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Proceedings Paper:
A Lightweight Hat: Simple Type-Preserving Instrumentation for Self-Tracing Lazy Functional Programs

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ABSTRACT
Existing methods for generating a detailed trace of a computation of a lazy functional program are complex. These complications limit the use of tracing in practice. However, such a detailed trace is desirable for understanding and debugging a lazy functional program. Here we present a lightweight method that instruments a program to generate such a trace, namely the augmented redex trail introduced by the Haskell tracer Hat. The new method is a major step towards an omniscient debugger for real-world Haskell programs.

CCS CONCEPTS
• Theory of computation → Operational semantics; • Software and its engineering → Functionality;

KEYWORDS
omniscient debugger, Haskell, Hat, augmented redex trail, lazy evaluation

ACM Reference format:

1 INTRODUCTION
A detailed trace of a computation is the basis for any so-called omniscient debugger for a programming language (Zeller 2009). A trace substantially supports the processes of understanding and debugging a program. Today’s computers provide gigabytes of volatile and non-volatile memory. Therefore storing a detailed trace of a substantial part of a computation poses no practical problem. The Big Data challenge for computer science is to define a trace structure, generate it and finally make good use of it. The Haskell tracer Hat defines the augmented redex trail (ART) as a trace structure and comprises tools for generating and using it (Section 9). This paper is about a better method for generating the ART.

Consider the Haskell program in Figure 1. A recogniser determines whether a given word is within a given LL(1) grammar. If a prefix of the given word is in the grammar, then a recogniser returns Just xs with xs being the remainder of the input word; otherwise the recogniser returns Nothing. Only the combinators necessary for defining the recogniser of a binary digit, which is 0 or 1, are given. Computation starts with evaluating main, which applies the recogniser to the empty list. The result is Nothing. Figure 2 shows the ART for our example. An ART is basically the graph produced by a naive implementation, a simple graph rewriting machine, except that a reduction step does not overwrite a redex by a reduct, but instead connects the redex node with a pre-fix of the given word is in the grammar, then a recogniser returns Just xs with xs being the remainder of the input word; otherwise the recogniser returns Nothing. Only the combinators necessary for defining the recogniser of a binary digit, which is 0 or 1, are given. Computation starts with evaluating main, which applies the recogniser to the empty list. The result is Nothing.

Figure 2 shows the ART for our example. An ART is basically the graph produced by a naive implementation, a simple graph rewriting machine, except that a reduction step does not overwrite a redex by a reduct, but instead connects the redex node with a reduction edge to the reduct node. The nodes of an ART are labelled with function and constructor identifiers or are application nodes App or indirection nodes Ind. For easy referencing we identify every node by a number. There are three sorts of edges:

• A **bold reduction edge** leads horizontally from the root of a redex to the root of its reduct. Starting for example at node 1, the redex `main` reduces to node 2, an application of `print`.

• A normal unbroken edge leads from a node down to one of its components. For example, following all component edges we find that node 2 represents the expression `print (binaryDigit [])`. Similarly node 45 represents the expression `lit ']'`. Here `r` represents an unknown value that lazy evaluation never demanded.
Figure 2: Visual representation of the ART for the program of Figure 1.

- Every node except for the start node `main` is part of a reduct. A dotted parent edge leads from every node to the root of its reduct. For example, the parent of `[]` is `main`.

The relative order of node identifiers is determined by the lazy evaluation strategy, but the edge structure of an ART is independent of the evaluation strategy. An ART can also represent an eager computation; then every application node always has two outgoing component edges.

An ART contains detailed information for debugging or understanding how a program works. In general, the ART is far too large and complex to be displayed in its entirety. Hence Hat provides various viewing tools for the ART. Each viewer enables the programmer to interactively explore a computation in a different way, seeing limited information at a time.

Hat transforms a Haskell program into a self-tracing Haskell program. When the latter program is executed, it has the same observable behaviour as the original but in addition generates an ART in a file. To generate all the edges connecting the nodes, Hat’s transformation is rather complex and changes all data types and types of all expressions in a program (Section 2.2).

In this paper we present a much simpler method for obtaining the very same ART for a Haskell program. A new program transformation changes only function bodies and leaves all types in a program unchanged. The transformation applies semantic identity functions, which produce side-effects using the function `unsafePerformIO`, to subexpressions. When the value of a subexpression is demanded, then the effect is produced, but otherwise the computation proceeds like in the original program, preserving the lazy evaluation order. The side-effects record a sequence of events. Through a single traversal of this sequence from beginning to end we can later reconstruct the ART.

Our method was inspired by the Haskell object observation debugger Hood (Gill 2001). The method is related to our earlier work on algorithmic debugging (Faddegon and Chitil 2015, 2016).

The paper makes the following contributions:
- Type- and semantics-preserving tracing combinators for instrumenting code such that during a computation an informative sequence of events is produced (Section 3).
- A simple program transformation that introduces the tracing combinators into a program (Section 4).
- An efficient translation of a sequence of events into an ART (Section 5).
- A prototype implementation for a small subset of Haskell (Section 6).

2 OUTLINE: PROBLEM AND SOLUTION IDEA

The ART was designed as a universal trace for lazy functional programs that contains the information to enable multiple different views of a computation (see Section 9). Sharing within the graph minimises the size of an ART, benefiting both generation time and storage space. Because of the size of an ART — it commonly has millions of nodes — and to decouple trace generation from multiple separate viewing tools, Hat generates the ART in a file.

2.1 The ART Data Structure

An ART file contains numerous details, such as source file names and source locations for all identifiers and their definitions. However, the Haskell types in Figure 3 describe its essential structure.
A Lightweight Hat

To represent the result, the parent pointer of the indirection is needed to ensure that from every reduct its redex can be reached via a parent pointer (Sparud and Runciman 1997a): When an applied function is a projection, an indirected node is added to the ART to represent the result. The parent pointer of the indirection is different from the parent pointer of its component.

At creation time of an application node these components are.

A reduction pointer. If there is no reduction, then the reduction is always well-defined. Indirection nodes are.

There are four different sorts of. In contrast, for an indirection that is, every subexpression is paired with a pointer.

Every function type is replaced by the new function type.

It is substantial work and difficult to implement Hat’s program transformation correctly. Another drawback is that the additional pointers in data structures and function parameters increase the space and time requirements of the program.

2.3 The Idea

During program execution we generate a sequence of events. This sequence could be held in memory or be written sequentially to file. Every new event is added to the end of the current sequence; earlier events are never changed. After the execution has terminated, a single traversal of the sequence from beginning to end translates the event sequence into an ART, which contains both backward and forward pointers.\footnote{We assume that a forward pointer in the ART can be updated in constant time. Although we also traverse parts of the already constructed ART, for all practical purposes the translation is linear in the length of the event sequence.}

In the next sections we assume that a program is just a sequence of top-level function definitions. In Section 7 we discuss further language constructs such as local definitions and constants.

2.3.1 “Identity” Functions with Side-Effects.

We can instrument any subexpression \( M \) of a program such that an event is recorded, either just before evaluation of \( M \) or just after evaluation of \( M \). We just replace \( M \) by \( \text{instPre} \) “begin” \( M \), respectively \( \text{instPost} \) “end” \( M \), where

\[
\text{instPre} :: \text{String} \rightarrow a \rightarrow a \\
\text{instPre} \text{ event exp } = \text{unsafePerformIO} \$ \text{do} \\
\text{sendEvent exp} \\
\text{return exp}
\]

\[
\text{instPost} :: \text{String} \rightarrow a \rightarrow a \\
\text{instPost} \text{ event exp } = \text{unsafePerformIO} \$ \text{do}
\]
exp `seq` sendEvent event
return exp

Here sendEvent :: String -> IO a adds the given string as an event to the end of our global sequence of events. The function unsafePerformIO :: IO a -> a turns the event recording into a side-effect, such that instPre “begin” and instPost “end” are polymorphic functions that do not change the type of their arguments. For the combinator instPost it is important that Haskell provides the parametrically polymorphic function seq :: a -> b -> b that forces evaluation to weak-head normal form of its first argument before returning its second argument. Therefore instPre first sends the event and then evaluates its argument and postPre evaluates in the opposite order.

2.3.2 Event References Record Expression Nesting. For each function symbol, data constructor and application we will generate an event. To be able to reconstruct whole nested expressions, events have to be able to refer to each other. Each event in our sequence of events can be identified by a unique event identifier; for simplicity we choose as event identifier the position of the event in the sequence, starting with 0. A later event in the sequence can refer to an earlier one by including the event identifier of the earlier one in the later event. Thus we can record an expression having two subexpressions by ensuring that the events for the two subexpressions refer to the event of the whole expression. For example, our transformation can replace e₁e₂ by app e₁e₂, where

app :: (a -> b) -> a -> b
app f x = unsafePerformIO $ do
    appId <- sendEvent “apply”
    return ((instPre (“left” ++ show appId) f) (instPre (“right” ++ show appId) x))

Here it does not matter whether we use instPre or instPost. We also note that eventually we should define a new data type for events instead of encoding them as strings.

We ensure that for every subexpression there is an event with a reference to the event of the surrounding expression. Because we add later events at the end of the sequence and never update earlier events, subexpressions have to refer up to events representing larger expressions, but never vice versa. When translating the event sequence in one linear traversal into an ART we have to invert all references to obtain component edges.

2.3.3 Delimit Chains of Reduction. Whenever evaluation of an expression is started, it will be rewritten in a sequence of steps until its value is reached; in terms of ART structure there is a chain of redexes with reduction edges until finally there is a non-redex.² Our ART of Figure 2 shows five such chains:

\[
\begin{array}{c}
1 & \rightarrow & 2 \\
7 & \rightarrow & 18 & \rightarrow & 60 \\
9 & \rightarrow & 10 \\
45 & \rightarrow & 58 \\
26 & \rightarrow & 42
\end{array}
\]

We can instrument any subexpression M of a program such that an event marking the start is recorded before evaluation of

\[
\begin{array}{c}
\text{myId} :: \text{Bool} \rightarrow \text{Bool} \\
\text{myId True} = \text{True} \\
\text{myId False} = \text{False} \\
\text{myNot} :: \text{Bool} \rightarrow \text{Bool} \\
\text{myNot True} = \text{myId False} \\
\text{myNot False} = \text{myId True} \\
z :: \text{Bool} \\
z = \text{myNot} (\text{myNot True})
\end{array}
\]

Figure 5: A program with expression nesting.

\[
\begin{array}{c}
\text{myId} :: \text{Bool} \rightarrow \text{Bool} \\
\text{myId True} = \text{instPre "True" True} \\
\text{myId False} = \text{instPre "False" False} \\
\text{myNot} :: \text{Bool} \rightarrow \text{Bool} \\
\text{myNot True} = \text{instPre "apply myId" (myId False)} \\
\text{myNot False} = \text{instPre "apply myId" (myId True)} \\
z :: \text{Bool} \\
z = \text{ev} (\text{instPre "apply myNot" (myNot (\text{ev} (\text{instPre "apply myNot" (myNot True)})))})
\end{array}
\]

Figure 6: Program with some tracing combinators.

\[
\begin{array}{c}
\text{begin} \\
\rightarrow & \text{apply myNot} \\
\rightarrow & \text{begin} \\
\rightarrow & \text{apply myNot} \\
\rightarrow & \text{apply myId} \\
\rightarrow & \text{False} \\
\rightarrow & \text{apply myId} \\
\rightarrow & \text{True} \\
\rightarrow & \text{end}
\end{array}
\]

Figure 7: Sequence of events generated by evaluation of z.

the subexpression starts, and another event marking the end is recorded after a value was reached. We just replace M by ev M, where

\[
\text{ev :: a -> a} \\
\text{ev = instPre "begin" . instPost "end"
}\]

Example. Figures 5 to 7 demonstrate how chains are recorded. For simplicity here we ignore the nesting of expressions but just record data constructors and function applications. We instrument the program of Figure 5 with the tracing combinators and obtain the program of Figure 6. When evaluating the expression z, the event sequence of Figure 7 is generated. The markings on the left emphasise that the events begin and end serve as start and end markers of chains. One chain of reductions is nested within another chain of reductions. The variable z reduces to an application of myNot which reduces to an application of myId, which reduces to the data

²We will discuss exceptions, including runtime errors and abortion of a computation by the programmer in Section 7.4.
As Figure 2 demonstrates, an ART contains nodes for variables such as `x` and `rr` in the example in Figure 1. As Figure 2 demonstrates, an ART contains nodes for variables such as `lit`, `binary_digit` and `<|>` but not for parameter variables.\textsuperscript{1} We call the recorded variables let-bound and the unrecorded parameter variables $\lambda$-bound.\textsuperscript{1} For example, the program equation

\((rl <|> rr)\) `xs` = `rl` `xs` `mplus` `rr` `xs`` uses the $\lambda$-bound variables `rl`, `rr` and `xs`. The program execution that yields the ART shown in Figure 2 uses the equation exactly once. Rewriting the equation without infix notation and annotating subexpressions with the corresponding node identifiers of the ART shows more clearly how the equation is used:

\[
(((<|>)^{14} \text{rl})^{12} \text{rr})^{10} \text{xs})^{7} =
((\text{mplus}^{22} (\text{rl} \text{xs})^{26})^{20} (\text{rr} \text{xs})^{45})^{18}
\]

The instrumented right-hand sides of the equations for `main` and `binary_digit` yield the ART nodes 14, 12, etc. that form the left-hand side of the equation for `<|>`. The instrumented right-hand side of the equation for `<|>` yields the ART nodes 22, 26, 20, etc. for the right-hand side of the equation. However, additionally that instrumented code has to connect the component edges of the App nodes 26 and 45 correctly.

We can identify every $\lambda$-bound variable of an equation by a list of left or right branches that indicate their location in a syntax tree of the left-hand side, starting at the root node. The left-hand side of the defining equation of `<|>` has the syntax tree shown in Figure 8. The tree yields for each $\lambda$-bound variable the following list of branches:

- `xs`: `[R]`
- `rr`: `[L,R]`
- `rl`: `[L,L,R]`

So each event generated for a $\lambda$-bound variable contains such a list. The list enables us to add a component edge: the parent of the $\lambda$-bound variable is the root node of the left-hand side in the ART and from there we can follow left and right as the branch list specifies to find the root node of the expression bound to the variable. So to add the component edge in the ART, a small part of the already constructed ART needs to be traversed.

\subsection{2.3.5 Summary}

We instrument every subexpression on the right-hand side of an equation. Thus during program execution we record variable and constructor identifiers, but also expression constructs such as applications. These events yield the nodes of the ART.

- The marker events `begin` and `enter` delimit a chain and enable us to construct the reduction edges of the ART.
- The nesting of chains reflects the evaluation order, not the nesting of expressions in the program. To construct the component edges of the ART, we add an event reference to the surrounding expression to each `Enter` event. The event for a $\lambda$-bound variable has a branch list that enables construction of the component edge.
- Finally the parent edges are actually fully determined by the reduction and component edges: the parent of a node in the middle of a chain is the preceding node of the chain (inverse of a reduction pointer); basically the parent of any other node is the same as the parent of the node that they are a component of (inverse of a component pointer).

\section{3 EVENTS AND TRACING COMBINATORS}

In the preceding section we discussed our ideas using strings as events and we used simplified tracing combinators. Now we combine these ideas to obtain a working tracing system.

Figure 9 gives the definition of events and related types. Every event in an event sequence has a unique `EventId`, which is its position in the sequence.

The subsequence from an `Enter` event to its corresponding `Value` event, without any nested subsequences, describes a chain of reductions. Thus we can later construct reduction edges. An `Enter` event has an `EventId` and a `Branch`, to specify which component of which node it is. This information enables us later to construct component edges.\textsuperscript{5} A constructor event has the name and arity of the constructor, and an event for a let-bound variable has the name of the variable. The event for a $\lambda$-bound variable has a list of branches as discussed in the preceding section. Finally, there is the application event `App`.

Figure 10 defines the tracing combinators that we use to generate the event sequence. We assume that `sendEvent` is a function that takes an event and adds it to the end of the global event sequence; it also returns the unique `EventId` of that event. The function `runH` initialises the global event sequence, evaluates the given IO-expression, transforms the event sequence into an ART as we will discuss in Section 4 and finally writes the ART to a file with the given name.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{ART_diagram.png}
\caption{Left side of the equation of `<|>` in Figure 1 as a tree.}
\end{figure}
type EventId = Int

data Branch = L | R

type Name = String

data Event =
  Enter EventId Branch
  | Value
  | Con Name Arity
  | Var Name
  | LamVar [Branch]
  | App

Figure 9: Events recorded in a sequence.

sendEvent :: Event -> IO EventId

runH :: FilePath -> IO a -> IO ()

eval :: EventId -> Branch -> a -> a
eval parent branch x = unsafePerformIO $ do
  sendEvent (Enter parent branch)
  x `seq` sendEvent Value
  return x

con :: Name -> Arity -> a -> a
con name arity x = unsafePerformIO $ do
  sendEvent (Con name arity)
  return x

var :: Name -> a -> a
var name var = unsafePerformIO $ do
  sendEvent (Var name)
  return var

lamVar :: [Branch] -> a -> a
lamVar pos var = unsafePerformIO $ do
  var `seq` sendEvent (LamVar pos)
  return var

app :: (a -> b) -> a -> b
app f x = unsafePerformIO $ do
  eventId <- sendEvent App
  return ((eval eventId L f) (eval eventId R x))

Figure 10: Tracing combinators.

The combinator eval marks the beginning and end of a chain of reductions as discussed in Section 2.3.3; it just takes an EventId and Branch as parameters, to include them in the Enter event. Combinators con and var generate constructor and let-bound variable events. The combinator lamVar generates the event for a λ-bound variable. The definition first forces the evaluation of the variable via seq, so that the chain of computation for the variable is recorded in the event sequence before the LamVar event is added. Finally the

Figure 11: Events for the example program in Figure 1.
When we generate an event sequence, we never update any event; writing processes: If the ART is stored in a sequential data structure we only join new events at the end. Thus an event sequence has

A transformation that inserts the tracing combinators instruments the event sequence shown in Figure 11. During the traversal the translation function reads expressions that define functions. However, all expressions are transformed by inserting tracing combinators. That transformation is straightforward, except that for each use of a λ-bound variable a list of branches is needed, which is obtained from the left-hand side of the equation as described in the previous section. The combinators that apply a function to arguments. The function main uses runH and starts by recording its own variable identifier in the event sequence. Executing this program yields the event sequence shown in Figure 11.

4 PROGRAM TRANSFORMATION

A transformation that inserts the tracing combinators instruments a program for tracing. Figure 12 shows the result of transforming our introductory program of Figure 1. A module import for the tracing library HatLight that defines the tracing combinators is added. The standard library Prelude is hidden and instead a tracing version of it, HatPrelude, is imported. All type definitions and type signatures remain unchanged, just like the left-hand sides of equations that define functions. However, all expressions are transformed by inserting tracing combinators. That transformation is straightforward, except that for each use of a λ-bound variable a list of branches is needed, which is obtained from the left-hand side of the equation as described in the previous section. The combinators that apply a function to arguments. The function main uses runH and starts by recording its own variable identifier in the event sequence. Executing this program yields the event sequence shown in Figure 11.

Figure 12 defines the translation as a Haskell function mkArt. During the traversal the translation function go keeps track of a stack of Chains and the NodeId = eventId of the event currently being processed. The function writeConnect adds one node to the ART data structure and modifies it in other places; that is, if the newly written node is the beginning of a chain, then the node that it is an argument of is updated (writeArg); otherwise it is a later entry in a chain and the reduction pointer of the preceding node is updated (updateReduction). Hence a component pointer always points to the first node of a reduction chain.

A variable of type Chain stores where the current chain belonging to the ART. At the beginning of a chain its value is the data constructor Context carrying the NodeId of the node of which the chain is a component and the Branch to identify exactly which component it is. Later the data constructor Last carries the NodeId of the last node of the chain that has already been translated. As chains are nested, our translation uses a stack of Chains (i.e. a list). Translation of an Enter event puts a new
data Chain = Context NodeId Branch | Last NodeId

mkArt :: [Event] -> ART
mkArt es = go es [] @ Map.empty

go :: [Event] -> [Chain] -> NodeId -> ART -> ART
go (Enter a b : es) cs id art =
  go es (Context a b : cs) (id+1) art
go (Value : es) (c:cs) id art =
  go es cs (id+1) art
go (Con name arity : es) cs id art =
  writeAndGo es cs id
    (\p -> TCon p name arity) art
go (App : es) cs id art =
  writeAndGo es cs id
    (\p -> TApp noId p noId noId) art
go (Var name : es) cs id art =
  writeAndGo es cs id
    (\p -> TVar noId p name) art
go (LamVar d : es) (Context a b : cs) id art =
  go es (Last n : cs) (id+1) (writeArg a b n art)
where
  n = directionLookup (getParent a art) d art
  go (LamVar d : es) cs id art =
    writeAndGo es cs id
      (\p -> TInd p (directionLookup p d art)) d art
  go [] [] _ art = art

writeAndGo :: [Event] -> [Chain] -> NodeId -> ART -> ART
writeAndGo es (c:cs) id newNode art =
  go es (Last id : cs) (id+1) .
    writeConnect c id newNode

writeConnect :: Chain -> NodeId -> ART
writeConnect (Context a b) id newNode art =
  writeArg a b id .
  Map.insert id (newNode (getParent a art)) $ art
writeConnect (Last l) id newNode art =
  updateReduction l id .
  Map.insert id (newNode l) $ art

Figure 13: Translation of an event sequence into an ART.

Context on the stack, translation of a Value event removes a chain from the stack.

The translation of Con, Var and even App events is relatively simple. Each gives rise to the construction of a corresponding ART node.

The translation of a LamVar event is more complex. Translation uses the function directionLookup, which given the node that represents the root of the left-hand side for this λ-bound variable plus the list of branches and the current partial ART, returns the node that is the root of the value of the variable. We have to distinguish two cases:

- If we are at the beginning of a chain, then the λ-variable is a component, not the right-hand side of an equation. We get the parent node of the context node; that is the root of the left-hand side of the equation in the ART. From that node directionLookup obtains the beginning of the chain of the λ-bound variable. The argument specified by the Context is updated with the node beginning that chain. That node is used for updating the argument specified by the Context.

  For example, the λ-bound variable xs of the equation for < > in Figure 1 has the branch list [R]. Hence the right argument of node 26 is the node 38 in Figures 2 and 4.

- If we are in the middle of a chain, then the λ-variable is the right-hand side of an equation. That equation defines a projection. From that last node directionLookup obtains the beginning of the chain of the λ-bound variable. That node is the component of the new indirection node that is added to the ART, connected by reduction pointer from the last node.

  For example, the right-hand side of the first equation of mplus in Figure 1 is just the λ-bound variable nr, which has the branch list [R]. Therefore the reduction pointer of node 18 points to an indirection node 60 whose component is node 45 in Figures 2 and 4.

6 A PROTOTYPE: HATLIGHT

HatLight is our prototype implementation of the new method for creating an ART. HatLight is mainly a Haskell library that defines the tracing combinators and the translation from event sequences to an ART. Both event sequence and ART are data structures in memory, not in files. HatLight outputs the event sequence and ART, but also writes the ART into a file using the DOT graph description language. Thus the ART can be visualised with a tool such as GraphViz. HatLight also includes a tracing standard library, which includes some frequently used functions and types. Currently HatLight consists of approximately 570 lines of Haskell code.

All the transformed programs, event sequences, ART data and visualisations of the ART in this paper have been obtained with HatLight. The definitions of the combinators and the translation are excerpts of HatLight.

To gain an insight into the overhead of tracing, we modified our prototype to write the event sequence into a file. The event sequence contains all information needed to construct an ART and it is of similar size. We measured the runtime of the original and traced versions of two programs, each with two different parameters. The program nfib determines by simple, exponential recursion the Fibonacci number of the parameter. The program perms outputs all permutations of the list of numbers from 1 to the parameter. It uses the definitions given in Section 9.4 of Hutton (2016); all list functions, including map, (+++) and concat are traced. The table in Figure 14 gives the measurements obtained on a MacBook Air with flash storage, after compilation with the Glasgow Haskell compiler version 7.8.3 with flag -O2.

\footnote{https://www.haskell.org/ghc}

\footnote{https://www.graphviz.org}

\footnote{https://en.wikipedia.org/wiki/DOT_(graph_description_language)}
The slowdown factor of runtime is substantial. The table also shows that the computations produce huge trace files, each of which contains many events. Therefore we wrote a Haskell program that just writes the same number of lines; each line is a constant string of length 9, so that the file size is similar to the corresponding event sequence file. The last column in the table gives the runtimes of this program. Thus we see that more than half of the runtime of a traced program is needed just for writing the event sequence file.

We can transform the right-hand side of each defining equation we do not transform type or class definitions, only the definitions of locally defined function. The function snoc appends an element to the end of a list.

\[
\text{snoc} :: a \to [a] \to [a]
\]

\[
\text{snoc} \ x \ \text{xs} = \text{go} \ \text{xs}
\]

\[
\text{where}
\]

\[
\text{go} \ [[] = [x]
\]

\[
\text{go} \ (y:ys) = y : \text{go} \ ys
\]

We can transform the right-hand side of each defining equation as before, but we face one problem: The variable \(x\) is used in the body of the definition of the local function \(\text{go}\), but it is \(\lambda\)-bound on the left-hand side of the enclosing definition of the top-level function \(\text{snoc}\). Hat generates an ART for this program, but it was noticed that presenting applications of a local function without the values of its free variables can yield to confusing views. For example, hat-observe could produce an output such as

\[
\text{go} \ [[] = [\emptyset]
\]

\[
\text{go} \ [[] = [42]
\]

However, Hat’s ART contains more information than the ART data structure given in Figure 3. Every variable node has a Boolean flag that indicates whether this is a local variable that may have free variables. Every variable node stores the beginning and end of its definition in the source code. Thus it is easy to determine whether one variable is defined locally within the definition of another variable. Although the chain of parents (parent, grandparent, grand-grandparent, etc.) of a node is information about the dynamics of a computation, for a local variable the chain of parents includes the redex roots of all enclosing variables. Thus the ART has the information to determine for any local variable the redex roots of all its enclosing variables. Hence hat-observe can produce an output like

\[
(\text{snoc} \ 0 \ []).\text{go} \ [] = [\emptyset]
\]

\[
(\text{snoc} \ 42 \ []).\text{go} \ [] = [42]
\]

We can extend HatLight to also record for every let-bound variable a Boolean flag and information about the beginning and end of its definition in the source. Furthermore, HatLight needs to include in the event for a \(\lambda\)-bound variable a counter of how many levels of enclosing redexes to go up before following the list of branches as described in Section 2.3.4. Therefore HatLight could generate the correct ART also for programs with local definitions as above.

7.3 Constants

Although by definition Haskell is only a non-strict language, all implementations provide a lazy semantics and thus ensure that every constant is computed at most once with its value being shared by all use occurrences. We call a let-bound variable in a program a constant, if it appears alone on the left-hand side of its defining equation, that is, it is not a function identifier with parameters on the left-hand side. 10 In our introductory example binaryDigit and main are constants and they are the only constants. Because each of these constants is used only once, our tracing method works fine. However, if a constant is used twice or more, then the tracing method fails. Consider

\[
\text{true} :: \text{Bool}
\]

\[
\text{true} = \text{True}
\]

\[
\text{This counter corresponds to the de Bruijn index of } \lambda\text{-calculus.}
\]

\[
\text{10There is a difference between the term constant and the established term constant applicative form (CAF). A constant bound to a } \lambda\text{-abstraction is not a CAF. In this paper we do not discuss } \lambda\text{-expressions, but Section 8 indicates that we also have to handle constants that are bound to } \lambda\text{-abstractions in the way described here.}
\]
Figure 15: An ART that is incomplete because of a constant.

Figure 16: An ART that shares the constant \textit{true} correctly.

\[
\text{main} = \text{print} \ (\text{true} \ \&\& \ \text{true})
\]

With our method we obtain the incomplete ART shown in Figure 15. The node 15: \textit{true} reduces to the result 16: \textit{true}, but there is no reduction edge for node 19: \textit{true}. The reason for the problem is simple: the constant \textit{bool} is only evaluated once and the resulting value \textit{True} is stored and not recomputed when the value of \textit{true} is demanded again; however, our tracing works by side-effects that only happen when computation happens. This effect may not only lead to missing information in an ART, but we may obtain an invalid event sequence that cannot be translated into an ART at all. That happens for example for the following program:

\[
\text{pair} :: (\text{Int}, \text{Int})
\]

\[
\text{pair} = (6,7)
\]

\[
\text{fst} \ (x,_) = x
\]

\[
\text{snd} \ (_,x) = x
\]

The first occurrence of \textit{pair} yields a reduction chain in the event sequence, but the second occurrence does not. However, the body of the function \textit{snd} is a \(\lambda\)-bound variable with branch list \{R, R\}. Following this direction in the partially constructed ART fails, because there is no second pair constructor in the ART.

\section{Exceptions}

A computation of a program may explicitly raise an exception. Any runtime error and also the abortion of a computation by the programmer raises an exception. We can handle these by adding an exception handler in the combinator \textit{eval}. When an exception is raised all reduction chains that are still open can be terminated with an exception value and the event \textit{Value}.

\section{Desugaring}

Haskell has many language features that can be desugared into a small subset of the language. For example, a list comprehension can be desugared into the use of a few list combinators. However, for the end user it is desirable that a view of the ART shows an expression as it is in the program. That will require extending the ART data structure and extending every view accordingly.

Desugaring is a temporary solution to obtain a tracing system for Haskell quickly, but in the long term every language construct will need to be supported directly.

\section{Challenges}

Haskell’s monadic input/output functions and also functions for imperative state such as those using the ST monad can be handled by HatLight in principle, by wrapping the untraced primitive functions, as outlined in Section 8. Hat even extends the definition of the ART for some simple output functions to record the characters that they output more directly. However, for tracing any program that makes substantial use of these functions we still have to find a good way of presenting the computation to the user.
By definition Haskell is a sequential language, but its most popular compiler, the Glasgow Haskell compiler, provides it with several different application interfaces for concurrent programming. Our lightweight tracing method generates a sequence of events; the order of these events is essential for reconstructing the ART. Hence our method works only for tracing a sequential computation, at best a single thread of a concurrent computation. The most simple extension to handle many concurrent threads would assume to have at runtime access to an identifier of the current thread and add this identifier to every event. Thus for every thread an event sequence could be determined and an ART-like trace be reconstructed. In practice, much further research will be needed to find a good way of presenting a concurrent computation to the user, probably specific to the particular concurrency application interface that the program uses.

8 UNTRACED CODE

Our new method works well for transforming and then tracing the computation of a complete program. However, in general programmers do not want to trace the computation of all code of a program. When a program uses a library, the programmer usually does not want to see the details of library-function computations. Additionally, tracing creates a time and space overhead that the program transformation does not want to see. Later Chitil (2005) and Silva et al. (2001) implemented this addition and the three views. Wallace et al. (2001) implemented this addition and the three views. Claessen et al. (2003) give the most extended examples of what Hat does from the user’s point of view. Later Chitil (2005) and Silva and Chitil (2006) explored further views and uses of the ART. Chitil et al. (2003) define Hat’s program transformation for generating an ART and later Chitil and Luo (2007) defined the ART structure formally and proved basic properties.

9 RELATED WORK

9.1 ART and Hat

The Haskell tracer Hat11 produces an ART for a Haskell program. The design of the structure of an ART started with the redex trail trace developed by Sparud and Runciman (1997a,b). That redex trail only allowed trace exploration as later implemented in hat-trail and described in Section 9.1. A comparison of three different tracing systems for Haskell lead to the conclusion that different views of a computation are useful (Chitil et al. 2001). A small addition to the redex trail structure, namely reduction pointers, yields an augmented redex trail (ART) that can support all three views. Wallace et al. (2001) implemented this addition and the three views. Claessen et al. (2003) give the most extended examples of what Hat does from the user’s point of view. Later Chitil (2005) and Silva and Chitil (2006) explored further views and uses of the ART. Chitil et al. (2003) define Hat’s program transformation for generating an ART and later Chitil and Luo (2007) defined the ART structure formally and proved basic properties.

Multiple Views. To appreciate the structure of the ART, we briefly review some of the views of an ART that Hat provides.

The viewing tool hat-observe is inspired by Hood (see Section 9.3). For a given function identifier it lists all the arguments that the function was applied to during a computation plus its results. For example, for the function identifier lit it shows

lit [] = Nothing

removing duplicates, and for the function identifier mplus it shows

mplus Nothing Nothing = Nothing

An observation can be obtained from a single linear traversal of the ART. When hat-observe is started, it first creates an index of every identifier occurring in the ART to speed up every later search. Component edges enable reconstruction of expressions and reduction edges point to the result value of a redex.

The viewing tool hat-trail allows exploring the history of an expression backwards: it tells that the argument Nothing of print was created by the reduction of mplus Nothing Nothing. The second Nothing of that redex was created by the reduction of lit []. The first application of that redex was created by the reduction of binaryDigit. Finally binaryDigit was created by the reduction of main. In every step the programmer can select any

11projects.haskell.org/hat/
Thus hat-trail enables exploring a computation backwards; debugging goes from a noticed failure backwards to the program defect that caused it. Parent edges are essential for hat-trail’s functionality; hat-trail reconstructs expressions from component edges.

The viewing tool hat-detect is an algorithmic debugger for semi-automatically locating a defect in a program. At the heart of algorithmic debugging is a computation tree, a structured representation of a computation. Figure 17 shows the computation tree, an evaluation dependence tree, constructed by hat-detect for our example. Every node is a computation statement: a redex plus its result value (we consider print Nothing as a value of type IO ()). Here we include the ART node identifier of the redex in each tree node to emphasise the relationship. The tree gives insight into the computation, but because our program shows no failure, we cannot do any debugging. The tool hat-detect constructs the evaluation dependence tree on the fly from the ART, using all three sorts of edges.

Most debuggers used in practice, especially for imperative programs, are stepping debuggers. A stepping debugger is a very special instance of an algorithmic debugger: the stepping debugger only allows a linear, forward traversal of the computation tree. This relation between stepping debugger and computation tree is central to the work of Braßel et al. (2007), which we discuss later. The ART could be used as basis for a stepping debugger similar to the one of Braßel et al. (2007).

Many other uses of an ART have been discussed and/or implemented, for example, a virtual stack trace and dynamic program slicing.

A Structural Differences. The ART structure as shown in Figure 2 and generated by our new method differs from Hat’s ART in one point: A component pointer is noId, when the component was never demanded during the computation. In contrast, Hat’s ART always has a valid component pointer to the root of an (unevaluated) expression. Recording such an unevaluated expression would be possible in principle, but substantially complicate our method. The additional information about unevaluated expressions seems of little use. To prevent information overload, displayed expressions should avoid any unnecessary information, and Hat’s viewing tools already offer showing such unevaluated expressions just as _.

9.2 Other Algorithmic Debuggers for Lazy Functional Languages

Besides hat-detect, several algorithmic debuggers (Shapiro 1983) for Haskell have been developed. Nilsson and Sparud (1997) define the evaluation dependence tree (EDT) as a suitable computation tree for algorithmic debugging of lazy functional programs. Nilsson’s algorithmic debugger Freja generates an EDT (Nilsson 1998, 2001). Freja does not generate a more general trace like the ART. Freja is a complete compiler for a subset of Haskell and compiler and runtime system together enable the generation of the EDT. Therefore debugging with Freja has only modest runtime overheads, but a complex tracing architecture integrated with a compiler makes supporting a large and evolving programming language such as Haskell very hard. In contrast our lightweight method permits us better to explore the design space of tracing and will hopefully enable us to build the first omniscient debugger that will be used for real-world Haskell programs. Freja already handles many language features discussed in Section 7. In particular, Freja records the names of all variables, including λ-bound variables, and for each locally defined variable it records the set of its free variables together with their values. Thus Freja can provide inspiration for an alternative, possibly more friendly user interface to some language features.

Freja requires all higher-order functions to be traced, even though the workings of trusted higher-order functions is not recorded; in contrast we outlined in Section 8 how we plan to use untraced higher-order functions.

Pope (2005, 2006) built the algorithmic debugger Buddha for Haskell. Generation of the computation tree is based on program transformation, which, however, is still integrated with an existing compiler, the Glasgow Haskell compiler. Buddha can represent functional values as finite maps and Pope stated that a computation tree with functional values as finite maps has to have a structure that is different from the EDT. Subsequently Chitil and Davie (2008) defined the new computation tree structure formally by relating it to the ART, named it the function dependence tree (FDT), and proved its soundness for algorithmic debugging.

9.3 Hood and Hoed

Our new method for obtaining an ART was inspired by Andy Gill’s work on observing the values of expressions in lazy functional
programs, which he implemented in his Haskell debugging library Hood (Gill 2001). A programmer using Hood annotates their program with the observe combinator. At runtime these annotations generate a sequence of events. Finally, when computation terminates, the Hood library reconstructs observed values from the sequence of events. These values can be values of data types, that is, applications of data constructors and primitive values such as 42 and 'a', or functional values. A functional value is represented extensionally, that is, as a finite map from arguments to results, as we discussed in Section 8. To sum up, Hood does not generate any trace structure from its sequence of events, but a set of values.

We identified and generalised Hood’s use of “identity” functions with side-effects and its use of event references to record expression nesting. Hood’s Enter events inspired our novel method of delimiting chains of reductions in the event sequence. Hood does not record such chains; it does not need them for observing only values.

Faddegon and Chitil (2015) combined Hood’s instrumentation with the cost centre stacks of the profiling system of the Glasgow Haskell compiler to obtain a computation tree for algorithmic debugging of Haskell programs. The implementation hoed-stack uses Hood’s event sequence to obtain computation statements as nodes of the computation tree and the cost centre stacks are used to connect these nodes to a tree. The computation tree is a function dependence tree, not an evaluation dependence tree (cf. Section 9.2).

Subsequently Faddegon and Chitil (2016) discovered that cost centre stacks are not needed, but that the very same sequence of events that Hood generates already contains sufficient information to connect the nodes of computation statements to a tree. The central insight is that events come in pairs, an Enter event is later followed by an event describing the weak-head normal form of a value. From the nesting structure of these event pairs the structure of the computation tree can be obtained. Because of higher-order functions, the relationship between nesting of event pairs and the computation tree structure is quite complex. The implementation of this algorithmic debugger is called hoed-pure.

Here, in this paper, we follow Hood in instrumenting a program with combinators that generate a sequence of events. However, Hood traces only values and except for function identifiers so does Hoed. To obtain the richer information needed for an ART, we use a richer set of events. For example, we have events for both let- and \( \lambda \)-bound variables. Instead of the event pairs of Hood we have chains of events, starting with an Enter and ending with a Value event, but with an unbound number of events in between. Hood’s and Hoed’s program annotations are far more lightweight than the instrumentation introduced by our program transformation. Hoed requires only one annotation in the definition of each function of interest. It’s observe combinator recursively traverses a data structure while recording it in the sequence of events. In contrast, we annotate every subexpression with a combinator. Thus we record a value when it is constructed by the program (the data constructor is instrumented), whereas Hood and Hoed record a value when that value passes through the observe combinator which otherwise behaves like the identity function.

Hood and Hoed have the great advantage that they require annotating only functions of interest; most of a program may be left unchanged. The connection of computation tree nodes based on nested event pairs works even when an arbitrary number of untraced function calls are performed in between. In contrast, our method for constructing an ART is based on transforming the complete program. This whole-program tracing is the premise for being able to transform the event sequence into the ART, a single connected graph. As we discussed in Section 8, extending our method to work with untransformed modules will probably require combining it with the method of hoed-pure.

Finally our method for constructing an ART has the advantage that it preserves sharing of expressions in the heap of the instrumented program, whereas the observe combinator loses sharing. Hence for Hood and Hoed the execution of an annotated program can require more space and the event sequence contains much duplication, compared to the ART.

9.4 Other Debuggers for Lazy Functional Languages

Perera et al. (2012) define another tracing model for lazy functional programs that is based on program slicing. They prove several desirable properties for their approach. It would be interesting to establish whether the ART meets similar properties, which the work of Silva and Chitil (2006) suggests.

Marlow et al. (2007) describe a different approach to debugging Haskell programs. They describe how a traditional stepping debugger can work and be implemented for a lazy functional language. Braefel et al. (2007) present a debugging approach for Haskell that views a computation in a combination of a traditionally stepping debugger and an algorithmic debugger. For eager evaluation these two views are closely related. The central idea is that a small trace states which reduction steps an eager evaluator should skip to perform exactly the same computations as a lazy evaluator. This trace is generated by an initial lazy computation of the program. The viewing tool then uses an eager evaluator of Haskell together with the small trace to provide a view of eager evaluation that “magically” skips unnecessary steps. This approach fits well with our observation that the ART structure is independent of the order of evaluation. The main obstacle in practice is that for a lazy language there is hardly ever an eager evaluator available but it must be implemented from scratch.

10 CONCLUSIONS

We have presented a new method for generating a detailed trace of a lazy functional computation. We have shown that the simple idea of instrumenting a high-level program such that it generates events at well-defined points of the computation can yield detailed information about how a computation works; this technique, first introduced by Gill (2001), clearly has many potential application areas. We have described and justified every step of the new method. Our implementation HatLight establishes that the method works.

The fact that our tracing combinators do not change types may be seen as a disadvantage: A mistake in Hat’s program transformation is likely to yield programs that do not compile but raise type errors. Thus such a mistake is soon noticed. However, in our experience also mistakes in the new program transformation are likely to yield programs that raise type errors.
We could complete HatLight to write the ART into a file in the same format as used by Hat, such that all of Hat’s viewing tools could be used. However, our aim in the near future is to use HatLight as an experimental platform for modifications and extensions as discussed in Sections 7 and 8. For that purpose HatLight needs to stay small and allow for useful variations of the ART that are incompatible with Hat. The difference discussed in Section 9.1 is already such a variation.

With different combinators our method should also work for strict functional programming languages. However, because these languages are generally not pure, recording of side-effects in the ART will be important. Hat currently supports basic input-output effects in its tracing and ART, but further work in this area will be required.

ACKNOWLEDGMENTS

We thank the reviewers, in particular Henrik Nilsson, for their valuable comments and helpful suggestions.

REFERENCES


