

CSE 114A

Foundations of Programming Languages

Polymorphism and Type Inference

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Roadmap

Past two weeks:

How do we *implement* a tiny functional language?

1. *Interpreter*: how do we *evaluate* a program given its AST?
2. *Parser*: how do we convert strings to ASTs?

This week: adding types

How do we check statically if our programs “make sense”?

1. *Type system*: formalizing the intuition about which expressions have which types
2. *Type inference*: computing the type of an expression

2

Reminder: Nano2

```
e ::= n | x           -- numbers, vars
    | e1 + e2         -- arithmetic
    | \x -> e          -- abstraction
    | e1 e2            -- application
    | let x = e1 in e2 -- let binding
```

3

Reminder: Nano2

Which one of these Nano2 programs is well-typed? *

- (A) $(\lambda x \rightarrow x) + 1$
- (B) $1\ 2$
- (C) $\text{let } f = \lambda x \rightarrow x + 1 \text{ in } f\ (y \rightarrow y)$
- (D) $\lambda x \rightarrow \lambda y \rightarrow x\ y$
- (D) $(\lambda y \rightarrow 1 + y)\ (1 + 2) \Rightarrow 1 + 1 + 2$
- (E) $\lambda x \rightarrow x\ x$



<http://tiny.cc/cse116-nanotype-ind>

4

Reminder: Nano2

Which one of these Nano2 programs is well-typed? *

- (A) $(\lambda x \rightarrow x) + 1$
- (B) $1\ 2$
- (C) $\text{let } f = \lambda x \rightarrow x + 1 \text{ in } f\ (y \rightarrow y)$
- (D) $\lambda x \rightarrow \lambda y \rightarrow x\ y$
- (D) $(\lambda y \rightarrow 1 + y)\ (1 + 2) \Rightarrow 1 + 1 + 2$
- (E) $\lambda x \rightarrow x\ x$



<http://tiny.cc/cse116-nanotype-grp>

5

QUIZ

Answer: D.

A adds a function;

B applies a number;

C defines f to take an `Int` and then passes in a function;

E requires a type `T` that is equal to `T -> T`, which doesn't exist.

6

Type system for Nano2

A **type system** defines what types an expression can have

To define a type system we need to define:

- the *syntax* of types: what do types look like?
- the *static semantics* of our language (i.e. the typing rules): assign types to expressions

7

Type system: take 1

Syntax of types:

```
T ::= Int      -- integers
    | T1 -> T2 -- function types
```

Now we want to define a *typing relation* $e :: T$ (e has type T)

We define this relation *inductively* through a set of *typing rules*:

```
[T-Num]  n :: Int

[T-Add]   $\frac{e1 :: Int \quad e2 :: Int}{e1 + e2 :: Int}$   -- premises -- conclusion
[T-Var]  x :: ???
```

What is the type of a variable?

We have to remember what type of expression it was bound to!

8

Type Environment

An expression has a type in a given **type environment** (also called **context**), which maps all its *free variables* to their *types*

```
G = x1:T1, x2:T2, ..., xn:Tn
```

Our *typing relation* should include the context G:

```
G |- e :: T (e has type T in context G)
```

9

Typing rules: take 2

[T-Num] $G \vdash n :: \text{Int}$

[T-Add]
$$\frac{G \vdash e_1 :: \text{Int} \quad G \vdash e_2 :: \text{Int}}{G \vdash e_1 + e_2 :: \text{Int}}$$

[T-Var] $G \vdash x :: T \quad \text{if } x:T \text{ in } G$

[T-Abs]
$$\frac{G, x:T_1 \vdash e :: T_2}{G \vdash \lambda x \rightarrow e :: T_1 \rightarrow T_2}$$

[T-App]
$$\frac{G \vdash e_1 :: T_1 \rightarrow T_2 \quad G \vdash e_2 :: T_1}{G \vdash e_1 e_2 :: T_2}$$

[T-Let]
$$\frac{G \vdash e_1 :: T_1 \quad G, x:T_1 \vdash e_2 :: T_2}{G \vdash \text{let } x = e_1 \text{ in } e_2 :: T_2}$$

10

Typing rules

$G \vdash e :: T$

An expression e has type T in G if we can derive $G \vdash e :: T$ using these rules

An expression e is **well-typed** in G if we can derive $G \vdash e :: T$ for some type T

- and **ill-typed** otherwise

11

Examples

Example 1:

Let's derive: $[] \vdash (\lambda x \rightarrow x) 2 :: \text{Int}$

[T-Var]
$$\frac{}{[x:\text{Int}] \vdash x :: \text{Int}}$$

[T-Abs]
$$\frac{}{[] \vdash \lambda x \rightarrow x :: \text{Int} \rightarrow \text{Int}} \quad \frac{}{[] \vdash 2 :: \text{Int}} \quad \text{[T-Num]}$$

[T-App]
$$\frac{}{[] \vdash (\lambda x \rightarrow x) 2 :: \text{Int}}$$

But we *cannot* derive: $[] \vdash 1 2 :: T$ for any type T

- Why?
- **T-App** only applies when LHS has a function type, but there's no rule to derive a function type for 1

12

Examples

Example 2:

Let's derive: $[] \mid\!-\ \text{let } x = 1 \text{ in } x + 2 :: \text{Int}$

```

      [T-Var]----- [T-Num]
            x:Int \|- x :: Int   x:Int \|- 2 :: Int
[T-Num] ----- [T-Add]
[] \|- 1 :: Int   x:Int \|- x + 2 :: Int
[T-Let] -----
[] \|- let x = 1 in x + 2 :: Int
```

But we *cannot* derive: $[] \mid\!-\ \text{let } x = \lambda y \rightarrow y \text{ in } x + 2 :: T$ for any type T

The $[T\text{-Var}]$ rule above will fail to derive $x :: \text{Int}$

13

Examples

Example 3:

We cannot derive: $[] \mid\!-\ (\lambda x \rightarrow x \ x) :: T$ for any type T

We cannot find any type T to fill in for x , because it has to be equal to $T \rightarrow T$

14

A note about typing rules

According to these rules, an expression can have *zero*, *one*, or *many* types

- examples?

$1 \ 2$ has no types; 1 has one type (Int)

$\lambda x \rightarrow x$ has many types:

- we can derive $[] \mid\!-\ \lambda x \rightarrow x :: \text{Int} \rightarrow \text{Int}$
- or $[] \mid\!-\ \lambda x \rightarrow x :: (\text{Int} \rightarrow \text{Int}) \rightarrow (\text{Int} \rightarrow \text{Int})$
- or $T \rightarrow T$ for any concrete T

We would like every well-typed expression to have a single **most general** type!

- most general type = allows most uses
- infer type once and reuse later

15

QUIZ

Is this program well-typed according to your intuition and according to our rules? *

```
let id = \x -> x in
  let y = id 5 in
    id (\z -> z + y)
```

- (A) Me: okay, rules: okay
- (B) Me: okay, rules: nope
- (C) Me: nope, rules: okay
- (D) Me: nope, rules: nope



<http://tiny.cc/cse116-typed-ind>

16

QUIZ

Is this program well-typed according to your intuition and according to our rules? *

```
let id = \x -> x in
  let y = id 5 in
    id (\z -> z + y)
```

- (A) Me: okay, rules: okay
- (B) Me: okay, rules: nope
- (C) Me: nope, rules: okay
- (D) Me: nope, rules: nope



<http://tiny.cc/cse116-typed-grp>

17

QUIZ

Answer: B.

18

Double identity

```
let id = \x -> x in
  let y = id 5 in
    id (\z -> z + y)
```

Intuitively this program looks okay, but our type system *rejects* it:

- in the first application, `id` needs to have type `Int -> Int`
- in the second application, `id` needs to have type `(Int -> Int) -> (Int -> Int)`
- the type system forces us to pick *just one type* for each variable, such as `id :`

What can we do?

19

Polymorphic types

Intuitively, we can describe the type of `id` like this:

- it's a function type where
- the argument type can be any type `T`
- the return type is then also `T`

20

Polymorphic types

We formalize this intuition as a **polymorphic type**: `forall a . a -> a`

- where `a` is a (bound) type variable
- also called a **type scheme**
- Haskell also has polymorphic types, but you don't usually write `forall a .`

We can **instantiate** this scheme into different types by replacing `a` in the body with some type, e.g.

- instantiating with `Int` yields `Int -> Int`
- instantiating with `Int -> Int` yields `(Int -> Int) -> Int -> Int`
- etc.

21

Inference with polymorphic types

With polymorphic types, we can derive `e :: Int -> Int` where `e` is

```
let id = \x -> x in
  let y = id 5 in
    id (\z -> z + y)
```

At a high level, inference works as follows:

1. When we have to pick a type `T` for `x`, we pick a **fresh type variable** `a`
2. So the type of `\x -> x` comes out as `a -> a`
3. We can **generalize** this type to `forall a . a -> a`
4. When we apply `id` the first time, we **instantiate** this polymorphic type with `Int`
5. When we apply `id` the second time, we **instantiate** this polymorphic type with `Int -> Int`

Let's formalize this intuition as a type system!

22

Type system: take 3

Syntax of types

```
-- Mono-types
T ::= Int      -- integers
   | T1 -> T2  -- function types
   | a         -- NEW: type variable

-- NEW: Poly-types (type schemes)
S ::= T        -- mono-type
   | forall a . S -- polymorphic type
```

where $a \in TVar$, $T \in Type$, $S \in Poly$

Type Environment

The type environment now maps variables to poly-types: `G : Var -> Poly`

- example, `G = [z: Int, id: forall a . a -> a]`

23

Type system: take 3

Type Substitutions

We need a mechanism for replacing all type variables in a type with another type

A **type substitution** is a finite map from type variables to types: `U : TVar -> Type`

- example: `U1 = [a / Int, b / (c -> c)]`

To **apply** a substitution `U` to a type `T` means replace all type vars in `T` with whatever they are mapped to in `U`

- example 1: `U1 (a -> a) = Int -> Int`
- example 2: `U1 Int = Int`

24

QUIZ

What is the result of the following substitution application? *

[a / Int, b / c -> c] (b -> d -> b)

- (A) c -> d -> c
- (B) (c -> c) -> d -> (c -> c)
- (C) Error: no mapping for type variable d
- (D) Error: type variable a is unused



<http://tiny.cc/cse116-subst-ind>

25

QUIZ

What is the result of the following substitution application? *

[a / Int, b / c -> c] (b -> d -> b)

- (A) c -> d -> c
- (B) (c -> c) -> d -> (c -> c)
- (C) Error: no mapping for type variable d
- (D) Error: type variable a is unused



<http://tiny.cc/cse116-subst-grp>

26

QUIZ

(B) (c -> c) -> d -> (c -> c)

Answer: B

27

Typing rules

We need to change the typing rules so that:

1. Variables (and their definitions) can have polymorphic types

[T-Var] $G \vdash x :: S \quad \text{if } x:S \text{ in } G$

[T-Let]
$$\frac{G \vdash e1 :: S \quad G, x:S \vdash e2 :: T}{G \vdash \text{let } x = e1 \text{ in } e2 :: T}$$

28

Typing rules

2. We can *instantiate* a type scheme into a type

[T-Inst]
$$\frac{G \vdash e :: \text{forall } a . S}{G \vdash e :: [a / T] S}$$

3. We can *generalize* a type with free type variables into a type scheme

[T-Gen]
$$\frac{G \vdash e :: S \quad \text{if not } (a \text{ in } \text{FTV}(G))}{G \vdash e :: \text{forall } a . S}$$

29

Typing rules

The rest of the rules are the same:

[T-Num] $G \vdash n :: \text{Int}$

[T-Add]
$$\frac{G \vdash e1 :: \text{Int} \quad G \vdash e2 :: \text{Int}}{G \vdash e1 + e2 :: \text{Int}}$$

[T-Abs]
$$\frac{G, x:T1 \vdash e :: T2}{G \vdash \lambda x . e :: T1 \rightarrow T2}$$

[T-App]
$$\frac{G \vdash e1 :: T1 \rightarrow T2 \quad G \vdash e2 :: T1}{G \vdash e1 e2 :: T2}$$

30

Examples

Example 1

Let's derive: $[] \vdash \lambda x \rightarrow x :: \text{forall } a . a \rightarrow a$

```
[T-Var] -----  
      [x:a] |- x :: a  
[T-Abs] -----  
      [] |- \x -> x :: a -> a  
[T-Gen] ----- not (a in FTV([]))  
      [] |- \x -> x :: forall a . a -> a
```

Can we derive: $[x:a] \vdash x :: \text{forall } a . a$?

No! The side condition of [T-Gen] is violated because **a** is present in the context

31

Examples

Example 2

Let's derive: $G1 \vdash \text{id } 5 :: \text{Int}$ where $G1 = [id : (\text{forall } a . a \rightarrow a)]$:

```
[T-Var]-----  
      G1 |- id :: forall a.a -> a  
[T-Inst]----- [T-Num]  
      G1 |- id :: Int -> Int      G1 |- 5 :: Int  
[T-App]-----  
      G1 |- id 5 :: Int
```

32

Examples

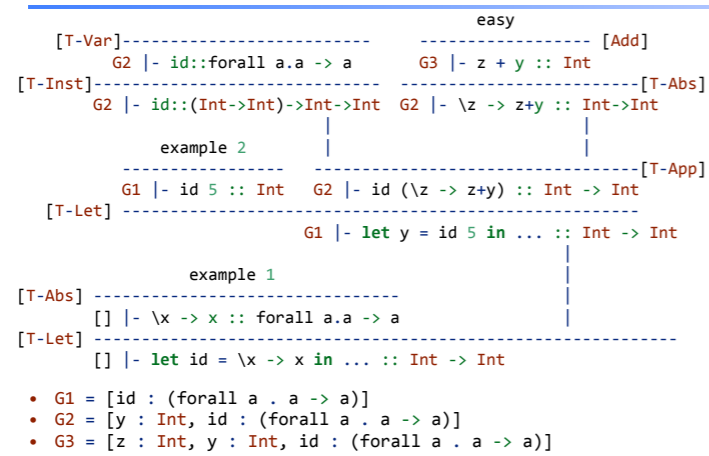
Example 3

Finally, we can derive:

```
(let id = \x -> x in  
 let y = id 5 in  
 id (\z -> z + y)) :: Int -> Int
```

33

Examples



34

Type inference algorithm

Our ultimate goal is to implement a Haskell function `infer` which

- given a context `G` and an expression `e`
- returns a type `T` such that `G |- e :: T`
- or reports a type error if `e` is ill-typed in `G`

35

Representing types

First, let's define a Haskell datatype to represent Nano2 types:

```

data Type
  = TInt          -- Int
  | Type :=> Type -- T1 -> T2
  | TVar String   -- a, b, c

data Poly = Mono Type
          | Forall TVar Poly

type TVar = String
type TEnv = [(Id, Poly)] -- type environment
type Subst = [(String, Type)] -- type substitution

```

36

Inference: main idea

Let's implement `infer` like this:

1. Depending on what kind of expression `e` is, find a typing rule that applies to it
2. If the rule has premises, recursively call `infer` to obtain the types of sub-expressions
3. Combine the types of sub-expression according to the conclusion of the rule
4. If no rule applies, report a type error

37

Inference: main idea

```
-- | This is not the final version!!!
infer :: TypeEnv -> Expr -> Type
infer _ (ENum _) = TInt
infer tEnv (EVar var) = lookup var tEnv
infer tEnv (EAdd e1 e2) =
  if t1 == TInt && t2 == TInt
  then return TInt
  else throw "type error: + expects Int operands"
  where
    t1 = infer tEnv e1
    t2 = infer tEnv e2
...
```

This doesn't quite work (for other cases). Why?

38

Inference: tricky bits

The trouble is that our typing rules are *nondeterministic*!

- When building derivations, sometimes we had to *guess* how to proceed

Problem 1: Guessing a type

```
-- oh, now we know!
[T-Var]-----
[x:?] |- x: Int    [x:?] |- 1 :: Int
[T-Add]-----
[x:?] |- x + 1 :: ?? -- what should "?" be?
[T-Abs]-----
[] |- (\x -> x + 1) :: ? -> ??
```

39

Inference: tricky bits

Problem 1: Guessing a type

So, if we want to implement

```
infer tEnv (ELam x e) = tX :=> tBody
  where
    tEnv' = extendTEnv x tX tEnv
    tX    = ??? -- what do we put here?
    tBody = infer tEnv' e
  ...
```

40

Inference: tricky bits

Problem 2: Guessing when to generalize

In the derivation for

```
(let id = \x -> x in
 let y = id 5 in
 id (\z -> z + y)) :: Int -> Int
```

we had to guess that the type of `id` should be generalized into

```
forall a . a -> a
```

Let's deal with problem 1 first

41

Constraint-based type inference

```
-- oh, now we know!
[T-Var]-----
[x:?] |- x: Int    [x:?] |- 1 :: Int
[T-Add]-----
[x:?] |- x + 1 :: ?? -- what should "?" be?
[T-Abs]-----
[] |- (\x -> x + 1) :: ? -> ??
```

Main idea:

1. Whenever you need to "guess" a type, don't.
 - just return a fresh type variable
 - *fresh* = not used anywhere else in the program
2. Whenever a rule *imposes a constraint* on a type (i.e. says it should have certain form):
 - try to find the right *substitution* for the free type vars to satisfy the constraint
 - this step is called **unification**

42

Example

Let's infer the type of $\lambda x \rightarrow x + 1$:

-- TEnv	Expression	Step	Subst	Inferred type
1 []	$\lambda x \rightarrow x + 1$	[T-Abs]	[]	
2 [x:a0]	$x + 1$	[T-Add]		
3	x	[T-Var]		a0
4	$x + 1$	unify a0 Int	[a0/Int]	
5 [x:Int]	1	[T-Num]		Int
6	$x + 1$	unify Int Int		
7	$x + 1$			Int
8 []	$\lambda x \rightarrow x + 1$			Int -> Int

43

Example

1. Infer the type of $(\lambda x \rightarrow x + 1)$ in [] (apply [T-Abs])
2. For the type of x , pick *fresh type variable* (say, a_0); infer the type of $x + 1$ in [x:a0] (apply [T-Add])
3. Infer the type of x in [x:a0] (apply [T-Var]); result: a_0
4. [T-Add] imposes a constraint: its LHS must be of type **Int**, so unify a_0 and **Int** and update the *current substitution* to [a0 / Int]
5. Apply the current substitution [a0/Int] to the type environment [x:a0] to get [x:Int]. Infer the type of 1 in [x:Int] (apply [T-Num]); result: **Int**
6. [T-Add] imposes a constraint: its RHS must be of type **Int**, so unify **Int** and **Int**; current substitution doesn't change
7. By conclusion of [T-Add]: return **Int** as the inferred type
8. By conclusion of [T-Lam]: return **Int -> Int** as the inferred type

44

Unification

The **unification** problem: given two types **T1** and **T2**, find a type substitution **U** such that $U T1 = U T2$.

Such a substitution is called a *unifier* of **T1** and **T2**

Examples:

The unifier of:

```
a      and Int      is [a / Int]
a -> a  and Int -> Int is [a / Int]
a -> Int and Int -> b  is [a / Int, b / Int]
Int     and Int      is []
a       and a        is []
Int     and Int -> Int cannot unify!
Int     and a -> a    cannot unify!
a       and a -> a    cannot unify!
```

45

QUIZ

What is the unifier of the following two types? *

1. $a \rightarrow \text{Int} \rightarrow \text{Int}$
2. $b \rightarrow c$

- (A) Cannot unify
- (B) $[a / \text{Int}, b / \text{Int} \rightarrow \text{Int}, c / \text{Int}]$
- (C) $[a / \text{Int}, b / \text{Int}, c / \text{Int} \rightarrow \text{Int}]$
- (D) $[b / a, c / \text{Int} \rightarrow \text{Int}]$
- (E) $[a / b, c / \text{Int} \rightarrow \text{Int}]$



<http://tiny.cc/cse116-unify-ind>

46

QUIZ

What is the unifier of the following two types? *

1. $a \rightarrow \text{Int} \rightarrow \text{Int}$
2. $b \rightarrow c$

- (A) Cannot unify
- (B) $[a / \text{Int}, b / \text{Int} \rightarrow \text{Int}, c / \text{Int}]$
- (C) $[a / \text{Int}, b / \text{Int}, c / \text{Int} \rightarrow \text{Int}]$
- (D) $[b / a, c / \text{Int} \rightarrow \text{Int}]$
- (E) $[a / b, c / \text{Int} \rightarrow \text{Int}]$



<http://tiny.cc/cse116-unify-grp>

47

QUIZ

(C), (D) and (E) are all unifiers!

But somehow (D) and (E) are *better* than (C)

- they make the *least commitment* required to make these types equal
- this is called the **most general unifier**

48

Infer: take 2

Let's add constraint-based typing to infer!

```
-- | Now has to keep track of current substitution!
infer :: Subst -> TypeEnv -> Expr -> (Subst, Type)
infer sub _ (ENum _) = (sub, TInt)
infer sub tEnv (EVar var) = (sub, lookup var tEnv)

-- Lambda case: simply generate fresh type variable!
infer sub tEnv (ELam x e) = (sub1, tX' :=> tBody)
  where
    tEnv' = extendTEEnv x tX tEnv
    tX = freshTV -- we'll get to this
    (sub1, tBody) = infer sub tEnv' e
    tX' = apply sub1 tX
```

49

Infer: take 2

```
-- Add case: recursively infer types of operands
-- and enforce constraint that they are both Int
infer sub tEnv (EAdd e1 e2) = (sub4, TInt)
  where
    (sub1, t1) = infer sub tEnv e1 -- 1. infer type of e1
    sub2 = unify sub1 t1 Int -- 2. constraint: t1 is Int
    tEnv' = apply sub2 tEnv -- 3. apply subst to context
    (sub3, t2) = infer sub2 tEnv' e2 -- 4. infer e2 type in new ctx
    sub4 = unify sub3 t2 Int -- 5. constraint: t2 is Int
```

Why are all these steps necessary? Can't we just return (sub, TInt)?

50

QUIZ

Which of these programs will type-check if we skip step 3? *

```
infer sub tEnv (EAdd e1 e2) = (sub4, TInt)
  where
    (sub1, t1) = infer sub tEnv e1 -- 1. infer type of e1
    sub2 = unify sub1 t1 Int -- 2. enforce constraint: t1 is Int
    tEnv' = apply sub2 tEnv -- 3. apply substitution to context
    (sub3, t2) = infer sub2 tEnv' e2 -- 4. infer type of e2 in new ctx
    sub4 = unify sub3 t2 Int -- 5. enforce constraint: t2 is Int
```

- (A) 1 2 + 3
- (B) 1 + 2 3
- (C) $(\lambda x \rightarrow x) + 1$
- (D) $1 + (\lambda x \rightarrow x)$
- (E) $\lambda x \rightarrow x + x 5$



<http://tiny.cc/cse116-infer-ind>

51

QUIZ

Which of these programs will type-check if we skip step 3? *

```
infer sub tEnv (EAdd e1 e2) = (sub4, TInt)
where
  (sub1, t1) = infer sub tEnv e1 -- 1. infer type of e1
  sub2      = unify sub1 t1 Int -- 2. enforce constraint: t1 is Int
  tEnv'     = apply sub2 tEnv  -- 3. apply substitution to context
  (sub3, t2) = infer sub2 tEnv' e2 -- 4. infer type of e2 in new c.t.x
  sub4      = unify sub3 t2 Int -- 5. enforce constraint: t2 is Int
```

- (A) 1 2 + 3
- (B) 1 + 2 3
- (C) (x -> x) + 1
- (D) 1 + (x -> x)
- (E) \x -> x + x 5



<http://tiny.cc/cse116-infer-grp>

52

QUIZ

Answer: E.

A fails in step 1 (LHS is ill-typed);

B fails in step 4 (RHS is ill-typed);

C fails in step 2 (LHS is not `Int`);

D fails in step 5 (RHS is not `Int`);

finally, E should fail because LHS and RHS by themselves are fine, but not together!

53

Fresh type variables

```
-- | Now has to keep track of current substitution!
infer :: Subst -> TypeEnv -> Expr -> (Subst, Type)
```

```
-- Lambda case: simply generate fresh type variable!
infer tEnv (ELam x e) = tX :=> tBody
where
  tEnv' = extendTEEnv x tX tEnv
  tX    = freshTV -- how do we do this?
  tBody = infer tEnv' e
```

Intended behavior:

- First time we call `freshTV` it returns `a0`
- Second time it returns `a1`
- .. and so on

Can we do that in Haskell?

No, Haskell is pure. Have to thread the counter through :(

54

Polymorphism: the final frontier

Back to double identity:

```
let id = \x -> x in -- Must generalize the type of id
let y = id 5 in -- Instantiate with Int
id (\z -> z + y) -- Instantiate with (Int -> Int)
```

- When should we to generalize a type like $a \rightarrow a$ into a polymorphic type like $\text{forall } a . a \rightarrow a$?
- When should we instantiate a polymorphic type like $\text{forall } a . a \rightarrow a$ and with what?

55

Polymorphism: the final frontier

Generalization and instantiation:

- Whenever we infer a type for a let-defined variable, generalize it!
 - it's safe to do so, even when not strictly necessary
- Whenever we see a variable with a polymorphic type, instantiate it
 - with what type?
 - well, what do we use when we don't know what type to use?
 - *fresh type variables!*

56

Example

Let's infer the type of `let id = \x -> x in id 5`:

-- TEnv	Expression	Step	Subst	Type
1 []	let id=\x->x in id 5	[T-Let]	[]	
2	\x->x	[T-Abs]		
3 [x:a0]	x	[T-Var]		a0
4	\x->x			a0 -> a0
5 []	let id=\x->x in id 5	generalize a0		
6 tEnv	id 5	[T-App]		
7	id	[T-Var]		
8	id	instantiate		a1 -> a1
9	5	[T-Num]		Int
10	id 5	unify (a1->a1)	(Int->a2) [a1/Int, a2/Int]	
10	id 5			Int
11 []	let id=\x->x in id 5			Int

Here tEnv = [id : forall a0.a0->a0]

57

What we learned this week

Type system: a set of rules about which expressions have which types

Type environment (or context): a mapping of variables to their types

Polymorphic type: a type parameterized with type variables that can be instantiated with any concrete type

Type substitution: a mapping of type variables to types; you can **apply** a substitution to a type by replacing all its variables with their values in the substitution

Unifier of two types: a substitution that makes them equal; **unification** is the process of finding a unifier

58

What we learned this week

Type inference: an algorithm to determine the type of an expression

Constraint-based type inference: a type inference technique that uses fresh type variables and unification

Generalization: turning a mono-type with free type variables into a polymorphic type (by binding its variables with a forall)

Instantiation: turning a polymorphic type into a mono-type by substituting type variables in its body with some types

59
