CSE P 501 – 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

!

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What do we need to know to compile this?

```
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);
  }
}
```

only one

type of a, a declared

type of a

where stored

C is a class

not declared in this scope otherwise

where is it in memory

no other main method in this class

with 1 int arg or float/dbl + can convert

public ctr

types match (= compatable)

declared type of c

setA method in type of C (public) has 1 int/dbl/etc arg

static or instance

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.

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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?

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Semantic Analysis

- Main tasks:
  - Extract types and other information from the program
  - Check language rules that go beyond the context-free grammar
  - Resolve names – connect declarations and uses
  - "Understand" the program – last phase of front end
- Key data structures: symbol tables
  - For each identifier in the program, record its attributes (kind, type, etc.)
  - Later: assign storage locations (stack frame offsets) for variables; add other annotations

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Some Kinds of Semantic Information

Information	*Generated From*	*Used to process*
Symbol tables	Declarations	Expressions, statements
Type information	Declarations, expressions	Operations
Constant/variable information	Declarations, expressions	Statements, expressions
Register & memory locations	Assigned by compiler	Code generation
Values	Constants	Expressions

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Semantic Checks

- For each language construct we want to know:
  - What semantic rules should be checked
    - Specified by language definition (type compatibility, required declarations, scope, etc., etc.)
  - For an expression, what is its type (is the expression legal in the current context?)
  - For declarations, what information needs to be captured to be used elsewhere?

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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

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A Sampling of Semantic Checks (1)

- Binary operator: exp_1 op exp_2
  - exp_1 and exp_2 have compatible types
    - Identical, or
    - Well-defined conversion to appropriate types
  - Inferred type is a function of the operator and operand types

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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 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 stored assigned by compiler

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A Sampling of Semantic Checks (3)

animal
mammal
cat

- Cast: (exp1) exp2
  - exp1 is a type
  - type of exp2 either
    - Has same type as exp1
    - rep. change — Can be converted to type exp1 (e.g., double to int)
    - ref type. — Is a superclass of exp1 (in general requires a runtime check to verify that exp2 has type exp1)
    - Is the same or a subclass of exp1 (trivial)
  - **Inferred type is exp1**

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A Sampling of Semantic Checks (4)

- Field reference: exp.f
  - exp is a reference type
  - The class of exp has a field named f
  - Inferred type is declared type of f

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m(int,int) [m(dbl,int) m(int,dbl)] m(1,2) m(1,2.0) m(1.0,2.0)

A Sampling of Semantic Checks (5)

m(dbl,dbl)
m(int,int)

m(1,2)
m(1.0,2.0)
m(1.0,2)

- Method call $exp.m(e_1, e_2, \ldots, e_n)$
  - exp is a reference type
  - The class of exp has a method named 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)

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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) – same test as for assignments and parameters
- Or
  - There's no expression (if the method is void)

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Semantic Analysis

- Parser builds abstract syntax tree
- Now need to extract semantic information and check constraints
  - Can sometimes be done during the parse, but often easier to organize as separate phases
    - And some things can't be done on the fly, e.g., information about identifiers that are used before they are declared (fields, classes)
- Information stored in *symbol tables*
  - Generated by semantic analysis, used there and later

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Attribute Grammars

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

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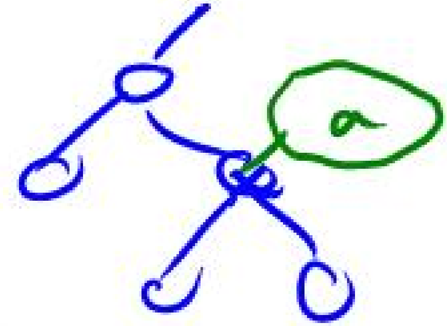
Attribute Grammars



- 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

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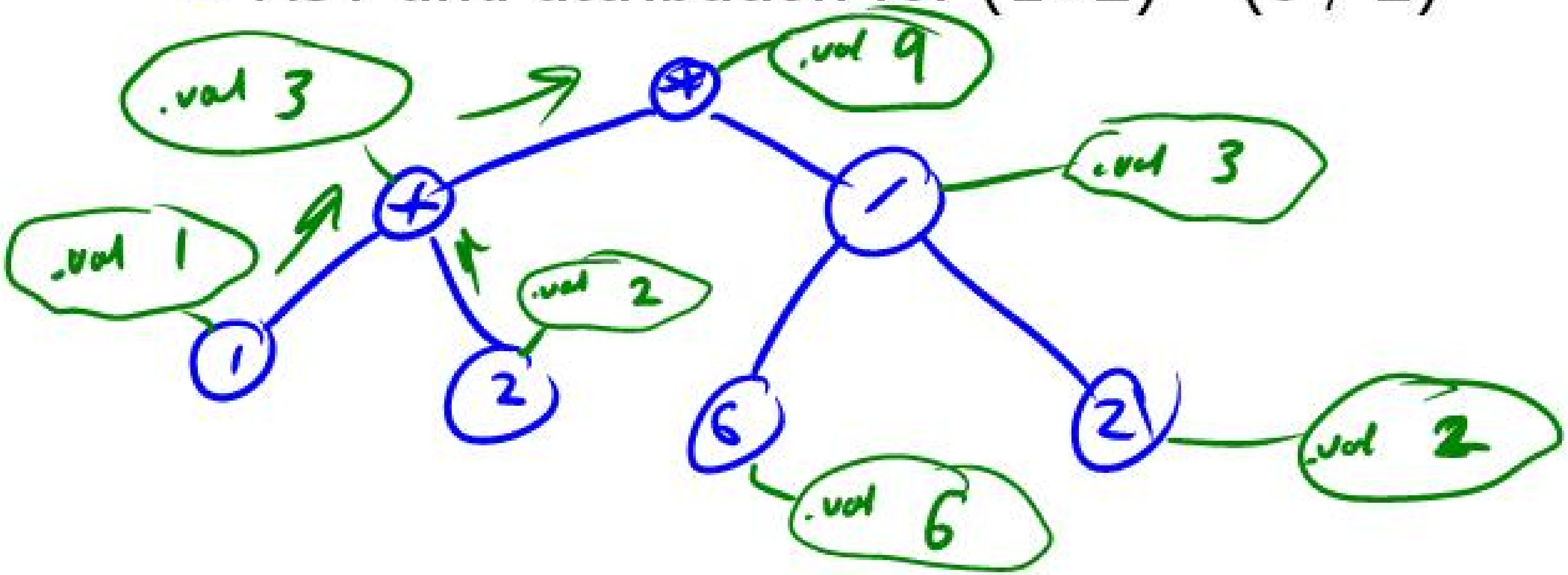
Attribute Example

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



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Inherited and Synthesized Attributes

- Given a production $X ::= Y_1\ Y_2\ \ldots\ Y_n$
- A *synthesized* attribute is 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 to, e.g., only Y's to the left (implications for evaluation)

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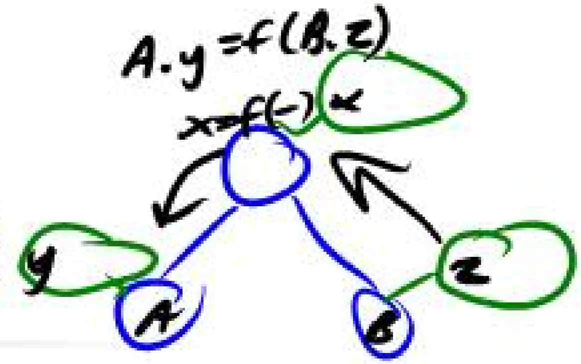
Attribute Equations



- 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

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Informal Example of Attribute Rules (1)

- Suppose we have the following grammar for a trivial language:

  program ::= decl stmt
  decl ::= int id;
  stmt ::= exp = exp ;
  exp ::= id | exp + exp | 1

- Give suitable attributes for types and lvalue/rvalue checking

Informal Example of Attribute Rules (2)

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

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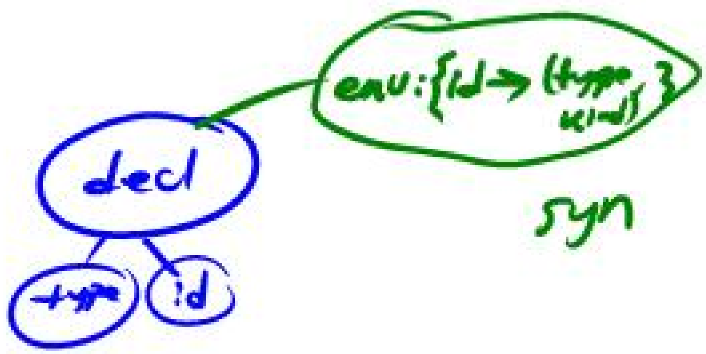
Attributes for Declarations

- decl ::= int id;
  - decl.env = {id, int, var}



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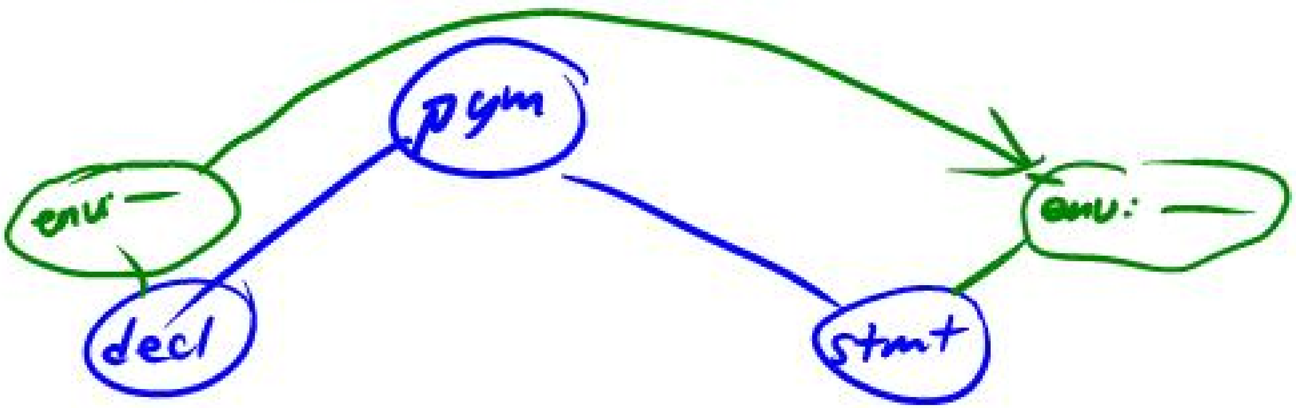
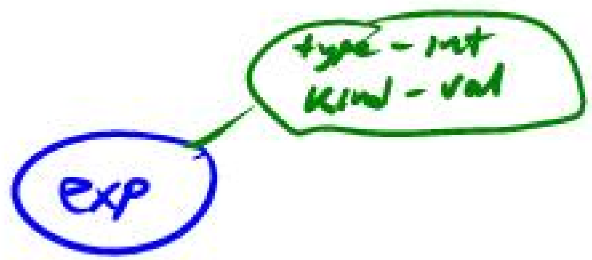
Attributes for Program

- program ::= decl stmt
  - stmt.env = decl.env



Attributes for Constants

- exp ::= 1
  - exp.kind = val
  - exp.type = int



Attributes for Expressions

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

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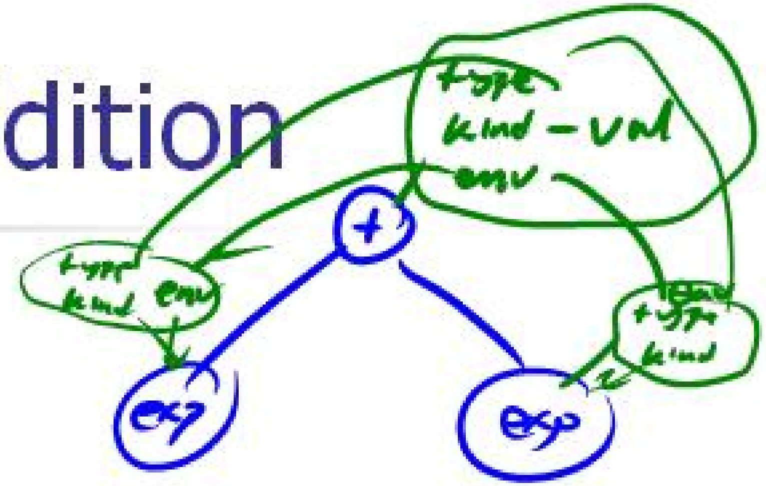
Attributes for Addition



- $exp ::= exp_1 + exp_2$
  - $exp_1.env = exp.env$
  - $exp_2.env = exp.env$
  - error if $exp_1.type \mathrel{!=} exp_2.type$
    - (or error if not combatable when rules are more complex)
  - $exp.type = exp_1.type$ (or $exp_2.type$)
  - $exp.kind = val$

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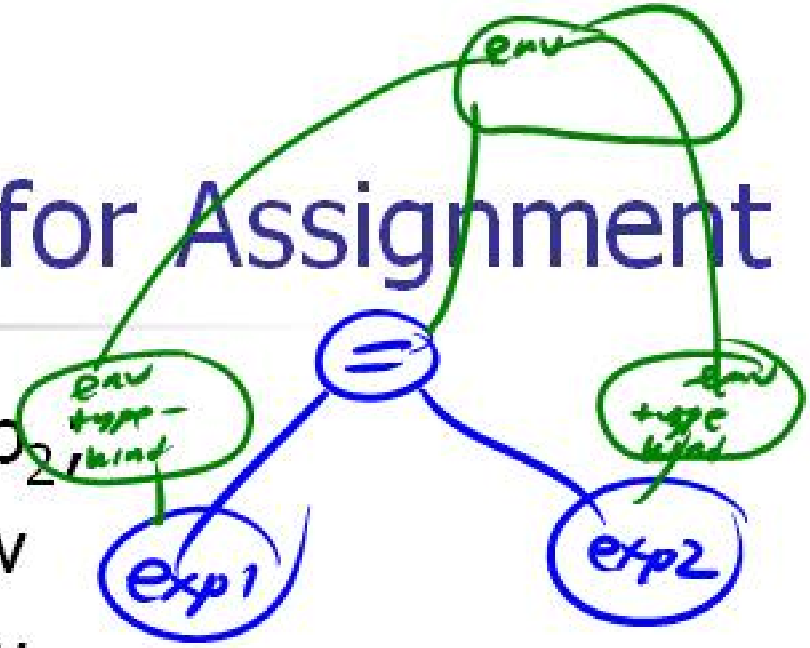
Attribute Rules for Assignment

- stmt ::= exp_1 = exp_2 ;
  - exp_1.env = stmt.env
  - exp_2.env = stmt.env
  - Error if exp2.type is not assignment compatibile with exp1.type
  - error if exp_1.kind is not var (can't be val)



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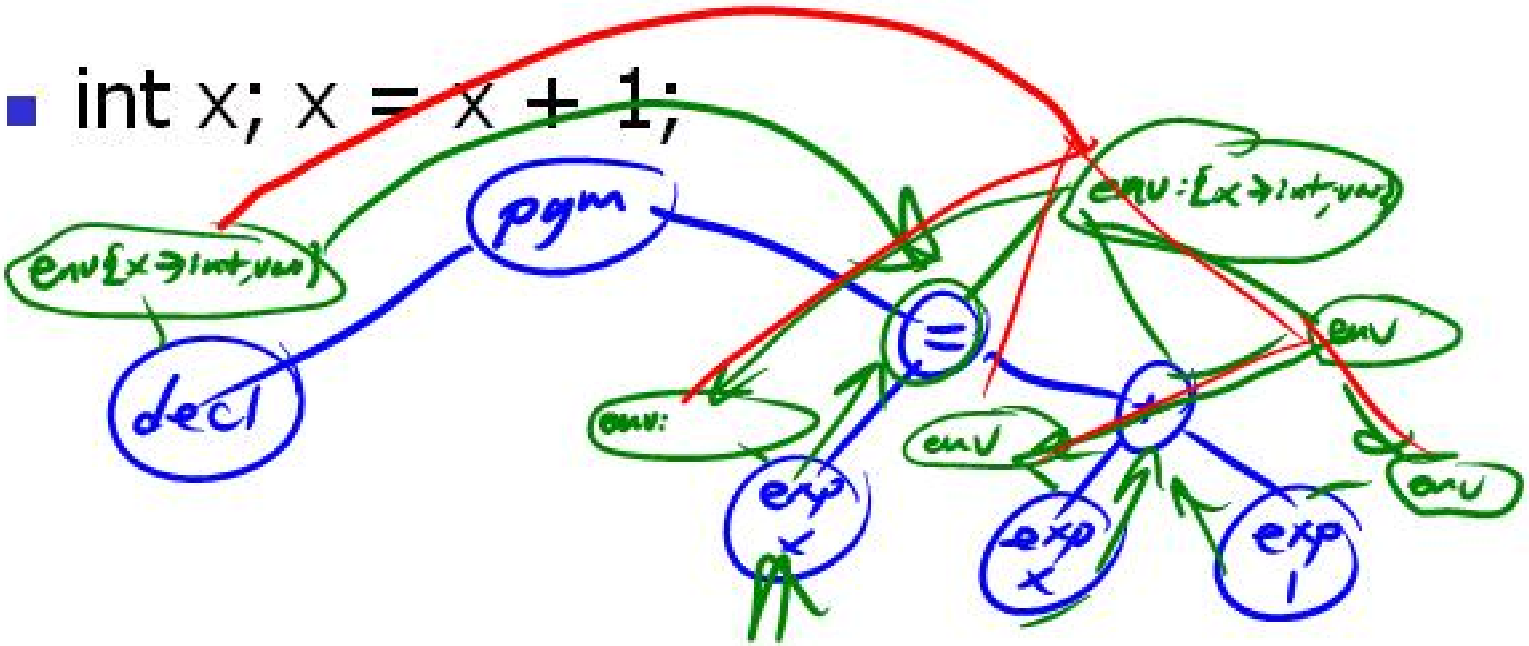
Example

- int x; x = x + 1;



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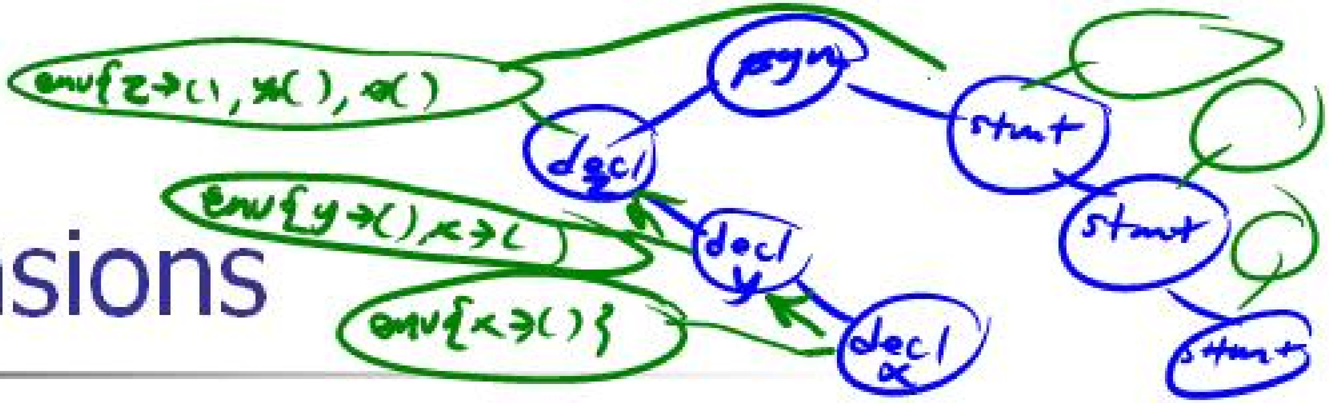
Extensions



- This can be extended to handle sequences of declarations and statements
  - Sequence of declarations builds up a combined environment – each decl synthesizes a new environment from previous plus new binding
  - Full environment is passed down to statements and expressions

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Observations

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

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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 heirarchy – most statements don't need types, for example

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Symbol Tables

- Map identifiers to
  <type, kind, location, other properties>
- Operations
  - Lookup(id) => information
  - Enter(id, information)
  - Open/close scopes
- Semantic pass
  - Build tables first from declarations
  - Use information 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 libraries (Java, C#, C++, ML, Haskell, etc.)
  - Then tune & optimize if it really matters
    - In production compilers, it really matters
- For Java:
  - Map (HashMap) will solve most cases
  - List (ArrayList) for ordered lists (parameters, etc.)

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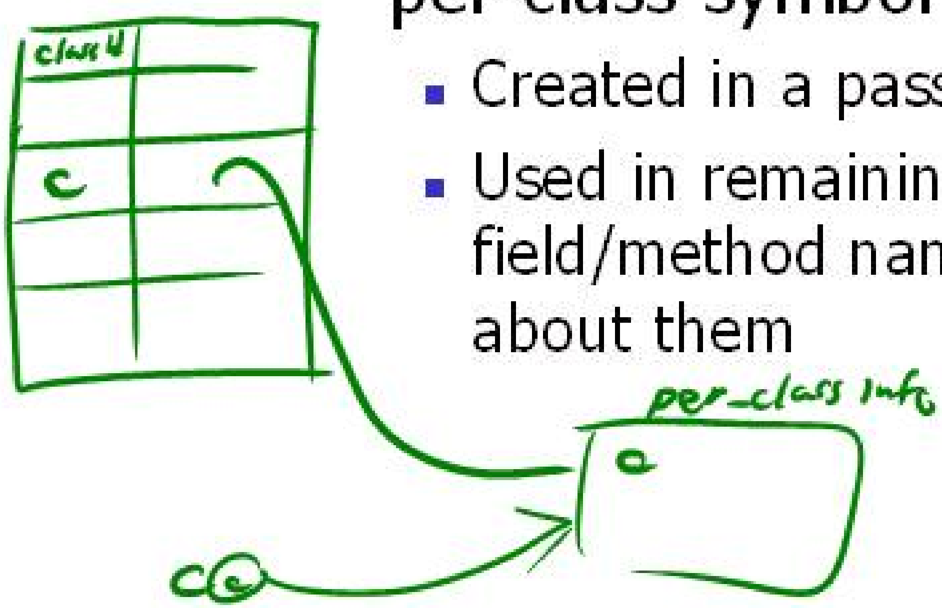
Symbol Tables for MiniJava (1)

- 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 field/method names and extract information about them



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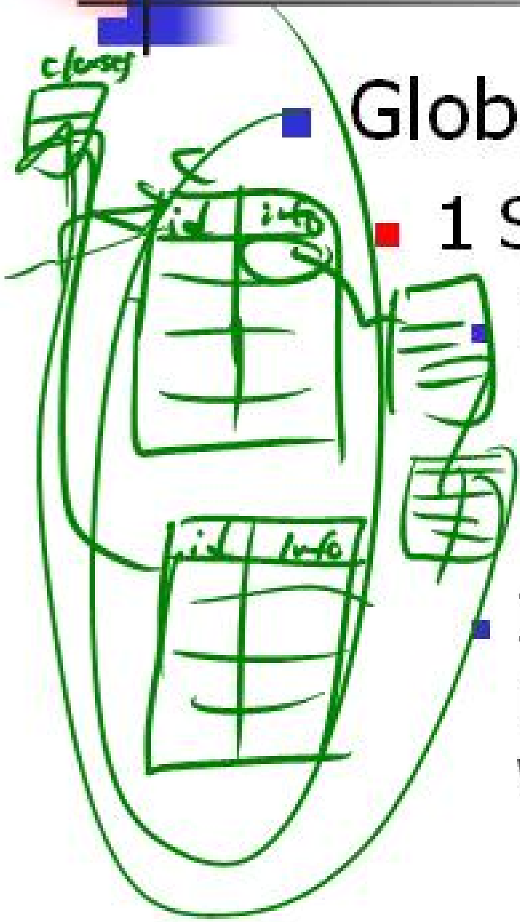
Symbol Tables for MiniJava (2)



- 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 or some way to handle multiple namespaces
      - Ex: The same identifier can name both a method and a field in a class.

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 files, MSIL data, link-time optimization information)

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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 method is processed in several passes the tables need to persist

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, Pascal, …)
- Basic idea: new symbol tables 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

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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

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Error Recovery

x = y+1;

{

y++;

k(y == 17)

- 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
    - Can avoid redundant error messages (how?)

maxInt

"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

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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

	static	dynamic
strong	Java, SML	Scheme, Ruby
weak	C	PERL

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Type Systems

- Base Types
  - Fundamental, atomic types
  - Typical examples: int, double, char
- Compound/Constructed Types
  - Built up from other types (recursively)
  - Constructors include arrays, records/ structs/classes, pointers, enumerations, functions, modules, …

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Representing Types in a Compiler

- Create a shallow class hierarchy, for example

```
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 types for semantics checks, 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

Basetype intType = new BaseType()
Basetype boolType = new BaseType

Base Types

v.type = intType

- For each base type (int, boolean, others in other languages), create a single object to represent it
  - Symbol table entries and AST nodes for expressions refer to these to represent type info
  - Usually create 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)

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Compound Types

- Basic idea: use appropriate "type constructor" object that refers to 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

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Class Types

- Type for: class Id { fields and methods }

```
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 as the representation of the class type.)

Array Types

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

  T[][][]

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


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Array Types for Pascal &c.

- Pascal allows arrays to be indexed by any discrete type
  - array[indexType] of elementType
- Element type can be any other type, including an array (i.e., 2-D array = 1-D array of 1-D arrays)

```
class GeneralArrayType extends Type {
  Type indexType;
  Type elementType;
}
```

Methods/Functions

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

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

T m(——)

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Type Equivalance

- 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 requires inserting cast/conversion AST nodes

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Type Equivalence for Compound Types

Type Complex{
  double re, im;
}
Type Point{
  double x, y;
}

- 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

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Type Equivalence and Inheritance

B v;
v = new E( )

- Suppose we have
  class Base { … }
  class Extended extends Base { … }
- A variable declared with type Base has a *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 *runtime type*

Various Notions of Equivalance

- 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)

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Useful Compiler Functions

- Create a handful of methods to decide different kinds of type compatibility:
  - Types are identical
  - Type t1 is assignment compatibile 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

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Implementing Type Checking for MiniJava

- Create multiple visitors for the AST
- First passe(s): 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
- Next set of passes: go through method bodies to check types, other semantic constraints

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Coming Attractions

- Need to start thinking about translating to object code (actually x86(-64?) assembly language, the default for this project)
- Next:
  - 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

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