

COSE212: Programming Languages

Lecture 14 — Type System (3) Manual Type Annotation

Hakjoo Oh
2026 Fall

Typing Rules

$$\overline{\Gamma \vdash n : \text{int}} \quad \overline{\Gamma \vdash x : \Gamma(x)}$$

$$\frac{\Gamma \vdash E_1 : \text{int} \quad \Gamma \vdash E_2 : \text{int}}{\Gamma \vdash E_1 + E_2 : \text{int}}$$

$$\frac{\Gamma \vdash E_1 : \text{int} \quad \Gamma \vdash E_2 : \text{int}}{\Gamma \vdash E_1 - E_2 : \text{int}}$$

$$\frac{\Gamma \vdash E : \text{int}}{\Gamma \vdash \text{iszero } E : \text{bool}}$$

$$\frac{\Gamma \vdash E_1 : \text{bool} \quad \Gamma \vdash E_2 : t \quad \Gamma \vdash E_3 : t}{\Gamma \vdash \text{if } E_1 \text{ then } E_2 \text{ else } E_3 : t}$$

$$\frac{\Gamma \vdash E_1 : t_1 \quad [x \mapsto t_1]\Gamma \vdash E_2 : t_2}{\Gamma \vdash \text{let } x = E_1 \text{ in } E_2 : t_2}$$

$$\frac{\Gamma \vdash E_1 : t_1 \rightarrow t_2 \quad \Gamma \vdash E_2 : t_1}{\Gamma \vdash E_1 E_2 : t_2}$$

$$\frac{[x \mapsto t_1]\Gamma \vdash E : t_2}{\Gamma \vdash \text{proc } x E : t_1 \rightarrow t_2}$$

Implementation: First Try

Can we implement the type checker recursively (like interpreter)?

```
let rec typeof  $\Gamma$   $E$  =  
  match  $E$  with  
  |  $n \rightarrow$  int  
  |  $x \rightarrow \Gamma(x)$   
  |  $E_1 + E_2 \rightarrow$   
    let  $t_1 = \text{typeof } \Gamma E_1$   
    let  $t_2 = \text{typeof } \Gamma E_2$   
    if  $t_1 = \text{int}$  and  $t_2 = \text{int}$  then int  
    else raise TypeError  
     $\vdots$   
  | proc  $x$   $E \rightarrow$ 
```

Challenge

Given a program E , how to check $[] \vdash E : t$? Nontrivial, because of the following type rule:

$$\frac{[x \mapsto t_1]\Gamma \vdash E : t_2}{\Gamma \vdash \text{proc } x \ E : t_1 \rightarrow t_2}$$

Two approaches:

- *Type Annotation*: Programmers are required to supply the type of the function argument. Used in C, C++, Java, etc.
- *Type Inference*: Type checker attempts to automatically infer types. Only possible if the language is carefully designed. Used in ML, Haskell, etc.

CHECKED: Language with Type Annotations

Consider the language with (recursive) procedures:

$$\begin{array}{lcl} E & \rightarrow & n \\ & | & x \\ & | & E + E \\ & | & E - E \\ & | & \text{iszero } E \\ & | & \text{if } E \text{ then } E \text{ else } E \\ & | & \text{let } x = E \text{ in } E \\ & | & \text{proc } (x : t) E \\ & | & \text{letrec } t_1 \ f(x : t_2) = E \text{ in } E \\ & | & E \ E \end{array}$$

Examples

- `proc (x:int) (x+1)`
- `letrec int double (x: int) =
 if iszero x then 0 else (double (x-1)) +2
in double 2`
- `proc (f: (bool -> int)) proc (n: int) (f (iszero n))`

Typing Rules

$$\frac{}{\Gamma \vdash n : \text{int}} \quad \frac{}{\Gamma \vdash x : \Gamma(x)}$$

$$\frac{\Gamma \vdash E_1 : \text{int} \quad \Gamma \vdash E_2 : \text{int}}{\Gamma \vdash E_1 + E_2 : \text{int}}$$

$$\frac{\Gamma \vdash E_1 : \text{int} \quad \Gamma \vdash E_2 : \text{int}}{\Gamma \vdash E_1 - E_2 : \text{int}}$$

$$\frac{\Gamma \vdash E : \text{int}}{\Gamma \vdash \text{iszero } E : \text{bool}}$$

$$\frac{\Gamma \vdash E_1 : \text{bool} \quad \Gamma \vdash E_2 : t \quad \Gamma \vdash E_3 : t}{\text{if } E_1 \text{ then } E_2 \text{ else } E_3 : t}$$

$$\frac{\Gamma \vdash E_1 : t_1 \quad [x \mapsto t_1] \Gamma \vdash E_2 : t_2}{\Gamma \vdash \text{let } x = E_1 \text{ in } E_2 : t_2}$$

$$\frac{\Gamma \vdash E_1 : t_1 \rightarrow t_2 \quad \Gamma \vdash E_2 : t_1}{\Gamma \vdash E_1 E_2 : t_2}$$

$$\frac{[x \mapsto t_1] \Gamma \vdash E : t_2}{\Gamma \vdash \text{proc } (x : t_1) E : t_1 \rightarrow t_2}$$

$$\frac{[x \mapsto t_2, f \mapsto (t_2 \rightarrow t_1)] \Gamma \vdash E_1 : t_1 \quad [f \mapsto (t_2 \rightarrow t_1)] \Gamma \vdash E_2 : t}{\Gamma \vdash \text{letrec } t_1 f(x : t_2) = E_1 \text{ in } E_2 : t}$$

Type Check Algorithm

Now we can implement the type checking algorithm recursively:

```
let rec typeof  $\Gamma$   $E$  =  
  match  $E$  with  
  | proc  $(x : t_1)$   $E_1 \rightarrow$   
    let  $t_2 = \mathbf{typeof} (\{x \mapsto t_1\}\Gamma)$   $E_1$   
    in  $t_1 \rightarrow t_2$   
  | letrec  $t_1$   $f(x : t_2) = E_1$  in  $E_2$   
    let  $t' = \mathbf{typeof} (\{x \mapsto t_2, f \mapsto (t_2 \rightarrow t_1)\}\Gamma)$   $E_1$   
    in if  $t' = t_1$  then typeof  $(\{f \mapsto (t_2 \rightarrow t_1)\}\Gamma)$   $E_2$   
       else raise TypeError  
  |  
  |
```