Compiler

Garbage Collection

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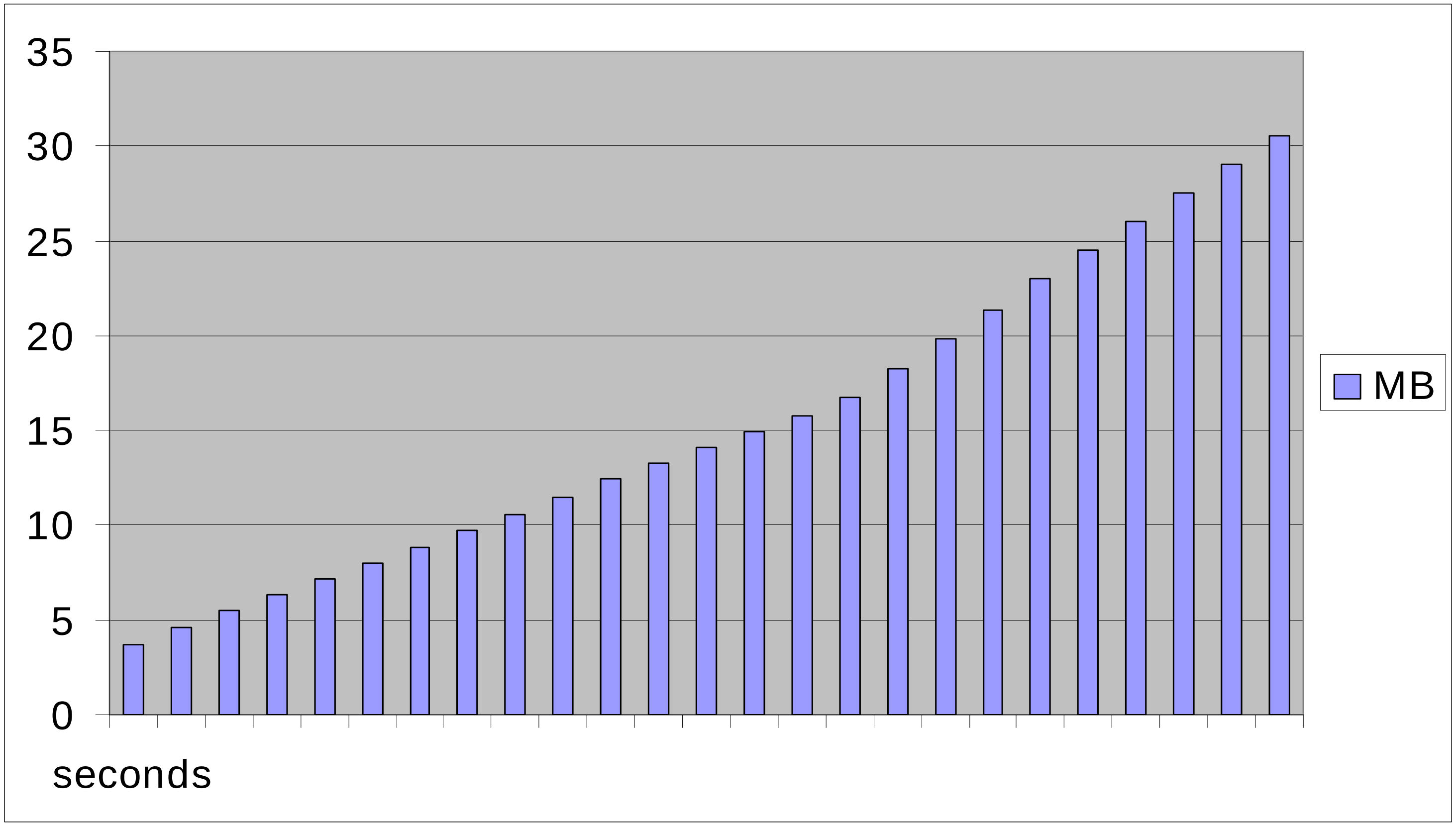
Garbage Collector

- is part of the run-time system: it reclaims heap-allocated records that are no longer used.
- A garbage collector should:
  - reclaim *all* unused records;
  - spend very little time per record;
  - not cause significant delays; and
  - allow all of memory to be used.
- These are difficult and often conflicting requirements.

Without Garbage Collection

- unused records must be explicitly deallocated;
- superior if done correctly;
- but it is easy to miss some records; and
- it is dangerous to handle pointers.

Memory leaks in real life (ical v.2.1)



Which records are in use?

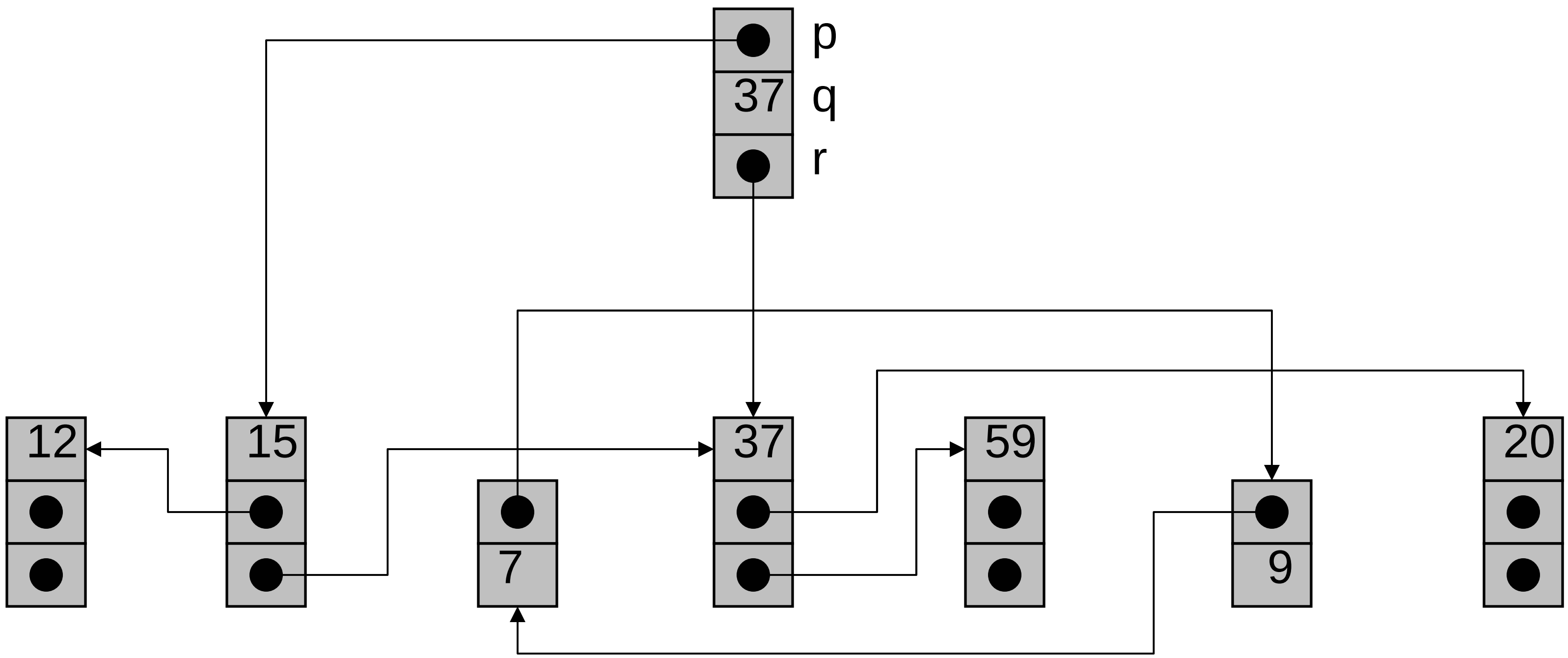
- Ideally, records that will never be accessed in the future execution of the program.
  - but that is of course undecidable...

- Basic conservative assumption:

A record is **live** *if it is reachable from a stack-based program variable.*

- Dead records may still be pointed to by other dead records.

Heap with Live and Dead Records



Mark and Sweep

- Algorithm
  - explore pointers starting from the program variables, and *mark* all
  - records encountered;
  - *sweep* through all records in the heap and reclaim the unmarked ones; also
  - unmark all marked records.

- Assumptions:
  - we know the size of each record;
  - we know which fields are pointers; and
  - reclaimed records are kept in a `freelist`.

Mark-and-sweep Code

```
function DFS(x)
   if  x is a pointer into the heap then
      if  record x is not marked then
         mark record x
         for  i in 1 .. |x| do
            DFS(x.f_i)
```

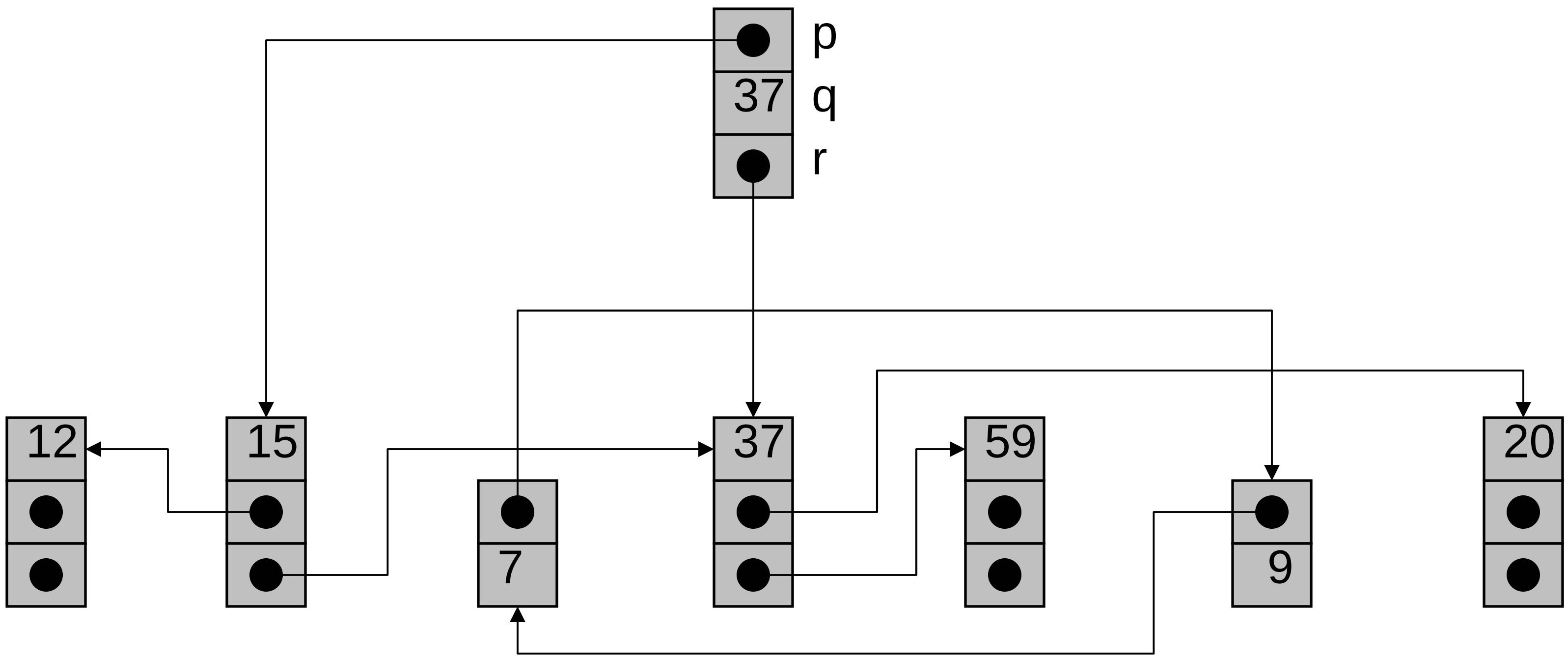
Mark-and-sweep Code

```
function Mark()
    for each program variable v do
        DFS(v)
```

Mark-and-sweep Code

```
function Sweep()
   p := first address in heap
    while p < last address in heap do
      if  record p is marked then
         unmark record p
      else
         p.f1 := freelist
         freelist := p
      p := p + sizeof(record p)
```

Example



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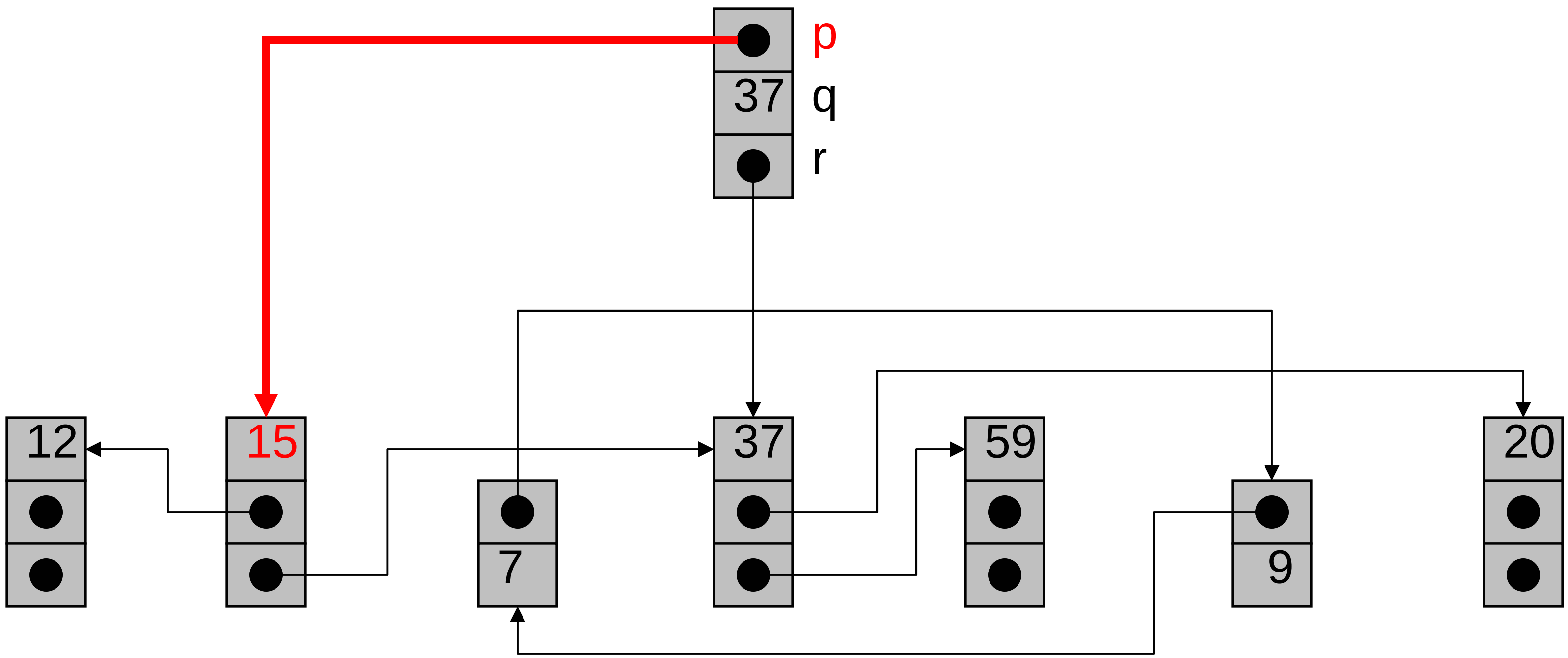

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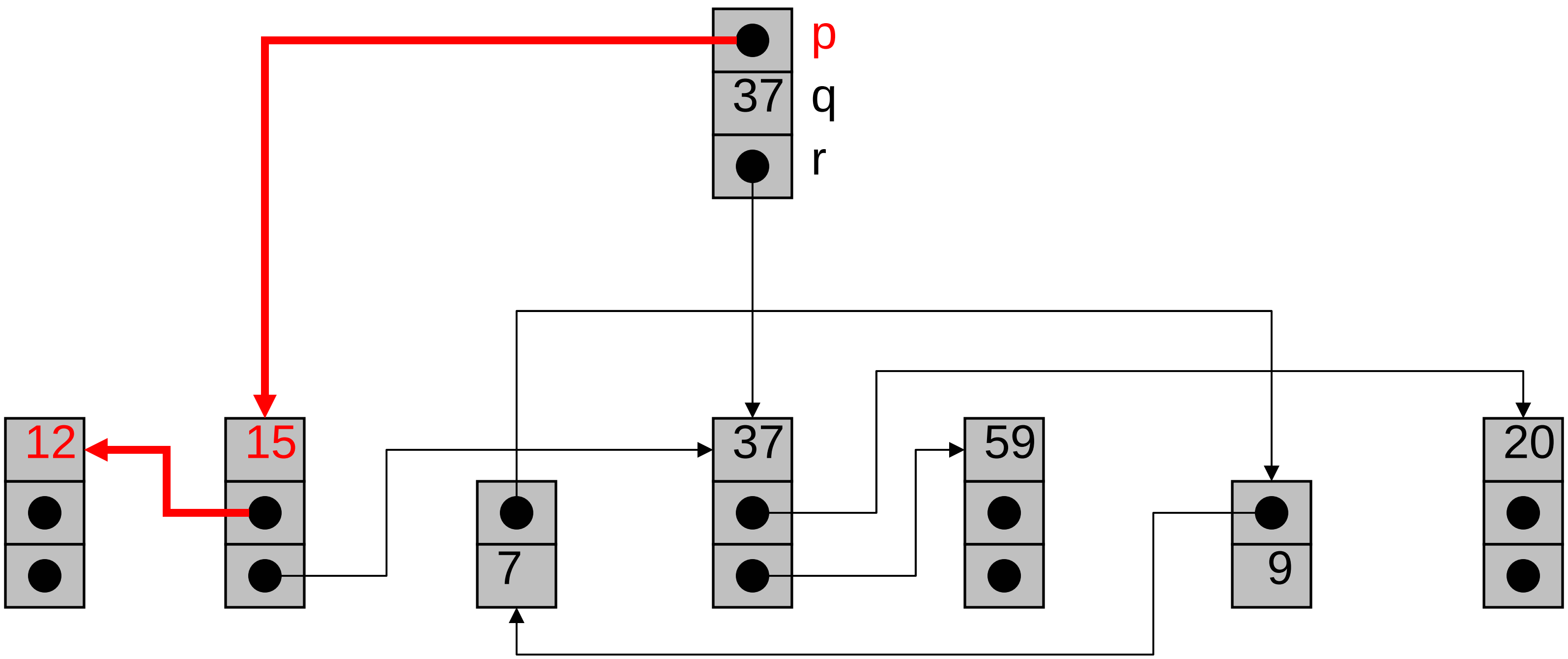

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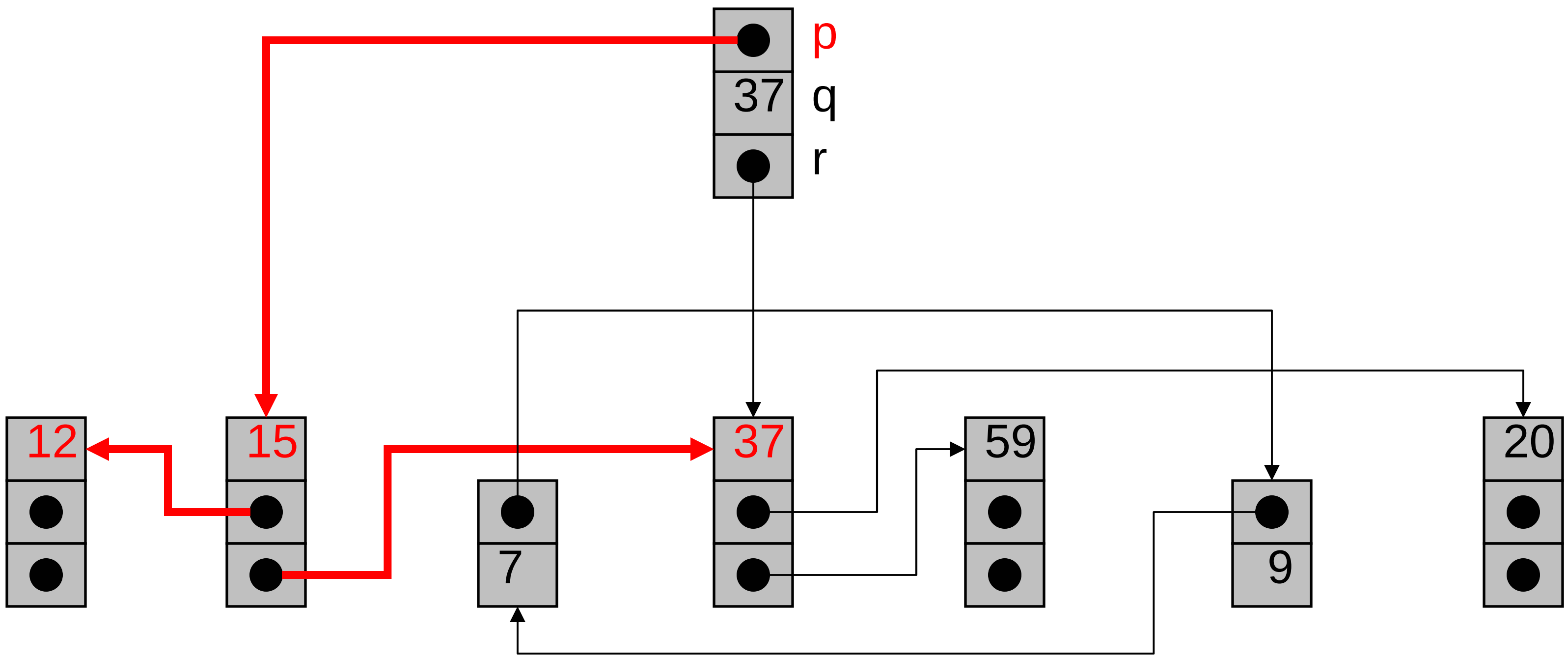
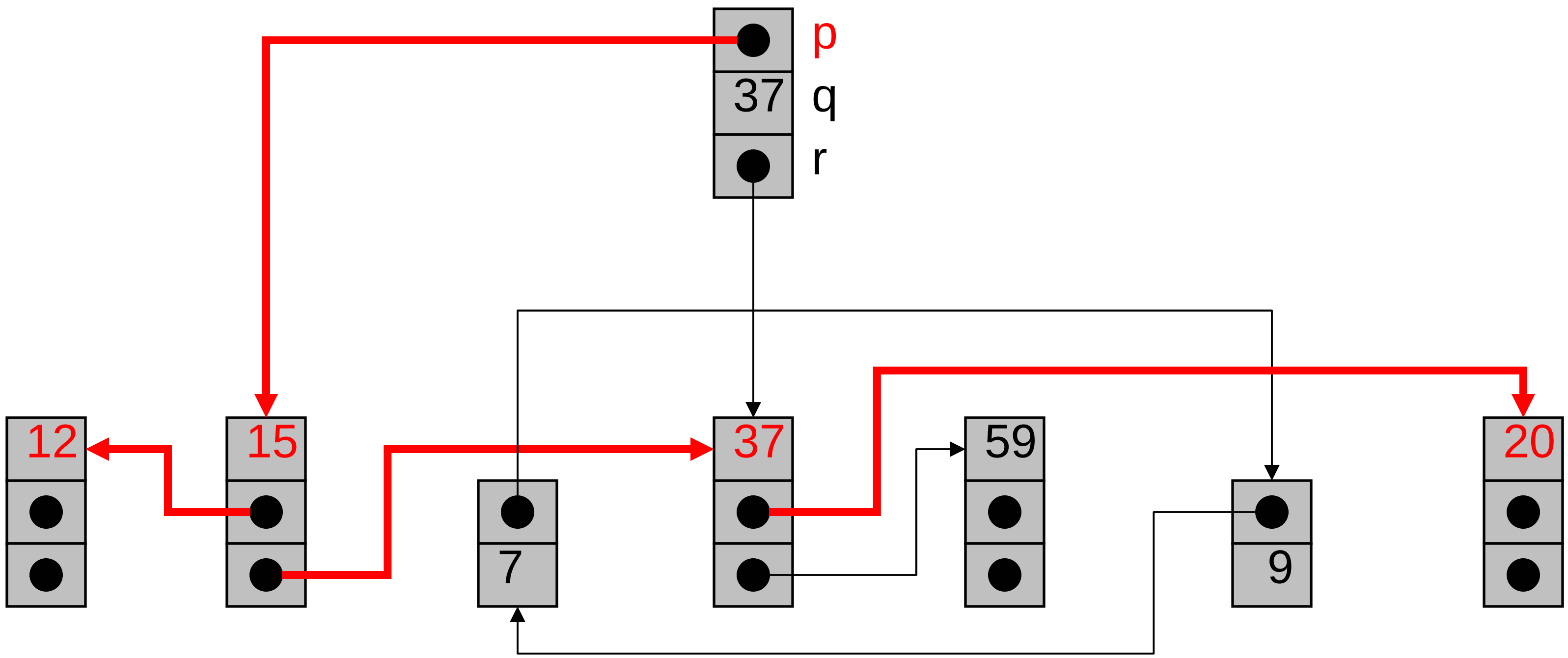
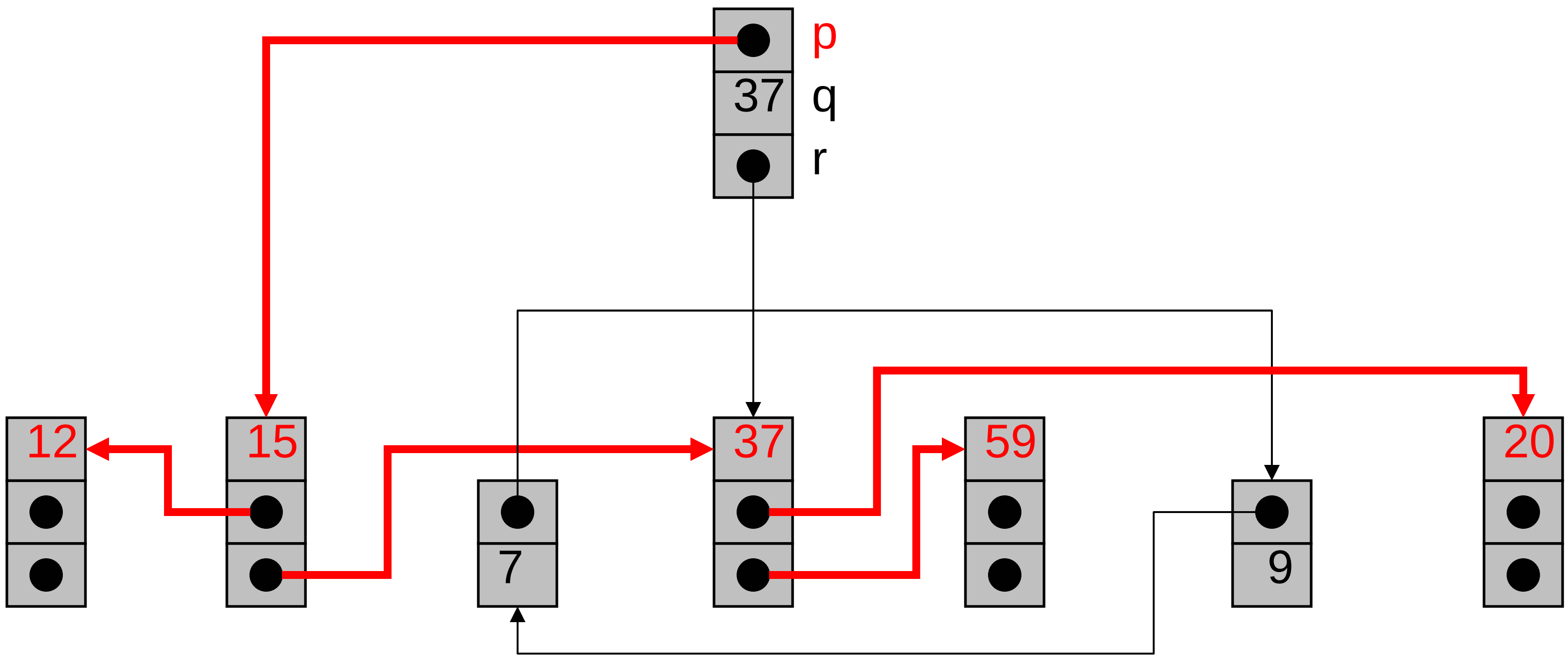


Example



Example



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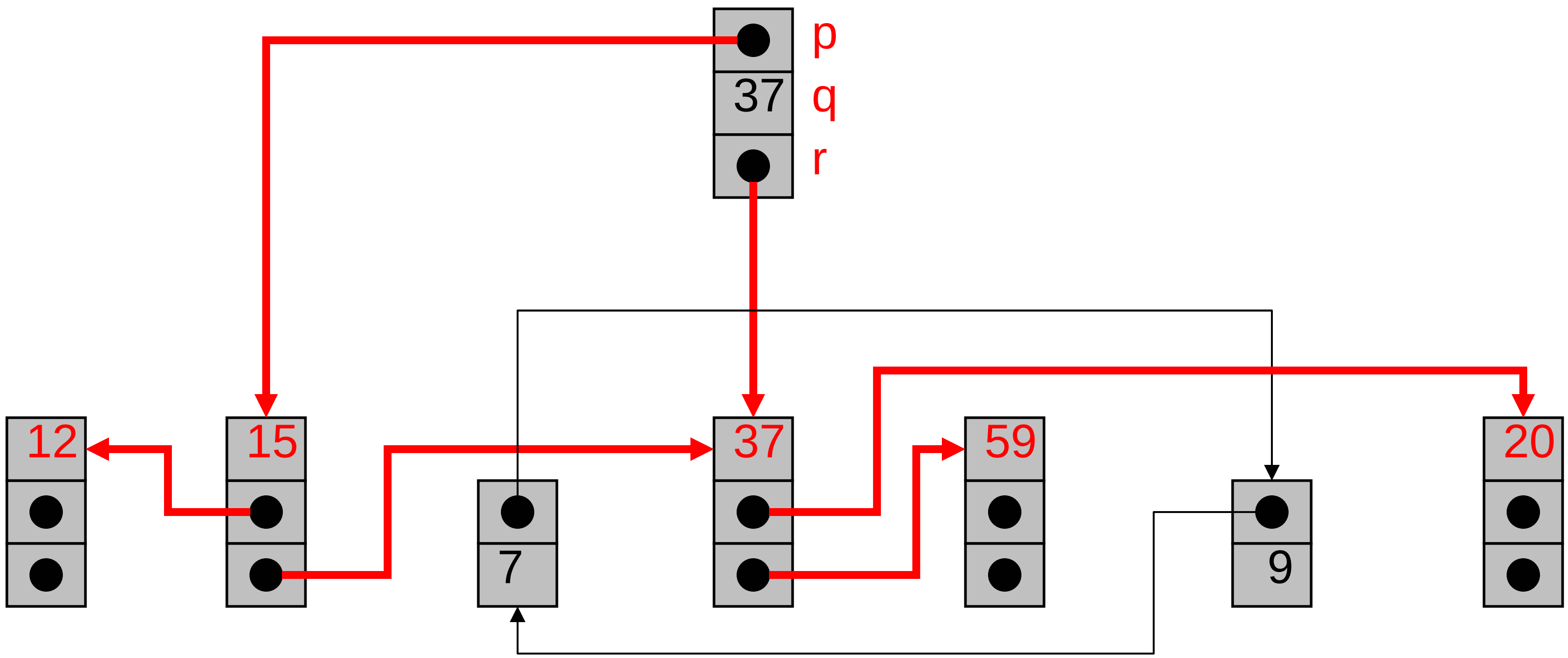

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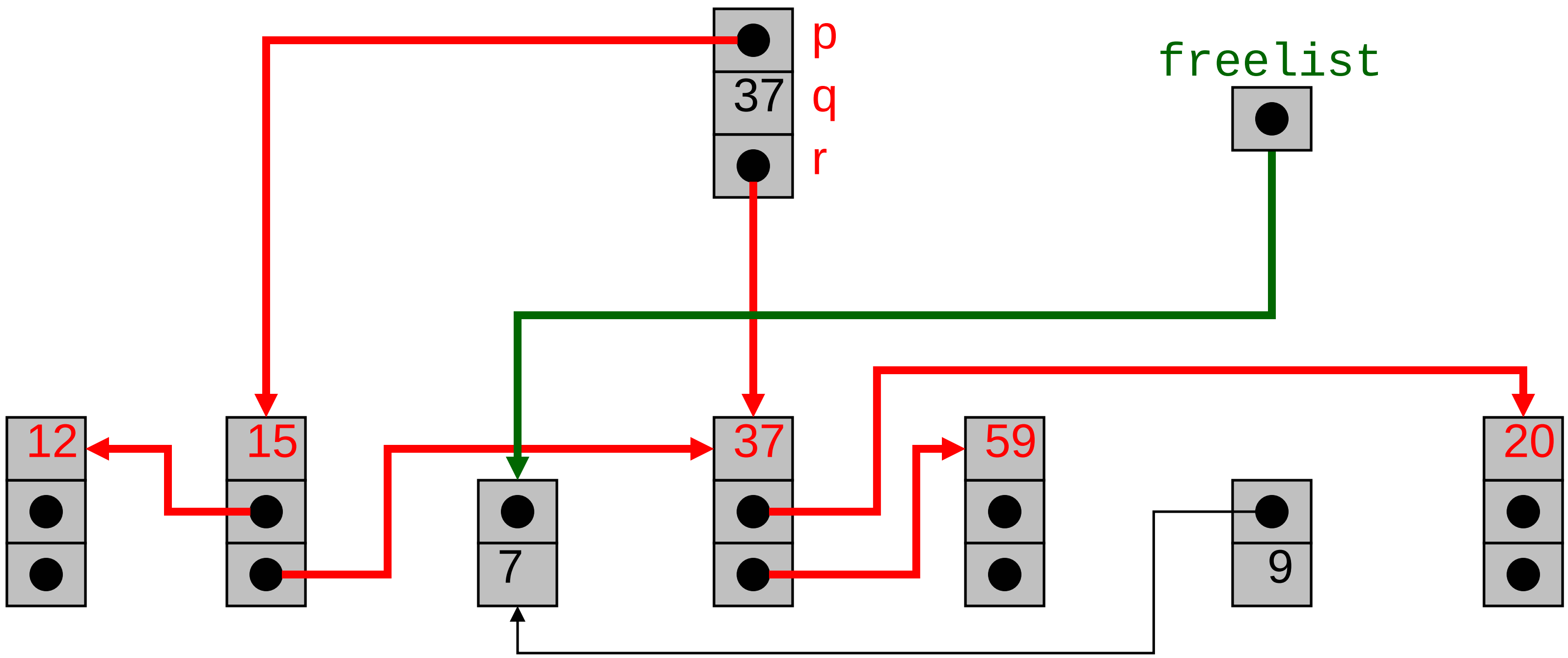

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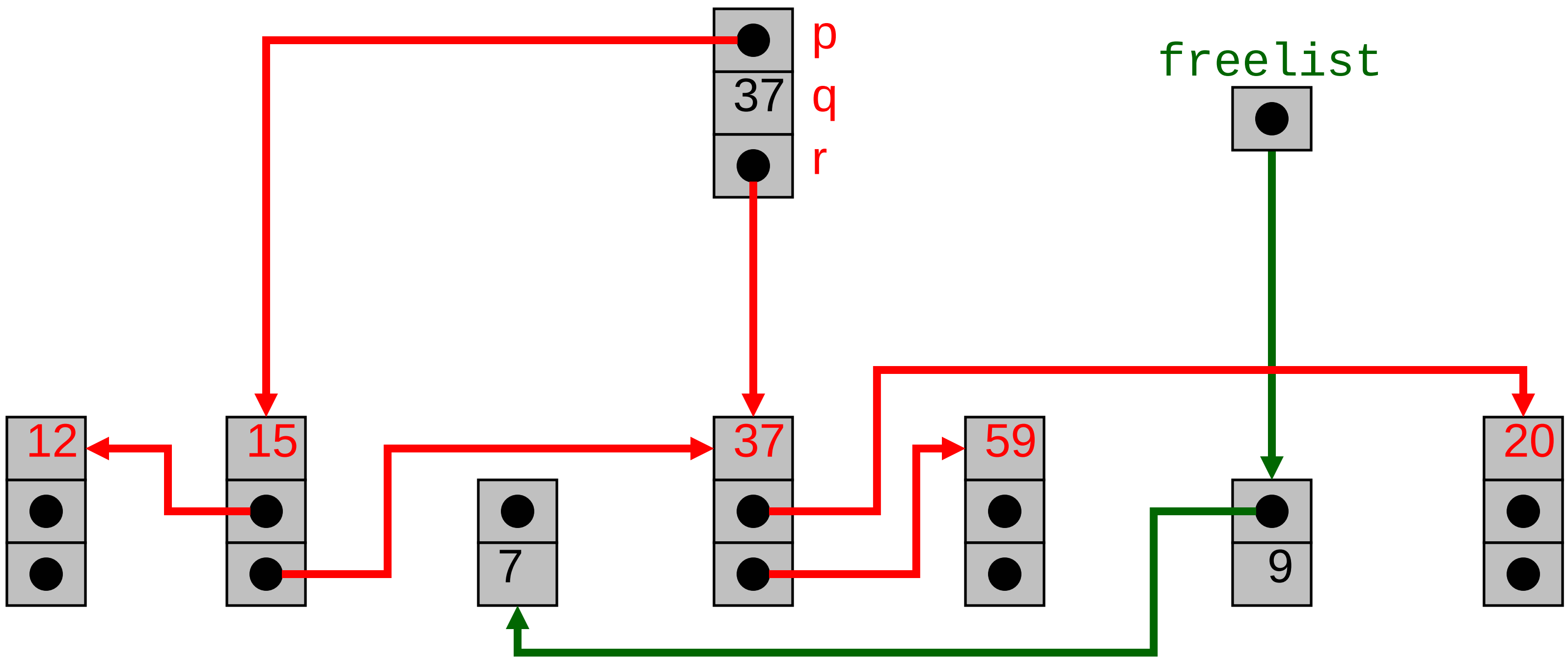


Analysis of Mark-and-Sweep

Assume the heap has R of H words that reachable.

The cost of garbage collection is:

$$c_1R + c_2H$$

Realistic values are:

$$10R + 3H$$

The cost per reclaimed word is:

$$(c_1R + c_2H)(H\text{-}R)$$

- if R is close to H, then this is expensive;
- the lower bound is c_2;
- increase the heap when $R > 0.5H$; then
- the cost per word is $c_1 + 2c_2 = 16$.

Other Issues

- The DFS recursion stack could have size *H* (and has at least size *log H*), which may be too much
  - however, the recursion stack can cleverly be embedded in the fields of marked records (pointer reversal).
- Records can be kept sorted by sizes in the `freelist`. Records may be split into smaller pieces if necessary.
- The heap may become *fragmented*: containing many small free records but none that are large enough.

Reference Counting

- Algorithm
  - maintain a counter of the references to each record;
  - for each assignment, update the counters appropriately; and
  - a record is dead when its counter is zero.
- Advantages:
  - is simple and attractive;
  - catches dead records immediately; and
  - does not cause long pauses.
- Disadvantages:
  - cannot detect cycles of dead records; and
  - is much too expensive.

Reference Counting Code

```
function Increment(x)
  x.count := x.count + 1

function Decrement(x)
  x.count := x.count – 1
  if x.count == 0 then
    PutOnFreeList(x)
```

Reference Counting Code

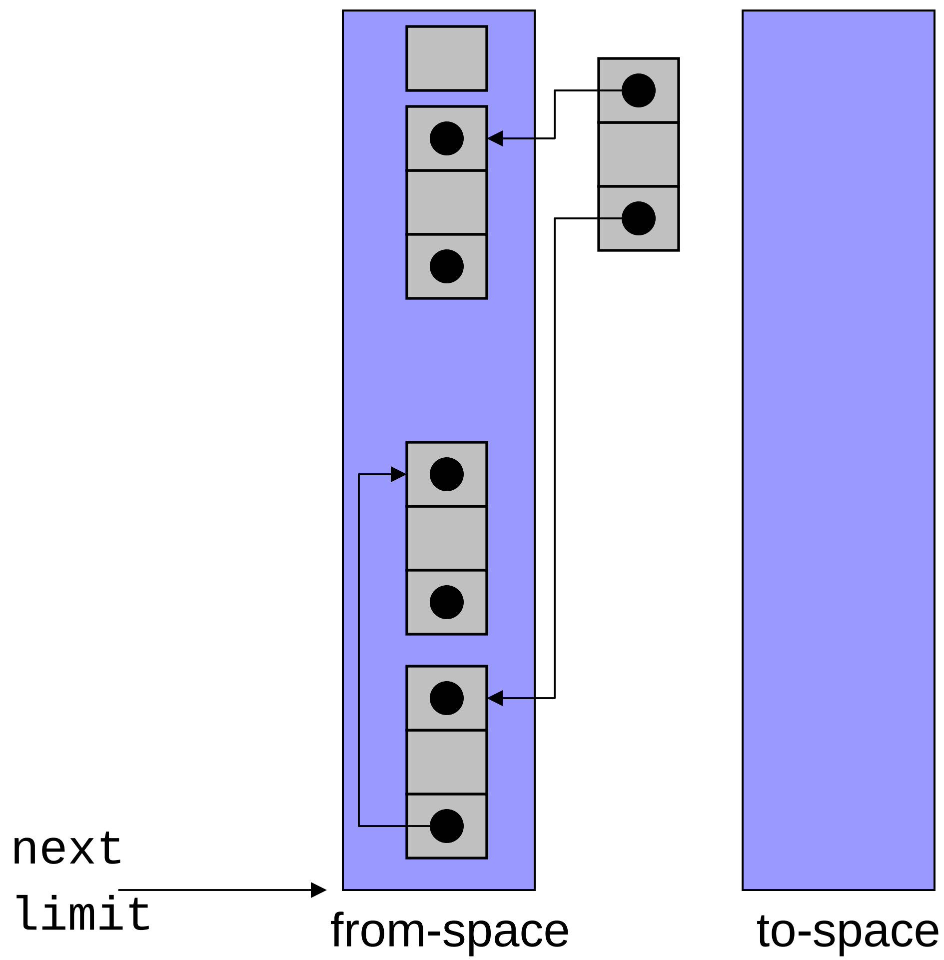
```
function PutOnFreelist(x)
  Decrement(x.f1)
  x.f1 := freelist
  freelist := x

function RemoveFromFreelist(x)
  for i in 2 … |x| do
    Decrement(x.fi)
```

Stop-and-Copy Counting

- Algorithm
  - divide the heap into two parts;
  - only use one part at a time;
  - when it runs full, copy live records to the other part; and
  - switch the roles of the two parts.
- Advantages:
  - allows fast allocation (no `freelist`);
  - avoids fragmentation;
  - collects in time proportional to *R*; and
  - avoids stack and pointer reversal.
- Disadvantage:
  - wastes half your memory.

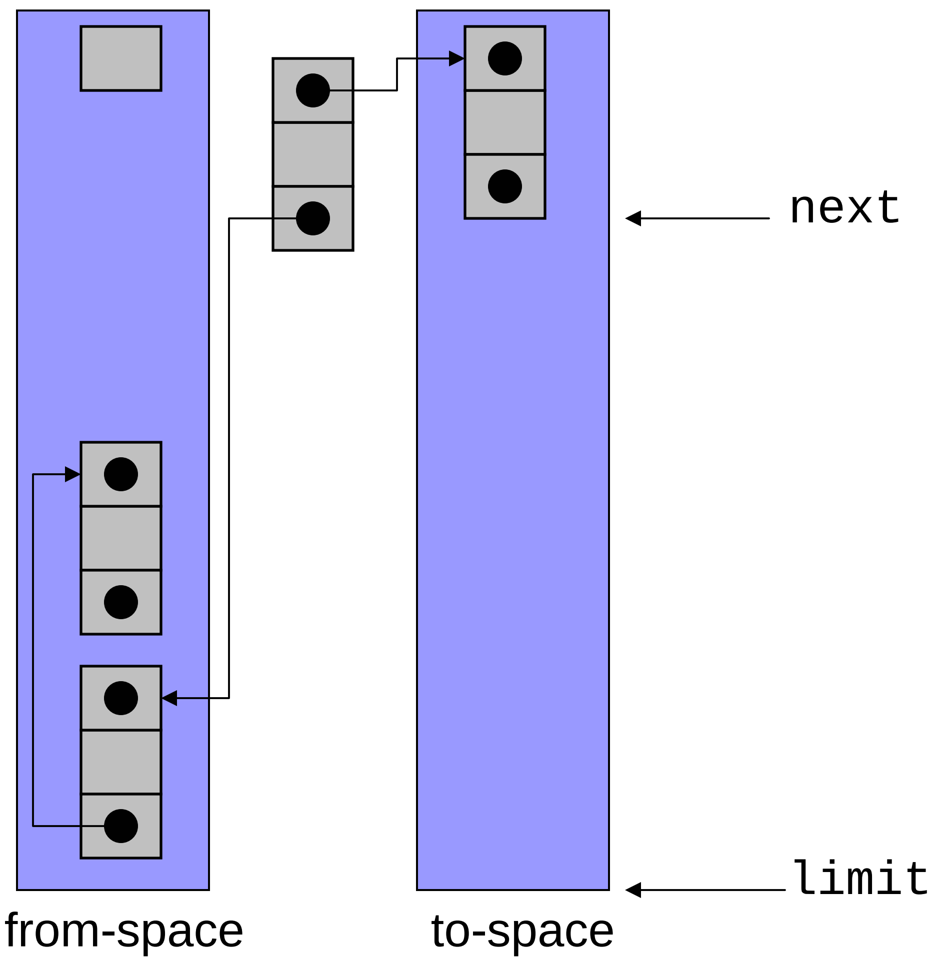
Example Stop-and-copy



`next` identifies address of a block of free memory

`limit` is maximum address

Example Stop-and-copy



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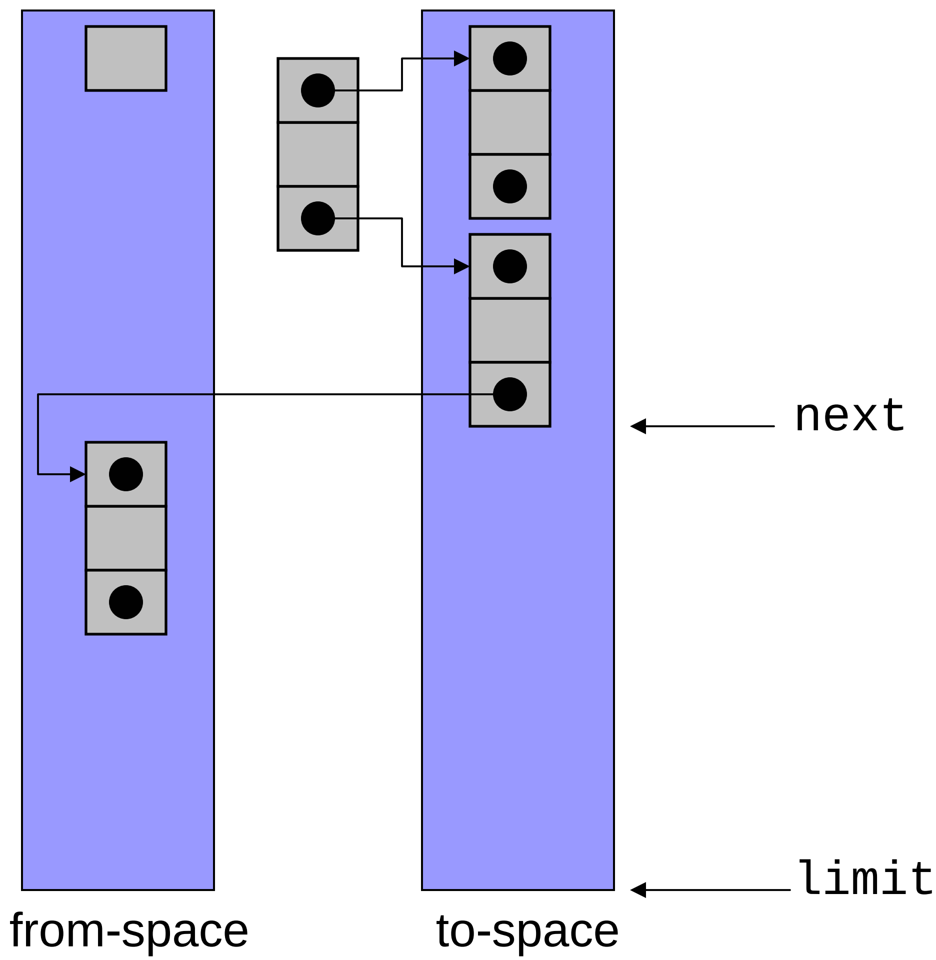
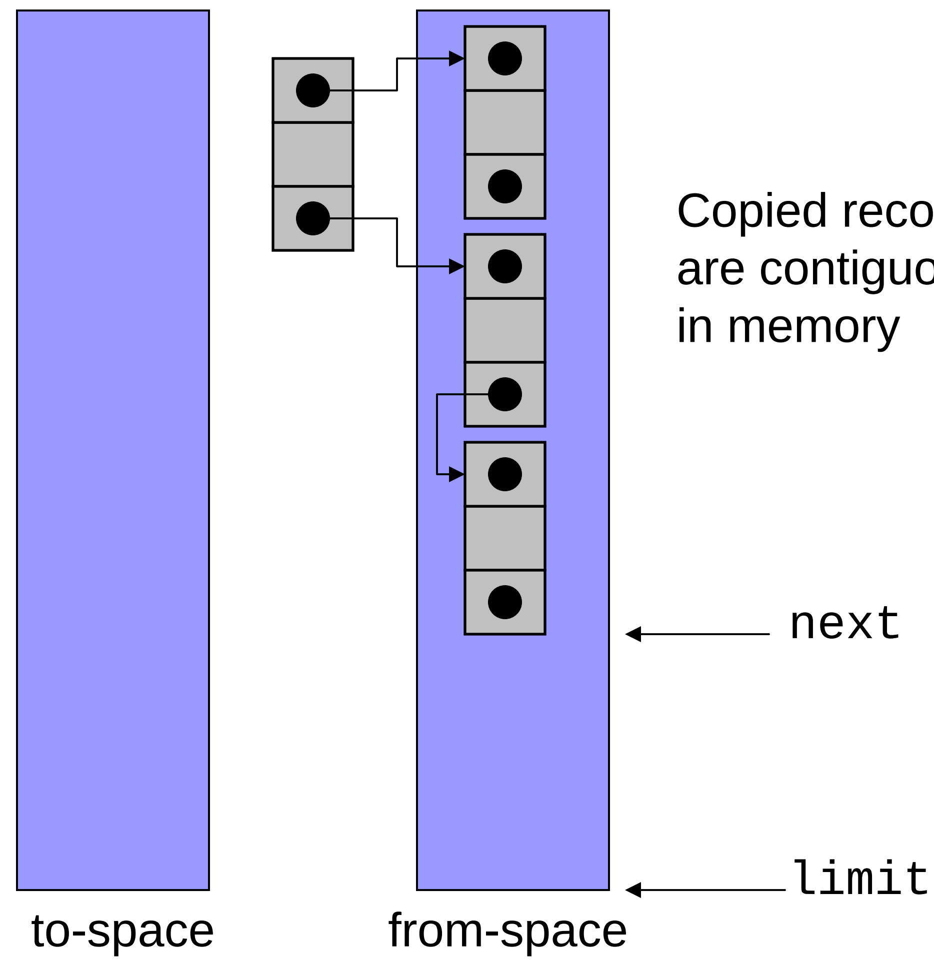


Example Stop-and-copy



Copy Code

```
function Copy()
    scan := next := start of to-space
    for each program variable v do
        v := Forward(v)
    while scan < next do
        for i in 1 .. |scan| do
            scan.f_i := Forward(scan.f_i)
        scan := scan + sizeof(record scan)
```

Copy Code

```
function Forward(p)
   if p in from-space then
     if p.f1 in to-space then
       return p.f1
     else
       for i in 1 .. |p| do
         next.fi := p.fi
       p.fi := next
       next := next + sizeof(record p)
       return p.f1
   else return p
```

Analysis of Stop-and-Copy

Assume the heap has R of H words that reachable.

The cost of garbage collection is:

$$c_3R$$

Realistic values are:

$$10R$$

The cost per reclaimed word is:

$$(c_3R)(H/2 - R)$$

- no lower bound as H grows;
- If $H = 4R$ then the cost is constant at approximately 10

Earlier Assumptions

We assumed

- we know the size of each record; and
- we know which fields are pointers.

For object-oriented languages, each record already contains a pointer to a class descriptor.

For general languages, we must sacrifice a few bytes per record.

For You To Do

- What algorithm should we use?
- Under what conditions?

Common Algorithms

- Mark-and-sweep or stop-and-copy
- Garbage collection is expensive
  - ~100 instructions for a small object
- Extensions
  - Generational and Region-based Collection
    - Identify objects that die around same time and collect them at once -- faster
  - Incremental and partial collection
    - Reclaim only a part of the heap at a time -- smoother

Generational Collection

- observation: the young die quickly;
- hence the collector should focus on young records;
- divide the heap into generations: G_0, G_1, G_2, …;
- all records in G_i are younger than records in G_{i+1};
- collect G_0 often, G_1 less often, and so on; and
- promote a record from G_i to G_{i+1} when it survives several collections.

Generational Collection

- How to collect the G_0 generation:
  - roots are no longer just program variables but also pointers from G_1, G_2, …;
  - it might be very expensive to find those pointers;
  - fortunately, they are rare; so we can try to remember them.
- Ways to remember:
  - maintain a list of all updated records (use marks to make this a set);
  - mark pages of memory that contain updated records (in hardware or software);
  - Syntactic extensions (e.g., RTJava scoped memory)

Incremental Collection

Garbage collection may cause long pauses
- this is undesirable for interactive or real-time programs; so
- try to interleave the garbage collection with the program execution.

Two players access the heap:
- the *mutator*: creates records and moves pointers around; and
- the *collector*: tries to collect garbage.

Some invariants are clearly required to make this work.
- The mutator will suffer some slowdown to maintain these invariants.