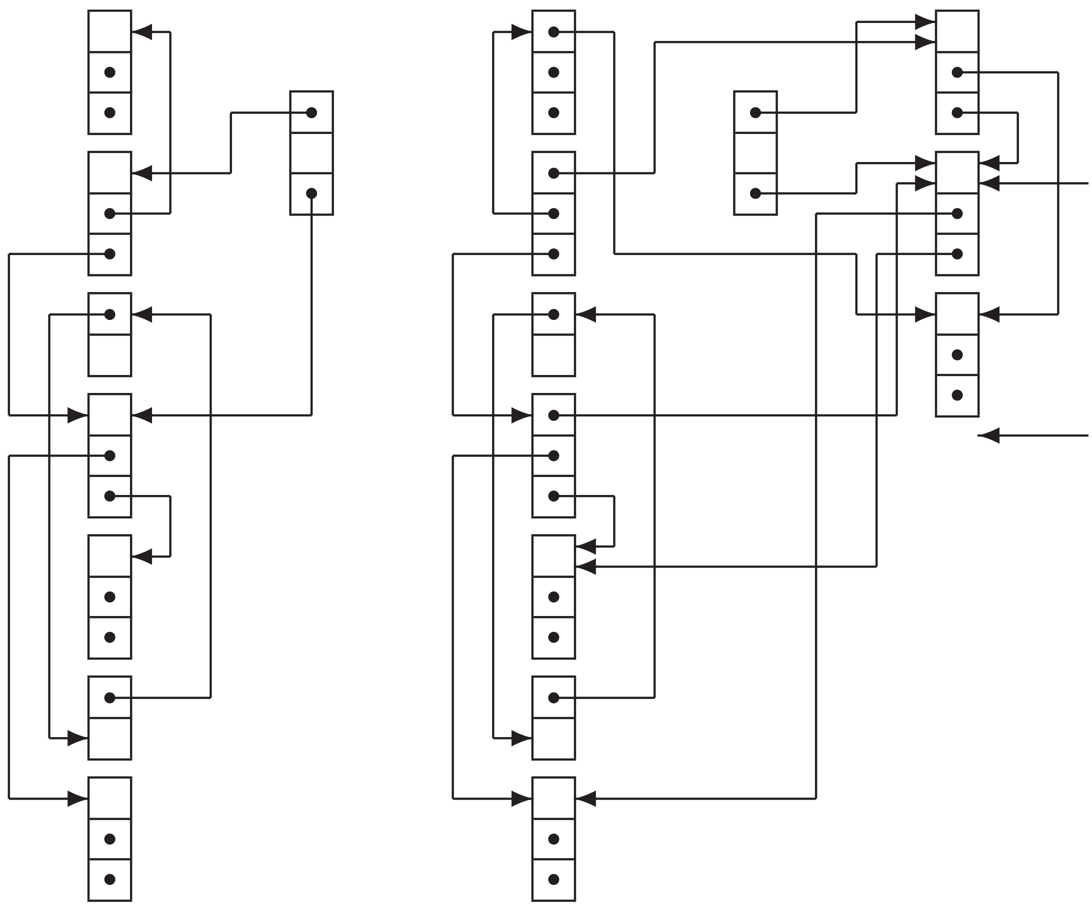
Garbage collection



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

A garbage collector should:

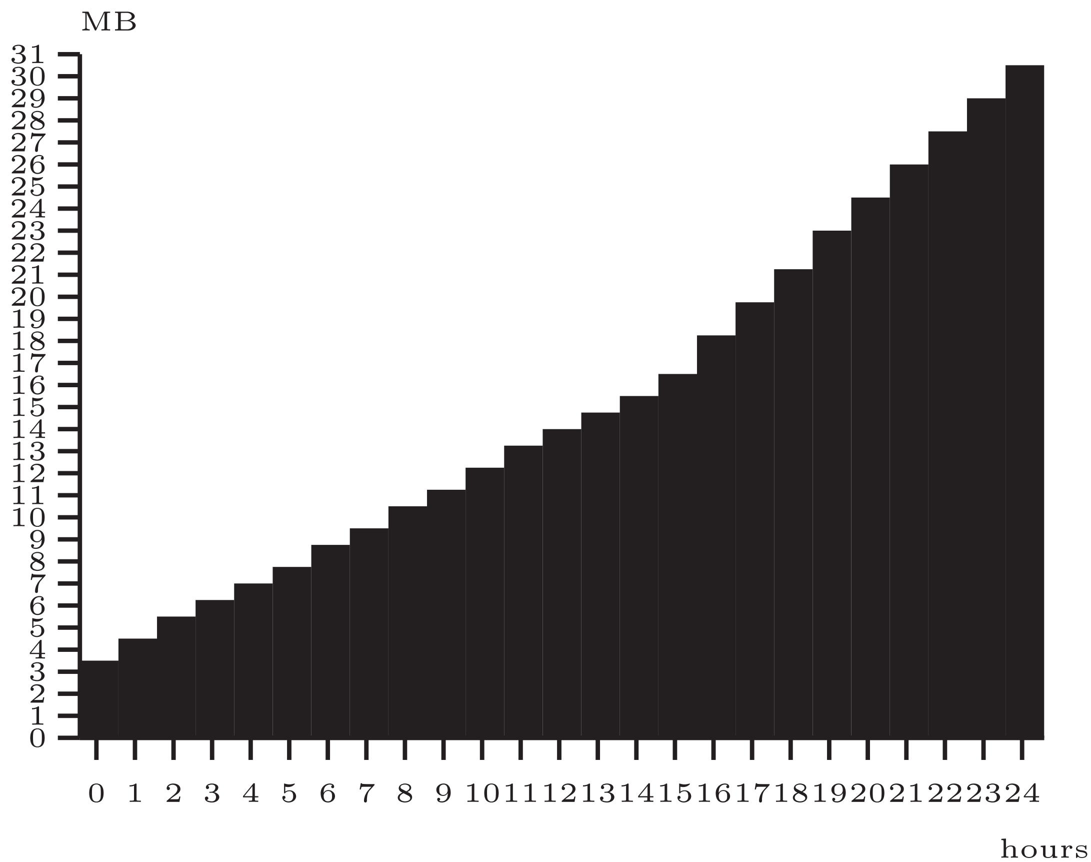
- reclaim *all* unused records;
- spend very little time per record;
- not cause significant delays; and
- allow all of memory to be used.

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.

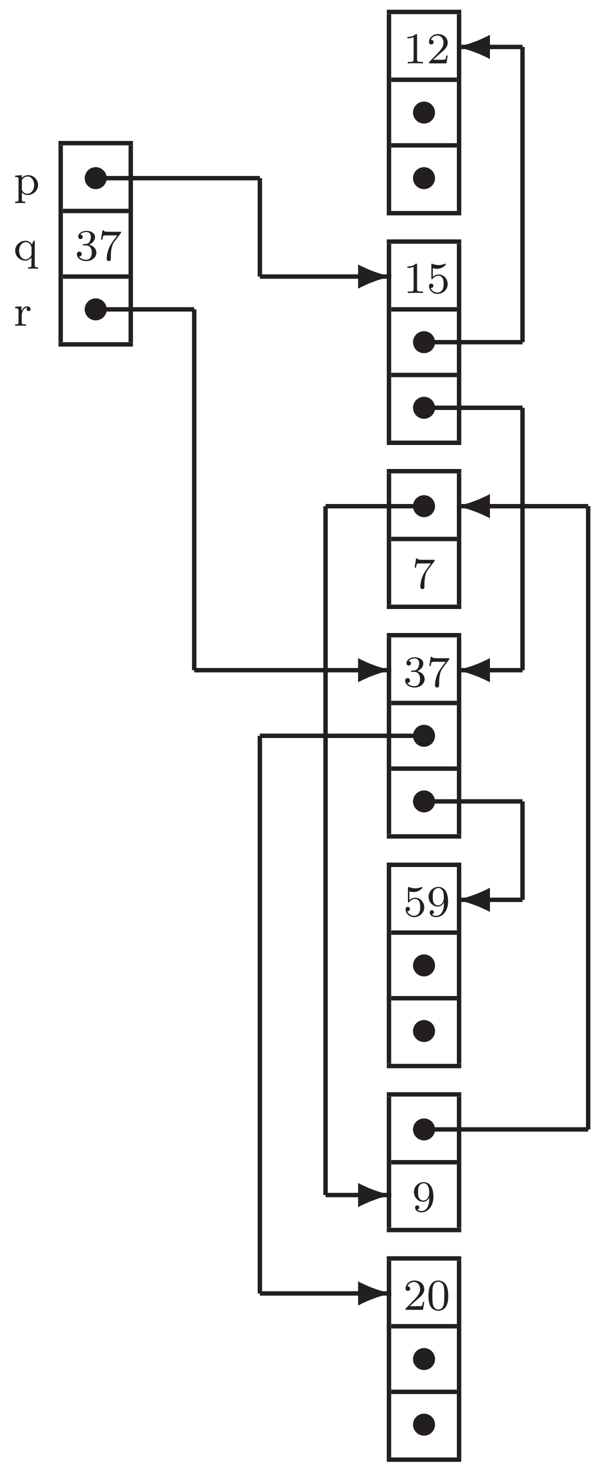
But that is of course undecidable...

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`.

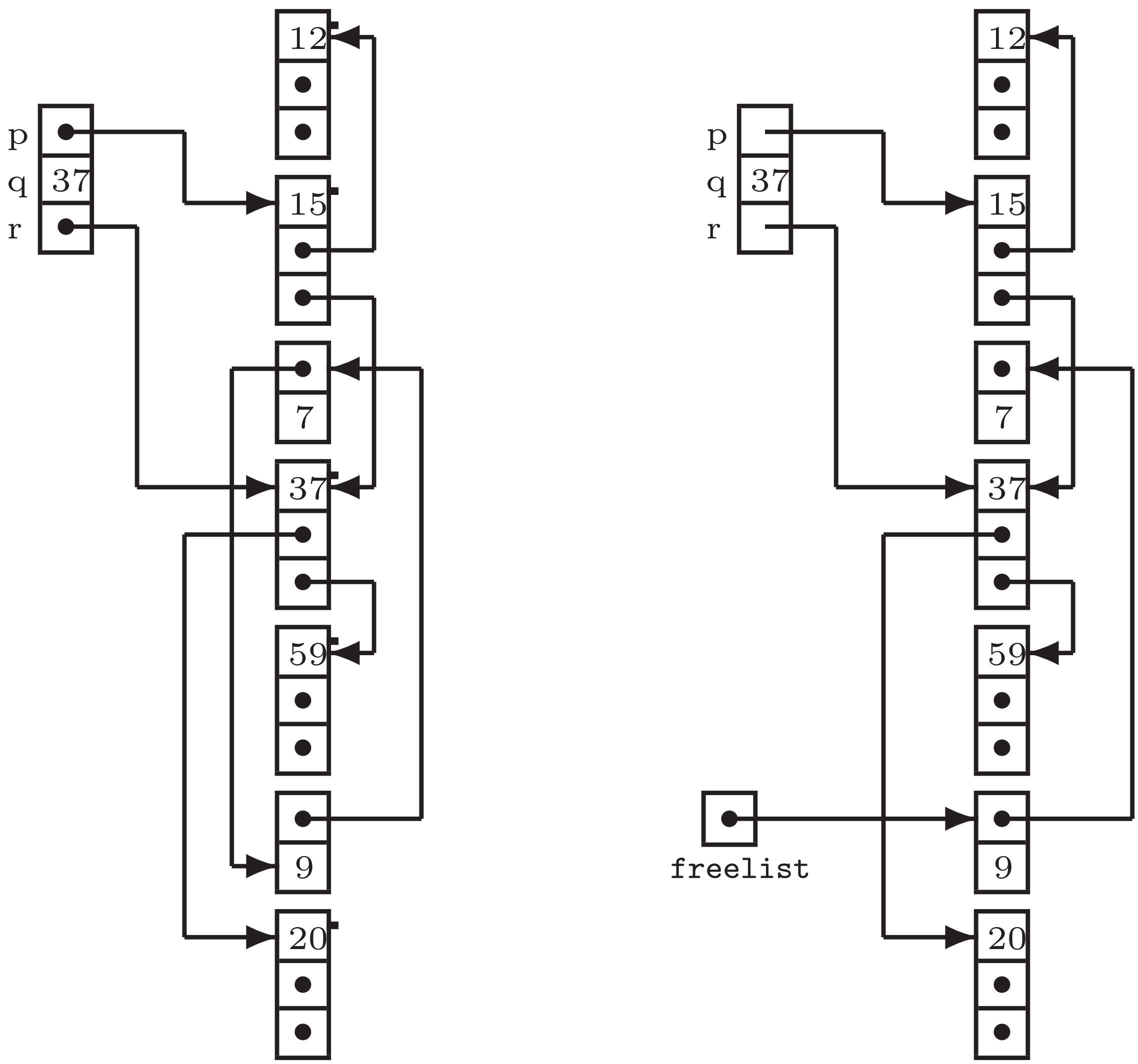
Pseudo code for mark-and-sweep:

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

function Mark()
    for each program variable $\boldsymbol{v}$ **do**
        DFS($\boldsymbol{v}$)

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

Marking and sweeping:



Analysis of mark-and-sweep:

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

The cost of garbage collection is:

$$\boldsymbol{c_1 R + c_2 H}$$

Realistic values are:

$$\boldsymbol{10R + 3H}$$

The cost per reclaimed word is:

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

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

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($\boldsymbol{x}$)
    $\boldsymbol{x}$.count := $\boldsymbol{x}$.count$\boldsymbol{+1}$

function Decrement($\boldsymbol{x}$)
    $\boldsymbol{x}$.count := $\boldsymbol{x}$.count$\boldsymbol{-1}$
    if $\boldsymbol{x}$.count=0 **then**
        PutOnFreelist($\boldsymbol{x}$)

function PutOnFreelist($\boldsymbol{x}$)
    Decrement($\boldsymbol{x.f_1}$)
    $\boldsymbol{x.f_1}$:= `freelist`
    `freelist` := $\boldsymbol{x}$

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

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.

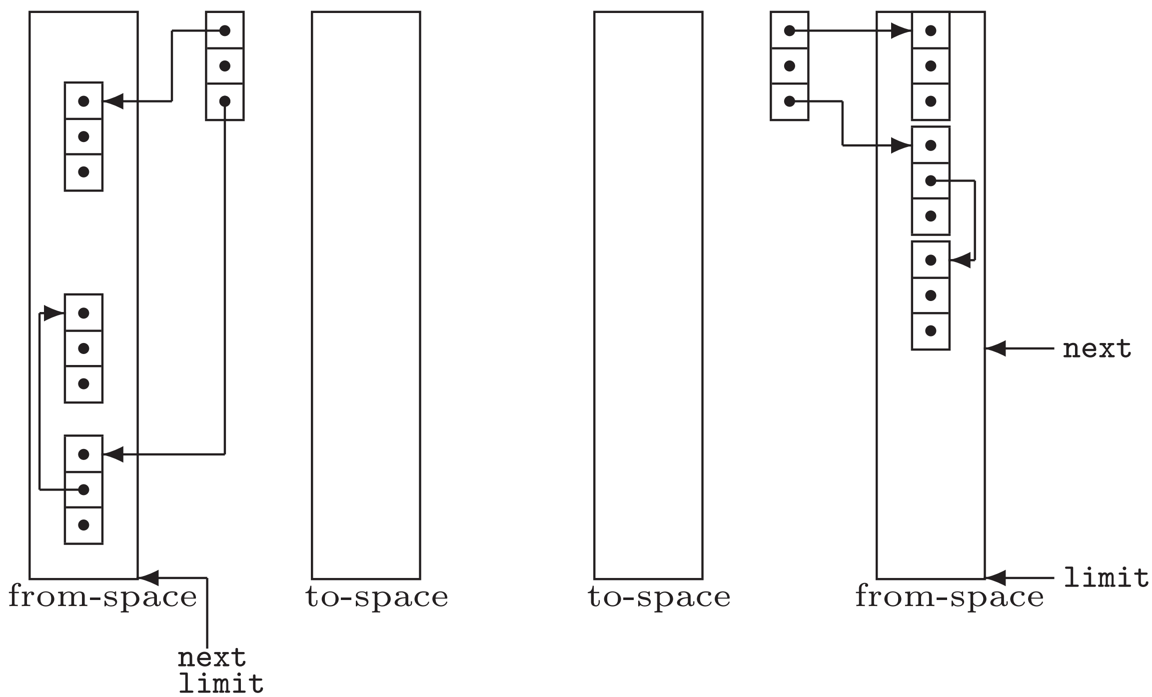
Advantages:

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

Disadvantage:

- wastes half your memory.

Before and after stop-and-copy:



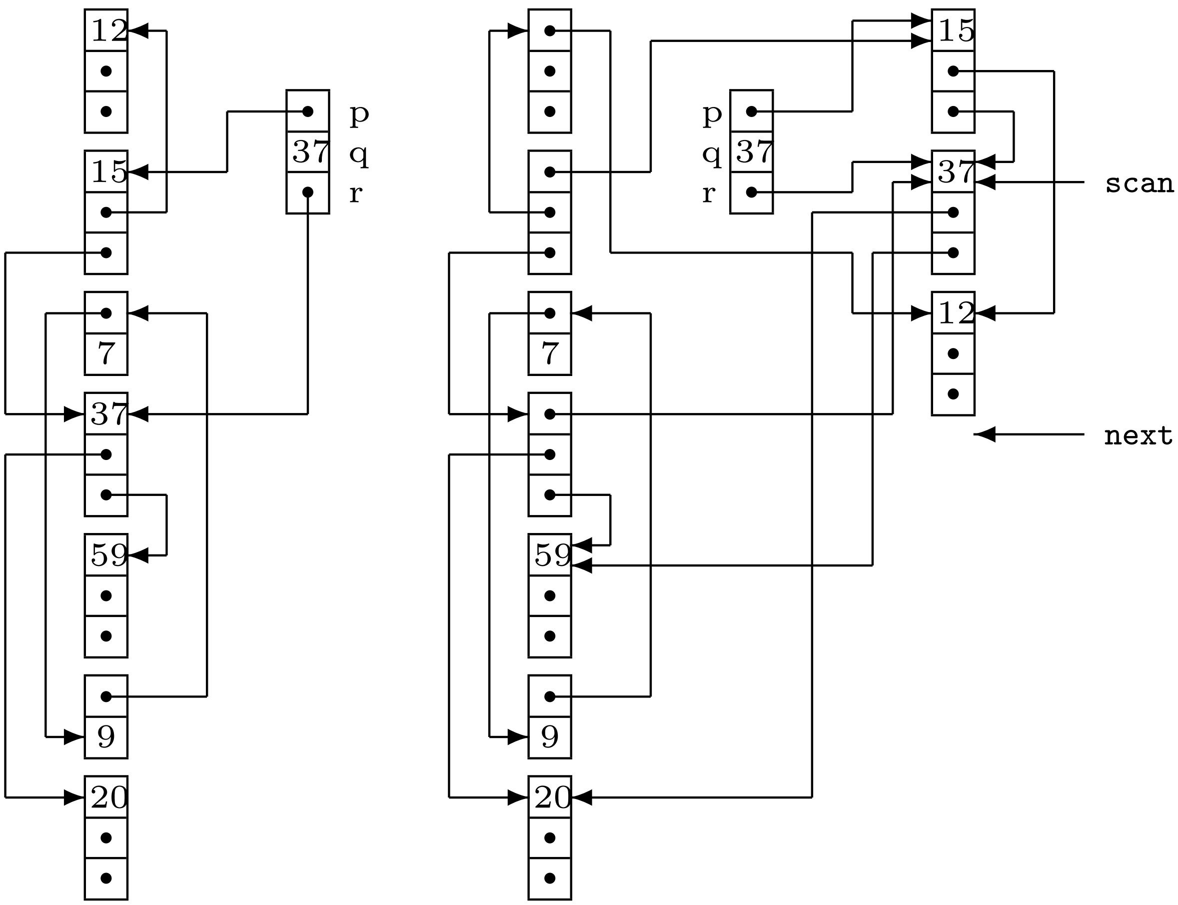
- `next` and `limit` indicate the available heap space; and
- copied records are contiguous in memory.

Pseudo code for stop-and-copy:

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

function Copy()
    `scan` := `next` := start of to-space
    for each program variable $\boldsymbol{v}$ **do**
        $\boldsymbol{v}$:= Forward($\boldsymbol{v}$)
    while `scan` < `next` **do**
        for $\boldsymbol{i}$:=1 **to** |`scan`| **do**
            `scan`.$\boldsymbol{f_i}$:= Forward(`scan`.$\boldsymbol{f_i}$)
        `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: $G_0, G_1, G_2, \ldots$;
- 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 $\boldsymbol{G_0}$ 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.