COMP 520 - Compilers

Lecture 11 (Thu Mar 3)

Contextual analysis: Type Checking

- Reading
  - PLPJ Contextual Analysis: Type Checking (secn 5.2)

Topics

- Type checking
  - examples of type checking
  - role of types in programming languages
  - structural vs.name equivalence in types

- A general framework for type checking
  - definitions
    - type synthesis
    - type constraints
  - examples

Type checking

- Basic examples
  - assignment statements
    - do target and expression type agree? `int x = 1 + 2;`
  - Expressions
    - what is the type of the result? `x + 3 != 4`
    - What are the types of the intermediate expressions?
  - function/procedure calls
    - do arguments types agree with parameter types?
    - does a function return a result of the appropriate type?
  - type definitions and variable declarations
    - is the type well-formed?
      - does a class type refer to an identified class?
      - void [ ] ?
- Systematically answering such questions is called “type checking”

Type analysis

- Where do we need to use type analysis
  - automatic conversions/coercions
    - convert byte or short to int or long
    - convert byte, short, int, long to float or double
    - automatic boxing/unboxing of int to/from Integer in Java
  - overload resolution
    - which definition of “+” should be used?
  - inheritance
    - which methods are available on an object?
    - can the invocation of an overridden method be *statically* determined?
  - type inference
    - variables or parameters without type declarations (e.g. python)
    - can a type be inferred for a missing declaration?

Types in modern programming languages

- What is a type?
  - a set of possible values (and their representation)
  - a set of permissible operations

- Purpose of types
  - safety and correctness
    - apply only permissible operations on values with correct representation
  - improve readability and comprehensibility
  - provide consistency checks on programs
  - provide information to improve efficiency of execution
    - eliminate run-time type checks
    - efficient space (re)use

Type safety

- Type safety is also known as “strong typing”
  - all operations applied to values with a known representation
    - pointer dereference can not be applied to arbitrary integers
    - arithmetic operations are applied to values of known representation
    - appropriate methods are applied to objects
  - strongly typed languages guarantee to detect any situation where this is not the case at compile time
    - Java, Triangle, modern C (C99 and later)
- Dynamic typing
  - the type is part of the value
    - python
  - type safety is checked at runtime, not compile time
    - so may result in runtime error

When does type checking take place?

- Compile time
  - statically typed
    - Java, Triangle, C++, Haskell, ...
- Run-time
  - dynamically typed
    - JavaScript, Perl, Python, PHP, Ruby, ...
    - Java casts
- Never
  - untyped
    - Assembler (but even this is changing towards strong typing)

Strong typing

Type wars

- Static vs. dynamic typing
  - static typing
    - catches many common programming errors at compile time
    - avoids run-time overhead of dynamic typing
  - dynamic typing
    - static type systems are restrictive
    - type declarations are wordy and slow the programmer down
- In practice
  - static type systems are restrictive so an escape system is added
    - e.g. C casts (void *) defeat typing
    - unclear whether this is the best or worst of the two worlds
  - static type systems are getting better
    - overloading, generics, type inference, virtual method invocation
    - dynamic typing used where static typing is too restrictive
      - “casts” with type checks and conversions

Type equivalence

- In many modern languages we can define *named* types

```
type Height = Integer
type Weight = Integer
var h : Height, w: Weight
...  h := 130;  w := 150;  h := h + w ...
```

is this OK?

- When are two types equivalent?
  - Structural equivalence
    - when they are the same following substitution of type definitions
      - example languages: C, Triangle
  - Name equivalence
    - only when they are the same named type
      - example languages: Ada, Pascal, (C++), (Java)

- The form of type equivalence has fundamental bearing on type checking

miniJava type checking

- Fairly simple – bottom up
  - leaves of the AST are Terminals: Identifiers, Literals, and Operators
    - We can assign each of these a specific TypeDenoter (BaseType, ClassType, or ArrayType)
      - The specific types are manifest (Literals) or extracted from the declaration of an Identifier
  - Expression, Reference, and Declaration nodes compute their type from their children
  - specific Statement nodes make some checks for type agreement
    - AssignStmt
    - IfStmt
  - special types
    - ERROR, UNSUPPORTED

Simple approach to type checking

- Define a set of possible types
  - set of base types and some ways to build new types
- Define a representation of programs
  - simple class of ASTs
- Define a type-assignment algorithm that
  - labels all nodes of an AST with zero or more types
  - handles many forms of overloading
    - essentially all languages have some form of overloading
      - addition: operation on integers or floats?
- Type checking
  - following type assignment each AST node is labeled with a set of types
    - program is type correct if all nodes have a single type
    - program contains type error(s) if some node has no type assignment or more than one possible type assignment

Characterization of a set of types

- Type values constructed from
  - basic types
    - Int, Real, Bool, ...
  - parameterized types
    (in the following, a *type variable* (α, β, ...) stands for any type)
    - tuple types
      $\alpha_1 \times ... \times \alpha_n$
    - function types
      $\alpha \rightarrow \beta$
    - array types
      Array(α)
  - named types
    - for name equivalence, if needed
      Complex = Real $\times$ Real

Characterization of a simple class of ASTs

- AST structure
  - Leaves: two kinds
    - constants
    - identifiers (applied occurrences)
      - denoting variables or functions (including operators)
  - interior nodes: two kinds
    - tuple constructor ()
    - function application •
  - Example
    - Concrete syntax: `a + 10`
    - AST:

Type values at leaves

- Declarations provide type value(s) for AST leaves
  - a variable type is obtained from its (unique) declaration

    a: Int

  - constants have a manifest (unique) type

    10: Int

    5.3: Real

    true: Bool

  - functions or operators may have multiple types as a result of overloading

    +: Int $\times$ Int $\rightarrow$ Int

    +: Real $\times$ Real $\rightarrow$ Real

- The declarations are external to our simple ASTs

Generate possible type assignments

- Step 1: generate possible type assignments $\tau(v)$ for each node v by bottom-up traversal of AST
  - v is a leaf of the AST
    - $\tau(v)$ = set of types associated with v
  - v is a tuple constructor $(v_1, \ldots, v_k)$
    - $\tau(v) = \{ t_1 \times \ldots \times t_k \mid t_1 \in \tau(v_1), \ldots, t_k \in \tau(v_k) \}$
  - v is function application f(a)
    - $\tau(v) = \{ r \mid (d \to r) \in \tau(f) \text{ and } d \in \tau(a) \}$

Constrain type assignments

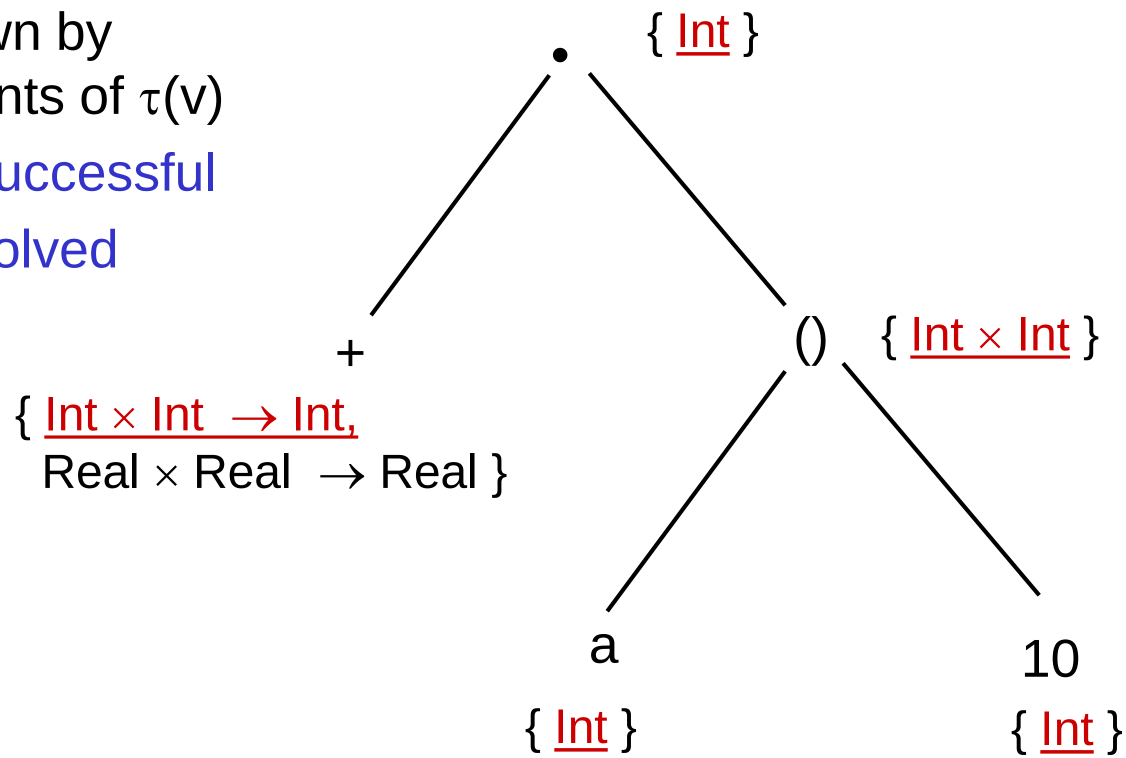
- Step 2: constrain type assignments $\sigma(v) \subseteq \tau(v)$ for each node v by top-down traversal of AST
  - v is root
    - $\sigma(v) = \tau(v)$
  - v is function application f(a)
    - $\sigma(f) = \{ d \to r \mid (d \to r) \in \tau(f) \text{ and } d \in \tau(a) \text{ and } r \in \sigma(v) \}$
    - $\sigma(a) = \{ d \mid (d \to r) \in \tau(f) \text{ and } d \in \tau(a) \text{ and } r \in \sigma(v) \}$
  - v is tuple constructor $(v_1, \ldots, v_k)$
    - $\sigma(v_i) = \{ t_i \mid t_1 \times \ldots \times t_i \times \ldots \times t_k \in \sigma(v) \}$

Type checking

- Type checking of an AST is successful if and only if $|\sigma(v)| = 1$ for every v in the AST
  - ex: a + 10

    $\tau(v)$ is shown as { ... }

    $\sigma(v) \subseteq \tau(v)$ is shown by underlining elements of $\tau(v)$
  - type checking is successful
  - overloading is resolved



More examples

- Declarations

  +: Real $\times$ Real $\rightarrow$ Real

  +: Complex $\times$ Complex $\rightarrow$ Complex

  +: Real $\times$ Real $\rightarrow$ Complex

  =: Real $\times$ Real $\rightarrow$ Bool

  =: Complex $\times$ Complex $\rightarrow$ Bool

  r: Real

  c: Complex

- Examples

  r + r = r

  r = c

  (r + r) = (r + r)

Extensions

- Parametric polymorphism (generic types)
  - parameterized types that include type variables that vary over all types

    index: $Array(\alpha) \times Int \to \alpha$

    =: $\alpha \times \alpha \to Bool$
  - substitute type variables in generate and constrain phases
  - ex
    - a: Array(Real), i: Int
    - type assignment for a[i]?

Commands

- Include commands in AST with a new type Stmt
  - parametric polymorphism: type variables α vary over all types

    ifCmd: Bool $\times$ Stmt $\times$ Stmt $\rightarrow$ Stmt

    assignCmd : $\alpha \times \alpha \rightarrow$ Stmt

    sequenceCmd : Stmt $\times$ Stmt $\rightarrow$ Stmt
  - ex
    - x: Int
    - type assignment for x := 3; x :=4 ?

Type inference

- No types declared for variables – types must be inferred
  - a type variable α_x is used to describe the type of each occurrence of program variable x
  - equality and membership become equations rather than true/false propositions (solved using resolution theorem proving)
    - types are inferred if there exists a unique solution for type equations at end of constrain phase
  - found in various languages including Haskell
  - Example

    What is the type assignment for *a*, *b* and *i*

    a[i] := b[i+1] * 5.5

    Given only the types for the operators (+, *, := , and indexing) as defined in these slides