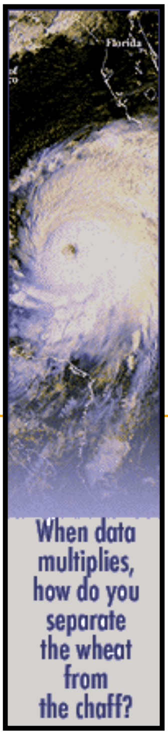
Garbage Collection

CS132

March 9, 2011



CS132

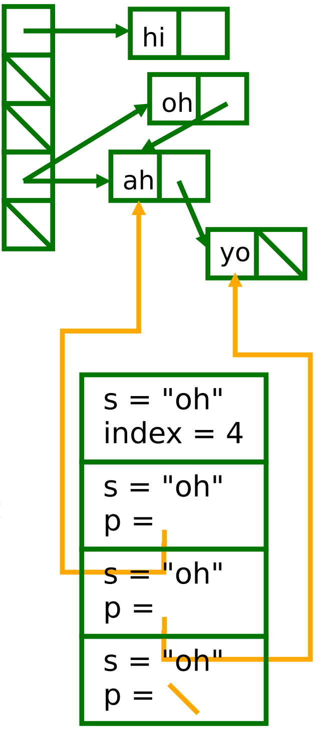
Review: Memory Usage

insert("oh")

```
Node* table[TABLESIZE];

void insert(string s) {
   int index = hashfunc(s) % TABLESIZE;
   if notInList(s, table[index]) {
      table[index] = new Node(s, table[index]);
   }
}

bool notInList(string s, Node* p) {
   if (p == NULL) return true;
   return (p->key_ != s) && notInList(p->next_);
}
```

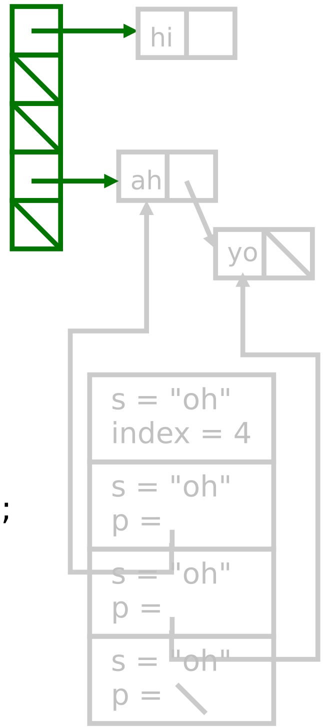


Static Allocation

```
Node* table[TABLESIZE];

void insert(string s) {
   int index = hashfunc(s) % TABLESIZE;
   if notInList(s, table[index]) {
      table[index] = new Node(s, table[index]);
   }
}

bool notInList(string s, Node* p) {
   if (p == NULL) return true;
   return (p->key_ != s) && notInList(p->next_);
}
```



hi

ah

yo

s = "oh"
index = 4

s = "oh"
p =

s = "oh"
p =

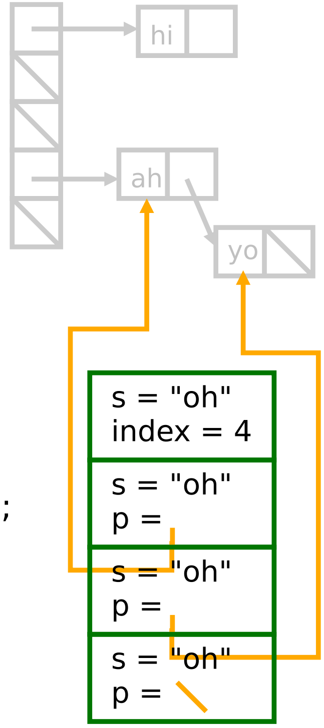
s = "oh"
p =

Stack Allocation

```
Node* table[TABLESIZE];

void insert(string s) {
   int index = hashfunc(s) % TABLESIZE;
   if notInList(s, table[index]) {
      table[index] = new Node(s, table[index]);
   }
}

bool notInList(string s, Node* p) {
   if (p == NULL) return true;
   return (p->key_ != s) && notInList(p->next_);
}
```



hi

ah

yo

s = "oh"
index = 4

s = "oh"
p =

s = "oh"
p =

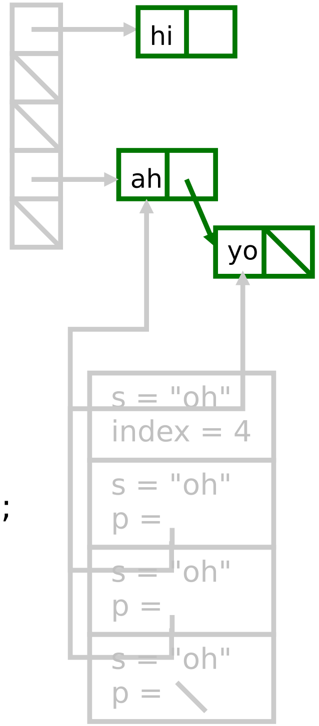
s = "oh"
p =

Dynamic (Heap) Allocation

```
Node* table[TABLESIZE];

void insert(string s) {
   int index = hashfunc(s) % TABLESIZE;
   if notInList(s, table[index]) {
     table[index] = new Node(s, table[index]);
   }
}

bool notInList(string s, Node* p) {
   if (p == NULL) return true;
   return (p->key_ != s) && notInList(p->next_);
}
```



Heap Options

Explicit

- User specifies allocation/deallocation.
- Potential for dangling pointers, memory leaks
- Who's responsible? ("Liveness is a global property")

Implicit

- User specifies only allocations
- Objects automatically deallocated when known to be safe.

Vocabulary

Object = data item on the heap (not necessarily OOP).

Live = will be needed later.

Dead = not live.

Garbage = objects that are dead.

A garbage collector detects and deallocates garbage.

- Deallocating *all* garbage is undecidable
- Thus collectors deallocate a subset of the dead objects

More Vocabulary

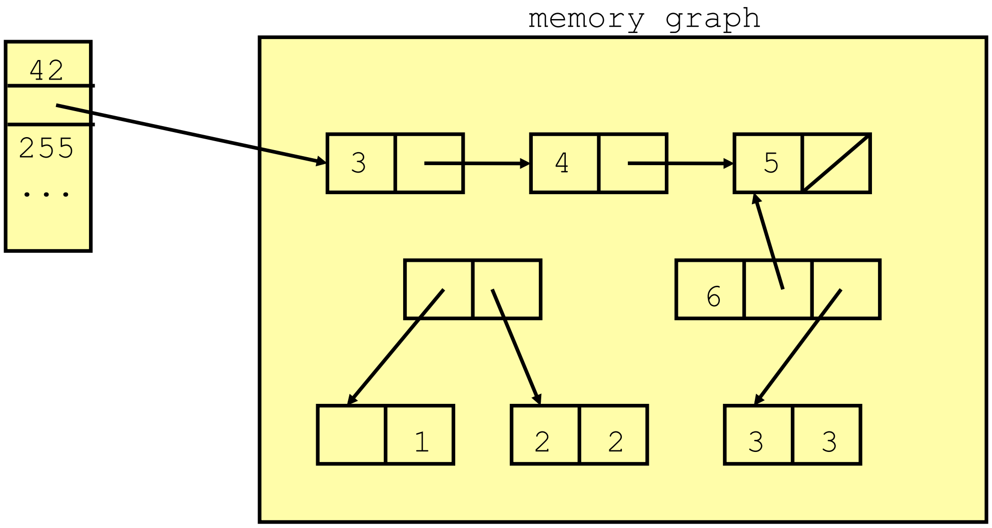
Roots = Pointers into the heap from outside

- 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 based on the idea *unreachable objects are garbage*.

Example



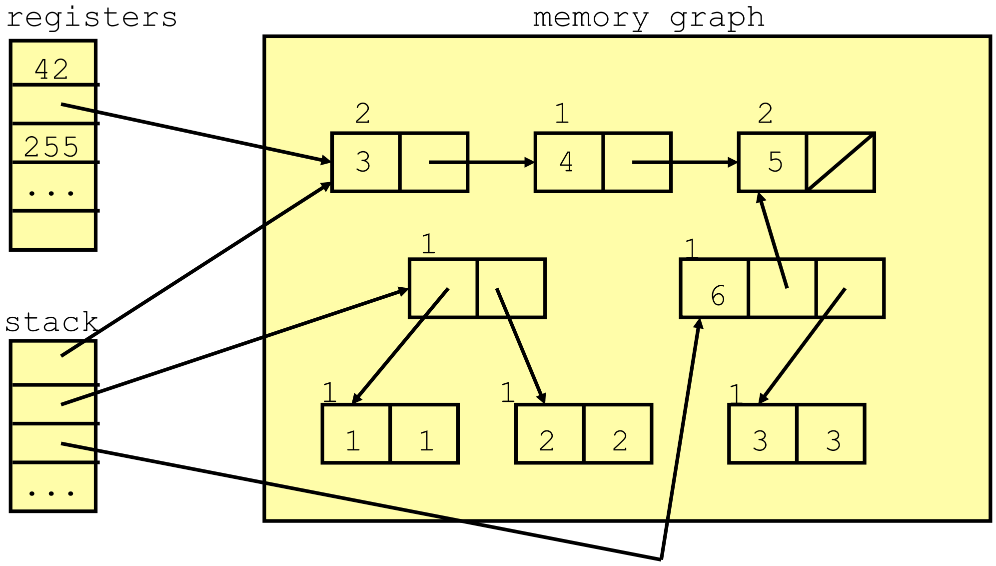
Reference Counting

For each object in the heap, keep track of its references.

Update the count when pointers are copied, overwritten, or discarded.

Deallocate any object whose count falls to zero

Initial Machine State



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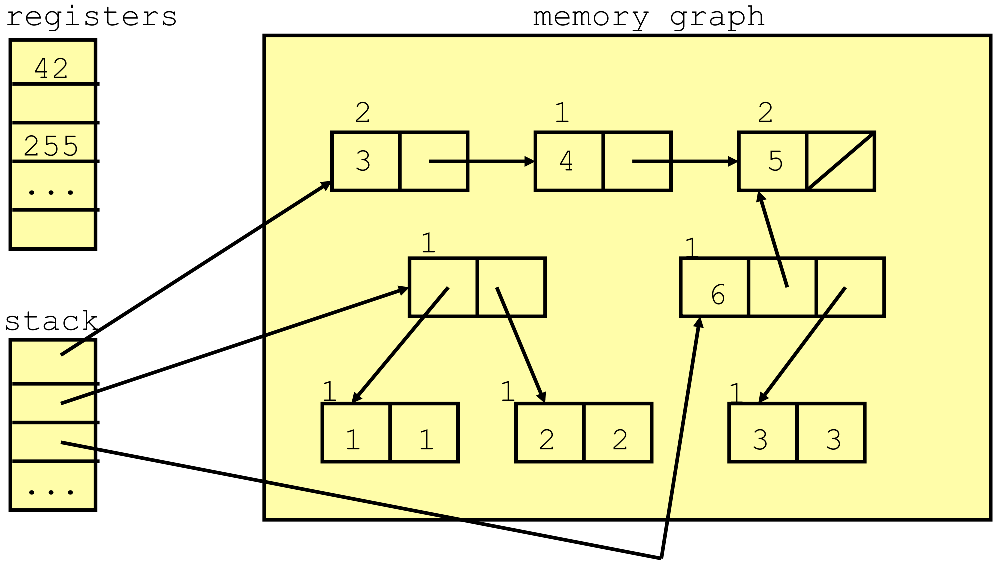

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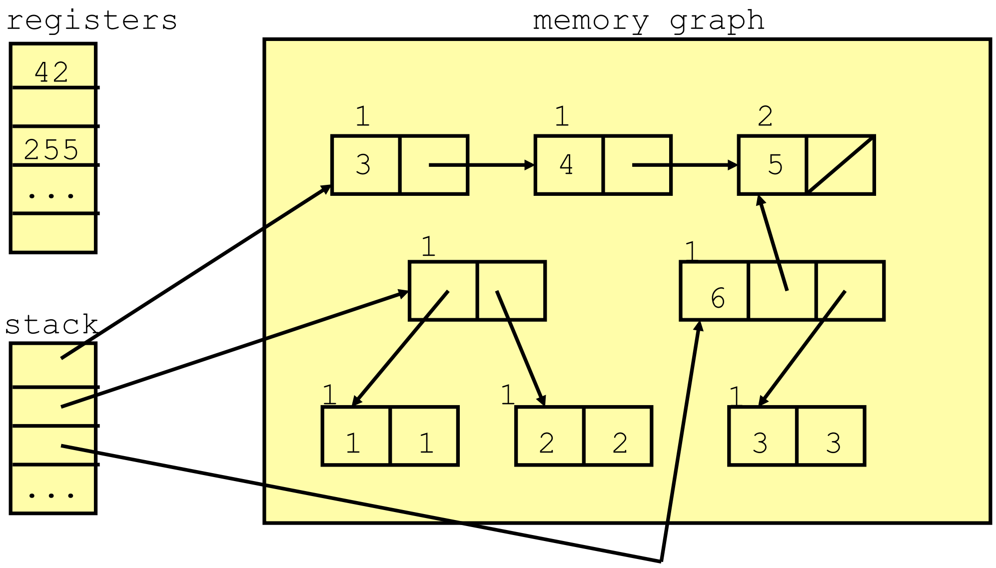

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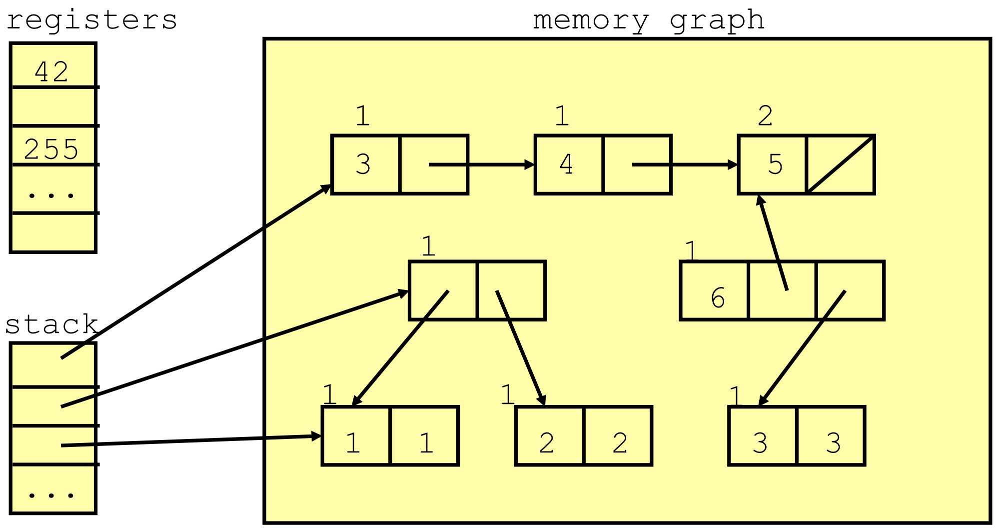

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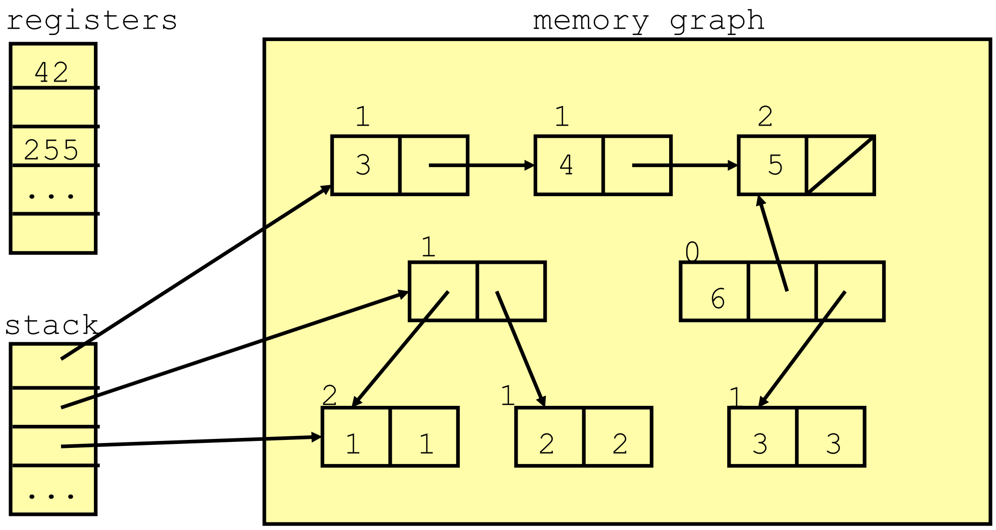

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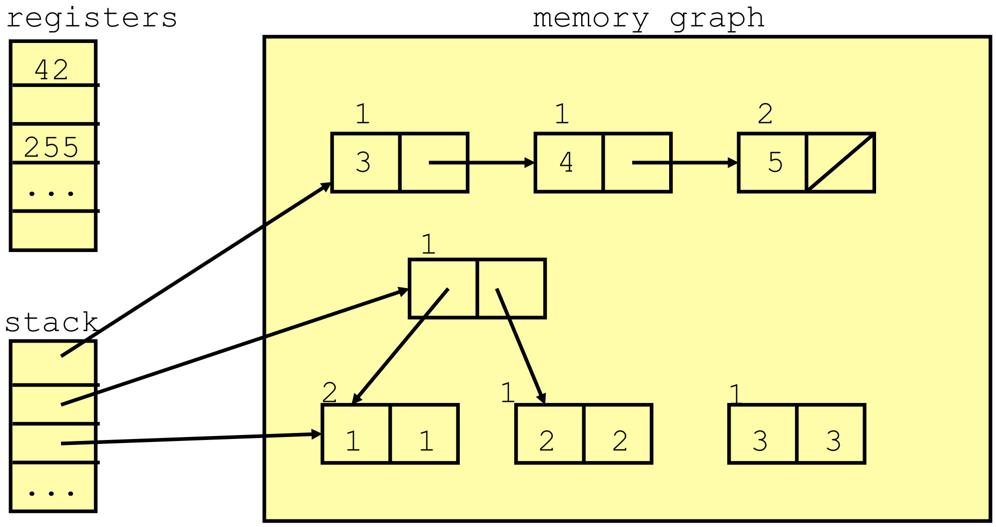

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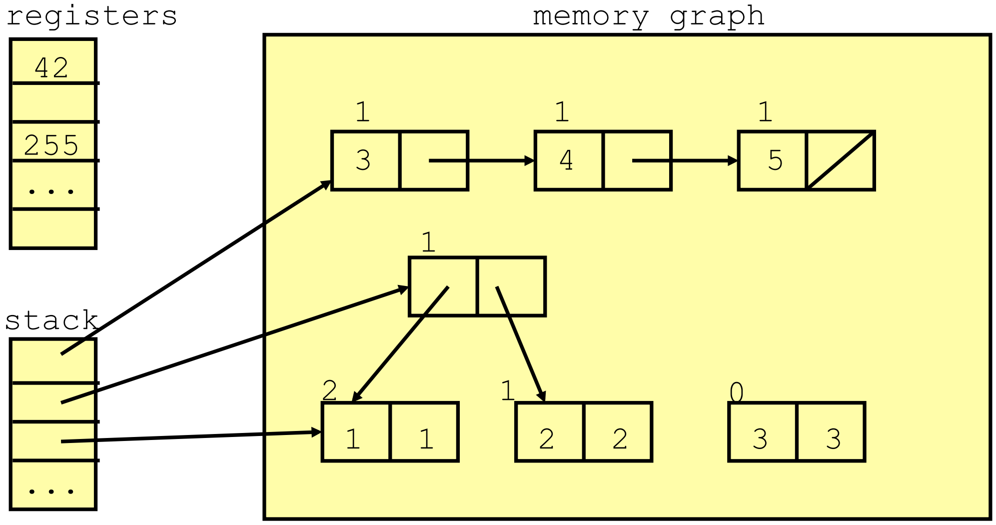

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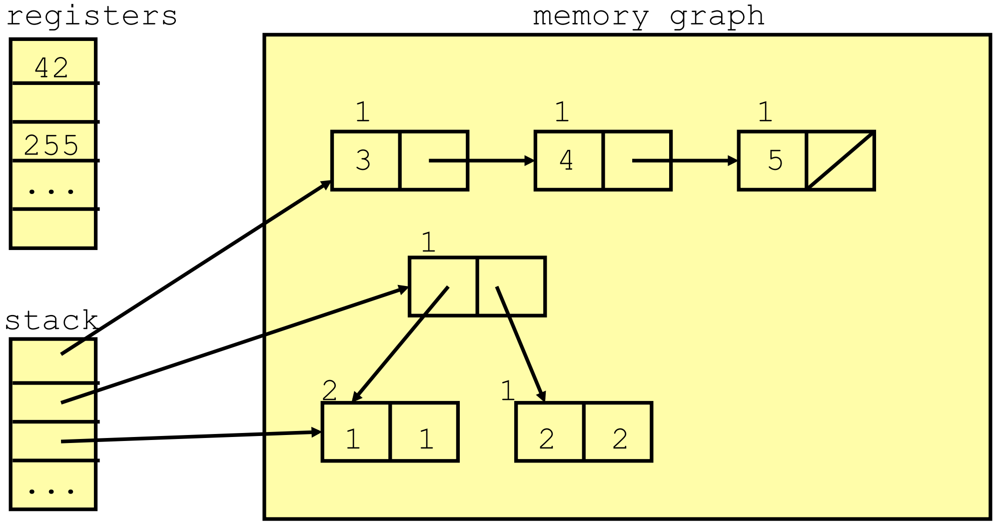
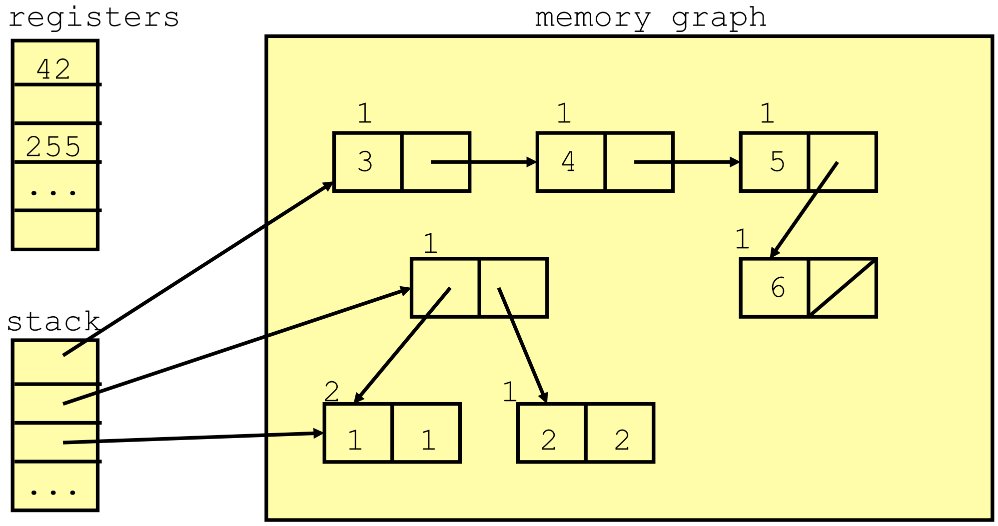


Program Resumes Allocating



Advantages

Conceptually simple

Memory can be re-used immediately

Can be applied just to difficult pieces of data.

Relatively few long pauses ("incremental" GC)

   Time proportional to amount of data freed at once

Can run finalizers (cleanup actions) immediately.

Disadvantages

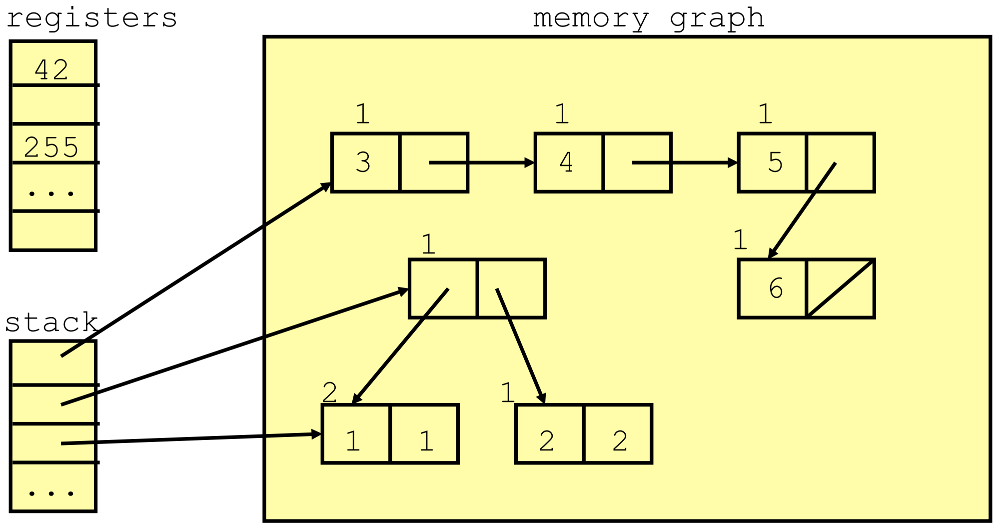
Very tricky and error-prone to do by hand

Cost of reference-count updates in space and time.

Space requirement for reference counts.

Cyclic data structures problematic.

Initial State



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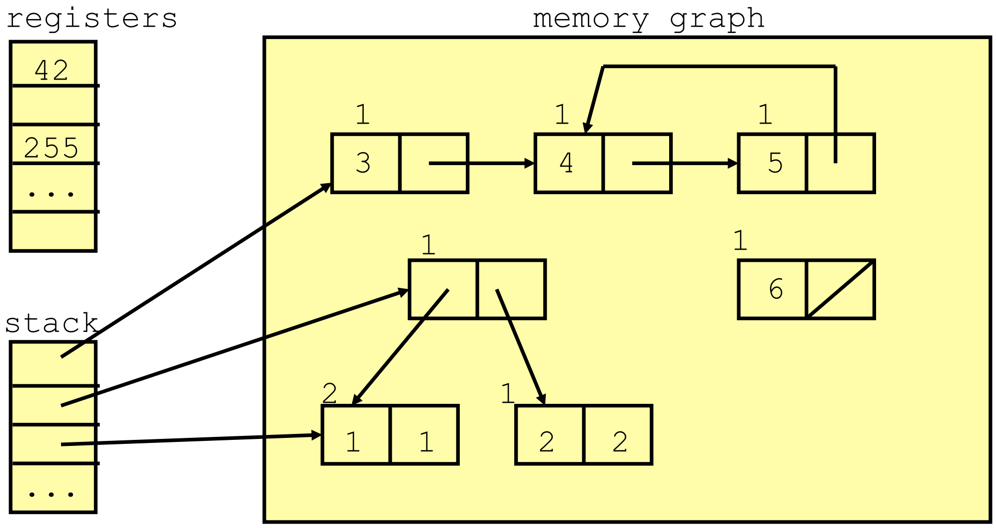

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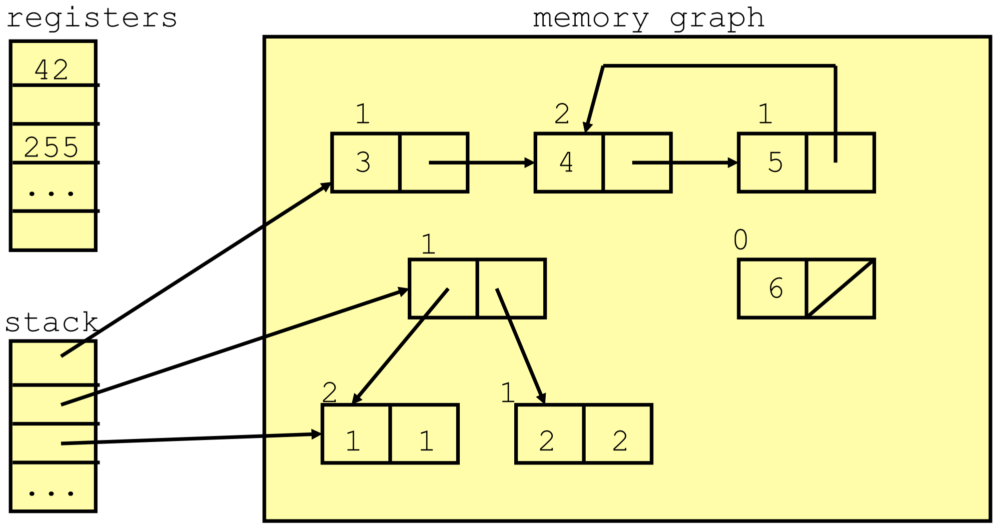
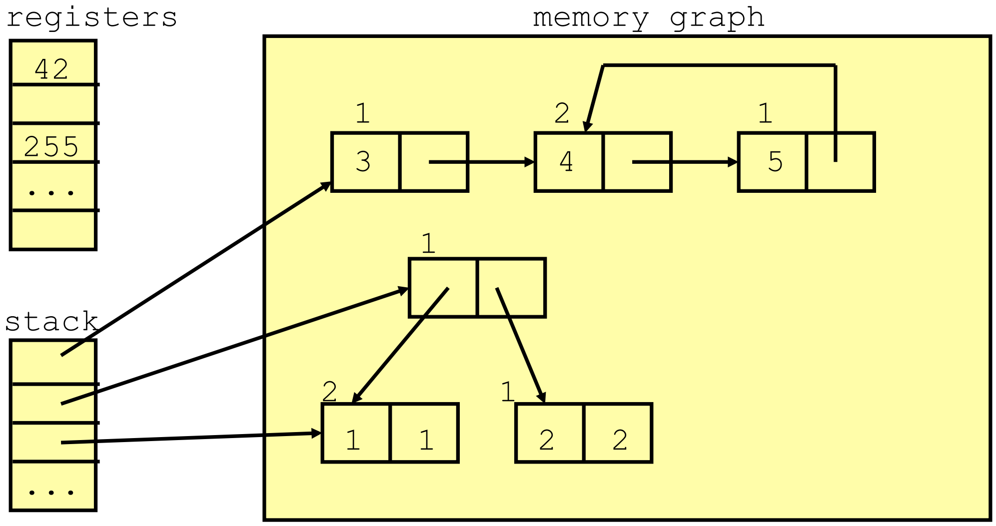


Program Continues On



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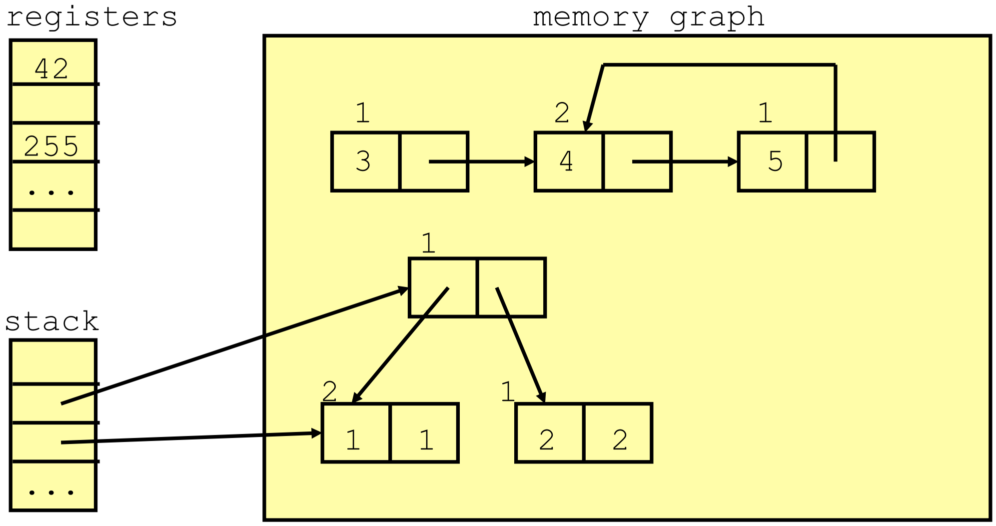

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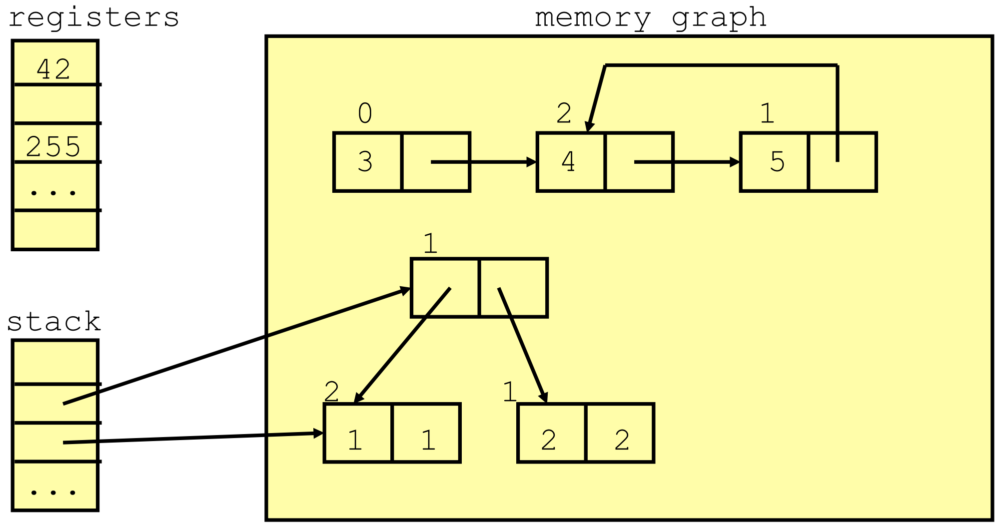

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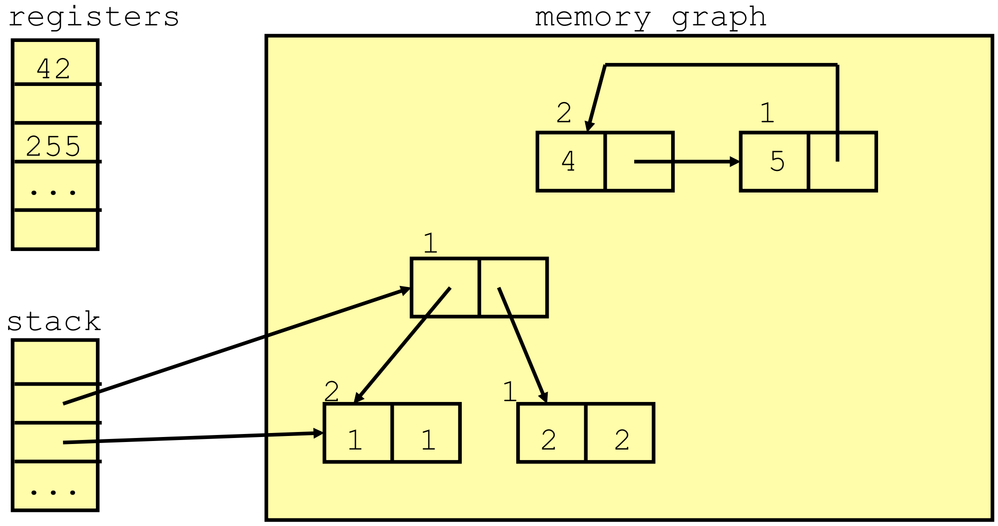

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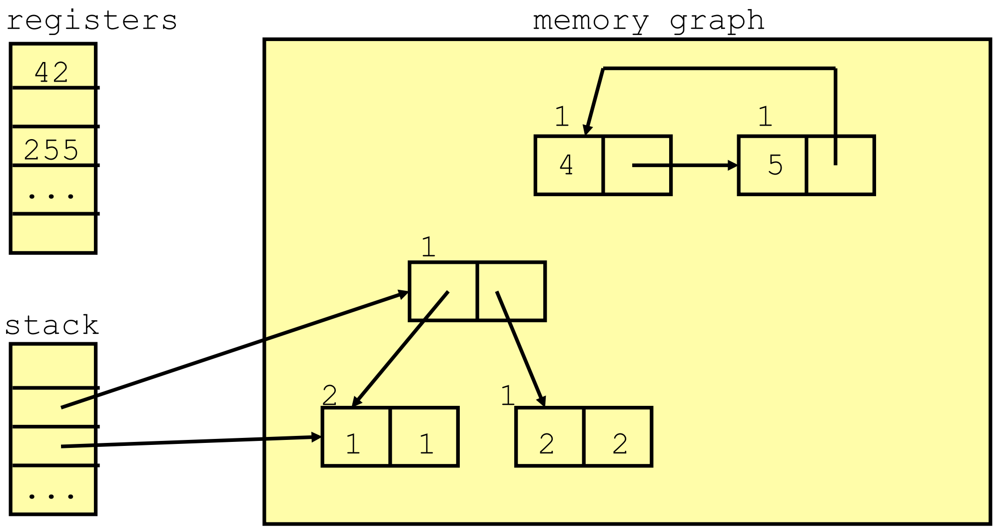
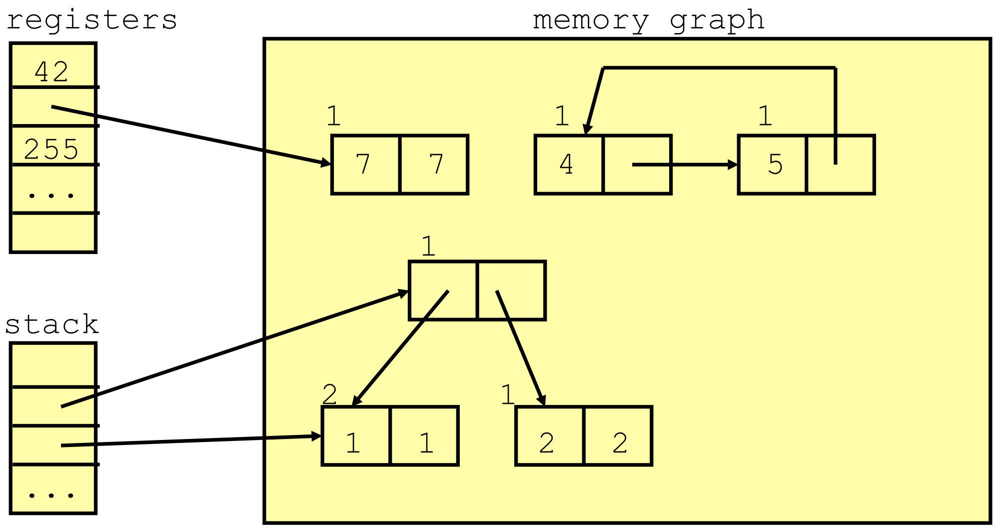


Allocation Resumes



Tracing GC

Allocate until memory is entirely filled

When more space is required, determine the reachable data, and deallocate the rest.

Two classical variants

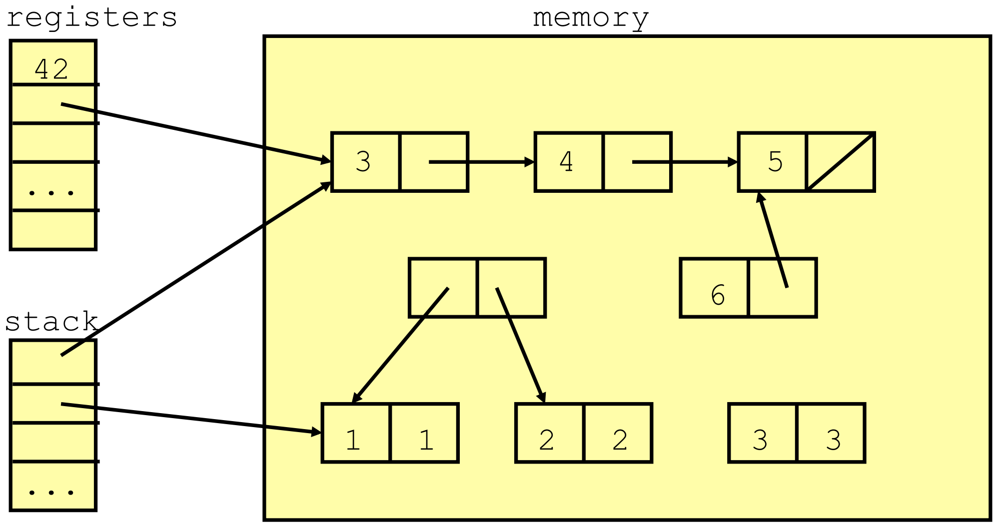
- *mark-sweep* collectors
- *copying* collectors

Mark-Sweep

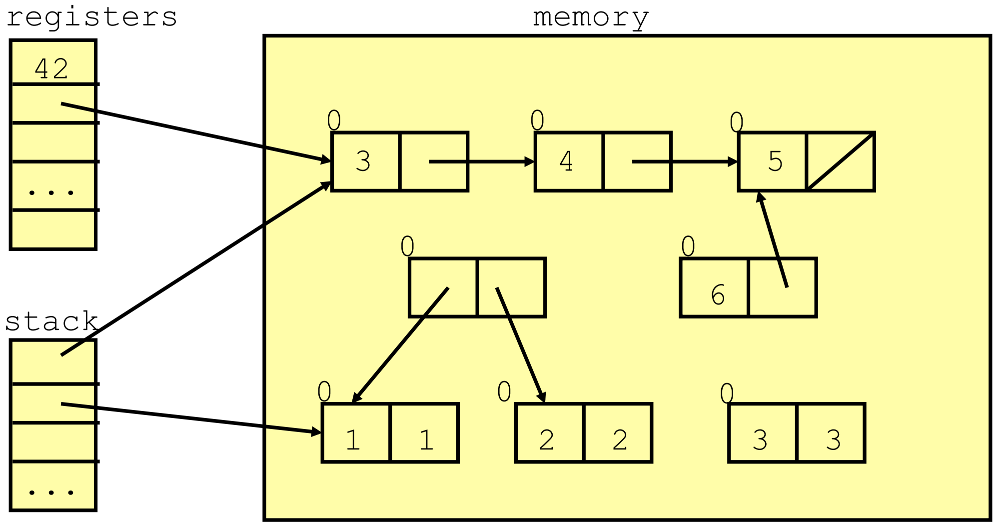
Collection occurs in two steps

- Traverse the graph of reachable data, and mark the reachable objects.
- Sequentially examine all the objects in the heap, deallocating the ones not marked.

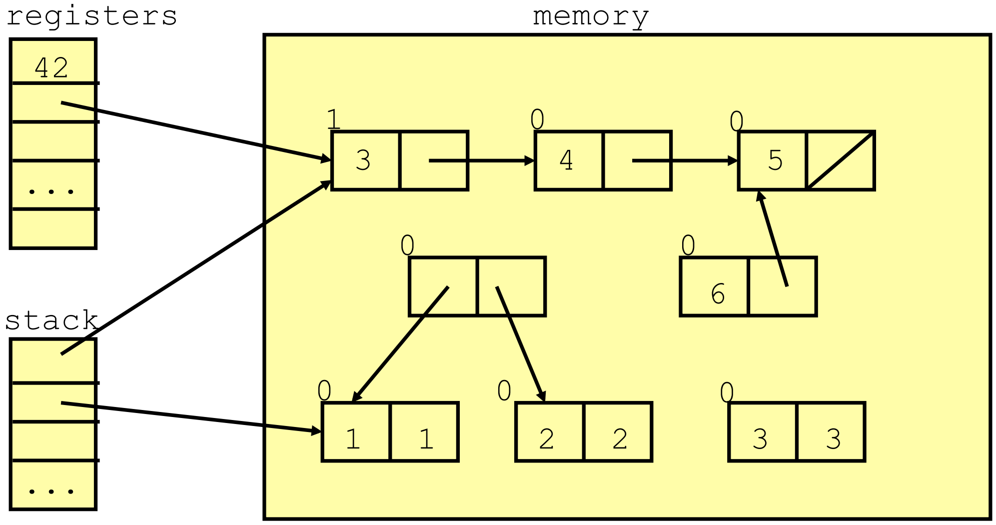
Initial State



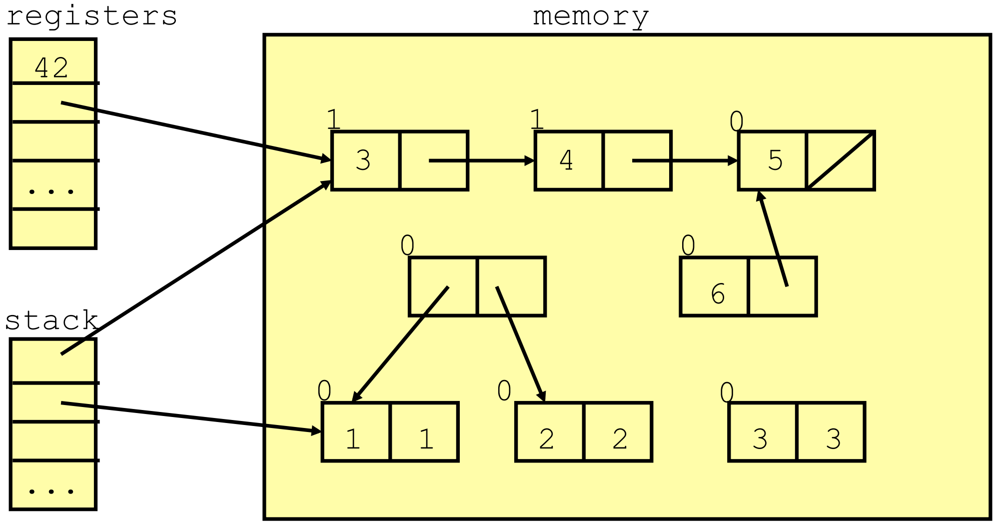
Beginning of Mark Phase



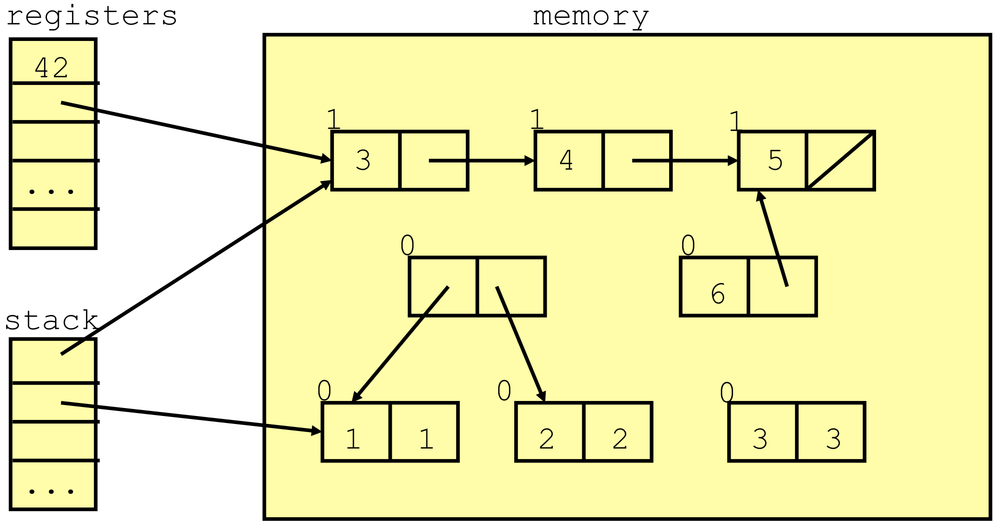
Mark Phase



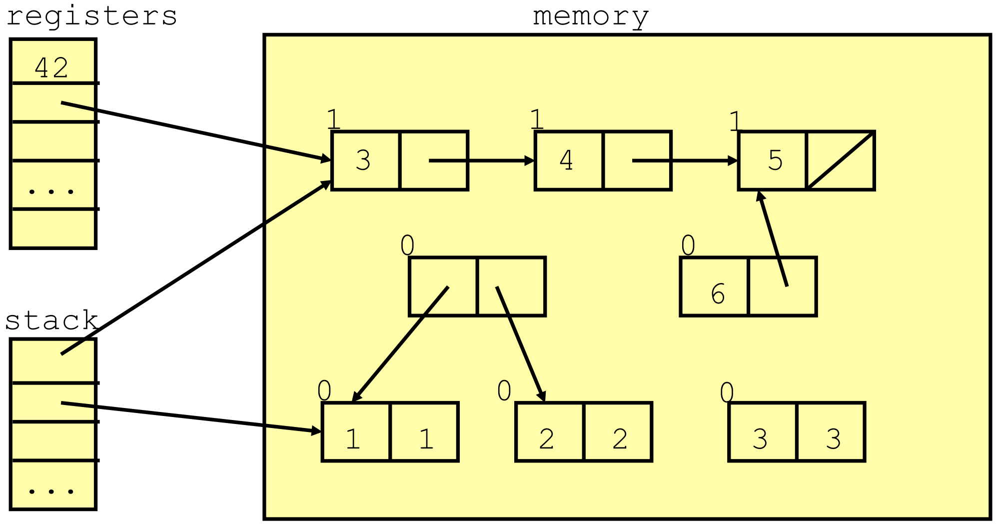
Mark Phase



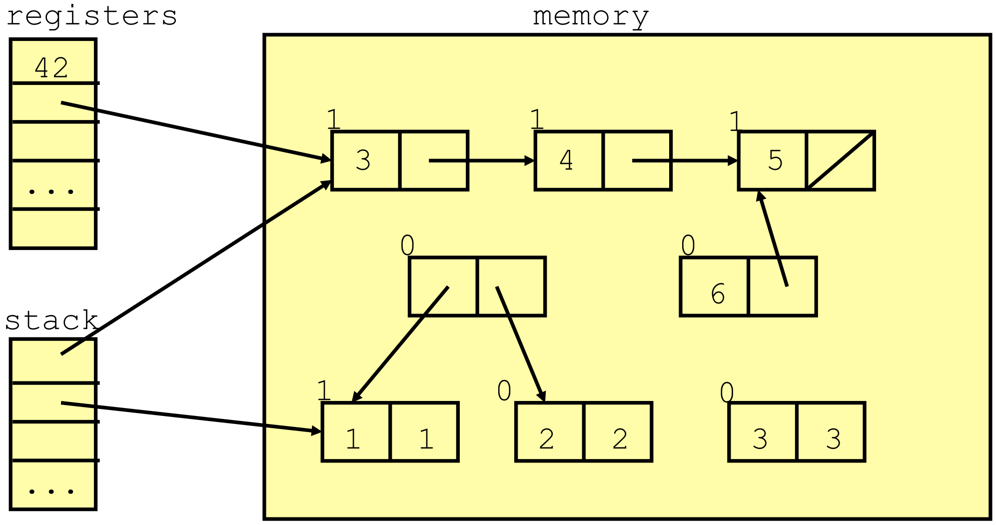
Mark Phase



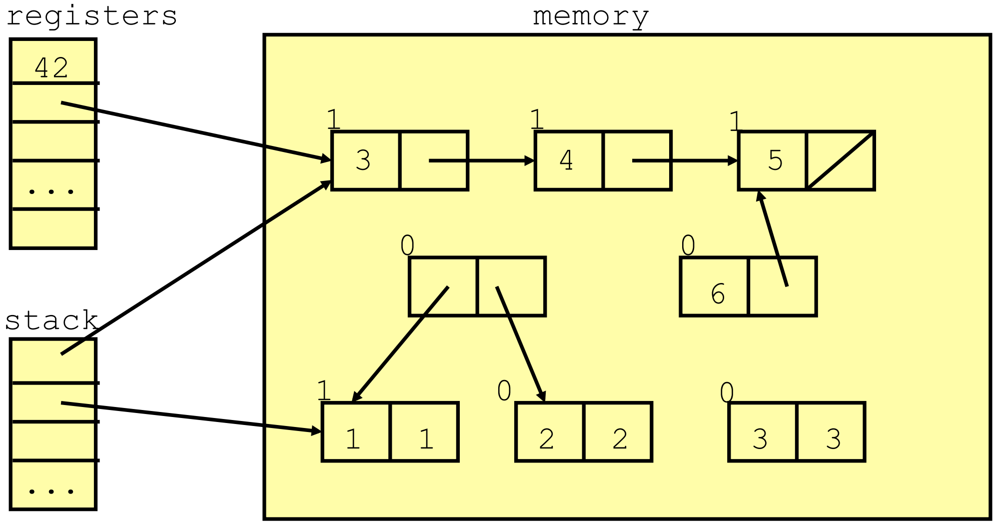
Mark Phase



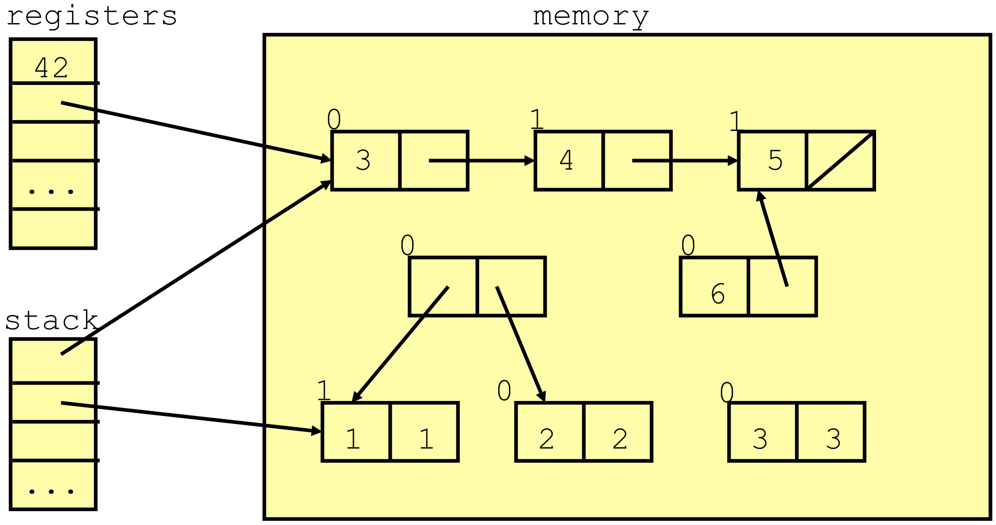
Mark Phase



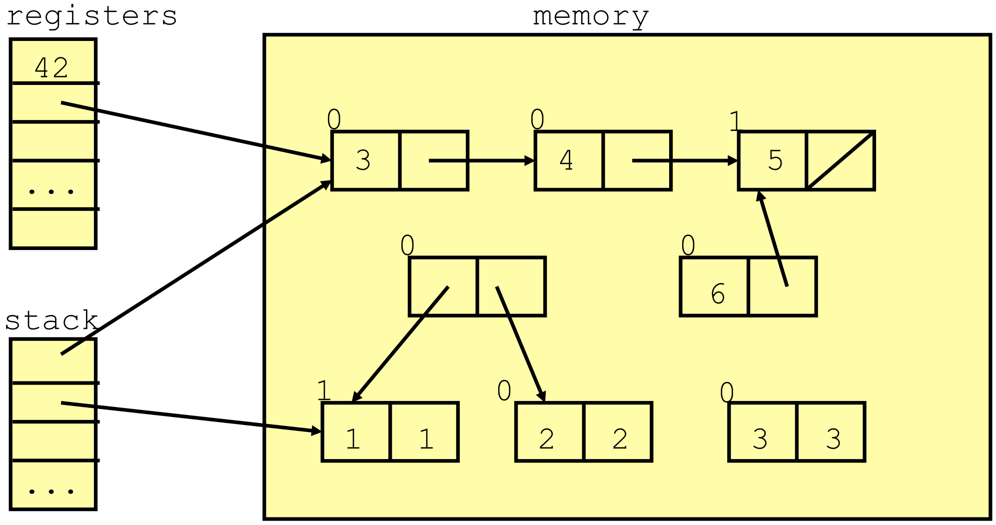
At Beginning of Sweep Phase



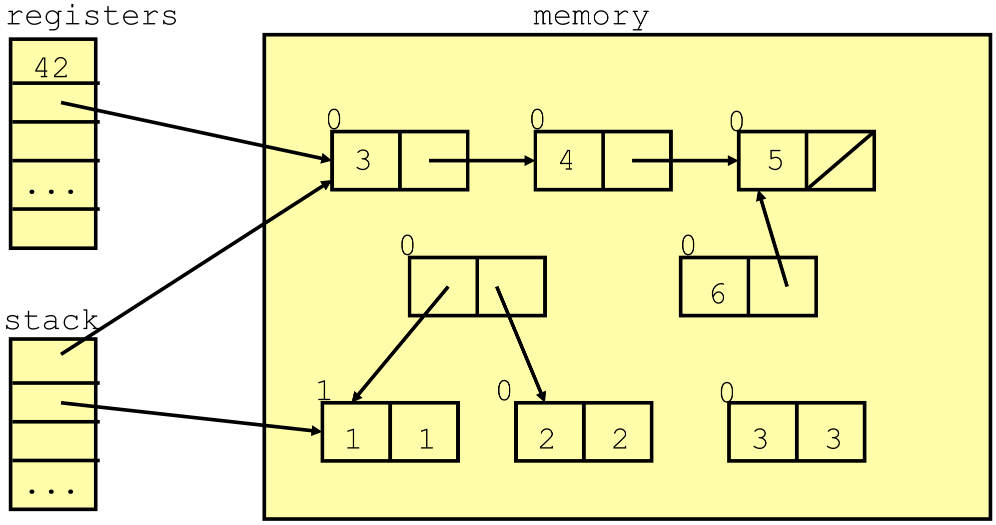
Sweep Phase



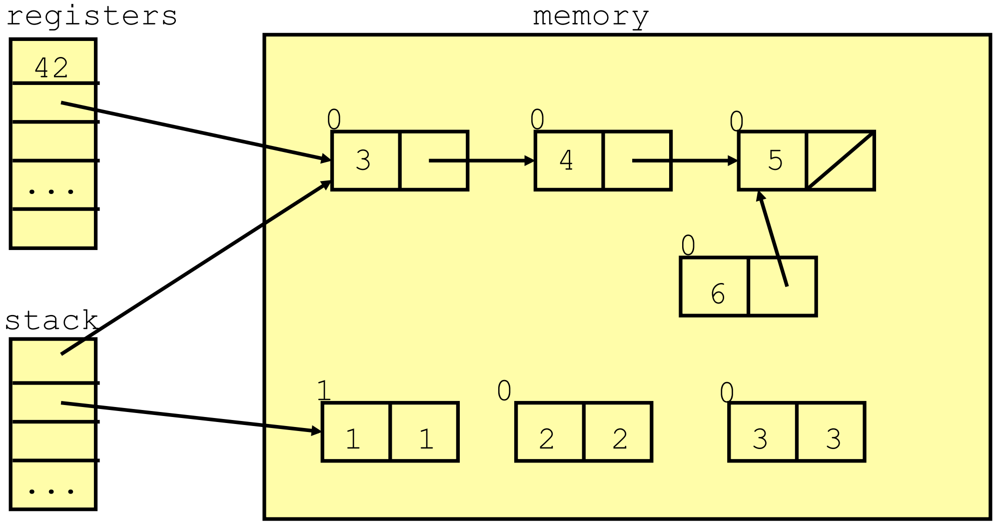
Sweep Phase



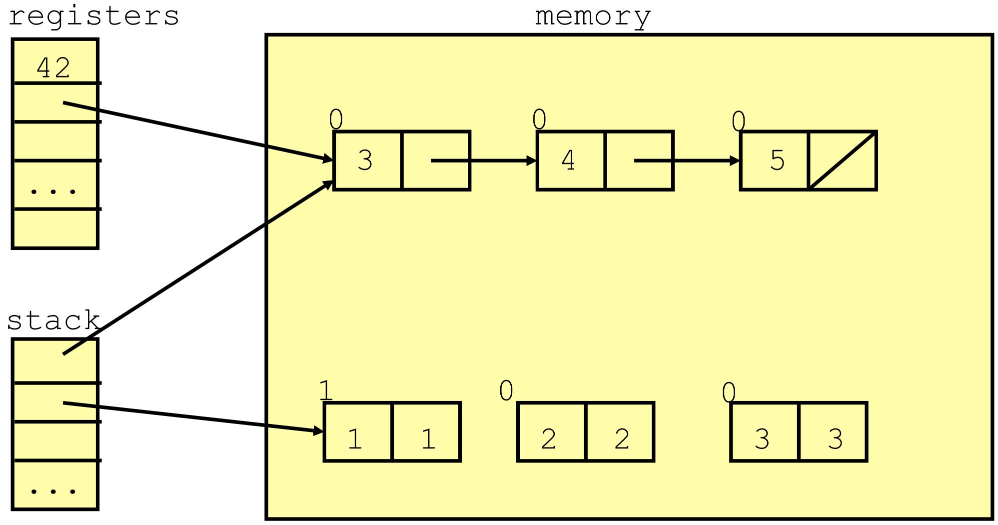
Sweep Phase



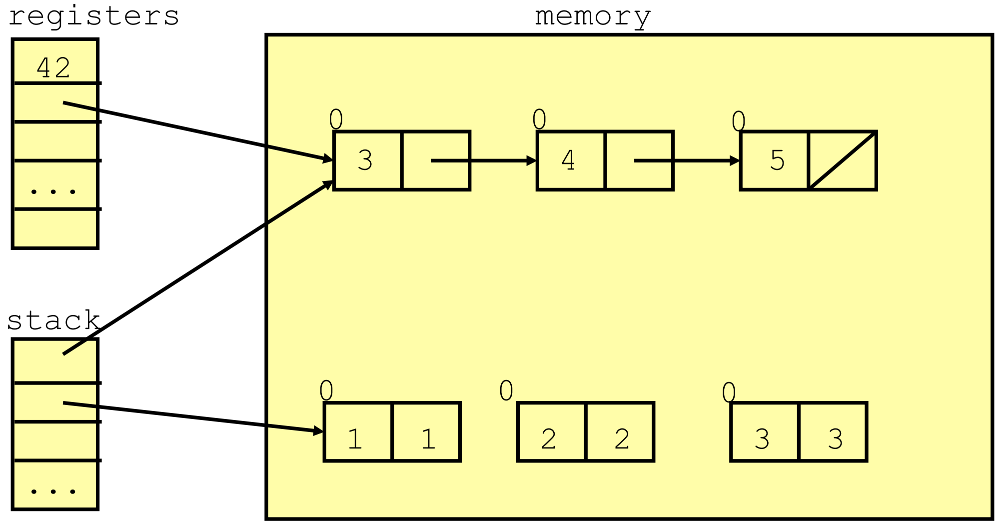
Sweep Phase



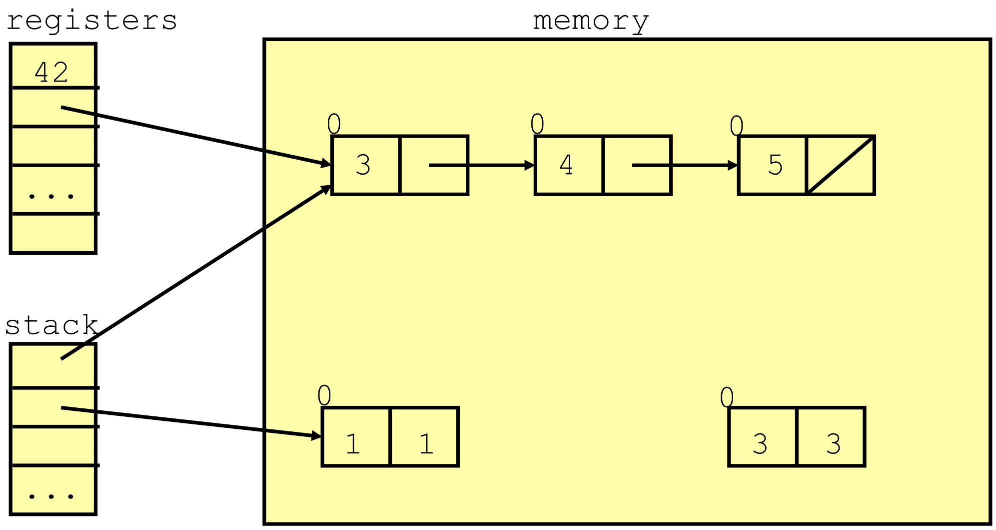
Sweep Phase



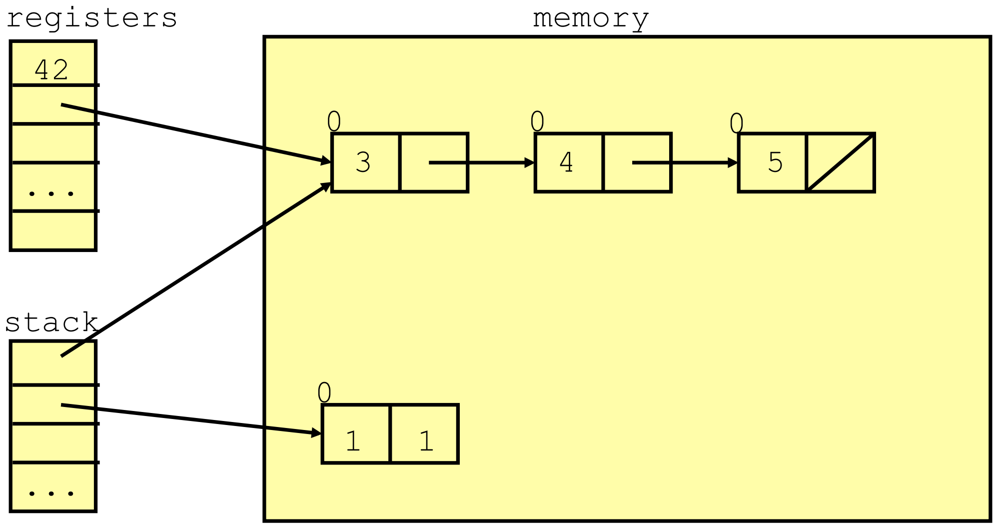
Sweep Phase



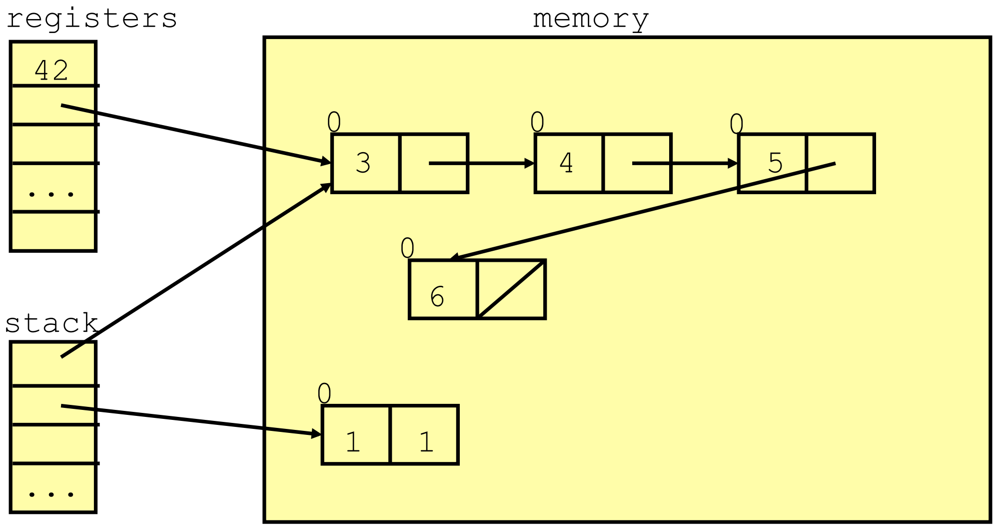
Sweep Phase



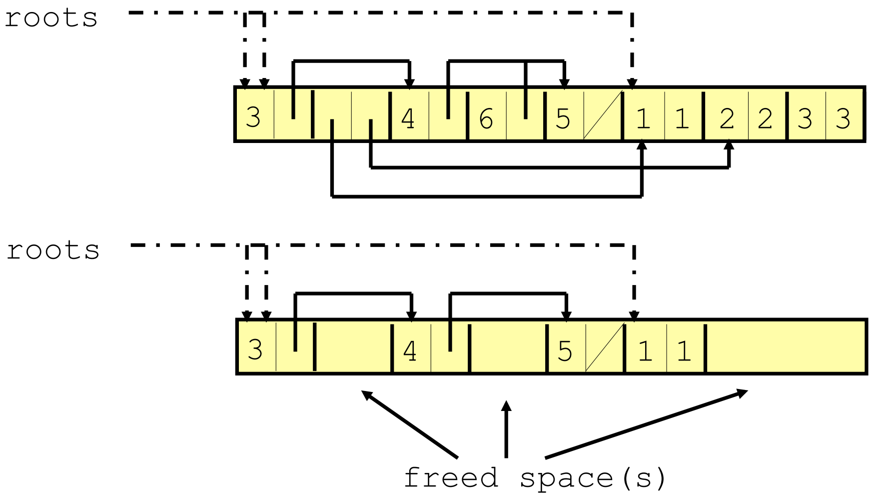
Sweep Phase



Program Continues Allocating



Before and After Summary



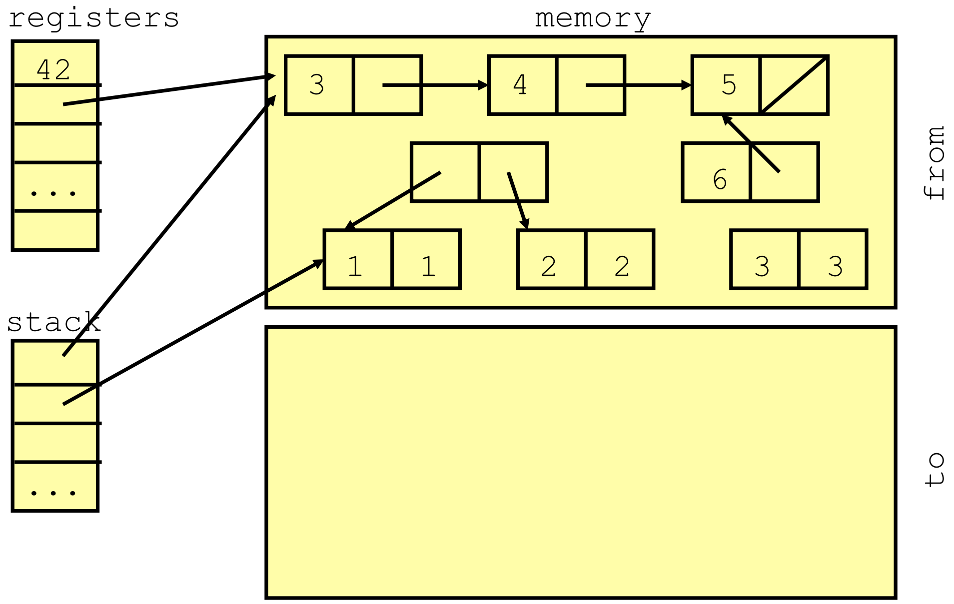
Copying Collector

Divide memory into halves (*fromspace* and *tospace*)

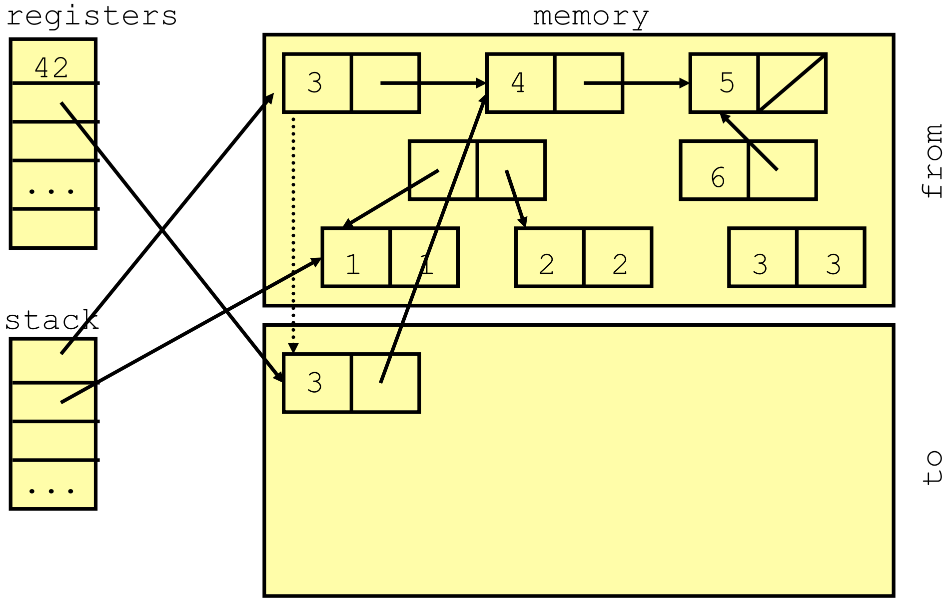
Allocate objects in fromspace until full. Then,

- Copy reachable data from the fromspace to the tospace.
- Swap the names "fromspace" and "tospace".
- Resume allocating

Fromspace Full: Start Collection



Copying



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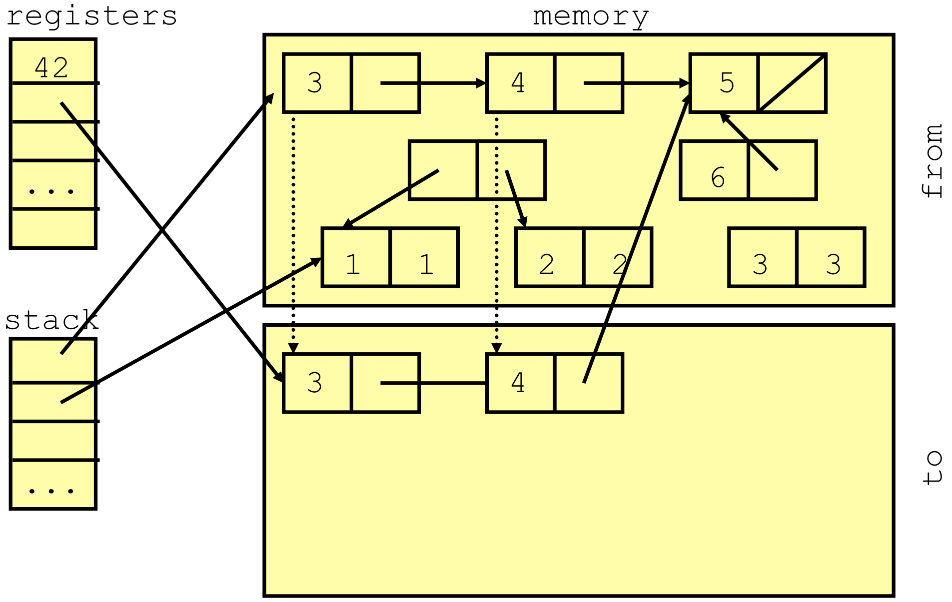

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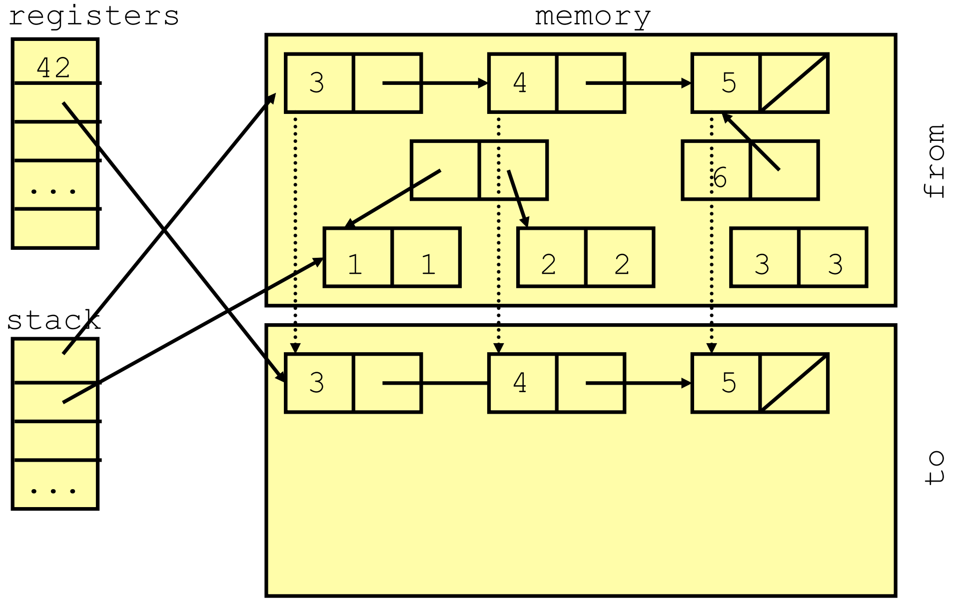

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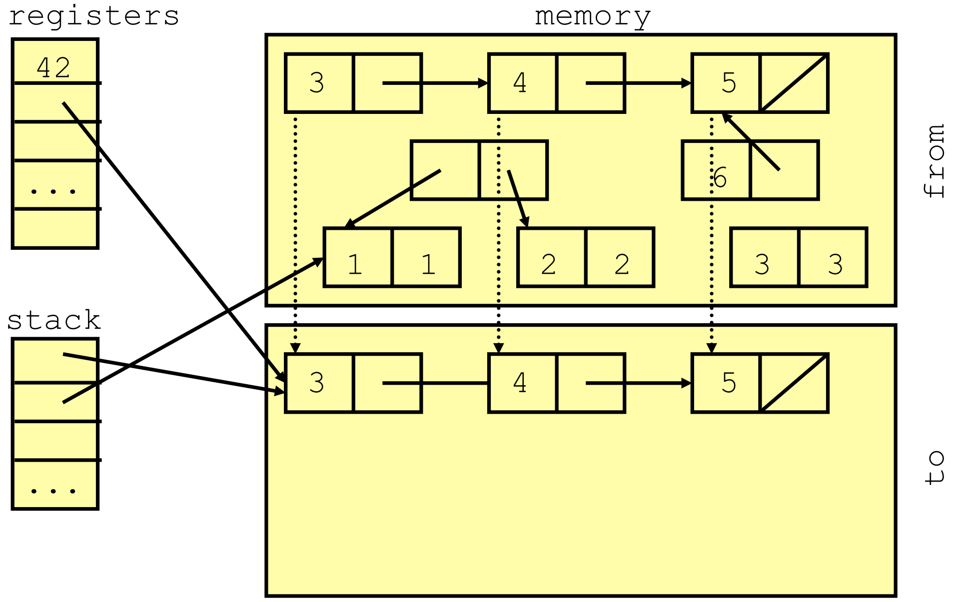

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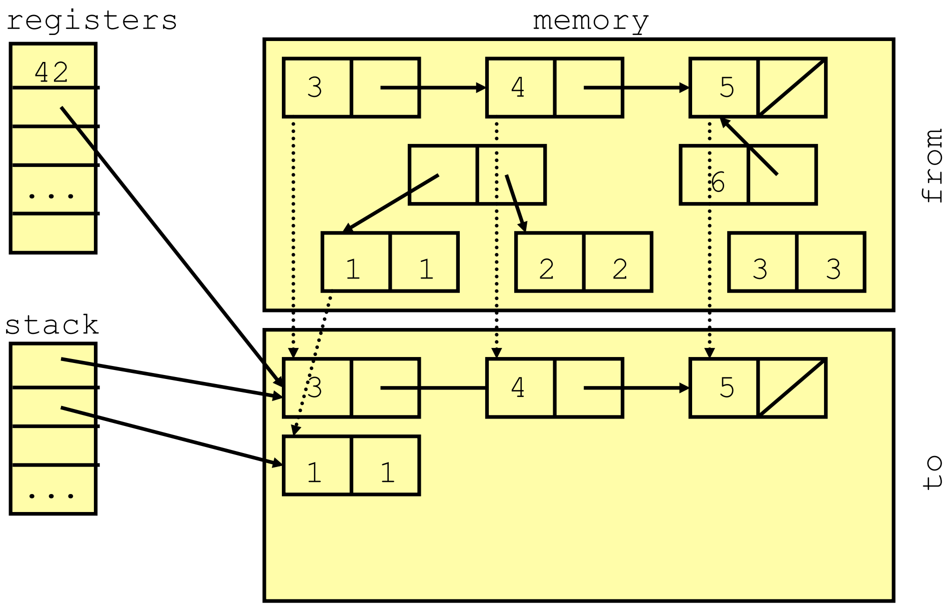
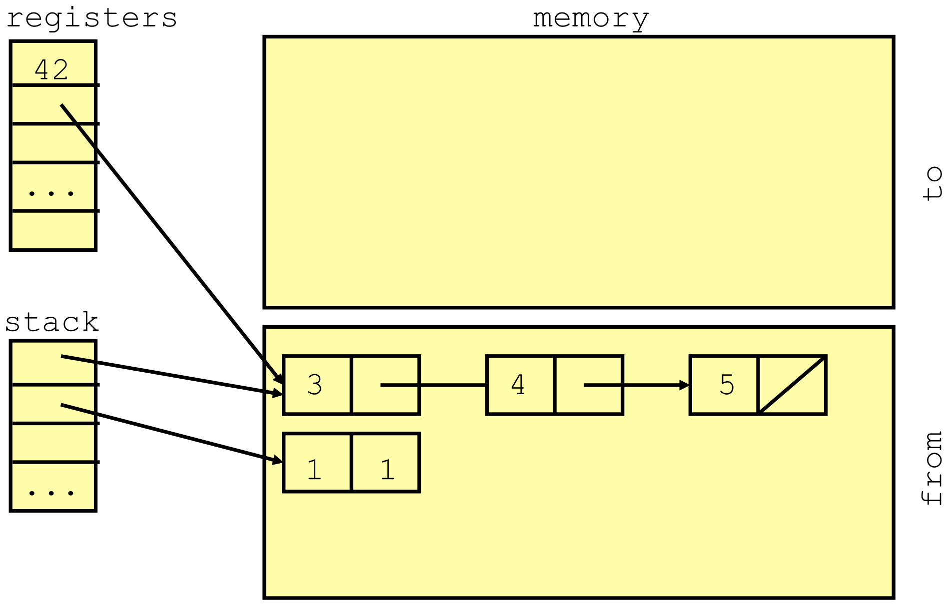
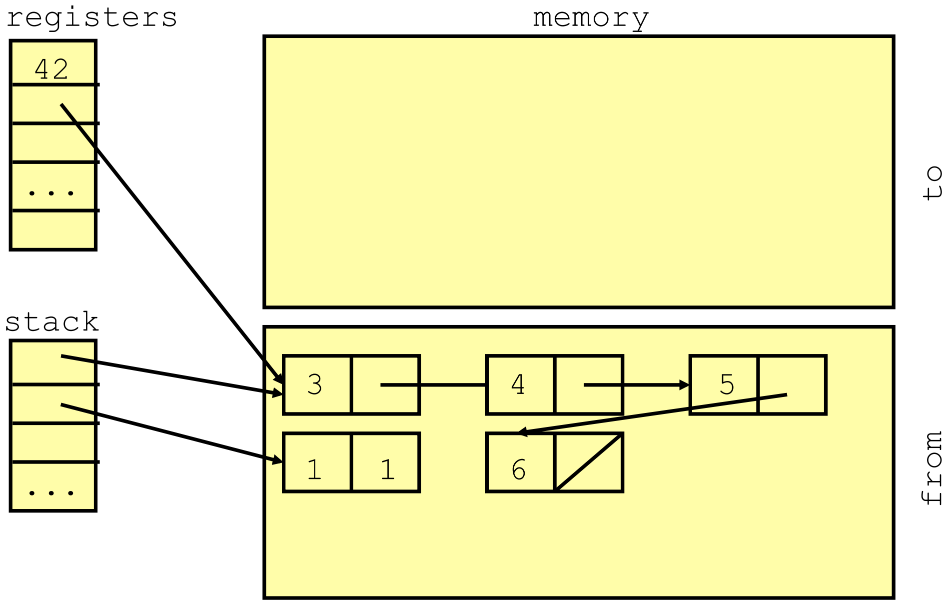


Final State



Program Continues Allocating



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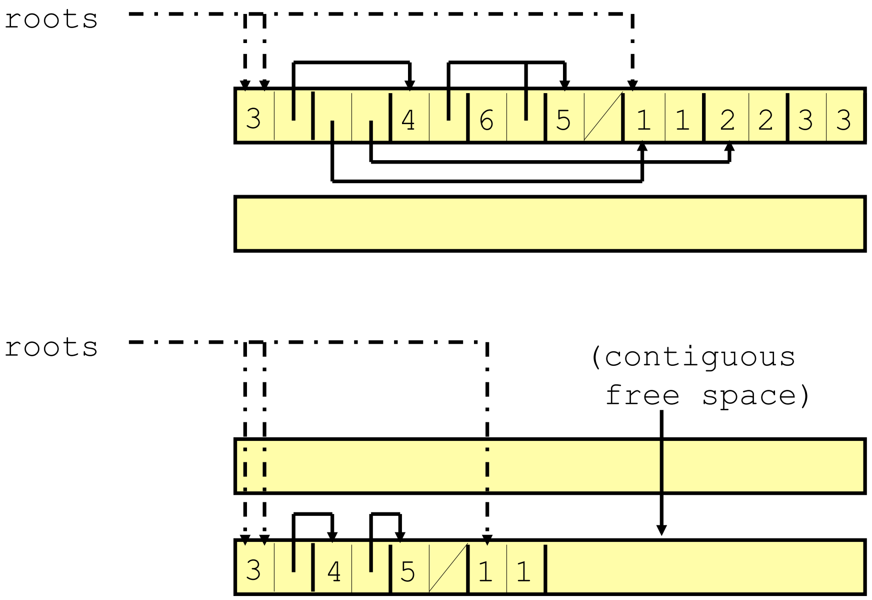


History

1960: McCarthy's LISP

Heap primarily contained "Cons cells" (pairs)

36-bit IBM 704 → Mark & Sweep.

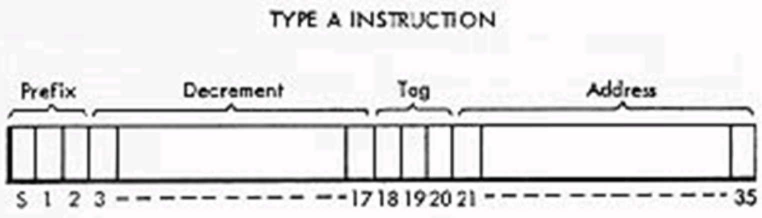


FIGURE 4

Within a year, 48-bit port used reference counting

First copying collector 3 years later.

Reference Counting

What could we do about cycles?

Reference Counting

What could we do about the space overhead?

- What if we only want 8-bit reference counts?
- 1-bit?

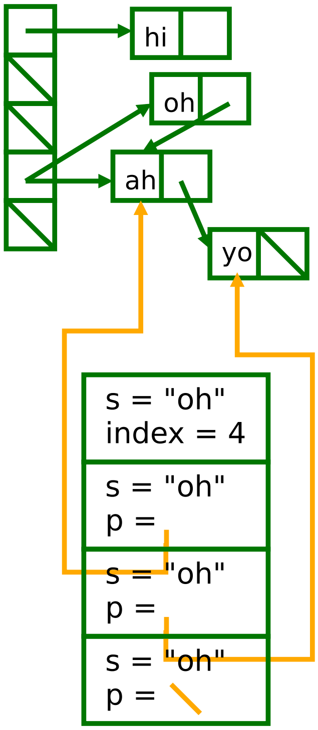
Reference Counting

Maintaining reference counts takes time.

Recall the initial hash-table implementation…

Maintaining Counts Takes Time

insert("oh")

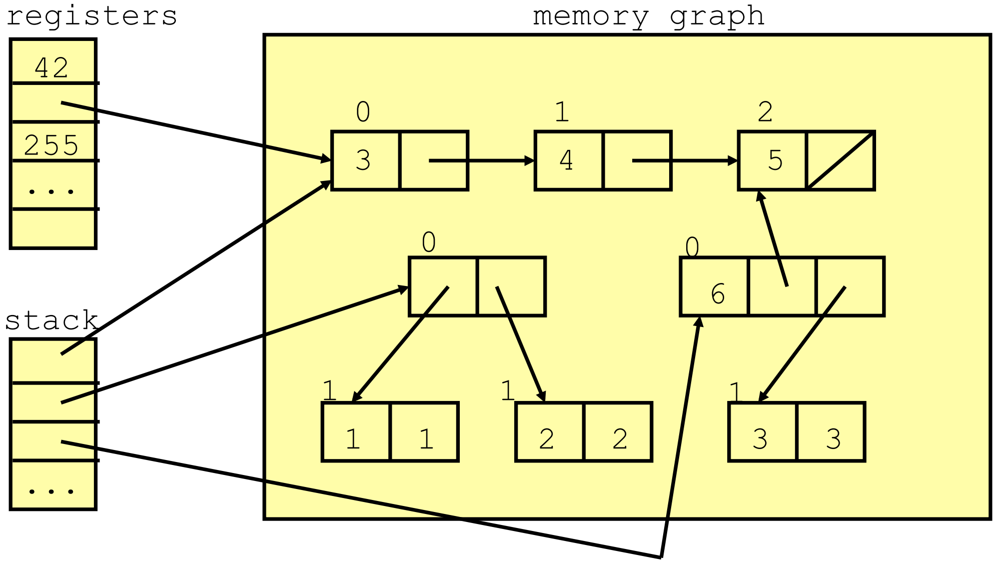


Suppose we only kept track of pointers from other heap objects?

Reference Counting

Suppose we only counted pointers from other heap objects?

Initial Machine State



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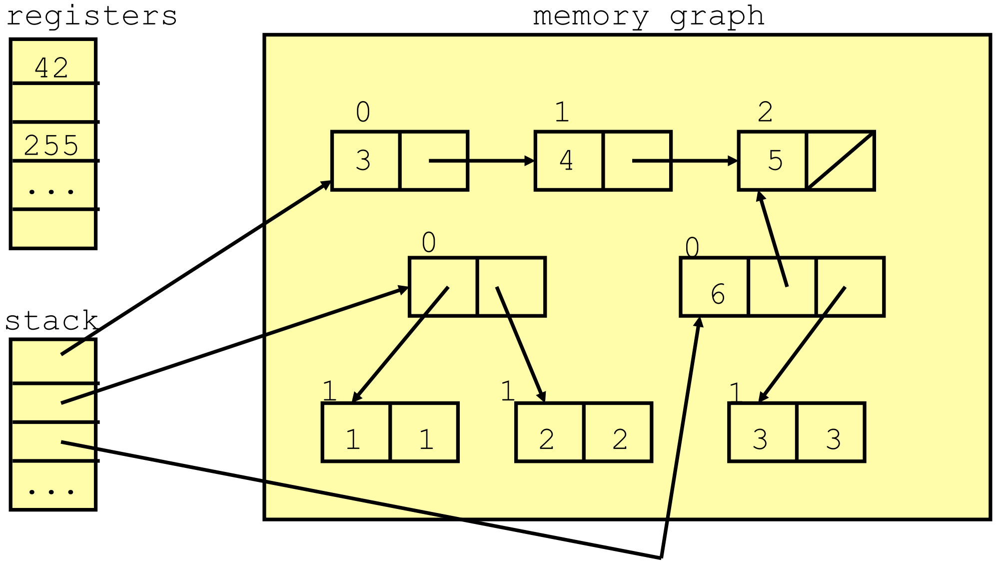

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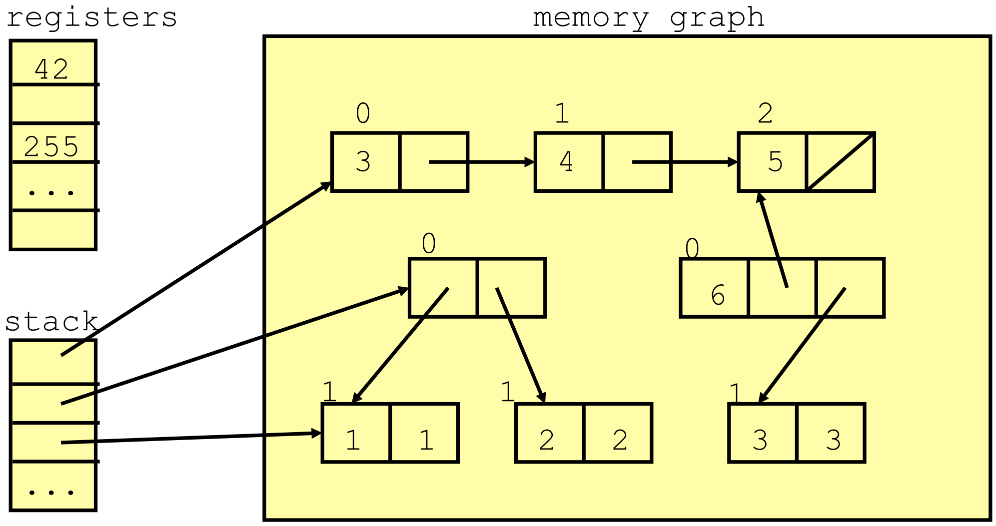


Mark-Sweep

What if we don't want mark bits attached to objects?

- Can we put the bits somewhere else?

Mark-Sweep

Graph traversal is naturally recursive.

There's a small but non-zero overhead to function calls.

Usually we don't care, but …

How could we avoid recursive calls?

Copying

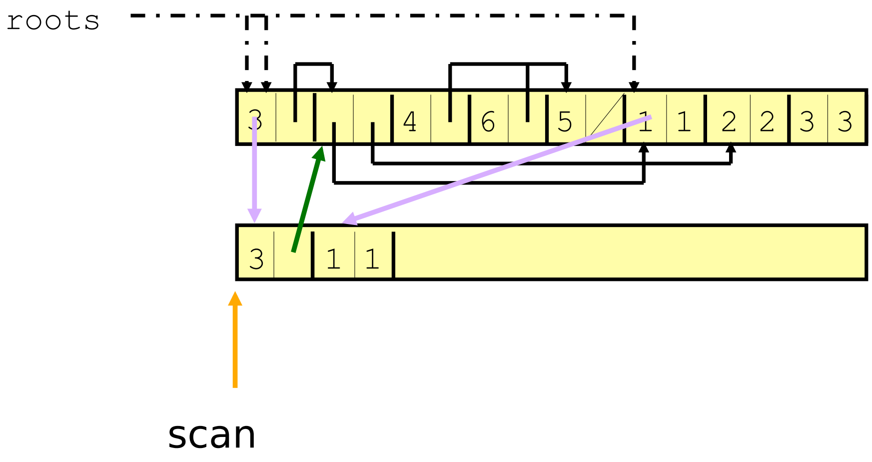
We're garbage collecting because the heap filled up.

But we need a stack (or something) for the graph traversal.

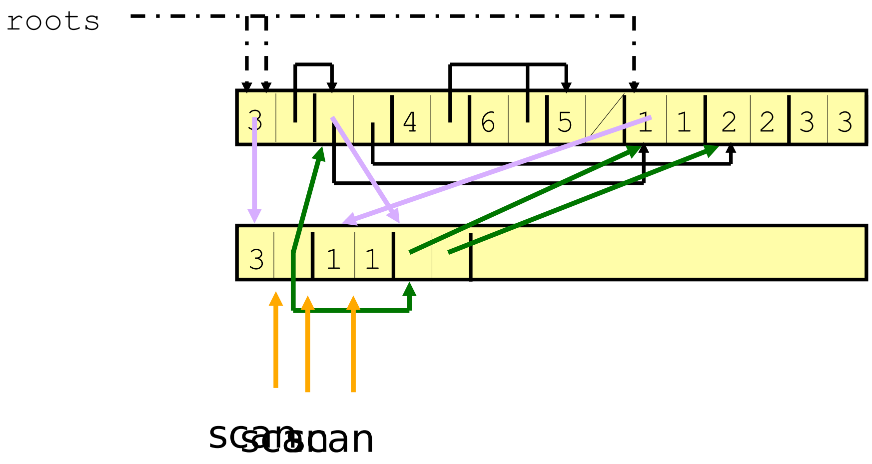
Where do we put it?

What if we run out of room?

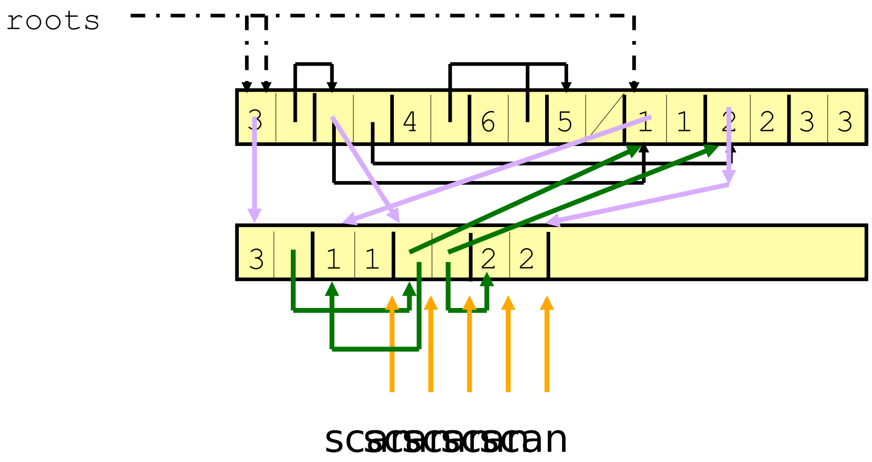
Cheney's Algorithm



Cheney's Algorithm



Cheney's Algorithm



Question

What sort of graph traversal does the Cheney Scan implement?

Does this have any advantages/disadvantages?

Tracing

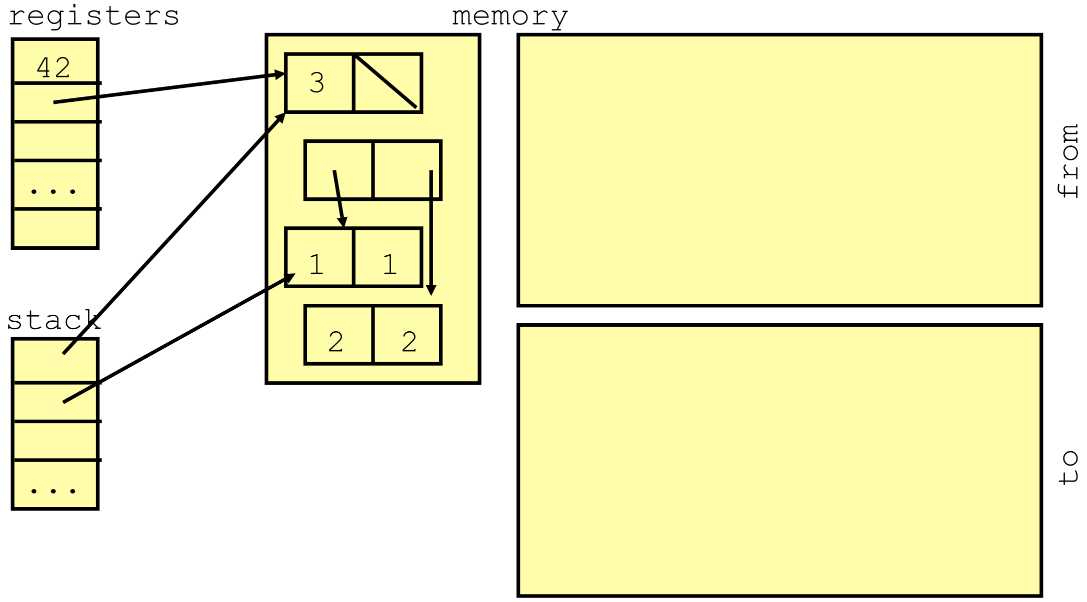
In a semispace collector, what happens to big objects that are used for a long time?

How might we improve this?

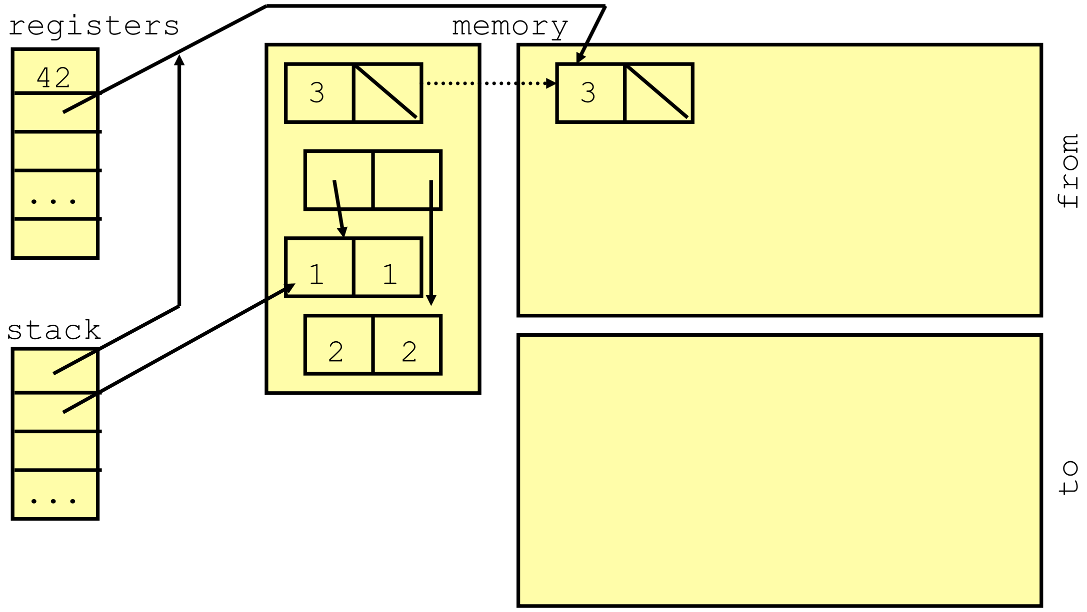
Generational GC

- Problem: long-lived data can be copied repeatedly
  - From fromspace to tospace on every collection
- Generational idea: Data that has survived a long time is presumably "important" and will survive
  - We should try to avoid processing old data during GC
- Separate heaps for young, old data ("generations")
  - Mostly GC only looks at the young data ("minor" GC)
  - Only look at older generation when it finally fills up
  - Can reduce bytes copied by orders of magnitude
    - e.g., 2.3M to 500, or 800M to 25M

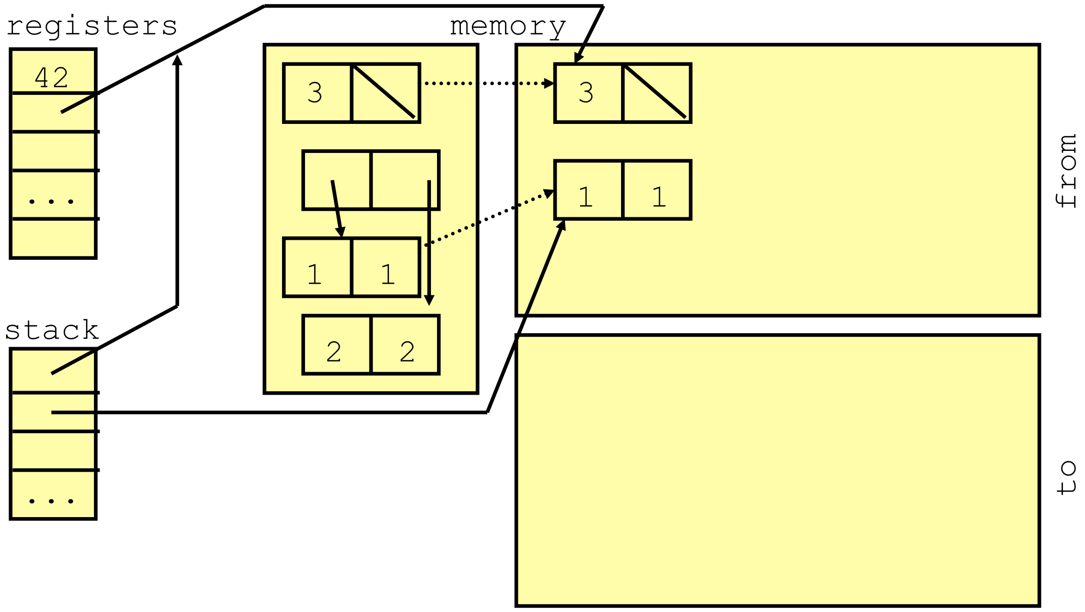
Nursery Full



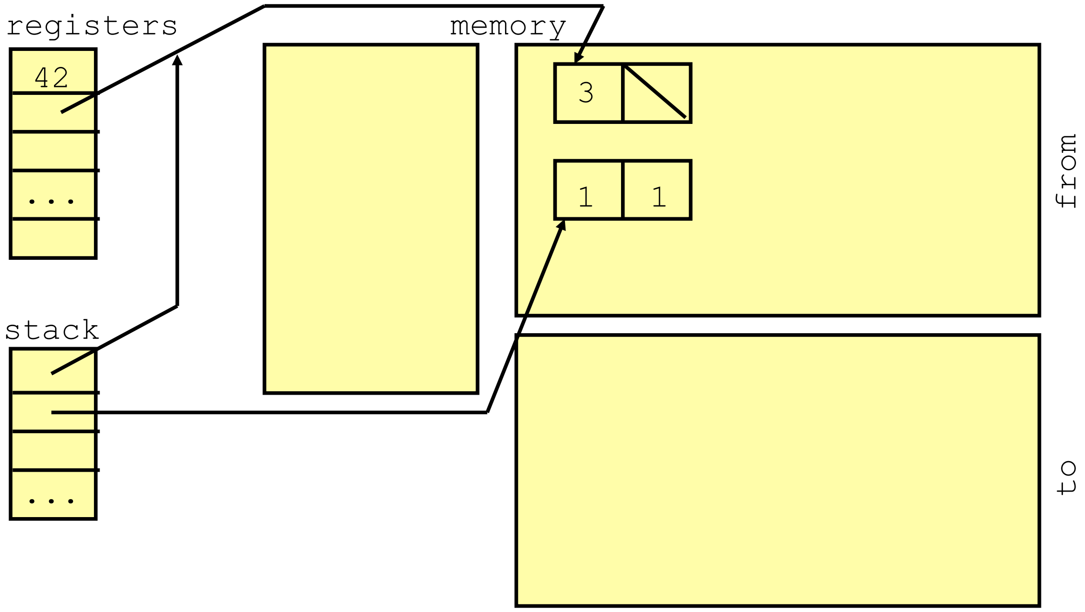
Minor GC



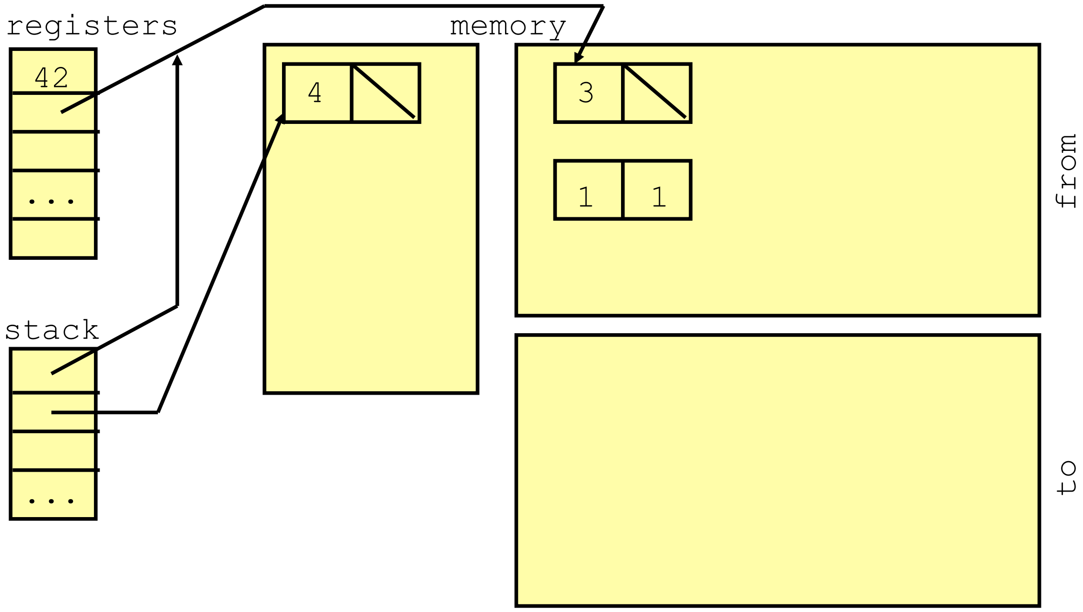
Minor GC



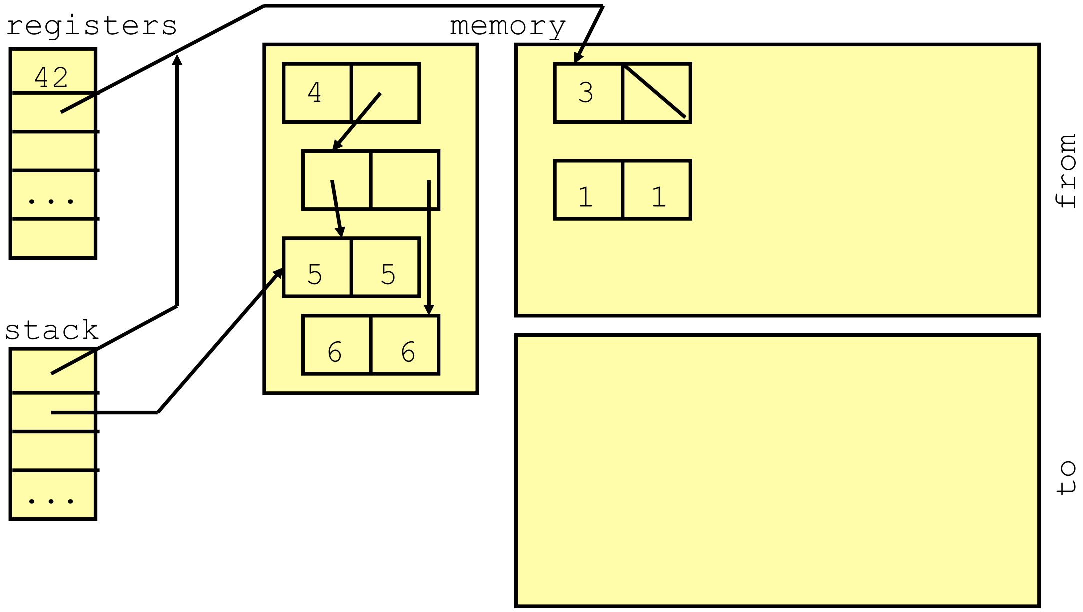
Ready to Continue Allocating



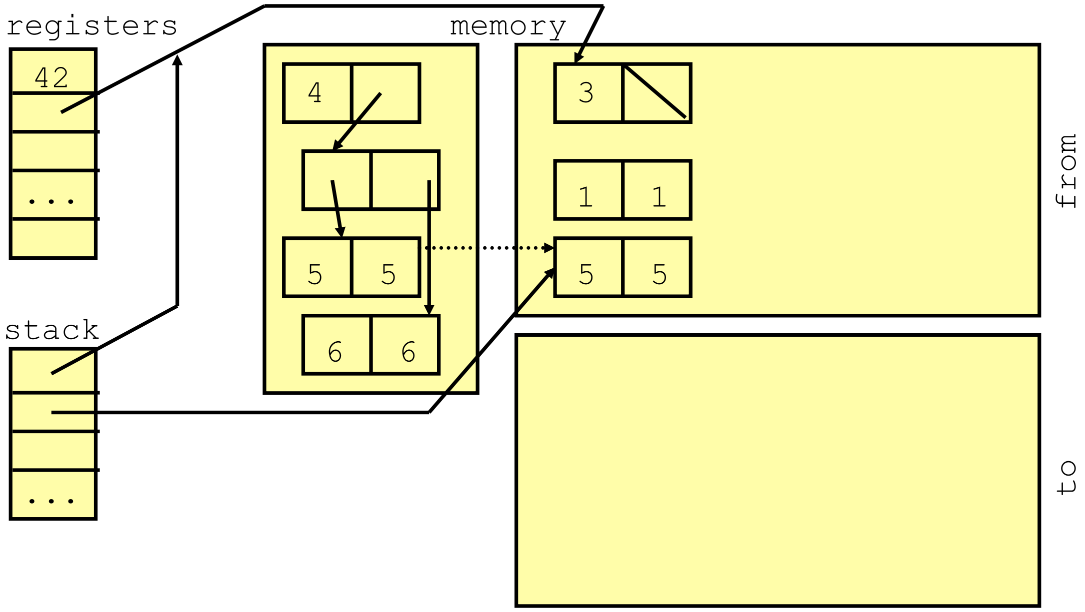
Continue Allocating



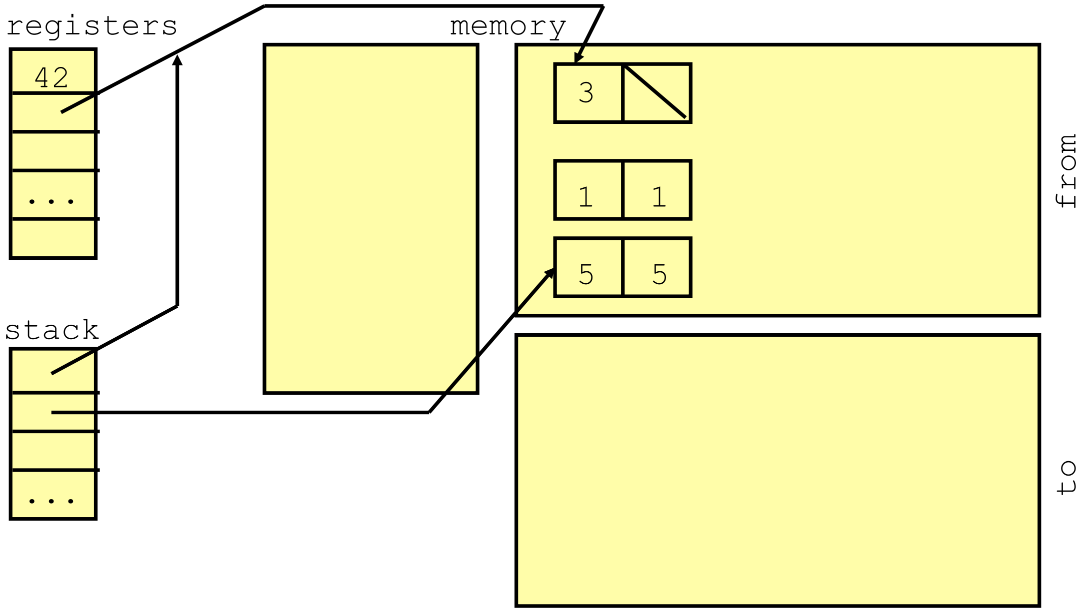
Nursery Full Again



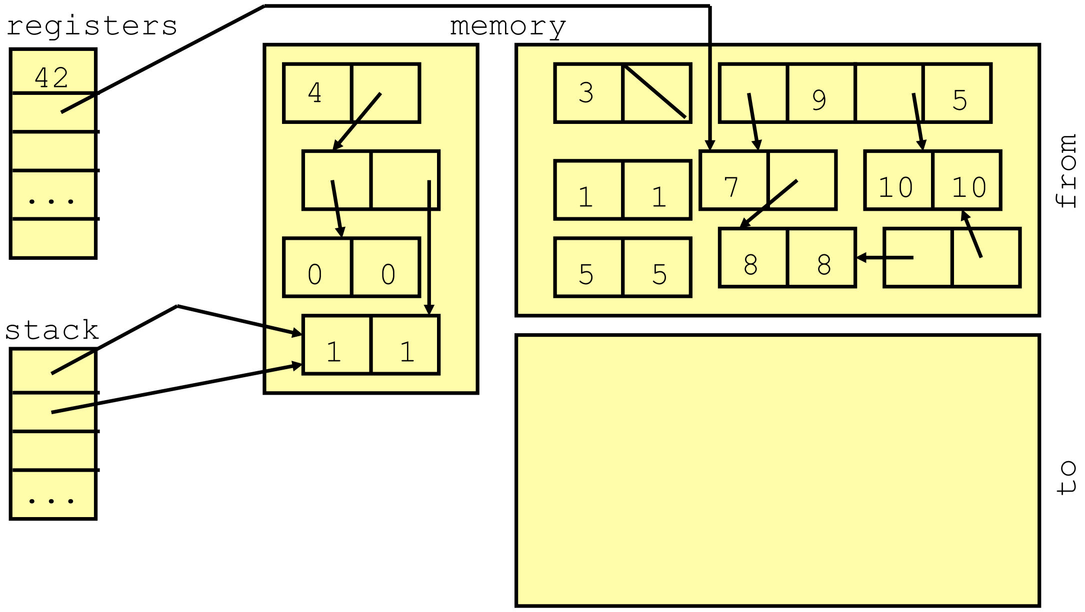
Minor GC Again



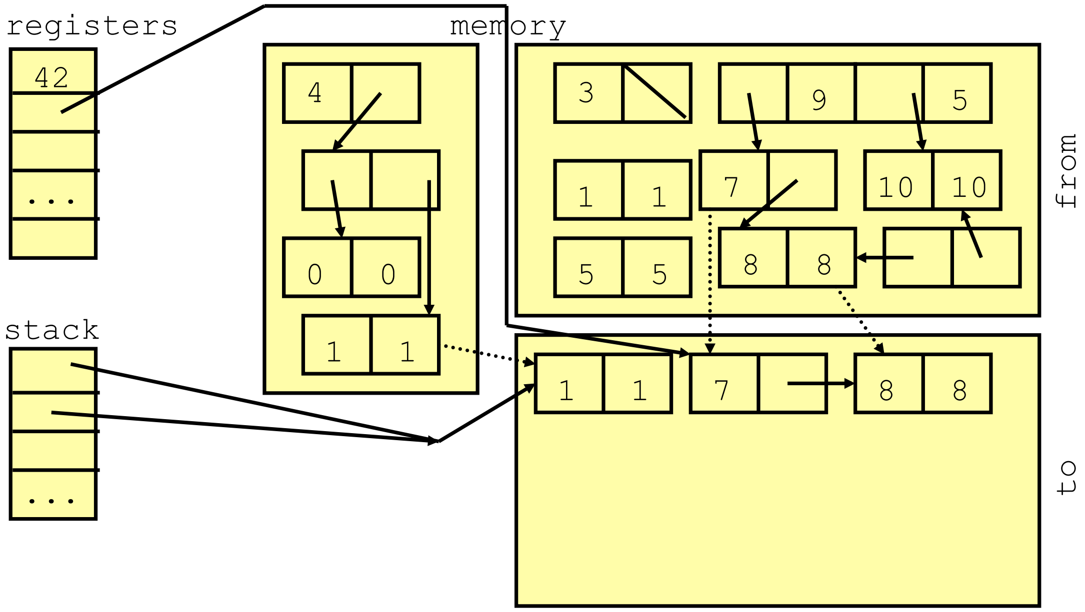
Continue On



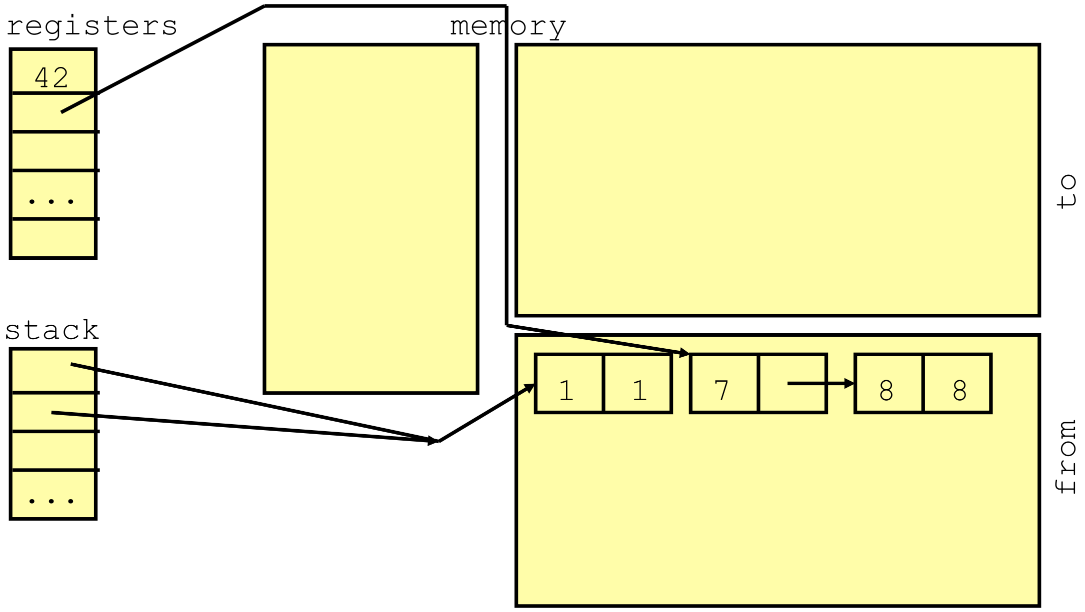
Eventually FromSpace Fills Up



Major GC



Continue On

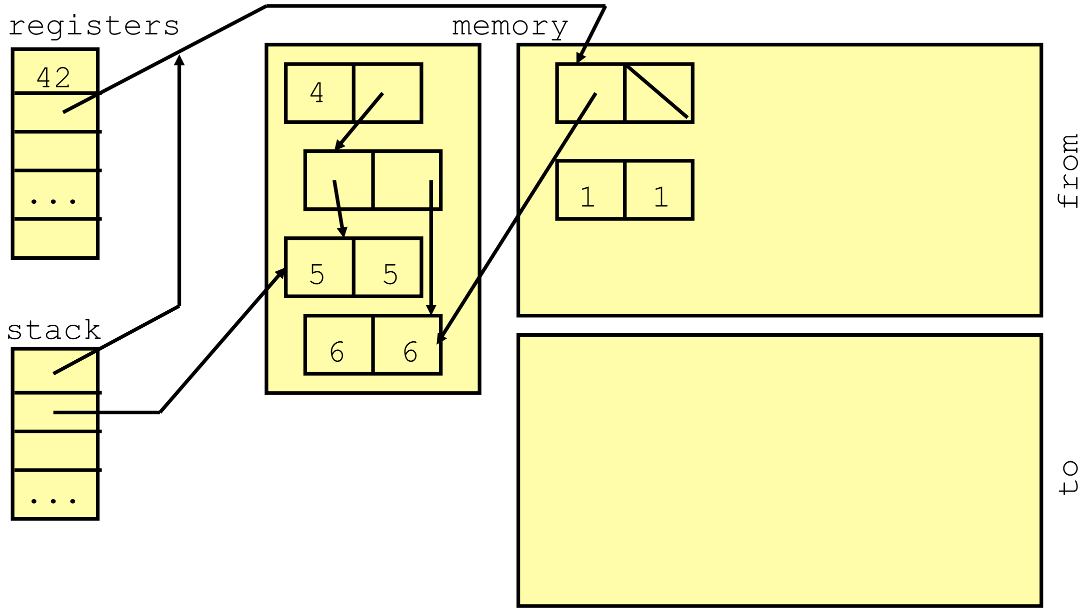


Is Young Independent of Old?

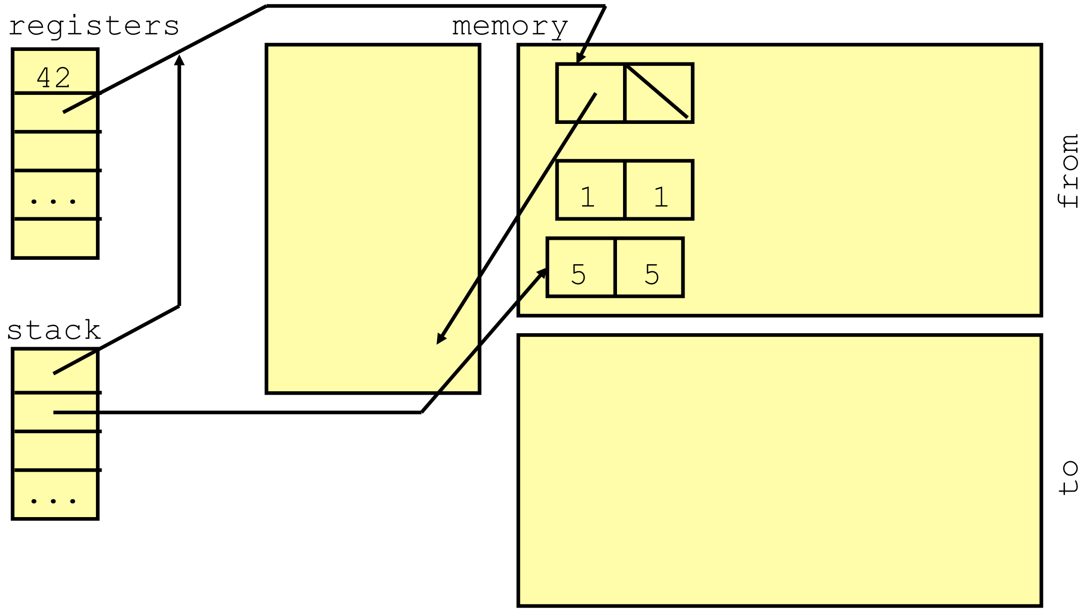
- What happens if old data points to young data?
  - That is, what if the fromspace contains pointers into the nursery
  - Such references are called "back-pointers"

- Why are these rare in Haskell?

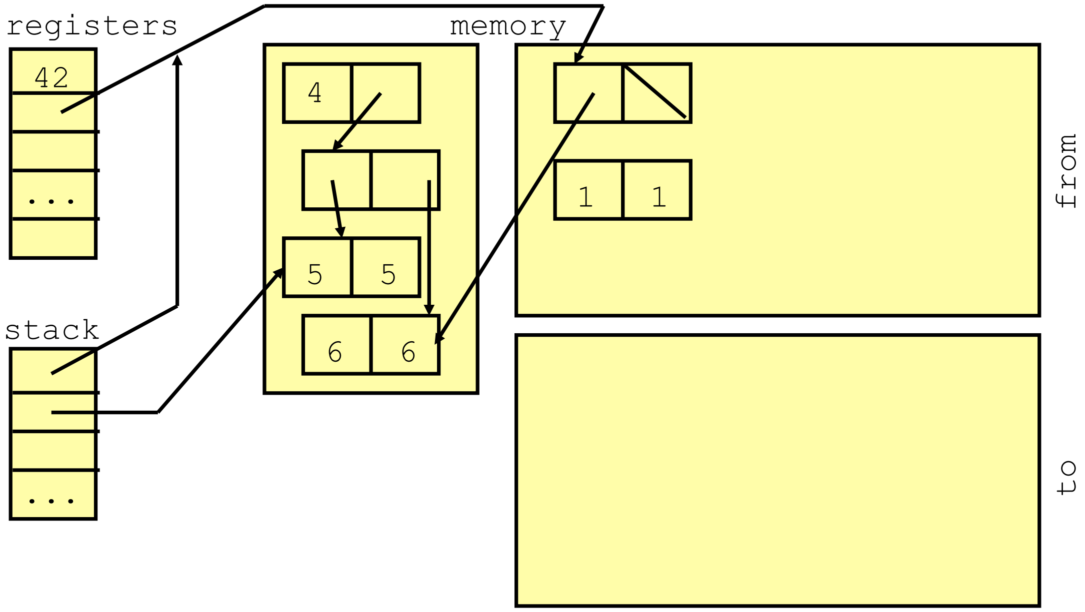
Example



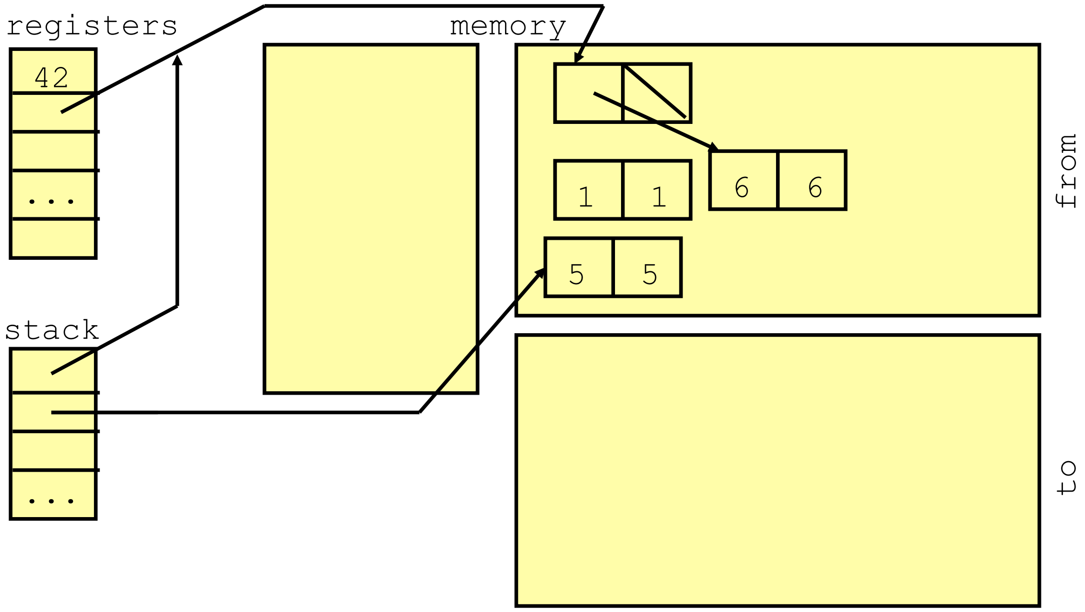
Wrong Answer



Same Example



Right Answer



Is Young Independent of Old?

- What happens if old data points to young data?
  - Need to treat backpointers 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 to get a backpointer is by modifying (assigning to) an object
  - General idea: "write barrier". Remember information about all (relevant) updates.

Generational Collection

- Advantages
  - Much shorter pauses
  - Often dramatically less copying
    - Sometimes orders of magnitude
- Disadvantages
  - Have to keep track of assignments
  - Can increase memory requirements.

Large Objects

- For large objects, copying even once can be overly expensive.
  - And larger objects are 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 Variations

- 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
- Distributed collectors
  - Heap is divided among several computers

Which Collector is Best?

- Nobody knows; performance depends on
  - Client program ("mutator") 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 research work collectors
  - Incremental, Parallel, Concurrent, Real-Time, …

Another Approch: *Regions*

Idea:
- Allocate into regions
- Each region is a heap that never deallocates
- Which region to use may be decided by the compiler.
- Deallocate each region as a whole when done with it.
- (Often, assume a stack of regions.)

Advantages:
- Very efficient allocation and deallocation.
- Can often detect values that are accessible but dead.

Disadvantages:
- Precise analysis can be tricky
- (in worst case, everything in 1 region)

Question

Assume we need to do a GC when

```
%eax = 0x01345568
%ebx = 0x01345560
%ecx = 0x00000003
%edx = 0xFFFFFFFF
%esi = 0x01345784
%esi = 0xDEADBEEF
```

What are the roots?

Assume a root points to address X in memory, where:

```
X[-8] = 0x01345568
X[-4] = 0x01345560
X[0]  = 0x00000003
X[4]  = 0xFFFFFFFF
X[8]  = 0x01345784
X[12] = 0xDEADBEEF
```

Which other objects are reachable?

Finding Roots

- Conservative Collection
  - Guess
- Tag bits
  - Take a bit (or two) from every machine word to denote pointer/non-pointer.
- Lookup tables
  - At compile time, generate information about contents of stack and registers for each point in program where GC could occur.

Parsing the Heap

- Bread crumbs
  - Tag heap objects with their 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 recursively the type and layout of every object it points to.
  - Much harder with polymorphism or abstract types