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:

```pseudocode
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:

Snapshots of stop-and-copy:

Pseudo code for stop-and-copy:

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

• next and limit indicate the available heap space; and
• copied records are contiguous in memory.
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:
$\approx 100$ 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 $G_0$ 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.