Memory Management
Chapter 5

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http://www.cs.tau.ac.il/~msagiv/courses/wcc10.html

Topics

- Heap allocation
- Manuel heap allocation
- Automatic memory reallocation (GC)

Limitations of Stack Frames

- A local variable of P cannot be stored in the activation record of P if its duration exceeds the duration of P
- Example: Dynamic allocation

```
int * f()  { return (int *) malloc(sizeof(int));
}
```

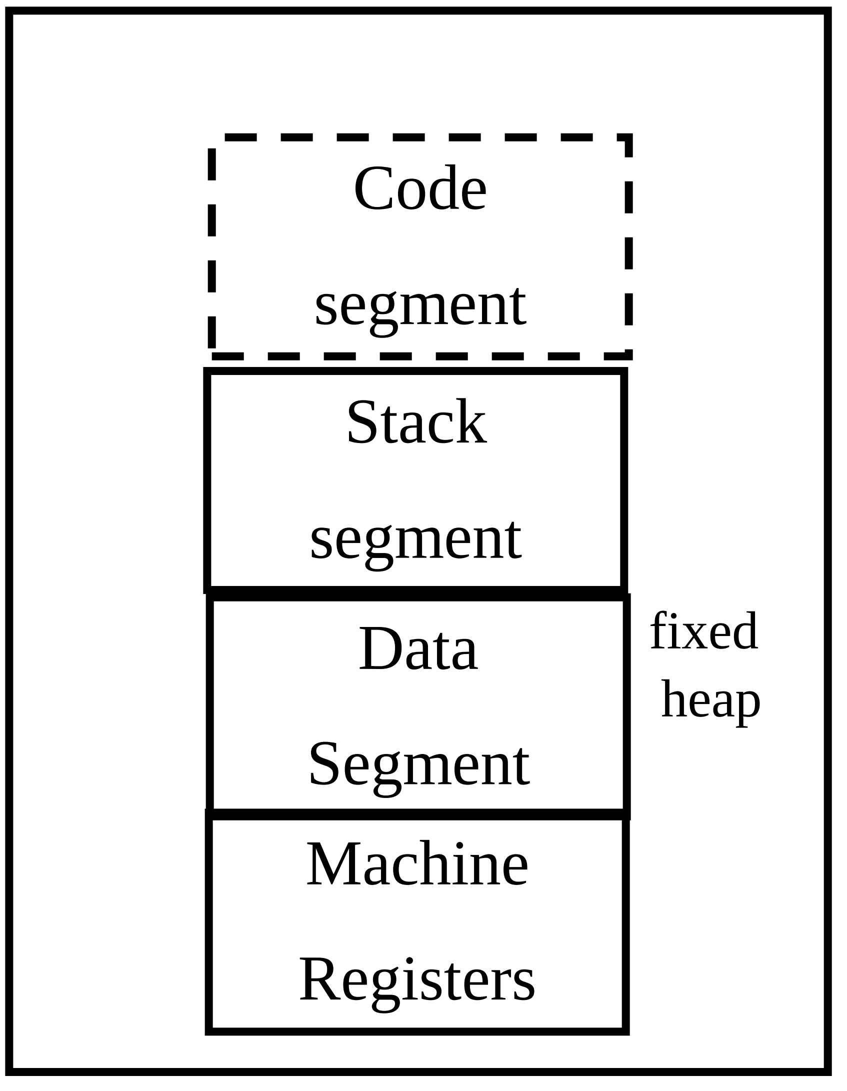
Currying Functions

```
int (*)() f(int x)
{
   int g(int y)
   {
       return x + y;
    }
    return g ;
 }

int (*h)() = f(3);
int (*j)()  = f(4);

int z = h(5);
int  w = j(7);
```

Program Runtime State



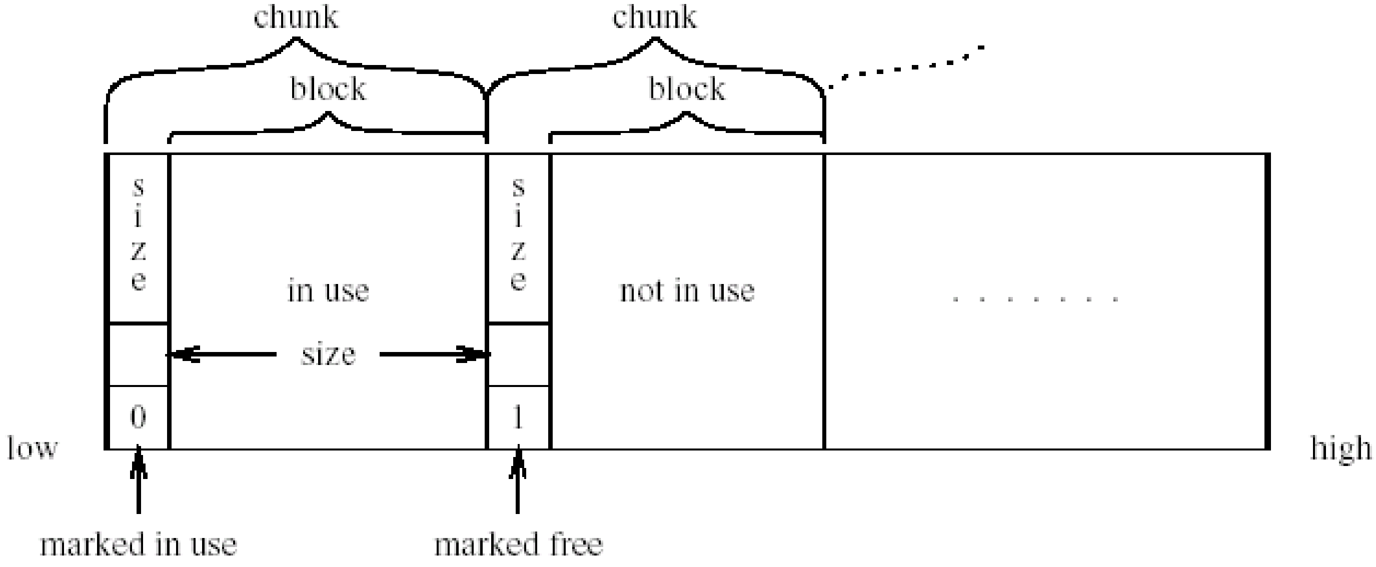
Data Allocation Methods

- Explicit deallocation
- Automatic deallocation

Explicit Deallocation

- Pascal, C, C++
- Two basic mechanisms
  - void * malloc(size_t size)
  - void free(void *ptr)
- Part of the language runtime
- Expensive
- Error prone
- Different implementations

Memory Structure used by malloc()/free()



Simple Implementation

```
SET the polymorphic chunk pointer First_chunk pointer TO
    Beginning of available memory;
SET the polymorphic chunk pointer One past available memory TO
    Beginning of available memory + Size of available memory;

SET First_chunk pointer .size TO Size of available memory;
SET First_chunk pointer .free TO True;

FUNCTION Malloc (Block size) RETURNING a polymorphic block pointer:
    SET Pointer TO Pointer to free block of size (Block size);
    IF Pointer /= Null pointer: RETURN Pointer;

    Coalesce free chunks;
    SET Pointer TO Pointer to free block of size (Block size);
    IF Pointer /= Null pointer: RETURN Pointer;

    RETURN Solution to out of memory condition (Block size);

PROCEDURE Free (Block pointer):
    SET Chunk pointer TO Block pointer - Administration size;
    SET Chunk pointer .free TO True;
```

call gc

Next Free Block

```
FUNCTION Pointer to free block of size (Block size)
    RETURNING a polymorphic block pointer:
    // Note that this is not a pure function
    SET Chunk pointer TO First_chunk pointer;
    SET Requested chunk size TO Administration size + Block size;

    WHILE Chunk pointer /= One past available memory:
        IF Chunk pointer .free:
            IF Chunk pointer .size - Requested chunk size >= 0:
                // large enough chunk found:
                Split chunk (Chunk pointer, Requested chunk size);
                SET Chunk pointer .free TO False;
                RETURN Chunk pointer + Administration size;
        // try next chunk:
        SET Chunk pointer TO Chunk pointer + Chunk pointer .size;
    RETURN Null pointer;
```

Splitting Chunks

```
PROCEDURE Split chunk (Chunk pointer, Requested chunk size):
    SET Left_over size TO Chunk pointer .size - Requested chunk size;
    IF Left_over size > Administration size:
        // there is a non-empty left-over chunk
        SET Chunk pointer .size TO Requested chunk size;
        SET Left_over chunk pointer TO
            Chunk pointer + Requested chunk size;
        SET Left_over chunk pointer .size TO Left_over size;
        SET Left_over chunk pointer .free TO True;
```

Coalescing Chunks

```
PROCEDURE Coalesce free chunks:
    SET Chunk pointer TO First_chunk pointer;

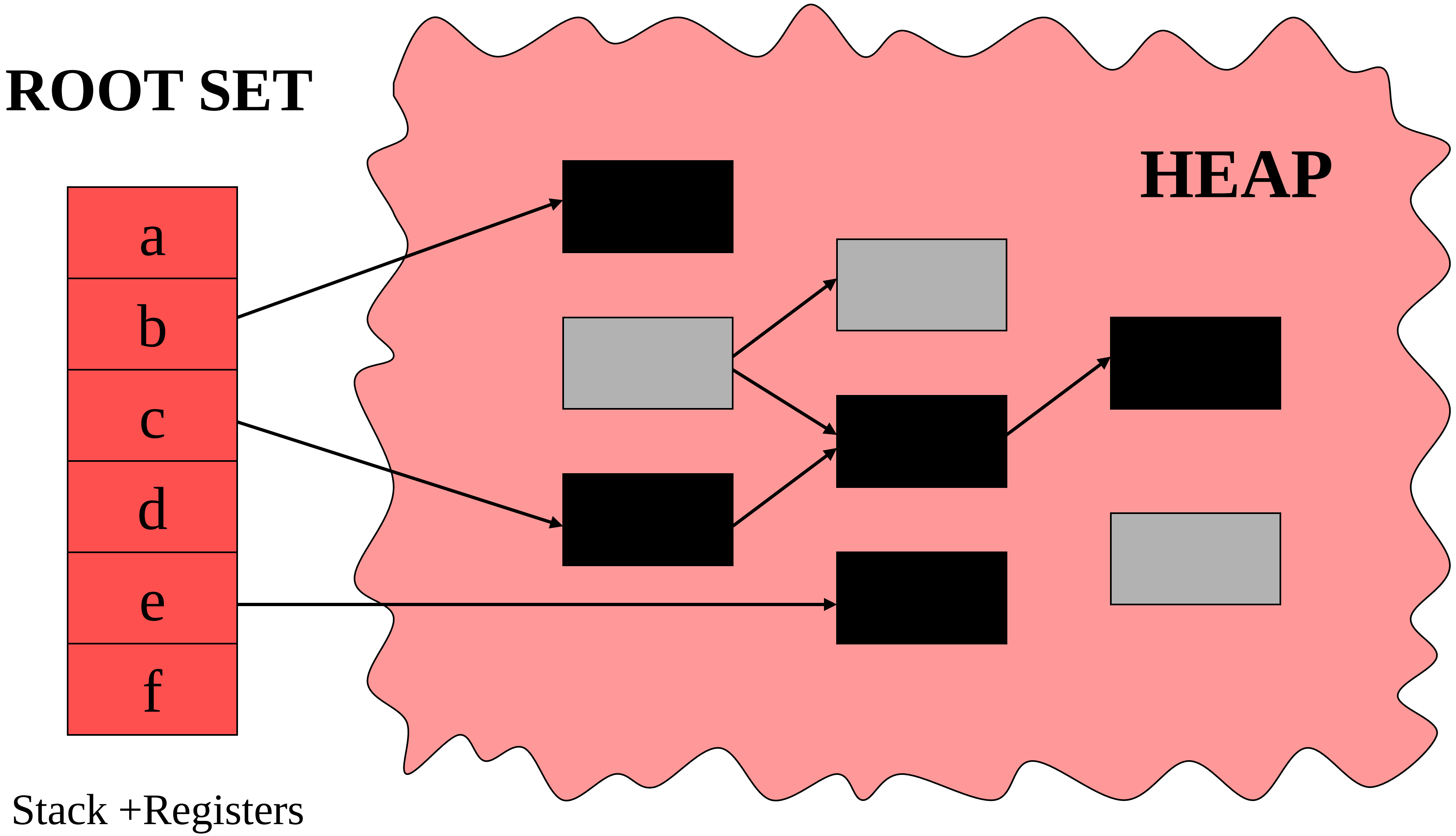
    WHILE Chunk pointer /= One past available memory:
        IF Chunk pointer .free:
            Coalesce with all following free chunks (Chunk pointer);
        SET Chunk pointer TO Chunk pointer + Chunk pointer .size;

PROCEDURE Coalesce with all following free chunks (Chunk pointer):
    SET Next_chunk pointer TO Chunk pointer + Chunk pointer .size;
    WHILE Next_chunk pointer /= One past available memory
        AND Next_chunk pointer .free:
        // Coalesce them:
        SET Chunk pointer .size TO
            Chunk pointer .size + Next_chunk pointer .size;
        SET Next_chunk pointer TO Chunk pointer + Chunk pointer .size;
```

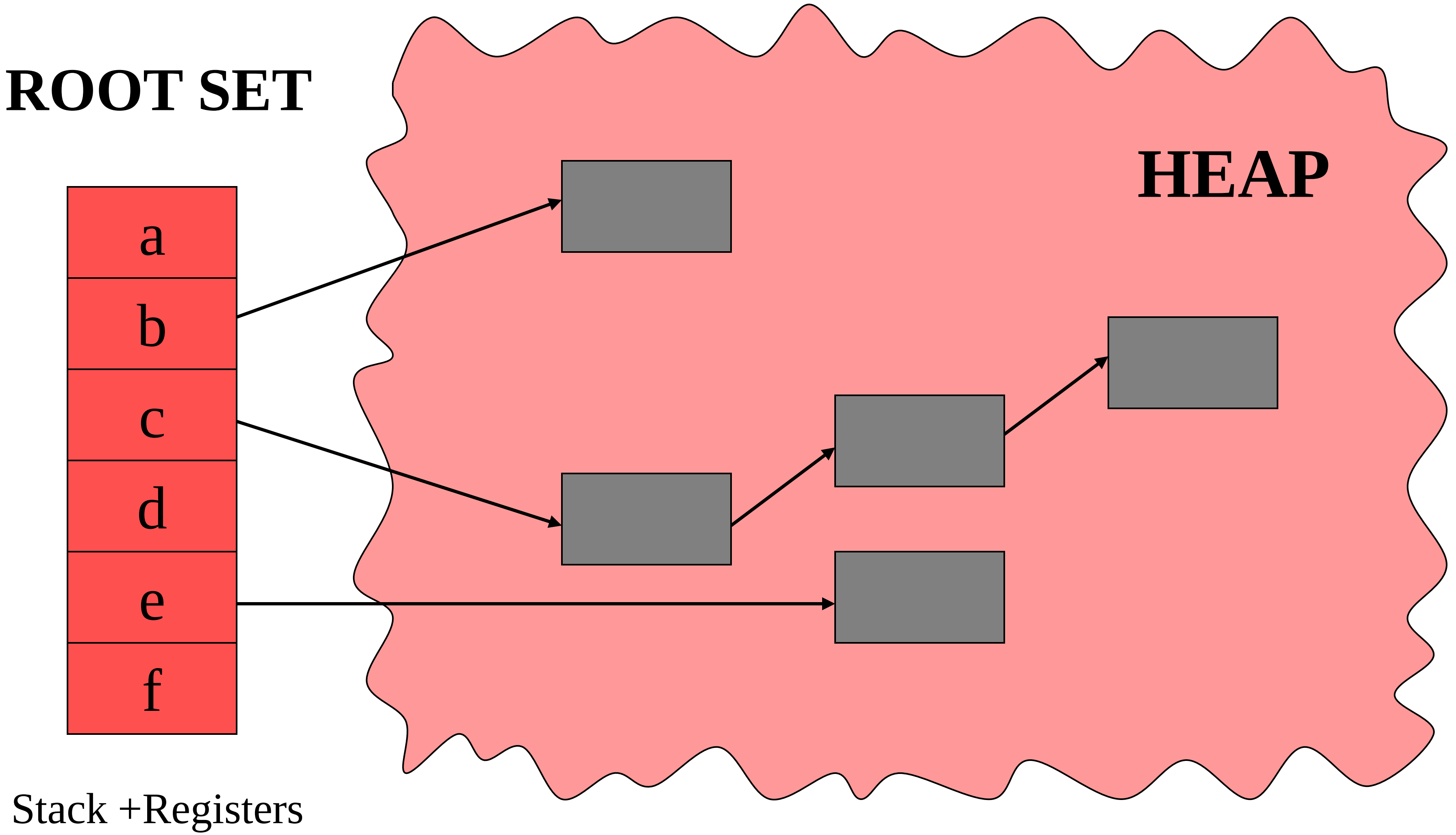
Fragmentation

- External
  - Too many small chunks
- Internal
  - A use of too big chunk without splitting the chunk
- Freelist may be implemented as an array of lists

Garbage Collection



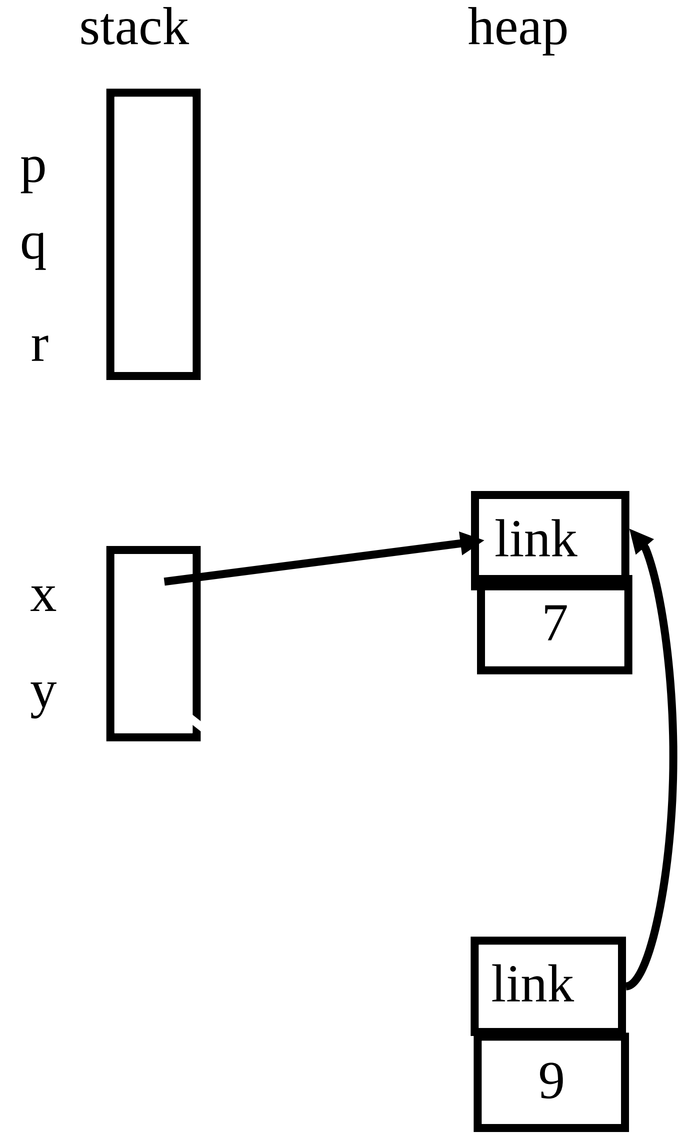
Garbage Collection



What is garbage collection

- The runtime environment reuse chunks that were allocated but are not subsequently used
- garbage chunks
  - not live
- It is undecidable to find the garbage chunks:
  - Decidability of liveness
  - Decidability of type information
- conservative collection
  - every live chunk is identified
  - some garbage runtime chunk are not identified
- Find the reachable chunks via pointer chains
- Often done in the allocation function

```
typedef struct list  {struct list *link; int key} *List;
typedef struct tree {int key;
                     struct tree *left:
                     struct tree *right} *Tree;
foo() {    List x = cons(NULL, 7);
    List y = cons(x, 9);
   x->link = y;
    }
void main() {
  Tree p, r; int q;
  foo();
  p = maketree();   r = p->right;
  q= r->key;
  showtree(r);}
```



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typedef struct tree {int key;

                     struct tree *left:

                     struct tree *right} *Tree;

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   List y = cons(x, 9);

  x->link = y;

    }

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 foo();

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 showtree(r);}
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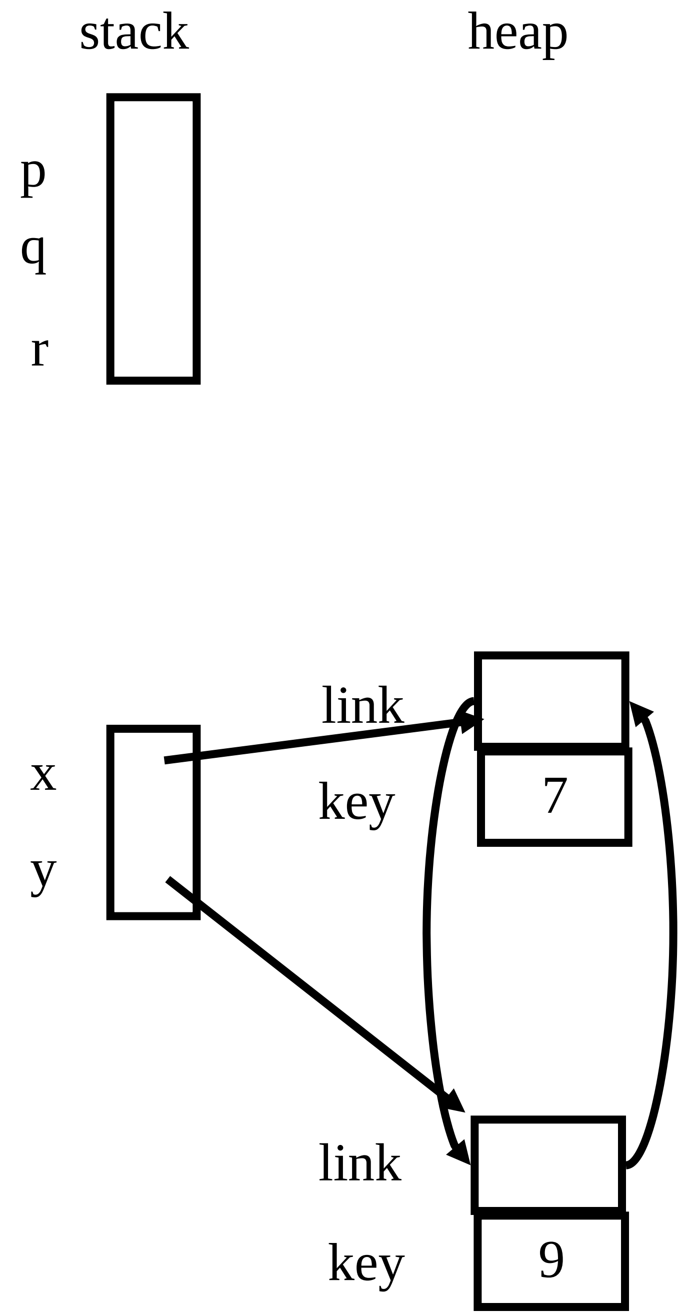

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    List y = create_list(x, 9);
   x->link = y;
    }
void main() {
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  foo();
  p = maketree();   r = p->right;
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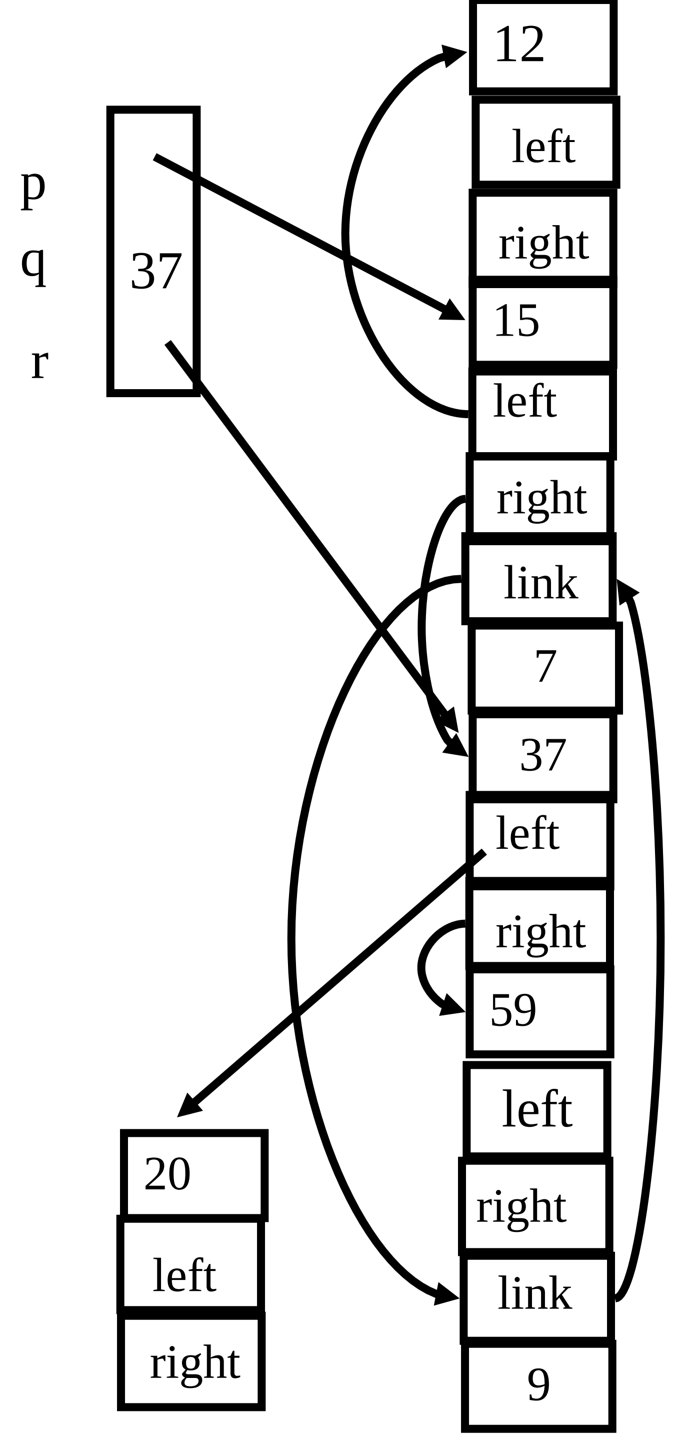
  showtree(r);}
```



Outline

- Why is it needed?
- Why is it taught?
- Reference Counts
- Mark-and-Sweep Collection
- Copying Collection
- Generational Collection
- Incremental Collection
- Interfaces to the Compiler

Tracing

A Pathological C Program

```
a =  malloc(…) ;

b = a;

free (a);

c = malloc (…);

if  (b == c)  printf(“unexpected equality”);
```

Garbage Collection vs. Explicit Memory Deallocation

- Faster program development
- Less error prone
- Can lead to faster programs
  - Can improve locality of references
- Support very general programming styles, e.g. higher order and OO programming
- Standard in ML, Java, C#
- Supported in C and C++ via separate libraries

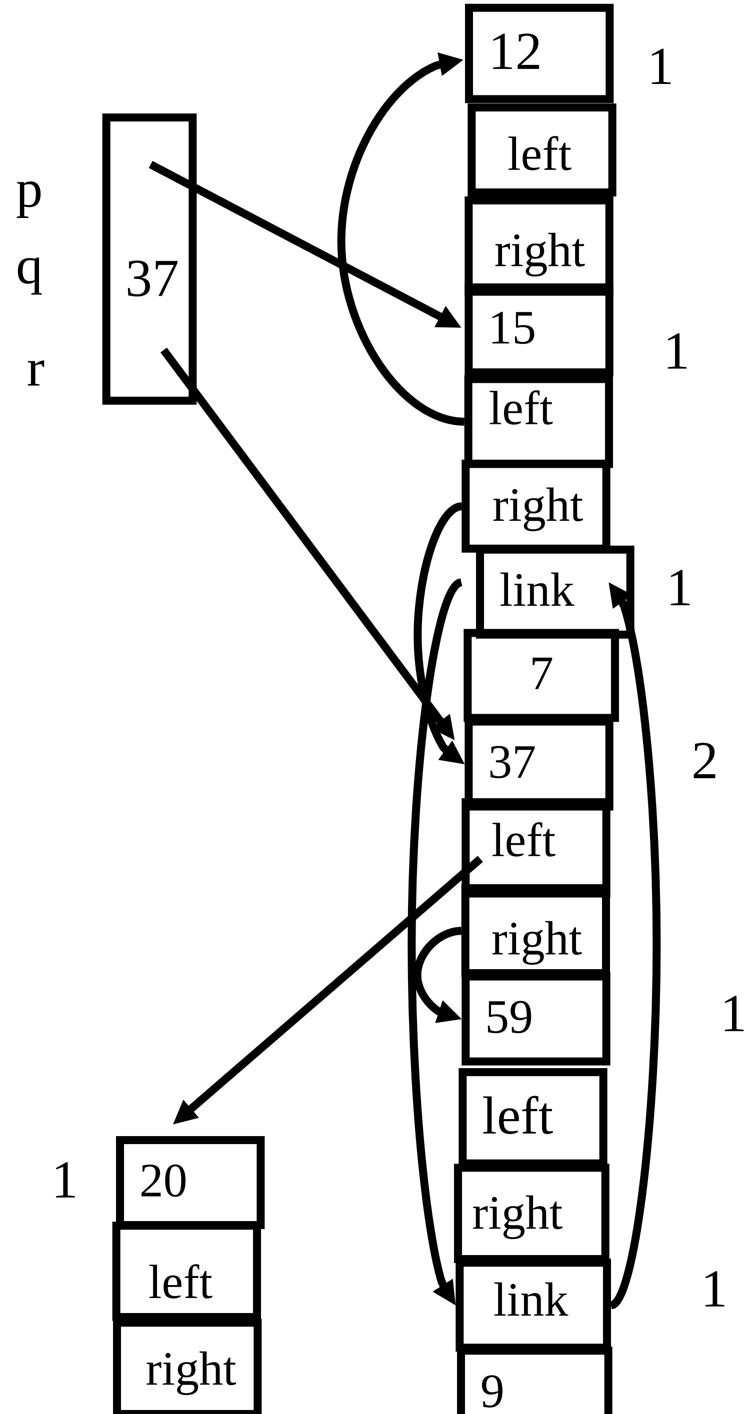
- May require more space
- Needs a large memory
- Can lead to long pauses
- Can change locality of references
- Effectiveness depends on programming language and style
- Hides documentation
- More trusted code

Interesting Aspects of Garbage Collection

- Data structures
- Non constant time costs
- Amortized algorithms
- Constant factors matter
- Interfaces between compilers and runtime environments
- Interfaces between compilers and virtual memory management

Reference Counts

- Maintain a counter per chunk
- The compiler generates code to update counter
- Constant overhead per instruction
- Cannot reclaim cyclic elements



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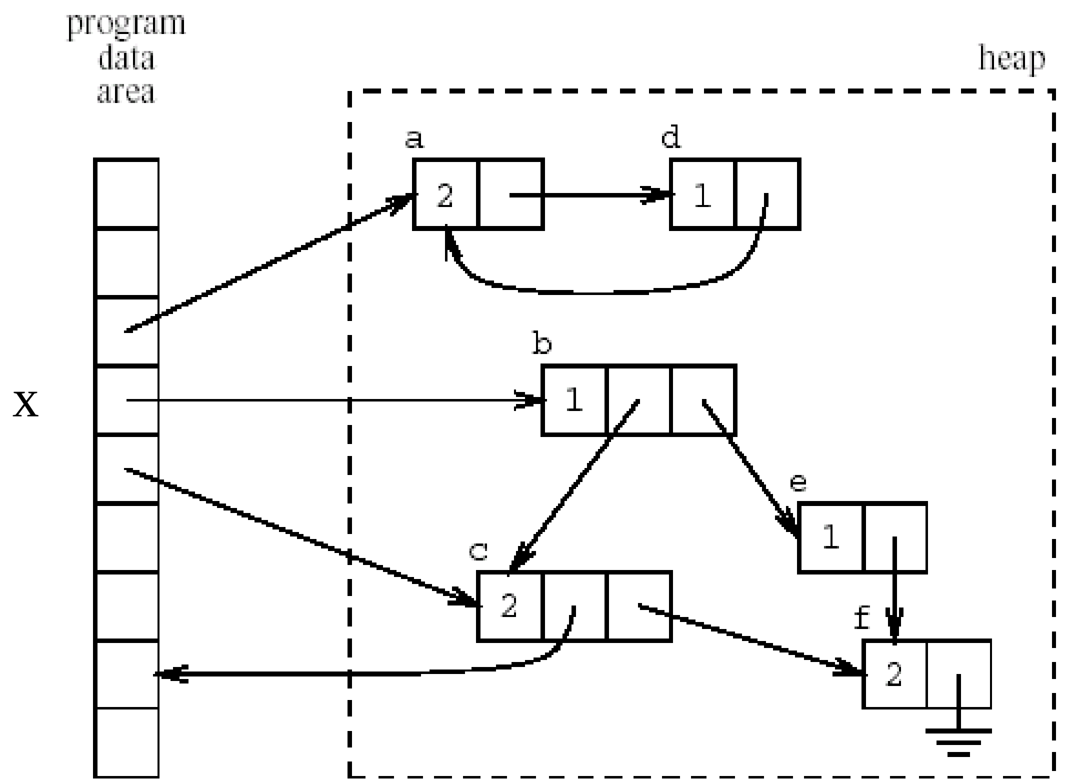
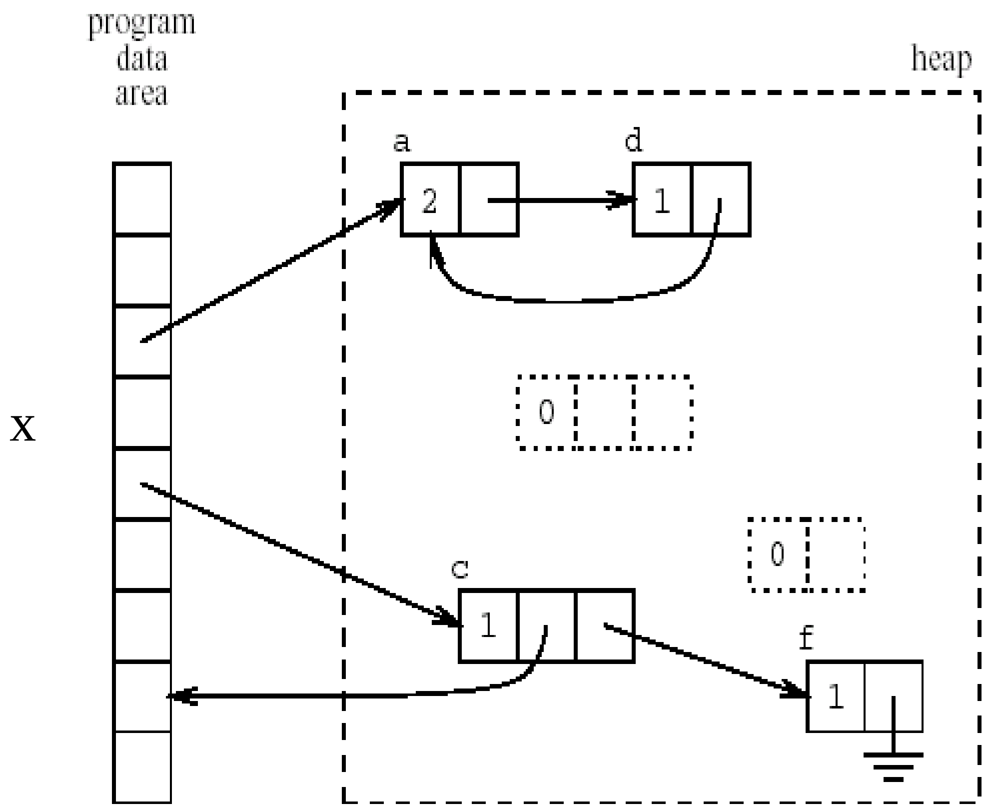
Another Example



Another Example (x→b=NULL)



Code for p := q

```
IF Points into the heap (q):
    Increment q .reference count;
IF Points into the heap (p):
    Decrement p .reference count;
    IF p .reference count = 0:
        Free recursively depending on reference counts (p);
SET p TO q;
```

Recursive Free

```
PROCEDURE Free recursively depending on reference counts(Pointer);
    WHILE Pointer /= No chunk:
        IF NOT Points into the heap (Pointer): RETURN;
        IF NOT Pointer .reference count = 0: RETURN;

        FOR EACH Index IN 1 .. Pointer .number of pointers - 1:
            Free recursively depending on reference counts
                (Pointer .pointer [Index]);

        SET Aux pointer TO Pointer;
        IF Pointer .number of pointers = 0:
            SET Pointer TO No chunk;
        ELSE Pointer .number of pointers > 0:
            SET Pointer TO
                Pointer .pointer [Pointer .number of pointers];
        Free chunk(Aux pointer);    // the actual freeing operation
```

Lazy Reference Counters

- Free one element
- Free more elements when required
- Constant time overhead
- But may require more space

Reference Counts (Summary)

- Fixed but big constant overhead
- Fragmentation
- Cyclic Data Structures
- Compiler optimizations can help
- Can delay updating reference counters from the stack
- Implemented in libraries and file systems
  - No language support
- But not currently popular
- Will it be popular for large heaps?

Mark-and-Sweep(Scan) Collection

- Mark the chunks reachable from the roots (stack, static variables and machine registers)
- Sweep the heap space by moving unreachable chunks to the freelist (Scan)

The Mark Phase

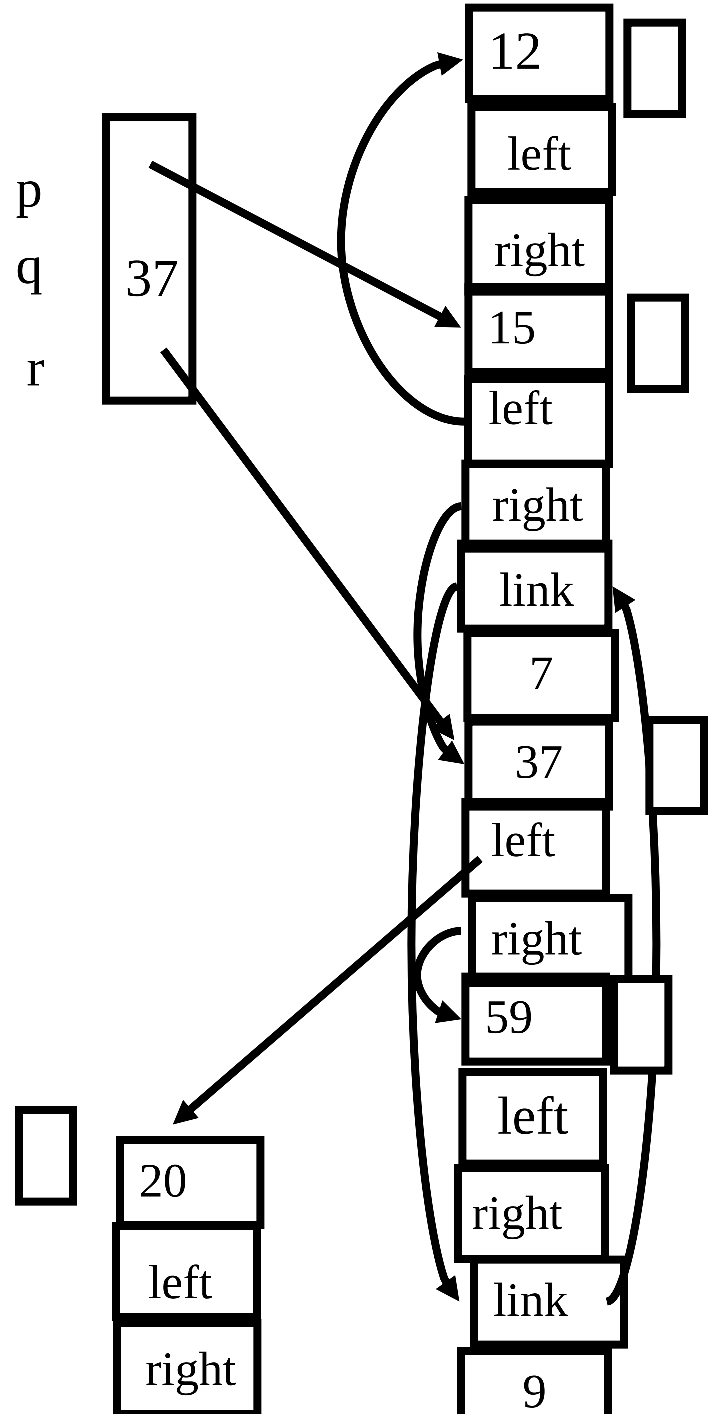
```
for each root v
   DFS(v)


function DFS(x)
   if x is a pointer and chunk x is not marked
            mark x
            for each reference field f_i of chunk x
                DFS(x.f_i)
```

The Sweep Phase

```
p := first address in heap
while p < last address in the heap
        if chunk p is marked
                unmark p
        else let f1 be the first pointer reference field in p
                p.f1 := freelist
                freelist := p
        p := p + size of chunk p
```

Mark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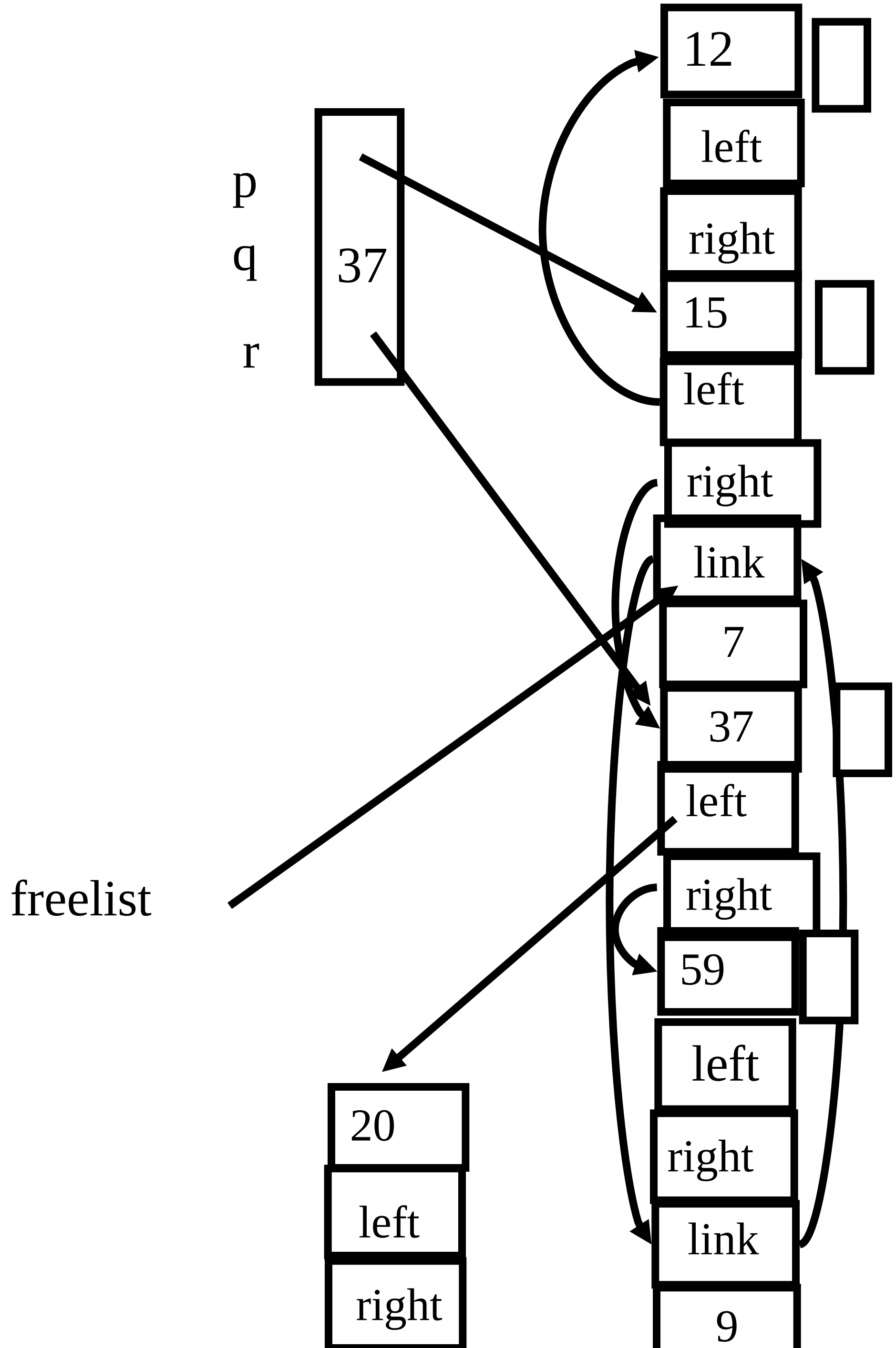
Sweep



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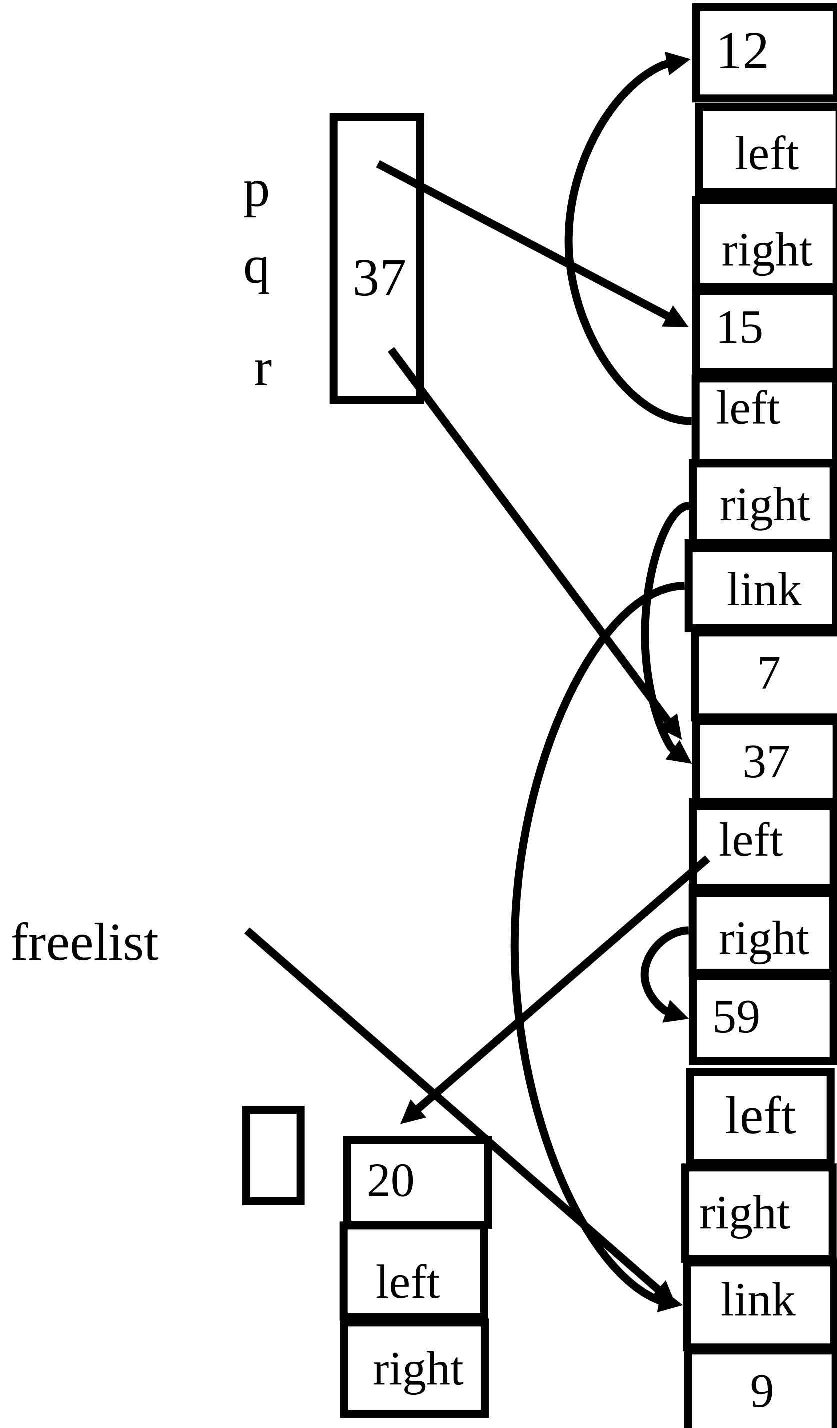
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Cost of GC

- The cost of a single garbage collection can be linear in the size of the store
  - may cause quadratic program slowdown
- Amortized cost
  - collection-time/storage reclaimed
  - Cost of one garbage collection
    - $c_1 R + c_2 H$
  - H - R Reclaimed chunks
  - Cost per reclaimed chunk
    - $(c_1 R + c_2 H)/ (H - R)$
  - If R/H > 0.5
    - increase H
  - if R/H < 0.5
    - cost per reclaimed word is $c_1 + 2c_2$ ~16
  - There is no lower bound

The Mark Phase

for each root v

  DFS(v)

function DFS(x)

  if x is a pointer and chunk x is not marked

    mark x

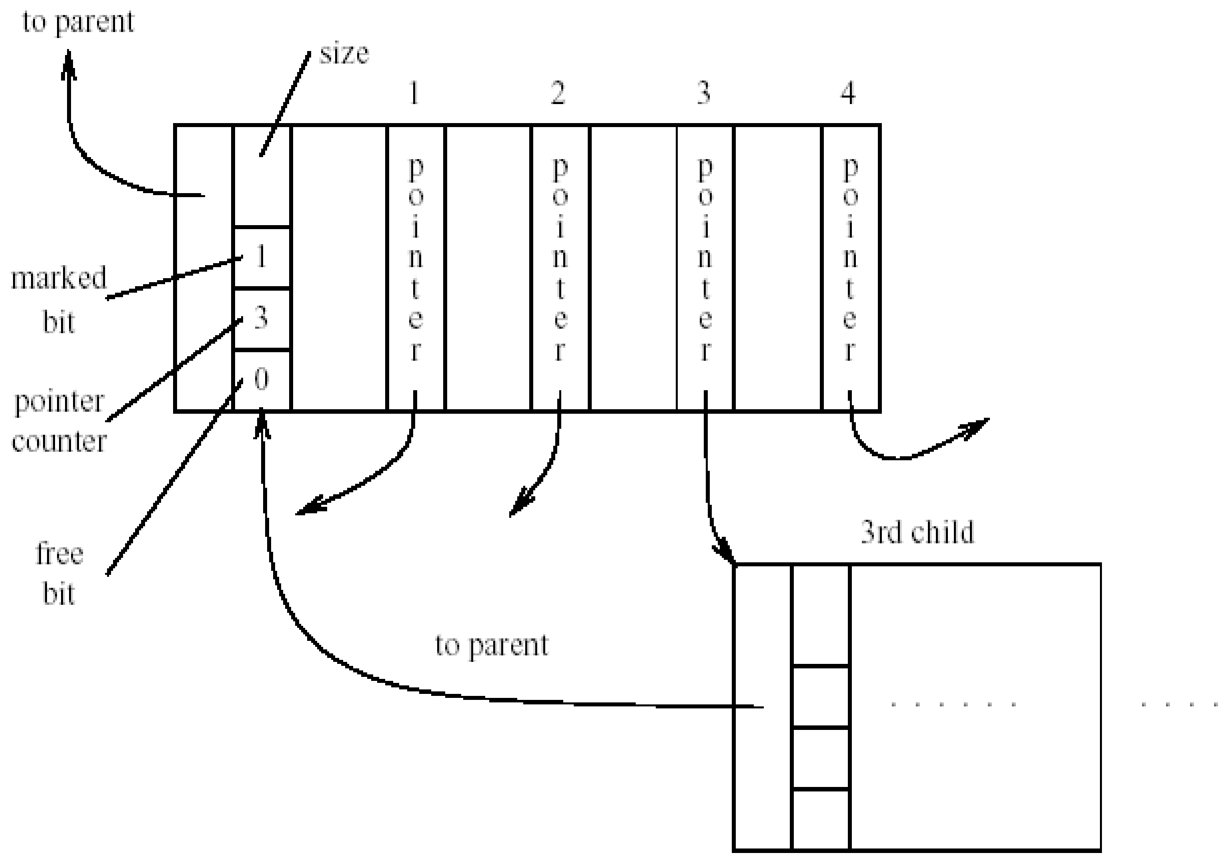
    for each reference field f_i of chunk x

      DFS($x.f_i$)

Efficient implementation of Mark(DFS)

- Explicit stack
- Parent pointers
- Pointer reversal
- Other data structures

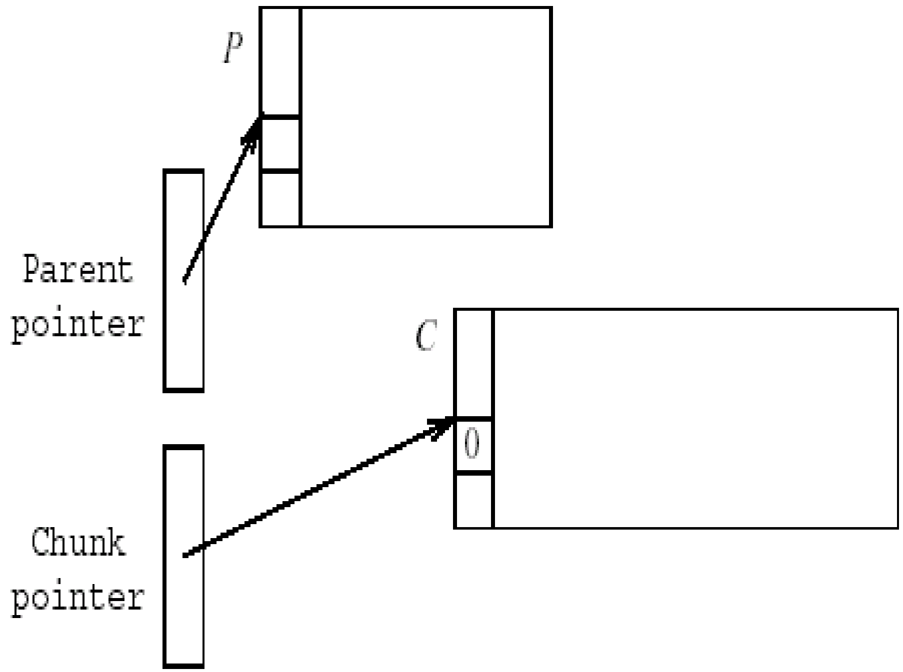
Adding Parent Pointer



Avoiding Parent Pointers (Deutch-Schorr-Waite)

- Depth first search can be implemented without recursion or stack
- Maintain a counter of visited children
- Observation:
  - The pointer link from a parent to a child is not needed when it is visited
  - Temporary store pointer to the parent (instead of the field)
  - Restore when the visit of child is finished

Arriving at C



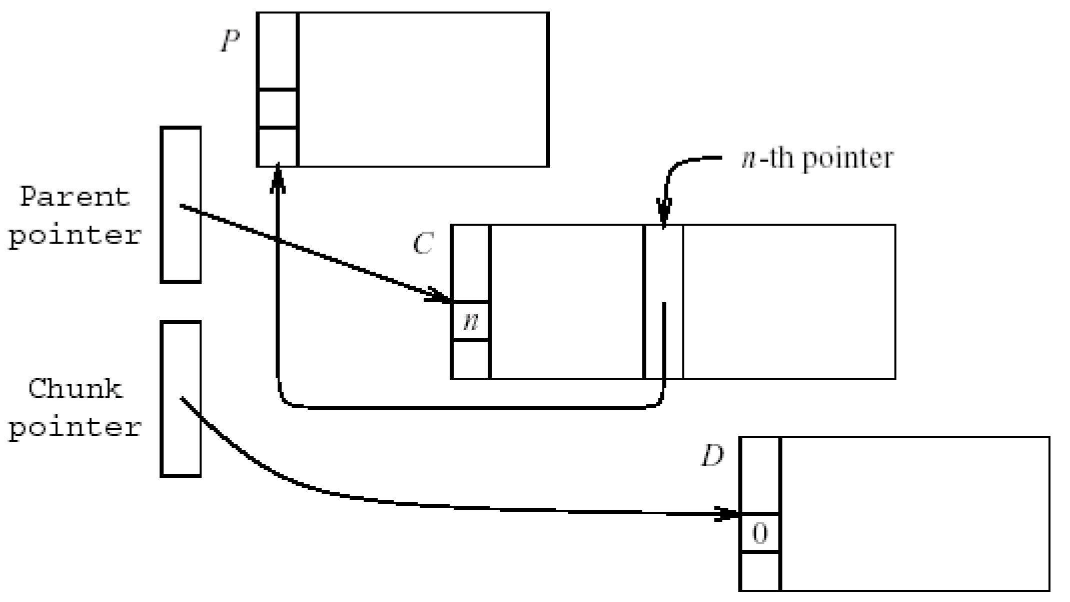
Visiting n-pointer field D

SET old parent pointer TO parent pointer ;

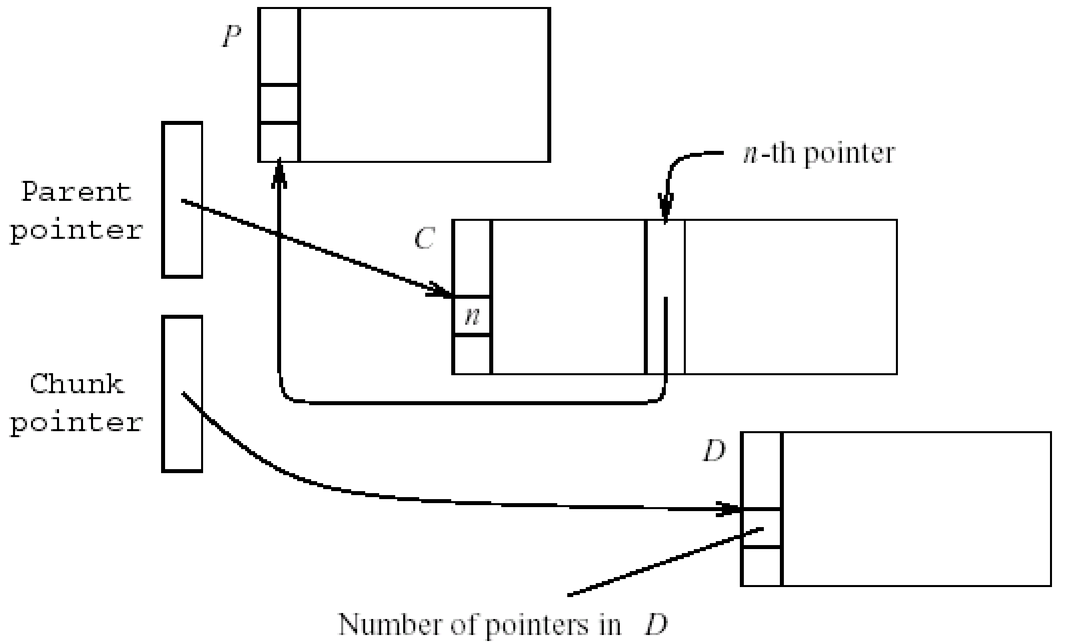
SET Parent pointer TO chunk pointer ;

SET Chunk pointer TO n-th pointer field of C;

SET n-th pointer field in C TO old parent pointer;



About to return from D



SET old parent pointer TO Parent pointer ;

SET Parent pointer TO n-th pointer field of C ;

SET n-th pointer field of C TO chunk pointer;

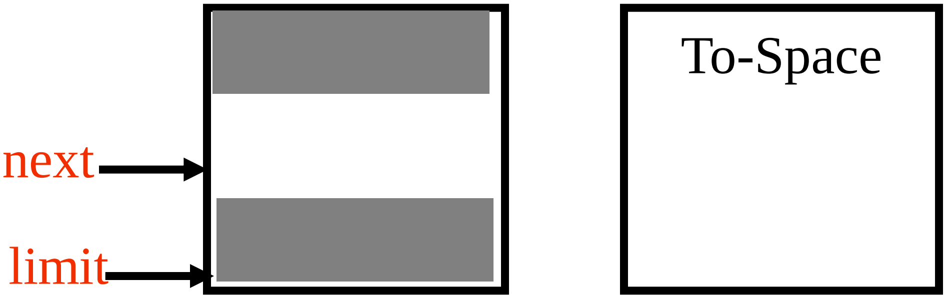
SET chunk pointer TO old parent pointer;

Compaction

- The sweep phase can compact adjacent chunks
- Reduce fragmentation

Copying Collection

- Maintains two separate heaps
  - from-space
  - to-space
- pointer next to the next free chunk in from-space
- A pointer limit to the last chunk in from-space
- If next = limit copy the reachable chunks from from-space into to-space
  - set next and limit
  - Switch from-space and to-space
- Requires type information

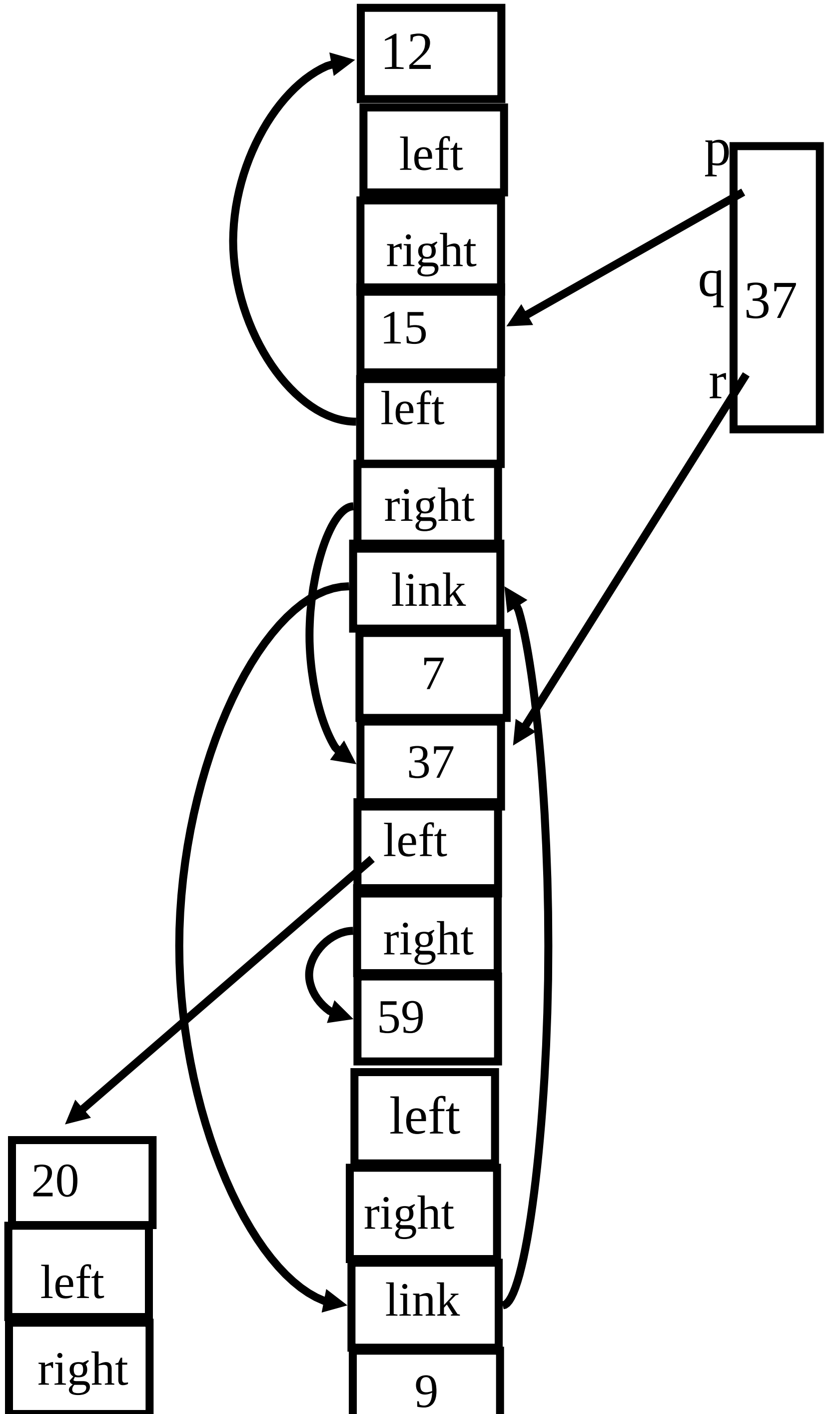


Breadth-first Copying Garbage Collection

```
next := beginning of to-space
scan := next
for each root r
    r := Forward(r)
while scan < next
        for each reference field f_i of chunk at scan
            scan.f_i := Forward(scan.f_i)
        scan := scan + size of chunk at scan
```

The Forwarding Procedure

```
function  Forward(p)
    if p points to from-space
        then if p.f1 points to to-space
            return p.f1
            else for each reference field fi of p
                next.fi := p.fi
              p.f1 := next
              next := next size of chunk p
              return p.f1
        else return p
```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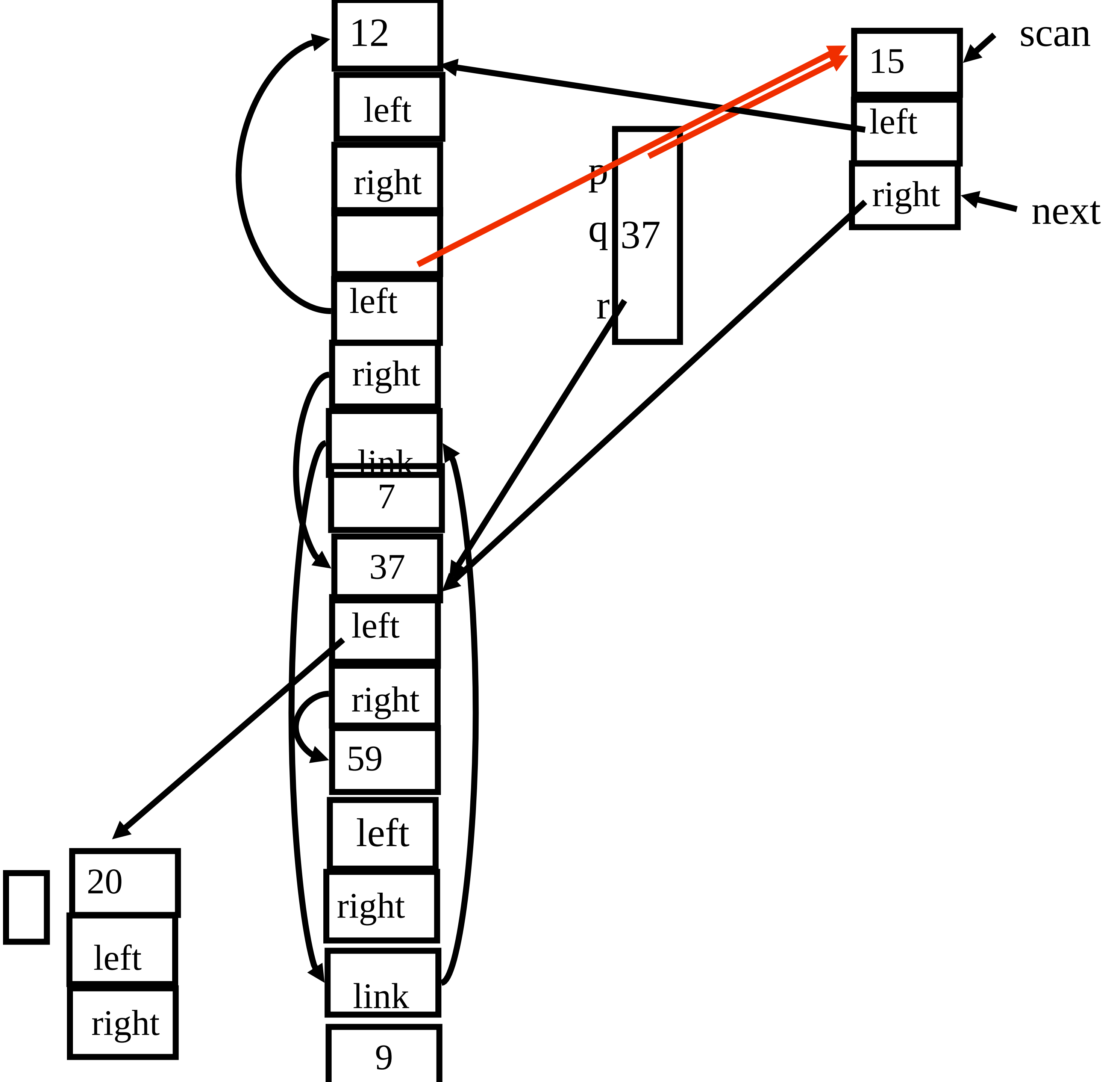
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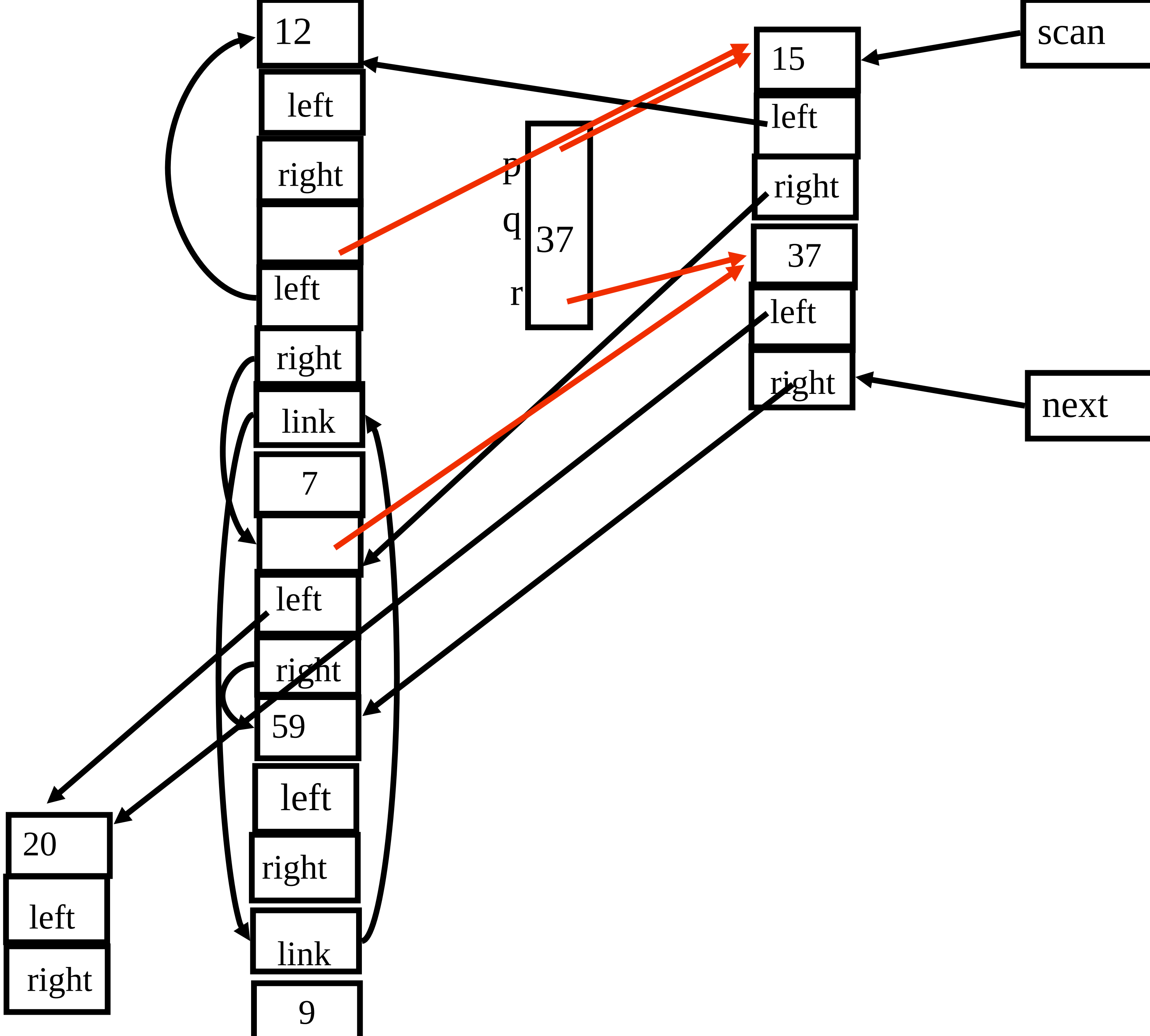
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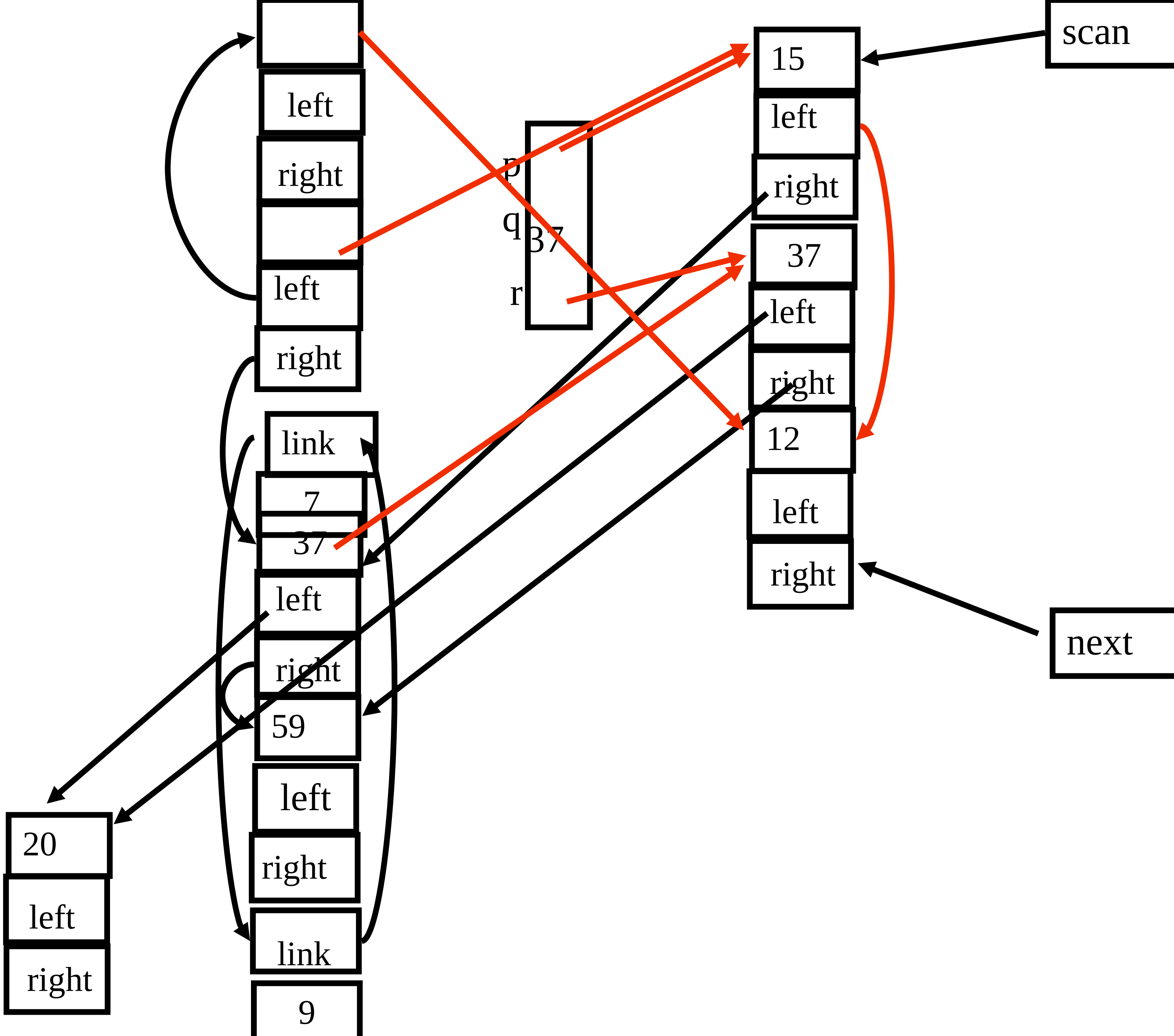
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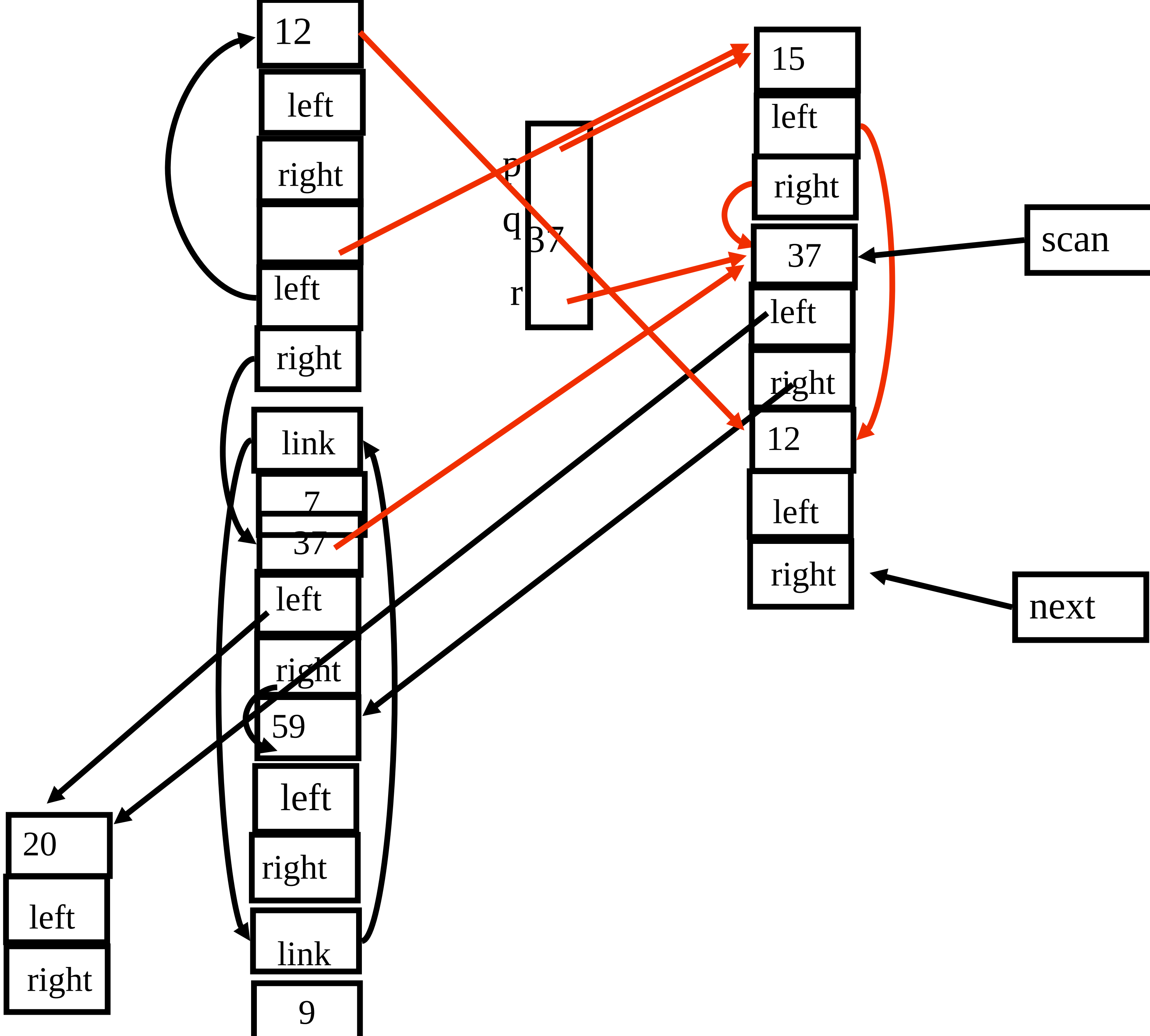
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Amortized Cost of Copy Collection

$c_3R / (H/2 - R)$

Locality of references

- Copy collection does not create fragmentation
- Cheney's algorithm may lead to subfields that point to far away chunks
  - poor virtual memory and cache performance
- DFS normally yields better locality but is harder to implement
- DFS may also be bad for locality for chunks with more than one pointer fields
- A compromise is a hybrid breadth first search with two levels down (Semi-depth first forwarding)
- Results can be improved using dynamic information

The New Forwarding Procedure

function Forward(p)

if p points to from-space

then if $p.f_1$ points to to-space

return $p.f_1$

else Chase(p); return $p.f_1$

else return p

function Chase(p)

repeat

q := next

next := next +size of chunk p

r := null

for each reference field f_i of p

$q.f_i := p.f_i$

if $q.f_i$ points to from-space and $q.f_i.f_1$ does not point to to-space

then $r := q.f_i$

$p.f_1 := q$

p := r

until p = null

Generational Garbage Collection

- Newly created objects contain higher percentage of garbage
- Partition the heap into generations G_1 and G_2
- First garbage collect the G_1 heap
  - chunks which are reachable
- After two or three collections chunks are promoted to G_2
- Once a while garbage collect G_2
- Can be generalized to more than two heaps
- But how can we garbage collect in G_1?

Scanning roots from older generations

- remembered list
  - The compiler generates code after each destructive update $b.f_i := a$
    to put b into a vector of updated objects scanned by the garbage collector
- remembered set
  - remembered-list + "set-bit"
- Card marking
  - Divide the memory into 2^k cards
- Page marking
  - k = page size
  - virtual memory system catches updates to old-generations using the dirty-bit

Incremental Collection

- Even the most efficient garbage collection can interrupt the program for quite a while
- Under certain conditions the collector can run concurrently with the program (mutator)
- Need to guarantee that mutator leaves the chunks in consistent state, e.g., may need to restart collection
- Two solutions
  - compile-time
    - Generate extra instructions at store/load
  - virtual-memory
    - Mark certain pages as read(write)-only
    - a write into (read from) this page by the program restart mutator

Tricolor marking

- Generalized GC
- Three kinds of chunks
  - White
    - Not visited (not marked or not copied)
  - Grey
    - Marked or copied but children have not been examined
  - Black
    - Marked and their children are marked

Basic Tricolor marking

while there are any grey objects

select a grey chunk p

for each reference field f_i of chunk p

if chunk p.f_i is white

color chunk p.f_i grey

color chunk p black

Invariants

- No black points to white
- Every grey is on the collector's (stack or queue) data structure

Establishing the invariants

- Dijkstra, Lamport, et al
  - Mutator stores a white pointer a into a black pointer b
    - color a grey (compile-time)
- Steele
  - Mutator stores a white pointer a into a black pointer b
    - color b grey (compile-time)
- Boehm, Demers, Shenker
  - All black pages are marked read-only
  - A store into black page mark all the objects in this page grey (virtual memory system)
- Baker
  - Whenever the mutator fetches a pointer b to a grey or white object
    - color b grey (compile-time)
- Appel, Ellis, Li
  - Whenever the mutator fetches a pointer b from a page containing a non black object
    - color every object on this page black and children grey (virtual memory system)

Interfaces to the Compiler

- The semantic analysis identifies chunk fields which are pointers and their size
- Generate runtime descriptors at the beginning of the chunks
  - Can employ different allocation/deallocation functions
- Pass the descriptors to the allocation function
- The compiler also passes pointer-map
  - the set of live pointer locals, temporaries, and registers
- Recorded at ?-time for every procedure

Summary

- Garbage collection is an effective technique
- Leads to more secure programs
- Tolerable cost
- But is not used in certain applications
  - Realtime
- Generational garbage collection works fast
  - Emulates stack
- But high synchronization costs
- Compiler can allocate data on stack
  - Escape analysis
- May be improved