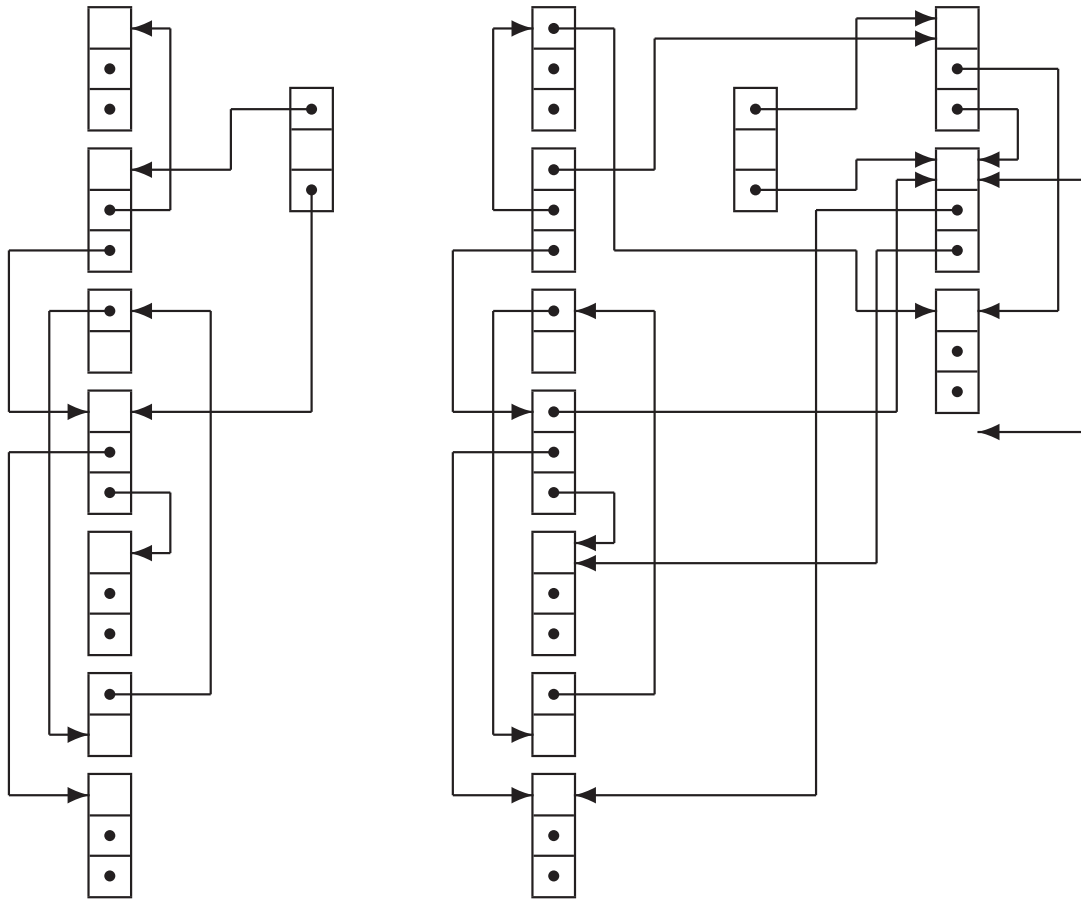# Garbage collection

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`):
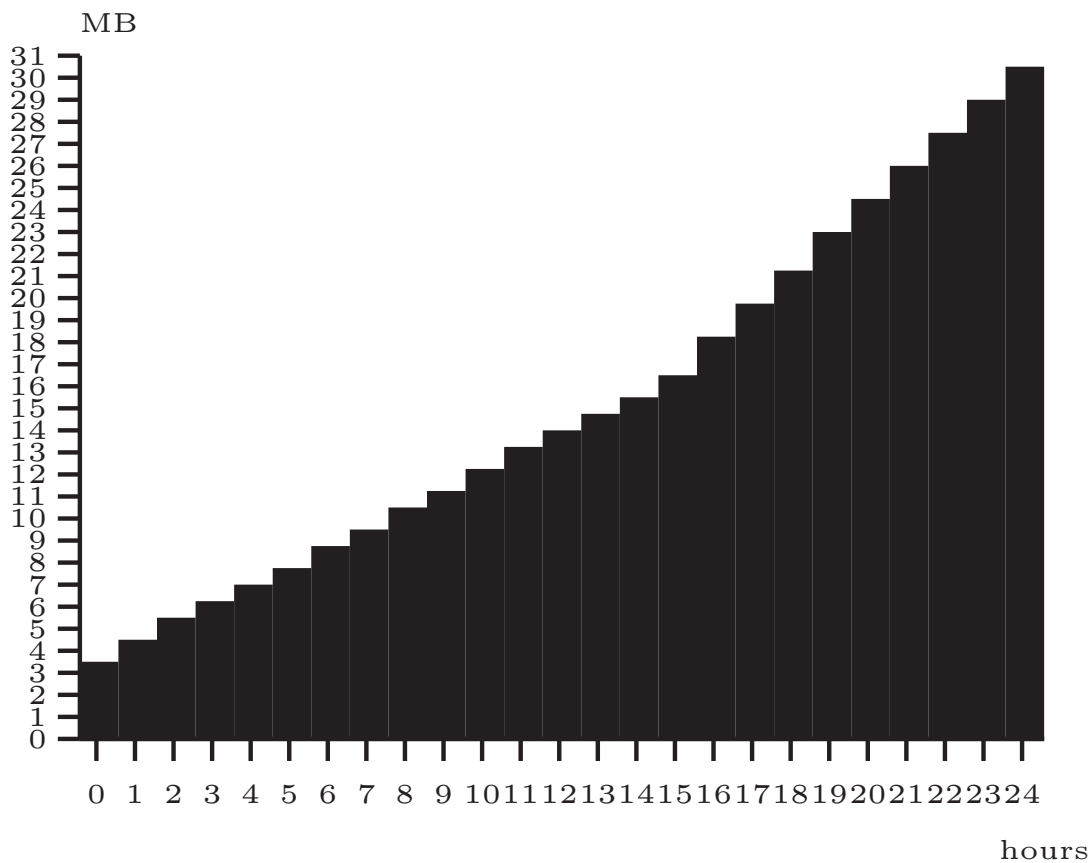
Which records are *dead*, i.e. no longer in use?

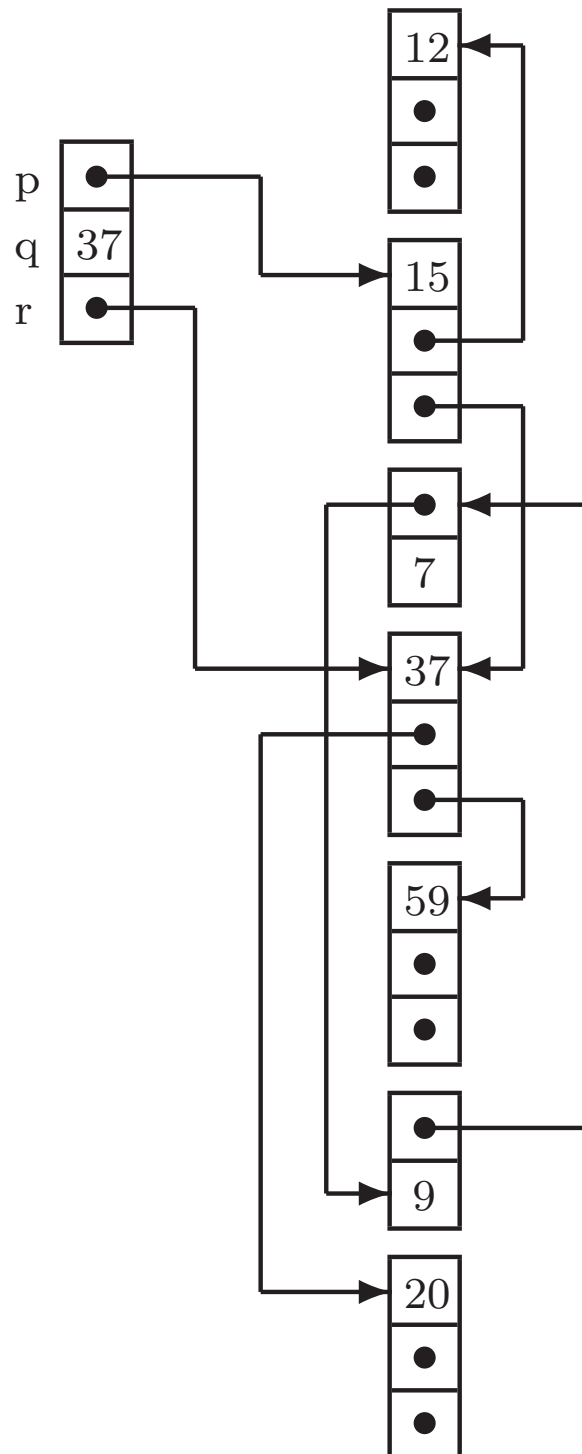Ideally, records that will never be accessed in the future execution of the program.

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:
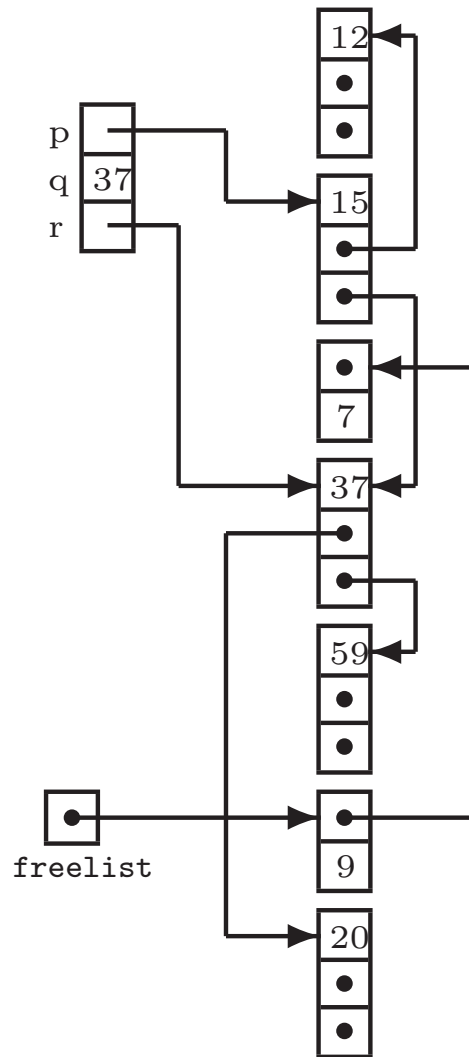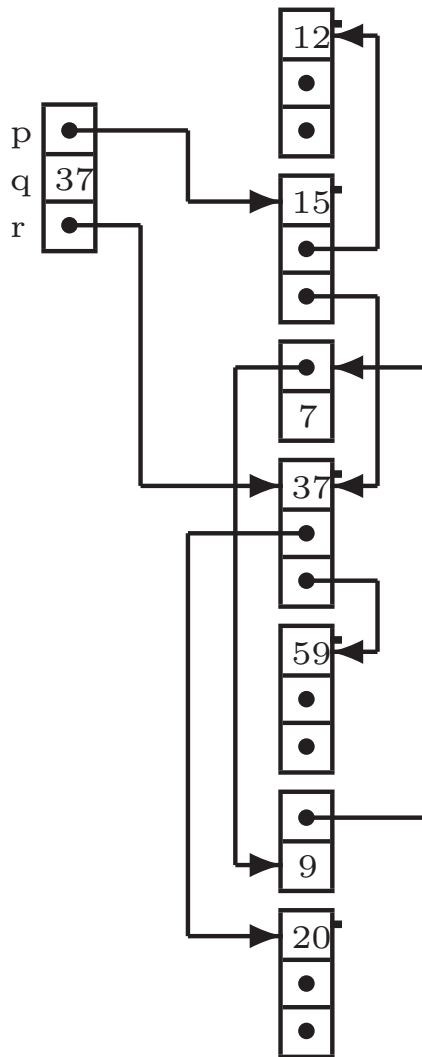
Analysis of mark-and-sweep:

- 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
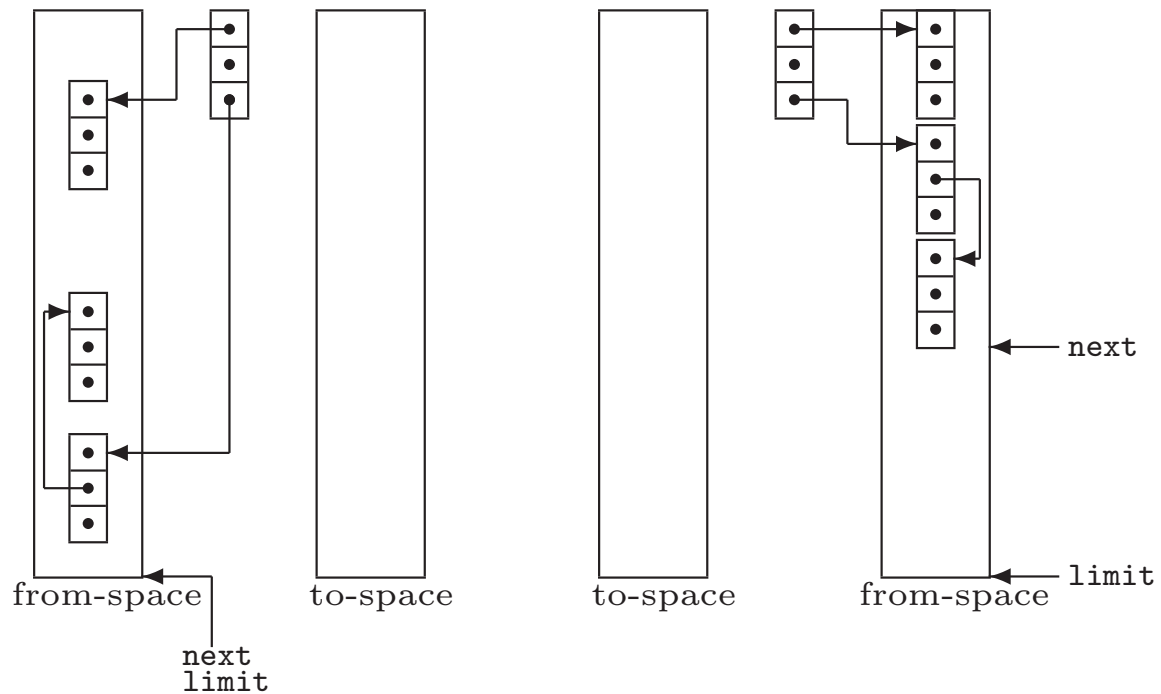
- switch the roles of the two parts.

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:
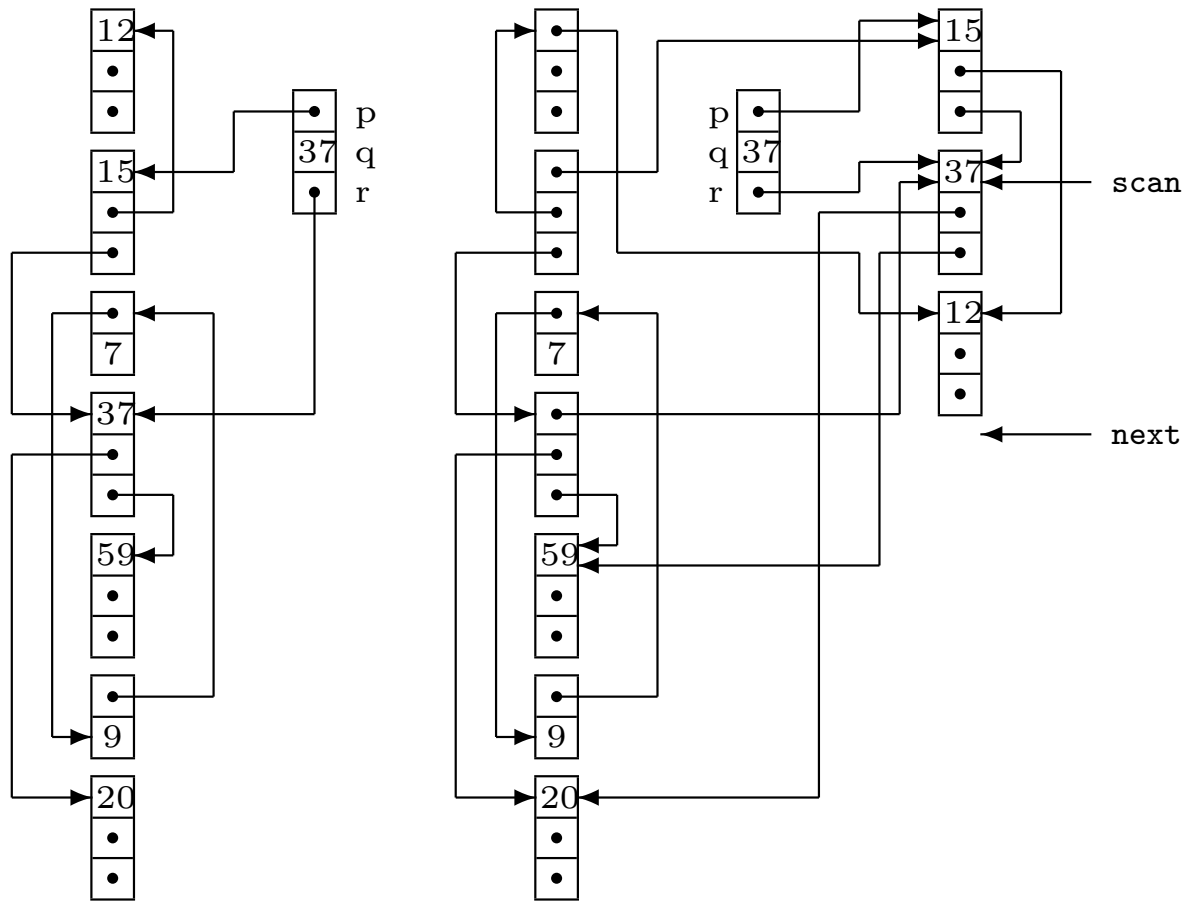
before

after forwarding p and q and scanning 1 record

Analysis of stop-and-copy:

- assume the heap has size H words; and

- assume that R words are reachable.

The cost of garbage collection is:

$$c_3 R$$

A realistic value is:

$$10R$$

The cost per reclaimed word is:

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

- this has no lower bound as H grows;

- if $H = 4R$ then the cost is $c_3 \approx 10$.

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:
≈ 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: $G_0, G_1, G_2, \ldots$;

- 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.

How to collect the G_0 generation:

- roots are no longer just program variables but also pointers from $G_1, G_2, \ldots$;

- 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.