Programming Languages and Compilers (CS 421)

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

Two Problems

- Type checking
  - Question: Does exp. e have type τ in env Γ?
  - Answer: Yes / No
  - Method: Type derivation
- Typability
  - Question Does exp. e have some type in env Γ? If so, what is it?
  - Answer: Type τ / error
  - Method: Type inference

Type Inference - Outline

- Begin by assigning a type variable as the type of the whole expression
- Decompose the expression into component expressions
- Use typing rules to generate constraints on components and whole
- Recursively find substitution that solves typing judgment of first subcomponent
- Apply substitution to next subcomponent and find substitution solving it; compose with first, ext
- Apply comp of all substitution to orig. type var. to get answer

Type Inference - Example

- What type can we give to

  (fun x -> fun f -> f (f x))

- Start with a type variable and then look at the way the term is constructed

Type Inference - Example

- First approximate:

  $[\ ]\ |\text{-}\ (\text{fun x -> fun f -> f (f x)}) : \alpha$

- Second approximate: use fun rule

$$\frac{[x : \beta]\ |\text{-}\ (\text{fun f -> f (f x)}) : \gamma}{[\ ]\ |\text{-}\ (\text{fun x -> fun f -> f (f x)}) : \alpha}$$

- Remember constraint $\alpha \equiv (\beta \rightarrow \gamma)$

Type Inference - Example

- Third approximate: use fun rule

$$\frac{\dfrac{[f : \delta\ ;\ x : \beta]\ |\text{-}\ f\ (f\ x) : \varepsilon}{[x : \beta]\ |\text{-}\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}}{[\ ]\ |\text{-}\ (\text{fun } x \text{ -> fun } f \text{ -> } f(f\ x)) : \alpha}$$

- $\alpha \equiv (\beta \rightarrow \gamma);\ \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Fourth approximate: use app rule

$$\frac{\dfrac{\dfrac{[f{:}\delta;\ x{:}\beta] \mid\!-\ f : \varphi \rightarrow \varepsilon \quad [f{:}\delta;\ x{:}\beta] \mid\!-\ f\ x : \varphi}{[f : \delta\ ;\ x : \beta] \mid\!-\ (f\ (f\ x)) : \varepsilon}}{[x : \beta] \mid\!-\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}}{[\ ] \mid\!-\ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}$$

- $\alpha \equiv (\beta \rightarrow \gamma);\ \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Fifth approximate: use var rule, get constraint $\delta \equiv \varphi \rightarrow \varepsilon$, Solve with same
- Apply to next sub-proof

$$\frac{\frac{\frac{\overline{[f:\delta;\ x:\beta] \mid\!-\ f : \varphi \rightarrow \varepsilon} \quad [f:\delta;\ x:\beta] \mid\!-\ f\ x : \varphi}{[f : \delta\ ;\ x : \beta]\ \mid\!-\ (f\ (f\ x)) : \varepsilon}}{[x : \beta]\ \mid\!-\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}}{[\ ]\ \mid\!-\ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}$$

- $\alpha \equiv (\beta \rightarrow \gamma);\ \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Current subst: $\{\delta \equiv \varphi \rightarrow \varepsilon\}$

$$\frac{\dfrac{\dfrac{\dots \quad [f:\varphi \rightarrow \varepsilon;\ x:\beta] \mid\!-\ f\ x : \varphi}{[f : \delta\ ;\ x : \beta] \mid\!-\ (f\ (f\ x)) : \varepsilon}}{[x : \beta] \mid\!-\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}}{[\ ] \mid\!-\ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}$$

- $\alpha \equiv (\beta \rightarrow \gamma);\ \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Current subst: $\{\delta \equiv \varphi \to \varepsilon\}$

$$\dfrac{\dfrac{\dfrac{[f:\varphi\to\varepsilon;\ x:\beta] \mid\!- f:\zeta\to\varphi \quad [f:\varphi\to\varepsilon;\ x:\beta] \mid\!- x:\zeta}{\ldots \quad [f:\varphi \to \varepsilon;\ x:\beta] \mid\!- f\ x : \varphi}}{[f : \delta\ ;\ x : \beta] \mid\!- (f\ (f\ x)) : \varepsilon}}{\dfrac{[x : \beta] \mid\!- (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}{[\ ] \mid\!- (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}}$$

- $\alpha \equiv (\beta \to \gamma);\ \gamma \equiv (\delta \to \varepsilon)$

Type Inference - Example

- Current subst: $\{\delta \equiv \varphi \rightarrow \varepsilon\}$
- Var rule: Solve $\zeta \rightarrow \varphi \equiv \varphi \rightarrow \varepsilon$ Unification

$$\dfrac{\dfrac{\dfrac{[f:\varphi \rightarrow \varepsilon;\ x:\beta] \mid\!-\ f:\zeta \rightarrow \varphi \quad [f:\varphi \rightarrow \varepsilon;\ x:\beta] \mid\!-\ x:\zeta}{\ldots \quad [f:\varphi \rightarrow \varepsilon;\ x:\beta] \mid\!-\ f\ x : \varphi}}{[f : \delta\ ;\ x : \beta] \mid\!-\ (f\ (f\ x)) : \varepsilon}}{\dfrac{[x : \beta] \mid\!-\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}{[\ ] \mid\!-\ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}}$$

- $\alpha \equiv (\beta \rightarrow \gamma);\ \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Current subst: $\{\zeta \equiv \varepsilon,\ \varphi \equiv \varepsilon\}$ o $\{\delta \equiv \varphi \rightarrow \varepsilon\}$
- Var rule: Solve $\zeta \rightarrow \varphi \equiv \varphi \rightarrow \varepsilon$ Unification

$$\dfrac{\dfrac{\dfrac{[f:\varphi\rightarrow\varepsilon;\ x:\beta] \mid\!-\ f:\zeta\rightarrow\varphi \qquad [f:\varphi\rightarrow\varepsilon;\ x:\beta] \mid\!-\ x:\zeta}{\ldots \qquad [f:\varphi \rightarrow \varepsilon;\ x:\beta] \mid\!-\ f\ x : \varphi}}{[f : \delta\ ;\ x : \beta] \mid\!-\ (f\ (f\ x)) : \varepsilon}}{\dfrac{[x : \beta] \mid\!-\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}{[\ ] \mid\!-\ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}}$$

- $\alpha \equiv (\beta \rightarrow \gamma);\ \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Current subst: $\{\zeta \equiv \varepsilon,\ \varphi \equiv \varepsilon,\ \delta \equiv \varepsilon \to \varepsilon\}$
- Apply to next sub-proof

$$\dfrac{\dfrac{\dots \qquad [f:\varepsilon \to \varepsilon;\ x:\beta] \mid\!- \ x:\varepsilon}{\dots \qquad [f:\varphi \to \varepsilon;\ x:\beta] \mid\!- \ f\ x : \varphi}}{\dfrac{\dfrac{[f : \delta\ ;\ x : \beta] \mid\!- \ (f\ (f\ x)) : \varepsilon}{[x : \beta] \mid\!- \ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}}{[\ ] \mid\!- \ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}}$$

- $\alpha \equiv (\beta \to \gamma);\ \gamma \equiv (\delta \to \varepsilon)$

Type Inference - Example

- Current subst: $\{\zeta \equiv \varepsilon,\ \varphi \equiv \varepsilon,\ \delta \equiv \varepsilon \rightarrow \varepsilon\}$
- Var rule: $\varepsilon \equiv \beta$

$$\dfrac{\dfrac{\dots \qquad \dfrac{}{[f:\varepsilon \rightarrow \varepsilon;\ x:\beta] \mid\!-\ x:\varepsilon}}{\dots \quad [f:\varphi \rightarrow \varepsilon;\ x:\beta] \mid\!-\ f\ x : \varphi}}{\dfrac{[f : \delta\ ;\ x : \beta] \mid\!-\ (f\ (f\ x)) : \varepsilon}{\dfrac{[x : \beta] \mid\!-\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}{[\ ] \mid\!-\ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}}}$$

- $\alpha \equiv (\beta \rightarrow \gamma);\ \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Current subst: $\{\varepsilon \equiv \beta\} \circ \{\zeta \equiv \varepsilon,\ \varphi \equiv \varepsilon,\ \delta \equiv \varepsilon \to \varepsilon\}$
- Solves subproof; return one layer

$$\dfrac{\dfrac{\dots \qquad \dfrac{}{[f:\varepsilon \to \varepsilon;\ x:\beta]\ |\text{-}\ x:\varepsilon}}{\dots \quad [f:\varphi \to \varepsilon;\ x:\beta]\ |\text{-}\ f\ x : \varphi}}{\dfrac{\dfrac{[f : \delta\ ;\ x : \beta]\ |\text{-}\ (f\ (f\ x)) : \varepsilon}{[x : \beta]\ |\text{-}\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}}{[\ ]\ |\text{-}\ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}}$$

- $\alpha \equiv (\beta \to \gamma);\ \gamma \equiv (\delta \to \varepsilon)$

Type Inference - Example

- Current subst: $\{\varepsilon \equiv \beta, \zeta \equiv \beta, \varphi \equiv \beta, \delta \equiv \beta \rightarrow \beta\}$
- Solves this subproof; return one layer

$$\dfrac{\dfrac{\overline{\quad \ldots \qquad [f:\varphi \rightarrow \varepsilon;\ x:\beta] \mid\!-\ f\ x : \varphi \quad}}{[f : \delta\ ;\ x : \beta] \mid\!-\ (f\ (f\ x)) : \varepsilon}}{\dfrac{[x : \beta] \mid\!-\ (\text{fun } f \text{ -> } f\ (f\ x)) : \gamma}{[\ ] \mid\!-\ (\text{fun } x \text{ -> fun } f \text{ -> } f\ (f\ x)) : \alpha}}$$

- $\alpha \equiv (\beta \rightarrow \gamma);\ \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Current subst: $\{\varepsilon \equiv \beta, \zeta \equiv \beta, \varphi \equiv \beta, \delta \equiv \beta \to \beta\}$
- Need to satisfy constraint $\gamma \equiv (\delta \to \varepsilon)$, given subst: $\gamma \equiv ((\beta \to \beta) \to \beta)$

$$\frac{\dfrac{\dfrac{}{[f : \delta \,;\, x : \beta] \mid\!- (f\,(f\,x)) : \varepsilon}}{[x : \beta] \mid\!- (\text{fun } f \to f\,(f\,x)) : \gamma}}{[\,] \mid\!- (\text{fun } x \to \text{fun } f \to f\,(f\,x)) : \alpha}$$

- $\alpha \equiv (\beta \to \gamma)$; $\gamma \equiv (\delta \to \varepsilon)$

Type Inference - Example

- Current subst:

$\{\gamma \equiv ((\beta \rightarrow \beta) \rightarrow \beta), \varepsilon \equiv \beta, \zeta \equiv \beta, \varphi \equiv \beta, \delta \equiv \beta \rightarrow \beta\}$

- Solves subproof; return one layer

$$\dfrac{\dfrac{\overline{[f : \delta ; x : \beta] \mid\!- (f\ (f\ x)) : \varepsilon}}{[x : \beta] \mid\!- (\text{fun } f \rightarrow f\ (f\ x)) : \gamma}}{[\ ]\ \mid\!- (\text{fun } x \rightarrow \text{fun } f \rightarrow f\ (f\ x)) : \alpha}$$

- $\alpha \equiv (\beta \rightarrow \gamma); \gamma \equiv (\delta \rightarrow \varepsilon)$

Type Inference - Example

- Current subst:

$\{\gamma \equiv ((\beta \rightarrow \beta) \rightarrow \beta), \varepsilon \equiv \beta, \zeta \equiv \beta, \varphi \equiv \beta, \delta \equiv \beta \rightarrow \beta\}$

- Need to satisfy constraint $\alpha \equiv (\beta \rightarrow \gamma)$ given subst: $\alpha \equiv (\beta \rightarrow ((\beta \rightarrow \beta) \rightarrow \beta))$

$$\dfrac{\dfrac{}{[x : \beta] \mid\!- (\text{fun } f \rightarrow f\ (f\ x)) : \gamma}}{[\ ] \mid\!- (\text{fun } x \rightarrow \text{fun } f \rightarrow f\ (f\ x)) : \alpha}$$

- $\alpha \equiv (\beta \rightarrow \gamma)$;

Type Inference - Example

- Current subst:

$\{\alpha \equiv (\beta \to ((\beta \to \beta) \to \beta)),$

$\gamma \equiv ((\beta \to \beta) \to \beta), \varepsilon \equiv \beta,\ \zeta \equiv \beta,\ \varphi \equiv \beta,\ \delta \equiv \beta \to \beta\}$

- Solves subproof; return one layer

$$\frac{\overline{\qquad\qquad\qquad\qquad}}{\frac{[x : \beta] \mid\!\!- (\text{fun } f \to f\ (f\ x)) : \gamma}{[\ ] \mid\!\!- (\text{fun } x \to \text{fun } f \to f\ (f\ x)) : \alpha}}$$

Type Inference - Example

- Current subst:

$\{\alpha \equiv (\beta \rightarrow ((\beta \rightarrow \beta) \rightarrow \beta)),$

$\gamma \equiv ((\beta \rightarrow \beta) \rightarrow \beta), \varepsilon \equiv \beta,\ \zeta \equiv \beta,\ \varphi \equiv \beta,\ \delta \equiv \beta \rightarrow \beta\}$

- Done: $\alpha \equiv (\beta \rightarrow ((\beta \rightarrow \beta) \rightarrow \beta))$

[ ] |- (fun x -> fun f -> f (f x)) : α

Type Inference Algorithm

Let infer $(\Gamma, e, \tau) = \sigma$

- Γ is a typing environment (giving polymorphic types to expression variables)
- e is an expression
- τ is a monomorphic type (with type variables),
- σ is a substitution of types for type variables
- Idea: σ is the constraints on type variables necessary for Γ |- $e : \tau$
- Should have $\sigma(\Gamma)$ |- $e : \sigma(\tau)$

Type Inference Algorithm

- freshInstance instantiates quantifier with new vars
- infer(Γ, *exp*, τ) =
- Case *exp* of
  - Var *v* --> return Unify{$\tau \equiv$ freshInstance(Γ(*v*))}
    - Replace all quantified type vars by fresh ones
  - Const *c* --> return Unify{$\tau \equiv$ freshInstance φ } where Γ |- *c* : φ by the constant rules
  - fun *x* -> *e* -->
    - Let α, β be fresh variables
    - Let σ = infer ([x: α] + Γ, *e*, β)
    - Return Unify({$\sigma(\tau) \equiv \sigma(\alpha \rightarrow \beta)$}) $\circ\ \sigma$

Type Inference Algorithm (cont)

- Case *exp* of
  - App (e_1 e_2) -->
    - Let α be a fresh variable
    - Let σ_1 = infer(Γ, e_1, $\alpha \to \tau$)
    - Let σ_2 = infer($\sigma_1(\Gamma)$, e_2, $\sigma_1(\alpha)$)
    - Return σ_2 o σ_1

Type Inference Algorithm (cont)

- Case *exp* of
  - If e_1 then e_2 else e_3 -->
    - Let σ_1 = infer(Γ, e_1, bool)
    - Let σ_2 = infer($\sigma_1\Gamma$, e_2, $\sigma_1(\tau)$)
    - Let σ_3 = infer($\sigma_2 \circ \sigma_1(\Gamma)$,$e_3$,$\sigma_2 \circ \sigma_1$ (τ))
    - Return $\sigma_3 \circ \sigma_2 \circ \sigma_1$

Type Inference Algorithm (cont)

- Case *exp* of
  - let $x = e_1$ in e_2 -->
    - Let α be a fresh variable
    - Let σ_1 = infer(Γ, e_1, α)
    - Let σ_2 = infer([x:GEN($\sigma_1(\Gamma)$, $\sigma_1(\alpha)$)] + $\sigma_1(\Gamma)$, e_2, $\sigma_1(\tau)$)
    - Return $\sigma_2 \circ \sigma_1$

Type Inference Algorithm (cont)

- Case *exp* of
  - let rec $x = e_1$ in e_2 -->
    - Let α be a fresh variable
    - Let σ_1 = infer([x: α] + Γ, e_1, α)
    - Let σ_2 = Infer([x:GEN($\sigma_1(\Gamma)$,$\sigma_1(\alpha)$)] + $\sigma_1(\Gamma)$, e_2, $\sigma_1(\tau)$)
    - Return $\sigma_2 \circ \sigma_1$

Type Inference Algorithm (cont)

- To infer a type, introduce type_of
- Let α be a fresh variable
- type_of (Γ, *e*) =
  - Let σ = infer (Γ, *e*, α)
  - Return σ (α)

- Need an algorithm for Unif (next time)