Lecture 22

Garbage Collection

Mark and Sweep, Stop and Copy, Reference Counting

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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 90’s 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

- new objects are created by new X

After a while there is no more unused space

- new X can no longer allocate objects

Some space occupied by objects is never to be used again

- This space can be freed to be reused

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 (but not all) objects that will never be used again

Observation: a program can use only the objects that it can find:

```
x = new A();
x = y;
```

After x = y, no way to access the newly allocated object

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

Clearly, 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();
y = new B();
x = y;
if alwaysTrue() { x = new A() }
else { x.foo(); }
```

After x = 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

Tracing Reachable Values

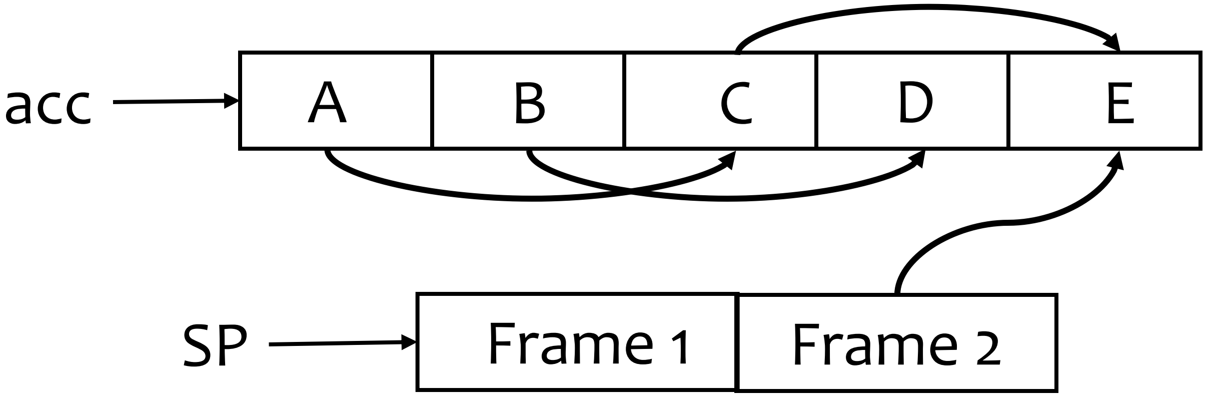
In a simple implementation, the only register is the accumulator

- it points to an object
- and this object may point to other objects, etc.

The stack (as in 164) 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

A Simple Example



We start tracing from acc and stack

- they are called the roots

B and D are unreachable from acc or the stack.

Thus we can reuse their storage.

Elements of Garbage Collection

Every garbage collector 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

Mark and Sweep

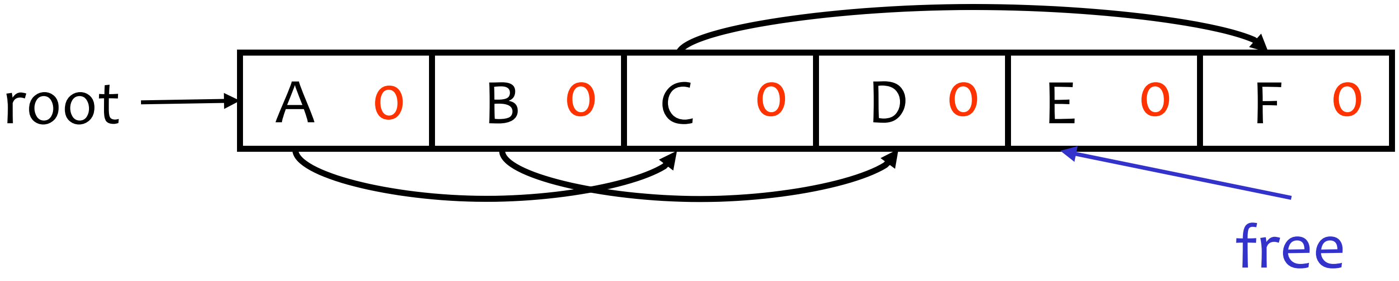
When memory runs out, GC executes two phases

- the mark phase: traces reachable objects
- the sweep phase: collects garbage objects

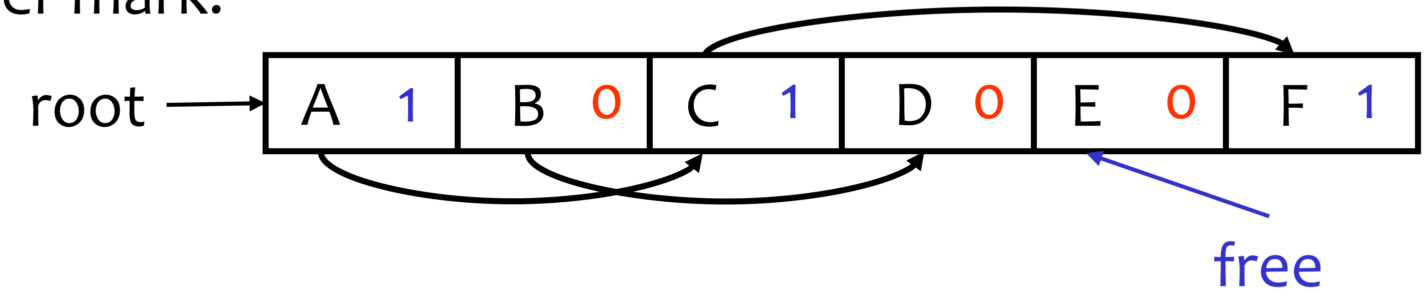
Every object has an extra bit: the mark bit

- reserved for memory management
- initially the mark bit is 0
- set to 1 for the reachable objects in the mark phase

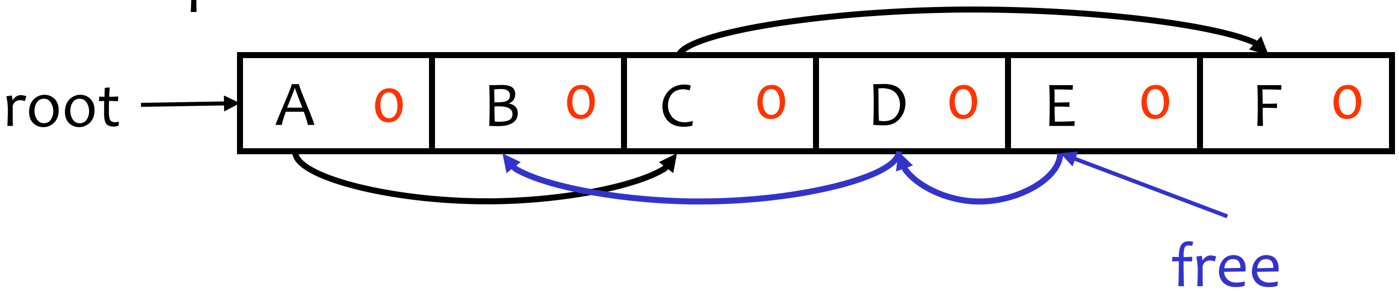
Mark and Sweep Example



After mark:



After sweep:



The Mark Phase

```
let todo = { all roots }
while todo $\neq \emptyset$ do
    pick v $\in$ todo
    todo $\leftarrow$ todo - { v }
    if mark(v) = 0 then      (* v is unmarked yet *)
       mark(v) $\leftarrow$ 1
       let $v_1,\ldots,v_n$ be the pointers contained in v
       todo $\leftarrow$ todo $\cup$ $\{v_1,\ldots,v_n\}$
   fi
od
```

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

Objects with a set mark bit 1 have their mark bit reset

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
```

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

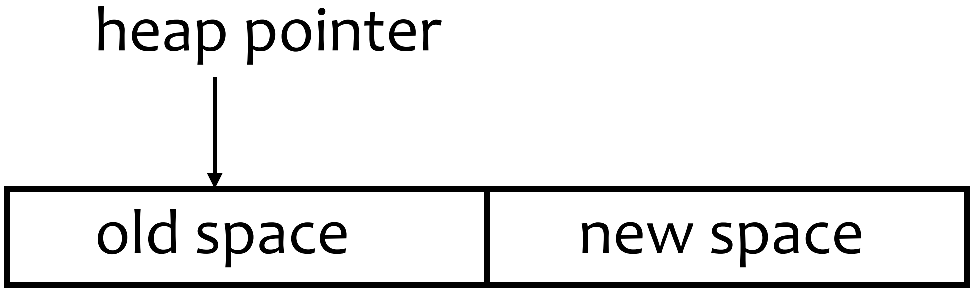
Advantage: objects are not moved during GC

- no need to update the pointers to objects
- works for languages like C and C++

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 Garbage Collection

Starts when the old space is full

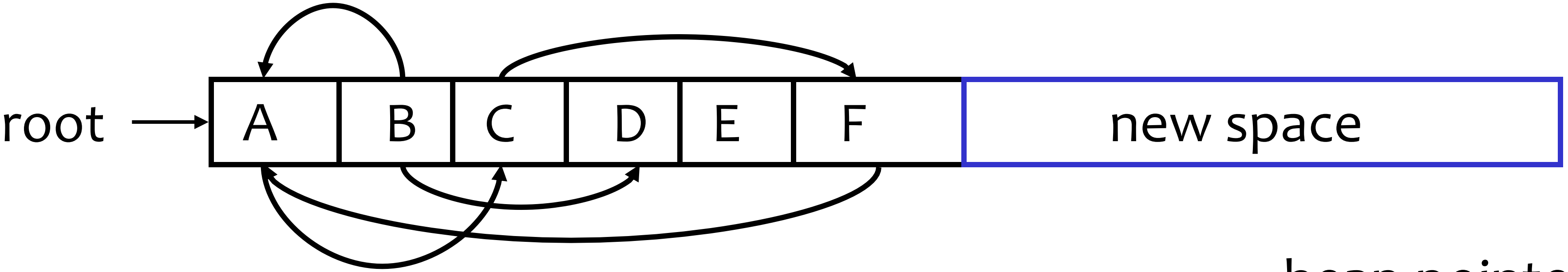
Copies all reachable objects from old space into new space

- garbage is left behind
- after the copy phase the new space uses less space than the old one before the collection

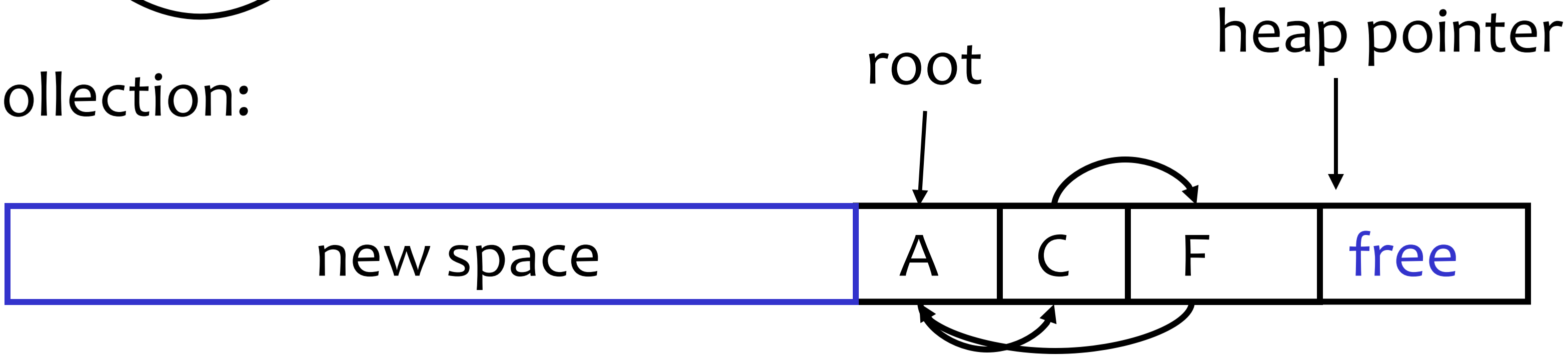
After the copy the roles of the old and new spaces are reversed and the program resumes

Stop and Copy Garbage Collection. Example

Before collection:



After collection:



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

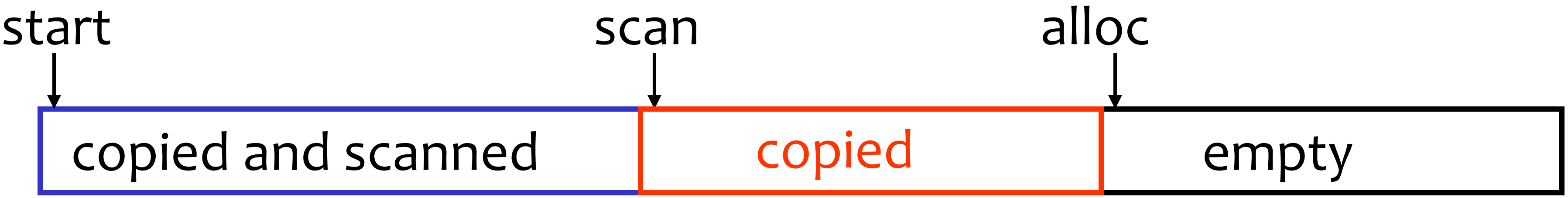
- when we later reach an object with a forwarding pointer we know it was already copied

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



start

scan

alloc

copied and scanned

copied

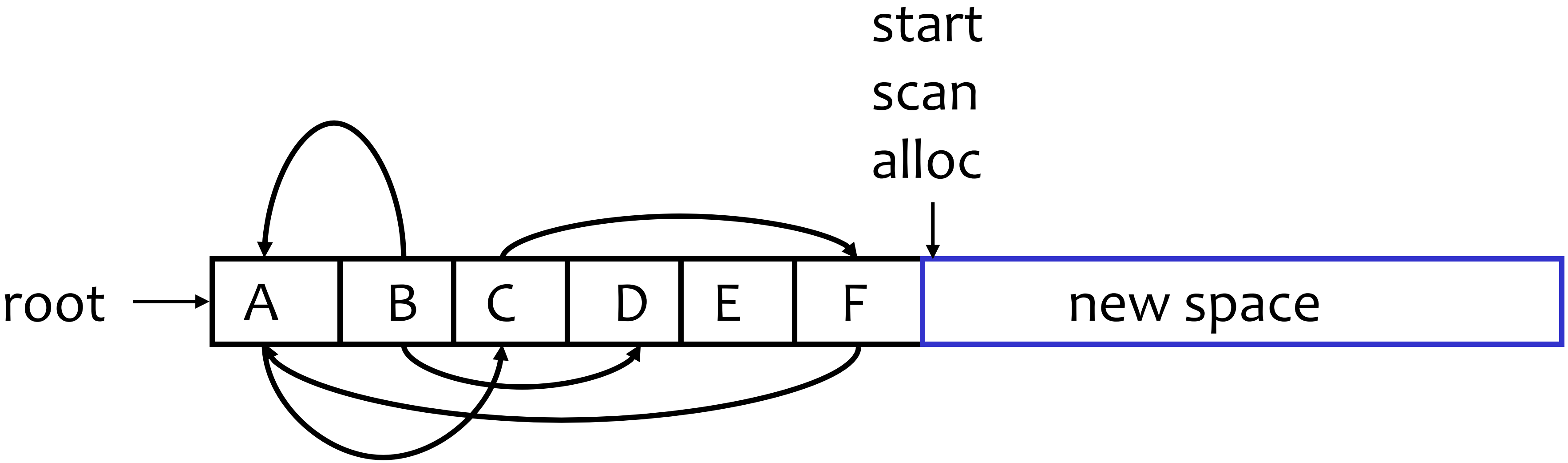
empty

copied objects
whose pointer
fields were followed
and fixed

copied objects
whose pointer
fields were NOT
followed

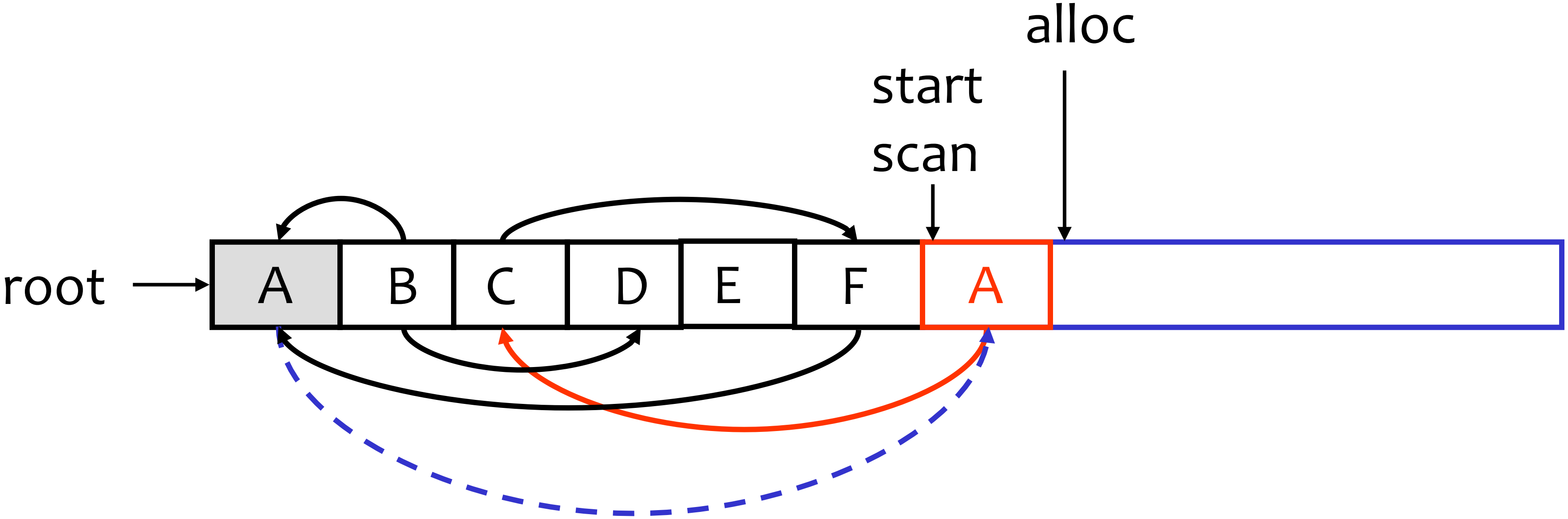
Stop and Copy. Example (1)

Before garbage collection



Stop and Copy. Example (3)

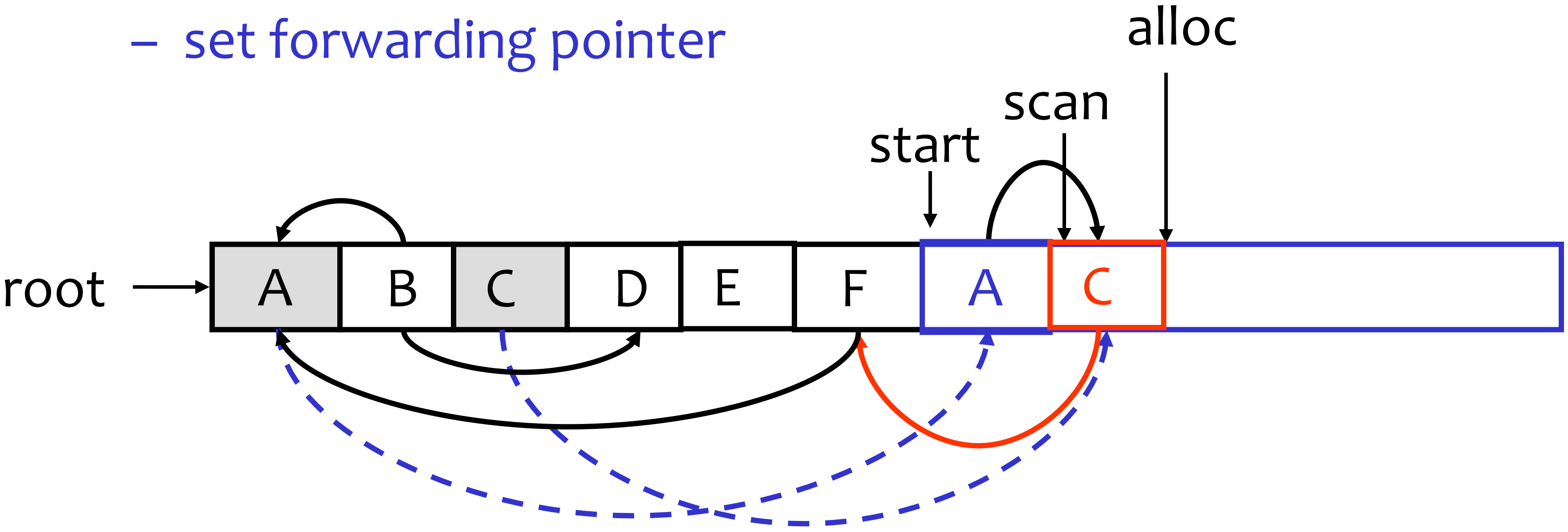
Step 1: Copy the objects pointed by roots and set forwarding pointers (dotted arrow)



Stop and Copy. Example (3)

Step 2: Follow the pointer in the next unscanned object (A)

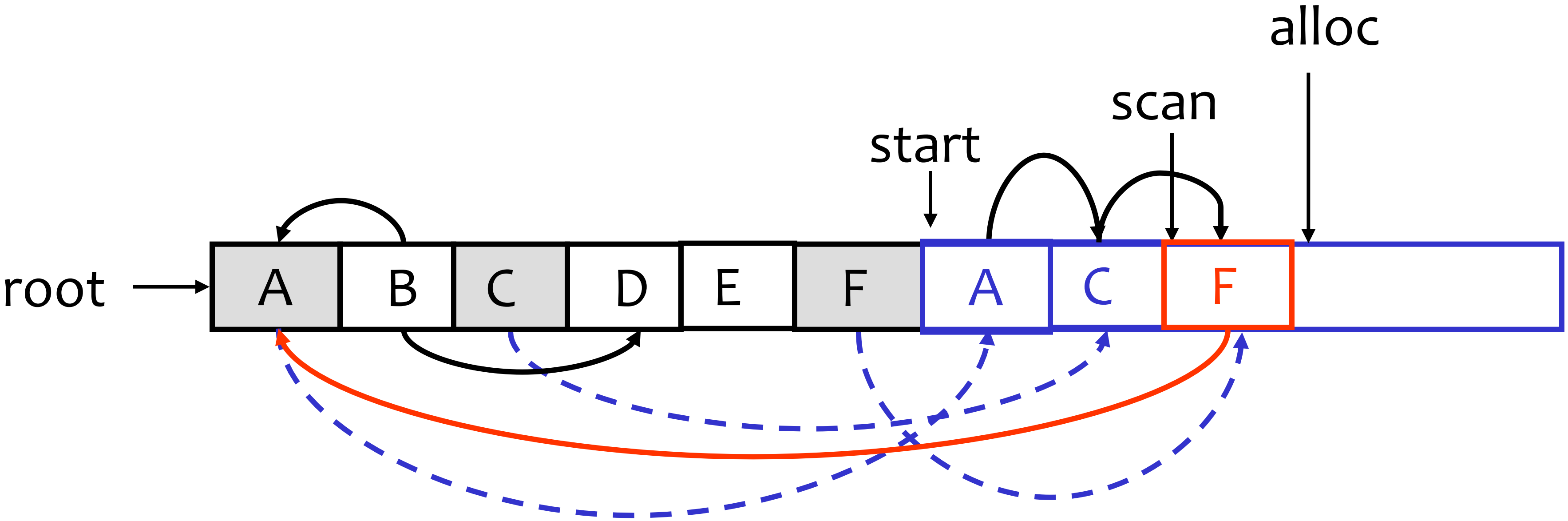
- copy the pointed objects (just C in this case)
- fix the pointer in A
- set forwarding pointer



Stop and Copy. Example (4)

Follow the pointer in the next unscanned object (C)

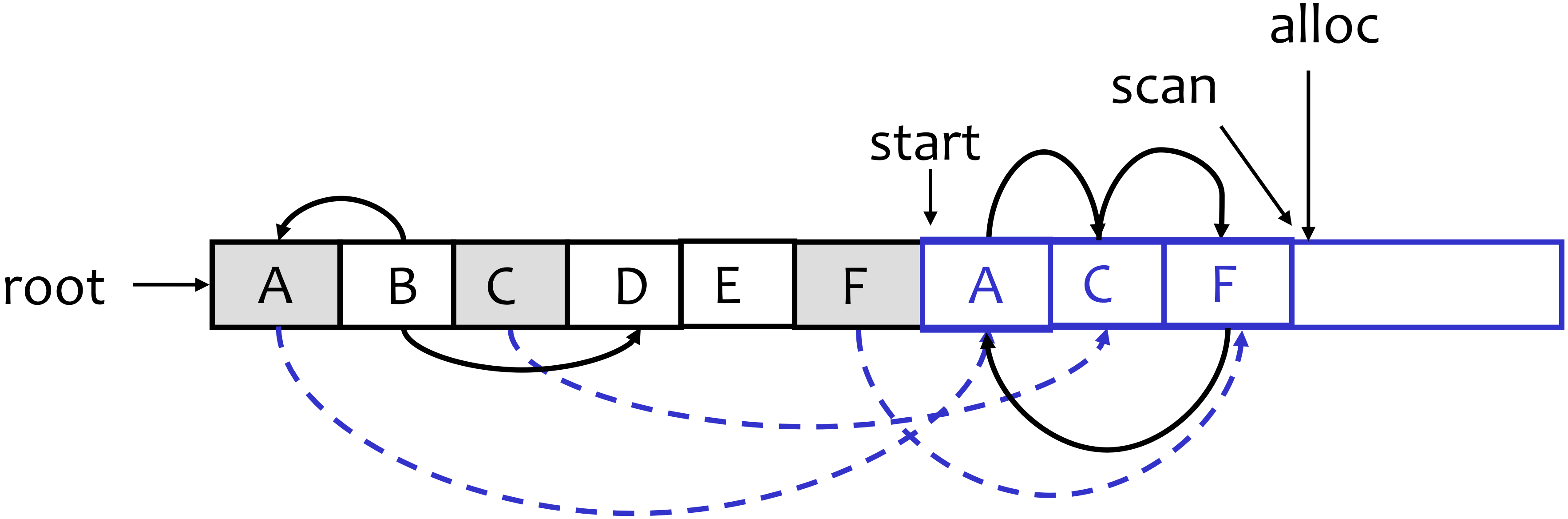
- copy the pointed objects (F in this case)



Stop and Copy. Example (5)

Follow the pointer in the next unscanned object (F)

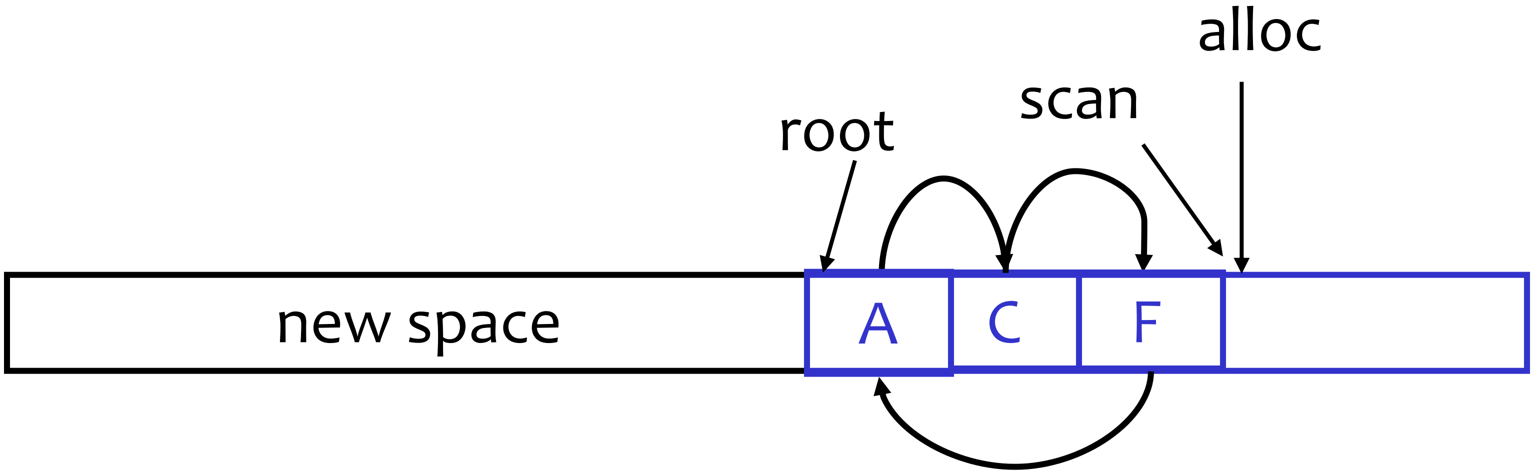
- the pointed object (A) was already copied. Set the pointer same as the forwading pointer



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 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 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?

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

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
```

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

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