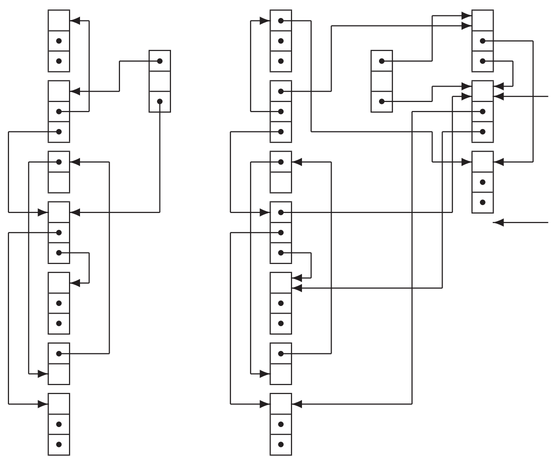
Garbage collection



A *garbage collector* is part of the run-time system: it reclaims heap-allocated records that are no longer used.

A garbage collector should:

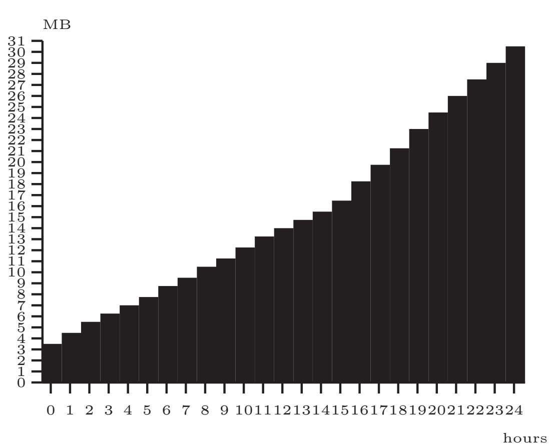
- reclaim *all* unused records;
- spend very little time per record;
- not cause significant delays; and
- allow all of memory to be used.

These are difficult and often conflicting requirements.

Life 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 *dead*, i.e. no longer in use?

Ideally, records that will never be accessed in the future execution of the program.

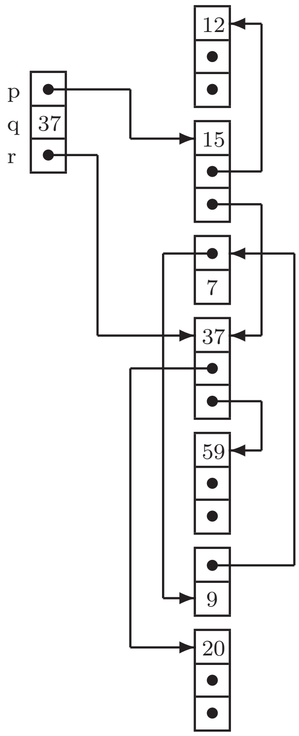
But that is of course undecidable...

Basic conservative assumption:

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

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

A heap with live and dead records:



The 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`.

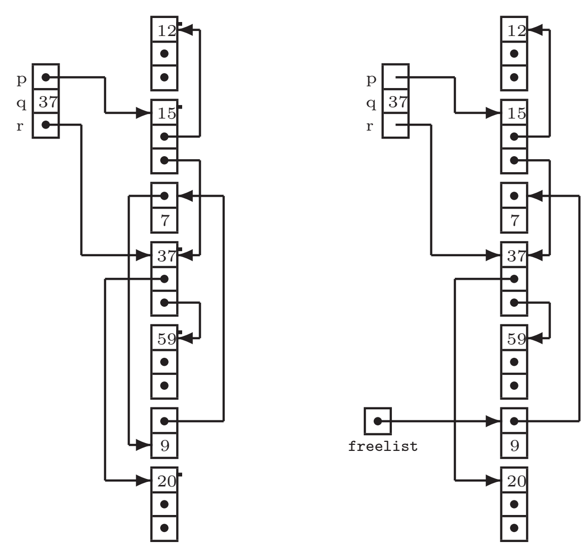
Pseudo code for mark-and-sweep:

function DFS(x)
    if x is a pointer into the heap **then**
        if record x is not marked **then**
            mark record x
            for i:=**1 to** $|x|$ **do**
                DFS($x.f_i$)

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

function Sweep()
    p := first address in heap
    while $p <$ last address in heap **do**
        if record p is marked **then**
            unmark record p
        else
            $p.f_1$:= `freelist`
            `freelist` := p
        p := p+sizeof(record p)

Marking and sweeping:



Analysis of mark-and-sweep:

- assume the heap has size H words; and
- assume that R words are reachable.

The cost of garbage collection is:

$$c_1 R + c_2 H$$

Realistic values are:

$$10R + 3H$$

The cost per reclaimed word is:

$$\frac{c_1 R + c_2 H}{H - R}$$

- 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 $c_1 + 2c_2 \approx 16$.

Other relevant 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.

The 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.

Pseudo code for reference counting:

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

function Decrement(x)
    x.count := x.count-1
    if x.count=0 **then**
        PutOnFreelist(x)

function PutOnFreelist(x)
    Decrement($x.f_1$)
    $x.f_1$:= `freelist`
    `freelist` := x

function RemoveFromFreelist(x)
    for i:=2 **to** $|x|$ **do**
        Decrement($x.f_i$)

The stop-and-copy 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.

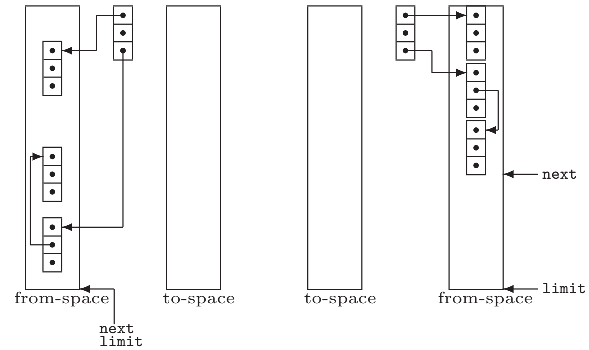
Advantages:

- allows fast allocation (no `freelist`);
- avoids fragmentation;
- collects in time proportional to R; and
- avoids stack and pointer reversal.

Disadvantage:

- wastes half your memory.

Before and after stop-and-copy:



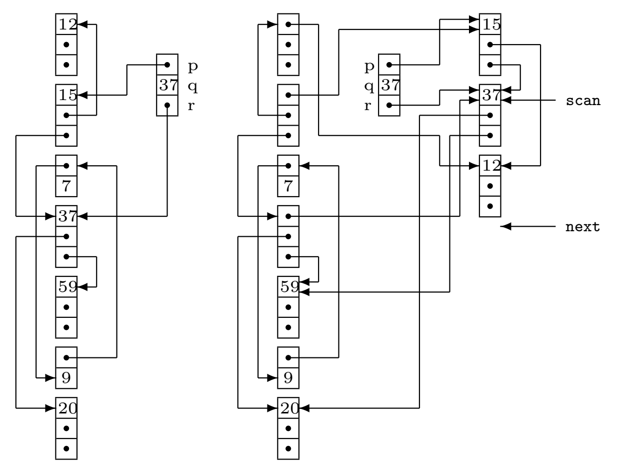
- `next` and `limit` indicate the available heap space; and
- copied records are contiguous in memory.

Pseudo code for stop-and-copy:

function Forward(p)
  if $p \in$ from-space **then**
    if $p.f_1 \in$ to-space **then**
      return $p.f_1$
    else
      for i:=1 **to** $|p|$ **do**
        `next`.f_i := $p.f_i$
      $p.f_1$:= `next`
      `next` := `next` + sizeof(record p)
      return $p.f_1$
  else return p

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

Snapshots of stop-and-copy:



before

after forwarding p and q and scanning 1 record

Analysis of stop-and-copy:

- assume the heap has size $\boldsymbol{H}$ words; and
- assume that $\boldsymbol{R}$ words are reachable.

The cost of garbage collection is:

$$\boldsymbol{c_3 R}$$

A realistic value is:

$$\boldsymbol{10R}$$

The cost per reclaimed word is:

$$\frac{\boldsymbol{c_3 R}}{\frac{\boldsymbol{H}}{\boldsymbol{2}} - \boldsymbol{R}}$$

- this has no lower bound as $\boldsymbol{H}$ grows;
- if $\boldsymbol{H = 4R}$ then the cost is $\boldsymbol{c_3 \approx 10}$.

Earlier assumptions:

- 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.

We use mark-and-sweep or stop-and-copy.

But garbage collection is still expensive: $\approx$ 100 instructions for a small object!

Each algorithm can be further extended by:

- generational collection (to make it run faster); and
- incremental (or concurrent) collection (to make it run smoother).

Generational collection:

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

How to collect the $\boldsymbol{G_0}$ generation:

- roots are no longer just program variables but also pointers from $\boldsymbol{G_1, G_2, \ldots}$;
- 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); or
- mark pages of memory that contain updated records (in hardware or software).

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.