38: Garbage Collection — Introduction

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Dynamic Memory Management

The run-time system linked in with the generated code should contain routines for allocation/deallocation of dynamic memory.

Pascal, C, C++, Modula-2  **Explicit deallocation** of dynamic memory only. I.e. the programmer is required to keep track of all allocated memory and when it’s safe to free it.

Eiffel  **Implicit deallocation** only. Dynamic memory which is no longer used is recycled by the garbage collector.

Ada  Implicit or explicit deallocation (implementation defined).

Modula-3  Implicit and explicit deallocation (programmer’s choice).
In a language such as C or Pascal, there are three ways to allocate memory:

1. Static allocation. Global variables are allocated at compile time, by reserving

2. Stack allocation. The stack is used to store activation records, which holds procedure call chains and local variables.

3. Dynamic allocation. The user can create new memory at will, by calling a new or (in unix) malloc procedure.

The compiler and run-time system divide the available address space (memory) into three sections, one for each type of allocation:
Memory Management...

1. The static section is generated by the compiler and cannot be extended at run-time. Called the uninitialized data section in unix’s a.out.

2. The stack. The stack grows and shrinks during execution, according to the depth of the call chain. Infinite recursion often leads to stack overflow. Large parameters can also result in the program running out of stack space.

3. The heap. When the program makes a request for more dynamic memory (by calling `malloc`, for example), a suitable chunk of memory is allocated on the heap.
Memory Management...

- **Static allocation** – Global variables
- **Stack allocation** – Procedure call chains, Local variables.
- **Dynamic allocation** – NEW, malloc, On the heap.

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Stack

Heap
Interface to Dynamic allocation

C, C++: `char* malloc(size)` and `free(char*)` are standard library routines.

Pascal: `new(pointer var)` and `dispose(pointer var)` are built-in standard procedures.

Java: `new(class name)` is a standard function.

LISP: `cons` creates new cells:
Explicit Deallocation

- Pascal’s `new/dispose`, Modula-2’s `ALLOCATE/DEALLOCATE`, C’s `malloc/free`, C++’s `new/delete`, Ada’s `new/unchecked_deallocation` (some implementations).

- **Problem 1:** Dangling references: \( p = \text{malloc}(); \ q = p; \ \text{free}(p); \).

- **Problem 2:** Memory leaks, Heap fragmentation.
Memory Leaks

DEFINITION MODULE Complex;
    TYPE T;
    PROCEDURE Create (Re, Im : REAL) : T;
    PROCEDURE Add (A, B : T) : T;
END Complex.

IMPLEMENTATION MODULE Complex;
    TYPE T = POINTER TO RECORD
        Re, Im : REAL; END;
    PROCEDURE Create (Re, Im : REAL) : T;
    BEGIN
        NEW(x); x^.Re := Re; x^.Im := Im;
        RETURN x; END Create;
    PROCEDURE Add (A, B : T) : T;
    BEGIN
        NEW(x); x^.Re := ···; x^.Im := ···;
        RETURN x; END Add;
    END Complex;
Memory Leaks...

MODULE Use;
    IMPORT Complex;
    VAR a, b, c, d : Complex.T;
BEGIN
    a := Complex.Create(1.0, 2.4);
    b := Complex.Create(3.4, 4.0);
    c := Complex.Create(9.4, 6.6);
    d := Complex.Add(a, Complex.Add(b, c));
END Use.

Complex.Add(b, c) creates a new object which can never be reclaimed.
Without compaction the last allocation will fail, even though enough memory is available.
Implicit Deallocation

- LISP, Prolog – Equal-sized cells; No changes to old cells.
- Eiffel, Modula-3 – Different-sized cells; Frequent changes to old cells.

When do we GC?
- **Stop-and-copy** Perform a GC whenever we run out of heap space (Modula-3).
- **Real-time/Incremental** Perform a partial GC for each pointer assignment or `new` (Eiffel, Modula-3).
- **Concurrent** Run the GC in a separate process.
Implicit Deallocation...

- Fragmentation – Compact the heap as a part of the GC, or only when the GC fails to return a large enough block.

- Algorithms: Reference counts, Mark/sweep, Copying, Generational.
Algorithm: Reference Counts

- An extra field is kept in each object containing a count of the number of pointers which point to the object.
- Each time a pointer is made to point to an object, that object’s count has to be incremented.
- Similarly, every time a pointer no longer points to an object, that object’s count has to be decremented.
- When we run out of dynamic memory we scan through the heap and put objects with a zero reference count back on the free-list.
- Maintaining the reference count is costly. Also, circular structures (circular linked lists, for example) will not be collected.
Algorithm: Reference Counts...

- Every object records the number of pointers pointing to it.
- When a pointer changes, the corresponding object’s reference count has to be updated.
- GC: reclaim objects with a zero count. Circular structures will not be reclaimed.
Algorithm: Reference Counts...

$\text{NEW}(p)$ is implemented as:

```
malloc(p); p↑.rc := 0;
```

$p↑.next:=q$ is implemented as:

```
z := p↑.next;
if z ≠ nil then
  z↑.rc--; if z↑.rc = 0 then reclaim z↑ endif;
endif;
p↑.next := q;
q↑.rc++;
```

This code sequence has to be inserted by the compiler for every pointer assignment in the program. This is very expensive.
Readings and References

- Read Scott, pp. 395–401.
- Aho, Hopcroft, Ullman. Data Structures and Algorithms, Chapter 12, Memory Management.
Readings and References...
