Compiler Construction

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

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Summer Semester 2014

Outline

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;
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Implementation:

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

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
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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 by 0)
  - upper index of array (actually redundant)
- Use data stack or index register to access array elements

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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)

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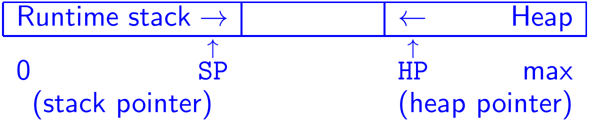
- Access by (implicit or explicit) pointers
- Deletion by explicit deallocation or garbage collection
  (= automatic deallocation of unreachable objects)
- Implementation: runtime stack not sufficient
  (lifetime of objects generally exceeds lifetime of procedure calls)

$\Longrightarrow$ new data structure: heap

- Simplest form of organization:



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")
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- But: collision check required for every operation which increases `SP` (e.g., expression evaluations)
- Efficient solution: add extreme stack pointer `EP`
  - points to topmost `SP` which will be used in the computation of current procedure
  - statically computable at compile time
  - set by procedure entry code
  - modified semantics of `NEW`:

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if HP - <SP> > EP
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Management of deallocated memory areas by free list (usually doubly-linked list)

- goal: reduction of fragmentation (= heap memory splitted in large number of non-contiguous free areas)
- coalescing of contiguous areas
- allocation strategies: first-fit vs. best-fit

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- 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:
    - 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 reallocated)

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$\Longrightarrow$ Adopt programming conventions (object ownership) or use automatic deallocation

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  - functional: Lisp (first GC), ML, Haskell
  - logic: Prolog
  - scripting: Perl
- Design goals for garbage collectors:
  - execution time: no significant increase of application run time
  - space usage: avoid memory fragmentation
  - pause time: minimize maximal pause time of application program caused by garbage collection (especially in real-time applications)

Preliminaries

- Object = allocated entity
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- Reference always to address at beginning of object ($\Longrightarrow$ all references to an object have same value)
- Mutator $=$ application program modifying objects in heap
  - creation of objects by acquiring storage
  - introduce/drop 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
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- 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
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- 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

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Reference-Counting Garbage Collectors I

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- Mutator operations maintain reference count:
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Example 18.3

(on the board)

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 (removing a reference may render many objects unreachable)
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  - proportional to number of mutator steps
    (and not to number of heap objects)

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Conclusion: use for real-time/interactive applications

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Mark-and-Sweep Garbage Collectors I

Working principle:

- Mutator runs and makes allocation requests
- Collector runs periodically
  (typically when space exhausted/below critical threshold)
  - computes set of reachable objects
  - 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* $Free$

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   for each o *in* $Heap$, *(* initialize reachability bit *)*
   let $r_o := \text{true}$ *iff* o *referenced by* $Root$
2. *let* $W := \{o \mid r_o = \text{true}\}$ *(* working set *)*
3. *while* $o \in W \neq \emptyset$ *do*
   1. *let* $W := W \setminus \{o\}$
   2. *for each* o' *referenced by* o *with* $r_{o'} = \text{false}$,
      let $r_{o'} = \text{true}; W := W \cup \{o'\}$
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(on the board)

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(sweeping phase inspects complete heap)

Mark-and-Sweep Garbage Collectors III

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Conclusion: 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)