

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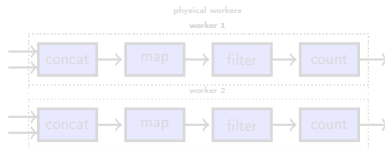
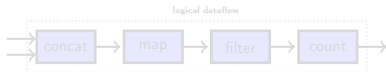
- Introduction
- Preliminaries
- Lazy Lists Processors
- Time-Aware Operators
- Case Study
- Next Steps

Introduction

Stream Processing

- 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
 - Timestamps: Metadata associating the data with some data collection
 - Watermarks: Metadata indicating the completion of a data collection

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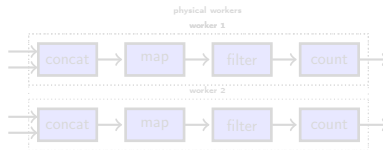
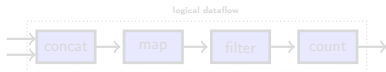
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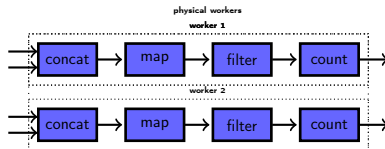
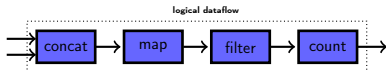
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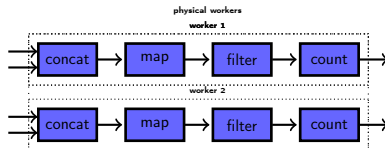
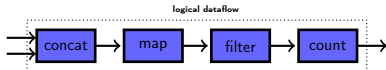
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Preliminaries

- 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

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- 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

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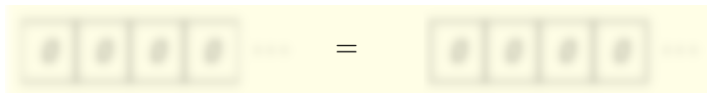
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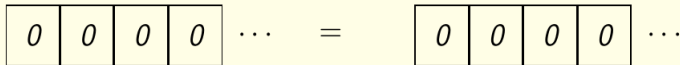
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- Recursion

```
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)
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- Friendly function

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

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friend_of_corec lshift where  
  xs @@ lxs = (case xs of  
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  | 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

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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)  
  
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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**

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

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

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

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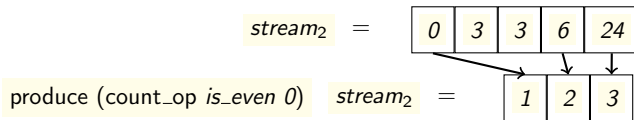
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Operators: Count

- 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 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

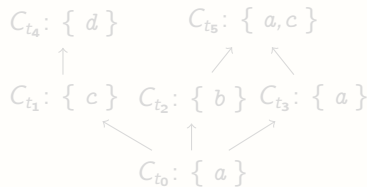
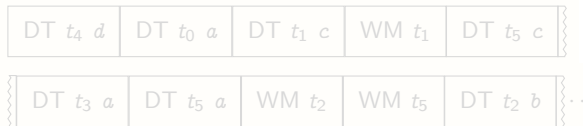
LNil: monotone LNil W

| LConsR: $(\forall wm' \in W. \neg wm' \geq wm) \longrightarrow \text{monotone } lxs (\{wm\} \cup W) \longrightarrow$
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| LConsL: $(\forall wm \in W. \neg wm \geq t) \longrightarrow \text{monotone } lxs W \longrightarrow$
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- Up to congruence coinduction principle
- Example:

$stream_3 =$



Monotone Time-Aware Streams

- Monotone: watermarks do not go back in time

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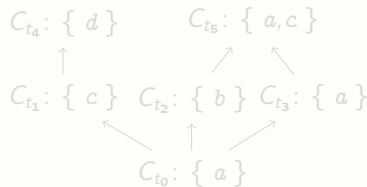
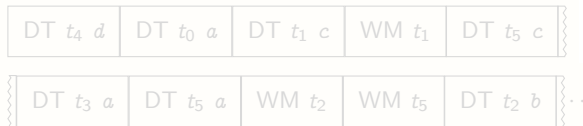
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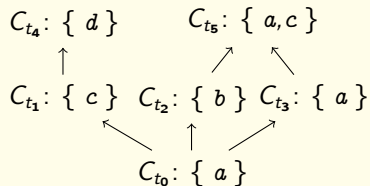
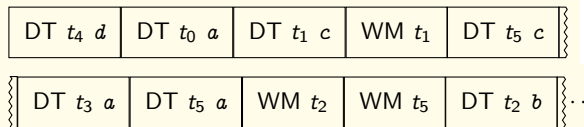
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Productive Time-Aware Streams

- 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)

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- Up to congruence coinduction principle

Building Blocks: Batch Operator

- Building Blocks: reusable operators
 - Batching and incremental computations
- `batch_op` : produces batches of accumulated data

`corec batch_op where`

```
batch_op buf = Logic (λev. case ev of DT t d ⇒ (batch_op (buf @ [(t, d)]), [])  
| WM wm ⇒ if ∃(t, d) ∈ set buf. t ≤ wm  
    then let out = filter (λ(t, _). t ≤ wm) buf;  
           buf' = filter (λ(t, _). ¬ t ≤ wm) buf  
           in (batch_op buf', [DT wm out, WM wm])  
    else (batch_op buf, [WM wm]))
```


Building Blocks: Batch Operator

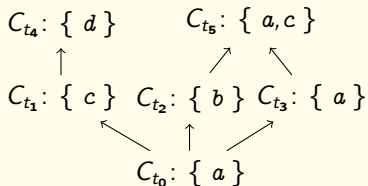
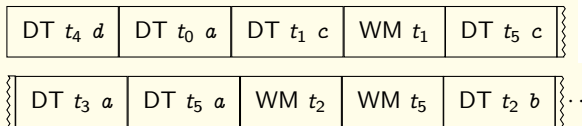
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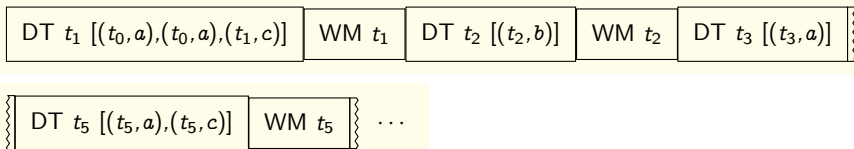
```
batch_op buf = Logic ( $\lambda$ ev. case ev of DT  $t\ d \Rightarrow$  (batch_op (buf @ [(t, d)]), [])  
| WM wm  $\Rightarrow$  if  $\exists(t, d) \in \text{set } \text{buf}. t \leq wm$   
  then let out = filter ( $\lambda(t, \_). t \leq wm$ ) buf;  
    buf' = filter ( $\lambda(t, \_). \neg t \leq wm$ ) buf  
    in (batch_op buf', [DT wm out, WM wm])  
  else (batch_op buf, [WM wm]))
```

Batch Operator: Soundness

$stream_3 =$



$\text{produce}(\text{batch_op}[(t_0, a)]) \text{ stream}_1 =$



Batch Operator: Completeness

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

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

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