Specialization

Concepts of Programming Languages

CAS CS 320

Outline

- Discuss **specialization** and how it relates to principal types
- Demo an implementation of **constraint-based type inference**
- Put the finishing touches on our discussion of type inference

Recap

Recall: Principal Types

$$\Gamma \vdash e : \tau \dashv \mathscr{C}$$

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i.e, the **principal type** of e (<u>note:</u> it may not exist). Every type we *could* give e is a *specialization* of $\forall \alpha_1, \ldots, \alpha_k . \mathscr{S}\tau$

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2. *Unification:* Solve $\mathscr{C}$ to get a most general unifier $\mathscr{S}$ (**TYPE ERROR** if this fails)

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3. *Generalization:* Quantify over the free variables in $\mathscr{S}\tau$ to get the principal type $\forall \alpha_1 \ldots \forall \alpha_k . \mathscr{S}\tau$ of e
4. Add $(x : \forall \alpha_1 \ldots \forall \alpha_k . \mathscr{S}\tau)$ to Γ

Recall: As a Type System

$$\frac{}{\Gamma \vdash \epsilon}\ \texttt{(emptyProg)}$$

$$\frac{\Gamma \vdash e : \tau \dashv \mathscr{C} \qquad \Gamma, x : \text{principal}(\tau, \mathscr{C}) \vdash P}{\Gamma \vdash \text{let } x = e\ P}\ \texttt{(topLet)}$$

We can also express this as a type system with judgments of the form $\Gamma \vdash P$, where P is a program (note there is no "$:$")

Recall: Example

```
let id = fun x -> x
let a = id (id 2 = 2)
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$\quad\vdash \varnothing \vdash$ `fun x -> x` $: \alpha \to \alpha \dashv \varnothing$ (...)

$\qquad\mid \ldots$ (...)

$\quad\vdash \{$`id` $: \forall \alpha . \alpha \to \alpha\} \vdash$ `let a = id (id 2 = 2)`

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... (...)

$\{$`id` $: \forall \alpha . \alpha \to \alpha$, `a` : `bool`$\} \vdash \epsilon$

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let id = fun x -> x
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$\varnothing \vdash$ `let id = fun x -> x let a = id (id 2 = 2)` (topLet)

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$\{$`id` $: \forall \alpha . \alpha \to \alpha\} \vdash$ `let a = id (id 2 = 2)` (topLet)

$\{$`id` $: \forall \alpha . \alpha \to \alpha\} \vdash$ `id (id 2 = 2)` $: \alpha \dashv \mathscr{C}$ (...)

... (...)

$\{$`id` $: \forall \alpha . \alpha \to \alpha$, `a` : `bool`$\} \vdash \epsilon$ (emptyProg)

Practice Problem

Show that let $f = \lambda x\,.\,x$ in $f\ (f\ 2 = 2)$ *has no principal type*

$\emptyset \vdash \text{let } f = \lambda x.\, x \text{ in } f\ (f\ 2 = 2) : \eta \dashv C$

$\emptyset \vdash \lambda x.\, x : \alpha \to \alpha \dashv \emptyset$

$\{x : \alpha\} \vdash x : \alpha \dashv \emptyset$

C

$\{f : \alpha \to \alpha\} \vdash f\ (f\ 2 = 2) : \eta \dashv \boxed{\alpha \to \alpha \doteq \text{bool} \to \eta,\ \beta \doteq \text{int},\ \alpha \to \alpha \doteq \text{int} \to \beta}$

$\{f : \alpha \to \alpha\} \vdash f : \alpha \to \alpha \dashv \emptyset$

Γ

$\{f : \alpha \to \alpha\} \vdash f\ 2 = 2 : \text{bool} \dashv \boxed{\beta} \doteq \boxed{\text{int}},\ \alpha \to \alpha \doteq \text{int} \to \beta$

$\Gamma \vdash f\ 2 : \boxed{\beta} \dashv \alpha \to \alpha \doteq \text{int} \to \beta$

$\Gamma \vdash f : \alpha \to \alpha \dashv \emptyset$

$\Gamma \vdash 2 : \text{int} \dashv \emptyset$

$\Gamma \vdash 2 : \boxed{\text{int}} \dashv \emptyset$

Practice Problem

Show that let $f = \lambda x\,.\,x$ in $f\,(f\;2 = 2)$ *has no principal type*

$$\boxed{\cancel{\alpha \to \alpha \doteq bool \to \eta},\ \cancel{\beta \doteq int},\ \cancel{\alpha \to \alpha \doteq int \to \beta}\ int}$$

(fun) (asgn) (func)

$\cancel{\alpha \doteq bool}$ (asgn)

$bool\ \cancel{\alpha} \doteq \eta$

$bool\ \cancel{\alpha} \doteq int$ ← ERROR

$bool\ \cancel{\alpha} \doteq int$

$\cancel{S = \{\ \beta \mapsto int,\ \alpha \mapsto bool}$

NO PRINCIPAL TYPE

Specialization

Recall: HM$^-$ (Syntax)

$$
\begin{aligned}
e ::= {} & \lambda x . e \mid ee \\
& \mid \text{let } x = e \text{ in } e \\
& \mid \text{if } e \text{ then } e \text{ else } e \\
& \mid e + e \mid e = e \\
& \mid n \mid x \\
\sigma ::= {} & \text{int} \mid \text{bool} \mid \alpha \mid \sigma \to \sigma \\
\tau ::= {} & \sigma \mid \forall \alpha . \tau
\end{aligned}
$$

Recall: HM$^-$ (Typing)

$$\frac{n \texttt{ is an integer}}{\Gamma \vdash n : \text{int} \dashv \varnothing}\ (\texttt{int})$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathscr{C}_1 \qquad \Gamma \vdash e_2 : \tau_2 \dashv \mathscr{C}_2 \qquad \Gamma \vdash e_3 : \tau_3 \dashv \mathscr{C}_3}{\Gamma \vdash \text{if } e_1 \text{ then } e_2 \text{ else } e_3 : \tau_3 \dashv \tau_1 \doteq \text{bool}, \tau_2 \doteq \tau_3, \mathscr{C}_1, \mathscr{C}_2, \mathscr{C}_3}\ (\texttt{if})$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathscr{C}_1 \qquad \Gamma \vdash e_2 : \tau_2 \dashv \mathscr{C}_2}{\Gamma \vdash e_1 = e_2 : \text{bool} \dashv \tau_1 \doteq \tau_2, \mathscr{C}_1, \mathscr{C}_2}\ (\texttt{eq})$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathscr{C}_1 \qquad \Gamma \vdash e_2 : \tau_2 \dashv \mathscr{C}_2}{\Gamma \vdash e_1 + e_2 : \text{int} \dashv \tau_1 \doteq \text{int}, \tau_2 \doteq \text{int}, \mathscr{C}_1, \mathscr{C}_2}\ (\texttt{add})$$

$$\frac{\alpha \texttt{ is fresh} \qquad \Gamma, x : \alpha \vdash e : \tau \dashv \mathscr{C}}{\Gamma \vdash \lambda x . e : \alpha \to \tau \dashv \mathscr{C}}\ (\texttt{fun})$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathscr{C}_1 \qquad \Gamma \vdash e_2 : \tau_2 \dashv \mathscr{C}_2 \qquad \alpha \texttt{ is fresh}}{\Gamma \vdash e_1 e_2 : \alpha \dashv \tau_1 \doteq \tau_2 \to \alpha, \mathscr{C}_1, \mathscr{C}_2}\ (\texttt{app})$$

Recall: HM$^-$ (Typing Variables)

$$\frac{(x : \forall \alpha_1 . \forall \alpha_2 \ldots \forall \alpha_k . \tau) \in \Gamma \qquad \beta_1, \ldots, \beta_k \text{ are fresh}}{\Gamma \vdash x : [\beta_1/\alpha_1] \ldots [\beta_k/\alpha_k]\tau \dashv \varnothing} \text{ (var)}$$

If x is declared in Γ, then x can be given the type τ *with all free variables replaced by* ***fresh variables***

This is where the polymorphism magic happens

Fresh variables can be unified with anything

An Alternative Formulation

$$\Gamma \vdash e : \tau$$

It's possible to give a type system for HM^- *without* constraints

It's very similar to the system from the first half of the course, but with some rules for dealing with **quantification** and **specialization**

HM^- (Alternative Typing)

$$\frac{n \texttt{ is an integer}}{\Gamma \vdash n : \mathsf{int}}\ \texttt{(int)}$$

$$\frac{\Gamma \vdash e_1 : \mathsf{bool} \qquad \Gamma \vdash e_2 : \tau \qquad \Gamma \vdash e_3 : \tau}{\Gamma \vdash \mathsf{if}\ e_1\ \mathsf{then}\ e_2\ \mathsf{else}\ e_3 : \tau}\ \texttt{(if)}$$

$$\frac{\Gamma \vdash e_1 : \tau \qquad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1 = e_2 : \mathsf{bool}}\ \texttt{(eq)}$$

$$\frac{\Gamma \vdash e_1 : \mathsf{int} \qquad \Gamma \vdash e_2 : \mathsf{int}}{\Gamma \vdash e_1 + e_2 : \mathsf{int}}\ \texttt{(add)}$$

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x\,.\,e : \tau_1 \to \tau_2}\ \texttt{(fun)}$$

$$\frac{\Gamma \vdash e_1 : \tau_2 \to \tau \qquad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau}\ \texttt{(app)}$$

$$\frac{\tau_1 \texttt{ is a monotype} \qquad \Gamma \vdash e_1 : \tau_1 \qquad \Gamma, x : \tau_1 \vdash e_2 : \tau_2}{\Gamma \vdash \mathsf{let}\ x = e_1\ \mathsf{in}\ e_2 : \tau_2}\ \texttt{(let)}$$

HM$^-$ (Alternative Typing)

familiar rules

$$\frac{n \texttt{ is an integer}}{\Gamma \vdash n : \mathsf{int}} \;(\texttt{int})$$

$$\frac{\Gamma \vdash e_1 : \mathsf{bool} \qquad \Gamma \vdash e_2 : \tau \qquad \Gamma \vdash e_3 : \tau}{\Gamma \vdash \mathsf{if}\ e_1\ \mathsf{then}\ e_2\ \mathsf{else}\ e_3 : \tau} \;(\texttt{if})$$

$$\frac{\Gamma \vdash e_1 : \tau \qquad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1 = e_2 : \mathsf{bool}} \;(\texttt{eq})$$

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$$\frac{\Gamma \vdash e_1 : \tau_2 \to \tau \qquad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau} \;(\texttt{app})$$

(no quantifiers)

$$\frac{\tau_1 \texttt{ is a monotype} \qquad \Gamma \vdash e_1 : \tau_1 \qquad \Gamma, x : \tau_1 \vdash e_2 : \tau_2}{\Gamma \vdash \mathsf{let}\ x = e_1\ \mathsf{in}\ e_2 : \tau_2} \;(\texttt{let})$$

Generalization and Specialization

not free

$$\frac{\Gamma \vdash e : \tau \qquad \alpha \ \texttt{not free in}\ \Gamma}{\Gamma \vdash e : \forall \alpha . \tau}\ \texttt{(gen)} \qquad \frac{(x : \tau) \in \Gamma \qquad \tau \sqsubseteq \tau'}{\Gamma \vdash x : \tau'}\ \texttt{(var)}$$

$$\dfrac{\dfrac{\dfrac{}{\{x : \alpha\} \vdash x : \alpha}}{\emptyset \vdash \lambda x . x : \alpha \to \alpha}}{\emptyset \vdash \lambda x . x : \forall \alpha . \alpha \to \alpha}$$

α is free

$$\dfrac{\{x : \alpha\} \vdash \cancel{x : \alpha}}{\{x : \alpha\} \vdash \cancel{x : \forall \alpha . \alpha}}$$

Generalization and Specialization

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The generalization rule allows us to create polymorphic types

Generalization and Specialization

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The generalization rule allows us to create polymorphic types

We also introduce a notion of **specialization** which allows us to *instantiate* polymorphic types at particular types

Generalization and Specialization

$$\{f : \forall\alpha.\alpha \to \alpha\} \vdash f : \mathrm{int} \to \mathrm{int}$$ more specific

$$\frac{\Gamma \vdash e : \tau \qquad \alpha \text{ not free in } \Gamma}{\Gamma \vdash e : \forall \alpha . \tau} \text{(gen)} \qquad \frac{(x : \tau) \in \Gamma \qquad \tau \sqsubseteq \tau'}{\Gamma \vdash x : \tau'} \text{(var)}$$

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"$\sqsubseteq$" defined a *partial order* on type schemes

Specialization (Informal)

$$\forall\alpha_1 \ldots \forall\alpha_m . \tau \sqsubseteq \forall\beta_1 \ldots \forall\beta_n . \tau'$$

A type scheme T_2 **specializes** T_1, written $T_1 \sqsubseteq T_2$ if T_2 the result of instantiating the bound variables of T_1 and generalizing over some of the variables introduced by the instantiation

$\forall\alpha . \alpha \to \alpha \sqsubseteq \forall\beta . (\beta \to int) \to (\beta \to int)$

$\sqsubseteq (bool \to int) \to (bool \to int)$

Specialization (Formal)

$$\frac{\tau_1, \ldots, \tau_m \text{ are monotypes} \quad \tau' = [\tau_m/\alpha_m]\ldots[\tau_1/\alpha_1]\tau \quad \beta_1, \ldots, \beta_n \notin \mathsf{FV}(\tau)\backslash\{\alpha_1, \ldots, \alpha_m\}}{\forall\alpha_1\ldots\forall\alpha_m\,.\,\tau \sqsubseteq \forall\beta_1\ldots\forall\beta_n\,.\,\tau'}$$

A *specialization* of a type scheme is an instantiation of its bound variable, together with some generalizations over remaining free variables

Examples

Examples

$$\forall \alpha . \forall \beta . \alpha \to \beta \to \alpha \sqsubseteq \forall \eta . \eta \to \mathsf{bool} \to \eta$$

$$\sqsubseteq \boxed{\mathsf{int}} \to \mathsf{bool} \to \boxed{\mathsf{int}}$$

Examples

$$\forall\alpha\,.\,\forall\beta\,.\,\alpha\to\beta\to\alpha \sqsubseteq \forall\eta\,.\,\eta\to\mathsf{bool}\to\eta$$
$$\sqsubseteq \mathsf{int}\to\mathsf{bool}\to\mathsf{int}$$

$$\forall\alpha\,.\,\forall\beta\,.\,\alpha\to\beta\to\alpha \sqsubseteq \forall\gamma\,.\,\mathsf{bool}\to(\gamma\to\gamma)\to\mathsf{bool}$$
$$\sqsubseteq \mathsf{bool}\to(\mathsf{int}\to\mathsf{int})\to\mathsf{bool}$$

Examples

$$\begin{aligned}\forall\alpha\,.\,\forall\beta\,.\,\alpha \to \beta \to \alpha &\sqsubseteq \forall\eta\,.\,\eta \to \mathsf{bool} \to \eta \\ &\sqsubseteq \mathsf{int} \to \mathsf{bool} \to \mathsf{int}\end{aligned}$$

$$\begin{aligned}\forall\alpha\,.\,\forall\beta\,.\,\alpha \to \beta \to \alpha &\sqsubseteq \forall\gamma\,.\,\mathsf{bool} \to (\gamma \to \gamma) \to \mathsf{bool} \\ &\sqsubseteq \mathsf{bool} \to (\mathsf{int} \to \mathsf{int}) \to \mathsf{bool}\end{aligned}$$

$$\begin{aligned}\forall\alpha\,.\,\forall\beta\,.\,\alpha \to \beta \to \alpha &\sqsubseteq \mathsf{bool} \to (\gamma \to \gamma) \to \mathsf{bool} \\ &\not\sqsubseteq \mathsf{bool} \to (\mathsf{int} \to \mathsf{int}) \to \mathsf{bool}\end{aligned}$$

Specialization and Principal Types

Specialization and Principal Types

Theorem. If $\Gamma \vdash e : \tau'$ then there is a type τ and constraints $\mathscr{C}$ such that $\Gamma \vdash e : \tau \dashv \mathscr{C}$ and $\underbrace{\text{principal}(\tau, \mathscr{C})}_{\text{more general}} \sqsubseteq \tau'$

Specialization and Principal Types

<u>Theorem.</u> If $\Gamma \vdash e : \tau'$ then there is a type τ and constraints $\mathscr{C}$ such that $\Gamma \vdash e : \tau \dashv \mathscr{C}$ and $\mathsf{principal}(\tau, \mathscr{C}) \sqsubseteq \tau'$

<u>Theorem.</u> If $\Gamma \vdash e : \tau \dashv \mathscr{C}$ and $\mathsf{principal}(\tau, \mathscr{C}) \sqsubseteq \tau'$ then $\Gamma \vdash e : \tau'$

Specialization and Principal Types

Theorem. If $\Gamma \vdash e : \tau'$ then there is a type τ and constraints $\mathscr{C}$ such that $\Gamma \vdash e : \tau \dashv \mathscr{C}$ and $\text{principal}(\tau, \mathscr{C}) \sqsubseteq \tau'$

Theorem. If $\Gamma \vdash e : \tau \dashv \mathscr{C}$ and $\text{principal}(\tau, \mathscr{C}) \sqsubseteq \tau'$ then $\Gamma \vdash e : \tau'$ also, if e has principal type τ, then $\Gamma \vdash e : \tau$

The principal type is the most general "lowest" type with respect to specialization

Example

$$\{f : \forall\alpha\,.\,\alpha \to \alpha\} \vdash f\ (f\ 2 = 2) : \mathsf{bool}$$

Exercise

Why use constraints at all?

$$\frac{(x : \tau) \in \Gamma \qquad \tau \sqsubseteq \tau'}{\Gamma \vdash x : \tau'} \ \texttt{(var)} \qquad \frac{(x : \forall \alpha_1 . \forall \alpha_2 \ldots \forall \alpha_k . \tau) \in \Gamma \qquad \beta_1, \ldots, \beta_k \ \texttt{are fresh}}{\Gamma \vdash x : [\beta_1/\alpha_1] \ldots [\beta_k/\alpha_k]\tau \dashv \varnothing} \ \texttt{(var)}$$

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The alternative type rules are theoretically nice but not *algorithmic*

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The alternative type rules are theoretically nice but not *algorithmic*

How do I choose which specialization to use in a derivation?

Why use constraints at all?

$$\frac{(x : \tau) \in \Gamma \qquad \tau \sqsubseteq \tau'}{\Gamma \vdash x : \tau'} \;\texttt{(var)} \qquad \frac{(x : \forall \alpha_1 . \forall \alpha_2 \ldots \forall \alpha_k . \tau) \in \Gamma \qquad \beta_1, \ldots, \beta_k \text{ are fresh}}{\Gamma \vdash x : [\beta_1/\alpha_1]\ldots[\beta_k/\alpha_k]\tau \dashv \varnothing} \;\texttt{(var)}$$

The alternative type rules are theoretically nice but not *algorithmic*

How do I choose which specialization to use in a derivation?

Constraints allow us to determine *which* specializations we should use *after the fact*

demo

(constraint-based inference)

HM^{-} (Typing Integers)

$$\frac{n \texttt{ is an integer}}{\Gamma \vdash n : \mathsf{int} \dashv \varnothing}\ (\texttt{int})$$

Recall: HM⁻ (Typing Addition)

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathscr{C}_1 \qquad \Gamma \vdash e_2 : \tau_2 \dashv \mathscr{C}_2}{\Gamma \vdash e_1 + e_2 : \textsf{int} \dashv \tau_1 \doteq \textsf{int}, \tau_2 \doteq \textsf{int}, \mathscr{C}_1, \mathscr{C}_2} \ (\texttt{add})$$

Recall: HM$^-$ (Typing Equality)

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathcal{C}_1 \qquad \Gamma \vdash e_2 : \tau_2 \dashv \mathcal{C}_2}{\Gamma \vdash e_1 = e_2 : \mathsf{bool} \dashv \tau_1 \doteq \tau_2, \mathcal{C}_1, \mathcal{C}_2} \text{ (eq)}$$

Recall: HM$^-$ (Typing If-Expressions)

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathcal{C}_1 \qquad \Gamma \vdash e_2 : \tau_2 \dashv \mathcal{C}_2 \qquad \Gamma \vdash e_3 : \tau_3 \dashv \mathcal{C}_3}{\Gamma \vdash \textsf{if } e_1 \textsf{ then } e_2 \textsf{ else } e_3 : \tau_3 \dashv \tau_1 \doteq \textsf{bool}, \tau_2 \doteq \tau_3, \mathcal{C}_1, \mathcal{C}_2, \mathcal{C}_3} \ \texttt{(if)}$$

HM⁻ (Typing Let-Expressions)

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathscr{C}_1 \qquad \Gamma, x : \tau_1 \vdash e_2 : \tau_2 \dashv \mathscr{C}_2}{\Gamma \vdash \textsf{let } x = e_1 \textsf{ in } e_2 : \tau_2 \dashv \mathscr{C}_1, \mathscr{C}_2} \;\texttt{(let)}$$

Recall: HM$^-$ (Typing Functions)

$$\frac{\alpha\ \texttt{is fresh} \qquad \Gamma, x : \alpha \vdash e : \tau \dashv \mathscr{C}}{\Gamma \vdash \lambda x \,.\, e : \alpha \to \tau \dashv \mathscr{C}}\ (\texttt{fun})$$

Recall: HM^{-} (Typing Applications)

$$\frac{\Gamma \vdash e_1 : \tau_1 \dashv \mathscr{C}_1 \qquad \Gamma \vdash e_2 : \tau_2 \dashv \mathscr{C}_2 \qquad \alpha \texttt{ is fresh}}{\Gamma \vdash e_1 e_2 : \alpha \dashv \tau_1 \doteq \tau_2 \to \alpha, \mathscr{C}_1, \mathscr{C}_2} \ (\texttt{app})$$

Recall: HM$^-$ (Typing Variables)

$$\frac{(x : \forall \alpha_1 . \forall \alpha_2 \ldots \forall \alpha_k . \tau) \in \Gamma \qquad \beta_1, \ldots, \beta_k \texttt{ are fresh}}{\Gamma \vdash x : [\beta_1/\alpha_1] \ldots [\beta_k/\alpha_k]\tau \dashv \varnothing} \; (\texttt{var})$$

Summary

The **principal type** of an expression is the most general type we could give it

Specialization defines a partial ordering on type schemes from most to least general

Our unification algorithm gives us a most general unifier, which will always give us the principal type of an expression