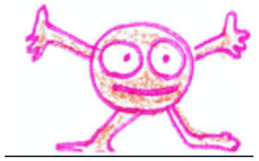
Session Types and Rust

Nobuko Yoshida, Huawei Workshop, Formal Methods for AI, 1st August 2024

UNIVERSITY OF OXFORD

Actor Models

1944-2020

Actor Models

- **Carl Hewitt (MIT)**

1944-2020

Actor Models

1944-2020

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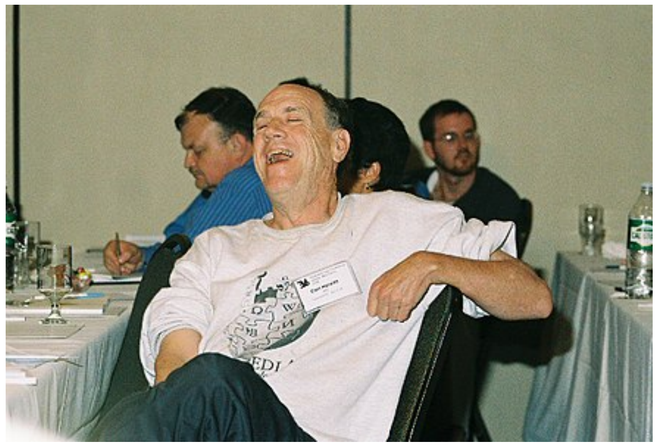
  - **Mathematical Models** for Concurrent Computations

Actor Models



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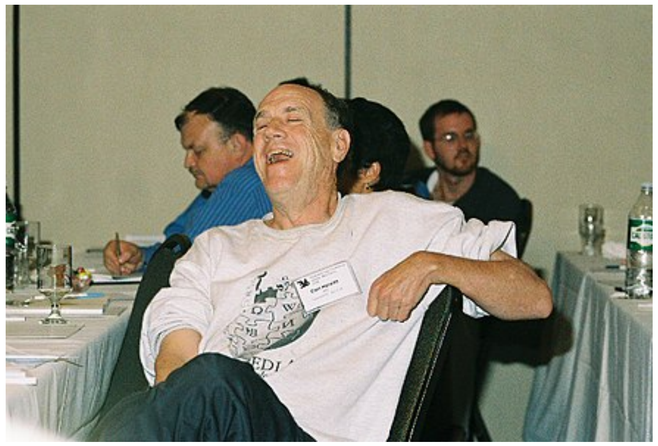
Actor Models



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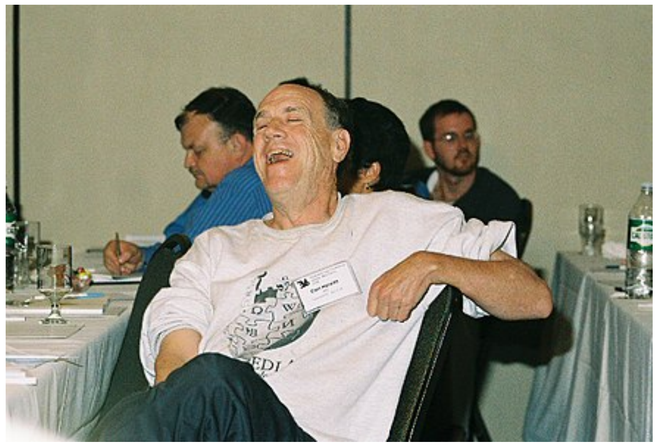

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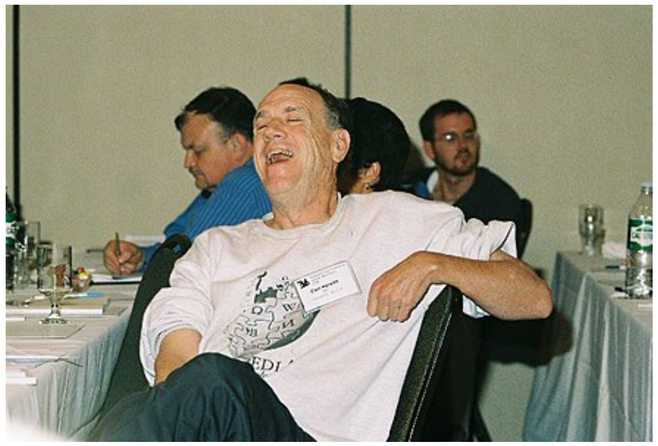

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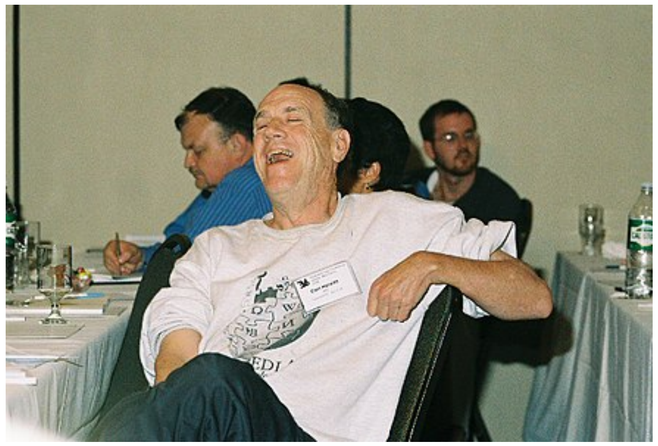
Actor Models



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    - Concurrent Object Oriented Languages
    - Multi Agent Systems
    - Web Services and Simple Object Access **Protocols** (SOAP)
    - Mathematical Models (Logics and Process Algebra)

Communications are Ubiquitous

- Increasingly, **communications** are the way to organise software and systems.
- Industry trend – programming languages with **explicit message-passing primitives.**

microservices

Problems: Concurrency Bugs

- Communications increase **concurrency bugs**
  - Survey of 4k users [golang.org]
  - Analysis of 6 large software systems [ASPLOS 19]

The Go Gopher

Do not communicate by sharing memory; share memory by communicating

– Go Philosophy

Problems: Concurrency Bugs

- Communications increase **concurrency bugs**
  - Survey of 4K users [golang.org]
  - Analysis of 6 large software systems [ASPLOS 19]

deadlock

channel errors

More than a half of concurrency bugs in Go are caused by communications.

The Go Gopher

Problems: Concurrency Bugs

- Communications increase **concurrency bugs**
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More than a half of concurrency bugs in Go are caused by communications.

Session Types

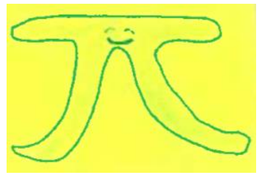
- Prevent concurrency bugs.
- Can abstract, implement and manage communications as **Protocols.**
- **Clean, Cheap** and **Retrofittable.**

Why Session Types, Why Now?

Significant academic and industry interests via fundamental breakthroughs

Milner, Honda, NY

Binary Session Types — ESOP'98



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Joined W3C Standardization — 2002

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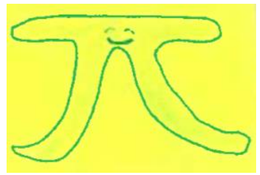

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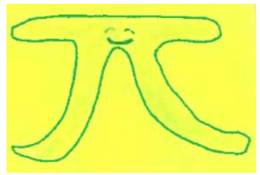

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largest open source company in the world

Red Hat

Scribble

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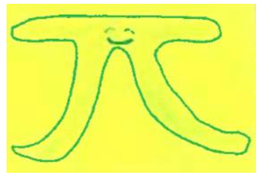

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Multiparty Session Types — POPL' 08

25M US$ large cyber infrastructures

middleware standardisations

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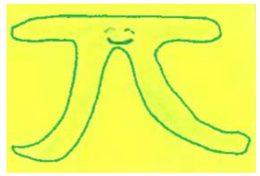

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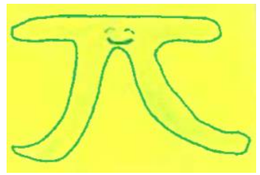
ETAPS Test Time Award 2019

Binary Session Types — ESOP'98



Joined W3C Standardization — 2002

POPL Influential Paper Award 2018

Multiparty Session Types — POPL' 08

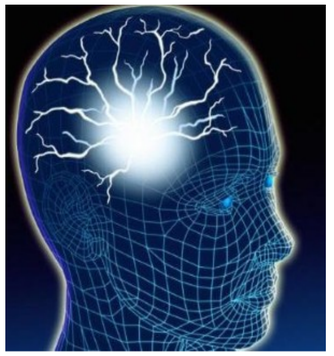
Distributed systems are:

focus on the

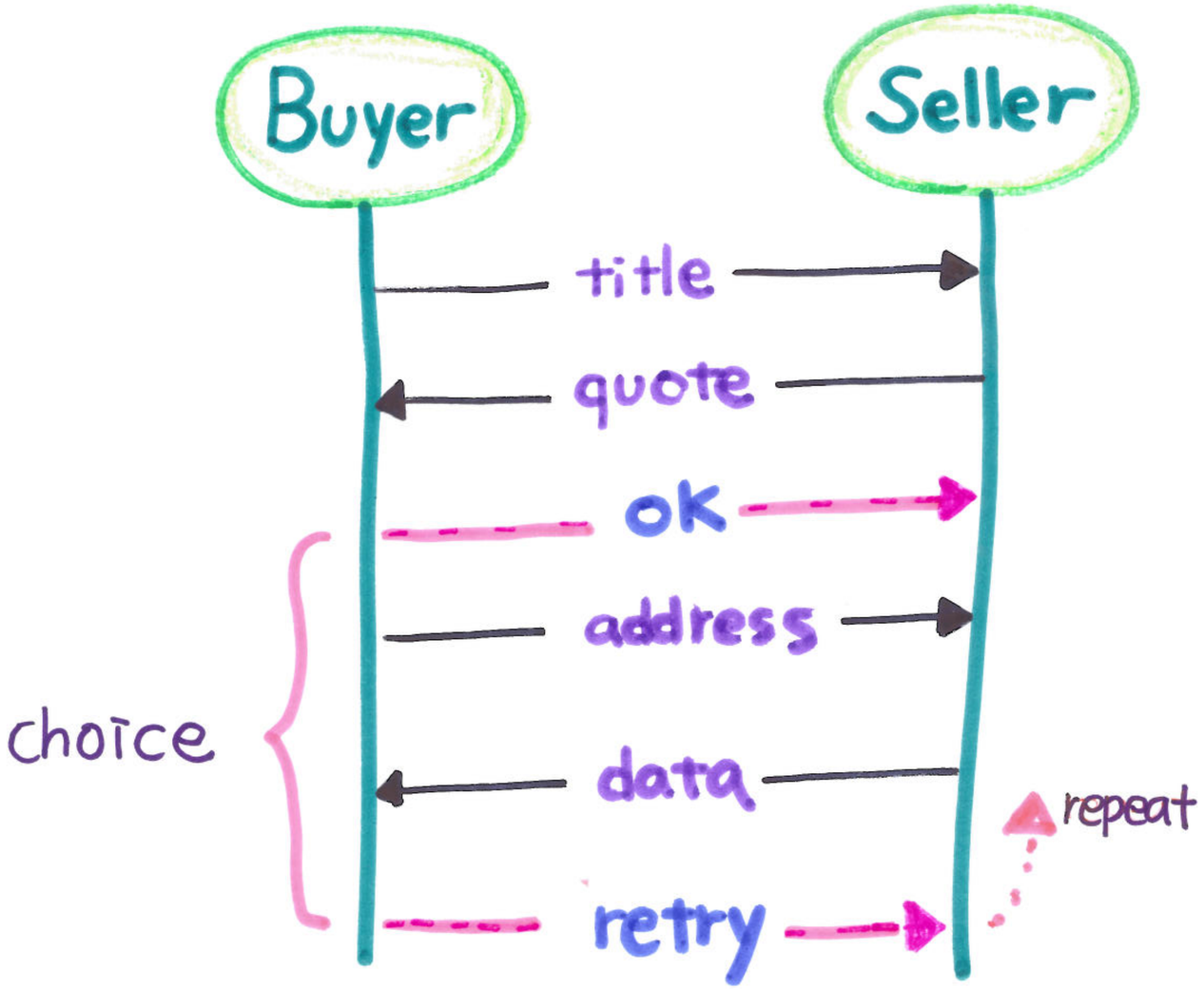
communication

not on

computation



Binary Session Types: Buyer - Seller Protocol



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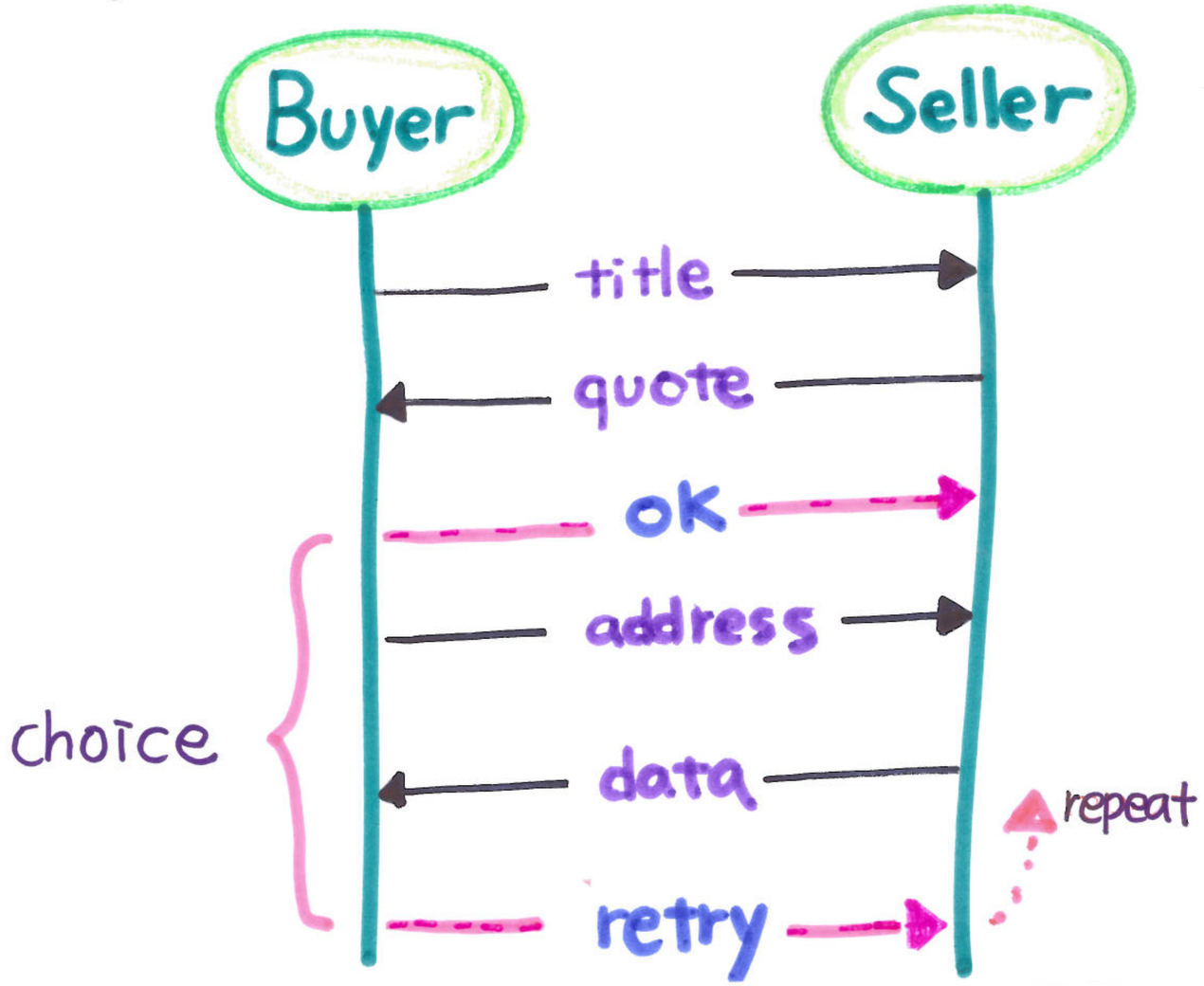
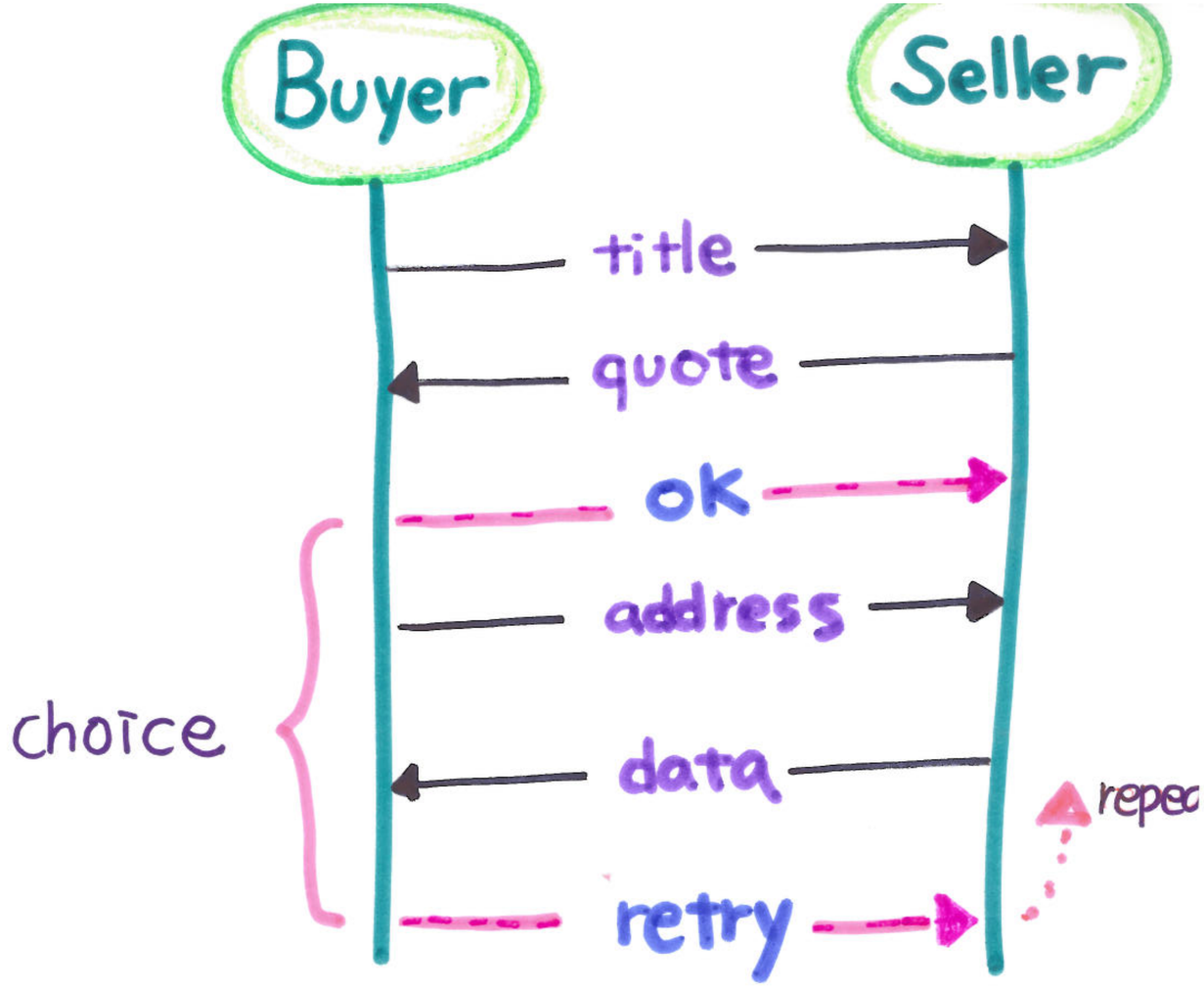


μt. ! Title ; ? Quote ; ! { ok : ! Add ; ? Date , retry : t }



P has T

Q has $\overline{T}$ dual

P | Q typable

$\mu t.!\,\text{Title};?\,\text{Quote};!\{\textbf{ok}:!\,\text{Add};?\,\text{Date},\ \textbf{retry}:t\}$

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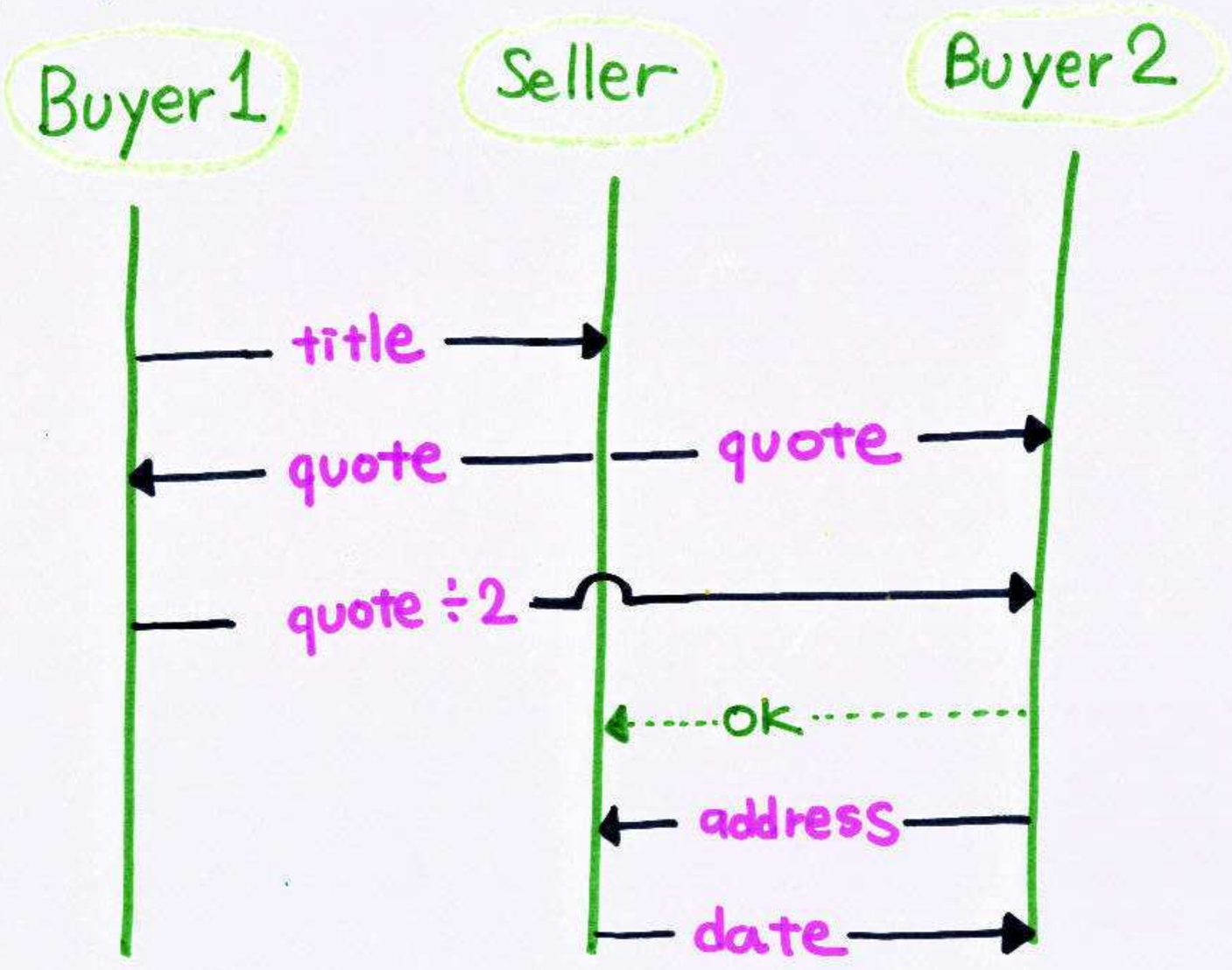
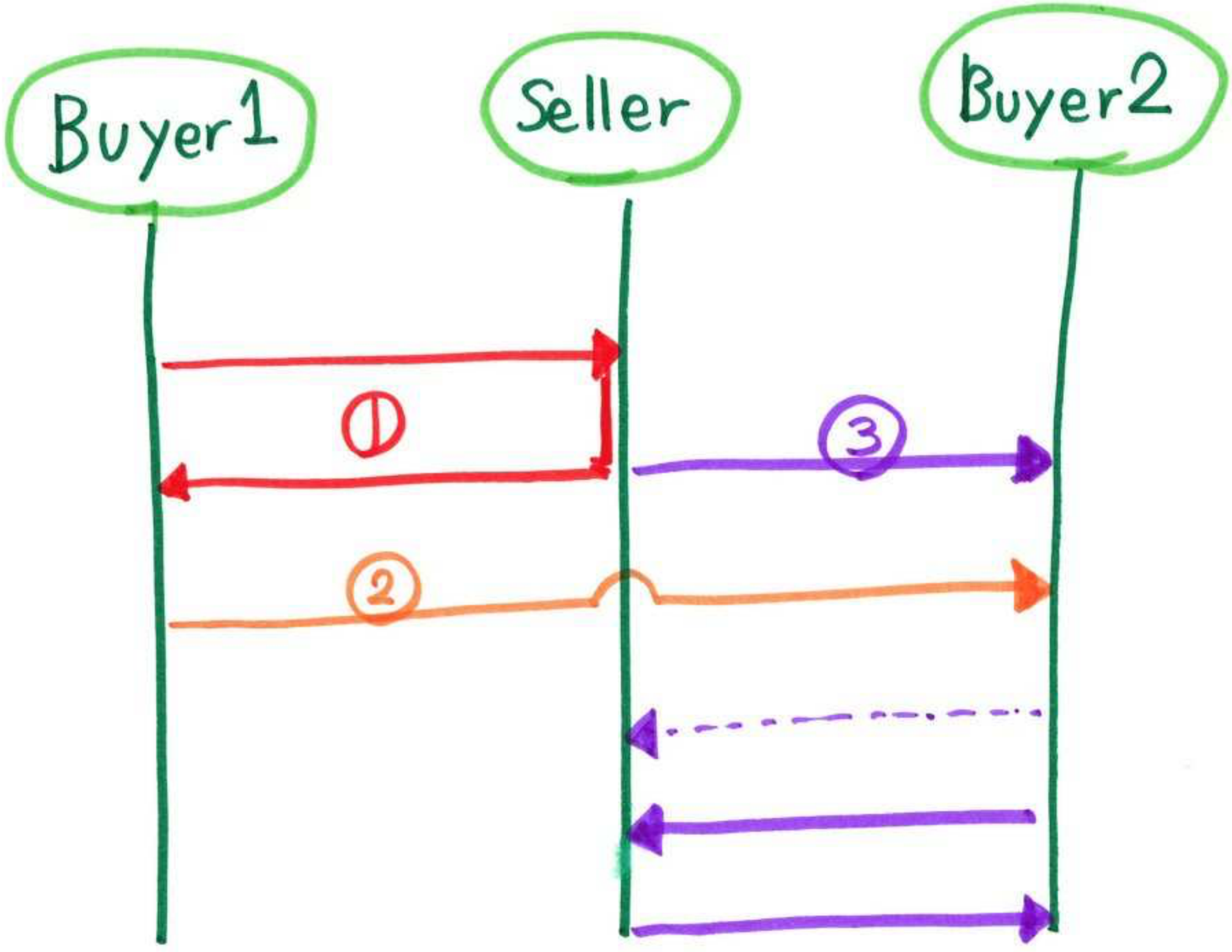
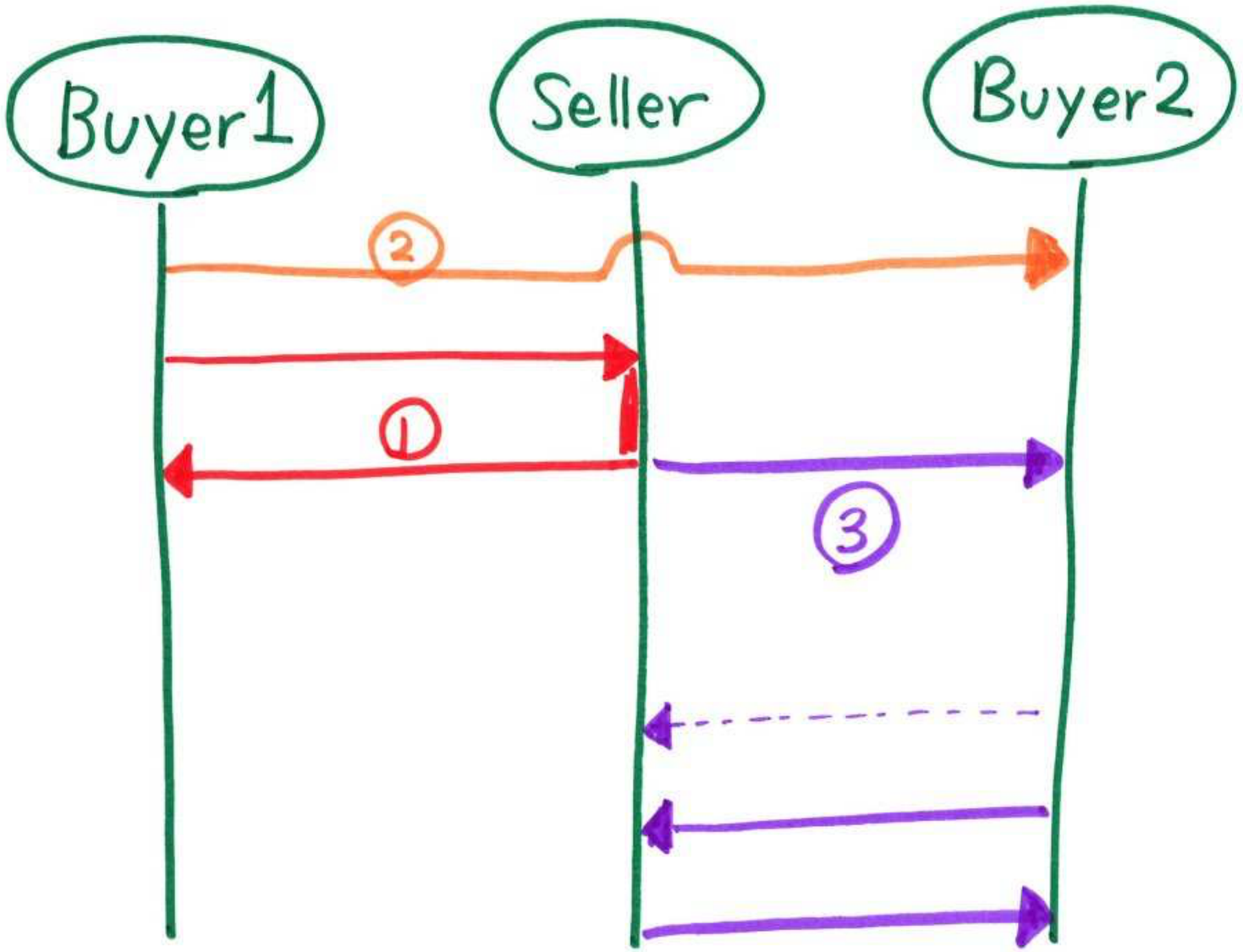
Multiparty Session Types




Buyer1
Seller
Buyer2
1
3
2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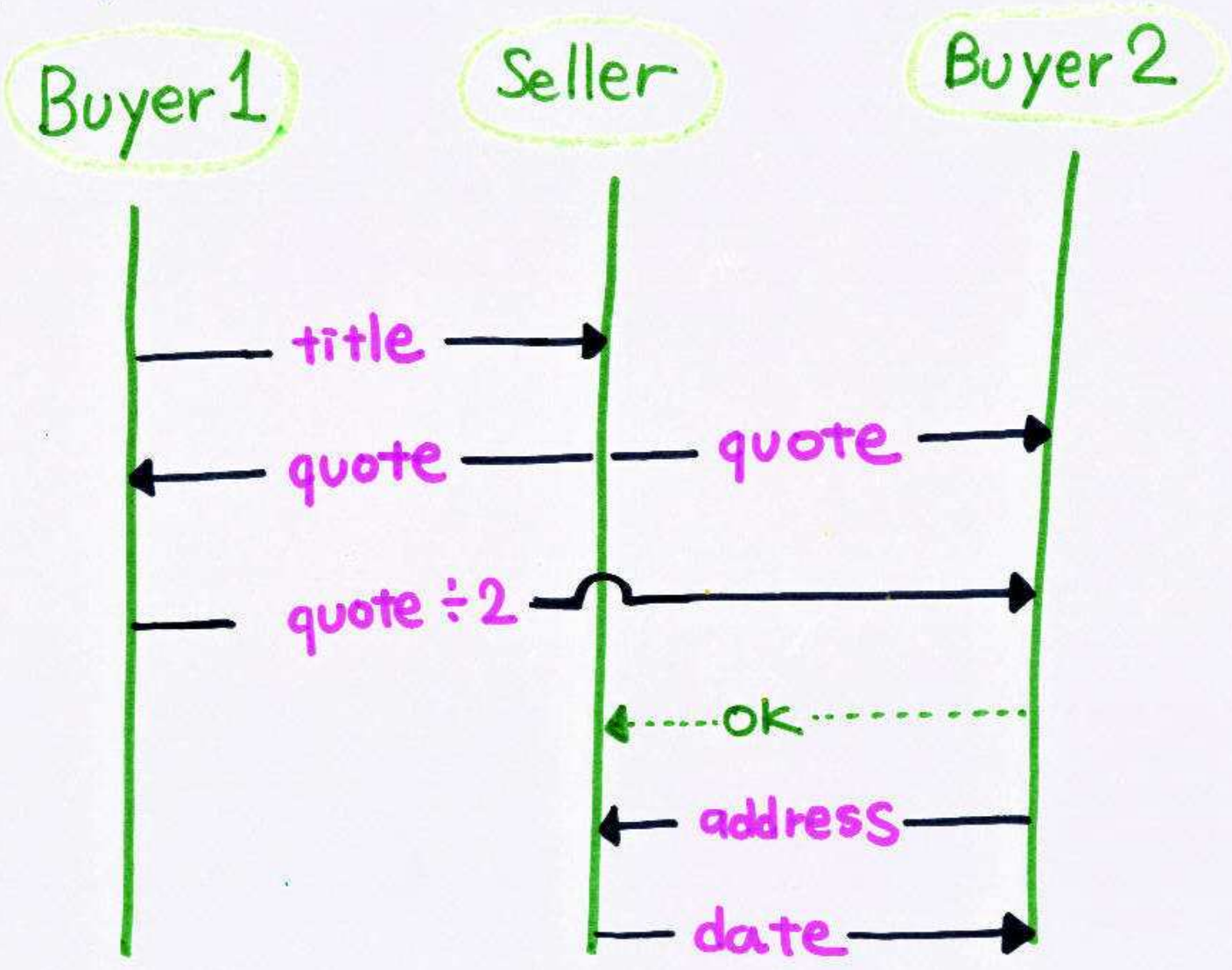
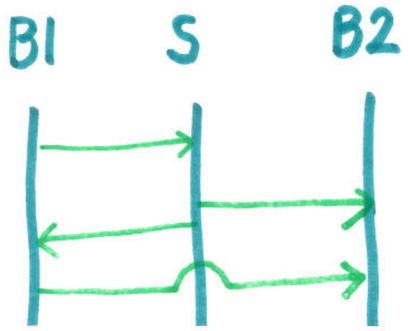
Multiparty Session Types



Multiparty Session Types [Honda, Yoshida, Carbone 2008]



G

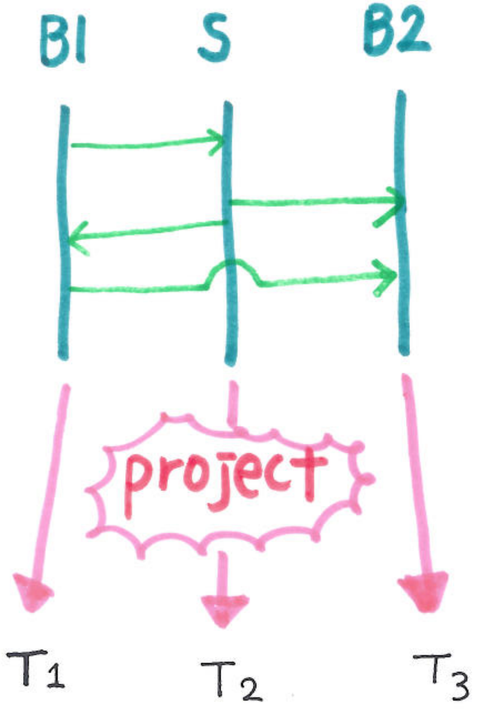
B1 → S Int.

S → B2 Char

STEP 1

Write Global Type

Multiparty Session Types [Honda, Yoshida, Carbone 2008]



G

$B1 \rightarrow S$ Int.

$S \rightarrow B2$ Char

T

$B_1?\text{Int}.B_2!\text{Char}$

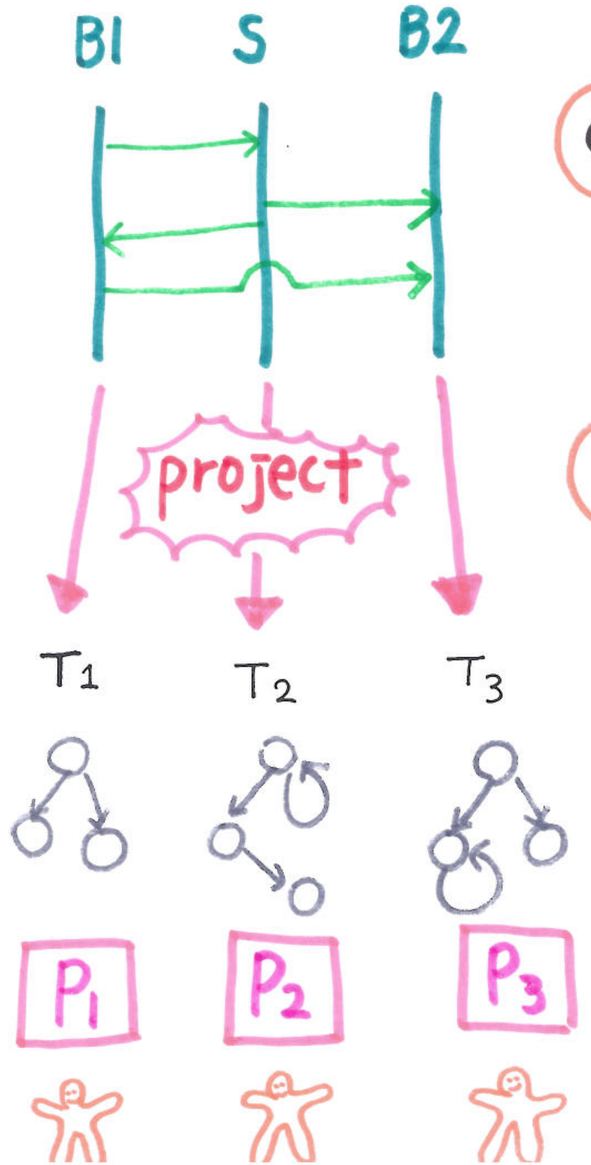
STEP 1

Write Global Type

STEP 2

Project to Local Types

Multiparty Session Types [Honda, Yoshida, Carbone 2008]



G $B1 \rightarrow S$ Int.
$S \rightarrow B2$ Char

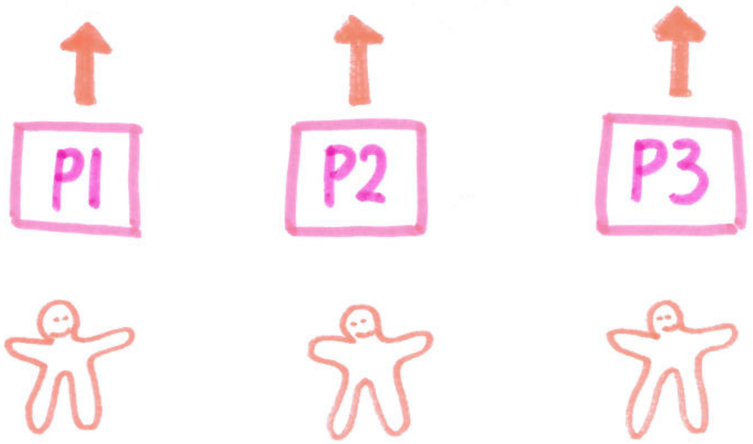
T $B_1?\text{Int}.B_2!\text{Char}$

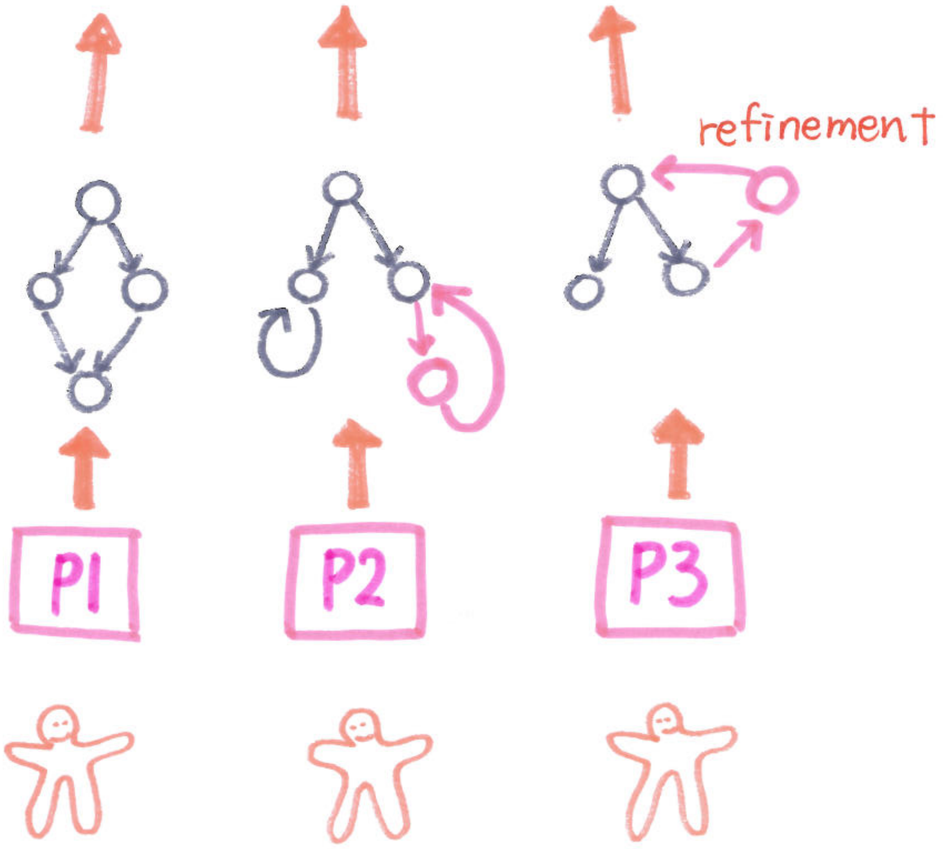
P $B_1?(x).B_2!\langle\text{"apple"}\rangle$

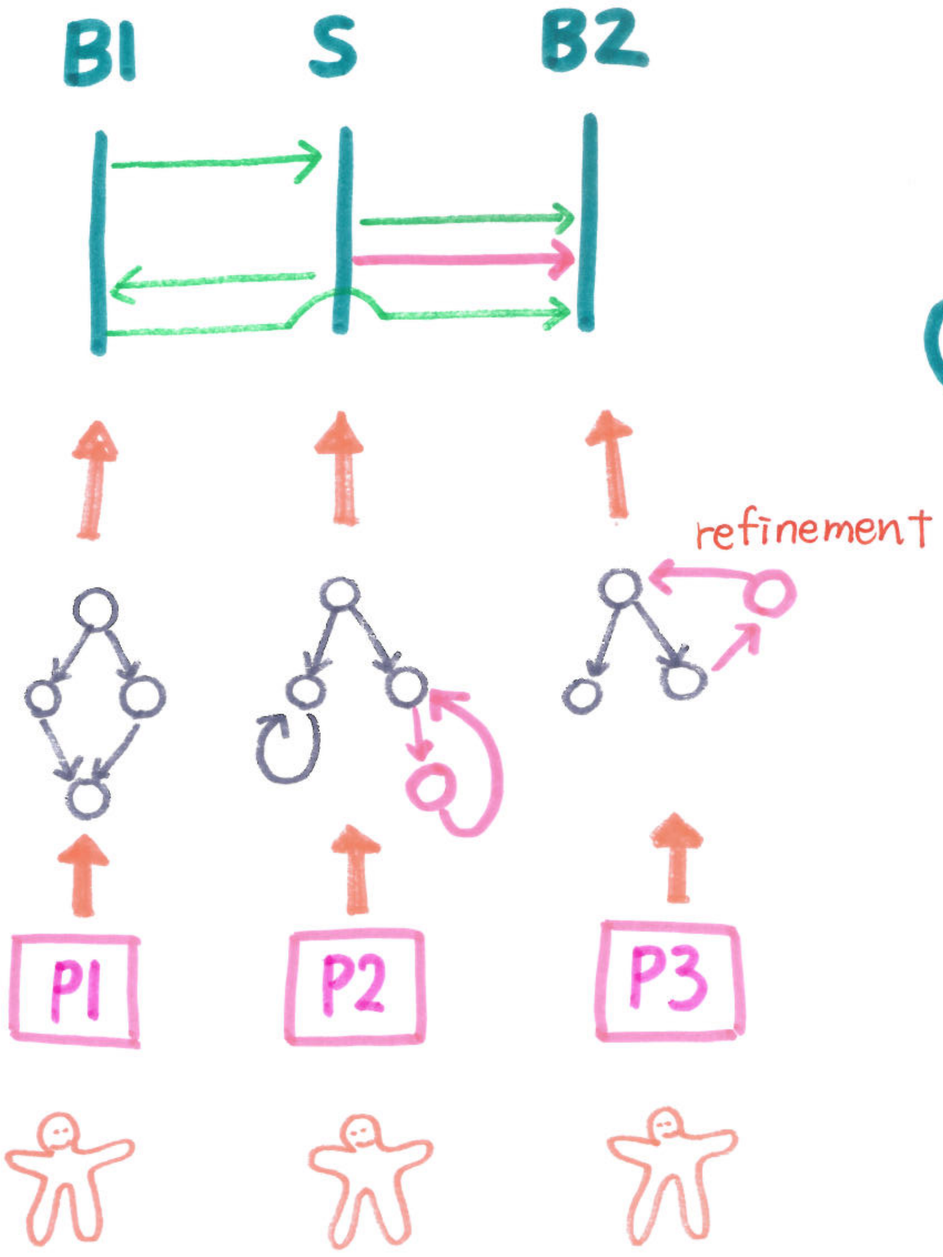
STEP 1
Write Global Type

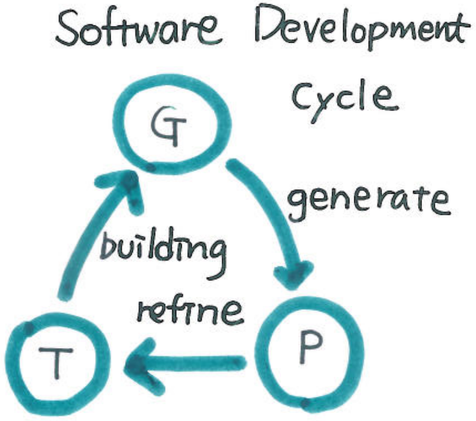
STEP 2
Project to Local Type

STEP 3
- Static Check
- Generate Code
- Run-time check


P1
P2
P3


refinement
P1
P2
P3

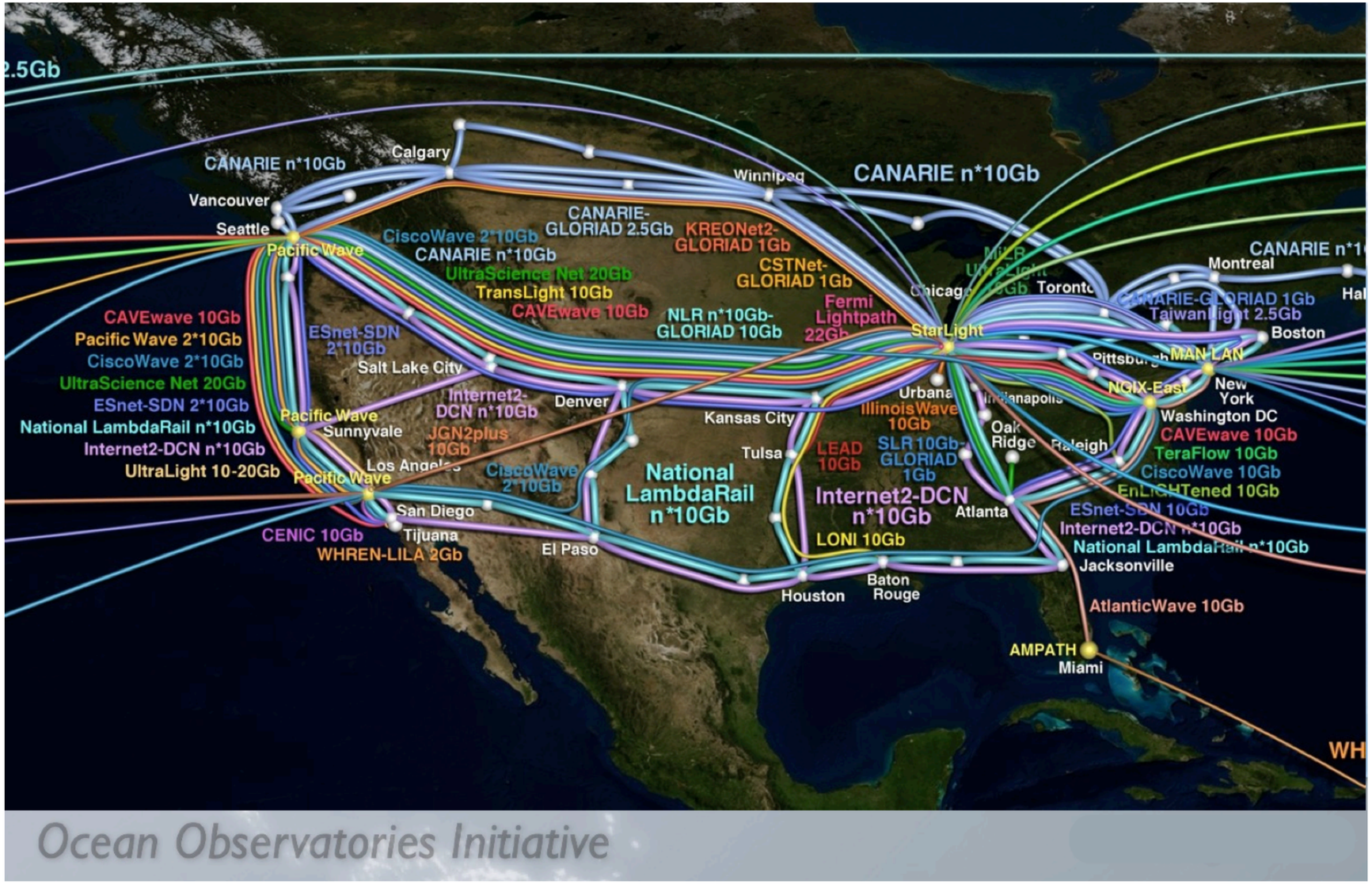




- Optimisation
- refinement
- Inference
- Testing

Mobility Reading Group http://mrg.cs.ox.ac.uk/

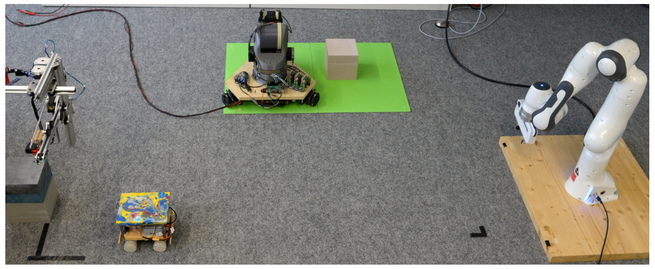
Some Applications on Multiparty Session Types



Distributed Tracing

OpenTelemetry

Robotics



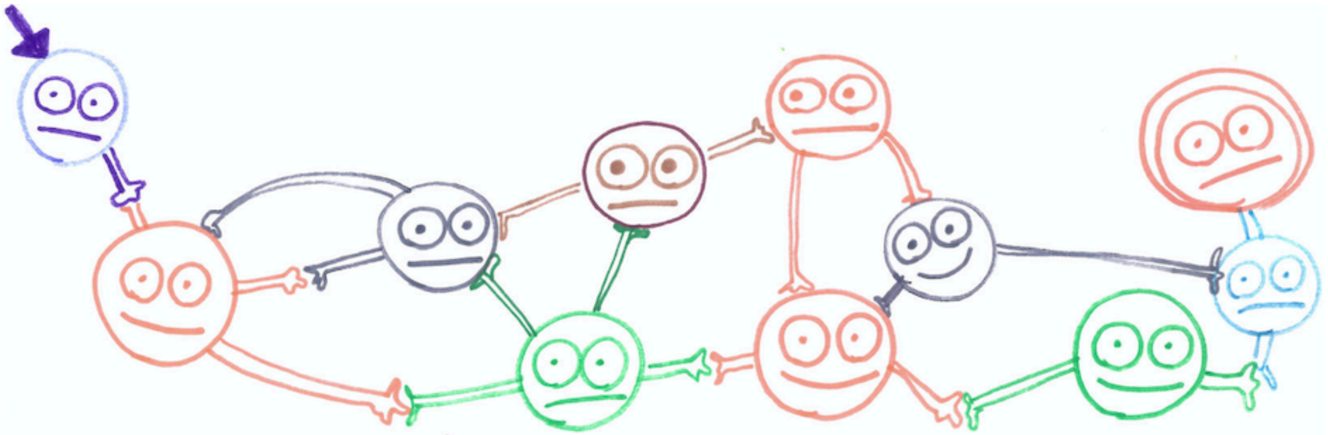
Mechanisation

Zooid

Multiparty Session Types in Rust

Deadlock-Free Message Reordering with Multiparty Session Types [PPoPP 2022]

Refinements for Multiparty Message-Passing Protocols: Specification-agnostic theory and implementation [ECOOP 2024]



Zak Cutner, Martin Vassor and NY

Introduction

Rust Language

- Modern systems language focussed on safety and performance

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- “Most loved language” for past five years on StackOverflow

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Introduction

Rust Language

- Modern systems language focussed on safety and performance
- “Most loved language” for past five years on StackOverflow
- Particular emphasis on safe concurrency using message passing
- Affine type system is well-suited to session types

Ring Protocol

Example

Global Type

$$\mathsf{G} = \mu \mathbf{t}.\mathbf{A} \to \mathbf{B} : \left\{ add(\texttt{i32}).\mathbf{B} \to \mathbf{C} : \left\{ \begin{array}{l} add(\texttt{i32}).\mathbf{C} \to \mathbf{A} : \{ add(\texttt{i32}).\mathbf{t} \} \\ sub(\texttt{i32}).\mathbf{C} \to \mathbf{A} : \{ sub(\texttt{i32}).\mathbf{t} \} \end{array} \right\} \right\}$$

Ring Protocol

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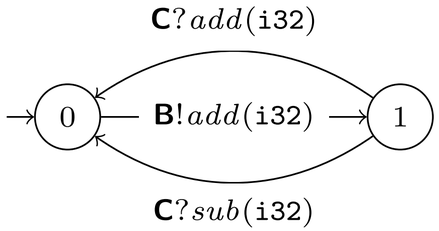
PROJECTION



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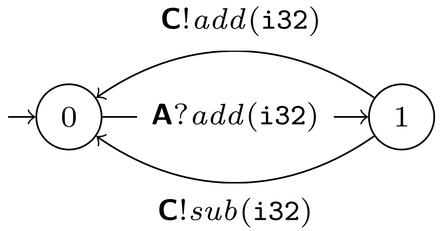

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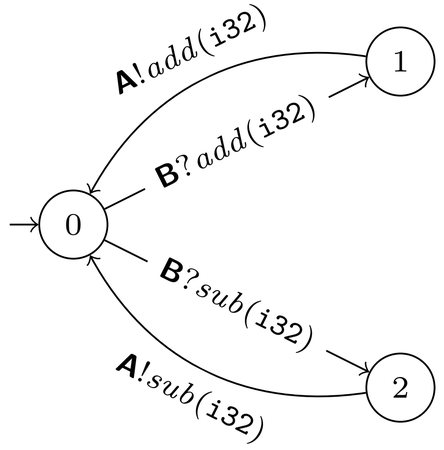

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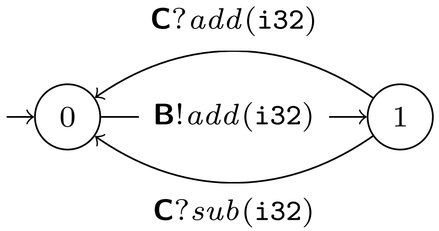

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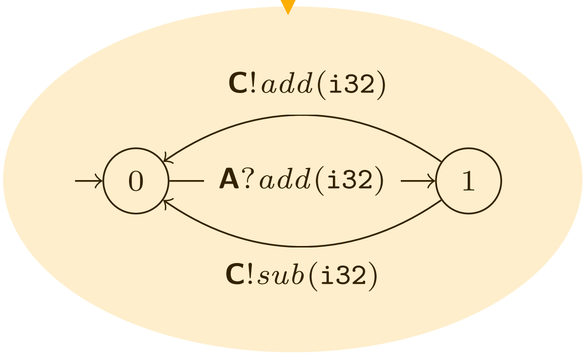

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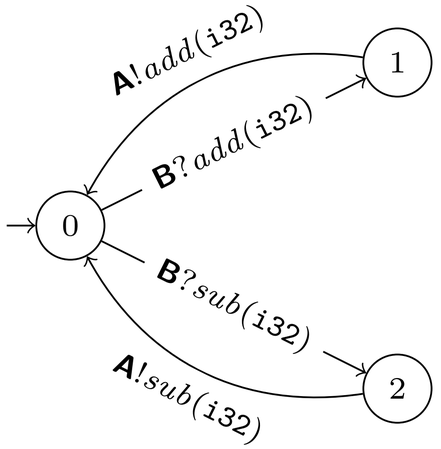


Challenge

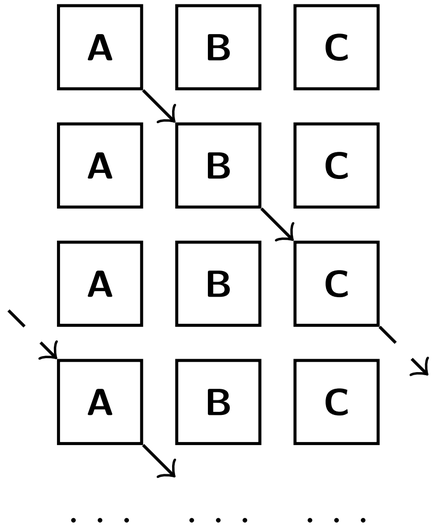
Asynchronous Orderings

- Global types are inherently synchronous

Challenge

Asynchronous Orderings

- Global types are inherently synchronous
  - Projection provides only one possible ordering



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Asynchronous Orderings

- Global types are inherently synchronous
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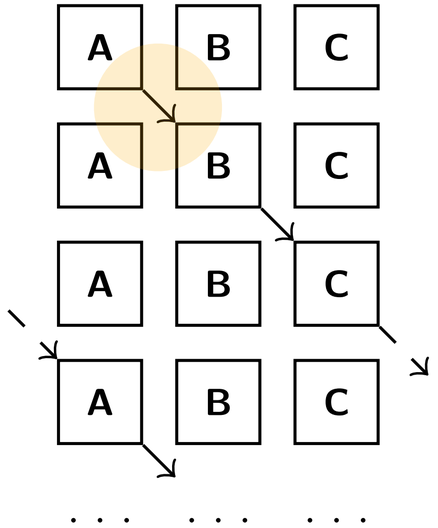

Challenge

Asynchronous Orderings

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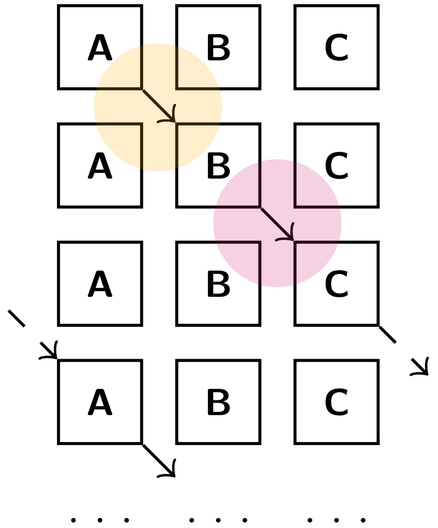

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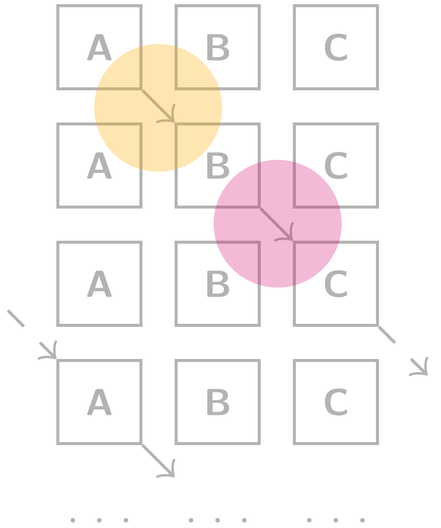

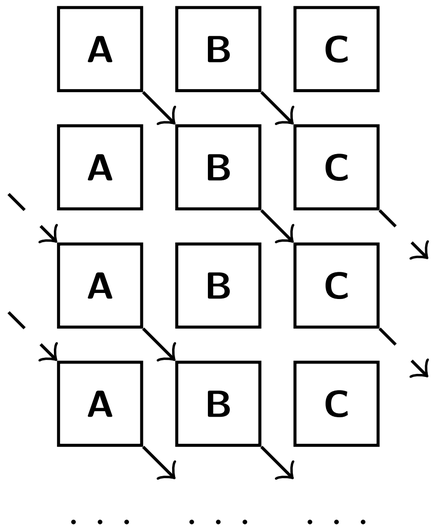

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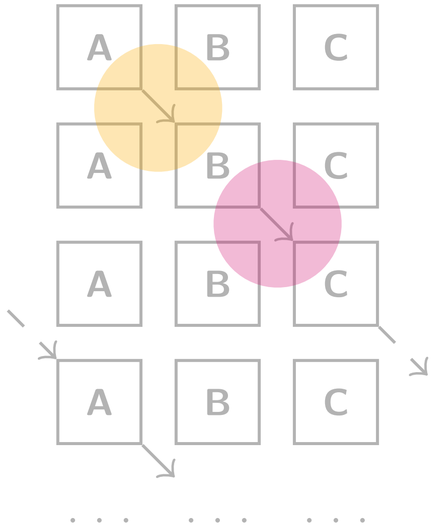

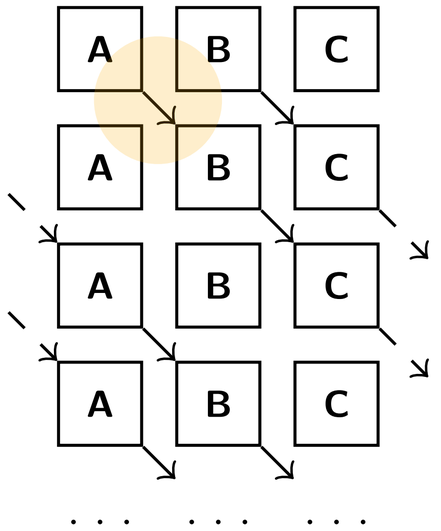

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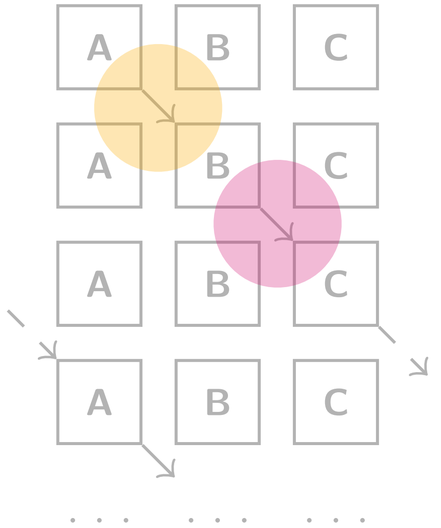

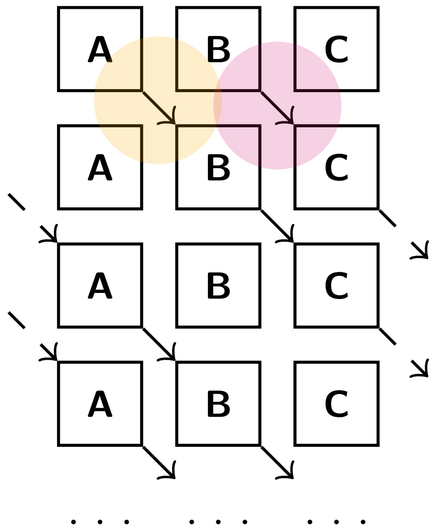

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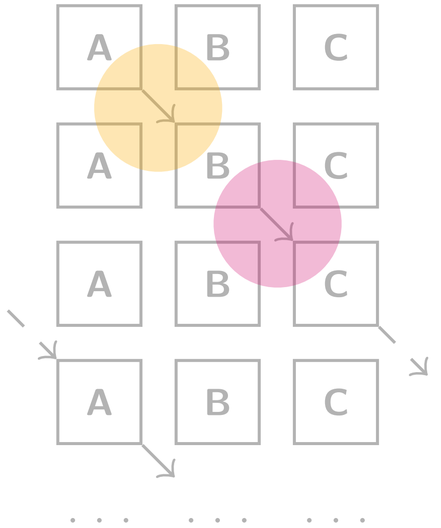
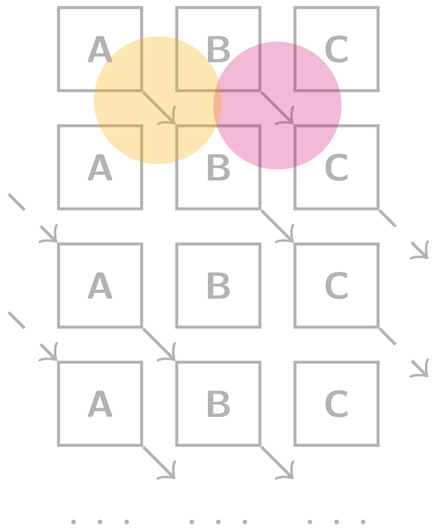
  1. Data dependencies must be preserved





Challenge

Asynchronous Orderings

- Global types are inherently synchronous
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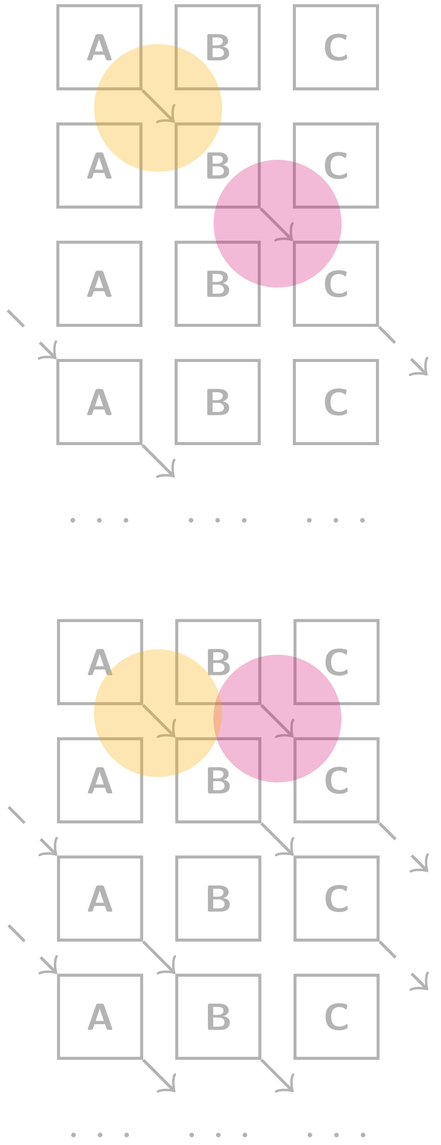
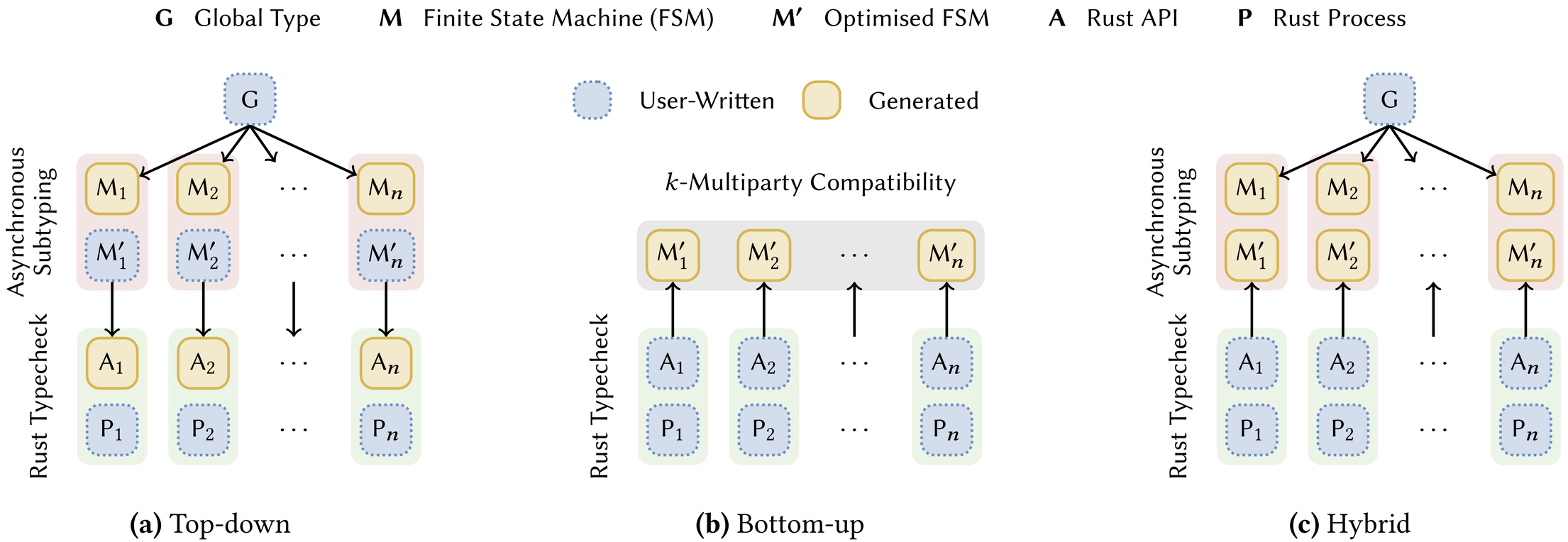
- Interactions can be reordered for efficiency while preserving safety
  1. Data dependencies must be preserved
  2. Sound and practical asynchronous reordering rules must be found



Rumpsteak Framework

Three Approaches



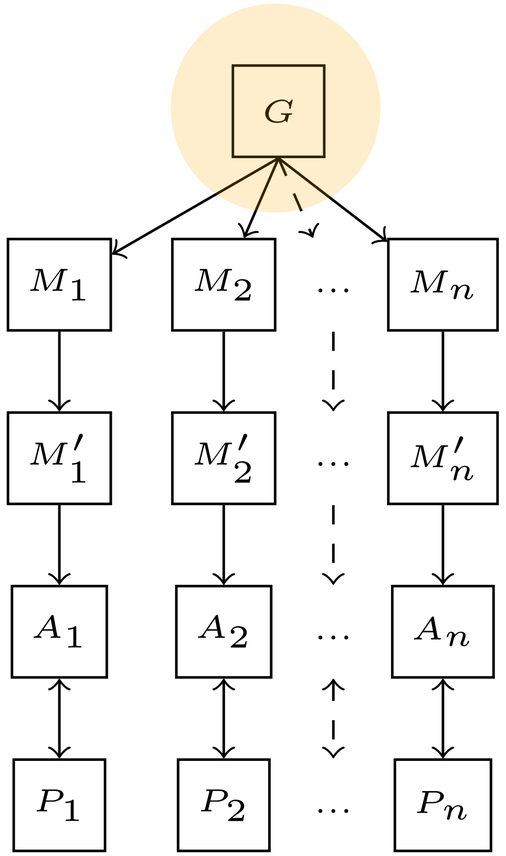
(a) Top-down

(b) Bottom-up

(c) Hybrid

Workflow

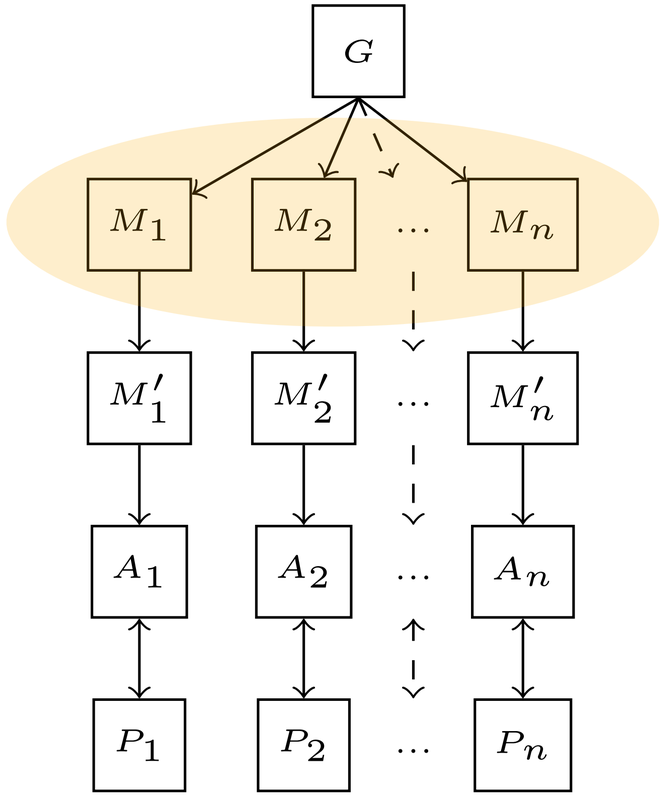
Top-Down Approach



Global Type

Workflow

Top-Down Approach

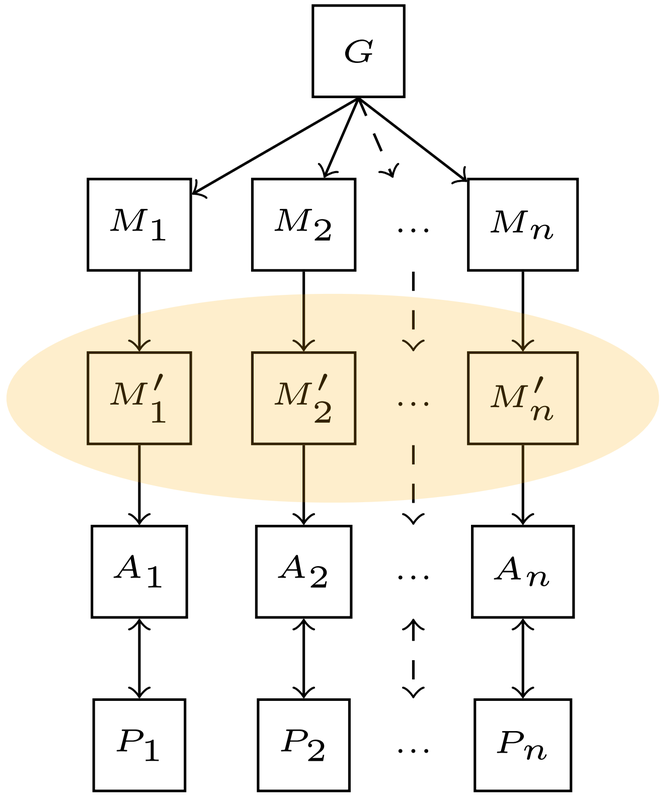


Global Type

Projected FSM

Workflow

Top-Down Approach



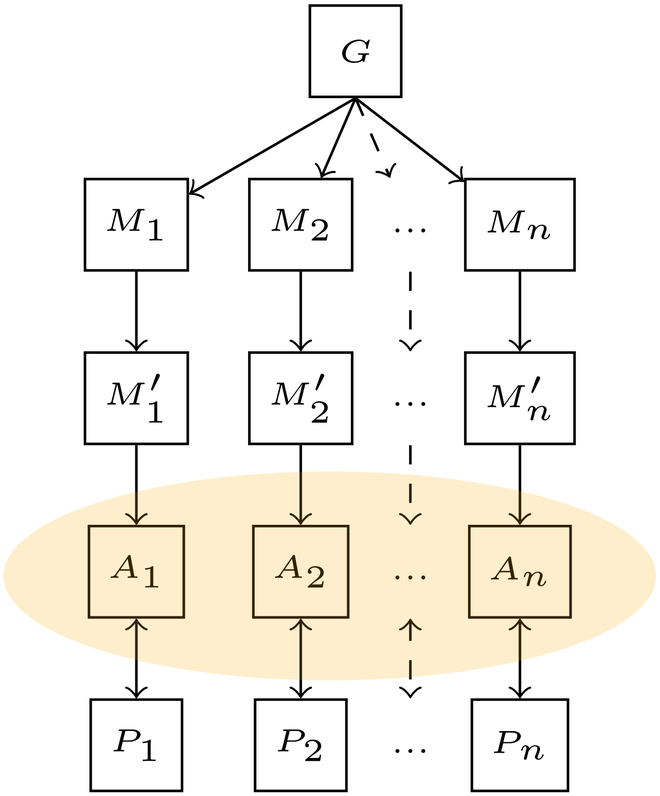
Global Type

Projected FSM

Optimised FSM

Workflow

Top-Down Approach



Global Type

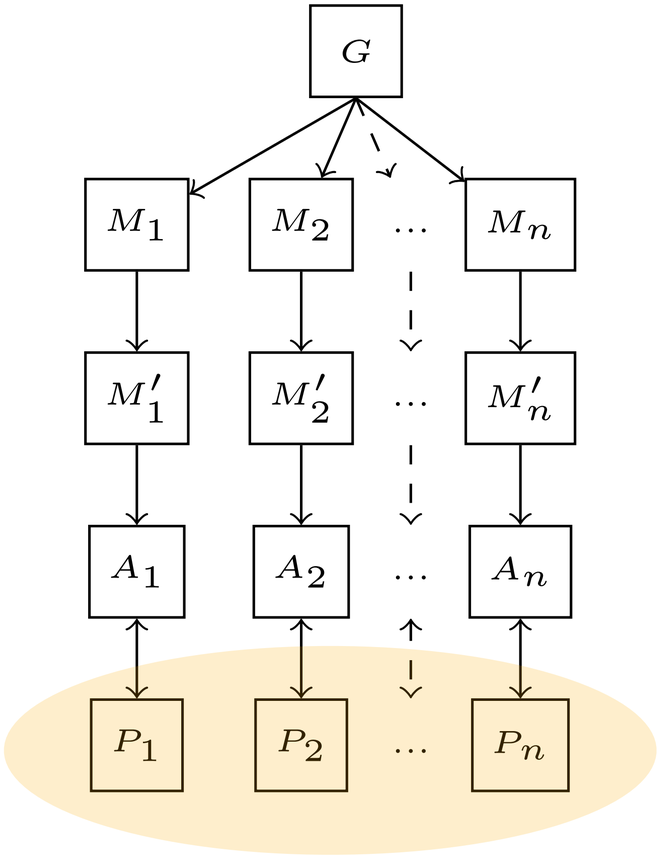
Projected FSM

Optimised FSM

Rust API

Workflow

Top-Down Approach



Global Type

Projected FSM

Optimised FSM

Rust API

Rust Implementation

Ring Protocol

Example

Global Type

$$\mathsf{G} = \mu \mathbf{t}.\mathbf{A} \to \mathbf{B} : \left\{ add(\texttt{i32}).\mathbf{B} \to \mathbf{C} : \left\{ \begin{array}{l} add(\texttt{i32}).\mathbf{C} \to \mathbf{A} : \{ add(\texttt{i32}).\mathbf{t} \} \\ sub(\texttt{i32}).\mathbf{C} \to \mathbf{A} : \{ sub(\texttt{i32}).\mathbf{t} \} \end{array} \right\} \right\}$$

Ring Protocol

Example

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Ring Protocol

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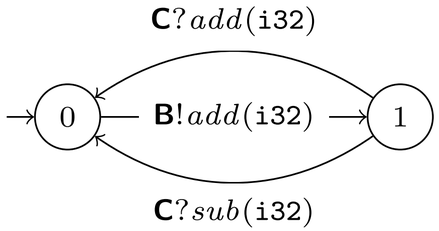
PROJECTION



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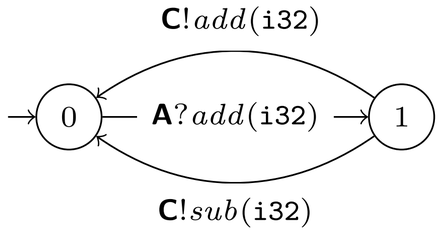

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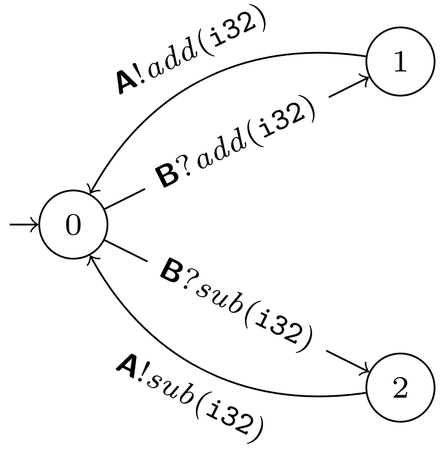
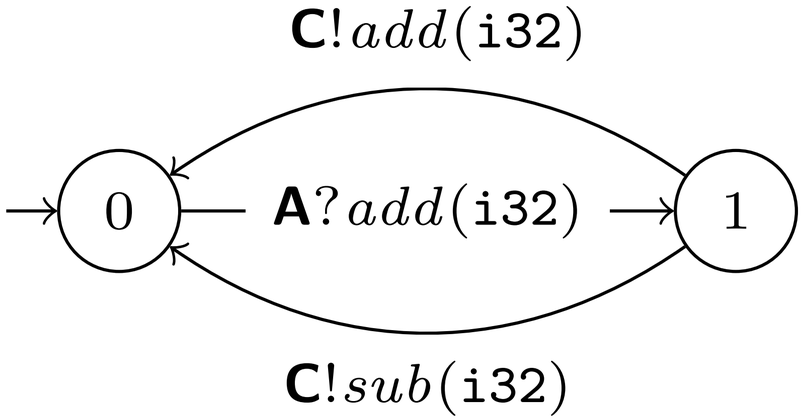


Ring Protocol

Example



Ring Protocol

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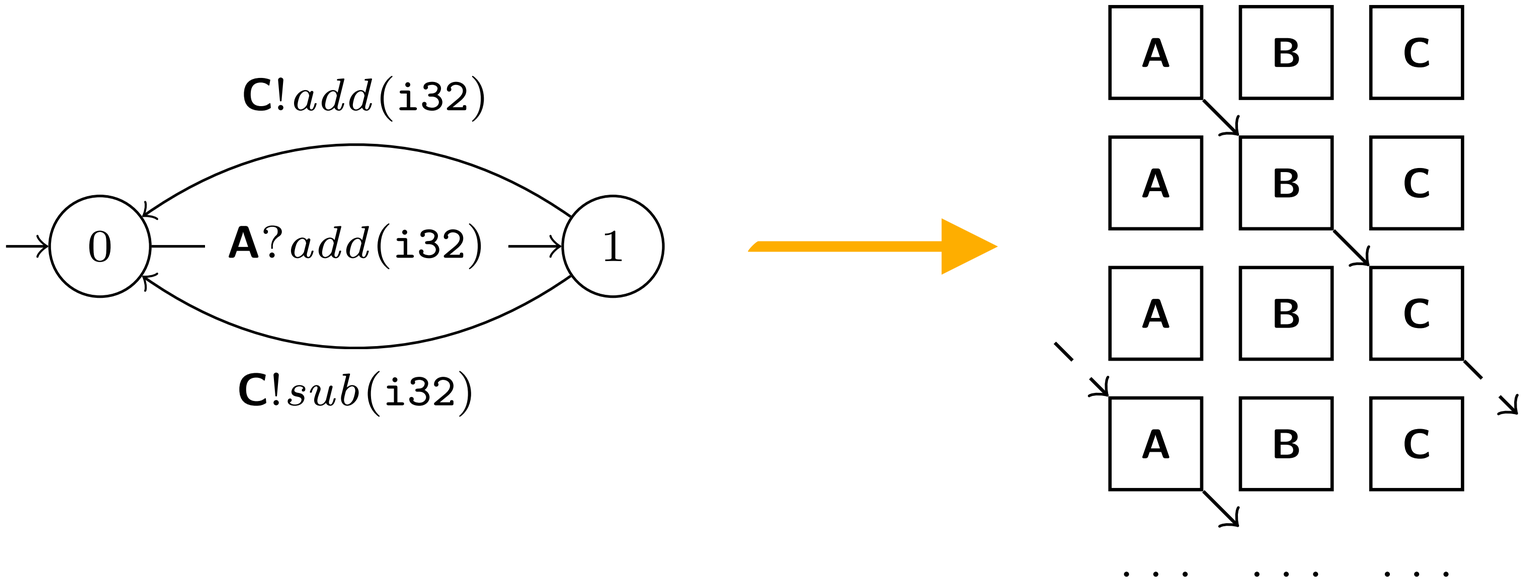
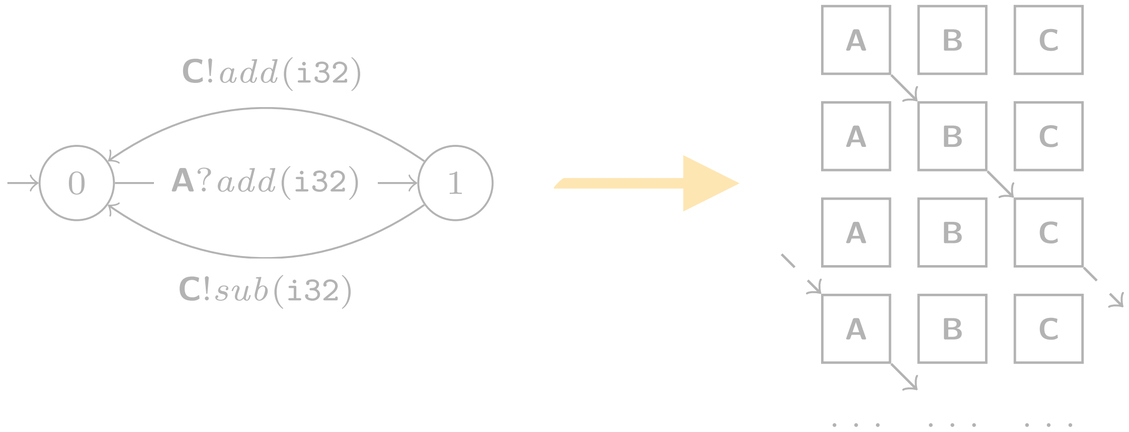
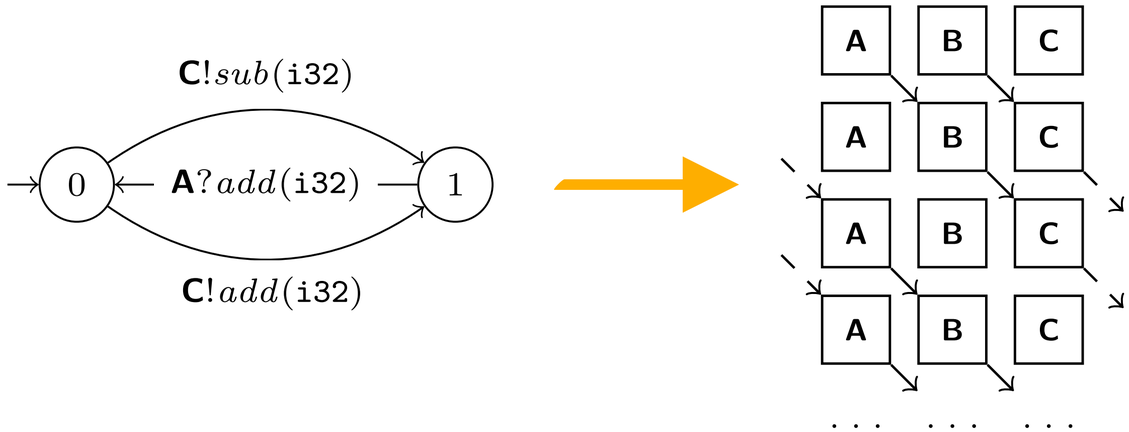


Ring Protocol

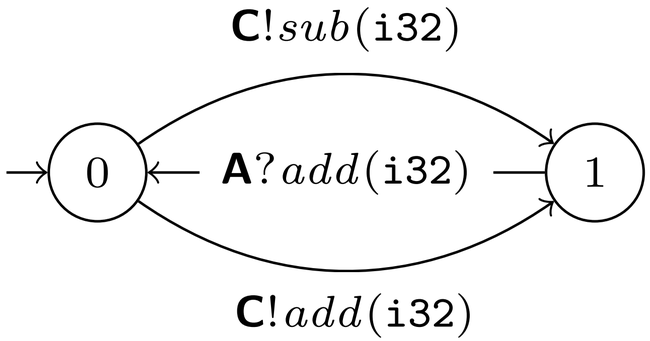
Example





Ring Protocol

Rust API



Ring Protocol

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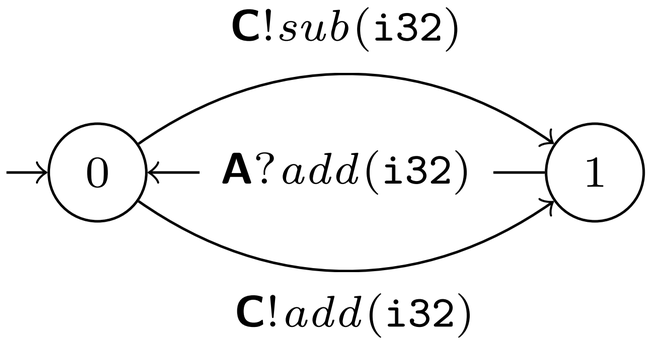


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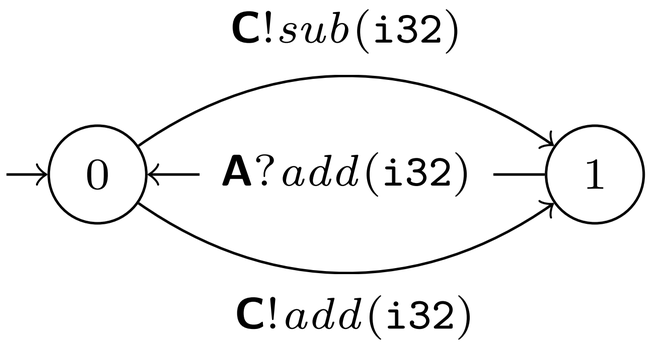
#[derive(Role)]
#[message(Label)]
struct B(#[route(A)] Receiver, #[route(C)] Sender);
```

Ring Protocol

Rust API

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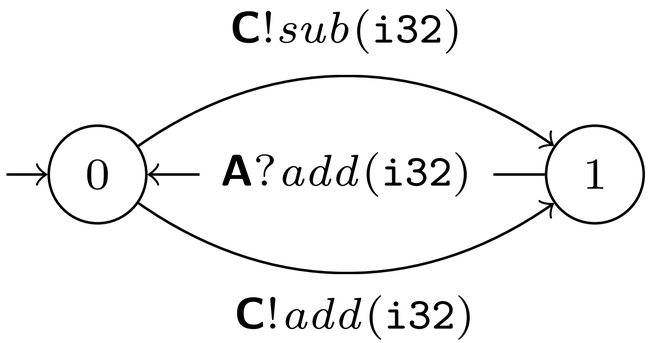
Ring Protocol

Rust API

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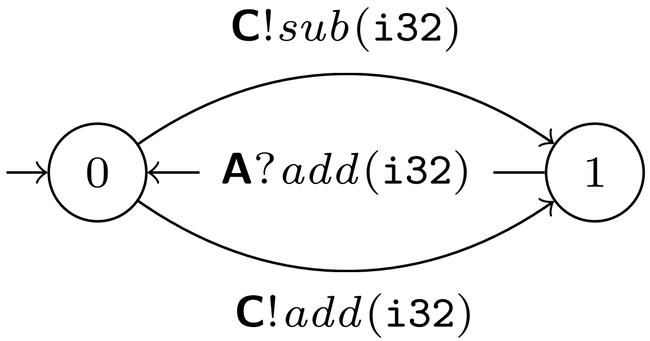


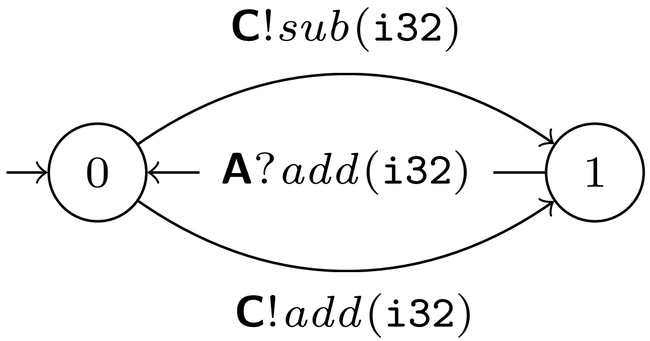

```rust
#[derive(Role)]
#[message(Label)]
struct B(#[route(A)] Receiver, #[route(C)] Sender);

#[derive(Message)]
enum Label {
    Add(Add),
    Sub(Sub),
}

struct Add(i32);
struct Sub(i32);
```

Ring Protocol

Rust API

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#[derive(Role)]
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#[derive(Message)]
enum Label {
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struct Add(i32);
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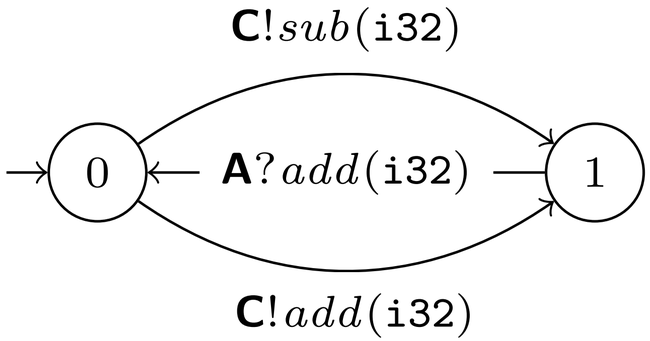
#[session]
type RingB = Select<C, RingBChoice>;

#[session]
enum RingBChoice {
    Add(Add, Receive<A, Add, RingB>),
    Sub(Sub, Receive<A, Add, RingB>),
}
```

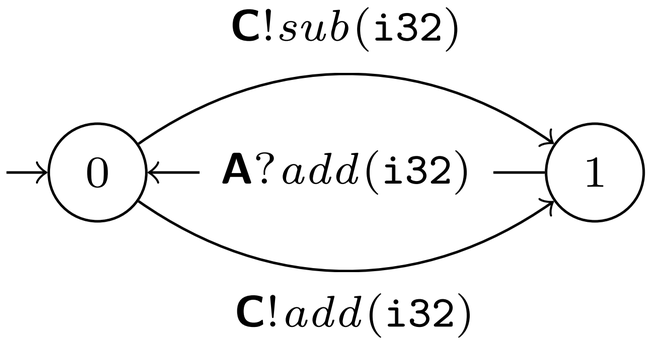
Ring Protocol

Rust API



Ring Protocol

Implementation



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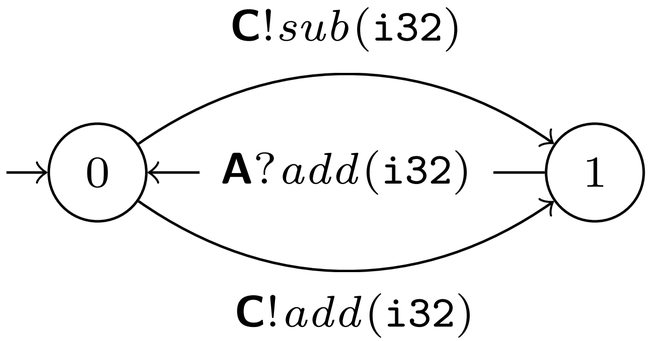


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                input = y + x;
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            } else {
                let s = s.select(Sub(x)).await?;
                let (Add(y), s) = s.receive().await?;
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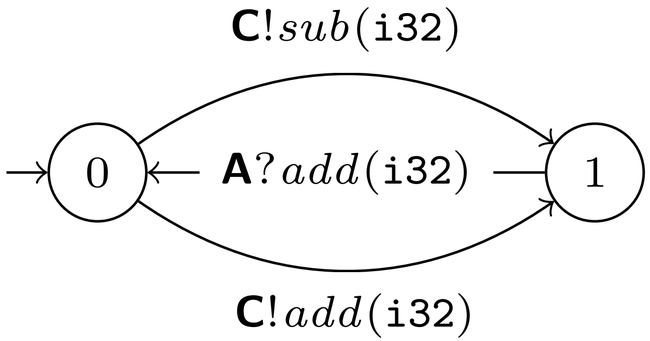
Ring Protocol

Implementation

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Ring Protocol

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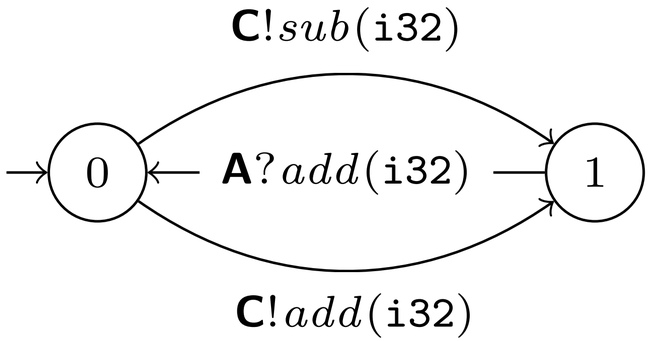


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Ring Protocol

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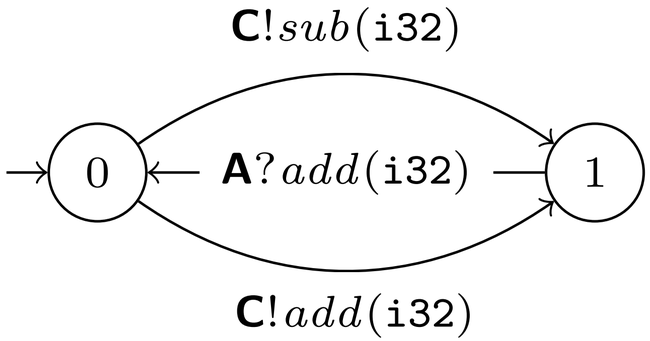


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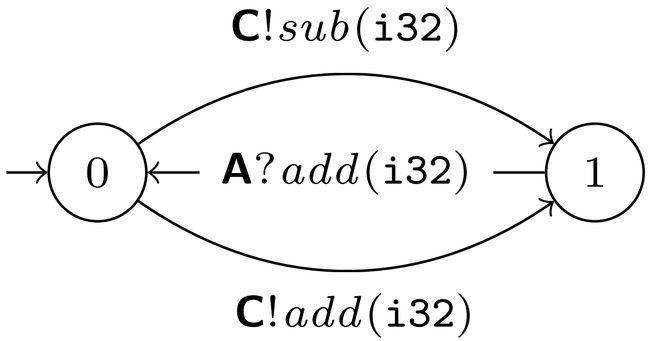
Ring Protocol

Implementation

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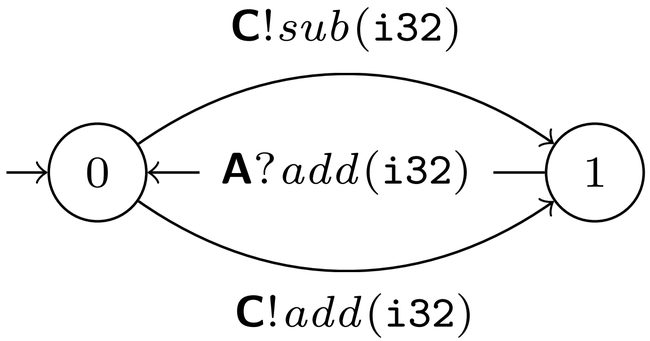
Ring Protocol

Implementation

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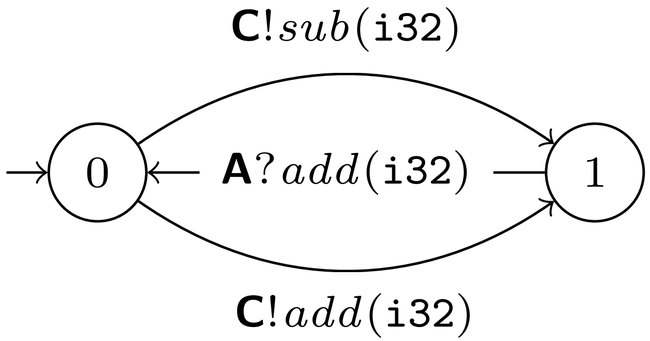
Ring Protocol

Implementation

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Ring Protocol

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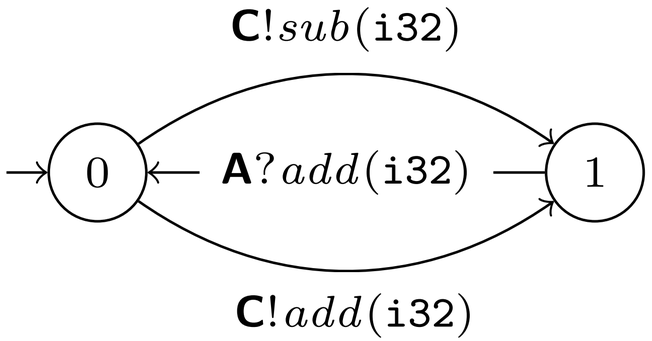


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    role: &mut B,
    mut input: i32,
) -> Result<Infallible> {
    try_session(role, |mut s: RingB<'_, _>| async {
        loop {
            let x = input * 2;

            s = if x > 0 {
                let s = s.select(Add(x)).await?;
                let (Add(y), s) = s.receive().await?;
                input = y + x;
                s
            } else {
                let s = s.select(Sub(x)).await?;
                let (Add(y), s) = s.receive().await?;
                input = y - x;
                s
            };
        }
    })
    .await
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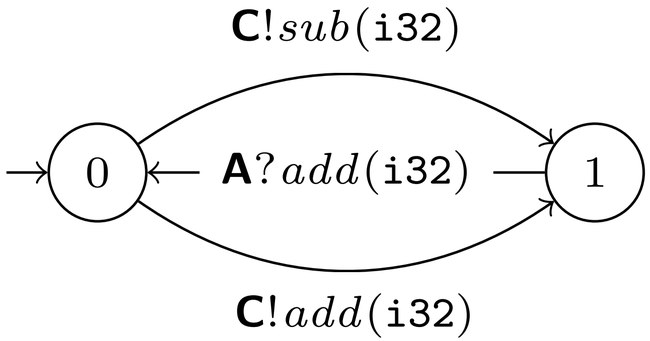
```

Ring Protocol

Implementation

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Ring Protocol

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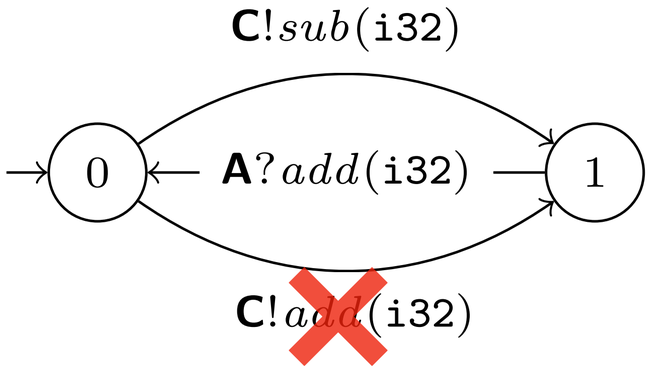


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Ring Protocol

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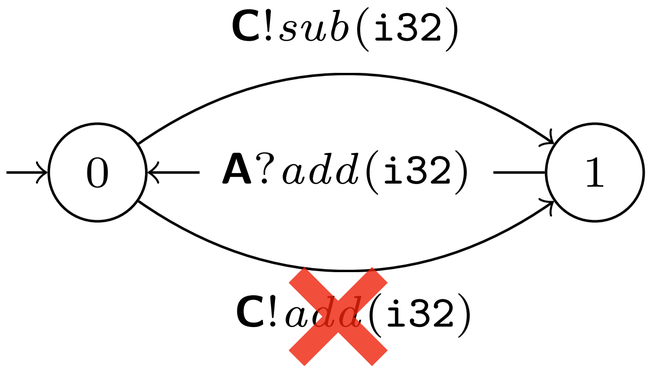


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            };
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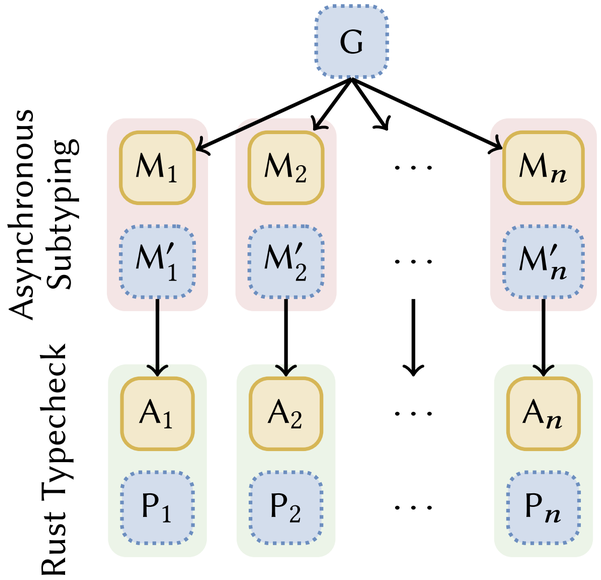
    })
    .await
}
```

```
method not found in `rumpsteak::Select<'_, B, C, RingBChoice<'_, B>>`
```

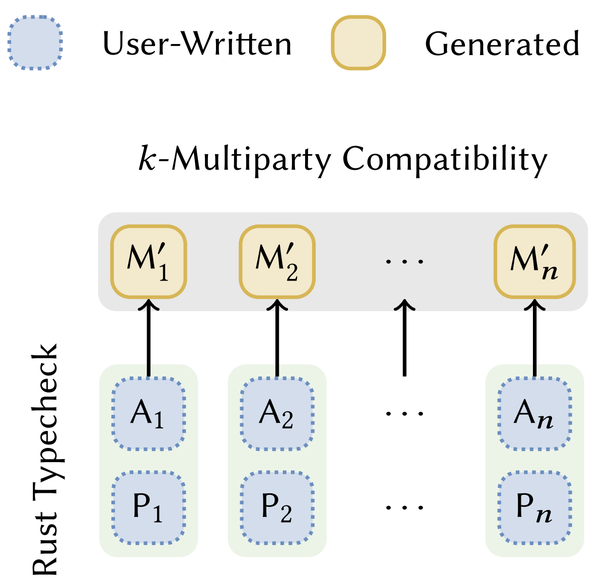
Rumpsteak Framework

Three Approaches

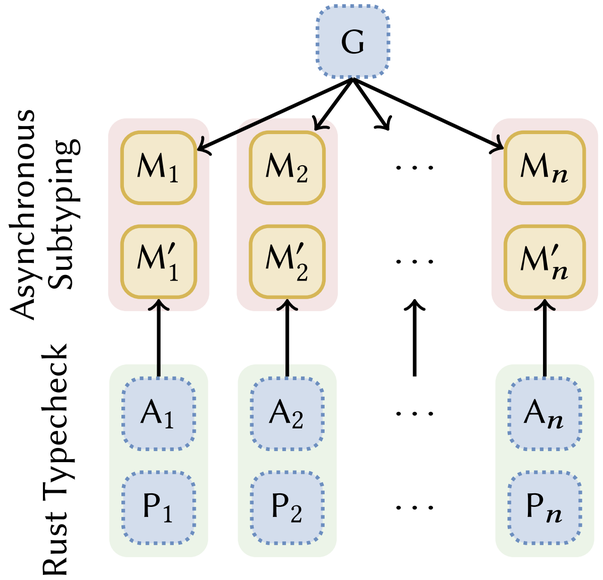
G Global Type **M** Finite State Machine (FSM) **M′** Optimised FSM **A** Rust API **P** Rust Process



(a) Top-down



(b) Bottom-up



(c) Hybrid

Theories for Communication Optimisation

Asynchronous Reordering Revisited

How do we check that asynchronous reorderings are safe?

Theories for Communication Optimisation

Asynchronous Reordering Revisited

How do we check that asynchronous reorderings are safe?

1. Asynchronous subtyping relation [Ghilezan et al., POPL'2021]

Theories for Communication Optimisation

Asynchronous Reordering Revisited

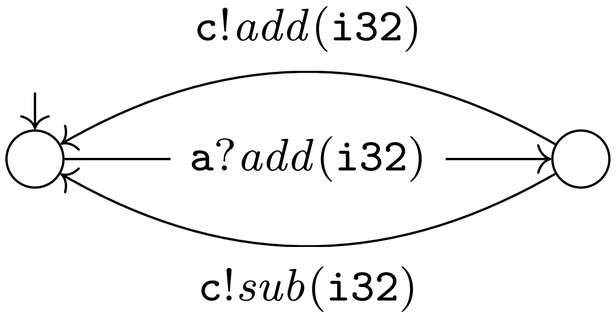
How do we check that asynchronous reorderings are safe?

1. Asynchronous subtyping relation [Ghilezan et al., POPL'2021]
2. *k*-multiparty compatibility [Lange and Yoshida, CAV'2019]

Safety

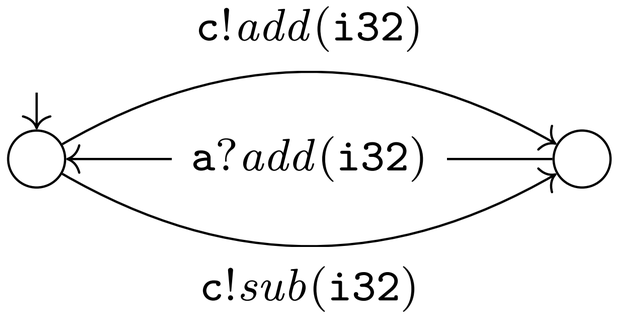
Asynchronous Subtyping

PROJECTED B



Safe?

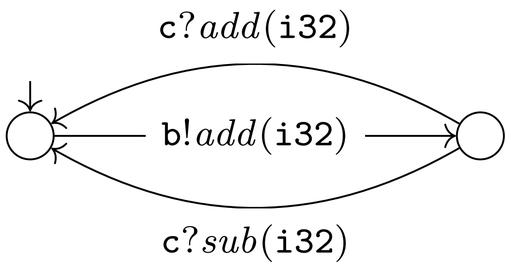
OPTIMISED B



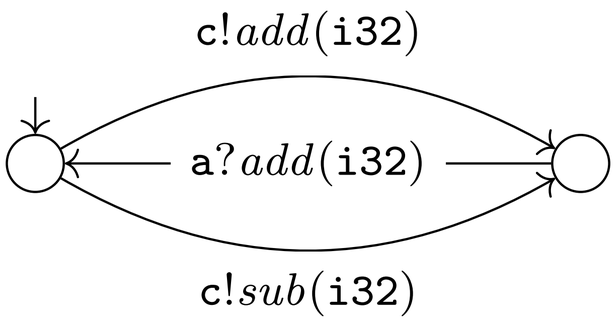
Safety

k-Multiparty Compatibility

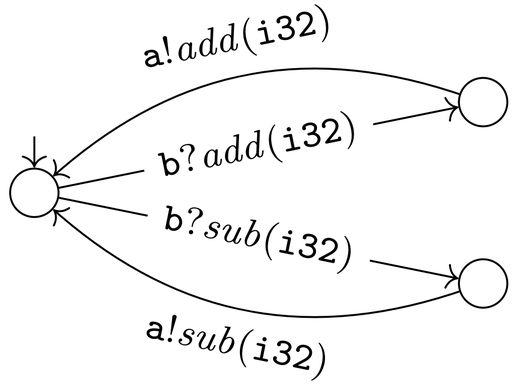
OPTIMISED A



OPTIMISED B



OPTIMISED C



Safe?

Asynchronous Subtyping

Existing work

- Relation given by [Ghilezan et al., POPL 2021]

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  - Sound ✅

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  - Decidable [Lange and Yoshida, FoSSaCs 2017] ❌

Asynchronous Subtyping

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- Relation given by [Ghilezan et al., POPL 2021]
  - Sound ✅
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- Our aim is a sound and decidable algorithm

Asynchronous Subtyping

Existing work

- Relation given by [Ghilezan et al., POPL 2021]
  - Sound ✅
  - Complete ✅
  - Decidable [Lange and Yoshida, FoSSaCs 2017] ❌
- Our aim is a sound and decidable algorithm
- **[POPL 2021] Theorem:** Internal and external choices can be decomposed into single input and single output trees

Algorithm for Asynchronous Subtyping

Practical, Sound and Terminating

1. Bound the number of times we unroll recursions
2. Only unwrap choice on demand

Asynchronous Subtyping

Session Type Prefix

$$
\begin{array}{rcll}
\pi, \rho & ::= & \epsilon & \text{empty prefix} \\
& | & \mathtt{p}!\ell(S) & \text{message send} \\
& | & \mathtt{p}?\ell(S) & \text{message receive} \\
& | & \pi_1.\pi_2 & \text{concatenation}
\end{array}
$$

Asynchronous Subtyping

Reduction Rules

$$\mathcal{A}^{(\mathtt{p})} \;::=\; \mathtt{q}?\ell(S) \mid \mathtt{q}?\ell(S).\mathcal{A}^{(\mathtt{p})} \qquad (\mathtt{p} \neq \mathtt{q})$$

$$\frac{S' \leq: S}{\left\langle \mathtt{p}?\ell(S).\pi, \mathcal{A}^{(\mathtt{p})}.\mathtt{p}?\ell(S').\pi' \right\rangle \to \left\langle \pi, \mathcal{A}^{(\mathtt{p})}.\pi' \right\rangle}\ [\textsc{red-}\mathcal{A}]$$

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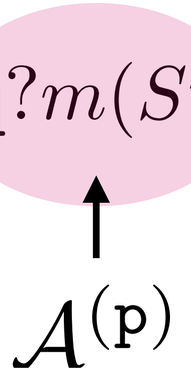

$$\mathcal{A}^{(\mathtt{p})}$$

✅

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Theorems

Termination, Soundness & Complexity

Lemma 3. *Given finite prefixes π and π', $\langle \pi \parallel \pi' \rangle$ can be reduced only a finite number of times.*

Theorem 4 (Termination)**.** *Our subtyping algorithm always eventually terminates.*

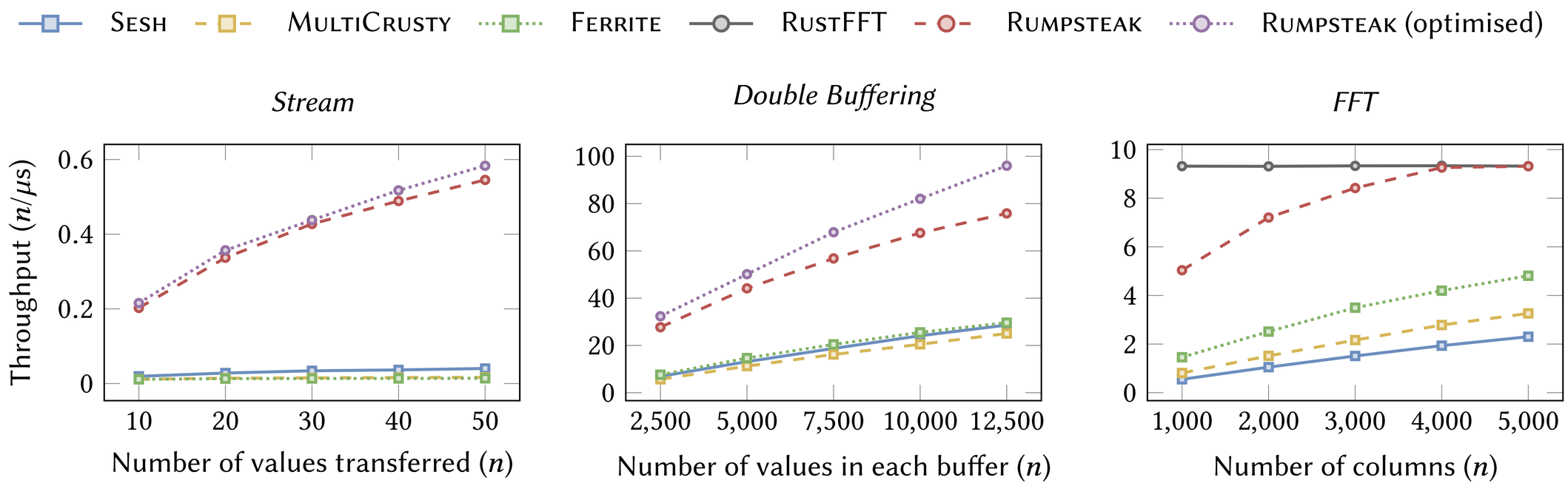
Theorem 5 (Soundness)**.** *Our subtyping algorithm is sound.*

Lemma 6. *Given finite prefixes π and π', the time complexity of reducing $\langle \pi \parallel \pi' \rangle$ is $O(\min(|\pi|, |\pi'|))$.*

Theorem 7 (Complexity)**.** *Consider* T *and* T' *as (possibly infinite) trees* $\mathcal{T}(\mathsf{T})$ *and* $\mathcal{T}(\mathsf{T}')$ *with* asymptotic branching factors b *and* b' *respectively. Our algorithm has time complexity* $O(n \min(b, b')^n)$ *and space complexity* $O(n \min(b, b'))$ *in the worst case to determine if* $\mathsf{T} \leq \mathsf{T}'$ *with bound* n.

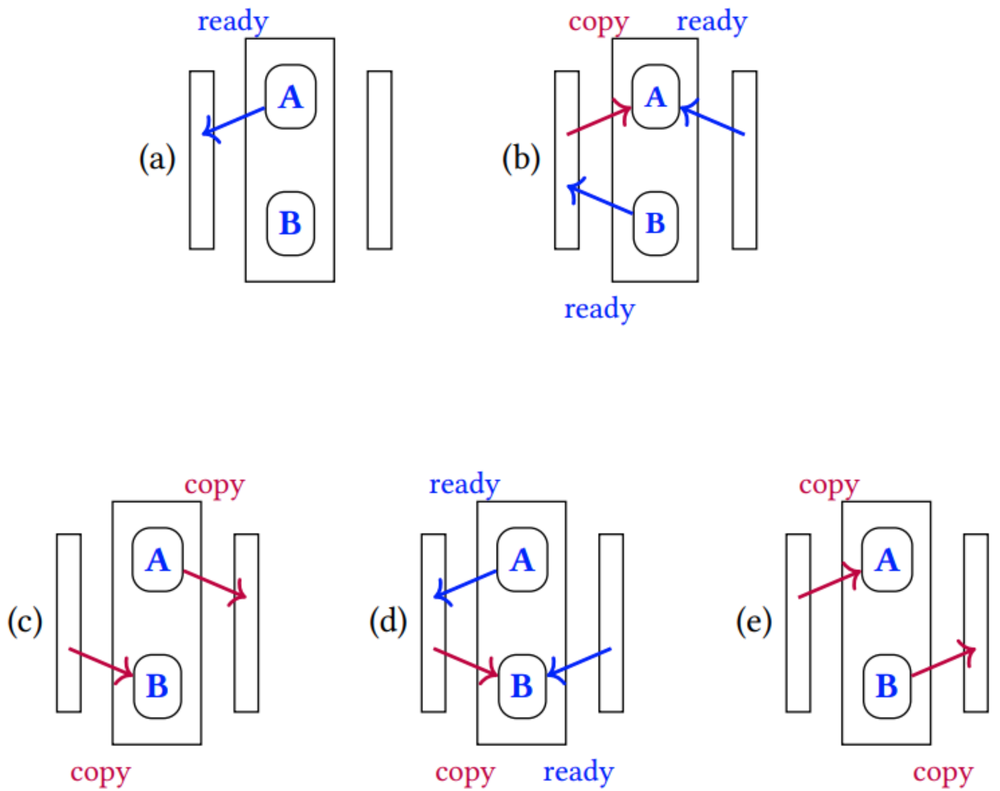
Evaluation

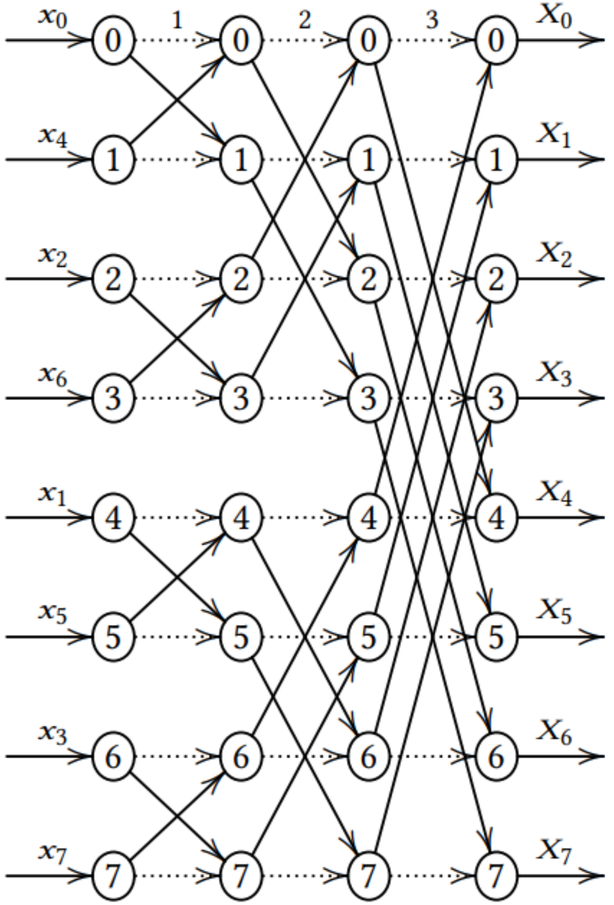
Rust Framework Benchmarks



16-core AMD OpteronTM 6200 Series CPU @ 2.6GHz with hyperthreading, 128GB of RAM, Ubuntu 18.04.5 LTS and Rust Nightly 2021-07-06.
We use version 0.3.5 of the Criterion.rs library and a multi-threaded asynchronous runtime from version 1.11.0 of the Tokio library.

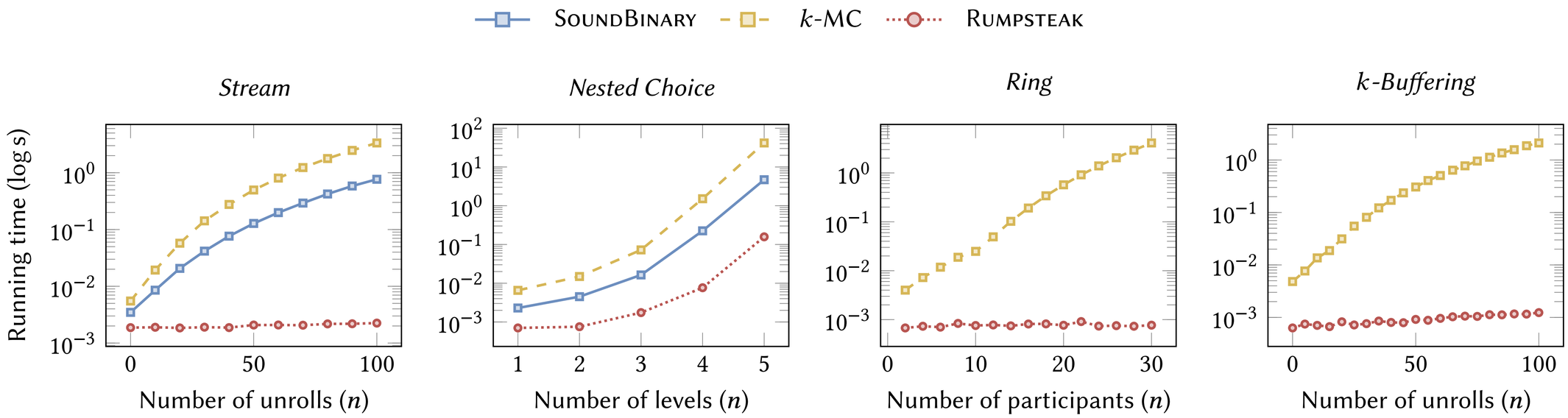
Double DB & Butterfly Topologies for FFT





Evaluation

Asynchronous Reordering Benchmarks



Evaluation

Expressiveness

Protocol	n	AMR	Sesh	Ferrite	MultiCrusty	Rumpsteak	k-MC	SoundBinary
Two Adder	2		✔	✔	✔	✔	✔	✔
Three Adder	3		✗	✗	✔	✔	✔	✗
Stream	2		✔	✔	✔	✔	✔	✔
Optimised Stream	2	✔	✗	✗	✗	✔	✔	✔
Ring	3		✗	✗	✔	✔	✔	✗
Optimised Ring	3	✔	✗	✗	✗	✔	✔	✗
Ring With Choice	3		✗	✗	✔	✔	✔	✗
Optimised Ring With Choice	3	✔	✗	✗	✗	✔	✔	✗
Double Buffering	3		✗	✗	✔	✔	✔	✗
Optimised Double Buffering	3	✔	✗	✗	✗	✔	✔	✗
Alternating Bit	2		✗	✗	✗	✔	✔	✔
Elevator	3	✔	✗	✗	✗	✔	✔	✗
FFT	8		✗	✗	✔	✔	✔	✗
Optimised FFT	8	✔	✗	✗	✗	✔	✔	✗
Authentication	3		✗	✗	✔	✔	✔	✗
Client-Server Log	3		✗	✗	✔	✔	✔	✗
Hospital	2	✔	✗	✗	✗	✗	✗	✔

n Number of participants **AMR** Asynchronous message reordering

✔ Expressible ✗ Expressible using endpoint types (but without deadlock-freedom guarantee) ✗ Not expressible

Refinement Multiparty Session Types

[ECOOP 2024]

- Limitation: will never terminate if keeping trying the wrong password

$$G = \mu \mathbf{T}.\mathsf{C} \to \mathsf{S} : \mathsf{Password}(\mathtt{String}) . \mathsf{S} \to \mathsf{C} \left\{ \begin{array}{l} \mathsf{Succeed}() . \mathtt{end} \\ \mathsf{Fail}() . \mathbf{T} \end{array} \right\}$$

- With **contraint**, can terminate the session program at some point

$$G = \mu \mathbf{T}.\mathsf{C} \to \mathsf{S} : \mathsf{Password}(\mathtt{String}) . \mathsf{S} \to \mathsf{C} \left\{ \begin{array}{l} \mathsf{Succeed}(\mathtt{int}) . \mathtt{end} \\ \mathsf{Fail}(\mathtt{int}) . \mathbf{T} \; \mathit{if}\, x < 10; x \Leftarrow x + 1 \\ \mathsf{Abort}(\mathtt{int}) . \mathtt{end} \end{array} \right\}$$

Summary

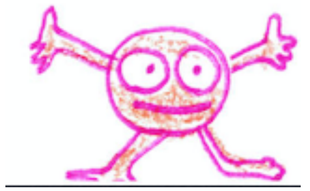
Multiparty Session Types in Rust

- Multiparty session type description language
  - 𝒮 **nuScr https://github.com/nuscr**
- Applications of multiparty session types using communicating automata
  - 🍖 **https://github.com/zakcutner/rumpsteak**
  - [ECOOP'24] **Refinements for Multiparty Message-Passing Protocols: Specification-agnostic theory and implementation** https://zenodo.org/records/12731834

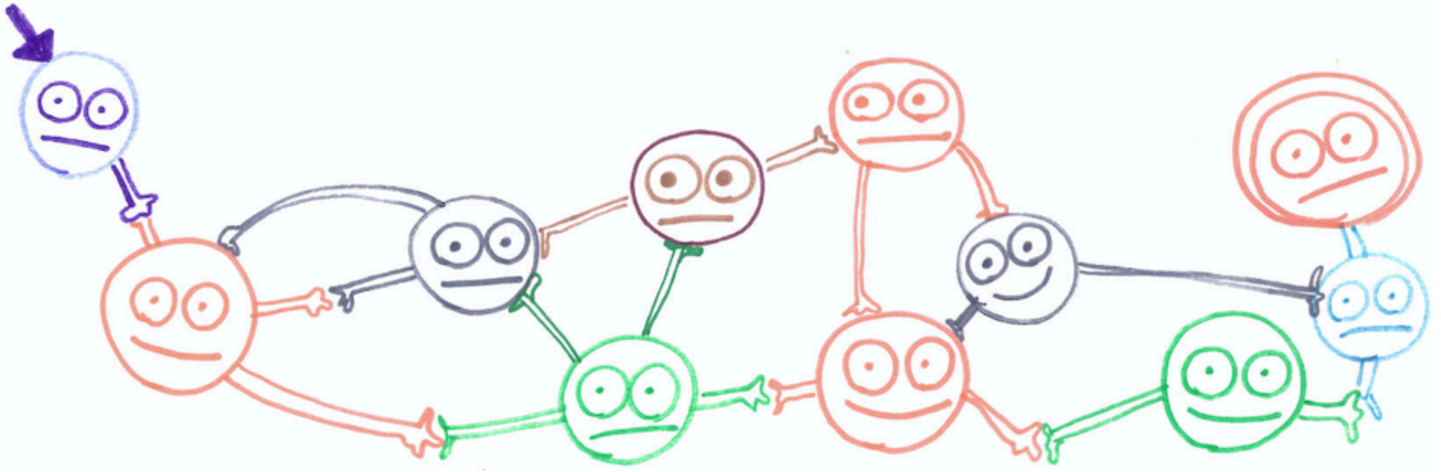




Thank you! Questions?



http://mrg.cs.ox.ac.uk/



CFSMs [1980 -] ITU notation SDL · MSCS ···

Def A CFSM $M = (Q, C, q0, \Sigma, \delta)$

Q a finite set of states

$C = \{ pq \in Participant^2 \mid p \neq q \}$

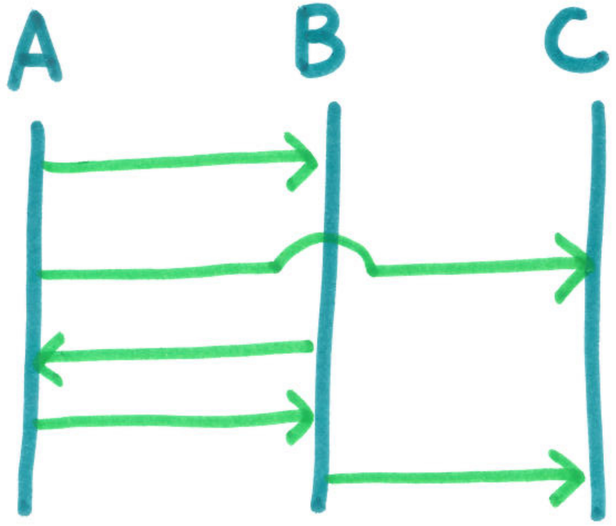
$q0$ initial state

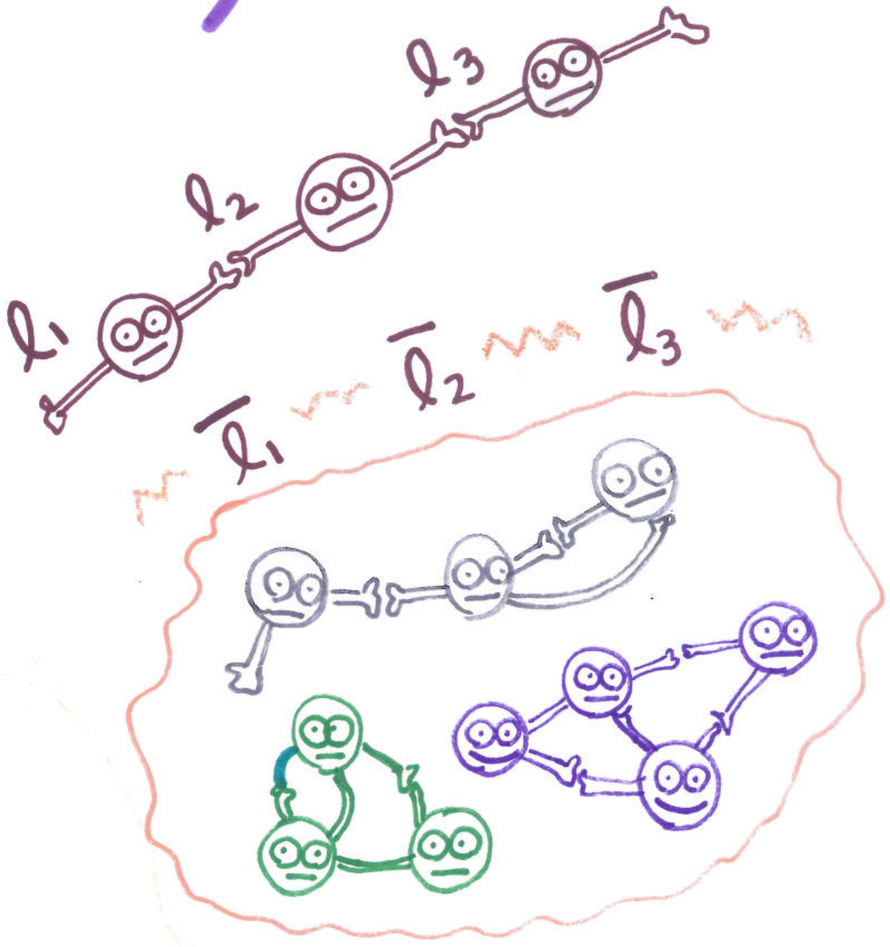
Σ a finite alphabet of messages

$\delta \subseteq Q \times (C \times \{!, ?\} \times \Sigma) \times Q$ a finite set of transitions

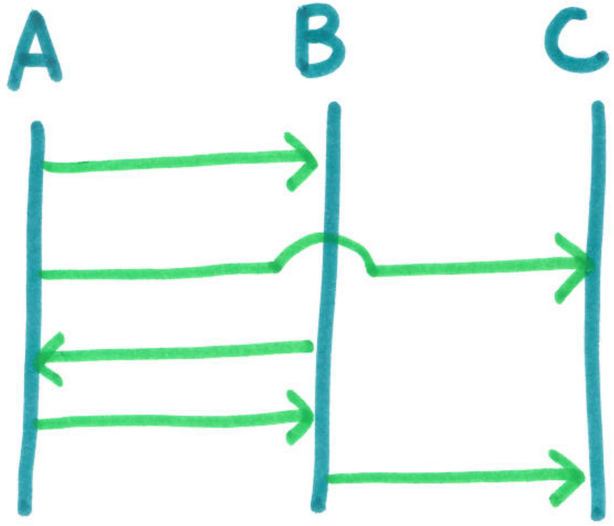
Def CS $S = (M_p)_{p \in Participant}$

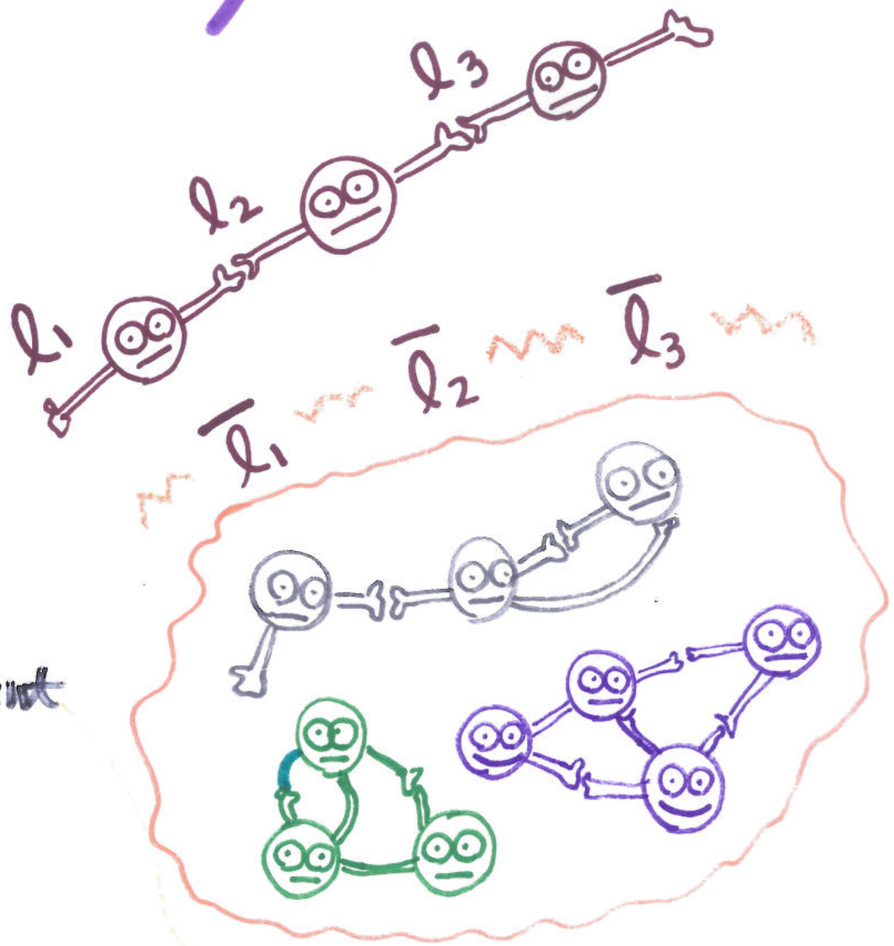
Multiparty Compatibility





Multiparty Compatibility





Def $S = (M_p)_{p \in Participant}$

$\forall s \,.\, s_0 \rightsquigarrow s$ (1-buffer execution)

if M_i does action ℓ

then $(M_j)_{j \in P \setminus i}$ do action $\bar{\ell}$

after some $\rightsquigarrow$

Multiparty Compatibility

Definition System $S = (M_p)_{p \in \mathcal{P}}$ is **MC** if for any 1-bound reachable state $s \in RS_1(S)$, and any output action $pq!a$ from s in M_p, there exists an alternation $\varphi.t$ from s in a system where $act(t) = pq?a$ and $p \notin act(\varphi)$

(Dual for Input)

$s \xrightarrow{t} s'$ configuration $s = (\vec{q}\,;\vec{w})$

states queues

q_p w_{pq}

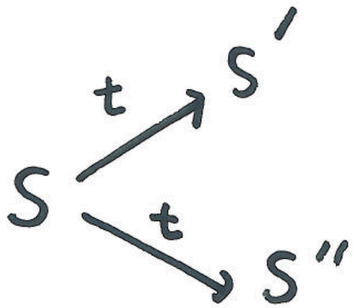
Send

$(\ldots q_p \ldots\,;\ldots w_{pq} \ldots) \xrightarrow{pq!\ell} (\ldots q_p' \ldots\,;\ldots w_{pq} \cdot \ell \ldots)$

Receive

$(\ldots q_q \ldots\,;\ldots \ell \cdot w_{pq} \ldots) \xrightarrow{pq?\ell} (\ldots q_q' \ldots\,;\ldots w_{pq} \ldots)$

Deteministic CFSM

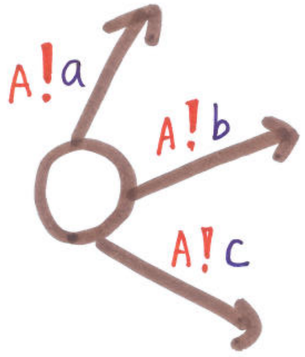


$\Rightarrow \quad s' = s''$

Basic CFSMs

A CFSM is **Basic** if **deterministic**

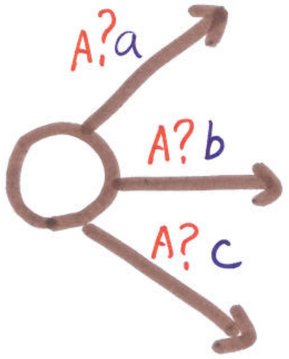
directed, has **no mixed states**



sending

✓

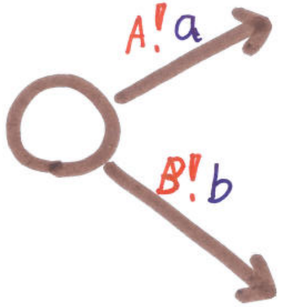
$T = A!\{a, b, c\}$



receiving

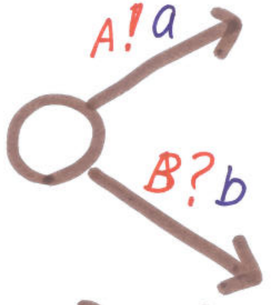
✓

$A?\{a, b, c\}$



non directed

✗



mixed

✗

k-Multiparty Compatibility [CAV'19]