Automatic Memory Management

One-Slide Summary

- An **automatic memory management** system deallocates objects when they are no longer used and reclaims their storage space.
- We must be **conservative** and only free objects that will not be used later.
- **Garbage collection** scans the heap from a set of **roots** to find **reachable** objects. **Mark and Sweep** and **Stop and Copy** are two GC algorithms.
- **Reference Counting** stores the number of pointers to an object with that object and frees it when that count reaches zero.

Lecture Outine

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

Why Automatic Memory Mgmt?

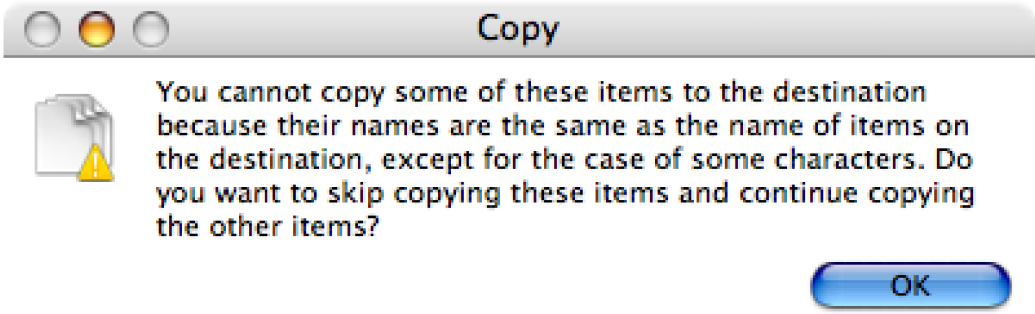
- Storage management is still a hard problem in modern programming
- C and C++ programs have many storage bugs
  - forgetting to free unused memory
  - dereferencing a dangling pointer
  - overwriting parts of a data structure by accident
  - and so on... (can be big security problems)
- Storage bugs 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 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 (= dead objects?)
- This space can be **freed** to be reused later

Dead Again?

- How can we tell whether an object will "never be used again"?
  - In general it is impossible (undecideable) 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 ← y** there is no way to access the newly allocated object

Garbage

- An object x is **reachable** if and only if:
  - A local variable (or 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 local variables and following all the pointers ("**transitive**")
- An unreachable object can never by referred to by the program
  - These objects are called **garbage**

Reachability is an Approximation

- Consider the program:

  x ← new Ant;

  y ← new Bat;

  x ← y;

  if alwaysTrue() then x ← new Cow else x.eat() fi

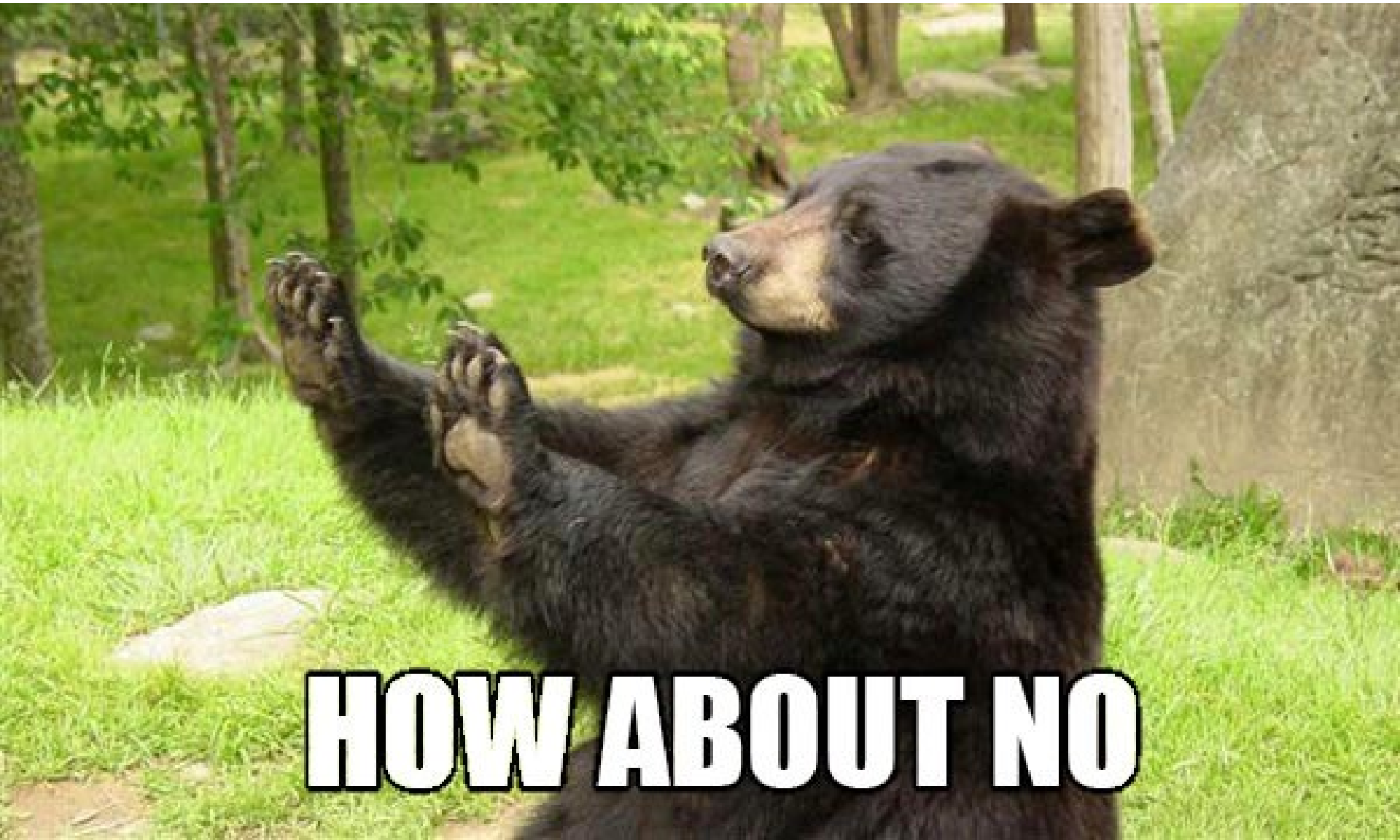
- After x ← y (assuming y becomes dead there)
  - The object Ant is not reachable anymore
  - The object Bat is reachable (through x)
  - Thus Bat is not garbage and is *not* collected
  - But object Bat is never going to be used

Cool Garbage

- At run-time we have two mappings:
  - Environment **E** maps variable identifiers to locations
  - Store **S** maps locations to values
- Proposed Cool Garbage Collector
  - for each location l $\in$ domain(**S**)
  - let can_reach = false
  - for each $(v, l_2) \in$ **E**
  - if l = l_2 then can_reach = true
  - if not can_reach then reclaim_location(l)

Does this work?

Does That Work?



Cooler Garbage

- Environment **E** maps variable identifiers to locations
- Store **S** maps locations to values

- Proposed Cool Garbage Collector
  - **for each location l ∈ domain(S)**
  - **let can_reach = false**
  - **for each (v,l_2) ∈ E**
  - **if l = l_2 then can_reach = true**
  - **for each l_3 ∈ v** *// v is X(..., a_i = l_i, ...)*
  - **if l = l_3 then can_reach = true**
  - **if not can_reach then reclaim_location(l)**

Garbage Analysis

- Could we use the proposed Cool Garbage Collector in real life?
- How long would it take?
- How much space would it take?
- Are we forgetting anything?
  - Hint: Yes. It's still wrong.

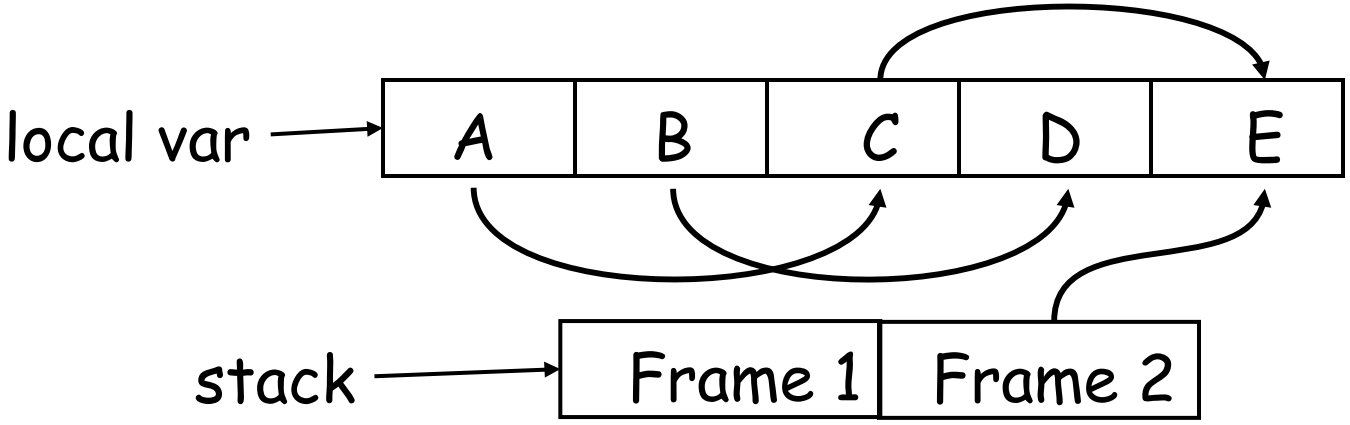
Tracing Reachable Values

- In Cool, local variables are easy to find
  - Use the environment mapping E
  - and one object may point to other objects, etc.
- The stack is more complex
  - each stack frame (activation record) contains:
    - method parameters (other objects)
- If we know the layout of a stack frame we can find the pointers (objects) in it

Reachability Can Be Tricky

- Many things may look legitimate and reachable but will turn out not to be.
- How can we figure this out systematically?

A Simple Example



- Start tracing from local vars and the stack
  - they are called the **roots**
- Note that B and D are not reachable from local vars or the stack
- Thus we can reuse their storage

Elements of Garbage Collection

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

Q: Games (545 / 842)

- This 1993 id Software game was the first truly popular first-person shooter (15 million estimated players). You play the role of a space marine and fight demons and zombies with shotguns, chainsaws and the BFG9000. It was controversial for diabolic overtones and has been dubbed a "mass murder simulator." CMU and Intel, among others, formed special policies to prevent people from playing it during working hours.

Q: Books (726 / 842)

- Paraphrase any one of Isaac Asimov's 1942 **Three Laws of Robotics**.

Q: Movie Music (428 / 842)

- What's "the biggest word" Dick Van Dyke had "ever heard" in the 1964 film "Mary Poppins"?

Real-World Languages

- This Romance language features about 80 million speakers, primarily from Europe. It derives from Latin, retaining that language's contrast between long and short consonants and much of its vocabulary. Its modern incarnation was formalized by Dante Alighieri in the fourteenth century. The letters j, k, w, x and y do not appear natively.
  - Example: lunedì, martedì, mercoledì, giovedì

Mark And Sweep

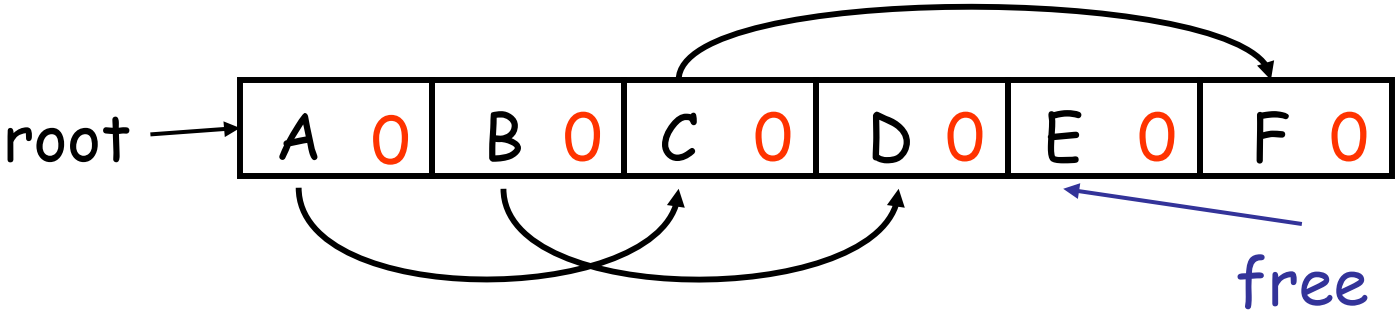
- Our first GC algorithm
- Two phases:
  - Mark
  - Sweep

Mark and Sweep

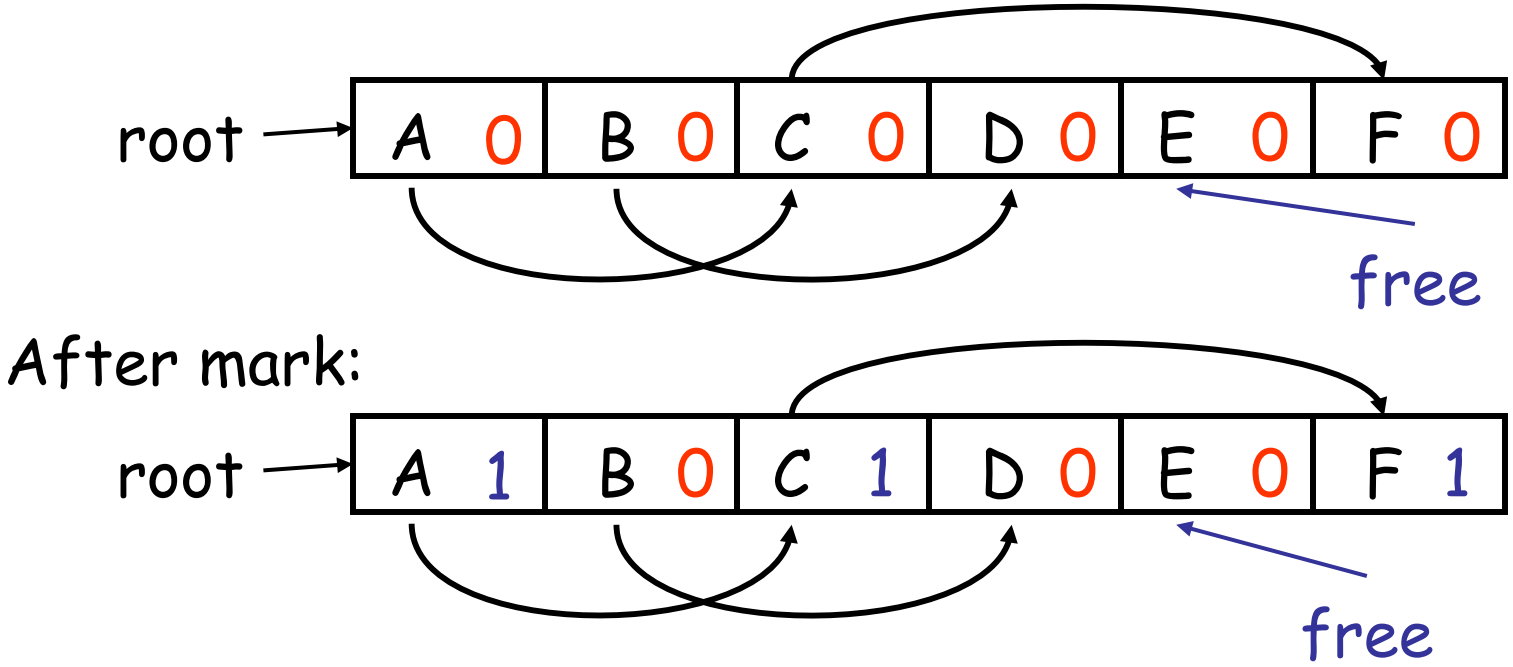
- When memory runs out, GC executes two phases
  - the **mark** phase: traces reachable objects
  - the **sweep** phase: collects garbage objects

- 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

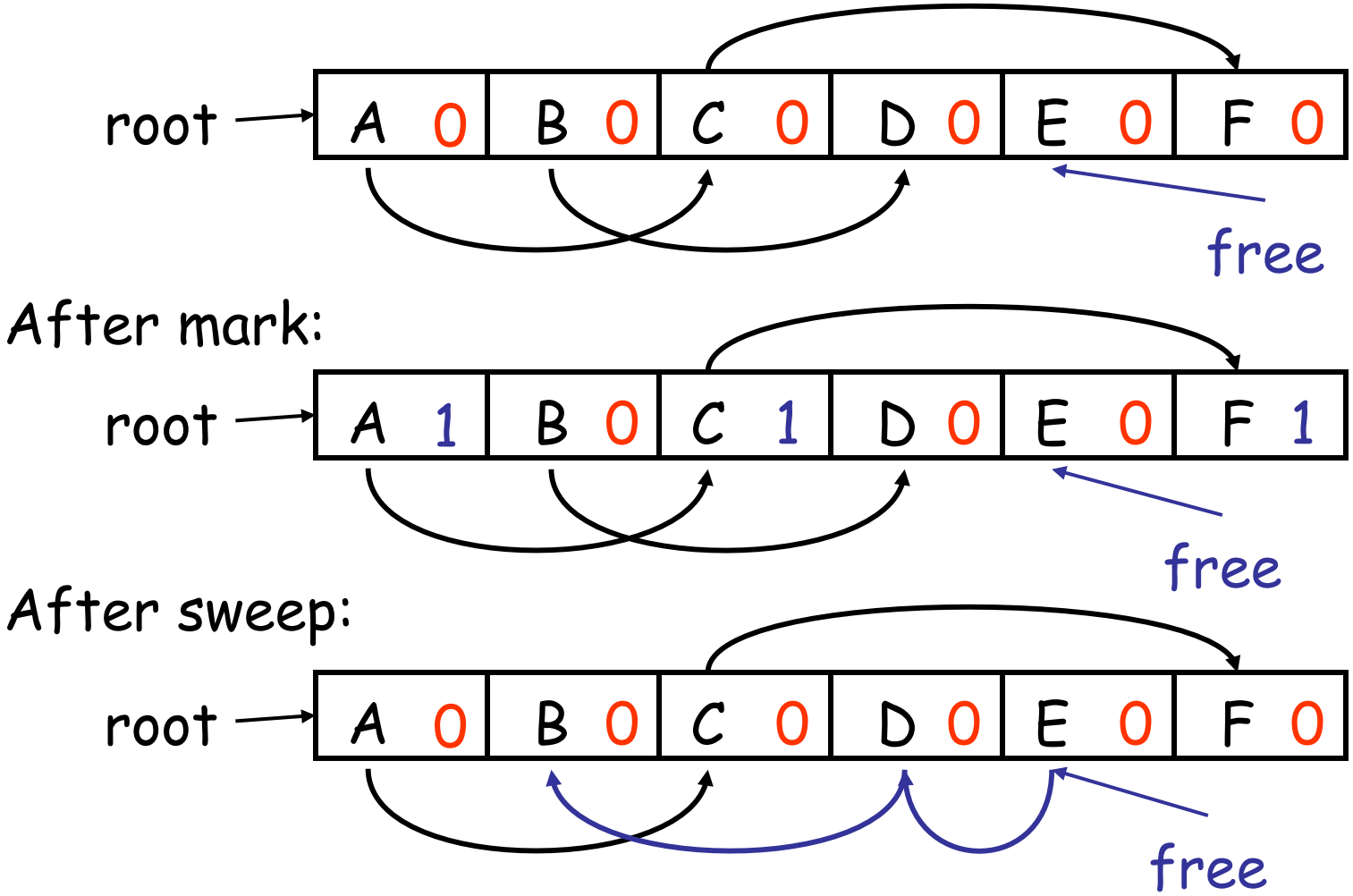
Mark and Sweep Example



Mark and Sweep Example



Mark and Sweep Example



The Mark Phase

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

The Sweep Phase

- The sweep phase scans the (entire) 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.)

```
/* sizeof(p) is 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
```

Mark and Sweep Analysis

- 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

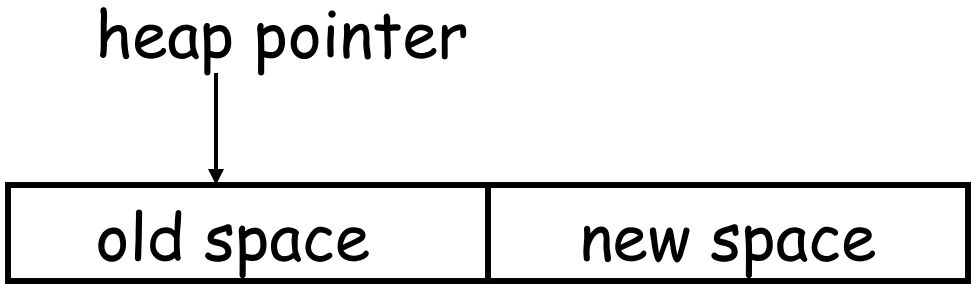
- The todo list is used as an auxiliary data structure to perform the reachability analysis
- There is a trick that allows the auxiliary data to be stored in the objects themselves
  - **pointer reversal**: when a pointer is followed it is reversed to point to its parent
- Similarly, the free list is 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** memory
- Advantage: objects are not moved during GC
  - no need to update the pointers to objects
  - works for languages like C and C++

Another Technique: Stop and Copy

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

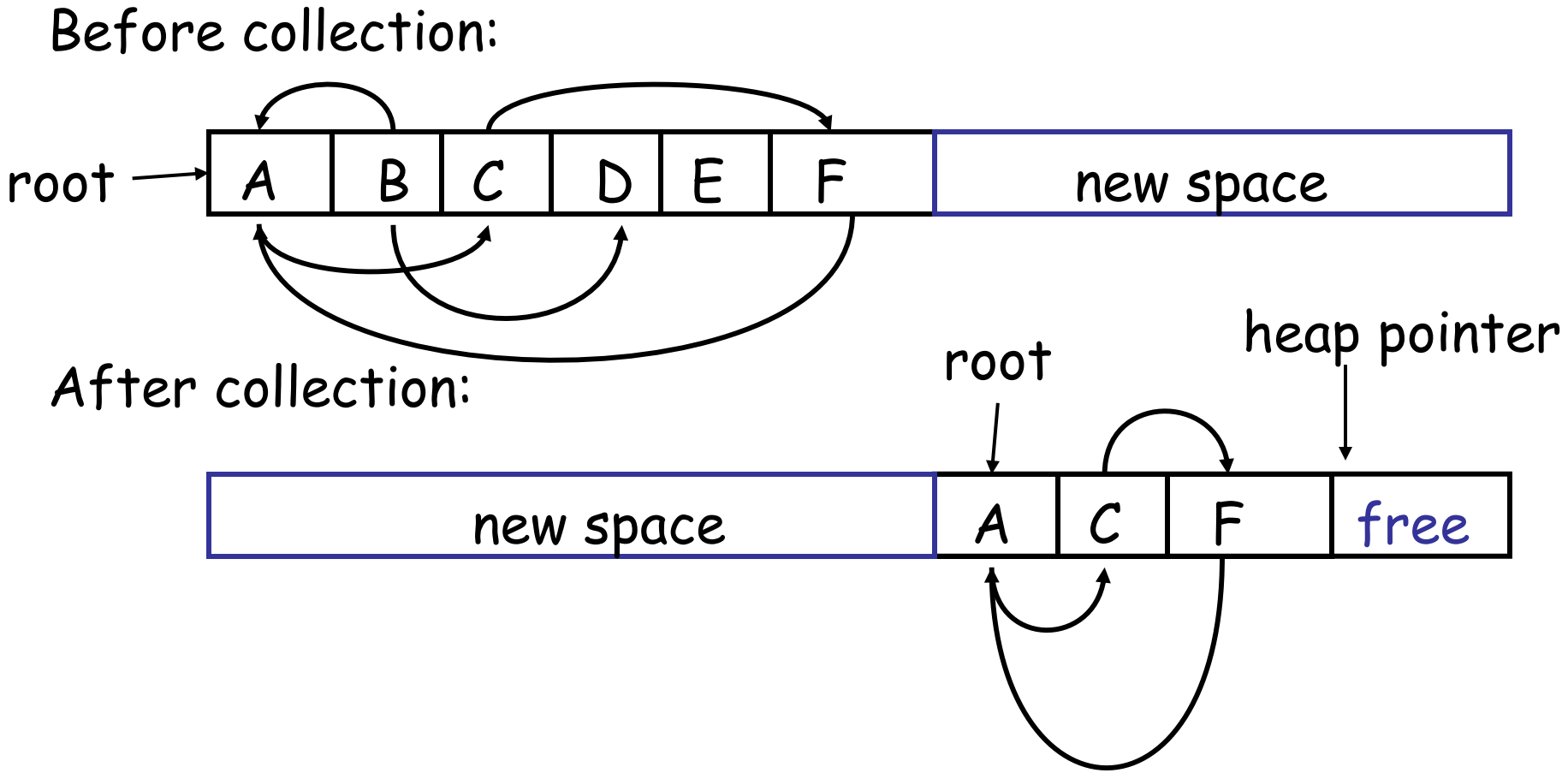


- The heap pointer points to the next free word in the old space
  - Allocation just advances the heap pointer

Stop and Copy GC

- 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



Q: Theatre (004 / 842)

- Identify the character singing these 1965 musical lines: *"Hear me now / Oh thou bleak and unbearable world, / Thou art base and debauched as can be; / And a knight with his banners all bravely unfurled / Now hurls down his gauntlet to thee! / I am I, ..."*

Q: General (480 / 842)

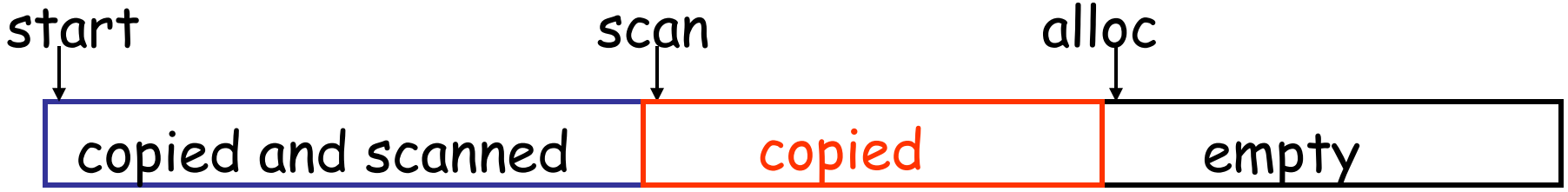
- This process, typically involving gamma rays, can be used to preserve perishable foods like strawberries, as well as to sterilize some tools like syringes and even to turn glass brown.

Implementing Stop and Copy

- We need to find all the reachable objects
  - Just as in 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
  - How can we identify forwarding pointers?

Implementation of Stop and Copy

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

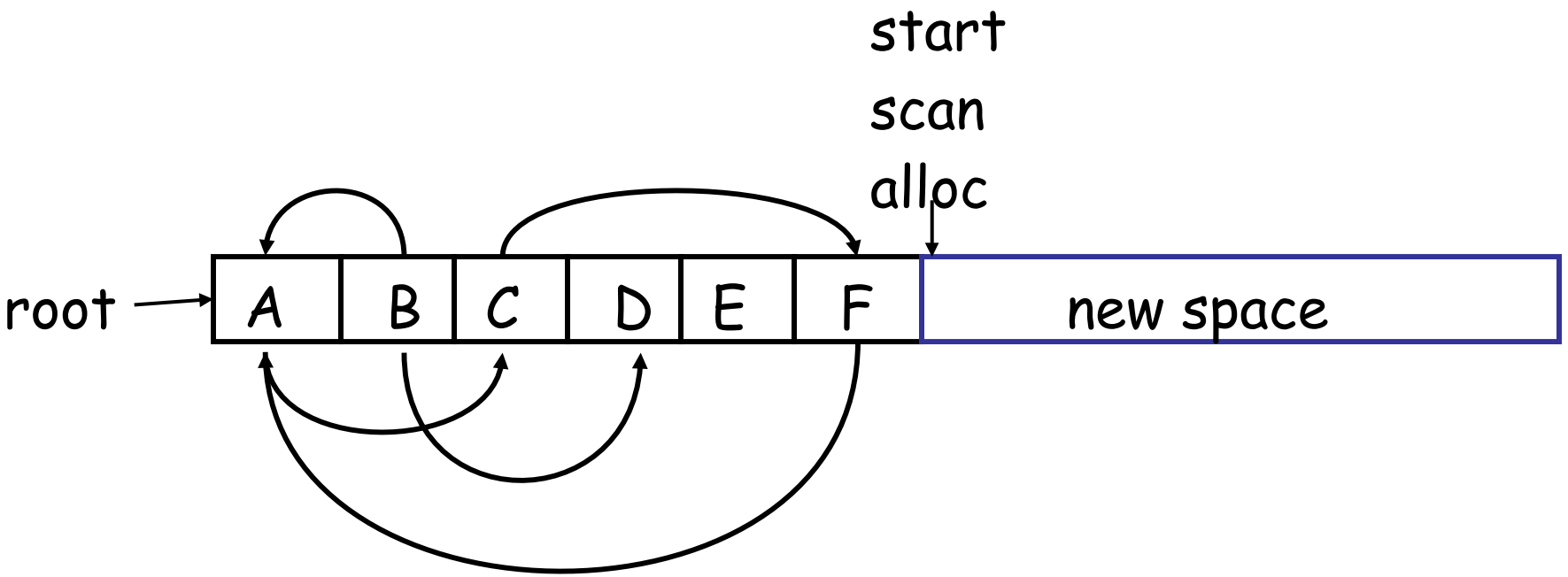


copied objects whose pointer fields were followed and fixed

copied objects whose pointer fields were NOT followed

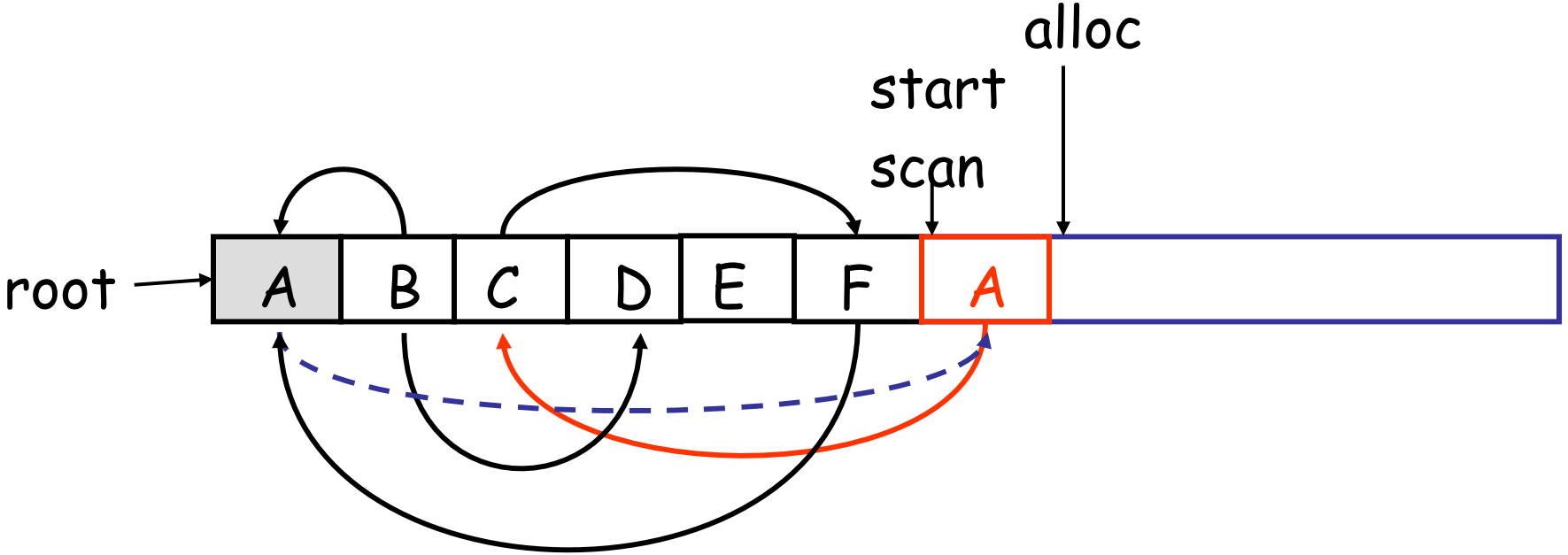
Stop and Copy. Example (1)

- Before garbage collection



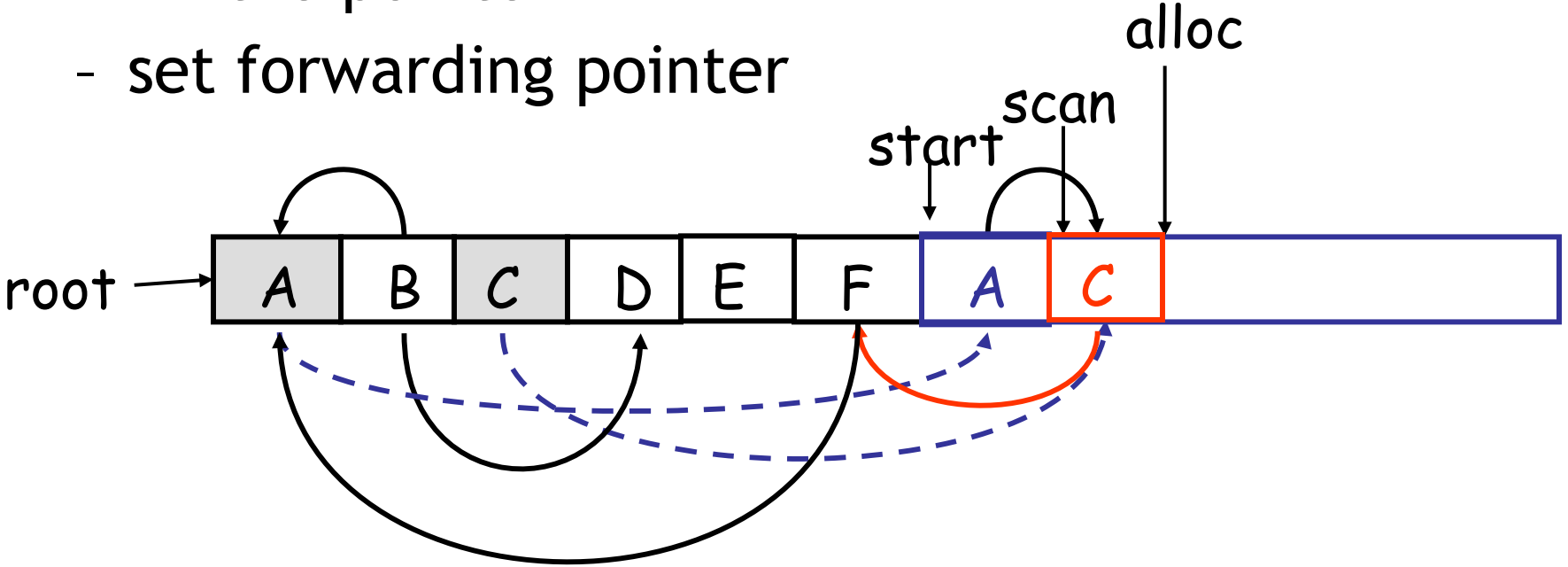
Stop and Copy. Example (2)

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



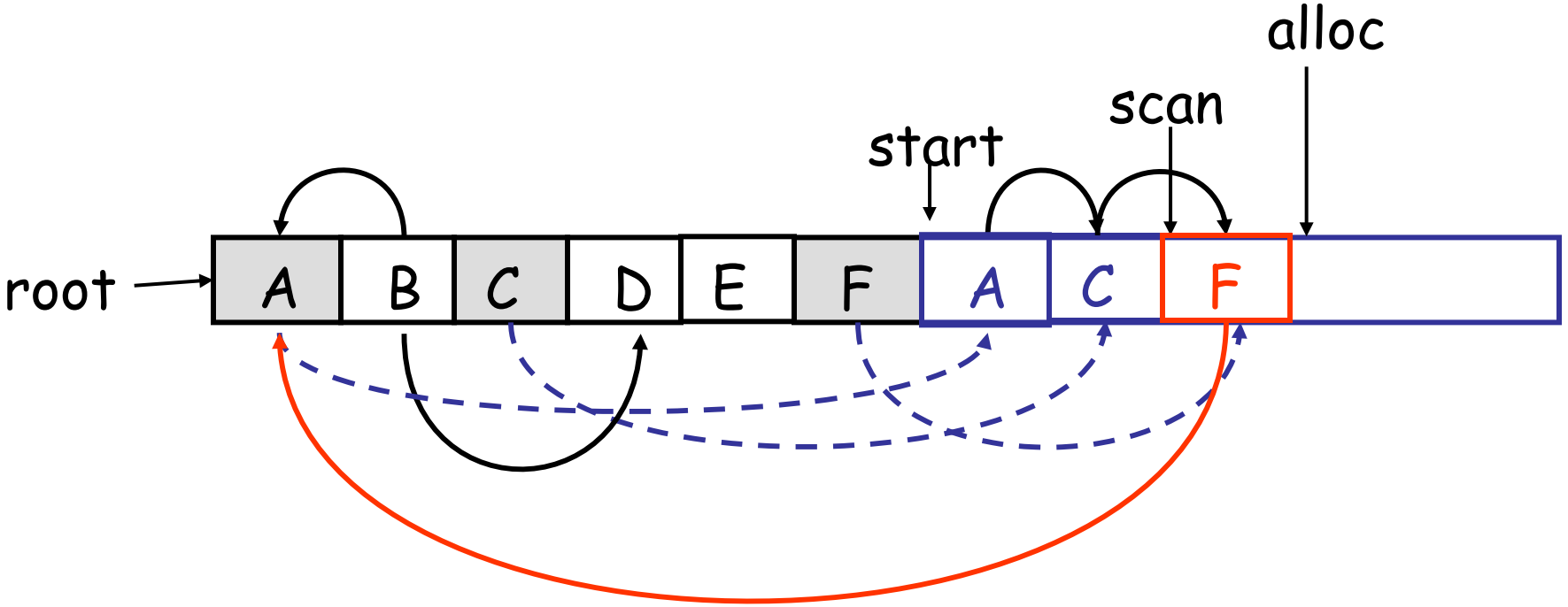
Stop and Copy. Example (3)

- 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



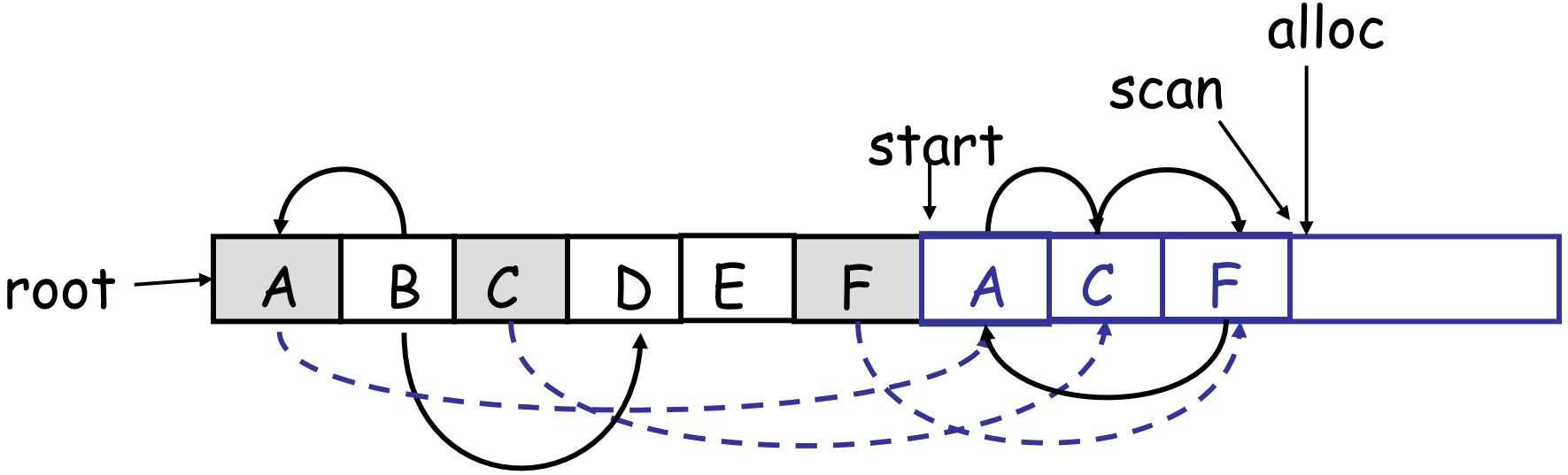
Stop and Copy. Example (4)

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



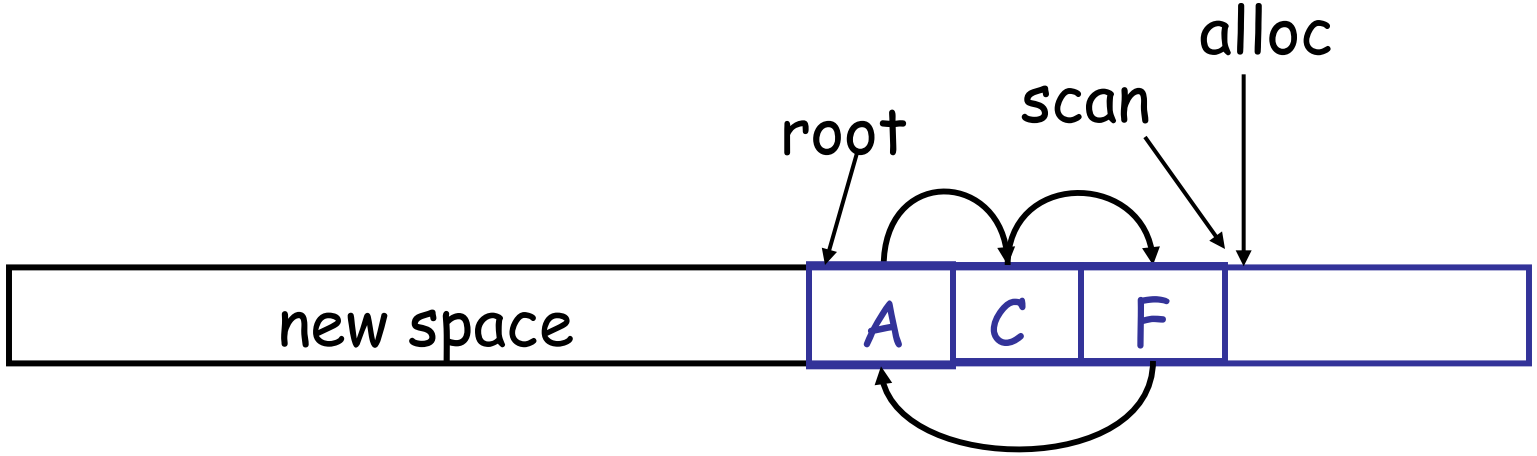
Stop and Copy. Example (5)

- 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 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
```

Stop and Copy Details

- As with mark and sweep, we must be able to tell how large an object is when we scan it
  - And we must also know where the pointers are 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 **conservative**:
  - If a memory word "looks like" a pointer it is considered to be a pointer
    - it must be aligned (what does this mean?)
    - 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?

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

Implementing Reference Counts

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

  $rc(y) \leftarrow rc(y) + 1$

  $rc(x) \leftarrow rc(x) - 1$

  if (rc(x) == 0) then mark x as free

  $x \leftarrow y$

Reference Counting Evaluation

- Advantages:
  - Easy to implement
  - Collects garbage incrementally without large pauses in the execution
    - *Why would we care about that?*
- Disadvantages:
  - Manipulating reference counts at each assignment is very slow
  - Cannot collect circular structures

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 (infant mortality)
  - Parallel: several collectors working in parallel
  - Real-Time / Incremental: no long pauses

In Real Life

- **Python** uses Reference Counting
  - Because of “extension modules”, they deem it too difficult to determine the root set
  - Has a special separate cycle detector
- **Perl** does Reference Counting + cycles
- **Ruby** does Mark and Sweep
- **OCaml** does (generational) Stop and Copy
- **Java** does (generational) Stop and Copy

Homework

- WA5 due
- Compilers: PA6 is creeping up ...