Reversible Session-Based Concurrency

An implementation in Haskell

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Problem

Concurrency is hard

Roadmap

Core Concepts: The pi-calculus, session types and reversibility

Moving Forward

Moving Backward

Core Concepts

- the pi-calculus: a calculus for concurrent computation
- session types: a type system for concurrent computation
- reversibility

The pi-calculus

The lambda calculus at its core has two concepts

1. function creation: `\x -> x`
2. function application: `f x`
3. reduction: `(\x -> x) 42 => 42`

The pi-calculus defines

1. send: $\bar{x}$`<y>.P` send value y over channel x, then run P
2. receive: `x(y).P` receive on channel x, bind the result to y, then run P
3. parallel: `P|Q` run P and Q simultaneously
4. reduction: $\bar{x}$`<a>.P | x(b).Q => P | Q`

Session Types

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

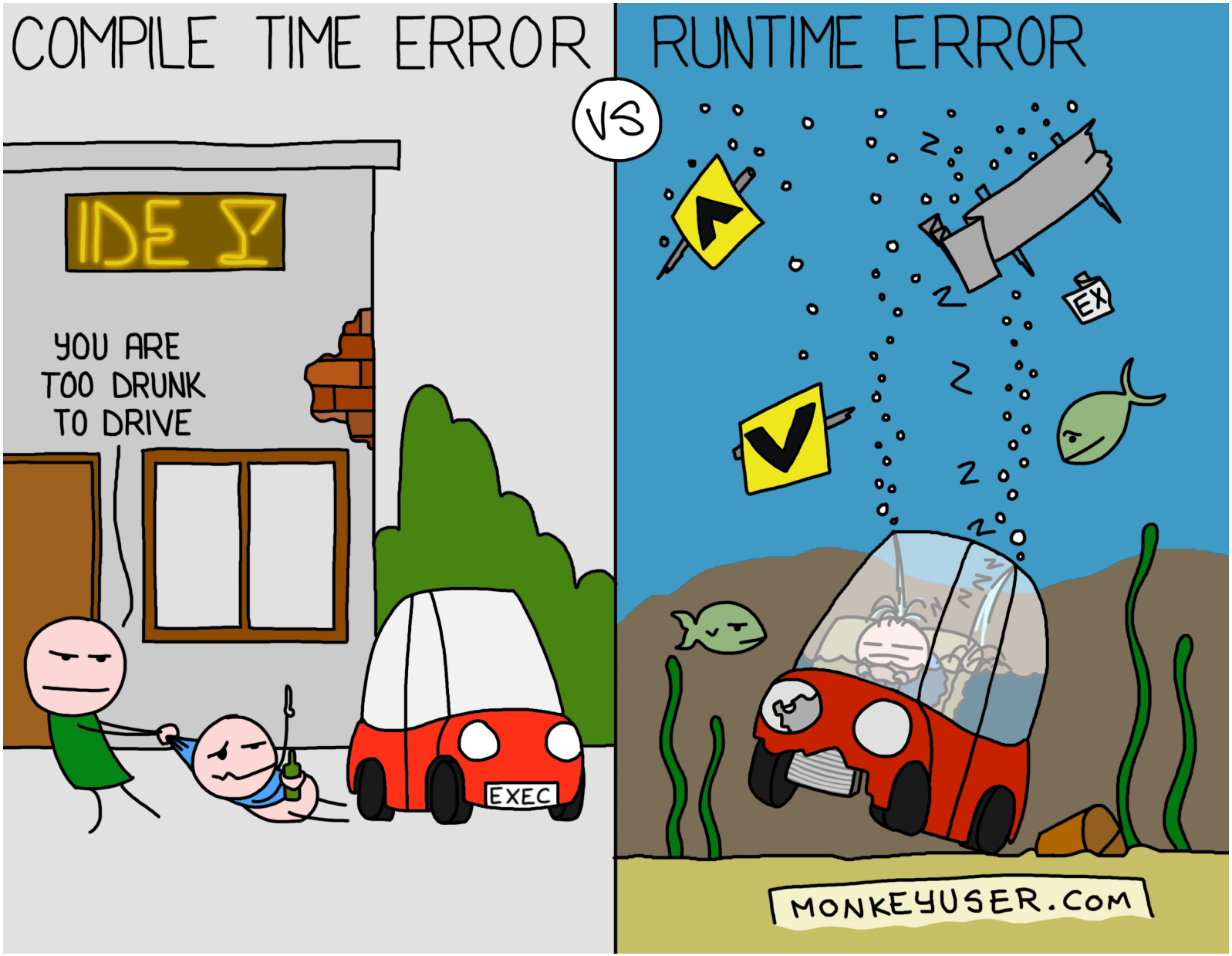
Session types prevent stupid mistakes in **communication**.

Session Types

"I will send Bob a `Bool`, and then I expect and `Int` from Alice"

- protocols become code
- we introduce ordering of communication
- messages are typed

Session Types: Static vs. Dynamic



Session Types: Static vs. Dynamic

We will always need dynamic session types

Because `RealWorld` systems are:

- opaque
- written in multiple languages

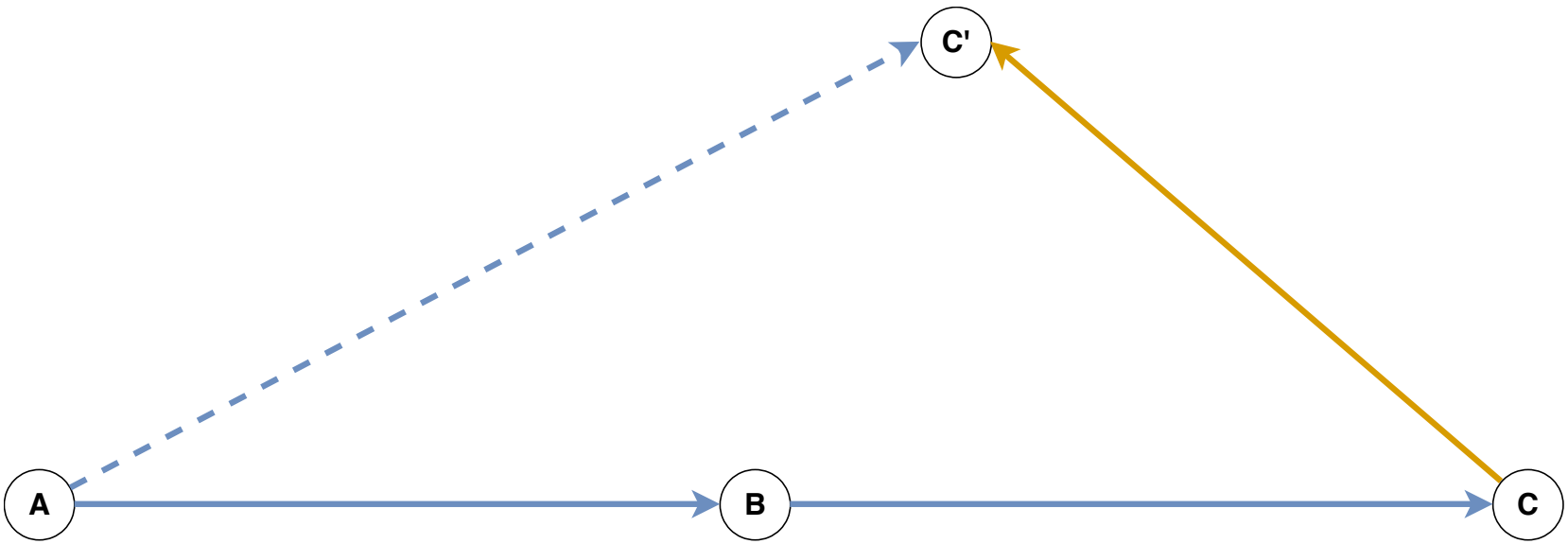
Reversibility

Goal: recover from errors

Reversibility

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

Causal Consistency: Any point we can reach (by going forward and backward) we can also reached by only going forward from the beginning



Reversibility

Leave behind a trail of breadcrumbs

So we can always find our way back

Problem

These three things are cool, can we let them work together in a nice way

in theory: yes, in practice? tbd

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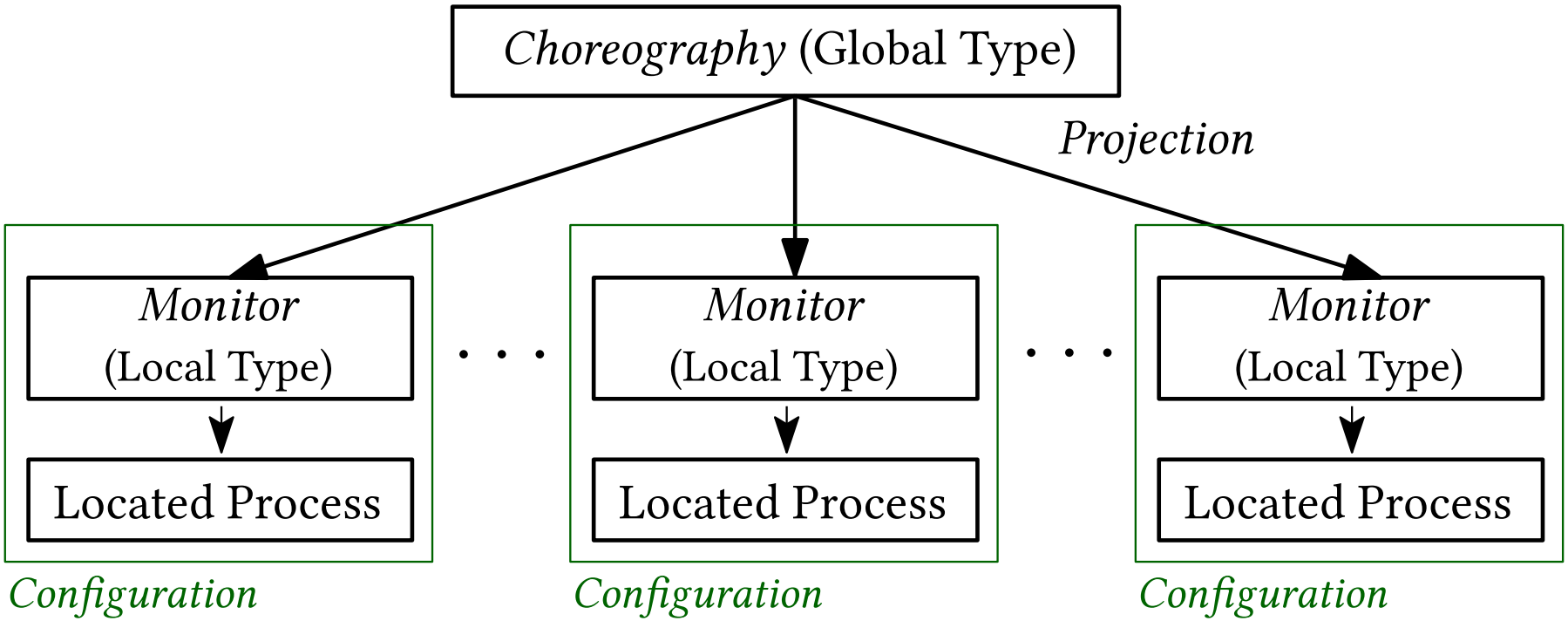
Implementing Session Types: Global and Local



Running Example: A Three-Buyer Protocol

Alice (A), Bob (B), and Carol (C) interact with a Vendor Vendor (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.

Implementing Session Types: Definition

```
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 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
```

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 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))
    | Application Participant Identifier value
    | NoOp
    -- syntactic sugar for better examples
    | Let Participant Identifier value next
    | IfThenElse Participant value next next
```

Improvements over the standard pi calculus:

- We can send part of a session over a channel
- Communication is decoupled with a queue

Implementing the Process Calculus: Use

Then use the `Free` monad to get nice syntax for free:

```
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
```

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Adding Reversibility: Types

```
data TypeContextF a previous
    = Empty
    | Transaction (LocalType.Transaction a 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
    | Spawning Location Location Location previous
    | R previous
    | Wk previous
    | V previous
    -- sugar
    | Branched { owner :: Participant, continuation :: previous }
    | Assignment { owner :: Participant, continuation :: previous }
```

Adding Reversibility: Processes

We also need to store

- used variable names
- unused branches in select, offer and if-then-else
- function applications: the function and the argument
- message values

All of these have their own stack

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, Progra
        , isFunction :: value -> Maybe (Identifier, Program value)
        }
```

Conclusion