Symbol tables are used to describe and analyse definitions and uses of identifiers.

Grammars are too weak; the language:

\[ \{ w \omega \mid w \in \Sigma^* \} \]

is not context-free.

A symbol table is a map from identifiers to meanings:

<table>
<thead>
<tr>
<th></th>
<th>local</th>
<th>int</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>done</td>
<td>local</td>
</tr>
<tr>
<td></td>
<td>insert</td>
<td>method</td>
</tr>
<tr>
<td>x</td>
<td>List</td>
<td>class</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>formal</td>
</tr>
<tr>
<td></td>
<td>:</td>
<td>:</td>
</tr>
</tbody>
</table>

We must construct a symbol table for every program point.

Using symbol tables to analyse JOOS:

- which classes are defined;
- what is the inheritance hierarchy;
- is the hierarchy well-formed;
- which fields are defined;
- which methods are defined;
- what are the signatures of methods;
- are identifiers defined twice;
- are identifiers defined when used; and
- are identifiers used properly?

Static, nested scope rules:

The standard of modern languages.
Old-style one-pass technology:

Still haunts some languages:

void weedPROGRAM(PROGRAM *p);
void weedCLASSFILE(CLASSFILE *c);
void weedCLASS(CLASS *c);

Forward declarations enable recursion.

The symbol table behaves like a stack:

The symbol table can be implemented as a simple stack:
- pushSymbol(SymbolTable *t, char *name, ...)
- popSymbol(SymbolTable *t)
- getSymbol(SymbolTable *t, char *name)

But how do we detect multiple definitions of an identifier at the same level?

Use bookmarks and a cactus stack:
- scopeSymbolTable(SymbolTable *t)
- putSymbol(SymbolTable *t, char *name, ...)
- unscopeSymbolTable(SymbolTable *t)
- getSymbol(SymbolTable *t, char *name)

Still just linear search, though.
Implement symbol tables as a cactus stack of hash tables:

- each hash table contains the identifiers in a level;
- push a new hash table when a level is entered;
- each identifier is entered in the top hash table;
- it is an error if it is already there;
- a use of an identifier is looked up in the hash tables from top to bottom;
- it is an error if it is not found;
- pop a hash table when a level is left.

What is a good hash function on identifiers?
Use the initial letter:
- codePROGRAM, codeMETHOD, codeEXP, ...

Use the sum of the letters:
- doesn’t distinguish letter order

Use the shifted sum of the letters:
\[
\begin{align*}
"j" &= 106 = 0000000001101010 \\
\text{shift} &= 000000011010100 \\
+ "o" &= 111 = 0000000001101111 \\
= &= 0000001011110110 \\
\text{shift} &= 0000101111011010 \\
+ "s" &= 115 = 0000000001110011 \\
= &= 0000110010111011 \\
= &= 1629
\end{align*}
\]

Hash tables for the JOOS source code:

```c
hash = *str;
```

```c
while (*str) hash = hash + *str++;
```

Hash tables for the JOOS source code:

```c
while (*str) hash = (hash << 1) + *str++;
```
# Symbol tables (13)

$ cat symbol.h  # data structure definitions

#define HashSize 317

typedef struct SymbolTable {
    SYMBOL *table[HashSize];
    struct SymbolTable *next;
} SymbolTable;

$ cat symbol.c  # data structure operations

int Hash(char *str) {
    unsigned int hash = 0;
    while (*str) hash = (hash << 1) + *str++;
    return hash % HashSize;
}

SymbolTable *initSymbolTable() {
    SymbolTable *t;
    int i;
    t = NEW(SymbolTable);
    for (i=0; i < HashSize; i++) t->table[i] = NULL;
    t->next = NULL;
    return t;
}

SymbolTable *scopeSymbolTable(SymbolTable *s) {
    SymbolTable *t = initSymbolTable();
    t->next = s;
    return t;
}

SYMBOL *putSymbol(SymbolTable *t, char *name, SymbolKind kind) {
    int i = Hash(name);
    SYMBOL *s;
    for (s = t->table[i]; s; s = s->next) {
        if (strcmp(s->name, name) == 0) return s;
    }
    s = NEW(Symbol);
    s->name = name;
    s->kind = kind;
    s->next = t->table[i];
    t->table[i] = s;
    return s;
}

SYMBOL *getSymbol(SymbolTable *t, char *name) {
    int i = Hash(name);
    SYMBOL *s;
    for (s = t->table[i]; s; s = s->next) {
        if (strcmp(s->name, name) == 0) return s;
    }
    if (t->next == NULL) return NULL;
    return getSymbol(t->next, name);
}

int defSymbol(SymbolTable *t, char *name) {
    int i = Hash(name);
    SYMBOL *s;
    for (s = t->table[i]; s; s = s->next) {
        if (strcmp(s->name, name) == 0) return 1;
    }
    return 0;
}

# Symbol tables (14)

How to handle mutual recursion:

A

...B...

B

...A...

A single traversal of the abstract syntax tree is not enough.

Make two traversals:

- collect definitions of identifiers; and
- analyse uses of identifiers.

For cases like recursive types, the definition is not completed before the second traversal.

# Symbol tables (15)

SYMBOL *putSymbol(SymbolTable *t, char *name, SymbolKind kind) {
    int i = Hash(name);
    SYMBOL *s;
    for (s = t->table[i]; s; s = s->next) {
        if (strcmp(s->name, name) == 0) return s;
    }
    s = NEW(Symbol);
    s->name = name;
    s->kind = kind;
    s->next = t->table[i];
    t->table[i] = s;
    return s;
}

SYMBOL *getSymbol(SymbolTable *t, char *name) {
    int i = Hash(name);
    SYMBOL *s;
    for (s = t->table[i]; s; s = s->next) {
        if (strcmp(s->name, name) == 0) return s;
    }
    if (t->next == NULL) return NULL;
    return getSymbol(t->next, name);
}

int defSymbol(SymbolTable *t, char *name) {
    int i = Hash(name);
    SYMBOL *s;
    for (s = t->table[i]; s; s = s->next) {
        if (strcmp(s->name, name) == 0) return 1;
    }
    return 0;
}

# Symbol tables (16)

Symbol information in JOOS:

$ cat tree.h

[...]

typedef enum{classSym, fieldSym, methodSym, formalSym, localSym} SymbolKind;

typedef struct SYMBOL {
    char *name;
    SymbolKind kind;
    union {
        struct CLASS *classS;
        struct FIELD *fieldS;
        struct METHOD *methodS;
        struct FORMAL *formalS;
        struct LOCAL *localS;
    } val;
    struct SYMBOL *next;
} SYMBOL;

[...]

The information refers to abstract syntax tree nodes.
Symbol tables are weaved together with abstract syntax trees:

```java
public class B extends A {
    protected A a;
    protected B b;
    public void m(A x, B y) {
        this.m(a,b);
    }
}
```

Complicated recursion in JOOS is resolved through multiple passes:

```
$ cat symbol.c

[...]
void symPROGRAM(PROGRAM *p)
{
    classlib = initSymbolTable();
    symInterfacePROGRAM(p,classlib);
    symInterfaceTypesPROGRAM(p,classlib);
    symImplementationPROGRAM(p);
}
[...]
```

Each pass goes into further detail:

- `symInterfacePROGRAM`:
  define classes and their interfaces;

- `symInterfaceTypesPROGRAM`:
  build hierarchy and analyse interface types; and

- `symImplementationPROGRAM`:
  define locals and analyse method bodies.

---

Defining a JOOS class:

```c
void symInterfaceCLASS(CLASS *c, SymbolTable *sym)
{
    SYMBOL *s;
    if (defSymbol(sym,c->name)) {
        reportStrError("class name %s already defined", c->name,c->lineno);
    } else {
        s = putSymbol(sym,c->name,classSym);
        s->val.classS = c;
        c->localsym = initSymbolTable();
        symInterfaceFIELD(c->fields,c->localsym);
        symInterfaceCONSTRUCTOR(c->constructors,
            c->name,c->localsym);
        symInterfaceMETHOD(c->methods,c->localsym);
    }
}
```

Defining a JOOS method:

```c
void symInterfaceMETHOD(METHOD *m, SymbolTable *sym)
{
    SYMBOL *s;
    if (m!=NULL) {
        symInterfaceMETHOD(m->next,sym);
        if (defSymbol(sym,m->name)) {
            reportStrError("method name %s already defined", m->name,m->lineno);
        } else {
            s = putSymbol(sym,m->name,methodSym);
            s->val.methodS = m;
        }
    }
}
```

and its signature:

```c
void symInterfaceTypesMETHOD(METHOD *m, SymbolTable *sym)
{
    if (m!=NULL) {
        symInterfaceTypesMETHOD(m->next,sym);
        symTYPE(m->returntype,sym);
        symInterfaceTypesFORMAL(m->formals,sym);
    }
}
```
Analysing a JOOS class implementation:

```c
void symImplementationCLASS(CLASS *c)
{
    SymbolTable *sym;
    sym = scopeSymbolTable(classlib);
    symImplementationFIELD(c->fields,sym);
    symImplementationCONSTRUCTOR(c->constructors,c,sym);
    symImplementationMETHOD(c->methods,c,sym);
}
```

Analysing a JOOS method implementation:

```c
void symImplementationMETHOD(METHOD *m,
CLASS *this,
SymbolTable *sym)
{
    SymbolTable *msym;
    if (m!=NULL) {
        symImplementationMETHOD(m->next,this,sym);
        msym = scopeSymbolTable(sym);
        symImplementationFORMAL(m->formals,msym);
        symImplementationSTATEMENT(m->statements,this,msym,
            m->modifier==staticMod);
    }
}
```

Analysing JOOS methods:

```c
void symImplementationSTATEMENT(STATEMENT *s, CLASS *this,
SymbolTable *sym, int stat)
{
    SymbolTable *ssym;
    if (s!=NULL) {
        switch (s->kind) {
        [...]
        case localK:
            symImplementationLOCAL(s->val.localS,sym);
            break;
        [...]
        case blockK:
            ssym = scopeSymbolTable(sym);
            symImplementationSTATEMENT(s->val.blockS.body,
                this,ssym,stat);
            break;
        [...]
        }
    }
}
```

Analysing JOOS local declarations:

```c
void symImplementationLOCAL(LOCAL *l, SymbolTable *sym)
{
    SYMBOL *s;
    if (l!=NULL) {
        symImplementationLOCAL(l->next,sym);
        symTYPE(l->type,sym);
        if (defSymbol(sym,l->name)) {
            reportStrError("local %s already declared",
                l->name,l->lineno);
        } else {
            s = putSymbol(sym,l->name,localSym);
            s->val.localS = l;
        }
    }
}
```

Identifier lookup in the JOOS class hierarchy:

```c
SYMBOL *lookupHierarchy(char *name, CLASS *start)
{
    SYMBOL *s;
    if (start==NULL) return NULL;
    s = getSymbol(start->localsym,name);
    if (s!=NULL) return s;
    if (start->parent==NULL) return NULL;
    return lookupHierarchy(name,start->parent);
}
```

```c
CLASS *lookupHierarchyClass(char *name, CLASS *start)
{
    SYMBOL *s;
    if (start==NULL) return NULL;
    s = getSymbol(start->localsym,name);
    if (s!=NULL) return start;
    if (start->parent==NULL) return NULL;
    return lookupHierarchyClass(name,start->parent);
}
```

For which class do we return NULL on line 5 of each function?
Analysing expressions:

```c
void symImplementationEXP(EXP *e, CLASS *this, SymbolTable *sym, int stat)
{
    switch (e->kind) {
    case idK:
        e->val.idE.idsym = symVar(e->val.idE.name,sym, this,e->lineno,stat);
        break;
    case assignK:
        e->val.assignE.leftsym =
            symVar(e->val.assignE.left,sym, this,e->lineno,stat);
        symImplementationEXP(e->val.assignE.right, this,sym,stat);
        break;
        [...]  
    }
}
```

Analysing an identifier:

```c
SYMBOL *symVar(char *name, SymbolTable *sym, CLASS *this, int lineno, int stat)
{
    SYMBOL *s;
    s = getSymbol(sym,name);
    if (s==NULL) {
        s = lookupHierarchy(name,this);
        if (s==NULL) {
            reportStrError("identifier %s not declared", name,lineno);
        } else {
            if (s->kind!=fieldSym)
                reportStrError("%s is not a variable as expected", name,lineno);
        }
    } else {
        if ((s->kind!=fieldSym) && (s->kind!=formalSym) &&
            (s->kind!=localSym))
            reportStrError("%s is not a variable as expected", name,lineno);
    }
    if (s!=NULL && s->kind==fieldSym && stat)
        reportStrError("illegal static reference to %s", name,lineno);
    return s;
}
```

The testing strategy for the symbol tables involves an extension of the pretty printer.

A textual representation of the symbol table is printed once for every scope area.

- In Java, use `toString()`.

These tables are then compared to a corresponding manual construction for a sufficient collection of programs.

Furthermore, every error message should be provoked by some test program.