Reversible Session-Based Concurrency

An Implementation in Haskell

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Problem

Concurrency is hard

How to bridge the gap between theory and practice?

Goal

A functional implementation of the model in the paper
"Causally Consistent Reversible Choreographies" (PPDP 2017)
by Mezzina and Pérez

Our contributions:

- practical validation of theoretical ideas
- a step toward reversible concurrent debuggers and using failure information
- a natural connection between reversibility and immutable data structures in pure functional languages

Core Concepts

- the pi-calculus: a calculus for concurrent computation
- session types: a type system for concurrent computation
- reversibility: moving backwards through a program

The lambda-calculus

Our favorite model for sequential computation: The lambda-calculus

$$
\begin{array}{lr}
M, N ::= x & \text{Variable} \\
\quad\mid (\lambda x.M) & \text{Function definition} \\
\quad\mid (M\,N) & \text{Applying a function to an argument}
\end{array}
$$

β-reduction:

$$(\lambda x.M)\,E \rightarrow (M[x/E])$$

There is one type per term

The pi-calculus

In contrast, the pi-calculus defines

$P, Q, R ::= \overline{x}\langle y \rangle.P$	Send the value y over channel x, then run P
$\mid\ x(y).P$	Receive on channel x, bind the result to y, then run P
$\mid\ P \mid Q$	Run P and Q simultaneously
$\mid\ (\nu x)P$	Create a new channel x and run P
$\mid\ !P$	Repeatedly spawn copies of P
$\mid\ 0$	Terminate the process
$\mid\ P + Q$	(Optionally) Nondeterministic choice

reduction:

$$\overline{x}\langle z \rangle.P \mid x(y).Q \to P \mid Q[z/y]$$

One type per channel, possibly many involving a term.

Session Types

Data types prevent us from making silly mistakes with **data**.

```
> Array(16).join("wat" -1) + " Batman!";
<· "NaNNaNNaNNaNNaNNaNNaNNaNNaNNaNNaNNaNNaNNaNNaN Batman!"
```

Session Types

Session types prevent common mistakes in **communication**.

- Send without a receive & receive without a send
- type mismatch between sent and expected value
- Sending/Receiving before you're supposed to
- undesired infinite recursion

An idea introduced in the late 90s by Honda, Kubo, and Vasconcelos (ESOP 1998), and widely studied ever since.

Session Types

Global Type

- There is a Transaction between Carol and Bob, a `Bool` is sent.
- There is a Transaction between Alice and Carol, an `Int` is sent.

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Properties:

- Order: enforced ordering of communication over a channel
- Progress: every sent message is eventually received
- Safety: sent values are typed, there can be no mismatch

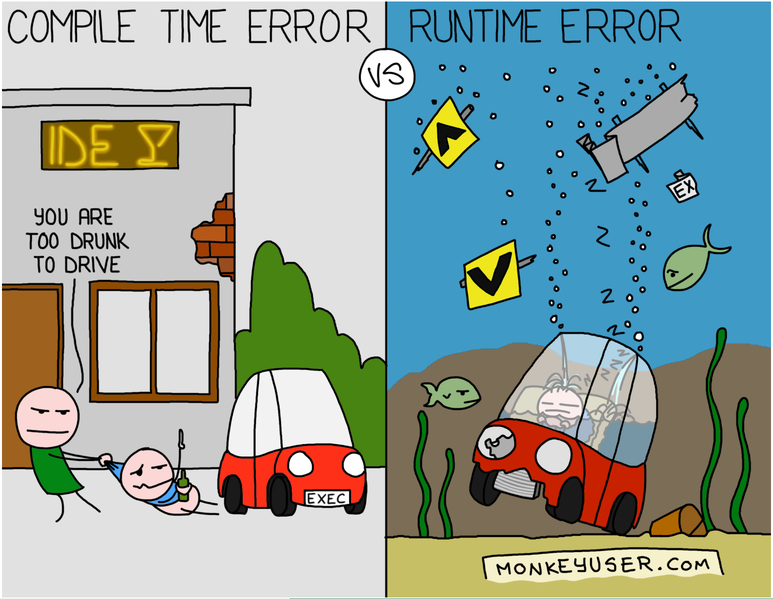
Running Example: A Three-Buyer Protocol

Alice ($\mathtt{A}$), Bob ($\mathtt{B}$), and Carol ($\mathtt{C}$) interact with a Vendor ($\mathtt{V}$) :

$$\begin{aligned} G = {} & \mathtt{A} \to \mathtt{V} : \langle \mathsf{title} \rangle.\ \ \mathtt{V} \to \{\mathtt{A}, \mathtt{B}\} : \langle \mathsf{price} \rangle. \\ & \mathtt{A} \to \mathtt{B} : \langle \mathsf{share} \rangle.\ \ \mathtt{B} \to \{\mathtt{A}, \mathtt{V}\} : \langle \mathsf{OK} \rangle. \\ & \mathtt{B} \to \mathtt{C} : \langle \mathsf{share} \rangle.\ \ \mathtt{B} \to \mathtt{C} : \langle \{\{\diamond\}\} \rangle. \\ & \mathtt{B} \to \mathtt{V} : \langle \mathsf{address} \rangle.\ \ \mathtt{V} \to \mathtt{B} : \langle \mathsf{date} \rangle.\mathtt{end} \end{aligned}$$

where $\{\{\diamond\}\}$ is a **thunk process**: a type (`() -> Process`).
Bob sends Carol some code with the protocol; she must activate it.

Session Types: Static vs. Dynamic



Session Types: Static vs. Dynamic

We will always need dynamic verification of our session types

Because `RealWorld` systems are:

- opaque
- written in multiple languages

Reversibility

Goal: make smart decisions when the circumstances change

Leave behind a trail of breadcrumbs

So we can always find our way back

Reversibility

Causal Consistency: Reversible steps lead to states that can be reached with forward steps only. No extra new states are introduced.

$$\texttt{backward} \circ \texttt{forward} \approx \texttt{identity}$$

Implementation

Combining these ideas in practice

Implementing Session Types: Global and Local

We aim to implement:

```
type Session a = StateT ExecutionState (Except Error) a
forward  :: Location -> Session ()
backward :: Location -> Session ()
```

where:

- `Session` models our computation
- `ExecutionState` contains our types and programs
- `Except Error` provides a way to fail
- `Location` models threads or machines

Implementing Session Types: Use

```
globalType :: GlobalType.GlobalType MyParticipants MyType
globalType = GlobalType.globalType $ do
    GlobalType.transaction A V Title
    GlobalType.transaction V A Price
    GlobalType.transaction V B Price
    GlobalType.transaction A B Share
    GlobalType.transaction B A Ok
    GlobalType.transaction B V Ok
    GlobalType.transaction B C Share
    GlobalType.transaction B C Thunk
    GlobalType.transaction B V Address
    GlobalType.transaction V B Date
    GlobalType.end
```

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    GlobalType.transaction B C Thunk
    GlobalType.transaction B V Address
    GlobalType.transaction V B Date
    GlobalType.end
```

Derived local type for A:

```
localType :: LocalType.LocalType MyParticipants MyType
localType = LocalType.localType $ do
    LocalType.sendTo V Title
    LocalType.receiveFrom V Price
    LocalType.sendTo B Share
    LocalType.receiveFrom B Ok
    LocalType.end
```

Implementing Session Types: Definition

```haskell
type GlobalType u = Fix (GlobalTypeF u)
data GlobalTypeF u next
    = Transaction
        { from :: Participant
        , to :: Participant
        , tipe :: u
        , continuation ::  next
        }
    | Choice
        { from :: Participant
        , to :: Participant
        , options :: Map String next
        }
    | RecursionPoint next
    | RecursionVariable
    | WeakenRecursion next
    | End
    deriving (Show, Functor)
```

Implementing the Process Calculus: Definition

Make a constructor for everything that we're interested in

```
data ProgramF value next
    -- passing messages
    = Send {..}
    | Receive {..}
    | Parallel next next
    -- choice
    | Offer Participant (List (String, next))
    | Select Participant (List (String, value, next))
    -- other
    | Application Participant Identifier value
    | NoOp
```

Improvements over the standard pi-calculus:

- Protocol delegation & ownership
- Asynchronous communication

Implementing the Process Calculus: Use

- StateT threads ownership through the computation
- Free provides nice syntax with do-notation

```
bob = do
    thunk <-
        H.function $ \_ -> do
            H.send (VString "accursedUnutterablePerformIO")
            d <- H.receive
            H.terminate
    price <- H.receive
    share <- H.receive
    H.send (VBool True)
    H.send (VBool True)
    H.send share
    H.send thunk

carol = do
    h <- H.receive
    code <- H.receive
    H.applyFunction code VUnit
```

Adding Reversibility: Types

```
data TypeContextF a previous
    = Transaction (LocalType.Transaction a previous)
    | Spawning Location Location Location previous
    | Selected
        { owner :: Participant
        , offerer :: Participant
        , selection :: Zipper (String, LocalType a)
        , continuation :: previous
        }
    | Offered
        { owner :: Participant
        , selector :: Participant
        , picked :: Zipper (String, LocalType a)
        , continuation :: previous
        }
    | Application Participant Identifier previous
    | Empty
    | R previous
    | Wk previous
    | V previous
```

Adding Reversibility: Processes

We also need to store

- used variable names

```
decision <- H.receive
H.send decision
H.send decision
```

- unused branches in select and offer

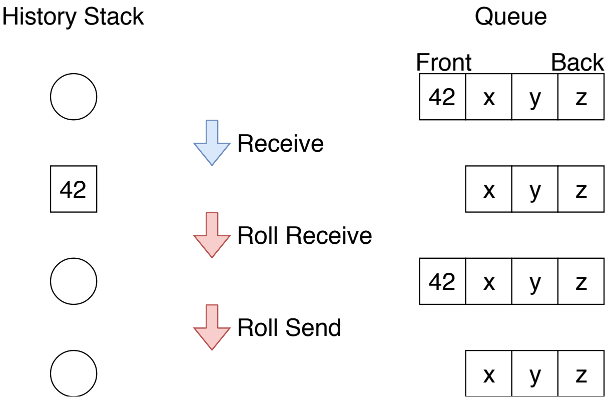
```
data OtherOptions
    = OtherSelections (Zipper (String, Value, Program Value))
    | OtherOffers (Zipper (String, Program Value))
```

- function applications: the function and the argument

```
Map Identifier (Value, Value)
```

Adding Reversibility: Processes

- message values



The Monitor and Synchronization

```
data Monitor value tipe =
    Monitor
        { _localType :: ( TypeContext tipe, LocalType tipe )
        , _recursiveVariableNumber :: Int
        , _recursionPoints :: List (LocalType tipe)
        , _usedVariables :: List Binding
        , _applicationHistory :: Map Identifier (value, value)
        , _store :: Map Identifier value
        }
data Binding =
    Binding { _visibleName :: Identifier, _internalName :: Identifier }
```

ExecutionState

```
data ExecutionState value =
    ExecutionState
        { variableCount :: Int
        , locationCount :: Int
        , applicationCount :: Int
        , queue :: Queue value
        , participants :: Map Participant (Monitor value String)
        , locations :: Map Location
                ( Participant
                , List OtherOptions
                , Program value
                )
        , isFunction :: value -> Maybe (Identifier, Program value)
        }
```

Conclusion

We have reported on the current state of our implementation of reversible, session-based concurrency in Haskell

- Embedding a sophisticated operational semantics in Haskell
- Causal consistency, from theory to practice
- The first functional implementation of a reversible debugger
- https://github.com/folkertdev/reversible-debugger/

Current and future work:

- Graphical interfaces
- Controlled reversibility (checkpoints)