Lecture 26 – Type Inference (2)
COSE212: Programming Languages

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PLRG

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- **Type inference** is the process of automatically inferring the types of expressions.

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- We have seen three examples to learn how the type inference works.

```
/* RFAE */ def sum(x) = if (x < 1) 0 else x + sum(x - 1); sum
```

```
/* RFAE */ val app = n => f => f(n); app(42)(x => x)
```

```
/* RFAE */ val id = x => x; val n = id(42); val b = id(true); b
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/* RFAE */ val id = x => x; val n = id(42); val b = id(true); b
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- In this lecture, let's learn the details of the type inference algorithm.

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/* RFAE */ val id = x => x; val n = id(42); val b = id(true); b
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- In this lecture, let's learn the details of the type inference algorithm.

- **TIFAE** – TRFAE with **type inference**.
    - **Type Checker** and **Typing Rules** with **Type Inference**
    - Interpreter and Natural Semantics

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Contents

1. Type Checker and Typing Rules with Type Inference

2. Type Unification

3. Type Inference with Let-Polymorphism

Type Checker and Typing Rules

Let's ❶ design **typing rules** of TIFAE to define when an expression is well-typed in the form of:

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

and ❷ implement a **type checker** in Scala according to typing rules:

```scala
def typeCheck(expr: Expr, tenv: TypeEnv): Type = ???
```

The type checker returns the **type** of e if it is well-typed, or rejects it and throws a **type error** otherwise.

We will keep track of the **variable types** using a **type environment** Γ as a mapping from variable names to their types.

$$\text{Type Environments} \quad \Gamma \in \mathbb{T} = \mathbb{X} \xrightarrow{\text{fin}} \mathbb{T} \quad (\texttt{TypeEnv})$$

```scala
type TypeEnv = Map[String, Type]
```

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In addition, we need to keep track of the **solution** for **type constraints** over **type variables** to infer the types of expressions.

```
/* RFAE */ def sum(x) = if (x < 1) 0 else x + sum(x - 1); sum
```
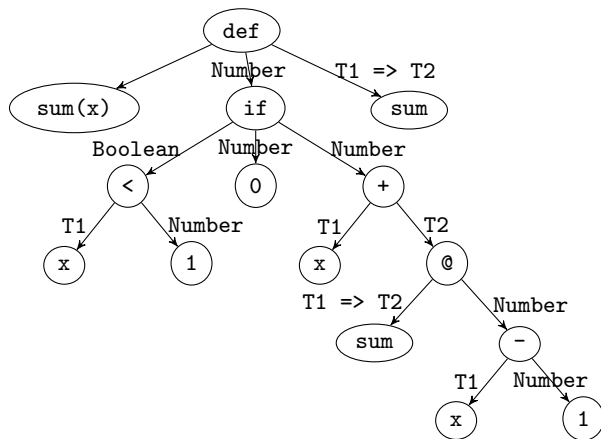

Type Environment

$\mathbb{X}$	$\mathbb{T}$
x	T1
sum	T1 => T2

Solution

$\mathbb{X}_\alpha$	$\mathbb{T}$
T1	Number
T2	Number

A **solution** is a mapping from **type variables** to **types**.

Solutions $\quad \psi \ \in \ \Psi = \mathbb{X}_\alpha \xrightarrow{\text{fin}} (\mathbb{T} \uplus \{\bullet\})$ (Solution)

Type Variables $\quad \alpha \ \in \ \mathbb{X}_\alpha$ (Int)

```
type Solution = Map[Int, Option[Type]]
```

Note that $\bullet$ (None) represents a **not yet solved** (**free**) type variable.

A **solution** is a mapping from **type variables** to **types**.

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Type Variables $\quad \alpha \ \in \ \mathbb{X}_\alpha$ (Int)

```
type Solution = Map[Int, Option[Type]]
```

Note that $\bullet$ (None) represents a **not yet solved** (**free**) type variable.

Now, we have new forms of **type checker** and **typing rules**.

```
def typeCheck(expr: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = ???
```

$$\Gamma, \psi \vdash e : \tau, \psi$$

Similar to the memory passing in MFAE for mutation, we will pass the solution ψ and update it during type checking.

Numbers

```
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...
  case Num(n) => (NumT, sol)
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau{-}\mathrm{Num} \ \frac{}{\Gamma, \psi \vdash n : \mathrm{num}, \psi}$$

```scala
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...
  case Add(l, r) =>
    val (lty, sol1) = typeCheck(l, tenv, sol)
    val (rty, sol2) = typeCheck(r, tenv, sol1)
    val sol3 = unify(lty, NumT, sol2)
    val sol4 = unify(rty, NumT, sol3)
    (ty, sol4)
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau-\texttt{Add} \ \frac{\Gamma, \psi_0 \vdash e_1 : \tau_1, \psi_1 \qquad \Gamma, \psi_1 \vdash e_2 : \tau_2, \psi_2}{\Gamma, \psi_0 \vdash e_1 + e_2 : \texttt{num}, \psi_4} \qquad \texttt{unify}(\tau_2, \texttt{num}, \psi_3) = \psi_4}{\Gamma, \psi_0 \vdash e_1 + e_2 : \texttt{num}, \psi_4}$$

The unify function that takes two types must be the same and updates the solution. We will see how it works later.

Conditionals

```scala
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...
  case If(c, t, e) =>
    val (cty, sol1) = typeCheck(c, tenv, sol)
    val (tty, sol2) = typeCheck(t, tenv, sol1)
    val (ety, sol3) = typeCheck(e, tenv, sol2)
    val sol4 = unify(cty, BoolT, sol3)
    val sol5 = unify(tty, ety, sol4)
    (tty, sol5)
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau\text{-If} \; \frac{\begin{array}{ccc} \Gamma, \psi \vdash e_c : \texttt{bool}, \psi_c & \Gamma, \psi_c \vdash e_t : \tau_t, \psi_t & \Gamma, \psi_t \vdash e_e : \tau_e, \psi_e \\ \texttt{unify}(\tau_c, \texttt{bool}, \psi_e) = \psi' & \texttt{unify}(\tau_t, \tau_e, \psi') = \psi'' \end{array}}{\Gamma, \psi \vdash \texttt{if } (e_c) \; e_t \texttt{ else } e_e : \tau_t, \psi''}$$

Immutable Variable Defs. and Identifier Lookup

```
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...

  case Val(x, e, b) =>
    val (ety, sol1) = typeCheck(e, tenv, sol)
    typeCheck(b, tenv + (x -> ety), sol1)

  case Id(x) => tenv.getOrElse(x, error(s"free identifier: $x"))
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau-\mathtt{Val} \ \frac{\Gamma, \psi_0 \vdash e_1 : \tau_1, \psi_1 \qquad \Gamma[x : \tau_1] \vdash e_2 : \tau_2, \psi_2}{\Gamma, \psi_0 \vdash \mathtt{val} \ x = e_1; \ e_2 : \tau_2, \psi_2}$$

$$\tau-\mathtt{Id} \ \frac{x \in \mathsf{Domain}(\Gamma)}{\Gamma, \psi \vdash x : \Gamma(x), \psi}$$

Function Definitions

```
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...
  case Fun(p, b) =>
    val (pty, sol1) = newTypeVar(sol)
    val (rty, sol2) = typeCheck(b, tenv + (p -> pty), sol1)
    (ArrowT(pty, rty), sol2)
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau-\text{Fun} \frac{\alpha_p \notin \psi \qquad \Gamma[x : \alpha_p], \psi[\alpha_p \mapsto \bullet] \vdash e : \tau, \psi'}{\Gamma, \psi \vdash \lambda x.e : \alpha_p \to \tau, \psi'}$$

Recursive Function Definitions

```scala
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...
  case Rec(f, p, b, s) =>
    val (pty, sol1) = newTypeVar(sol)
    val (rty, sol2) = newTypeVar(sol1)
    val fty = ArrowT(pty, rty)
    val tenv1 = tenv + (f -> fty)
    val tenv2 = tenv1 + (p -> pty)
    val (bty, sol3) = typeCheck(b, tenv2, sol2)
    val sol4 = unify(bty, rty, sol3)
    typeCheck(s, tenv1, sol4)
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau{-}\text{Rec} \ \frac{\begin{array}{c} \alpha_p, \alpha_r \notin \psi \qquad \alpha_p \neq \alpha_r \qquad \Gamma_1 = \Gamma[x_f \mapsto (\alpha_p \to \alpha_r)] \\ \Gamma_2 = \Gamma_1[x_p \mapsto \alpha_p] \qquad \Gamma_2, \psi[\alpha \mapsto \bullet, \alpha' \mapsto \bullet] \vdash e_b : \tau_b, \psi_b \\ \texttt{unify}(\tau_b, \alpha_r, \psi_b) = \psi_r \qquad \Gamma_1, \psi_r \vdash e_s : \tau_s, \psi_s \end{array}}{\Gamma, \psi \vdash \texttt{def } x_f(x_p) = e_b; \ e_s : \tau_s, \psi_s}$$

Function Applications

```
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...
  case App(f, a) =>
    val (fty, sol1) = typeCheck(f, tenv, sol)
    val (aty, sol2) = typeCheck(a, tenv, sol1)
    val (rty, sol3) = newTypeVar(sol2)
    val sol4 = unify(ArrowT(aty, rty), fty, sol3)
    (rty, sol4)
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau{-}\mathtt{App} \, \frac{\Gamma, \psi \vdash e_f : \tau_f, \psi_f \qquad \Gamma, \psi_f \vdash e_a : \tau_a, \psi_a \qquad \alpha_r \notin \psi_a \qquad \mathtt{unify}(\tau_a \to \alpha_r, \tau_f, \psi_a[\alpha_r \mapsto \bullet]) = \psi'}{\Gamma, \psi \vdash e_1(e_2) : \alpha_r, \psi'}$$

Contents

Type Unification

Definition (Type Unification)

Type unification is the process of updating a solution to make two types equal. If the types are not unifiable, then this process fails and throws an exception.

$$\texttt{unify} : (\mathbb{T} \times \mathbb{T} \times \Psi) \rightharpoonup \Psi$$

For example, if we unify a type variable α and the number type num, the empty solution $\varnothing$ is updated to $[\alpha \mapsto \texttt{num}]$.

$$\texttt{unify}(\alpha, \texttt{num}, \varnothing) = [\alpha \mapsto \texttt{num}]$$

Type Unification

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$$\texttt{unify}(\alpha, \texttt{num}, \varnothing) = [\alpha \mapsto \texttt{num}]$$

Before, we define the type unification, we need to define the **type resolving** and **occurrence checking** functions.

1. **Type resolving** is the process of recursively resolving a type variable to its representative type to deal with the **type aliasing**.
2. **Occurrence checking** is the process of checking whether a type variable occurs in a type to detect **cyclic types**.

To understand why we need the **type resolving** function, let's consider the following example:

$$\texttt{unify}(\alpha_1, \alpha_2, \psi_1) = \psi_2 \qquad \texttt{unify}(\alpha_1, \texttt{num}, \psi_2) = \psi_3$$

$$\psi_1 = \begin{array}{|c|c|} \hline \multicolumn{2}{|c|}{\text{Solution}} \\ \hline \mathbb{X}_\alpha & \mathbb{T} \\ \hline \alpha_1 & \bullet \\ \hline \alpha_2 & \bullet \\ \hline \end{array} \qquad \psi_2 = \begin{array}{|c|c|} \hline \multicolumn{2}{|c|}{\text{Solution}} \\ \hline \mathbb{X}_\alpha & \mathbb{T} \\ \hline \alpha_1 & \alpha_2 \\ \hline \alpha_2 & \bullet \\ \hline \end{array} \qquad \psi_3 = \begin{array}{|c|c|} \hline \multicolumn{2}{|c|}{\text{Solution}} \\ \hline \mathbb{X}_\alpha & \mathbb{T} \\ \hline \alpha_1 & \texttt{num} \\ \hline \alpha_2 & \bullet \\ \hline \end{array}$$

Type Resolving

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Type Resolving

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Unfortunately, we cannot know that α_2 are num with the solution ψ_3.

We need to **resolve** the type variable α_1 to find its **representative type** and update its solution to num to deal with the **type aliasing**.

$$\text{unify}(\text{resolve}(\alpha_1, \psi_2), \text{num}, \psi_2) = \psi_3' = \begin{array}{|c|c|} \hline \multicolumn{2}{c}{\text{Solution}} \\ \hline \mathbb{X}_\alpha & \mathbb{T} \\ \hline \alpha_1 & \alpha_2 \\ \hline \alpha_2 & \text{num} \\ \hline \end{array}$$

Type Resolving

We can define the **type resolving** function as follows:

$$\texttt{resolve} : (\mathbb{T} \times \Psi) \to \mathbb{T}$$

$$\texttt{resolve}(\tau, \psi) = \begin{cases} \texttt{resolve}(\tau', \psi) & \text{if } \tau = \alpha \wedge \psi(\alpha) = \tau' \\ \tau & \text{otherwise} \end{cases}$$

and implement it in Scala as follows:

```scala
def resolve(ty: Type, sol: Solution): Type = ty match
  case VarT(k) => sol(k) match
    case Some(ty) => resolve(ty, sol)
    case None => ty
  case _ => ty
```

Let's understand why we need the **occurrence checking** function:

$$\mathtt{unify}(\alpha_1, \mathtt{num} \to \alpha_1, \psi) = \psi'$$

It actually fails because the type variable α_1 occurs in the type $\mathtt{num} \to \alpha_1$, which means it requires **cyclic types** not supported in our type system.

Occurrence Checking

Let's understand why we need the **occurrence checking** function:

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Let's define the **occurrence checking** function as follows:

$$\boxed{\texttt{occur} : (\mathbb{X}_\alpha \times \mathbb{T} \times \Psi) \to \texttt{bool}}$$

$$\texttt{occur}(\alpha, \tau, \psi) = \begin{cases} \texttt{true} & \text{if } \tau = \alpha \\ \texttt{occur}(\alpha, \tau_p, \psi) \vee \texttt{occur}(\alpha, \tau_r, \psi) & \text{if } \tau = (\tau_p \to \tau_r) \\ \texttt{false} & \text{otherwise} \end{cases}$$

and implement it in Scala as follows:

```scala
def occurs(k: Int, ty: Type, sol: Solution): Boolean = resolve(ty, sol) match
  case VarT(l) => k == l
  case ArrowT(pty, rty) => occurs(k, pty, sol) || occurs(k, rty, sol)
  case _ => false
```

Using the **type resolving** and **occurrence checking** functions, we could define the **type unification** as a partial function:

$$\texttt{unify} : (\mathbb{T} \times \mathbb{T} \times \Psi) \rightharpoonup \Psi$$

$$
\texttt{unify}(\tau_1, \tau_2, \psi) =
\begin{cases}
\psi & \text{if } \tau_1' = \texttt{num} \wedge \tau_2' = \texttt{num} \\
\psi & \text{if } \tau_1' = \texttt{bool} \wedge \tau_2' = \texttt{bool} \\
\texttt{unify}(\tau_{1,r}, \tau_{2,r}, \texttt{unify}(\tau_{1,p}, \tau_{2,p}, \psi)) & \text{if } \tau_1' = (\tau_{1,p} \to \tau_{1,r}) \wedge \tau_2' = (\tau_{2,p} \to \tau_{2,r}) \\
\psi & \text{if } \tau_1' = \alpha = \tau_2' \\
\psi[\alpha \mapsto \tau_2'] & \text{if } \tau_1' = \alpha \wedge \neg\texttt{occur}(\alpha, \tau_2') \\
\psi[\alpha \mapsto \tau_1'] & \text{if } \tau_2' = \alpha \wedge \neg\texttt{occur}(\alpha, \tau_1')
\end{cases}
$$

where $\tau_1' = \texttt{resolve}(\tau_1, \psi)$ and $\tau_2' = \texttt{resolve}(\tau_2, \psi)$.

1 First, it resolves the types τ_1 and τ_2 with the current solution ψ into τ_1' and τ_2' using the **type resolving** function resolve.

2 If only one of them (τ_1' or τ_2') is a type variable, it checks cyclic types using the **occurrence checking** function occur.

3 Then, it unifies types τ_1' and τ_2' and updates the solution ψ.
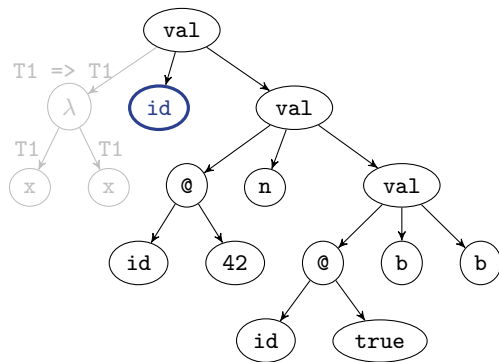
Type Unification

And, we can implement the **type unification** function in Scala as follows:

```scala
def unify(lty: Type, rty: Type, sol: Solution): Solution =
  (resolve(lty, sol), resolve(rty, sol)) match
    case (NumT, NumT) => sol
    case (BoolT, BoolT) => sol
    case (ArrowT(lpty, lrty), ArrowT(rpty, rrty)) =>
      unify(lrty, rrty, unify(lpty, rpty, sol))
    case (VarT(k), VarT(l)) if k == l => sol
    case (VarT(k), rty) if !occurs(k, rty, sol) => sol + (k -> Some(rty))
    case (lty, VarT(k)) if !occurs(k, lty, sol) => sol + (k -> Some(lty))
    case _ => error(s"Cannot unify ${lty.str} and ${rty.str}")
```

$$
\mathtt{unify}(\tau_1, \tau_2, \psi) =
\begin{cases}
\psi & \text{if } \tau_1' = \mathtt{num} \wedge \tau_2' = \mathtt{num} \\
\psi & \text{if } \tau_1' = \mathtt{bool} \wedge \tau_2' = \mathtt{bool} \\
\mathtt{unify}(\tau_{1,r}, \tau_{2,r}, \mathtt{unify}(\tau_{1,p}, \tau_{2,p}, \psi)) & \text{if } \tau_1' = (\tau_{1,p} \rightarrow \tau_{1,r}) \wedge \tau_2' = (\tau_{2,p} \rightarrow \tau_{2,r}) \\
\psi & \text{if } \tau_1' = \alpha = \tau_2' \\
\psi[\alpha \mapsto \tau_2'] & \text{if } \tau_1' = \alpha \wedge \neg\mathtt{occur}(\alpha, \tau_2') \\
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\end{cases}
$$

where $\tau_1' = \mathtt{resolve}(\tau_1, \psi)$ and $\tau_2' = \mathtt{resolve}(\tau_2, \psi)$.

Contents

Type Environment

$\mathbb{X}$	$\mathbb{T}$
id	[T1] { T1 => T1 }

Solution

$\mathbb{X}_\alpha$	$\mathbb{T}$
T1	–

Let's **generalize** the type T1 => T1 into a **polymorphic type** for id with
type variable T1 as a **type parameter**.
We call this **let-polymorphism** because it only introduces polymorphism
for the let-binding (e.g., val).

We need to extend the **type environment** to support **polymorphic types**.

Type Environments $\qquad\qquad \Gamma \in \mathbb{T} = \mathbb{X} \xrightarrow{\text{fin}} \mathbb{T}^\forall$ (TypeEnv)

Polymorphic Types $\quad \tau^\forall = \forall \alpha^*.\tau \in \mathbb{T}^\forall = \mathbb{X}_\alpha^* \times \mathbb{T}$ (PolyType)

```
// type environments
type TypeEnv = Map[String, PolyType]

// polymorphic types
case class PolyType(ks: List[Int], ty: Type)
```

We can define the **type generalization** function gen as follows:

$$\boxed{\texttt{gen} : (\mathbb{T} \times \Gamma \times \Psi) \to \mathbb{T}^\forall}$$

$$\texttt{gen}(\tau, \Gamma, \psi) = \forall \alpha_1, \ldots, \alpha_m.\tau \qquad \text{where} \qquad \texttt{free}_\tau(\tau, \psi) \setminus \texttt{free}_\Gamma(\Gamma, \psi) = \{\alpha_1, \ldots, \alpha_m\}$$

We can define the **type generalization** function gen as follows:

$$\boxed{\texttt{gen} : (\mathbb{T} \times \Gamma \times \Psi) \to \mathbb{T}^{\forall}}$$

$$\texttt{gen}(\tau, \Gamma, \psi) = \forall \alpha_1, \ldots, \alpha_m.\tau \qquad \text{where} \qquad \texttt{free}_\tau(\tau, \psi) \setminus \texttt{free}_\Gamma(\Gamma, \psi) = \{\alpha_1, \ldots, \alpha_m\}$$

and the **free type variables** in each component as follows:

$$\boxed{\texttt{free}_\tau : (\mathbb{T} \times \Psi) \to \mathcal{P}(\mathbb{X}_\alpha)}$$

$$\texttt{free}_\tau(\tau, \psi) = \begin{cases} \texttt{free}_{\tau'}(\tau', \psi) & \text{if } \tau = \alpha \wedge \psi(\alpha) = \tau' \\ \{\alpha\} & \text{if } \tau = \alpha \wedge \psi(\alpha) = \bullet \\ \texttt{free}_{\tau_p}(\tau_p, \psi) \cup \texttt{free}_{\tau_r}(\tau_r, \psi) & \text{if } \tau = (\tau_p \to \tau_r) \\ \varnothing & \text{otherwise} \end{cases}$$

$$\boxed{\texttt{free}_{\tau^\forall} : (\mathbb{T}^{\forall} \times \Psi) \to \mathcal{P}(\mathbb{X}_\alpha)}$$

$$\texttt{free}_{\tau^\forall}(\forall \alpha_1, \ldots, \alpha_m.\tau, \psi) = \texttt{free}_\tau(\tau, \psi) \setminus \{\alpha_1, \ldots, \alpha_m\}$$

$$\boxed{\texttt{free}_\Gamma : (\Gamma \times \Psi) \to \mathcal{P}(\mathbb{X}_\alpha)}$$

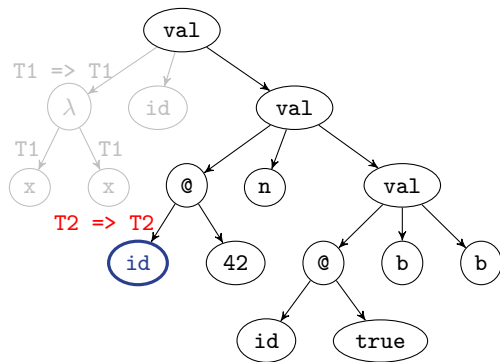$$\texttt{free}_\Gamma([x_1 : \tau_1^{\forall}, \ldots, x_n : \tau_n^{\forall}], \psi) = \texttt{free}_{\tau_1^\forall}(\tau_1^{\forall}, \psi) \cup \ldots \cup \texttt{free}_{\tau_n^\forall}(\tau_n^{\forall}, \psi)$$

Immutable Variable Defs. with Type Generalization ◆PLRG

```
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...

  case Val(x, e, b) =>
    val (ety, sol1) = typeCheck(e, tenv, sol)
    val polyty = gen(ety, tenv, sol1)
    typeCheck(b, tenv + (x -> polyty), sol1)
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau{-}\mathtt{Val} \quad \frac{\Gamma, \psi_0 \vdash e_1 : \tau_1, \psi_1 \qquad \mathsf{gen}(\tau_1, \Gamma, \psi_1) = \tau_1^{\forall} \qquad \Gamma[x : \tau_1^{\forall}] \vdash e_2 : \tau_2, \psi_2}{\Gamma, \psi_0 \vdash \mathtt{val}\ x = e_1;\ e_2 : \tau_2, \psi_2}$$
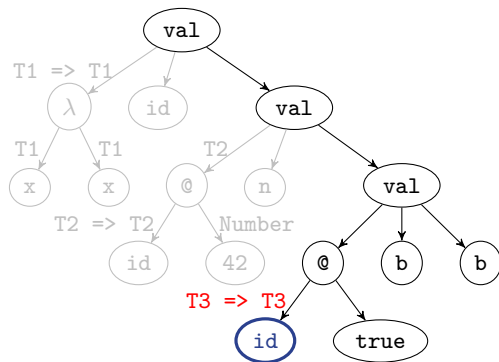
Type Environment

$\mathbb{X}$	$\mathbb{T}$
id	[T1] { T1 => T1 }

Solution

$\mathbb{X}_\alpha$	$\mathbb{T}$
T1	–
T2	–

Let's define a new **type variable** T2 to **instantiate** the **type variable** T1. And, **substitute** T1 with T2.

Type Environment

$\mathbb{X}$	$\mathbb{T}$
id	[T1] { T1 => T1 }
n	T2

Solution

$\mathbb{X}_\alpha$	$\mathbb{T}$
T1	–
T2	Number
T3	–

Let's define a new **type variable** T3 to **instantiate** the **type variable** T1. And, **substitute** T1 with T3.

Type Instantiation

We can define the **type instantiation** function inst as follows:

$$\boxed{\texttt{inst} : (\mathbb{T}^\forall \times \Psi) \to (\mathbb{T} \times \Psi)}$$

$$
\begin{aligned}
&\texttt{inst}(\forall \alpha_1, \ldots, \alpha_m.\tau, \psi) = (\\
&\quad \texttt{subst}(\tau, \psi[\alpha_1 \mapsto \alpha_1', \ldots, \alpha_m \mapsto \alpha_m']), \\
&\quad \psi[\alpha_1' \mapsto \bullet, \ldots, \alpha_m' \mapsto \bullet] \\
&)
\end{aligned}
$$

where $\quad \alpha_1', \ldots, \alpha_m' \notin \psi \wedge \forall 1 \le i < j \le m.\ \alpha_i' \ne \alpha_j'$

Type Instantiation

We can define the **type instantiation** function inst as follows:

$$\boxed{\texttt{inst} : (\mathbb{T}^{\forall} \times \Psi) \to (\mathbb{T} \times \Psi)}$$

$$
\begin{aligned}
\texttt{inst}(\forall \alpha_1, \ldots, \alpha_m.\tau, \psi) = (\ & \\
& \texttt{subst}(\tau, \psi[\alpha_1 \mapsto \alpha_1', \ldots, \alpha_m \mapsto \alpha_m']), \\
& \psi[\alpha_1' \mapsto \bullet, \ldots, \alpha_m' \mapsto \bullet] \\
)
\end{aligned}
$$

$$\text{where} \qquad \alpha_1', \ldots, \alpha_m' \notin \psi \wedge \forall 1 \le i < j \le m.\ \alpha_i' \ne \alpha_j'$$

and the **type substitution** function subst as follows:

$$\boxed{\texttt{subst} : (\mathbb{T} \times \Psi) \to \mathbb{T}}$$

$$
\texttt{subst}(\tau, \psi) = \begin{cases}
\texttt{subst}(\tau', \psi) & \text{if } \tau = \alpha \wedge \psi(\alpha) = \tau' \\
\texttt{subst}(\tau_p, \psi) \to \texttt{subst}(\tau_r, \psi) & \text{if } \tau = (\tau_p \to \tau_r) \\
\tau & \text{otherwise}
\end{cases}
$$

Identifier Lookup with Type Instantiation

```
def typeCheck(e: Expr, tenv: TypeEnv, sol: Solution): (Type, Solution) = e match
  ...

  case Id(x) =>
    val ty = tenv.getOrElse(x, error(s"free identifier: $x"))
    inst(ty, sol)
```

$$\boxed{\Gamma, \psi \vdash e : \tau, \psi}$$

$$\tau{-}\mathrm{Id} \ \frac{\Gamma(x) = \tau^{\forall} \qquad \mathtt{inst}(\tau^{\forall}, \psi) = (\tau, \psi')}{\Gamma, \psi \vdash x : \tau, \psi'}$$

1. Type Checker and Typing Rules with Type Inference
> Solutions for Type Constraints
> Numbers
> Additions
> Conditionals
> Immutable Variable Definitions and Identifier Lookup
> Function Definitions
> Recursive Function Definitions
> Function Applications

2. Type Unification
> Type Resolving
> Occurrence Checking
> Type Unification

3. Type Inference with Let-Polymorphism
> Type Generalization
> Type Instantiation

PLRG

- Please see this document[1] on GitHub.
  - Implement typeCheck function.
  - Implement interp function.

- It is just an exercise, and you **don't need to submit** anything.

- However, some exam questions might be related to this exercise.

Final Exam

- The final exam will be given in class.
- **Date:** 13:30-14:45 (1 hour 15 minutes), December 20 (Wed.).
- **Location:** 535, Asan Science Building (아산이학관)
- **Coverage:** Lectures 14 – 24
- **Format:** 7–9 questions with closed book and closed notes
    - Fill in the blank in a Scala code snippet.
    - Define the syntax or semantics of extended language features.
    - Write the evaluation results of given expressions.
    - Yes/No questions about concepts in programming languages.
    - etc.
- Note that there is **no class** on **December 18 (Mon.)**.

Next Lecture

- Course Review

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