CSE 401 – Compilers

Static Semantics
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Agenda

- Static semantics
- Types
- Attribute grammars
- Representing types
- Symbol tables
- Disclaimer: There’s more here than the subset you need for the project
What do we need to know to compile & check this?

```java
class C {
    int a;
    C(int initial) {
        a = initial;
    }
    void setA(int val) {
        a = val;
    }
}

class Main {
    public static void main() {
        C c = new C(17);
        c.setA(42);
    }
}
```
Beyond Syntax

- There is a level of correctness that is not captured by a context-free grammar
  - Has a variable been declared?
  - Are types consistent in an expression?
  - In the assignment $x=y$, is $y$ assignable to $x$?
  - Does a method call have the right number and types of parameters?
  - In a selector $p.q$, is $q$ a method or field of class instance $p$?
  - Is variable $x$ guaranteed to be initialized before it is used?
  - Could $p$ be null when $p.q$ is executed?
  - Etc. etc. etc.
What else do we need to know to generate code?

- Where are fields allocated in an object?
- How big are objects? (i.e., how much storage needs to be allocated by new)
- Where are local variables stored when a method is called?
- Which methods are associated with an object/class?
  - In particular, how do we figure out which method to call based on the run-time type of an object?
Semantic Analysis

- **Main tasks:**
  - Extract types and other information from the program
  - Check language rules that go beyond the context-free grammar
  - Resolve names
    - Relate declarations and uses of each variable
  - “Understand” the program well enough for synthesis

- **Key data structure: Symbol tables**
  - Map each identifier in the program to information about it (kind, type, etc.)

- This is the final part of the analysis phase or front end of the compiler
## Some Kinds of Semantic Information

<table>
<thead>
<tr>
<th>Information</th>
<th>Generated From</th>
<th>Used to process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol tables</td>
<td>Declarations</td>
<td>Expressions, statements</td>
</tr>
<tr>
<td>Type information</td>
<td>Declarations, expressions</td>
<td>Operations</td>
</tr>
<tr>
<td>Constant/variable information</td>
<td>Declarations, expressions</td>
<td>Statements, expressions</td>
</tr>
<tr>
<td>Register &amp; memory locations</td>
<td>Assigned by compiler</td>
<td>Code generation</td>
</tr>
<tr>
<td>Values</td>
<td>Constants</td>
<td>Expressions</td>
</tr>
</tbody>
</table>
Semantic Checks

For each language construct we want to know:

- What semantic rules should be checked
  - Specified by language definition (type compatibility, required initialization, etc.)
- For an expression, what is its type (used to check whether the expression is legal in the current context)
- For declarations, what information needs to be captured to use elsewhere
A Sampling of Semantic Checks (0)

- Appearance of a name: id
  - id has been declared and is in scope
  - Inferred type of id is its declared type
  - Memory location assigned by compiler
- Constant: v
  - Inferred type and value are explicit
A Sampling of Semantic Checks (1)

- Binary operator: \( \text{exp}_1 \text{ op } \text{exp}_2 \)
  - \( \text{exp}_1 \) and \( \text{exp}_2 \) have compatible types
    - Either identical, or
    - Well-defined conversion to appropriate types
  - Inferred type is a function of the operator and operand types
A Sampling of Semantic Checks (2)

- Assignment: $exp_1 = exp_2$
  - $exp_1$ is assignable (not a constant or expression)
  - $exp_1$ and $exp_2$ have (assignment-)compatible types
    - Identical, or
    - $exp_2$ can be converted to $exp_1$ (e.g., char to int), or
    - Type of $exp_2$ is a subclass of type of $exp_1$ (can be decided at compile time)
  - Inferred type is type of $exp_1$
  - Location where value is stored is assigned by the compiler
A Sampling of Semantic Checks (3)

- **Cast:** \((\text{exp1}) \text{ exp2}\)
  - \text{exp1} is a type
  - \text{exp2} either
    - Has same type as \text{exp1}
    - Can be converted to type \text{exp1} (e.g., double to int)
    - Downcast: is a superclass of \text{exp1} (in general this requires a runtime check to verify; at compile time we can at least decide if it could be true)
  - Upcast (Trivial): is the same or a subclass of \text{exp1}
- Inferred type is \text{exp1}
A Sampling of Semantic Checks (4)

- Field reference: exp.f
  - exp is a reference type (class instance)
  - The class of exp has a field named f
  - Inferred type is declared type of f
A Sampling of Semantic Checks (5)

- Method call: \( \text{exp.m}(e_1, e_2, ..., e_n) \)
  - \text{exp} is a reference type (class instance)
  - The class of \text{exp} has a method named \text{m}
  - The method has \( n \) parameters
  - Each argument has a type that can be assigned to the associated parameter
  - Inferred type is given by method declaration (or is void)
A Sampling of Semantic Checks (6)

- Return statement:
  - return exp;
  - return;

- Either
  - The expression can be assigned to a variable with the declared type of the method (if the method is not void) – exactly the same test as for assignment statement
  - or
  - There’s no expression (if the method is void)
Attribute Grammars

- A systematic way to think about semantic analysis
- Sometimes used directly, but even when not, AGs are a useful way to organize the analysis and thinking about it
Attribute Grammars

- Idea: associate attributes with each node in the (abstract) syntax tree
- Examples of attributes
  - Type information
  - Storage location
  - Assignable (e.g., expression vs variable – lvalue vs rvalue for C/C++ programmers)
  - Value (for constant expressions)
  - etc. ...
- Notation: X.a if a is an attribute of node X
Attribute Example

- Assume that each node has a .val attribute giving the computed value of that node
- AST and attribution for \((1+2) * (6 / 2)\)
Inherited and Synthesized Attributes

- Given a production $X ::= Y_1 \ Y_2 \ \ldots \ Y_n$
- A *synthesized* attribute $X.a$ is a function of some combination of attributes of $Y_i$'s (bottom up)
- An *inherited* attribute $Y_i.b$ is a function of some combination of attributes $X.a$ and other $Y_j.c$ (top down)
  - Sometimes restricted a bit: only $Y$'s to the left can be used (has implications for evaluation)
Attribute Equations

- For each kind of node we give a set of equations relating attribute values of the node and its children.
  
  Example: `plus.val = exp1.val + exp2.val`

- Attribution (evaluation) means implicitly finding a solution that satisfies all of the equations in the tree.
Informal Example of Attribute Rules (1)

- Suppose we have the following grammar for a trivial language:
  
  \[
  \text{program ::= decl stmt} \\
  \text{decl ::= int id;} \\
  \text{stmt ::= exp = exp ;} \\
  \text{exp ::= id | exp + exp | 1}
  \]

- We want to give suitable attributes for basic type and lvalue/rvalue checking.
Informal Example of Attribute Rules (2)

Attributes of nodes

- env (environment, e.g., symbol table); synthesized by decl, inherited by stmt
  - Each entry maps a name to its type and kind
- type (expression type); synthesized
- kind (variable [var or lvalue] vs value [val or rvalue]); synthesized
Attributes for Declarations

- decl ::= int id;
  - decl.env = \{id, int, var\}
Attributes for Program

- program ::= decl stmt
  - stmt.env = decl.env
Attributes for Constants

- \( \text{exp ::= 1} \)
  - \( \text{exp.kind = val} \)
  - \( \text{exp.type = int} \)
Attributes for Identifier Exprs.

- exp ::= id
  - id.type = exp.env.lookup(id)
  - exp.type = id.type
  - exp.kind = id.kind
Attributes for Addition

- exp ::= exp₁ + exp₂
  - exp₁.env = exp.env
  - exp₂.env = exp.env
  - error if exp₁.type != exp₂.type
    - (or error if not combatable if rules are move complex)
  - exp.type = exp₁.type (or exp₂.type)
  - exp.kind = val
Attribute Rules for Assignment

- stmt ::= exp₁ = exp₂;
  - exp₁.env = stmt.env
  - exp₂.env = stmt.env
  - Error if exp₂.type is not assignment compatible with exp₁.type
  - Error if exp₁.kind is not var (can’t be val)
Example

- int x; x = x + 1;
Extensions

- This can be extended to handle sequences of declarations and statements
  - Sequences of declarations create larger environments, where each one copies the previous one and adds the new id binding
  - Full environment is passed down to statements and expressions
Observations

- These are equational (functional) computations
- This can be automated, provided the attribute equations are non-circular
- But implementation problems
  - Non-local computation
  - Can’t afford to literally pass around copies of large, aggregate structures like environments
In Practice

- Attribute grammars give us a good way of thinking about how to structure semantic checks
- Symbol tables will hold environment information
- Add fields to AST nodes to refer to appropriate attributes (symbol table entries for identifiers, types for expressions, etc.)
  - Put in appropriate places in AST class inheritance tree – most statements don’t need types, for example
Symbol Tables

- Map identifiers to <type, kind, location, other properties>

Operations
- Lookup(id) => information
- Enter(id, information)
- Open/close scopes

Build & use during semantics pass
- Build first from declarations
- Then use to check semantic rules
Aside: Implementing Symbol Tables

- Big topic in classical compiler courses: implementing a hashed symbol table
- These days: use the collection classes that are provided with the standard language libraries (Java, C#, C++, ML, Haskell, etc.)
  - Then tune & optimize if it really matters
    - In production compilers, it really matters
- Java:
  - Map (HashMap) will handle most cases
  - List (ArrayList) for ordered lists (parameters, etc.)
Symbol Tables for MiniJava (1)

- Global – Per Program Information
  - Single global table to map class names to per-class symbol tables
    - Created in a pass over class definitions in AST
    - Used in remaining parts of compiler to check class types and their field/method names and extract information about them
Symbol Tables for MiniJava (2)

- Global – Per Class Information
  - 1 Symbol table for each class
    - 1 entry per method/field declared in the class
      - Contents: type information, public/private, parameter types (for methods), storage locations (later), etc.
  - In full Java, need multiple symbol tables (or more complex symbol table) per class
    - Ex.: Java allows the same identifier to name both a method and a field in a class – multiple namespaces
Symbol Tables for MiniJava (3)

- Global (cont)
  - All global tables persist throughout the compilation
    - And beyond in a real Java or C# compiler...
      - (e.g., symbolic information in Java .class or MSIL files, link-time optimization information in gcc)
Symbol Tables for MiniJava (4)

- 1 local symbol table for each method
  - 1 entry for each local variable or parameter
    - Contents: type information, storage locations (later), etc.
  - Needed only while compiling the method; can discard when done
    - But if type checking and code gen, etc. are done in separate passes, this table needs to persist until we’re done with it
Beyond MiniJava

- What we aren’t dealing with: nested scopes
  - Inner classes
  - Nested scopes in methods – reuse of identifiers in parallel or inner scopes; nested functions (ML, ...)

- Basic idea: new symbol table for inner scopes, linked to surrounding scope’s table
  - Look for identifier in inner scope; if not found look in surrounding scope (recursively)
  - Pop back up on scope exit
Engineering Issues

- In practice, want to retain $O(1)$ lookup
  - Use hash tables with additional information to get the scope nesting right
    - Scope entry/exit operations
- In multipass compilers, symbol table info needs to persist after analysis of inner scopes for use on later passes
  - See a compiler textbook for ideas & details
Error Recovery

What to do when an undeclared identifier is encountered?

- Only complain once (Why?)
- Can forge a symbol table entry for it once you’ve complained so it will be found in the future
- Assign the forged entry a type of “unknown”
- “Unknown” is the type of all malformed expressions and is compatible with all other types
  - Allows you to only complain once! (How?)
“Predefined” Things

- Many languages have some “predefined” items (functions, classes, standard library, …)
- Include initialization code or declarations in the compiler to manually create symbol table entries for these when the compiler starts up
  - Rest of compiler generally doesn’t need to know the difference between “predeclared” items and ones found in the program
  - Possible to put “standard prelude” information in a file or data resource and use that to initialize
    - Tradeoffs?
Types

- Classical roles of types in programming languages
  - Run-time safety
  - Compile-time error detection
  - Improved expressiveness (method or operator overloading, for example)
  - Provide information to optimizer
Type Checking Terminology

Static vs. dynamic typing
- static: checking done prior to execution (e.g. compile-time)
- dynamic: checking during execution

Strong vs. weak typing
- strong: guarantees no illegal operations performed
- weak: can’t make guarantees

Caveats:
- Hybrids common
- Inconsistent usage common
- “untyped,” “typeless” could mean dynamic or weak

<table>
<thead>
<tr>
<th></th>
<th>static</th>
<th>dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong</td>
<td>Java, SML</td>
<td>Scheme, Ruby</td>
</tr>
<tr>
<td>weak</td>
<td>C</td>
<td>PERL</td>
</tr>
</tbody>
</table>
Type Systems

- **Base Types**
  - Fundamental, atomic types
  - Typical examples: int, double, char, bool

- **Compound/Constructed Types**
  - Built up from other types (recursively)
  - Constructors include arrays, records/structs/classes, pointers, enumerations, functions, modules, ...
Type Representation

- Create a shallow class hierarchy, for example:
  
  ```java
  abstract class Type { ... } // or interface
  class ClassType extends Type { ... }
  class BaseType extends Type { ... }
  ```

  - Should not need too many of these
Types vs ASTs

- Types are not AST nodes!
- AST = abstract representation of source program (including source program type info)
- Types = abstract representation of type semantics for type checking, inference, etc.
  - Can include information not explicitly represented in the source code, or may describe types in ways more convenient for processing
- Be sure you have a separate “type” class hierarchy in your compiler distinct from the AST
Base Types

- For each base type (int, boolean, others in other languages), create a single object to represent it
  - Base types in symbol table entries and AST nodes are direct references to these objects
  - Base type objects usually created at compiler startup
- Useful to create a type “void” object to tag functions that do not return a value
- Also useful to create a type “unknown” object for errors
  - (“void” and “unknown” types reduce the need for special case code in various places in the type checker)
Compound Types

- Basic idea: use an appropriate “type constructor” object that refers to the component types
  - Limited number of these – correspond directly to type constructors in the language (record/struct/class, array, function,...)
  - A compound type is a graph
Class Types

- Type for: class Id { fields and methods }

```java
class ClassType extends Type {
    Type baseClassType; // ref to base class
    Map fields; // type info for fields
    Map methods; // type info for methods
}
```

- (Note: may not want to do this literally, depending on how class symbol tables are represented; i.e., class symbol tables might be useful or sufficient as the representation of the class type.)
Array Types

For regular Java this is simple: only possibility is # of dimensions and element type

class ArrayType extends Type {
    int nDims;
    Type elementType;
}

Array Types for Pascal &c

- Pascal allows arrays to be indexed by any discrete type like an enum, char, subrange of int, or other discrete type
  
  \[
  \text{array } [\text{indexType}] \text{ of elementType}
  \]

- Element type can be any other type, including an array (e.g., 2-D array = 1-D array of 1-D array)

  \[
  \text{class GeneralArrayType extends Type } \{ \\
  \quad \text{Type indexType;} \\
  \quad \text{Type elementType;} \\
  \}
  \]
Methods/Functions

- Type of a method is its result type plus an ordered list of parameter types

```java
class MethodType extends Type {
    Type resultType; // type or "void"
    List parameterTypes;
}
```
Type Equivalence

For base types this is simple

- Types are the same if they are identical
  - Pointer comparison in the type checker
- Normally there are well defined rules for coercions between arithmetic types
  - Compiler inserts these automatically or when requested by programmer (casts) – often involves inserting cast/conversion nodes in AST
Type Equivalence for Compound Types

- Two basic strategies
  - *Structural equivalence*: two types are the same if they are the same kind of type and their component types are equivalent, recursively
  - *Name equivalence*: two types are the same only if they have the same name, even if their structures match

- Different language design philosophies
Structural Equivalence

- Structural equivalence says two types are equal iff they have the same structure
  - Atomic types are tautologically the same structure
  - If type constructors:
    - Same constructor
    - Recursively, equivalent arguments to constructor
- Ex: Atomic types, array types, ML record types
- Implement with recursive implementation of equals, or by canonicalization of types when types created then use pointer equality
Name Equivalence

- Name equivalence says that two types are equal iff they came from the same textual occurrence of a type constructor
  - Ex: class types, C struct types (struct tag name), datatypes in ML
  - special case: type synonyms (e.g. typedef in C) do not define new types
- Implement with pointer equality assuming appropriate representation of type info
Type Equivalence and Inheritance

- Suppose we have
  class Base { ... }
  class Extended extends Base { ... }

- A variable declared with type Base has a \textit{compile-time type} of Base

- During execution, that variable may refer to an object of class Base or any of its subclasses like Extended (or can be null, which is compatible with all class types)
  - Sometimes called the \textit{runtime type}
Type Casts

- In most languages, one can explicitly cast an object of one type to another
  - sometimes cast means a conversion (e.g., casts between numeric types)
  - sometimes cast means a change of static type without doing any computation (casts between pointer types or pointer and numeric types)
Type Conversions and Coercions

- In Java, we can explicitly convert an value of type double to one of type int
  - can represent as unary operator
  - typecheck, codegen normally

- In Java, can implicitly coerce an value of type int to one of type double
  - compiler must insert unary conversion operators, based on result of type checking
C and Java: type casts

- In C: safety/correctness of casts not checked
  - allows writing low-level code that’s type-unsafe
  - more often used to work around limitations in C’s static type system
- In Java: downcasts from superclass to subclass need run-time check to preserve type safety
  - static typechecker allows the cast
  - codegen introduces run-time check
    - (same code needed to handle “instanceof”)
  - Java’s main form of dynamic type checking
Various Notions of Equivalence

- There are usually several relations on types that we need to deal with:
  - “is the same as”
  - “is assignable to”
  - “is same or a subclass of”
  - “is convertible to”

- Be sure to check for the right one(s)
Useful Compiler Functions

- Create a handful of methods to decide different kinds of type compatibility:
  - Types are identical
  - Type t1 is assignment compatible with t2
  - Parameter list is compatible with types of expressions in the call

- Usual modularity reasons: isolates these decisions in one place and hides the actual type representation from the rest of the compiler

- Probably belongs in the same package with the type representation classes
Implementing Type Checking for MiniJava

- Create multiple visitors for the AST
- First pass/passes: gather information
  - Collect global type information for classes
  - Could do this in one pass, or might want to do one pass to collect class information, then a second one to collect per-class information about fields, methods – you decide
- Next set of passes: go through method bodies to check types, other semantic constraints
This discussion of semantics, type representation, etc. should give you a good idea of what needs to be done in your project, but you’ll need to adapt the ideas to the project specifics.

You’ll also find good ideas in your compiler book...
Coming Attractions

- Need to start thinking about translating to object code (actually x86(-64) assembly language, the default for this project)
- Next lectures
  - x86 overview (as a target for simple compilers)
  - Runtime representation of classes, objects, data, and method stack frames
  - Assembly language code for higher-level language statements
- And there’s a midterm in there somewhere…