CSE 401/M501 – Compilers

Static Semantics

Hal Perkins

Autumn 2022

Administrivia

- Parser/AST/print visitors due next Thurs., 11pm
  - Usual late days if you (and your partner) need them have them available
  - How's it going?
- Mini-hw3 on LL grammars due 11/1. Out shortly.
  - More on LL grammars in sections next week
  - Only 1 late day max so we can hand out solutions before…
- … Midterm exam on Fri. 11/4
  - Will get topic list and old exams on web soon
  - Review in sections on Thur. 11/3

New Testing Framework

- Thanks to Apollo, with testing by Armand, we now have an experimental framework for organizing and running compiler project tests
  - Completely optional, but take a look and take advantage of it if you (+ partner) find it useful
  - Info linked on main project page at the top of the "resources" section
  - Questions, comments, tips, and anything else: let's use ed to figure out how to best use this!

Administrivia (added Mon. 10/24)

- Reminder: parser/ast due Thursday
  - Re-read assignment and MiniJava overview carefully when you think you're "done" ☺
- HW2 sample solution available after class
  - Grading/feedback should be out shortly
- HW3 out now, due next Monday night, 11 pm
  - only 1 late day max
- Sections this week: more on LL grammars and exercises on semantics

Midterm exam – time to start thinking about this….

- Friday, Nov. 4 in class
- Closed book, no notes except for one 5x8 index card, hand-written only; will include brief reference info on exam as needed
  - Blank index cards available in class later this week
- Contents: up to basics of static semantics (i.e., review this week's lectures and know general issues, not detailed coding that is the next part of the project)
- Old exams and midterm topic list on the web now
- Last-minute review/Q&A in sections Nov. 3

Agenda

- Static semantics
- Symbol tables & semantics checking
- 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;
      }
}

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

Some things to check:

-

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?

Agenda

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

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

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

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 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: exp.m(e_1, e_2, …, 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 and method call-by-value argument/parameter types
  - If the method is void: There is no expression

Agenda

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

Semantics Checking

- Idea: check static semantics using (multiple) visitor passes over the AST – collect information first, then check detailed language rules in a later pass
- Symbol tables will hold environment information
  - i.e., properties of every name declared or used in the code
- Add fields to AST nodes to refer to appropriate attributes (symbol table entries for identifiers, types for expressions including identifiers, 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.

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

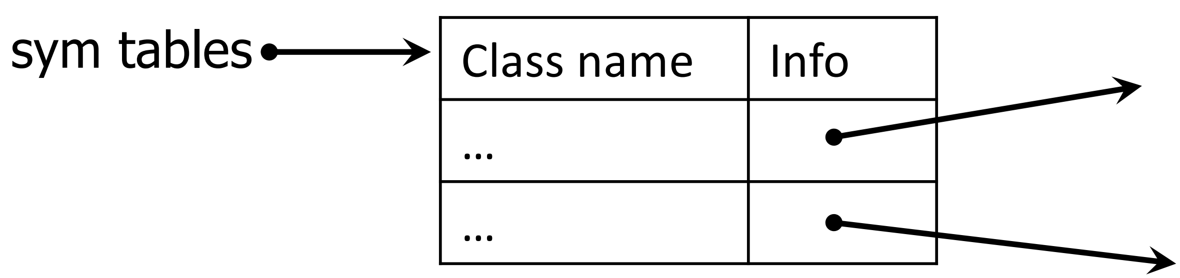
- Big topic in classical (i.e., ancient) compiler courses: implementing a hashed symbol table
- These days: use the collection classes that are provided with the standard language libraries (Java, C#, C++, ML, Haskell, etc.)
  - Then tune & optimize if it really matters
    - In production compilers,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

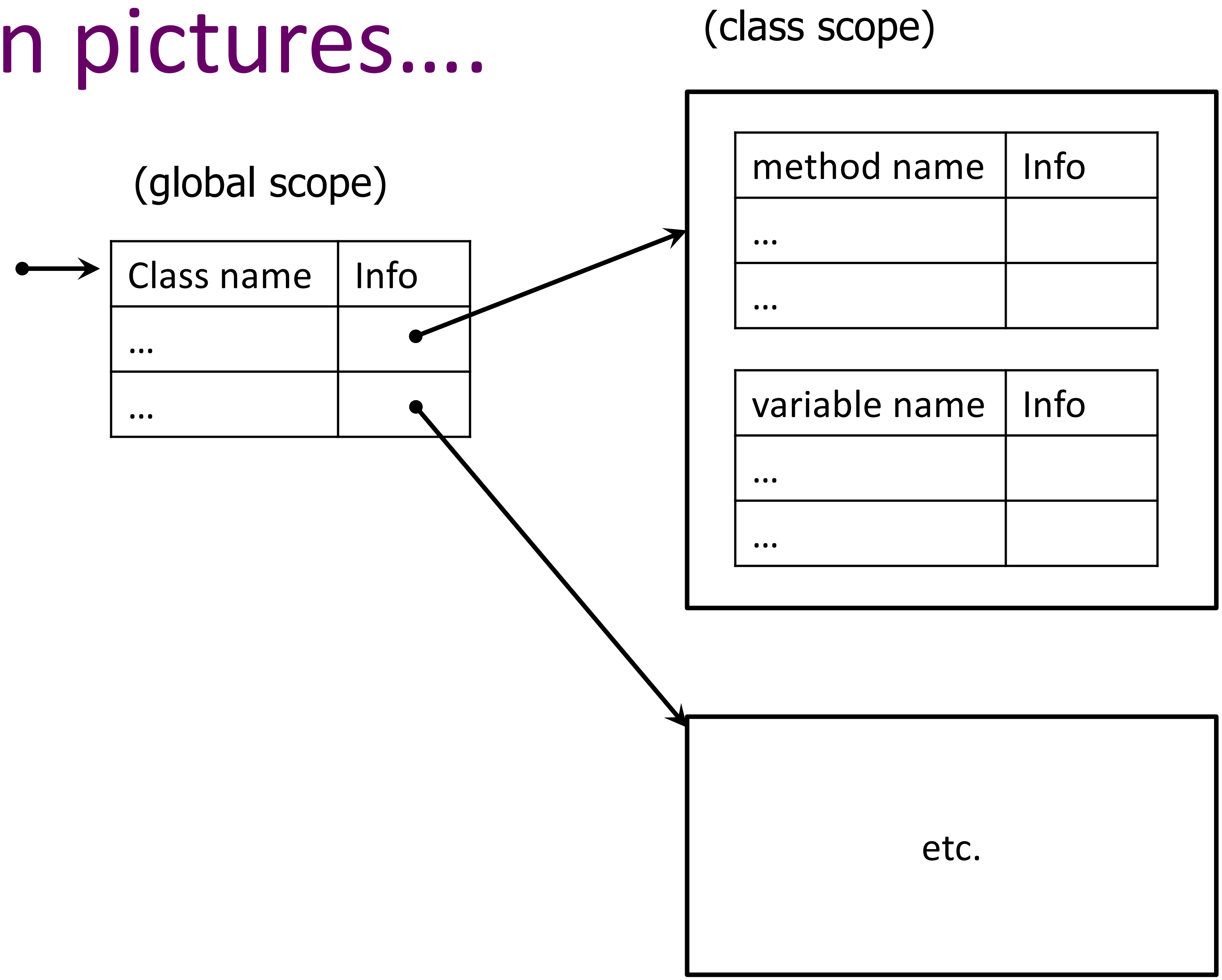
- Global – Per Program Information
  - Single global table to map class names to per-class symbol tables
    - Created in a pass over class definitions in AST
    - Used in remaining parts of compiler to check class types and their field/method names and extract information about them



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….



(class scope)
(global scope)
Class name
Info
…
…
method name
Info
…
…
variable name
Info
…
…
etc.

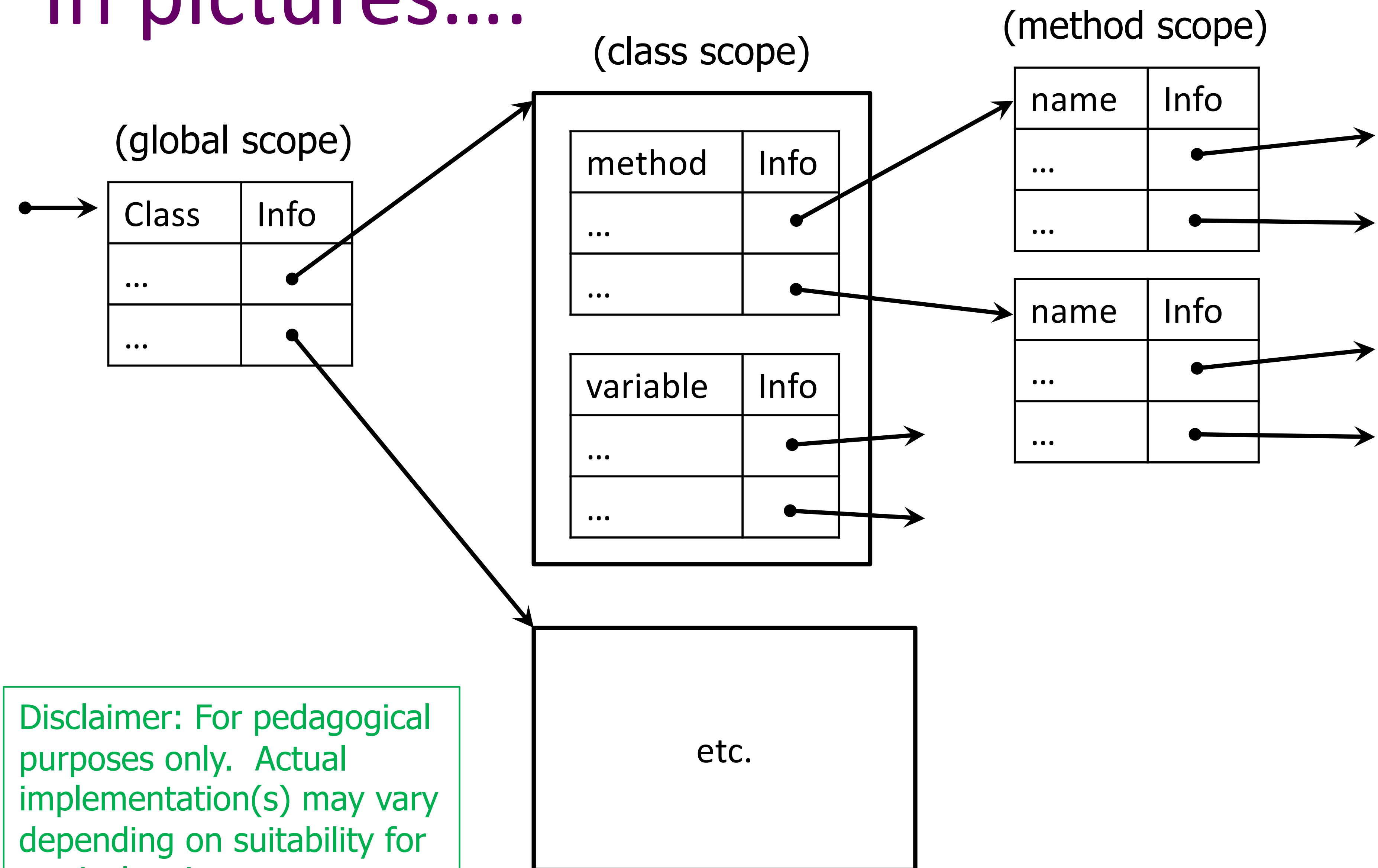
Symbol Tables for MiniJava: Global/Class

- 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*(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?

Agenda

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

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 grammar representing 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 source-code 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, etc.)

Compound Types

- Basic idea: use a appropriate "compound type" or "type constructor" object that contains references 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 & others 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 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<Type> parameterTypes;
}
```

- Sometimes called the method "signature"

Type Equivalance

- 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 are the same type if they are equal
  - 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: Java 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 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 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 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
- Symbol tables & semantics checking
- 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 target code for higher-level language statements, method calls, dynamic dispatch, …
  - But first, a more general look at IRs (next time)