Compilers and computer architecture: Garbage collection

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December 2019

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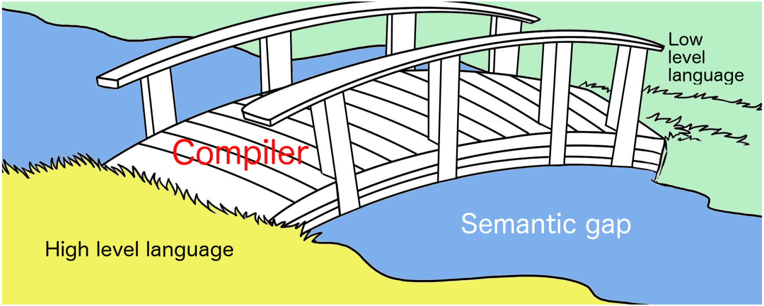
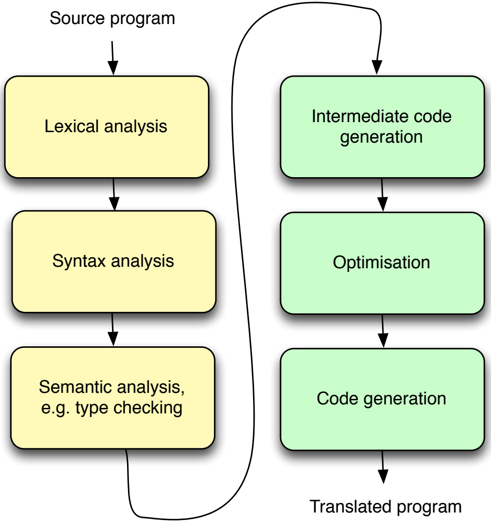
Recall the function of compilers



Recall the structure of compilers



"There is nothing difficult in GC, except to get it to run fast. That's 30-40 years of research." J. Vitek, personal communication, 2016.

What is the question GC is the answer to?

Memory management

Consider the following Java fragment

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while(serverRunning) {
    NetConnection conn = new NetConnection( ... );
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    cust.act();
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(See `prog/IntroExample.java`)

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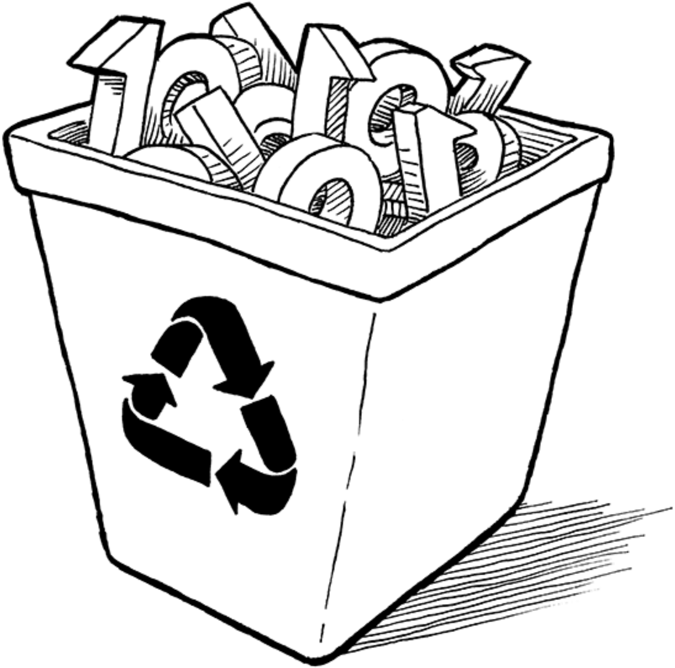
How do we heap reuse storage?



Reusing storage

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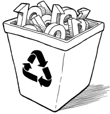

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Let's look at the first two in turn.

Manually reusing storage

In C/C++-like languages we would have to write something like this:

```
while(serverRunning) {
   NetConnection conn = new NetConnection( ... );
   Customer cust = new Customer(conn);
   cust.act();
   if( ... ) serverRunning = false;
   free(cust);
   free(conn);
}
```

To understand what `free` is really doing, let's look at (a simplified model of) what `new` does.

Heap management

Remember we need a heap because some things in the memory outlive procedure/method activations, e.g. this:

```
public Thing doStuff() {
   Thing thing  = new Thing();
   ...
   return thing;
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We cannot store `thing` the activation record of `doStuff`, because `thing` might be used after `doStuff` has returned, and ARs are removed from the stack when the method returns.

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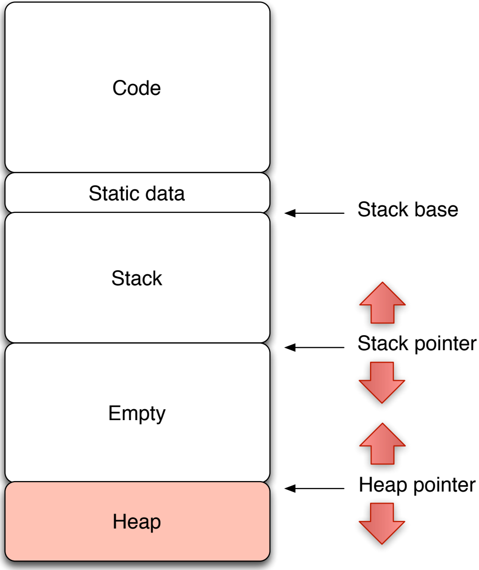
We use the **heap** for such long-lived objects.

Please remember that the concept of heap in compilers has nothing to do with heaps you learn about in algorithms/data structures.

Heap management



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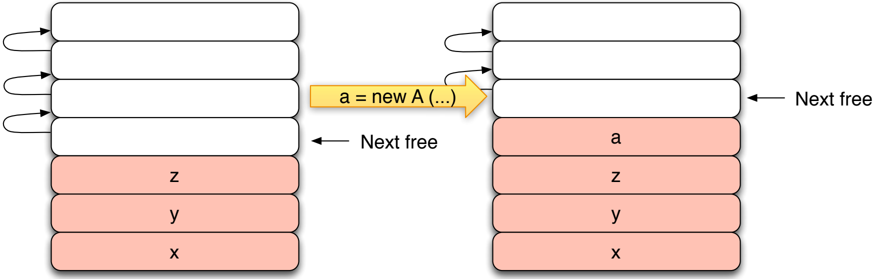
Let's look at a very simplified model of heap management.

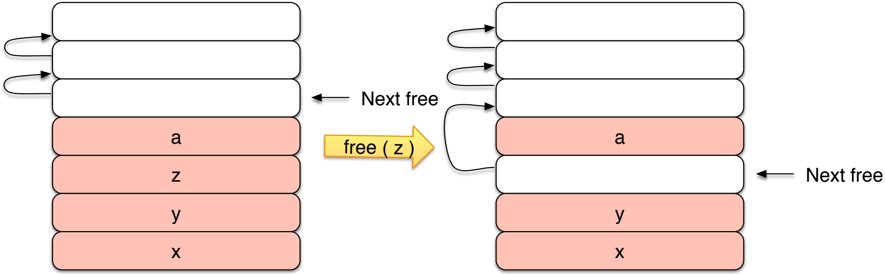
Heap management: allocating memory

Here is a simplified picture of what happens when we allocate memory on the heap, e.g. by `a = new A (...)`.



Heap management: freeing memory

Here is a simplified picture of what happens when we free memory on the heap, e.g. by `free(z)`.



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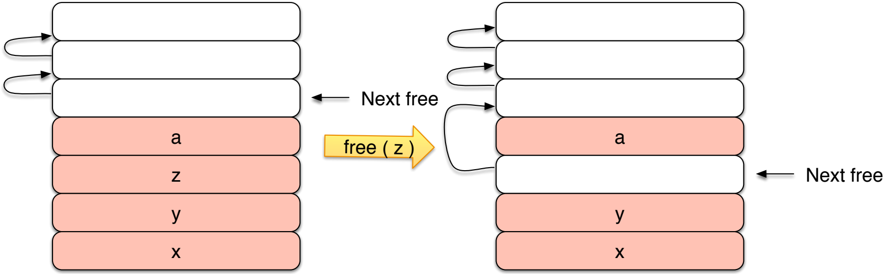

Note that this is a simplification, e.g. heap allocated memory is not always of the same size.

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Fear of the above problems leading to **defensive programming** which can be inefficient and exhibit awkward software style.

Manual heap management: problems

Here is an example of using memory after it has been freed, and reallocated.

```
a = new A (); // a stored starting at memory
              // cell 1234
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free(a);
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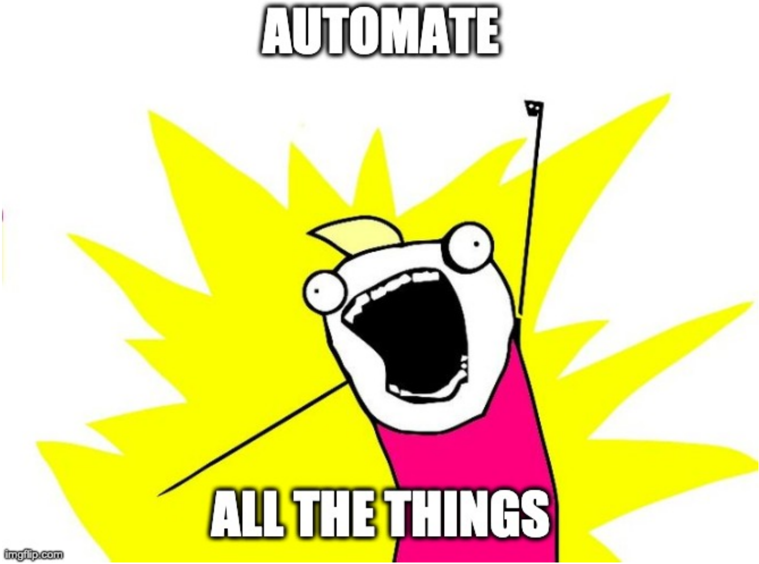
What can we do about this?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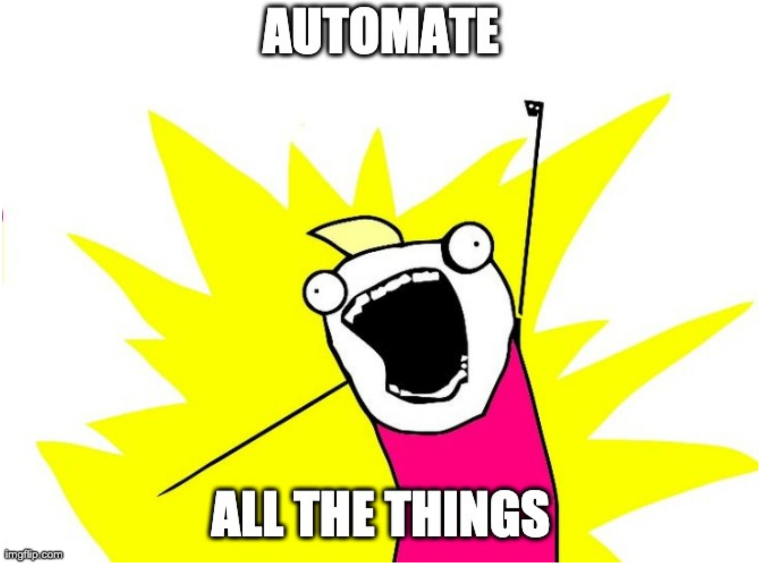

Memory management is tedious, so why not let the computer do it?

Automatic heap management

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Type-based

GC (Garbage collection)

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Rust is fairly new and is only now (2019) hitting the mainstream.

GC

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Originally GC was slow, and resented for that reason. But by now GC is **typically** almost as fast as manual memory management, but **much safer.** (There are edge cases where GC can be much slower.)

GC speed

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Fortunately, we've spent those 30-40 years, and you can reap the benefits!

Automatic heap management

GC becoming mainstream is probably the single biggest programming language improvement (in the sense of reducing bugs) in the last two decades.

Garbage collection

```
int [] a = new int[] { 1,2,3 };
a = new int[] { 9,8,7,6,5,4,3,2 };
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Hence: memory that is no longer reachable can be reused.

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Before we can study GCs in more detail, we must be more precise what it means for memory to be reachable by a program.

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Let's look at an example.

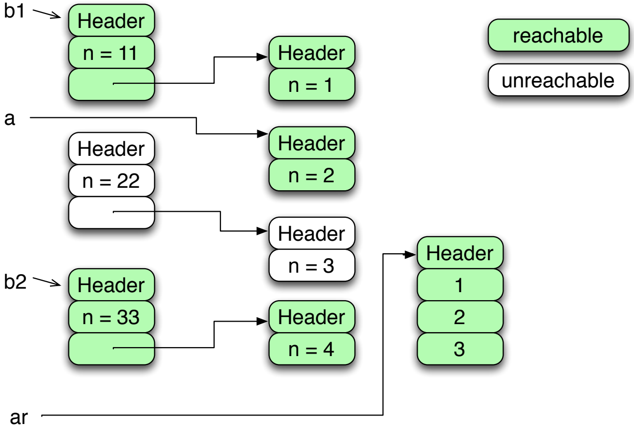
Reachability

```
class A {
    public int n;
    public A(int n) { this.n = n; } }

class B {
    public int n;
    public A a;
    public B(int n, A a) {
        this.n = n;
        this.a = a; } }
...
    public static void main ( String [] args ) {
        A a  = new A ( 1 );
        B b1 = new B ( 11, a );
          a  = new A ( 2 );
        B b2 = new B ( 22, new A ( 3 ) );
          b2 = new B ( 33, new A ( 4 ) );
        int[] ar = new int[] { 1,2,3 };
        ...
```

Reachability

The picture below shows the heap just after the array `ar` has been allocated.



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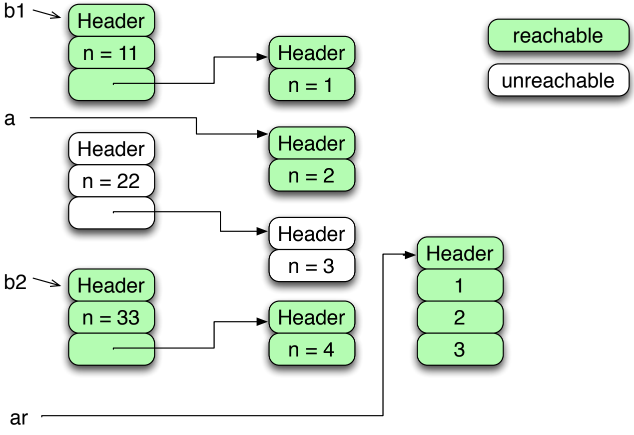

Some cells are reachable directly from the variables `b1`, `a`, `b2` and `ar`. But some are reachable only indirectly through **embedded pointers.**

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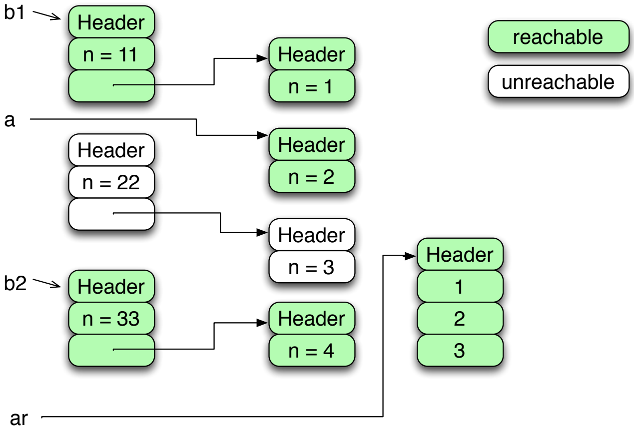

Question: why don't we have to worry about the pointers to the method tables in the headers?

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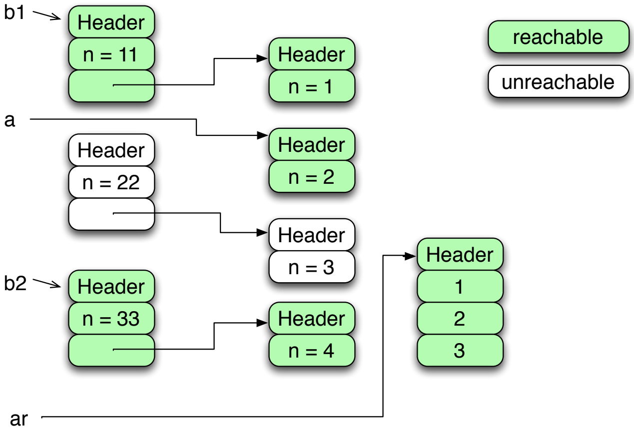

Answer: methods are statically allocated. They don't change during program execution (in Java).

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That's it ...

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- Resume program execution.

Many variants of this scheme exist, e.g. run the GC not when memory has run out, but periodically.

Live variables - Example

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What are the live variables at program points 1, ..., 5?

```
A a = new A();
               // point 1
while ( true ) {
               // point 2
   NetConnection conn = new NetConnection ( ... );
               // point 3
   Customer cust = new Customer ( conn );
               // point 4
   ...
   if ( ... ) break;
}
               // point 5
```

Solve in class

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There are many different ways to do this.

What are the pointers in a language?

Consider the simple language we used to explain code generation.

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Question: What are the pointers/references into the heap?

Answer: there are none. All variables are procedure parameters. They are stored on the stack in activation records. They live on the stack and are automatically freed when the corresponding AR is popped of the stack.

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In a language like Java, pointers into the heap are created whenever you call `new`. So in

```
A   a = new A ( ... );
B[] b = new B[] { ... };
int n = 3;
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the variables `a` and `b` **point** into the heap, unlike `n`.

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But GC executes at run-time, so to find the roots at run-time, we must know where variables are located.

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Answer: combintion of using type-information available at compile-time, together with type information stored in headers at run-time. Details of this are quite tricky ... (and beyond scope of this course)

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Languages where integers can be used as pointers (i.e. C/C++) cannot really be GCed (at least not well) for this reason.

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Consider the following slightly artificial program.

```
A tmp = new A ();
   // can mem pointed to by "a"
   // affect future of computation?
if ( ... ) {
   B b = new B() // might trigger GC
                 // tmp is root here
   b.f( 17 )
   return "hello" }
else { ... }
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After the first line, the memory allocated by `new` in the first line can never be used again, hence cannot affect rest of computation. But it is reachable (from root `tmp` which is in scope in `then ...`), so cannot be GCed inside of `then`.

Reachability must be an approximation

Programs like

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Approximations are necessary! To be on the safe side, the memory allocated by the initial `new` is considered reachable before and inside the loop.

(Remember Rice's theorem?)

The algorithm for computing reachability

```
reach( roots ) =
  for each r in roots
    if ( r not yet processed )
      mark heap memory that r points to as reachable
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There are several ways of mark memory as reachable. In OO languages, we reserve a bit in the header of each object that can be stored in the heap.

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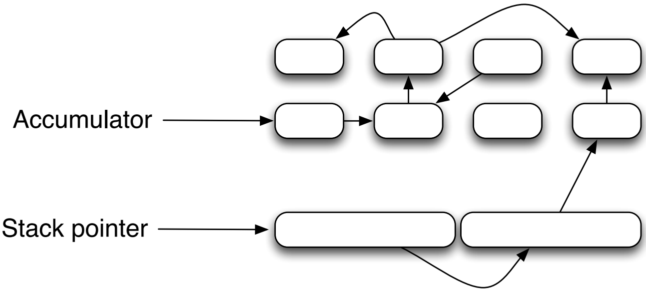

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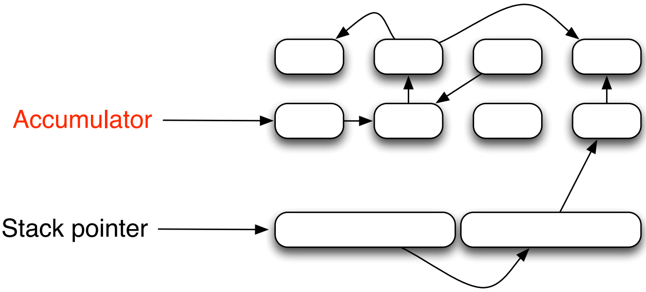

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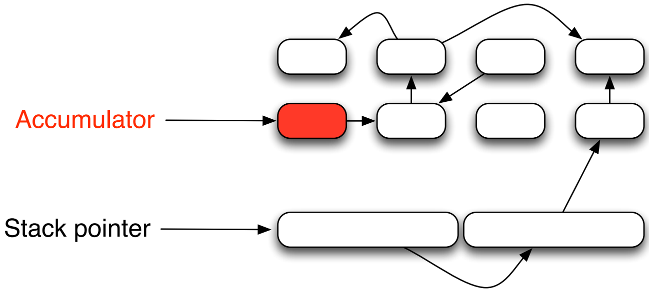

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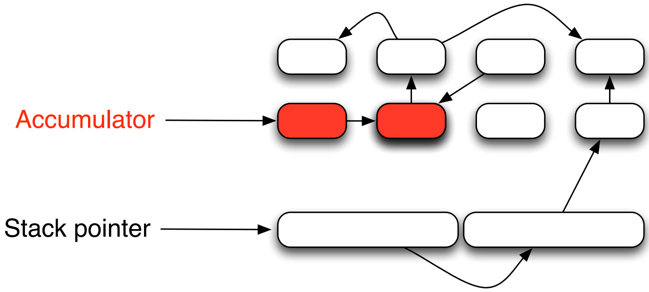

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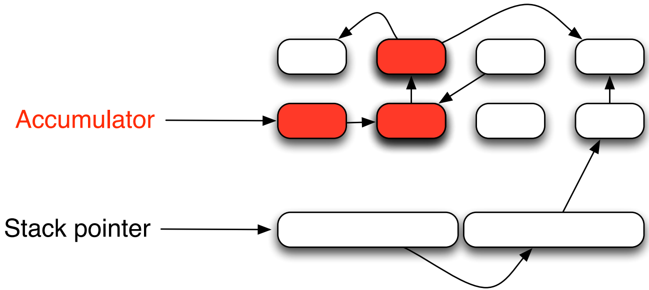

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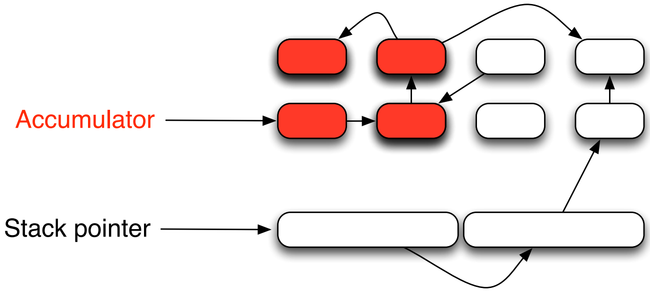

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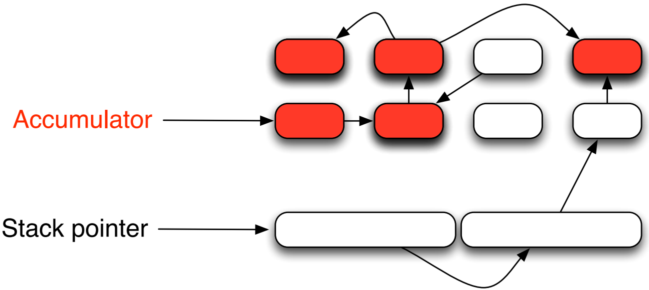

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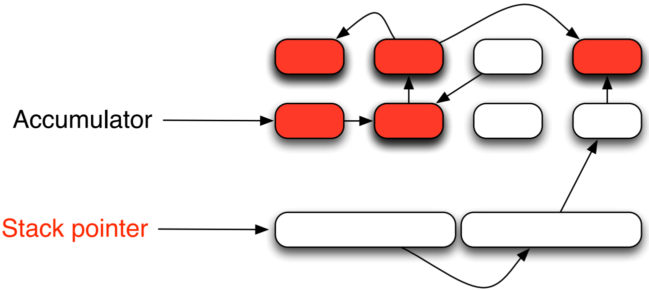

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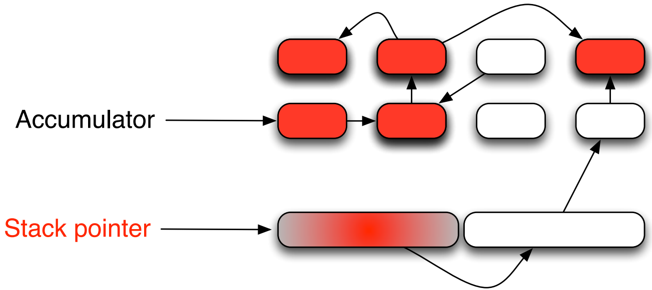

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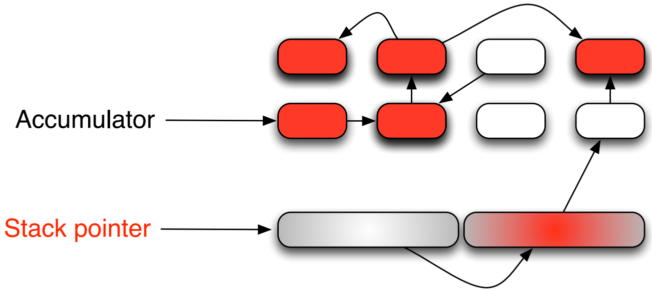

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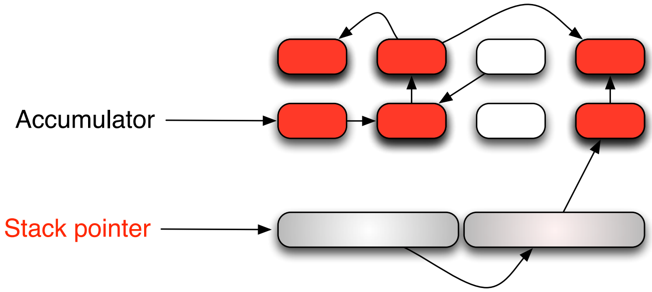

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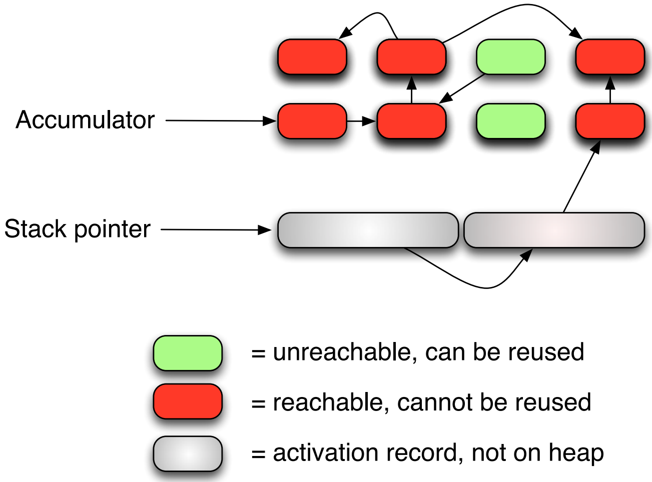

Two GC algorithms

We are going to look at two GC algorithms.

- Mark and sweep
- Stop and copy

Mark and sweep

The mark and sweep algorithm has two phases:

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In addition, we need a **free list** which holds the memory that is available for allocation (free).

Mark phase

We run the algorithm shown a few slides ago that sets the mark bit to 1 in each heap object reachable from the roots.

```
reach( roots ) =
  for each r in roots
    if ( r not yet processed )
      r.markbit := 1
      let [r1, ..., rn] be the pointers contained in r
      reach( [r1, ..., rn] )
```

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```
sweep( heap ) =
   for each cell c in heap
      if ( c.markbit == 1 )
         c.markbit := 0
      else
         putOnFreeList ( c )
```

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There are some very neat algorithms for this purpose (google Schorr-Waite graph marking algorithm aka Pointer Reversal).

Schorr-Waite algorithm (not exam relevant)

A clever algorithm to explore a graph without additional memory (except one pointer). It can be used to reset the mark bits. The key idea is:

- Follow a pointer to a new node
- Reverse the pointer we just followed so we can go back
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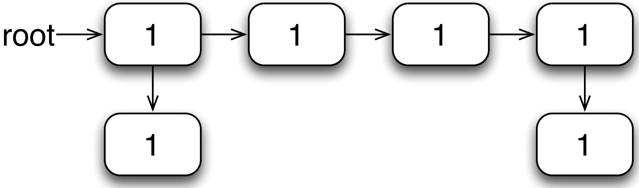

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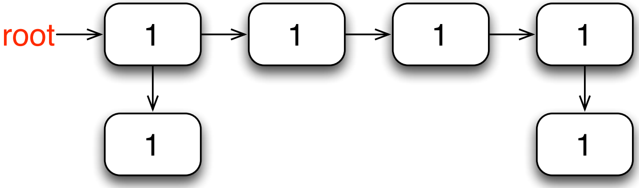

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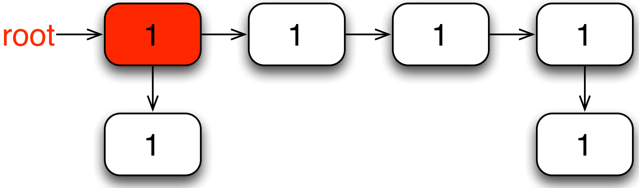

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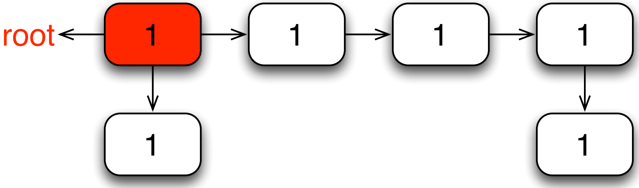

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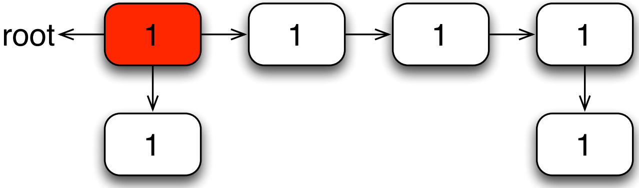

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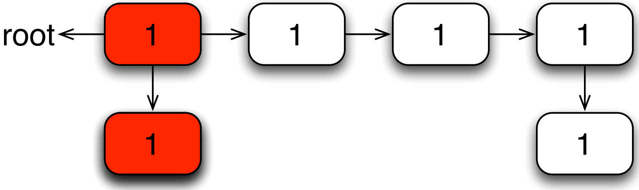

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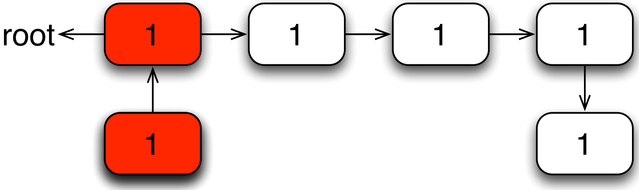

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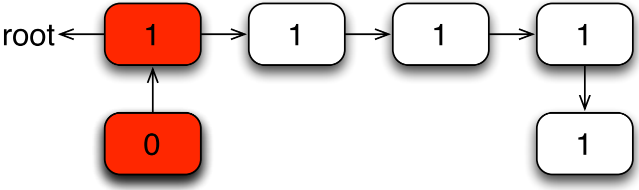

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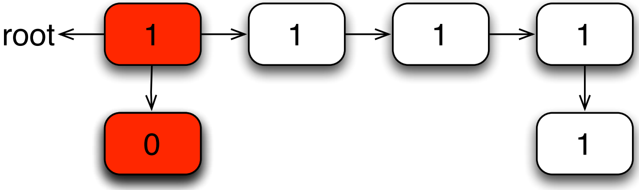

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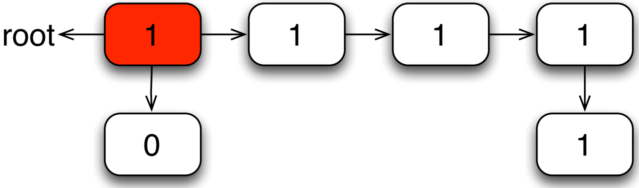

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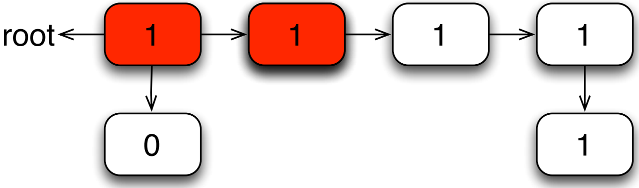

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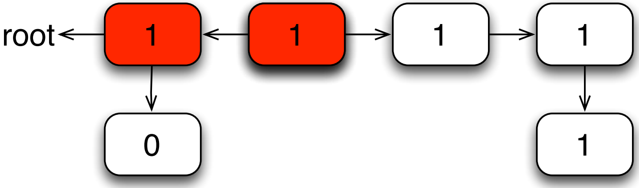

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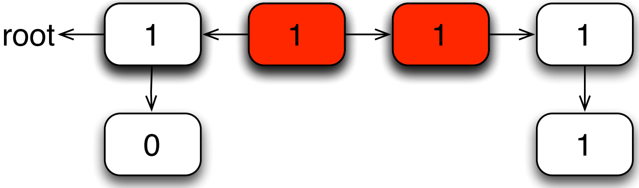

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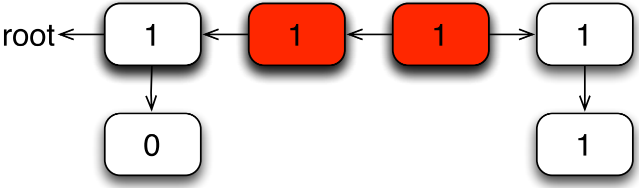

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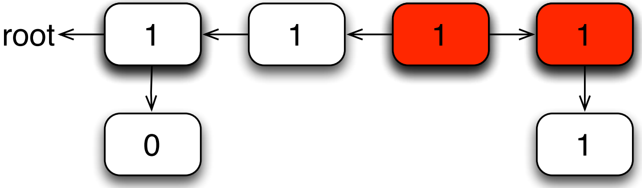

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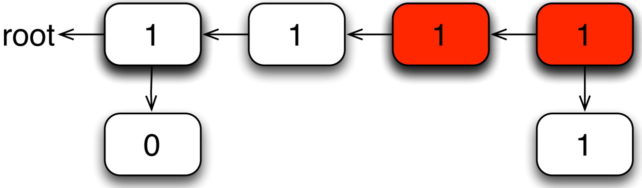

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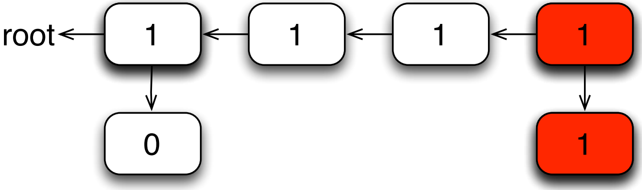

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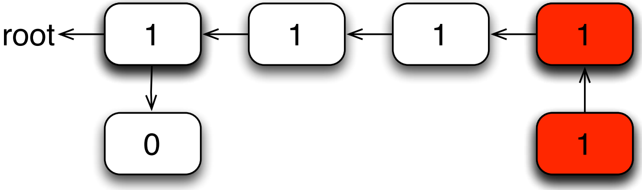

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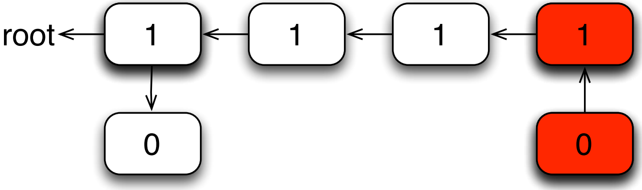

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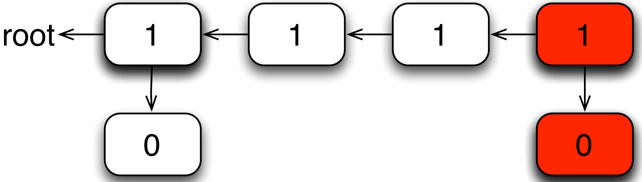

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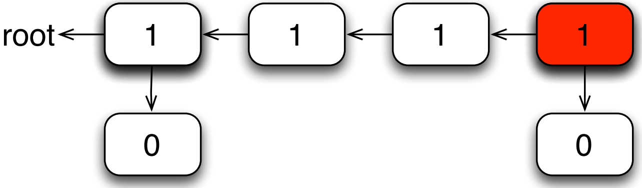

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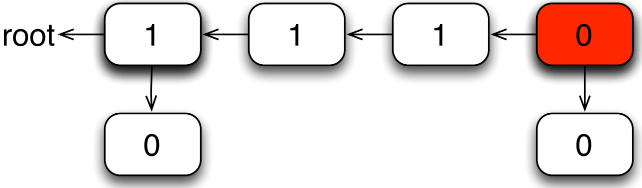

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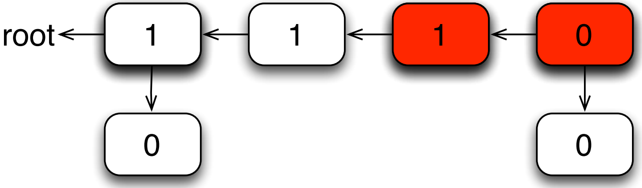

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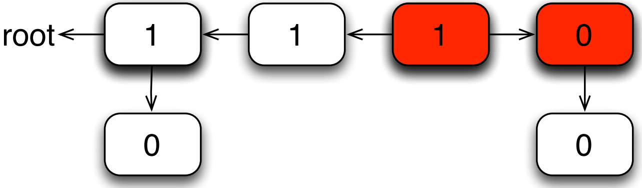

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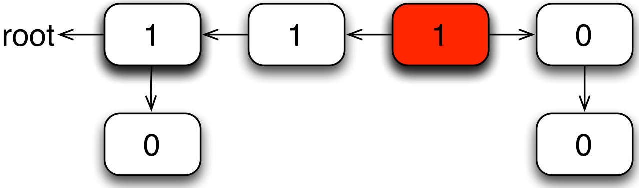

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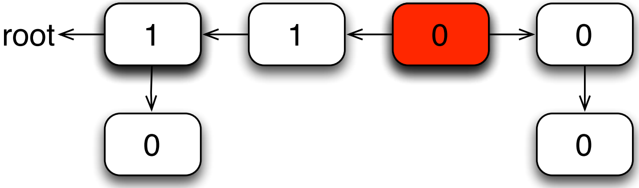

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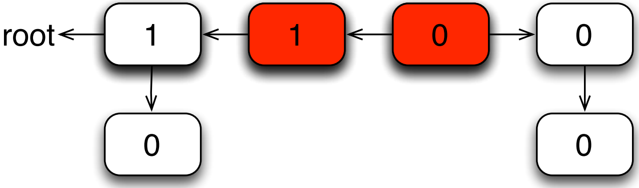

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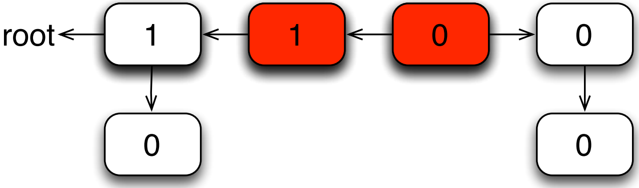

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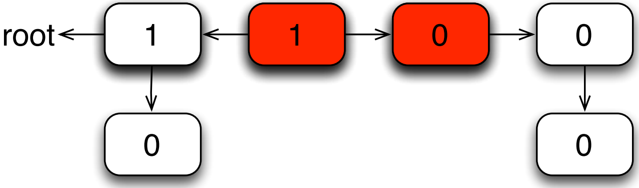

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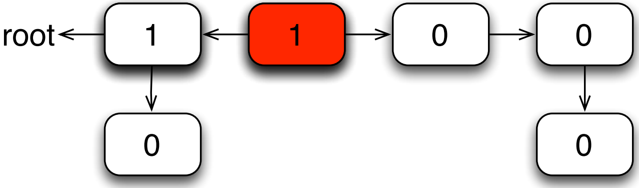

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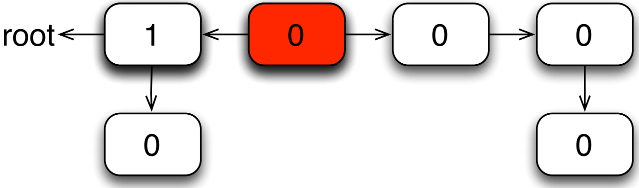

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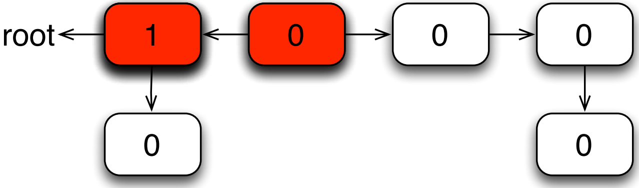

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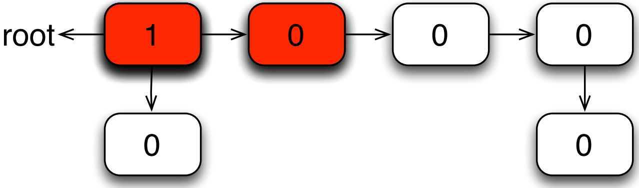

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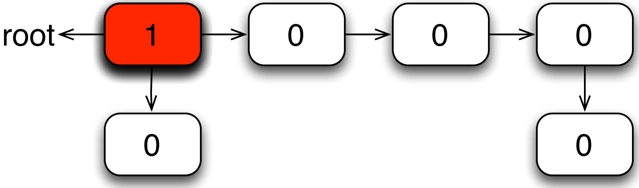

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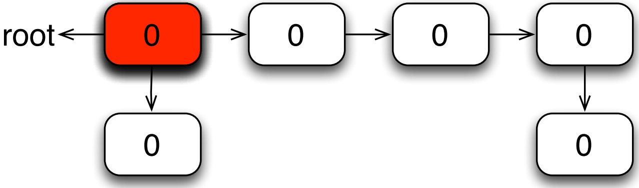

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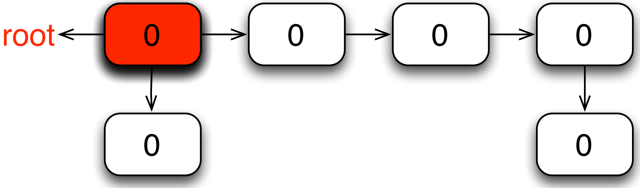

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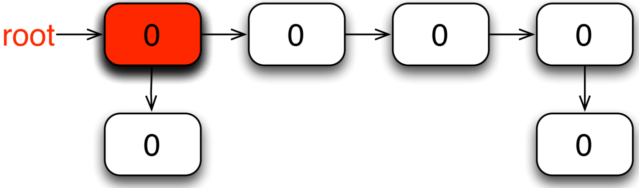

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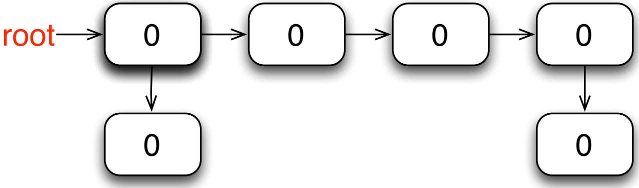

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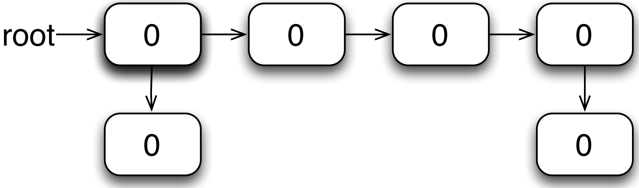

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Idea: use the free space itself to construct the free list.

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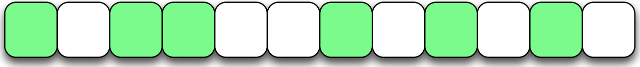

free

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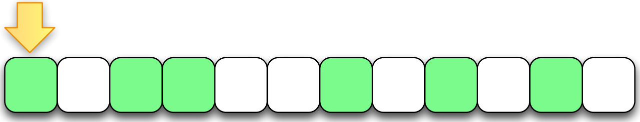

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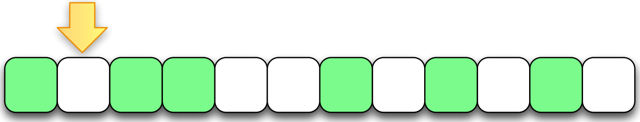

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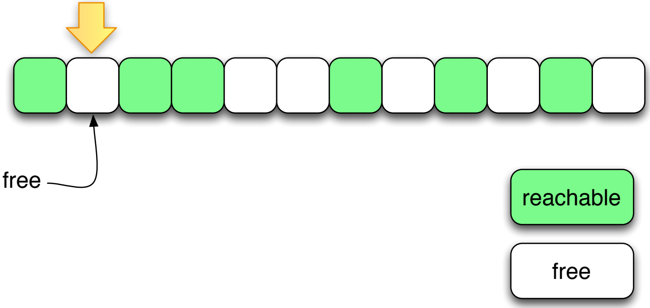

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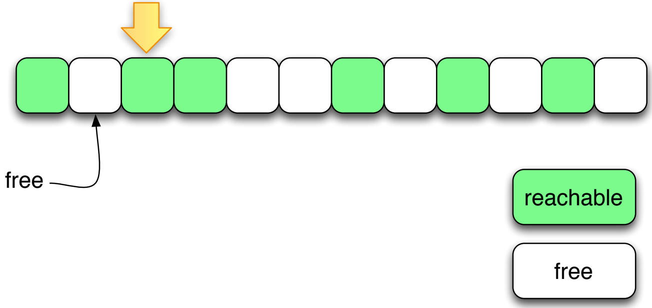

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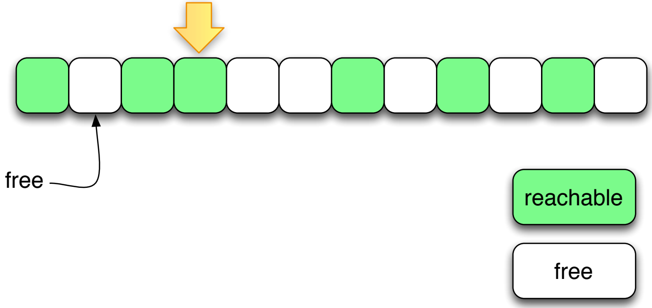

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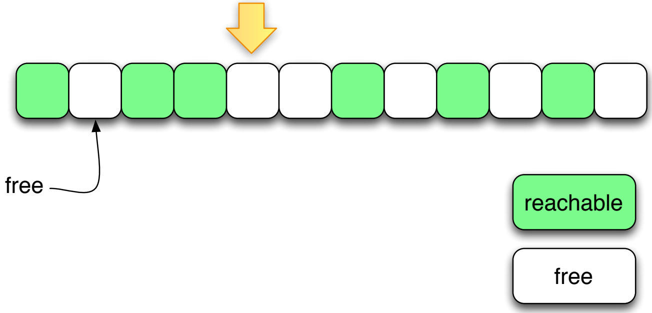

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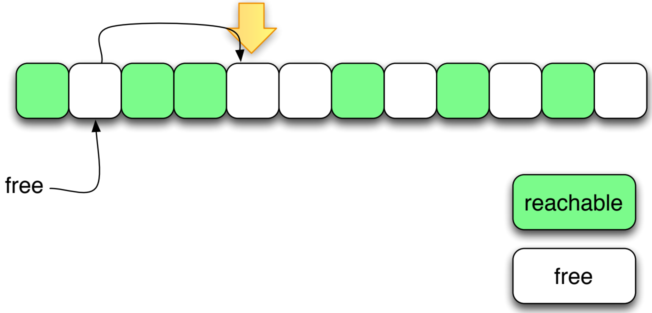

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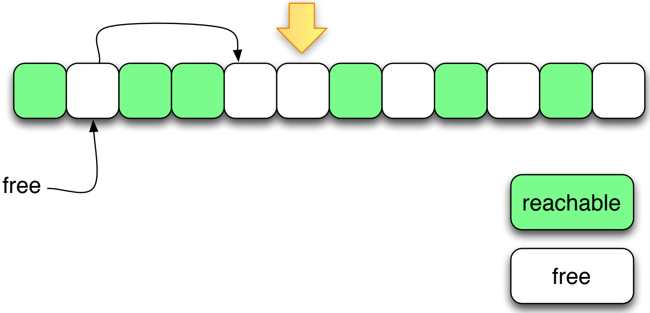

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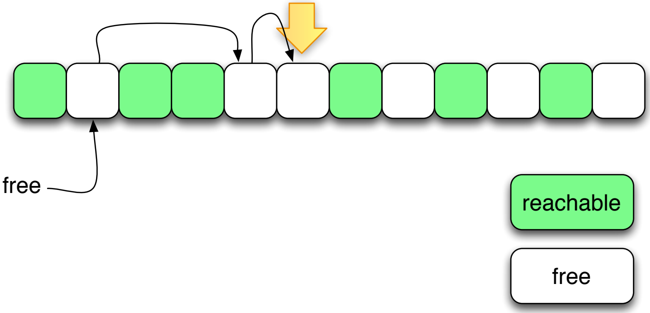

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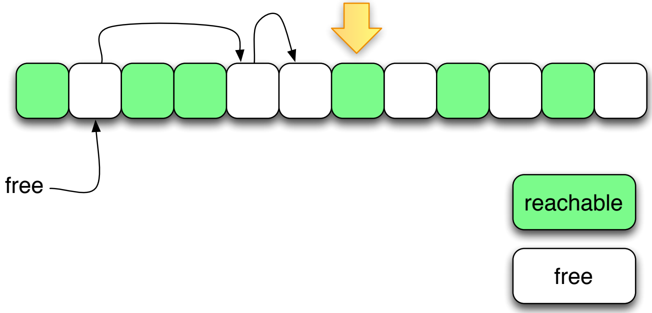

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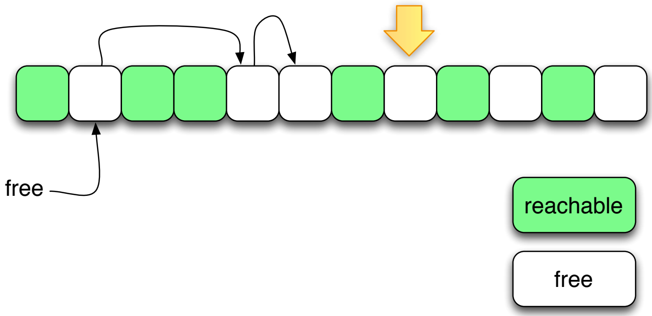

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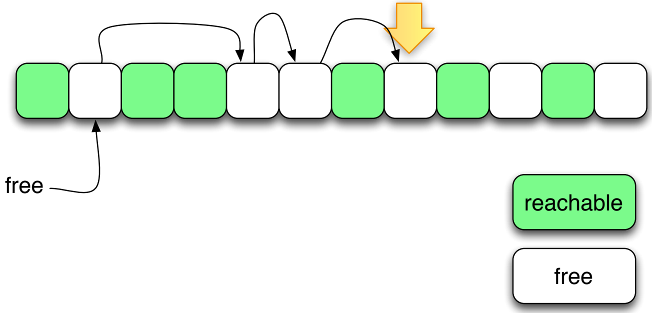

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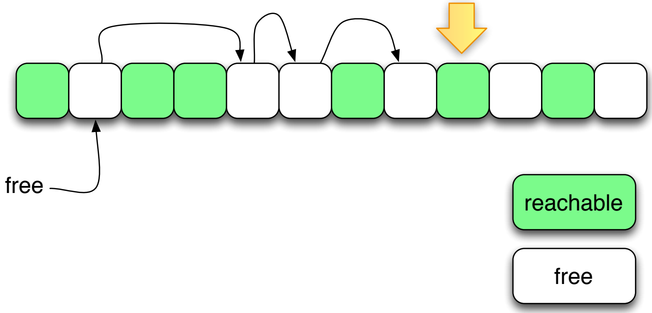

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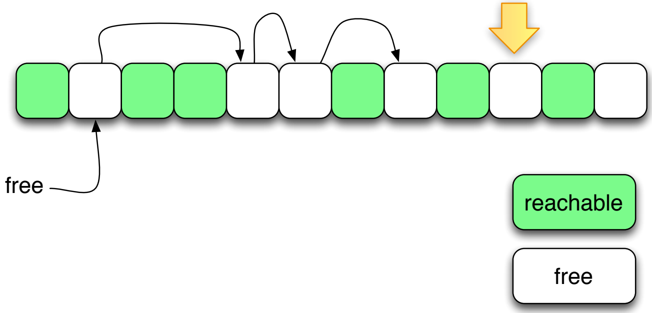

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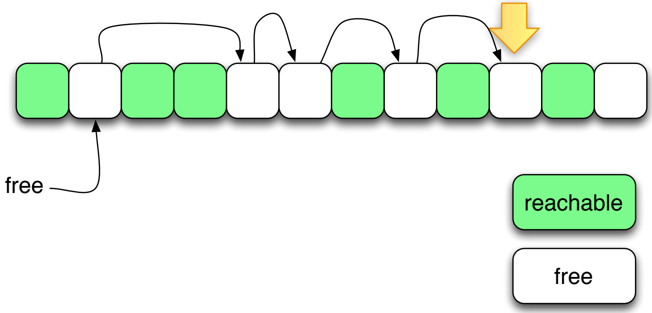

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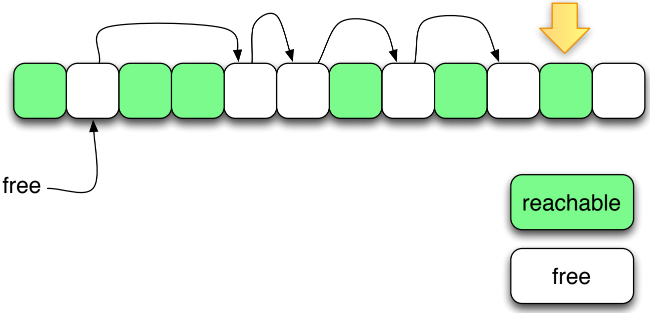

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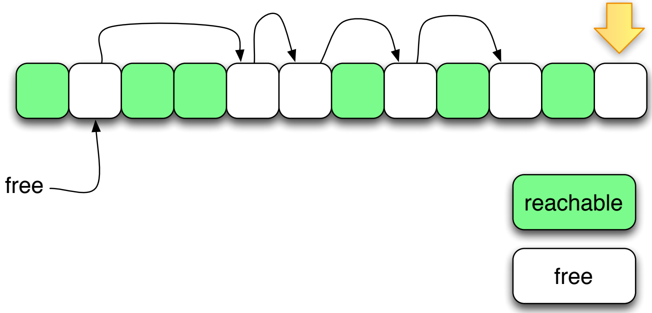

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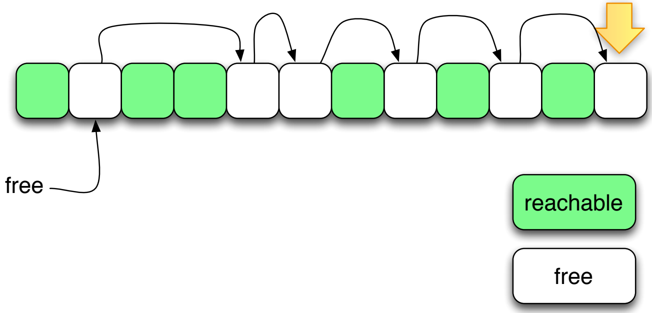

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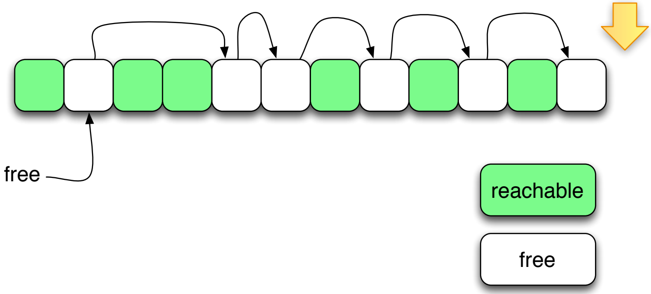

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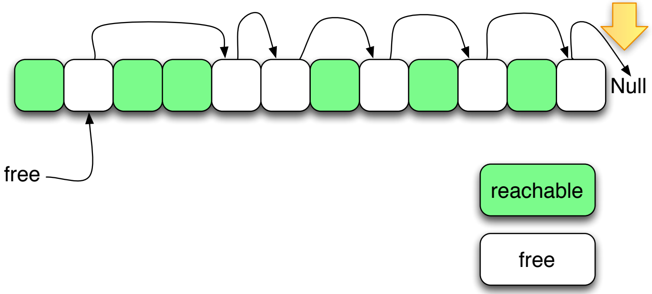

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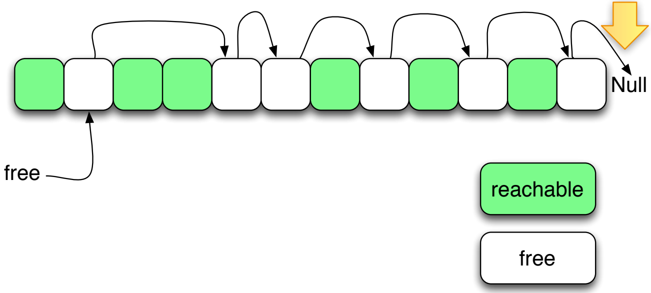

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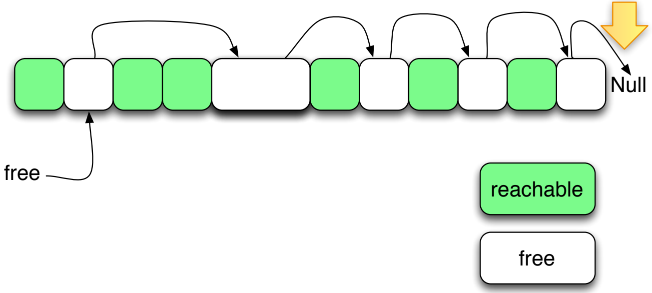

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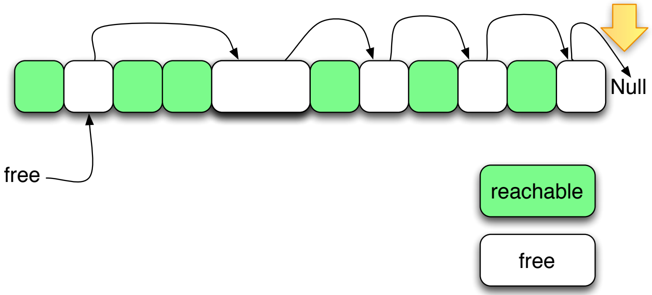

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Clearly this way of constructing the free list also doesn't need (much) additional memory, so we can use it if we run out of heap space.

Stop & Copy

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Here is how Stop & Copy works.

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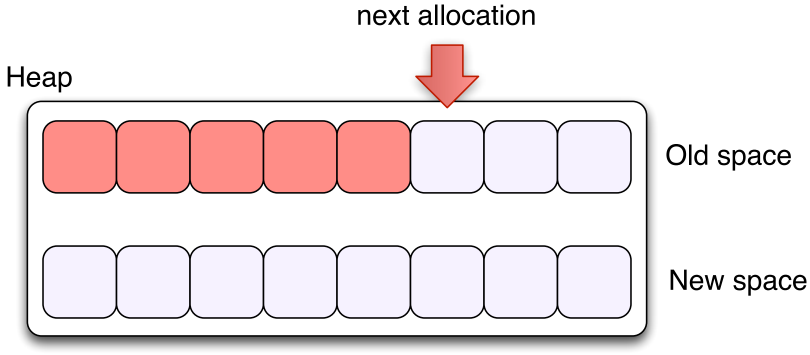

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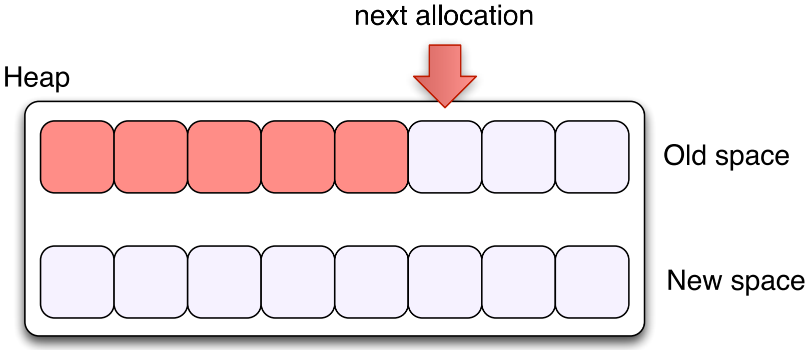

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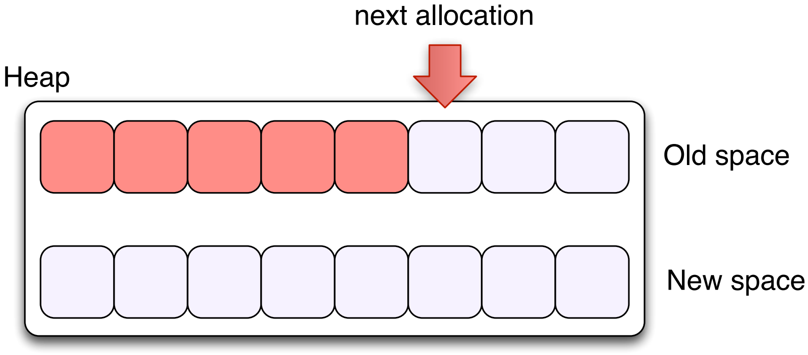

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GC happens when the Old space is full.

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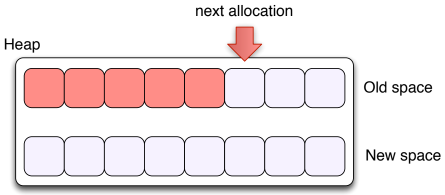

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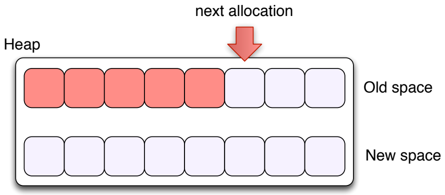

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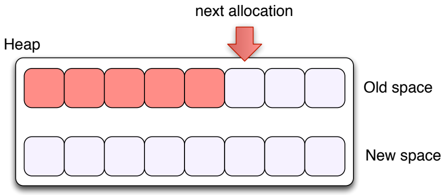

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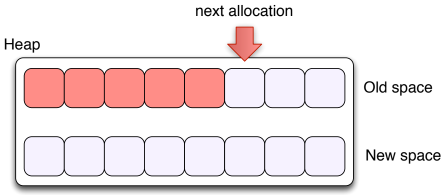

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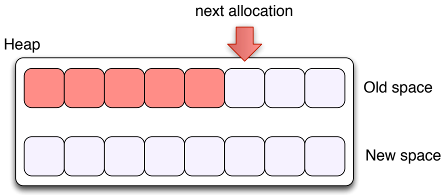

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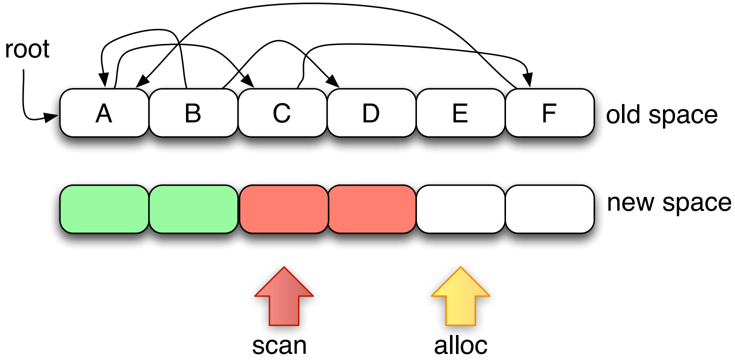
Finally we swap the role of Old and New space.

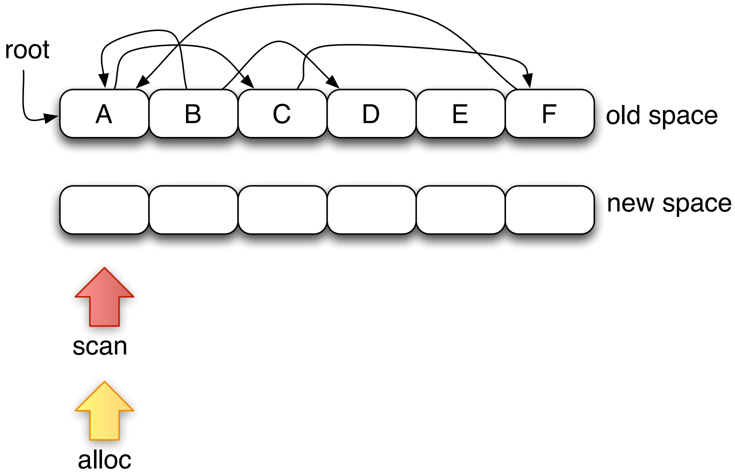
Stop & Copy

To implement the rewriting of addresses after copying, we partition the New space into three parts.



Left of the `scan` pointer, objects are processed (all pointers have been rewritten). The memory between `scan` and `alloc` is copied, but some pointers are still poining to the Old space. Memory from `alloc` on is free.

Example of Stop & Copy



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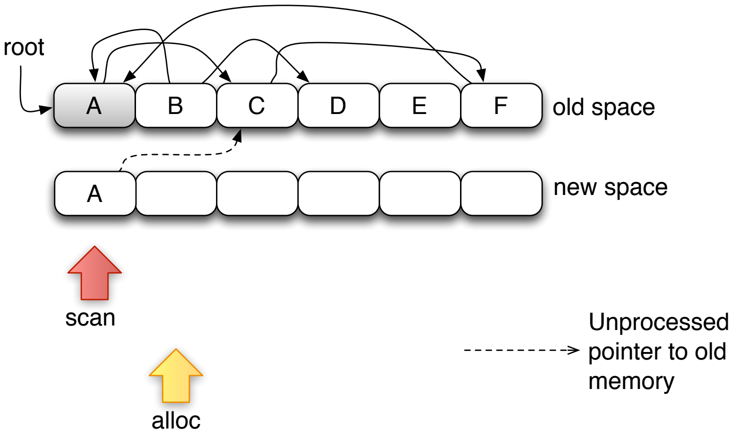

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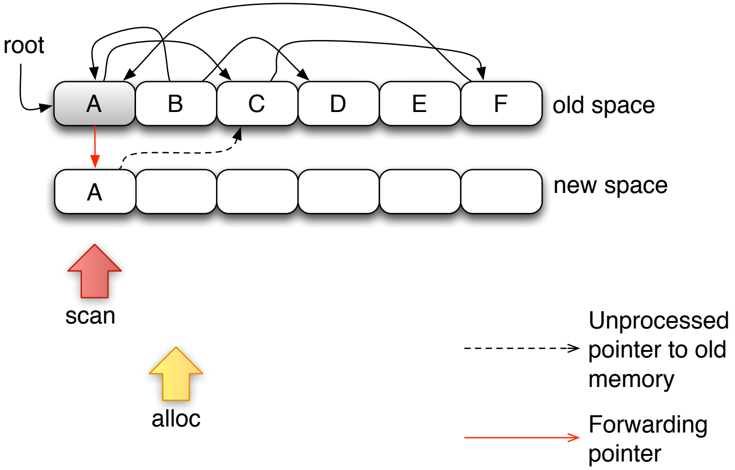

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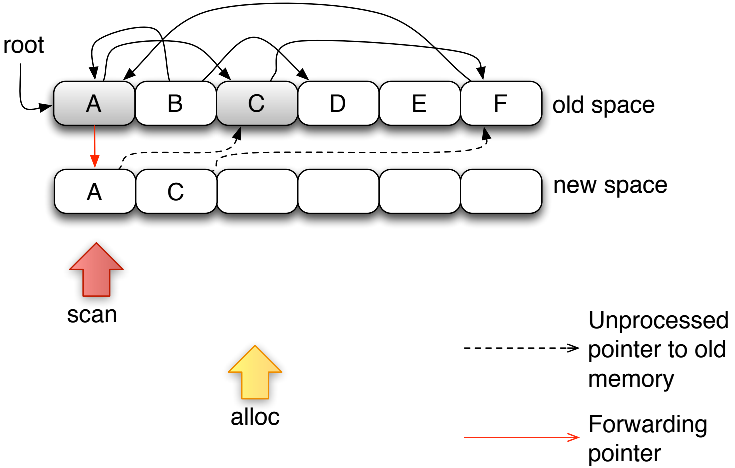

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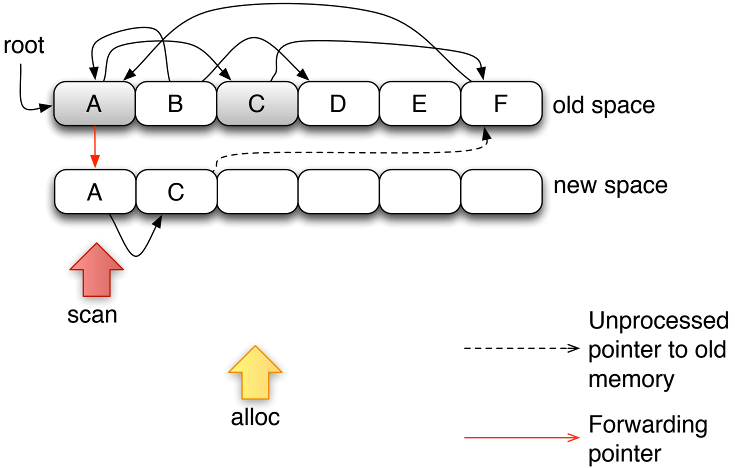

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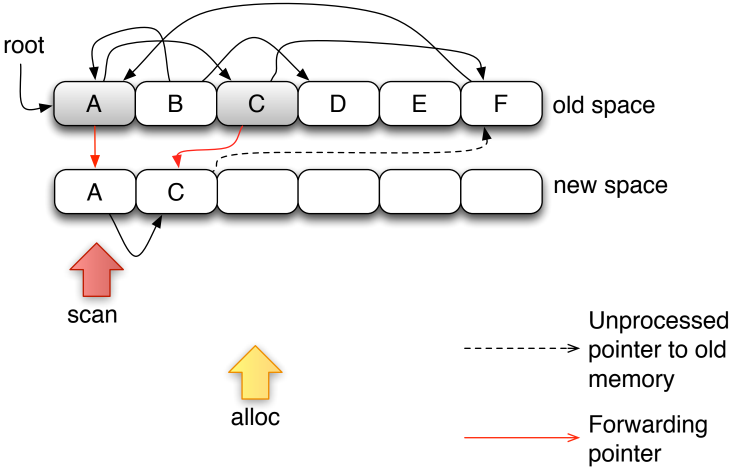

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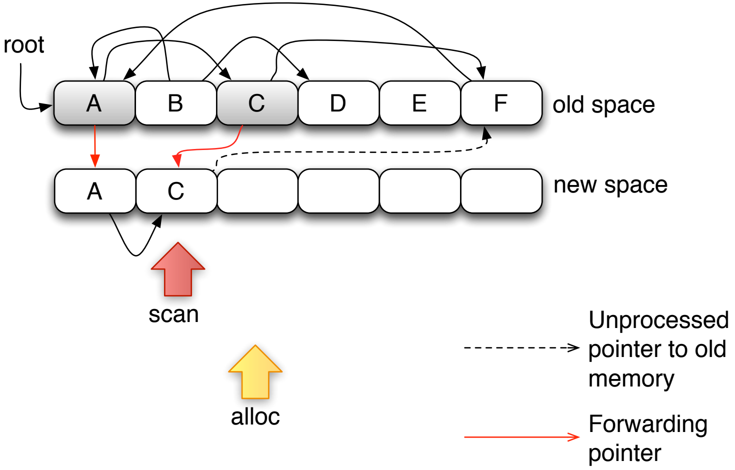

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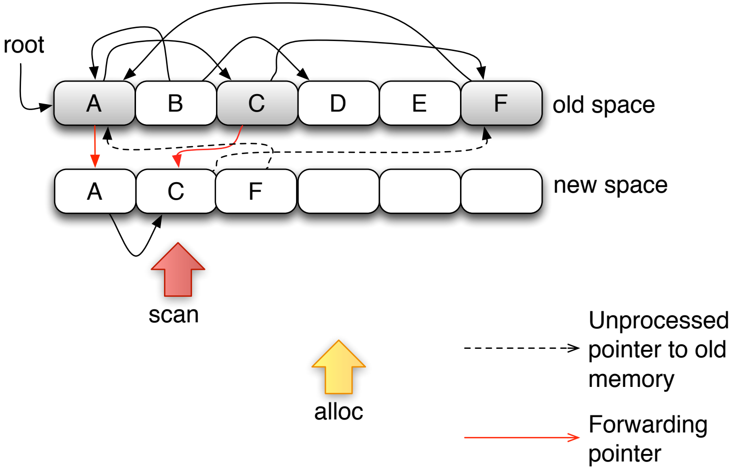

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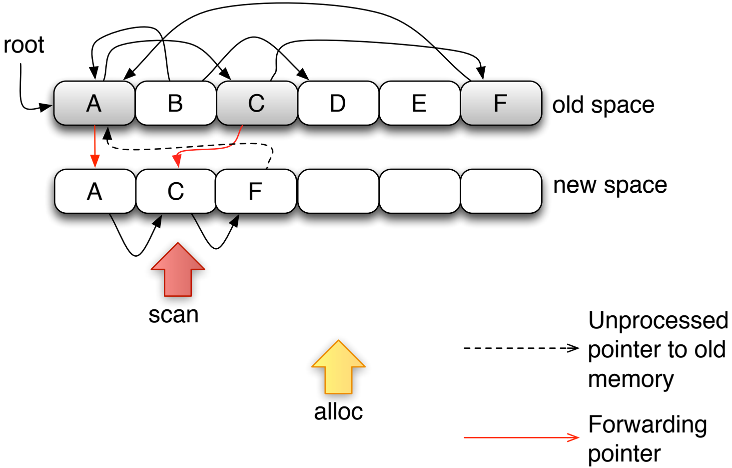

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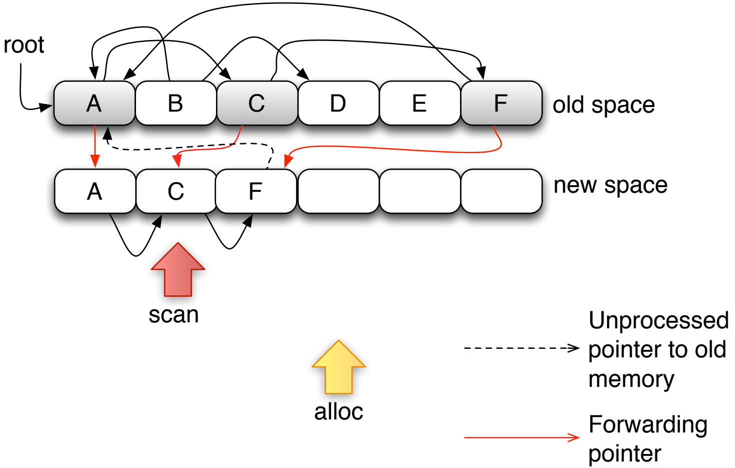

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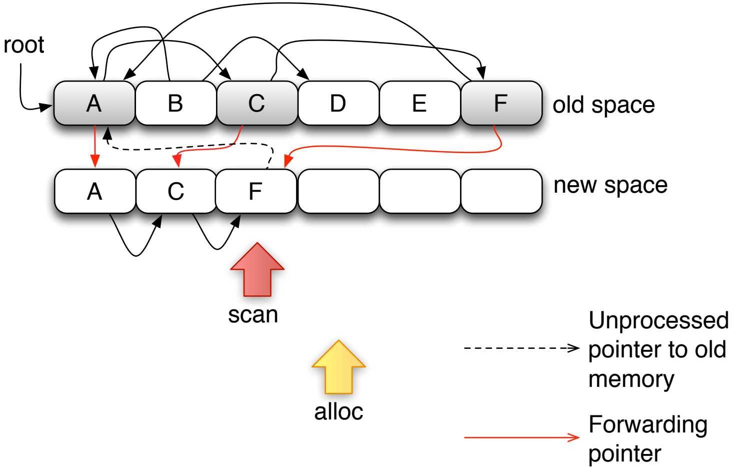

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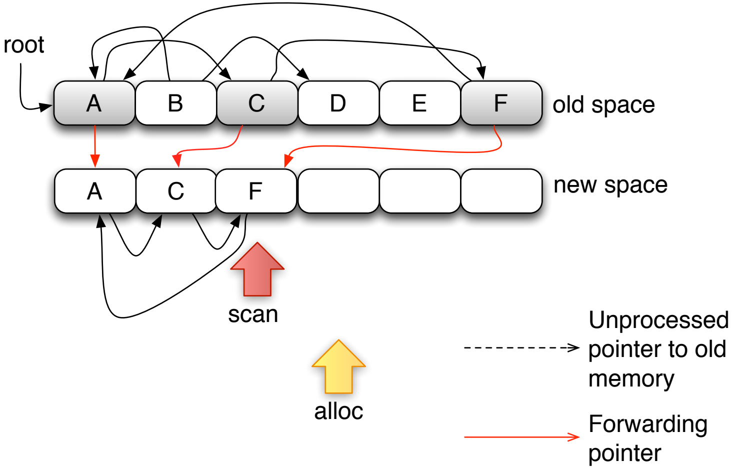

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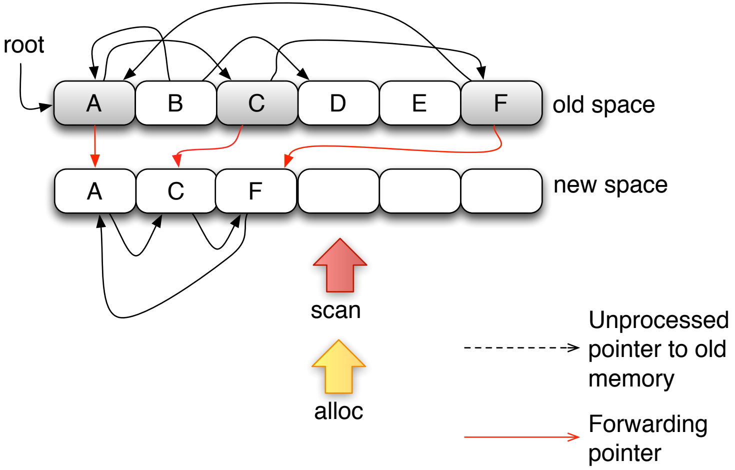

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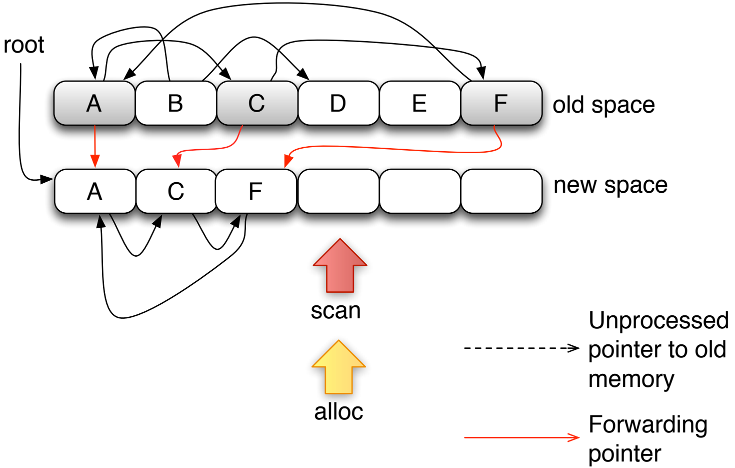

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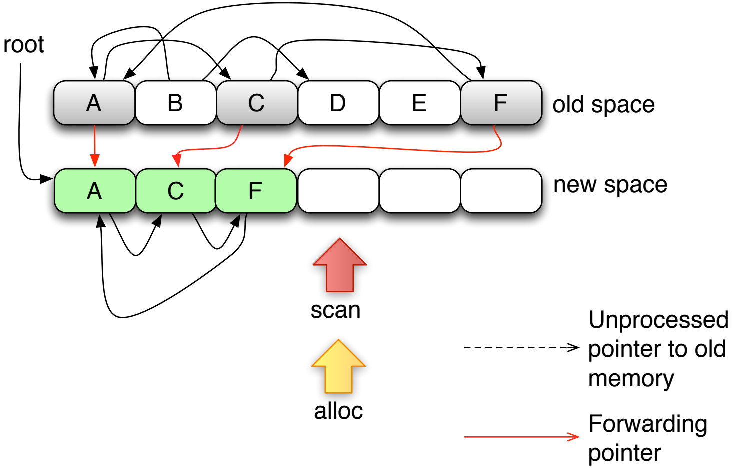

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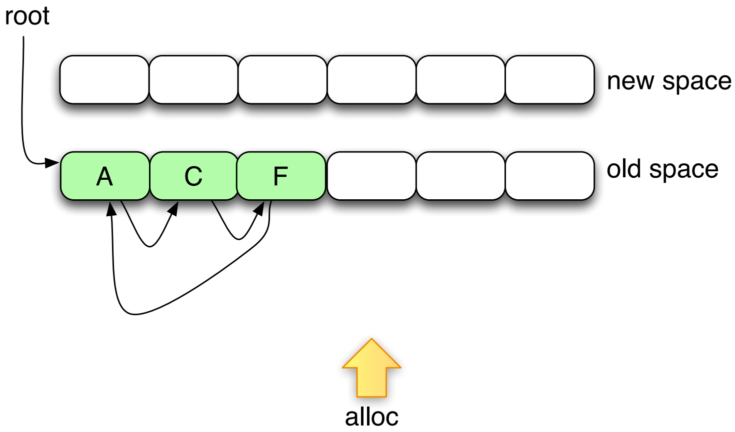

Stop & Copy algorithm

```
while scan < alloc
   let o be the object at scan
   for each embedded pointer p in o
      find o′ that p points to
      if o′ has no forwarding pointer
         copy o′ to new space
         alloc = alloc + size( o′ )
         set forwarding pointer in old o′ to new o′
                      (this marks old o′ as copied)
         change pointer p to point to new o′
      else
         set p in o equal to forwarding pointer
   scan = scan + size( o )
```

We also must rewrite pointers in roots (e.g. activation records).

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Just like with Mark & Sweep, we need to know the size and the types of objects. This can be done by embedding this information in the object's header, and/or using type information. If this information is not available we cannot do GC.

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Disadvantages: only uses half heap, and pointers get rewritten (prevents e.g. adress arithmetic).

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The GC (or OS kernel) itself has to be written in a language that doesn't have GC!

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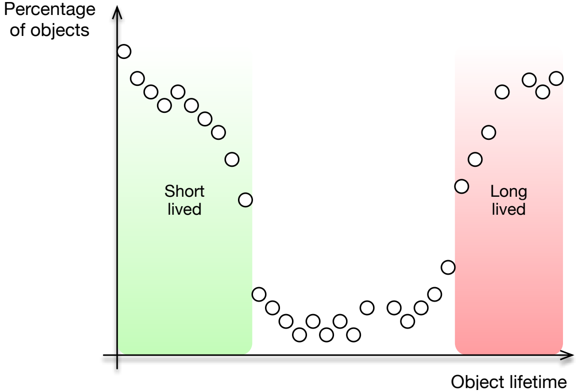
Generational GC

Generational GC is based on the following empirical insight about the lifetimes of objects in the heap.



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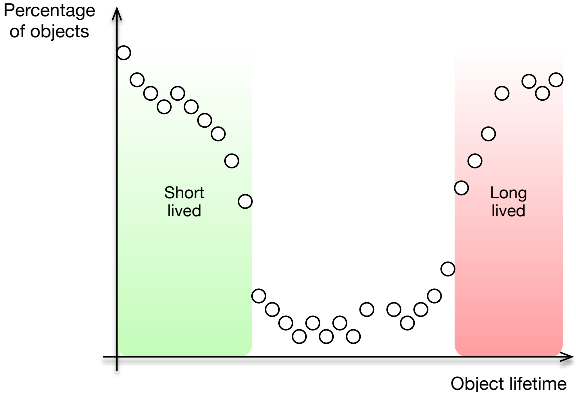

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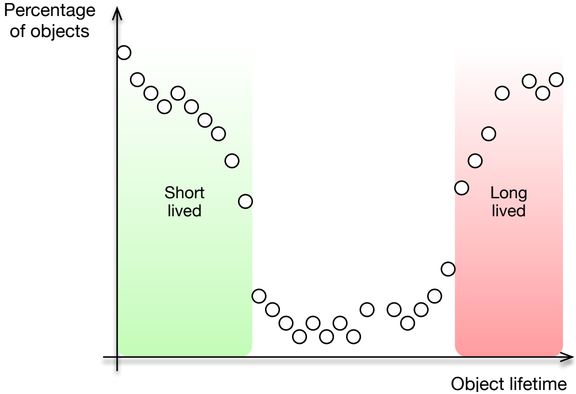

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Since moving objects is a requirement for generational GC, it's especially suitable for combination with Stop & Copy GC.

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Note that these complicated GC structures are the result of intensive empirical investigations into memory usage by real-world programs.

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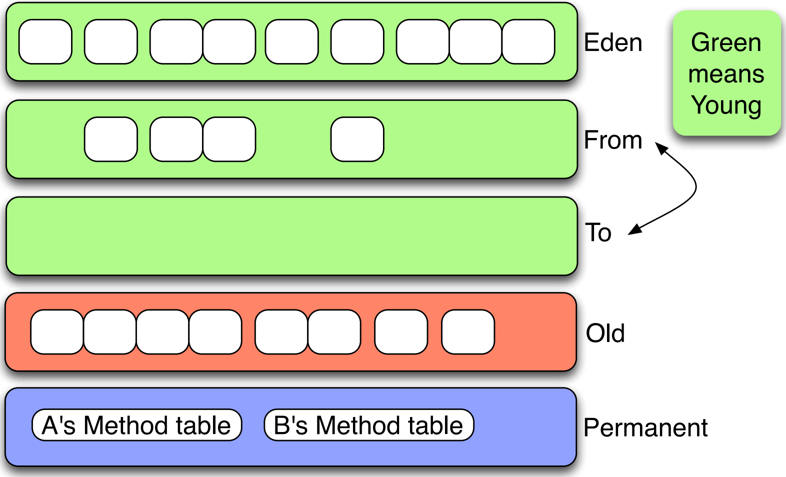
The survivor spaces hold objects that have survived at least one young generation collection and have thus been given additional chances to die before being considered "old enough" to be moved to the Old Generation. Survivor spaces holds such objects (we have 2 to do stop/copy with them).

Heap structure in the JVM (simplified)



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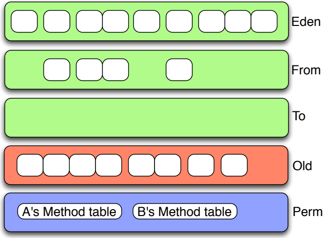

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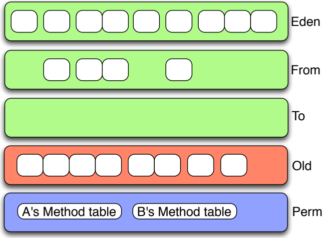

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When the Young Generation fills up, a Young Generation collection (sometimes referred to as a minor collection) of just that generation is performed. When an Eden object survives on collection, it is moved to a Survivor heap (To or From). When an object has survived some number of collections in a Survivor heap, it is moved to the Old Generation heap.

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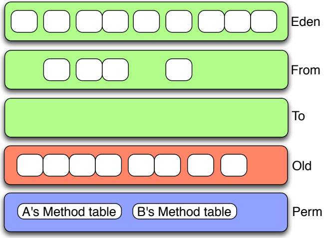

Objects are (mostly) created in Eden.

When the Young Generation fills up, a Young Generation collection (sometimes referred to as a minor collection) of just that generation is performed. When an Eden object survives on collection, it is moved to a Survivor heap (To or From). When an object has survived some number of collections in a Survivor heap, it is moved to the Old Generation heap.

When the Old Generation fills up, a full collection (aka major collection) is done. Note that old generation doesn't have to be Stop & Copy since objects there are not moved.

Example `stanford-gc.pdf`

GC in the JVM

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Example: `java -verbose:gc prog/Measure.java`

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As memory gets bigger, (as of 6. December 2019 the biggest memory you can rent on Amazon’s EC2 is **24 TB**) GC algorithms have to be, and are being rethought: GC, and memory management is an **active** area of research (see also Rust).

GC summary

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Modern GC system tend to be generational (a collection of ’smaller’ GCs) that can move live objects from one GC to another. The key assumption is that “most objects die young”.

Understanding GC is vital for high-performance programs, both for the normal programmer dealing with big data, and the compiler writer.

Last words

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Feel free to talk to me about this.


Merry
Christmas

Happy
Newyear