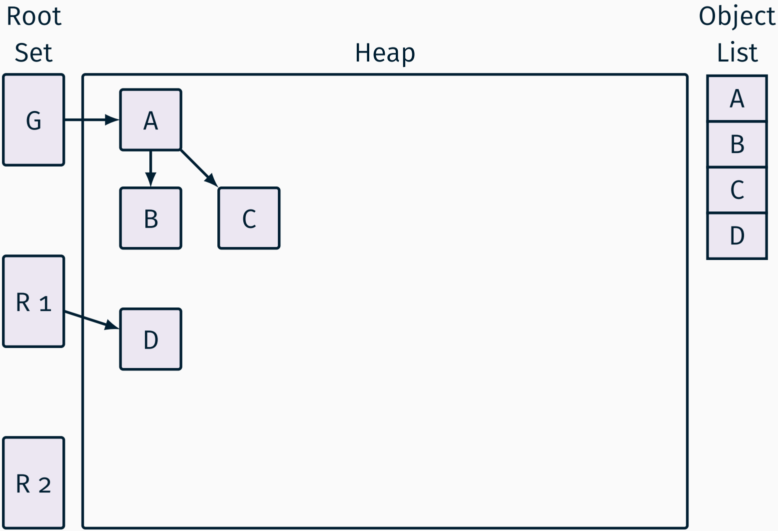


Mark-and-Sweep GC by Example: Sweep Phase



Mark-and-Sweep GC by Example: Reset Mark Bits



Generational Garbage Collection

Insight: Young objects are more likely to die!

Treat young and old objects differently:

- collect young generation often
- collect old generation less frequently

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Important

Pointers from old generation into young generation must be tracked!

There Is No Free Lunch!

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Problems

- both schemes require to stop the world

  $\rightarrow$ long pauses
- intolerable for GUI applications and web services

“Mostly-Parallel Garbage Collection” by Boehm et al.

Mostly Concurrent Garbage Collection

Grand Idea

Run GC *concurrently* with application (*mutator*) for shorter pauses

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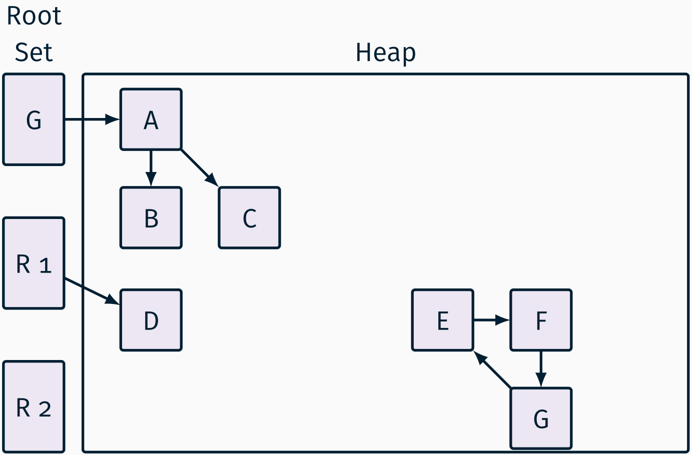
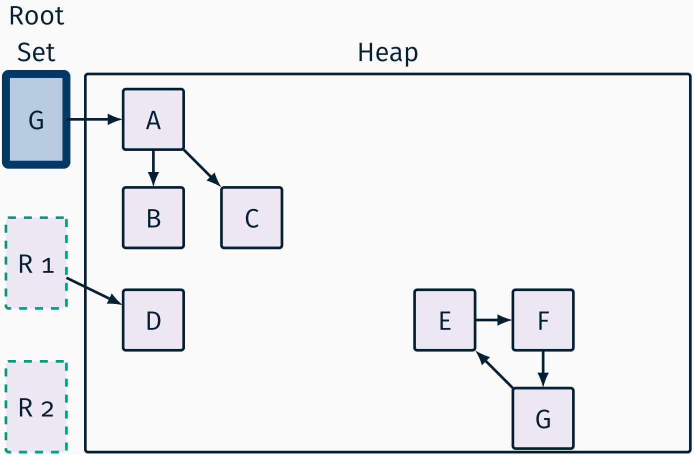
Problem

Mutator changes objects while GC traverses heap!

Problem of the Lost Objects: GC Invocation



Problem of the Lost Objects: Marking



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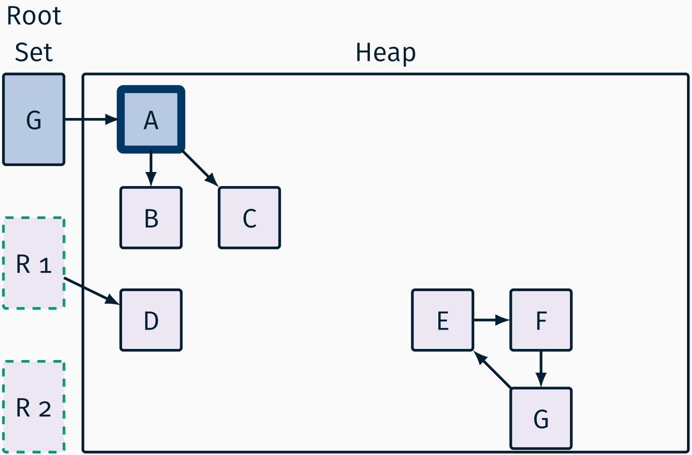

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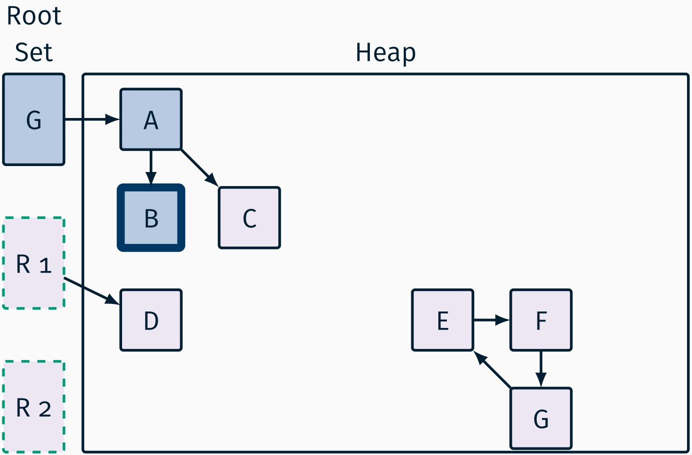

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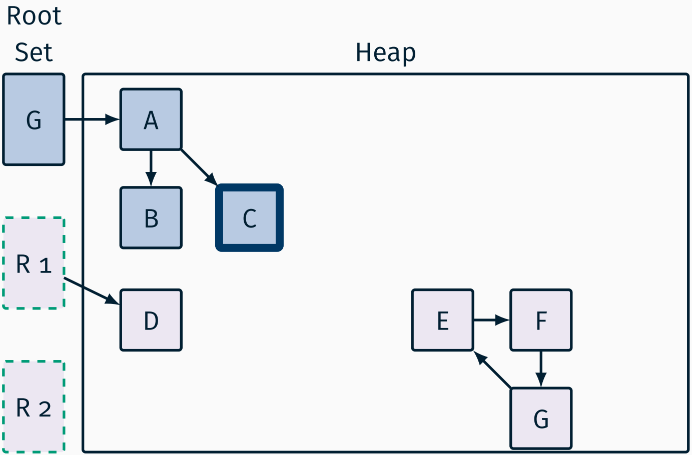

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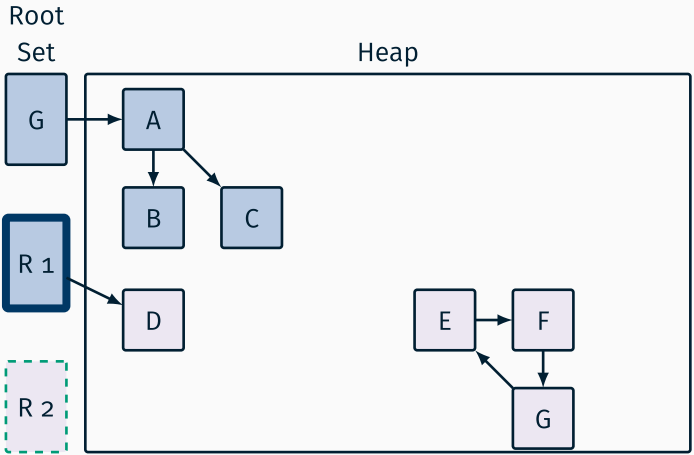

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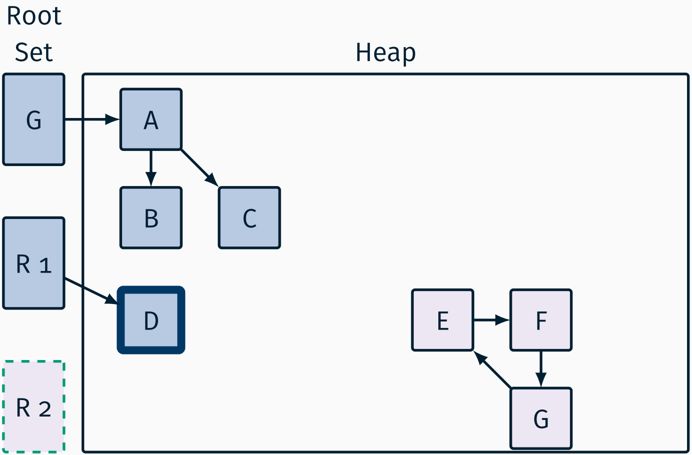
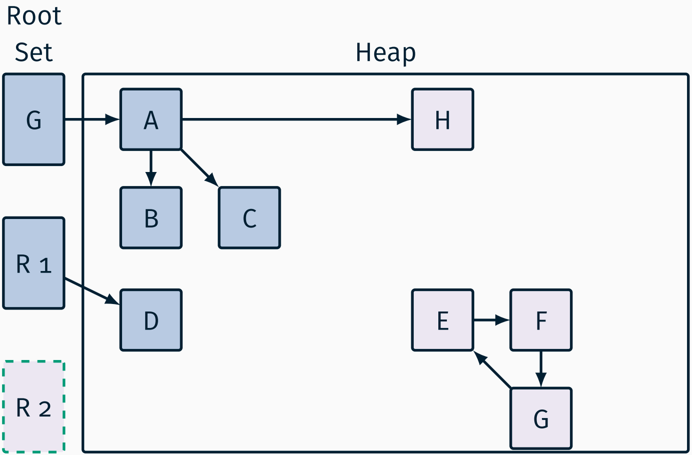
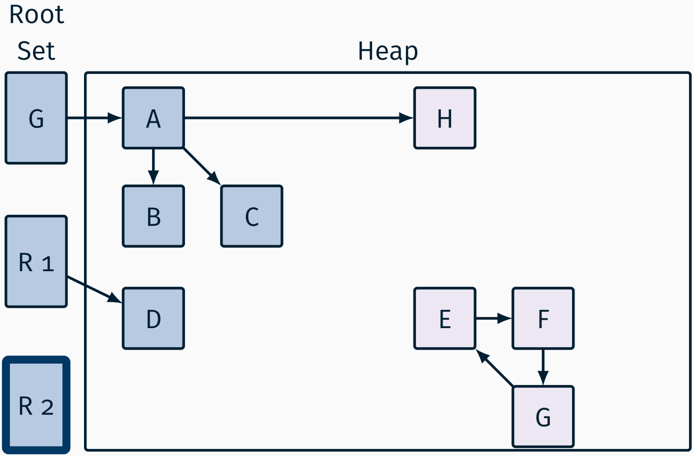


Problem of the Lost Objects: Program Allocates New Object



Problem of the Lost Objects: Marking Complete



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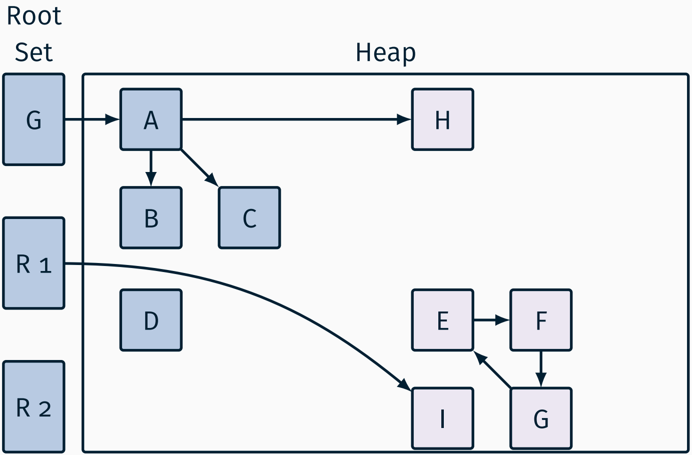
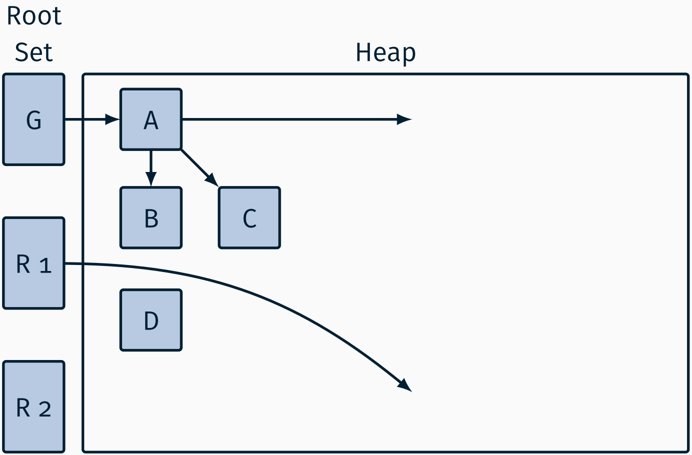
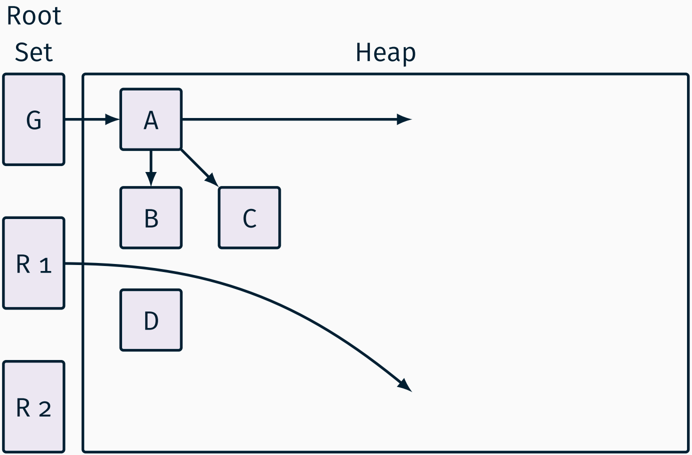


Problem of the Lost Objects: Sweep of Unmarked Objects



Problem of the Lost Objects: GC Cycle Complete



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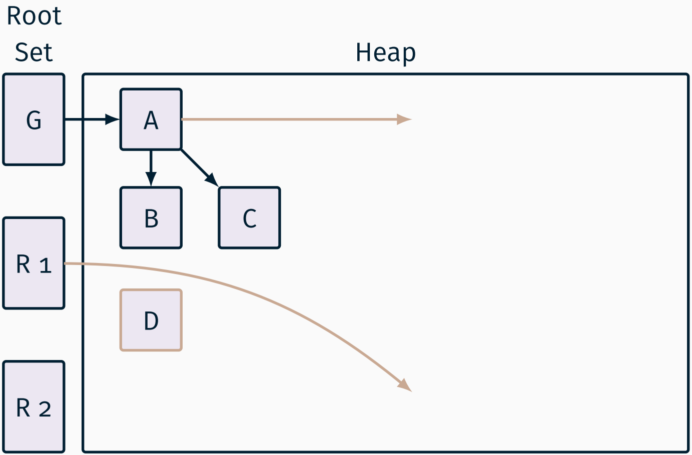


Problems

two still-needed objects removed, unneeded object retained

Mostly Concurrent Garbage Collection

Grand Idea

Run GC *concurrently* with application (*mutator*) for shorter pauses

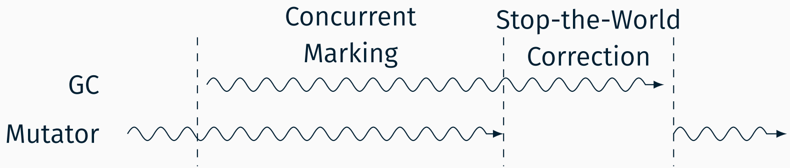
Problem

Mutator changes objects while GC traverses heap!

Solution: Synchronisation

→ mark in parallel with mutator and record all writes to objects

→ short stop-the-world correction phase



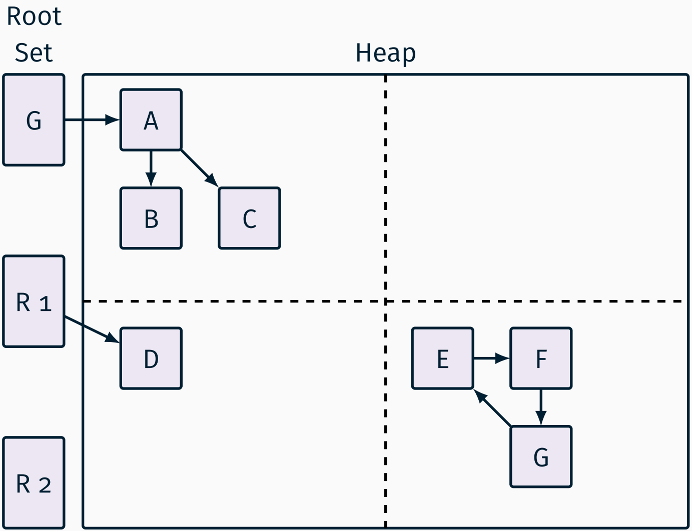
Proposed Algorithm

- Use MMU for recording writes:
  - Dirty page bits indicate writes with page-size granularity
  - if clean, traversed graph is correct: no references from marked to unmarked objects could have been added
  - if dirty, rescan the page: marking from marked objects suffices
- generational collection: marked objects are *old*
- conservative: works even without explicit compiler assistance

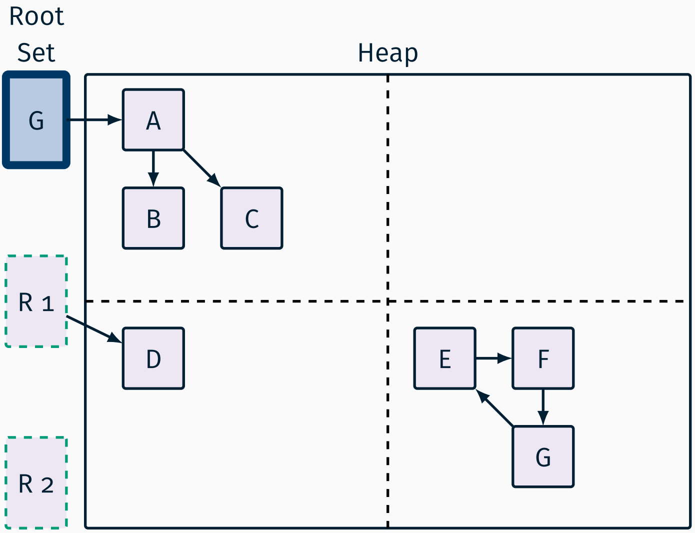
Full Collection

1. Clear all mark and dirty bits
2. Mark all objects in the root set and recursively trace from them
3. Stop the world
4. Trace from registers and all marked objects on dirty pages
5. Clear dirty bits and restart the world

Full Collection: GC Invocation



Concurrent Marking



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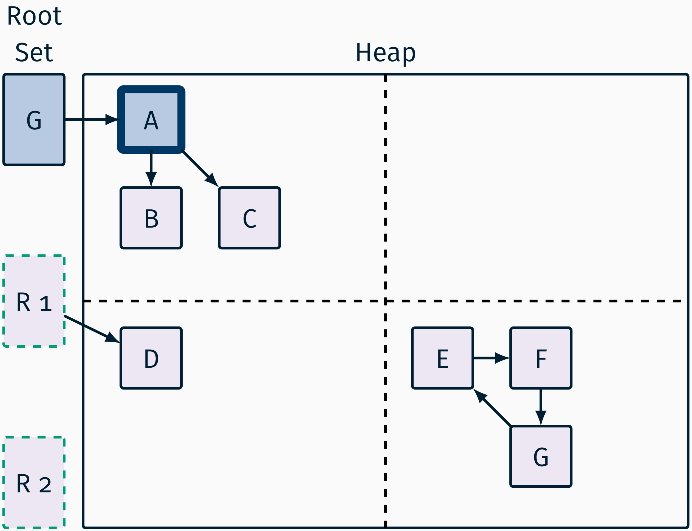

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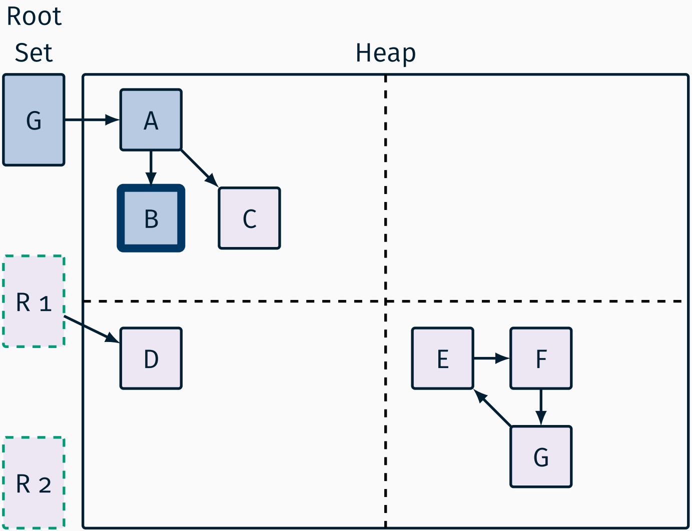

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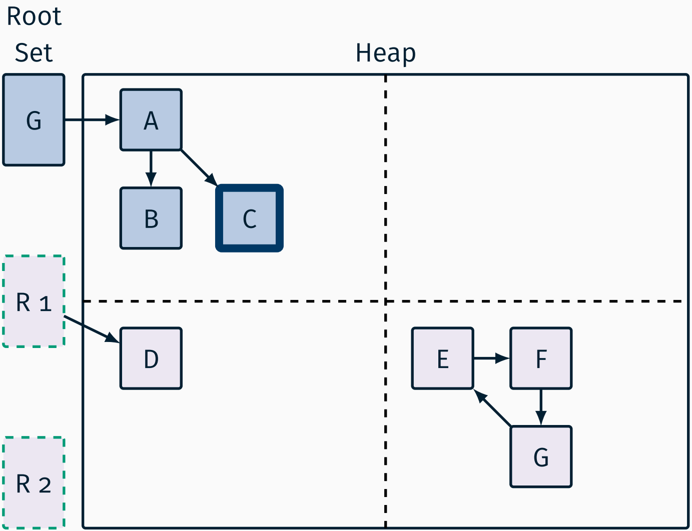

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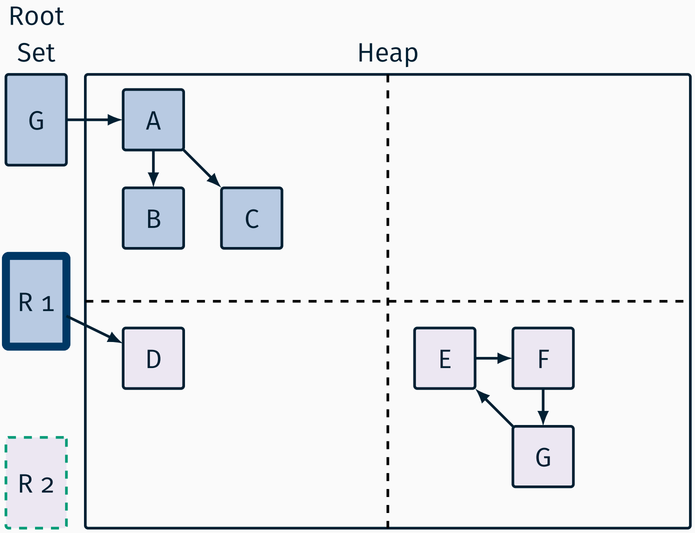

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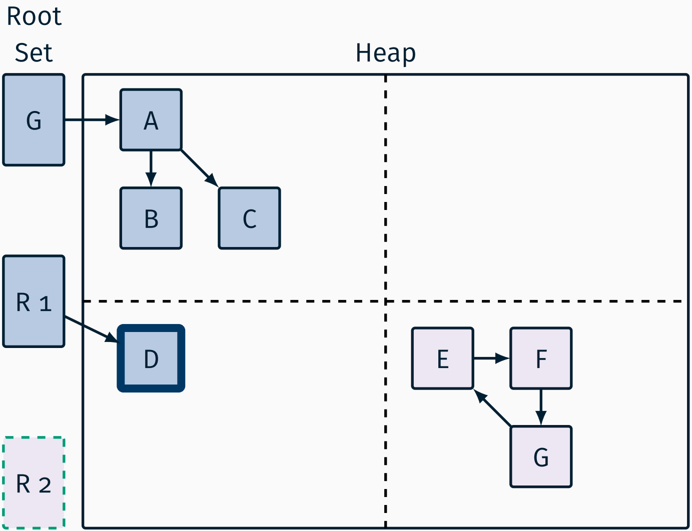
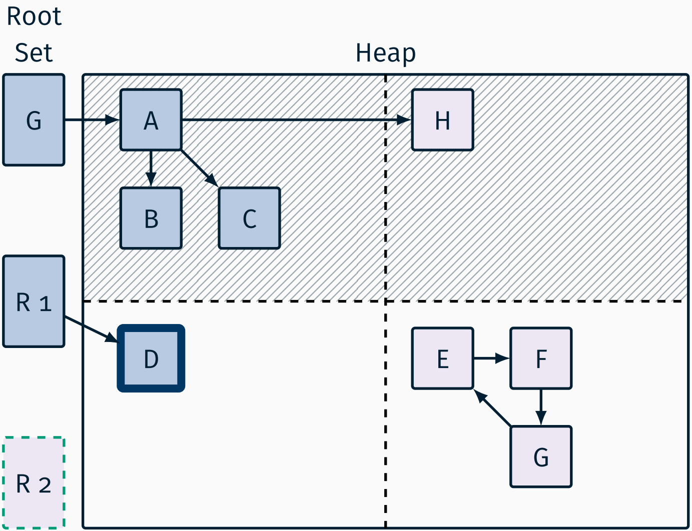
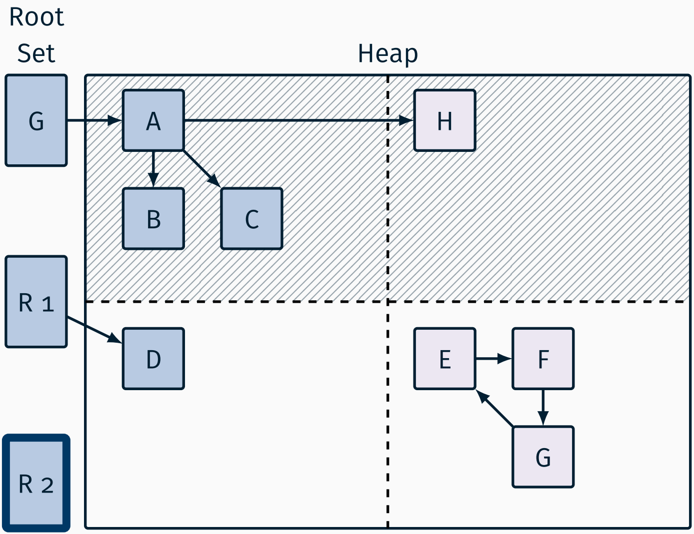


Program Allocates New Object



Concurrent Marking Complete



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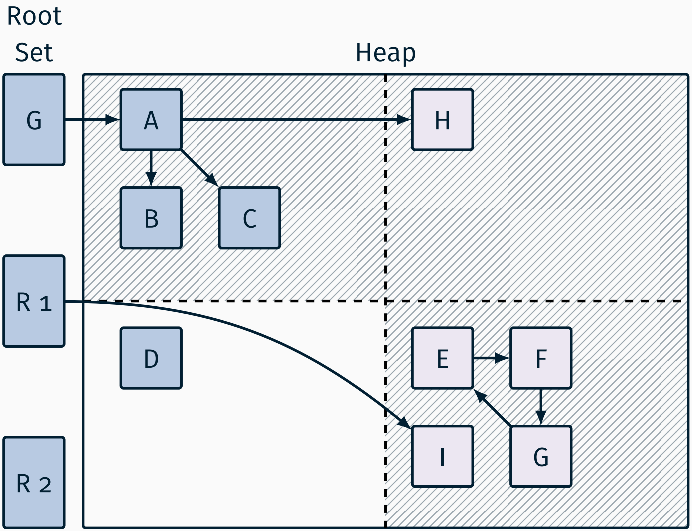
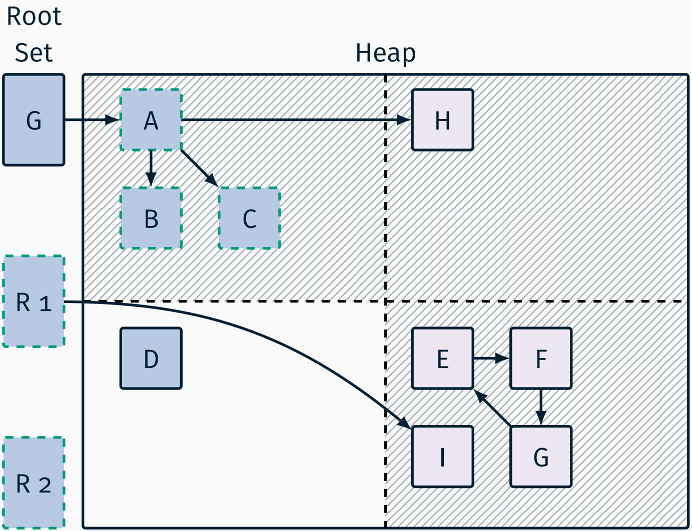


STW Correction Marking From Marked Objects on Dirty Pages



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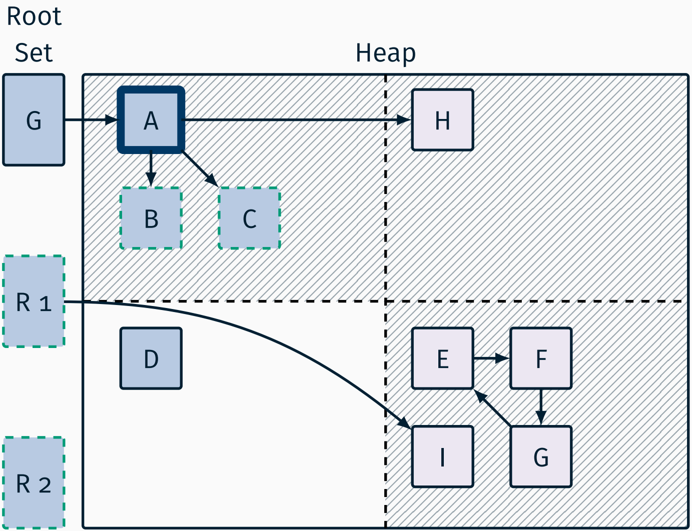

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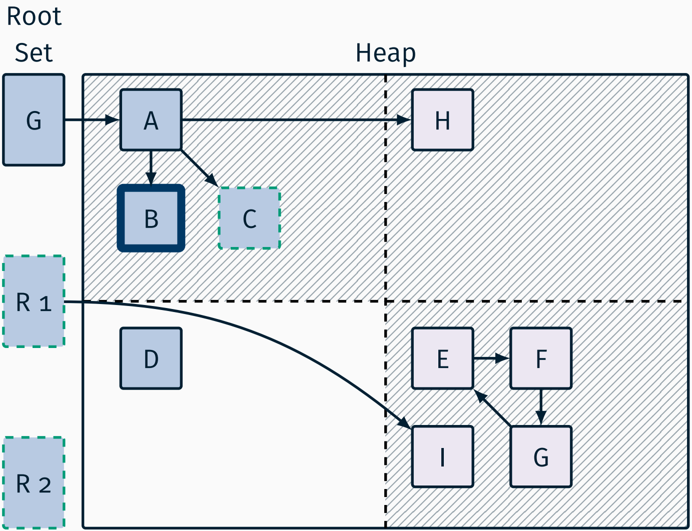

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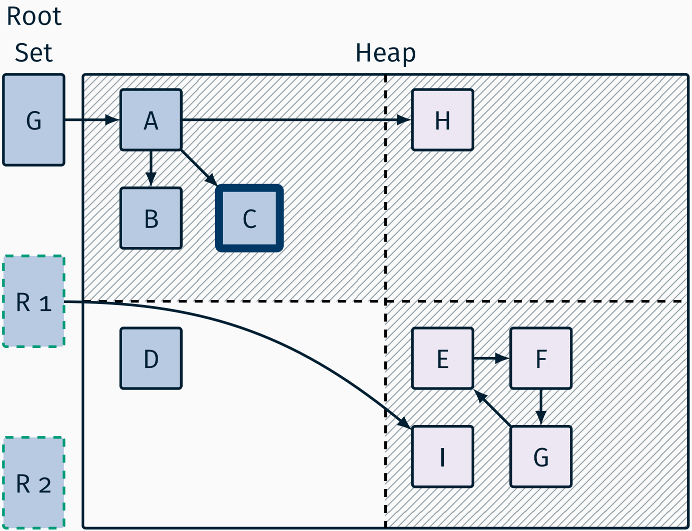

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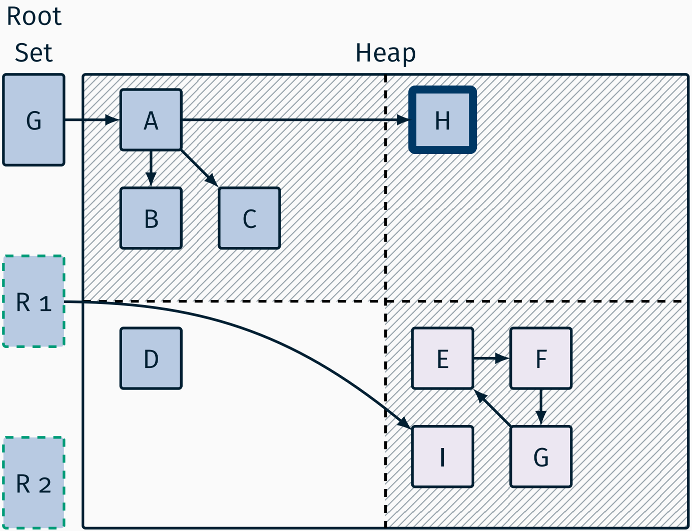
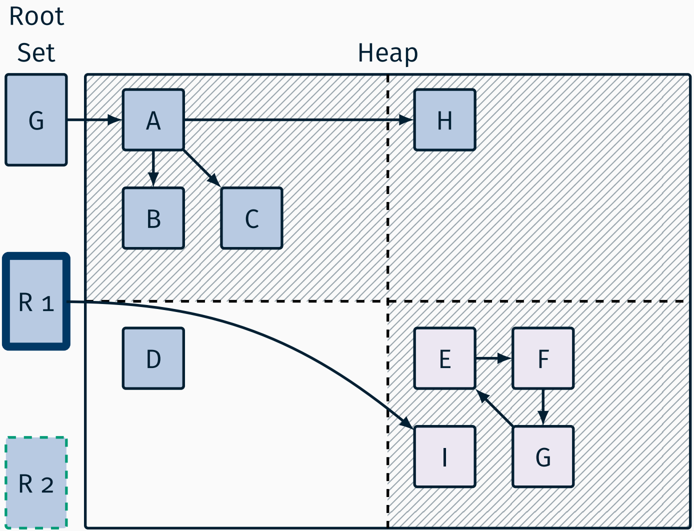


STW Correction Marking From Registers



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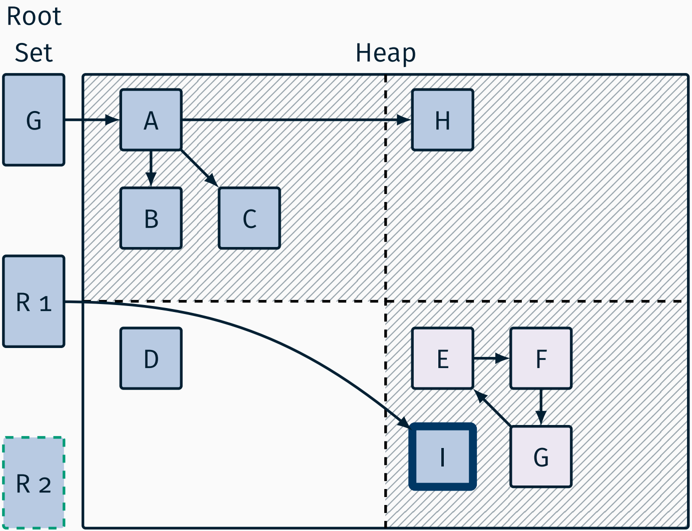

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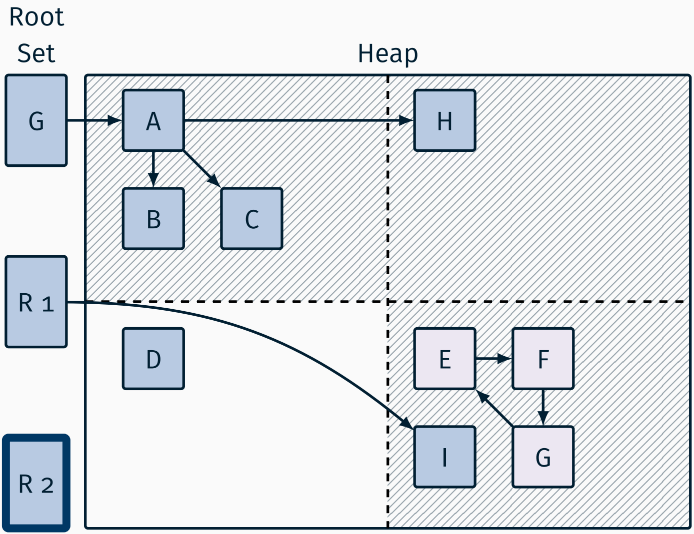
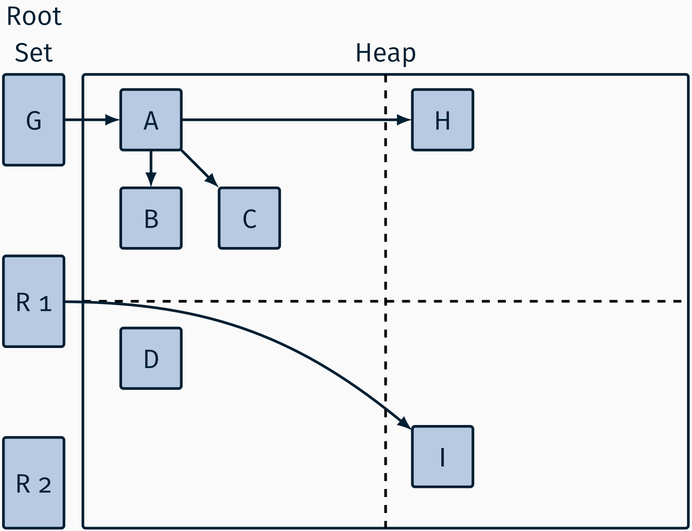


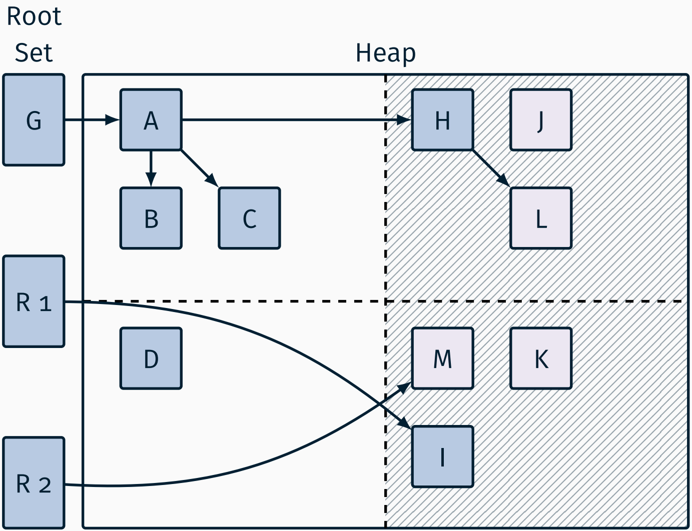
Full Collection Cycle Complete



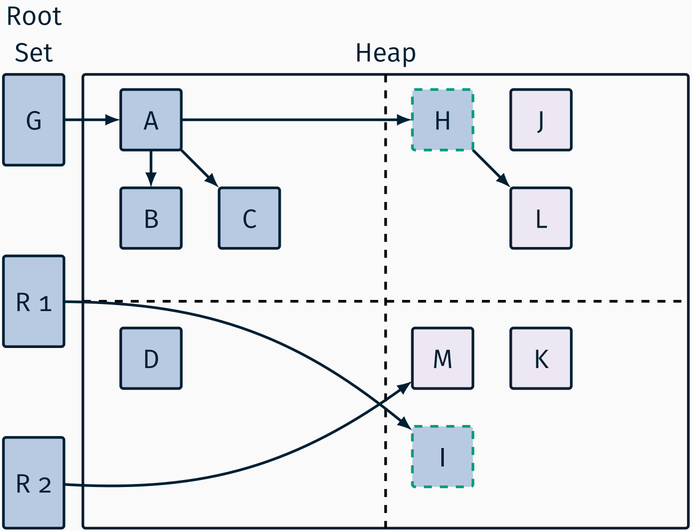
Partial (Young) Collection

1. Atomically retrieve and clear dirty bits of all pages
2. Trace from the marked objects on the retrieved dirty pages
3. Stop the world
4. Trace from registers and all marked objects on dirty pages
5. Clear dirty bits and restart the world

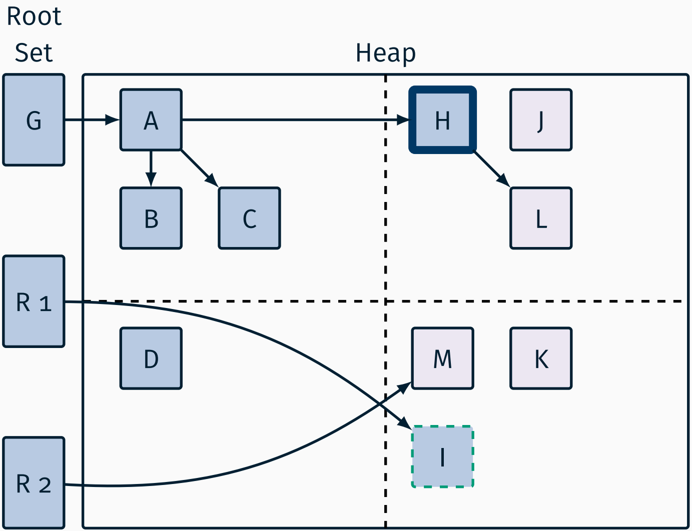
Partial Collection by Example



Clear Dirty Bits and Remember Pages



Concurrent Marking from Marked Objects on Dirty Pages



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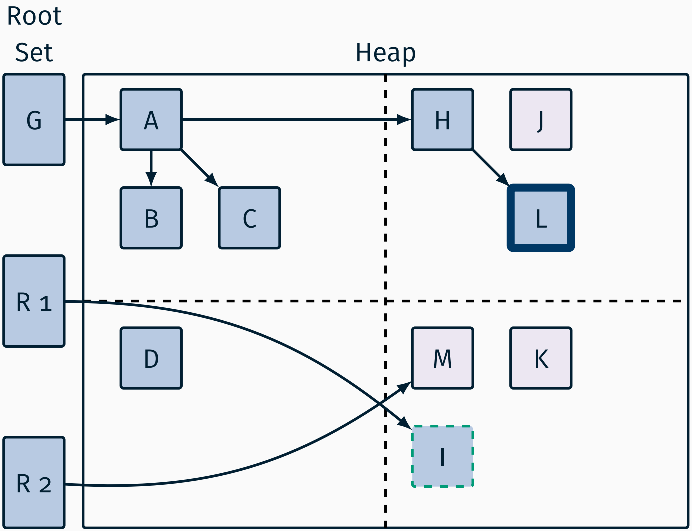

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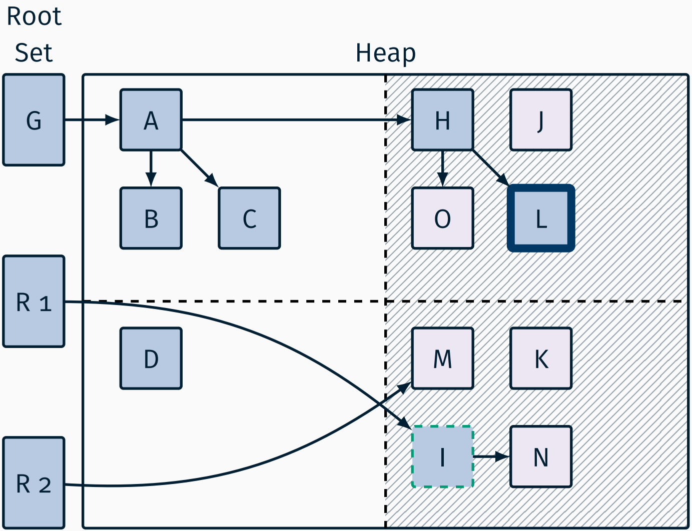
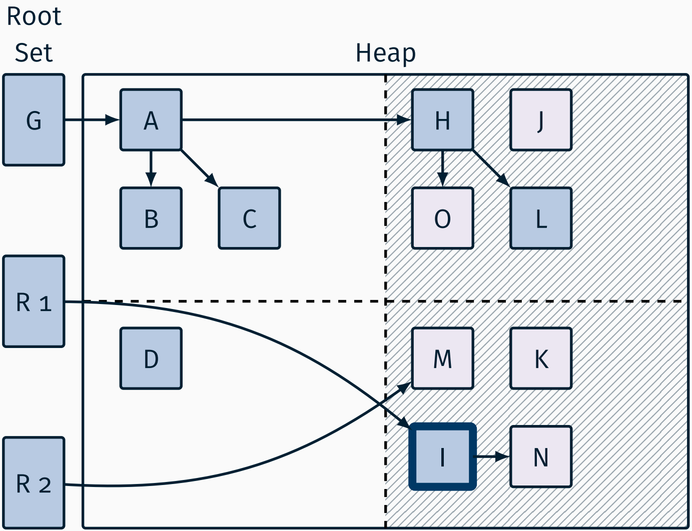


Concurrent Marking Continues



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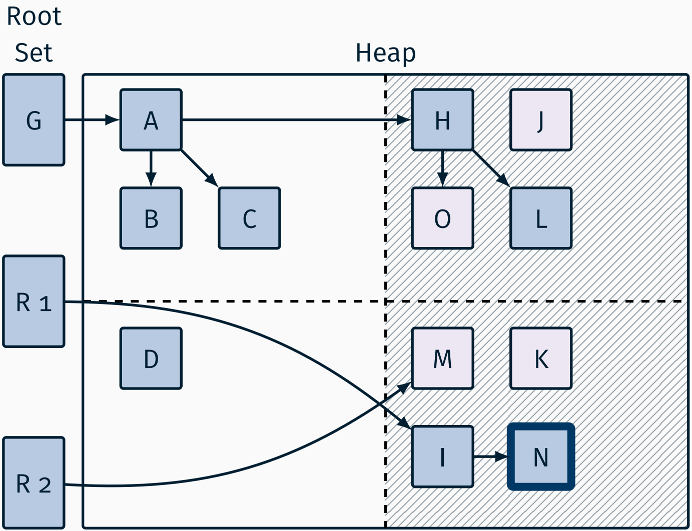

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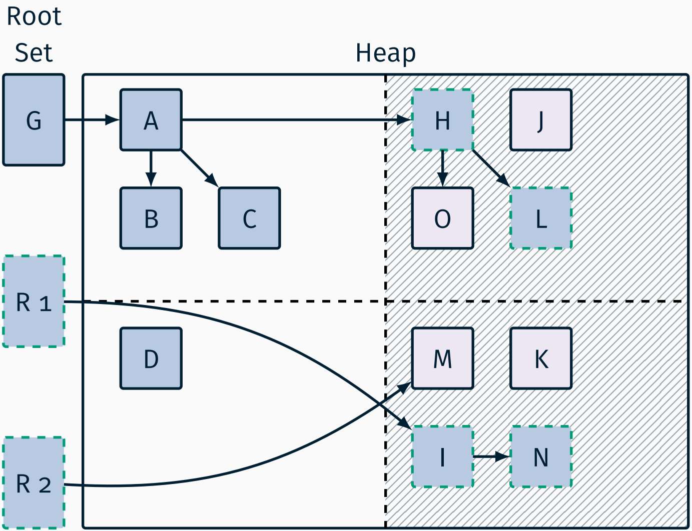

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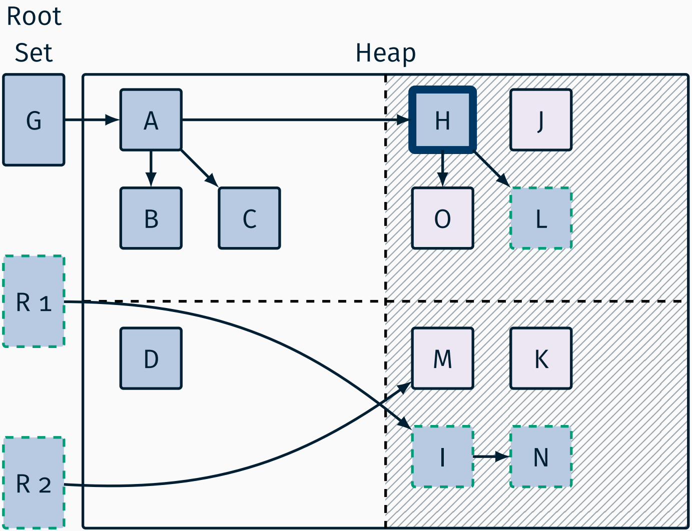

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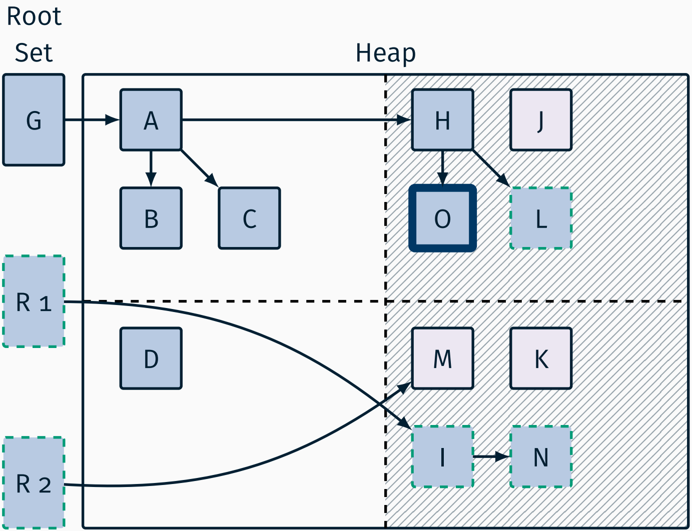

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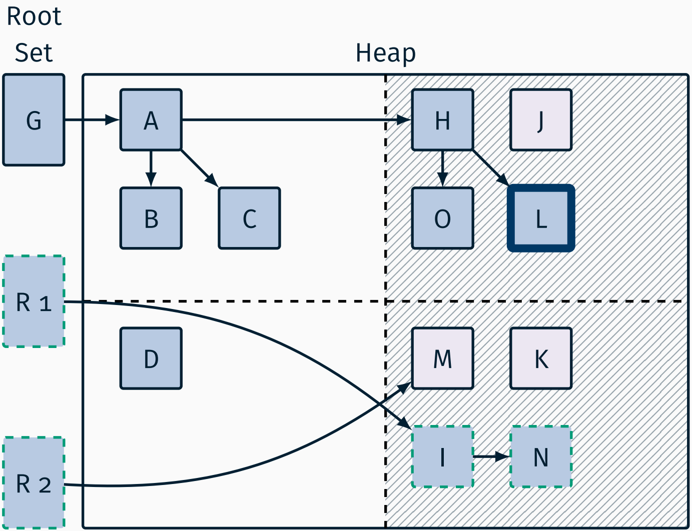

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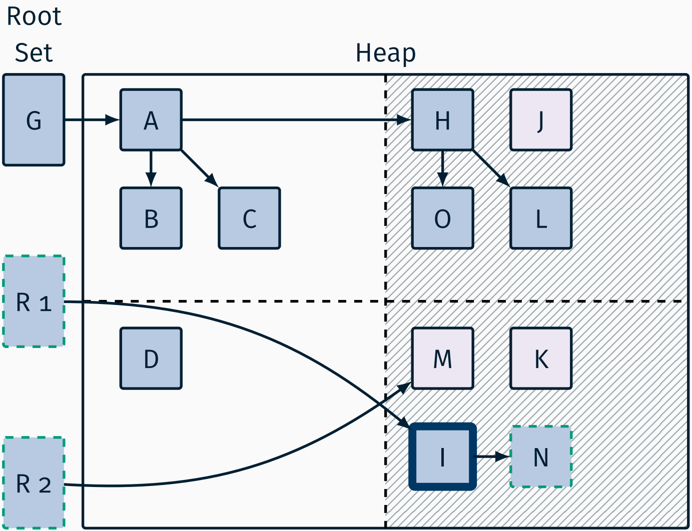
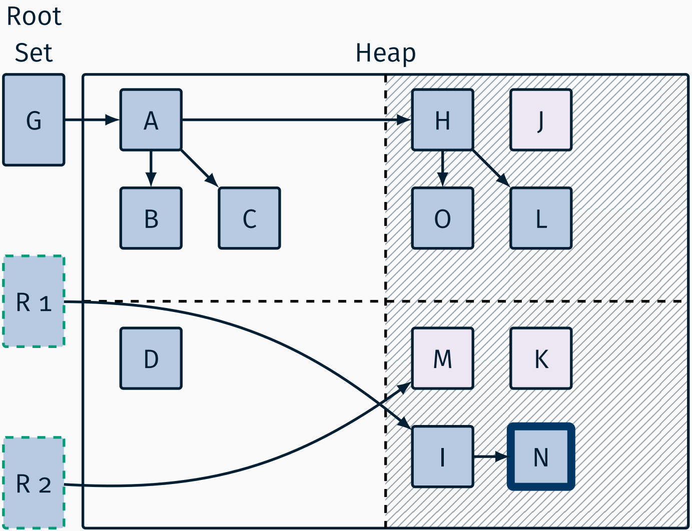
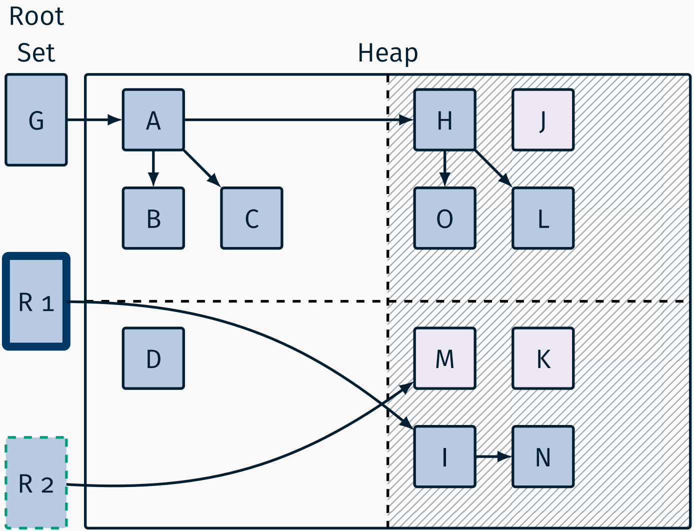


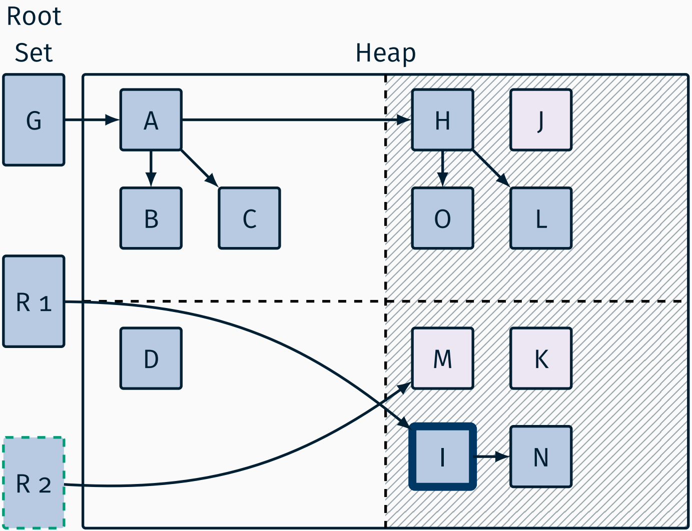
STW Marking from Marked Objects on Dirty Pages



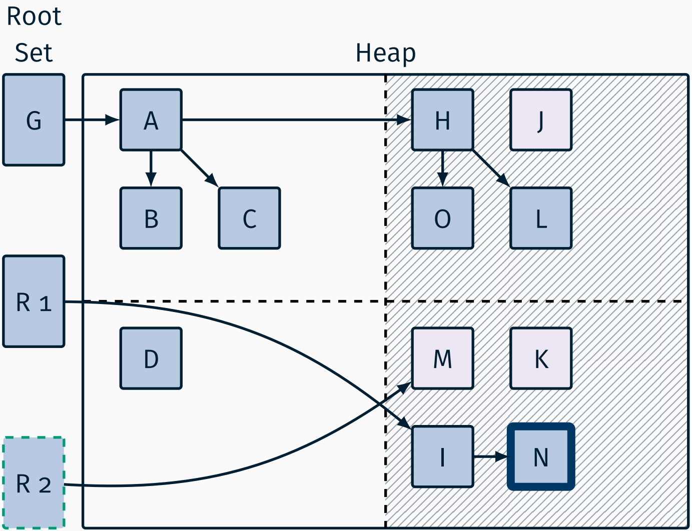
STW Marking from Registers



STW Marking from Registers



STW Marking from Registers



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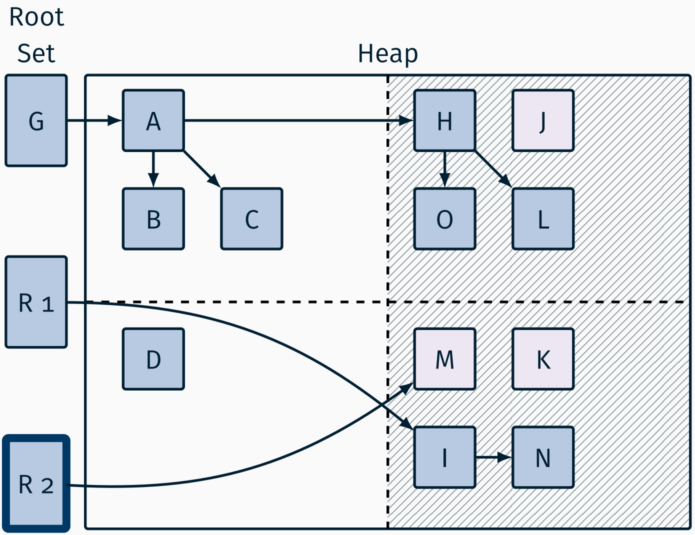
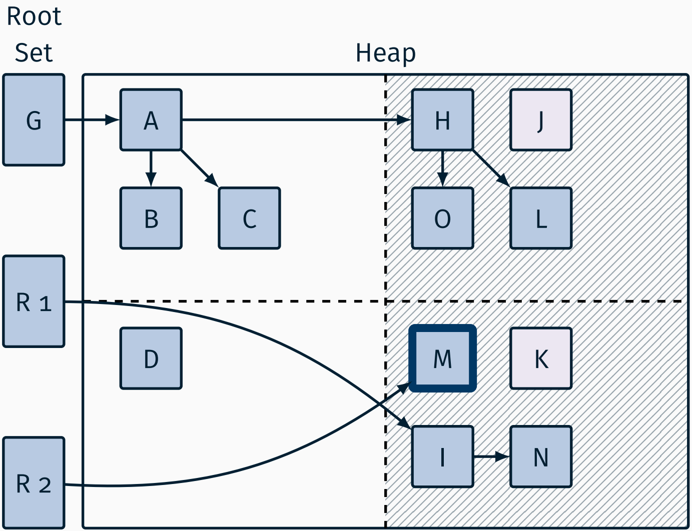
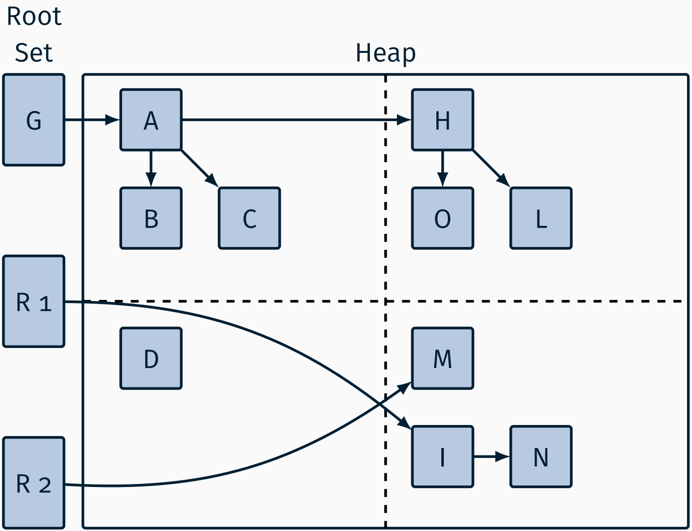


STW Marking from Registers



GC Cycle Complete



Discussion

Problems

- many objects are scanned unnecessarily
- some garbage remains until next full collection
- heap is potentially heavily fragmented

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Main Contribution

General scheme for transforming many STW GCs to mostly concurrent versions

Modern GC Algorithms on the JVM

- compiler can assist in cooperation between mutator and GC
- large heap sizes (multiple 100 GB)
- almost all GC algorithms are generational

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Garbage-First Garbage Collector (G1GC)

→ splits heap in same-sized individually collectible regions

→ *compacting*, STW young-generation collection

→ synchronisation during old collection: compiler-inserted write barrier records all pointer changes

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- various different algorithms and approaches in practice and academia
- STW GC causes long pauses on large heaps

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- concurrent collection can reduce pause times at the cost of more collection work
- general scheme: mark concurrently and then fix in short stop-the-world pauses

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- STW GC causes long pauses on large heaps

“Mostly-Parallel Garbage Collection”

- concurrent collection can reduce pause times at the cost of more collection work
- general scheme: mark concurrently and then fix in short stop-the-world pauses

State on the JVM

- high degree of mutator cooperation
- mostly concurrent, but very different implementations

Thank you!

Thank you!
Questions?

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