CMPT 379
Compilers

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Goal of Semantic Analysis

- Ensure that program obeys certain kinds of sanity checks
  - all used variables are defined
  - types are used correctly
  - method calls have correct number and types of parameters and return value

Symbol Tables

- Symbol tables map **identifiers** (strings) to **descriptors** (information about identifiers)
- Basic Operation: Lookup
  - Given a string, find a descriptor
  - Typical Implementation: hash table
- Examples
  - Given a class name, find class descriptor
  - Given variable name, find descriptor
  - local descriptor, parameter descriptor, field descriptor

Parameter Descriptors

- When build parameter descriptor, have
  - name of type
  - name of parameter
- What is the check? Must make sure name of type identifies a valid type
  - look up use of identifier (in context) in the symbol table
  - if not there, fails semantic check

Local Symbol Table

- When building a local symbol table, have a list of local descriptors
- What to check for?
  - duplicate variable names
  - shadowed variable names
- When to check?
  - when descriptor is inserted into the local symbol table
- Parameter and field symbol tables are similar

Symbol Tables

- Compilers use symbol tables to produce:
  - Object layout in memory
  - Code to
    - Access Object Fields
    - Access Local Variables
    - Access Parameters
    - Invoke methods

Hierarchy In Symbol Tables

- Hierarchy Comes From
  - Nested Scopes: Local scope inside field scope
  - Inheritance: Child class inside parent class
- Nested scopes are annotations on the parse tree
- Symbol table hierarchy reflects the hierarchy
- Lookup proceeds up hierarchy until descriptor is found

Liveness Analysis

- Hierarchy in symbol tables can be implemented in various ways:
  - Using the nodes in the parse tree as part of the descriptor, and using bottom-up traversal from the variable use to detect valid use
  - Based on the local scoping binding for identifiers can be inserted and then after they go out of scope, the binding is deleted from the symbol table

Load Instruction

- Check instructions that store values into variables
- Source contains identifier with variable name
- Look up variable name:
  - If in local symbol table, reference local descriptor
  - If in parameter symbol table, reference parameter descriptor
  - If in field symbol table, reference field descriptor
  - If not found, semantic error

Load Array Instruction

- Check instructions that load array variables
  - Variable name
  - Array index expression
- Semantic check:
  - Look up variable name (if not there, semantic error)
  - Check type of expression (if not integer, semantic error)

Binary operators

- Check instructions that combine two expressions with a binary operator like + or *
- What can go wrong?
  - expressions have wrong type
  - both must be integers (for example)
- So compiler checks type of expressions
  - load instructions record type of accessed variable
  - operations record type of produced expression
  - so just check types, if wrong, semantic error

Type Inference for Bin-op

- Most languages let you add floats, ints, doubles
- What are issues?
  - Types of result of add operation
  - Coercions on operands of add operation
- Standard rules usually apply
  - If add an int and a float, coerce the int to a float, do the add with the floats, and the result is a float.
  - If add a float and a double, coerce the float to a double, do the add with the doubles, result is double

Summary of Semantic Checks

- Do semantic checks when build IR
- Many correspond to making sure entities are there to build correct IR
- Others correspond to simple sanity checks
- Each language has a list that must be checked
- Can flag many potential errors at compile time

Type Systems

- So far we have seen simple cases of type checking and coercion
- Basic types for data types: *boolean*, *char*, *integer*, *real*
- A basic type for lack of a type: *void*
- A basic type for a type error: *type_error*
- Based on these basic types we can build new types using type constructors

Type Constructors

- Arrays: int p[10];
  - type: *array(10, integer)*
- Products/tuples: pair<int, char> p(10,'a');
  - type: $integer \times char$
- Records: struct { int p; char q; } data;
  - Type: $record((p \times integer) \times (q \times char))$
- Pointers: int *p;
  - Type: *pointer(integer)*

Type Constructors

- Functions: int foo (int p, char q) { return 2; }
  - Type: $integer \times char \rightarrow int$
  - A function maps elements from the domain to the range
  - Function types map a domain type D to a range type R
  - A type for a function is denoted by $D \rightarrow R$
- In addition, type expressions can contain type variables
  - Example: $\alpha \times \beta \rightarrow \alpha$

Equivalence of Type Exprs

- Check equivalence of type exprs: s and t
- If s and t are basic types, then return true
- If $s = array(s_1, s_2)$ and $t = array(t_1, t_2)$ then return true if equal(s_1, t_1) and equal(s_2, t_2)
- If s = $s_1 \times s_2$ and $t = t_1 \times t_2$ then return true if equal(s_1, t_1) and equal(s_2, t_2)
- If $s = pointer(s_1)$ and $t = pointer(t_1)$ then return true if equal(s_1, t_1)

Polymorphic Functions

- Consider the following ML program:

```
fun null [] = true
  | null (_::_) = false;
fun tl (_::xs) = xs;
fun length (alist) =
    if null(alist) then 0
    else length(tl(alist)) + 1;
```

- *null* tests if a list is empty
- *tl* removes first element and returns rest

Polymorphic Functions

- *length* is a polymorphic function (different from polymorphism in object inheritance)
- The function *length* accepts lists with elements of any basic type:

  length([‘a’, ‘b’, ‘c’])

  length([1, 2, 3])

  length([1,2,3], [4,5,6])
- The type for *length* is *list(α)* $\rightarrow$ *integer*
- α can stand for any basic type: *integer* or *char*

Polymorphic Functions

- Consider the following ML program:

  fun *map f [] = []*

  | *map f (x::xs) = (f(x)) :: map f xs;*

- *map* takes two arguments: a function *f* and a list
- It applies *f* to each element of the list and creates a new list with the range of *f*
- Type of *map*: $(\alpha \rightarrow \beta) \rightarrow list(\alpha) \rightarrow list(\beta)$

Type Inference

- *Type inference* is the problem of determining the type of a statement from its body
- Similar to type checking and coercion
- But inference can be much more expressive when type variables can be used
- For example, the type of the *map* function on previous page uses type variables

Type Variable Substitution

- We can take a type variable in a type expression and substitute a value
- In *list(α)* we can substitute the type *integer* for the variable α to get *list(integer)*
- *list(integer)* < *list(α)* means *list(integer)* is an instance of *list(α)*
- *S(t)* is a substitution for type expr *t*
- Replacing *integer* for α is a substitution

Type Variable Substitution

- $s < t$ means s is an instance of t
- Or s is more specific than t
- Or t is more general than s
- Some more examples:
  - $integer \rightarrow integer < \alpha \rightarrow \alpha$
  - $(integer \rightarrow integer) \rightarrow (integer \rightarrow integer) < \alpha \rightarrow \alpha$
  - $list(\alpha) < \beta$
  - $\alpha < \beta$

Type Expr Unification

- Incorrect type variable substitutions:
  - *integer* < *boolean*
  - *integer* → *boolean* < α → α
  - *integer* → α < α → α
- In general, there are many possible substitutions
- Type exprs *s* and *t* unify if there is a substitution *S* that is most general such that *S(s)* = *S(t)*
- Such a substitution *S* is the *most general unifier* which imposes the fewest constraints on variables

Example of Type Inference

- Example:

  fun *length (alist) =*

  if *null(alist)* ***then*** *0*

  else *length(tl(alist)) + 1;*

- *length* : α_1
- *null* : *list*(α_2) $\rightarrow$ *boolean*
- *alist* : *list*(α_2)
- *null(alist)* : *boolean*

Example (cont'd)

- $0 : integer$
- $tl : list(\alpha_3) \rightarrow list(\alpha_3)$
- $tl(alist) : list(\alpha_2)$
- $length : list(\alpha_2) \rightarrow \alpha_4$ $\qquad list(\alpha_2) \rightarrow \alpha_4 < \alpha_1$
- $length(tl(alist)) : \alpha_4$
- $1 : integer$
- $+ : integer \times integer \rightarrow integer$ $\qquad integer < \alpha_5$
- $if : boolean \times \alpha_5 \times \alpha_5 \rightarrow \alpha_5$
- $length : list(\alpha_2) \rightarrow integer$ $\qquad integer < \alpha_4$

Unification

- Algorithm for finding the ***most general substitution*** S such that $S(s) = S(t)$
- Also called the ***most general unifier***
- *unify(m, n)* unifies two type exprs *m* and *n* and returns true/false if they can be unified
- Side effect is to keep track of the *mgu* substitution for unification to succeed

Unification Algorithm

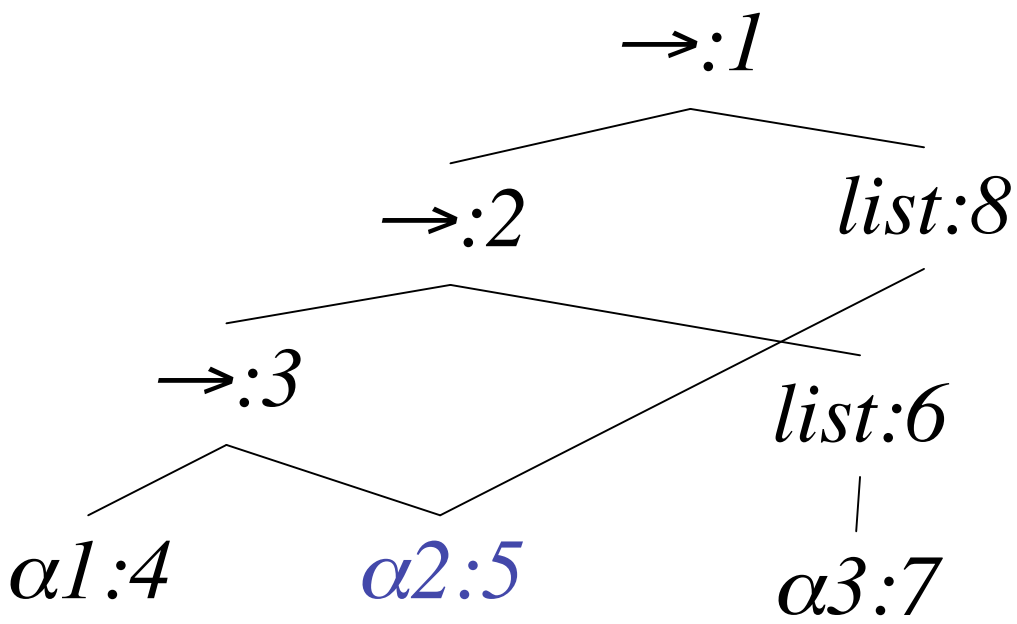
- We will explain the algorithm using an example:
  - E: $((\alpha 1 \rightarrow \alpha 2) \rightarrow list(\alpha 3)) \rightarrow list(\alpha 2)$
  - F: $((\alpha 3 \rightarrow \alpha 4) \rightarrow list(\alpha 3)) \rightarrow \alpha 5$
- What is the most general unifier?
  - $S_1(E) = S_1(F)$ $((\alpha 1 \rightarrow \alpha 1) \rightarrow list(\alpha 1)) \rightarrow list(\alpha 1)$

√ – $S_2(E) = S_2(F)$ $((\alpha 1 \rightarrow \alpha 2) \rightarrow list(\alpha 1)) \rightarrow list(\alpha 2)$

√ – $S_3(E) = S_3(F)$ $((\alpha 3 \rightarrow \alpha 2) \rightarrow list(\alpha 3)) \rightarrow list(\alpha 2)$

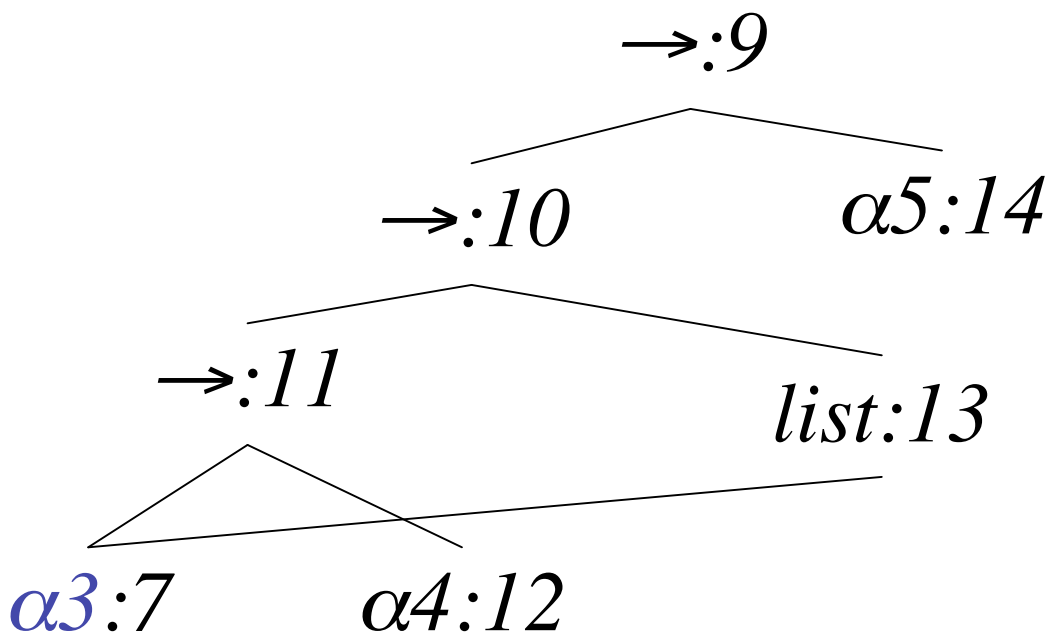
Unification Algorithm

E: $((\alpha 1 \rightarrow \alpha 2) \rightarrow list(\alpha 3)) \rightarrow list(\alpha 2)$

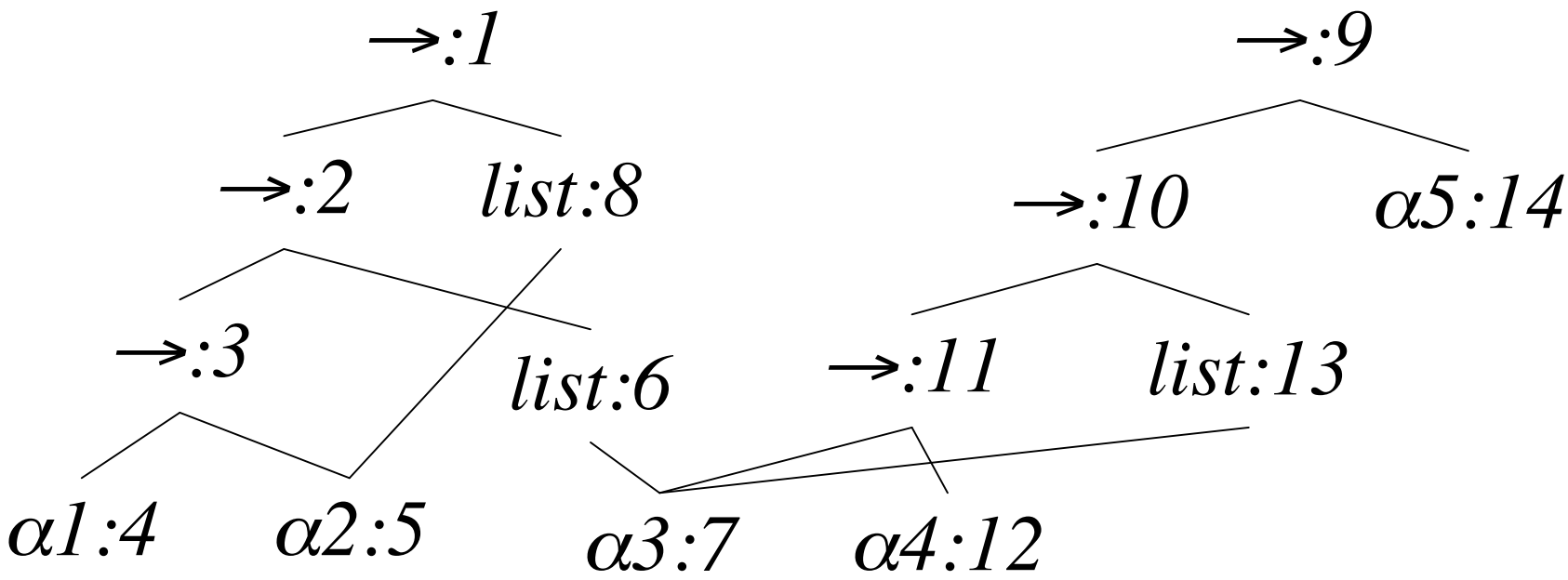


Unification Algorithm

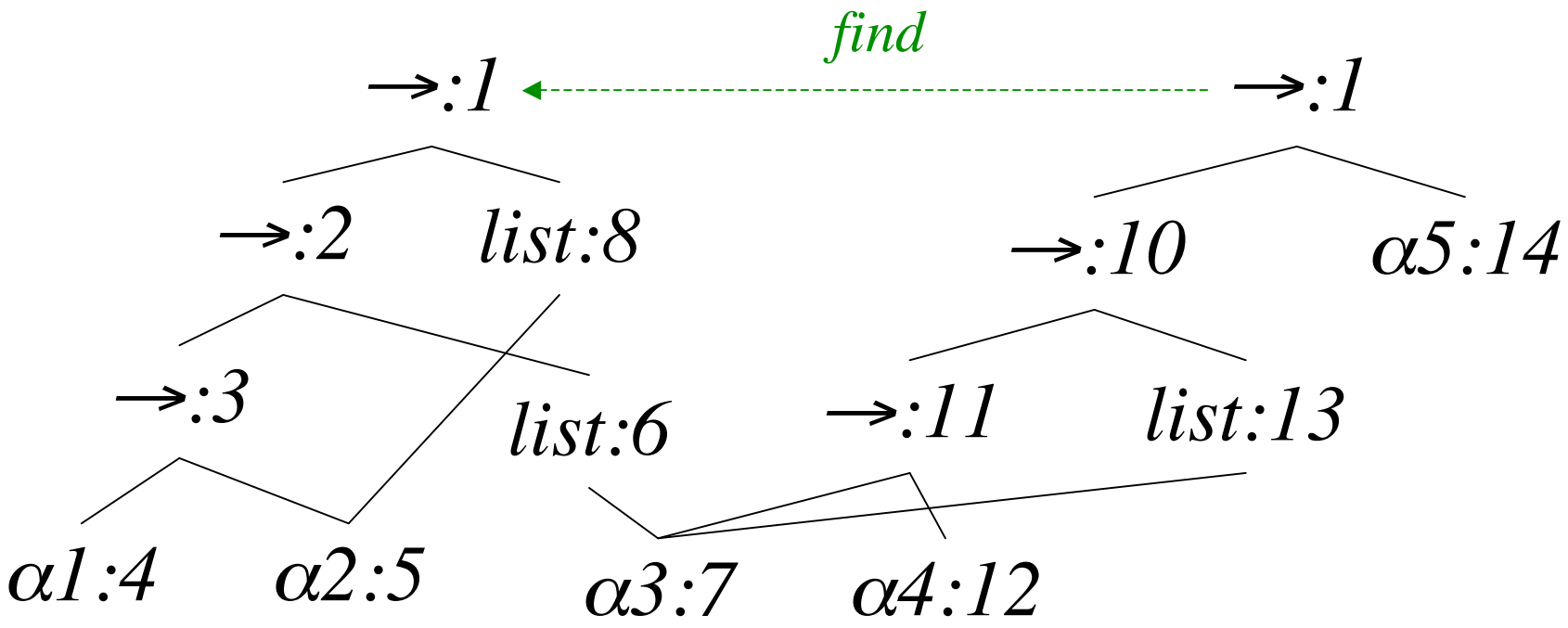
F: $((\alpha 3 \rightarrow \alpha 4) \rightarrow list(\alpha 3)) \rightarrow \alpha 5$



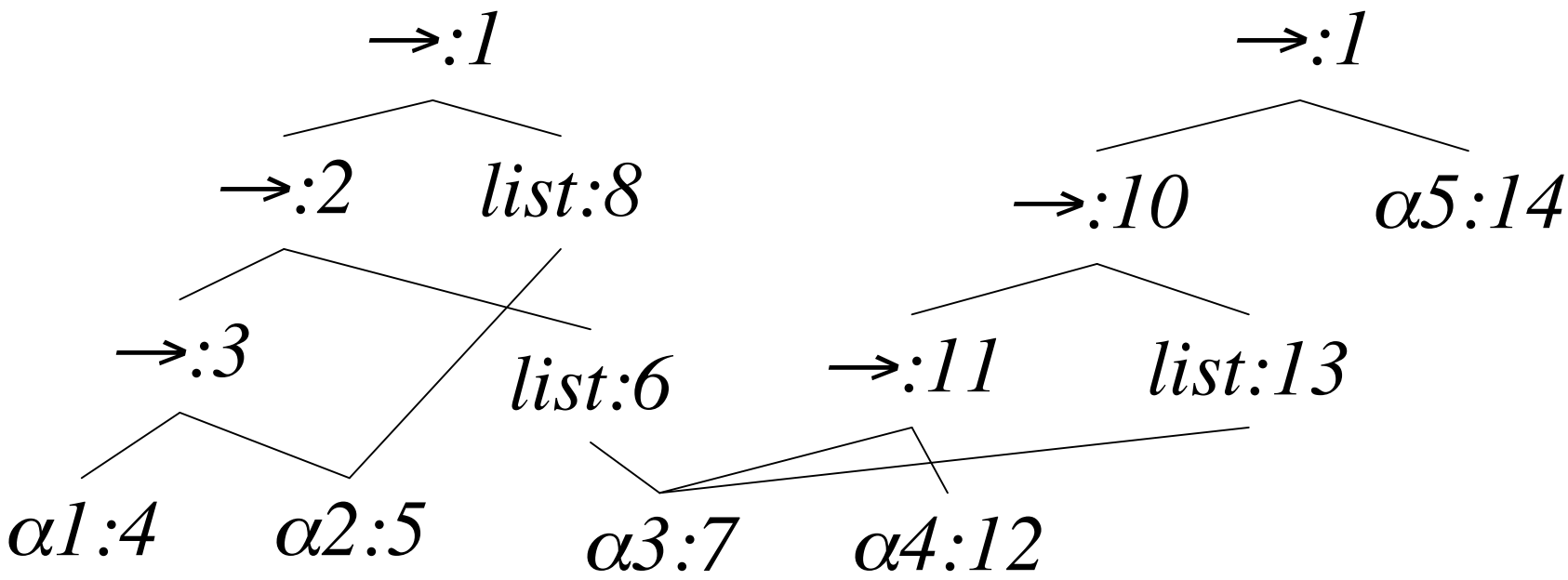
Unify(1,9)



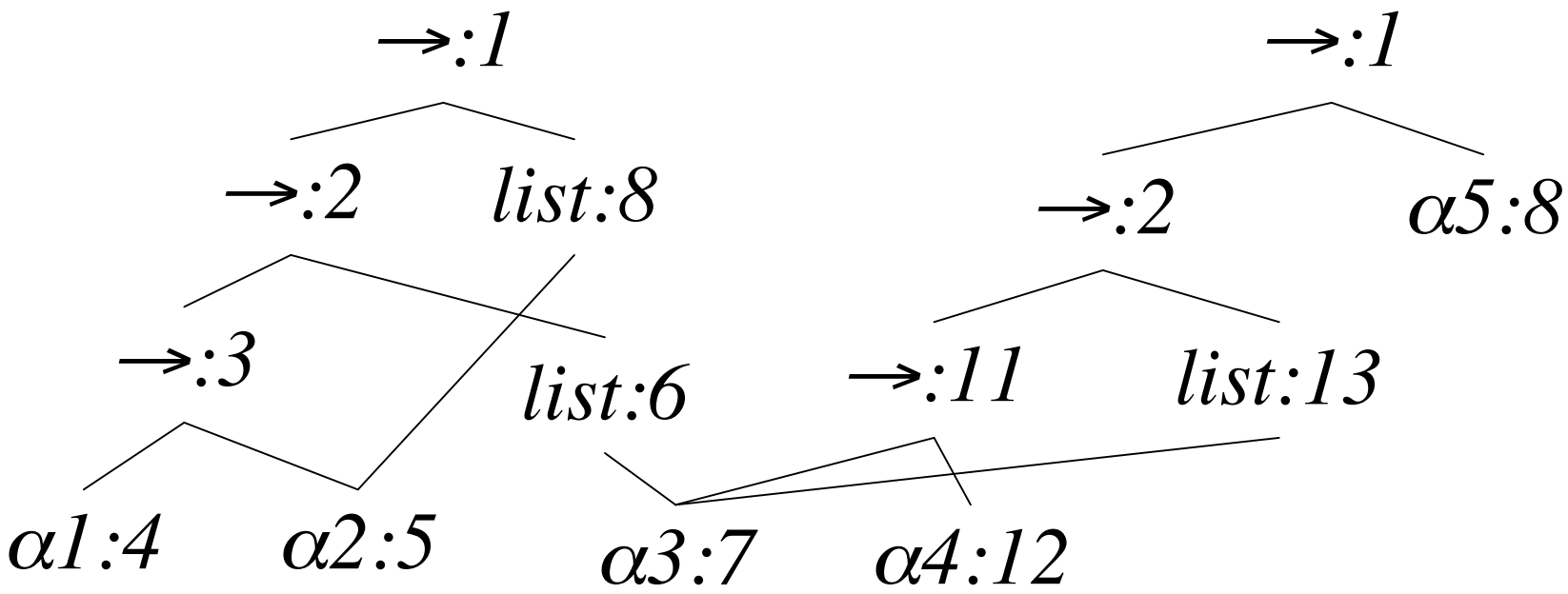
Unify(1,9)



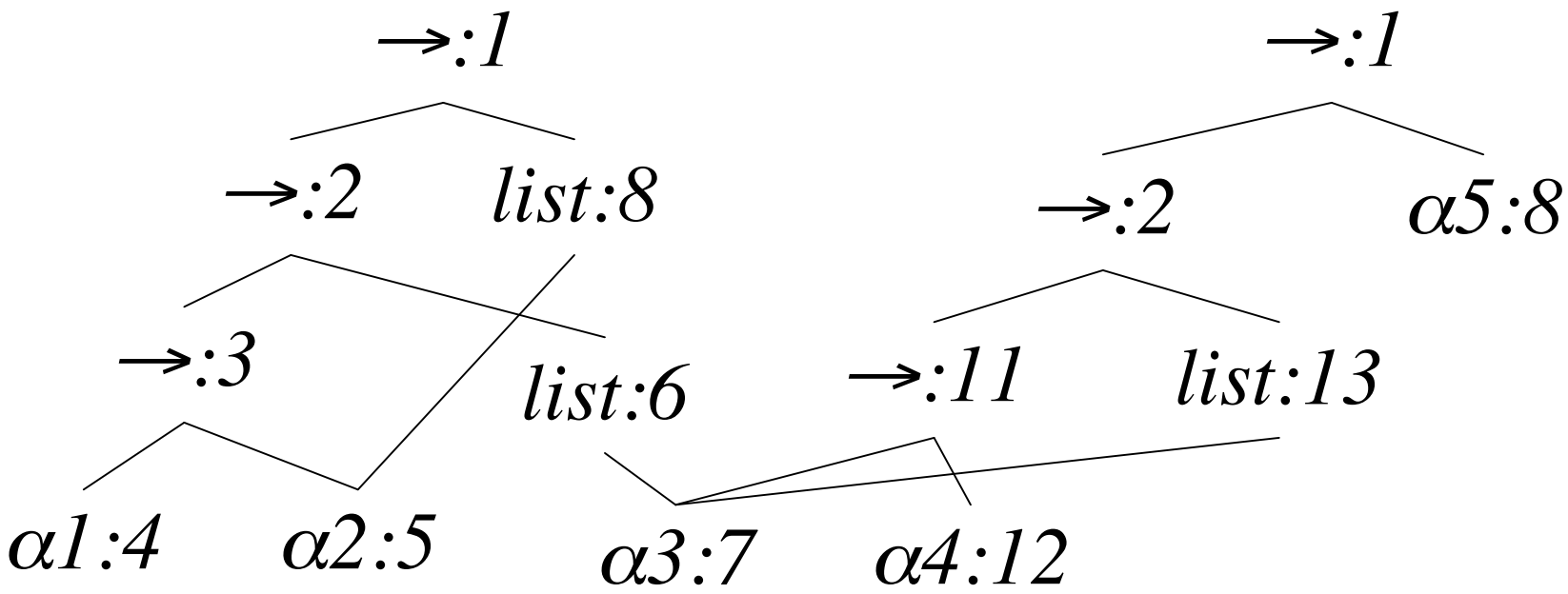
Unify(2,10) *and* Unify(8,14)



Unify(2,10) *and* Unify(8,14)



Unify(3,11) *and* Unify(6,13)



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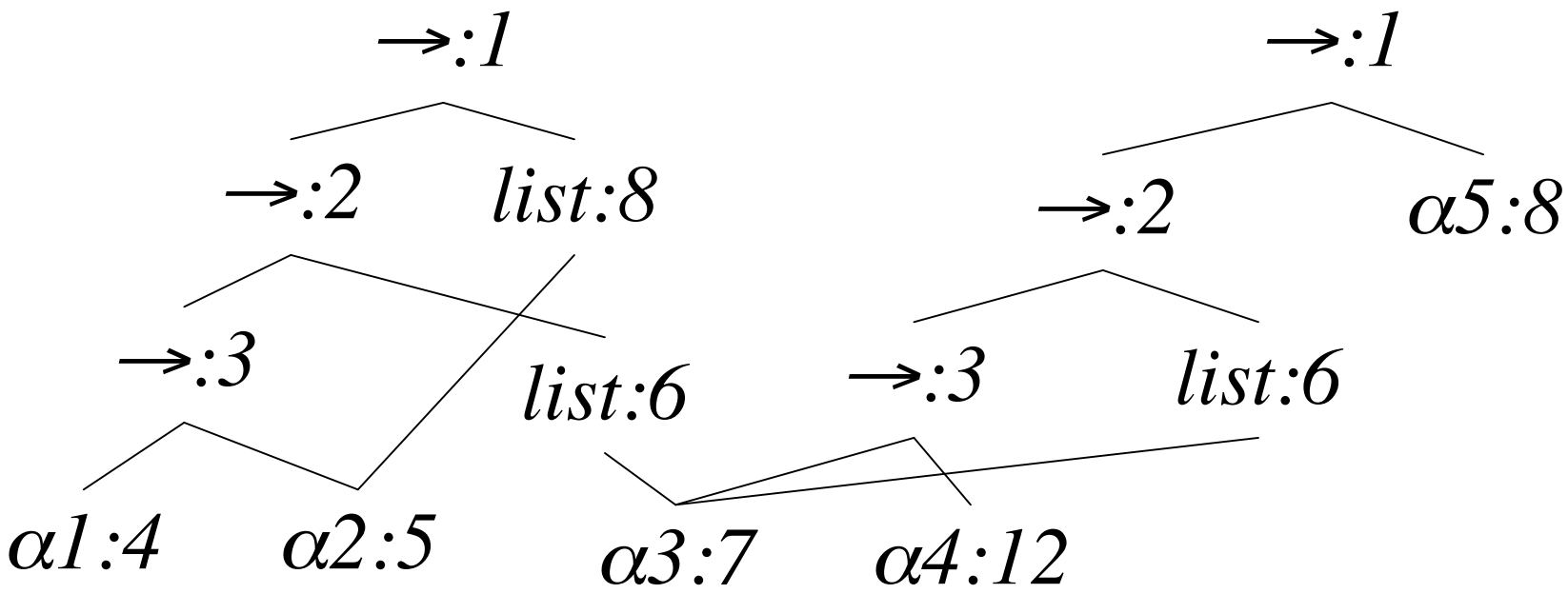
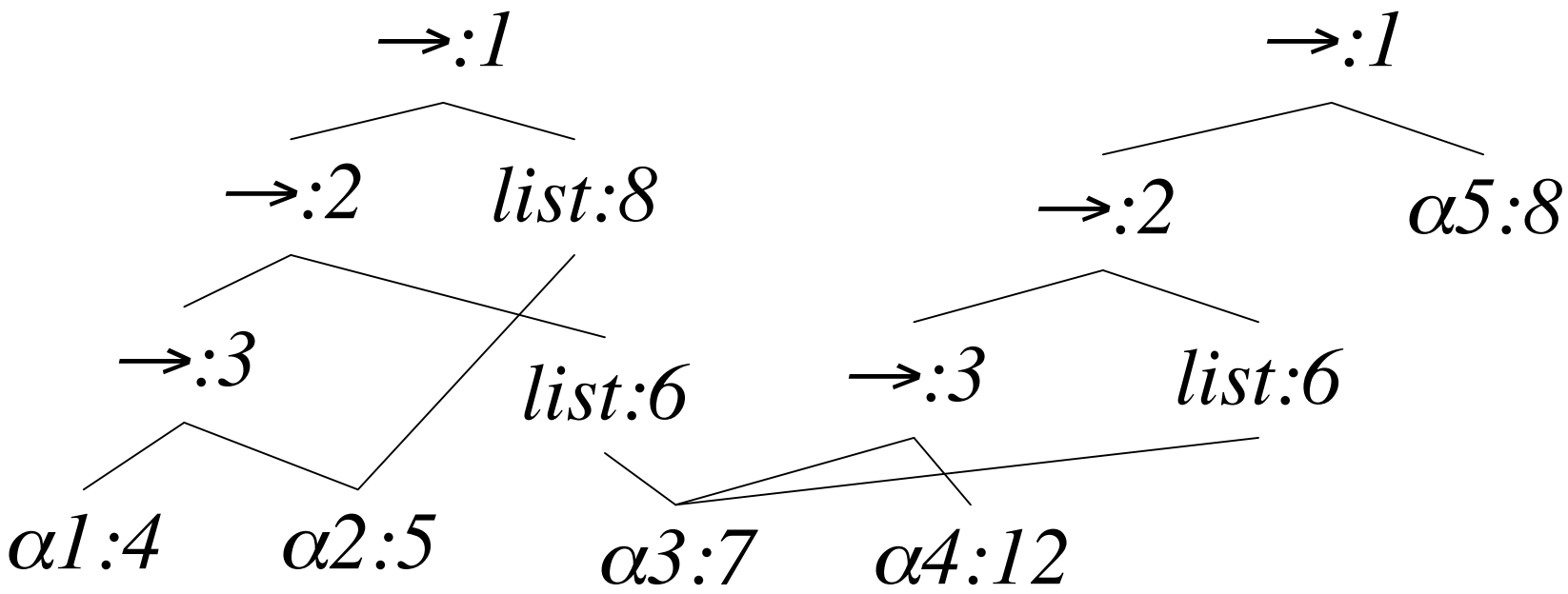
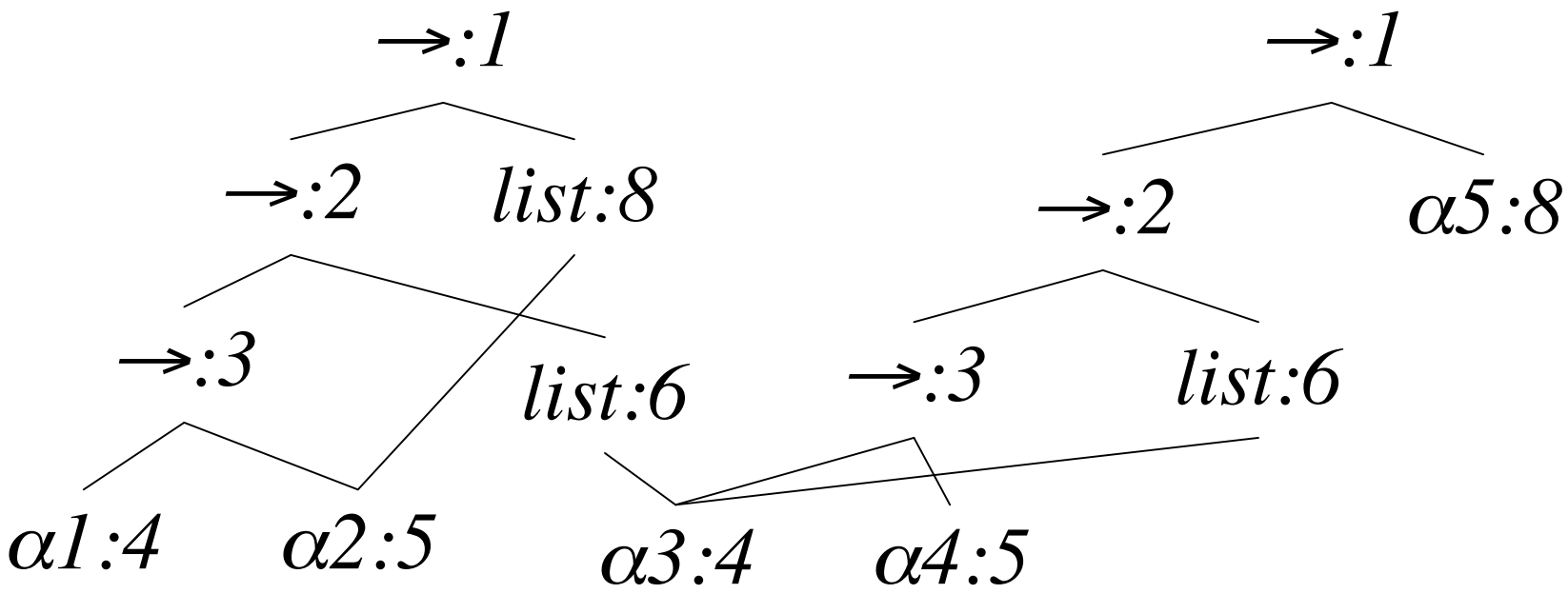


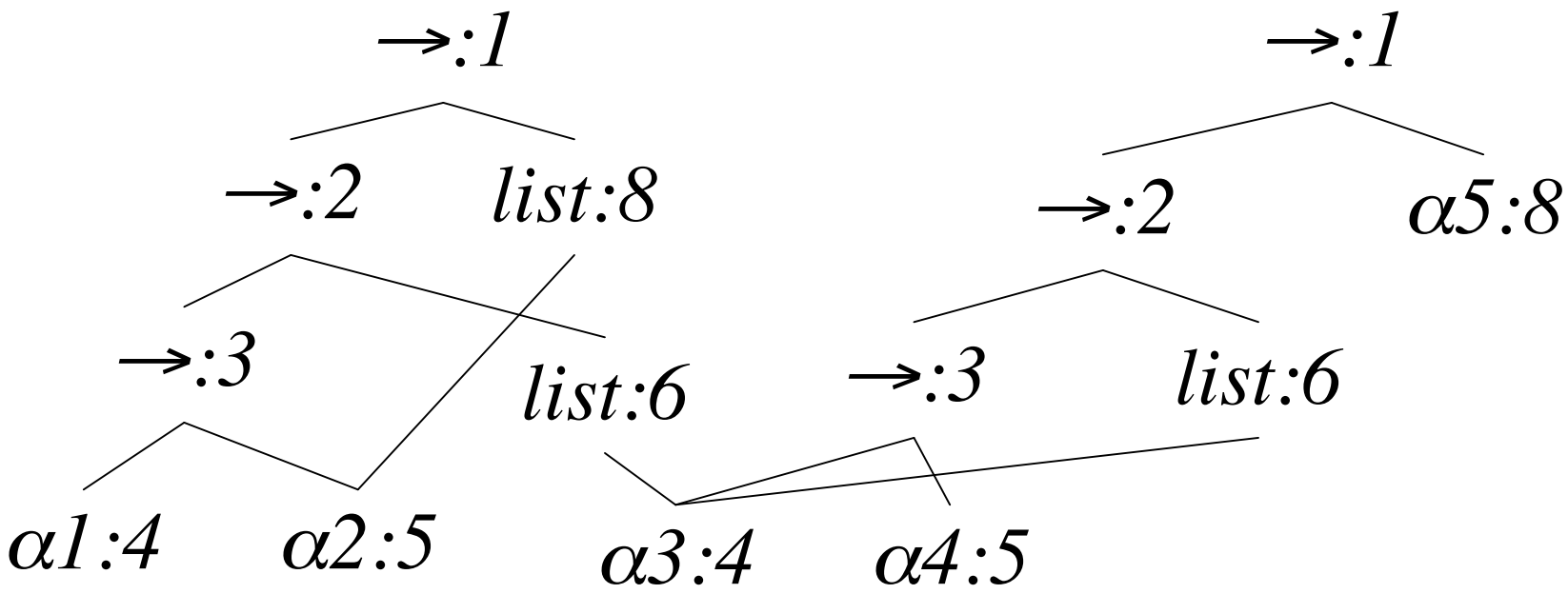
Unify(4,7) *and* Unify(5,12)



Unify(4,7) *and* Unify(5,12)



Unification success



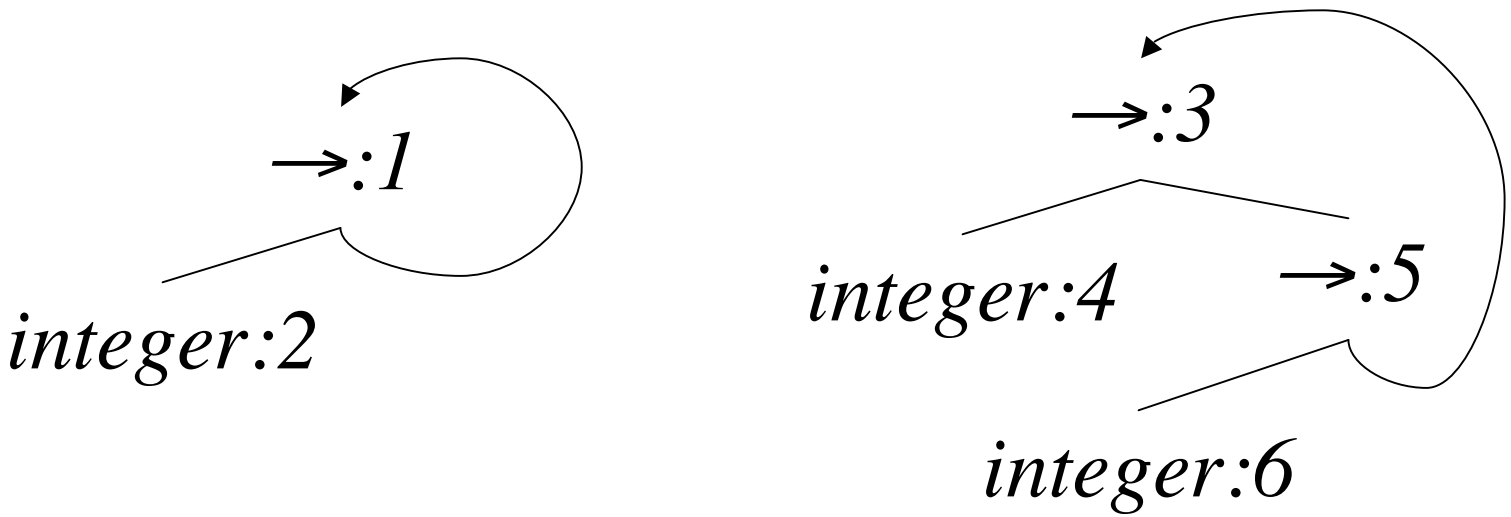
$((\alpha 1 \rightarrow \alpha 2) \rightarrow list(\alpha 1)) \rightarrow list(\alpha 2)$

Recursive type equivalence

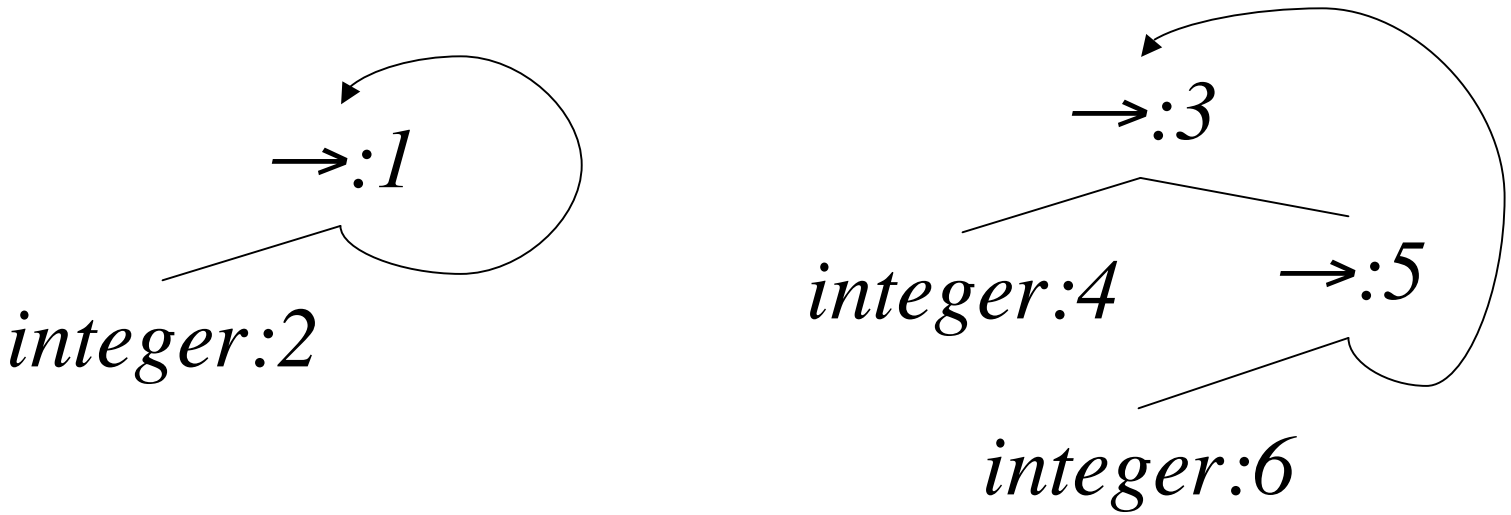
- Are these recursive type expressions equivalent:

  $\alpha 1 = integer \rightarrow \alpha 1$

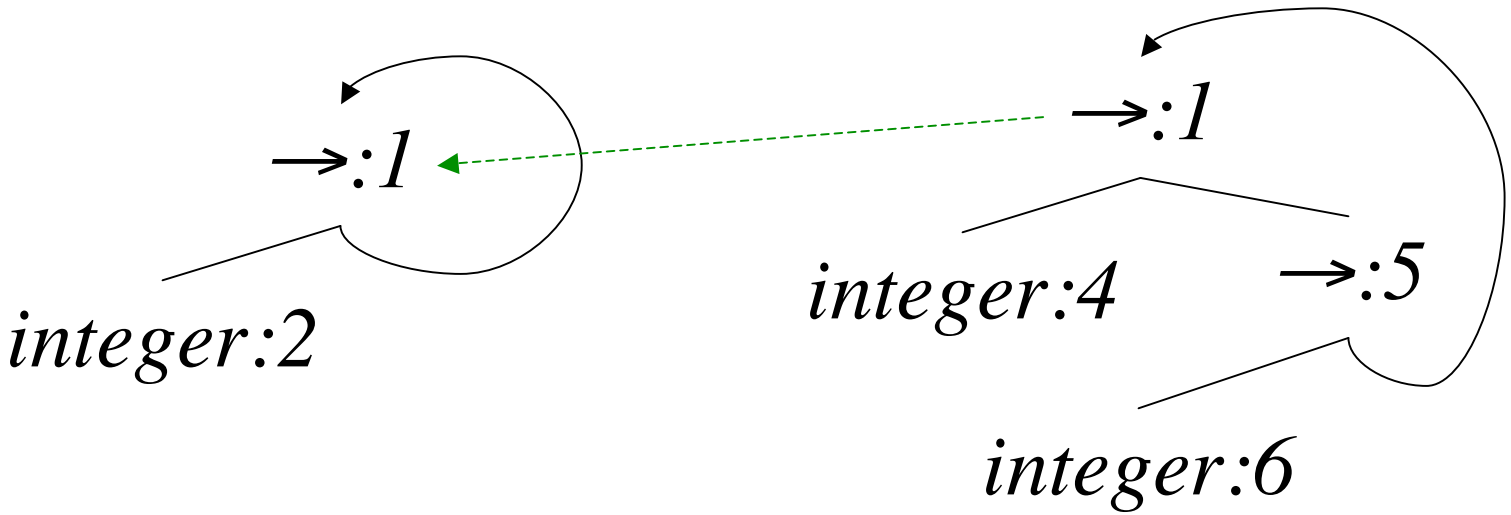
  $\alpha 2 = integer \rightarrow (integer \rightarrow \alpha 2)$



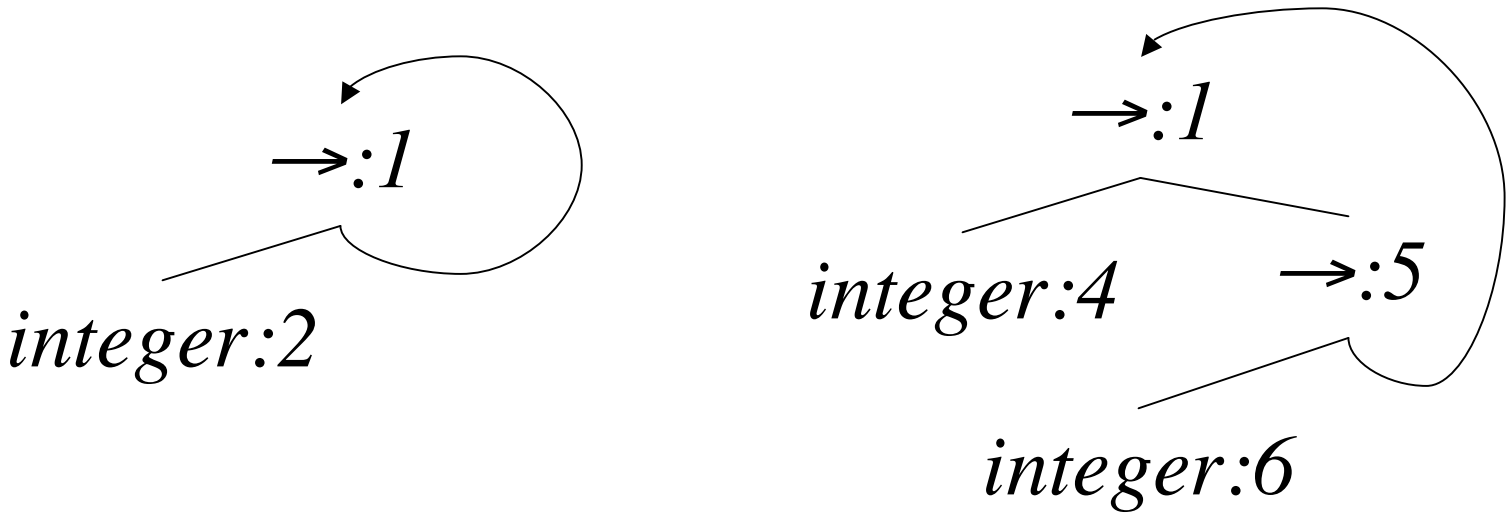
Unify(1,3)



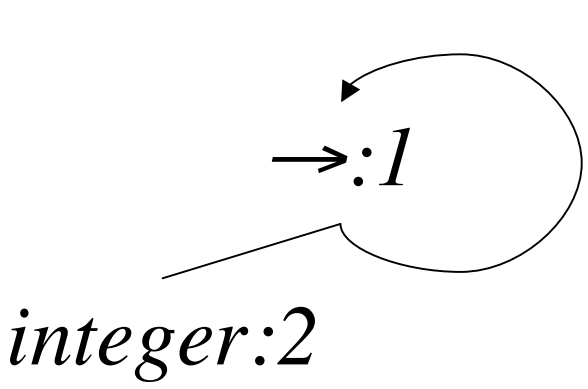
Unify(1,3)

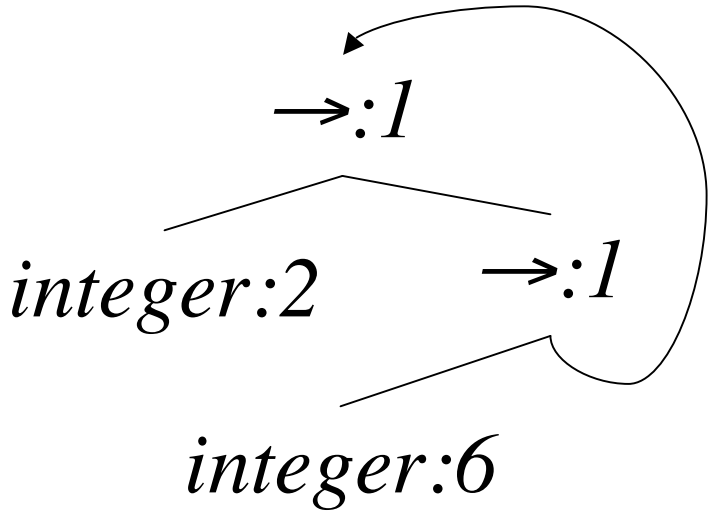


Unify(2,4) *and* Unify(1,5)

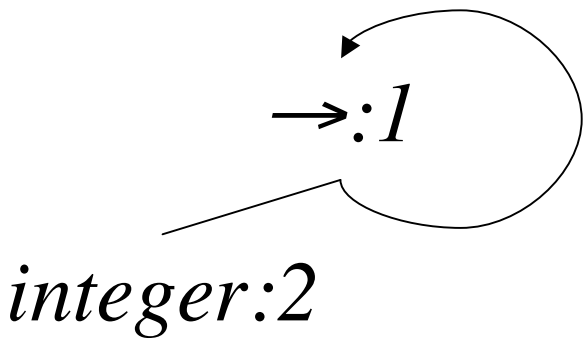


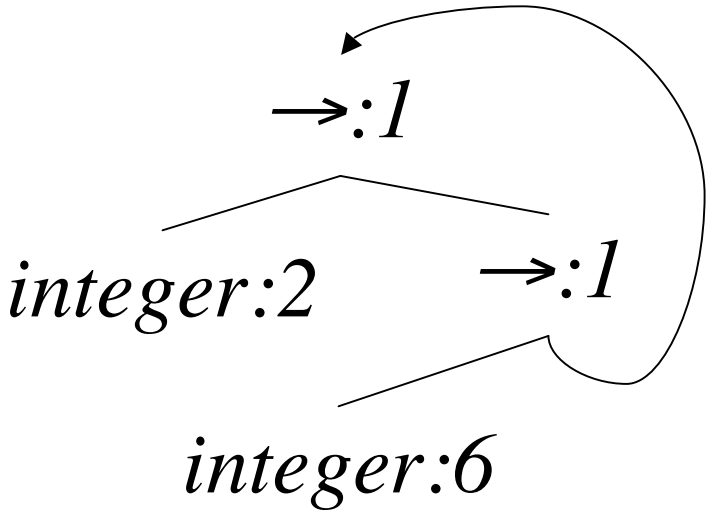
Unify(2,4) *and* Unify(1,5)





Unify(2,6) *and* Unify(1,1)





Unify(2,6) *and* Unify(1,1)