Specialization

Concepts of Programming Languages
Lecture 24

CAS CS 320

Outline

- Discuss **specialization** and how it relates to principle types

- Demo an implementation of **constraint-based type inference**

- Put the finishing touches on our discussion of type inference

Recap

Recall: Principle Types

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

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

Recall: Putting everything together

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FOR EACH top-level let-expression $\text{let } x = e$ in P:

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3. *Generalization:* Quantify over the free variables in $\mathscr{S}\tau$ to get the principle 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

Example

Determine the principle type of $\lambda f.\lambda x.f\,x+1$

1 Inference

$$\cdot \vdash \lambda f.\ \lambda x.\ f\ x + 1 \dashv \overset{\tau}{\boxed{\alpha \to \beta \to \gamma}} \dashv \mathcal{C}$$

$$\{f : \alpha\} \vdash \lambda x.\ f\ x + 1 : \beta \to \gamma \dashv \mathcal{C}$$

$$\{f : \alpha,\ x : \beta\} \vdash f\ x + 1 : int \dashv \overset{\mathcal{C}}{\boxed{\gamma \doteq int,\ int \doteq int,\ \alpha \doteq \beta \to \gamma}}$$

$$\{f : \alpha, x : \beta\} \vdash f\ x : \gamma \dashv \alpha \doteq \beta \to \gamma$$

$$\{f : \alpha,\ x : \beta\} \vdash f : \alpha \dashv \emptyset$$

$$\{f : \alpha,\ x : \beta\} \vdash x : \beta \dashv \emptyset$$

$$\{f : \alpha, x : \beta\} \vdash 1 : int \dashv \emptyset$$

Example

Determine the principle type of $\lambda f.\lambda x.f\,x+1$

C

② Unification

$$\boxed{\gamma \doteq int,\ int \doteq int,\ \alpha \doteq \beta \to \gamma}$$

$\cancel{\gamma \doteq int}$ v≐t

$\cancel{int \doteq int}$ eq

$\cancel{\alpha \doteq \beta \to \cancel{\gamma}\ int}$ v≐t

$$\boxed{S = \{\gamma \mapsto int,\ \alpha \mapsto \beta \to int\}}$$

$S_T =$

$S(\alpha \to \beta \to \gamma) =$

$[\boxed{\beta \to int}/\alpha][\boxed{int}/\gamma](\alpha \to \beta \to \gamma) =$

$(\beta \to int) \to \beta \to int$

③ Generalization

$\forall \alpha_1 \ldots \alpha_k .\ S_T$ where $FV(S_T) = \{\alpha_1, \ldots \alpha_k\}$

$$\boxed{\text{Principle Type: } \forall \beta.\,(\beta \to int) \to \beta \to int}$$

Example

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

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

T

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

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

$\{f : \alpha \to \alpha\} \vdash f\ (f\ 2 = 2) : \gamma \dashv$

C

$\alpha \to \alpha \doteq bool \to \gamma,\ \beta \doteq int,$
$\alpha \to \alpha \doteq int \to \beta$

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

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

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

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

$\{f : \alpha \to \alpha\} \vdash 2 : int \dashv \emptyset$

$\{f : \alpha \to \alpha\} \vdash 2 : int \dashv \emptyset$

Example

Show that $\mathsf{let}\ f = \lambda x\,.\,x\ \mathsf{in}\ f\ (f\ 2 = 2)$ *has no principle type*

C

$$\boxed{\begin{array}{l}\alpha \to \alpha \doteq \mathsf{bool} \to \gamma,\ \beta \doteq \mathsf{int} \\ \qquad\qquad\qquad \alpha \to \alpha \doteq \mathsf{int} \to \beta\end{array}}$$

$\cancel{\alpha \to \alpha \doteq \mathsf{bool} \to \gamma}$ funty $\doteq$ funty

$\cancel{\beta \doteq \mathsf{int}}$ $v \doteq t$

$\cancel{\alpha \to \alpha \doteq \mathsf{int} \to \cancel{\beta}\ \mathsf{int}}$ funty $\doteq$ funty

$\cancel{\alpha \doteq \mathsf{bool}}$ $v \doteq t$

$\cancel{\mathsf{bool}\ \cancel{\alpha} \doteq \gamma}$ $t \doteq v$

$\boxed{\mathsf{bool}\ \cancel{\alpha} \doteq \mathsf{int}}$ $\mathsf{bool}\ \cancel{\alpha} \doteq \cancel{\beta}\ \mathsf{int}$

UNIFICATION FAILURE

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

Specialization

Recall: HM$^-$ (Syntax)

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

Recall: HM^{-} (Typing)

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

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

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

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

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

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

Recall: $\mathbf{HM}^{-}$ (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 our 320Caml system, but with some rules for dealing with **quantification** and **specialization**

HM$^-$ (Alternative Typing)

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

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

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

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

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

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

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

HM$^-$ (Alternative Typing)

familiar rules

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

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

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2 \dashv \mathscr{C}}{\Gamma \vdash \lambda x . e : \tau_1 \to \tau_2 \dashv \mathscr{C}}\ (\texttt{fun}) \qquad \frac{\Gamma \vdash e_1 : \tau_2 \to \tau \qquad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau}\ (\texttt{app})$$

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Generalization and Specialization

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

Generalization and Specialization

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The generalization rule is like the one from System F

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<u>The main difference:</u> we introduce a notion of **specialization** which allows us to *instantiate* polymorphic functions at particular types

"$\sqsubseteq$" 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

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

$$\sqsubseteq \forall \gamma . \forall \beta . (\gamma \to \gamma) \to \beta$$

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

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

Examples

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

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

$$\sqsubseteq \forall\gamma.\forall\varepsilon.\forall\beta\,.\,\alpha \to (\gamma \to \varepsilon) \to \alpha \sqsubseteq$$

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

$$\sqsubseteq \mathsf{bool} \to (\mathsf{int} \to \mathsf{int}) \to \mathsf{bool}$$

Examples

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

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

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

$\forall\alpha.\,\alpha \sqsubseteq T$

Specialization and Principle Types

Specialization and Principle 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 $\mathsf{principle}(\tau, \mathscr{C}) \sqsubseteq \tau'$

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Specialization and Principle 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 $\text{principle}(\tau, \mathscr{C}) \sqsubseteq \tau'$

at least a general as τ'

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

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

Example

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

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

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

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

Why use constraints at all?

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

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)

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

Recall: HM⁻ (Typing Equality)

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

Recall: HM⁻ (Typing If-Expressions)

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

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 **principle 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 principle type of an expression