Types and Static Semantic Analysis

COMS W4115

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Data Types

What is a type?

A restriction on the possible interpretations of a segment of memory or other program construct.

Useful for two reasons:

Runtime optimization: earlier binding leads to fewer runtime decisions. E.g., Addition in C efficient because type of operands known.

Error avoidance: prevent programmer from putting round peg in square hole. E.g., In Java, can't open a complex number, only a file.

Are Data Types Necessary?

No: many languages operate just fine without them.

Assembly languages usually view memory as undifferentiated array of bytes. Operators are typed, registers may be, data is not.

Basic idea of stored-program computer is that programs be indistinguishable from data.

Everything's a string in Tcl including numbers, lists, etc.

C's Type System: Base Types/Pointers

Base types match typical processor

Typical sizes:	8	16	32	64
	char	short	int	long
			float	double

Pointers (addresses)

```
int *i;   /* i is a pointer to an int */
char **j; /* j is a pointer to
             a pointer to a char */
```

C's Type System: Arrays, Functions

Arrays

```
char c[10]; /* c[0] ... c[9] are chars */
double a[10][3][2]; /* array of 10
                       arrays of 3 arrays
                       of 2 doubles */
```

Functions

```
/* function of two arguments
   returning a char */
char foo(int, double);
```

C's Type System: Structs and Unions

Structures: each field has own storage

```
struct box {
  int x, y, h, w;
  char *name;
};
```

Unions: fields share same memory

```
union token {
  int i;
  double d;
  char *s;
};
```

Composite Types: Records

A record is an object with a collection of fields, each with a potentially different type. In C,

```
struct rectangle {
  int n, s, e, w;
  char *label;
  color col;
  struct rectangle *next;
};

struct rectangle r;
r.n = 10;
r.label = "Rectangle";
```

Applications of Records

Records are the precursors of objects:

Group and restrict what can be stored in an object, but not what operations they permit.

Can fake object-oriented programming:

```
struct poly { ... };

struct poly *poly_create();
void poly_destroy(struct poly *p);
void poly_draw(struct poly *p);
void poly_move(struct poly *p, int x, int y);
int poly_area(struct poly *p);
```

Composite Types: Variant Records

A record object holds all of its fields. A variant record holds only one of its fields at once. In C,

```
union token {
  int i;
  float f;
  char *string;
};

union token t;
t.i = 10;
t.f = 3.14159;        /* overwrites t.i */
char *s = t.string;  /* returns gibberish */
```

Applications of Variant Records

A primitive form of polymorphism:

```
struct poly {
  int x, y;
  int type;
  union { int radius;
          int size;
          float angle; } d;
};
```

If **poly.type == CIRCLE**, use **poly.d.radius**.

If **poly.type == SQUARE**, use **poly.d.size**.

If **poly.type == LINE**, use **poly.d.angle**.

Layout of Records and Unions

Modern processors have byte-addressable memory.

0
1
2
3
4

Many data types (integers, addresses, floating-point numbers) are wider than a byte.

16-bit integer:			1	0
32-bit integer:	3	2	1	0

Layout of Records and Unions

Modern memory systems read data in 32-, 64-, or 128-bit chunks:

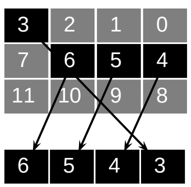
3	2	1	0
7	6	5	4
11	10	9	8

Reading an aligned 32-bit value is fast: a single operation.

3	2	1	0
7	6	5	4
11	10	9	8

Layout of Records and Unions

Slower to read an unaligned value: two reads plus shift.



SPARC prohibits unaligned accesses.

MIPS has special unaligned load/store instructions.

x86, 68k run more slowly with unaligned accesses.

Layout of Records and Unions

Most languages "pad" the layout of records to ensure alignment restrictions.

```
struct padded {
  int x;   /* 4 bytes */
  char z;  /* 1 byte */
  short y; /* 2 bytes */
  char w;  /* 1 byte */
};
```

x	x	x	x	
y	y		z	: Added padding
			w	

C's Type System: Enumerations

```
enum weekday {sun, mon, tue, wed,
              thu, fri, sat};

enum weekday day = mon;
```

Enumeration constants in the same scope must be unique:

```
enum days {sun, wed, sat};

enum class {mon, wed};  /* error: mon, wed
                           redefined */
```

C's Type System

Types may be intermixed at will:

```
struct {
  int i;
  union {
    char (*one)(int);
    char (*two)(int, int);
  } u;
  double b[20][10];
} *a[10];
```

Array of ten pointers to structures. Each structure contains an int, a 2D array of doubles, and a union that contains a pointer to a char function of one or two arguments.

Strongly-typed Languages

Strongly-typed: no run-time type clashes.

C is definitely not strongly-typed:

```
float g;
union { float f; int i } u;
u.i = 3;
g = u.f + 3.14159; /* u.f is meaningless */
```

Is Java strongly-typed?

Is Tiger strongly-typed?

Statically-Typed Languages

Statically-typed: compiler can determine types.

Dynamically-typed: types determined at run time.

Is Java statically-typed?

```
class Foo {
   public void x() { ... }
}
class Bar extends Foo {
   public void x() { ... }
}
void baz(Foo f) {
  f.x();
}
```

Polymorphism

Say you write a sort routine:

```
void sort(int a[], int n)
{
  int i, j;
  for ( i = 0 ; i < n-1 ; i++ )
    for ( j = i + 1 ; j < n ; j++ )
      if (a[j] < a[i]) {
        int tmp = a[i];
        a[i] = a[j];
        a[j] = tmp;
      }
}
```

Polymorphism

To sort doubles, only need to change a few types:

```
void sort(double a[], int n)
{
  int i, j;
  for ( i = 0 ; i < n-1 ; i++ )
    for ( j = i + 1 ; j < n ; j++ )
      if (a[j] < a[i]) {
        double tmp = a[i];
        a[i] = a[j];
        a[j] = tmp;
      }
}
```

C++ Templates

```
template <class T> void sort(T a[], int n)
{
  int i, j;
  for ( i = 0 ; i < n-1 ; i++ )
    for ( j = i + 1 ; j < n ; j++ )
      if (a[j] < a[i]) {
        T tmp = a[i];
        a[i] = a[j];
        a[j] = tmp;
      }
}
int a[10];
sort<int>(a, 10);
```

C++ Templates

C++ templates are essentially language-aware macros. Each instance generates a different refinement of the same code.

```
sort<int>(a, 10);

sort<double>(b, 30);

sort<char *>(c, 20);
```

Fast code, but lots of it.

Faking Polymorphism with Objects

```
class Sortable {
  bool lessthan(Sortable s) = 0;
}
void sort(Sortable a[], int n) {
  int i, j;
  for ( i = 0 ; i < n-1 ; i++ )
    for ( j = i + 1 ; j < n ; j++ )
      if ( a[j].lessthan(a[i]) ) {
        Sortable tmp = a[i];
        a[i] = a[j];
        a[j] = tmp;
      }
}
```

Faking Polymorphism with Objects

This **`sort`** works with any array of objects derived from **`Sortable`**.

Same code is used for every type of object.

Types resolved at run-time (dynamic method dispatch).

Does not run as quickly as the C++ template version.

Arrays

Most languages provide array types:

```
char i[10];                      /* C */

character(10) i                  ! FORTRAN

i : array (0..9) of character;   -- Ada

var i : array [0 .. 9] of char; { Pascal }
```

Array Address Calculation

In C,

`struct foo a[10];`

`a[i]` is at $a + i *$ **`sizeof(struct foo)`**

`struct foo a[10][20];`

`a[i][j]` is at $a + (j + 20 * i) *$ **`sizeof(struct foo)`**

$\Rightarrow$ Array bounds must be known to access 2D+ arrays

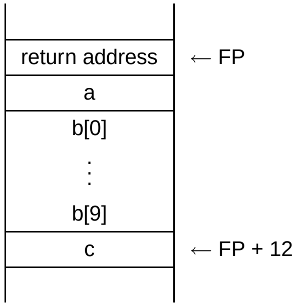
Allocating Arrays

```
int a[10];           /* static */

void foo(int n)
{
  int b[15];         /* stacked */
  int c[n];          /* stacked: tricky */
  int d[];           /* on heap */
  vector<int> e;     /* on heap */

  d = new int[n*2];  /* fixes size */
  e.append(1);       /* may resize */
  e.append(2);       /* may resize */
}
```

Allocating Fixed-Size Arrays

Local arrays with fixed size are easy to stack.

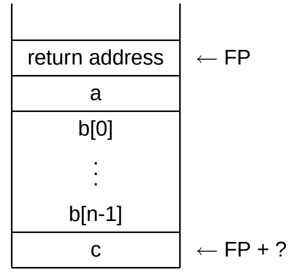
```
void foo()
{
  int a;
  int b[10];
  int c;
}
```



Allocating Variable-Sized Arrays

Variable-sized local arrays aren't as easy.

```
void foo(int n)
{
  int a;
  int b[n];
  int c;
}
```

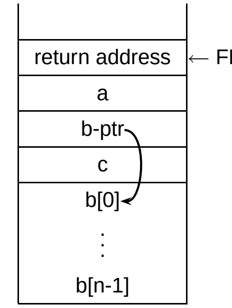


Doesn't work: generated code expects a fixed offset for c.
Even worse for multi-dimensional arrays.

Allocating Variable-Sized Arrays

As always:
add a level of indirection

```
void foo(int n)
{
  int a;
  int b[n];
  int c;
}
```



Variables remain constant offset from frame pointer.

Static Semantic Analysis

Static Semantic Analysis

Lexical analysis: Make sure tokens are valid

```
if i 3 "This"              /* valid */
#a1123                     /* invalid */
```

Syntactic analysis: Makes sure tokens appear in correct order

```
for i := 1 to 5 do 1 + break /* valid */
if i 3                     /* invalid */
```

Semantic analysis: Makes sure program is consistent

```
let v := 3 in v + 8 end      /* valid */
let v := "f" in v(3) + v end /* invalid */
```

Tiger's Type System

Explicit built-in types:

int	**1 15 20 5 + 3**
string	**"Hello There"**

Implicit built-in types (unnamed):

"nil"	**nil**
"void"	**()**, **a := 3**, **if a then b := 2**

Tiger's Type System

Array types:

```
type ia = array of int
type ba = array of bar
```

Record types:

```
type point = { x : int, y : int,
               name : string }
```

Tiger's Type System: Nil

The nil keyword is a stand-in for the null pointer.

Can be assigned to any record, but nothing else.

```
let
  type rec = { x : int, y : int }
  var a : rec := nil
in if a = nil then a := rec { x=10, y=20 }
end
```

Is not a valid type

```
let
  var b := nil /* ERROR */
in end
```

Tiger's Type System: Void

There's an implicit void type:

```
()
a := 3
for i := 1 to 10 do b := b + i
while i < 10 do i := i + 1
```

Can't be assigned to anything, but certain expressions must be void.

```
a := ()                          /* ERROR */
for i := 1 to 10 do i            /* ERROR */
for i := 1 to 10 do ( i ; () ) /* OK */
```

Name vs. Structural Equivalence

```
let
  type a = { x: int, y: int }
  type b = { x: int, y: int }
  var i : a := a { x = 1, y = 2 }
  var j : b := b { x = 0, y = 0 }
in
  i := j
end
```

Not legal because **a** and **b** are considered distinct types.

Name vs. Structural Equivalence

```
let
  type a = { x: int, y: int }
  type b = a
  var i : a := a { x = 1, y = 2 }
  var j : b := b { x = 0, y = 0 }
in
  i := j
end
```

Legal because **b** is an alias for type **a**.

`{ x: int, y: int }` creates a new type, not the **`type`** keyword.

Things to Check

Make sure variables and functions are defined.

```
let var i := 10
in  i(10,20) /* Error: i is a variable */
end
```

Verifies each expression's types are consistent.

```
let var i := 10
    var j := "Hello"
in  i + j /* Error: i is int, j is string */
end
```

Things to Check

- Used identifiers must be defined
- Function calls must refer to functions
- Identifier references must be to variables
- The types of operands for unary and binary operators must be consistent.
- The first expression in an **`if`** and **`while`** must be an integer.
- It must be possible to assign the type on the right side of an assignment to the lvalue on the left.
- . . .

Static Semantic Analysis

Basic paradigm: recursively check AST nodes.

`1 + break`

```
  +
 / \
1  break
```

check(+)
  check(1) = int
  check(break) = void
  FAIL: int $\neq$ void

`1 - 5`

```
  -
 / \
1   5
```

check(**-**)
  check(1) = int
  check(5) = int
  Types match, return int

Ask yourself: at a particular node type, what must be true?

Programming Assignment 2

Perform static semantic analysis of the Tiger program.

Complete **`TigerSemant.g`**, an AST tree walker that verifies the program's types are consistent.

I've written classes for types and symbol tables in a package called **`Semant`**.

Your job:

- Finish the rules for checking a program.
- Create test programs that verify your rules.

Implementing Static Semantics

Recursive walk over the AST.

Analysis of a node returns its type or signals an error.

Implicit "environment" maintains information about what symbols are currently in scope.

`TigerSemant.g` is a tree grammar that does this.

TigerSemant.g

```
expr returns [Type t]
{ Type a, b, c; t = env.getVoidType();}
: "nil" { t = env.getNilType(); }
| t=lvalue
| STRING { t = env.getStringType(); }
| NUMBER { t = env.getIntType(); }
| #( NEG a=expr
     { /* Verify expr is an int */
       if ( !(a instanceof Semant.INT))
          semantError(#expr,
                      "Operand not integer");
       t = env.getIntType();
     } )
```

Type Classes

```
package Semant;
public abstract class Type {
    public Type actual()
    public boolean coerceTo(Type t)
}

public INT()           // int
public STRING()        // string
public NIL()           // nil
public VOID()          // ()
public NAME(String n)  // type a = b
public ARRAY(Type e)   // array of int
public RECORD(String n, Type t, RECORD next)
```

Type Classes

The NIL type corresponds to the **`nil`** keyword.

The VOID type corresponds to expressions that return no value.

```
()
let v := 8 in end
if a < 3 then t := 4
```

Type Classes

The RECORD class is a linked list representation of record types.

```
type point = { x: int, y: int }

new RECORD("x", intType,
           new RECORD("y", intType, null))
```

Type Classes

actual() returns the actual type of an alias, e.g.,

```
type a = int
type b = a
type c = b
```

c.actual() will return the INT type.

Type Classes

coerceTo() answers the “can this be assigned to” question.

```
type a = {x:int}
type b = a
```

nil.coerceTo(a) is true

b.coerceTo(a) is true

a.coerceTo(nil) is false

Environment.java

```
package Semant;

public class Environment {
    public Table vars = new Table();
    public Table types = new Table();
    public INT getIntType()
    public VOID getVoidType()
    public NIL getNilType()
    public STRING getStringType()

    public void enterScope()
    public void leaveScope()
}
```

Symbol Tables

```
package Semant;

public class Table {
    public Table()
    public Object get(String key)
    public void put(String key, Object value)
    public void enterScope()
    public void leaveScope()
}
```

Symbol Tables

Operations:

`put(String key, Object value)` inserts a new named object in the table, replacing any existing one in the current scope.

`Object get(String key)` returns the object of the given name, or **`null`** if there isn't one.

Symbol Table Scopes

`void enterScope()` pushes a new scope on a stack.
`void leaveScope()` removes the topmost one.

```
Table t = new Table();
t.put("a", new VarEntry(env.getIntType()));
t.put("a", new VarEntry(env.getStringType()));
t.get("a"); // string
t.enterScope();
t.get("a"); // string
t.put("a", new VarEntry(env.getIntType()));
t.get("a"); // int
t.leaveScope();
t.get("a"); // string
```

Symbol Table Objects

Discriminates between variables and functions.

Stores extra information for each.

```
package Semant;

public VarEntry(Type t)
public FunEntry(RECORD f, Type r)
```

RECORD argument represents the function arguments; other is the return type.

Symbol Tables and the Environment

The environment has two symbol tables:

- **`types`** for types
  Objects stored in symbol table are **`Types`**
- **`vars`** for variables and functions
  Objects are **`VarEntry`**s and **`FunEntry`**s.

Rule for an Identifier

```
lvalue returns [Type t]
{ Type a, b; t = env.getVoidType(); }

: i:ID {
Entry e = (Entry) env.vars.get(i.getText());
if ( e == null )
  semantError(i, i.getText()+" undefined");
if ( !(e instanceof VarEntry) )
  semantError(i, i.getText()+" not variable");
VarEntry v = (VarEntry) e;
t = v.ty;
}
```

Rule for Let

```
| #( "let"
     { env.enterScope(); }
     #(DECLS (#(DECLS (decl)+ ))* )
     a=expr
     {
       env.leaveScope();
       t = a;
     }
   )
```

Partial rule for Var

```
decl { Type a, b; }
: #( "var" i:ID
     (a=type | "nil" { a = null; } )
     b=expr
   {
     /* Verify a=b if a != null */
     /* Make sure b != nil if a == null */
     env.vars.put(i.getText(), new VarEntry(b));
   }
  )
```

Partial rule for BINOP

```
| #( BINOP a=expr b=expr {
  String op = #expr.getText();
  if ( op.equals("+") || op.equals("-") ||
       op.equals("*") || op.equals("/") ) {
    if (!(a instanceof Semant.INT) ||
        !(b instanceof Semant.INT))
      semantError(#expr, op+" operands not int");
    t = a;
  } else {
    /* Check other operators */
  }
}
)
```

Static Semantics Assignment

Augment **`TigerSemant.g`** with rules for every node.

Create test cases to test your code. Should have a test for every error message, every successful rule.

You may use, change, or ignore anything in the **`Semant`** package.

No Makefiles this time: we will compile it ourselves.

TC.java is a front-end that invokes TigerSemant.

A working scanner and parser are available as .class files. Feel free to use them or your own.