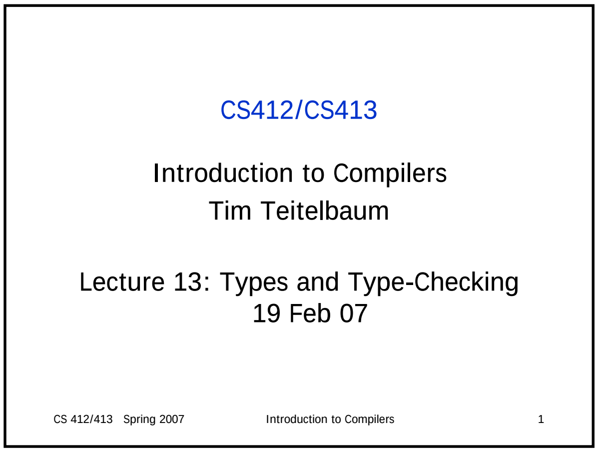

CS412/CS413

Introduction to Compilers
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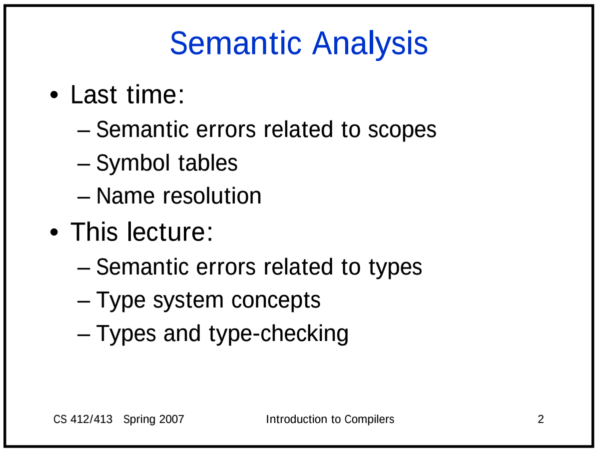
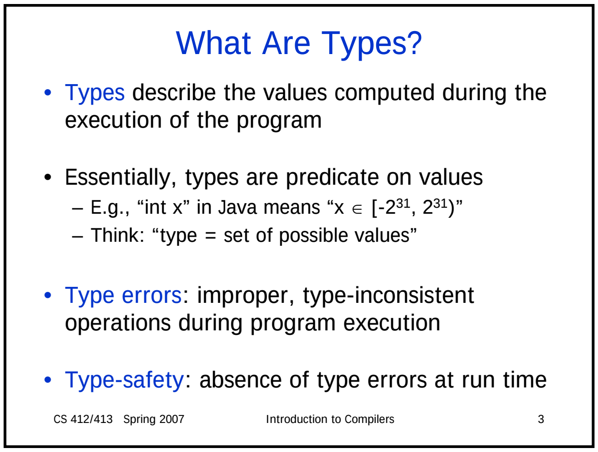
Lecture 13: Types and Type-Checking
19 Feb 07



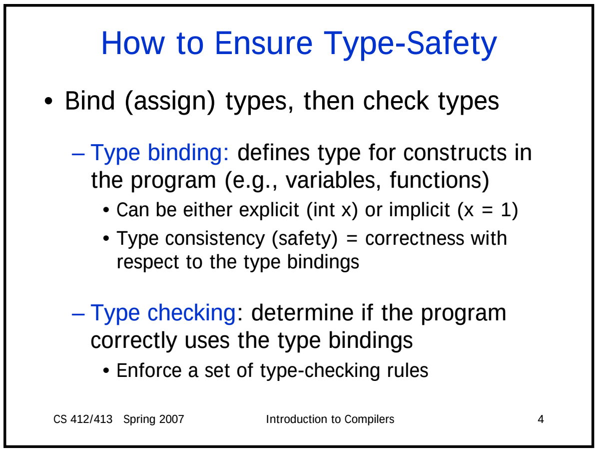
Semantic Analysis

- Last time:
  - Semantic errors related to scopes
  - Symbol tables
  - Name resolution
- This lecture:
  - Semantic errors related to types
  - Type system concepts
  - Types and type-checking



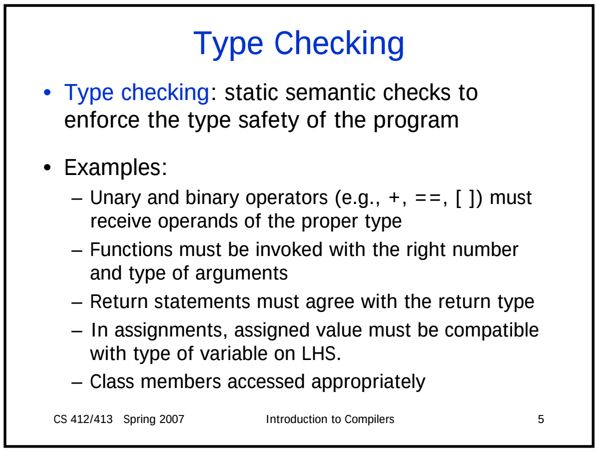
What Are Types?

- Types describe the values computed during the execution of the program
- Essentially, types are predicate on values
  - E.g., “int x” in Java means “$x \in [-2^{31}, 2^{31})$”
  - Think: “type = set of possible values”
- Type errors: improper, type-inconsistent operations during program execution
- Type-safety: absence of type errors at run time



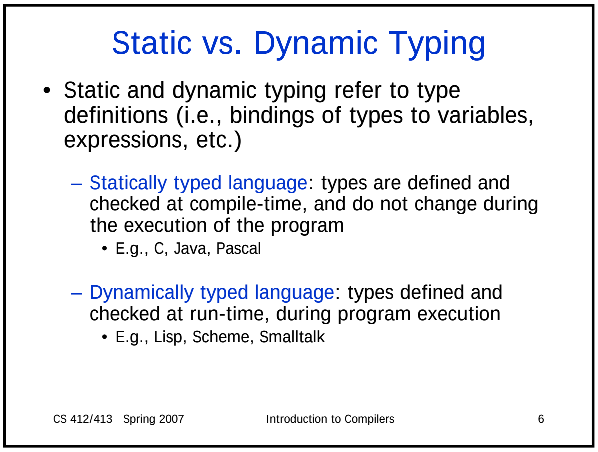
How to Ensure Type-Safety

- Bind (assign) types, then check types
  - Type binding: defines type for constructs in the program (e.g., variables, functions)
    - Can be either explicit (int x) or implicit (x = 1)
    - Type consistency (safety) = correctness with respect to the type bindings
  - Type checking: determine if the program correctly uses the type bindings
    - Enforce a set of type-checking rules



Type Checking

- Type checking: static semantic checks to enforce the type safety of the program
- Examples:
  - Unary and binary operators (e.g., +, ==, [ ]) must receive operands of the proper type
  - Functions must be invoked with the right number and type of arguments
  - Return statements must agree with the return type
  - In assignments, assigned value must be compatible with type of variable on LHS.
  - Class members accessed appropriately



Static vs. Dynamic Typing

- Static and dynamic typing refer to type definitions (i.e., bindings of types to variables, expressions, etc.)
  - Statically typed language: types are defined and checked at compile-time, and do not change during the execution of the program
    - E.g., C, Java, Pascal
  - Dynamically typed language: types defined and checked at run-time, during program execution
    - E.g., Lisp, Scheme, Smalltalk

Strong vs. Weak Typing

- Strong and weak typing refer to how much type consistency is enforced
  - Strongly typed languages: guarantees that accepted programs are type-safe
  - Weakly typed languages: allow programs that contain type errors
- Can achieve strong typing using either static or dynamic typing

Soundness

- Sound type systems: can statically ensure that the program is type-safe
- Soundness implies strong typing
- Static type safety requires a conservative approximation of the values that may occur during all possible executions
  - May reject type-safe programs
  - Need to be expressive: reject as few type-safe programs as possible

Concept Summary

- Static vs dynamic typing: when to define/check types?
- Strong vs weak typing: how many type errors?
- Sound type systems: statically catch all type errors

Classification

	Strong Typing	Weak Typing
Static Typing	ML Pascal Java Modula-3	C C++
Dynamic Typing	Scheme PostScript Smalltalk	assembly code

Why Static Checking?

- Efficient code
  - Dynamic checks slow down the program
- Guarantees that all executions will be safe
  - Dynamic checking gives safety guarantees only for some execution of the program
- But is conservative for sound systems
  - Needs to be expressive: reject few type-safe programs

Type Systems

- Type is predicate on value
- Type expressions: describe the possible types in the program: int, string, array[], Object, etc.
- Type system: defines types for language constructs (e.g., expressions, statements)

Type Expressions

- Languages have basic types
  (a.k.a. primitive types or ground types)
  - E.g., int, char, boolean
- Build type expressions using basic types:
  - Type constructors
  - Type aliases

Array Types

- Various kinds of array types in different programming languages
- array(T) : array with elements of type T and no bounds
  - C, Java: int [ ], Modula-3: array of integer
- array(T, S) : array with size
  - C: int[10], Modula-3: array[10] of integer
  - May be indexed 0..size-1
- array(T,L,U) : array with upper/lower bounds
  - Pascal or Ada: array[2 .. 5] of integer
- array(T, S_1, ..., S_n) : multi-dimensional arrays
  - FORTRAN: real(3,5)

Record Types

- A record is $\{id_1: T_1, \ldots, id_n: T_n\}$ for some identifiers id_i and types T_i
- Supports access operations on each field, with corresponding type
- C: struct { int a; float b; }
- Pascal: record a: integer; b: real; end
- Objects: generalize the notion of records

Pointer Types

- Pointer types characterize values that are addresses of variables of other types
- Pointer(T) : pointer to an object of type T
- C pointers: T* (e.g., int *x;)
- Pascal pointers: ^T (e.g., x: ^integer;)
- Java: object references

Function Types

- Type: $T_1 \times T_2 \times \ldots \times T_n \to T_r$
- Function value can be invoked with some argument expressions with types T_i, returns return type T_r
- C functions: int pow(int x, int y)
  type: int × int → int
- Java: methods have function types
- Some languages have first-class functions
  - usually in functional languages, e.g., ML, LISP
  - C and C++ have function pointers
  - Java doesn't

Type Aliases

- Some languages allow type aliases (type definitions, equates)
  - C: typedef int int_array[ ];
  - Modula-3: type int_array = array of int;
  - Java doesn't allow type aliases
- Aliases are not type constructors!
  - int_array is the same type as int [ ]
- Different type expressions may denote the same type

Implementation

- Use a separate class hierarchy for types:

```
class BaseType extends Type { ... }
class IntType extends BaseType { ... }
class BoolType extends Base Type { ... }
class ArrayType extends Type { Type elemType; }
class FunctionType extends Type { ... }
```

- Semantic analysis translates all type expressions to type objects
- Symbol table binds name to type object

Type Comparison

- Option 1: implement a method T1.Equals(T2)
  - Must compare type trees of T1 and T2
  - For object-oriented language: also need sub-typing: T1.SubtypeOf(T2)
- Option 2: use unique objects for each distinct type
  - each type expression (e.g., array[int]) resolved to same type object everywhere
  - Faster type comparison: can use ==
  - Object-oriented: check subtyping of type objects

Creating Type Objects

- Build types while parsing – use a syntax-directed definition:

```
non terminal Type type
type ::= BOOLEAN
            {: RESULT = new BoolType(); :}
     |   ARRAY LBRACKET type:t RBRACKET
            {: RESULT = new ArrayType(t); :}
```

- Type objects = AST nodes for type expressions

Processing Type Declarations

- Type declarations add new identifiers and their types in the symbol tables
- Class definitions must be added to symbol table:

```
class_defn ::= CLASS ID:id { decls:d }
```

- Forward references require multiple passes over AST to collect legal names

```
class A { B b; }
class B { ... }
```

Type-Checking

- Type-checking = verify typing rules

  "operands of + must be integer expressions; the result is an integer expression"

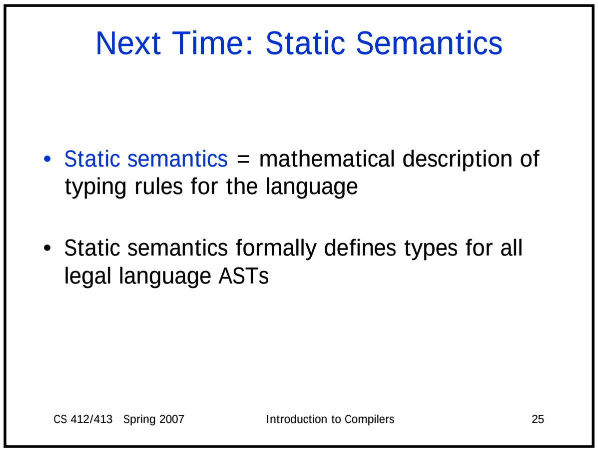
- Option 1: Implement using syntax-directed definitions (type-check during the parsing)

```
expr ::= expr:t1 PLUS expr:t2
   {:  if (t1 == IntType && t2 == IntType)
             RESULT = IntType;
        else throw new TypeCheckError("+");
   :}
```

Type-Checking

Option 2: implement type-checking by an AST visitor

```
class typeCheck implements Visitor {
      Object visit(Add e, Object symbolTable)  {
          Type t1 = (int) e.e1.accept(this, symbolTable);
          Type t2 = (int) e.e2.accept(this, symbolTable);
          if (t1 == Int && t2 == Int) return Int;
          else throw new TypeCheckError("+");
          }
      Object visit(Num e, Object symbolTable)   {
          return Int;
          }
      Object visit(Id e, Object symbolTable)   {
          return (SymbolTable)symbolTable.lookupType(e);
          }
  }
```



Next Time: Static Semantics

- Static semantics = mathematical description of typing rules for the language
- Static semantics formally defines types for all legal language ASTs