Hack Your Language!

CSE401 Winter 2016

Introduction to Compiler Construction

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Lecture 18: Code optimization and Garbage Collection

Using solvers for code generation
Garbage collection in managed runtimes

Announcements

- HW4
  - Due tonight at 11pm (no late days)

- 50-min final quiz this Thursday in section
  - 2 pages of single-sided hand written notes
  - practice exams on course website
  - please attend your assigned section

Outline for today

- Techniques for code generation (continued)
  - Classical and solver-based techniques
- Managed runtimes
  - Garbage collection

Code optimization

(complete slides including from last lecture)

Scope of optimizations

Scope of study for optimizations:

- **peephole**: look at adjacent instructions
- **local**: look at straight-line sequence of statements
- **global**(**int*ra*procedural**): look at whole procedure
- **int*er*procedural**: look across procedures

Larger scope ⇒ better optimization,
but more cost & complexity

Style of optimizations

How is the program is improved

- **naïve**: no optimization after code generation
- **rewrite rules:** used in peephole optimization
- **instruction selection**: tree covering
- **deductive**: derive equivalent programs
- **superoptimization** and synthesis: search for a correct program

Naïve code generation

Naïve code generation

For each AST node, generate a sequence of instructions.

each node code-generated individually

The same as bytecode generation (see previous lectures).

Generation of assembly code is the same but with labels.

Pros: simple

each node code-generated individually

Cons: suboptimal code

each node code-generated individually

Peephole optimization

Peephole optimizations

Replace a sequence of adjacent instructions with a more optimal sequence

```
sw $8, 12($fp)
lw $12, 12($fp)
```

$\Rightarrow$

```
sw $8, 12($fp)
mv $12, $8
```

```
sub sp, 4, sp
mov r1, 0(sp)
```

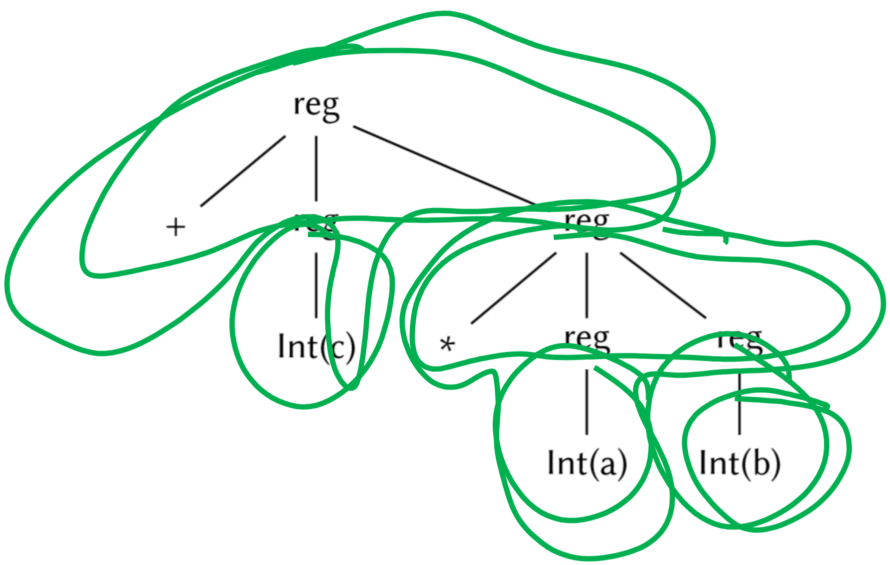
$\Rightarrow$

```
mov r1, -(sp)
```

Instruction selection via tree coverage

Better code-gen rules

Rather than translating one AST node to an instruction sequence, we map multiple nodes to a sequence.

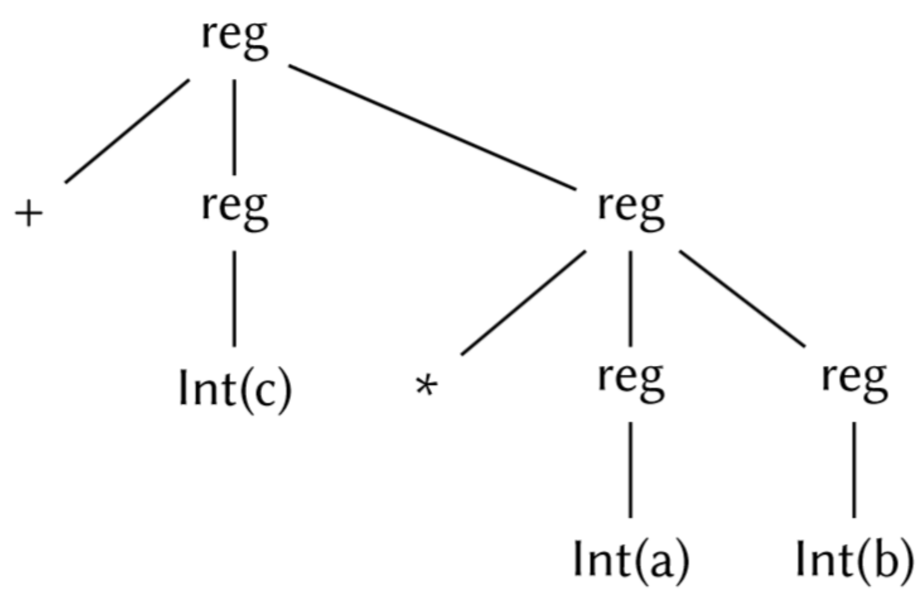


mul r1, c
add r1, c

```
mv  ra,a
mv  rb,b
mul ra,rb
mv  rc,c
add ra,rc
```

mv ra, b
mul ra, a
add ra, c

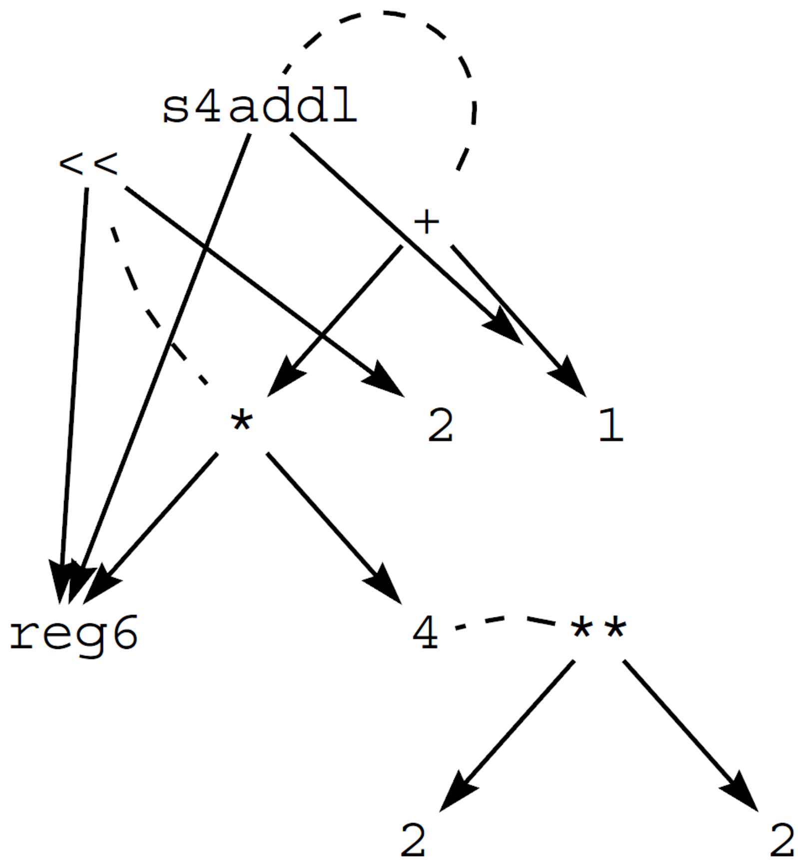
Tree covering as parsing



Deductive optimizers

Denali: synthesis with axioms and E-graphs

[Joshi, Nelson, Randall PLDI'02]



$$\forall\, n\, .\; 2^n = 2{*}{*}n$$

$$\forall\, k,n\, .\; k * 2^n = k{<}{<}n$$

$$\forall k,n{:}{:}\; k * 4 + n \;=\; \texttt{s4addl}(k,n)$$

$\texttt{\textbf{reg6}} * 4 + 1$ → $\texttt{s4addl}(\texttt{\textbf{reg6}},1)$

specification → synthesized program

Two kinds of axioms

Instruction semantics: defines the language

$$\forall\, n\,.\; 2^n = 2{*}{*}n$$

$$\forall\, k,n\,.\; k * 2^n = k{<}{<}n$$

Algebraic properties: associativity of add64, memory modeling, …

$$\forall k,n{::}\; k*4+n \;=\; \mathtt{s4addl}(k,n)$$

$$(\forall\, x,y :: \mathtt{add64}(x,y) = \mathtt{add64}(y,x))$$

$$(\forall\, x,y,z :: \mathtt{add64}(x,\mathtt{add64}(y,z)) = \mathtt{add64}(\mathtt{add64}(x,y),z))$$

$$(\forall\, x :: \mathtt{add64}(x,0) = x)$$

$$(\forall\, a,i,j,x \;:: i = j \;\lor\; \mathtt{select}(\mathtt{store}(a,i,x),j) = \mathtt{select}(a,j))$$

Two kinds of axioms

Instruction semantics: defines the language

$$\forall\ k, n\ .\ k * 2^n = k \texttt{<<} n$$

$$\forall k, n :: \ k * 4 + n \ = \texttt{s4addl}(k, n)$$

Algebraic properties: associativity of add64, memory modeling, …

$$\forall\ n\ .\ 2^n = 2 \texttt{**} n$$

$$(\forall\ x, y :: \texttt{add64}(x, y) = \texttt{add64}(y, x))$$

$$(\forall\ x, y, z :: \texttt{add64}(x, \texttt{add64}(y, z)) = \texttt{add64}(\texttt{add64}(x, y), z))$$

$$(\forall\ x :: \texttt{add64}(x, 0) = x)$$

$$(\forall\ a, i, j, x\ :: i = j \\ \vee\ \texttt{select}(\texttt{store}(a, i, x), j) = \texttt{select}(a, j))$$

Properties of deductive synthesizers

Efficient and provably correct

- thanks to semantics-preserving rules
- only correct programs are explored

Similar systems were built for axiomatizable domains

- expression equivalence (Denali)
- linear filters (FFTW, Spiral)
- linear algebra (FLAME)
- statistical calculations (AutoBayes)
- data structures as relational DBs (P2; Hawkins et al.)

Downsides of deductive optimizers

Completeness hinges on sufficient axioms

- some domains hard to axiomatize (e.g., sparse matrices)

Control over the “shape” of the synthesized program

- we often want predictable, human-readable programs

Solver-based Inductive synthesis achieves these

- see next section

Superoptimization

Massalin's superoptimization (1987)

Search nearly exhaustively for an optimal program.

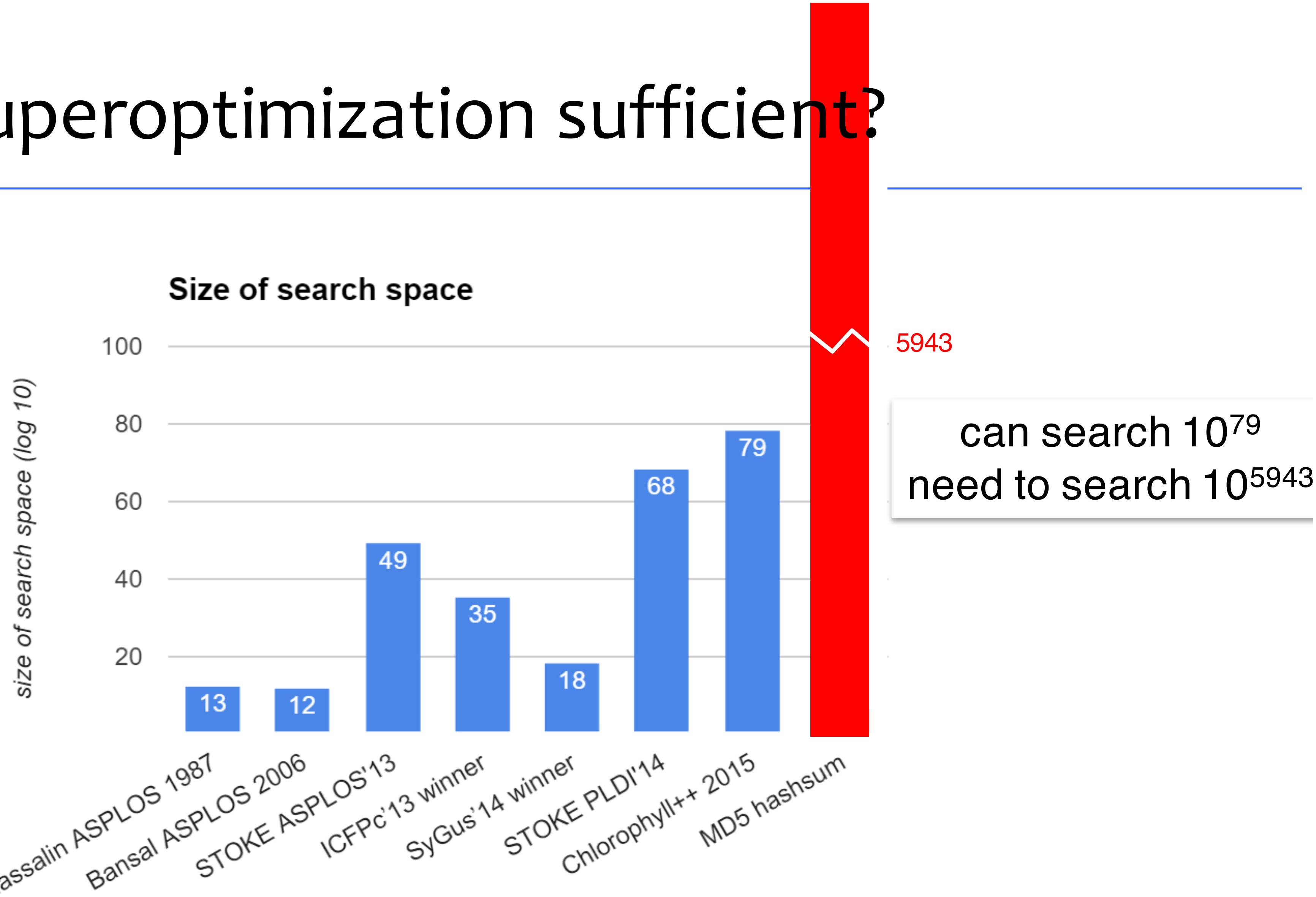
```
signum(x)
int       x;
{
          if(x > 0)           return 1;
          else if(x < 0)      return -1;
          else                return 0;
}
```

superoptimization

```
add.l   d0,d0    |add d0 to itself
subx.l  d1,d1    |subtract (d1 + Carry) from d1
negx.l  d0       |put (0 - d0 - Carry) into d0
addx.l  d1,d1    |add (d1 + Carry) to d1
```

[Alexia Henry Massalin, Superoptimizer: a look at the smallest program, ASPLOS 1987]

Is superoptimization sufficient?



The scope of superoptimization alone is limited.

Lesson: think of it as a tactical tool.

Synthesis with partial programs

see example of SIMD matrix transpose from previous lecture

Preparing your language for synthesis

Extend the language with two constructs

spec:

```
int foo (int x) {
    return x +
}
```

$\phi(x, y)$: $y = \textbf{foo}(x)$

sketch:

```
int bar (int x) implements foo {
    return x << ??;
}
```

?? substituted with an int constant satisfying ϕ

result:

```
int bar (int x) implements foo {
    return x << 1;
}
```

instead of **`implements`**, assertions over safety properties can be used

Synthesis as search over candidate programs

Partial program (sketch) defines a candidate space

we search this space for a program that satisfies ϕ

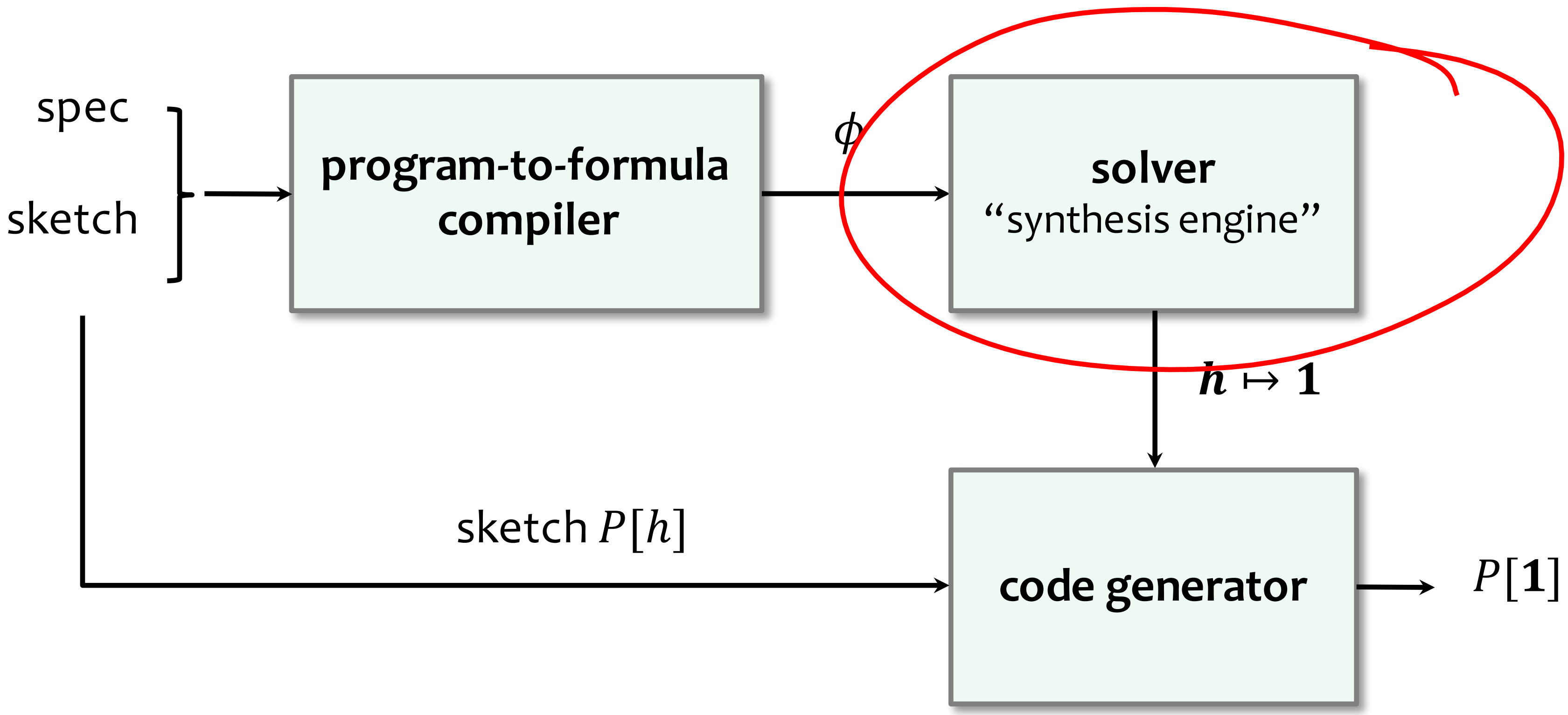
Usually can't search this space by enumeration

space is too large ($\gg 10^{10}$)

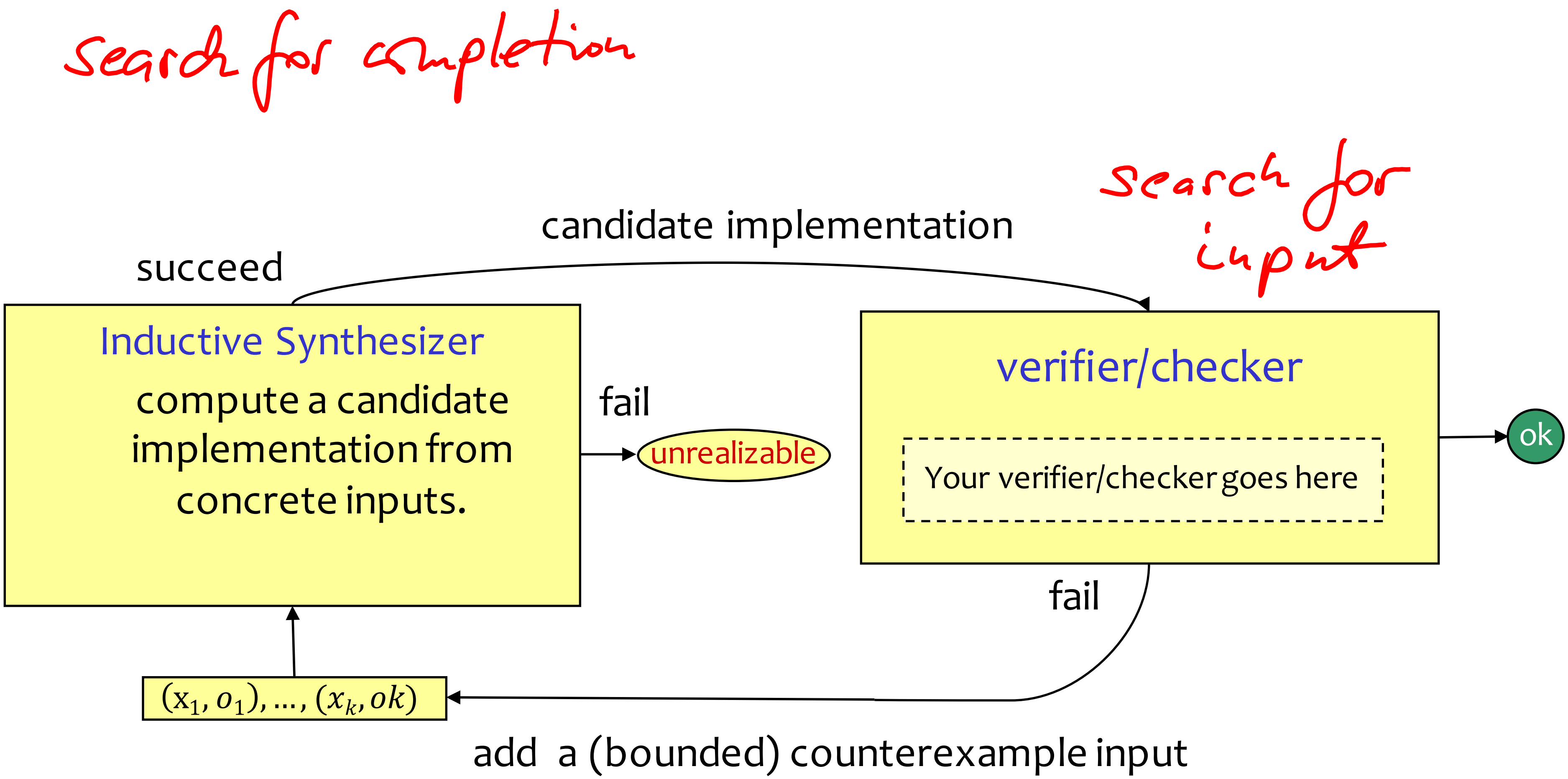
Describe the space **symbolically**

solution to constraints encoded in a logical formula gives values of holes, indirectly identifying a correct program

Synthesis from partial programs



CounterExample -Guided Inductive Synthesis (CEGIS)



Garbage Collection

Slides courtesy of Profs. Alex Aiken and George Necula

Lecture Outine

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

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

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

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

The Basic Idea

- When an object that takes memory space is created, unused space is automatically allocated
  - In 401, new objects are created by new X
- JS memory manager keeps track of all allocated objects and amount unused heap space
- 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

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:

```
lambda f () { def a = new A() }
f()
```

  - After f() there is no way to access the newly allocated object

Garbage

- An object x is reachable if and only if:
  - an interpreter frame (sym table) contains a pointer to x, or
  - another reachable object y contains a pointer to x
- You can find all reachable objects by starting from interpreter frames and following all the pointers
- An unreachable object can never by referred by the program
  - these objects are called garbage

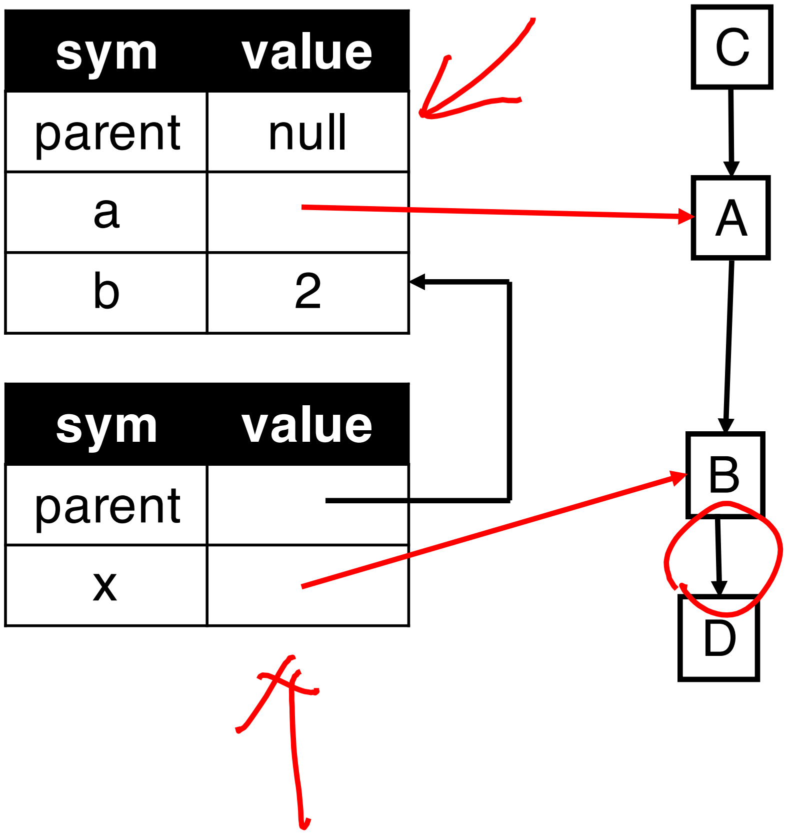
Reachability is an Approximation

- Consider the program:

```
x = new A() // p1
y = new B() // p2
x = y
if (alwaysTrue) { x = new A() } // p3
else { x.foo() }
```

- After x = y (assuming y becomes dead there)
  - the object A @ p1 is not reachable anymore
  - the object B @ p2 is reachable (through x)
  - thus B @ p2 is not garbage and is not collected
  - but object B @ p2 is never going to be used

A Simple Example



- We start tracing from pointers from all frames
  - These are called roots
- C is not reachable from any frames
- Thus we can reuse its storage

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 (by tracing objects reachable from the "root")
     b) Free the space used by objects not found in (a)
- Some strategies perform garbage collection before the space actually runs out

Algorithm 1: Mark and Sweep

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

The Mark Phase

```
def todo = { roots }
while todo ≠ ∅ {
    pick v ∈ todo
    todo = todo - { v }
    if mark(v) == 0 {      // v is unmarked yet
        mark(v) = 1
        v1,...,vn = pointers that v points to
        todo = todo ∪ {v1,...,vn}
    }
}
```

The Sweep Phase

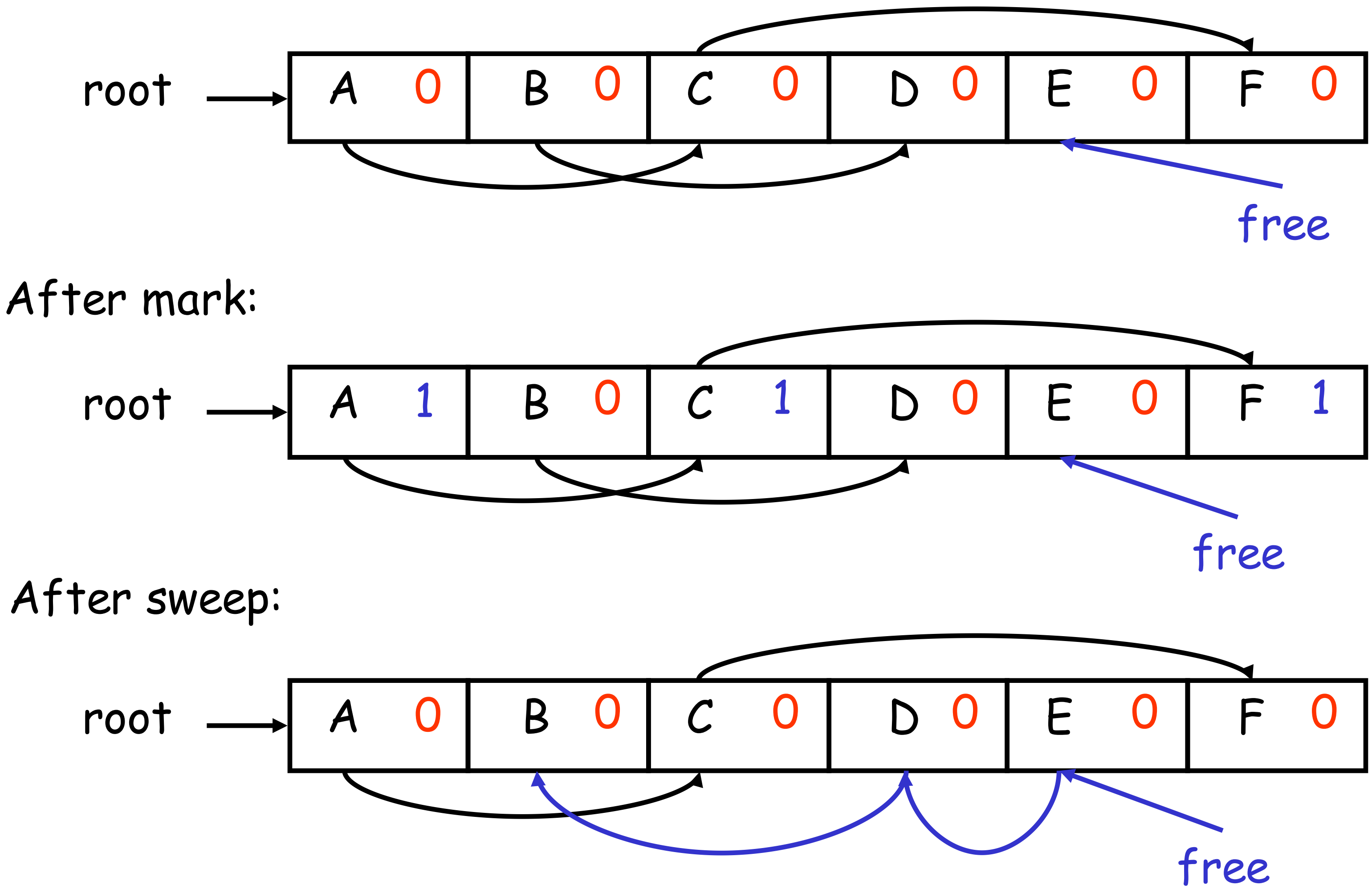
- The sweep phase scans the heap looking for objects with mark bit 0
  - these objects have not been visited in the mark phase
  - they are garbage
- Any such object is added to the free list
- The objects with a mark bit 1 have their mark bit reset to 0

The Sweep Phase (Cont.)

```
for (obj : allocatedObjs) {
  if (mark(obj) == 1) {
     mark(obj) = 0
  } else {
     // free obj and add it back to unallocated heap
  }
}
```

- Memory manager keeps track of each object's size
  - This can be done using types
- Memory manager typically maintains a "free list"
  - Removes an entry from free list when `new T` is called

Mark and Sweep Example



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

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

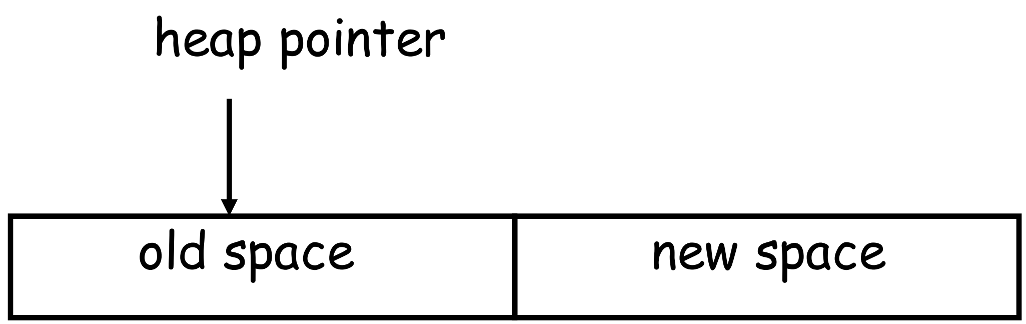
Mark and Sweep. Evaluation

- 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++

Algorithm 2: Stop and copy

Stop and Copy

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

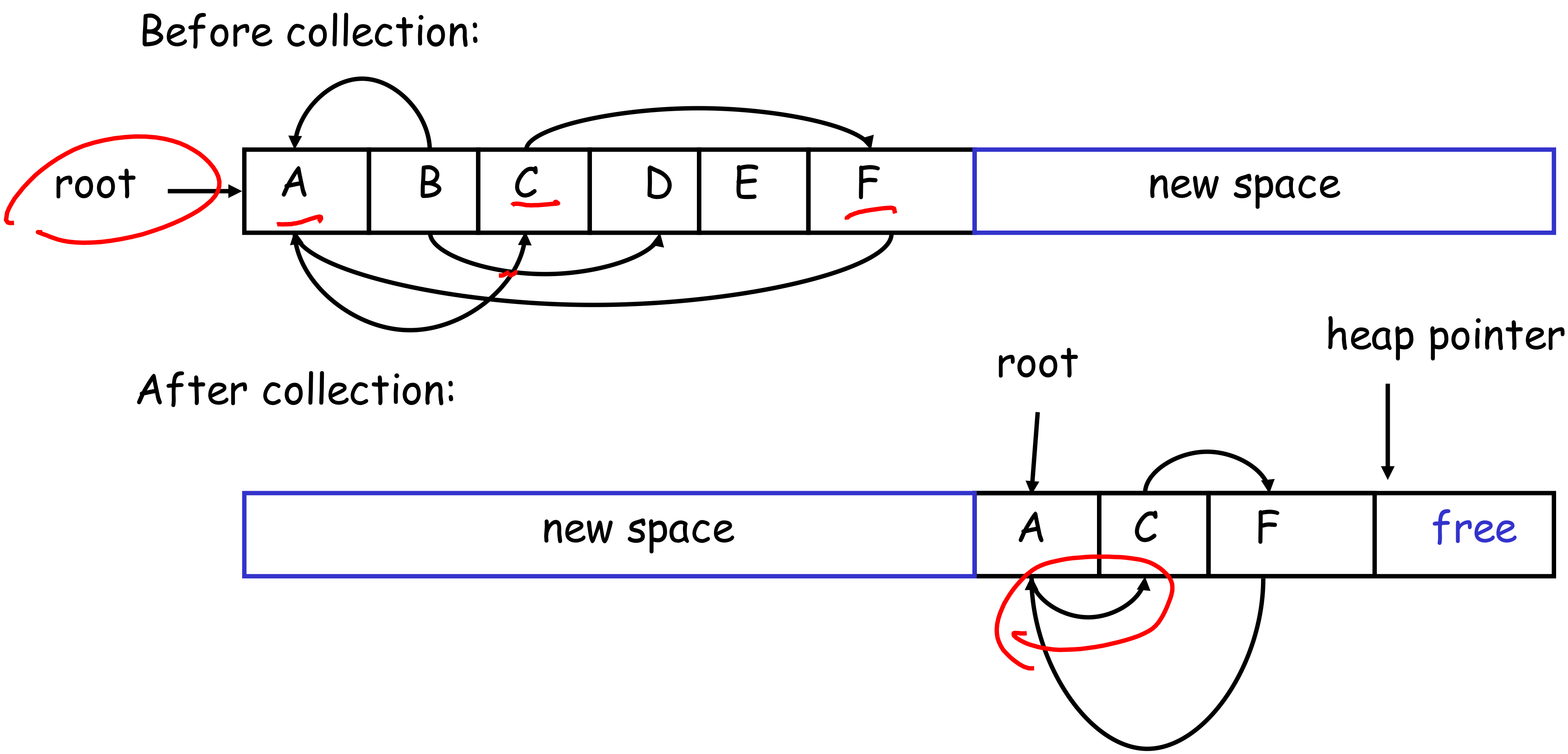


- The heap pointer points to the next free word in the old space
  - allocation just advances the heap pointer

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

Stop and Copy Garbage Collection. Example

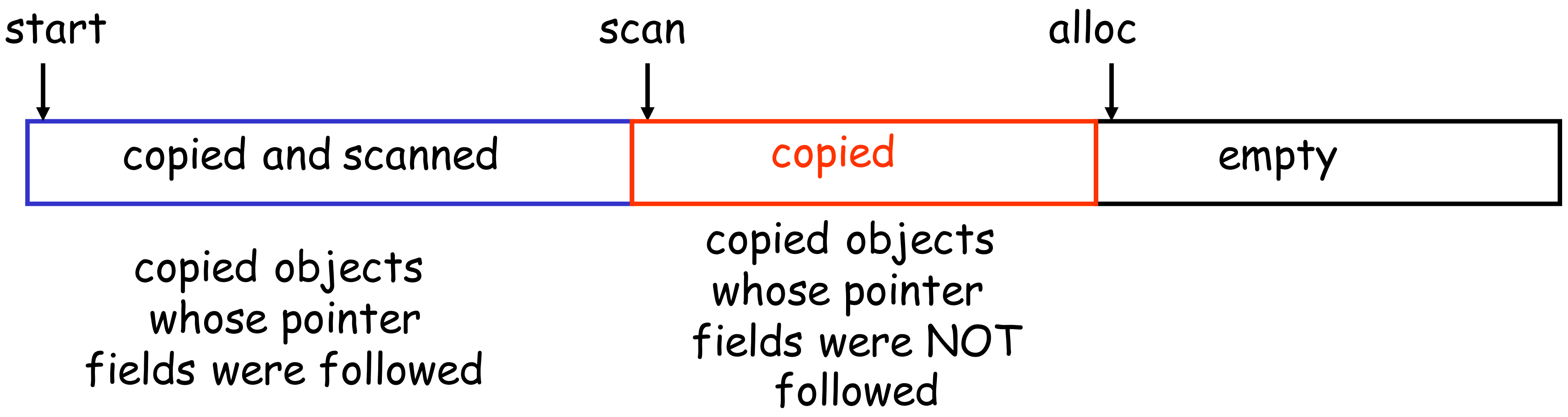


Implementation of Stop and Copy

- 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

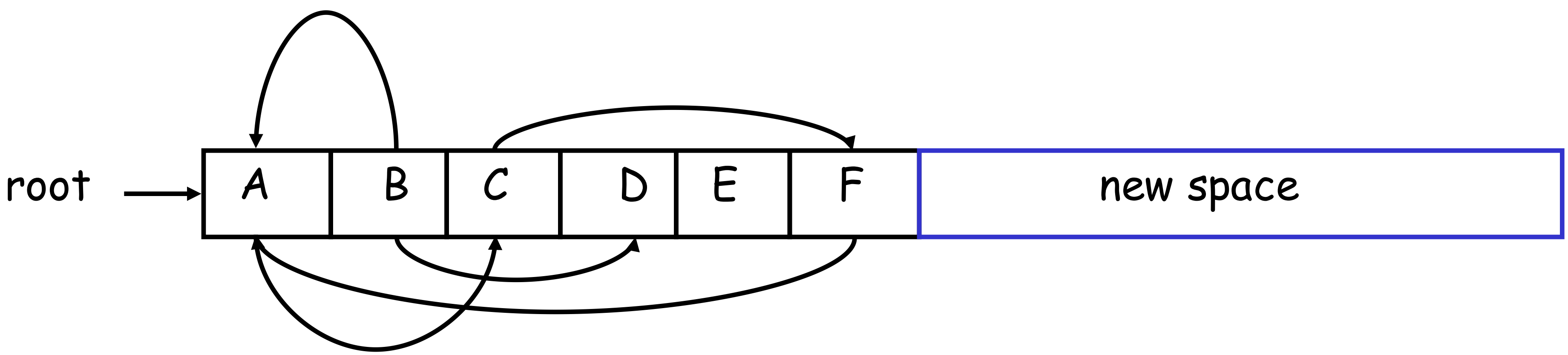
Implementation of Stop and Copy (Cont.)

- 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



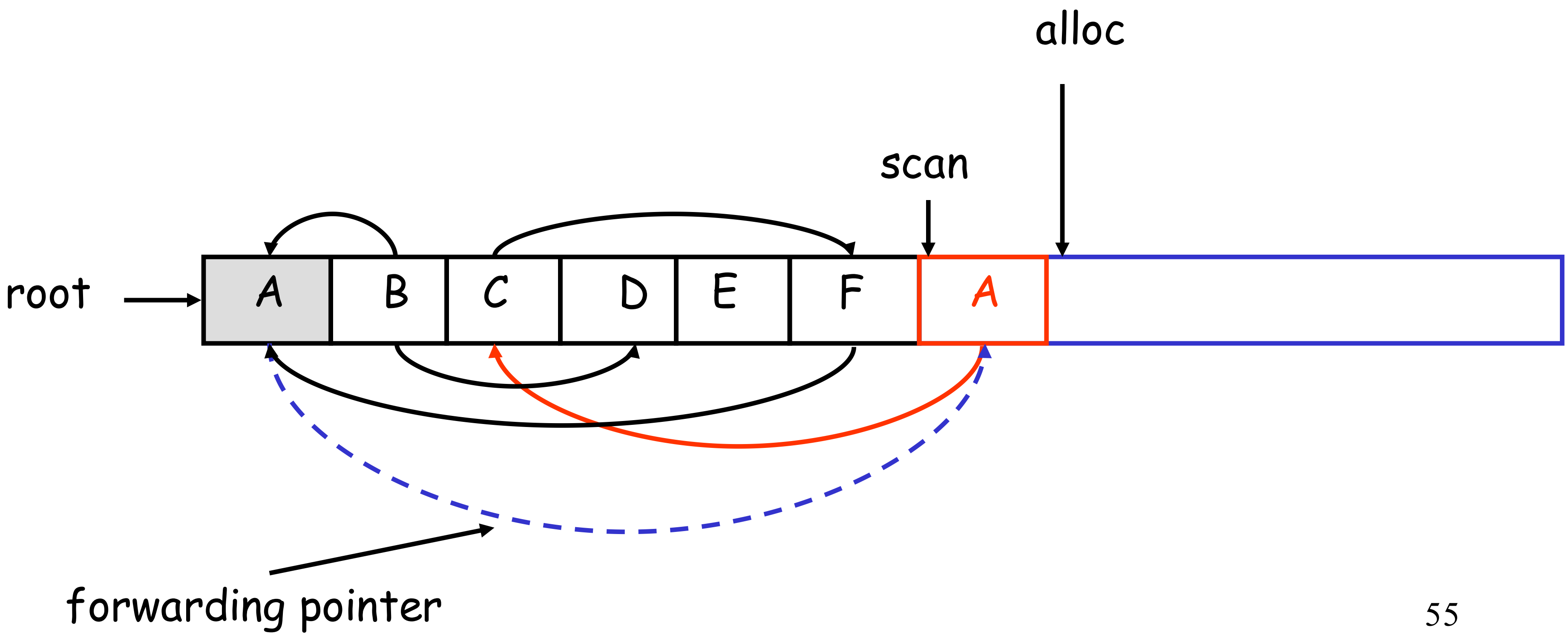
Stop and Copy. Example (1)

- Before garbage collection



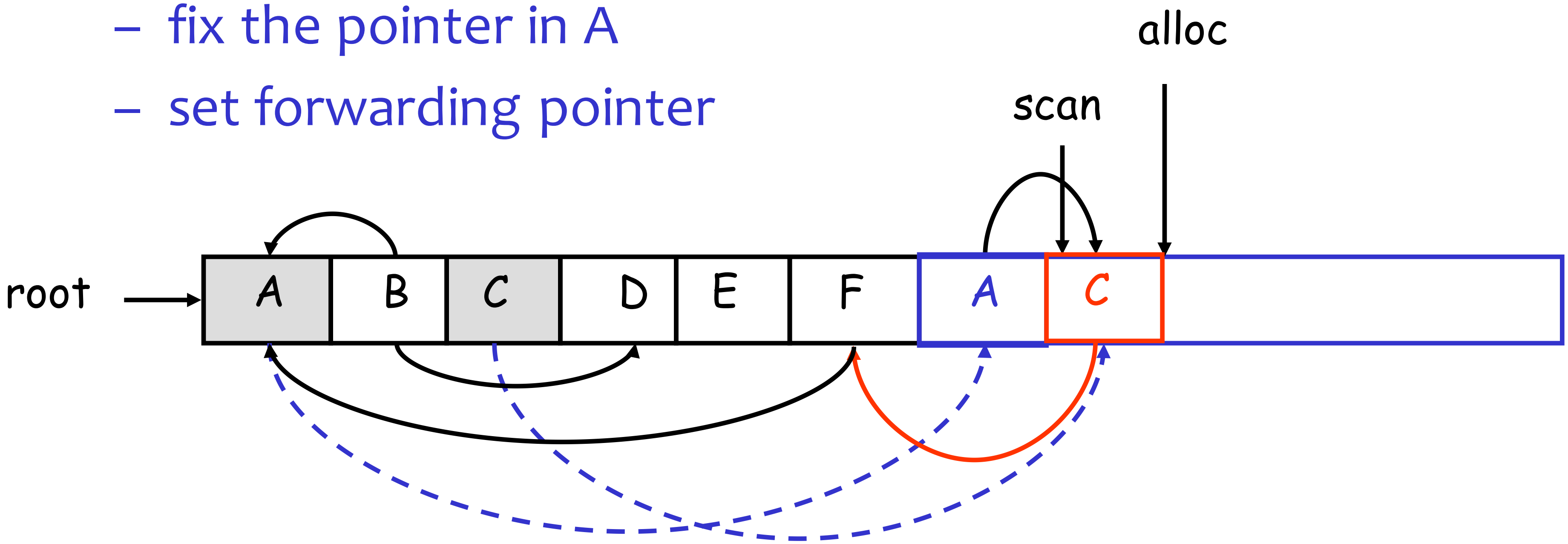
Stop and Copy. Example (3)

- Step 1: Copy the objects pointed by roots and set forwarding pointers



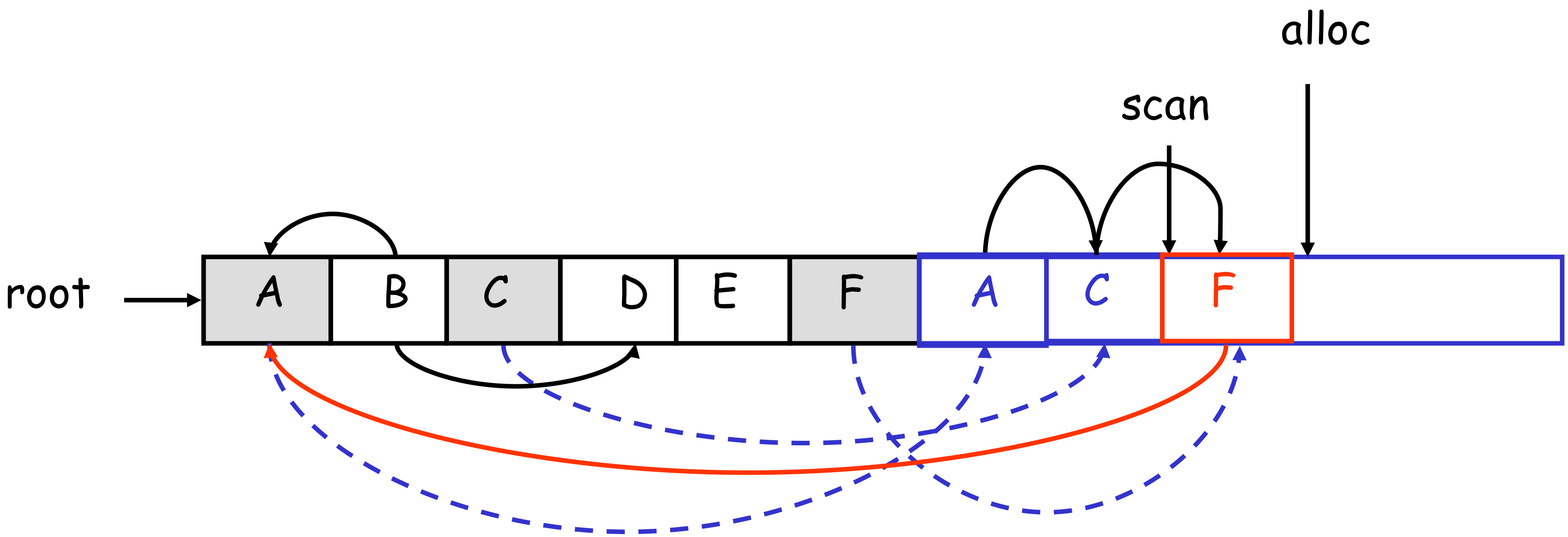
Stop and Copy. Example (3)

- 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



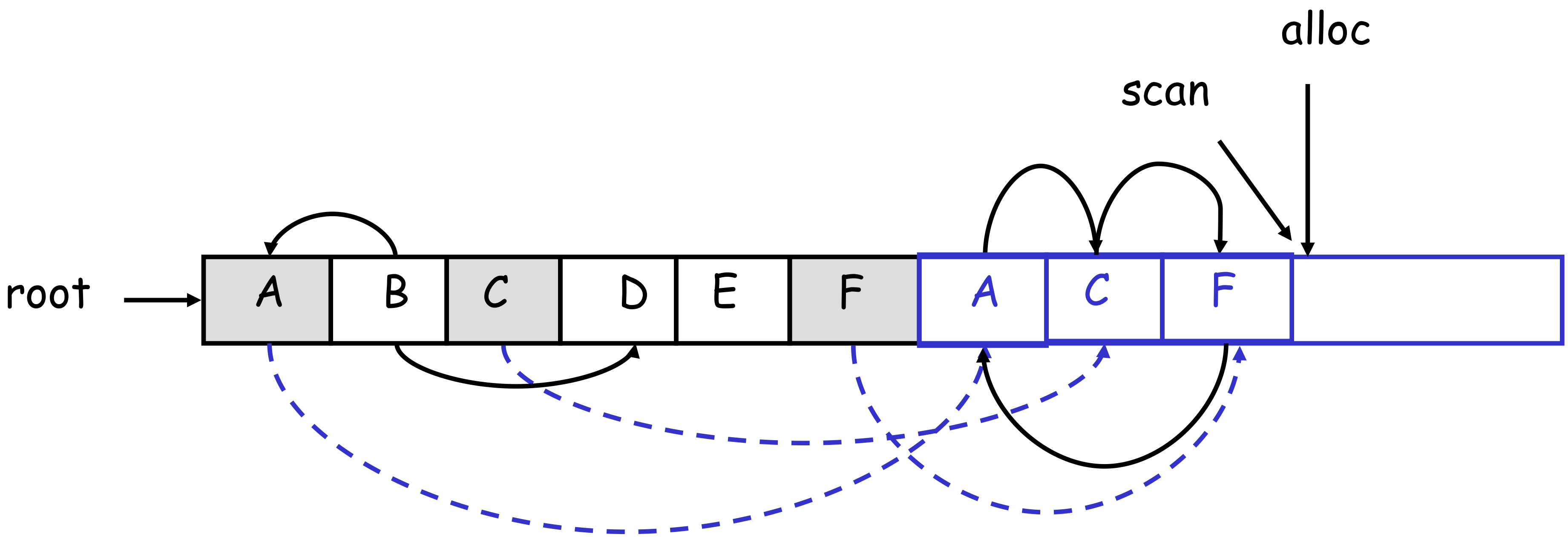
Stop and Copy. Example (4)

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



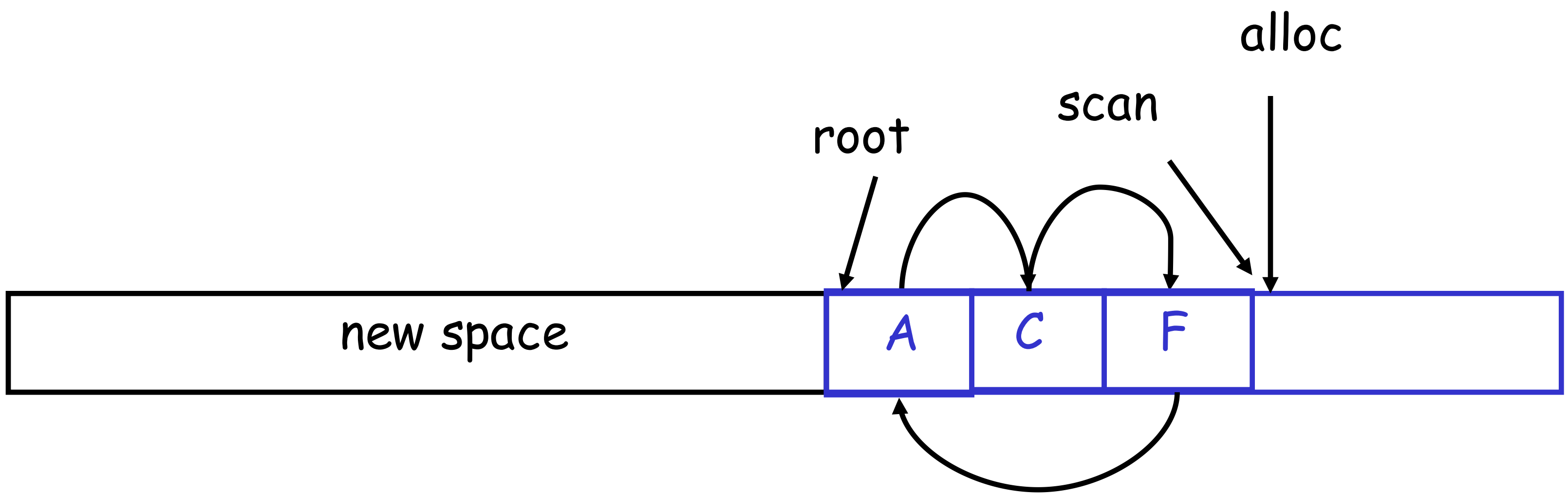
Stop and Copy. Example (5)

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



Stop and Copy. Example (6)

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



The Stop and Copy Algorithm

```
while (scan != alloc) {
    O = the object at scan pointer
    for (each pointer p contained in O) {
       find O' that p points to
       if (O' is without a forwarding pointer) {
            copy O' to new space (update alloc pointer)
            set 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
       }
    }
    increment scan pointer to the next object
}
```

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

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++)

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

Conservative Garbage Collection

- But it is Ok to be <u>conservative</u>:
  - 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?

Algorithm 3: Reference Counting

Reference Counting

- Rather that 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

- C++: smart pointers (boost library), memory header (C++11)
  - Requires writing code to explicitly transfer object ownership

Implementation of Reference Counting

- `new` returns an object with a reference count of 1
- If `x` points to an object then let `rc(x)` point to its reference count
- Every assignment `x = y` must be changed:

```
// increase ref count of obj pointed to by y
rc(y) = rc(y) + 1
// reduce ref count of obj pointed to previously by x
rc(x) = rc(x) - 1
if(rc(x) == 0) { mark x as free }
x = y   // perform actual assignment
```

Reference Counting Evaluation

- Advantages:
  - easy to implement
  - collects garbage incrementally without large pauses in the execution
- Disadvantages:
  - cannot collect circular structures
  - manipulating reference counts at each assignment is very slow

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 implementation stop the execution during collection
  - not acceptable in real-time applications

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