Overview of Semantic Analysis

Lecture 9



## Announcements

- WA2 due today
  - Electronic hand-in
  - Or after class
  - Or under my office door by 5pm
- PA2 due tonight
  - Electronic hand-in
- Regrades
  - One deduction for each error
  - But you have to prove it to us . . .



## Midterm Thursday

- In class
  - SCPD students come to campus for the exam
- Material through lecture 8
- Four sheets hand- or type-written notes



## Outline

- The role of semantic analysis in a compiler
  - A laundry list of tasks
- Scope
  - Implementation: symbol tables
- Types



## The Compiler So Far

- Lexical analysis
  - Detects inputs with illegal tokens
- Parsing
  - Detects inputs with ill-formed parse trees
- Semantic analysis
  - Last “front end” phase
  - Catches all remaining errors



## Why a Separate Semantic Analysis?

- Parsing cannot catch some errors
- Some language constructs not context-free

## What Does Semantic Analysis Do?

- Checks of many kinds . . . coolc checks:
  1. All identifiers are declared
  2. Types
  3. Inheritance relationships
  4. Classes defined only once
  5. Methods in a class defined only once
  6. Reserved identifiers are not misused

  And others . . .

- The requirements depend on the language



## Scope

- Matching identifier declarations with uses
  - Important static analysis step in most languages
  - Including COOL!



## What's Wrong?

- Example 1

  Let y: String ← "abc" in y + 3

- Example 2

  Let y: Int in x + 3

*Note: An example property that is not context free.*



## Scope (Cont.)

- The *scope* of an identifier is the portion of a program in which that identifier is accessible

- The same identifier may refer to different things in different parts of the program
  - Different scopes for same name don't overlap

- An identifier may have restricted scope



## Static vs. Dynamic Scope

- Most languages have *static* scope
  - Scope depends only on the program text, not run-time behavior
  - Cool has static scope

- A few languages are *dynamically* scoped
  - Lisp, SNOBOL
  - Lisp has changed to mostly static scoping
  - Scope depends on execution of the program



## Static Scoping Example

```
let x: Int <- 0 in
  {
      x;
      let x: Int <- 1 in
          x;
      x;
  }
```

## Static Scoping Example (Cont.)

```
let x: Int <- 0 in
  {
     x;
     let x: Int <- 1 in
        x;
     x;
  }
```

Uses of x refer to closest enclosing definition



## Dynamic Scope

- A dynamically-scoped variable refers to the closest enclosing binding in the execution of the program
- Example
  ```
  g(y) = let a ← 4 in f(3);
  f(x) = a;
  ```
- More about dynamic scope later in the course



## Scope in Cool

- Cool identifier bindings are introduced by
  - Class declarations (introduce class names)
  - Method definitions (introduce method names)
  - Let expressions (introduce object id's)
  - Formal parameters (introduce object id's)
  - Attribute definitions (introduce object id's)
  - Case expressions (introduce object id's)



## Scope in Cool (Cont.)

- Not all kinds of identifiers follow the most-closely nested rule
- For example, class definitions in Cool
  - Cannot be nested
  - Are *globally visible* throughout the program
- In other words, a class name can be used before it is defined



## Example: Use Before Definition

```
Class Foo {
   . . . let y: Bar in . . .
};

Class Bar {
   . . .
};
```



## More Scope in Cool

Attribute names are global within the class in which they are defined

```
Class Foo {
   f(): Int { a };
   a: Int ← 0;
}
```

## More Scope (Cont.)

- Method/attribute names have complex rules
- A method need not be defined in the class in which it is used, but in some parent class
- Methods may also be redefined (overridden)



## Implementing the Most-Closely Nested Rule

- Much of semantic analysis can be expressed as a recursive descent of an AST
  - *Before*: Process an AST node *n*
  - *Recurse*: Process the children of *n*
  - *After*: Finish processing the AST node *n*
- When performing semantic analysis on a portion of the the AST, we need to know which identifiers are defined



## Implementing . . . (Cont.)

- Example: the scope of let bindings is one subtree of the AST:

let x: Int ← 0 in e

- x is defined in subtree e



## Symbol Tables

- Consider again: let x: Int ← 0 in e
- Idea:
  - *Before* processing e, add definition of x to current definitions, overriding any other definition of x
  - *Recurse*
  - *After* processing e, remove definition of x and restore old definition of x
- A *symbol table* is a data structure that tracks the current bindings of identifiers



## A Simple Symbol Table Implementation

- Structure is a stack
- Operations
  - add_symbol(x) push x and associated info, such as x's type, on the stack
  - find_symbol(x) search stack, starting from top, for x. Return first x found or NULL if none found
  - remove_symbol() pop the stack
- Why does this work?



## Limitations

- The simple symbol table works for let
  - Symbols added one at a time
  - Declarations are perfectly nested
- What doesn't it work for?

## A Fancier Symbol Table

- enter_scope() start a new nested scope
- find_symbol(x) finds current x (or null)
- add_symbol(x) add a symbol x to the table
- check_scope(x) true if x defined in current scope
- exit_scope() exit current scope

We will supply a symbol table manager for your project



## Class Definitions

- Class names can be used before being defined
- We can't check class names
  - using a symbol table
  - or even in one pass
- Solution
  - Pass 1: Gather all class names
  - Pass 2: Do the checking
- Semantic analysis requires multiple passes
  - Probably more than two



## Types

- What is a type?
  - The notion varies from language to language
- Consensus
  - A set of values
  - A set of operations on those values
- Classes are one instantiation of the modern notion of type



## Why Do We Need Type Systems?

Consider the assembly language fragment

add $r1, $r2, $r3

What are the types of $r1, $r2, $r3?



## Types and Operations

- Certain operations are legal for values of each type
  - It doesn't make sense to add a function pointer and an integer in C
  - It does make sense to add two integers
  - But both have the same assembly language implementation!



## Type Systems

- A language's type system specifies which operations are valid for which types
- The goal of type checking is to ensure that operations are used with the correct types
  - Enforces intended interpretation of values, because nothing else will!

## Type Checking Overview

- Three kinds of languages:
  - *Statically typed*: All or almost all checking of types is done as part of compilation (C, Java, Cool)
  - *Dynamically typed*: Almost all checking of types is done as part of program execution (Scheme, Python)
  - *Untyped*: No type checking (machine code)



## The Type Wars

- Competing views on static vs. dynamic typing
- Static typing proponents say:
  - Static checking catches many programming errors at compile time
  - Avoids overhead of runtime type checks
- Dynamic typing proponents say:
  - Static type systems are restrictive
  - Rapid prototyping difficult within a static type system



## The Type Wars (Cont.)

- In practice, much code is written in statically typed languages with an "escape" mechanism
  - Unsafe casts in C, Java
- It's debatable whether this compromise represents the best or worst of both worlds



## Types Outline

- Type concepts in COOL
- Notation for type rules
  - Logical rules of inference
- COOL type rules
- General properties of type systems



## Cool Types

- The types are:
  - Class Names
  - SELF_TYPE
- The user declares types for identifiers
- The compiler infers types for expressions
  - Infers a type for *every* expression



## Type Checking and Type Inference

- *Type Checking* is the process of verifying fully typed programs
- *Type Inference* is the process of filling in missing type information
- The two are different, but the terms are often used interchangeably

## Rules of Inference

- We have seen two examples of formal notation specifying parts of a compiler
  - Regular expressions
  - Context-free grammars
- The appropriate formalism for type checking is logical rules of inference



## Why Rules of Inference?

- Inference rules have the form
  *If Hypothesis is true, then Conclusion is true*
- Type checking computes via reasoning
  *If $E_1$ and $E_2$ have certain types, then $E_3$ has a certain type*
- Rules of inference are a compact notation for "If-Then" statements



## From English to an Inference Rule

- The notation is easy to read with practice
- Start with a simplified system and gradually add features
- Building blocks
  - Symbol $\wedge$ is "and"
  - Symbol $\Rightarrow$ is "if-then"
  - x:T is "x has type T"



## From English to an Inference Rule (2)

If $e_1$ has type Int and $e_2$ has type Int,
then $e_1 + e_2$ has type Int

($e_1$ has type Int $\wedge$ $e_2$ has type Int) $\Rightarrow$
$e_1 + e_2$ has type Int

$(e_1\text{: Int} \wedge e_2\text{: Int}) \Rightarrow e_1 + e_2\text{: Int}$



## From English to an Inference Rule (3)

The statement

$$(e_1\text{: Int} \wedge e_2\text{: Int}) \Rightarrow e_1 + e_2\text{: Int}$$

is a special case of

$$\text{Hypothesis}_1 \wedge \ldots \wedge \text{Hypothesis}_n \Rightarrow \text{Conclusion}$$

This is an inference rule



## Notation for Inference Rules

- By tradition inference rules are written

$$\frac{\text{Hypothesis}_1 \cdots \quad \text{Hypothesis}_n}{\text{Conclusion}}$$

- Cool type rules have hypotheses and conclusions

  ` e:T

- ` means "it is provable that . . ."

## Two Rules

$$\frac{i \text{ is an integer}}{\vdash i: \text{Int}} \quad [\text{Int}]$$

$$\frac{\vdash e_1 : \text{Int} \qquad \vdash e_2 : \text{Int}}{\vdash e_1 + e_2 : \text{Int}} \quad [\text{Add}]$$



## Two Rules (Cont.)

- These rules give templates describing how to type integers and + expressions
- By filling in the templates, we can produce complete typings for expressions



## Example: 1 + 2

$$\frac{\dfrac{1 \text{ is an integer}}{\vdash 1: \text{Int}} \qquad \dfrac{2 \text{ is an integer}}{\vdash 2: \text{Int}}}{\vdash 1+2: \text{Int}}$$



## Soundness

- A type system is *sound* if
  - Whenever $\vdash$ e:T
  - Then e evaluates to a value of type T
- We only want sound rules
  - But some sound rules are better than others:

$$\frac{i \text{ is an integer}}{\vdash i:\text{Object}}$$



## Type Checking Proofs

- Type checking proves facts e: T
  - Proof is on the structure of the AST
  - Proof has the shape of the AST
  - One type rule is used for each AST node
- In the type rule used for a node e:
  - Hypotheses are the proofs of types of e's subexpressions
  - Conclusion is the type of e
- Types are computed in a bottom-up pass over the AST



## Rules for Constants

$$\frac{}{\vdash \text{false}: \text{Bool}} \quad [\text{Bool}]$$

$$\frac{s \text{ is a string constant}}{\vdash s: \text{String}} \quad [\text{String}]$$

## Rule for New

new T produces an object of type T

- Ignore SELF_TYPE for now . . .

$$\frac{}{\text{` new T: T}} \quad \text{[New]}$$



## Two More Rules

$$\frac{\text{` e: Bool}}{\text{` }\neg\text{e: Bool}} \quad \text{[Not]}$$

$$\frac{\text{` } e_1\text{: Bool} \qquad \text{` } e_2\text{: T}}{\text{` while } e_1 \text{ loop } e_2 \text{ pool: Object}} \quad \text{[Loop]}$$



## A Problem

- What is the type of a variable reference?

$$\frac{\text{x is an identifier}}{\text{` x: ?}} \quad \text{[Var]}$$

- The local, structural rule does not carry enough information to give x a type.



## A Solution

- Put more information in the rules!
- A *type environment* gives types for *free* variables
  - A type environment is a function from ObjectIdentifiers to Types
  - A variable is free in an expression if it is not defined within the expression



## Type Environments

Let O be a function from ObjectIdentifiers to Types

The sentence

O ` e: T

is read: Under the assumption that variables have the types given by O, it is provable that the expression e has the type T



## Modified Rules

The type environment is added to the earlier rules:

$$\frac{\text{i is an integer}}{\text{O ` i: Int}} \quad \text{[Int]}$$

$$\frac{\text{O ` } e_1 \text{: Int} \qquad \text{O ` } e_2 \text{: Int}}{\text{O ` } e_1 + e_2 \text{: Int}} \quad \text{[Add]}$$

## New Rules

And we can write new rules:

$$\frac{O(x) = T}{O \text{ ` } x : T} \quad \text{[Var]}$$



## Let

$$\frac{O[T_0/x] \text{ ` } e_1 : T_1}{O \text{ ` } \text{let } x{:}T_0 \text{ in } e_1 : T_1} \quad \text{[Let-No-Init]}$$

$O[T/y]$ means $O$ modified to return $T$ on argument $y$

Note that the let-rule enforces variable scope



## Notes

- The type environment gives types to the free identifiers in the current scope
- The type environment is passed down the AST from the root towards the leaves
- Types are computed up the AST from the leaves towards the root



## Let with Initialization

Now consider let with initialization:

$$\frac{\begin{array}{l} O \text{ ` } e_0 : T_0 \\ O[T_0/x] \text{ ` } e_1 : T_1 \end{array}}{O \text{ ` } \text{let } x{:}T_0 \leftarrow e_0 \text{ in } e_1 : T_1} \quad \text{[Let-Init]}$$

This rule is weak. Why?



## Subtyping

- Define a relation $\leq$ on classes
  - $X \leq X$
  - $X \leq Y$ if $X$ inherits from $Y$
  - $X \leq Z$ if $X \leq Y$ and $Y \leq Z$
- An improvement

$$\frac{\begin{array}{l} O \text{ ` } e_0 : T \\ T \leq T_0 \\ O[T_0/x] \text{ ` } e_1 : T_1 \end{array}}{O \text{ ` } \text{let } x{:}T_0 \leftarrow e_0 \text{ in } e_1 : T_1} \quad \text{[Let-Init]}$$



## Assignment

- Both let rules are sound, but more programs typecheck with the second one
- More uses of subtyping:

$$\frac{\begin{array}{l} O(Id) = T_0 \\ O \text{ ` } e_1 : T_1 \\ T_1 \leq T_0 \end{array}}{O \text{ ` } Id \leftarrow e_1 : T_1} \quad \text{[Assign]}$$

## Initialized Attributes

- Let $O_C(x) = T$ for all attributes $x{:}T$ in class $C$
- Attribute initialization is similar to let, except for the scope of names

$$\frac{\begin{array}{l} O_C(Id) = T_0 \\ O_C \vdash e_1 : T_1 \\ T_1 \le T_0 \end{array}}{O_C \vdash Id{:}T_0 \leftarrow e_1;} \quad \text{[Attr-Init]}$$



## If-Then-Else

- Consider:
  if $e_0$ then $e_1$ else $e_2$ fi
- The result can be either $e_1$ or $e_2$
- The type is either $e_1$'s type of $e_2$'s type
- The best we can do is the smallest supertype larger than the type of $e_1$ or $e_2$



## Least Upper Bounds

- lub(X,Y), the least upper bound of X and Y, is Z if
  - $X \le Z \wedge Y \le Z$
    Z is an upper bound
  - $X \le Z' \wedge Y \le Z' \Rightarrow Z \le Z'$
    Z is least among upper bounds
- In COOL, the least upper bound of two types is their least common ancestor in the inheritance tree



## If-Then-Else Revisited

$$\frac{\begin{array}{l} O \vdash e_0 : Bool \\ O \vdash e_1 : T_1 \\ O \vdash e_2 : T_2 \end{array}}{O \vdash \text{if } e_0 \text{ then } e_1 \text{ else } e_2 \text{ fi} : lub(T_1, T_2)} \quad \text{[If-Then-Else]}$$



## Case

- The rule for case expressions takes a lub over all branches

$$\frac{\begin{array}{l} O \vdash e_0 : T_0 \\ O[T_1 / x_1] \vdash e_1 : T_1' \\ \vdots \\ O[T_n / x_n] \vdash e_n : T_n' \end{array}}{O \vdash \text{case } e_0 \text{ of } x_1{:}T_1 \Rightarrow e_1; \ldots; x_n{:}T_n \Rightarrow e_n; \text{ esac} : lub(T_1',\ldots,T_n')} \quad \text{[Case]}$$



## Method Dispatch

- There is a problem with type checking method calls:

$$\frac{\begin{array}{l} O \vdash e_0 : T_0 \\ O \vdash e_1 : T_1 \\ \vdots \\ O \vdash e_n : T_n \end{array}}{O \vdash e_0.f(e1,\ldots,e_n) : ?} \quad \text{[Dispatch]}$$

- We need information about the formal parameters and return type of f

## Notes on Dispatch

- In Cool, method and object identifiers live in different name spaces
  - A method foo and an object foo can coexist in the same scope
- In the type rules, this is reflected by a separate mapping M for method signatures

$$M(C,f) = (T_1, \ldots T_n, T_{n+1})$$

means in class C there is a method f

$$f(x_1{:}T_1, \ldots, x_n{:}T_n) : T_{n+1}$$



## The Dispatch Rule Revisited

$$\frac{\begin{array}{l} O,M\ \text{`}\ e_0 : T_0 \\ O,M\ \text{`}\ e_1 : T_1 \\ \vdots \\ O,M\ \text{`}\ e_n : T_n \\ M(T_0, f) = (T_1', \ldots, T_n', T_{n+1}') \\ T_i \le T_i' \text{ for } 1 \le i \le n \end{array}}{O,M\ \text{`}\ e_0.f(e1,\ldots,e_n) : T'_{n+1}} \quad \text{[Dispatch]}$$



## Static Dispatch

- Static dispatch is a variation on normal dispatch
- The method is found in the class explicitly named by the programmer
- The inferred type of the dispatch expression must conform to the specified type



## Static Dispatch (Cont.)

$$\frac{\begin{array}{l} O,M\ \text{`}\ e_0 : T_0 \\ O,M\ \text{`}\ e_1 : T_1 \\ \vdots \\ O,M\ \text{`}\ e_n : T_n \\ T_0 \le T \\ M(T, f) = (T_1', \ldots, T_n', T_{n+1}') \\ T_i \le T_i' \text{ for } 1 \le i \le n \end{array}}{O,M\ \text{`}\ e_0@T.f(e1,\ldots,e_n) : T'_{n+1}} \quad \text{[StaticDispatch]}$$



## The Method Environment

- The method environment must be added to all rules
- In most cases, M is passed down but not actually used
  - Only the dispatch rules use M

$$\frac{\begin{array}{l} O,M\ \text{`}\ e_1 : \text{Int} \\ O,M\ \text{`}\ e_2 : \text{Int} \end{array}}{O,M\ \text{`}\ e_1 + e_2 : \text{Int}} \quad \text{[Add]}$$



## More Environments

- For some cases involving SELF_TYPE, we need to know the class in which an expression appears
- The full type environment for COOL:
  - A mapping O giving types to object id's
  - A mapping M giving types to methods
  - The current class C

## Sentences

The form of a *sentence* in the logic is

$$O,M,C \vdash e : T$$

Example:

$$\frac{O,M,C \vdash e_1 : \text{int} \qquad O,M,C \vdash e_2 : \text{int}}{O,M,C \vdash e_1 + e_2 : \text{int}} \quad \text{[Add]}$$



## Type Systems

- The rules in this lecture are COOL-specific
  - More info on rules for self next time
  - Other languages have very different rules
- General themes
  - Type rules are defined on the structure of expressions
  - Types of variables are modeled by an environment
- Warning: Type rules are very compact!



## One-Pass Type Checking

- COOL type checking can be implemented in a single traversal over the AST
- Type environment is passed down the tree
  - From parent to child
- Types are passed up the tree
  - From child to parent



## Implementing Type Systems

$$\frac{O,M,C \vdash e_1 : \text{Int} \qquad O,M,C \vdash e_2 : \text{Int}}{O,M,C \vdash e_1 + e_2 : \text{Int}} \quad \text{[Add]}$$

```
TypeCheck(Environment, e1 + e2) = {
  T1 = TypeCheck(Environment, e1);
  T2 = TypeCheck(Environment, e2);
  Check T1 == T2 == Int;
  return Int; }
```