

# Foundations of Software Fall 2023

## Week 9 based on slides by Martin Odersky

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### Type Checking and Type Reconstruction

We now come to the question of type checking and type reconstruction.

- ▶ **Type checking:**

Given  $\Gamma$ ,  $t$  and  $T$ , check whether  $\Gamma \vdash t : T$

- ▶ **Type reconstruction:**

Given  $\Gamma$  and  $t$ , find a type  $T$  such that  $\Gamma \vdash t : T$

Type checking and reconstruction seem difficult since parameters in lambda calculus do not carry their types with them.

Type reconstruction also suffers from the problem that a term can have many types.

**Idea:** We construct all type derivations in parallel, reducing type reconstruction to a unification problem.

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## From Judgements to Equations

$TP : \text{Judgement} \longrightarrow \text{Equations}$

$TP(\Gamma \vdash t : T) =$

case  $t$  of

$x$  :  $\{\Gamma(x) \triangleq T\}$

$\lambda x. t_1$  : let  $a, b$  fresh in

$\{(a \rightarrow b) \triangleq T\} \cup$

$TP(\Gamma, x : a \vdash t_1 : b)$

$t_1 \ t_2$  : let  $a$  fresh in

$TP(\Gamma \vdash t_1 : a \rightarrow T) \cup$

$TP(\Gamma \vdash t_2 : a)$

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## Example

Let  $\text{twice} = \lambda f. \lambda x. f \ (f \ x)$ .

Then  $\text{twice}$  gives rise to the following equations (see blackboard).

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## Soundness and Completeness I

*0.1 Definition:* In general, a type reconstruction algorithm  $\mathcal{A}$  assigns to an environment  $\Gamma$  and a term  $t$  a set of types  $\mathcal{A}(\Gamma, t)$ . The algorithm is *sound* if for every type  $T \in \mathcal{A}(\Gamma, t)$  we can prove the judgement  $\Gamma \vdash t : T$ .

The algorithm is *complete* if for every provable judgement  $\Gamma \vdash t : T$  we have that  $T \in \mathcal{A}(\Gamma, t)$ .

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*0.2 Theorem:*  $\text{TP}$  is sound and complete. Specifically:

$$\Gamma \vdash t : T \text{ iff } \exists \bar{b}. [a \mapsto T] \text{EQNS}$$

where

$a$  is a new type variable  
 $\text{EQNS} = \text{TP}(\Gamma \vdash t : a)$   
 $\bar{b} = \text{FV}(\text{EQNS}) \setminus \text{FV}(\Gamma)$

Here,  $\text{FV}$  denotes the set of free type variables (of a term, and environment, an equation set).

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## Type Reconstruction and Unification

**Problem:** Transform set of equations

$$\{T_i \hat{=} U_i\}_{i=1, \dots, m}$$

into an equivalent substitution

$$\{a_j \mapsto T'_j\}_{j=1, \dots, n}$$

where type variables do not appear recursively on their right hand sides (directly or indirectly). That is:

$$a_j \notin FV(T'_k) \quad \text{for } j = 1, \dots, n, k = j, \dots, n$$

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## Substitutions

A *substitution*  $s$  is an idempotent mapping from type variables to types which maps all but a finite number of type variables to themselves.

We often represent a substitution  $s$  as a set of equations  $a \hat{=} T$  with  $a$  not in  $FV(T)$ .

Substitutions can be generalized to mappings from types to types by defining

$$s(T \rightarrow U) = sT \rightarrow sU$$

Substitutions are idempotent mappings from types to types, i.e.

$$s(s(T)) = s(T). \quad (\text{why?})$$

The  $\circ$  operator denotes composition of substitutions (or other functions):  $(f \circ g)(x) = f(g(x))$ .

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## A Unification Algorithm

We present an incremental version of Robinson's algorithm (1965).

$$\begin{array}{ll}
 \text{mgu} & : \quad (\text{Type} \hat{=} \text{Type}) \rightarrow \text{Subst} \rightarrow \text{Subst} \\
 \text{mgu}(T \hat{=} U)s & = \text{mgu}'(sT \hat{=} sU)s \\
 \text{mgu}'(a \hat{=} a)s & = s \\
 \text{mgu}'(a \hat{=} T)s & = s \cup \{a \mapsto T\} \quad \text{if } a \notin FV(T) \\
 \text{mgu}'(T \hat{=} a)s & = s \cup \{a \mapsto T\} \quad \text{if } a \notin FV(T) \\
 \text{mgu}'(T_1 \rightarrow T_2 \hat{=} U_1 \rightarrow U_2)s & = (\text{mgu}(T_2 \hat{=} U_2) \circ \text{mgu}(T_1 \hat{=} U_1))s \\
 \text{mgu}'(T \hat{=} U)s & = \text{error} \quad \text{in all other cases}
 \end{array}$$

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## Soundness and Completeness of Unification

*0.3 Definition:* A substitution  $u$  is a *unifier* of a set of equations  $\{T_i \hat{=} U_i\}_{i=1, \dots, m}$  if  $uT_i = uU_i$ , for all  $i$ . It is a *most general unifier* if for every other unifier  $u'$  of the same equations there exists a substitution  $s$  such that  $u' = s \circ u$ .

*0.4 Theorem:* Given a set of equations  $EQNS$ . If  $EQNS$  has a unifier then  $\text{mgu}(EQNS)(\emptyset)$  computes the most general unifier of  $EQNS$ . If  $EQNS$  has no unifier then  $\text{mgu}(EQNS)(\emptyset)$  fails.

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## From Judgements to Substitutions

```
TP : Judgement → Subst → Subst
TP(Γ ⊢ t : T) =
  case t of
    x          : mgu(Γ(x) ≐ T)
    λx.t1     : let a, b fresh in
                  mgu((a → b) ≐ T) ◦
                  TP(Γ, x : a ⊢ t1 : b)
    t1 t2    : let a fresh in
                  TP(Γ ⊢ t1 : a → T) ◦
                  TP(Γ ⊢ t2 : a)
```

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## Soundness and Completeness II

One can show by comparison with the previous algorithm:

0.5 Theorem: TP is sound and complete. Specifically:

```
Γ ⊢ t : T  iff  T = r(s(a))
               where
                 a is a new type variable
                 s = TP(Γ ⊢ t : a)(∅)
                 r is a substitution on FV(s(a)) \ FV(s(Γ))
```

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## Polymorphism

In the simply typed lambda calculus, a term can have many types. But a variable or parameter has only one type.

Example:

$$(\lambda x. x \ x)(\lambda y. y)$$

is untypable. But if we substitute actual parameter for formal, we obtain

$$(\lambda y. y)(\lambda y. y) : a \rightarrow a$$

Functions which can be applied to arguments of many types are called *polymorphic*.

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## Polymorphism in Programming

Polymorphism is essential for many program patterns.

Example: `map`

```
def map f xs =  
  if (isEmpty xs) then nil  
  else cons (f (head xs)) (map (f (tail xs)))  
...  
names: List[String]  
nums : List[Int]  
...  
map toUpperCase names  
map increment nums
```

Without a polymorphic type for `map` one of the last two lines is always illegal!

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## Forms of Polymorphism

Polymorphism means “having many forms”.

Polymorphism also comes in several forms.

- ▶ *Universal polymorphism*, sometimes also called *generic types*: The ability to instantiate type variables.
- ▶ *Inclusion polymorphism*, sometimes also called *subtyping*: The ability to treat a value of a subtype as a value of one of its supertypes.
- ▶ *Ad-hoc polymorphism*, sometimes also called *overloading*: The ability to define several versions of the same function name, with different types.

We first concentrate on universal polymorphism.

Two basic approaches: *explicit* or *implicit*.

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## Explicit Polymorphism

We introduce a polymorphic type  $\forall a. T$ , which can be used just as any other type.

We then need to make introduction and elimination of  $\forall$ 's explicit.

Typing rules:

$$\frac{\Gamma, X \vdash t_2 : T_2}{\Gamma \vdash \lambda X. t_2 : \forall X. T_2} \quad (\text{T-TABS})$$

$$\frac{\Gamma \vdash t_1 : \forall X. T_{12}}{\Gamma \vdash t_1 [T_2] : [X \mapsto T_2] T_{12}} \quad (\text{T-TAPP})$$

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We also need to give all parameter types, so programs become verbose.

Example:

```
def map [a] [b] (f: a => b) (xs: List[a]) =  
  if (isEmpty [a] (xs)) then nil [b]  
  else  
    cons [b]  
      (f (head [a] xs))  
      (map [a] [b] (f) (tail [a] xs))  
  
...  
names: List[String]  
nums : List[Int]  
...  
map [String] [String] toUpperCase names  
map [Int] [Int] increment nums
```

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## Translating to System F

The translation of `map` into a System-F term is as follows: (See blackboard)

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## Implicit Polymorphism

Implicit polymorphism does not require annotations for parameter types or type instantiations.

**Idea:** In addition to types (as in simply typed lambda calculus), we have a new syntactic category of *type schemes*. Syntax:

Type Scheme  $S ::= T \mid \forall X. S$

Type schemes are not fully general types; they are used only to type named values, introduced by a `val` construct.

The resulting type system is called the *Hindley/Milner system*, after its inventors. (The original treatment uses `let ... in ...` rather than `val ... ; ...`).

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## Hindley/Milner Typing rules

$$\begin{array}{c}
 \frac{x \notin \text{dom}(\Gamma')}{\Gamma, x : S, \Gamma' \vdash x : S} \quad (\text{T-VAR}) \\
 \frac{\Gamma, X \vdash t : T_1 \quad X \notin FV(\Gamma)}{\Gamma \vdash t : \forall X. T_1} \quad (\text{T-TABS}) \\
 \frac{\Gamma \vdash t : \forall X. T_1 \quad \Gamma \vdash t : [X \mapsto T_2]T_1}{\Gamma \vdash t : T_1} \quad (\text{T-TAPP}) \\
 \frac{\Gamma \vdash t_1 : S \quad \Gamma, x : S \vdash t_2 : T}{\Gamma \vdash \text{let } x = t_1 \text{ in } t_2 : T} \quad (\text{T-LET})
 \end{array}$$

The other two rules are as in simply typed lambda calculus:

$$\begin{array}{c}
 \frac{\Gamma, x : T_1 \vdash t_2 : T_2}{\Gamma \vdash \lambda x. t_2 : T_1 \rightarrow T_2} \quad (\text{T-ABS}) \\
 \frac{\Gamma \vdash t_1 : T_2 \rightarrow T \quad \Gamma \vdash t_2 : T_2}{\Gamma \vdash t_1 \ t_2 : T} \quad (\text{T-APP})
 \end{array}$$

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## Type Reconstruction for Hindley/Milner

Type reconstruction for the Hindley/Milner system works as for simply typed lambda calculus. We only have to add a clause for `let` expressions and refine the rules for variables.

$TP : Judgement \rightarrow Subst \rightarrow Subst$

$TP(\Gamma \vdash t : T)(s) =$   
case  $t$  of  
...  
let  $x = t_1$  in  $t_2$  : let  $a, b$  fresh in  
let  $s_1 = TP(\Gamma \vdash t_1 : a)$  in  
 $TP(\Gamma, x : gen(s_1(\Gamma), s_1(a)) \vdash t_2 : b)(s_1)$

where  $gen(\Gamma, T) = \forall X_1. \dots \forall X_n. T$  with  $X_i \in FV(T) \setminus FV(\Gamma)$ .

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## Variables in Environments

When comparing with the type of a variable in an environment, we have to make sure we create a new instance of their type as follows:

$newInstance(\forall X_1. \dots \forall X_n. S) =$   
let  $b_1, \dots, b_n$  fresh in  
 $[X_1 \mapsto b_1, \dots, X_n \mapsto b_n]S$   
 $TP(\Gamma \vdash t : T) =$   
case  $t$  of  
   $x$  :  $\{ newInstance(\Gamma(x)) \hat{=} T \}$   
  ...

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## Hindley/Milner in Programming Languages

Here is a formulation of the map example in the Hindley/Milner system.

```
let map =  $\lambda f. \lambda xs$  in
  if (isEmpty xs) then nil
  else cons (f (head xs)) (map f (tail xs))
...
// names: List[String]
// nums : List[Int]
// map  :  $\forall X. \forall Y. (X \rightarrow Y) \rightarrow \text{List}[X] \rightarrow \text{List}[Y]$ 
...
map toUpperCase names
map increment nums
```

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## Limitations of Hindley/Milner

Hindley/Milner still does not allow parameter types to be polymorphic. For example,

$$(\lambda x. x \ x)(\lambda y. y)$$

is still ill-typed, even though the following is well-typed:

```
let id =  $\lambda y. y$  in (id id)
```

With explicit polymorphism the expression could be completed to a well-typed term:

$$(\lambda A. \lambda x: (\forall B: B \rightarrow B). \ x \ [A \rightarrow A] \ (x \ [A])) (\lambda C. \lambda y: C. y)$$

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## The Essence of **let**

We regard

`let x = t1 in t2`

as a shorthand for

`[x ↦ t1]t2`

We use this equivalence to get a revised Hindley/Milner system.

*0.6 Definition:* Let **HM'** be the type system that results if we replace rule **LET** from the Hindley/Milner system **HM** by:

$$\frac{\Gamma \vdash t_1 : T_1 \quad \Gamma \vdash [x \mapsto t_1]t_2 : T}{\Gamma \vdash \text{let } x = t_1 \text{ in } t_2 : T} \quad (\text{T-LET}')$$

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## Equivalence of the two systems

*0.7 Theorem:*  $\Gamma \vdash_{\text{HM}} t : S$  iff  $\Gamma \vdash_{\text{HM}'} t : S$

The theorem establishes the following connection between the Hindley/Milner system and the simply typed lambda calculus **F<sub>1</sub>**:

*0.8 Corollary:* Let **t\*** be the result of expanding all **let**'s in **t** according to the rule

$$\text{let } x = t_1 \text{ in } t_2 \rightarrow [x \mapsto t_1]t_2$$

Then

$$\Gamma \vdash_{\text{HM}} t : T \implies \Gamma \vdash_{F_1} t^* : T$$

Furthermore, if every **let**-bound name is used at least once, we also have the reverse:

$$\Gamma \vdash_{F_1} t^* : T \implies \Gamma \vdash_{\text{HM}} t : T$$

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## Principal Types

0.9 Definition: A type  $T$  is a *generic instance* of a type scheme  $S = \forall \alpha_1 \dots \forall \alpha_n. T'$  if there is a substitution  $s$  on  $\alpha_1, \dots, \alpha_n$  such that  $T = sT'$ . We write in this case  $S \leq T$ .

0.10 Definition: A type scheme  $S'$  is a generic instance of a type scheme  $S$  iff for all types  $T$

$$S' \leq T \implies S \leq T$$

We write in this case  $S \leq S'$ .

0.11 Definition: A type scheme  $S$  is *principal* (or: *most general*) for  $\Gamma$  and  $t$  iff

- ▶  $\Gamma \vdash t : S$
- ▶  $\Gamma \vdash t : S'$  implies  $S \leq S'$

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0.12 Definition: A type system  $TS$  has the *principal typing property* iff, whenever  $\Gamma \vdash_{TS} t : S$  then there exists a principal type scheme for  $\Gamma$  and  $t$ .

- 0.13 Theorem:
1.  $HM'$  without `let` has the p.t.p.
  2.  $HM'$  with `let` has the p.t.p.
  3.  $HM$  has the p.t.p.

Proof sketch:

1. Use type reconstruction result for the simply typed lambda calculus.
2. Expand all `let`'s and apply (1.).
3. Use equivalence between  $HM$  and  $HM'$ .

These observations could be used to come up with a type reconstruction algorithm for  $HM$ . But in practice one takes a more direct approach.

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