Programming Languages and Compilers (CS 421)

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Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha

Type Inference

- *Type inference*: A program analysis to assign a type to an expression from the program context of the expression
  - Fully static type inference first introduced by Robin Miller in ML
  - Haskle, OCAML, SML all use type inference
    - Records are a problem for type inference

Format of Type Judgments

- A *type judgement* has the form

$$\Gamma \text{ |- exp} : \tau$$

- Γ is a typing environment
  - Supplies the types of variables (and function names when function names are not variables)
  - Γ is a set of the form $\{ x : \sigma , \ldots \}$
  - For any x at most one σ such that $(x : \sigma \in \Gamma)$
- exp is a program expression
- τ is a type to be assigned to exp
- |- pronounced "turnstyle", or "entails" (or "satisfies" or, informally, "shows")

Axioms - Constants

$$\frac{}{\Gamma \mid\!- \; n : \text{int}}$$ (assuming *n* is an integer constant)

$$\frac{}{\Gamma \mid\!- \text{ true : bool}} \qquad \frac{}{\Gamma \mid\!- \text{ false : bool}}$$

- These rules are true with any typing environment
- Γ, *n* are meta-variables

Axioms – Variables (Monomorphic Rule)

Notation: Let $\Gamma(x) = \sigma$ if $x : \sigma \in \Gamma$

Note: if such σ exits, its unique

Variable axiom:

$$\frac{}{\Gamma \mid\!- x : \sigma} \quad \text{if } \Gamma(x) = \sigma$$

Simple Rules - Arithmetic

Primitive Binary operators ($\oplus \in \{ +, -, *, \ldots\}$):

$$\frac{\Gamma \mid\!\!- e_1 : \tau_1 \qquad \Gamma \mid\!\!- e_2 : \tau_2 \qquad (\oplus) : \tau_1 \rightarrow \tau_2 \rightarrow \tau_3}{\Gamma \mid\!\!- e_1 \oplus e_2 : \tau_3}$$

Special case: Relations ($\sim \in \{ <, >, =, <=, >= \}$):

$$\frac{\Gamma \mid\!\!- e_1 : \tau \quad \Gamma \mid\!\!- e_2 : \tau \quad (\sim) : \tau \rightarrow \tau \rightarrow \text{bool}}{\Gamma \mid\!\!- e_1 \sim e_2 : \text{bool}}$$

For the moment, think τ is int

Example: {x:int} |- x + 2 = 3 :bool

What do we need to show first?

{x:int} |- x + 2 = 3 : bool

Example: {x:int} |- x + 2 = 3 :bool

What do we need for the left side?

$$\frac{\{x : int\} \mid\!- x + 2 : int \qquad \{x:int\} \mid\!- 3 :int}{\{x:int\} \mid\!- x + 2 = 3 : bool}\text{Bin}$$

Example: {x:int} |- x + 2 = 3 :bool

How to finish?

$$\dfrac{\dfrac{\{x:int\} \mid\!- x:int \quad \{x:int\} \mid\!- 2:int}{\{x : int\} \mid\!- x + 2 : int}\,\text{Bin} \qquad \{x:int\} \mid\!- 3 :int}{\{x:int\} \mid\!- x + 2 = 3 : bool}\,\text{Bin}$$

Example: {x:int} |- x + 2 = 3 :bool

Complete Proof (type derivation)

$$\dfrac{\dfrac{\dfrac{}{\{x{:}int\} \mid\!- x{:}int}\text{Var} \quad \dfrac{}{\{x{:}int\} \mid\!- 2{:}int}\text{Const}}{\{x : int\} \mid\!- x + 2 : int}\text{Bin} \quad \dfrac{}{\{x{:}int\} \mid\!- 3 : int}\text{Const}}{\{x{:}int\} \mid\!- x + 2 = 3 : bool}\text{Bin}$$

Simple Rules - Booleans

Connectives

$$\frac{\Gamma \text{ |- } e_1 : \text{bool} \qquad \Gamma \text{ |- } e_2 : \text{bool}}{\Gamma \text{ |- } e_1 \text{ \&\& } e_2 : \text{bool}}$$

$$\frac{\Gamma \text{ |- } e_1 : \text{bool} \qquad \Gamma \text{ |- } e_2 : \text{bool}}{\Gamma \text{ |- } e_1 \text{ || } e_2 : \text{bool}}$$

Type Variables in Rules

- If_then_else rule:

$$\frac{\Gamma \mid\!- \; e_1 : \text{bool} \quad \Gamma \mid\!- \; e_2 : \tau \quad \Gamma \mid\!- \; e_3 : \tau}{\Gamma \mid\!- \; (\text{if } e_1 \text{ then } e_2 \text{ else } e_3) : \tau}$$

- τ is a type variable (meta-variable)
- Can take any type at all
- All instances in a rule application must get same type
- Then branch, else branch and if_then_else must all have same type

Function Application

- Application rule:

$$\frac{\Gamma \mid\!\!- e_1 : \tau_1 \to \tau_2 \quad \Gamma \mid\!\!- e_2 : \tau_1}{\Gamma \mid\!\!- (e_1\ e_2) : \tau_2}$$

- If you have a function expression e_1 of type $\tau_1 \to \tau_2$ applied to an argument e_2 of type τ_1, the resulting expression $e_1 e_2$ has type τ_2

Fun Rule

- Rules describe types, but also how the environment Γ may change
- Can only do what rule allows!
- fun rule:

$$\frac{\{x : \tau_1\} + \Gamma \ |\text{-}\ e : \tau_2}{\Gamma \ |\text{-}\ \texttt{fun}\ x \ \texttt{->}\ e : \tau_1 \rightarrow \tau_2}$$

Fun Examples

$$\frac{\{y : \text{int}\} + \Gamma \mid\!- \ y + 3 : \text{int}}{\Gamma \mid\!- \ \text{fun } y \text{ -> } y + 3 : \text{int} \rightarrow \text{int}}$$

$$\frac{\{f : \text{int} \rightarrow \text{bool}\} + \Gamma \mid\!- \ f\ \ 2 :: [\text{true}] : \text{bool list}}{\Gamma \mid\!- \ (\text{fun } f \text{ -> } (f\ \ 2) :: [\text{true}]) : (\text{int} \rightarrow \text{bool}) \rightarrow \text{bool list}}$$

(Monomorphic) Let and Let Rec

- let rule:

$$\frac{\Gamma \mid\!- e_1 : \tau_1 \qquad \{x : \tau_1\} + \Gamma \mid\!- e_2 : \tau_2}{\Gamma \mid\!- (\text{let } x = e_1 \text{ in } e_2) : \tau_2}$$

- let rec rule:

$$\frac{\{x: \tau_1\} + \Gamma \mid\!- e_1 : \tau_1 \quad \{x: \tau_1\} + \Gamma \mid\!- e_2 : \tau_2}{\Gamma \mid\!- (\text{let rec } x = e_1 \text{ in } e_2) : \tau_2}$$

Example

- Which rule do we apply?

$$\frac{?}{\{\} \mid\!- \text{(let rec one = 1 :: one in let x = 2 in fun y -> (x :: y :: one)) : int} \rightarrow \text{int list}}$$

Example

- Let rec rule: ② {one : int list} |- (let x = 2 in fun y -> (x :: y :: one)) : int → int list

① {one : int list} |- (1 :: one) : int list

{} |- (let rec one = 1 :: one in
let x = 2 in
fun y -> (x :: y :: one)) : int → int list

Proof of 1

- Which rule?

{one : int list} |- (1 :: one) : int list

Proof of 1

- Binary Operator

③ {one : int list} |- 1: int

④ {one : int list} |- one : int list

{one : int list} |- (1 :: one) : int list

where (::) : int → int list → int list

Proof of 1

③ Constant Rule
{one : int list} |-
1: int

④ Variable Rule
{one : int list} |-
one : int list

{one : int list} |- (1 :: one) : int list

Proof of 2

- Let Rule

{x:int; one : int list} |- fun y -> (x :: y :: one)) : int → int list

{one : int list} |- 2:int

{one : int list} |- (let x = 2 in fun y -> (x :: y :: one)) : int → int list

Proof of 2

- Constant

⑤ {x:int; one : int list} |-
fun y ->
(x :: y :: one))
: int → int list

{one : int list} |- 2:int

{one : int list} |- (let x = 2 in
fun y -> (x :: y :: one)) : int → int list

Proof of 5

$$\frac{?}{\{x{:}int;\ one : int\ list\}\ |\text{-}\ fun\ y \text{ -> } (x :: y :: one)) : int \rightarrow int\ list}$$

Proof of 5

?

{y:int; x:int; one : int list} |- (x :: y :: one) : int list

{x:int; one : int list} |- fun y -> (x :: y :: one))

: int $\rightarrow$ int list

By the Fun Rule

Proof of 5

(6) (7)

{y:int; x:int; one:int list} |- x:int   {y:int; x:int; one:int list} |- (y :: one) : int list

---

{y:int; x:int; one : int list} |- (x :: y :: one) : int list

{x:int; one : int list} |- fun y -> (x :: y :: one))
: int → int list

By BinOp where (::) : int → int list → int list

Proof of 6

⑥ ⑦

Variable Rule

{y:int; x:int; one:int list} |- x:int

{y:int; x:int; one:int list} |- (y :: one) : int list

{y:int; x:int; one : int list} |- (x :: y :: one) : int list

{x:int; one : int list} |- fun y -> (x :: y :: one)) : int → int list

Proof of 7

- Binary Operation Rule

$$\frac{\{y:int; \ldots\} \mid\!- \; y:int \qquad \begin{array}{c}\{\ldots;\ one:int\ list;\ldots\}\\ \mid\!- \; one : int\ list\end{array}}{\{y:int;\ x:int;\ one : int\ list\} \mid\!- \; (y :: one) : int\ list}$$

By BinOp where (::) : int → int list → int list

Proof of 7

Variable Rule

{...; one:int list;...}

Variable Rule

{y:int; ...} |- y:int |- one : int list

{y:int; x:int; one : int list}|- (y :: one) : int list

Curry - Howard Isomorphism

- Type Systems are logics; logics are type systems
- Types are propositions; propositions are types
- Terms are proofs; proofs are terms

- Function space arrow corresponds to implication; application corresponds to modus ponens

Curry - Howard Isomorphism

- Modus Ponens

$$\frac{A \Rightarrow B \quad A}{B}$$

- Application

$$\frac{\Gamma \mid\!- \; e_1 : \alpha \rightarrow \beta \quad \Gamma \mid\!- \; e_2 : \alpha}{\Gamma \mid\!- \; (e_1 \; e_2) : \beta}$$

Review: In Class Activity

ACT 4

Mea Culpa

- The above system can’t handle polymorphism as in OCAML
- No type variables in type language (only meta-variable in the logic)
- Would need:
  - Object level type variables and some kind of type quantification
  - **let** and **let rec** rules to introduce polymorphism
  - Explicit rule to eliminate (instantiate) polymorphism

Support for Polymorphic Types

- Monomorpic Types (τ):
  - Basic Types: int, bool, float, string, unit, …
  - Type Variables: α, β, γ, δ, ε
  - Compound Types: $\alpha \rightarrow \beta$, int * string, bool list, …
- Polymorphic Types:
  - Monomorphic types τ
  - Universally quantified monomorphic types
  - $\forall \alpha_1, \ldots, \alpha_n . \tau$
  - Can think of τ as same as $\forall . \tau$

Example FreeVars Calculations

- Vars('a -> (int -> 'b) -> 'a) ={'a , 'b}
- FreeVars (All 'b. 'a -> (int -> 'b) -> 'a) =
-   {'a , 'b} – {'b}= {'a}
- FreeVars {x : All 'b. 'a -> (int -> 'b) -> 'a,
- id: All 'c. 'c -> 'c,
- y: All 'c. 'a -> 'b -> 'c} =
- {'a} U {} U {'a, 'b} = {'a, 'b}

Support for Polymorphic Types

- Typing Environment Γ supplies polymorphic types (which will often just be monomorphic) for variables
- Free variables of monomorphic type just type variables that occur in it
  - Write FreeVars(τ)
- Free variables of polymorphic type removes variables that are universally quantified
  - FreeVars($\forall\alpha_1, \ldots , \alpha_n . \tau$) = FreeVars($\tau$) – $\{\alpha_1, \ldots , \alpha_n \}$
- FreeVars(Γ) = all FreeVars of types in range of Γ

Monomorphic to Polymorphic

- Given:
  - type environment Γ
  - monomorphic type τ
  - τ shares type variables with Γ
- Want most polymorphic type for τ that doesn't break sharing type variables with Γ
- $Gen(\tau, \Gamma) = \forall \alpha_1, \ldots , \alpha_n . \tau$ where $\{\alpha_1, \ldots , \alpha_n\} = freeVars(\tau) - freeVars(\Gamma)$

Polymorphic Typing Rules

- A *type judgement* has the form

$$\Gamma \mid\!- \text{exp} : \tau$$

  - Γ uses polymorphic types
  - τ still monomorphic
- Most rules stay same (except use more general typing environments)
- Rules that change:
  - Variables
  - Let and Let Rec
  - Allow polymorphic constants
- Worth noting functions again

Polymorphic Let and Let Rec

- let rule:

$$\frac{\Gamma \mid\!- \ e_1 : \tau_1 \quad \{x : \mathrm{Gen}(\tau_1,\Gamma)\} + \Gamma \mid\!- \ e_2 : \tau_2}{\Gamma \mid\!- \ (\text{let } x = e_1 \text{ in } e_2) : \tau_2}$$

- let rec rule:

$$\frac{\{x : \tau_1\} + \Gamma \mid\!- \ e_1 : \tau_1 \quad \{x : \mathrm{Gen}(\tau_1,\Gamma)\} + \Gamma \mid\!- \ e_2 : \tau_2}{\Gamma \mid\!- \ (\text{let rec } x = e_1 \text{ in } e_2) : \tau_2}$$

Polymorphic Variables (Identifiers)

Variable axiom:

$$\frac{}{\Gamma \mid\!- \, x : \varphi(\tau)} \quad \text{if } \Gamma(x) = \forall \alpha_1, \ldots, \alpha_n \,.\, \tau$$

- Where φ replaces all occurrences of $\alpha_1, \ldots, \alpha_n$ by monotypes $\tau_1, \ldots, \tau_n$
- Note: Monomorphic rule special case:

$$\frac{}{\Gamma \mid\!- \, x : \tau} \quad \text{if } \Gamma(x) = \tau$$

- Constants treated same way

Fun Rule Stays the Same

- fun rule:

$$\frac{\{x : \tau_1\} + \Gamma \mid\!- \; e : \tau_2}{\Gamma \mid\!- \text{fun } x \text{ -> } e : \tau_1 \rightarrow \tau_2}$$

- Types τ_1, τ_2 monomorphic
- Function argument must always be used at same type in function body

Polymorphic Example

- Assume additional constants and primitive operators:
- hd : $\forall\alpha.\ \alpha$ list -> α
- tl: $\forall\alpha.\ \alpha$ list -> α list
- is_empty : $\forall\alpha.\ \alpha$ list -> bool
- (::) : $\forall\alpha.\ \alpha$ -> α list -> α list
- [] : $\forall\alpha.\ \alpha$ list

Polymorphic Example

- Show:

?

{} |- let rec length =

fun l -> if is_empty l then 0

else 1 + length (tl l)

in length (2 :: []) + length(true :: []) : int

Polymorphic Example: Let Rec Rule

- Show: (1) (2)

(1)

{length:α list -> int}
|- fun l -> …
: α list -> int

(2)

{length:∀α. α list -> int}
|- length (2 :: []) +
length(true :: []) : int

{} |- let rec length =
fun l -> if is_empty l then 0
else 1 + length (tl l)
in length (2 :: []) + length(true :: []) : int

Polymorphic Example (1)

- Show:

?

{length:α list -> int} |-

fun l -> if is_empty l then 0

else 1 + length (tl l)

: α list -> int

Polymorphic Example (1): Fun Rule

- Show: (3)

{length:α list -> int, l: α list } |-
if is_empty l then 0
else length (hd l) + length (tl l) : int

{length:α list -> int} |-
fun l -> if is_empty l then 0
else 1 + length (tl l)
: α list -> int

Polymorphic Example (3)

- Let Γ ={length:α list -> int, l: α list }
- Show

$$\frac{?}{\Gamma \mid\!\!- \text{ if is\_empty l then 0 else 1 + length (tl l) : int}}$$

Polymorphic Example (3):IfThenElse

- Let Γ ={length:α list -> int, l: α list }
- Show

$$\frac{\overset{(4)}{\Gamma \text{|- is\_empty l : bool}} \quad \overset{(5)}{\Gamma \text{|- 0:int}} \quad \overset{(6)}{\Gamma \text{|- 1 + length (tl l) : int}}}{\Gamma \text{|- if is\_empty l then 0 else 1 + length (tl l) : int}}$$

Polymorphic Example (4)

- Let Γ ={length:α list -> int, l: α list }
- Show

$$\frac{?}{\Gamma \text{|- is\_empty l : bool}}$$

Polymorphic Example (4):Application

- Let Γ ={length:α list -> int, l: α list }
- Show

$$\dfrac{\dfrac{?}{\Gamma \vdash \text{is\_empty} : \alpha\ \text{list} \to \text{bool}} \qquad \dfrac{?}{\Gamma \vdash \text{l} : \alpha\ \text{list}}}{\Gamma \vdash \text{is\_empty l} : \text{bool}}$$

Polymorphic Example (4)

- Let Γ ={length:α list -> int, l: α list }
- Show

By Const since α list -> bool is
instance of $\forall\alpha.\ \alpha$ list -> bool ?

$$\frac{\dfrac{}{\Gamma \mid\!- \text{is\_empty} : \alpha \text{ list} \to \text{bool}} \qquad \dfrac{}{\Gamma \mid\!- \text{l} : \alpha \text{ list}}}{\Gamma \mid\!- \text{is\_empty l} : \text{bool}}$$

Polymorphic Example (4)

- Let Γ ={length:α list -> int, l: α list }
- Show

By Const since α list -> bool is instance of $\forall\alpha.\ \alpha$ list -> bool

By Variable Γ(l) = α list

$$\dfrac{\dfrac{\text{By Const since } \alpha \text{ list -> bool is instance of } \forall\alpha.\ \alpha \text{ list -> bool}}{\Gamma \text{|- is\_empty : } \alpha \text{ list -> bool}} \qquad \dfrac{\text{By Variable } \Gamma(\text{l}) = \alpha \text{ list}}{\Gamma \text{|- l : } \alpha \text{ list}}}{\Gamma \text{|- is\_empty l : bool}}$$

- This finishes (4)

Polymorphic Example (5):Const

- Let Γ ={length:α list -> int, l: α list }
- Show

By Const Rule

$$\frac{}{\Gamma |\text{-}\ 0\text{:int}}$$

Polymorphic Example (6):Arith Op

- Let Γ ={length:α list -> int, l: α list }
- Show

$$
\dfrac{\dfrac{}{\Gamma \mid\!- \; 1 : \text{int}}\ \text{By Const} \qquad \dfrac{\dfrac{}{\Gamma \mid\!- \; \text{length} : \alpha \text{ list} \to \text{int}}\ \text{By Variable} \qquad \Gamma \mid\!- \; (\text{tl } l) : \alpha \text{ list}\ \ (7)}{\Gamma \mid\!- \; \text{length } (\text{tl } l) : \text{int}}}{\Gamma \mid\!- \; 1 + \text{length } (\text{tl } l) : \text{int}}
$$

Polymorphic Example (7):App Rule

- Let Γ ={length:α list -> int, l: α list }
- Show

By Const / By Variable

$$\frac{\dfrac{\text{By Const}}{\Gamma \text{|- tl} : \alpha \text{ list -> } \alpha \text{ list}} \qquad \dfrac{\text{By Variable}}{\Gamma \text{|- l} : \alpha \text{ list}}}{\Gamma \text{|- (tl l)} : \alpha \text{ list}}$$

By Const since α list -> α list is instance of $\forall\alpha.$ α list -> α list

Polymorphic Example: (2) by ArithOp

- Let Γ' = {length:$\forall\alpha$. α list -> int}
- Show:

$$\frac{\overset{(8)}{\Gamma' \;|\text{-}\; \text{length }(2 :: [\,]) : \text{int}} \qquad \overset{(9)}{\Gamma' \;|\text{-}\; \text{length}(\text{true} :: [\,]) : \text{int}}}{\{\text{length}:\forall\alpha.\ \alpha \text{ list -> int}\} \;|\text{-}\; \text{length }(2 :: [\,]) + \text{length}(\text{true} :: [\,]) : \text{int}}$$

Polymorphic Example: (8)AppRule

- Let Γ' = {length: $\forall\alpha.\ \alpha$ list -> int}
- Show:

$$\frac{\Gamma' \text{ |- length : int list ->int} \quad \Gamma' \text{ |- (2 :: []) :int list}}{\Gamma' \text{ |- length (2 :: []) :int}}$$