Type Error Slicing

What is a type error and how do you locate one?

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Overview

- Concepts.
- Examples.
- Algorithms.
- Completeness and Minimality.
- Conclusion.
Consider this Standard ML (SML) fragment:

\[
\text{fn } x \Rightarrow \text{fn } y \Rightarrow \text{let } \text{val } w = x + 1 \\text{in } w::y \text{ end}
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Algorithm $M$ algorithm gives this location:

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Most existing compilers make no effort to accurately locate type errors.

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As a result, many programmers find type error messages unhelpful, especially for higher-order languages with implicit typing.

For example, a comp.lang.ml posting:

“Even though I have some experience with SML/NJ and OCaml, I often find myself mired in type errors that take me forever to resolve.”
For each type error:

- Identify *all* program points that contribute to the error.
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Type Error Slices to the Rescue

For each type error:

- Identify all program points that contribute to the error.
- Display this set of program points or a program slice as the error location.

The error slice should have the following properties:

- **Completeness.** The error should be explainable independently, just by looking at the slice.
- **Minimality.** Every proper subslice should be type-error-free.
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Example 1

val average = fn weight => fn list => let
val iterator = fn (x,(sum,length)) => (sum + weight x , length+1)
   val (sum,length) = foldl iterator (0,0) list
in sum div length end end

val find_best = fn weight => fn lists => let
val average = average weight
val iterator = fn (list,(best,max)) =>
   let val avg_list = average list
   in if avg_list > max then (list,avg_list)
   else (best,max)
   end
   val (best,_)) = foldl iterator (nil,0) lists
in best end end

val find_best_simple = find_best 1
An Incomplete Error Location

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    val (best,_) = foldl iterator (nil,0) lists
  in best end

val find_best_simple = find_best 1
type constructor clash, endpoints: function vs. int

(.. val average = fn weight =>
   (.. weight (..) ..)

.. val find_best = fn weight =>
   (.. average weight ..)

.. find_best 1 ..)
A Possible Fix

type constructor clash,
endpoints: function vs. int

(.. val average = fn weight =>
   (.. weight * (..) ..)

.. val find_best = fn weight =>
   (.. average weight ..)

.. find_best 1 ..)
Another Possible Fix

type constructor clash,
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(.. val average = fn weight =>
  (.. weight (..) ..)

.. val find_best = fn weight =>
  (.. average weight ..)

.. find_best (fn x => x) ..)
Yet Another Possible Fix

type constructor clash,
endpoints: function vs. int

(\[ .. \text{val average} = \text{fn weight} => \\
(\[ .. \text{weight} \] (..) ..) \\
\]

(\[ .. \text{val find\_best} = \text{fn weight} => \\
(\[ .. \text{average} (\text{fn x} => \text{weight} \times x) \] ..) \\
\]

(\[ .. \text{find\_best 1} ..) \]
Example 2

val mapActL = fn iterator => fn (list,state) =>

  let val iterator' = fn (x,(list, state)) =>
    let val (x, state) = iterator (x, state)
    in (list @ x, state) end

  in foldl iterator' (nil, state) list end

val isEven = fn n => n mod 2 = 0

val doubleOdds = fn list =>

  let val iterator = fn (n, inc) => if isEven n then
    ( n , inc )
  else
    ( 2 * n , inc + n )

  in mapActL iterator (list, 0) end
val mapActL = fn iterator => fn (list,state) =>
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Fixing Overlapping Slice #1

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type constructor clash,
endpoints: \texttt{int} vs. \texttt{list}

\begin{verbatim}
(.. val mapActL = fn iterator => 
   (.. val (x, (..)) = iterator (..)
    (.. (..) @ [ x ] ..)

   .. val iterator = fn (.. n ..) =>
      if (..) then
        ( n, (..) )
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   .. mapActL iterator ..)
\end{verbatim}
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```scala
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   (.. val (x, (..)) = iterator (..)
     .. (..) @ x ..)

.. val iterator = fn (.. n ..) =>
   if (..) then
     ([ n ] , (..) )
   else
     (.. (..) + n ..)

.. mapActL iterator ..)
```
Fixing Overlapping Type Errors

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- The rationale is that a single programming mistake can cause several type incompatibilities in other locations.

- However, there are cases where this does not hold. For example, when the programmer starts changing a representation and has not finished.
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- Concepts.
- Examples.

**Algorithms.**

- **Step 1:** Associate a set of type constraints with each program point.
- **Step 2:** Find minimal unsolvable sets of constraints.
- **Step 3:** Compute slice representations.

- Completeness and Minimality.
- Conclusion.
Avoiding Hindley/Milner Type System

- No type schemes.
  (Polymorphism through universal types. “System $\forall$”)

Type Error Slicing – p.23/38
Avoiding Hindley/Milner Type System

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- For SML’s let-polymorphism, System \( \mathcal{W} \) and System \( \mathcal{T} \) permit the same well-typed closed terms.
- But the type inference algorithms differ. Algorithm \( \mathcal{T} \) is more convenient for accurately tracking error locations.
Generating Type Constraints

\[ M \downarrow \langle \Gamma, ty, C \rangle \]

\[ C \text{ is a set of labeled type constraints}, \quad ty_1 \overset{l}{=} ty_2 \]
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\( C \) is a set of labeled type constraints, \( ty_1 \overset{l}{=} ty_2 \)

**Spec:**
If \((M \Downarrow \langle \Gamma, ty, C \rangle)\) and \(s\) is a solution of \(C\), then \(\langle s(\Gamma), s(ty)\rangle\) is a principal typing of \(M\).

The labels are needed so that unification can track which program location caused each constraint.
Generating Type Constraints

For each subexpression, generate a fresh type variable that represents the type of this subexpression.
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M \downarrow \langle \Gamma[x \mapsto S], \ ty, \ C \rangle; \\
(\lambda x^k.M)^l \downarrow \langle \Gamma[x \mapsto \{\}], \ C_{\text{new}} \cup C \rangle
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where \( C_{\text{new}} = \)
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\text{where } C_{new} = \{a_k \rightarrow ty \overset{l}{=} a_l\}
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Completeness and Minimality.

Conclusion.
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\text{unify}(C') = \begin{cases} 
\text{Success}(\sigma) & \text{if } C' \text{ is solvable} \\
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If \( \text{unify}(C') = \text{Error}(L) \), then:

- \( \Pi_L(C') \) is unsolvable, ...
- ... but not necessarily minimally unsolvable.
- In our experience, it is usually small (close to minimal).
Finding Minimal Errors

Minimizing a small error:

Given a small error of size $n$, one can minimize it by running history-recording unification at most $n$ times on subsets of the small error.
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Finding several small errors:

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We don’t know how to enumerate all minimal errors in a realistic time, even if the number of minimal errors is not large.

We have a simple procedure that finds a few different small errors fast, and then gives up. It runs unification several times on large constraint sets.
Finding Minimal Errors, Summary

We know how to find several, but not always all, minimal errors in a reasonably efficient way, by repeatedly using a history-recording unification algorithm.
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- SML type inference is worst-case DEXPTIME-complete, but in practice behaves almost linearly, so similarly we hope that this behaves reasonably in practice. Anyway, it is not necessary to enumerate all type error slices.
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- **Step 3: Compute slice representations.**

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Extend expression syntax class by:

\[ sl \in \text{Slice} \quad ::= \quad \ldots \quad | \quad \text{dots}(sl_1, \ldots, sl_k) \quad | \quad \ldots \]
Computing Slice Representation

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For example:

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\lambda x. \text{dots}(x \text{ dots}(), x + \text{dots}())
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Textual presentation:

\[ \text{fn x} \Rightarrow (\ldots \, x \, (\ldots) \ldots \, x \, + \, (\ldots) \ldots) \]
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Textual presentation:

\[ \text{fn } x \Rightarrow (\ldots x (\ldots) \ldots x + (\ldots) \ldots) \]

\[ \text{slice} : \text{LabelSet} \times \text{Exp} \rightarrow \text{Slice} \]

\( \text{slice}(L, M) \) replaces all syntax nodes of \( M \) that are not contained in \( L \) by dots-nodes.
Algorithms, Summary

TypeErrorSlicing =

Slice o FindMinErrors o GenerateConstraints
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Completeness

Additional typing rule for slices:

\[
\frac{\Gamma \vdash sl_i : ty_i \quad \text{for all } i \text{ in } \{1, \ldots, k\}}{\Gamma \vdash \text{dots}(sl_1, \ldots, sl_k) : ty}
\]
Completeness

Additional typing rule for slices:

\[ \Gamma \vdash sl_i : ty_i \quad \text{for all } i \in \{1, \ldots, k\} \]
\[ \Gamma \vdash \text{dots}(sl_1, \ldots, sl_k) : ty \]

Theorem (Completeness).
A program slice that is returned by TypeErrorSlicing has a type error (i.e. is not typable).
Minimality

Define *subslice ordering* on slices:

\[ sl_1 \sqsubseteq sl_2 \]

iff \( sl_1 \) is obtained from \( sl_2 \) by replacing additional non-dots-nodes by dots-nodes.
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**Theorem (Minimality).**
Every proper subslice of a slice \( sl \) returned by TypeErrorSlicing has no type error (i.e. is typable), provided all bound variables of \( sl \) are distinct.
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Our Contributions

- An explanation of how to represent type error locations as program slices.
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- A formal characterization of when a slice is a complete and minimal representation of a type error.

Proofs that our algorithms yield minimal and complete slices.

A demonstration implementation available via our web page at http://www.macs.hw.ac.uk/ultra/compositional-analysis/type-error-slicing/slicing.cgi.
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Related Work

Directly inspirational:
- Wand: Locating Sources of Type Errors
- Dinesh and Tip: Type error slicing for languages with explicit type annotations
- Yang, Michaelson, Trinder, (Wells): UAE algorithm
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Related Work

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Other work on type errors: Bernstein and Stark, Duggan and Bent, McAdam, Chitil, Flanagan et al. (MrSpidey), etc.
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- Equality types and overloading.
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- Interactive navigation through location sets.
- Animation/rewriting of error slices to help explain them.
- More efficient and more compositional algorithms.
- Handle object-oriented languages (both class-based and object-based).
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Type Error Slicing – p.39/38
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