Chapter 6

Symbol tables

Course “Compiler Construction”
Martin Steffen
Spring 2024

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Chapter 6

Learning Targets of Chapter “Symbol tables”.

1. symbol table data structure
2. design and implementation choices
3. how to deal with scopes
4. connection to attribute grammars

Chapter 6

Outline of Chapter “Symbol tables”.

Introduction

Symbol table design and interface

Implementing symbol tables

Block-structure, scoping, binding, name-space organization

Symbol tables as attributes in an AG

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Introduction

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Symbol tables, in general

- central data structure
- "data base" or repository associating properties with "names" (identifiers, symbols)[1]
- declarations
  - constants
  - type declarationss
  - variable declarations
  - procedure declarations
  - class declarations
  - ...
- *declaring* occurrences vs. *use* occurrences of names (e.g. variables)

[1]Remember the (general) notion of "attribute".

Storing information

- goal: associate attributes (properties) to syntactic elements (names/symbols)
- storing once calculated: (costs memory) $\leftrightarrow$ recalculating on demand (costs time)
- most often: storing preferred
- but: can't I store it in the nodes of the *AST*?
    - remember: *attribute grammar*
    - however, fancy attribute grammars with many rules and complex synthesized/inherited attribute (whose evaluation traverses up and down and across the tree):
        - might be intransparent
        - storing info *in* the tree: might not be efficient

$\Rightarrow$ central repository (= symbol table) better

So: do I need a symbol table?

In theory, alternatives exists; in practice, yes, symbol tables is the way to go; most compilers do use symbol tables.

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Symbol table design and interface

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Symbol table as abstract data type

- separate interface from implementation
- ST: "nothing else" than a lookup-table or *dictionary*
- associating "keys" with "values"
- here: keys = names (id's, symbols), values the attribute(s)

Schematic interface: two core functions (+ more)

- *insert*: add new binding
- *lookup*: retrieve

besides the core functionality:

- structure of (different?) *name spaces* in the implemented language, *scoping* rules
- typically: not one single "flat" namespace ⇒ typically not one big *flat* look-up table

⇒ influence on the design/interface of the ST (and indirectly the choice of implementation)

- necessary to "delete" or "hide" information (*delete*)

Two main philosophies

traditional table(s)

- central repository, separate from AST
- interface
  - $lookup(name)$,
  - $insert(name, decl)$,
  - $delete(name)$
- last 2: update ST for declarations *and* when entering/exiting *blocks*

decls. in the AST nodes

- do look-up ⇒ tree-*search*
- insert/delete: implicit, depending on relative positioning in the tree
- look-up:
  - efficiency?
  - however: optimizations exist, e.g. "redundant" extra table (similar to the traditional ST)

Here, for concreteness, *declarations* are the attributes stored in the ST. In general, it is not the only possible stored attribute. Also, there may be more than one ST.

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Implementing symbol tables

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Data structures to implement a symbol table

- different ways to implement *dictionaries* (or look-up tables etc.)
  - simple (association) lists
  - trees
    - balanced trees (AVL, B, red-black, binary-search trees)
  - hash tables, often method of choice
  - functional vs. imperative implementation
- careful choice influences efficiency
- influenced also by the language being implemented
- in particular, by its scoping rules (or the structure of the name space in general) etc.[2]

[2] Also the language used for implementation (and the availability of libraries therein) may play a role.

Nested block / lexical scope

for instance: *C*

```
{ int i; ... ; double d;
  void p(...);
  {
     int i;
     ...
  }
  int j;
  ...
```

more later

Blocks in other languages

TEX

```
\def\x{a}
{
  \def\x{b}
  \x
}
\x
\bye
```

LATEX

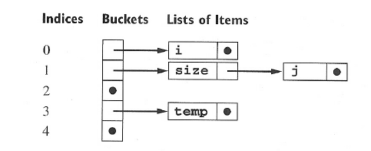
```
\documentclass{article}
\newcommand{\x}{a}
\begin{document}
\x
{\renewcommand{\x}{b}
  \x
}
\x
\end{document}
```

But remember: static vs. dynamic binding (see later)

Hash tables

- classical and common implementation for STs
- "hash table":
  - generic term itself, different general forms of HTs exists
  - e.g. *separate chaining* vs. *open addressing*

Separate chaining



Code snippet

```
{
  int temp;
  int j;
  real i;
  void size (....) {
    {
        ....
    }
  }
}
```

Block structures in programming languages

- almost no language has one global namespace (at least not for variables)
- pretty old concept, seriously started with ALGOL60

Block

- "region" in the program code
- delimited often by `{` and `}` or `BEGIN` and `END` or similar
- organizes the scope of declarations (i.e., the name space)
- can be nested

Block-structured scopes (in C)

```c
int i, j;

int f(int size)
{ char i, temp;
  ...
  { double j;
    ..
  }
  ...
  { char * j;
    ...
  }
}
```

Nested procedures in Pascal

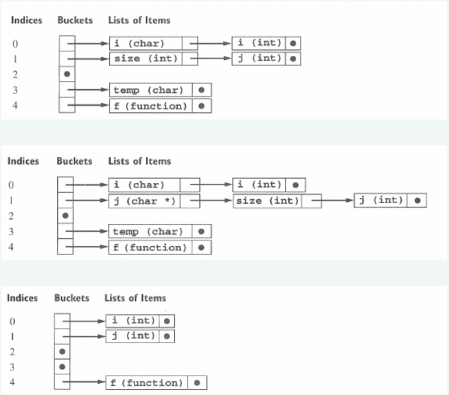
```
program Ex;
var i,j : integer

function f(size : integer) : integer;
var i, temp : char;
   procedure g;
   var j : real;
   begin
      ...
   end;
   procedure h;
   var j : ^char;
   begin
      ...
   end;

begin (* f's body *)
 ...
end;
begin  (* main program *)
   ...
end.
```

Block-strucured via stack-organized separate chaining

C code snippet

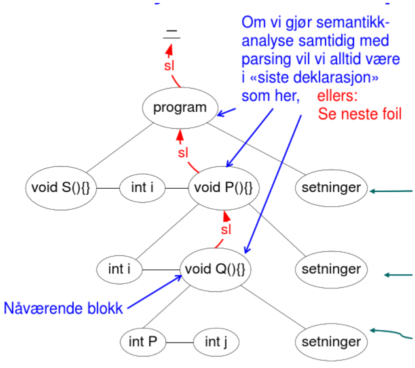
```
int i, j;

int f(int size)
{ char i, temp;
  ...
  { double j;
     ..
  }
  ...
  { char * j;
     ...
  }
}
```

"Evolution" of the hash table



Using the syntax tree for lookup following (static links)

```
lookup (string n) {
   k = current, surrounding block
   do                // search for n in  decl for block k;
      k = k.sl       // one nesting level  up
   until found or k == none
}
```

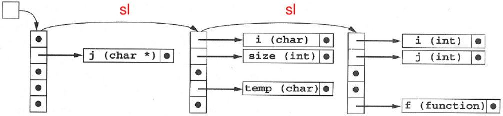


Alternative representation

- arrangement different from 1 table with stack-organized external chaining
- each *block* with its own hash table.
- standard hashing within each block
- static links to link the block levels

⇒ "tree-of-hashtables"

- AKA: *sheaf-of-tables* or *chained symbol tables* representation



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Block-structure, scoping, binding, name-space organization

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Block-structured scoping with chained symbol tables

- remember the *interface*
- look-up: following the static link (as seen)
- Enter a block
  - create new (empty) symbol table
  - set static link from there to the "old" (= previously current) one
  - set the current block to the newly created one
- at exit
  - move the *current block* one level up
  - note: no *deletion* of bindings, just made *inaccessible*

Lexical scoping & beyond

- block-structured lexical scoping: central in programming languages (ever since ALGOL60 ...)
- but: other scoping mechanisms exist (and exist side-by-side)
- example: C^{++}
  - member functions *declared* inside a class
  - *defined* outside
- still: method supposed to be able to access names defined in the *scope of the class* definition (i.e., other members, e.g. using `this`)

C^{++} class and member function

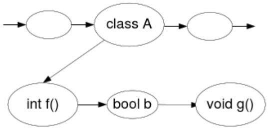
```
class A {
  ... int f(); ... // member funct
}

A::f() {}
// def. of f ``in'' A
```

Java analogon

```
class A {
    int f() {...};
    boolean b;
    void h() {...};
}
```

Scope resolution in C^{++}

- class *name* introduces a name for the scope[3] (not only in C^{++})
- scope resolution operator `::`
- allows to explicitly refer to a "scope"'
- to implement
  - such flexibility,
  - also for *remote access* like `a.f()`
- declarations are kept separately for each block (e.g. one hash table per class, record, etc., appropriately chained up)



[3] Besides that, class names themselves are subject to scoping themselves, of course ...

Same-level declarations

Same level

```
typedef int i
int i;
```

- often forbidden (e.g. in C)
- *insert*: requires check (= *lookup*) first

Sequential vs. "collateral" declarations

```
int i = 1;
void f(void)
  { int i = 2, j = i+1,
      ...
  }
```

```
let i = 1;;
let i = 2 and j = i+1;;

print_int(j);;
```

Recursive declarations/definitions

- for instance for functions/procedures
- also classes and their members

Direct recursion

```
int gcd(int n, int m) {
  if    (m == 0) return n;
  else return gcd(m,n % m);
}
```

Indirect recursion/mutual recursive def's

```
void f(void) {
    ... g() ... }
void g(void) {
  ... f() ...}
```

Mutual recursive definitions

```
void g(void);  /* function prototype decl. */

void f(void) {
    ... g() ... }
void g(void) {
  ... f() ...}
```

- different solutions possible
- Pascal: *forward declarations*
- or: treat all function definitions (within a block or similar) as mutually recursive
- or: special grouping syntax

Example syntax-es for mutual recursion

ocaml

```
let rec  f (x:int): int  =
    g(x+1)
and g(x:int) : int =
    f(x+1);;
```

Go

```
func f(x int) (int) {
        return g(x) +1
}
func g(x int) (int) {
        return f(x) −1
}
func main() {
        f(0)
```

Static vs dynamic scope

- concentration so far on:
  - lexical scoping/block structure, static binding
  - some minor complications/adaptations (recursion, duplicate declarations, ...)
- big variation: dynamic binding / dynamic scope
- for variables: *static* binding/ *lexical scoping* the norm
- however: cf. late-bound methods in OO

Static scoping in C

Code snippet

```
#include <stdio.h>

int i = 1;
void f(void) {
  printf("%d\n",i);
}

void main(void) {
  int  i = 2;
  f();
  return 0;
}
```

which value of `i` is printed then?

Dynamic binding example

```
void Y () {
  int i;
  void P() {
    int i;
    ...;
    Q();
  }
  void Q(){
    ...;
    i := 5;   // which i is meant?
  }
  ...;

  P();
  ...;
}
```

Dynamic binding example

```
1  void Y () {
2    int i;
3    void P() {
4      int i;
5      ...;
6     Q();
7    }
8    void Q(){
9      ...;
10     i := 5;  // which i is meant?
11   }
12   ...;
13
14   P();
15   ...;
16 }
```

for dynamic binding: the one from line 4

Static or dynamic?

TEX

```
\def\astring{a1}
\def\x{\astring}
\x
{
  \def\astring{a2}
  \x
}
\x
\bye
```

LATEX

```
\documentclass{article}
\newcommand{\astring}{a1}
\newcommand{\x}{\astring}
\begin{document}
\x
{
  \renewcommand{\astring}{a2}
  \x
}
\x
\end{document}
```

emacs lisp (not Scheme)

```
(setq astring "a1")   ;; "assignment"
(defun x() astring)   ;; define "variable" x"
(x)                   ;; read value
(let ((astring "a2"))
     (x))
```

```
package main
import ("fmt")

var f = func ()    {
  var x = 0
  var g = func() {fmt.Printf(" x = %v", x)}
  x = x + 1
    {
      var x = 40                    // local variable
      g()
      fmt.Printf(" x = %v", x)}
}
func main() {
  f()
}
```

Static binding is not about "value"

- the "static" in static binding is about
  - binding to the declaration / memory location,
  - not about the *value*
- nested functions used in the example (Go)
- `g` declared inside `f`

```
package main
import ("fmt")

var f = func ()   {
  var x = 0
  var g = func() {fmt.Printf(" x = %v", x)}
  x = x + 1
    {
      var x = 40                    // local variable
      g()
      fmt.Printf(" x = %v", x)}
}
func main() {
  f()
}
```

Static binding can become tricky

```
package main
import ("fmt")

var f = func () (func (int) int)  {
        var x = 40                          // local variable
        var g = func (y int) int { // nested function
                return x + 1
        }
        x = x+1                            // update x
        return g                           // function as return value
}

func main() {
        var x = 0
        var h = f()
        fmt.Println(x)
        var r = h (4)
        fmt.Printf(" r = %v", r)
}
```

- example uses *higher-order* functions

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Symbol tables as attributes in an AG

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Nested lets in ocaml

$$
\begin{array}{rcl}
S & \rightarrow & \mathit{exp} \\
\mathit{exp} & \rightarrow & (\ \mathit{exp}\ ) \ \mid\ \mathit{exp} + \mathit{exp} \ \mid\ \mathbf{id} \ \mid\ \mathit{num} \ \mid\ \mathbf{let}\ \ \mathit{dec\text{-}list}\ \mathbf{in}\ \ \mathit{exp} \\
\mathit{dec\text{-}list} & \rightarrow & \mathit{dec\text{-}list}\mathbf{,}\ \ \mathit{decl} \ \mid\ \mathit{decl} \\
\mathit{decl} & \rightarrow & \mathbf{id} = \mathit{exp}
\end{array}
$$

Expressions and declarations: grammar

```
let x = 2 and y = 3 in
  (let x = x+2 and y =
       (let z = 4 in x+y+z)
   in print_int (x+y))
```

Informal rules governing declarations

1. no identical names in the same let-block
2. used names must be declared
3. most-closely nested binding counts
4. sequential (non-simultaneous) declaration ($\neq$ ocaml/ML/Haskell ...)

```
let x = 2, x = 3 in x + 1         (* no, duplicate  *)

let x = 2  in  x+y                (* no, y unbound *)

let x = 2 in (let x = 3 in x)    (* decl. with 3 counts *)

let x = 2, y = x+1                (* one after the other *)
in  (let x = x+y,
         y = x+y
     in y)
```

Goal

Design an *attribute grammar* (using a *symbol table*) specifying those rules. Focus on: error attribute.

Attributes and ST interface

symbol	attributes	kind
exp	symtab	inherited
	nestlevel	inherited
	err	synthesized
dec-list, *decl*	intab	inherited
	outtab	synthesized
	nestlevel	inherited
id	name	injected by scanner

Symbol table functions

- insert(tab,name,lev): returns a new table
- isin(tab,name): boolean check
- lookup(tab,name): gives back *level*
- emptytable: you have to start somewhere
- errtab: error from declaration (but not stored as attribute)

Attribute grammar (1): expressions

Grammar Rule	Semantic Rules
$S \rightarrow exp$	$exp.symtab = emptytable$ $exp.nestlevel = 0$ $S.err = exp.err$
$exp_1 \rightarrow exp_2$ **+** exp_3	$exp_2.symtab = exp_1.symtab$ $exp_3.symtab = exp_1.symtab$ $exp_2.nestlevel = exp_1.nestlevel$ $exp_3.nestlevel = exp_1.nestlevel$ $exp_1.err = exp_2.err$ **or** $exp_3.err$
$exp_1 \rightarrow$ **(** exp_2 **)**	$exp_2.symtab = exp_1.symtab$ $exp_2.nestlevel = exp_1.nestlevel$ $exp_1.err = exp_2.err$
$exp \rightarrow$ **id**	$exp.err =$ **not** $isin(exp.symtab,$ **id**$.name)$ } 2
$exp \rightarrow$ **num**	$exp.err =$ **false**
$exp_1 \rightarrow$ **let** $dec\text{-}list$ **in** exp_2	$dec\text{-}list.intab = exp_1.symtab$ $dec\text{-}list.nestlevel = exp_1.nestlevel + 1$ $exp_2.symtab = dec\text{-}list.outtab$ } 3 $exp_2.nestlevel = dec\text{-}list.nestlevel$ $exp_1.err = (decl\text{-}list.outtab = errtab)$ **or** $exp_2.err$

- note: expressions in let's can introduce scopes themselves!
- interpretation of nesting level: expressions vs. declarations

Attribute grammar (2): declarations

$dec\text{-}list_1 \rightarrow dec\text{-}list_2$ **,** $decl$	$dec\text{-}list_2.intab = dec\text{-}list_1.intab$ $dec\text{-}list_2.nestlevel = dec\text{-}list_1.nestlevel$ $decl.intab = dec\text{-}list_2.outtab$ $decl.nestlevel = dec\text{-}list_2.nestlevel$ $dec\text{-}list_1.outtab = decl.outtab$	4 (next to: $decl.intab = dec\text{-}list_2.outtab$; $decl.nestlevel = dec\text{-}list_2.nestlevel$)
$dec\text{-}list \rightarrow decl$	$decl.intab = dec\text{-}list.intab$ $decl.nestlevel = dec\text{-}list.nestlevel$ $dec\text{-}list.outtab = decl.outtab$	4
$decl \rightarrow$ **id** = exp	$exp.symtab = decl.intab$ $exp.nestlevel = decl.nestlevel$ $decl.outtab =$ **if** ($decl.intab = errtab$) **or** $exp.err$ **then** $errtab$ **else if** ($lookup(decl.intab,$ **id** $.name) =$ $decl.nestlevel$) **then** $errtab$ **else** $insert(decl.intab,$ **id** $.name, decl.nestlevel)$	1 (next to: else if … then $errtab$)

Final remarks concerning symbol tables

- *strings* as symbols i.e., as keys in the ST: might be improved
- name spaces can get complex in modern languages,
- more than one “hierarchy”
  - lexical blocks
  - inheritance or similar
  - (nested) modules
- not all bindings (of course) can be solved at compile time: *dynamic binding*
- can e.g. variables and types have same name (and still be distinguished)
- *overloading* (see next slide)

Final remarks: name resolution via overloading

- corresponds to "in abuse of notation" in textbooks
- disambiguation not by name, but differently especially by "argument types" etc.
- variants :
  - method or function overloading
  - operator overloading
  - user defined?

```
i + j    // integer addition
r + s    // real-addition

void f(int i)
void f(int i,int j)
void f(double r)
```

References I

Bibliography

[1] Louden, K. (1997). *Compiler Construction, Principles and Practice*. PWS Publishing.