

Verified Time-Aware Stream Processing

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What is this PhD/Status seminar about?

- Distributed Systems
 - Stream processing frameworks
 - Dataflow models
 - Time-Aware Computations
- Formal Methods
 - Verification using proof assistants
 - Isabelle proofs
 - Verified + executable + efficient code
- Formalization of Time-Aware Stream Processing

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- Introduction
- Preliminaries
- Lazy Lists Processors
- Time-Aware Operators
- Case Study
- Next Steps

Introduction

Dataflow Models

- Stream Processing: Abstraction for processing data when the input is not completely presented in the beginning of the computation
- Dataflow Model:
 - Directed graph of interconnected operators that perform event-wise transformations
 - Examples: Apache Flink, Apache Samza, Apache Spark, Google Cloud Dataflow, and Timely Dataflow



- Highly Parallel
- Time-Aware Computations
 - Explain watermarks
- Bugs in Stream Processing

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Cloud
DataFlow



Flink



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Preliminaries

- Classical higher-order logic (HOL): Simple Typed Lambda Calculus + (Hilbert) axiom of choice + axiom of infinity + rank-1 polymorphism
- Isabelle: A generic proof assistant



- Isabelle/HOL: Isabelle's flavor of HOL
- All functions in Isabelle/HOL must be total

Isabelle/HOL: (Co)datatypes

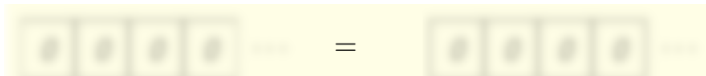
- Datatypes and Codatatypes

```
codatatype (lset: 'a) llist = lnull: LNil | LCons (lhd: 'a) (ltl: 'a llist)  
for map: lmap where ltl LNil = LNil
```

- Examples:

- LNil
- LCons 1 (LCons 2 (LCons 3 LNil))
- LCons 0 (LCons 0 (LCons 0 (...)))

- Induction principle assuming membership in the lazy list
- Coinductive principle for lazy list equality:
 - Show that there is a pair of goggles that makes them to look the same, which implies that:
 - The first lazy list is empty iff second is
 - They have the same head
 - Their tail looks the same



Isabelle/HOL: (Co)datatypes

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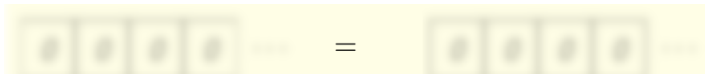
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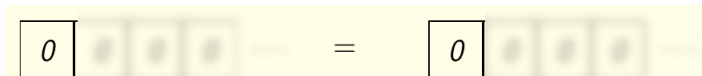
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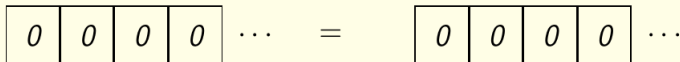
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- Recursion

```
fun lshift :: 'a list  $\Rightarrow$  'a llist  $\Rightarrow$  'a llist (infixr @@ 65) where  
  lshift [] lxs = lxs  
| lshift (x # xs) lxs = LCons x (lshift xs lxs)
```

- While Combinator

```
definition while_option :: ('a  $\Rightarrow$  bool)  $\Rightarrow$  ('a  $\Rightarrow$  'a)  $\Rightarrow$  'a  $\Rightarrow$  'a option where  
  while_option b c s = ...
```

- While rule for invariant reasoning (hoare-style):
 - There is something that holds before a step; that thing still holds after the step

Isabelle/HOL: Corecursion and Friends

- Corecursion is like recursion, but instead of always eventually reducing an argument it always eventually produces something

- Corec:

```
corec lapp :: 'a llist  $\Rightarrow$  'a llist  $\Rightarrow$  'a llist where  
  lapp lxs lys = case lxs of LNil  $\Rightarrow$  lys | LCons x lxs'  $\Rightarrow$  LCons x (lapp lxs' lys)
```

- Friendly function

- Preserves productivity: it may consume at most one constructor to produce one constructor.

```
friend_of_corec lshift where  
  xs @@ lxs = (case xs of  
    []  $\Rightarrow$  (case lxs of LNil  $\Rightarrow$  LNil | LCons x lxs'  $\Rightarrow$  LCons x lxs')  
  | x#xs'  $\Rightarrow$  LCons x (xs' @@ lxs))  
  by (auto split: list.splits llist.splits) (transfer_prover)
```

```
lconcat lxs = case lxs of LNil  $\Rightarrow$  LNil | LCons xs lxs'  $\Rightarrow$  lshift xs (lconcat lxs')
```

- Coinduction up to congruence: Coinduction for Lazy list equality can be extended to compare an entire finite prefix through a congruence relation

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Isabelle/HOL: (Co)inductive Predicates

- Inductive predicate
 - Finite number of introduction rule applications

```
inductive in_llist :: 'a  $\Rightarrow$  'a llist  $\Rightarrow$  bool where  
  In_llist: in_llist x (LCons x lxs)  
| Next_llist: in_llist x lxs  $\Rightarrow$  in_llist x (LCons y lxs)  
  
in_llist 2 (LCons 1 (LCons (2 (...))))
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- Coinduction principle

Lazy Lists Processors

Operator formalization

- Operator as a codatatype
 - Taking `'i` as the input type, and `'o` as the output type:
`codatatype ('o, 'i) op = Logic (apply: ('i \Rightarrow ('o, 'i) op \times 'o list))`
 - Infinite trees: applying the selector `apply` “walks” a branch of the tree

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- Produce function: applies the logic (co)recursively throughout a lazy list

definition $\text{produce}_1' \text{ op } lxs = \text{while_option}$

$(\lambda(\text{op}, lxs). \neg \text{Inull } lxs \wedge \text{snd } (\text{apply } \text{op } (\text{lhs } lxs))) = [])$

$(\lambda(\text{op}, lxs). (\text{fst } (\text{apply } \text{op } (\text{lhs } lxs)), \text{tl } lxs)) (\text{op}, lxs)$

definition $\text{produce}_1 \text{ op } lxs =$

$(\text{case } \text{produce}_1' \text{ op } lxs \text{ of } \text{None} \Rightarrow \text{None}$

$| \text{Some } (\text{op}', lxs') \Rightarrow \text{if } \text{Inull } lxs' \text{ then } \text{None} \text{ else}$

$\text{let } (\text{op}'', \text{out}) = \text{apply } \text{op}' (\text{lhs } lxs') \text{ in } \text{Some } (\text{op}'', \text{hd } \text{out}, \text{tl } \text{out}, \text{tl } lxs'))$

corec **produce** **where**

$\text{produce } \text{op } lxs = (\text{case } \text{produce}_1 \text{ op } lxs \text{ of } \text{None} \Rightarrow \text{LNil}$

$| \text{Some } (\text{op}', x, xs, lxs') \Rightarrow \text{LCons } x (xs \text{ @@ } \text{produce } \text{op}' lxs'))$

- produce_1 has an induction principle based on the while invariant rule

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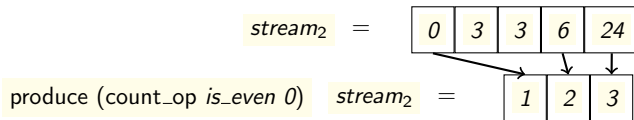
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Operators: Count

- Example:

```
corec count_op where count_op P n =  
  Logic (λe. if P e then (count_op P (n + 1), [n+1]) else (count_op P n, []))
```



Sequential Composition

- Sequential composition: take the output of the first operator and give it as input to the second operator.

```
definition fproduce  $op\ xs = \text{fold } (\lambda e\ (op,\ out)).$   
  let  $(op',\ out') = \text{apply } op\ e\ \text{in } (op',\ out\ @\ out')$  xs (op, [])  
corec comp_op where  
  comp_op  $op_1\ op_2 = \text{Logic } (\lambda ev.$   
    let  $(op_1',\ out) = \text{apply } op_1\ ev;$   $(op_2',\ out') = \text{fproduce } op_2\ out$   
    in  $(\text{comp\_op } op_1'\ op_2',\ out')$ 
```

Sequential Composition: Correctness

- Correctness:

$\text{produce } (\text{comp_op } op_1 \ op_2) \ xs = \text{produce } op_2 \ (\text{produce } op_1 \ xs)$

- Proof: coinduction principle for lazy list equality and produce_1 induction principle
 - Generalization: we must be able to reason about elements in arbitrary positions

corec skip_op where

$\text{skip_op } op \ n = \text{Logic } (\lambda ev. \text{let } (op', out) = \text{apply } op \ ev \text{ in}$
if $\text{length } out < n$ then $(\text{skip_op } op' \ (n - \text{length } out), [])$
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Time-Aware Operators

- Time-Aware lazy lists

```
datatype ('t::order, 'd) event = DT (tmp: 't) (data: 'd) | WM (wmk: 't)
```

- Generalization to partial orders
 - Cycles
 - Operators with multiple inputs

Time-Aware Streams

- Time-Aware lazy lists

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Monotone Time-Aware Streams

- Monotone: watermarks do not go back in time

coinductive monotone $:: ('t::\text{order}, 'd) \text{ event llist} \Rightarrow 't \text{ set} \Rightarrow \text{bool}$ where

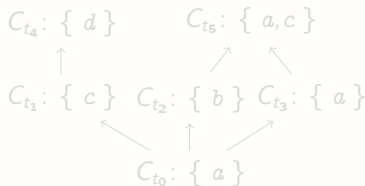
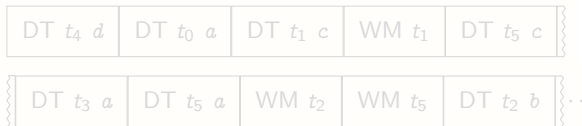
LNil: monotone LNil W

| LConsR: $(\forall wm' \in W. \neg wm' \geq wm) \longrightarrow \text{monotone } lxs (\{wm\} \cup W) \longrightarrow$
monotone (LCons (WM wm) lxs) W

| LConsL: $(\forall wm \in W. \neg wm \geq t) \longrightarrow \text{monotone } lxs W \longrightarrow$
monotone (LCons (DT $t d$) lxs) W

- Up to congruence coinduction principle
- Example:

$stream_3 =$



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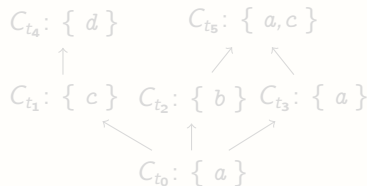
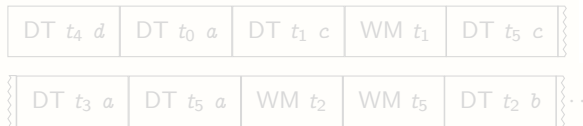
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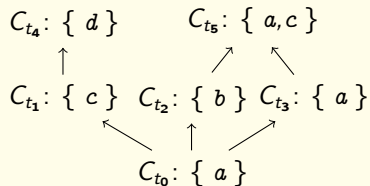
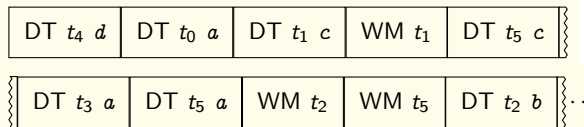
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 monotone (LCons (DT $t d$) lxs) W

- Up to congruence coinduction principle
- Example:

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Productive Time-Aware Streams

- Productive: always eventually allows the production

- Batching operators: accumulate data until its completion
- Data is always eventually completed by some watermark

coinductive productive where

LFinite: lfinite $lxs \rightarrow$ productive lxs

| EnvWM: \neg lfinite $lxs \rightarrow (\exists u \in \text{vimage WM } (\text{lset } lxs). u \geq t) \rightarrow$
productive $lxs \rightarrow$ productive (LCons (DT t d) lxs)

| SkipWM: \neg lfinite $lxs \rightarrow$ productive $lxs \rightarrow$
productive (LCons (WM t) lxs)

- Up to congruence coinduction principle

Productive Time-Aware Streams

- Productive: always eventually allows the production
 - Batching operators: accumulate data until its completion
 - Data is always eventually completed by some watermark

coinductive productive where

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 $\text{productive } lxs \longrightarrow \text{productive } (\text{LCons } (\text{DT } t \ d) \ lxs)$

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Building Blocks: Batch Operator

Batch Operator: Soundness

Batch Operator: Completeness

- Uses soundness of `batch_op`
- Proof by induction over `n`

$$\begin{aligned} \text{mono_prod } lxs \ W \longrightarrow & (\exists i \ d. \text{ enat } i < \text{length } lxs \wedge \text{Inth } lxs \ i = \text{DT } t \ d \wedge n = \text{Suc } i) \vee \\ n = 0 \wedge t \in \text{set_t } buf \longrightarrow & (\forall t' \in \text{set_t } buf. \text{Ifinite } lxs \vee \exists wm \geq t'. \text{WM } wm \in \text{lset } lxs) \longrightarrow \\ \exists wm \ batch. \text{DT } wm \ batch \in \text{lset } & (\text{produce } (\text{batch_op } buf) \ lxs) \wedge t \in \text{set_t } batch \vee \\ (\forall k \in \{n .. < \text{the_enat } & (\text{length } lxs)\} . \neg (\exists t' \geq t. \text{Inth } lxs \ k = \text{WM } t')) \wedge \text{Ifinite } lxs \end{aligned} \quad (1)$$

Batch Operator: Monotone

Batch Operator: Productive

Building Blocks: Incremental Operator

Batch Operator: Soundness

Batch Operator: Completeness

Batch Operator: Monotone

Batch Operator: Productive

Case Study

Histogram

Histogram: Soundness

Histogram: Completeness

Histogram: Monotone

Histogram: Productive

Efficient Histogram

- Foo

Join: Completeness

Join: Monotone

Next Steps

Next Steps

Questions, comments and suggestions