Garbage Collection

April 2, 2001
CS 132: Compiler Design

Flavors of Memory Allocation

1. Static
   - Size, locations determined at compile-time
2. Stack
   - Memory allocated for a single procedure call
   - Size might vary depending on arguments
   - Space automatically freed when function exits
3. Heap
   - Arbitrary order of allocation/de-allocation

Heap Management

- Explicit
  - User specifies when objects are allocated and deallocated.
  - Potential for dangling pointers, memory leaks
  - User must keep track: who is responsible for deallocating memory?
- Implicit
  - User only specifies allocations
  - Objects automatically deallocated when determined to be safe.

Vocabulary

- We will call any data item on the heap an *object*.
- An object is *live* if it will be used later in the execution of the program.
- An object that is not live is said to be *dead* or to be *garbage*.

- A *garbage collector* detects and deallocates garbage.
  - Deallocating *all* garbage is undecidable
  - Thus collectors deallocate some subset of the dead objects

More Vocabulary

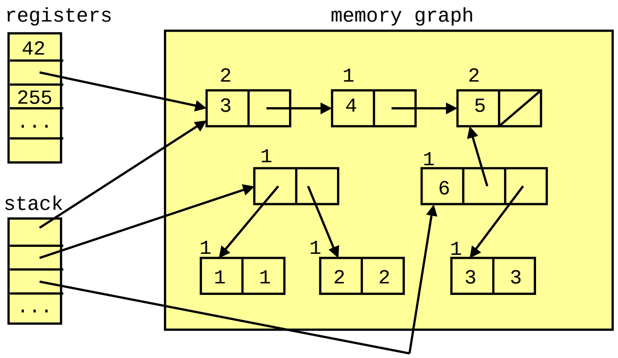
- The pointers into the heap that a program maintains are called *roots*
  - Roots found in registers, static memory, and the stack
- Data on the heap is said to be *reachable* if it can be accessed by following pointers through the heap, starting with one of the roots; *unreachable* otherwise.

- >99% of garbage collectors are based on the idea that *unreachable objects are garbage*.

Method 1: Reference Counting

- Idea: For each object in the heap, record how many pointers there are to this object
  - In registers
  - In static memory
  - On the stack
  - In other heap objects.
- Update this count when pointers are copied or overwritten or discarded.
- Deallocate any object whose count falls to zero, because it's not reachable.

Initial Machine State



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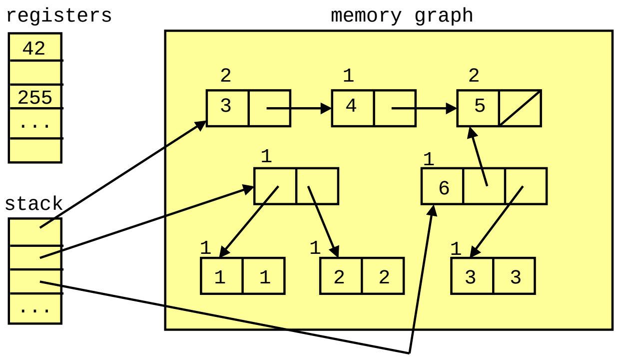

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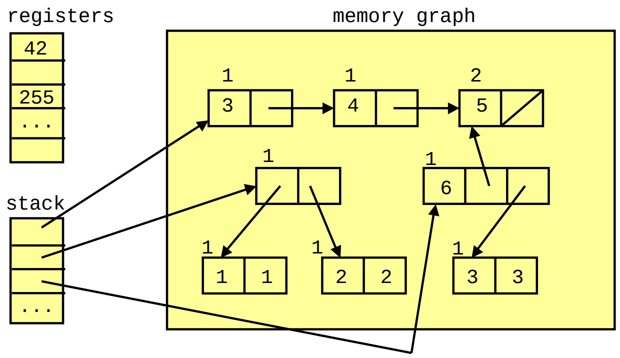

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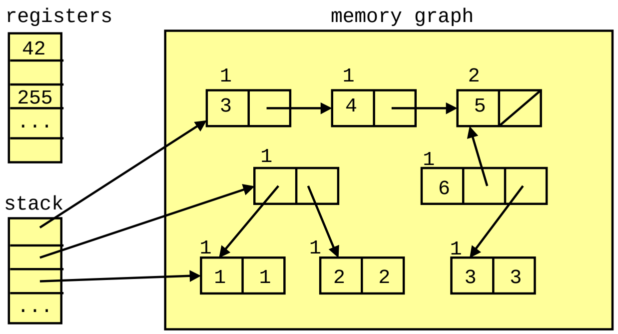

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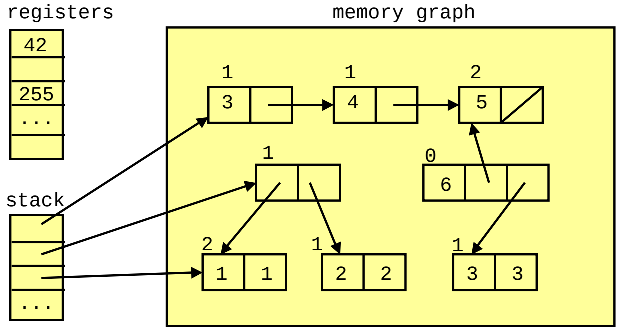

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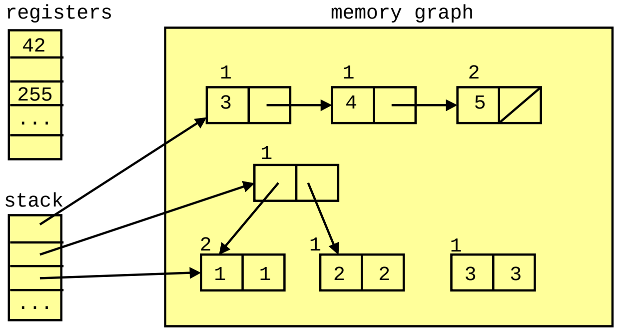

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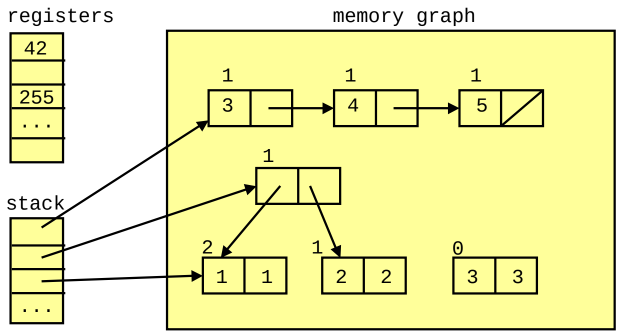

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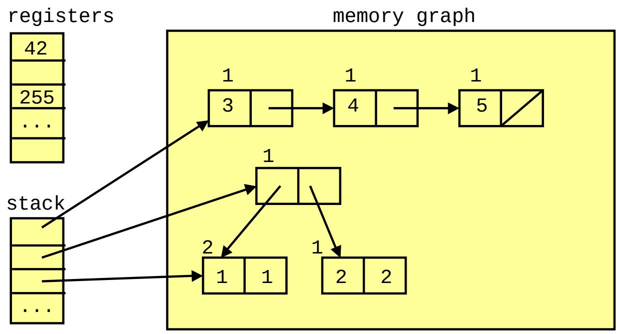
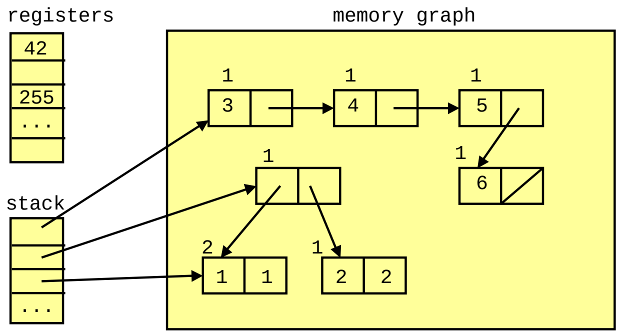


Program Resumes Allocating



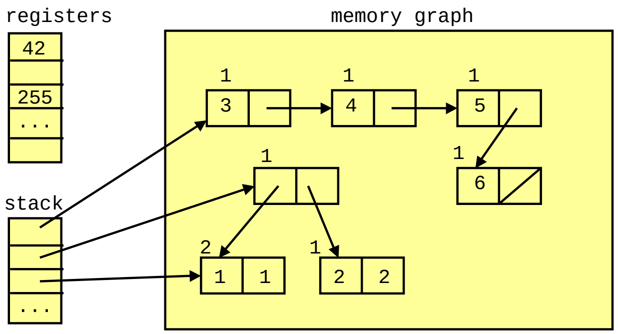
Advantages

1. Conceptually simple
2. Memory can be re-used immediately
3. Can be applied only to pieces of data with ill-defined lifetimes.
4. Memory management is (sort-of) incremental
    - Pause time proportional to amount of data freed at once
5. Can run finalizers (cleanup actions) as soon as an object becomes unreachable.

Disadvantages

1. Very tricky and error-prone if maintaining reference counts by hand.
2. Cost of reference-count updates.
3. Space requirement for reference counts.
4. Cyclic data structures problematic.

Initial State



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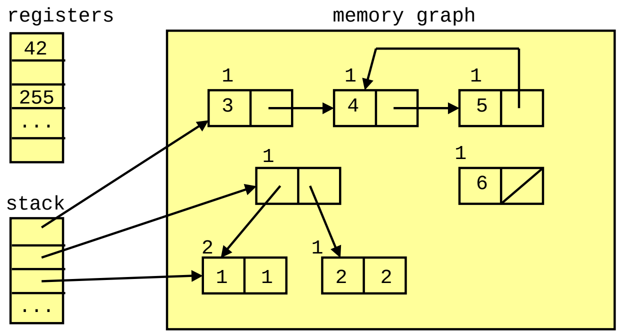

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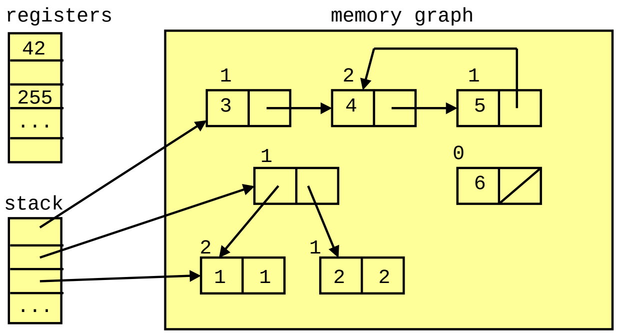

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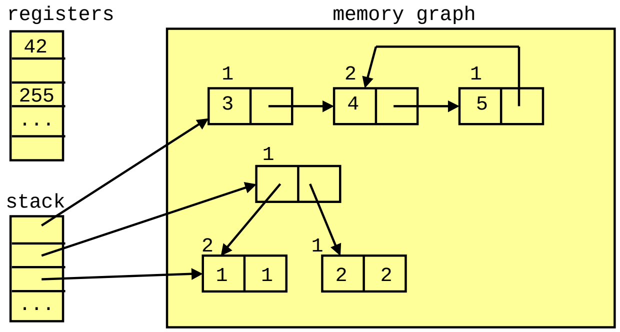

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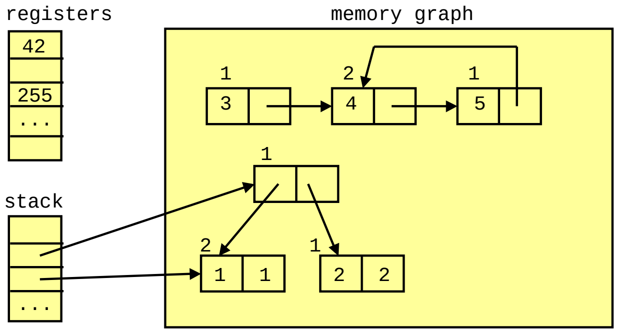

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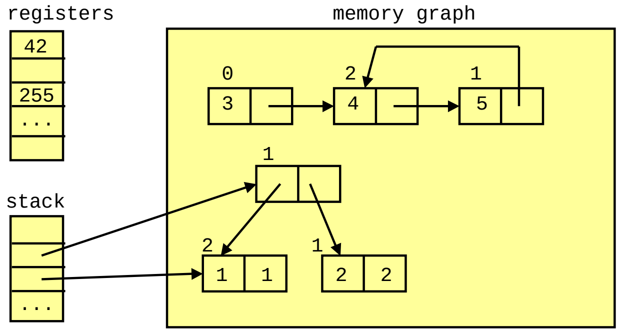

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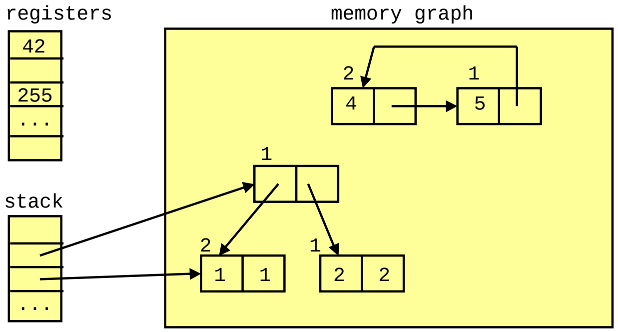

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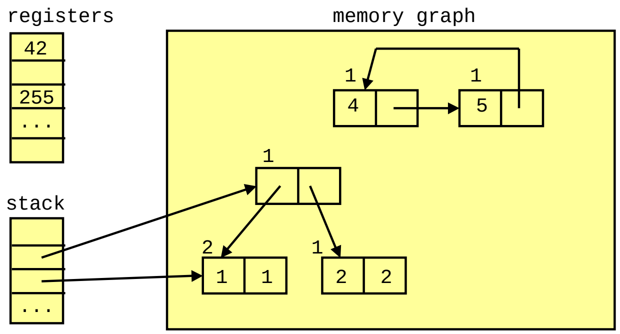
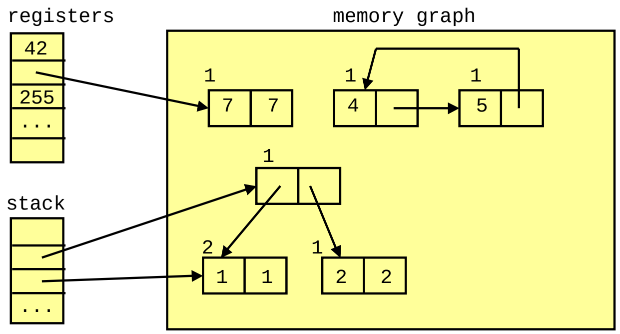


Allocation Resumes



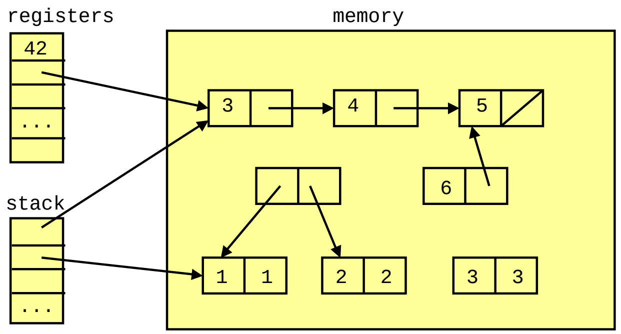
Method 2: Tracing GC

- Idea:
  - Allocate until memory exhausted
  - When more space is required, determine the reachable data, and deallocate the rest.
- Two classical variants
  - *mark-sweep* collectors
  - *copying* collectors

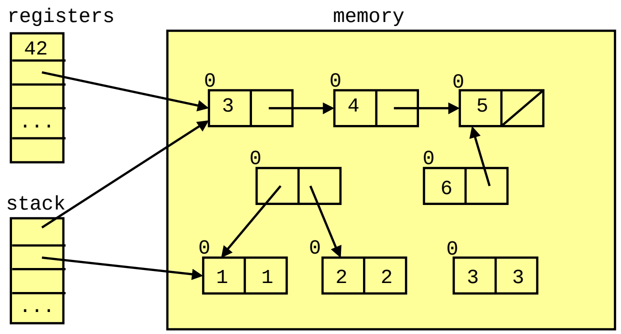
Mark-Sweep

- Each object has a "mark bit"
- Collection occurs in two steps
  1. Traverse the graph of reachable data, and set the mark bit on all reachable objects
  2. Sequentially examine all the objects in the heap
     - If mark bit was not set, deallocate the object
     - Otherwise clear the mark bit (for the next GC)

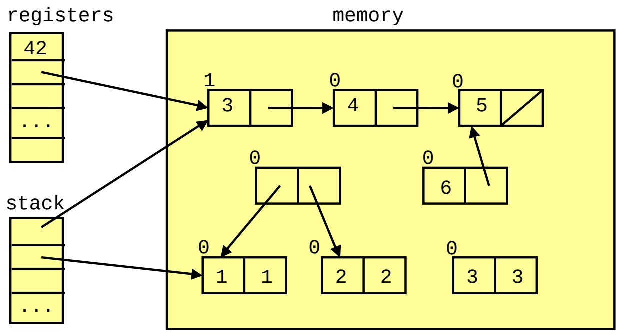
Initial State



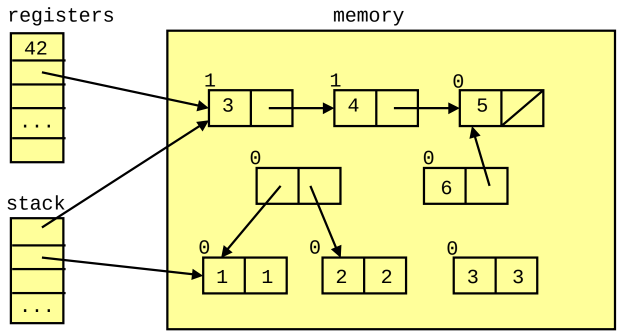
Beginning of Mark Phase



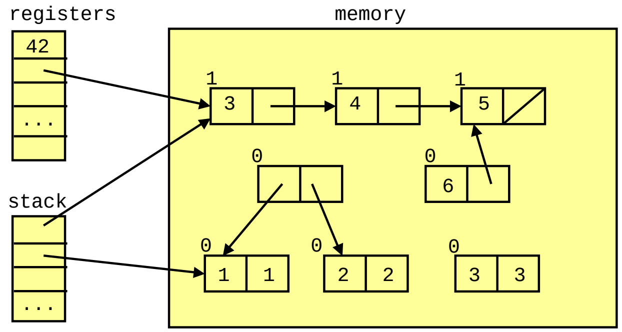
Mark Phase



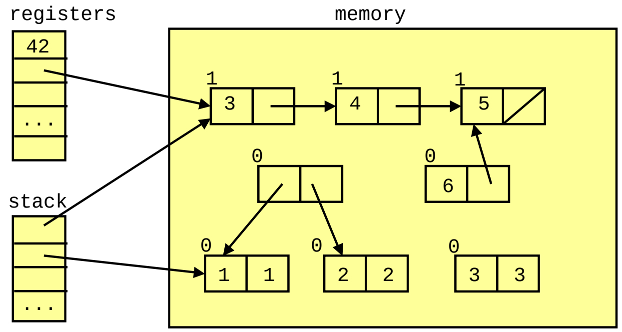
Mark Phase



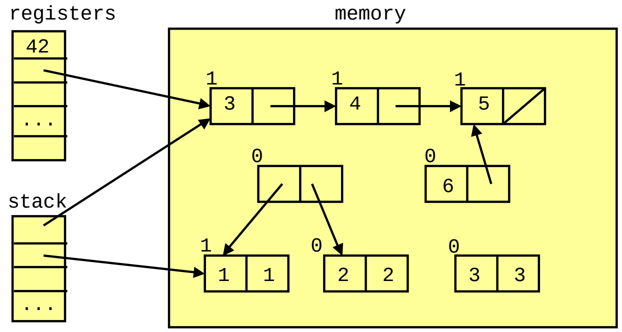
Mark Phase



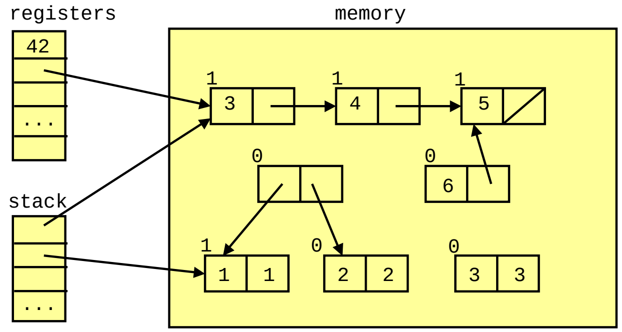
Mark Phase



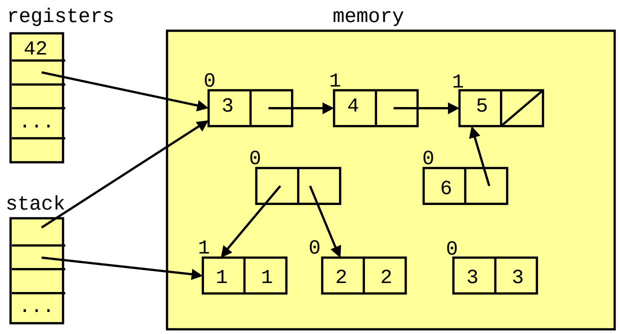
Mark Phase



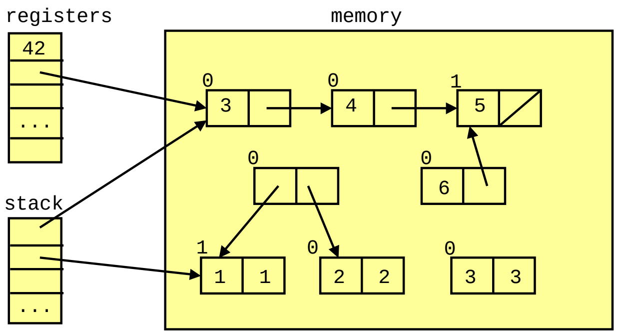
At Beginning of Sweep Phase



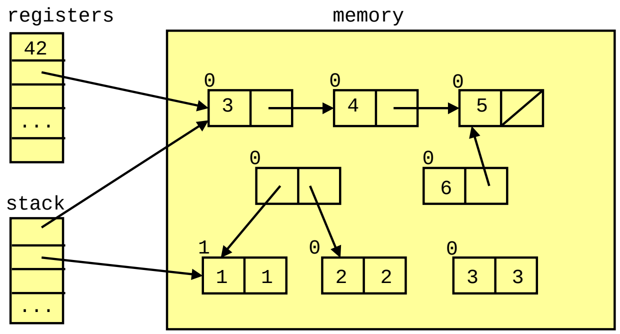
Sweep Phase



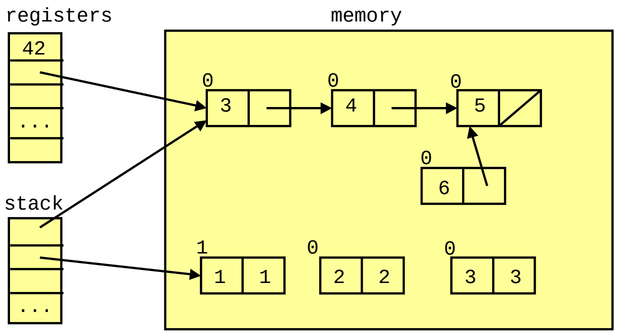
Sweep Phase



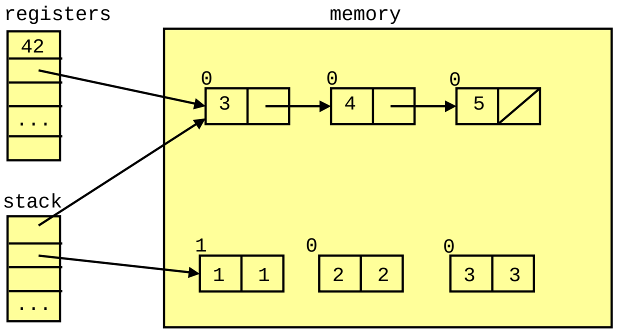
Sweep Phase



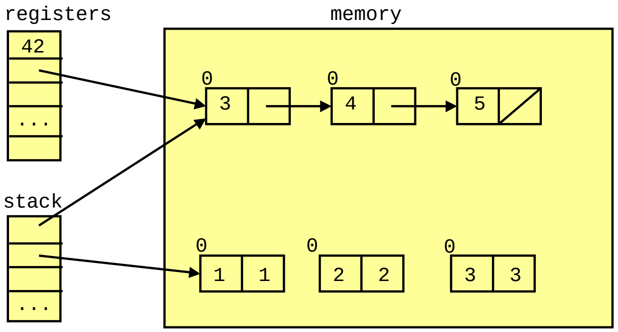
Sweep Phase



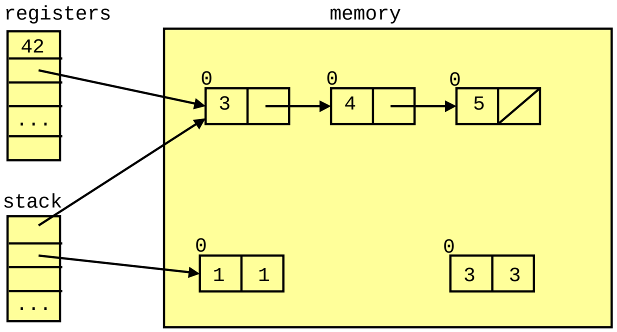
Sweep Phase



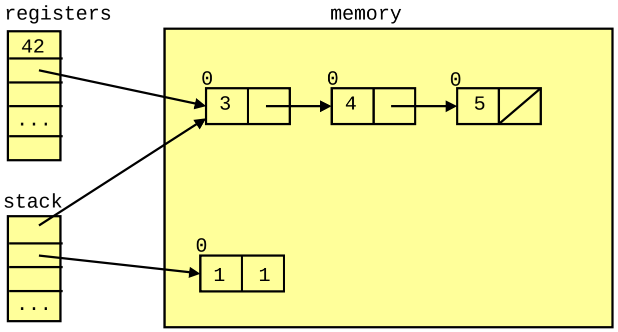
Sweep Phase



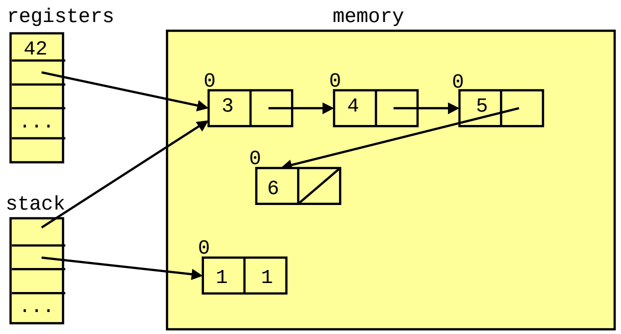
Sweep Phase



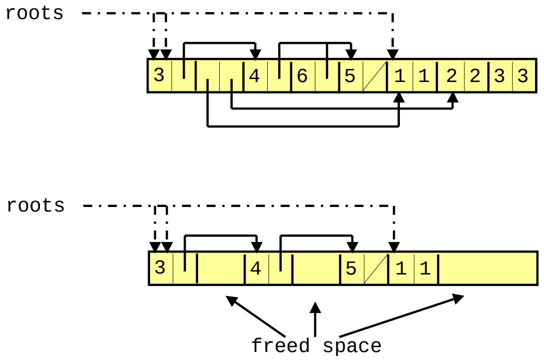
Sweep Phase



Program Continues Allocating



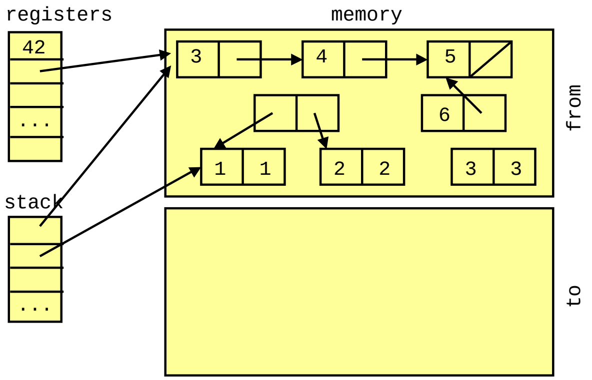
Before and After Summary



Copying Collector

- Divide memory into halves
  - called *fromspace* and *tospace*.
- Allocate objects in fromspace until full
- Then,
  - Copy all reachable data from the fromspace into the tospace.
  - Swap the names "fromspace" and "tospace".
  - Resume allocating in the fromspace (the old tospace)

Fromspace Full: Start Collection



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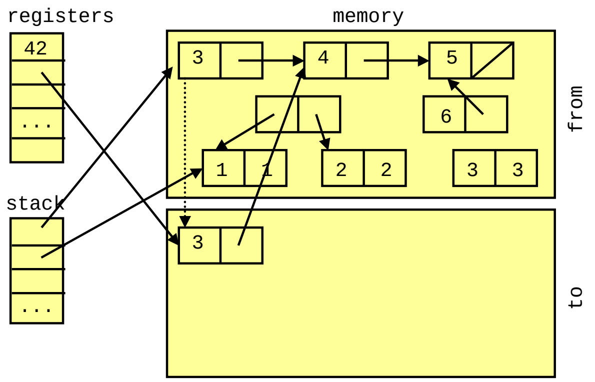

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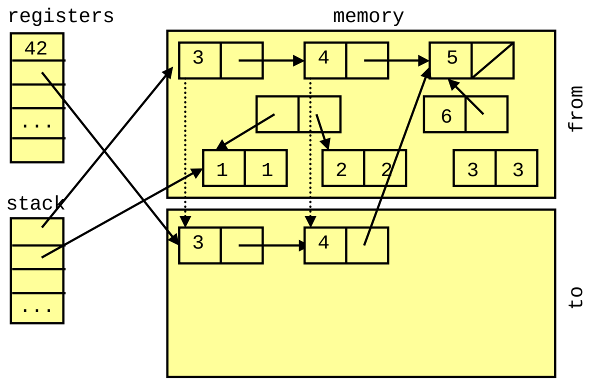

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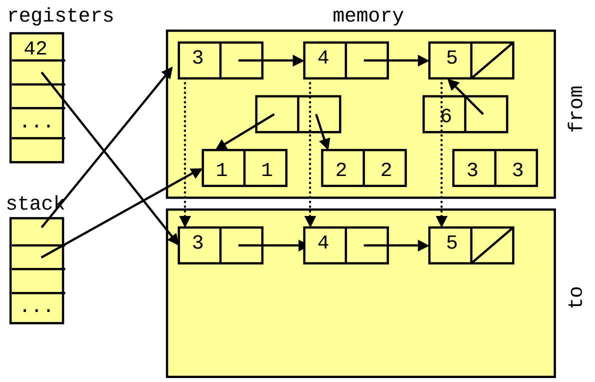

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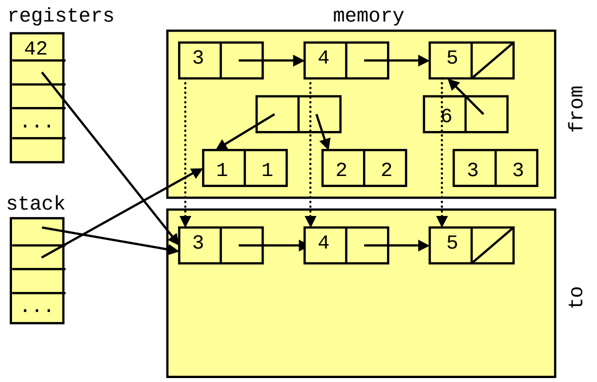

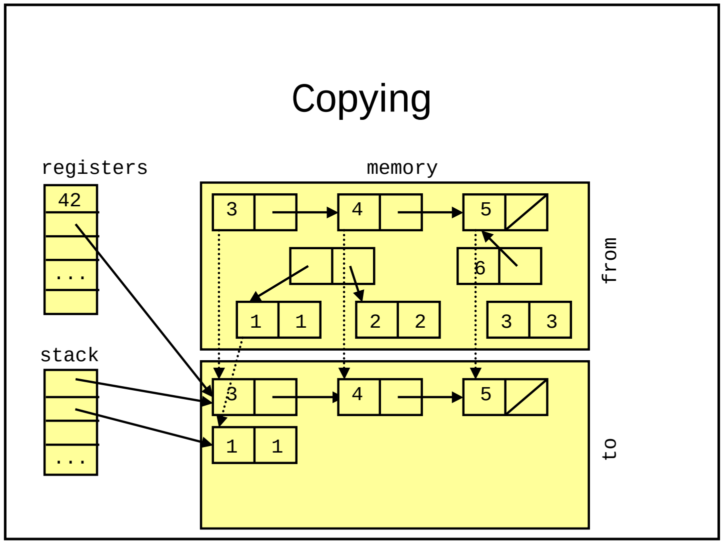

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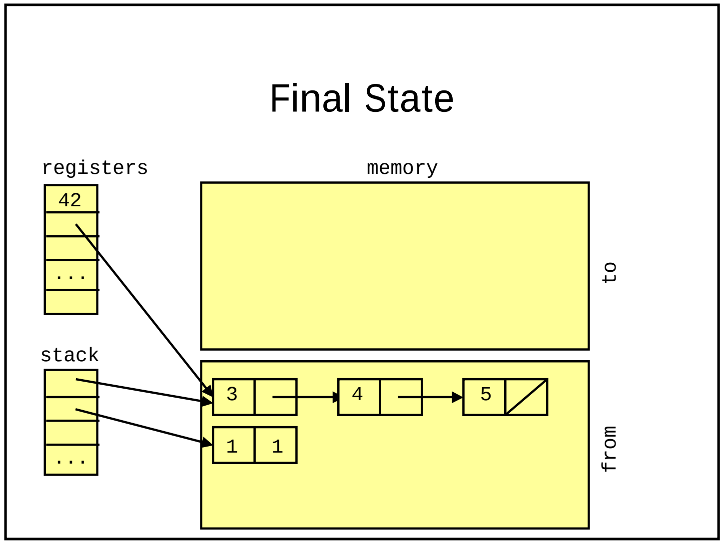
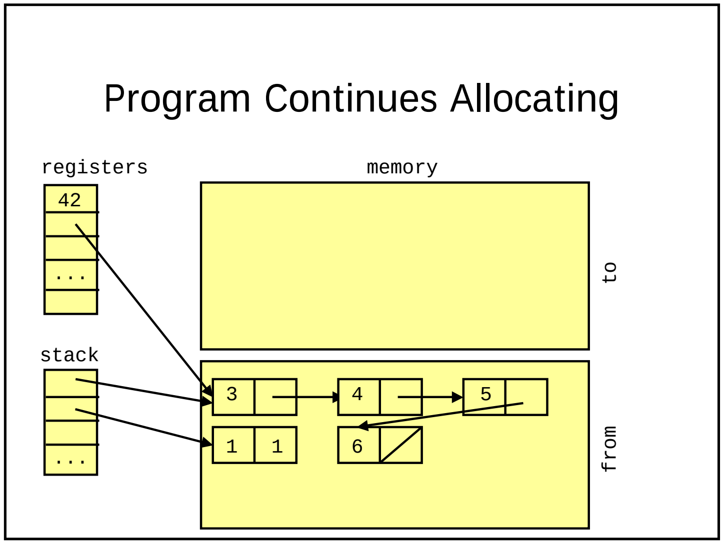
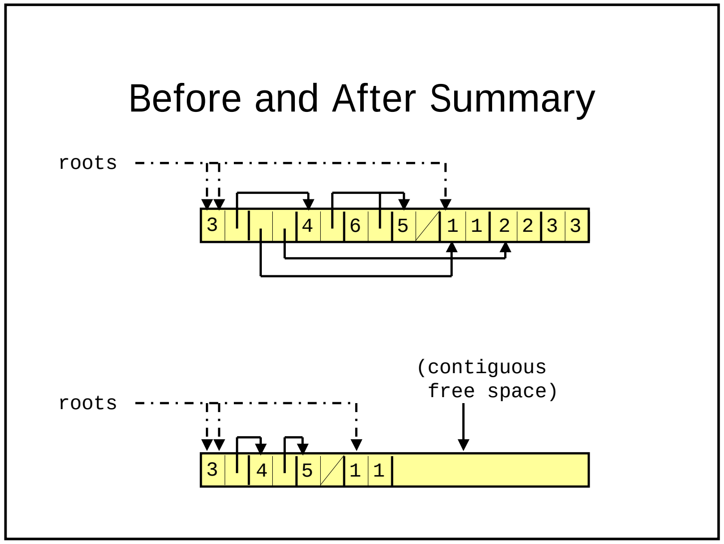


Final State



Program Continues Allocating



Before and After Summary

Tracing Collectors: Comparison

- Mark-Sweep
  - Collection time proportional to number of objects (live and dead) in the heap.
- Copying
  - Collection time proportional to bytes of live data
  - Copying compacts (defragments) heap
  - Requires twice as much memory (at worst.)
  - Allocation extremely cheap
- Both
  - No problems with cycles in heap
  - Performance degrades as live data increases

How is Tracing Possible?

- It's time to do a garbage collection. Which registers and which stack locations contain pointers into the heap?
  - And of the pointers, which are live?
- What sort of objects are being pointed to?
  - How big?
  - Do they contain pointers? Where?

Finding Roots

- Guess [Conservative Collection]
  - Assume that any register or stack location containing a value that "looks like" a pointer is a pointer
- Tag bits
  - Take a bit (or two) from every word to denote pointer/non-pointer.
- Lookup tables
  - At compile time, generate information about stack frames and register sets at each point in program where GC could occur.

Parsing the Heap

- Bread crumbs
  - Tag heap objects with object's size
  - Tag objects with pointer locations
    - Or just guess, or assume tag bits
- Types
  - From the types of pointers, deduce the object's layout (and the type of every object it points to)
  - Much harder with polymorphism or abstract types
- Segregate objects by shape (BIBOP)

Generational GC

- Problem: long-lived data is copied repeatedly
  - From fromspace to tospace on every collection
- Generational idea:
  - Most data dies young; most young data dies
  - Therefore, create separate heaps for young and old data (the "generations")
  - Young data that survives collection(s) is promoted to an older generation.
  - Try to GC younger generations without touching older generations.

Is Young Independent of Old?

- What happens if old data points to young data?
  - Need to treat such pointers as roots.
  - When young objects moves, need to update the pointers to them in the older generations.
- How do we find these pointers without scanning the older generations (doing as much work as a full GC)?
  - The only way old can point to young is if somebody did an update to the old data
  - General idea: "write barrier". Remember information about all (relevant) updates.

Generational Collection

- Advantages
  - Much shorter pauses
  - Often dramatically less copying.
    - Actually, the generational idea can be used in mark-sweep collectors as well
- Disadvantages
  - Have to keep track of assignments
    - For languages that don't do many assignments, generational GC can work really well.
  - Can increase memory requirements.

Large Objects

- For large objects, copying even once can be overly expensive.
  - And larger objects likely to be long-lived
- Some generational collectors contain a special heap for large objects
  - Anything large gets automatically allocated there
  - May be managed differently (e.g., mark-sweep)

More Embellishments

- Incremental collectors
  - Do small amounts of collection, more frequently
  - Real-time: hard bound on amount of work done by the collector in each step
  - Increases total collection time, decreases maximum pause
- Parallel collectors
  - Several processors cooperating together on collection
- Concurrent collectors
  - Main program and GC run simultaneously
- Hybrid collectors
  - Variants that combine copying/mark-sweep/ref counts

Which Collector is Best?

- Nobody knows; performance depends on
  - Client program behavior
    - Frequency of allocation
    - Sizes of objects
    - Number of reads / writes / pointer copies / etc.
  - Cache and virtual memory performance
  - Order of memory traversal (DFS, BFS, …)
  - When garbage collections occur
- Lots of work on improving collectors