Generating Incremental Type Services

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Abstract

In this vision paper, we propose a method for generating fully functional incremental type services from declarations of type rules. Our general strategy is to translate type rules into Datalog, for which efficient incremental solvers are already available. However, many aspects of type rules don’t naturally translate to Datalog and need non-trivial translation. We demonstrate that such translation may be feasible by outlining the translation rules needed for a language with typing contexts (name binding) and bidirectional type rules (local type inference). We envision that even rich type systems of DSLs can be incrementalized by translation to Datalog in the future.

CCS Concepts → Theory of computation → Type structures: Program analysis.

Keywords incremental, bidirectional type checking

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1 Introduction

Static typing helps developers to debug their code, and it helps IDEs to provide semantic editor services like code completion. To be effective, type information needs to be available immediately while developers edit code. However, DSLs in particular often lack such incremental type services because the development effort for these services is too high.

Our goal is a technique for generating incremental type services from declarations of type rules. An incremental type service must not only react to code changes quickly, but also allow various type-related queries, for example:

1. Given an expression, find its type.
2. Given an expression and a type, check conformance.
3. Given a type, find variables in scope of that type.
4. Given a type, find expressions of that type.

Existing generic solutions to incremental type checking [2, 6, 13] suffer two problems. First, they support a limited set of type features only, e.g. struggling with transitive subtyping. Second, they only support basic typing queries like (1.) and (2.) but not queries of editor services like (3.) and (4.).

We propose to generate incremental type services by compiling type rules to Datalog. Datalog [4] is a logic programming language that can be used to derive relations from input facts via logical rules. Efficient incremental solvers already exist for Datalog, updating the relations when the input facts change [10, 11]. In our setup, the input facts describe the user code while the derived relations describe the code’s name and typing information. We believe our approach can avoid the problems from above. First, Datalog is a flexible language in which many computations can be embedded easily, for example encoding subtyping as the transitive closure over inheritance. Second, Datalog relations can be queried in any direction, allowing us to answer all queries introduced above.

But Datalog and its incremental solvers also come with specific requirements, which prevent a natural translation of type rules to Datalog. Specifically, Datalog relations must range over finite domains. However, the typing relation ranges over typing contexts $\text{Ctx}$ and types $\text{Type}$, both of which are infinite domains in most languages. The domain of $\text{Type}$ is infinite due to structural types like pair, record, struct, and function types. The domain of $\text{Ctx}$ is infinite because it contains $\text{Type}$. Only the names in $\text{Ctx}$ and the expressions $\text{Exp}$ are finite because they are restricted to fragments of the current user code. If we want to compile type rules to Datalog, we need to find a way to avoid the infinite domains $\text{Ctx}$ and $\text{Type}$.

The contributions of this vision paper are:

- We propose the generation of incremental type services by compilation of type rules to Datalog.
- We identify the challenges of this approach, namely we need to avoid the infinite domains $\text{Ctx}$ and $\text{Type}$.
- We propose translation steps for type rules that preserve their meaning yet make them compatible to Datalog. We illustrate the translations for a bidirectional type checker of the simply typed lambda calculus.

2 A Bidirectional Type Checker

We introduce a simple type system to illustrate the challenges that occur in the translation to Datalog and to showcase how we solve these challenges. Specifically, Listing 1 shows a bidirectional type checker for the simply typed lambda calculus (STLC) with numbers implemented in Haskell. A bidirectional type checker [7] utilizes two mutually recursive
yielding the result type \( \text{ty2} \). If one of these steps does not succeed, \( \text{infer} \) will yield the first error it encounters.

Based on this type checker, we can better explain the challenges involved in translating to Datalog. Datalog programs describe relations and incremental Datalog solvers eagerly enumerate all tuples of these relations. But such enumeration can only terminate if the relation inputs come from finite domains. However, Type and Ctx define infinite domains and therefore cannot be used as relation inputs. This precludes a direct translation to Datalog for our functions \( \text{lookup}, \text{infer}, \) or \( \text{check} \). Note that while Term also defines an infinite domain, in practice we will only consider a particular instance of \( \text{Term} \), namely the current user program. Infinite domains in function outputs are not problematic because of their functional dependency \([8]\) on the inputs.

In the next section, we will show how to transform the type checker into one that avoids infinite domains as function inputs. But as first step we will instrument the type checker to find all type errors in a program, not just the first one. This is useful for providing feedback anyway, but it also yields better incremental performance because if the user fixes one type error, the remaining Typed results remain valid.

### 3 Translation to Datalog

In this section, we will show how we tackle the previously identified challenges by transforming the type checker.

#### 3.1 Computing All Types and Type Errors

The type checker from Listing 1 stops as soon as it finds a type error. This can be seen in the single error message that Error accepts. However, to enable a wide range of type services, we want to compute all types and type errors of a program and continue even after the first type error was found. This is what our first translation step does.

We introduce an auxiliary type Any that we use whenever the actual type cannot be computed. The use of Any is inspired by gradual typing, where the static type checker also uses such a catch-all type for the parts of the code that don’t have a static type \([3]\). In our type checker, we want to use Any whenever type inference fails. For example, in the case for function application \( \text{App} \), when type inference of \( \text{t1} \) fails, we want to approximate its type as Any so that we can continue checking \( \text{t2} \). We can introduce this behavior by adopting the monad for Typed to continue after an error using a catch-all value top (which is Any for Type):

```haskell
instance Monad Typed where
  return a = a
  case t of
    Error err1 -> Error err1
    Error err2 -> Error (err1 ++ err2)
```
We use a restricted monad \texttt{RMonad} that only accepts types that are instances of type class \texttt{WithTop}. In the bind function \texttt{>>=}, when \texttt{t} is an error, we call \texttt{f} anyway using the top value. We make sure to propagate any errors encountered afterwards.

Down the line, we are using \texttt{matchFun} to deconstruct function types and \texttt{matchType} to compare types. We have to adapt these functions to take the new Any type into account. As in gradual typing, the Any type can be treated as a function (Fun Any Any). When comparing types, we use the ordering \texttt{\geq} to ensure the given type is at least as specific as the expect type. Type Any is larger than all other types and, in contrast to subtyping, \texttt{\geq} is covariant for functions in the argument and result type.

\begin{verbatim}
mismatchFun :: Type \rightarrow Type
mismatchFun (Fun ty1 ty2) = return (ty1, ty2)
mismatchFun Any = return (Any, Any)
mismatchType _ _ = fail "Type_is_not_a_function"
mismatchType :: Type \rightarrow Type

matchType expect given | expect\geqgiven = return ()
mismatchType _ _ = fail "Types_do_not_match"

For the App case, when \texttt{infer ctx t1} fails with errors, we continue with the Any type for \texttt{ty}. The call to \texttt{matchFun ty} will then yield Any for both \texttt{ty1} and \texttt{ty2}. We thus check the function argument against Any, which will succeed as long as the argument is typeable at all. If the check yields further type errors, we propagate those together with the errors of the infer call.

\subsection{Eliminating the Type Argument}

Our type checker has two kinds of infinite input domains: types and contexts. In this translation step, we eliminate the type input; we deal with contexts in the next subsection.

Function \texttt{check} is the only function that receives a type as input. The type prescribes the expected type of an expression. Our idea is to reverse the data flow of type arguments: Instead of passing a type down, we require the type from above when we need it. Specifically, we introduce a new function

\texttt{required :: Ctx \rightarrow Term \rightarrow Typed Type}

that computes the type that is required of a checked expression. We rewrite \texttt{check\textsubscript{old}} to \texttt{check\textsubscript{new}} by calling \texttt{required} whenever the input type is needed, such that:

\begin{verbatim}
check\textsubscript{new} c e = check\textsubscript{old} c e (required c e)
\end{verbatim}

The difficulty lies in generating \texttt{required}. The idea is that \texttt{required} reconstructs the type argument of \texttt{check\textsubscript{old}}, but on demand. To this end, \texttt{required} contains one case for each \texttt{call site} of \texttt{check\textsubscript{old}}. We show the derived code of \texttt{required} in \texttt{Listing 2} and explain each case below.

The first call of \texttt{check\textsubscript{old}} in \texttt{Listing 1} is in the Succ case of \texttt{infer}. The code says that sub-expression \texttt{t} of (Succ \texttt{t}) must have type \texttt{Nat}. This call site becomes a case in \texttt{required} stating that the required type of \texttt{t} is \texttt{Nat} if the parent of \texttt{t} is (Succ \texttt{t}). The call site of \texttt{check\textsubscript{old}} for Anno can be translated similarly, but yielding the annotated type.

The call site of \texttt{check\textsubscript{old}} for (App \texttt{t1 t2}) is more complicated because the type argument is computed. Specifically, we call \texttt{infer} and \texttt{matchFun} to determine the argument type of \texttt{t1}, against which we check the argument expression \texttt{t2}. This call site illustrates the general translation scheme we use to derive the cases of \texttt{required}:

1. Match the parent term to identify the call site of \texttt{check} belonging to the current term.
2. Compute the program slice for the type argument of the call site.
3. Copy the program slice into \texttt{required}.
4. Return the type argument as result of \texttt{required}.

For App, this means we copy the calls of \texttt{infer} and \texttt{matchFun} into \texttt{required}, yielding the argument type as result.

The case for \texttt{Lam} follows the same scheme, but has to deal with two specific issues. First, the invocation of \texttt{check} for \texttt{Lam} was a recursive call. Therefore, when computing the program slice, we need to replace any reference to check’s type argument with a recursive call of \texttt{required} on the parent. The second issue is that the call of \texttt{check} was passed an extended context. However, we need to interpret the slice using the original context. To this end, we invert the context construction by deconstructing it again, yielding \texttt{ctx'}.

Based on \texttt{required}, we obtain \texttt{check\textsubscript{new}} code that behaves the same as \texttt{check\textsubscript{old}} yet does not need a type argument:

\begin{verbatim}
check :: Ctx \rightarrow Term \rightarrow Typed ()
check ctx (Lam x t p) = do
  ty <- required ctx (Lam x t p)
  (ty1, ty2) <- mismatchFun ty
  check (Bind ctx name ty1) t
check ctx t = do
  ty <- required ctx t
  ty' <- infer ctx t
  mismatchType ty ty'
\end{verbatim}

\subsection{Eliminating the Context Argument}

To run the type checker in Datalog, we finally need to eliminate the context argument. We eliminate the context by
We have proposed three transformations steps for translating a type checker into a Datalog-compatible one. The final type checker is compatible with Datalog because the functions only take finite domains as input for any given program. To confirm this compatibility, we reimplemented the final type checker in a Datalog dialect called IncA [10, 11]. While we don’t have space to show the IncA code, the translation was eased by IncA’s notation, which resembles functional programming. The only difference to the type checker shown here is that type errors (invocations of fail) are collected in a separate AST traversal. We have manually tested the IncA type checker and confirmed that type results are updated incrementally when the input program changes. Thus, we have successfully derived incremental type services for a single language so far. We want to study to which languages we can generalize the proposed method. For example, we want to investigate how to support subtyping, records, objects, nominal typing, type classes, dependent types, and other features.

Type system DSL. We would like to define a domain-specific language that can be used to declare rich type systems. This DSL would be the basis for a compiler that has IncA as a compilation target. We will draw inspiration from existing type system DSLs [1, 12].

Transformation mechanization. The transformations outlined in the previous section have not yet been rigorously spelled out. To clarify the exact prerequisites and behavior of the transformations, we will mechanize their definition. We hope this will also enable us to validate that the transformations preserve the type system semantics.

Performance. Finally, we want to evaluate the performance of our derived Datalog type services. We are mostly interested in the incremental performance: How long does it take to receive fully updated typing information after a program change.

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References


