Unit – 3
TYPE CHECKING

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Type Checking

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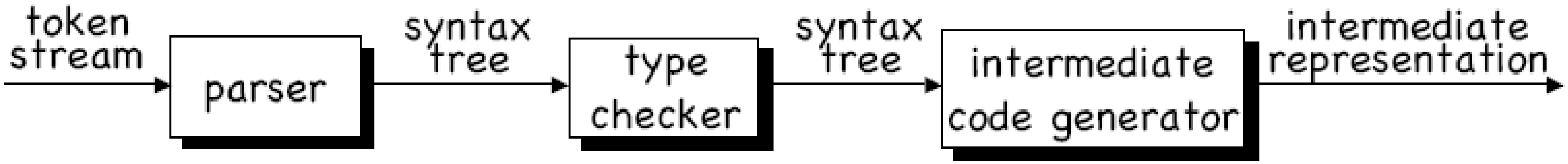


- TYPE CHECKING is the main activity in semantic analysis.
- **Goal: calculate and ensure consistency of the type of every expression in a program**
- If there are type errors, we need to notify the user.
- Otherwise, we need the type information to generate code that is correct.

Type Systems and Type Expressions

Type systems

- Every language has a set of types and rules for assigning types to language constructs.
- Example from the C specification:

  "The result of the unary & operator is a pointer to the object referred to by the operand. If the type of the operand is '…' then the type of the result is 'pointer to …'

- Usually, every expression has a type.
- Type have **structure**: **the type 'pointer to int' is CONSTRUCTED from the type 'int'**

Basic vs. constructed types

- Most programming languages have basic and constructed types.
- **BASIC TYPES** are the atomic types provided by the language.
  - Pascal: boolean, character, integer, real
  - C: char, int, float, double
- **CONSTRUCTED TYPES** are built up from basic types.
  - Pascal: arrays, records, sets, pointers
  - C: arrays, structs, pointers

Type expressions

- We denote the type of language constructs with **TYPE EXPRESSIONS.**

- Type expressions are built up with **TYPE CONSTRUCTORS**.

1. A basic type is **a type expression**. The basic types are **boolean**, **char, integer, and real.** The special basic type **type_error** signifies an error. The special type void signifies **“no type”**
2. **A type name is a type expression** (type names are like typedefs in C)

Type expressions

3. **A type constructor applied to type expressions is a type expression**.
   a. **Arrays**: if T is a type expression, then pointer(T) is a type expression denoting the type “pointer to an object of type T”
      - Array(I,T) ← I: index set, T: element type
   b. **Products**: if T1 and T2 are type expressions, then their Cartesian product T1 × T2 is also a type expression.
   c. **Records**: a record is a special kind of product in which the fields have names (examples below)
   d. **Pointers**: if T is a type expression, then pointer(T) is a type expression denoting the type “pointer to an object of type T”
   e. **Functions**: functions map elements of a domain D to a range R, so we write D -> R to denote “function mapping objects of type D to objects of type R” (examples below)
4. **Type expressions may contain variables, whose values are themselves type expressions.** ← **polymorphism**

Record type expressions

The Pascal code

```
type row   = record
                        address: integer;
                        lexeme: array[1..15] of char
                  end;
var table: array[1..10] of row;
```

associates type expression

record((address × integer) × (lexeme × array(1..15,char)))

with the variable row, and the type expression

array(1..101,record((address × integer) × (lexeme × array(1..15,char))

with the variable table

Function type expressions

The C declaration

int *foo(char a, char b);

would associate type expression

char × char -> pointer(integer)

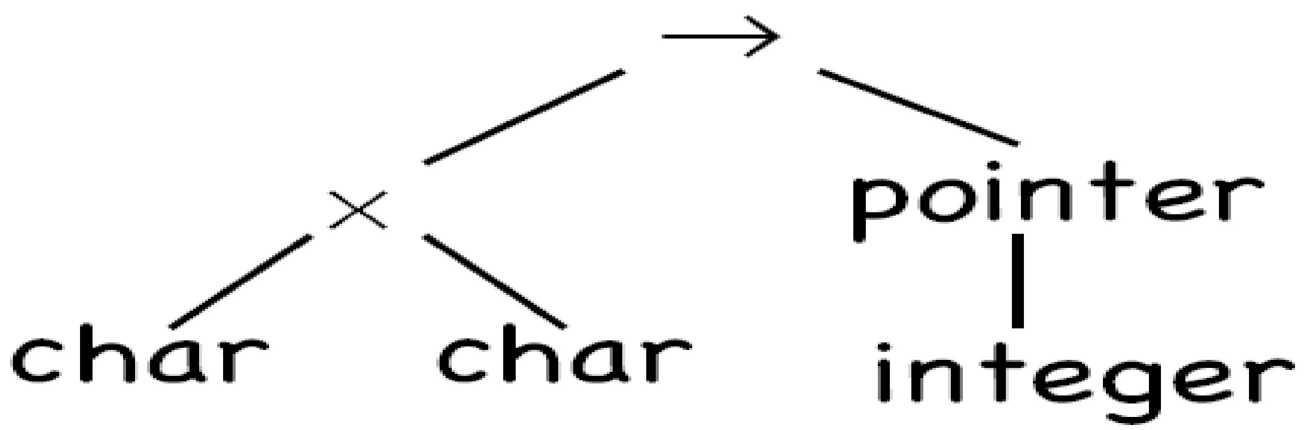
with foo. Some languages (like ML) allow all sorts of crazy function types, e.g.

(integer -> integer) -> (integer -> integer)

denotes functions taking a function as input and returning another function

Graph representation of type expressions

- The recursive structure of a type can be represented with a tree, **e.g. for char × char -> pointer(integer):**



- Some compilers explicitly use graphs like these to represent the types of expressions.

Type systems and checkers

- A **TYPE SYSTEM** is a set of rules for assigning type expressions to the parts of a program.
- Every type checker implements some type system.
- **Syntax-directed type checking is a simple method to implement a type checker.**

Static vs. dynamic type checking

- **STATIC** type checking is done at compile time.
- **DYNAMIC** type checking is done at run time.
- Any kind of type checking **CAN be done at run time**.
- But this reduces run-time efficiency, so we want to do static checking when possible.
- A **SOUND** type system is one in which **ALL type errors can be found statically.**
- If the compiler guarantees that every program it accepts will run without type errors, then the language is **STRONGLY TYPED.**

An Example Type Checker

Example type checker

- Let's build a translation scheme to synthesize the type of every expression from its subexpressions.
- Here is a Pascal-like grammar for a sequence of declarations (D) followed by an expression (E)

P → D ; E

D → D ; D | id : T

T → char | integer | array [num] of T | ↑ T

E → literal | num | id | E mod E | E [E] | E ↑

- **Example program: key: integer;**

  key mod 1999

The type system

- The basic types are char and integer. **type_error** signals an error.
- All arrays start at 1, so array[256] of char leads to type **expression: array(1..256,char)**
- The **symbol** ↑ in an declaration specifies a pointer type, so ↑ integer leads to type expression: pointer(integer)

Translation scheme for declarations

$P \rightarrow D\ ;\ E$	
$D \rightarrow D\ ;\ D$	
$D \rightarrow \text{id} : T$	{ addtype(id.entry, T.type) }
$T \rightarrow \text{char}$	{ T.type := char }
$T \rightarrow \text{integer}$	{ T.type := integer }
$T \rightarrow \uparrow T_1$	{ T.type := pointer(T_1.type) }
$T \rightarrow \text{array [num] of } T_1$	{ T.type := array(1 .. num.val, T_1.type) }

Try to derive the annotated parse tree for the declaration

X: array[100] of ↑ char

Type checking for expressions

Once the identifiers and their types have been inserted into the symbol table, we can check the type of the elements of an expression:

E → literal	**{ E.type := char }**
E → num	**{ E.type := integer }**
E → id	**{ E.type := lookup(id.entry) }**
E → E_1 mod E_2	**{ if E_1.type =integer and E_2.type = integer**
	then E.type := integer
	else E.type := type_error }
E → E_1 [E_2]	**{ if E_2.type = integer and E_1.type = array(s,t)**
	then E.type := t else E.type := type_error }
E → E_1↑	**{ if E_1.type = pointer(t)**
	then E.type := t else E.type := type-error }

How about boolean types?

Try adding

T -> boolean

Relational operators < <= = >= > <>

Logical connectives **and or not**

to the grammar, then add appropriate type checking semantic actions.

Type checking for statements

- Usually we assign the type VOID to statements.
  - ❖ If a type error is found during type checking, though, we should set the type to type_error
  - ❖ Let's change our grammar allow statements:

    $$P \rightarrow D \; ; \; S$$

  - ❖ i.e., a program is a sequence of declarations followed by a sequence of statements.

Type checking for statements

Now we need to add productions and semantic actions:

$S \rightarrow$ **id** := E	{ **if id**.type = E.type **then** S.type := void **else** S.type := type_error }
$S \rightarrow$ **if** E **then** S_1	{ **if** E.type = boolean **then** S.type := S_1.type **else** S.type := type_error }
$S \rightarrow$ **while** E **do** S_1	{ **if** E.type = boolean **then** S.type := S_1.type **else** S.type := type_error }
$S \rightarrow S_1 ; S_2$	{ **if** S_1.type = void **and** S_2.type = void **then** S.type := void **else** S.type := type_error.

Type checking for function calls

- Suppose we add a production $E \rightarrow E\ (\ E\ )$
- Then we need productions for function declarations:

$T \rightarrow T_1 \rightarrow T_2$	{ $T.type := T_1.type \rightarrow T2.type$ }

and function calls:

$E \rightarrow E_1\ (\ E_2\ )$	{ **if** $E_2.type = s$ **and** $E_1.type = s \rightarrow t$
	then $E.type := t$
	else $E.type := type\_error$ }

Type checking for function calls

Multiple-argument functions, however, can be modeled as functions that take a single PRODUCT argument.

$$\textbf{root} : (\textbf{real} \rightarrow \textbf{real}) \times \textbf{real} \rightarrow \textbf{real}$$

this would model a function that takes a real function over the reals, and a real, and returns a real. In C:

```
float root( float (*f)(float), float x );
```

Type expression equivalence

- Type checkers need to ask questions like:
    - **"if E1.type == E2.type, then …"**
- **What does it mean for two type expressions to be equal?**

- **STRUCTURAL EQUIVALENCE** says two types are the same if they are made up of the same basic types and constructors.
- **NAME EQUIVALENCE** says two types are the same if their constituents have the **SAME NAMES.**

Structural Equivalence

boolean sequiv(s, t)

{

if s and t are the same basic type

return TRUE;

else if s == array(s_1, s_2) and t == array(t_1, t_2)

return sequiv(s_1, t_1) and sequiv(s_2, t_2)

else s == s_1 x s_2 and t = t_1 x t_2 then

return sequiv(s_1, t_1) and sequiv(s_2, t_2)

else if s == pointer(s_1) and t == pointer(t_1)

return sequiv(s_1, t_1)

else if s == $s_1 \rightarrow s_2$ and t == $t_1 \rightarrow t_2$ then

return sequiv(s_1, t_1) and sequiv(s_2, t_2)

return false}

Try: int foo(int, float)

Relaxing structural equivalence

- We don't always want strict structural equivalence.
  - **E.g. for arrays, we want to write functions that accept arrays of any length.**
- To accomplish this, we would modify sequiv() to accept any bounds:

…

else if s == array(s_1, s_2) and t == array(t_1, t_2)

return sequiv(s_2, t_2)

…

Encoding types

- Recursive routines are very slow.
- Recursive type checking routines increase the **compiler's run time.**
- In the compilers of the 1970's and 1980's, compilers took too long time to run.
- So designers came up with **ENCODINGS** for types that allowed for faster type checking.

Name equivalence

- Most languages allow association of names with type expressions. This makes type equivalence trickier.

Example from Pascal:

type link = ↑cell;

var next: link;

last: link;

p: ↑ cell;

q,r: ↑ cell;

Do next, last, p, q, and r have the same type?

In Pascal, it depends on the implementation!

In structural equivalence, the types would be the same.

But **NAME EQUIVALENCE** requires identical **NAMES**.

Handling cyclic types

Suppose we had the Pascal declaration

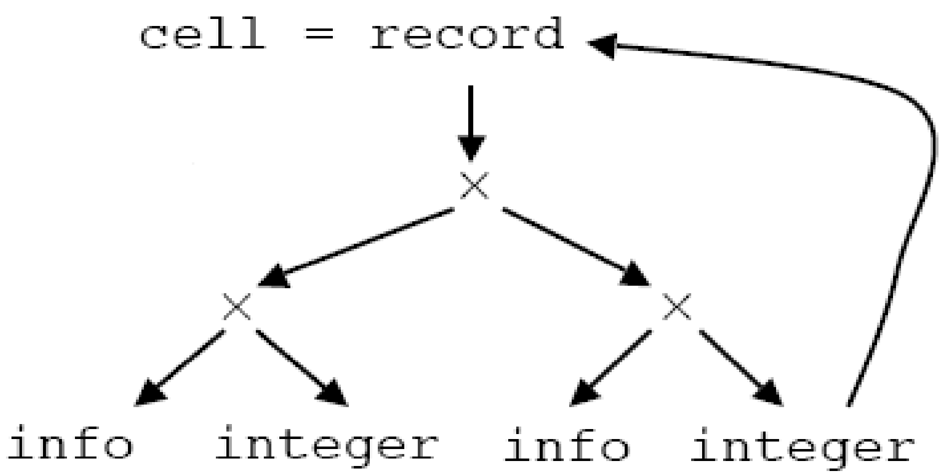
type link = ↑cell;

cell = record

info: integer;

next: link;

end;



The declaration of cell contains itself (via the next pointer).

The graph for this type therefore contains a cycle.

Cyclic types

The situation in C is slightly different, since it is impossible to refer to an undeclared name.

```
typedef struct _cell {
        int info;
        struct _cell *next;
} cell;
typedef *cell link;
```

But the name link is just shorthand for **(struct _cell *).**

C uses name equivalence for structs to avoid recursion (after expanding typedef's). But it uses structural equivalence elsewhere.

Type conversion

- Suppose we encounter an expression x+i where x has type float and i has type int.
- CPU instructions for addition could take EITHER float OR int as operands, but not a mix.
- This means the compiler must sometimes convert the operands of arithmetic expressions to ensure that operands are consistent with operators.
- With postfix as an intermediate language for expressions,

we could express the conversion as follows:

x i inttoreal float+

where **real+** is the floating point addition operation.

Type coercion

- If type conversion is done by the compiler without the programmer requesting it, it is called **IMPLICIT** conversion or type **COERCION**.

- **EXPLICIT** conversions are those that the programmer specifices, e.g. x = (int)y * 2;

- Implicit conversion of **CONSTANT** expressions should be done at compile time.

Type checking example with coercion

Production	Semantic Rule
E -> num	E.type := integer
E -> num . num	E.type := real
E -> id	E.type := lookup(id.entry)
E -> E_1 op E_2	E.type := if E_1.type == integer and E_2.type == integer
	then integer
	else if E_1.type == integer and E_2.type == real
	then real
	else if E_1.type == real and E_2.type == integer
	then real
	else if E_1.type == real and E_2.type == real
	then real
	else type_error

END OF TYPE CHECKING