

Type Checking

Outline

- General properties of type systems
- Types in programming languages
- Notation for type rules
 - Logical rules of inference
- Common type rules

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Static Checking

- Refers to the compile-time checking of programs in order to ensure that the semantic conditions of the language are being followed

Examples of static checks include:

- Type checks
- Flow-of-control checks
- Uniqueness checks
- Name-related checks

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Static Checking (Cont.)

Flow-of-control checks: statements that cause flow of control to leave a construct must have some place where control can be transferred;

e.g., *break statements in C*

Uniqueness checks: a language may dictate that in some contexts, an entity can be defined exactly once;

e.g., *identifier declarations, labels, values in case expressions*

Name-related checks: Sometimes the same name must appear two or more times;

e.g., *in Ada a loop or block can have a name that must then appear both at the beginning and at the end*

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Types and Type Checking

- A *type* is a set of values together with a set of operations that can be performed on them
- The purpose of *type checking* is to verify that operations performed on a value are in fact permissible
- The type of an identifier is typically available from declarations, but we may have to keep track of the type of intermediate expressions

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Type Expressions and Type Constructors

A language usually provides a set of *base types* that it supports together with ways to construct other types using *type constructors*

Through *type expressions* we are able to represent types that are defined in a program

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Type Expressions

- A base type is a type expression
- A type name (e.g., a record name) is a type expression
- A type constructor applied to type expressions is a type expression. E.g.,
 - arrays: If T is a type expression and I is a range of integers, then $\text{array}(I, T)$ is a type expression
 - records: If T_1, \dots, T_n are type expressions and f_1, \dots, f_n are field names, then $\text{record}((f_1, T_1), \dots, (f_n, T_n))$ is a type expression
 - pointers: If T is a type expression, then $\text{pointer}(T)$ is a type expression
 - functions: If T_1, \dots, T_n , and T are type expressions, then so is $(T_1, \dots, T_n) \rightarrow T$

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Notions of Type Equivalence

Name equivalence: In many languages, e.g. Pascal, types can be given names. Name equivalence views each distinct name as a distinct type. So, two type expressions are name equivalent if and only if they are identical.

Structural equivalence: Two expressions are structurally equivalent if and only if they have the same structure; i.e., if they are formed by applying the same constructor to structurally equivalent type expressions.

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Example of Type Equivalence

In the Pascal fragment

```
type nextptr = ^node;
   prevptr = ^node;
var  p : nextptr;
     q : prevptr;
```

`p` is not name equivalent to `q`,
but `p` and `q` are structurally equivalent.

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Static Type Systems & their Expressiveness

- A static type system enables a compiler to detect many common programming errors
- The cost is that some correct programs are disallowed
 - Some argue for dynamic type checking instead
 - Others argue for more expressive static type checking
 - But more expressive type systems are also more complex

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Compile-time Representation of Types

- Need to represent type expressions in a way that is both easy to construct and easy to check

Approach 1: Type Graphs

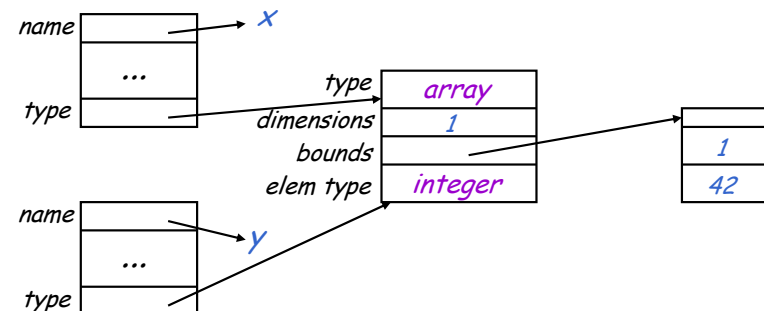
- Basic types can have predefined "internal values", e.g., small integer values
- Named types can be represented using a pointer into a hash table
- Composite type expressions: the node for $f(T_1, \dots, T_n)$ contains a value representing the type constructor f , and pointers to the nodes for the expressions T_1, \dots, T_n

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Compile-time Representation of Types (Cont.)

Example:

```
var x, y : array[1..42] of integer;
```



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Compile-Time Representation of Types

Approach 2: Type Encodings

Basic types use a predefined encoding of the low-order bits

<u>BASIC TYPE</u>	<u>ENCODING</u>
boolean	0000
char	0001
integer	0002

The encoding of a type expression $op(T)$ is obtained by concatenating the bits encoding op to the left of the encoding of T . E.g.:

<u>TYPE EXPRESSION</u>	<u>ENCODING</u>
char	00 00 00 0001
array(char)	00 00 01 0001
ptr(array(char))	00 10 01 0001
ptr(ptr(array(char)))	10 10 01 0001

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Compile-Time Representation of Types: Notes

- Type encodings are simple and efficient
- On the other hand, named types and type constructors that take more than one type expression as argument are hard to represent as encodings. Also, recursive types cannot be represented directly.
- Recursive types (e.g. lists, trees) are not a problem for type graphs: the graph simply contains a cycle

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Types in an Example Programming Language

- Let's assume that types are:
 - integers & floats (base types)
 - arrays of a base type
 - booleans (used in conditional expressions)
- The user declares types for all identifiers
- The compiler infers types for expressions
 - Infers a type for *every* expression

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Type Checking and Type Inference

Type Checking is the process of verifying fully typed programs

Type Inference is the process of filling in missing type information

- The two are different, but are often used interchangeably

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Rules of Inference

- We have seen two examples of formal notation specifying parts of a compiler
 - Regular expressions (for the lexer)
 - Context-free grammars (for the parser)
- The appropriate formalism for type checking is logical rules of inference

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Why Rules of Inference?

- Inference rules have the form
If Hypothesis is true, then Conclusion is true
- Type checking computes via reasoning
If E_1 and E_2 have certain types, then E_3 has a certain type
- Rules of inference are a compact notation for "If-Then" statements

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From English to an Inference Rule

- The notation is easy to read (with practice)
- Start with a simplified system and gradually add features
- Building blocks
 - Symbol \wedge is "and"
 - Symbol \Rightarrow is "if-then"
 - $x:T$ is "x has type T"

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From English to an Inference Rule (2)

If e_1 has type `int` and e_2 has type `int`,
then $e_1 + e_2$ has type `int`

$(e_1 \text{ has type } \text{int} \wedge e_2 \text{ has type } \text{int}) \Rightarrow$
 $e_1 + e_2 \text{ has type } \text{int}$

$(e_1: \text{int} \wedge e_2: \text{int}) \Rightarrow e_1 + e_2: \text{int}$

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From English to an Inference Rule (3)

The statement

$$(e_1: \text{int} \wedge e_2: \text{int}) \Rightarrow e_1 + e_2: \text{int}$$

is a special case of

$$\text{Hypothesis}_1 \wedge \dots \wedge \text{Hypothesis}_n \Rightarrow \text{Conclusion}$$

This is an inference rule

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Notation for Inference Rules

- By tradition inference rules are written

$$\frac{\vdash \text{Hypothesis}_1 \quad \dots \quad \vdash \text{Hypothesis}_n}{\vdash \text{Conclusion}}$$

- Type rules have hypotheses and conclusions of the form:

$$\vdash e : T$$

- \vdash means "it is provable that ..."

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Two Rules

$$\frac{i \text{ is an integer}}{\vdash i : \text{int}} \quad [\text{Int}]$$

$$\frac{\vdash e_1 : \text{int} \quad \vdash e_2 : \text{int}}{\vdash e_1 + e_2 : \text{int}} \quad [\text{Add}]$$

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Two Rules (Cont.)

- These rules give templates describing how to type integers and + expressions
- By filling in the templates, we can produce complete typings for expressions

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Example: 1 + 2

$$\frac{\frac{1 \text{ is an integer}}{\vdash 1 : \text{int}} \quad \frac{2 \text{ is an integer}}{\vdash 2 : \text{int}}}{\vdash 1 + 2 : \text{int}}$$

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Soundness

- A type system is *sound* if
 - Whenever $\vdash e : T$
 - Then e evaluates to a value of type T
- We only want sound rules
 - But some sound rules are better than others:

$$\frac{i \text{ is an integer}}{\vdash i : \text{number}}$$

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Type Checking Proofs

- Type checking proves facts $e : T$
 - Proof is on the structure of the AST
 - Proof has the shape of the AST
 - One type rule is used for each kind of AST node
- In the type rule used for a node e :
 - Hypotheses are the proofs of types of e 's subexpressions
 - Conclusion is the type of e
- Types are computed in a bottom-up pass over the AST

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Rules for Constants

$$\frac{}{\vdash \text{true} : \text{bool}} \quad [\text{Bool}] \quad \frac{}{\vdash \text{false} : \text{bool}} \quad [\text{Bool}]$$

$$\frac{f \text{ is a floating point number}}{\vdash f : \text{float}} \quad [\text{Float}]$$

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Two More Rules

$$\frac{\vdash e : \text{bool}}{\vdash \text{not } e : \text{bool}} \quad [\text{Not}]$$

$$\frac{\vdash e_1 : \text{bool} \quad \vdash e_2 : T}{\vdash \text{while } e_1 \text{ do } e_2 : T} \quad [\text{While}]$$

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A Problem

- What is the type of a variable reference?

$$\frac{x \text{ is an identifier}}{\vdash x : ?} \quad [\text{Var}]$$

- The local, structural rule does not carry enough information to give x a type

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A Solution

- Put more information in the rules!
- A *type environment* gives types for *free* variables
 - A type environment is a function from **Identifiers** to **Types**
 - A variable is free in an expression if it is not defined within the expression

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Type Environments

Let E be a function from **Identifiers** to **Types**

The sentence $E \vdash e : T$

is read:

Under the assumption that variables have the types given by E , it is provable that the expression e has the type T

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Modified Rules

The type environment is added to the earlier rules:

$$\frac{i \text{ is an integer}}{E \vdash i : \text{int}} \quad [\text{Int}]$$

$$\frac{E \vdash e_1 : \text{int} \quad E \vdash e_2 : \text{int}}{E \vdash e_1 + e_2 : \text{int}} \quad [\text{Add}]$$

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New Rules

And we can now write a rule for variables:

$$\frac{E(x) = T}{E \vdash x : T} \quad [\text{Var}]$$

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Type Checking of Expressions

Production	Semantic Rules
$E \rightarrow id$	{ if (declared(id.name)) then E.type := lookup(id.name).type else E.type := error(); }
$E \rightarrow int$	{ E.type := integer; }
$E \rightarrow E1 + E2$	{ if (E1.type == integer AND E2.type == integer) then E.type := integer; else E.type := error(); }

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Type Checking of Expressions (Cont.)

May have automatic *type coercion*, e.g.

E1.type	E2.type	E.type
integer	integer	integer
integer	float	float
float	integer	float
float	float	float

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Type Checking of Statements: Assignment

Semantic Rules:

$S \rightarrow Lval := Rval \quad \{\text{check_types}(Lval.type, Rval.type)\}$

Note that in general $Lval$ can be a variable or it may be a more complicated expression, e.g., a dereferenced pointer, an array element, a record field, etc.

Type checking involves ensuring that:

- $Lval$ is a type that can be assigned to, e.g. it is not a function or a procedure
- the types of $Lval$ and $Rval$ are "compatible", i.e, that the language rules provide for coercion of the type of $Rval$ to the type of $Lval$

Type Checking of Statements: Loops, Conditionals

Semantic Rules:

$Loop \rightarrow \text{while } E \text{ do } S \quad \{\text{check_types}(E.type, \text{bool})\}$

$Cond \rightarrow \text{if } E \text{ then } S1 \text{ else } S2$
 $\{\text{check_types}(E.type, \text{bool})\}$