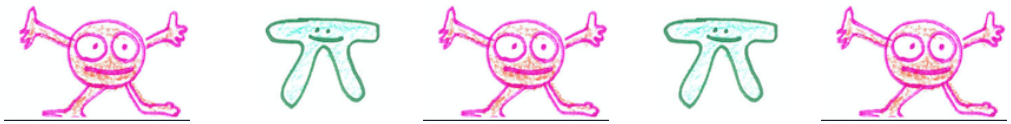
Multiparty Session Types and Communicating Automata

FCT 2021: 23rd International Symposium on Fundamentals of Computation Theory



Nobuko Yoshida

Imperial College London

Communications are Ubiquitous

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

microservices






Problems: Ambiguity

- Protocol descriptions are **ambiguous**
- **SMTP: simple mail transfer protocol**
  - They are written in English, often very long

RFC 821 August 1982
Simple Mail Transfer Protocol

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Problems: Ambiguity

- Protocol descriptions are **ambiguous**
- **SMTP: simple mail transfer protocol**
  - They are written in English, often very long

3.1. MAIL

There are three steps to SMTP mail transactions. The transaction is started with a MAIL command which gives the sender identification. A series of one or more RCPT commands follows giving the receiver information. Then a DATA command gives the mail data. And finally, the end of mail data indicator confirms the transaction.

The first step in the procedure is the MAIL command. The <reverse-path> contains the source mailbox.

MAIL <SP> FROM:<reverse-path> <CRLF>

This command tells the SMTP-receiver that a new mail transaction is starting and to reset all its state tables and buffers, including any recipients or mail data. It gives the reverse-path which can be used to report errors. If accepted, the receiver-SMTP returns a 250 OK reply.

The <reverse-path> can contain more than just a mailbox. The <reverse-path> is a reverse source routing list of hosts and source mailbox. The first host in the <reverse-path> should be the host sending this command.

The second step in the procedure is the RCPT command.

RCPT <SP> TO:<forward-path> <CRLF>

This command gives a forward-path identifying one recipient. If accepted, the receiver-SMTP returns a 250 OK reply, and stores the forward-path. If the recipient is unknown the receiver-SMTP returns a 550 Failure reply. This second step of the procedure can be repeated any number of times.

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**
  - Survey of 4k users [golang.org]
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More than a half of concurrency bugs in Go are caused by communications.

Session Types

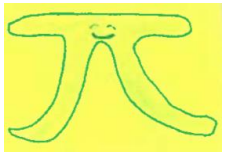
- Prevent concurrency bugs.
- Can abstract, implement and manage communications as **Protocols.**
- **Clean, Cheap** and **Retrofittable.**

Why Session Types, Why Now?

Significant academic and industry interests via fundamental breakthroughs

Milner, Honda, NY

Binary Session Types — ESOP'98



Joined W3C Standardization — 2002

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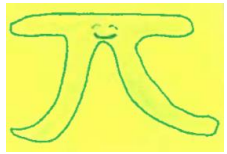

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Multiparty Session Types — POPL' 08

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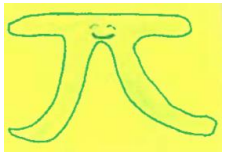

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Joined W3C Standardization — 2002

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Multiparty Session Types — POPL' 08

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largest open source company in the world

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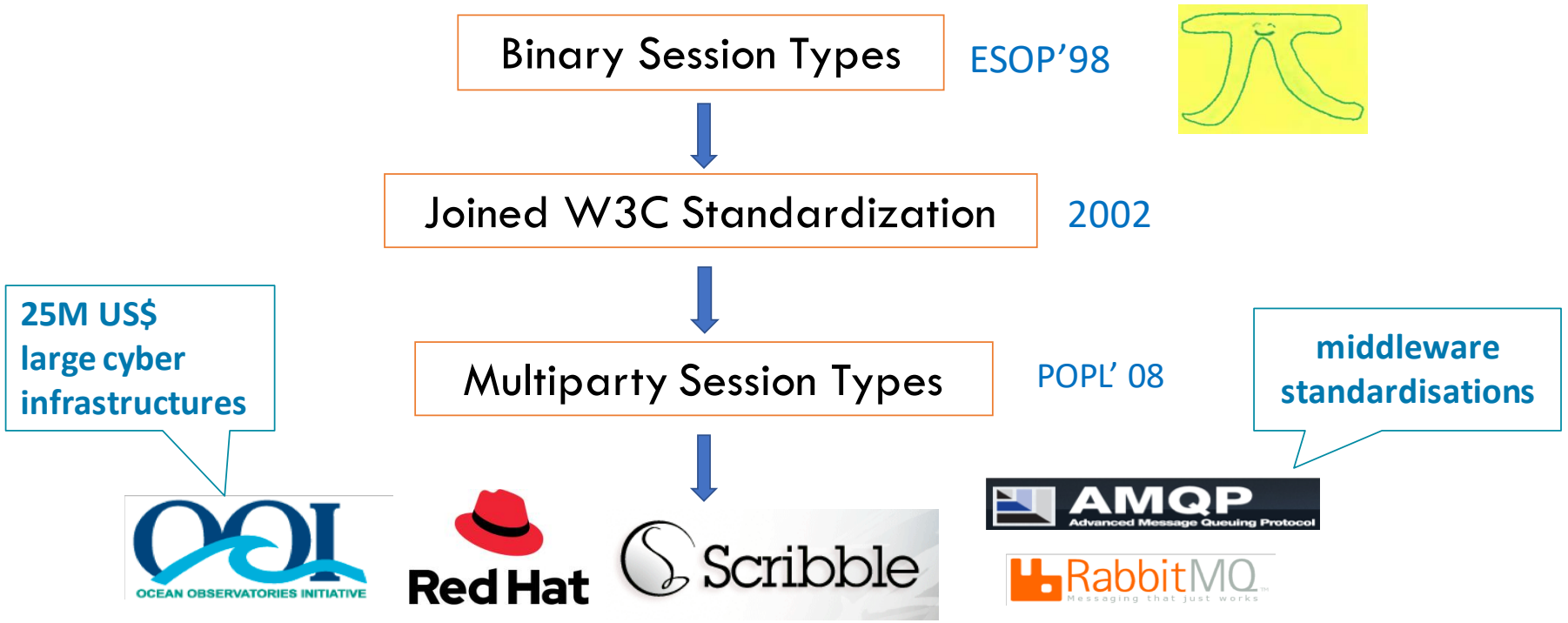

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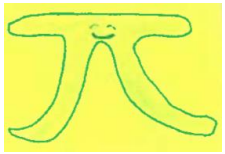

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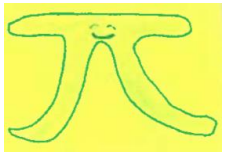
Why Session Types, Why Now?

Significant academic and industry interests via fundamental breakthroughs

ETAPS Test Time Award 2019

Binary Session Types — ESOP'98

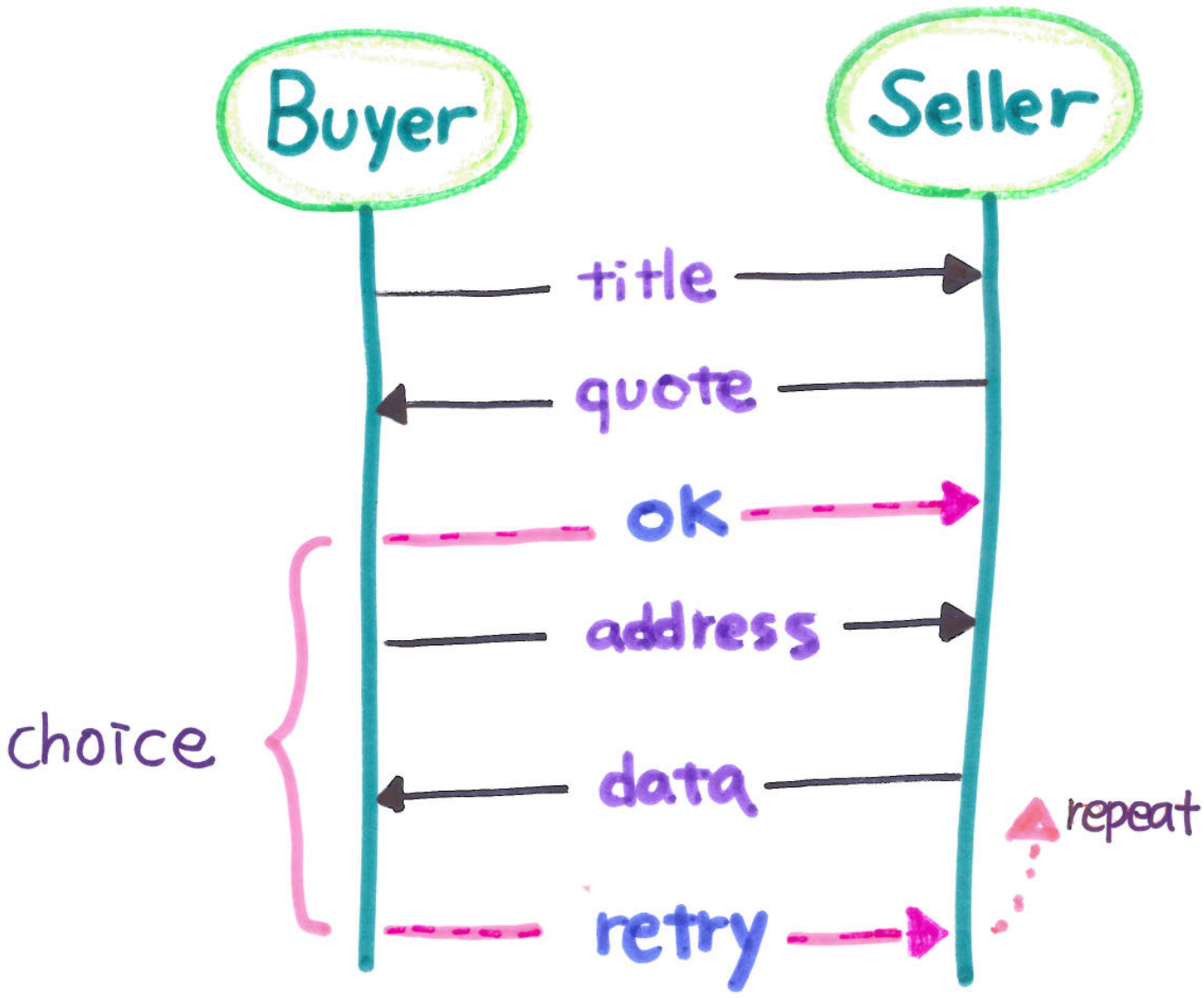


Joined W3C Standardization — 2002

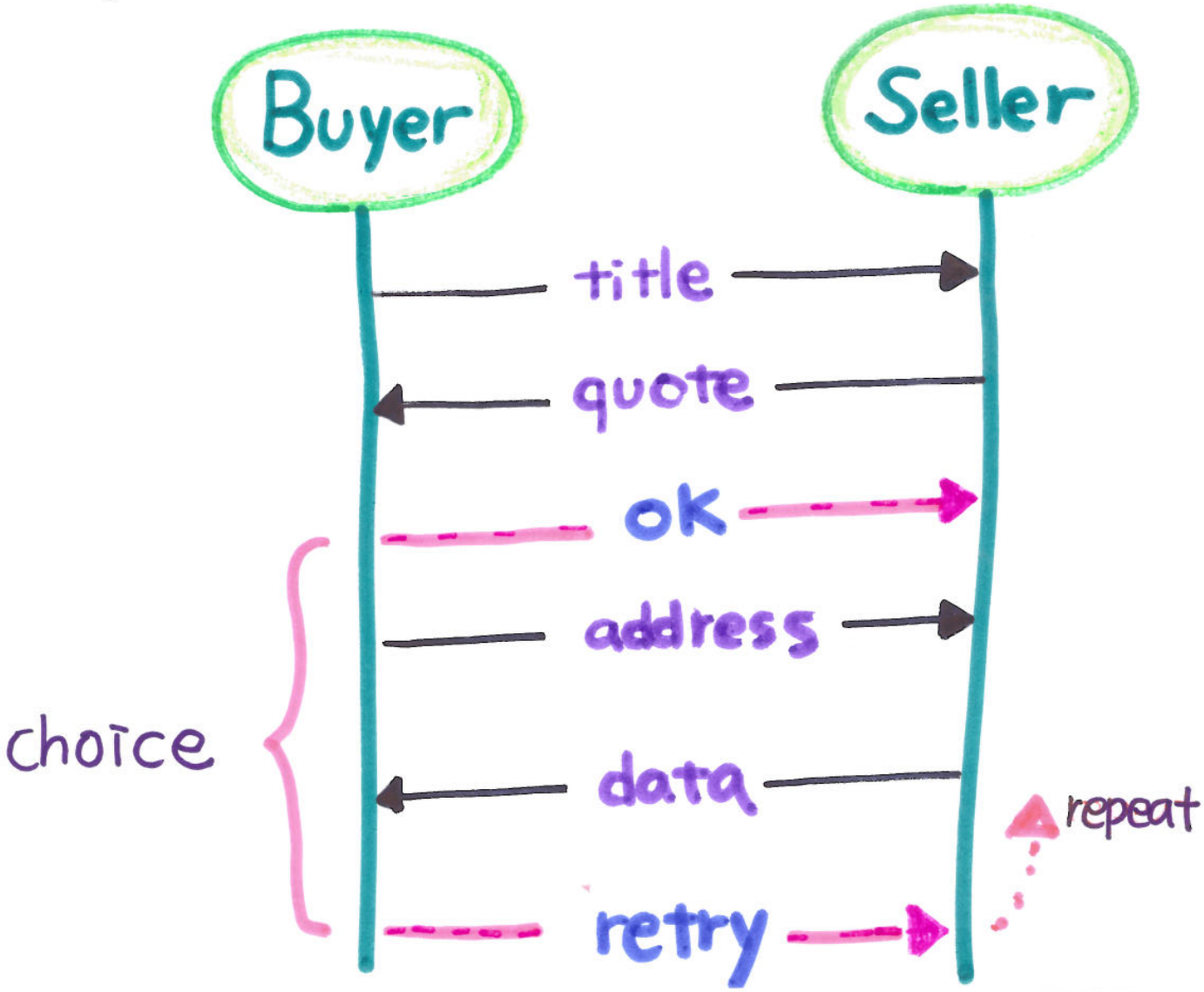
POPL Influential Paper Award 2018

Multiparty Session Types — POPL' 08

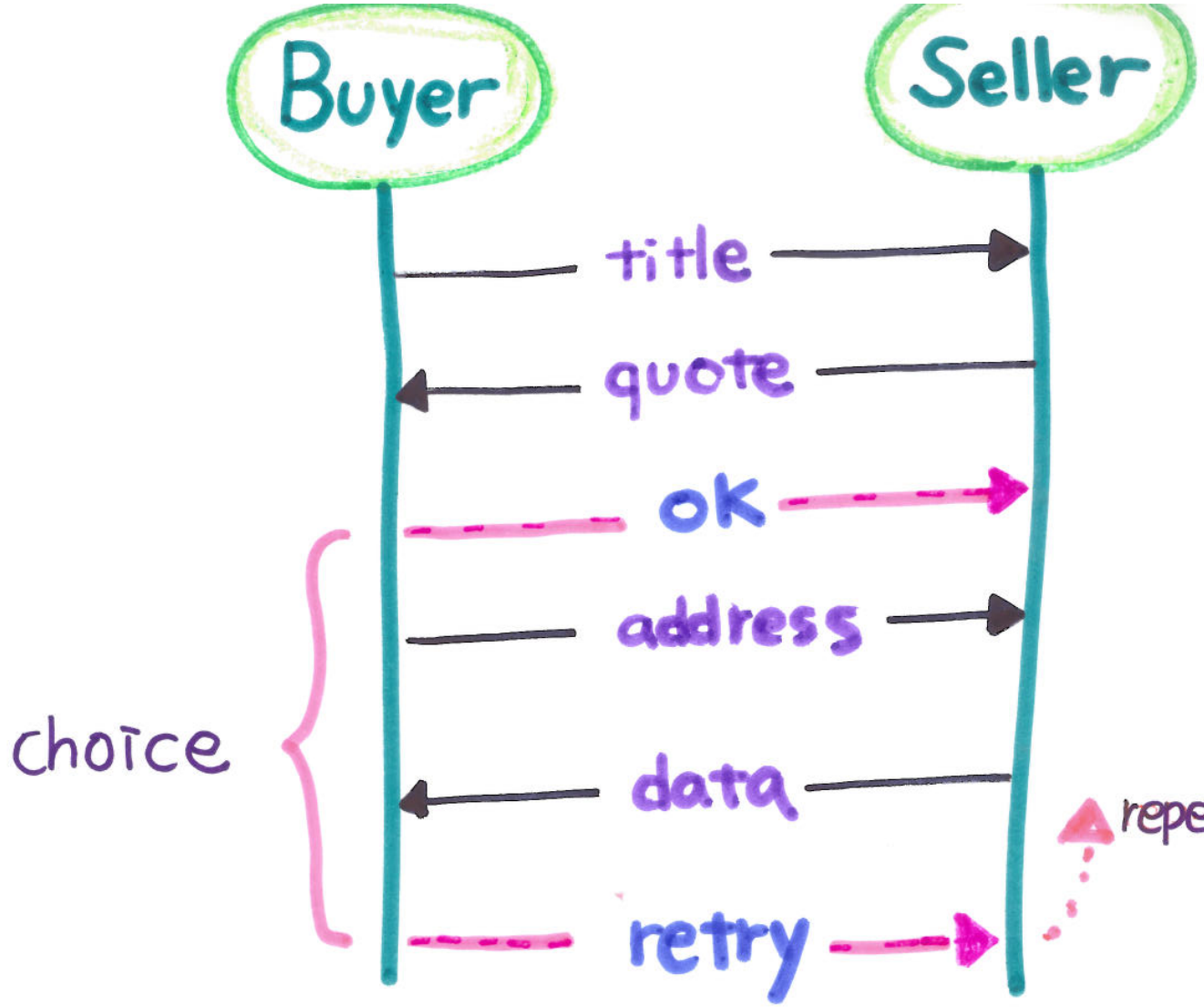
Binary Session Types: Buyer - Seller Protocol



Binary Session Types: Buyer - Seller Protocol



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



P has T

Q has $\overline{T}$

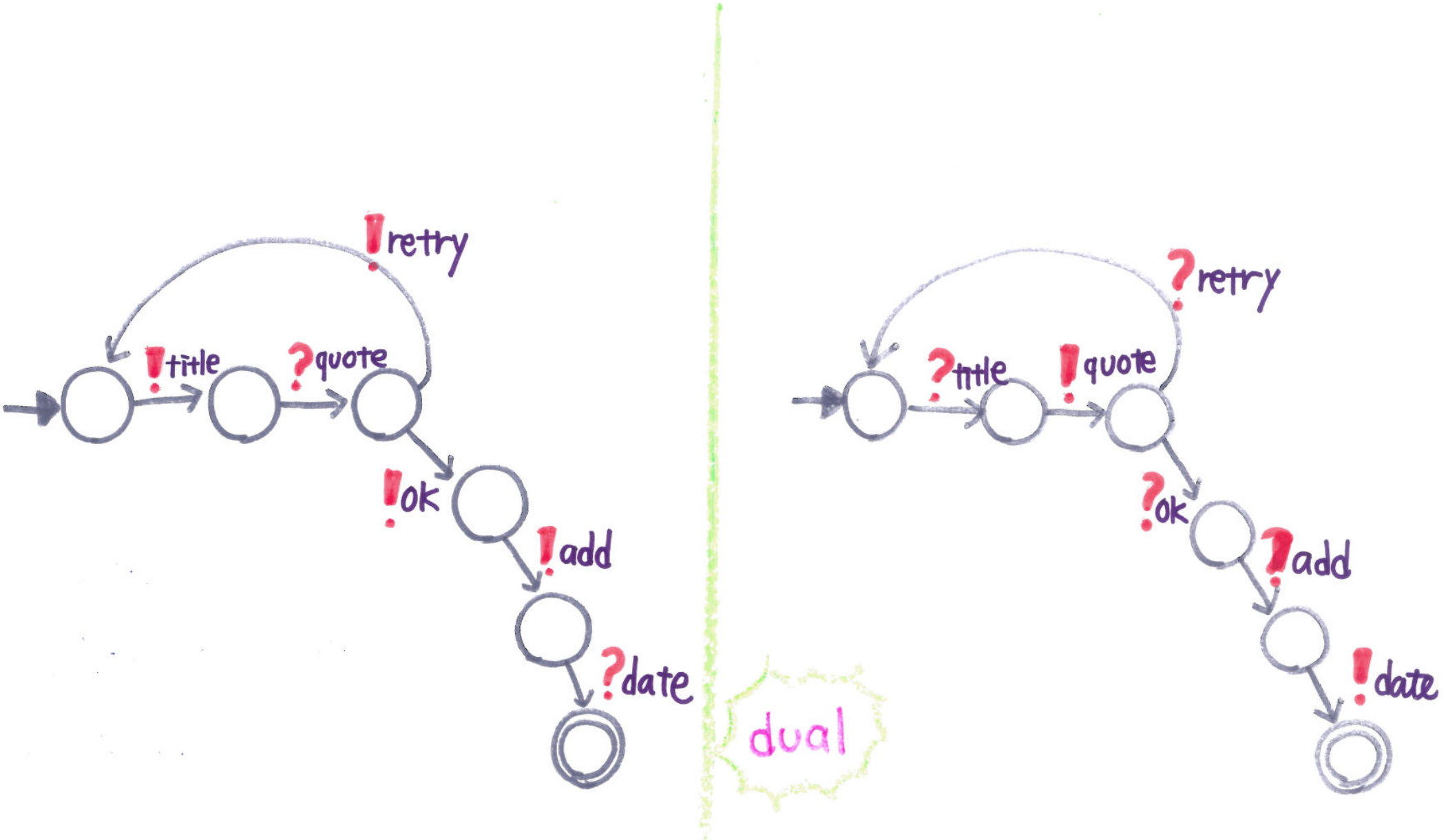
dual

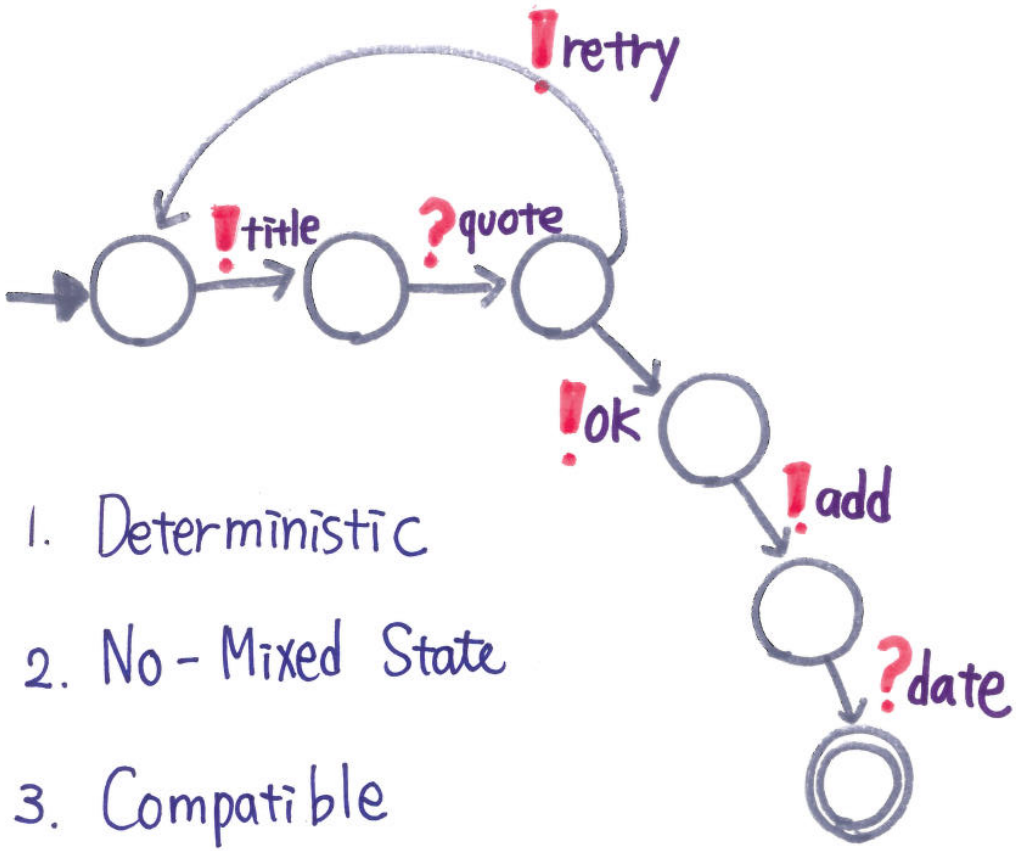
P | Q typable

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

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

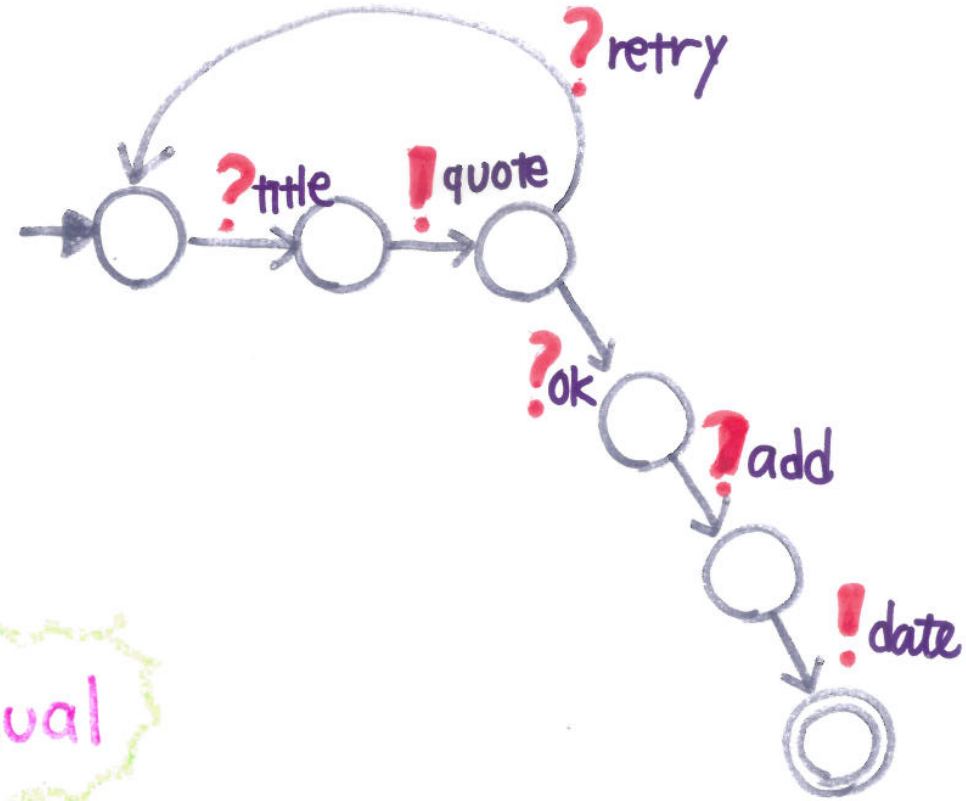
Communicating Automata [1980s]





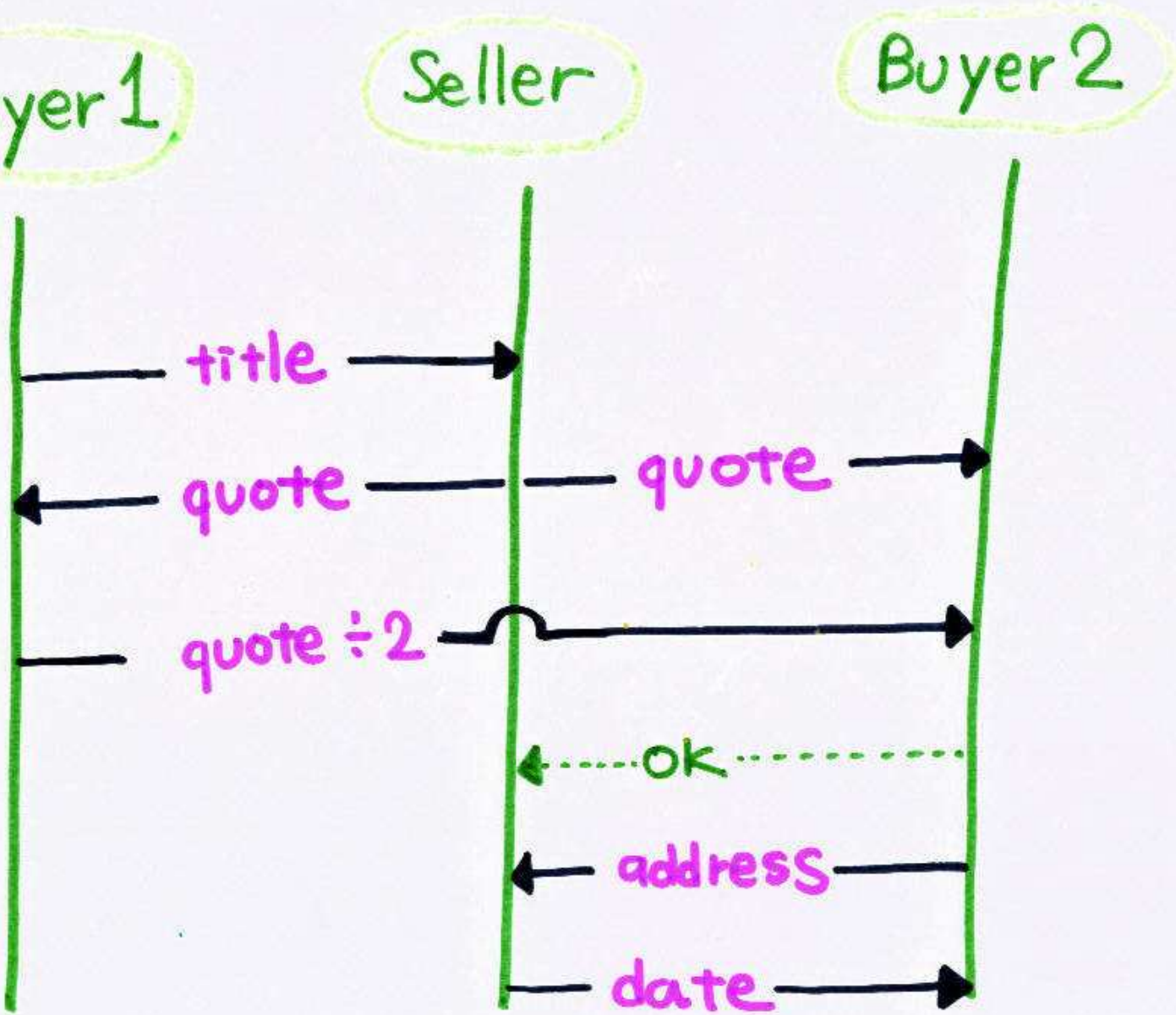
1. Deterministic
2. No-Mixed State
3. Compatible

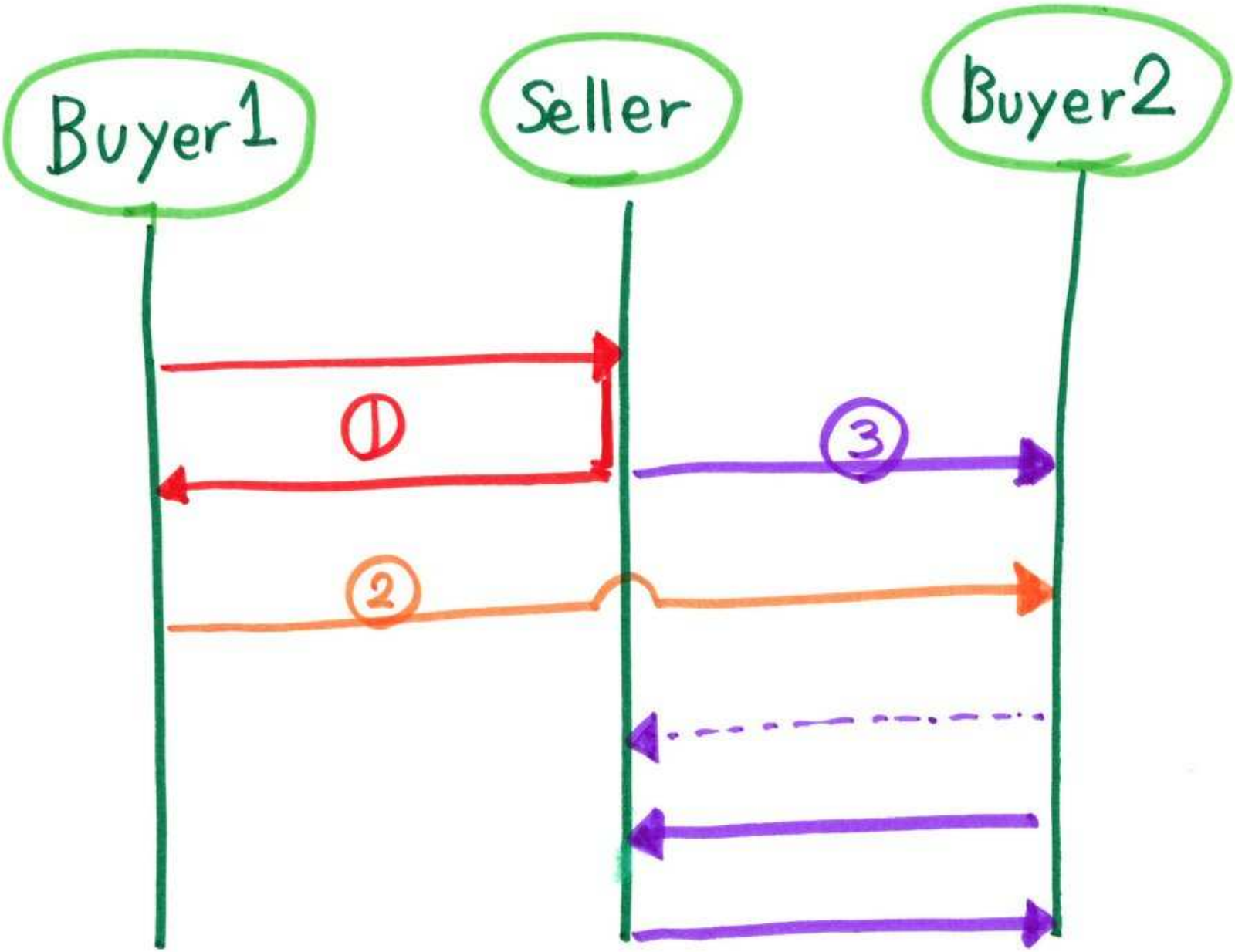
dual

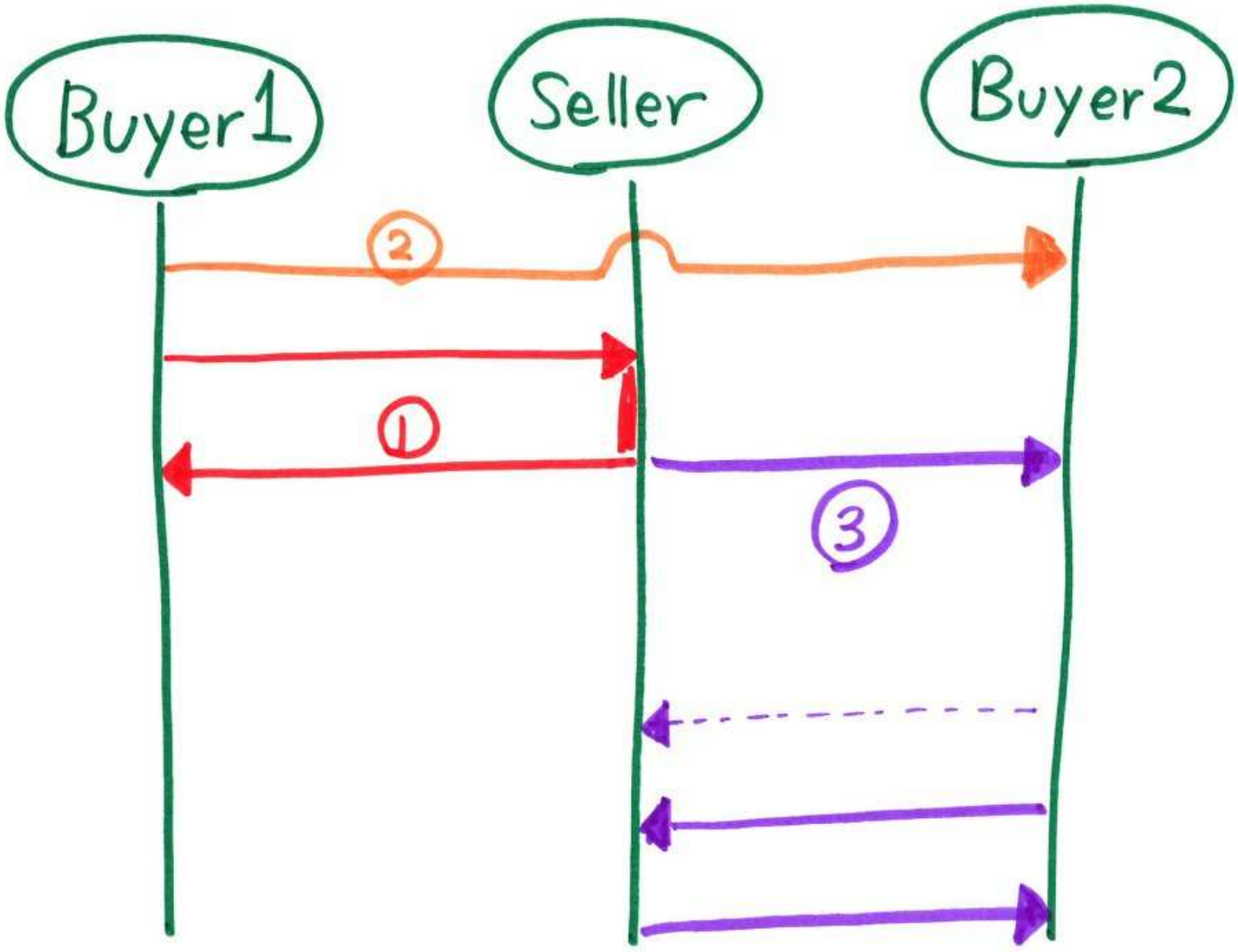


[Gouda et al 1986] Two compatible machines without mixed states which are deterministic satisfy deadlock-freedom.

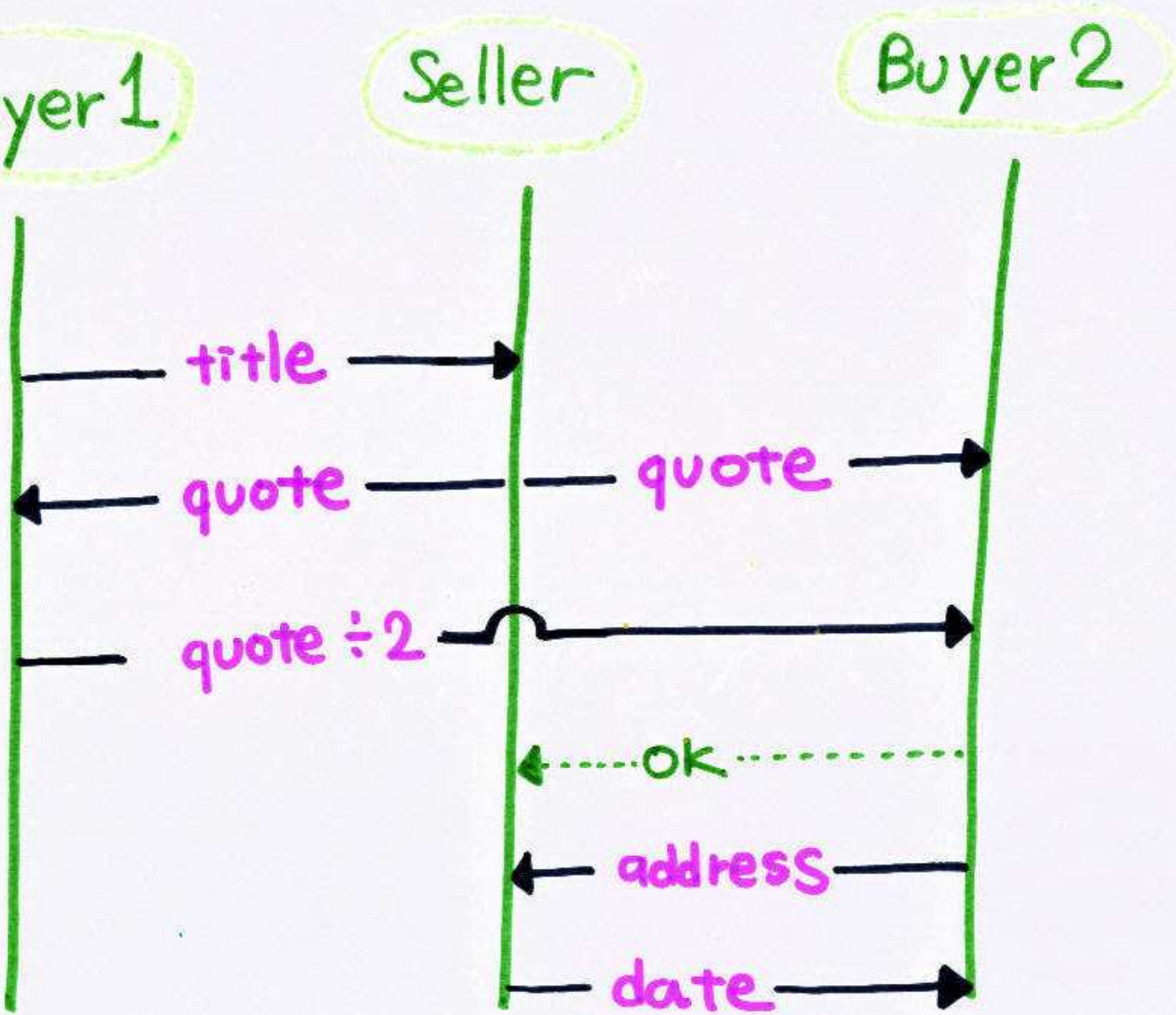
Multiparty Session Types

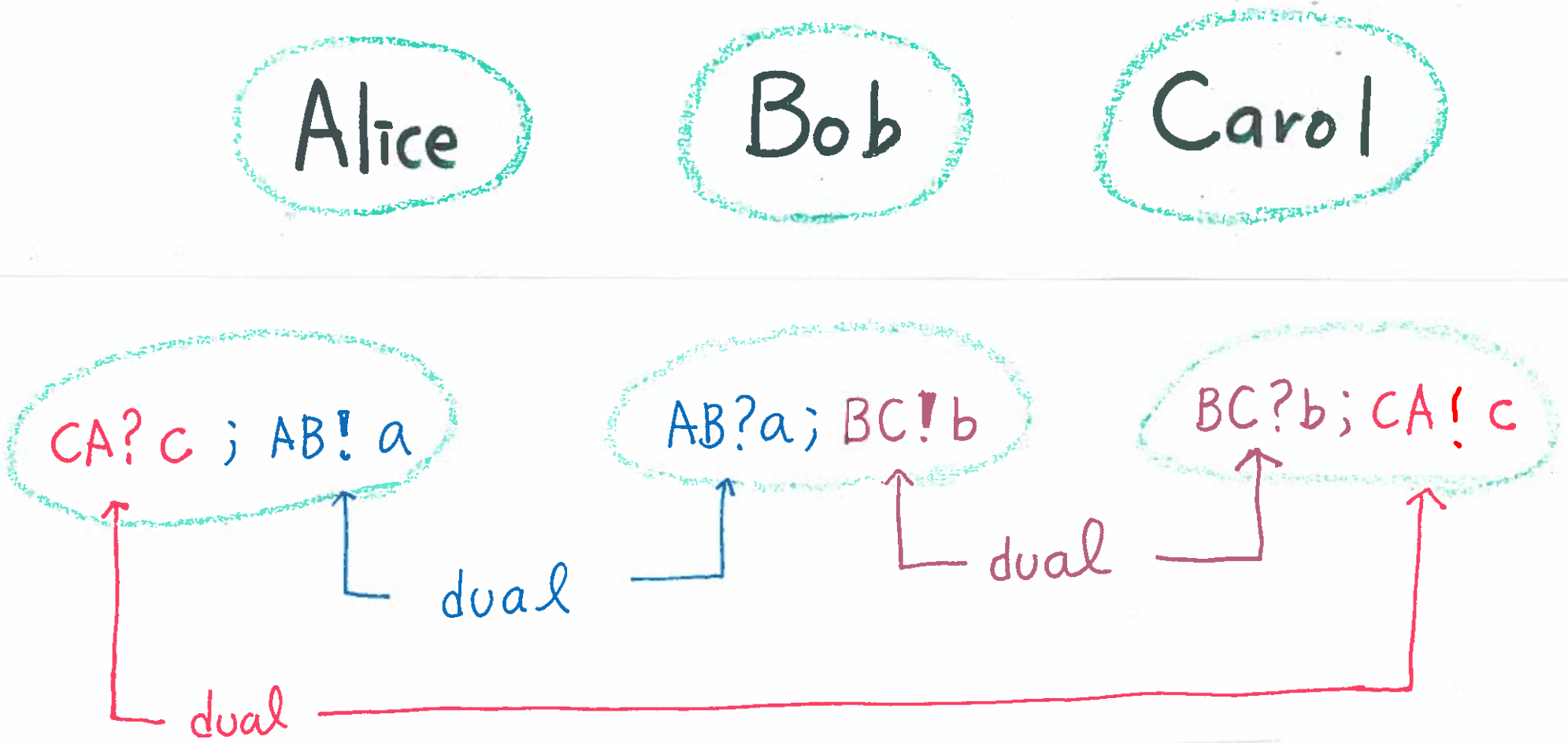



Buyer1
Seller
Buyer2
1
3
2


Buyer1
Seller
Buyer2
2
1
3

Multiparty Session Types



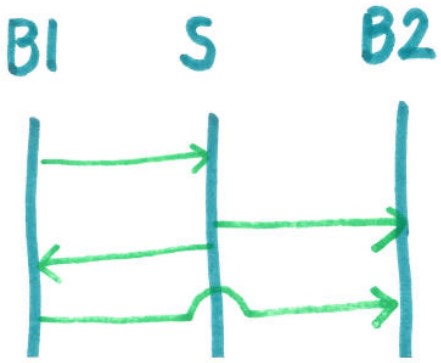


3 dual pairs

If you use binary Session Types ....

Deadlock!

Multiparty Session Types [Honda, Yoshida, Carbone 2008]



G

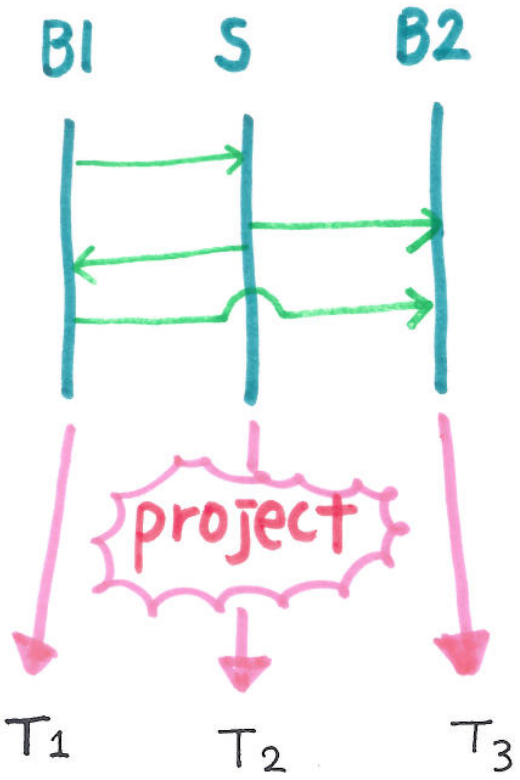
B1 → S Int.

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

$B_1?$ Int. $B_2!$ Char

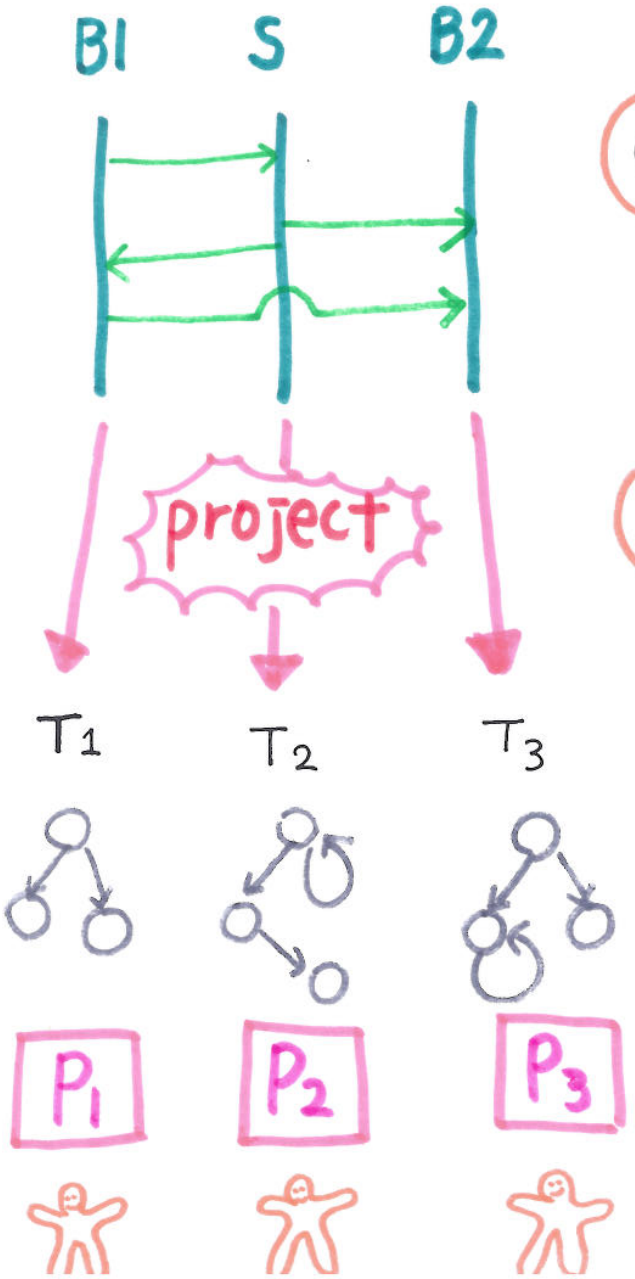
STEP 1

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

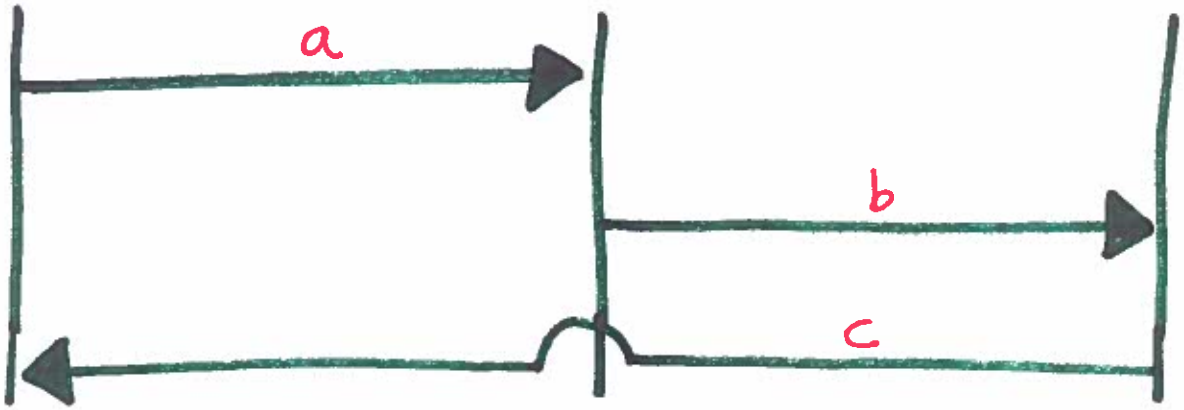
P $B_1?(x).\, B_2!\langle\text{"apple"}\rangle$

STEP 1
Write Global Type

STEP 2
Project to Local Type

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

Alice Bob Carol



Global Type

Projection

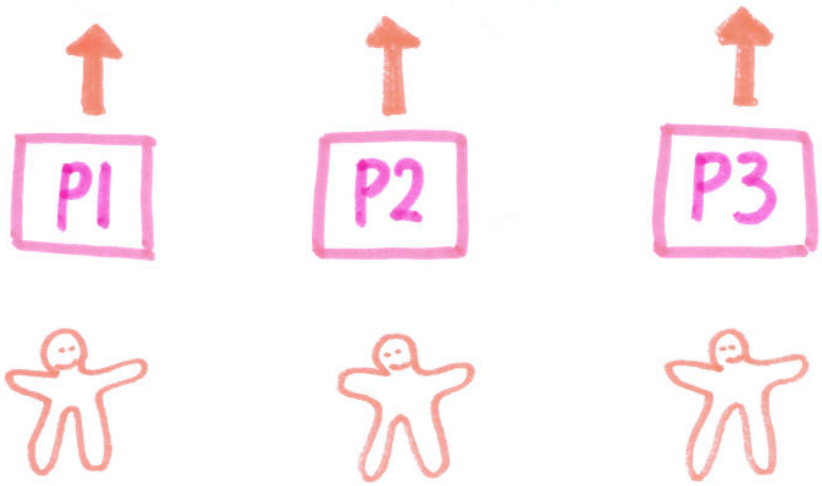
Alice AB!a;CA?c

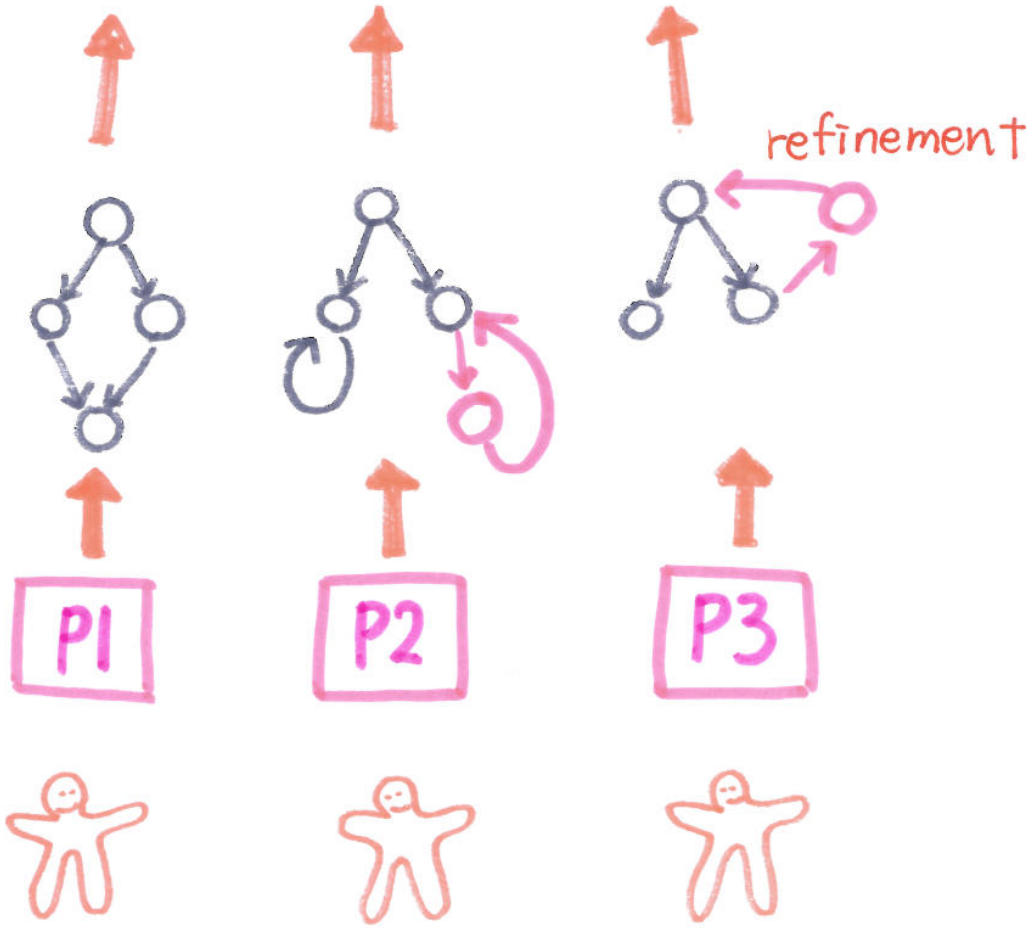
Bob AB?a;BC!b

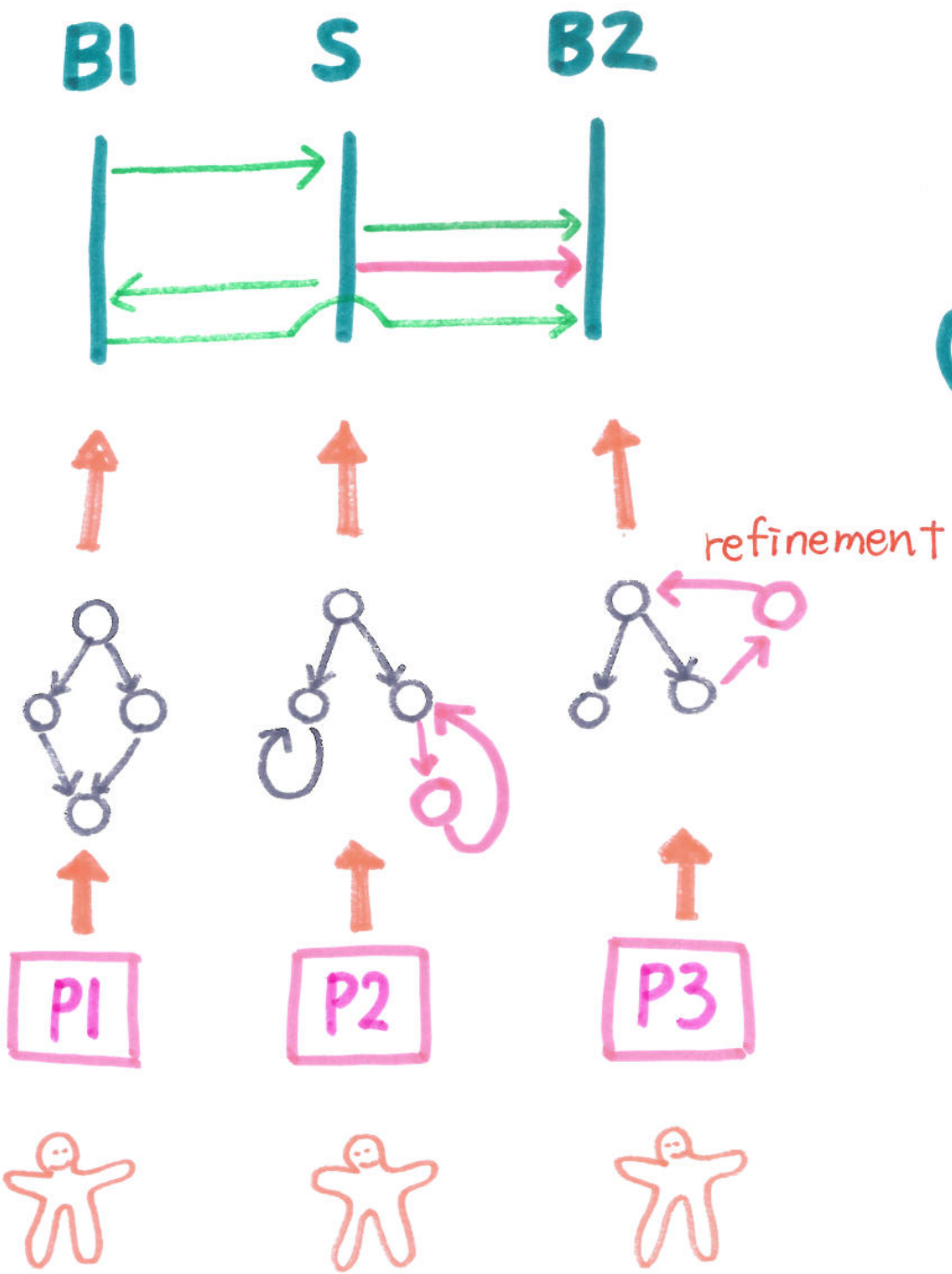
Carol BC?b;CA!c;

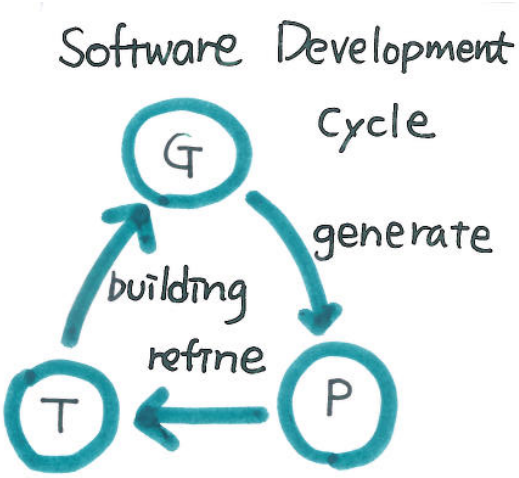
LOCAL TYPES

NO Deadlock


P1
P2
P3


refinement
P1
P2
P3





- Optimisation
- refinement
- Inference
- Testing

Global Types

$$G ::= p \to p' : \{ a_j . G_j \}_{j \in J}$$

$$\mid \quad \mu t . G$$

$$\mid \quad t$$

$$\mid \quad \text{end}$$

Local Types

$$T ::= p ! \{ a_j . T_j \}_{j \in J}$$

$$\mid \; p ? \{ a_j . T_j \}_{j \in J}$$

$$\mid \; \mu t . T$$

$$\mid \; t$$

$$\mid \; \text{end}$$

$p, p', \ldots$ Participant

a, b, c Σ Alphabet

Projection from G onto q $\quad G \upharpoonright q$

$$\left(p \to p' : \{a_j . G_j\}_{j \in J}\right) \upharpoonright q$$

$$= \begin{cases} p' ! \{a_j . G_j \upharpoonright q\}_{j \in J} & q = p \\ p ? \{a_j . G_j \upharpoonright q\}_{j \in J} & q = p' \\ G_1 \upharpoonright q = G_j \upharpoonright q & \forall j \in J \quad \text{otherwise} \end{cases}$$

Projection from G onto q $\quad G\upharpoonright q$

$$(p \to p' : \{a_j . G_j\}_{j \in J})\upharpoonright q$$

$$= \begin{cases} p'!\{a_j . G_j\upharpoonright q\}_{j \in J} & q = p \\ p?\{a_j . G_j\upharpoonright q\}_{j \in J} & q = p' \\ G_1\upharpoonright q = G_j\upharpoonright q & \forall j \in J \quad \text{otherwise} \end{cases}$$

Bad $\quad A \to B : \{a . C \to D : c \;,\; b . C \to D : d\}$

Good $\quad A \to B : \{a . C \to D : c \;,\; b . C \to D : c\}$

LTS Local Types $\ell ::= pq!a \mid pq?a$

$$q!\{a_i.T_i\}_{i\in I} \xrightarrow{pq!a_i} T_i \qquad q?\{a_i.T_i\}_{i\in I} \xrightarrow{qp?a_i} T_i$$

$$\frac{T[\mu t.T/t] \xrightarrow{\ell} T'}{\mu t.T \xrightarrow{\ell} T'}$$

$(\vec{T};\vec{w})$ w_{pq} queue

Send $T_p \xrightarrow{pq!\ell} T_p' \Rightarrow$

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

Receive $T_q \xrightarrow{pq?\ell} T_q' \Rightarrow$

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

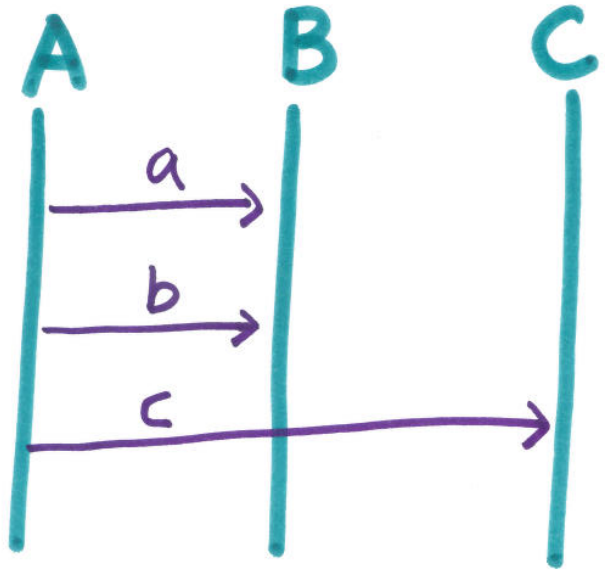
LTS Global Types

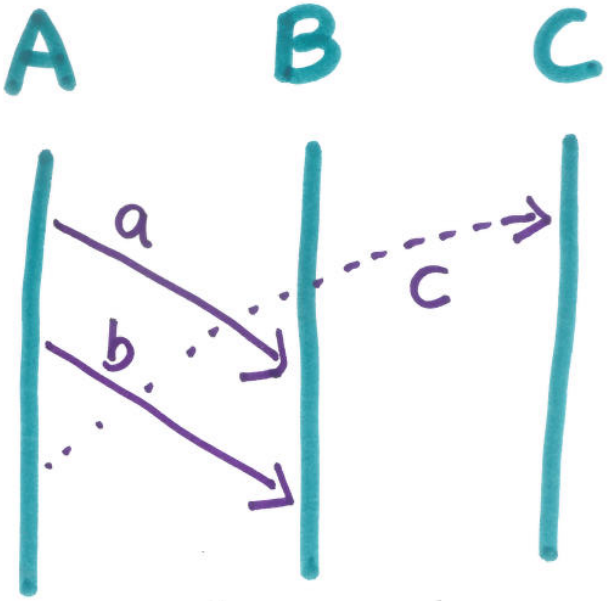
$p \rightsquigarrow p' : \tilde{\jmath}\, \{a_i . G_i\}_{i \in I}$

put $\quad p \to p' : \{a_i . G_i\}_{i \in I} \xrightarrow{pp'!a_j} p \rightsquigarrow p' : \tilde{\jmath}\, \{a_i . G_i\}_{i \in I}$

get $\quad p \rightsquigarrow p' : \tilde{\jmath}\, \{a_i . G_i\}_{i \in I} \xrightarrow{pp'?a_j} G_j$

$$\frac{\forall j \in I \quad G_j \xrightarrow{\ell} G_j' \qquad p, q \notin \mathrm{sub}(\ell)}{p \to p' : \{a_i . G_i\}_{i \in I} \xrightarrow{\ell} p \to p' : \{a_i . G_i'\}_{i \in I}} \qquad \frac{G_j \xrightarrow{\ell} G_j' \qquad q \notin \mathrm{sub}(\ell) \qquad \forall i \in I \setminus j \;\; G_i' = G_i}{p \rightsquigarrow q : \tilde{\jmath}\, \{a_i . G_i\}_{i \in I} \xrightarrow{\ell} p \rightsquigarrow q : \tilde{\jmath}\, \{a_i . G_i'\}_{i \in I}}$$





$A \to B:a \,.\, A \to B:b \,.\, A \to C:c$

↓ AB!a OUT

$A \rightsquigarrow B:a \,.\, A \to B:b \,.\, A \to C:c$

↓ AB?a IN

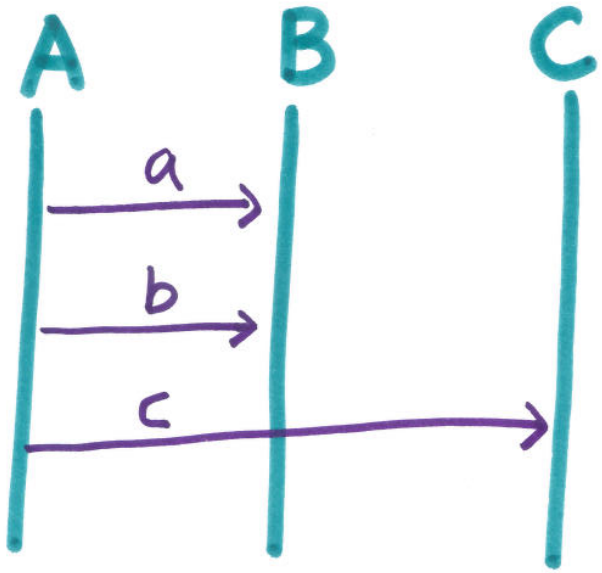
$A \to B:b \;\; A \to C:c$

↓ AB!b OUT

$A \rightsquigarrow B:b \;\; A \to C:c$

↓ AB?b IN

$A \to C:c$



$A \to B:a.\ A \to B:b,\ A \to C:c$

↓ AB!a OUT

$A \rightsquigarrow B:a.\ A \to B:b.\ A \to C:c$

↓ AB?a IN

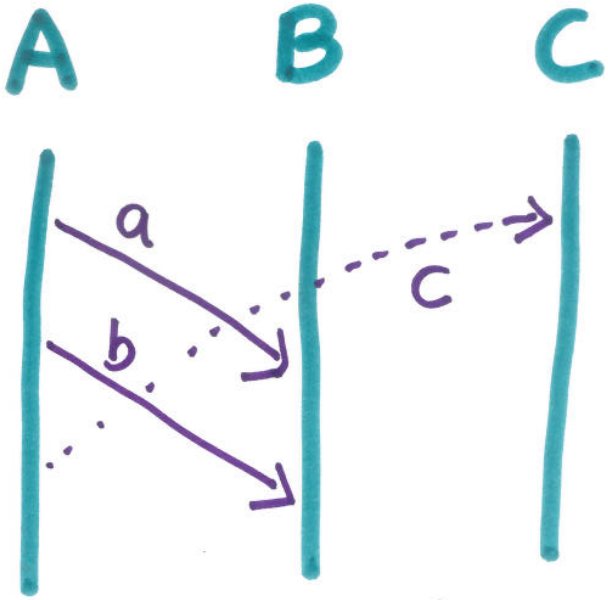
$A \to B:b\ \ A \to C:c$

↓ AB!b OUT

$A \rightsquigarrow B:b\ \ A \to C:c$

↓ AB?b IN

$A \to C:c$



$A \to B:a.\ A \to B:b.\ A \to C:c$

↓ AB!a OUT

↓ AB!b OUT

↓ AC!c OUT

$A \rightsquigarrow B:a.\ A \rightsquigarrow B:b.\ A \rightsquigarrow C:c$

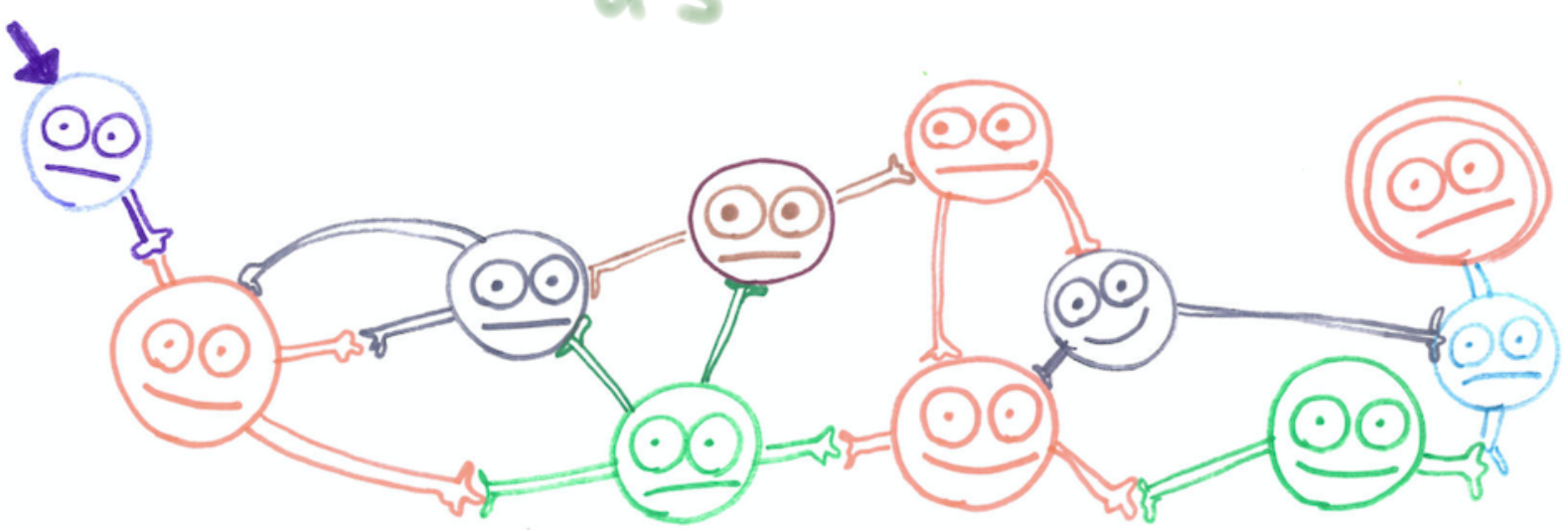
↓ AC?c IN

$A \rightsquigarrow B:a.\ A \rightsquigarrow B:b$

↓ AB?a IN

$A \rightsquigarrow B:b$

Multiparty Session Types as



?? Communicating Automata ??

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

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

states queues

q_p w_{pq}

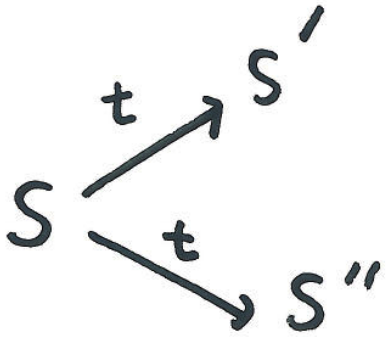
Send

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

Receive

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

Deteministic CFSM

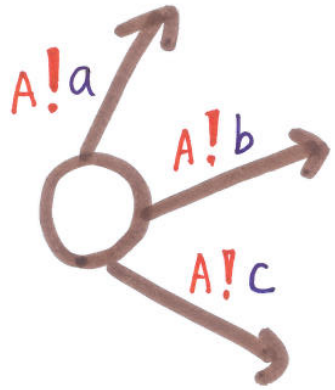


$\Rightarrow \quad S' = S''$

Basic CFSMs

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

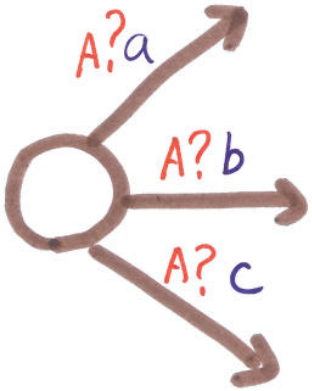
directed, has **no mixed states**



sending

✓

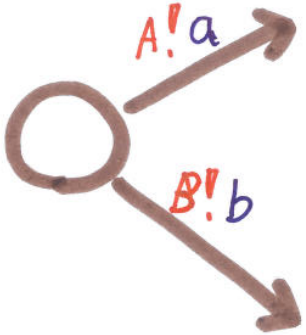
$T = A!\{a, b, c\}$



receiving

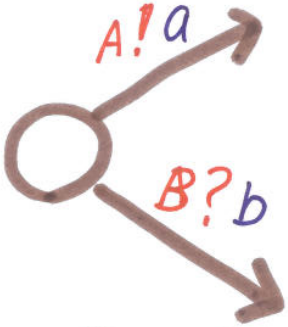
✓

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



non directed

✗



mixed

✗

Theorem 1 $Tr(G) \approx Tr(\{G\lceil p\}_{p \in Participant})$

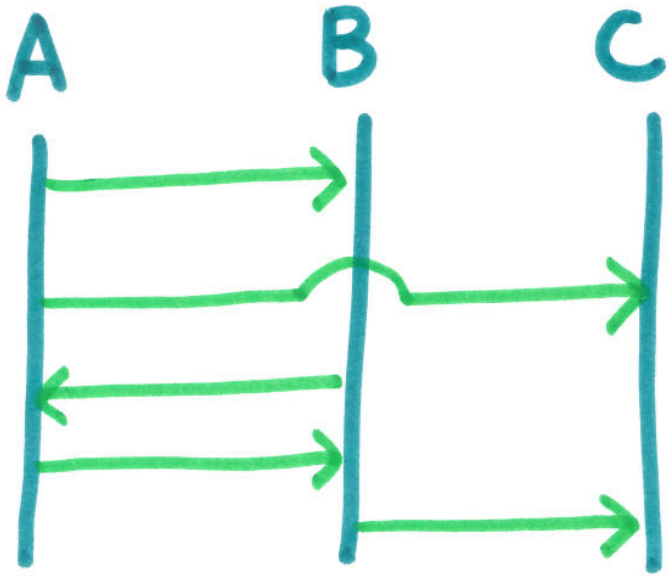
Soundness and Completeness between a global type and projected local types

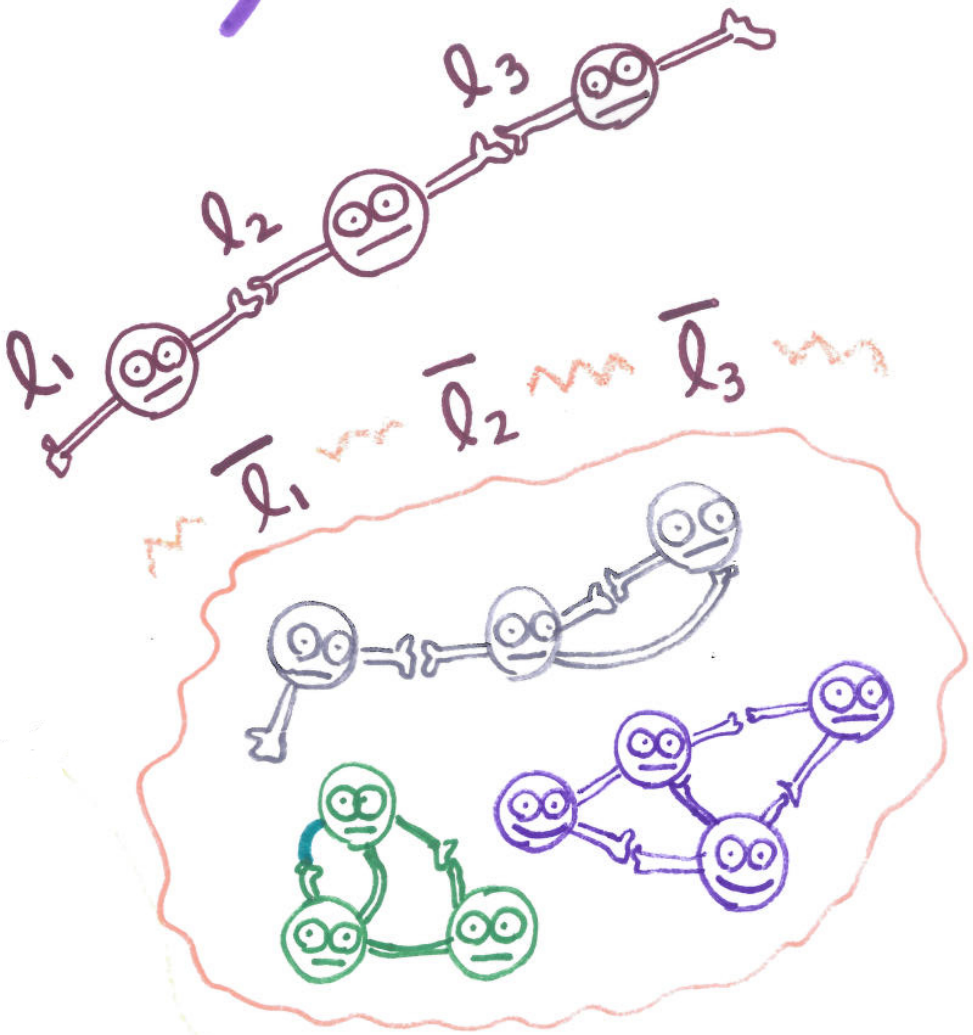
Theorem 2 $Tr(T) \approx Tr(A(T))$ T basic

Soundness and Completeness between a local type and a basic CFSM of T

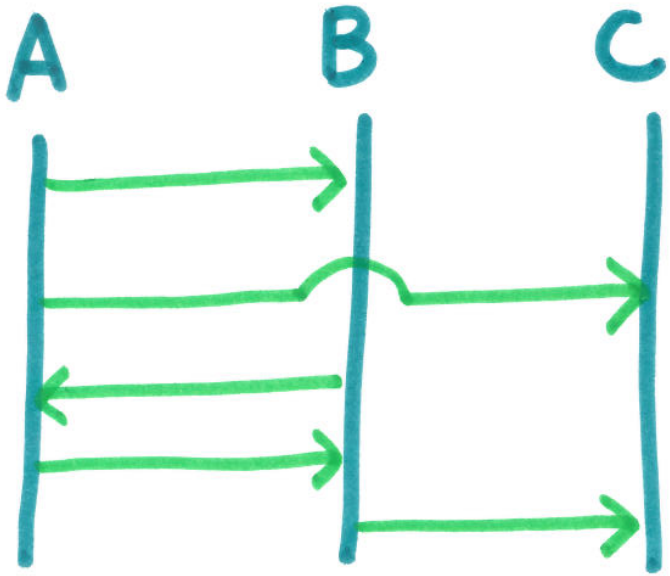
T

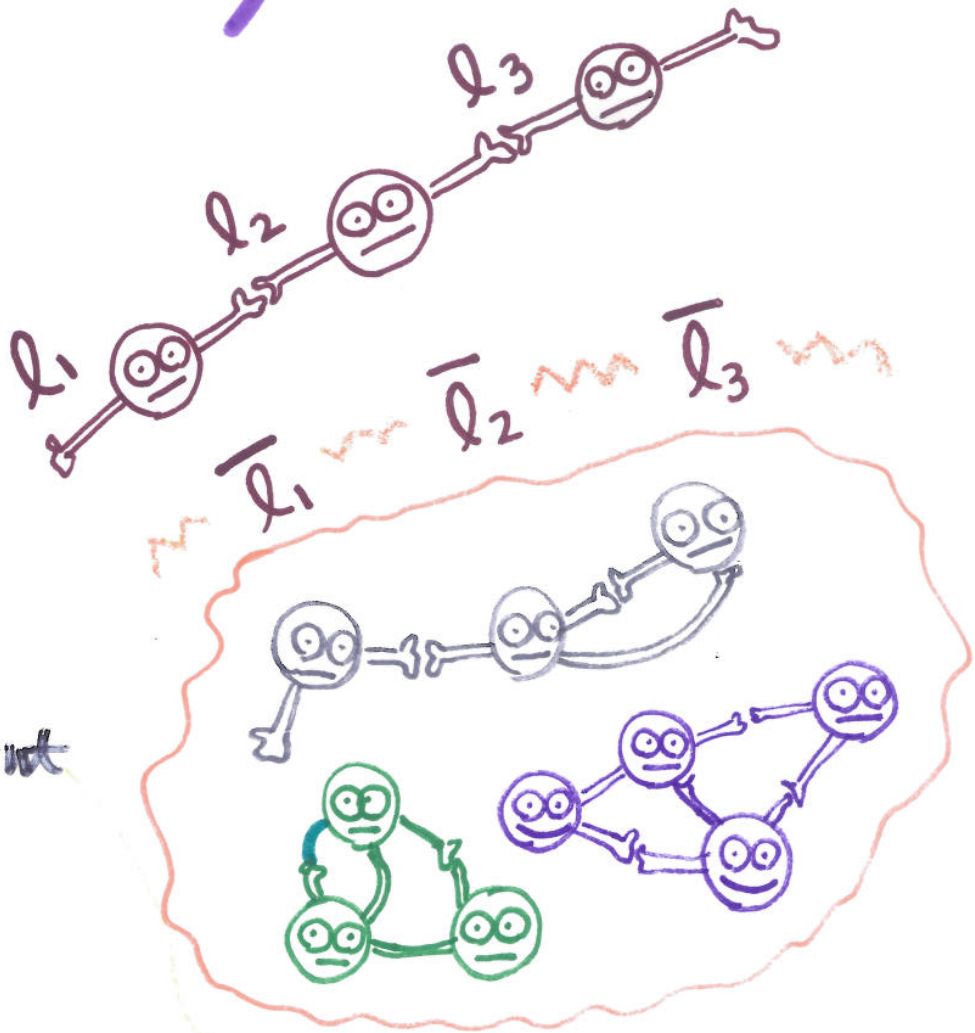
Multiparty Compatibility





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 $\rightsquigarrow$

Theorem (Safety) Suppose S is basic and multiparty compatible. Then S is free from the following errors. Let $S = (\vec{q}; \vec{w})$

Deadlock if $\vec{w} = \vec{\varepsilon}$ and not final, each q_p is receiving

Orphan Message all q are final, but $\vec{w} \neq \vec{\varepsilon}$

Unspecified Reception $(q_p, pq?\underline{a}, q'_p)$ implies $|w_{pq}| > 1$ and $w_{pq} \notin \underline{a} \cdot \Sigma^*$

Proposition Soundness $A(\{ G\upharpoonright p \}_{p \in \text{Participant}})$ is multiparty compatible.

projection

Proposition Multiparty Compatibility is decidable.

Mobility Reading Group

http://mrg.doc.ic.ac.uk/