

Automatic Memory Management

Lecture 26

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Why Automatic Memory Management?

- Storage management is still a hard problem in modern programming
- C and C++ programs have many storage bugs
 - forgetting to free unused memory
 - dereferencing a dangling pointer
 - overwriting parts of a data structure by accident
 - and so on...
- Storage bugs are hard to find
 - a bug can lead to a visible effect far away in time and program text from the source

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Automatic Memory Management

- This is an old problem:
 - Studied since the 1950s for LISP
- There are several well-known techniques for performing completely automatic memory management
- Until recently they were unpopular outside the Lisp family of languages
 - just like type safety used to be unpopular

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Lecture Outline

- Why Automatic Memory Management?
- Garbage Collection
- Three Techniques
 - Mark and Sweep
 - Stop and Copy
 - Reference Counting

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Type Safety and Memory Management

- Some storage bugs can be prevented in a strongly typed language
 - e.g., you cannot overrun the array limits
- Can types prevent errors in programs with manual allocation and deallocation of memory?
 - Some fancy type systems (linear types) were designed for this purpose but they complicate programming significantly
- If you want type safety then you must use automatic memory management

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The Basic Idea

- When an object that takes memory space is created, unused space is automatically allocated
 - In Cool, new objects are created by `new X`
- After a while there is no more unused space
- Some space is occupied by objects that will never be used again
- This space can be freed to be reused later

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The Basic Idea (Cont.)

- How can we tell whether an object will “never be used again”?
 - In general it is impossible to tell
 - We will have to use a heuristic to find many (not all) objects that will never be used again
- Observation: a program can use only the objects that it can find:


```
let x : A ← new A in { x ← y; ... }
```

 - After $x \leftarrow y$ there is no way to access the newly allocated object

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Garbage

- An object x is reachable if and only if:
 - A register contains a pointer to x , or
 - Another reachable object y contains a pointer to x
- You can find all reachable objects by starting from registers and following all the pointers
- An unreachable object can never be referred by the program
 - These objects are called garbage

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Reachability is an Approximation

- Consider the program:


```
x ← new A;
y ← new B
x ← y;
if alwaysTrue() then x ← new A else x.foo() fi
```
- After $x \leftarrow y$ (assuming y becomes dead there)
 - The object A is not reachable anymore
 - The object B is reachable (through x)
 - Thus B is not garbage and is not collected
 - But object B is never going to be used

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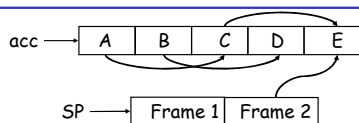
Tracing Reachable Values in Coolc

- In coolc, the only register is the accumulator
 - it points to an object
 - and this object may point to other objects, etc.
- The stack is more complex
 - each stack frame contains pointers
 - e.g., method parameters
 - each stack frame also contains non-pointers
 - e.g., return address
 - if we know the layout of the frame we can find the pointers in it

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A Simple Example



- In Coolc we start tracing from acc and stack
 - they are called the roots
- Note that B and D are not reachable from acc or the stack
- Thus we can reuse their storage

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Elements of Garbage Collection

- Every garbage collection scheme has the following steps
 1. Allocate space as needed for new objects
 2. When space runs out:
 - a) Compute what objects might be used again (generally by tracing objects reachable from a set of “root” registers)
 - b) Free the space used by objects not found in (a)
- Some strategies perform garbage collection before the space actually runs out

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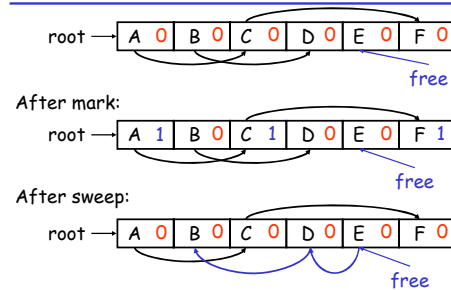
First Technique: Mark and Sweep

- When memory runs out, GC executes two phases
 - the mark phase: traces reachable objects
 - the sweep phase: collects garbage objects
- Every object has an extra bit: the mark bit
 - reserved for memory management
 - initially the mark bit is 0
 - set to 1 for the reachable objects in the mark phase

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Mark and Sweep Example



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The Mark Phase

```

let todo = { all roots }
while todo ≠ ∅ do
  pick v ∈ todo
  todo ← todo - { v }
  if mark(v) = 0 then    (* v is unmarked yet *)
    mark(v) ← 1
    let v1, ..., vn be the pointers contained in v
    todo ← todo ∪ {v1, ..., vn}
  fi
od
  
```

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The Sweep Phase

- The sweep phase scans the heap looking for objects with mark bit 0
 - these objects have not been visited in the mark phase
 - they are garbage
- Any such object is added to the free list
- The objects with a mark bit 1 have their mark bit reset to 0

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The Sweep Phase (Cont.)

```

/* sizeof(p) is the size of block starting at p */
p ← bottom of heap
while p < top of heap do
  if mark(p) = 1 then
    mark(p) ← 0
  else
    add block p...(p+sizeof(p)-1) to freelist
  fi
  p ← p + sizeof(p)
od
  
```

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Details

- While conceptually simple, this algorithm has a number of tricky details
 - this is typical of GC algorithms
- A serious problem with the mark phase
 - it is invoked when we are out of space
 - yet it needs space to construct the todo list
 - the size of the todo list is unbounded so we cannot reserve space for it a priori

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Mark and Sweep: Details

- The todo list is used as an auxiliary data structure to perform the reachability analysis
- There is a trick that allows the auxiliary data to be stored in the objects themselves
 - pointer reversal: when a pointer is followed it is reversed to point to its parent
- Similarly, the free list is stored in the free objects themselves

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Mark and Sweep. Evaluation

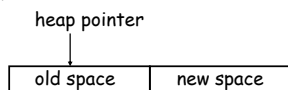
- Space for a new object is allocated from the new list
 - a block large enough is picked
 - an area of the necessary size is allocated from it
 - the left-over is put back in the free list
- Mark and sweep can fragment the memory
- Advantage: objects are not moved during GC
 - no need to update the pointers to objects
 - works for languages like C and C++

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Another Technique: Stop and Copy

- Memory is organized into two areas
 - Old space: used for allocation
 - New space: used as a reserve for GC



- The heap pointer points to the next free word in the old space
 - Allocation just advances the heap pointer

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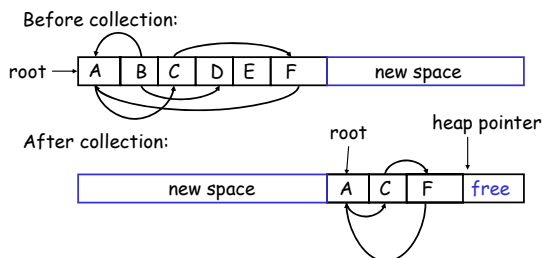
Stop and Copy Garbage Collection

- Starts when the old space is full
- Copies all reachable objects from old space into new space
 - garbage is left behind
 - after the copy phase the new space uses less space than the old one before the collection
- After the copy the roles of the old and new spaces are reversed and the program resumes

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Stop and Copy Garbage Collection. Example



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Implementation of Stop and Copy

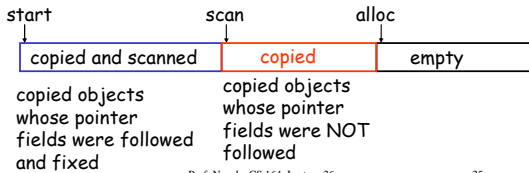
- We need to find all the reachable objects, as for mark and sweep
- As we find a reachable object we copy it into the new space
 - And we have to fix ALL pointers pointing to it!
- As we copy an object we store in the old copy a forwarding pointer to the new copy
 - when we later reach an object with a forwarding pointer we know it was already copied

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Implementation of Stop and Copy (Cont.)

- We still have the issue of how to implement the traversal without using extra space
- The following trick solves the problem:
 - partition the new space in three contiguous regions

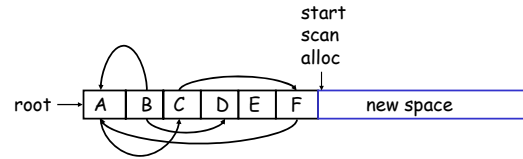


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Stop and Copy. Example (1)

- Before garbage collection

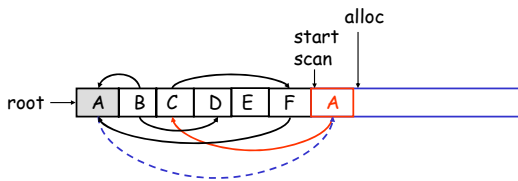


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Stop and Copy. Example (3)

- Step 1: Copy the objects pointed by roots and set forwarding pointers (dotted arrow)

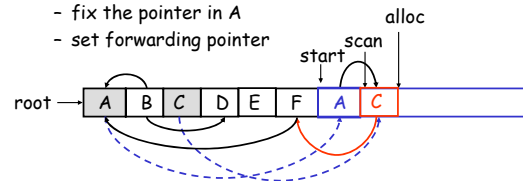


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Stop and Copy. Example (3)

- Step 2: Follow the pointer in the next unscanned object (A)
 - copy the pointed objects (just C in this case)
 - fix the pointer in A
 - set forwarding pointer

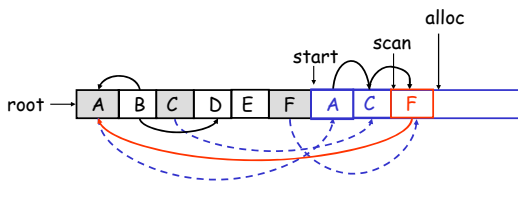


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Stop and Copy. Example (4)

- Follow the pointer in the next unscanned object (C)
 - copy the pointed objects (F in this case)

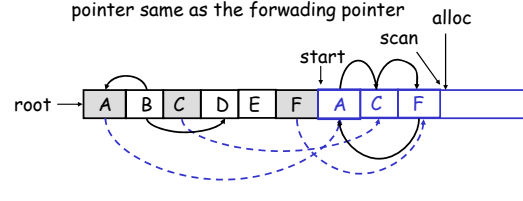


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Stop and Copy. Example (5)

- Follow the pointer in the next unscanned object (F)
 - the pointed object (A) was already copied. Set the pointer same as the forwarding pointer

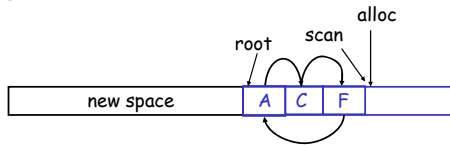


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Stop and Copy. Example (6)

- Since scan caught up with alloc we are done
- Swap the role of the spaces and resume the program



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The Stop and Copy Algorithm

```
while scan <> alloc do
  let O be the object at scan pointer
  for each pointer p contained in O do
    find O' that p points to
    if O' is without a forwarding pointer
      copy O' to new space (update alloc pointer)
      set 1st word of old O' to point to the new copy
      change p to point to the new copy of O'
    else
      set p in O equal to the forwarding pointer
  fi
end for
increment scan pointer to the next object
od
```

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Stop and Copy. Details.

- As with mark and sweep, we must be able to tell how large is an object when we scan it
 - And we must also know where are the pointers inside the object
- We must also copy any objects pointed to by the stack and update pointers in the stack
 - This can be an expensive operation

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Stop and Copy. Evaluation

- Stop and copy is generally believed to be the fastest GC technique
- Allocation is very cheap
 - Just increment the heap pointer
- Collection is relatively cheap
 - Especially if there is a lot of garbage
 - Only touch reachable objects
- But some languages do not allow copying (C, C++)

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Why Doesn't C Allow Copying?

- Garbage collection relies on being able to find all reachable objects
 - And it needs to find all pointers in an object
- In C or C++ it is impossible to identify the contents of objects in memory
 - E.g., how can you tell that a sequence of two memory words is a list cell (with data and next fields) or a binary tree node (with a left and right fields)?
 - Thus we cannot tell where all the pointers are

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Conservative Garbage Collection

- But it is OK to be conservative:
 - If a memory word looks like a pointer it is considered a pointer
 - it must be aligned
 - it must point to a valid address in the data segment
 - All such pointers are followed and we overestimate the reachable objects
- But we still cannot move objects because we cannot update pointers to them
 - What if what we thought to be a pointer is actually an account number?

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Technique 3: Reference Counting

- Rather than wait for memory to be exhausted, try to collect an object when there are no more pointers to it
- Store in each object the number of pointers to that object
 - This is the reference count
- Each assignment operation has to manipulate the reference count

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Implementation of Reference Counting

- `new` returns an object with a reference count of 1
- If `x` points to an object then let `rc(x)` refer to the object's reference count
- Every assignment `x ← y` must be changed:

```
rc(y) ← rc(y) + 1
rc(x) ← rc(x) - 1
if(rc(x) == 0) then mark x as free
x ← y
```

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Reference Counting. Evaluation

- Advantages:
 - Easy to implement
 - Collects garbage incrementally without large pauses in the execution
- Disadvantages:
 - Manipulating reference counts at each assignment is very slow
 - Cannot collect circular structures

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Garbage Collection. Evaluation

- Automatic memory management avoids some serious storage bugs
- But it takes away control from the programmer
 - e.g., layout of data in memory
 - e.g., when is memory deallocated
- Most garbage collection implementations stop the execution during collection
 - not acceptable in real-time applications

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Garbage Collection. Evaluation

- Garbage collection is going to be around for a while
- Researchers are working on advanced garbage collection algorithms:
 - Concurrent: allow the program to run while the collection is happening
 - Generational: do not scan long-lived objects at every collection
 - Parallel: several collectors working in parallel

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