

CSE 401/M501 – Compilers

Static Semantics

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Autumn 2020

Administrivia

- Parser/AST/print visitors due next Thurs., 11pm
 - Usual late days if you (and your partner) need and (both) have them available
 - How's it going?
- HW3 covering LL grammars and recursive-descent parsing out later today – due a week after parser / ast / visitor

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 to compile & check 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);  
    }  
}
```

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}
```

Some things to check:

- ?

Let's try breaking into small groups for this. Here's the plan:

- Everyone will be joining a Zoom breakout group of 4-5 people in a moment
- One person in each group should open up this slide (the downloadable one posted last night) in powerpoint or somewhere thing else where you can edit it
- That person should share their screen with the rest of the group
- Then collectively see how many semantic checks you can find and create a list here (hint: there are many!)
- Staff will drift into and out of groups as you work
- We'll reconvene in about 5 min. to compare results...
- Have fun!

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    }  
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```

```
class Main {  
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    }  
}
```

Some things to check (from the chat board):

- variables “exist” (meaning “declared”) in scope
- Costr matches class name
- method call: right number and types of parameters
- can’t assign to final var
- return stmt – can’t exist if void method
- only 1 main method in a public class
- Class C exists
- C has constructor with one int parameter
- Var. c has type C
- c not prev. declared in this scope
- type C of c has a setA method with one int parameter
- in a=val, a exists (class var)
- val exists and is declared (param)
- value of “val” has to have a type that’s assignment compatible with type of a

What do we need to know to compile & check this?

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    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);
    }
}
```

Some things to check (another list):

- C(init) type of init should be int
- a=initial, type of initial should be asg. compatible with a (also a=val, etc.)
- C has method setA with int parameter
- C exists and has C(int) ctr
- check vars declared and get types before use
- main method exists (sortof)
- In main, c has not been declared yet (only decl once per scope)
- Class C has not been declared elsewhere (same with main)
- public/private methods used appropriately
- in C, a is not final
- check return types of methods match use in expressions
- and so forth....

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?
 - 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; 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: exp is a reference type (not primitive type)
 - Check: The type of exp has a method named m
 - (inherited or declared as part of the type)
 - Check: The method m has n parameters
 - Or, if overloading is 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 as “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
 - If the method is void: There is no expression

Agenda

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- **Attribute grammars**
- Symbol tables
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Attribute Grammars

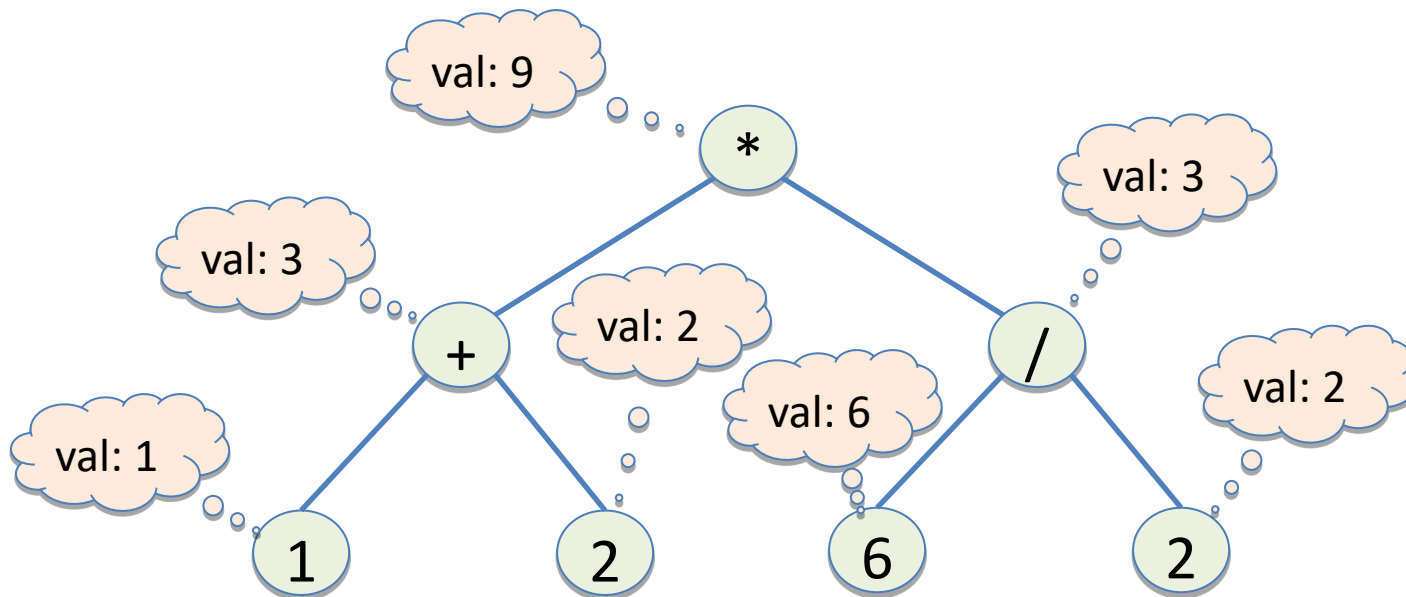
- A systematic way to think about semantic analysis
- Formalize properties checked and computed during semantic analysis and relate them to grammar productions in the CFG (or AST)
- Sometimes used directly, but even when not, AGs are a useful way to organize the analysis and think about it

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 – same as: rvalue vs lvalue 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 $(1+2) * (6 / 2)$



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 (has implications for attribute evaluation)

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)?

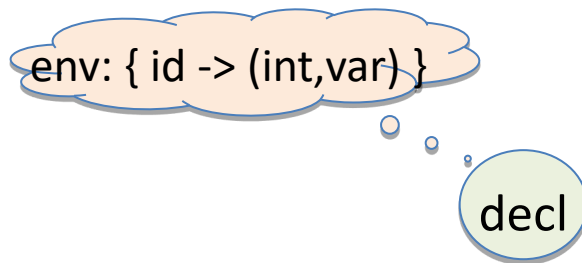
Informal Example of Attribute Rules (2)

- 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

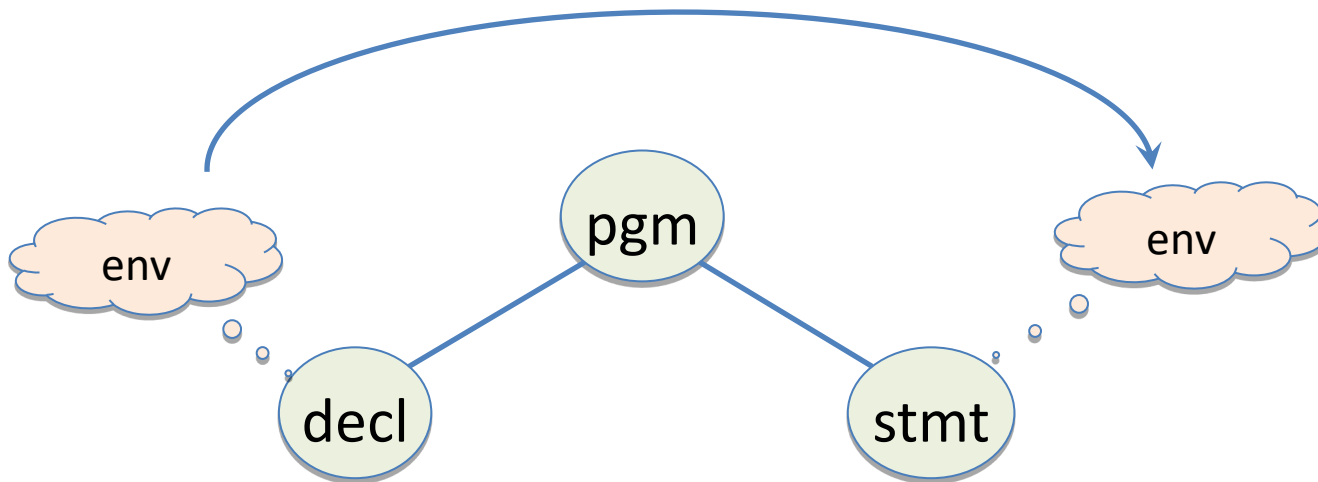
`decl ::= int id;`

`decl.env = {id → (int, var)}`



Attributes for Program

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

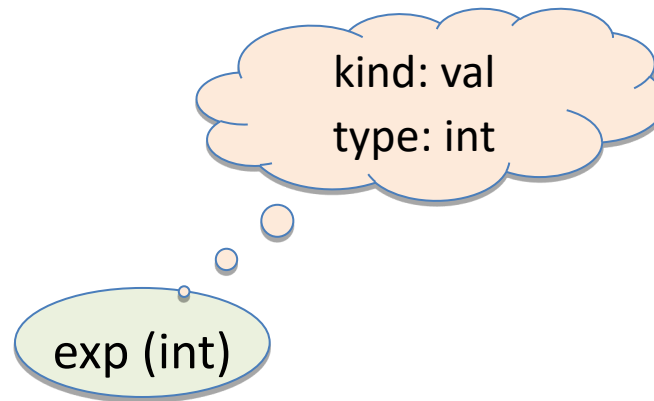


Attributes for Constants

`exp ::= 1`

`exp.kind = val`

`exp.type = int`



Attributes for Identifier Exprs.

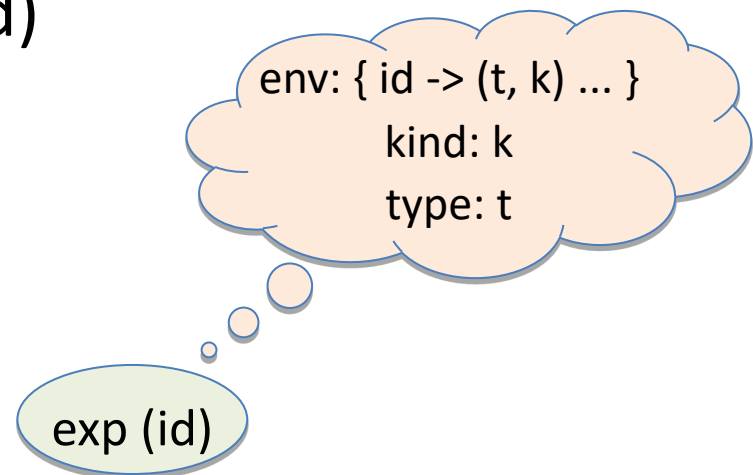
`exp ::= id`

`(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

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

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

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

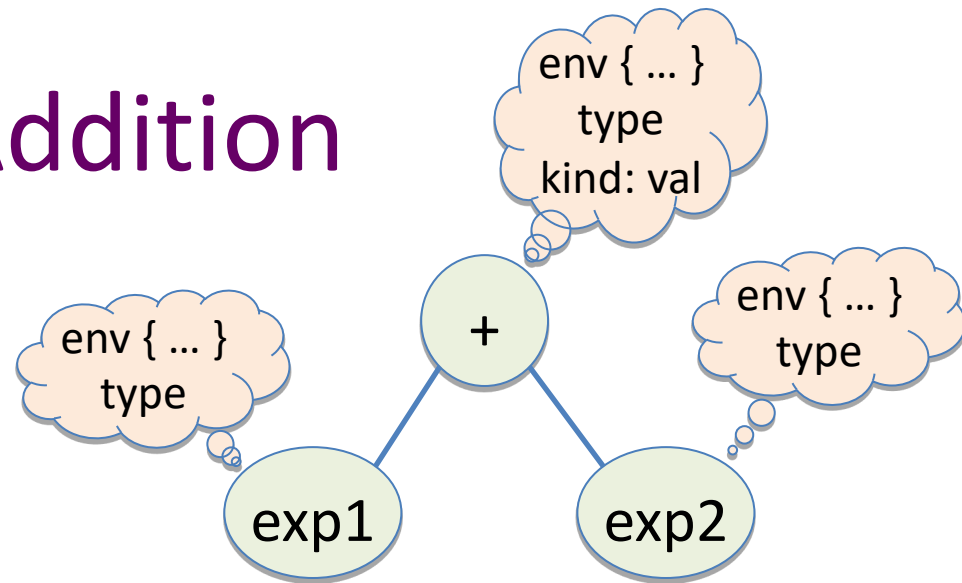
error if $\text{exp}_1.\text{type} \neq \text{exp}_2.\text{type}$

(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

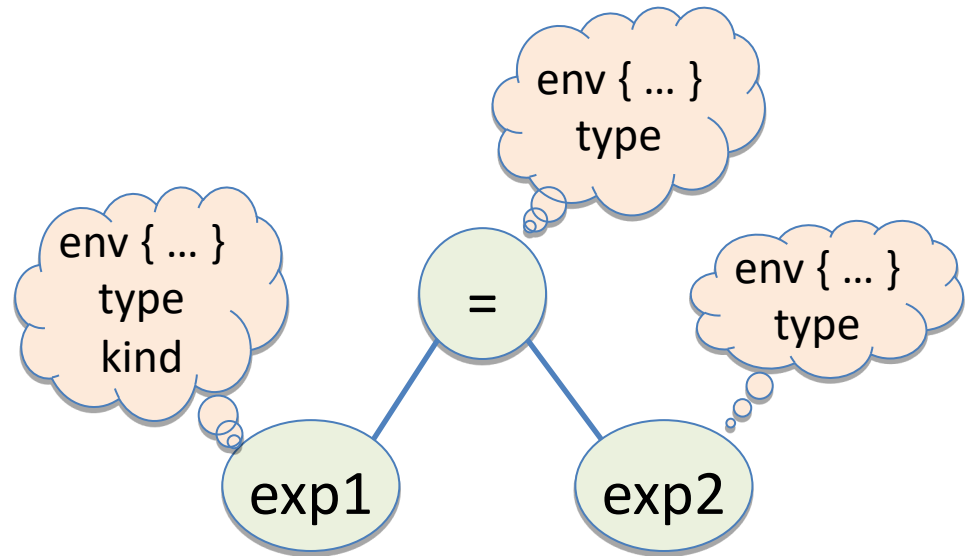
$\text{stmt} ::= \text{exp}_1 = \text{exp}_2;$

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

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

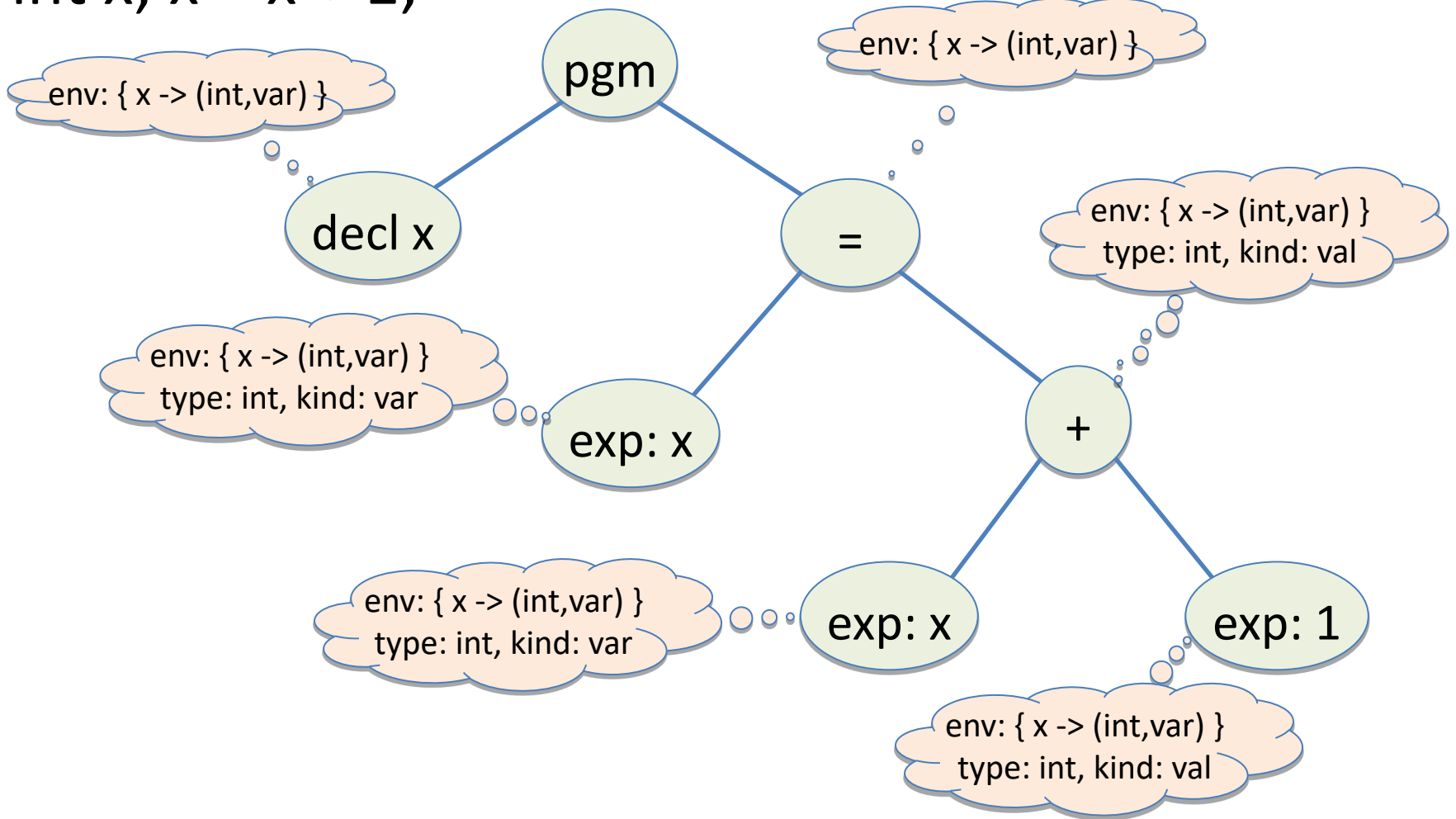
error if $\text{exp}_2.\text{type}$ is not assignment compatible with $\text{exp}_1.\text{type}$

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

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- **Symbol tables**
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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

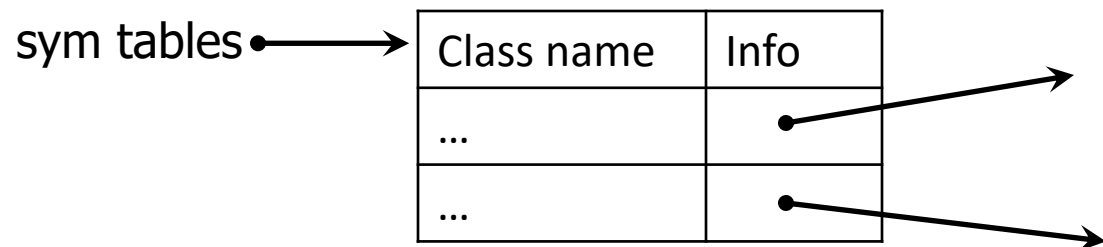
- Big topic in classical (i.e., ancient) compiler courses: implementing a hashed symbol table
- These days: use the collection classes that are provided with the standard language libraries (Java, C#, C++, ML, Haskell, etc.)
 - Then tune & optimize if it really matters
 - In production compilers, it really matters
 - Up to a point...
- In 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

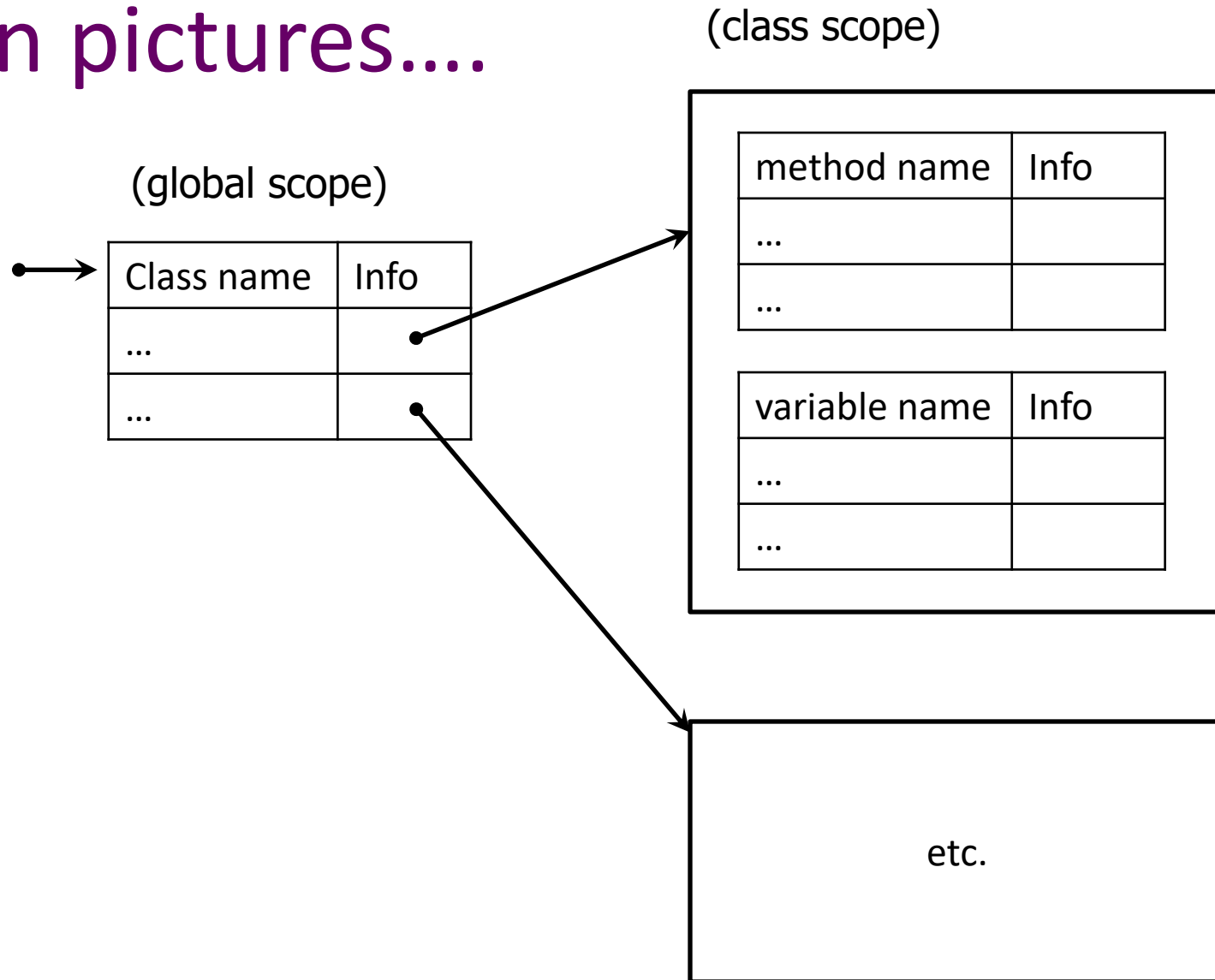
- Global – Per Program Information
 - Single global table to map class names to per-class symbol tables
 - Created in a pass over class definitions in AST
 - Used in remaining parts of compiler to check class types and their field/method names and extract information about them



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....



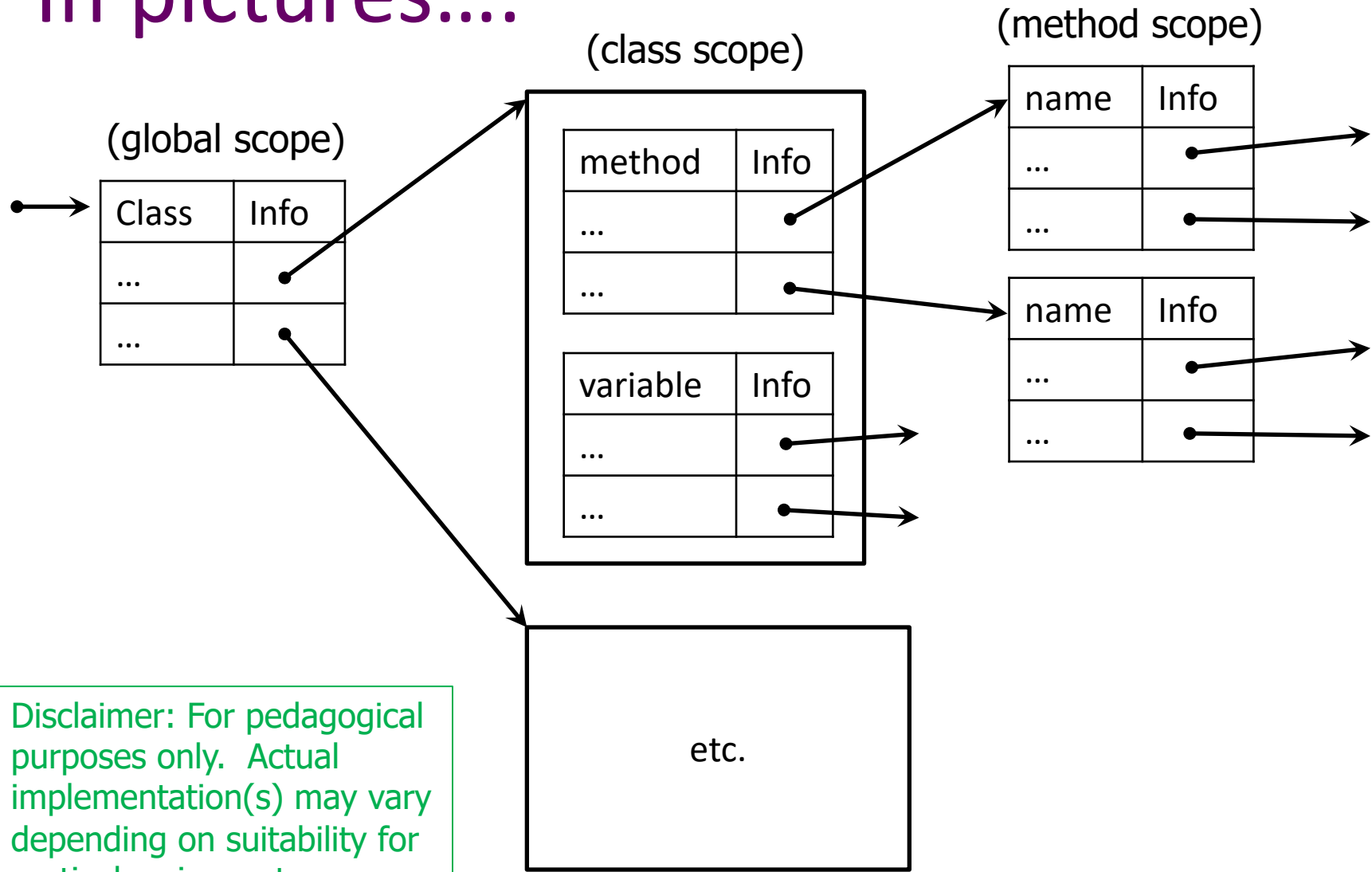
Symbol Tables for MiniJava: Global/Class

- 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 .o files)
 - 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 (add later), etc.
 - Needed only while compiling the method; could discard when done if 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 (top); 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 table needs to persist to use in later passes
 - Can't really 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 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 (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
 - Possible to put “standard prelude” information in a file or data resource and use that to initialize
 - Tradeoffs?

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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 ClassType extends Type { ... }
```

```
class BaseType 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 a single 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)

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 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, int subrange, 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 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;  
}
```

- 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 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
 - 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 are 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 Extended 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 Extended (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 object of one type to another
 - sometimes a 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 an value of type double to one of type int
 - can represent as unary operator in the AST
 - typecheck, codegen as usual
- 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 type-unsafe
 - 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 analyze 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 (probably uses assignment compatibility)
- Usual modularity reasons: isolate these decisions in one place and hide the actual type representation from the rest of the compiler
- Likely belongs 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

- Need to start thinking about translating to target code (x86-64 assembly language for our project)
- Next lectures
 - X86-64 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, method calls, dynamic dispatch, ...