Compiler Construction

Lecture 18: Code Generation IV (Implementation of Dynamic Data Structures)

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https://moves.rwth-aachen.de/teaching/ws-1819/cc/

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Modified Syntax of EPL

Definition (Modified syntax of EPL)

The modified syntax of EPL is defined as follows (where $n \geq 1$):

$$
\begin{array}{lll}
\mathbb{Z}: & z & \text{(* } z \text{ is an integer *)} \\
\mathbb{B}: & b ::= \texttt{true} \mid \texttt{false} & \text{(* } b \text{ is a Boolean *)} \\
\mathbb{R}: & r & \text{(* } r \text{ is a real number *)} \\
Con: & c ::= z \mid b \mid r & \text{(* } c \text{ is a constant *)} \\
Ide: & I, J & \text{(* } I, J \text{ are identifiers *)} \\
Type: & T ::= \texttt{bool} \mid \texttt{int} \mid \texttt{real} \mid I \mid \texttt{array}[z_1 \texttt{..} z_2] \texttt{ of } T \mid & \\
 & \quad \texttt{record } I_1 \texttt{:} T_1 \texttt{;} \ldots \texttt{;} I_n \texttt{:} T_n \texttt{ end} & \\
Var: & V ::= I \mid V[E] \mid V.I & \\
Exp: & E ::= c \mid V \mid E_1 + E_2 \mid E_1 < E_2 \mid E_1 \texttt{ and } E_2 \mid \ldots & \\
Cmd: & C ::= V \texttt{:=} E \mid C_1 \texttt{;} C_2 \mid \texttt{if } E \texttt{ then } C_1 \texttt{ else } C_2 \mid \texttt{while } E \texttt{ do } C & \\
Dcl: & D ::= D_C\ D_T\ D_V & \\
 & D_C ::= \varepsilon \mid \texttt{const } I_1 \texttt{ := } c_1 \texttt{;} \ldots \texttt{;} I_n \texttt{ := } c_n \texttt{;} & \\
 & D_T ::= \varepsilon \mid \texttt{type } I_1 \texttt{ := } T_1 \texttt{;} \ldots \texttt{;} I_n \texttt{ := } T_n \texttt{;} & \\
 & D_V ::= \varepsilon \mid \texttt{var } I_1 \texttt{ : } T_1 \texttt{;} \ldots \texttt{;} I_n \texttt{ : } T_n \texttt{;} & \\
Pgm: & P ::= D\ C &
\end{array}
$$

Pseudo-Dynamic Data Structures

Variant Records

Example 18.1 (Variant records in Pascal)

```
TYPE Coordinate = RECORD
                    nr: INTEGER;
                    CASE type: (cartesian, polar) OF
                      cartesian: (x, y: REAL);
                      polar: (r : REAL; phi: INTEGER )
                    END
                  END;
VAR pt: Coordinate;
pt.type := cartesian; pt.x := 0.5; pt.y := 1.2;
```

Implementation:

- Allocate memory for “biggest” variant
- Share memory between variant fields

Pseudo-Dynamic Data Structures

Dynamic Arrays

Example 18.2 (Dynamic arrays in Pascal)

```
FUNCTION Sum(VAR a: ARRAY OF REAL): REAL;
  VAR
    i: INTEGER; s: REAL;
  BEGIN
    s := 0.0; FOR i := 0 to HIGH(a) do s := s + a[i] END; Sum := s
  END
```

Implementation:

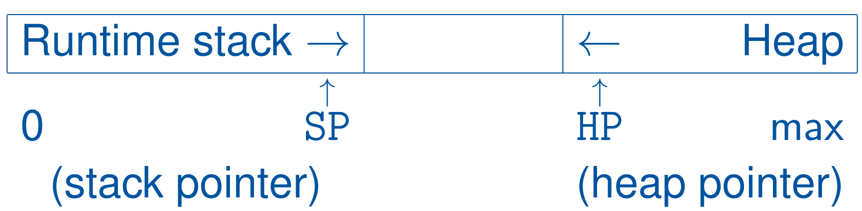
- Memory requirements unknown at compile time but determined by actual function/procedure parameters $\Longrightarrow$ no heap required
- Use array descriptor with following fields as parameter value:
  - starting memory address of array
  - size of array
  - lower index of array (possibly fixed to 0)
  - upper index of array (actually redundant)
- Use data stack or index register to access array elements

Dynamic Memory Allocation I

- Dynamically manipulated data structures (lists, trees, graphs, ...)
- So far: creation of (static) objects by declaration
- Now: creation of (dynamic) objects by explicit memory allocation
- Access by (implicit or explicit) pointers
- Deletion by explicit deallocation or garbage collection
  (= automatic deallocation of unreachable objects)
- Implementation: runtime stack not sufficient
  (lifetime of objects generally exceeds lifetime of procedure calls)

$\Rightarrow$ new data structure: heap

- Simplest form of organisation:



Dynamic Memory Allocation II

- New instruction: `NEW` (“`malloc`”, ...)
  - allocates *n* memory cells (where *n* = topmost value of runtime stack)
  - returns address of first cell
  - formal semantics (`SP` = stack pointer, `HP` = heap pointer, `<.>` = dereferencing):

```
if HP - <SP> > SP
  then HP := HP - <SP>; <SP> := HP
  else error("memory overflow")
```

- But: collision check also required for every operation which increases `SP` (in particular, for expression evaluations)
- Efficient solution: add extreme stack pointer `EP`
  - points to topmost `SP` which will be used by current procedure (except for calls)
  - statically computable at compile time for each procedure
  - set by procedure entry code upon call
  - modified semantics of `NEW`:

```
if HP - <SP> > EP
  then HP := HP - <SP>; <SP> := HP
  else error("memory overflow")
```

Memory Deallocation

Releasing of memory areas that have become unused

- explicitly by programmer
- automatically by runtime system (garbage collection)

Management of deallocated memory areas (chunks) by free list

- usually organised as doubly-linked list, possible ordered by size
- goal: reduction of fragmentation
  (= heap memory split in large number of non-contiguous chunks)
- coalescing of contiguous chunks
- allocation strategies: first-fit vs. best-fit

Memory Deallocation

Explicit Deallocation

- Manually releasing memory areas that have become unused
  - Pascal: `dispose`
  - C: `free`
- **Problems** with manual deallocation:
  - memory leaks:
    - failing to eventually delete data that cannot be referenced anymore
    - critical for long-running/reactive programs (operating systems, server code, ...)
  - dangling pointer dereference (“use after free”):
    - referencing of deleted data
    - may lead to runtime error (if deallocated pointer reset to nil) or produce side effects (if deallocated pointer keeps value and storage later re-used)

$\Rightarrow$ Adopt programming conventions (object ownership, ...) or use automatic deallocation

Garbage Collection

- Garbage = data that cannot be referenced (anymore)
- Garbage collection = automatic deallocation of unreachable data
- Supported by many programming languages:
  - object-oriented: Java, Smalltalk
  - functional: Lisp (first GC), ML, Haskell
  - logic: Prolog
  - scripting: Perl
- Design goals for garbage collectors:
  - execution time: no significant increase of application runtime
  - space usage: avoid memory fragmentation
  - pause time: (worst-case) maximal pause time of application program caused by garbage collection (especially in real-time applications)

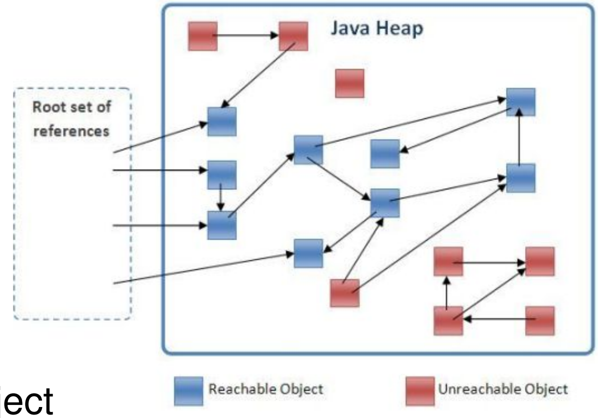
Garbage Collection

Preliminaries

- Object = allocated entity
- Object has type known at runtime, defining
  - size of object
  - references to other objects

  $\Longrightarrow$ excludes type-unsafe languages that allow manipulation of pointers (C, C++)
- Reference always to address at beginning of object
  ($\Longrightarrow$ all references to an object have same value)
- Mutator = application program modifying objects in heap
  - creates objects by acquiring storage
  - introduces/drops references to existing objects
- Objects become garbage when not (indirectly) reachable by mutator

Reachability of Objects



- Root set = heap data that is directly accessible by mutator
  - for Java: static field members and variables on stack
  - yields directly reachable objects
- Every object with a reference that is stored in a reachable object is indirectly reachable
- Mutator operations that affect reachability:
  - object allocation: memory manager returns reference to new object
    - creates new reachable object
  - parameter passing and return values: passing of object references from calling site to called procedure or vice versa
    - propagates reachability of objects
  - reference assignment: assignments `p := q` with references `p` and `q`
    - creates second reference to object referred to by `q`, propagating reachability
    - destroys orginal reference in `p`, potentially causing unreachability
  - procedure return: removes local variables
    - potentially causes unreachability of objects
- Objects becoming unreachable can cause more objects to become unreachable

Identifying Unreachable Objects

Principal approaches:

- Catch program steps that turn reachable into unreachable objects
  $\Longrightarrow$ reference counting
- Periodically locate all reachable objects; others then unreachable
  $\Longrightarrow$ mark-and-sweep

Reference-Counting Garbage Collectors I

Working principle

- Add reference count field to each heap object (= number of references to that object)
- Mutator operations maintain reference count:
  - object allocation: set reference count of new object to 1
  - parameter passing: increment reference count of each object passed to procedure (multiple increment if shared)
  - reference assignment `p := q`: decrement/increment reference count of object referred to by `p`/`q`
  - procedure return: decrement reference count of each object that a local variable refers to (multiple decrement if shared)
- Moreover: transitive loss of reachability
  - when reference count of object becomes zero:
    decrement reference count of each object pointed to (and add object storage to free list)

Example 18.3

(on the board)

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Reference-Counting Garbage Collectors II

Advantage: Incrementality

- collector operations spread over mutator's computation
  - short pause times (good for real-time/interactive applications)
  - immediate collection of garbage (low space usage)
- exception: transitive loss of reachability (reference removal may produce further garbage)
- but: recursive modification can be deferred

Disadvantages

- Incompleteness: cannot collect unreachable cyclic data structures (cf. Example 18.3)
- High overhead:
  - additional operations for assignments and procedure calls/exits
  - proportional to number of mutator steps (and not to number of heap objects)

Conclusion

Use for real-time/interactive applications

Mark-and-Sweep Garbage Collectors I

Working principle

- Mutator runs and makes allocation requests
- Collector runs periodically (typically when space exhausted/at critical threshold)
  - computes set of reachable objects (by attaching reachability flags)
  - reclaims storage for objects in complement set

Mark-and-Sweep Garbage Collectors II

Algorithm 18.4 (Mark-and-sweep garbage collection)

Input: heap *Heap*, root set *Root*, free list *Free*

Procedure:
1. (* Marking phase *)
   for each o in *Heap*, let $r_o := \text{true}$ iff o referenced by *Root* (* initialise r flags *)
2. let $W := \{o \mid r_o = \text{true}\}$ (* initialise working set *)
3. while $o \in W \neq \emptyset$ do
   i. let $W := W \setminus \{o\}$
   ii. for each o' referenced by o with $r_{o'} = \text{false}$, let $r_{o'} = \text{true}$; $W := W \cup \{o'\}$
4. (* Sweeping phase *)
   for each o in *Heap* with $r_o = \text{false}$, add o to *Free*

Output: modified free list

Example 18.5

(on the board)

Mark-and-Sweep Garbage Collectors III

Advantages

- Completeness: identifies all unreachable objects
- Time complexity proportional to number of objects in heap

Disadvantage: “stop-the-world” style

- May introduce long pauses into mutator execution (sweeping inspects complete heap)

Solution: refine to short-pause garbage collection

- Incremental collection: divide work in time by interleaving mutation and collection
- Partial collection: divide work in space by collecting subset of garbage at a time
- see Chapter 7 of A.V. Aho, M.S. Lam, R. Sethi, J.D. Ullman: *Compilers – Principles, Techniques, and Tools; 2nd ed.*, Addison-Wesley, 2007

Interface Between Compiler and Garbage Collector

Compiler interface

Compiler interacts with garbage collector by

- generating code for memory allocation
- generating description of root locations (for each garbage-collecting cycle)
- generating description of memory layout of objects
- for (some variants of) incremental collection:
  generating instructions to implement read/write barriers