Heuristics for type error discovery and recovery

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Overview

1. Motivation and context
2. The heuristics
3. Examples
4. Implementation
5. Summary and validation

Context

- Strongly-typed, higher-order, polymorphic functional languages.
- Typically, type inferencers perform unifications during an AST traversal.
  - Results in a substitution or an error message.
- Unification merges a piece of type information into the substitution.
- Consequence: unifications towards the end of the program get the blame.
  - artifact of inferencing process, not programming
- When an error is discovered, we do not know how we got there.
- Constraint based type systems are certainly an improvement
  - (often) small and mobile pieces of information (reordering)
  - special solvers can be built for them, and reused a lot
- Still, type inferencing is done one constraint at the time (bias)

Contributions

- We consider sets of constraints at the time, not a single constraint
  - approximately a whole binding group at the time
- We map these to a special datastructure, a type graph
  - Essentially, it can also represent inconsistent sets of unifications
- This structure is amenable to the definition of various heuristics
  - general heuristics
  - programming language dependent heuristics
  - programmer dependent heuristics
- We implemented quite a number of these (own, others, folklore)
  - It is easy to define and plug-in new heuristics
- Heuristics encapsulate *expert knowledge* and *remove bias*
- A voting mechanism decides between competing heuristics
- Debugging mechanism: see the Appendix of the paper

Additional benefits

- The usual for using constraints:
  - decoupling of type system specification and inference algorithm
  - many solvers can be defined, each with their own specialty
  - amenable to reuse: many languages use the same kind of constraints
- Global analysis gives more flexibility, and when done cleverly doesn't degrade efficiency much
- Outcome can help us determine which kind of mistakes are made most often
  - Simply consider which heuristic is used most (if used correctly)
  - Helium has a logging facility (60,000 programs thus far)

"Limitations"

- In this talk, I consider only sets of unification (equality) constraints.
- However, we do handle polymorphism (efficiently), but at a different level.
  - Between binding groups versus within binding groups
- I can tell you what we did, but not how.
  - More information in the paper, more in a technical report and even more in Bastiaan Heeren's PhD.

Haskell versus Helium

- A stronger limitation: Helium is a subset of Haskell
- Limited overloading:
  - overloading yes/no is an option
  - no user-definable classes and instances
  - only support for `Enum`,`Eq`,`Num`,`Ord`,`Show`, all instances derived
  - no overloading on numerals... ever.
- No records, $n + k$ patterns, `newtype`, qualified imports, literate programming,...
- Check the website for the current status

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We have much of Haskell98, but not all (making our life a little easier).

The list of heuristics (a selection)

- high participation rate [28 LOC]
  - enforces that when one int goes against ten booleans, the int loses
- Repair heuristics (selectors) with voting mechanism
  - sibling functions [43] and literals [40]
  - application heuristic [177]
  - tuple heuristic [50]
    - application like heuristic for tuples
  - function binding has too many arguments [32]
    - $f\ x = 0$ although $f :: Int$
  - variable function [40]
    - variable is not an application unless it has some arguments
- Tie breakers (if nothing else helps), mainly to avoid constraints
  - that should not be blamed [10] (type of let and type of body)
  - that are trusted [7] (explicit types, Prelude functions)
  - that give bad error messages [7] (folklore constraints)
- The final tie breaker: first come first blamed [5].

A first example

```
doubleList :: [Int] -> [Int]
doubleList xs = map (*2)
```

Second error message

```
(3,17): Type error in application
 expression        : map (* 2)
 term              : map
   type            : (a   -> b  ) -> [a] -> [b]
   does not match  : (Int -> Int) -> [Int]
 probable fix      : insert a second argument
```

Multi-example

```
elem :: a -> [a] -> Bool
elem = undefined

f :: a -> a
f = if (elem [1,3..] 2) then (\z -> z)
    else (\x -> x) == (\y -> y)
```

First error message

```
(5,9): Type error in application
 expression        : elem [1, 3 .. ] 2
 term              : elem
   type            : a      -> [a] -> Bool
   does not match  : [Int] -> Int -> Bool
 probable fix      : re-order arguments
```

Multi-example

```
elem :: a -> [a] -> Bool
elem = undefined

f :: a -> a
f = if (elem [1,3..] 2) then (\z -> z)
    else (\x -> x) == (\y -> y)
```

Second error message

```
(6,20): Type error in infix application
 expression       : (\x -> x) == (\y -> y)
 operator         : ==
   type           : Int      -> Int      -> Bool
   does not match : (a -> a) -> (b -> b) -> c -> c
```

Multi-example

```
elem :: a -> [a] -> Bool
elem = undefined

f :: a -> a
f = if (elem [1,3..] 2) then (\z -> z)
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Second error message

```
(6,20): Type error in infix application
 expression       : (\x -> x) == (\y -> y)
 operator         : ==
   type           : Int      -> Int      -> Bool
   does not match : (a -> a) -> (b -> b) -> c -> c
 probable fix     : use . instead        -- with siblings
```

Tie-breaker example

```
f :: Bool
f = (\x -> x) == (\y -> y)
```

Error message

```
(2,15): Type error in infix application
 expression        : (\x -> x) == (\y -> y)
 operator          : ==
   type            : Int      -> Int      -> Bool
   does not match  : (a -> a) -> (b -> b) -> Bool
```

Trusted constraint tie-breaker avoids suggesting to change type of ==

Heuristics

- Heuristics encapsulate expert knowledge on how to discover mistakes
- Many of them are obvious, folklore, or thought up by others,
  - but we implemented them within an infrastructure,
  - and added some of our own.
- What does a heuristic look like?
  - No time. Check out the Helium compiler or ask me to show you
  - I did give some code lengths earlier on
- How do we apply them?
  - basically a list of heuristic functions
  - applied in the given order
  - but some elements of this list can be lists with a voting mechanism.

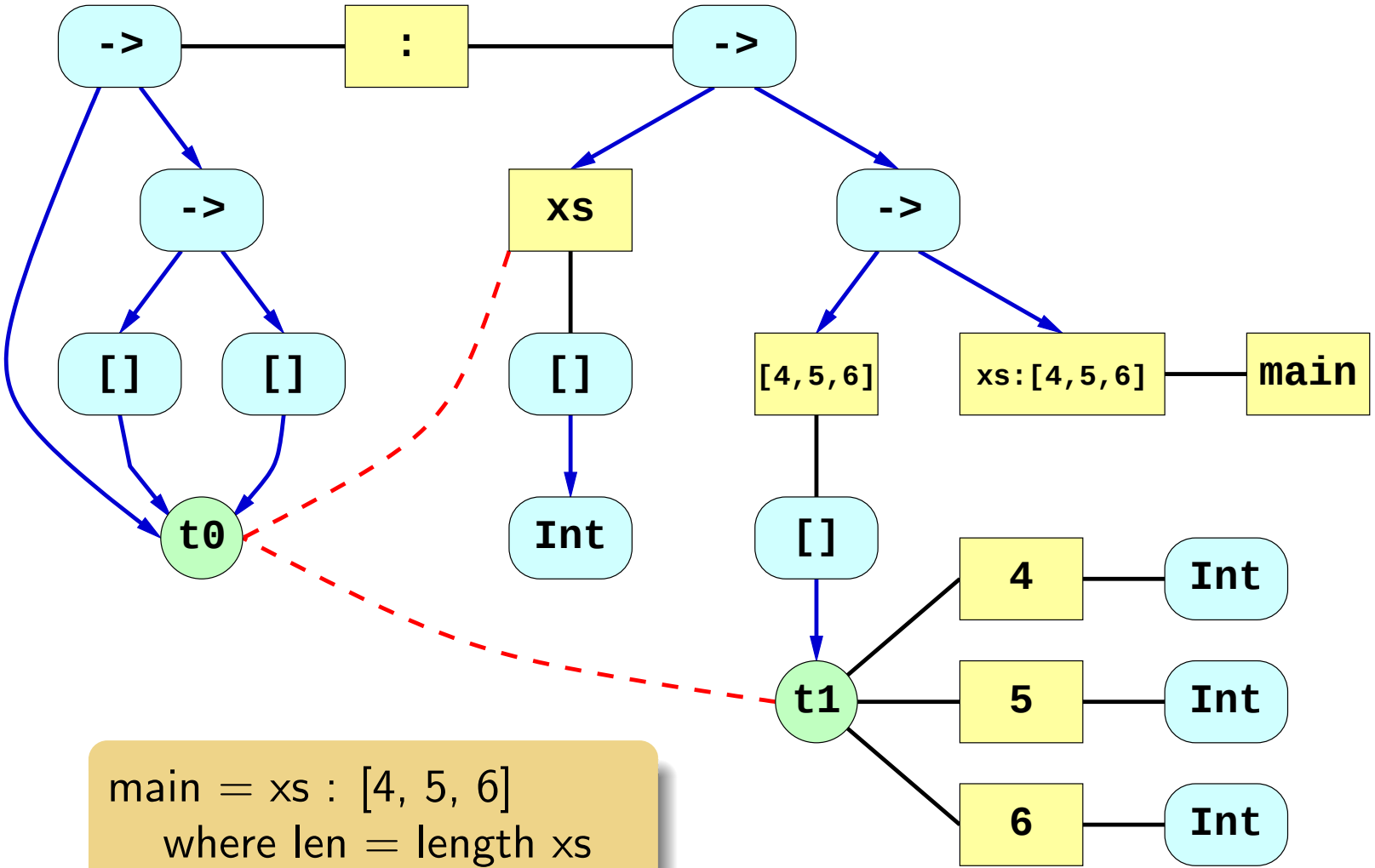
The list in Haskell form

```
listOfHeuristics siblings path =
[ highlyTrustedFilter
, highParticipation 0.95 path
] ++
[ Heuristic (Voting
      [ siblingFunctions siblings
      , similarLiterals
      , applicationEdge
      , tupleEdge
      , fbHasTooManyArguments
      , variableFunction])
] ++
[ applicationResult
, negationResult
, trustFactorOfConstraint
, isTopDownEdge
, positionInList]
```

Type graphs

- Global analysis by considering sets of constraints at the time.
- Polymorphic types have been instantiated.
  - Recall: type graph handles one binding group at the time.
- Indeed, in Helium we usually perform type inferencing greedily, solving one constraint at the time.
- Only when an error occurs in a binding group do we restart type inferencing *only* for that binding group.
- Heuristics are basically graph traversing algorithms
  - And relatively short and simple ones at that

Type graphs



main = xs : [4, 5, 6]
where len = length xs
xs = [1, 2, 3]

How are type graphs used?

- Consider a set of equivalence constraints
- Build the type graph:
  - every type constants, type variable and type application becomes a vertex
  - every constraint becomes an edge
  - but might give rise to derived edges: $a \rightarrow b \equiv b \rightarrow c$
- When two different type constants $(Int, \rightarrow)$ or type application are in the same clique:
  - consider paths between these vertices
  - remove edges (constraints) on these paths
  - until all such paths have disappeared.
- Heuristics help to discover which constraints should be removed.
- When all conflicts are resolved a substitution is easy to compute.

Complications

- Type graphs grow large quickly, and have many derived edges
  - Represent cliques explicitly, merge and split as needed
- Number of error paths grows fast too
  - If error path p contains q then removing a constraint from q also removes p
  - Avoid "detours" (see technical report)
- Infinite types need special treatment (see paper)
- Handling type synonyms

Summary

- We use type graphs for representing sets of equivalence constraints.
- Therefore we can "globally analyze" type constraints.
  - Global $\approx$ per binding group
- We implemented many heuristics, embedded in an infrastructure
  - Adding new heuristics is quite easy, the infrastructure is there
- Heuristics are
  - general ones (weighting),
  - programming language dependent (application), or
  - programmer dependent (siblings)

A small questionnaire

- Validation of our kind of work can only be done experimentally.
- What kind of experiment(ally derived information) would convince you that
  - it works?
  - it is useful?
- Let me know at your convenience.

Any questions?