

# CSE P 501 – Compilers

Static Semantics

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# Administrivia

- Parser+AST+print visitors due next Mon. 11pm
  - How's it going?
- “scanner-final” and “parser-final” git tags must be *exactly* that
- Next part of project: semantics + type check out by early next week

# Agenda

- Static semantics
- Attribute grammars
- Symbol tables
- Types & type checking
- Wrapup

Disclaimer: There's (lots) more here than the what we need for the project

# What do we need to know and check to verify that this is a legal program?

```
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);  
    }  
}
```

# What do we need to know and check to verify that this is a legal program?

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

Some things to check:

- 

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

# Beyond Syntax

- There is a level of correctness 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?
  - 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 well enough for synthesis
- Key data structure: Symbol tables
  - Map each identifier in the program to information about it (kind, type, etc.)
  - Later: assign storage locations (stack frame offsets) for variables, add other annotations
- This is the final part of the analysis phase (front end) of the compiler

# Some Kinds of Semantic Information

<i>Information</i>	<i>Generated From</i>	<i>Used to process</i>
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

# 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 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:  $id$ 
  - Check:  $id$  has been declared and is in scope
  - Compute: Inferred type of  $id$  is its declared type
- Constant:  $v$ 
  - Compute: Inferred type and value are explicit

# A Sampling of Semantic Checks (1)

- Binary operator:  $exp_1 \text{ op } exp_2$ 
  - Check:  $exp_1$  and  $exp_2$  have compatible types
    - Either identical, or
    - Well-defined conversion to appropriate types
  - Compute: Inferred type is a function of the operator and operand types

# A Sampling of Semantic Checks (2)

- Assignment:  $exp_1 = exp_2$ 
  - Check:  $exp_1$  is assignable (not a constant or expression)
  - Check:  $exp_1$  and  $exp_2$  have (assignment-)compatible types
    - Identical, or
    - $exp_2$  can be converted to  $exp_1$  (e.g., int to double), or
    - Type of  $exp_2$  is a subclass of type of  $exp_1$  (can be decided at compile time)
  - Compute: Inferred type is type of  $exp_1$

# A Sampling of Semantic Checks (3)

- Cast:  $(exp_1) exp_2$ 
  - Check:  $exp_1$  is a type
  - Check:  $exp_2$  either
    - Has same type as  $exp_1$
    - Can be converted to type  $exp_1$  (e.g., double to int)
    - Downcast: is a superclass of  $exp_1$  (in general this requires a runtime check to verify type safety; at compile time we can at least decide if it could be true)
    - Upcast (Trivial): is the same or a subclass of  $exp_1$
  - Compute: Inferred type is  $exp_1$

# A Sampling of Semantic Checks (4)

- Field reference: `exp.f`
  - Check: `exp` is a reference type (not primitive type)
  - Check: The class of `exp` has a field named `f`
  - Compute: Inferred type is declared type of `f`



# A Sampling of Semantic Checks (5)

- Method call:  $\text{exp.m}(e_1, e_2, \dots, e_n)$ 
  - Check:  $\text{exp}$  is a reference type (not primitive type)
  - Check: The type of  $\text{exp}$  has a method named  $m$ 
    - (inherited or declared as part of the type)
  - Check: The method  $m$  has  $n$  parameters
    - Or, if overloading allowed, at least one version of  $m$  exists with  $n$  parameters
  - Check: Each argument has a type that can be assigned to the associated parameter
    - Same “assignment compatible” check for assignment
    - Overloading: need to find a “best match” among available methods if more than one is compatible – or reject if result is ambiguous (e.g., full Java, C++, others)
  - Compute: Inferred (result) type is given by method declaration (or could be void)

# A Sampling of Semantic Checks (6)

- Return statement: `return exp;` or: `return;`
- Check:
  - If the method is not void: The expression can be assigned to a variable that has the declared return type of the method – exactly the same test as for assignment statement and method call-by-value argument/parameter types
  - If the method is void: There is no expression

# Agenda

- Static semantics
- Attribute grammars
- Symbol tables
- Types & type checking
- Wrapup

# Attribute Grammars

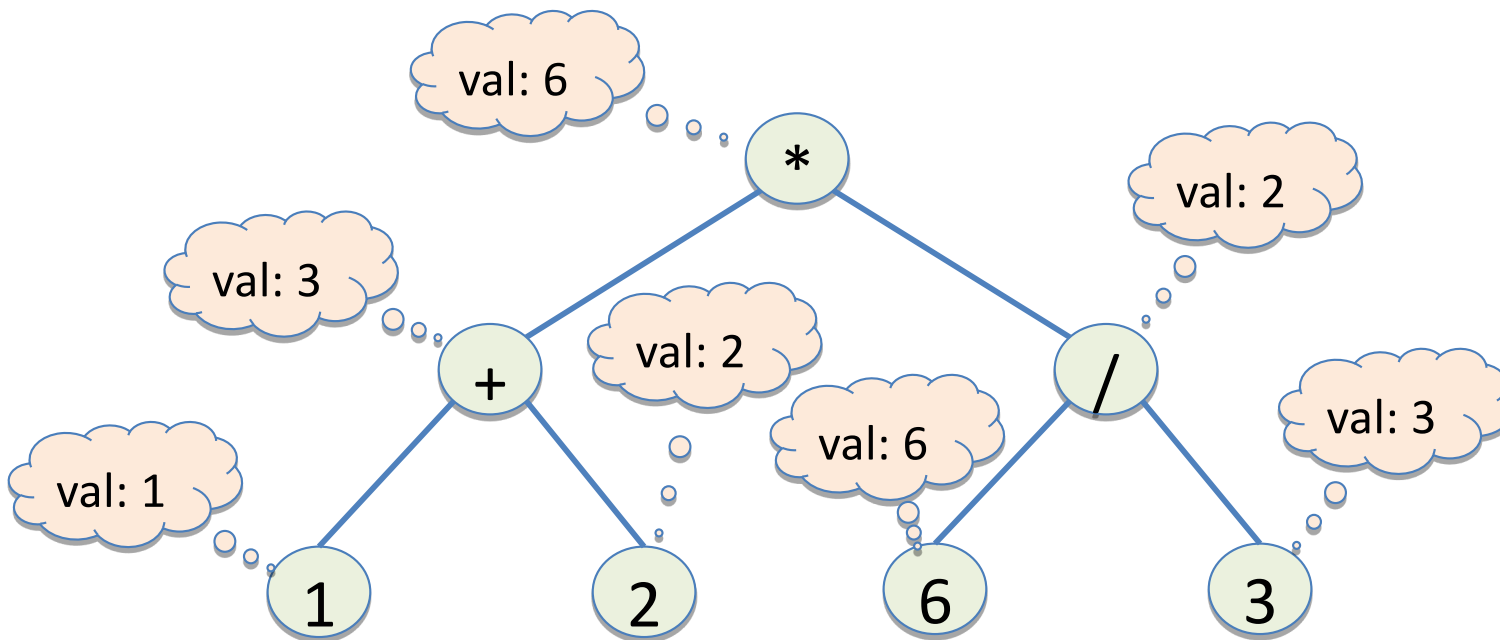
- A systematic way to think about semantic analysis
- Formalize properties checked and computed during semantic analysis and relate them to grammar productions in the CFG (or AST)
- Sometimes used directly, but even when not, AGs are a useful way to organize the analysis and think about it

# 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/location – lvalue vs rvalue in C/C++ terms)
  - 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  $(1+2) * (6 / 3)$



# Inherited and Synthesized Attributes

Given a production  $X ::= Y_1 Y_2 \dots Y_n$

- A *synthesized* attribute  $X.a$  is a function of some combination of the attributes of the  $Y_i$ '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)
  - Often restricted a bit. Example: only  $Y$ 's to the left can be used (implications for attribute evaluation order)

# Attribute Equations

- For each kind of node we give a set of equations (*not* assignments) relating attribute values of the node and its children
  - Example:  $\text{plus.val} = \text{exp}_1.\text{val} + \text{exp}_2.\text{val}$
- Attribution (evaluation) means finding a solution that satisfies all of the equations in the tree
  - This is an example of a constraint language



# 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

- What attributes would we create to check types and assignability (lvalue vs rvalue)?

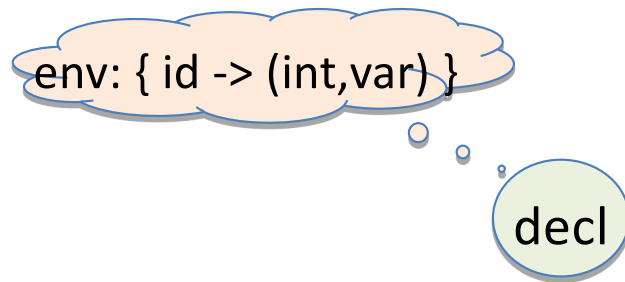
# Informal Example of Attribute Rules (2)

- Attributes of nodes
  - env (environment, e.g., list of known names and their properties)
    - 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

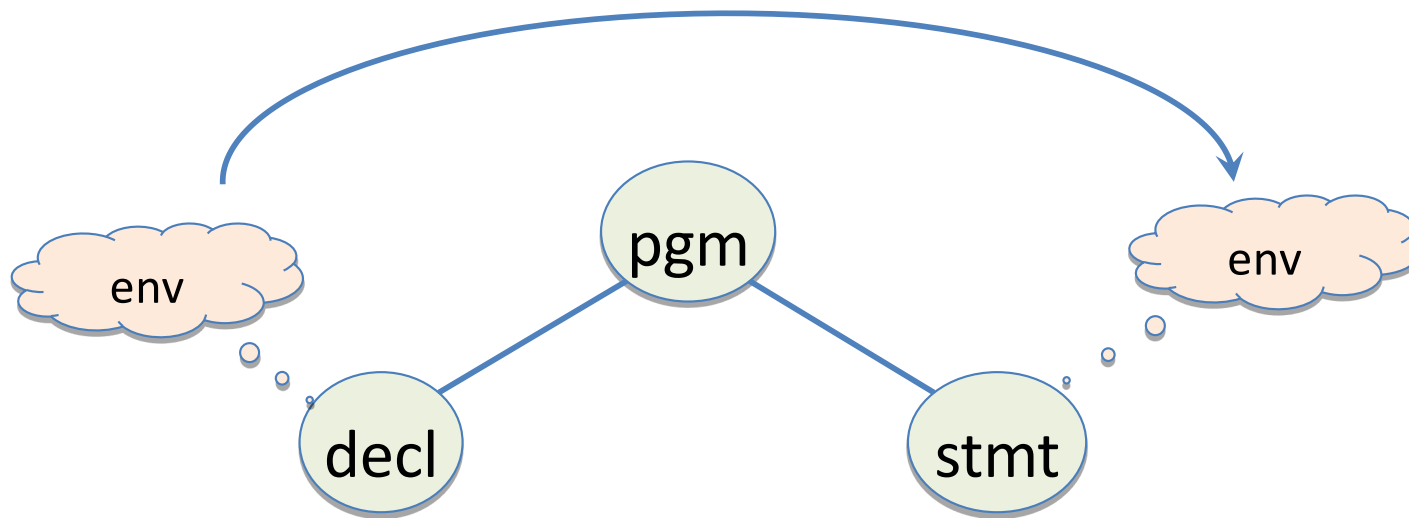
`decl ::= int id;`

`decl.env = {id → (int, var)}`



# Attributes for Program

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

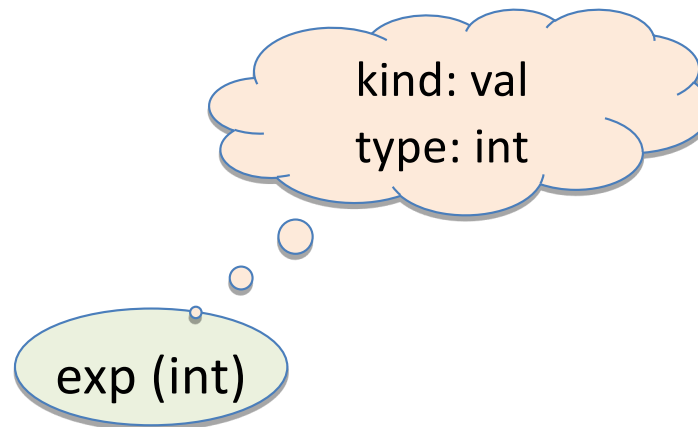


# Attributes for Constants

`exp ::= 1`

`exp.kind = val`

`exp.type = int`



# Attributes for Identifier Exprs.

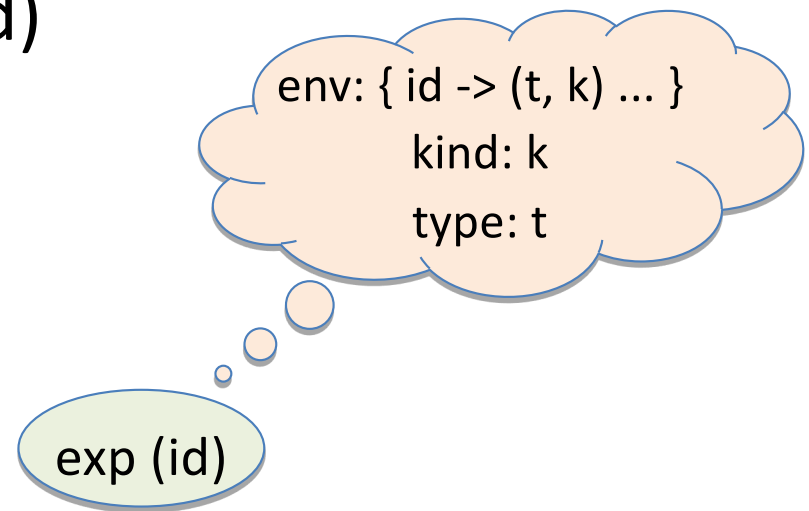
`exp ::= id`

`(type, kind) = exp.env.lookup(id)`

error if id not found in env

`exp.type = type` (i.e., id type)

`exp.kind = kind` (i.e., id kind)



# Attributes for Addition

$\text{exp} ::= \text{exp}_1 + \text{exp}_2$

$\text{exp}_1.\text{env} = \text{exp}.\text{env}$

$\text{exp}_2.\text{env} = \text{exp}.\text{env}$

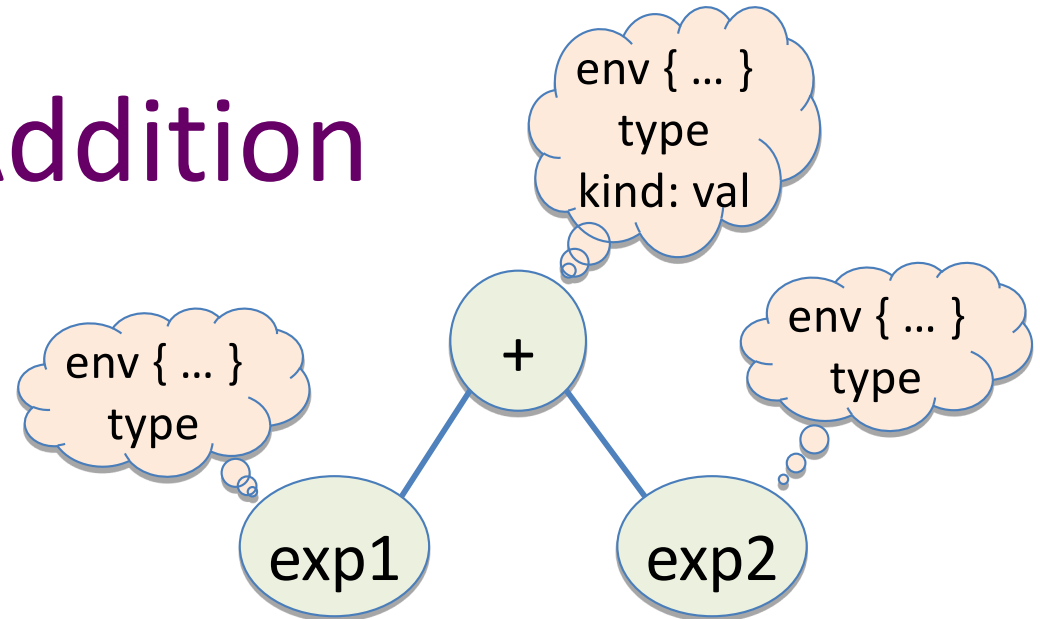
error if  $\text{exp}_1.\text{type} \neq \text{exp}_2.\text{type}$

(or error if not compatible, depending on language rules)

$\text{exp}.\text{type} = \text{exp}_1.\text{type}$  (or  $\text{exp}_2.\text{type}$ )

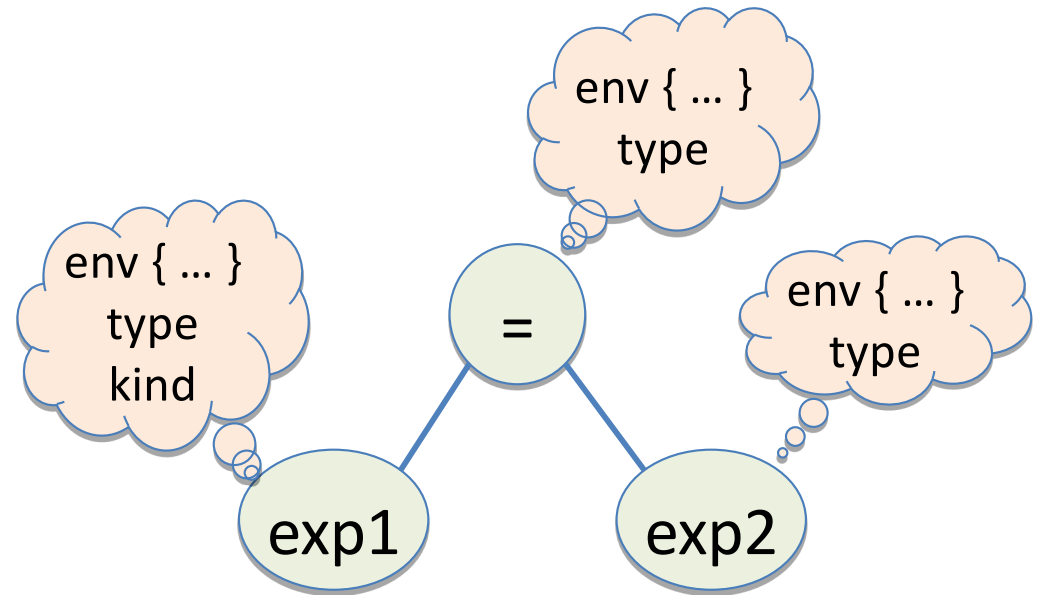
(or whatever type the language rules specify)

$\text{exp}.\text{kind} = \text{val}$



# Attribute Rules for Assignment

$\text{stmt} ::= \text{exp}_1 = \text{exp}_2;$   
 $\text{exp}_1.\text{env} = \text{stmt}.\text{env}$   
 $\text{exp}_2.\text{env} = \text{stmt}.\text{env}$



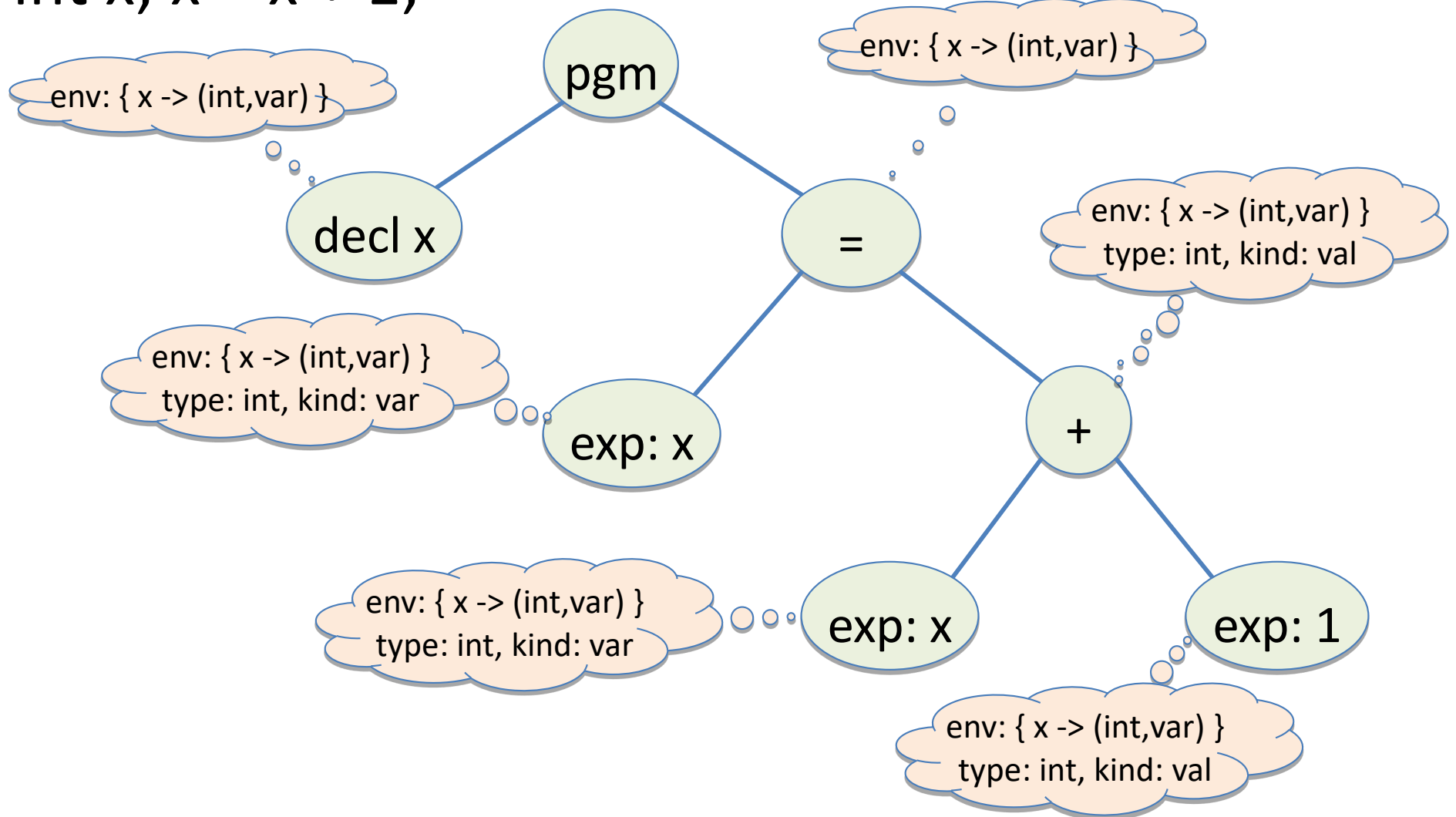
error if  $\text{exp}_2.\text{type}$  is not assignment compatible with  $\text{exp}_1.\text{type}$

error if  $\text{exp}_1.\text{kind}$  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 builds up larger environments, each decl synthesizes a new env from previous one plus the new binding
  - Full environment is passed down to statements and expressions

# Observations

- These are equational computations
  - Think functional programming, no side effects
- Solver can be automated, provided the attribute equations are non-circular
- But implementation problems
  - Non-local computation
  - Can't afford to literally make/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 and exploit inheritance so nodes have appropriate fields. Most statements don't need types, for example, but all expressions do.

# Agenda

- Static semantics
- Attribute grammars
- **Symbol tables**
- Types & type checking
- Wrapup

# 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
- Use (and augment) in later compiler phases

# Aside:

## Implementing Symbol Tables

- Big topic in classical (i.e., ancient) 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
      - Up to a point...
- Java:
  - Map (HashMap) will handle most cases
  - List (ArrayList) for ordered lists (parameters, etc.)

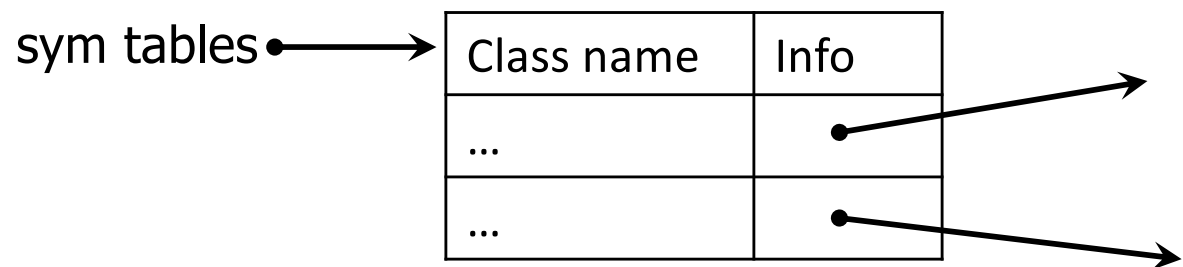
# Symbol Tables for MiniJava

- We'll outline a scheme that does what we need, but feel free to modify/adapt as needed
- Mix of global and local tables
- A few more features here than needed for our MiniJava project



# Symbol Tables for MiniJava: Global

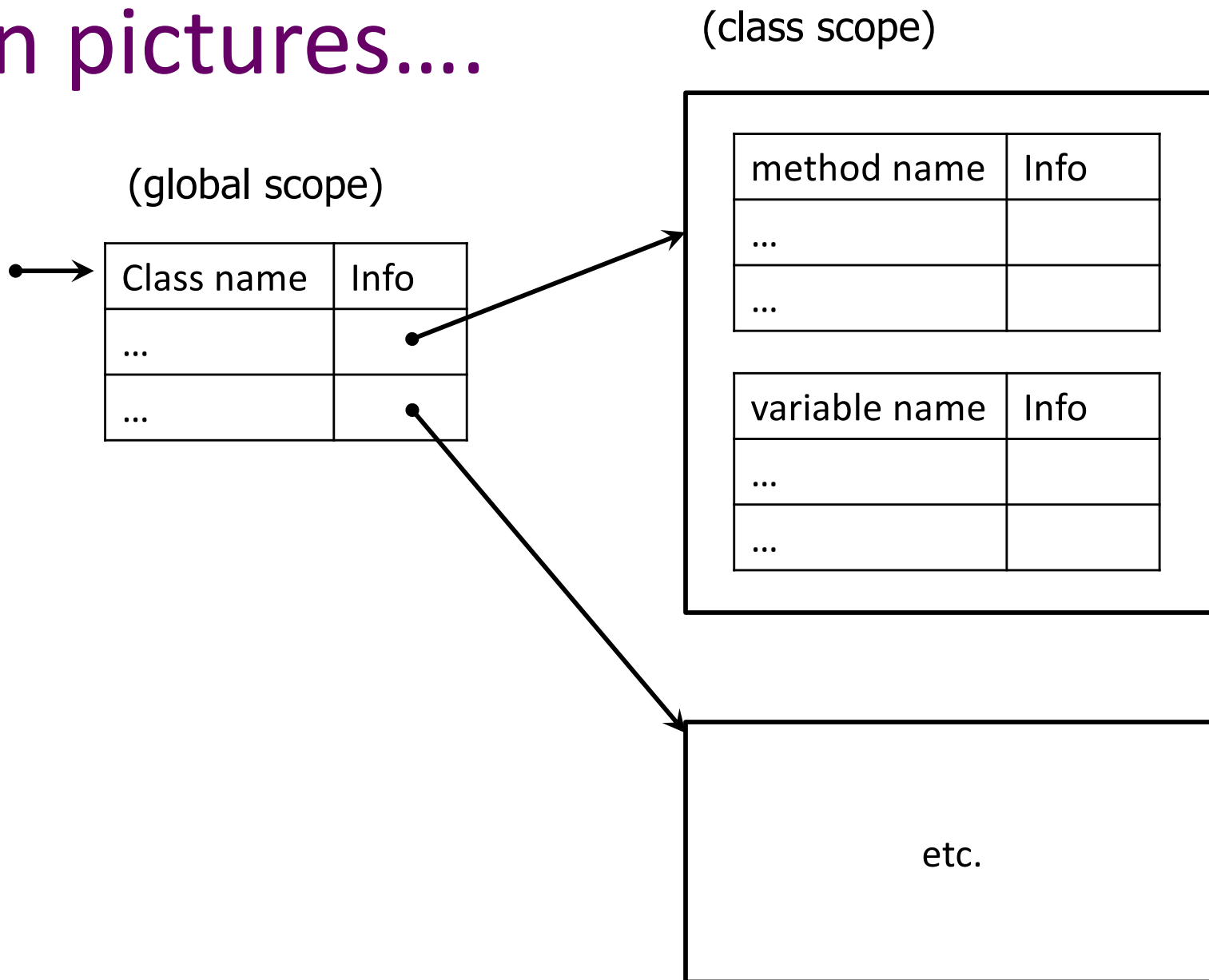
- Global – Per Program Information
  - Single global table to map class names to per-class symbol tables
    - Created in a pass over class definitions in AST
    - Used in remaining parts of compiler to check class types and their field/method names and extract information about them



# Symbol Tables for MiniJava: Class

- One symbol table for each class
  - One entry per method/field declared in the class
    - Contents: type information, public/private, parameter types (for methods), storage locations (later), etc.
- Reached from global table of class names
- For Java, we actually need multiple symbol tables (or more complex symbol table) per class
  - The same identifier can be used for both a method name and a field name in a single class
    - We will support this in our MiniJava project

# In pictures....



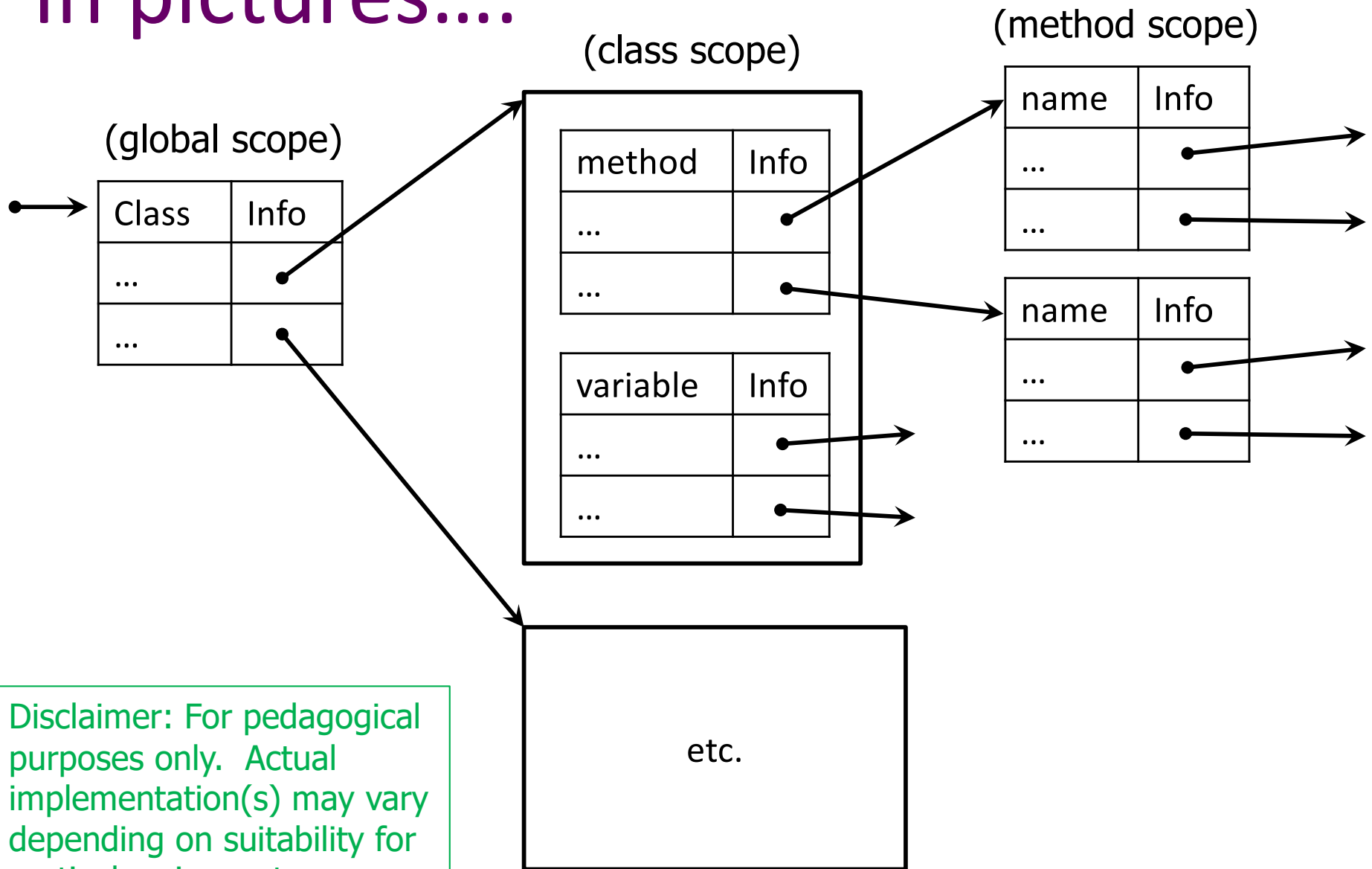
# Symbol Tables for MiniJava: Global/Class

- All global tables persist throughout the compilation
  - And beyond in a real compiler...
    - Symbolic information in Java .class or MSIL files, link-time optimization information in gcc)
    - Debug information in .o and .exe files
    - Some or all of this information in library files (.a, .so)
    - Type information for garbage collector

# Symbol Tables for MiniJava: Methods

- One local symbol table for each method
  - One entry for each local variable or parameter
    - Contents: type info, storage locations (later), etc.
  - Needed only while compiling the method; can discard when done in a single pass compiler
    - But if type checking and code gen, etc. are done in separate passes, this table needs to persist until we're done with it
      - And beyond: may need type info for runtime debugging, memory management/GC, exception handling try/catch block info, etc.
    - For our MiniJava compiler we will have multiple passes

# In pictures....



Disclaimer: For pedagogical purposes only. Actual implementation(s) may vary depending on suitability for particular circumstances.

# Beyond MiniJava

- What we aren't dealing with: nested scopes
  - Inner classes
  - Nested scopes in methods – reuse of identifiers in parallel or inner scopes (most languages); nested functions (ML etc. ...)
  - Lambdas and function closures (Racket, JavaScript, Java, C#, , ...)
- Basic idea: new symbol table for inner scopes, linked to surrounding scope's table (i.e., stack of symbol tables, top = current innermost scope, bottom = global scope)
  - Look for identifier in inner scope; if not found look in surrounding scope (recursively)
  - Pop symbol table when we exit a scope
- Also ignoring static fields/methods, accessibility (public, protected, private), package scopes, ...

# Engineering Issues (1)

- In multipass compilers, inner scope symbol tables need to persist for use in later passes
  - So really can't delete symbol tables on scope exit
  - Retain tables and add a pointer to the parent scope table (effectively a reverse tree of symbol tables for nested scopes with root = global table)
    - Keep a pointer to current innermost scope (usually a leaf but could be interior node) and start looking for symbols there



# Engineering Issues (2)

- In practice, often want to retain  $O(1)$  lookup or something close to it
  - Would like to avoid  $O(\text{depth of scope nesting})$ , although some compilers assume this will be small enough not to matter
  - When it matters, use hash tables with additional information (linked lists of various sorts) to get the scope nesting right
    - Usually need some sort of scope entry/exit operations
  - See a compiler textbook for ideas & details

# Error Recovery

- What to do when an undeclared identifier is encountered?
  - Goal: only complain once (Why?)
  - Can forge a symbol table entry for id 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 (constants, functions, classes, namespaces, standard libraries, ...)
- Include initialization code or declarations to manually create symbol table entries for these in an outermost scope 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
  - Can put “standard prelude” information in a file or data resource and use that to initialize
    - Tradeoffs?

# Agenda

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# 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
    - In strongly typed languages, allows compiler to make assumptions about possible values
    - Qualifiers like `const`, `final`, or `restrict` (in C) allow for other assumptions

# 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

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

# Type Systems

- Base Types
  - Fundamental, atomic types
  - Typical examples: int, double, char, bool
- Compound/Constructed Types
  - Built up from other types (recursively)
  - Constructors include records/structs/classes, arrays, pointers, enumerations, functions, modules, ...
    - Most language provide a small collection of these

# How to Represent Types in a Compiler?

One solution: create a shallow class hierarchy

- Example:

```
abstract class Type { ... } // or interface
```

```
class BaseType extends Type { ... }
```

```
class ClassType extends Type { ... }
```

- Should not need too many of these



# Types vs ASTs

- Types nodes 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. (i.e., an ADT)
  - May 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 for typechecking that is *not* part of the AST class hierarchy

# Base Types

- For each base type (int, boolean, char, double, etc.) create exactly one object to represent it (singleton!)
  - 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 for the result “type” of 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; don’t have to return “null” for “no type” or “not declared” cases, etc.)

# Compound Types

- Basic idea: use an appropriate “compound type” or “type constructor” object that contains references to the component types
  - Limited number of these – correspond directly to type constructors in the language (pointer, array, record/struct/class, function,...)
  - So a compound type is represented as a graph
- Some examples...

# 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  
}

(MiniJava project note: May not want to represent class types exactly like this. Depending on how class symbol tables are represented, the class symbol table(s) might be a sufficient representation of a class type.)

# Array Types

- For regular Java this is simple: only possibility is # of dimensions and element type (which can be another array type or anything else)

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

# Array Types for Other Languages

- Example: Pascal allowed arrays to be indexed by any discrete type like an enum, char, subrange of int, or other discrete type

```
array [indexType] of elementType
```

(fantastic idea – would be nice if it became popular again)

- Element type can be any other type, including an array (e.g., 2-D array = 1-D array of 1-D array in many languages – or might have explicit # of dimensions)

```
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;  
}
```

- Sometimes called the method “signature”

# Type Equivalence

- For base types this is simple: types are the same if they are identical
  - Can use pointer comparison in the type checker if you have a singleton object for each base type
- Normally there are well defined rules for coercions between arithmetic types
  - Compiler inserts these automatically where required by the language spec or when written explicitly by programmer (casts) – often involves inserting cast or conversion nodes in AST



# Type Equivalence for Compound Types

- Two basic choices
  - *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
  - e.g., are Complex and Rectangular2DPoint the same?
  - e.g., are Point (Cartesian) and Point (Polar) the same?

# Structural Equivalence

- Structural equivalence says two types are equal iff they have same structure
  - Atomic types are tautologically the same structure and equal if they are the same type
  - For type constructors: equal if the same constructor and, recursively, type components are equal
- 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/ref. 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
  - But: (special case) type synonyms (e.g. typedef in C) do not define new types, they introduce another name for an existing type
- Implement with pointer equality assuming appropriate representation of type info

# Type Equivalence and Inheritance

- Suppose we have

```
class Base { ... }  
class Derived extends Base { ... }
```
- A variable declared with type Base has a *compile-time type* or *static type* of Base
- During execution, that variable may refer to an object of class Base or any of its subclasses like Derived (or can be null), often called the *runtime type* or *dynamic type*
  - Since subclass is guaranteed to have all fields/methods of base class, type checker only needs to deal with declared (compile-time) types of variables and, in fact, can't track runtime types of all possible values assigned to variables

# Type Casts

- In most languages, one can explicitly cast an expression of one type to another
  - sometimes cast means a conversion (e.g., casts between numeric types)
  - sometimes a cast means a change of static type without doing any computation (casts between pointer types or (in C/C++) pointer and numeric types)
  - for objects can be a upcast (free and always safe) or downcast (requires runtime check to be safe)

# Type Conversions and Coercions

- In full Java, we can explicitly convert a value of type double to one of type int
  - can represent as unary operator in the AST
  - typecheck, codegen normally
- In full Java, can implicitly coerce a value of type int to one of type double
  - compiler must insert unary conversion operators into AST, based on results of type checking

# C and Java: type casts

- In C/C++: safety/correctness of casts not checked
  - allows writing low-level code that's not type-safe
  - C++ has more elaborate casts, and one of them does require runtime checks
- In Java: downcasts from superclass to subclass need runtime check to preserve type safety
  - static typechecker allows the cast
  - typechecker/codegen inserts runtime check
    - (same code needed to handle “instanceof”)
  - Java's primary need for dynamic type checking

# Various Notions of Type Compatibility

- There are usually several relations on types that we need to evaluate in a compiler:
  - “is the same as”
  - “is assignable to”
  - “is same or a subclass of”
  - “is convertible to”
- Exact meanings and checks needed depend on the language spec.
- 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  $t_1$  is assignment compatible with  $t_2$
  - Parameter list is compatible with types of expressions in the method call (likely uses assignment compatibility)
- Usual modularity reasons: isolate these decisions in one place and hide the actual type representation from the rest of the compiler
- Very likely belong in the same package (ADT) 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 and methods – you decide
- Next set of passes: go through method bodies to check types, other semantic constraints

# Agenda

- Static semantics
- Attribute grammars
- Symbol tables
- Types & type checking
- **Wrapup**

# Disclaimer

- This overview of semantics, type representation, etc. should give you a decent 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...
- And remember that these slides cover more than is needed for our specific project

# Coming Attractions

- To get a running compiler we need:
  - Execution model for language constructs
  - x86-64 assembly language for compiler writers
  - Code generation and runtime bootstrap details
- We'll also spend considerable time on compiler optimization
  - Intermediate reps., graphs, SSA, dataflow
  - Optimization analysis and transformations