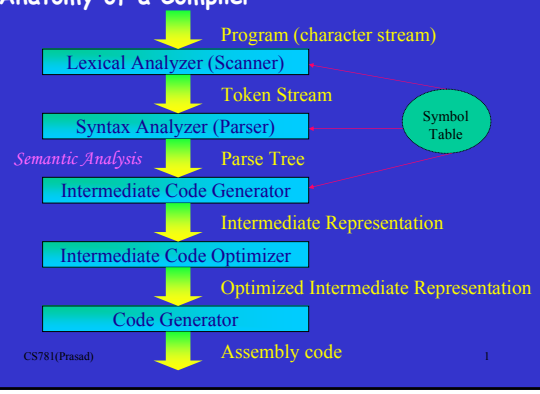
Anatomy of a Compiler



1. Reading-in the Program: Lexing, Parsing, & Analysis
   - Regular expressions, scanner generators.
   - Syntax analysis, bottom-up parsing.
     - LR(0), LR(1) & LALR(1) parsing algorithm & parsing tables.
     - Classification of context free grammars and languages,
     - Error handling
   - Semantic analysis and Type checking.
2. Executing the Program: Code Generation
   - Generation of intermediate code
   - Generation of unoptimized code

3. Making the Program Run Fast: Code Optimization

- Control-flow analysis
- Data-flow analysis

- Traditional Optimizations
- Redundancy Elimination Optimizations
- Loop Optimizations
- Procedure Optimizations
- Register Allocation
- Instruction Scheduling
- Instruction Optimizations

Overview of Semantic Analysis

Adapted from Lectures by

Profs. Alex Aiken and George Necula (UCB)
and Profs. Martin Rinard and Saman Amarasinghe (MIT)

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 are not context-free.
- Static Check:
  - Identifier declaration and use
    - An abstract version of the problem is:

      $\{ wcw \mid w \in (a + b)^* \}$
    - The 1st w represents a declaration; the 2nd w represents a use.
- Dynamic Check:
  - Array bounds check
  - Null pointer dereference check

What Does Semantic Analysis Do?

Checks of many kinds . . .

coolc checks:

1. All identifiers are declared.
2. Type compatibility.
3. Inheritance relationships (e.g., acyclic).
4. Classes defined only once.
5. Methods in a class defined only once.
6. Reserved identifiers are not misused.

...

More on Semantic Checks

Establish that a program conforms to language definition. (Requirements language dependent)

- Flow of control checks
  - Declaration of a variable should be *before* use.
    - (Java) Local variables initialized before first use.
  - Each exit path returns a value of the correct type.
    - (Java) Statement reachability check (Dead-code).
- Uniqueness Checks
  - No identifier can be used for two different definitions in the same scope.

(cont'd)

- Type checks
  - Number of arguments (in call) matches the number of formals (in declaration) and the corresponding types are equivalent.
  - Each access of a variable should match the declaration (arrays, structures etc.).
  - Identifiers in an expression should be "evaluatable".
  - LHS of an assignment should be "assignable".
  - In an expression, all the types of variables, method return types and operators should be "compatible".

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

Scope (Cont.)

- A *declaration* introduces *an entity* into a program and includes *an identifier*.
- The *scope* of a declaration is the portion of the program text in which the declared entity can be referred to using the identifier.
  - The same identifier may refer to different things in different parts of the program.
  - 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;
  }
```

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;

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 in a class (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.
  - Cf. static vs lexical scoping
- 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.
  - No explicit *forward* declarations necessary.

Example: Use Before Definition

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

- Attribute names are "global" within the class in which they are defined.

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


More Scope (Cont.)

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

Scope in Java : Resolving Names

- Scopes can overlap.
- To disambiguate a name:
  - Use contextual information to determine if it refers to a *package*, a *type*, a *method*, a *label*, a *variable* (field/local/formal) etc.
  - Use signature to resolve method names.
  - Within nested scopes, type names & variable names resolved by *hiding* or *overriding*.
    - Otherwise, "Ambiguity error".
    - Possible remedy: *use fully qualified name.*

Meaning of a Name Context Dependent

```
package Reuse;
class Reuse {
        Reuse  Reuse(Reuse    Reuse) {
                Reuse :  for (;;) {
                        if  (Reuse . Reuse (Reuse) == Reuse)
                                break  Reuse;
                        }
                return  Reuse;
        }
}
```


Implementing the Most-Closely Nested Rule

- Much of semantic analysis can be expressed as a *recursive descent* of an AST.
  - Process an AST node *n*
  - Process the children of *n*
  - Finish processing the AST node *n*
- When performing semantic analysis on a portion of the AST, we need to know which identifiers are defined.
  - Example: the scope of let bindings is subtree e

    let x: Int ← 0 in 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
  - 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.
- Doesn't work for
  - foo(x: Int, x: String);
    - Mutual Recursion

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

Class Definitions

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

Further Issues relevant to Symbol Tables

- Language Implementation Issues
  - Techniques for efficient access: Hash Tables
- Language Design Issues
  - Object-based languages (E.g., Ada, Modula-2)
    - Importing and exporting names
    - Static fields vs Instance fields
      - E.g., Interpreters developed in CS784
  - Object-oriented languages (E.g., C++, Java, Eiffel)
    - Name spaces/Environments: Class and Package hierarchy
    - Access control : `private, protected, public, …`
      - E.g., Java Language Spec discussed in CS884

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

addi $r1, $r2, $r3

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

- 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).
  - *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, most 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.

A simple typed language

- A language that has a sequence of declarations followed by a single expression

  $P \rightarrow D; E$

  $D \rightarrow D; D \mid \textbf{id} : T$

  $T \rightarrow \textbf{char} \mid \textbf{integer} \mid \textbf{array} [\ \textbf{num}\ ]\ \textbf{of}\ T$

  $E \rightarrow \textbf{literal} \mid \textbf{num} \mid \textbf{id} \mid E + E \mid E [\ E\ ]$
- Example Program

  `var: integer; var + 1023`
- What are the semantic rules of this language?

Parser actions

$P \rightarrow D; E$

$D \rightarrow D; D$

$D \rightarrow \textbf{id} : T$ { addtype(id.name, T.type); }

$T \rightarrow \text{char}$ { T.type = char; }

$T \rightarrow \text{integer}$ { T.type = integer; }

$T \rightarrow \text{array} [\ \text{num}\ ]\ \text{of}\ T_1$
{ T.type = array(T_1.type, num.val); }

Parser actions

$E \rightarrow \text{literal}$ { E.type = char; }

$E \rightarrow \text{num}$ { E.type = integer; }

$E \rightarrow \text{id}$ { E.type = lookup_type(id.name); }

$E \rightarrow E_1 + E_2$ { if E_1.type == integer and
E_2 .type == integer then
E.type = integer
else
E.type = type_error
}

Parser actions

$E \rightarrow E_1 [E_2]$ { if E_2.type == integer and
E_1.type == array(s, t) then
E.type = s
else
E.type = type_error
}

Symbol Table for OOPL

Symbol Table Structure Sketch

- Program Symbol Table (Class Descriptors)
- Class Descriptors
  - ➲ Field Symbol Table (Field Descriptors)
    - ➲ Field Symbol Table for SuperClass
  - ➲ Method Symbol Table (Method Descriptors)
    - ➲ Method Symbol Table for Superclass
- Method Descriptors
  - ➲ Local Variable Symbol Table (Local Variable Descriptors)
    - ➲ Parameter Symbol Table (Parameter Descriptors)
      - ➲ Field Symbol Table of Receiver Class
- Local, Parameter and Field Descriptors
  - ➲ Type Descriptors in Type Symbol Table or Class Descriptors

Hierarchy in Symbol Tables

- Symbol Table Hierarchy reflects hierarchy due to
  - Nested/Lexical Scopes
    - E.g, Nested procedures, nested blocks, inner classes, etc
  - Inheritance
    - E.g., Child Class inside Parent Class
- Lookup proceeds up the hierarchy until a suitable descriptor is found
  - (cf. CS784 Interpreter for OOPL)