Motivation for Universal Types

Lack of code reuse!

Example:

\[
\begin{align*}
doubleNat &= \lambda f : \text{Nat} \to \text{Nat}. f (f (x)) \\
doubleBool &= \lambda f : \text{Bool} \to \text{Bool}. f (f (x)) \\
doubleFun &= \lambda f : (\text{Nat} \to \text{Nat}) \to (\text{Nat} \to \text{Nat}). f (f (x))
\end{align*}
\]

Properties of Let Polymorphism

- allows for easy type reconstruction
- restricted to the let construct
- problems with references
  (restricted to values on the RHS of \(=\)).

Idea of Universal Types

Abstract over type!

\[
\begin{align*}
double &= \lambda X. \lambda f : X \to X. \lambda x : X. f (f (x)) \\
&> double : \forall X. (X \to X) \to X \to X \\
double [\text{Nat}] \\
&> \text{<fun>} : (\text{Nat} \to \text{Nat}) \to \text{Nat} \to \text{Nat} \\
double [\text{Bool}] \\
&> \text{<fun>} : (\text{Bool} \to \text{Bool}) \to \text{Bool} \to \text{Bool}
\end{align*}
\]
**Evaluation (Type Abstraction/Application)**

\[
\frac{t_1 \rightarrow t'_1}{t_1[T_2] \rightarrow t'_1[T_2]} \quad \text{(E-TApp)}
\]

\[
\frac{(\lambda X. t) [T] \rightarrow [X \mapsto T] t}{(\lambda X. t)\ [T] \rightarrow [X \mapsto T] t} \quad \text{(E-TAppTAbs)}
\]

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**Example: Identity Function**

Creating the polymorphic identity function:

\[
\text{id} = \lambda X. \lambda x : X. x
\]

\[
> \text{id} : \forall X. X \rightarrow X
\]

Using the polymorphic identity function:

\[
\text{id} [\text{Nat}]
\]

\[
> <\text{fun}> : \text{Nat} \rightarrow \text{Nat}
\]

\[
\text{id} [\text{Bool}] \text{ true}
\]

\[
> \text{true} : \text{Bool}
\]

---

**Typing (Type Abstraction/Application)**

\[
\frac{\Gamma, X \vdash t : T}{\Gamma \vdash \lambda X. t : \forall X. T} \quad \text{(T-TAbs)}
\]

\[
\frac{\Gamma \vdash t_1 : \forall X. T_1}{\Gamma \vdash t_1[T_2] : [X \mapsto T_2] T_1} \quad \text{(T-TApp)}
\]

---

**Example: Self-Application**

We can apply a function to itself (in System F). Define

\[
\text{selfApp} = \lambda x : \forall X. X \rightarrow X. (x [\forall X. X \rightarrow X]) x
\]

\[
> \text{selfApp} : (\forall X. X \rightarrow X) \rightarrow (\forall X. X \rightarrow X)
\]

One use of self-application is:

\[
\text{quadruple} = \text{selfApp double}
\]

\[
> \text{quadruple} : \forall X. (X \rightarrow X) \rightarrow (X \rightarrow X)
\]

Exercise: show that above is the same as:

\[
\text{quadruple} = \lambda X. \text{double} [X \mapsto X] \text{ (double [X])}
\]
Example: Polymorphic List

Assume that type constructor List is given with the following primitives:

- `nil : ∀ X. List X`
- `cons : ∀ X. X → List X → List X`
- `isnil : ∀ X. List X → Bool`
- `head : ∀ X. List X → X`
- `tail : ∀ X. List X → List X`

System F: Soundness Properties

Preservation Theorem:

\[
\text{If } \Gamma \vdash t : T \text{ and } t \rightarrow t' \text{ then } \Gamma \vdash t' : T
\]

Progress Theorem

If \( t \) is a closed well-typed term, then either \( t \) is a value or else there is some \( t' \) with \( t \rightarrow t' \).

Example: Map

With the help of `fix`, we can write a polymorphic map operation, as follows:

\[
\text{map} = \lambda X. \lambda Y. \lambda f : X \rightarrow Y.
\text{fix} (\lambda m : (\text{List} X) \rightarrow (\text{List} Y).
\lambda l : \text{List} X.
\text{if isnil} [X] l \text{ then nil} [Y]
\text{else} \text{cons} [Y] (f (\text{head} [X] l))
\text{(m (tail} [X] l)))
\]

> \text{map} : ∀X. ∀Y. (X \rightarrow Y) \rightarrow \text{List} X \rightarrow \text{List} Y

System F: Normalisation

A term is normalizing if there is no infinite evaluation

\[
t \rightarrow t_1 \rightarrow t_2 \rightarrow t_3 \rightarrow \ldots
\]

Well-typed System F terms (without the fix-point operator) are normalizing.
**System F: Historical Background**

- Discovered by Jean-Yves Girard in 1972 for proof theory.
- Independently developed by John Reynolds 1974 as *polymorphic lambda calculus*.
- Normalization: quite innovative inductive proof technique due to Tait (1968) and Girard (1972).
- Type reconstruction: was open problem until 1994!

**Undecidability of Type Reconstruction for System F.**

Wells 1994: it is **undecidable** when given a closed term $m$ of the untyped lambda calculus, if there is some well-typed term $t$ in System F such that $\text{erase}(t) = m$.

The type erasure operation is defined as:

\[
\begin{align*}
\text{erase}(x) &= x \\
\text{erase}(\lambda. x : T. t) &= \lambda. x. \text{erase}(t) \\
\text{erase}(t_1 t_2) &= \text{erase}(t_1) \text{erase}(t_2) \\
\text{erase}(\lambda. x : X. t) &= \text{erase}(t) \\
\text{erase}(t[T]) &= \text{erase}(t)
\end{align*}
\]

**What to do with Undecidability?**

Restrict the language:

- let polymorphism of ML, rank-2 polymorphism, etc.

Partial Type Reconstruction:

- correct but incomplete approaches such as local type inference, greedy type inference, etc.

**Parametricity**

Polymorphic programs operate uniformly over any input, independently of their type.

Language implementations benefit from this *parametricity* by generating only one machine code version for polymorphic functions. Also, certain theorems come for free.

At runtime, type application does not result in any computation. This is exemplified by OCaml’s let polymorphism, where no type application is needed.
**Motivation for Existential Type**

We emphasize the operational reading, supported by the notation:

\[
\{ \exists X, T \}
\]

Terms of such type have the form:

\[
\{ *S, t \}
\]

We call such terms “modules” with the hidden type \(S\) and the term component \(t\).

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**Example**

The term

\[
\{ *\text{Nat}, \{a=5, f=\lambda x:\text{Nat. succ}(x)\} \}
\]

has type

\[
\{ \exists X, \{a:X,f:X \to X\} \}
\]

but it may also have type:

\[
\{ \exists X, \{a:X,f:X \to \text{Nat}\} \}
\]

Solution: use ascription to force a unique type for module.

\[
\{ *\text{Nat}, \{a=5, f=\lambda x:\text{Nat. succ}(x)\} \} \text{ as } \{ \exists X, \{a:X,f:X \to X\} \}
\]

---

**Elements of Existential Types**

The hidden type of different elements can be different.

\[
p4 = \{ *\text{Nat}, \{a=5, f=\lambda x:\text{Nat. succ}(x)\} \} \text{ as } \{ \exists X, \{a:X,f:X \to \text{Nat}\} \}
\]

\[
p5 = \{ *\text{Bool}, \{a=\text{true}, f=\lambda x:\text{Bool. 0}\} \} \text{ as } \{ \exists X, \{a:X,f:X \to \text{Nat}\} \}
\]

In effect, the module type is parameterised over the internal type. Elements of existential types use internal types, but these are not visible where the elements are used.

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**Violations of Abstraction**

We must not make assumption about internal type, nor could it be exposed to a location out of its scope.

\[
\text{let } \{X,x\}=p4 \text{ in succ}(x.a)
\]

> Error: argument of succ is not a number.

\[
\text{let } \{X,x\}=p4 \text{ in } x.a
\]

> Error: scoping error!

where:

\[
p4 = \{ *\text{Nat}, \{a=5, f=\lambda x:\text{Nat. succ}(x)\} \} \text{ as } \{ \exists X, \{a:X,f:X \to \text{Nat}\} \}
\]
Syntax of Existential Types

- \( t ::= \ldots \)
  - \( \{*T, t\} \) as \( T \)
  - let \( \{X, x\} = t \) in \( t \)

- \( v ::= \ldots \)
  - \( \{*T, v\} \) as \( T \)
  - package value

- \( T ::= \ldots \)
  - \( \{X, T\} \)
  - existential type

Typing Rules

\[
\Gamma \vdash t : [X \mapsto U] T \\
\vdash \{U, t\} \text{ as } \{\exists X, T\} : \{\exists X, T\} \quad (T\text{-Pack})
\]

\[
\Gamma \vdash t_1 : \{X, T\} \quad \Gamma, X, x : T_1 \vdash t_2 : T_2 \\
\vdash \text{let } \{X, x\} = t_1 \text{ in } t_2 : T_2 \quad (T\text{-Unpack})
\]

Evaluation Rules

\[
t \rightarrow t' \\
\vdash \{U, t\} \rightarrow \{U, t'\} \quad \text{(E-Pack)}
\]

\[
t_1 \rightarrow t_1' \\
\vdash \text{let } \{X, x\} = t_1 \text{ in } t_2 \rightarrow \text{let } \{X, x\} = t_1' \text{ in } t_2 \\
\vdash \text{let } \{X, x\} = \{U, v\} \text{ in } t \rightarrow [X \mapsto T, x \mapsto v] t \quad \text{(E-Unpack)}
\]

Abstract Data Types

ADT counter =
- type Counter
- representation Nat
- signature
  - new : Counter,
  - get : Counter \rightarrow Nat,
  - inc : Counter \rightarrow Counter;
- operations
  - new = 1;
  - get = \lambda i : \text{Nat. } i
  - inc = \lambda i : \text{Nat. } \text{succ}(i)
Translation using Existential Types

counterADT =
{*Nat,
  {new = 1,
   get = \lambda i:Nat. i
   inc = \lambda i:Nat. succ(i) } }
as { \exists Counter,
  {new : Counter,
    get : Counter \rightarrow Nat,
    inc : Counter \rightarrow Counter} }

> counterADT : { \exists Counter, {new : Counter,
                                get : Counter \rightarrow Counter, inc : Counter \rightarrow Counter}}

Using Abstract Data Types

let {Counter,ctr} = counterADT in
ctr.get (ctr.inc ctr.new)
> 2 : Nat

let add3 = \lambda c:Counter.
ctr.inc(ctr.inc(ctr.inc c)) in ctr.get(add3 ctr.new)
> 4 : Nat

Structure of Programs using ADTs

Each ADT can use all previously declared ADTs.

let {ADT,m1} = <ADT1 package> in
let {ADT,m2} = <ADT2 package> in
...
let {ADT,mn} = <ADTn package> in

<main program>

Representation Independence

Abstract data type enjoy representation independence. They can be replaced by alternative implementations without affecting the rest of the programs, as long as the existential type is not modified. Example:

counterADT =
{* {x:Nat},
  {new = {x=1},
    get = \lambda i: {x:Nat}. i.x
    inc = \lambda i: {x:Nat}. {x=succ(i.x)} } }
as { \exists Counter,
  {new : Counter,
    get : Counter \rightarrow Nat,
    inc : Counter \rightarrow Counter} }
Motivation for Bounded Quantification

Arises when subtyping is combined with polymorphism.

Consider:
\[
\begin{align*}
f & = \lambda x: \{a: \text{Nat}\}. x \\
> f & : \{a: \text{Nat}\} \rightarrow \{a: \text{Nat}\}
\end{align*}
\]

Now, what is the type of?

\[
\begin{align*}
f \{a=0\} \\
> \{a=0\} : \{a: \text{Nat}\}
\end{align*}
\]

\[
\begin{align*}
f \{a=1, b=4\} \\
> \{a=1, b=4\} : \{a: \text{Nat}\}
\end{align*}
\]

Solution: Bounded Quantification

Quantified type may be \emph{bounded} by a subtyping relation:

\[
\begin{align*}
f & = \lambda X <:\{a: \text{Nat}\} \cdot \lambda x: X. \{x.a, x\} \\
> f & : \forall X <:\{a: \text{Nat}\}. X \rightarrow \{\text{Nat}, X\}
\end{align*}
\]

This is the core of System $F_{<:}$: More details in Pierce’s book!

Problem

Note that below is ill-typed! Why?

```haskell
let c = f \{a=1, b=4\} in
c.b
```

One solution is to use universal type:

\[
\begin{align*}
f & = \lambda X. \lambda x: X. x \\
> f & : \forall X. X \rightarrow X
\end{align*}
\]

But how to handle:

\[
\begin{align*}
f & = \lambda x: \{a: \text{Nat}\}. \{x.a, x\} \\
> f & : \{a: \text{Nat}\} \rightarrow \{a: \text{Nat}\}
\end{align*}
\]

Certainly not!

\[
\begin{align*}
f & = \lambda X. \lambda x: X. \{x.a, x\}
\end{align*}
\]