

CSE P 501 – Compilers

Static Semantics

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Administrivia

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

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 check if this is legal and compile it?

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

decl + not already decl
decl
unique in scope
decl
types decl
decl
types decl

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

types
decl
new C(17)
something
variable name
setA is a method in class of c
arg can be assigned to param type

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? $a+b$
 - In the assignment $x=y$, is y assignable to x ? $x+y=17?$
 - 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.

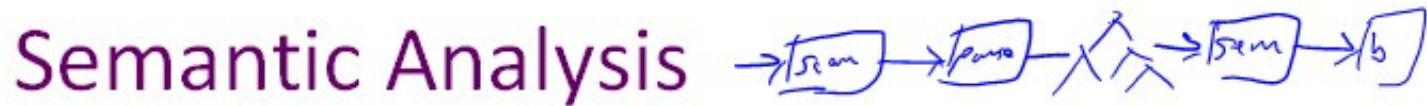
What else do we need to know to generate code?

- 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

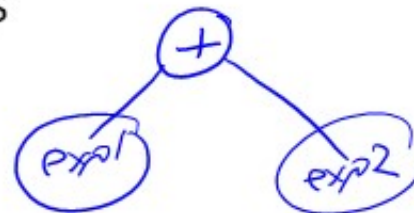
A Sampling of Semantic Checks (0)

- Appearance of a name: id 
 - Check: id has been declared and is in scope
 - Compute: Inferred type of id is its declared type

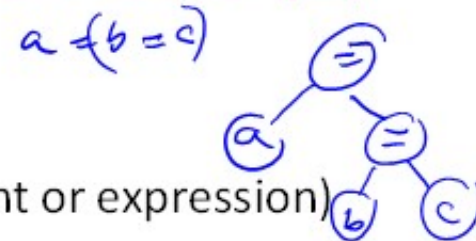
- Constant: v 
 - Compute: Inferred type and value are explicit

A Sampling of Semantic Checks (1)

- Binary operator: $\text{exp}_1 \text{ op } \text{exp}_2$
 - Check: exp_1 and exp_2 have compatible types
 - 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., char to int), 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)

(type) exp₂

(int)*

- Cast: (exp₁) exp₂
 - ✓ – Check: exp₁ is a type
 - ✓ – Check: exp₂ either
 - Has same type as exp₁
 - Can be converted to type exp₁ (e.g., double to int)
 - Downcast: is a superclass of exp₁ (usually 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 exp₁
 - ✓ – Compute: Inferred type is exp₁

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) $m(\text{int}, \text{double})$ (b) $m(\text{double}, \text{int})$ (c) $m(\text{double}, \text{double})$

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 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., C++, others)
 - Compute: Inferred type is given by method declaration (or could be void)

(a) $m(1, 17.0)$

(b) $m(42.0, 17)$

(c) $m(1, 2, 3, 4)$

~~$m(1, 2)$~~

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

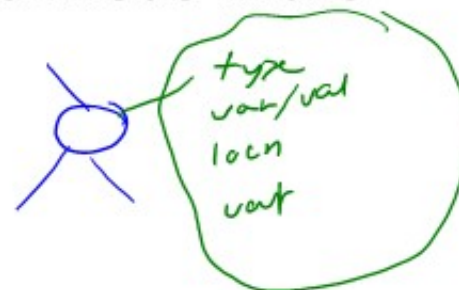
- Static semantics
- Attribute grammars
- Symbol tables
- Types & type checking
- Wrapup

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

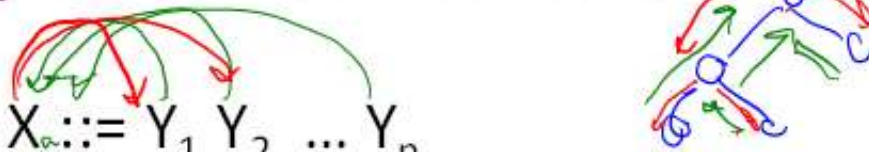
Attribute Grammars

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



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: 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 (*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)?

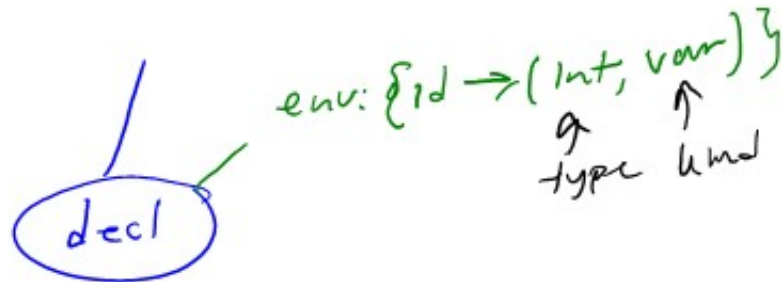
Informal Example of Attribute Rules (2)

- Attributes of nodes
 - env (environment, e.g., 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;

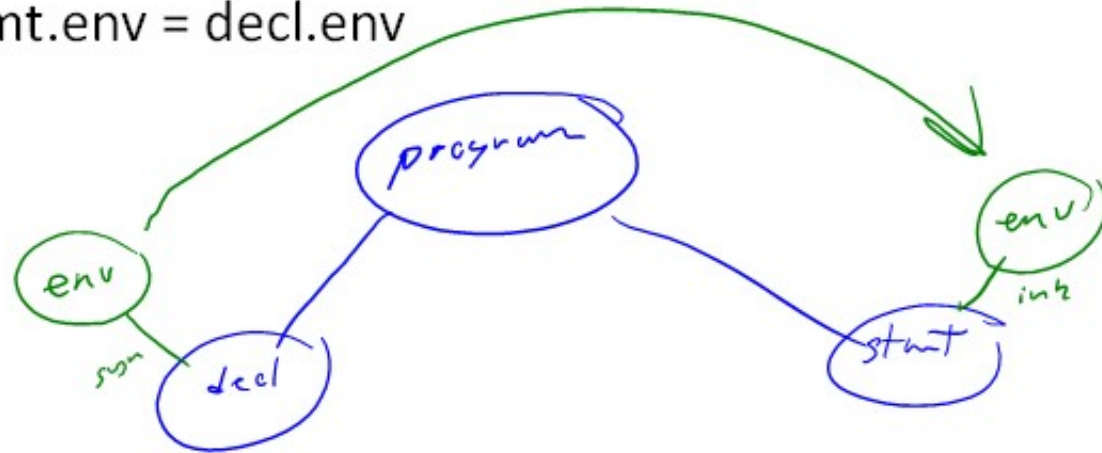
_{syn} decl.env = {id → (int, var)}



Attributes for Program

program ::= decl stmt

— stmt.env = decl.env



Attributes for Constants

`exp ::= 1`

`exp.kind = val`

`exp.type = int`



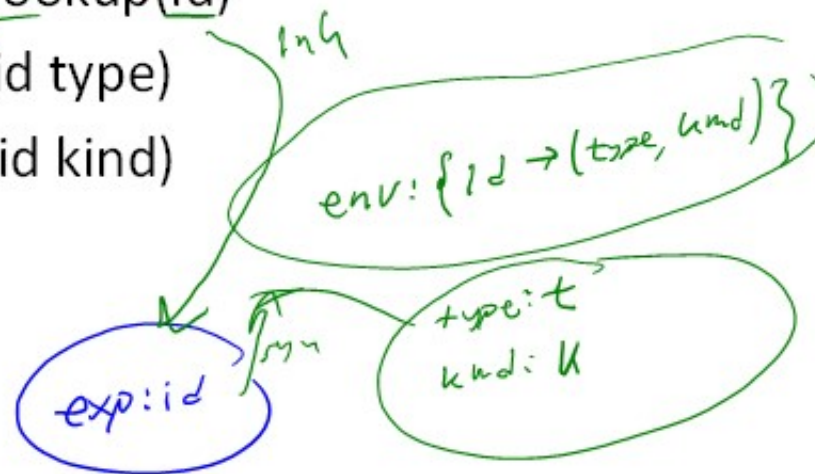
Attributes for Identifier Expressions

exp ::= id

(^ttype, ^kkind) = exp.env.lookup(id)

✓ exp.type = type (i.e., id type)

✓ exp.kind = kind (i.e., id kind)



Attributes for Addition

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

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

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

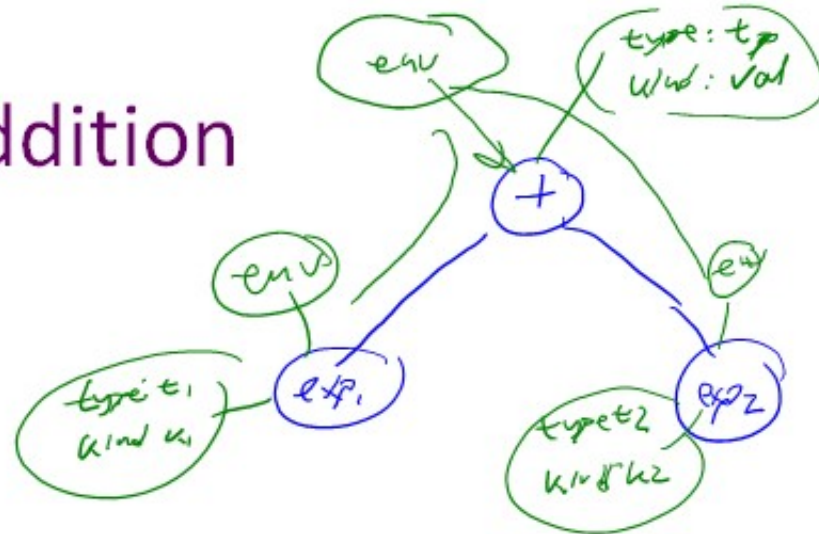
error if $\text{exp}_1.\text{type} \neq \text{exp}_2.\text{type}$

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

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

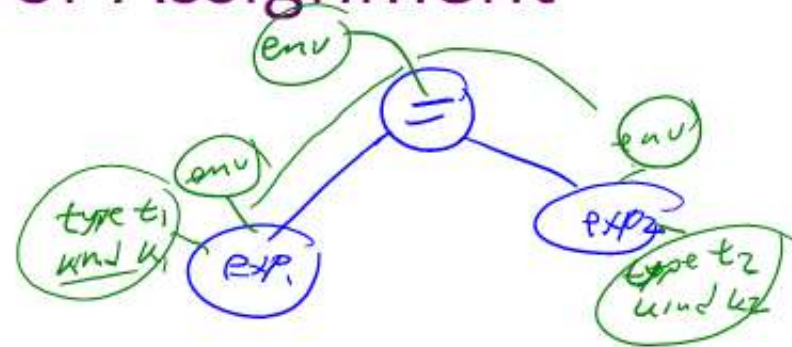
(or whatever type that language rules specify)

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



Attribute Rules for Assignment

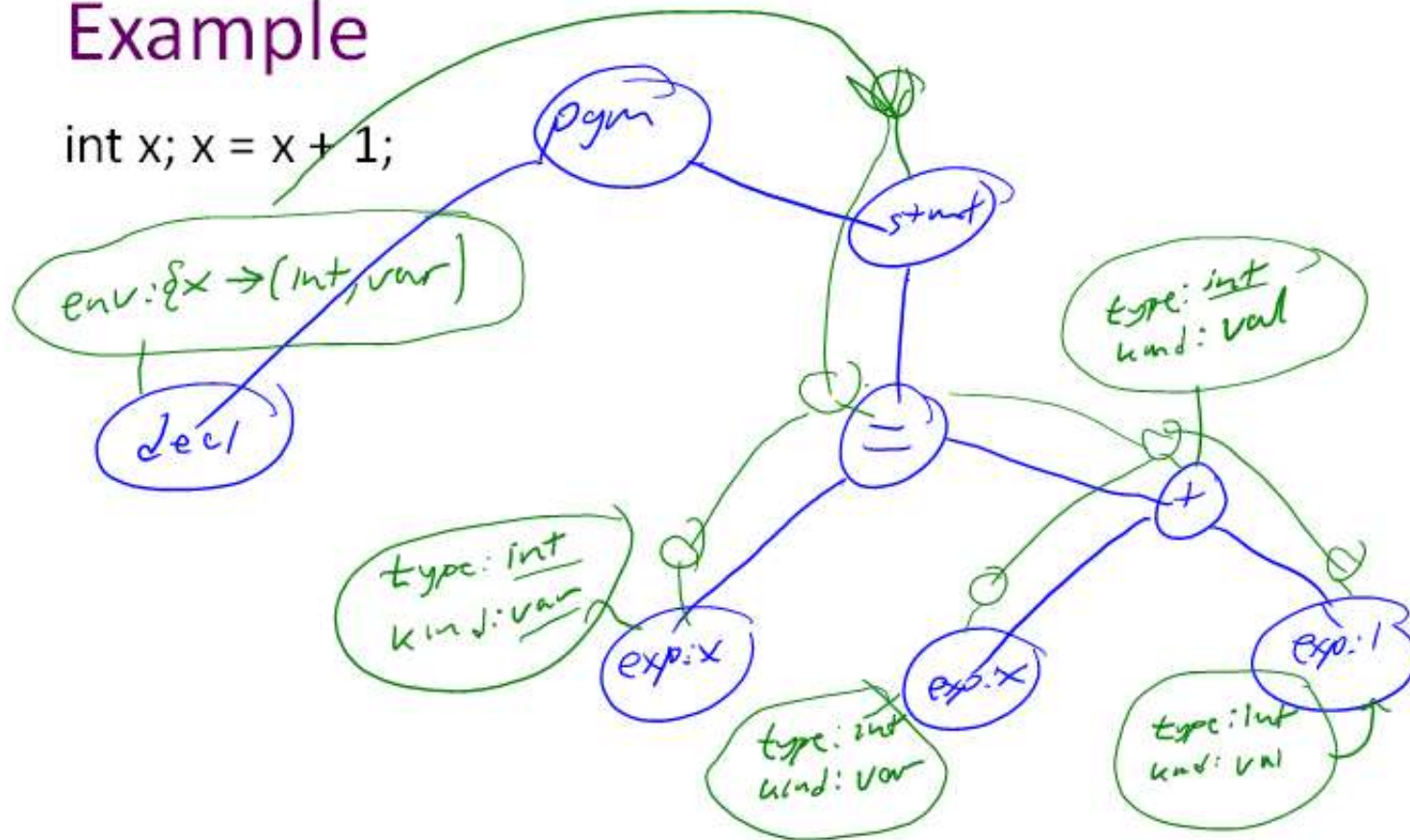
$\text{stmt} ::= \text{exp}_1 = \text{exp}_2;$
 $\text{exp}_1.\text{env} = \text{stmt}.\text{env}$
 $\text{exp}_2.\text{env} = \text{stmt}.\text{env}$



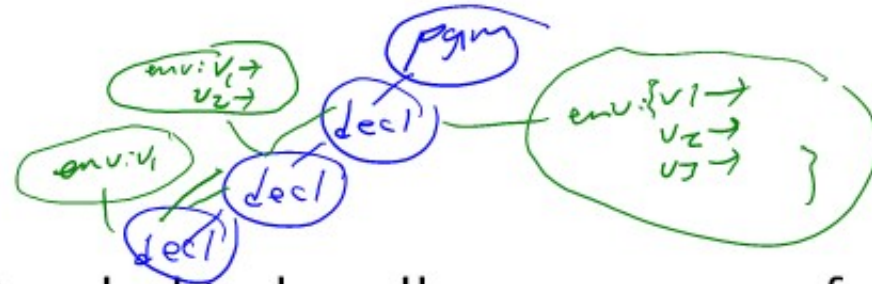
- ✓ Error if $\text{exp}_2.\text{type}$ is not assignment compatible with $\text{exp}_1.\text{type}$
- ✓ Error if $\text{exp}_1.\text{kind}$ is not var (can't be val)

Example

int x; x = x + 1;



Extensions



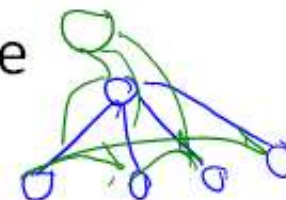
- This can be extended to handle sequences of declarations and statements
 - Sequences of declarations builds up larger environments, each decl synthesizes a new env from previous one plus the new binding
 - Full environment is passed down to statements and expressions

Observations

$$x.kind = y.kind$$



- 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 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. 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

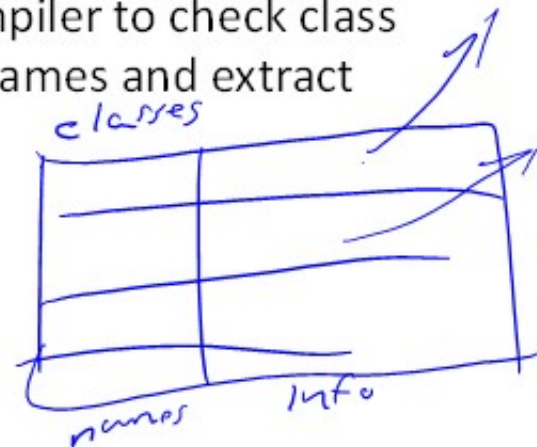
- Big topic in classical (i.e., ancient) compiler courses: implementing a hashed symbol table
- These days: use the collection classes that are provided with the standard language libraries (Java, C#, C++, ML, Haskell, etc.)
 - Then tune & optimize if it really matters
 - ✓• In production compilers,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

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

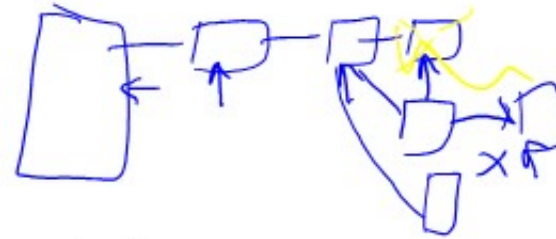
Symbol Tables for MiniJava: Global/Class

- 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 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: often need type info for runtime debugging, memory management/garbage collection, etc.
 - For us, MiniJava compiler will be multiple passes

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, ...)
 - Lambdas and function closures
- Basic idea: new symbol table for inner scopes, linked to surrounding scope's table (i.e., stack of symbol tables, top = current innermost 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 (effectively a reverse tree of scope symbol tables with root = global table)
 - Keep a pointer to current innermost scope (leaf) 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 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?

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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.
 - 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, 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 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; don’t have to return “null” for “no type” or “not declared” cases)

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 (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; e.g., 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)

```
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 Point 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 (constructor) 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
 - 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

Base b =
b.f(-)

- 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 all possible runtime types

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 in C)
 - 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
 - typecheck, codegen normally
- In full 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/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
 - codegen introduces runtime check
 - (same code needed to handle "instanceof")
 - Java's main 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
- 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

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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