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:

\textbf{function} DFS(\(x\))
\begin{align*}
    &\text{if } x \text{ is a pointer into the heap} \text{ then} \\
    &\quad \text{if record } x \text{ is not marked} \text{ then} \\
    &\quad\quad \text{mark record } x \\
    &\quad\quad \text{for } i:=1 \text{ to } |x| \text{ do} \\
    &\quad\quad\quad \text{DFS}(x.f_i)
\end{align*}

\textbf{function} Mark()
\begin{align*}
    &\text{for each program variable } v \text{ do} \\
    &\quad \text{DFS}(v)
\end{align*}

\textbf{function} Sweep()
\begin{align*}
    &p := \text{first address in heap} \\
    &\text{while } p < \text{last address in heap} \text{ do} \\
    &\quad \text{if record } p \text{ is marked} \text{ then} \\
    &\quad\quad \text{unmark record } p \\
    &\quad \text{else} \\
    &\quad\quad p.f_1 := \text{freelist} \\
    &\quad\quad \text{freelist} := p \\
    &\quad p := p + \text{sizeof(record } p) \\
\end{align*}
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 ∈ 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)
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:
\[ \approx 100 \text{ instructions for a small object!} \]

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.