

# Hailstorm : A Statically-Typed, Purely Functional Language for IoT Applications

Abhiroop Sarkar  
sarkara@chalmers.se  
Chalmers University  
Gothenburg, Sweden

Mary Sheeran  
mary.sheeran@chalmers.se  
Chalmers University  
Gothenburg, Sweden

## ABSTRACT

With the growing ubiquity of *Internet of Things* (IoT), more complex logic is being programmed on resource-constrained IoT devices, almost exclusively using the C programming language. While C provides low-level control over memory, it lacks a number of high-level programming abstractions such as higher-order functions, polymorphism, strong static typing, memory safety, and automatic memory management.

We present Hailstorm, a statically-typed, purely functional programming language that attempts to address the above problem. It is a high-level programming language with a strict typing discipline. It supports features like higher-order functions, tail-recursion, and automatic memory management, to program IoT devices in a declarative manner. Applications running on these devices tend to be heavily dominated by I/O. Hailstorm tracks side effects like I/O in its type system using *resource types*. This choice allowed us to explore the design of a purely functional standalone language, in an area where it is more common to embed a functional core in an imperative shell. The language borrows the combinators of arrowized FRP, but has discrete-time semantics. The design of the full set of combinators is work in progress, driven by examples. So far, we have evaluated Hailstorm by writing standard examples from the literature (earthquake detection, a railway crossing system and various other clocked systems), and also running examples on the GRiSP embedded systems board, through generation of Erlang.

## CCS CONCEPTS

• **Software and its engineering** → **Compilers; Domain specific languages**; • **Computer systems organization** → **Sensors and actuators; Embedded software**.

## KEYWORDS

functional programming, IoT, compilers, embedded systems

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## 1 INTRODUCTION

As the density of IoT devices and diversity in IoT applications continue to increase, both industry and academia are moving towards decentralized system architectures like *edge computing* [38]. In edge computation, devices such as sensors, and client applications are provided greater computational power rather than pushing the data to a backend cloud service for computation. This results in improved response time and saves network bandwidth and energy consumption [50]. In a growing number of applications such as aeronautics and automated vehicles, the real-time computation is more robust and responsive if the edge devices are compute capable.

In a more traditional centralized architecture, the sensors and actuators have little logic in them; they rather act as data relaying services. In such cases, the firmware on the devices is relatively simple and programmed almost exclusively using the C programming language. However with the growing popularity of edge computation, more complex logic is moving to the edge IoT devices. In such circumstances, programs written using C tend to be verbose, error-prone and unsafe [17, 27]. Additionally IoT applications written in low-level languages are highly prone to security vulnerabilities [7, 57].

Hailstorm is a domain-specific language that attempts to address these issues by bringing ideas and abstractions from the functional and reactive programming communities to programming IoT applications. Hailstorm is a *pure, statically-typed* functional programming language. Unlike *impure* functional languages like ML and Scheme, Hailstorm restricts arbitrary side-effects and makes dataflow explicit. The purity and static typing features of the language, aside from providing a preliminary static-analysis tool, provides an essential foundation for embedding advanced language-based security techniques [54] in the future.

The programming model of Hailstorm draws inspiration from the extensive work on Functional Reactive Programming (FRP) [18]. FRP provides an interface to write *reactive* programs such as graphic animations using (1) continuous time-varying values called *Behaviours* and (2) discrete values called *Events*. The original formulation of FRP suffered from a number of shortcomings such as space-leaks [41] and a restrictive form of *stream based I/O*.

A later FRP formulation, *arrowized* FRP [46], fixed space leaks, and in more recent work Winograd-Cort et al. introduced a notion of *resource types* [65] to overcome the shortcomings of the stream based I/O model. The work on resource types is a library in Haskell, and is not suitable to run directly on resource-constrained hardware. Hailstorm uses resource types to uniquely identify each I/O

resource. It treats each resource as a signal function to track its lifetime, and prevents resource duplication through the type system. Hailstorm currently has a simple discrete time semantics, though we hope to explore extensions later.

A Hailstorm program is compiled to a dataflow graph, which is executed synchronously. The core of the language is a pure call-by-value implementation of the lambda calculus. The synchronous language of arrowized-FRP provides a minimal set of combinators to which the pure core constructs of Hailstorm can be raised. This language of arrows then enforces a purely functional way to interact with I/O, using resource types.

Hailstorm, in its current version, is a work-in-progress compiler which does not address the reliability concerns associated with node and communication failures plaguing edge devices [57]. We discuss the future extensions of the language to tackle both reliability and security concerns in Section 7. We summarize the contributions of Hailstorm as follows:

- **A statically-typed purely functional language for IoT applications.** Hailstorm provides a tailored, purely functional alternative to the current state of programming resource constrained IoT devices.
- **Resource Types based I/O.** Hailstorm builds on Winograd-Cort et al's work to provide the semantics and implementation of an alternate model of I/O for pure functional languages using *resource types* - which fits the streaming programming model of IoT applications. (Section 4.1)
- **Discrete time implementation** Hailstorm uses the combinators of arrowized FRP in a discrete time setting (Section 3).
- **An implementation of the Hailstorm language.** We implement Hailstorm as a standalone compiler, with Erlang and LLVM backends. We have run case studies on the GRiSP embedded system boards [59], to evaluate the features of the language. (Section 4). The compiler implementation and the examples presented in the paper are made publicly available<sup>1</sup>.

## 2 LANGUAGE OVERVIEW

In this section we demonstrate the core features and syntax of Hailstorm using various running examples. We start with a simple pure function which computes the  $n^{th}$  Fibonacci number.

```
def main : Int = fib 6

def fib : (Int -> Int)
  = fib_help 0 1

def fib_help (a : Int) (b : Int) (n : Int) : Int
  = if n == 0
    then a
    else fib_help (a + b) a (n - 1)
```

The simple program above, besides showing the ML-like syntax of Hailstorm, demonstrates some features like (1) higher-order functions (2) recursion (3) partial application (4) tail-call optimization and (5) static typing. All top-level functions in a Hailstorm program have to be annotated with the types of the arguments and

the return type, which currently allows only monomorphic types. However certain built-in combinators supported by the language are polymorphic which will be discussed in the following section.

The pure core of the language only allows writing pure functions which have no form of interactions with the outside world. To introduce I/O and other side effects we need to describe the concept of a *signal function*.

### 2.1 Signal Functions

A fundamental concept underlying the programming model of Hailstorm is that of a *Signal Function*. Signal Functions, derived from the work on arrowized-FRP [46], describes functions that *always* accepts an input and *always* returns an output.

Signal functions are analogous to the nodes of a dataflow graph. Signal functions operate on *signals* which do not have any concrete representation in the language. A signal denotes a discrete value at a give point of time. Nilsson et al, compares the notion of a signal and signal function to an electric circuit where a signal is equivalent to the wire and the current flowing through it whereas the signal functions are equivalent to the various circuit elements. An important distinction between Hailstorm and both classic and arrowized-FRP is that signals are always treated as discrete entities in Hailstorm unlike the continuous semantics enforced by FRP.

To create larger programs Hailstorm provides a number of built-in combinators to compose signal functions. These combinators are drawn from the Arrow framework [31] which is a generalization of monads. Arrows allow structuring programs in a *point-free* style while providing mathematical laws for composition. We start by presenting some of the core Hailstorm combinators<sup>2</sup> and their types for composing signal functions.

```
mapSignal# : (a -> b) -> SF a b
(>>>) : SF a b -> SF b c -> SF a c
(&&&) : SF a b -> SF a c -> SF a (b, c)
(***) : SF a b -> SF c d -> SF (a, c) (b, d)
```

As mentioned in the previous section, some of the built-in combinators in Hailstorm are polymorphic and the type parameters *a*, *b* and *c* represent the polymorphic types. `mapSignal#` is the core combinator which lifts a pure Hailstorm function to the synchronous language of arrows, as a signal function (See Fig 1).

Hailstorm then provides the rest of the built-in combinators to compose signal functions while satisfying nine arrow laws [39]. One of the advantages of having a pure functional language is such laws can be freely utilized by an optimizing compiler to aggressively inline and produce optimized code. The semantics of composing signals with the arrow combinators is visually depicted in Fig 1.

<sup>1</sup><https://abhiroop.github.io/ppdp-2020-artifact.zip>

<sup>2</sup>Non-symbolic built-in combinators & driver functions in Hailstorm end with #

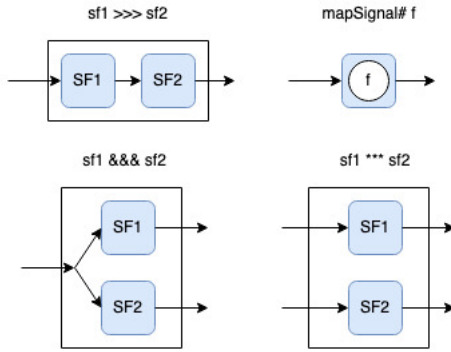


Figure 1: Arrow combinators for signal functions

Now where do signals actually come from? To answer this question - a natural extension to signal functions is using them to interact with I/O, which we discuss in the next section.

## 2.2 I/O

Hailstorm adopts a streaming programming model, where an effectful program is conceived by composing various signal functions in the program. The final program is embedded in a stream of input flowing in and the program transforms that into the output.

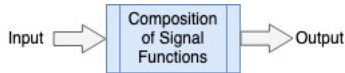


Figure 2: A Hailstorm program interacting with the real world

While this model of I/O adapts well with a pure functional language, it is reminiscent of the now abandoned stream-based I/O interface in Haskell. In Haskell's early stream-based I/O model the type of the main function was  $[Response] \rightarrow [Request]$ . The major problems with this model are :

- All forms of I/O are restricted to happen at the main function leading to non-modular programs, especially in case of applications running on IoT devices where I/O functions dominate the majority of the program.
- It is non-extensible as the concrete types of Request and Response need to be altered every time any new I/O facility has to be added [48].
- There is also no clear mapping between an individual Request and its Response [48].

Winograd-Cort et al. attempts to address the above problem in their work on resource types [65] by *virtualizing* real-world devices as signal functions. What we mean here by "virtualizing" is that the scope of a program is extended so that devices like sensors and actuators are represented using signal functions. For example:

```
sensor : SF () Int
uart_rx : SF () Byte
actuator : SF Bool ()
```

We adopt this model in Hailstorm. The type parameter  $()$  represents a *void* type. There are no *values* in the language which inhabit the  $()$  type. The  $()$  type always appears within a signal function. So given an example like `sensor : SF () Int` - this represents an *action* which when called, produces an integer.

One of the key aspects of designing a pure functional language is this distinction between an expression which returns a *value* and an *action*. When an action (like `sensor : SF () Int`) is evaluated, it returns a representation of that function call rather than actually *executing* the call itself. This distinction is the key to equational reasoning in a purely functional program. In the absence of such a distinction the following two expressions are no longer equivalent although they represent the same programs.

```
-- Expression 1 : accepts an input and
-- duplicates that input to return a pair
let x = getInput -- makes one I/O call
in (x,x)

-- Expression 2 : accepts two inputs
-- returns both of them as a pair
(getInput, getInput) -- makes two I/O calls
```

After enforcing a difference between values and action in the language we soon encounter one of the pitfalls of treating a real-world object as a virtual device - it allows a programmer to write programs with unclear semantics. For example:

```
def foo : SF () (Int, Int) = sensor &&& sensor
```

Although the above program is currently type correct, it can have two conflicting semantics - (1) either `sensor &&& sensor` implies two consecutive calls to the sensor device or (2) a single call emitting a pair. Given the type of the sensor function, the latter is not supported and the former is incompatible with Hailstorm's discrete, synchronous semantics.

The notion of *Resource Types* seeks to solve this problem by labeling each device with a type-level identifier, such that duplicating a device becomes impossible in the program. We change the type of sensor to :

```
resource S
sensor : SF S () Int
```

The *resource* keyword in Hailstorm declares a type level identifier which is used for labeling various signal functions like sensor above. All the built-in arrow combinators introduced previously are now enriched with new *type-level* rules for composition as follows:

```
mapSignal# : (a -> b) -> SF Empty a b
(>>>) : SF r1 a b -> SF r2 b c -> SF (r1 ∪ r2) a c
(&&&) : SF r1 a b -> SF r2 a c -> SF (r1 ∪ r2) a (b, c)
(***) : SF r1 a b -> SF r2 c d -> SF (r1 ∪ r2) (a, c) (b, d)
```

In the combinators above, the type parameters  $r_1, r_2$  represent polymorphic resource type variables which act as labels for the effectful signal functions. The combinator `mapSignal#` lifts a pure

Hailstorm function to a signal function without any effectful operations, as a result the resource type is `Empty`. The combinators `>>>`, `&&&` and `**` compose signal functions, and result in a disjoint-union of the two resource types. This type-level disjoint union prevents us from copying the same resource using any of these combinators. So in Hailstorm if we try this,

```
def foo : SF (S ∪ S) () (Int, Int) = sensor &&& sensor
```

we currently get the following upon compilation:

```
Type-Checking Error:
Error in "foo":
  Cannot compose resources : S S containing same resource
  Encountered in
    sensor &&& sensor
```

The type rules associated with composing Hailstorm combinators and their operational semantics are presented formally in Section 3.2 and 3.3 respectively.

**2.2.1 Example of performing I/O.** We can distinguish the read and write interface of a resource distinctively using two separate resource types. For example, to repeatedly blink an LED we need two APIs - (1) to *read* its status (2) to *write* to it. The drivers for these two functions have the following types:

```
readLed# : SF R () Int
writeLed# : SF W Int ()
```

We use the integer 1 to represent light ON status and 0 for OFF. The program for blinking the LED would be:

```
def main : SF (R ∪ W) () () =
  readLed# >>> mapSignal# flip >>> writeLed#

def flip (s : Int) : Int =
  if (s == 0) then 1 else 0
```

The above program runs the function `main` infinitely. It is possible to adjust the rate at which we want to run this program, discussed later in Section 2.5. This treatment of I/O as signal functions has the limitation that each device (as well as their various APIs) has to be statically encoded as a resource type in the program.

## 2.3 State

Hailstorm supports stateful operations on signals using the `loop#` combinator.

```
loop# : c -> SF Empty (a, c) (b, c) -> SF Empty a b
```

The type of the `loop#` combinator is slightly different from the type provided by the `ArrowLoop` typeclass in Haskell, in that it allows initializing the state type variable `c`. The internal body of the signal function encapsulates a polymorphic state entity. This entity is repeatedly fed back as an additional input, upon completion of a whole step of signal processing by the entire dataflow graph. Fig 3 represents the combinator visually.

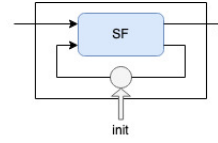


Figure 3: The stateful `loop#` function

The `loop#` combinator can be used to construct the delay function as found in synchronous languages like Lustre [26], for encoding state.

```
def delay (x : Int) : SF Empty Int Int =
  (loop# x (mapSignal# swap))

def swap (a : Int, s : Int) : (Int, Int) = (s, a)
```

## 2.4 A sample application

Now we will use all the combinators introduced till now to demonstrate a Hailstorm program for a sample application. The application that we choose is a simplified version of an earthquake detection algorithm [64] which was first used by Mainland et al. to demonstrate their domain specific language for wireless sensor networks [42]. The figure below demonstrates the core dataflow graph of the algorithm.

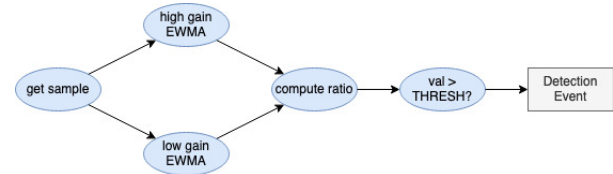


Figure 4: The earthquake detection dataflow graph

The exponentially weighted moving average (EWMA) component above is a stateful element. We assume the `getSample` input function is a wrapper around a seismometer providing readings of discrete samples. At the rightmost end, the `Detection Event` would be another stateful entity which would include some form of an *edge detector*. The entire program for the earthquake detection is given in Fig 5.

The function `edge` in Fig 5 is a stateful edge detector which generates an action if a boolean signal changes from `False` to `True`. To program this, we use an imaginary actuator (like an LED) in a GRiSP board, which would glow red once if the input to it is 1, signalling danger, and otherwise stay green signalling no earthquake.

## 2.5 Sampling rate

The combinators introduced till now now execute *instantaneously* using a logical clock. In Hailstorm one logical time step chronologically involves the following -

- accepting a discrete sample of data from each of its connected input device
- passing the discrete sample through the dataflow graph
- finally passing a signal to the responsible actuator

```

resource S
resource E

def main : SF (S ∪ E) () () =
  getSample >>> detect >>> edge

def detect : SF Empty Float Bool
  = (ewma high &&& ewma low)
  >>> (mapSignal# (\(hi : Float, lo : Float) =>
    (hi / lo) > thresh))

def ewma (α : Float) : SF Empty Float Float
  = let func = \ (x : Float, xold : Float) =>
    let xnew = (α * x) + (1.0 - α) * xold
    in (xnew, xnew)
  in loop# 0.0 (mapSignal# func)

-- constants
def low : Float = ...
def high : Float = ...
def thresh : Float = ...

def edge : SF E Bool () =
  loop# False (mapSignal# edgeDetector) >>>
  actuator

def edgeDetector (a : Bool, c : Bool) : (Int, Bool) =
  if (c == False && a == True)
  then (1, a)
  else (0, a)

-- getSample : SF S () Float - Erlang driver
-- actuator : SF E Int () - Erlang driver

```

Figure 5: The earthquake detection algorithm

A program returning a signal function continuously loops around, streaming in input and executing the above steps, at the speed it takes for the instructions to execute. However under most circumstances we might wish to set a slower rate for the program. The `rate#` combinator is used for that purpose,

```
rate# : Float -> SF r a b -> SF r a b
```

The first argument to `rate#` is the length of the wall clock time at which we wish to set the speed of sampling input. This provides us a method to provide a relation between the wall clock time and Hailstorm's logical clock. We demonstrate the utility of the `rate#` combinator using a *Stopwatch* example.

**2.5.1 Stopwatch.** We program a hypothetical stopwatch which accepts an input stream of Ints where 1 represents START, 2 represents RESET and 3 represents STOP.

```

def f (g : Float) (a : Int, c : Float) : (Float, Float) =
  let inc = c +. g in
  case a of
    1 ~> (inc, inc);
    2 ~> (0.0, 0.0);

```

```
- ~> (c, c)
```

```
def stopwatch (g : Float) : SF Empty Int Float
  = rate# g (loop# 0.0 (mapSignal# (f g)))
```

```
def main : SF (I ∪ O) () () =
  input >>> stopwatch 1.0 >>> output
```

In the above program the `rate#` combinator uses the argument `g` to set the sampling rate to 1 second which in turn fixes the granularity of the stopwatch as 1 second.

**2.5.2 Limitation.** In the current implementation of Hailstorm, an operation like `(rate# t2 (rate# t1 sf1))` would result in setting the final sampling rate as `t2` overwriting the value of `t1`. In the programs presented here we use a single clock and hence a single sampling rate. Libraries like Yampa [14] provide combinators like `delay :: Time → a → SF a a` which allow *oversampling* for dealing with multiple discrete sampling rates. As future work we hope to adopt oversampling operators for communication among signal functions with different sampling rates.

## 2.6 Switches

A Hailstorm dataflow graph allows a form of *dynamic*, data-driven switching within the graph. It accomplishes this using the `switch#` combinator:

```
switch# : SF r1 a b -> (b -> SF r2 b c) -> SF (r1 ∪ r2) a c
```

The first argument to `switch#` accepts a signal function whose output data is used to switch between the various signal functions. The strict typing of Hailstorm restricts the various branches of the switch to be of the same type, including the resource type. This constraint is not too restrictive as long as the switching doesn't happen at the actuator edge of the graph. While switching actuators it is idiomatic in Hailstorm to use the `***` operator which supplies an *action* signal to the activated actuator and a *no action* signal to the other actuators. The switching dataflow is visually presented in Fig 6.

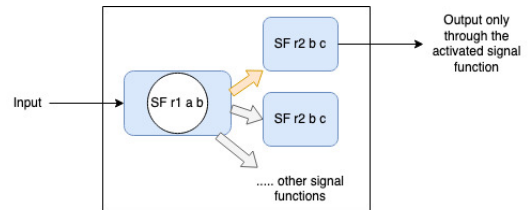


Figure 6: A switch activating only the top signal function

We present more examples using the various combinators in Section 5.

## 3 SYNTAX, SEMANTICS AND TYPES

In the previous sections we have given an informal treatment to the most important syntactic parts of Hailstorm, for IoT applications, and described the programming model using them. In this section

we formally present the core syntax and type rules of the language. Followed by that we provide a big-step operational semantics of the main parts of the language.

### 3.1 Syntax

The set of types in the source language is given by the following grammar.

$$\tau ::= () \mid \text{Int} \mid \text{Float} \mid \text{Bool} \mid \tau_1 \rightarrow \tau_2 \mid \tau_1 \xRightarrow{r} \tau_2(\tau_1, \tau_2)$$

The type  $\tau_1 \xRightarrow{r} \tau_2$  represents a signal function type from  $a$  to  $b$  with the resource type  $r$  i.e.  $\text{SF } r \ a \ b$ .

The abstract syntax of the core *expressions* of Hailstorm is given by the following grammar. The meta-variable  $x \in \text{Var}$  ranges over variables of the source language. Additionally we let  $i \in \mathbb{Z}$  and  $f \in \mathbb{R}$ . We use  $e$  and  $e_{sf}$  separately to denote ordinary expressions and arrow based signal function expressions respectively.

$$\begin{aligned} e &::= x \mid \bar{i} \mid \bar{f} \mid \text{True} \mid \text{False} \mid i_1 \text{ binop}_i i_2 \mid f_1 \text{ binop}_f f_2 \\ &\mid e_1 \text{ relop } e_2 \mid \text{if } e_1 \text{ then } e_2 \text{ else } e_3 \mid \lambda x : \tau. e \mid (e_1 \ e_2) \\ &\mid \text{let } x = e_1 \text{ in } e_2 \mid (e_1, e_2) \mid \text{fst} \# e \mid \text{snd} \# e \\ e_{sf} &::= \text{mapSignal} \# (\lambda x. e) \mid e_{sf1} >>> e_{sf2} \\ &\mid e_{sf1} \&\&\& e_{sf2} \mid e_{sf1} * * * e_{sf2} \mid \text{loop} \# e_1 \ e_2 \\ &\mid \text{switch} \# e_1 (\lambda x. e) \mid \text{read} \# \mid \text{write} \# \\ \text{binop}_i &::= + \mid - \mid * \\ \text{binop}_f &::= +. \mid -. \mid *. \mid / \\ \text{relop} &::= > \mid < \mid >= \mid <= \mid == \end{aligned}$$

In the grammar above we describe two primitives for I/O called `read#` and `write#`. In practise, as Hailstorm deals with a number of I/O drivers there exists a variety of I/O primitives with varied parameters and return types. However for the purpose of presenting the operational semantics, we abstract away the complexity of the drivers and use the abstracted `read#` and `write#` to describe the semantics in Section 3.3.

### 3.2 Type rules

Hailstorm uses a fairly standard set of type rules except for the notion of *resource types*. The typing context of Hailstorm employs *dual contexts*, in that it maintains (1)  $\Gamma$  - a finite map from variables to their types and (2)  $\Delta$  - a finite set which tracks all the I/O resources connected to the program.

$$\Delta; \Gamma ::= \cdot \mid \Gamma, x : \tau$$

An empty context is given by  $\cdot$ . Additionally  $\text{dom}(\Gamma)$  provides the set of variables bound by a typing context.

In Fig 7 we show the most relevant type rules concerning signal functions and their composition. The remaining expressions follow standard set of type rules which is provided in its entirety in the Appendix B.

Looking at the rule T-Mapsignal, a signal function such as  $\tau_1 \xRightarrow{\emptyset} \tau_2$  denotes the result of applying `mapSignal#` to a pure function.

This results in an expression with an empty resource type denoted by  $\emptyset$ . A missing rule is the introduction of a new resource type in the resource type context  $\Delta$ . The resource type context is an append-only store and a new resource is introduced using the keyword `resource`. It can be defined using this simple reduction semantics

$$\frac{}{\Delta; \Gamma \vdash \text{resource } r \rightsquigarrow \Delta \cup r; \Gamma}$$

where  $\rightsquigarrow$  denotes one step of reduction which occurs at compile-time. The rules such as T-Compose, T-Fanout, T-Combine, T-Switch apply a type-level *disjoint union* to prevent resource duplication.

### 3.3 Big-step Operational Semantics

In this section we provide a big-step operational semantics of our implementation of the Hailstorm language, by mapping the meaning of the terms to the lambda calculus. We begin by defining the *values* in lambda calculus which cannot be further reduced:

$$V ::= i \mid f \mid \lambda x. E$$

$i$  and  $f$  represent integer and float constants respectively. We use  $n$  to represent variables and the last term denotes a lambda expression. The syntax that we use for defining our judgements is of the form :

$$s_1 \vdash M \Downarrow V, s_2$$

In the above, the variables  $s_1, s_2$  are finite partial functions from variables  $n$  to their bound values  $V$ . In case a variable  $n$  is unbound and  $s$  is called with that argument it returns -  $\emptyset$ . The above judgement is read as *starting at state  $s_1$  and evaluating the term  $M$  results in the irreducible value  $V$  while setting the final state to  $s_2$ .*

The first judgement essential for our semantics is this,

$$\frac{}{s \vdash V \Downarrow V, s}$$

which means, as we have stated earlier, that the values  $V$  cannot be reduced further.

We use a shorthand notation  $\rho(n, s)$  to signify *lookup the variable  $n$  in  $s$* . Additionally to make the semantics more compact we use pairs -  $\langle a, b \rangle$  and their first and second projections - `fst`, `snd`. They do not belong to  $V$  but it is possible to represent all three of them using plain lambdas and function application - shown in the Appendix C

In Fig 8 we show the most relevant big-step operational semantics concerning signal function based combinators. The remaining expressions have standard semantics and the complete rule set is provided in Appendix D. In the rule `eval-Rate` we use  $\Psi$  to store the sampling rate. In our current implementation when composing signal functions with different sampling rates, the state transition from  $s_2$  to  $s_3$  overwrites the first sampling rate.

In `eval-Loop-Init` and `eval-Loop` the subscript  $n$  represents a variable name that is used as a key, in the global state map  $s$ , to identify each individual state.

For the rule `eval-Switch`,  $\sigma_b[\lambda c. E_1, \lambda c. E_2, \dots \lambda c. E_n]$  represents a conditional expression which uses the value of  $b$  i.e.  $(V_1 \ a)$  to *choose* one of the several branches -  $\lambda c. E_n$  - and then supplies  $(V_1 \ a)$  again to the selected branch to actually generate a value of the stream.

Of special interest in Fig 8 are the rules `eval-Read` and `eval-Write`. We need to extend our lambda calculus based abstract machine with



$$\begin{array}{c}
\frac{\Delta; \Gamma \vdash e : \tau_1 \rightarrow \tau_2}{\Delta; \Gamma \vdash \text{mapSignal}\# e : \tau_1 \xRightarrow{\emptyset} \tau_2} \text{ (T-Mapsignal)} \\
\\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \xRightarrow{r_1} \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_2 \xRightarrow{r_2} \tau_3 \quad r_1, r_2 \in \Delta \quad r_1 \cap r_2 = \emptyset}{\Delta; \Gamma \vdash e_1 >>> e_2 : \tau_1 \xRightarrow{r_1 \cup r_2} \tau_3} \text{ (T-Compose)} \\
\\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \xRightarrow{r_1} \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_1 \xRightarrow{r_2} \tau_3 \quad r_1, r_2 \in \Delta \quad r_1 \cap r_2 = \emptyset}{\Delta; \Gamma \vdash e_1 \&\&\& e_2 : \tau_1 \xRightarrow{r_1 \cup r_2} (\tau_2, \tau_3)} \text{ (T-Fanout)} \\
\\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \xRightarrow{r_1} \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_3 \xRightarrow{r_2} \tau_4 \quad r_1, r_2 \in \Delta \quad r_1 \cap r_2 = \emptyset}{\Delta; \Gamma \vdash e_1 *** e_2 : (\tau_1, \tau_3) \xRightarrow{r_1 \cup r_2} (\tau_2, \tau_4)} \text{ (T-Combine)} \\
\\
\frac{\Delta; \Gamma \vdash e : (\tau_1, \tau_c) \xRightarrow{\emptyset} (\tau_2, \tau_c) \quad \Delta; \Gamma \vdash c : \tau_c}{\Delta; \Gamma \vdash \text{loop}\# c e : \tau_1 \xRightarrow{\emptyset} \tau_2} \text{ (T-Loop)} \quad \frac{\Delta; \Gamma \vdash t : \text{Float} \quad \Delta; \Gamma \vdash e : \tau_1 \xRightarrow{r} \tau_2 \quad r \in \Delta}{\Delta; \Gamma \vdash \text{rate}\# t e : \tau_1 \xRightarrow{r} \tau_2} \text{ (T-Rate)} \\
\\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \xRightarrow{r_1} \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_2 \rightarrow \tau_2 \xRightarrow{r_2} \tau_3 \quad r_1, r_2 \in \Delta \quad r_1 \cap r_2 = \emptyset}{\Delta; \Gamma \vdash \text{switch}\# e_1 e_2 : \tau_1 \xRightarrow{r_1 \cup r_2} \tau_3} \text{ (T-Switch)} \\
\\
\frac{r \in \Delta}{\Delta; \Gamma \vdash \text{read}\# : () \xRightarrow{r} \tau} \text{ (T-Read)} \quad \frac{r \in \Delta}{\Delta; \Gamma \vdash \text{write}\# : \tau \xRightarrow{r} ()} \text{ (T-Write)}
\end{array}$$

Figure 7: Typing rules of signal functions in Hailstorm

$$\begin{array}{c}
\frac{s \vdash \text{exp} \Downarrow \lambda x.E, s}{s \vdash \text{mapSignal}\# \text{exp} \Downarrow \lambda x.E, s} \text{ (eval-Mapsignal)} \quad \frac{s_1 \vdash \text{exp}_1 \Downarrow V_1, s_2 \quad s_2 \vdash \text{exp}_2 \Downarrow V_2, s_3}{s_1 \vdash \text{exp}_1 >>> \text{exp}_2 \Downarrow \lambda x.V_2(V_1 x), s_3} \text{ (eval-Compose)} \\
\\
\frac{s_1 \vdash \text{exp}_1 \Downarrow V_1, s_2 \quad s_2 \vdash \text{exp}_2 \Downarrow V_2, s_3}{s_1 \vdash \text{exp}_1 \&\&\& \text{exp}_2 \Downarrow \lambda x. < V_1 x, V_2 x >, s_3} \text{ (eval-Fanout)} \\
\\
\frac{s_1 \vdash \text{exp}_1 \Downarrow V_1, s_2 \quad s_2 \vdash \text{exp}_2 \Downarrow V_2, s_3}{s_1 \vdash \text{exp}_1 *** \text{exp}_2 \Downarrow \lambda x. \lambda y. < V_1 x, V_2 y >, s_3} \text{ (eval-Combine)} \\
\\
\frac{s_1 \vdash \text{init} \Downarrow V_i, s_2 \quad s_2 \vdash \text{exp} \Downarrow V_1, s_3 \quad n \notin \text{dom}(s_3)}{s_1 \vdash \text{loop}\#_n \text{init exp} \Downarrow \lambda x. \text{fst}(V_1(x, V_s)), s_3[n \mapsto \text{snd}(V_1(x, V_i))]} \text{ (eval-Loop-Init)} \\
\\
\frac{s_1 \vdash \text{init} \Downarrow V_i, s_2 \quad s_2 \vdash \text{exp} \Downarrow V_1, s_3 \quad n \in \text{dom}(s_3)}{s_1 \vdash \text{loop}\#_n \text{init exp} \Downarrow \lambda x. \text{fst}(V_1(x, \rho(n, s_3))), s_3[n \mapsto \text{snd}(V_1(x, \rho(n, s_3)))]} \text{ (eval-Loop)} \\
\\
\frac{s_1 \vdash e_2 \Downarrow V, s_2 \quad s_2 \vdash e_1 \Downarrow \lambda x.E_1, s_3 \quad s_3 \vdash E_1[x \mapsto V] \Downarrow V_f, s_4}{s_1 \vdash (e_1 e_2) \Downarrow V_f, s_3} \text{ (eval-App)} \quad \frac{s_1 \vdash t \Downarrow V_t, s_2 \quad s_2 \vdash \text{exp} \Downarrow V, s_3[\Psi \mapsto V_t]}{s_1 \vdash \text{rate}\# t \text{exp} \Downarrow V, s_3[\Psi \mapsto V_t]} \text{ (eval-Rate)} \\
\\
\frac{s_1 \vdash \text{exp}_1 \Downarrow V_1, s_2 \quad s_2 \vdash \text{exp}_2 \Downarrow \lambda b. \sigma_b[\lambda c.E_1, \lambda c.E_2, \dots \lambda c.E_n], s_3}{s_1 \vdash \text{switch}\# \text{exp}_1 \text{exp}_2 \Downarrow \lambda a. ((\lambda b. \sigma_b[\lambda c.E_1, \lambda c.E_2, \dots \lambda c.E_n])(V_1 a)) (V_1 a), s_3} \text{ (eval-Switch)} \\
\\
\frac{}{s \vdash \text{read}\# \Downarrow \lambda x. \text{read}, s} \text{ (eval-Read)} \quad \frac{}{s \vdash \text{write}\# \Downarrow \lambda x. (\text{write } x), s} \text{ (eval-Write)}
\end{array}$$

Figure 8: Big-Step Operational Semantics of signal functions in Hailstorm

the operations - read and write - to allow any form of I/O. We can see that the effectful operations - read and write are guarded by  $\lambda s$  to prevent any further evaluation and as a result treating them as values. This method is essential to ensure the purity of the language - by treating effectful operations as values.

The program undergoes a *partial evaluation* transformation which evaluates the entire program to get rid of all the  $\lambda s$  guarding the read operations. Given the expression  $\lambda x. \text{read}$  the compiler supplies a compile time token of type  $()$  which removes the *lambda* and exposes the effectful function read. The partially evaluated

program is then prepared to conduct I/O. This approach is detailed further in Section 4.1.

The big-step semantics of the language shows its evaluation strategy. However to understand the streaming, infinite nature of an effectful Hailstorm program we need an additional semantic rule. A Hailstorm function definition is itself an expression and a program is made of a list of such functions,

$$\begin{aligned}
\text{Program} &::= \text{main} : [\text{Function}] \\
\text{Function} &::= e|e_{sf}
\end{aligned}$$

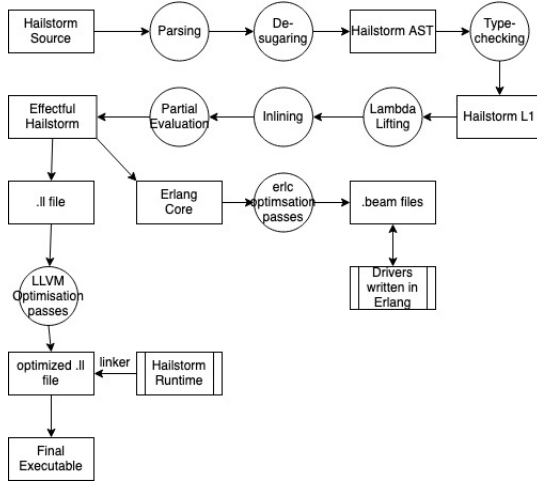
Each Hailstorm program compulsorily has a main function. After the entire program is *partially evaluated* (described in Section 4.1) and given that the main function causes a side effect (denoted by  $()$  below), we have the following rule.

$$\frac{s_1 \vdash \text{main} \Downarrow (), s_2}{s_1 \vdash \text{main} \Downarrow \text{main}, s_2} \text{ (eval-Main)}$$

The eval-Main rule demonstrates the streaming and infinite nature of a Hailstorm program when the main function is a signal function itself. After causing a side effect, it calls itself again and continues the stream of effects while evaluating the program using the semantics of Fig 8.

## 4 IMPLEMENTATION

Here we describe an implementation of the Hailstorm language and programming model presented in the previous sections. We implement the language as a *compiler* - the Hailstorm compiler - whose compilation architecture is described below.



**Figure 9: The Hailstorm compilation architecture**

The compiler pipeline starts by parsing a Hailstorm source file and *desugaring* small syntactic conveniences provided to reduce code size (such as case expressions). After desugaring, the Hailstorm AST constituted of the grammar described in Section 3.1 is generated. Followed by that typechecking of the AST using the type rules of Fig 7 is done. After a program is typechecked it is transformed into the Hailstorm core language called L1.

The L1 language is an enriched version of the simply typed lambda calculus (STLC) with only nine constructors. Unlike STLC, L1 supports recursion by calling the name of a global function. It is currently incapable of recursion using a *let* binding. L1 has a simpler type system than the Hailstorm source, as it *erases* the notion of resource types - which are exclusively used during type checking.

The L1 language being considerably simpler, forms a sufficient foundation for running correctness preserving optimization passes. L1 attempts to get rid of all closures with free variables, as they are primarily responsible for dynamic memory allocation. Additionally it attempts to inline expressions (primarily partial applications)

to further reduce both stack and heap memory allocation. The optimization passes are described in further detail in Section 4.2.

The final optimization pass in L1 is a *partial evaluation* pass which specializes the program to convert it into an effectful program. Before this pass all I/O inducing functions are treated as values by guarding them inside a  $\lambda$  abstraction. This pass evaluates those expressions by passing a compile-time token and turning the L1 non-effectful program into an effectful one. This pass is discussed in further detail in Section 4.1.

Finally the effectful Hailstorm program gets connected to one of its backends. Recursion is individually handled in each of the backends by using a global symbol table. We currently support an LLVM backend [36] and a BEAM backend [4].

### 4.1 I/O

The I/O handling mechanism of the Hailstorm compiler is the essential component in making the language *pure*. A pure functional language allows a programmer to equationally reason about their code. The entire program is written as an *order independent* set of equations. However for performing I/O in a programming language it is necessary to (1) enforce an order on the I/O interactions, as they involve *chronological* effects visible to the user and (2) interact with the real world and actually perform an effect.

To solve (1) we use the eval-App rule described in Fig 8. Hailstorm, being a *call-by-value* implementation of the lambda calculus, follows *ordering* in function application by always evaluating the function argument before passing it to the function. This semantics of function application allows us to introduce some form of ordering to the equations.

To solve (2) we have extended our pure lambda calculus core to involve effectful operations like read and write. Again as observed in the semantic rules - eval-Read and eval-Write from Fig 8 - the effectful operations are guarded by a  $\lambda$  abstraction to treat them as values, rather than operations causing side-effects. This allows us to freely inline or apply any other optimization passes while preserving the correctness of the code. However to finally perform the side effect we need to resolve this lambda abstraction at compile time. We do that by *partially evaluating* [33] our program. Below we describe the semantics of the partial evaluation step.

A Hailstorm program is always enforced (by the typechecker in our implementation) to contain a *main* function. We shall address the case of an effectful program i.e a *main* function whose return type is an effectful signal function such as  $SF \ r \ () \ ()$ . The  $()$  type in the input and output parameters reflect that this function reads from a real world source like a sensor and causes an effect such as moving an actuator. The partial application pass is only fired when the program contains the  $()$  type in either one of its signal function parameter.

Let us name the main function above with the return type of  $SF \ r \ () \ ()$  as  $\text{main}_{sf}$ . Now  $\text{main}_{sf}$  is itself a function, embedded in a stream of input and transforming the input to an output, causing an effect. As it is a function we can write:  $\text{main}_{sf} = \lambda t.E$ .

Additionally in our implementation, after typechecking, a signal function type  $\tau_1 \xRightarrow{r} \tau_2$  is reduced to a plain arrow type -  $\tau_1 \rightarrow \tau_2$ . Now using the two aforementioned definitions we can write the following reduction semantics:



$$\frac{\text{main}_{sf} = \lambda t.E \quad \text{main}_{sf} : () \xrightarrow{r} () \quad \tau_1 \xrightarrow{r} \tau_2 \rightsquigarrow \tau_1 \rightarrow \tau_2}{\frac{\lambda t.E : () \xrightarrow{r} () \rightsquigarrow \lambda t.E : () \rightarrow ()}{\lambda t.E : () \rightarrow () \rightsquigarrow E[t \mapsto \theta : ()]} \text{ (eval-Partial)}}$$

where  $\rightsquigarrow$  denotes one step of reduction and  $\theta$  denotes an arbitrary compile time token of type  $()$ . The final step, which produces the expression  $E[t \mapsto \theta : ()]$ , is the partial evaluation step. We demonstrate this reduction semantics in action using an example:

```
read# : SF STDIN () Int
write# : SF STDOUT Int ()

def main : SF (STDIN U STDOUT) () () = read# >>> write#
```

We use the `eval-Read`, `eval-Write` and `eval-Compose` rules to translate the *main* function above to

```
main = λt. (λy. write y) ((λx. read) t)
```

Given the above definition of *main*, we can apply the reduction rule eval-Partial and eval-App to get the following,

$$\lambda t. (\lambda y. \text{write } y) ((\lambda x. \text{read}) t) \rightsquigarrow_* (\lambda y. \text{write } y) (\text{read}) \quad \text{(Partial evaluation)}$$

Now the program is ready to create a *side effect* as the read function is no longer guarded by a  $\lambda$  abstraction. The eval-App rule guarantees that read is evaluated first and only then the value is fed to write owing to the *call-by-value* semantics of Hailstorm.

**4.1.1 Limitation.** The Hailstorm type system doesn't prevent a programmer from writing `write# >>> read#`. The type of such a program would be `SF (STDOUT U STDIN) Int Int`. As the types do not reflect the `()` type, the partial evaluation pass is not fired and the program simply generates an unevaluated closure - which is an expected result given the meaningless nature of the program. However the type would allow composing it with other pure functions and producing bad behaviour if those programs are connected to meaningful I/O functions. This is simply solved by adding the following type rule:

$$\frac{r \in \Delta \quad r \neq \emptyset \quad \Delta; \Gamma \vdash \tau_1 : () \vee \tau_2 : ()}{exp : \tau_1 \xRightarrow{r} \tau_2} \text{ (T-Unsafe)}$$

## 4.2 Optimizations

**4.2.1 Lambda Lifting.** Hailstorm, being a functional language, supports higher order functions (HOFs). HOFs frequently capture free variables which survive the scope of a function call. For example:

```
1 def addFive (nr : Int) : Int =
2   let x = 5 in
3   let addX = \(y:Int) => x + y in
4   addX nr
```

Our implementation treats HOFs as closures which are capable of capturing an environment by allocating the environment on the heap. In line no. 3 above, the value of the variable `x` is heap allocated. However in resource constrained devices heap memory allocation is highly restrictive and any language targeting such devices should attempt to minimize any unwanted allocation.

Hailstorm applies a *lambda-lifting* [32] transformation to address this. Lambda-lifting lifts a lambda expression with free variables to a top-level function and then updates related call sites with a call to the top-level function. The free variables then act as arguments to the function. This effectively allocates them on the

stack (or registers). Owing to our restricted language and the lack of polymorphism, our algorithm is less sophisticated than the original algorithm devised by Johnsson et al. We describe the operational semantics of our algorithm in the `lambda-lifting` rule below.

We use a slightly different notation from Section 3.3 here.  $P_n$  is used to describe the entire program with its collection of top level functions. We identify a modified program with  $- P_n[G(x).E]$  to mean a new program with an additional global function  $G$  which accepts an argument  $x$  and returns an expression  $E$ . Finally the  $fv$  function is used find the set of free variables in a Hailstorm expression.

$$\frac{P_1 \vdash \text{exp} \Downarrow \lambda x. E, P_2 \quad f v(\lambda x. E) \neq \emptyset \quad f v(\lambda x. E) = \{i_1, \dots, i_n\} \quad P_2 \vdash \lambda x. E \Downarrow E', P_3[G(i_1, \dots, i_n, x) . E]}{P_1 \vdash \text{exp} \Downarrow E', P_3[G(i_1, \dots, i_n, x) . E]}$$

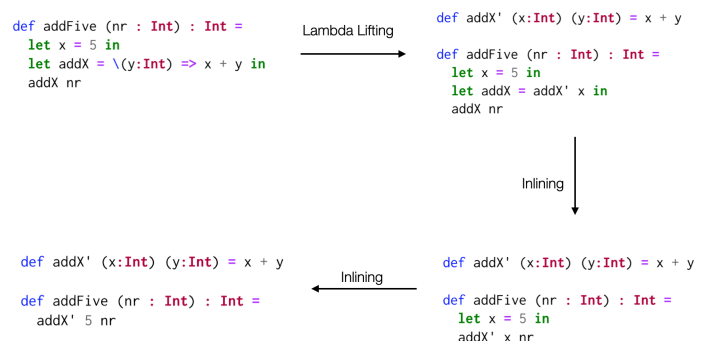
The above rule returns a modified expression  $E'$  which comprises of a function call to  $G(i_1, \dots, i_n, x) . E$  with the free variables  $i_1, \dots, i_n$  as arguments. This rule is repeatedly ran on local lambda expressions till there are none of them with free variables. It transforms the program `foo` above to :

```
def addX' (x: Int) (y: Int) = x + y

def addFive (nr : Int) : Int =
  let x = 5 in
    addX' x nr
```

**4.2.2 Inlining.** The inlining transformation works in tandem with the lambda lifter to reduce memory allocations. Inlining a lambda calculus based language reduces to plain  $\beta$  reduction. i.e.  $((\lambda x. M) E) \rightsquigarrow M[x \mapsto E]$ . Inlining subsumes optimization passes like *copy-propagation* in a functional language. Our prototype inliner is relatively conservative in that (1) it doesn't attempt to inline recursive functions and (2) it doesn't attempt inter-function inlining.

However it attempts to cooperate with the lambda-lifter to remove all possible sites of partial applications, which are also heap allocated, to minimize memory allocation. The program shown in the previous section, undergoes the cycle in Fig. 10



**Figure 10: Lambda-lifting and inlining in action**

The lambda lifting pass produces a partial application which is further inlined to a single function call where the arguments can be passed using registers. We show the generated LLVM code before and after the optimization passes are run in Appendix A. Notable

are the absence of any calls to `malloc` in the optimized version of the code. Our inliner doesn't employ any novel techniques but it still has to deal with engineering challenges like dealing with *name capture* [5], which it solves using techniques from the GHC inliner [34].

### 4.3 Code Generation

The Hailstorm compiler is designed as a linear pass through a tower of interpreters which compile away high level features, in the tradition of Reynolds [51]. Here we show the final code generation for two of the more interesting combinators using C-like notation:

**4.3.1 loop#.** The `loop#` combinator models a traditional Mealy machine whose output depends on the input as well as the current state of the machine. In the following we see the code generated for the delay combinator described in Section 2.3 which is itself described using `loop#`.

```
def main : SF (R U W) () () =
  readIntStream# >>> foo >>> writeIntStream#

def foo : SF Empty Int Int =
  delay 0 >>> (mapSignal# (\(x:Int) => x + 5))
```

→

```
int foo_state = 0;

int foo (int x) {return (x + 5);}

void main(){
  while (1) {
    int val = readInt();
    int temp = 0;
    int (*fun_ptr)(int) = foo;
    temp = foo_state;
    foo_state = val;
    writeInt(fun_ptr(temp));
  }
}
```

In Erlang the global variable of `foo_state` is modeled recursively using a global state map which is updated on every time step. In the LLVM backend the translation is very similar to the C-notation shown above.

**4.3.2 switch#.** We show an example of the `switch#` combinator when dealing with stateful branches

```
int s1 = 0; int s2 = 1;

int f(int x){return (x*2);}
int g(int x){return (x*3);}

def main : SF (R U W) () () =
  switch# readIntStream#
  (\(b:Int) =>
    if b%2 == 0
    then delay 0 >>> (mapSignal# (\(x:Int) => x * 5))
    else delay 1 >>> (mapSignal# (\(x:Int) => x * 3))
  ) >>> writeIntStream#
```

→

```
void main(){
  while(1){
    int val = readInt();
    int temp = 0;
    if (val%2 == 0){
      int (*fun_ptr1)(int) = f;
      temp = s1; s1 = val;
      writeInt(fun_ptr1(temp));
    }else{
      int (*fun_ptr2)(int) = g;
      temp = s2; s2 = val;
      writeInt(fun_ptr2(temp));
    }
  }
}
```

**Figure 11: Code generation for switch#**

The second parameter in the `switch#` type -  $(b \rightarrow SF \ b \ c)$  - acts like a macro which is unfolded into an if-then-else expression in the L1 core language. The core language contains primops for *getting* and *setting* state variables. The final L1 fragment that is generated

for the  $(b \rightarrow SF \ b \ c)$  component of `switch#` (post *partial evaluation* phase) is given below:

```
... -- s1 and s2 recursively in scope
let x = readInt() in
((λ val .
  if(val % 2 == 0)
  then (λ val2 .
    let temp = s1 in
    let _ = (set s1 to val2) in
    writeInt (f temp))
  else (λ val3 .
    let temp = s2 in
    let _ = (set s2 to val3) in
    writeInt (f temp))
) x) x ....
```

From the above L1 fragment the C like imperative code shown in Fig. 11 is generated. The if-then-else expressions are translated to case expressions in Erlang and the LLVM translation is very similar to the C code. The global state map now stores two state variables which are updated depending on the value of `x`. To make the operational aspect of the combinator clearer, we show the evolution of the state variables through the various timesteps of the program:

```
INPUT:  - 2 3 4 5 6 7...
s1:      0 2 2 4 4 6 6...
s2:      1 1 3 3 5 5 7...
OUTPUT: - 0 3 4 9 8 15...
```

### 4.4 Pull Semantics

In this section we discuss the semantics of data consumption in our compiler. There exists two principle approaches (1) demand-driven pull and (2) data-driven push of data. As Hailstorm's signal function semantics assume a continuous streaming flow of data triggering the dataflow graph, our compiler adopts a pull based approach which continuously *polls* the I/O drivers for data. The program blocks until more data is available from the I/O drivers.

Let us take the earthquake detection example from Section 2.4. The `getSample` input function in the dataflow graph (Fig. 4) is a wrapper around the driver for a seismometer, which when polled for data provides a reading. The rightmost edge of the graph for the Detection Event pulls on the dataflow graph after it completes an action and the rest of the graph in turn pulls on `getSample` - which polls the seismometer.

However in certain devices such as UART, a push based model is more prevalent where data is asynchronously pushed to the drivers. In such cases, to avoid dropping data the wrapper function (such as `getSample`) needs to be stateful and introduce buffers which store the data. The pseudocode of the wrapper function for such a driver, written for our Erlang backend, would look like Fig 12.

```

loop(State)
  receive
    {hailstormcall, From, Datasize} ->
      (Data, NewState) = extract_Data(Datasize, State),
      From ! {ok, Data},
      loop(NewState);
    {uartdriver, Message} ->
      NewState = buffer(Message, State),
      loop(NewState);
  end.

```

Figure 12: Enforcing pull semantics on push-based data

In Fig 12 there are two separate message calls that are handled. The data transmission from the drivers are handled using the `uartdriver` message call which continuously buffers the data. On the other hand the Hailstorm program upon finishing one cycle of computation requests for more data using the `hailstormcall` message and proceeds with the rest of the cycle

**4.4.1 Limitation.** Elliott has criticized the use of pull semantics [19] as being wasteful in terms of the re-computation required in the dataflow graph. He advocates a hybrid *push-pull* approach which in case of continuously changing data adopts the pull model but in the absence of any change in the data doesn't trigger the dataflow graph. This approach could be useful in resource constrained devices where energy consumption is an important parameter and we hope to experiment with this approach in future work.

## 4.5 The digital - analog interface

The runtime of Hailstorm has to deal with the boundary of discrete digital systems and continuous analog devices. The input drivers have to frequently discretize events that occur at some unknown point of time into a stream of discrete data. An example is the Stopwatch simulation from Section 2.5.1. The pressing of an ON button in a stopwatch translates to the stream of ones (111...) and when switched OFF the simulation treats that as a stream of zeroes. This stream transformation is handled by the wrapper functions around the input drivers.

On the contrary, for the output drivers a reverse translation of discrete to continuous is necessary. We can take the example of operating traffic lights (related demonstration in Section 5.1.2). When operating any particular signal like GREEN supplying a discrete stream of data (even at the lowest granularity) will lead to a *flickering* quality of the light. In that case the wrapper function for the light drivers employs a stateful edge detector, as discussed in Section 2.4, to supply a new signal only in case of change.

## 4.6 Backend specific implementation

There are a few other backend specific implementation details like,

- **Memory management.** The compiler attempts to minimize the amount of dynamically allocated memory using lambda-lifting and inlining such that the respective garbage collectors have to work less. Future work hopes to experiment with static memory management schemes like *regions* [60].
- **Tail call optimization (TCO).** Erlang itself does TCO and LLVM supports TCO when using the *fastcc* calling convention.

## 5 EVALUATION

### 5.1 Case Studies

In this section we demonstrate examples from the synchronous language literature [30] written in Hailstorm.

**5.1.1 Watchdog process.** A watchdog process involves monitoring a sequential order processing system. It raises an alarm if processing an order takes more than a threshold time. It has two input signals - (1) *order* :  $SF\ O\ ()\ Bool$  which emits *True* when an order is placed and *False* otherwise, (2) *done* :  $SF\ D\ ()\ Bool$  which also emits *True* only when an order is done. For output we use - *alarm* :  $SF\ A\ Bool\ ()$  where an alarm is rung only when *True* is supplied. In the program below we keep a threshold time for order processing as 3 seconds.

```

def f ((order : Bool, done : Bool),
      (time : Int, openOrder : Bool)) : (Bool, (Int, Bool))
= if (openOrder == True && time > 3)
  then (True, (time + 1, False)) -- set alarm once
  else if (done == True)
    then (False, (0, False)) -- reset
    else if (order == True)
      then (False, (0, True))
      else (False, (time + 1, openOrder))

def watchdog : SF (O ∪ D ∪ A) () () = (order &&& done) >>>
  (loop# (0, False) (mapSignal# f)) >>> alarm

def main : SF (O ∪ D ∪ A) () () = rate# 1.0 watchdog

```

**5.1.2 A simplified traffic light system.** We take the classic example of a simplified traffic light system from the Lustre literature [53]. The system consists of two traffic lights, governing a junction of two (one-way) streets. In the default case, traffic light 1 is green, traffic light 2 is red. When a car is detected at traffic light 2, the system switches traffic light 1 to red, light 2 to green, waits for 20 seconds, and then switches back to the default situation.

We use a sensor - *sensor* :  $SF\ S\ ()\ Bool$  - which keeps returning *True* as long as it detects a car. The system upon detecting a subsequent car resets the wait time to another 20 seconds. We sample from the sensor every second. In case of the traffic lights, we use 1 to indicate green and 0 for red.

```

def lightSwitcher (sig : Bool, time : Int) : ((Int, Int), Int)
= if (time > 0)
  then ((0, 1), time - 1)
  else if (sig == True)
    then ((0, 1), 20) -- reset
    else ((1, 0), 0) -- default

def lightController : SF (S ∪ TL1 ∪ TL2) () () =
  sensor >>> (loop# 0 (mapSignal# lightSwitcher)) >>>
  (trafficLight1 *** trafficLight2)

def main : SF (S ∪ TL1 ∪ TL2) () () =
  rate# 1.0 lightController

-- sensor : SF S () Bool
-- trafficLight1 : SF TL1 Int ()
-- trafficLight2 : SF TL1 Int ()

```

**5.1.3 A railway level crossing.**

*The problem.* We consider a two-tracks railway level crossing area that is protected by barriers, that must be closed in time on the arrival of a train, on one or the other track. They remain closed until all trains have left the area. The barriers must be closed 30 seconds before the expected time of arrival of a train. When the area becomes free, barriers could be opened, but it's not secure to open them for less than 15 s. So the controller must be warned 45 s before a train arrives. Since the speed of trains may be very different, this speed has to be measured, by detecting the train in two points separated by a known distance. A first detector is placed 2500 m before the crossing, and a second one 100 m after this first. A third is placed after the crossing area, and records the train's leaving. We divide our solution into three programs.

*The Detect Process.* The passage of a train is detected by a mechanical device, producing a *True* pulse - *pulse* : *SF P () Bool* - only when a wheel runs on it (otherwise *False*). The detect process receives all these pulses, but warns the controller only once, on the first wheel. All following pulses are ignored.

```
def f (curr : Bool, old : Bool) : (Bool, Bool) =
  if (curr == True && old == False)
  then (True, curr) else (False, curr)

def detect : SF P () Bool =
  pulse >>> loop# False (mapSignal# f)
```

*A Track Controller.* On each track, a controller receives signals from two detectors. From Detect1 and Detect2, it must compute the train's speed, and warn the barriers 45 seconds before expected time of arrival at crossing. At the maximum speed of 180 km/h, the 100 m between Detect1 and Detect2 are covered in 2 s. So, a clock pulse every 0.1 s would be of good accuracy.

```
def t ((d1 : Bool, d2 : Bool), time:Float) : (Float, Float)
= case (d1, d2) of
  (True, False) ~> (0.0, 0.0);
  (False, True) ~> ((24.0 *. (time +. 0.1) -. 45.0), 0.0);
  _ ~> (0.0, time +. 0.1)

def timer : SF Empty (Bool, Bool) Float
= rate# 0.1 (loop# 0.0 (mapSignal# t))

def trackController : SF (P1 ∪ P2) () Float
= (detect1 &&& detect2) >>> timer

def detect1 : SF P1 () Bool = ...
def detect2 : SF P2 () Bool = ...
```

When a train approaches, the trackController calculates the time for the train to reach the barrier and sends that value. In the absence of a train it sends zeroes.

*The Barriers Controller.* It consists of an alarm - *alarm* : *SF (P1 ∪ P2) () Bool* which consumes the time values from the trackController and returns *True* when an alarm is to be rung. The trackController is also sampled every 0.1 second.

```
def g (sig : Float, time : Float) : (Bool, Float) =
  if (sig > 0.0)
  then (False, sig)
  else if (time == 0.1)
  then (True, 0.0)
```

```
else (False, time -. 0.1)

def alarm : SF (P1 ∪ P2) () Bool
= trackController >>> rate# 0.1 (loop# 0.0 (mapSignal# g))
```

Given the alarms from the two separate tracks, the barrier controller sends an open/close signal represented by 0 and 1 respectively. In case a train is approaching in both of the tracks at the same speed - the barrier for only track 1 is opened.

```
def alarm1 : SF (P1 ∪ P2) () Bool = ...
def alarm2 : SF (P3 ∪ P4) () Bool = ...

def openclose (sig : (Bool, Bool)) : (Int, Int) =
  case sig of
    (True, False) ~> (0, 1);
    (False, True) ~> (1, 0);
    (True, True) ~> (0, 1);
    _ ~> (0, 0) -- (False, False)

def barrierController : SF (P1 ∪ P2 ∪ P3 ∪ P4) () (Int, Int) =
  alarm1 &&& alarm2 >>> (mapSignal# openclose)
```

Finally before sending the signal to the actuators (i.e the barriers) we need an additional system clock which keeps each barrier open for 45 seconds and ignores other signals in that interim. The handling of the discrete signals to continuous is done by the drivers for the actuators as discussed in Section 4.5.

```
def gate ((x : Int, y : Int),
  (t : Float, old : (Int, Int))) :
  ((Int, Int), (Float, (Int, Int))) =
  if (old ≠ (0,0) ∧ t > 0.0)
  then old, ((t -. 0.1), old)) -- persisting a signal
  else if (x == 1 ∨ y == 1)
  then ((x,y), (45.0, (x, y)))
  else ((x,y), (0.0, (x,y)))

def main : SF (P1 ∪ P2 ∪ P3 ∪ P4 ∪ B1 ∪ B2) () ((), ()) =
  rate# 0.1 (barrierController >>>
    (loop# (0.0, (0,0)) (mapSignal# gate)) >>>
    (barrier1 *** barrier2))

-- barrier1 : SF B1 Int ()
-- barrier2 : SF B2 Int ()
```

Note that the three instances of *rate#* all sample at the same interval of 0.1 seconds. Hailstorm currently doesn't have well defined semantics for programs with multiple clock rates.

## 5.2 Microbenchmarks

Here we provide memory consumption and response-time microbenchmarks for the examples presented above using the Erlang backend.



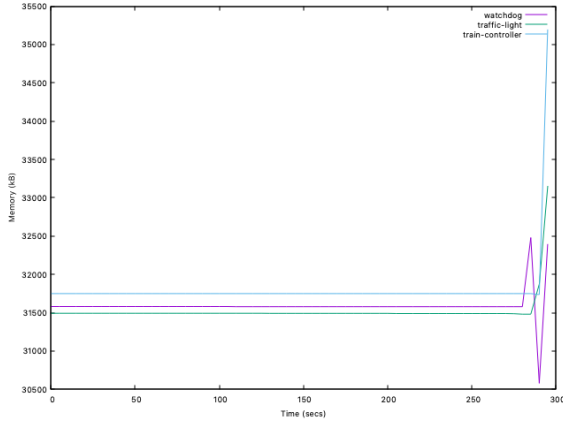


Figure 13: Memory consumption of programs

We measure the mean memory consumption for each program over five runs, each of five minutes duration. Given the I/O driven nature of the programs, the memory consumption shows little to no fluctuations in their behaviour. The Erlang runtime (ERTS) upon initialization sets up the garbage collector, initializes the lookup table and sets up the bytecode-interpreter which occupies 30 MB of memory on average. The actual program and its associated book-keeping structures takes up an average of 1.5 MB of memory in the programs above. The garbage collector remains inactive throughout the program run. The memory spike visible upon termination is the garbage collector pausing the program and collecting all residual memory.

Program	Run <sub>1</sub> (ms)	Run <sub>2</sub> (ms)	Run <sub>3</sub> (ms)
watchdog	7.7	8.65	11.4
traffic-light	3.81	3.04	2.12
train controller	29.72	28.05	29.8

Table 1: Response time measured in milliseconds

Table 1 shows the response time for the programs measured in milliseconds. We measure the CPU Kernel time (CPUT) - which calculates the time taken by the dataflow graph to finish one cycle of computation. We show three separate runs where the Erlang virtual machine is killed and restarted to reset the garbage collector. Each of the numbers are an average of twenty iterations of data processing. We use the `erlang:statistics` module for measuring time and in the applications I/O happens over the command line interface, which explains the overall slow behaviour (tens of milliseconds). The metrics are run on the `erts-10.6.4` runtime and virtual machine running on a Macbook-Pro with a 2.9 GHz Intel Core i9 processor. A common observation is that the computation takes less than 1% of the total wall clock time involved in the response rate, showing that the I/O reading/writing times dominate the final response rate.

An alternate benchmarking strategy which we used was to model the input from the sensors as an in-memory structure (in Erlang) and compute the total response time for processing those values using the `timer:tc` module -

Program	Run <sub>1</sub> ( $\mu$ s)	Run <sub>2</sub> ( $\mu$ s)	Run <sub>3</sub> ( $\mu$ s)
watchdog	97.3	106.7	98.7
traffic-light	110.8	120.2	115.1
train controller	404060	404159	404130

The above values are all measured in microseconds which are averaged over forty iterations each. As expected, using an in-memory structure the graph processing time is much faster compared to Table 1. An interesting observation is the `train controller` takes about 404 ms - much higher than the CPUT registered in Table 1. This is because `timer:tc` measures the total time - including reading from the in-memory structures. As the `train controller` program involves reading from four sensors - the overhead from reading and iterating four in-memory structures adds to the total time.

## 6 RELATED WORK

### 6.1 Programming Languages for IoT

There has been recent work on designing embedded DSLs (EDSLs) for IoT applications [11]. In EDSLs, I/O is handled by embedding a pure core language inside a host language's I/O model - which is an approach that Hailstorm deliberately avoids. Given the I/O dominated nature of IoT apps, we choose to focus much of our attention on designing a composable stream based I/O model rather than the pure core language on which EDSLs put most of their efforts on.

Other approaches like Velox VM [61] runs general purpose languages like Scheme on specialized virtual machines for IoT devices. A separate line of work has been exploring restrictive, Turing-incomplete, rule-based languages like IoTDSL [2] and CypriOT [9].

Juniper [29] is one of the few dedicated languages for IoT but it exclusively targets Arduino boards. Emfrp [55] and its successor XFRP [58] are most closely related to the goals of Hailstorm. However their model of I/O involves writing glue code in C/C++ and embedding the pure functional language inside it. Hailstorm has a more sophisticated I/O integration in the language.

While IoT stands for an umbrella term for a large collection of software areas, there has been research on *declarative* languages for older and *specialized* application areas like:

- *Wireless Sensor Networks (WSNs)*. There exists EDSLs like Flask [42] and macroprogramming languages like Regiment [45] and Kairos [24] for WSNs.
- *Real Time Systems*. Synchronous language like Esterel [10], Lustre [26] are a restrictive set of languages designed specifically for real time systems. Further extensions of these languages like Lucid Synchrone [12], ReactiveML [44], Lucy-n [43] have attempted to make them more expressive.

The applications demonstrated in the paper are expressible in synchronous languages, albeit using a very different interface from Hailstorm. While languages like Lustre and its extensions are *pure* they restrict their synchronous calculus to the pure core language and handle I/O using the old stream based I/O model of Haskell [48]. Hailstorm explores the design space of *pure* functional programming with the programming model and purity encompassing the I/O parts as well.

In Lustre, a type system called the clock calculus ensures that programs can run without any implicit buffering inside the program. Strong safety properties such as determinism and absence of deadlock are ensured at compile time, and programs are compiled into statically scheduled executable code. This comes at the price of reduced flexibility compared to synchronous dataflow-like systems, particularly in the ease with which bounded buffers can be introduced and used. Mandel et al have studied n-synchronous systems in an attempt to bring greater flexibility to synchronous languages [43]. Hailstorm, in the presence of recursion, is unable to statically predict memory usage but we plan future work on type level encoding of buffer sizes to make memory usage more predictable. *Polychronous* languages like SIGNAL [8] and FRP libraries like Rhine [6] provide static guarantees on correctness of systems with multiple clocks - something that we hope to experiment with in the future.

## 6.2 FRP

Hailstorm draws influence from the FRP programming model. Since the original FRP paper [18], it has seen extensive research over various formulations like arrowized FRP [46], asynchronous FRP [16], higher-order FRP [35], monadic stream functions [47].

Implementation-wise there has been attempts to tradeoff between a static structure of the dataflow graph like Elm [15] or dynamic structure in most Haskell FRP libraries [3] as well as FrTime in Racket [13]. The dynamic graph structure makes the language/library more expressive by writing programs like sieves [25]. The higher-order FRP implementation offers almost the local maxima of tradeoffs, but at the cost of an extremely sophisticated type system which infests into the source language compromising its simplicity.

The `loop#` combinator in Hailstorm (devised independently) is similar to the  $\mu$ -combinator first introduced by Sheeran et al [56] and to the `loopB` combinator in the Causal Commutative Arrows (CCA) paper [40]. CCA presents a number of mathematical laws on arrows and utilizes them to compile away intermediate structures and generate efficient FRP code - a promising avenue for future work in Hailstorm.

FRP has seen adoption in various application areas. However most closely related to our target areas of IoT applications are - robotics [63], real-time systems [62], vehicle simulations [21] and DSLs discussed in detail in the previous section.

## 6.3 Functional I/O

A detailed summary of approaches to functional I/O was presented by Gordon et al. [22]. Since then monadic I/O [23] has become the standard norm for I/O in pure functional languages, with the exception of Clean's I/O system [1] based on uniqueness types.

More recently there has been attempts at non monadic I/O using a state passing trick in the Universe framework [20]. The latest work has been on the notion of resource types, proposed by Winograd-Cort et al. [65], which is explored as a library in Haskell. In effect their library utilizes Haskell's monadic I/O model, however they mention possible future work on designing a dedicated language for resource types. Hailstorm explores that possibility by integrating the idea of resource types natively in a language's I/O model. FRPNow! [49] provides an alternate monadic approach to integrate I/O with FRP.

## 7 FUTURE WORK

Hailstorm is an ongoing work to run a pure, statically-typed, functional programming language on memory constrained edge devices. As such, there are a number of open avenues for research:

- *Security*. We hope to integrate support for Information Flow Control (IFC) [28] - which uses language based privacy policies to determine safe dataflow - in Hailstorm. Given that the effectful combinators are based on the Arrow framework, we expect to build on two lines of work - (1) integrating IFC with the Arrow typeclass in Haskell [37] (2) a typeclass based technique to integrate IFC without modifying the compiler [52] but one which relies on the purity and static typing of the language.

- *Reliability*. Hailstorm currently doesn't provide any fault tolerance strategies to mitigate various node/communication failures. However being hosted on the Erlang backend we plan to experiment with distributed versions of the arrow combinators where the underlying runtime would use *supervision trees* to handle failures. This would be a much more invasive change as the synchronous dataflow model of the language is not practically suitable in a distributed scenario - leading to more interesting research directions on *macro-programming models* [24].

- *Memory constrained devices*. The evaluation of this paper is carried out on GRiSP boards which are relatively powerful boards. We are currently working on developing a small virtual machine which can interpret a functional bytecode instruction set and run on much more memory constrained devices like STM32 microcontrollers.

## 8 CONCLUSION

We have presented the design and implementation of Hailstorm, a domain specific language targeting IoT applications. Our evaluation suggests that Hailstorm can be used to declaratively program moderately complex applications in a concise and safe manner. In the future, we hope to use the purity and type system of Hailstorm to enforce language-based security constraints, as well as to increase its expressiveness to enable the description of interacting IoT devices in a distributed system.

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## REFERENCES

- [1] Peter Achten and Rinus Plasmeijer. 1995. The ins and outs of Clean I/O. *Journal of Functional Programming* 5, 1 (1995), 81–110.
- [2] Moussa Amrani, Fabian Gilson, Abdelmounaim Debieche, and Vincent Englebert. 2017. Towards User-centric DSLs to Manage IoT Systems.. In *MODELSWARD*. 569–576.
- [3] Edward Amsden. 2011. A survey of functional reactive programming. *Rochester Institute of Technology* (2011).
- [4] Joe Armstrong. 1997. The development of Erlang. In *Proceedings of the second ACM SIGPLAN international conference on Functional programming*. 196–203.
- [5] Hendrik P Barendregt et al. 1984. *The lambda calculus*. Vol. 3. North-Holland Amsterdam.
- [6] Manuel Bärenz and Ivan Perez. 2018. Rhine: FRP with type-level clocks. *ACM SIGPLAN Notices* 53, 7 (2018), 145–157.
- [7] Iulia Bastys, Musard Balliu, and Andrei Sabelfeld. 2018. If this then what? Controlling flows in IoT apps. In *Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security*. 1102–1119.
- [8] Albert Benveniste, Paul Le Guernic, and Christian Jacquemot. 1991. Synchronous programming with events and relations: the SIGNAL language and its semantics. *Science of computer programming* 16, 2 (1991), 103–149.

- [9] Imad Berrouyne, Mehdi Adda, Jean-Marie Mottu, Jean-Claude Royer, and Massimo Tisi. 2019. CypIoT: framework for modelling and controlling network-based IoT applications. In *Proceedings of the 34th ACM/SIGAPP Symposium on Applied Computing*. 832–841.
- [10] Gérard Berry and Georges Gonthier. 1992. The Esterel synchronous programming language: Design, semantics, implementation. *Science of computer programming* 19, 2 (1992), 87–152.
- [11] Ben Calus, Bob Reynders, Dominique Devriese, Job Noorman, and Frank Piessens. 2017. FRP IoT modules as a Scala DSL. In *Proceedings of the 4th ACM SIGPLAN International Workshop on Reactive and Event-Based Languages and Systems*. 15–20.
- [12] Paul Caspi, Grégoire Hamon, and Marc Pouzet. 2008. Synchronous functional programming: The lucid synchrone experiment. *Real-Time Systems: Description and Verification Techniques: Theory and Tools. Hermes* (2008).
- [13] Gregory H Cooper and Shriram Krishnamurthi. 2006. Embedding dynamic dataflow in a call-by-value language. In *European Symposium on Programming*. Springer, 294–308.
- [14] Antony Courtney, Henrik Nilsson, and John Peterson. 2003. The yampa arcade. In *Proceedings of the 2003 ACM SIGPLAN workshop on Haskell*. 7–18.
- [15] Evan Czaplicki. 2012. Elm: Concurrent frp for functional guis. *Senior thesis, Harvard University* (2012).
- [16] Evan Czaplicki and Stephen Chong. 2013. Asynchronous functional reactive programming for GUIs. *ACM SIGPLAN Notices* 48, 6 (2013), 411–422.
- [17] Zakir Durumeric, Frank Li, James Kasten, Johanna Amann, Jethro Beekman, Mathias Payer, Nicolas Weaver, David Adrian, Vern Paxson, Michael Bailey, et al. 2014. The matter of heartbleed. In *Proceedings of the 2014 conference on internet measurement conference*. 475–488.
- [18] Conal Elliott and Paul Hudak. 1997. Functional reactive animation. In *Proceedings of the second ACM SIGPLAN international conference on Functional programming*. 263–273.
- [19] Conal M Elliott. 2009. Push-pull functional reactive programming. In *Proceedings of the 2nd ACM SIGPLAN symposium on Haskell*. 25–36.
- [20] Matthias Felleisen, Robert Bruce Findler, Matthew Flatt, and Shriram Krishnamurthi. 2009. A functional I/O system or, fun for freshman kids. *ACM Sigplan Notices* 44, 9 (2009), 47–58.
- [21] Bernd Finkbeiner, Felix Klein, Ruzica Piskac, and Mark Santolucito. 2017. Vehicle platooning simulations with functional reactive programming. In *Proceedings of the 1st International Workshop on Safe Control of Connected and Autonomous Vehicles*. 43–47.
- [22] Andrew D Gordon. 1994. *Functional programming and input/output*. Number 8. Cambridge University Press.
- [23] Andrew D Gordon and Kevin Hammond. 1995. Monadic i/o in haskell 1.3. In *Proceedings of the haskell Workshop*. 50–69.
- [24] Ramakrishna Gummadu, Omprakash Gnawali, and Ramesh Govindan. 2005. Macro-programming wireless sensor networks using Kairos. In *International Conference on Distributed Computing in Sensor Systems*. Springer, 126–140.
- [25] Heine Halberstam and Hans Egon Richert. 2013. *Sieve methods*. Courier Corporation.
- [26] Nicholas Halbwachs, Paul Caspi, Pascal Raymond, and Daniel Pilaud. 1991. The synchronous data flow programming language LUSTRE. *Proc. IEEE* 79, 9 (1991), 1305–1320.
- [27] Eric Haugh and Matt Bishop. 2003. Testing C Programs for Buffer Overflow Vulnerabilities.. In *NDSS*. Citeseer.
- [28] Daniel Hedin and Andrei Sabelfeld. 2012. A Perspective on Information-Flow Control. *Software safety and security* 33 (2012), 319–347.
- [29] Caleb Helbling and Samuel Z Guyer. 2016. Juniper: a functional reactive programming language for the Arduino. In *Proceedings of the 4th International Workshop on Functional Art, Music, Modelling, and Design*. 8–16.
- [30] Bernard Houssais. 2002. The synchronous programming language signal: A tutorial. *IRISA, April* (2002).
- [31] John Hughes. 2000. Generalising monads to arrows. *Science of computer programming* 37, 1-3 (2000), 67–111.
- [32] Thomas Johnsson. 1985. Lambda lifting: Transforming programs to recursive equations. In *Conference on Functional programming languages and computer architecture*. Springer, 190–203.
- [33] Neil D Jones, Carsten K Gomard, and Peter Sestoft. 1993. *Partial evaluation and automatic program generation*. Peter Sestoft.
- [34] Simon Peyton Jones and Simon Marlow. 2002. Secrets of the glasgow haskell compiler inliner. *Journal of Functional Programming* 12, 4-5 (2002), 393–434.
- [35] Neelakantan R Krishnaswami. 2013. Higher-order functional reactive programming without spacetime leaks. *ACM SIGPLAN Notices* 48, 9 (2013), 221–232.
- [36] Chris Lattner and Vikram Adve. 2004. LLVM: A compilation framework for lifelong program analysis & transformation. In *International Symposium on Code Generation and Optimization, 2004. CGO 2004*. IEEE, 75–86.
- [37] Peng Li and Steve Zdancewicz. 2010. Arrows for secure information flow. *Theoretical computer science* 411, 19 (2010), 1974–1994.
- [38] Jie Lin, Wei Yu, Nan Zhang, Xinyu Yang, Hanlin Zhang, and Wei Zhao. 2017. A survey on internet of things: Architecture, enabling technologies, security and privacy, and applications. *IEEE Internet of Things Journal* 4, 5 (2017), 1125–1142.
- [39] Sam Lindley, Philip Wadler, and Jeremy Yallop. 2010. The arrow calculus. *Journal of Functional Programming* 20, 1 (2010), 51–69.
- [40] Hai Liu, Eric Cheng, and Paul Hudak. 2009. Causal commutative arrows and their optimization. *ACM Sigplan Notices* 44, 9 (2009), 35–46.
- [41] Hai Liu and Paul Hudak. 2007. Plugging a space leak with an arrow. *Electronic Notes in Theoretical Computer Science* 193 (2007), 29–45.
- [42] Geoffrey Mainland, Greg Morrisett, and Matt Welsh. 2008. Flask: Staged functional programming for sensor networks. In *Proceedings of the 13th ACM SIGPLAN international conference on Functional programming*. 335–346.
- [43] Louis Mandel, Florence Plateau, and Marc Pouzet. 2010. Lucy-n: a n-synchronous extension of Lustre. In *International Conference on Mathematics of Program Construction*. Springer, 288–309.
- [44] Louis Mandel and Marc Pouzet. 2005. ReactiveML: a reactive extension to ML. In *Proceedings of the 7th ACM SIGPLAN international conference on Principles and practice of declarative programming*. 82–93.
- [45] Ryan Newton, Greg Morrisett, and Matt Welsh. 2007. The regiment macroprogramming system. In *2007 6th International Symposium on Information Processing in Sensor Networks*. IEEE, 489–498.
- [46] Henrik Nilsson, Antony Courtney, and John Peterson. 2002. Functional reactive programming, continued. In *Proceedings of the 2002 ACM SIGPLAN workshop on Haskell*. 51–64.
- [47] Ivan Perez, Manuel Bärenz, and Henrik Nilsson. 2016. Functional reactive programming, refactored. *ACM SIGPLAN Notices* 51, 12 (2016), 33–44.
- [48] Simon Peyton Jones. 2001. Tackling the awkward squad: monadic input/output, concurrency, exceptions, and foreign-language calls in Haskell. *Engineering theories of software construction* 180 (2001), 47.
- [49] Atze van der Ploeg and Koen Claessen. 2015. Practical principled FRP: forget the past, change the future, FRPNow!. In *Proceedings of the 20th ACM SIGPLAN International Conference on Functional Programming*. 302–314.
- [50] Qifan Pu, Ganesh Ananthanarayanan, Peter Bodik, Srikanth Kandula, Aditya Akella, Paramvir Bahl, and Ion Stoica. 2015. Low latency geo-distributed data analytics. *ACM SIGCOMM Computer Communication Review* 45, 4 (2015), 421–434.
- [51] John C Reynolds. 1972. Definitional interpreters for higher-order programming languages. In *Proceedings of the ACM annual conference-Volume 2*. 717–740.
- [52] Alejandro Russo. 2015. Functional pearl: two can keep a secret, if one of them uses Haskell. *ACM SIGPLAN Notices* 50, 9 (2015), 280–288.
- [53] Philipp Råijmmer. 2014 (accessed May 13, 2020). *An Introduction to Lustre*. [http://www.it.uu.se/edu/course/homepage/modbasutv/ht14/Lectures/lustre\\_slides\\_141006.pdf](http://www.it.uu.se/edu/course/homepage/modbasutv/ht14/Lectures/lustre_slides_141006.pdf)
- [54] Andrei Sabelfeld and Andrew C Myers. 2003. Language-based information-flow security. *IEEE Journal on selected areas in communications* 21, 1 (2003), 5–19.
- [55] Kensuke Sawada and Takuo Watanabe. 2016. Emfrp: a functional reactive programming language for small-scale embedded systems. In *Companion Proceedings of the 15th International Conference on Modularity*. 36–44.
- [56] Mary Sheeran. 1984. muFP, A Language for VLSI design. In *Proceedings of the 1984 ACM Symposium on LISP and functional programming*. 104–112.
- [57] Weisong Shi, Jie Cao, Quan Zhang, Youhuizi Li, and Lanyu Xu. 2016. Edge computing: Vision and challenges. *IEEE internet of things journal* 3, 5 (2016), 637–646.
- [58] Kazuhiro Shibani and Takuo Watanabe. 2018. Distributed functional reactive programming on actor-based runtime. In *Proceedings of the 8th ACM SIGPLAN International Workshop on Programming Based on Actors, Agents, and Decentralized Control*. 13–22.
- [59] Peer Stritzinger. (accessed May 13, 2020). *GRISP embedded system boards*. <https://www.grisp.org/>
- [60] Mads Tofte and Jean-Pierre Talpin. 1997. Region-based memory management. *Information and computation* 132, 2 (1997), 109–176.
- [61] Nicolas Tsiftes and Thimo Voigt. 2018. Velox VM: A safe execution environment for resource-constrained IoT applications. *Journal of Network and Computer Applications* 118 (2018), 61–73.
- [62] Zhanyong Wan, Walid Taha, and Paul Hudak. 2001. Real-time FRP. In *Proceedings of the sixth ACM SIGPLAN international conference on Functional programming*. 146–156.
- [63] Zhanyong Wan, Walid Taha, and Paul Hudak. 2002. Event-driven FRP. In *International Symposium on Practical Aspects of Declarative Languages*. Springer, 155–172.
- [64] Geoffrey Werner-Allen, Jeff Johnson, Mario Ruiz, Jonathan Lees, and Matt Welsh. 2005. Monitoring volcanic eruptions with a wireless sensor network. In *Proceedings of the Second European Workshop on Wireless Sensor Networks, 2005. IEEE*, 108–120.
- [65] Daniel Winograd-Cort, Hai Liu, and Paul Hudak. 2012. Virtualizing real-world objects in FRP. In *International Symposium on Practical Aspects of Declarative Languages*. Springer, 227–241.



## 9 APPENDICES

### A UNOPTIMIZED AND OPTIMIZED GENERATED CODE FOR LLVM

Given the following program,

```
def main : Int = addFive 5

def addFive (nr : Int) : Int =
  let x = 5 in
  let addX = \(y:Int) => x + y in
  addX nr
```

the unoptimized LLVM code that is generated is given below:

```
; ModuleID = 'Hailstorm-LLVM Module'

declare external ccc i8* @malloc(i32)

@__main_argc = constant i32 0

define external ccc i32 @__entry_point(i32* %argv) {
entry:
  %0 = call fastcc i32 @main()
  ret i32 %0
}

define external fastcc i32 @main() {
entry:
  %0 = call fastcc i32 @hailstorm_addFive(i32 5)
  ret i32 %0
}

define private fastcc i32 @__closure_0(i8* __env, i32 %y)
entry:
  %0 = bitcast i8* __env to {i32}*
  %1 = getelementptr {i32}, {i32}* %0, i32 0, i32 0
  %2 = load i32, i32* %1
  %3 = add i32 %2, %y
  ret i32 %3
}

define private fastcc i32 @hailstorm_addFive(i32 %nr) {
entry:
  %0 = getelementptr {i32}, {i32}* zeroinitializer, i32 1
  %1 = ptrtoint {i32}* %0 to i32
  %2 = call ccc i8* @malloc(i32 %1)
  %3 = bitcast i8* %2 to {i32}*
  %4 = getelementptr {i32}, {i32}* %3, i32 0, i32 0
  store i32 5, i32* %4
  %5 = insertvalue {i32 (i8*, i32)*, i8*} undef, i32 (i8*, i32)*
    @__closure_0, 0
  %6 = insertvalue {i32 (i8*, i32)*, i8*} %5, i8* %2, 1
  %7 = extractvalue {i32 (i8*, i32)*, i8*} %6, 0
  %8 = extractvalue {i32 (i8*, i32)*, i8*} %6, 1
  %9 = call fastcc i32 %7(i8* %8, i32 %nr)
  ret i32 %9
}
```

The following shows the LLVM code generated after applying *lambda-lifting* and *inlining*.

```
; ModuleID = 'Hailstorm-LLVM Module'

declare external ccc i8* @malloc(i32)

@__main_argc = constant i32 0

define external ccc i32 @__entry_point(i32* %argv) {
entry:
  %0 = call fastcc i32 @main()
  ret i32 %0
}

define external fastcc i32 @main() {
entry:
  %0 = call fastcc i32 @hailstorm_addFive(i32 5)
  ret i32 %0
}

define private fastcc i32 @newClos1052(i8* __env, i32 %__arg_1053)
entry:
  %0 = call fastcc i32 @hailstorm_liftedFunc1051(i32 5, i32 %__arg_1053)
  ret i32 %0
}

define private fastcc i32 @hailstorm_liftedFunc1051(i32 %x, i32 %y)
entry:
  %0 = add i32 %x, %y
  ret i32 %0
}

define private fastcc i32 @__closure_0(i8* __env, i32 %y) {
entry:
  %0 = bitcast i8* __env to {i32}*
  %1 = getelementptr {i32}, {i32}* %0, i32 0, i32 0
  %2 = load i32, i32* %1
  ret i32 %2
}

define private fastcc i32 @hailstorm_addFive(i32 %nr) {
entry:
  %0 = insertvalue {i32 (i8*, i32)*, i8*} undef, i32 (i8*, i32)* @newClos1052, 0
  %1 = insertvalue {i32 (i8*, i32)*, i8*} %0, i8* zeroinitializer, 1
  %2 = extractvalue {i32 (i8*, i32)*, i8*} %1, 0
  %3 = extractvalue {i32 (i8*, i32)*, i8*} %1, 1
  %4 = call fastcc i32 %2(i8* %3, i32 %nr)
  ret i32 %4
}
```

The final generated LLVM code notably lacks any call to `malloc` for heap memory allocation.

## B TYPE RULES FOR HAILSTORM

The type rules for type-checking the Hailstorm AST is provided below:

$$\begin{array}{c}
\frac{x \in \text{dom}(\Gamma)}{\Delta; \Gamma \vdash x : \tau} \text{ (T-Var)} \quad \frac{}{\Delta; \Gamma \vdash \tilde{i} : \text{Int}} \text{ (T-Int)} \quad \frac{}{\Delta; \Gamma \vdash \tilde{f} : \text{Float}} \text{ (T-Float)} \\
\frac{}{\Delta; \Gamma \vdash \text{True} : \text{Bool}} \text{ (T-True)} \quad \frac{}{\Delta; \Gamma \vdash \text{False} : \text{Bool}} \text{ (T-False)} \\
\frac{\Delta; \Gamma \vdash e_1 : \text{Int} \quad \Delta; \Gamma \vdash e_2 : \text{Int}}{\Delta; \Gamma \vdash e_1 \text{ binop}_i e_2 : \text{Int}} \text{ (T-BinOpInt)} \quad \frac{\Delta; \Gamma \vdash e_1 : \text{Float} \quad \Delta; \Gamma \vdash e_2 : \text{Float}}{\Delta; \Gamma \vdash e_1 \text{ binop}_f e_2 : \text{Float}} \text{ (T-BinOpFloat)} \\
\frac{\Delta; \Gamma \vdash e_1 : \text{Bool} \quad \Delta; \Gamma \vdash e_2 : \tau \quad \Delta; \Gamma \vdash e_3 : \tau}{\Delta; \Gamma \vdash \text{if } e_1 \text{ then } e_2 \text{ else } e_3 : \tau} \text{ (T-If)} \quad \frac{\Delta; \Gamma \vdash e_1 : \tau \quad \Delta; \Gamma \vdash e_2 : \tau \quad \tau \in \{\text{Int}, \text{Float}, \text{Bool}, (\tau_1, \tau_2)\}}{\Delta; \Gamma \vdash e_1 == e_2 : \text{Bool}} \text{ (T-Eq)} \\
\frac{\Delta; \Gamma \vdash e_1 : \tau \quad \Delta; \Gamma \vdash e_2 : \tau \quad \tau \in \{\text{Int}, \text{Float}\}}{\Delta; \Gamma \vdash e_1 \text{ relop } >, <, >=, <= e_2 : \text{Bool}} \text{ (T-RelOp)} \\
\frac{\Delta; \Gamma, x : \tau_1 \vdash e : \tau_2}{\Delta; \Gamma \vdash \lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2} \text{ (T-Lambda)} \quad \frac{\Delta; \Gamma \vdash e_1 : \tau_1 \rightarrow \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_1}{\Delta; \Gamma \vdash (e_1 \ e_2) : \tau_2} \text{ (T-App)} \\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \quad \Delta; \Gamma, x : \tau_1 \vdash e_2 : \tau_2}{\Delta; \Gamma \vdash \text{let } x = e_1 \text{ in } e_2 : \tau_2} \text{ (T-Let)} \quad \frac{\Delta; \Gamma \vdash e_1 : \tau_1 \quad \Delta; \Gamma \vdash e_2 : \tau_2}{\Delta; \Gamma \vdash (e_1, e_2) : (\tau_1, \tau_2)} \text{ (T-Pair)} \\
\frac{\Delta; \Gamma \vdash e : (\tau_1, \tau_2)}{\Delta; \Gamma \vdash \text{fst} \# e : \tau_1} \text{ (T-Fst)} \quad \frac{\Delta; \Gamma \vdash e : (\tau_1, \tau_2)}{\Delta; \Gamma \vdash \text{snd} \# e : \tau_2} \text{ (T-Snd)} \\
\frac{\Delta; \Gamma \vdash e : \tau_1 \rightarrow \tau_2}{\Delta; \Gamma \vdash \text{mapSignal} \# e : \tau_1 \xRightarrow{\emptyset} \tau_2} \text{ (T-Mapsignal)} \\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \xRightarrow{r_1} \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_2 \xRightarrow{r_2} \tau_3 \quad r_1, r_2 \in \Delta \quad r_1 \cap r_2 = \emptyset}{\Delta; \Gamma \vdash e_1 >>> e_2 : \tau_1 \xRightarrow{r_1 \cup r_2} \tau_3} \text{ (T-Compose)} \\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \xRightarrow{r_1} \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_1 \xRightarrow{r_2} \tau_3 \quad r_1, r_2 \in \Delta \quad r_1 \cap r_2 = \emptyset}{\Delta; \Gamma \vdash e_1 \&\&\& e_2 : \tau_1 \xRightarrow{r_1 \cup r_2} (\tau_2, \tau_3)} \text{ (T-Fanout)} \\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \xRightarrow{r_1} \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_3 \xRightarrow{r_2} \tau_4 \quad r_1, r_2 \in \Delta \quad r_1 \cap r_2 = \emptyset}{\Delta; \Gamma \vdash e_1 *** e_2 : (\tau_1, \tau_3) \xRightarrow{r_1 \cup r_2} (\tau_2, \tau_4)} \text{ (T-Combine)} \\
\frac{\Delta; \Gamma \vdash e : (\tau_1, \tau_c) \xRightarrow{\emptyset} (\tau_2, \tau_c) \quad \Delta; \Gamma \vdash c : \tau_c}{\Delta; \Gamma \vdash \text{loop} \# c e : \tau_1 \xRightarrow{\emptyset} \tau_2} \text{ (T-Loop)} \quad \frac{\Delta; \Gamma \vdash t : \text{Float} \quad \Delta; \Gamma \vdash e : \tau_1 \xRightarrow{r} \tau_2 \quad r \in \Delta}{\Delta; \Gamma \vdash \text{rate} \# t e : \tau_1 \xRightarrow{r} \tau_2} \text{ (T-Rate)} \\
\frac{\Delta; \Gamma \vdash e_1 : \tau_1 \xRightarrow{r_1} \tau_2 \quad \Delta; \Gamma \vdash e_2 : \tau_2 \rightarrow \tau_3 \xRightarrow{r_2} \tau_3 \quad r_1, r_2 \in \Delta \quad r_1 \cap r_2 = \emptyset}{\Delta; \Gamma \vdash \text{switch} \# e_1 e_2 : \tau_1 \xRightarrow{r_1 \cup r_2} \tau_3} \text{ (T-Switch)} \\
\frac{r \in \Delta}{\Delta; \Gamma \vdash \text{read} \# : () \xRightarrow{r} \tau} \text{ (T-Read)} \quad \frac{r \in \Delta}{\Delta; \Gamma \vdash \text{write} \# : \tau \xRightarrow{r} ()} \text{ (T-Write)}
\end{array}$$

Figure 14: Typing rules of Hailstorm

## C PAIR AND ITS PROJECTIONS

A pair and its first and second projections in plain lambda calculus:

$$\begin{aligned}
\langle M_1, M_2 \rangle &\equiv \lambda v. v \ M_1 \ M_2 \\
fst &\equiv \lambda p. p \ (\lambda x. \lambda y. x) \\
snd &\equiv \lambda p. p \ (\lambda x. \lambda y. y)
\end{aligned}$$

## D OPERATIONAL SEMANTICS OF HAILSTORM

The big-step operational semantics of the full Hailstorm AST is provided below:

$$\begin{array}{c}
\frac{}{s \vdash i \Downarrow i, s} \text{ (eval-Int)} \qquad \frac{}{s \vdash f \Downarrow f, s} \text{ (eval-Float)} \qquad \frac{}{s \vdash \text{True} \Downarrow \text{True}, s} \text{ (eval-True)} \\
\frac{}{s \vdash \text{False} \Downarrow \text{False}, s} \text{ (eval-False)} \\
\frac{s_1 \vdash e_1 \Downarrow V_1, s_2[x \mapsto V_1] \quad s_2 \vdash e_2 \Downarrow V_f, s_3}{s_1 \vdash \text{let } x = e_1 \text{ in } e_2 \Downarrow V_f, s_3} \text{ (eval-Let)} \\
\frac{s_1 \vdash e_1 \Downarrow \lambda x. E_1, s_2 \quad s_2 \vdash e_2 \Downarrow V_2, s_3 \quad s_3 \vdash E_1[x \mapsto V_2] \Downarrow V_f, s_4}{s_1 \vdash (e_1 \ e_2) \Downarrow V_f, s_3} \text{ (eval-App)} \\
\frac{s_1 \vdash e_1 \Downarrow \text{True}, s_2 \quad s_2 \vdash e_2 \Downarrow V, s_3}{s_1 \vdash \text{if } e_1 \text{ then } e_2 \text{ else } e_3 \Downarrow V, s_3} \text{ (eval-IfThen)} \qquad \frac{s_1 \vdash e_1 \Downarrow \text{False}, s_2 \quad s_2 \vdash e_3 \Downarrow V, s_3}{s_1 \vdash \text{if } e_1 \text{ then } e_2 \text{ else } e_3 \Downarrow V, s_3} \text{ (eval-IfElse)} \\
\frac{s_1 \vdash e_1 \Downarrow V_1, s_2 \quad s_2 \vdash e_2 \Downarrow V_2, s_3}{s_1 \vdash e_1 \text{ relop } e_2 \Downarrow \text{True}, s_3} \text{ (eval-RelopTrue)} \qquad \frac{s_1 \vdash e_1 \Downarrow V_1, s_2 \quad s_2 \vdash e_2 \Downarrow V_2, s_3}{s_1 \vdash e_1 \text{ relop } e_2 \Downarrow \text{False}, s_3} \text{ (eval-RelopFalse)} \\
\frac{s_1 \vdash e_1 \Downarrow i_1, s_2 \quad s_2 \vdash e_2 \Downarrow i_2, s_3 \quad s_3 \vdash i_1 \text{ binop}_i i_2 \Downarrow i_f, s_4}{s_1 \vdash e_1 \text{ binop}_i e_2 \Downarrow i_f, s_4} \text{ (eval-BinOpInt)} \\
\frac{s_1 \vdash e_1 \Downarrow f_1, s_2 \quad s_2 \vdash e_2 \Downarrow f_2, s_3 \quad s_3 \vdash f_1 \text{ binop}_f f_2 \Downarrow f_f, s_4}{s_1 \vdash e_1 \text{ binop}_f e_2 \Downarrow f_f, s_4} \text{ (eval-BinOpFloat)} \\
\frac{s_1 \vdash \text{exp} \Downarrow V, s_2 \quad s_2 \vdash (\text{fst } V) \Downarrow V_f, s_3}{s_1 \vdash \text{fst} \# \text{exp} \Downarrow V_f, s_3} \text{ (eval-Fst)} \qquad \frac{s_1 \vdash \text{exp} \Downarrow V, s_2 \quad s_2 \vdash (\text{snd } V) \Downarrow V_f, s_3}{s_1 \vdash \text{snd} \# \text{exp} \Downarrow V_f, s_3} \text{ (eval-Snd)} \\
\frac{s \vdash \text{exp} \Downarrow V, s}{s \vdash \text{mapSignal} \# \text{exp} \Downarrow V, s} \text{ (eval-Mapsignal)} \qquad \frac{s_1 \vdash \text{exp}_1 \Downarrow V_1, s_2 \quad s_2 \vdash \text{exp}_2 \Downarrow V_2, s_3}{s_1 \vdash \text{exp}_1 \ \&\&\& \ \text{exp}_2 \Downarrow \lambda x. \langle V_1 \ x, V_2 \ x \rangle, s_3} \text{ (eval-Fanout)} \\
\frac{s_1 \vdash \text{exp}_1 \Downarrow V_1, s_2 \quad s_2 \vdash \text{exp}_2 \Downarrow V_2, s_3}{s_1 \vdash \text{exp}_1 \ \&\&\& \ \text{exp}_2 \Downarrow \lambda x. \lambda y. \langle V_1 \ x, V_2 \ y \rangle, s_3} \text{ (eval-Combine)} \\
\frac{s_1 \vdash \text{init} \Downarrow V_i, s_2 \quad s_2 \vdash \text{exp} \Downarrow V_1, s_3 \quad n \notin \text{dom}(s_3)}{s_1 \vdash \text{loop} \# \text{init } \text{exp} \Downarrow \lambda x. \text{fst } (V_1 \ (x, V_s)), s_3[n \mapsto \text{snd } (V_1 \ (x, V_i))]} \text{ (eval-Loop-Init)} \\
\frac{s_1 \vdash \text{init} \Downarrow V_i, s_2 \quad s_2 \vdash \text{exp} \Downarrow V_1, s_3 \quad n \in \text{dom}(s_3)}{s_1 \vdash \text{loop} \# \text{init } \text{exp} \Downarrow \lambda x. \text{fst } (V_1 \ (x, \rho(n, s_3))), s_3[n \mapsto \text{snd } (V_1 \ (x, \rho(n, s_3)))]} \text{ (eval-Loop)} \\
\frac{s_1 \vdash t \Downarrow V_t, s_2 \quad s_2 \vdash \text{exp} \Downarrow V, s_2[\Psi \mapsto V_t]}{s_1 \vdash \text{rate} \# t \ \text{exp} \Downarrow V, s_2[\Psi \mapsto V_t]} \text{ (eval-Rate)} \\
\frac{s_1 \vdash \text{exp}_1 \Downarrow V_1, s_2 \quad s_2 \vdash \text{exp}_2 \Downarrow \lambda b. \sigma_b[\lambda c. E_1, \lambda c. E_2, \dots \lambda c. E_n], s_3}{s_1 \vdash \text{switch} \# \text{exp}_1 \ \text{exp}_2 \Downarrow \lambda a. ((\lambda b. \sigma_b[\lambda c. E_1, \lambda c. E_2, \dots \lambda c. E_n])(V_1 \ a)) \ (V_1 \ a), s_3} \text{ (eval-Switch)} \\
\frac{}{s \vdash \text{read} \# \Downarrow \lambda x. \text{read}, s} \text{ (eval-Read)} \qquad \frac{}{s \vdash \text{write} \# \Downarrow \lambda x. (\text{write } x), s} \text{ (eval-Write)}
\end{array}$$

Figure 15: Big-Step Operational Semantics of Hailstorm