fun ty (IFX (e1, e2, e3)) =
  if eqType (ty e1, booltype) then
    let val (t2, t3) = (ty e2, ty e3)
    in ... YOU FILL IN 1 ... end
  else
    ... YOU FILL IN 2 ...
  end

| ty (SET (x, e)) =
  let val tau_x = find (x, Gamma)
    val tau_e = ty e
  in ... YOU FILL IN 3 ... end
Typechecking review, part II

fun ty (APPLY (f, actuals)) =
  let val atys = map ty actuals
  in  case ty f
       of FUNTY (formals, result) =>
           if eqTypes (atys, formals) then
               ... YOU FILL IN 4 ...
           else
               ... YOU FILL IN 5 ...
               | _ => ... YOU FILL IN 6 ...
       end
Monomorphic types are limiting

Each new type constructor requires

• Special syntax
• New type rules
• New internal representation (type formation)
• New code in type checker (intro, elim)
• New or revised proof of soundness
Monomorphic burden: Array types

**Formation:**

\[ \tau \text{ is a type} \]

\[ \text{ARRAY}(\tau) \text{ is a type} \]

**Introduction:**

\[ \Gamma \vdash e_1 : \text{INT} \quad \Gamma \vdash e_2 : \tau \]

\[ \Gamma \vdash \text{AMAKE}(e_1, e_2) : \text{ARRAY}(\tau) \]

**Elimination:**

\[ \Gamma \vdash e_1 : \text{ARRAY}(\tau) \quad \Gamma \vdash e_2 : \text{INT} \quad \Gamma \vdash e_3 : \tau \]

\[ \Gamma \vdash \text{AAT}(e_1, e_2) : \tau \]

\[ \Gamma \vdash e_1 : \text{ARRAY}(\tau) \quad \Gamma \vdash e_2 : \text{INT} \quad \Gamma \vdash e_3 : \tau \]

\[ \Gamma \vdash \text{APUT}(e_1, e_2, e_3) : \tau \]

\[ \Gamma \vdash e : \text{ARRAY}(\tau) \]

\[ \Gamma \vdash \text{ASIZE}(e) : \text{INT} \]
Monomorphism hurts programmers too

Monomorphism leads to code duplication

User-defined functions are monomorphic:

(define int lengthI ([xs : (list int)]))
  (if (null? xs) 0 (+ 1 (lengthI (cdr xs)))))
(define int lengthB ([xs : (list bool)]))
  (if (null? xs) 0 (+ 1 (lengthB (cdr xs)))))
(define int lengthS ([xs : (list sym)]))
  (if (null? xs) 0 (+ 1 (lengthS (cdr xs)))))
Quantified types

Heart of polymorphism: $\forall \alpha_1, \ldots, \alpha_n . \tau$.

In Typed $\mu$Scheme: (forall ('a1 ... 'an) type)

Two ideas:

- Type variable 'a stands for an unknown type
- Quantified type (with forall) enables substitution

```
length : $\forall \alpha . \alpha$ list $\rightarrow$ int
cons   : $\forall \alpha . \alpha \times \alpha$ list $\rightarrow$ $\alpha$ list
car    : $\forall \alpha . \alpha$ list $\rightarrow$ $\alpha$
cdr    : $\forall \alpha . \alpha$ list $\rightarrow$ $\alpha$ list
'()     : $\forall \alpha . \alpha$ list
```
“Type variable”???

Back up here—what types do we have?
Type formation: Composing types

Typed Impcore:
- Closed world (no new types)
- Simple formation rules

Typed $\mu$-Scheme:
- Semi-closed world (new type variables)
- How are types formed (from other types)?

Standard ML:
- Open world (programmers create new types)
- How are types formed (from other types)?

Can’t add new syntactic forms and new type formation rules for every new type.
Representing type constructors generically

Start with monomorphic fragment (Typed $\mu$Scheme):

datatype tyex
    = TYCON of name
    | CONAPP of tyex * tyex list
    | FUNTY of tyex list * tyex (* I’m special *)

Examples: bool, (list int), (int int -> bool)

    TYCON "bool"
    CONAPP (TYCON "list", [TYCON "int"])
    CONAPP (FUNTY [TYCON "int", TYCON "int"],
            TYCON "bool")

Hard to read, but easy to write code for.
Question: How would you represent an array of pairs of booleans?

datatype tyex
  = TYCON of name
  | CONAPP of tyex * tyex list
  | FUNTY of tyex list * tyex

( bool * bool ) array ML
(array (pair bool bool)) Typed μScheme
Question: How would you represent an array of pairs of booleans?

datatype tyex
   = TYCON of name
   | CONAPP of tyex * tyex list
   | FUNTY of tyex list * tyex

( bool * bool) array  ML
(array (pair bool bool)) Typed μScheme

   CONAPP (TYCON "array",
      [ CONAPP (TYCON "pair",
               [TYCON "bool", TYCON "bool"])
      ])

Well-formed types

We still need to classify type expressions into:

- types that classify terms (e.g., `int`)
- type constructors that build types (e.g., `list`)
- nonsense that means nothing (e.g., `int int`)

Idea: kinds classify types

\[ \Delta \vdash \tau :: \kappa \quad \text{“Type } \tau \text{ has kind } \kappa \text{”} \]

\[ \Delta \vdash \tau :: * \quad \text{Special case: “} \tau \text{ is a type”} \]

Replaces one-off type-formation rules

*Kind environment* \( \Delta \) tracks type constructors, vars
Return to quantified types

Heart of polymorphism: $\forall \alpha_1, \ldots, \alpha_n . \tau$.

In Typed $\mu$Scheme: (forall (’a1 ... ’an) type)

Two ideas:

- Type variable ’a stands for an unknown type
- Quantified type (with forall) enables substitution

\[
\begin{align*}
\text{length} & : \forall \alpha . \alpha \text{ list } \rightarrow \text{ int} \\
\text{cons} & : \forall \alpha . \alpha \times \alpha \text{ list } \rightarrow \alpha \text{ list} \\
\text{car} & : \forall \alpha . \alpha \text{ list } \rightarrow \alpha \\
\text{cdr} & : \forall \alpha . \alpha \text{ list } \rightarrow \alpha \text{ list} \\
\text{'}() & : \forall \alpha . \alpha \text{ list}
\end{align*}
\]
Representing quantified types

Two new alternatives for \texttt{tyex}:

datatype \texttt{tyex}
\begin{verbatim}
    = TYCON of name
| CONAPP of tyex * tyex list
| FUNTY of tyex list * tyex
| TYVAR of name
| FORALL of name list * tyex
\end{verbatim}
Formation rules for quantified types

Reminder: $\Delta \vdash \tau :: *$ means “$\tau$ is a type”

$$
\Delta \{\alpha_1 :: *, \ldots, \alpha_n :: *\} \vdash \tau :: *
$$

($\text{KindAll}$)

$$
\Delta \vdash \text{FORALL}([\alpha_1, \ldots, \alpha_n], \tau) :: *
$$

($\text{KindIntroVar}$)

$$
\alpha \in \text{dom} \Delta \\
\Delta \vdash \text{TYVAR}(\alpha) :: \Delta(\alpha)
$$
Programming with quantified types

Substitute for quantified variables

-> length
<procedure> : (forall ('a) ((list 'a) -> int))
-> (@ length int)
<procedure> : ((list int) -> int)
-> (length '(1 2 3))
type error: function is polymorphic; instantiate before applying
-> (((@ length int) '(1 2 3))
3 : int
Substitute what you like

-> length
<procedure> : (forall ('a) ((list 'a) -> int))
-> (@ length bool)
<procedure> : ((list bool) -> int)
-> ((@ length bool) '(#t #f))
2 : int
More “Instantiations”

-> (val length-int (@ length int))
length-int : ((list int) -> int)

-> (val cons-bool (@ cons bool))
cons-bool : ((bool (list bool)) -> (list bool))

-> (val cdr-sym (@ cdr sym))
cdr-sym : ((list sym) -> (list sym))

-> (val empty-int (@ '() int))
() : (list int)
Create your own!

Abstract over unknown type using type-lambda

\[ (\text{val id (type-lambda } [\text{'a}] \negrightarrow \text{ (lambda } ([\text{x : \text{'a}}]) \text{ x })) \text{) ) \]

\[ \text{id : (forall } (\text{'a}) (\text{'a }\negrightarrow \text{'a})) \]

\text{'a is type parameter (an } \text{unknown} \text{ type)}

This feature is parametric polymorphism
Power comes at notational cost

Function composition

\[ \to \ (\text{val} \ o \ (\text{type-lambda} \ ['a \ 'b \ 'c] \ (\lambda ([f \ : \ ('b \to \ 'c)] \ [g \ : \ ('a \to \ 'b)]) \ (\lambda ([x \ : \ 'a]) \ (f \ (g \ x)))))) \]

\[ o : (\forall ('a \ 'b \ 'c) \ ((('b \to \ 'c) ('a \to \ 'b) \to ('a \to \ 'c))) \]

Aka \( o : \forall \alpha, \beta, \gamma . (\beta \to \gamma) \times (\alpha \to \beta) \to (\alpha \to \gamma) \)
Instantiate by substitution

∀ elimination:

- Concrete syntax \((@ e \tau_1 \cdots \tau_n)\)
- Rule (note new judgment form \(\Delta, \Gamma \vdash e : \tau\)):

\[
\Delta, \Gamma \vdash e : \forall \alpha_1, \ldots, \alpha_n. \tau
\]

\[
\Delta, \Gamma \vdash \text{TYAPPLY}(e, \tau_1, \ldots, \tau_n) : \tau[\alpha_1 \mapsto \tau_1, \ldots, \alpha_n \mapsto \tau_n]
\]

Substitution is in the book as function \(\text{tysubst}\)

(Also in the book: \(\text{instantiate}\))
Generalize with type-lambda

∀ introduction:
  • Concrete syntax \texttt{(type-lambda $[\alpha_1 \cdots \alpha_n] e$)}
  • Rule:

\[
\Delta\{\alpha_1 :: *, \ldots, \alpha_n :: *\}, \Gamma \vdash e : \tau \\
\alpha_i \not\in \text{ftv}(\Gamma), \quad 1 \leq i \leq n\\n\hline
\Delta, \Gamma \vdash \text{TYLAMBDA}(\alpha_1, \ldots, \alpha_n, e) : \forall \alpha_1, \ldots, \alpha_n. \tau
\]

\textit{(FORALL INTRODUCTION)}

\Delta \text{ is kind environment (remembers } \alpha_i \text{'s are types)}
A phase distinction embodied in code

-> (val x 3)
3 : int
-> (val y (+ x x))
6 : int

fun processDef (d, (delta, gamma, rho)) =
  let val (gamma', tystring) = elabdef (d, gamma, delta)
    val (rho', valstring) = evaldef (d, rho)
    val _ = print (valstring ^ " : " ^ tystring)
in  (delta, gamma', rho')
end
Return to well-formed types

To classify type expressions into:
- **types** that classify terms (e.g., `int`)
- **type constructors** that build types (e.g., `list`)
- **nonsense** that means nothing (e.g., `int int`)

Use judgment

\[ \Delta \vdash \tau :: \kappa \]
Type formation through kinds

Each type constructor has a kind.

Type constructors of kind \( \star \) classify terms

\((\text{int} :: \star, \text{bool} :: \star)\)

\[ \star \text{ is a kind} \]

Type constructors of arrow kinds are “types in waiting”

\((\text{list} :: \star \Rightarrow \star, \text{pair} :: \star \times \star \Rightarrow \star)\)

\[ \kappa_1, \ldots, \kappa_n \text{ are kinds} \quad \kappa \text{ is a kind} \]

\[ \kappa_1 \times \cdots \times \kappa_n \Rightarrow \kappa \text{ is a kind} \]

(KINDFORMATION Arrow)

(KINDFORMATION Type)
Use kinds to give arities

Examples: int :: *, list :: * ⇒ *, pair :: * × * ⇒ *

Non-Examples: int int and bool × list have no kind because they are nonsense.

Kinds classify type expressions just as types classify terms
The kinding judgment

\[ \Delta \vdash \tau :: \kappa \quad \text{“Type } \tau \text{ has kind } \kappa \text{”} \]

\[ \Delta \vdash \tau :: * \quad \text{Special case: “} \tau \text{ is a type”} \]

Replaces one-off type-formation rules

*Kind environment* $\Delta$ tracks type constructor names and kinds.
Kinding rules for types

\[ \mu \in \text{dom } \Delta \]
\[ \Delta(\mu) = \kappa \]
\[ \Delta \vdash \text{TYCON}(\mu) :: \kappa \]  \hspace{1cm} (\text{KINDINTROCON})

\[ \Delta \vdash \tau :: \kappa_1 \times \cdots \times \kappa_n \Rightarrow \kappa \]
\[ \Delta \vdash \tau_i :: \kappa_i, \hspace{1cm} 1 \leq i \leq n \]
\[ \Delta \vdash \text{CONAPP}(\tau, [\tau_1, \ldots, \tau_n]) :: \kappa \]  \hspace{1cm} (\text{KINDAPP})

These two rules replace all formation rules.

(Check out book functions kindaof and asType)
Kinds of primitive type constructors

\( \Delta(\text{int}) = * \)

\( \Delta(\text{bool}) = * \)

\( \Delta(\text{list}) = * \Rightarrow * \)

\( \Delta(\text{option}) = * \Rightarrow * \)

\( \Delta(\text{pair}) = * \times * \Rightarrow * \)

\( \Delta(\text{queue}) = \text{You fill in} \)

\( \Delta(\text{unit}) = \text{You fill in} \)
Three environments — what happens?

\[ \Delta \] maps names (of tycons and tyvars) to kinds
\[ \Gamma \] maps names (of variables) to types
\[ \rho \] maps names (of variables) to values or locations

New val def
val x = 33

New type def
type 'a transformer = 'a -> 'a

New datatype def
datatype color = RED | GREEN | BLUE
Three environments revealed

\(\Delta\) maps names (of tycons and tyvars) to kinds
\(\Gamma\) maps names (of variables) to types
\(\rho\) maps names (of variables) to values or locations

New val def modifies \(\Gamma, \rho\)
\[
\text{val } x = 33 \text{ means } \Gamma\{x : \text{int}\}, \rho\{x \mapsto 33\}
\]

New type def modifies \(\Delta\)
\[
\text{type } 'a \text{ transformer} = 'a \text{ list } \ast 'a \text{ list}
\text{means } \Delta\{\text{transformer} :: \ast \Rightarrow \ast\}
\]

New datatype def modifies \(\Delta, \Gamma, \rho\)
\[
\text{datatype color} = \text{RED } | \text{ GREEN } | \text{ BLUE}
\text{means } \Delta\{\text{color} :: \ast\}, \Gamma\{\text{RED} : \text{color}, \text{GREEN} : \text{color}, \text{BLUE} : \text{color}\}, \\
\rho\{\text{RED} \mapsto 0, \text{GREEN} \mapsto 1, \text{BLUE} \mapsto 2\}
Exercise: Three environments

datatype ‘a tree
    = NODE of ‘a tree * ‘a * ‘a tree
    | EMPTY

means
\(\Delta\{\text{tree} \mapsto \ast \Rightarrow \ast\}\),
\(\Gamma\{\text{NODE} \mapsto \forall \text{‘a} . \ \text{‘a tree} \ast \text{‘a} \ast \text{‘a tree} \rightarrow \text{‘a tree},\)
    \(\ \text{EMPTY} \mapsto \forall \text{‘a} . \ \text{‘a tree}\},\)
\(\rho\{\text{NODE} \mapsto \lambda(l,x,r) . \cdots , \text{EMPTY} \mapsto 1\}\)