Multiparty Session Types and their Applications

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

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Current: Communication is Ubiquitous

- The way to organise software is increasingly based on communications (Cloud Computing, many cores, message-passing parallel computation, ...)
- Question
  - How to formally abstract/specify/implement/control communications?
  - How to apply mobile processes and their type theories to real distributed applications and programming languages?

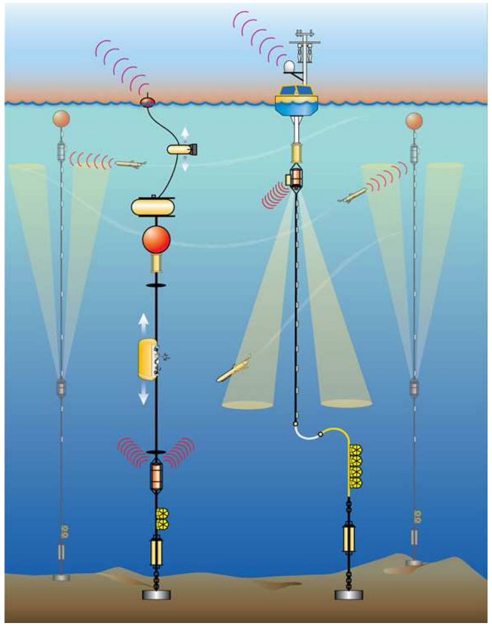
Current: Communication is Ubiquitous

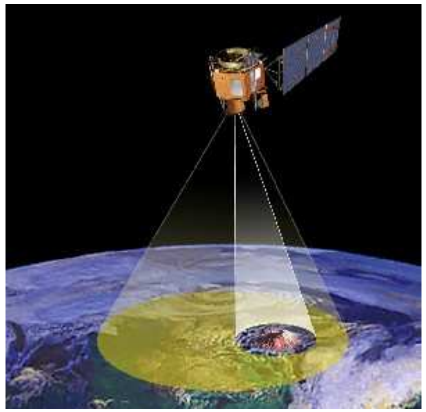
- The way to organise software is increasingly based on communications (Cloud Computing, many cores, message-passing parallel computation, ...)
- Question $\Longrightarrow$ Multiparty session type theory
  - How to formally abstract/specify/implement/control communications?
  - How to apply mobile processes and their type theories to real distributed applications and programming languages?

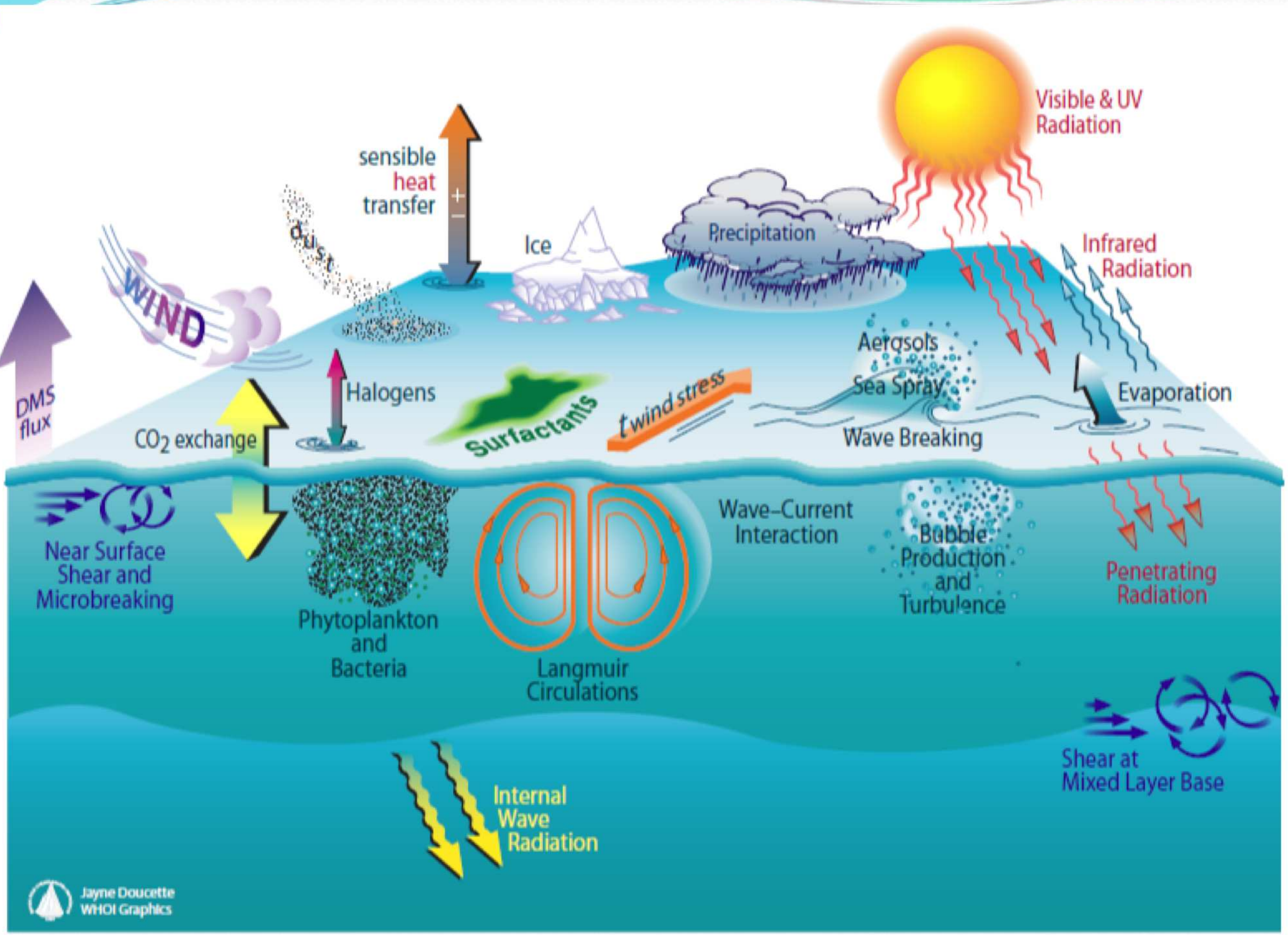
    $\Longrightarrow$ large-scale cyberinfrastructure for e-Science

Ocean Observatories Initiative

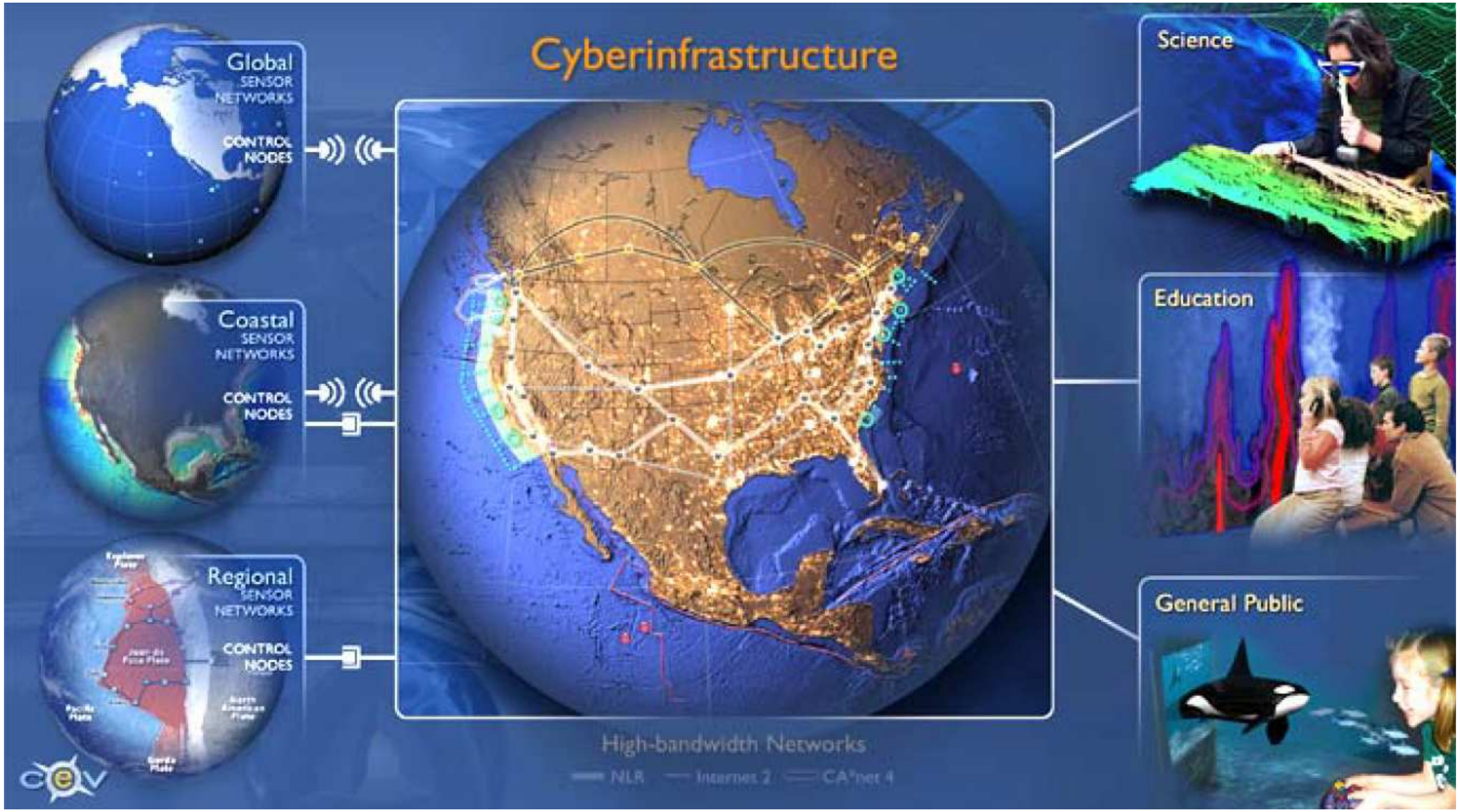
- A NSF project (400M$, 5 Years) to build a cyberinfrastructure for observing oceans around US and beyond.
- Real-time sensor data constantly coming from both off-shore and on-shore (e.g. buoys, submarines, under-water cameras, satellites), transmitted via high-speed networks.

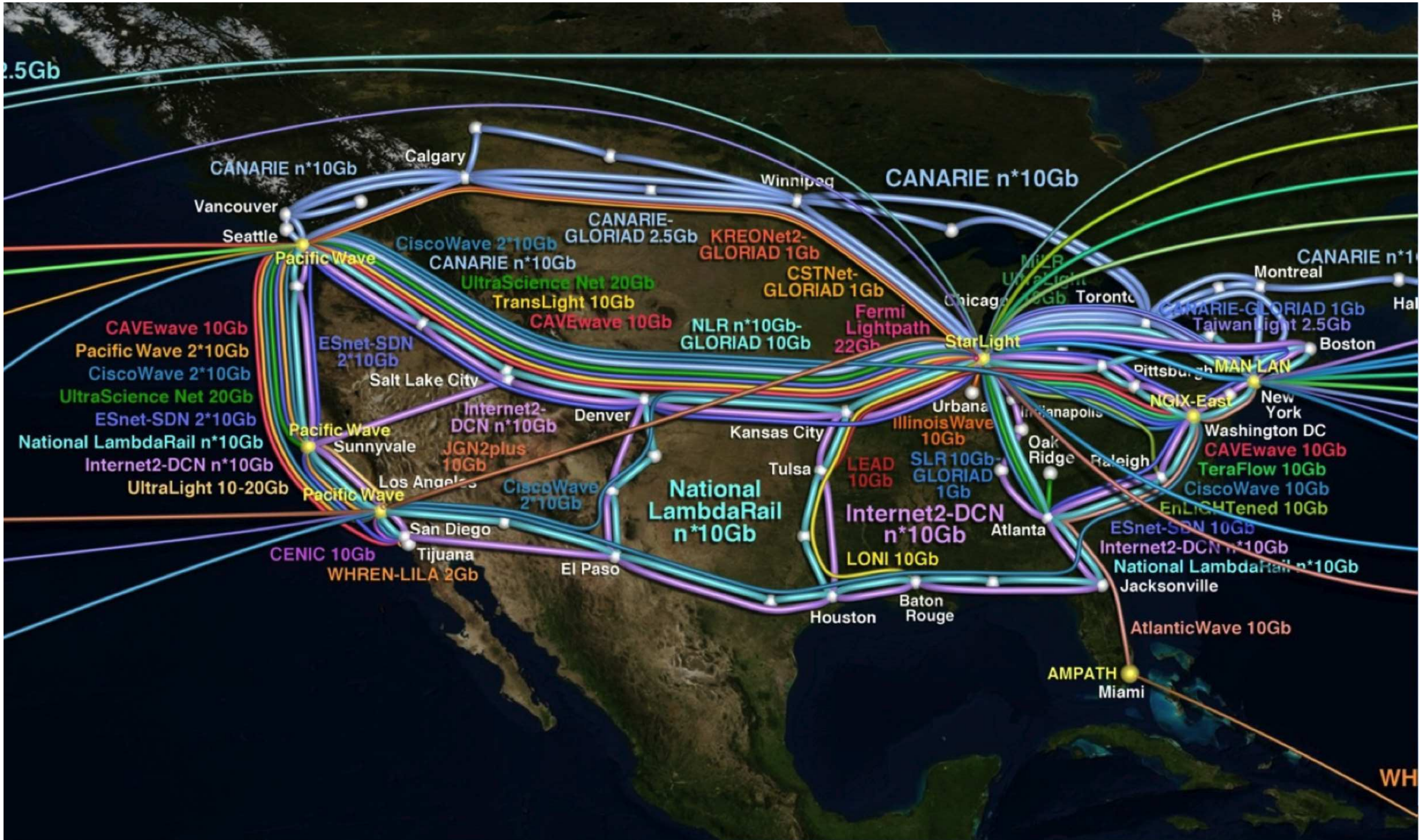





Visible & UV Radiation
sensible heat transfer
dust
Ice
Precipitation
Infrared Radiation
WIND
Aerosols
Sea Spray
Evaporation
DMS flux
Halogens
Surfactants
τ wind stress
Wave Breaking
CO_2 exchange
Near Surface Shear and Microbreaking
Wave–Current Interaction
Bubble Production and Turbulence
Penetrating Radiation
Phytoplankton and Bacteria
Langmuir Circulations
Shear at Mixed Layer Base
Internal Wave Radiation
Jayne Doucette WHOI Graphics

Ocean Observatories Initiative





Ocean Observatories Initiative

Challenges

- The need to specify, catalogue, program, implement and manage *multiparty message passing protocols*.
- Communication assurance
  - Correct message ordering and synchronisation
  - Deadlock-freedom, progress and liveness
  - Dynamic message monitoring and recovery
  - Logical constraints on message values
- Shared and used over a long-term period (e.g. 30 years in OOI).

Why Multiparty Session Types?

- Robin Milner (2002): *Types are the leaven of computer programming; they make it digestible*.

  $\Longrightarrow$ Can describe communication protocols as *types*

  $\Longrightarrow$ Can be materialised as *new communications programming languages* and *tool chains*.

- *Scalable* automatic verifications (deadlock-freedom, safety and liveness) without *state-space explosion problems* (*polynomial time complexity*).

- Extendable to *logical verifications* and flexible *dynamic monitoring*.

Dialogue between Industry and Academia

Binary Session Types [PARL'94, ESOP'98]

⇓

Milner, Honda and Yoshida joined W3C WS-CDL (2002)

⇓

Formalisation of W3C WS-CDL [ESOP'07]

⇓

Scribble at π4 Technology

CDL Equivalent

- Basic example:

```
package HelloWorld {
    roleType YouRole, WorldRole;
    participantType You{YouRole}, World{WorldRole};
    relationshipType YouWorldRel between YouRole and WorldRole;
    channelType WorldChannelType with roleType WorldRole;

    choreography Main {
        WorldChannelType worldChannel;

        interaction operation=hello from=YouRole to=WorldRole
                relationship=YouWorldRel channel=worldChannel {
            request messageType=Hello;
        }
    }
}
```

Dr Gary Brown (Pi4 Tech) in 2007

Scribble Protocol

- *"Scribbling is necessary for architects, either physical or computing, since all great ideas of architectural construction come from that unconscious moment, when you do not realise what it is, when there is no concrete shape, only a whisper which is not a whisper, an image which is not an image, somehow it starts to urge you in your mind, in so small a voice but how persistent it is, at that point you start scribbling" - Kohei Honda 2007*

- Basic example:

```
protocol HelloWorld {
    role You, World;
    Hello from You to World;
}
```

Dialogue between Industry and Academia

Binary Session Types [PARL'94, ESOP'98]

$\Downarrow$

Milner, Honda and Yoshida joined W3C WS-CDL (2002)

$\Downarrow$

Formalisation of W3C WS-CDL [ESOP'07]

$\Downarrow$

Scribble at π4 Technology

$\Downarrow$

Multiparty Session Types [POPL'08]

$\Downarrow$

Scribble redhat

Dialogue between Industry and Academia

Binary Session Types [PARL'94, ESOP'98]

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Formalisation of W3C WS-CDL [ESOP'07]

$\Downarrow$

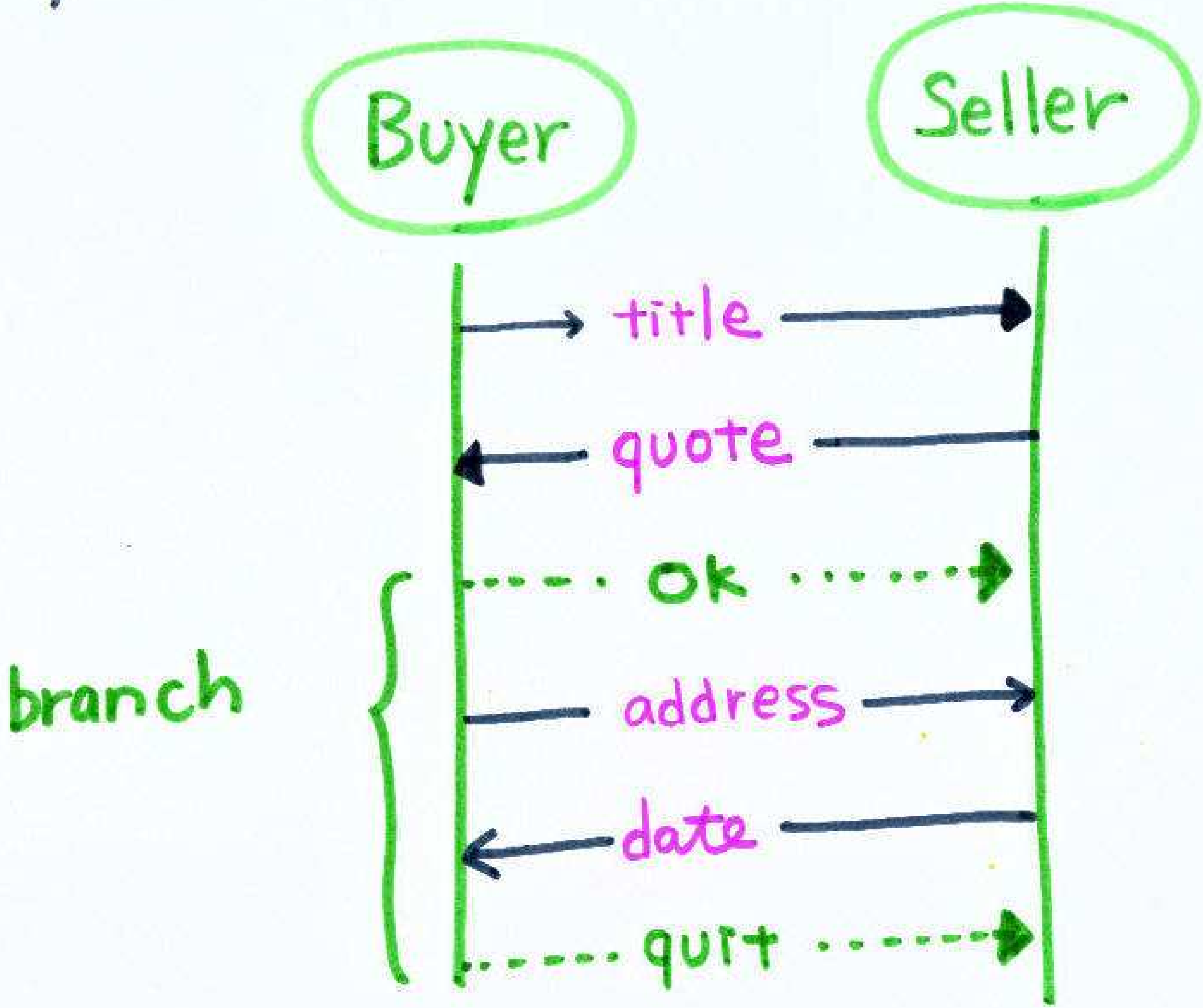
Scribble at π4 Technology

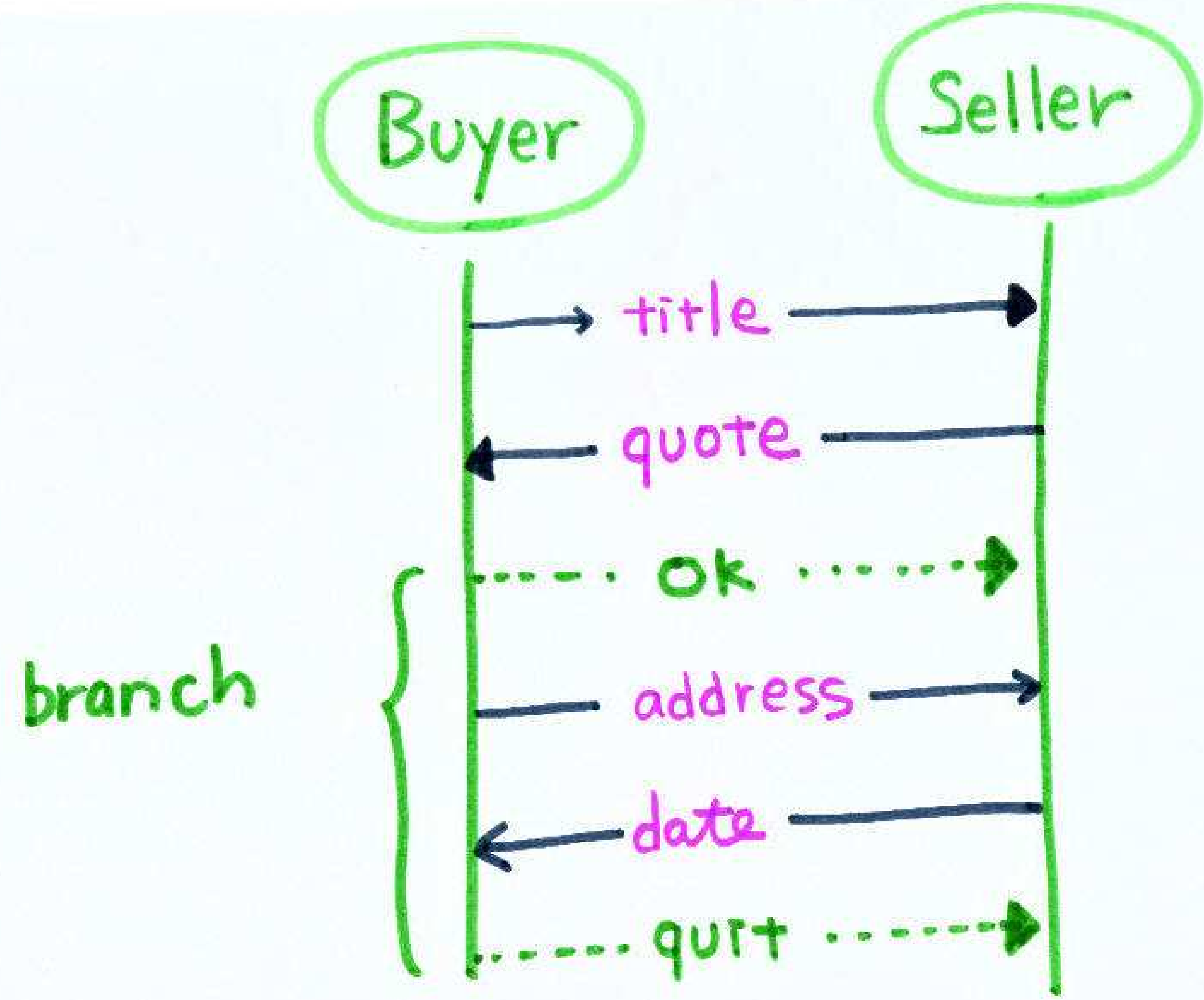
$\Downarrow$

Multiparty Session Types [POPL'08]

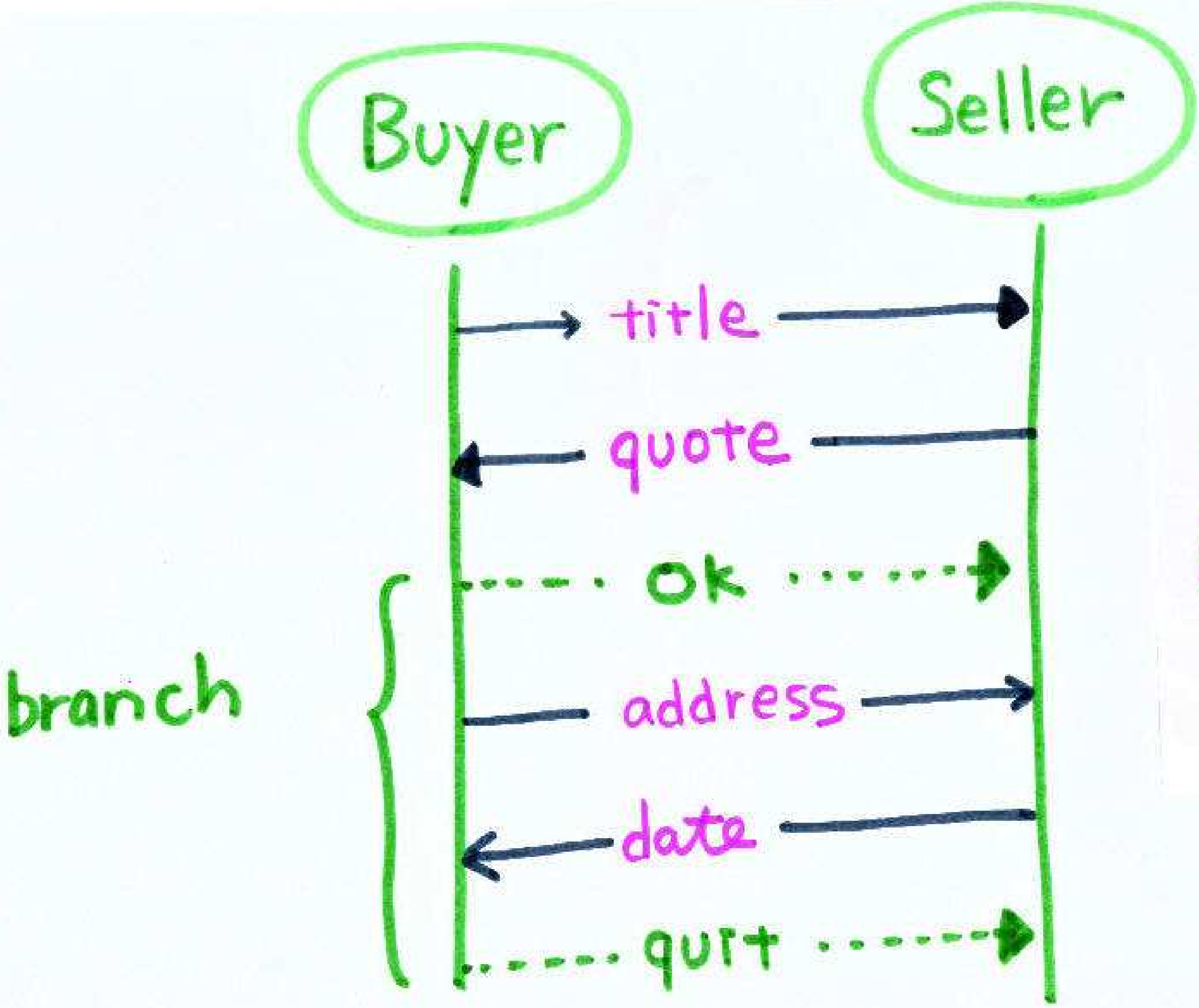
$\Downarrow$

Binary Session Types : Buyer - Seller Protocol





$$!\,String\,;\,?\,Int\,;\ \oplus\{ok : !String\,;\,?Date\,;end,\ quit : end\}$$



P has T

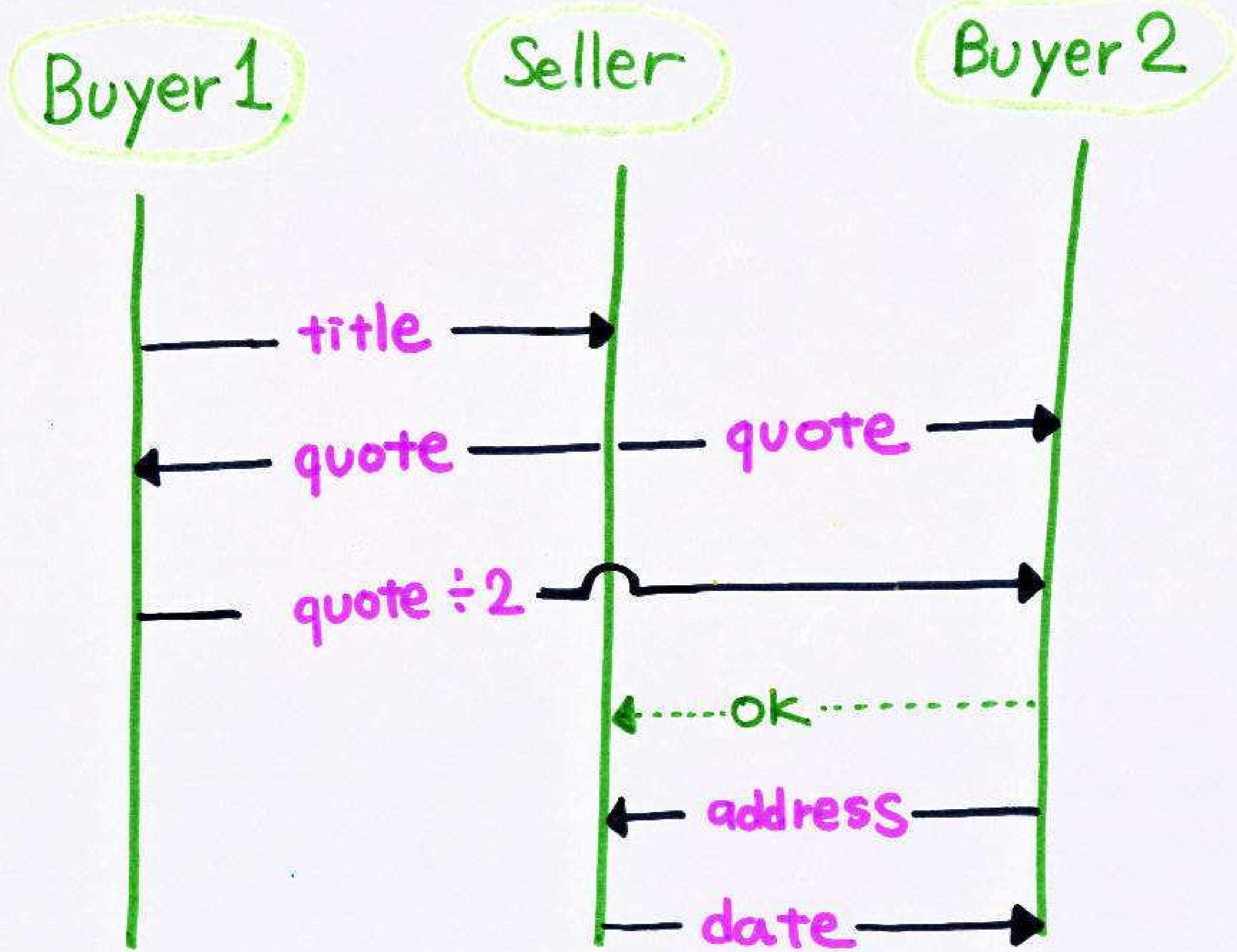
Q has $\overline{T}$ dual

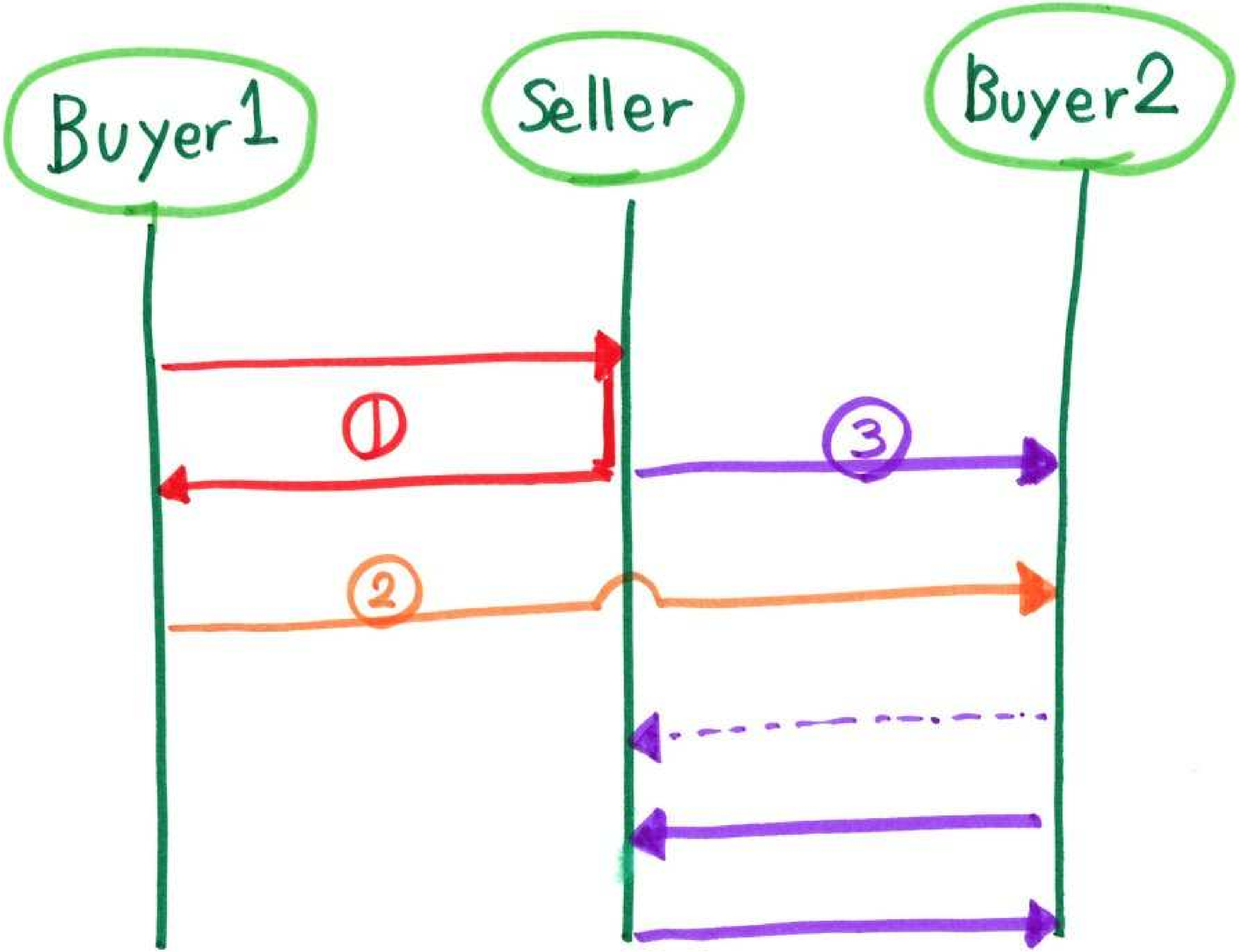
P | Q typable

$$!\,\mathrm{String}\,;\,?\,\mathrm{Int}\,;\,\oplus\{\mathrm{ok}: !\,\mathrm{String}\,;\,?\,\mathrm{Date}\,;\mathrm{end},\ \mathrm{quit}:\mathrm{end}\}$$

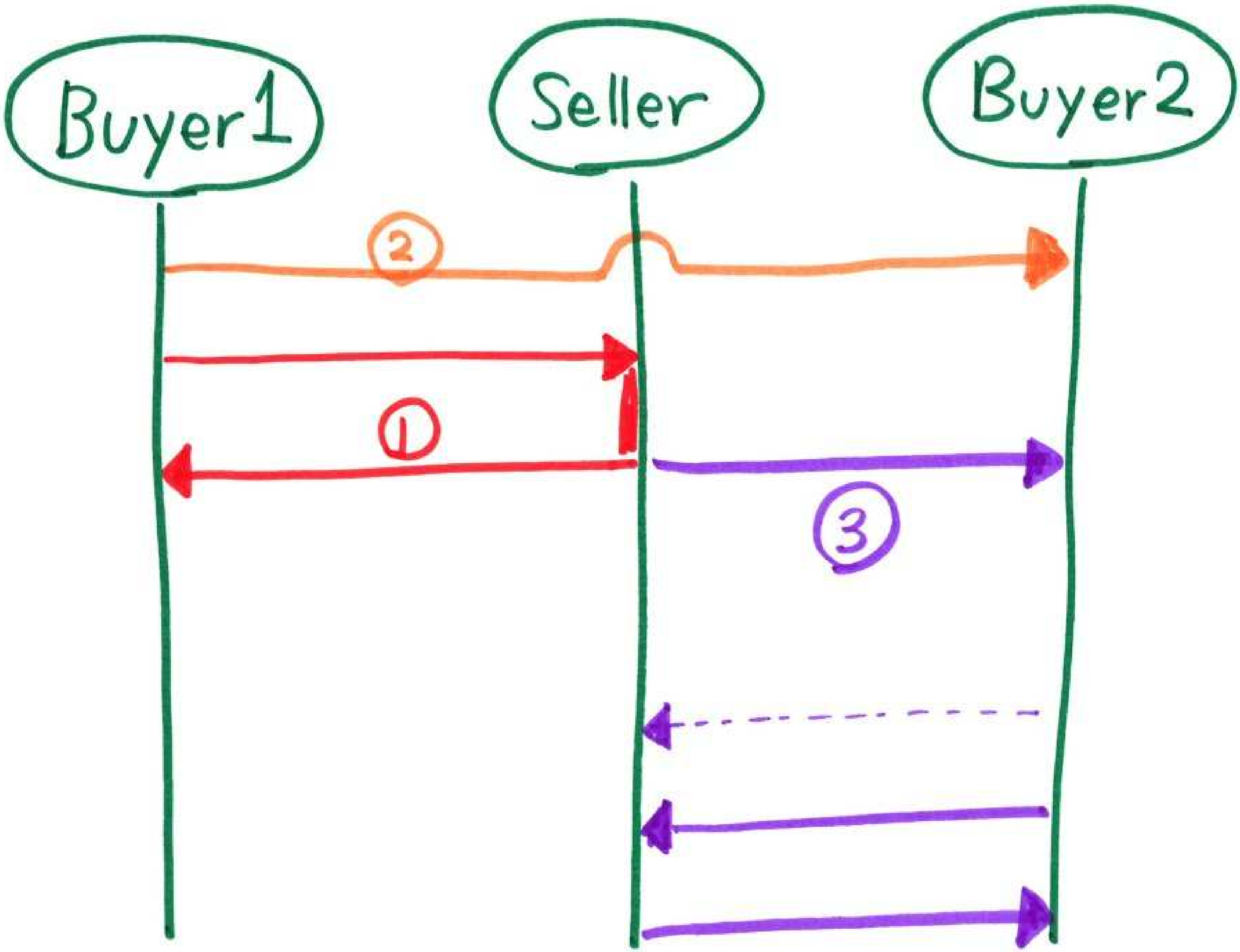
dual $$?\,\mathrm{String}\,;\,!\,\mathrm{Int}\,;\,\&\{\mathrm{ok}: ?\,\mathrm{String}\,;\,!\,\mathrm{Date}\,;\mathrm{end},\ \mathrm{quit}:\mathrm{end}\}$$

Multiparty Session Types



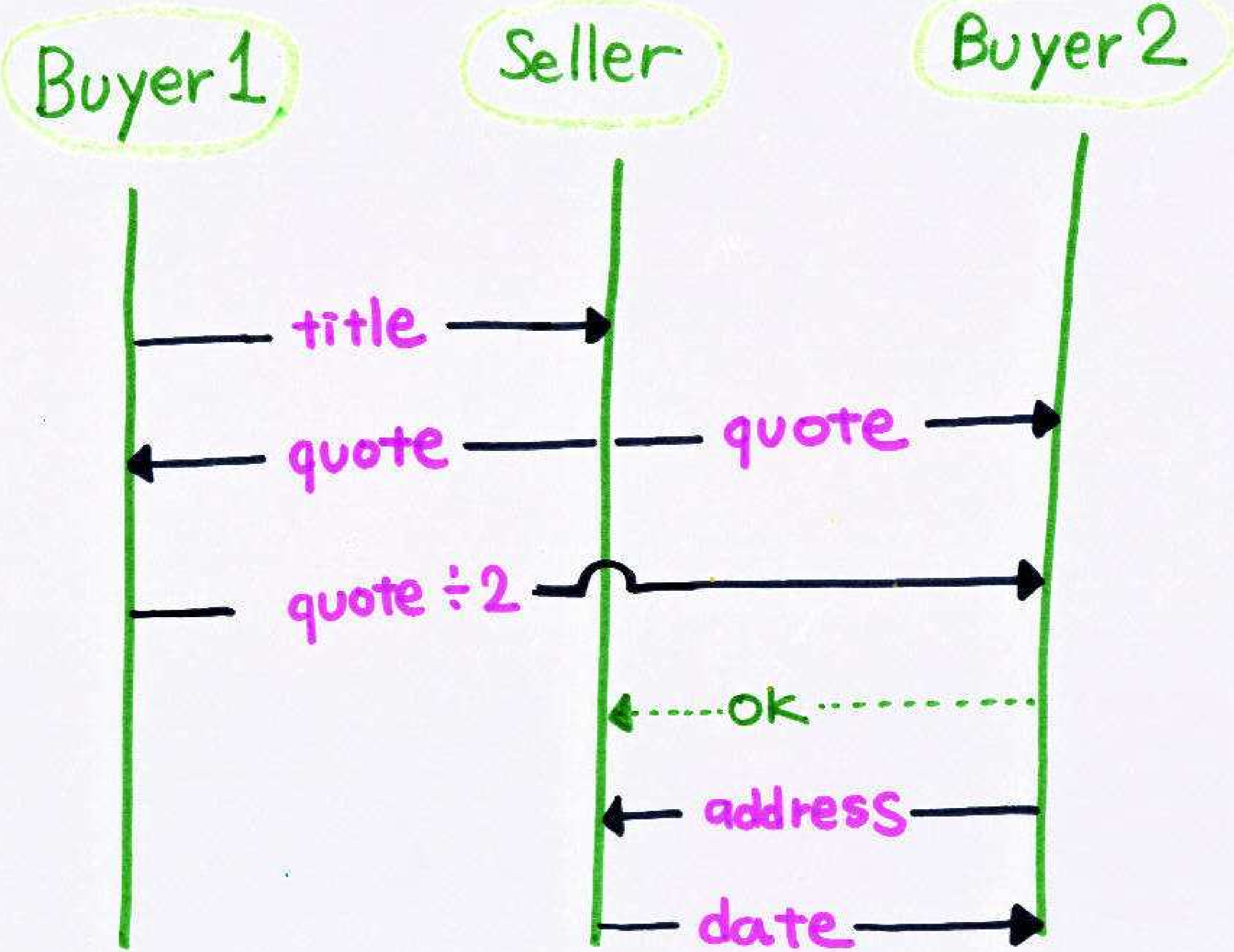


Buyer1
Seller
Buyer2
1
3
2

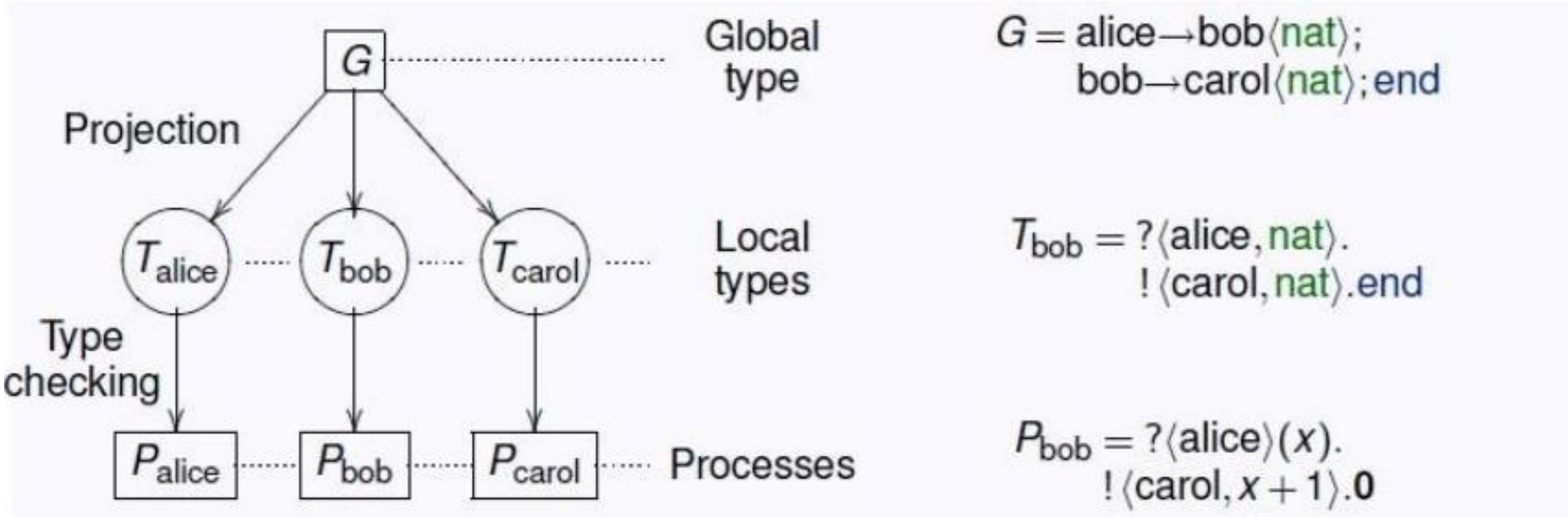


Buyer1
Seller
Buyer2
2
1
3

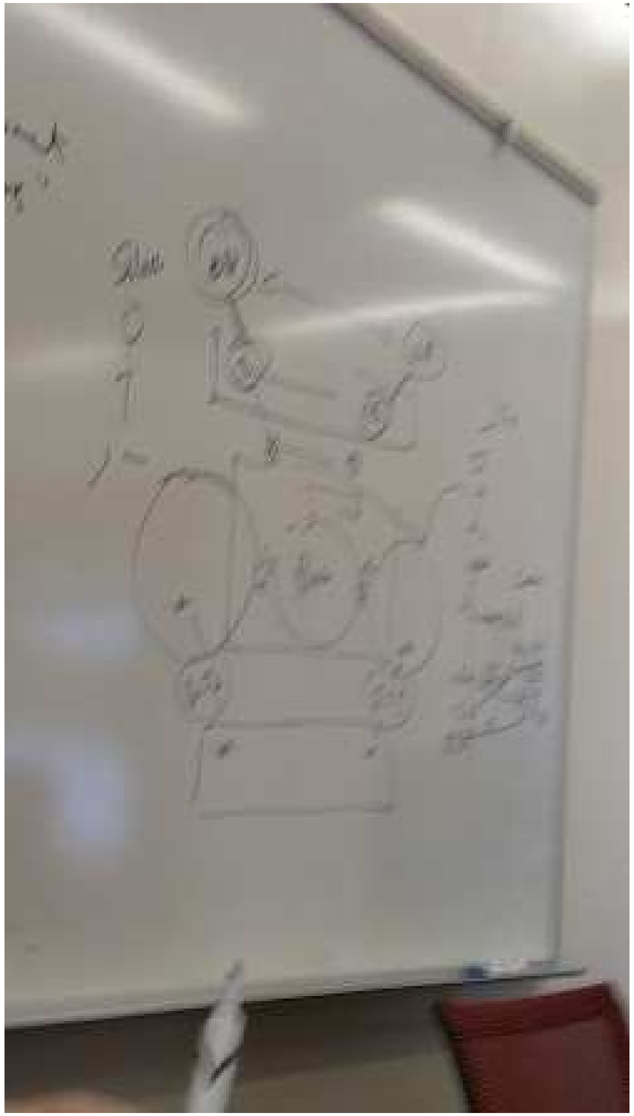
Multiparty Session Types



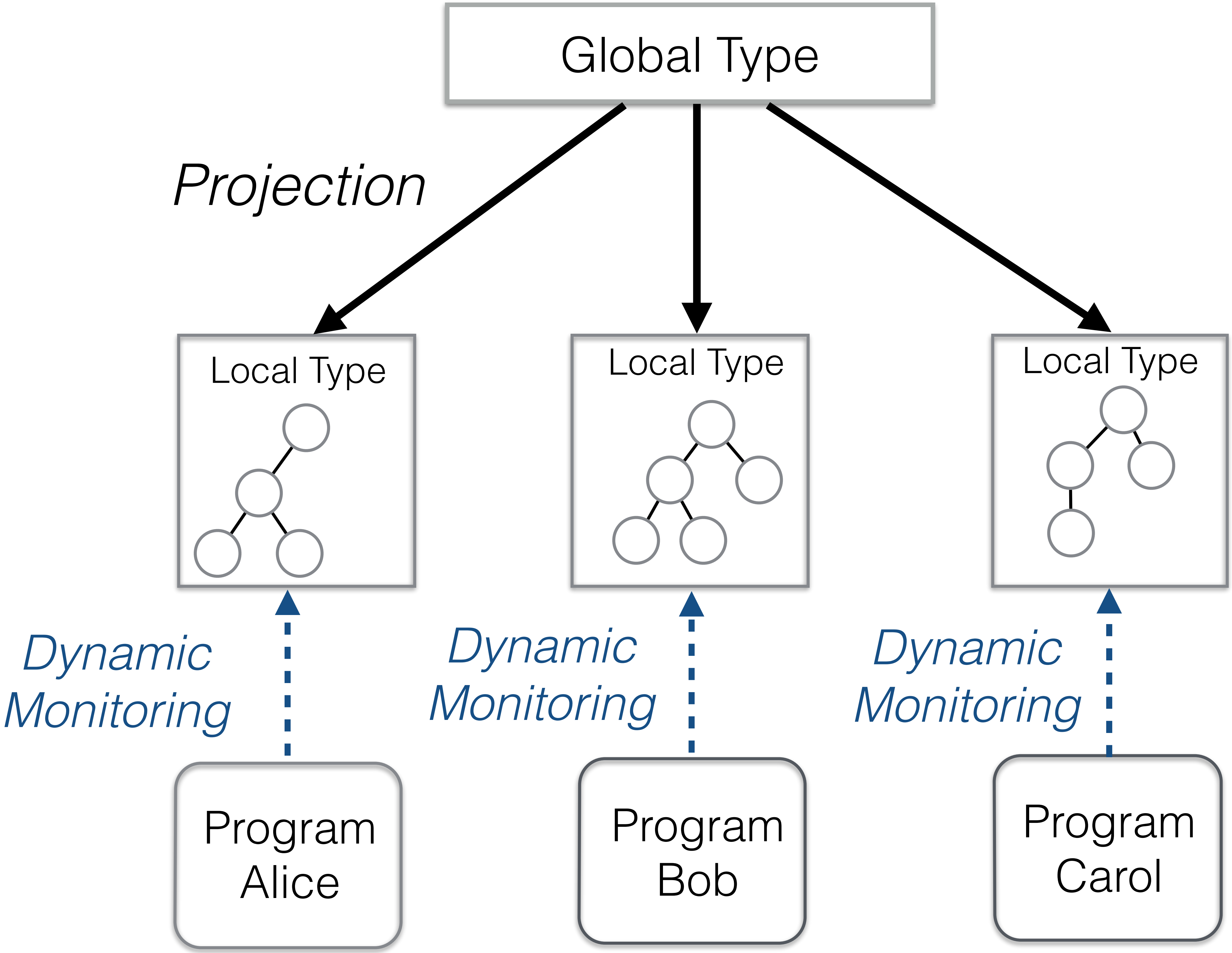
Session Types Overview



- Properties
  - Communication safety (no communication mismatch)
  - Communication fidelity (the communication follow the protocol)
  - Progress (no deadlock/stuck in a session)

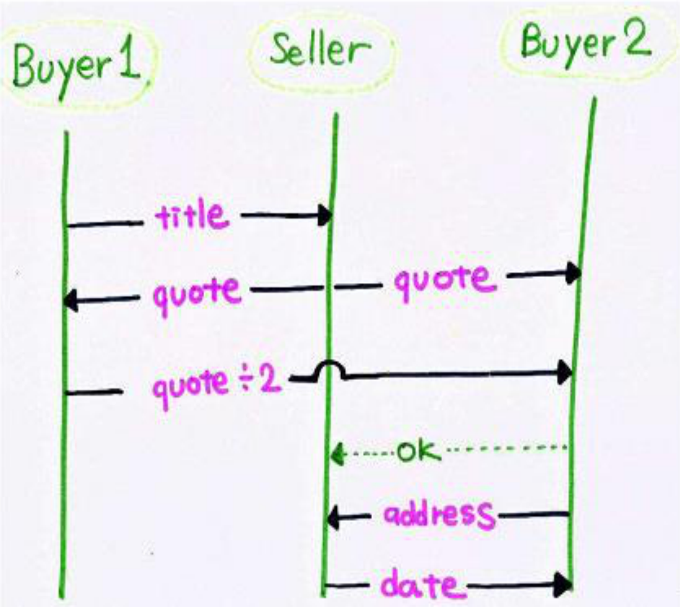


Dynamic Monitoring
[RV'13, COORDINATION'14, FMSD'15]



Two Buyer Protocol in Scribble

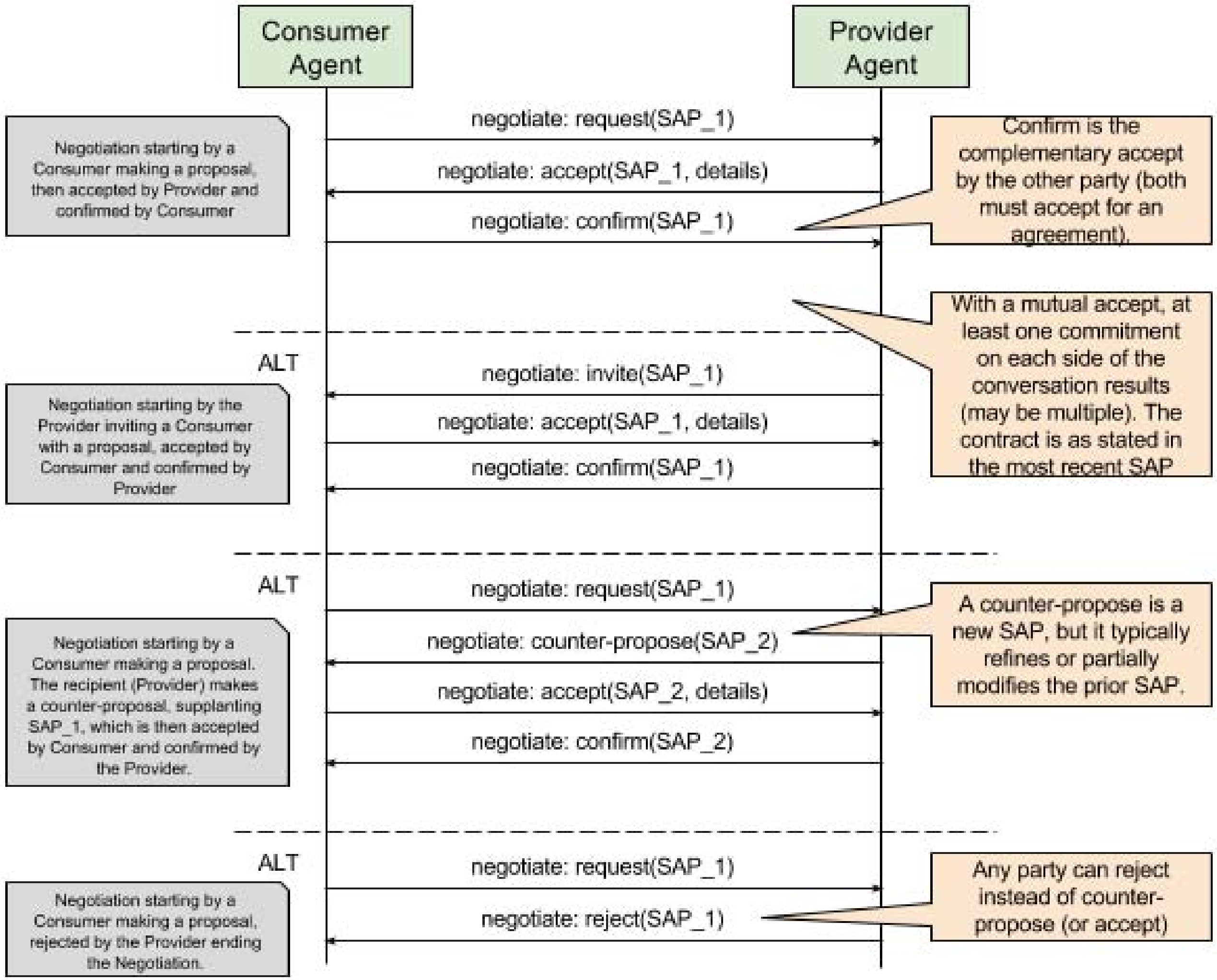
```
type <java> "java.lang.String" from "rt.jar" as String

global protocol TwoBuyers(role A, role B, role S) {
    title(String) from A to S;
    quote(Integer) from S to A, B;
    rec LOOP {
        share(Integer) from A to B;
        choice at B {
            accept(address:String) from B to A,
            date(String) from S to B;
        } or {
            retry() from B to A, S;
            continue LOOP;
        } or {
            quit() from B to A, S;
}   }   }
```



Buyer: A local projection

```
module Bookstore_TwoBuyers_A;

type <java> "java.lang.Integer" from "rt.jar" as Integer;
type <java> "java.lang.String" from "rt.jar" as String;

local protocol TwoBuyers_A at A(role A, role B, role S) {
 title(String) to S;
 quote(Integer) from S;
 rec LOOP {
  share(Integer) to B;
  choice at B {
   accept(address:String) from B;
  } or {
   retry() from B;
   continue LOOP;
  } or {
   quit() from B;
} } }
```

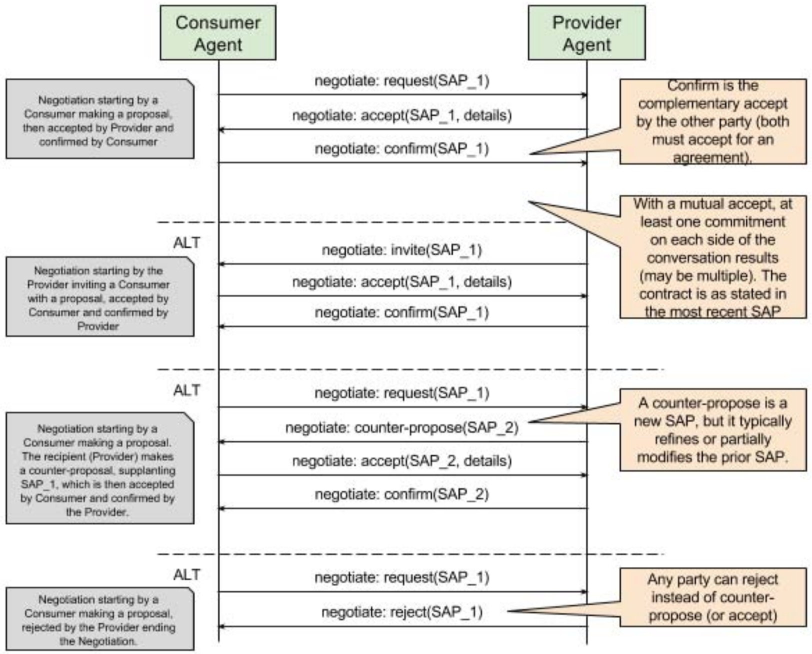
OOI agent negotiation 1/5



- https://confluence.oceanobservatories.org/display/syseng/CIAD+COI+OV+Negotiate+Protocol

OOI agent negotiation 2/5

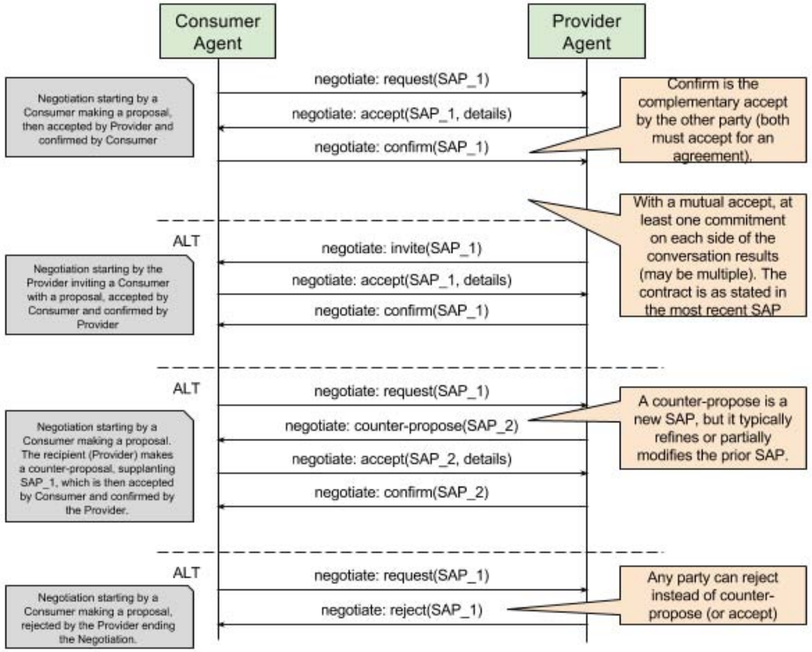
```
type <yml> "SAPDoc1" from "SAPDoc1.yml" as SAP;

global protocol Negotiate(role Consumer as C, role Producer as P) {
```




```
}
```

OOI agent negotiation 3/5 (choice)

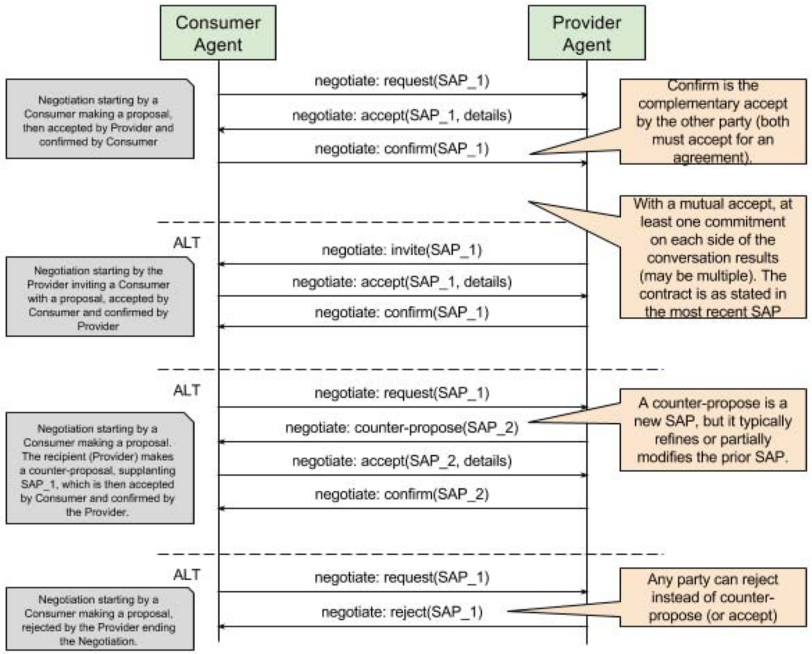
```
type <yml> "SAPDoc1" from "SAPDoc1.yml" as SAP;

global protocol Negotiate(role Consumer as C, role Producer as P) {
  propose(SAP) from C to P;

    choice at P {
      accept() from P to C;
      confirm() from C to P;
    } or {
      reject() from P to C;
    } or {
      propose(SAP) from P to C;
```




```
} }
```

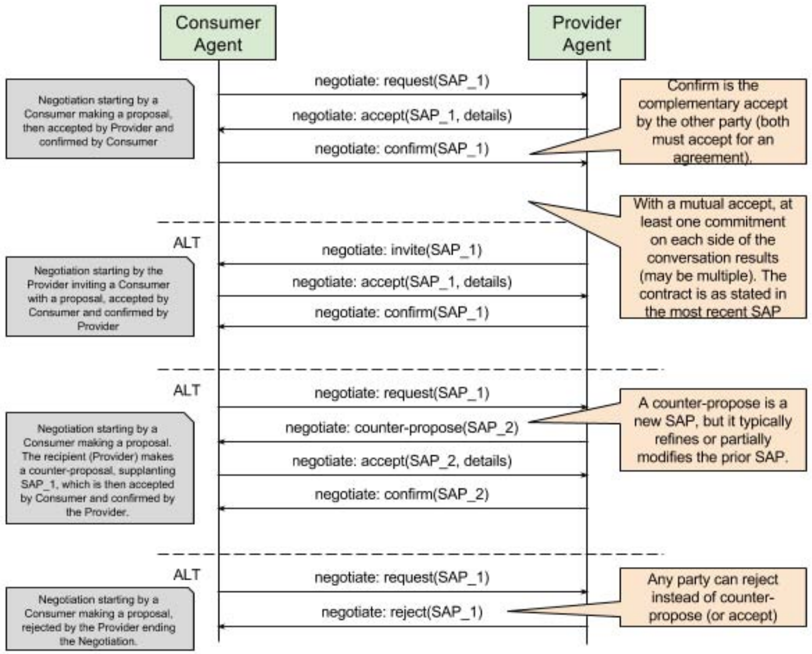
OOI agent negotiation 4/5

```
type <yml> "SAPDoc1" from "SAPDoc1.yml" as SAP;

global protocol Negotiate(role Consumer as C, role Producer as P) {
  propose(SAP) from C to P;

    choice at P {
      accept() from P to C;
      confirm() from C to P;
    } or {
      reject() from P to C;
    } or {
      propose(SAP) from P to C;
      choice at C {
        accept() from C to P;
        confirm() from P to C;
      } or {
        reject() from C to P;
      } or {
        propose(SAP) from C to P;

} } }
```



OOI agent negotiation 5/5 (recursion)

```
type <yml> "SAPDoc1" from "SAPDoc1.yml" as SAP;

global protocol Negotiate(role Consumer as C, role Producer as P) {
  propose(SAP) from C to P;
  rec X {
    choice at P {
      accept() from P to C;
      confirm() from C to P;
    } or {
      reject() from P to C;
    } or {
      propose(SAP) from P to C;
      choice at C {
        accept() from C to P;
        confirm() from P to C;
      } or {
        reject() from C to P;
      } or {
        propose(SAP) from C to P;
        continue X;
      }
    }
```

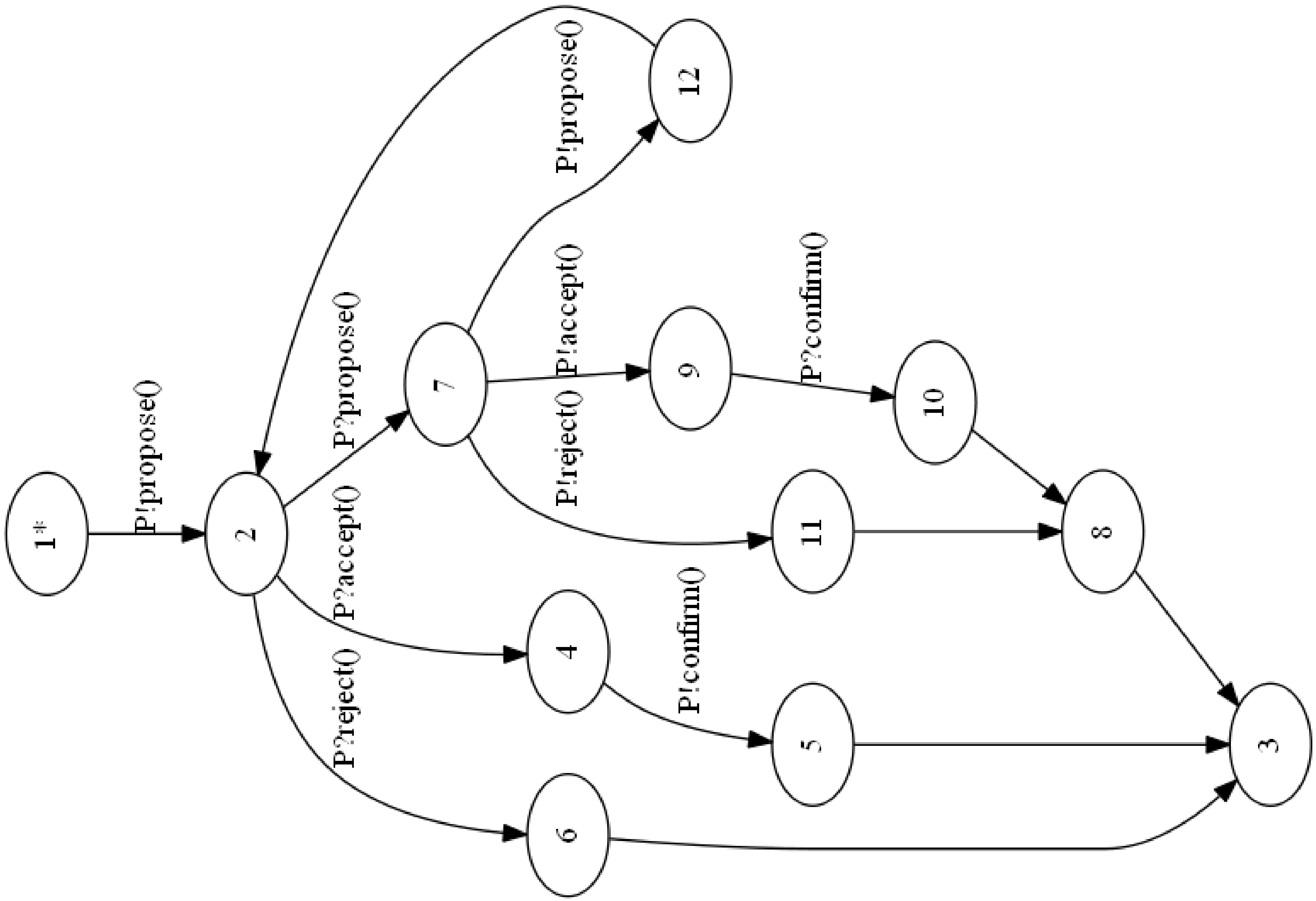


Local protocol projection (Negotiation Consumer)

```
// Global
propose(SAP) from C to P;
rec START {
  choice at P {
    accept() from P to C;
    confirm() from C to P;
  } or {
    reject() from P to C;
  } or {
    propose(SAP) from P to C;
    choice at C {
      accept() from C to P;
      confirm() from P to C;
    } or {
      reject() from C to P;
    } or {
      propose(SAP) from C to P;
      continue START;
} } }
```

```
// Projection for Consumer
propose(SAP) to P;
rec START {
  choice at P {
    accept() from P;
    confirm() to P;
  } or {
    reject() from P;
  } or {
    propose(SAP) from P;
    choice at C {
      accept() to P;
      confirm() from P;
    } or {
      reject() to P;
    } or {
      propose(SAP) to P;
      continue START;
} } }
```

FSM generation (Negotiation Consumer)



Scribble Community

- Webpage:
  - www.scribble.org
- GitHub:
  - https://github.com/scribble
- Tutorial:
  - www.doc.ic.ac.uk/~rhu/scribble/tutorial.html
- Specification (0.3)
  - www.doc.ic.ac.uk/~rhu/scribble/langref.html

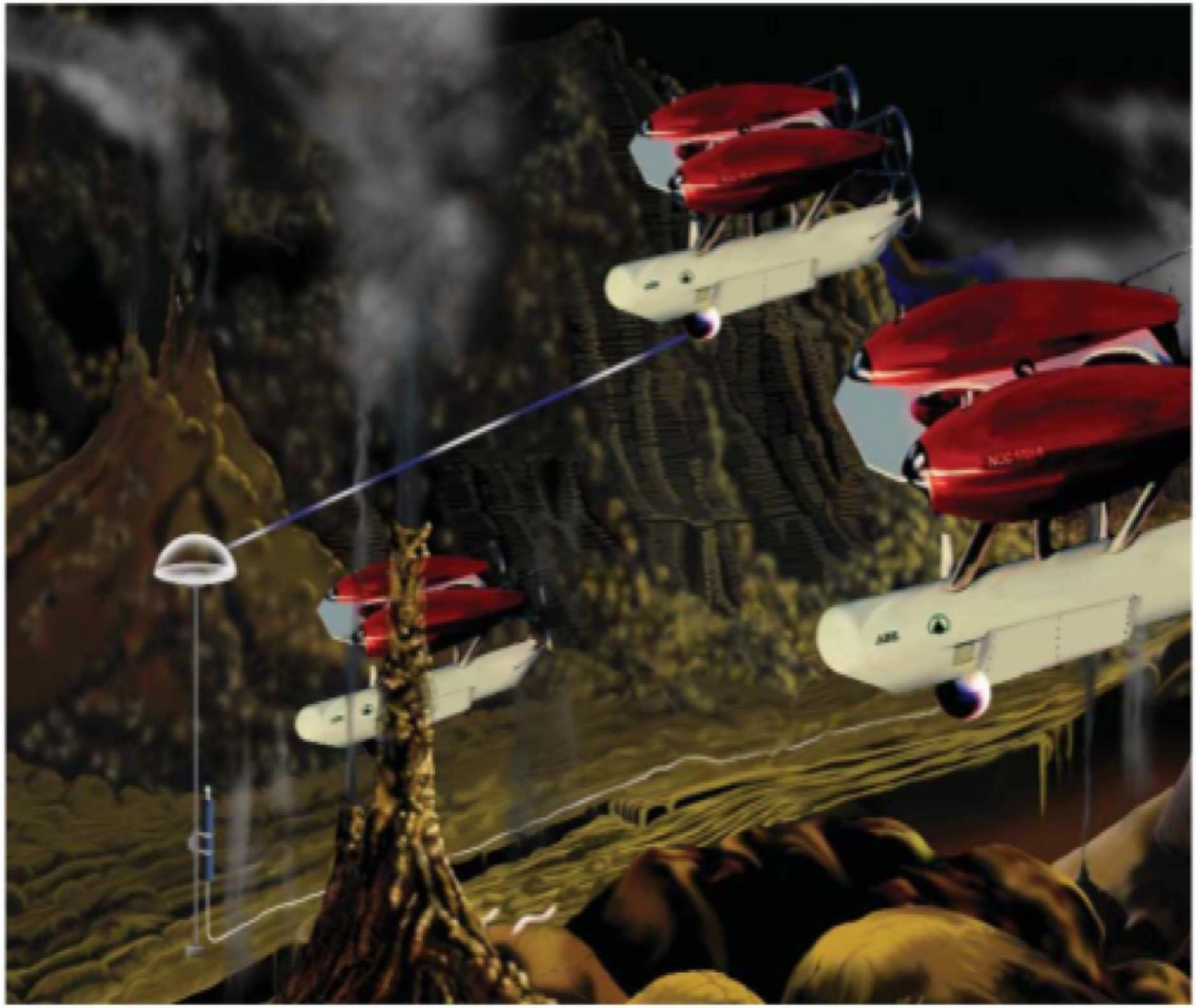


Figure 5: A coordinated set of autonomous underwater vehicles

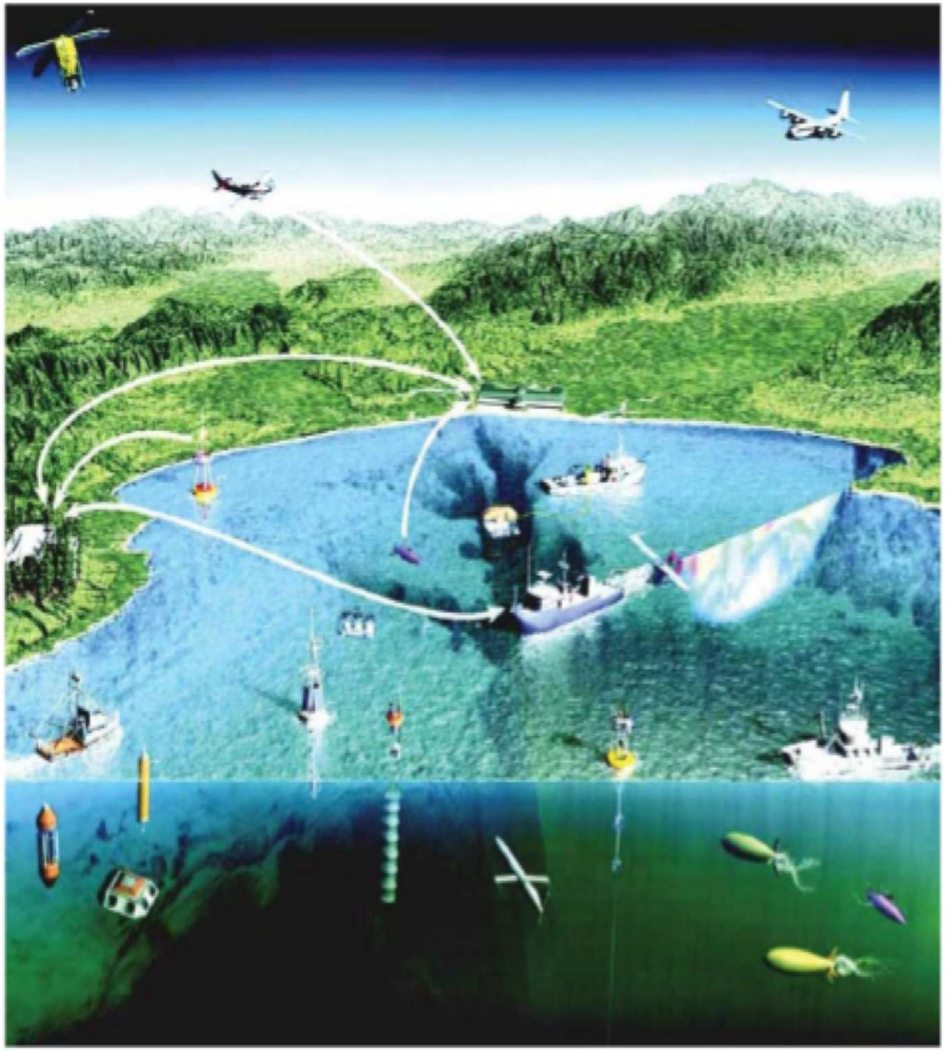
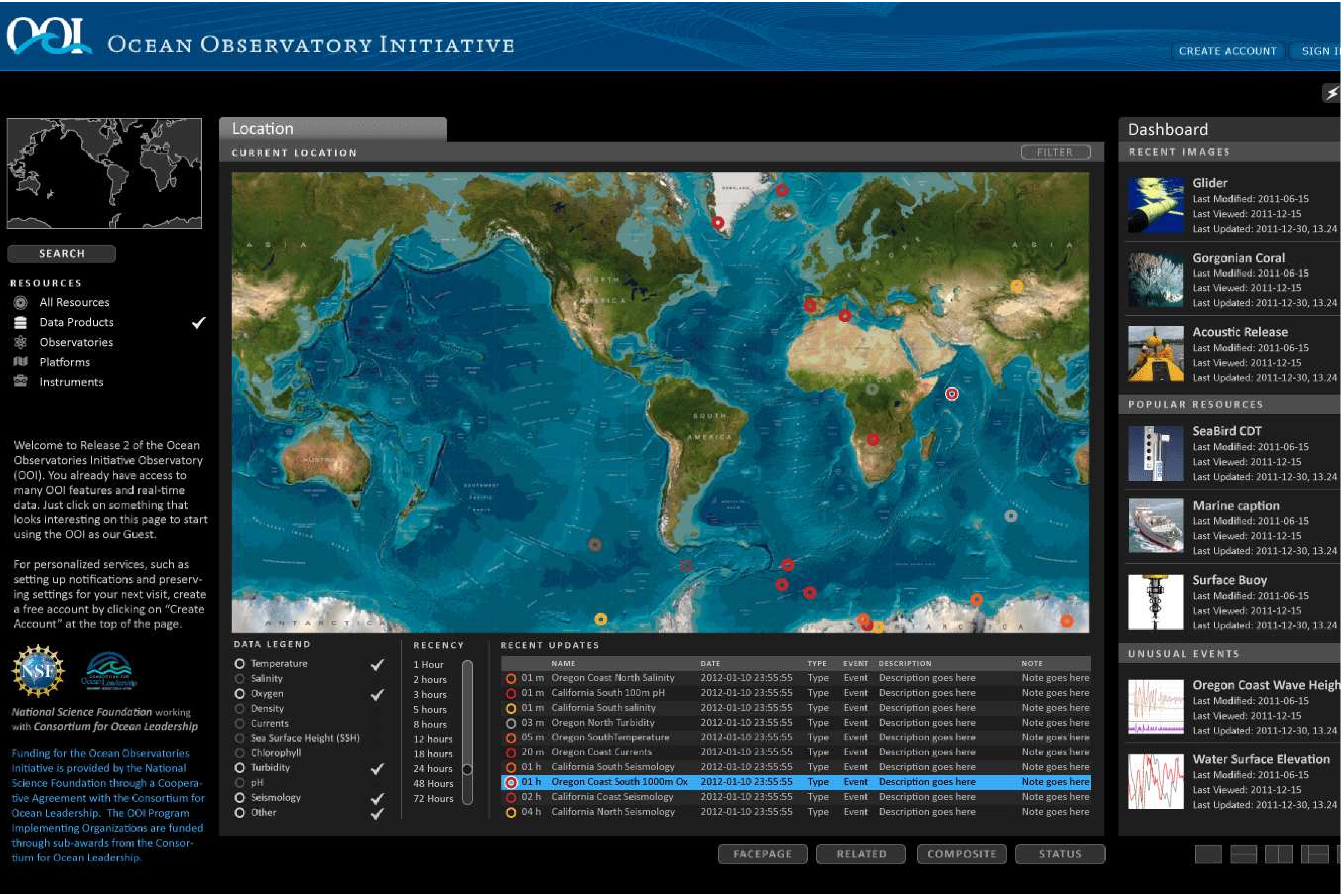
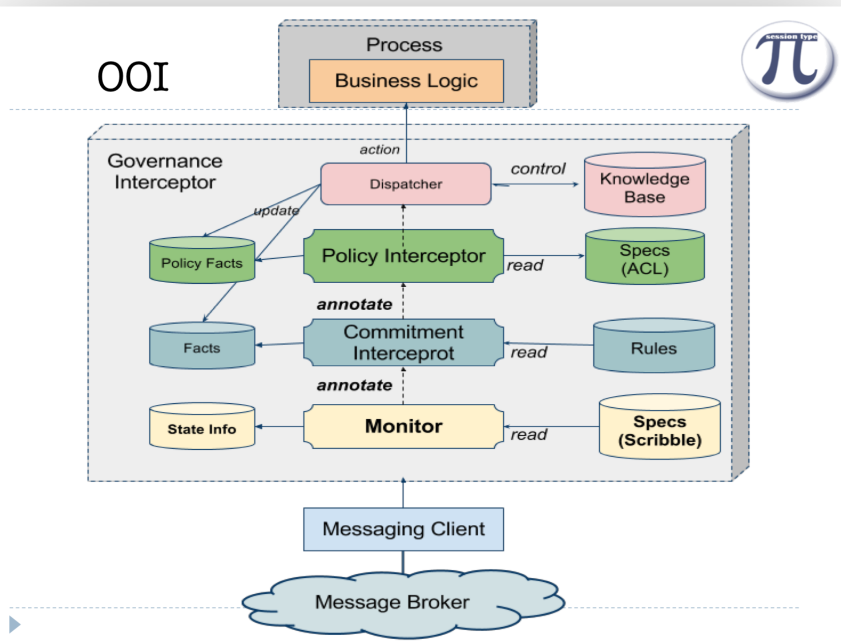


Figure 3: Observatory comprised of ships, aircraft and autonomous vehicles linked to assimilation modeling capabilities on shore

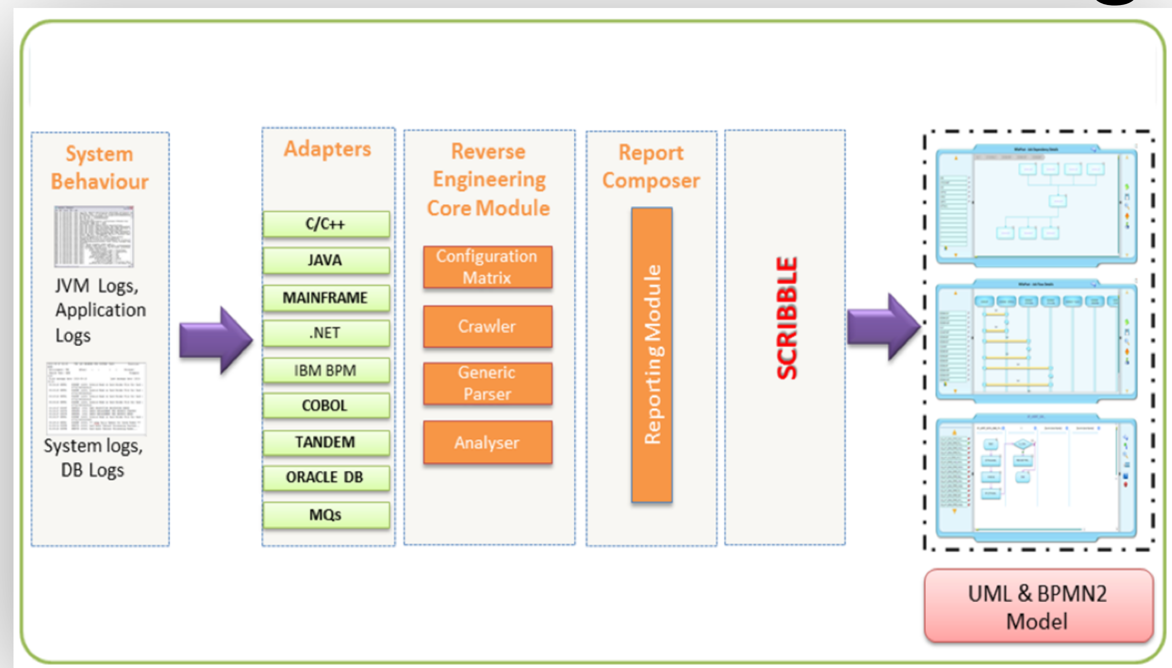

OCEAN OBSERVATORY INITIATIVE
CREATE ACCOUNT
SIGN I
SEARCH
RESOURCES
All Resources
Data Products
Observatories
Platforms
Instruments
Welcome to Release 2 of the Ocean Observatories Initiative Observatory (OOI). You already have access to many OOI features and real-time data. Just click on something that looks interesting on this page to start using the OOI as our Guest.
For personalized services, such as setting up notifications and preserving settings for your next visit, create a free account by clicking on "Create Account" at the top of the page.
National Science Foundation working with Consortium for Ocean Leadership
Funding for the Ocean Observatories Initiative is provided by the National Science Foundation through a Cooperative Agreement with the Consortium for Ocean Leadership. The OOI Program Implementing Organizations are funded through sub-awards from the Consortium for Ocean Leadership.
Location
CURRENT LOCATION
FILTER
ASIA
NORTH AMERICA
SOUTH AMERICA
ANTARCTICA
DATA LEGEND
Temperature
Salinity
Oxygen
Density
Currents
Sea Surface Height (SSH)
Chlorophyll
Turbidity
pH
Seismology
Other
RECENCY
1 Hour
2 hours
3 hours
5 hours
8 hours
12 hours
18 hours
24 hours
48 Hours
72 Hours
RECENT UPDATES
NAME DATE TYPE EVENT DESCRIPTION NOTE
01 m Oregon Coast North Salinity 2012-01-10 23:55:55 Type Event Description goes here Note goes here
01 m California South 100m pH 2012-01-10 23:55:55 Type Event Description goes here Note goes here
01 m California South salinity 2012-01-10 23:55:55 Type Event Description goes here Note goes here
03 m Oregon North Turbidity 2012-01-10 23:55:55 Type Event Description goes here Note goes here
05 m Oregon SouthTemperature 2012-01-10 23:55:55 Type Event Description goes here Note goes here
20 m Oregon Coast Currents 2012-01-10 23:55:55 Type Event Description goes here Note goes here
01 h California South Seismology 2012-01-10 23:55:55 Type Event Description goes here Note goes here
01 h Oregon Coast South 1000m Ox 2012-01-10 23:55:55 Type Event Description goes here Note goes here
02 h California Coast Seismology 2012-01-10 23:55:55 Type Event Description goes here Note goes here
04 h California North Seismology 2012-01-10 23:55:55 Type Event Description goes here Note goes here
FACEPAGE
RELATED
COMPOSITE
STATUS
Dashboard
RECENT IMAGES
Glider
Last Modified: 2011-06-15
Last Viewed: 2011-12-15
Last Updated: 2011-12-30, 13.24
Gorgonian Coral
Last Modified: 2011-06-15
Last Viewed: 2011-12-15
Last Updated: 2011-12-30, 13.24
Acoustic Release
Last Modified: 2011-06-15
Last Viewed: 2011-12-15
Last Updated: 2011-12-30, 13.24
POPULAR RESOURCES
SeaBird CDT
Last Modified: 2011-06-15
Last Viewed: 2011-12-15
Last Updated: 2011-12-30, 13.24
Marine caption
Last Modified: 2011-06-15
Last Viewed: 2011-12-15
Last Updated: 2011-12-30, 13.24
Surface Buoy
Last Modified: 2011-06-15
Last Viewed: 2011-12-15
Last Updated: 2011-12-30, 13.24
UNUSUAL EVENTS
Oregon Coast Wave Heigh
Last Modified: 2011-06-15
Last Viewed: 2011-12-15
Last Updated: 2011-12-30, 13.24
Water Surface Elevation
Last Modified: 2011-06-15
Last Viewed: 2011-12-15
Last Updated: 2011-12-30, 13.24

Applications

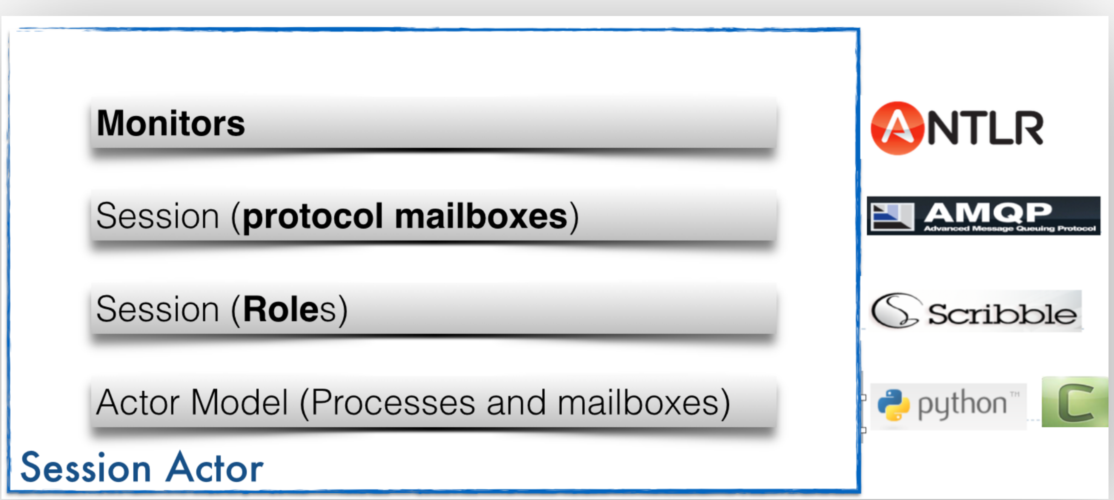
OOI Governance



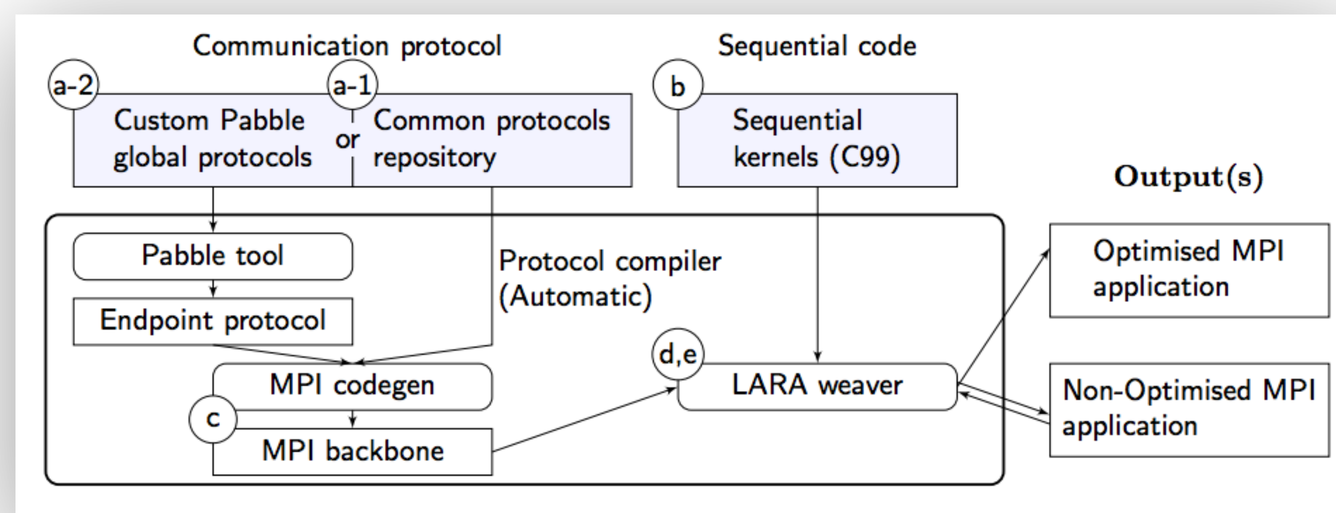
ZDLC: Process Modeling



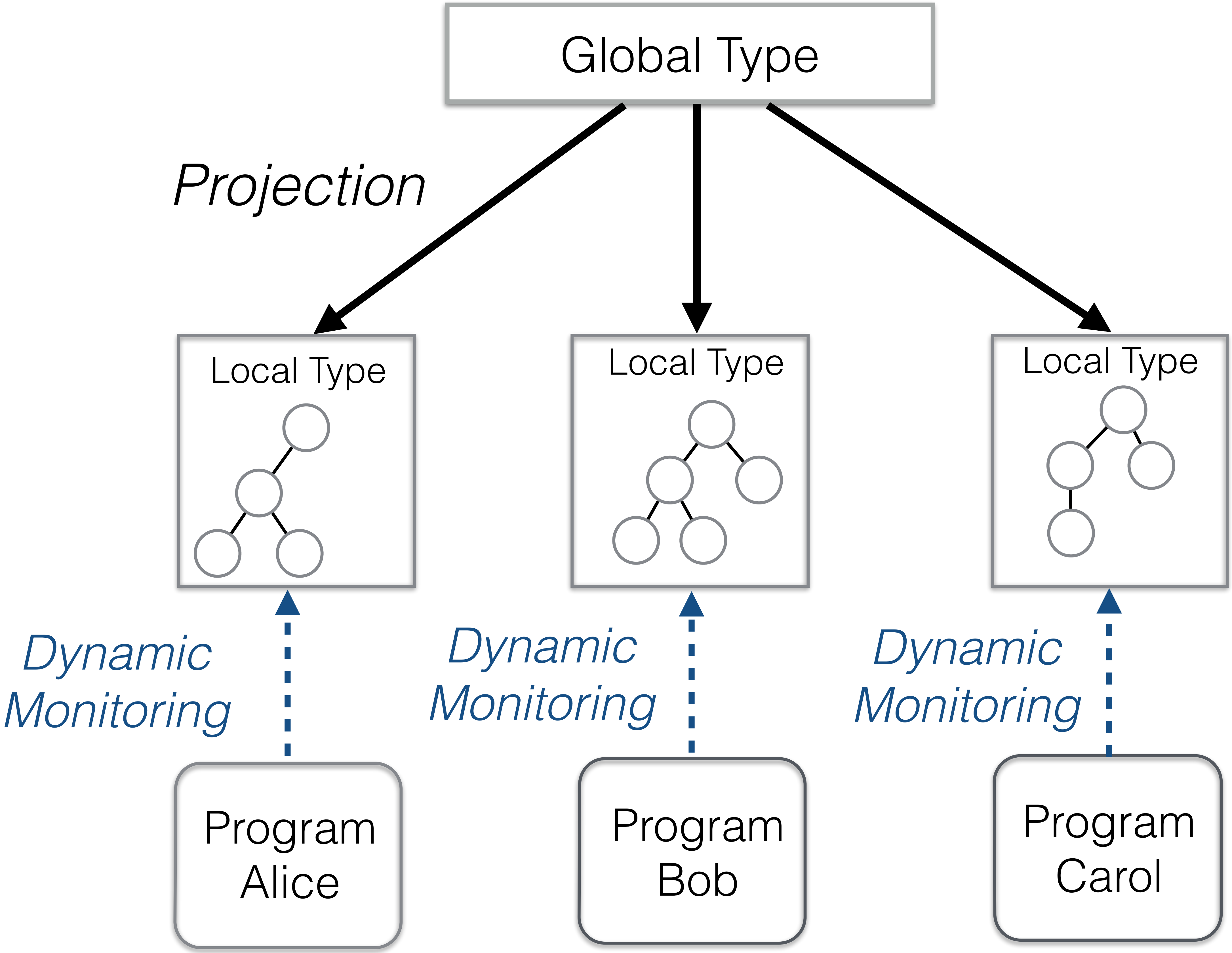
Protocol Verification



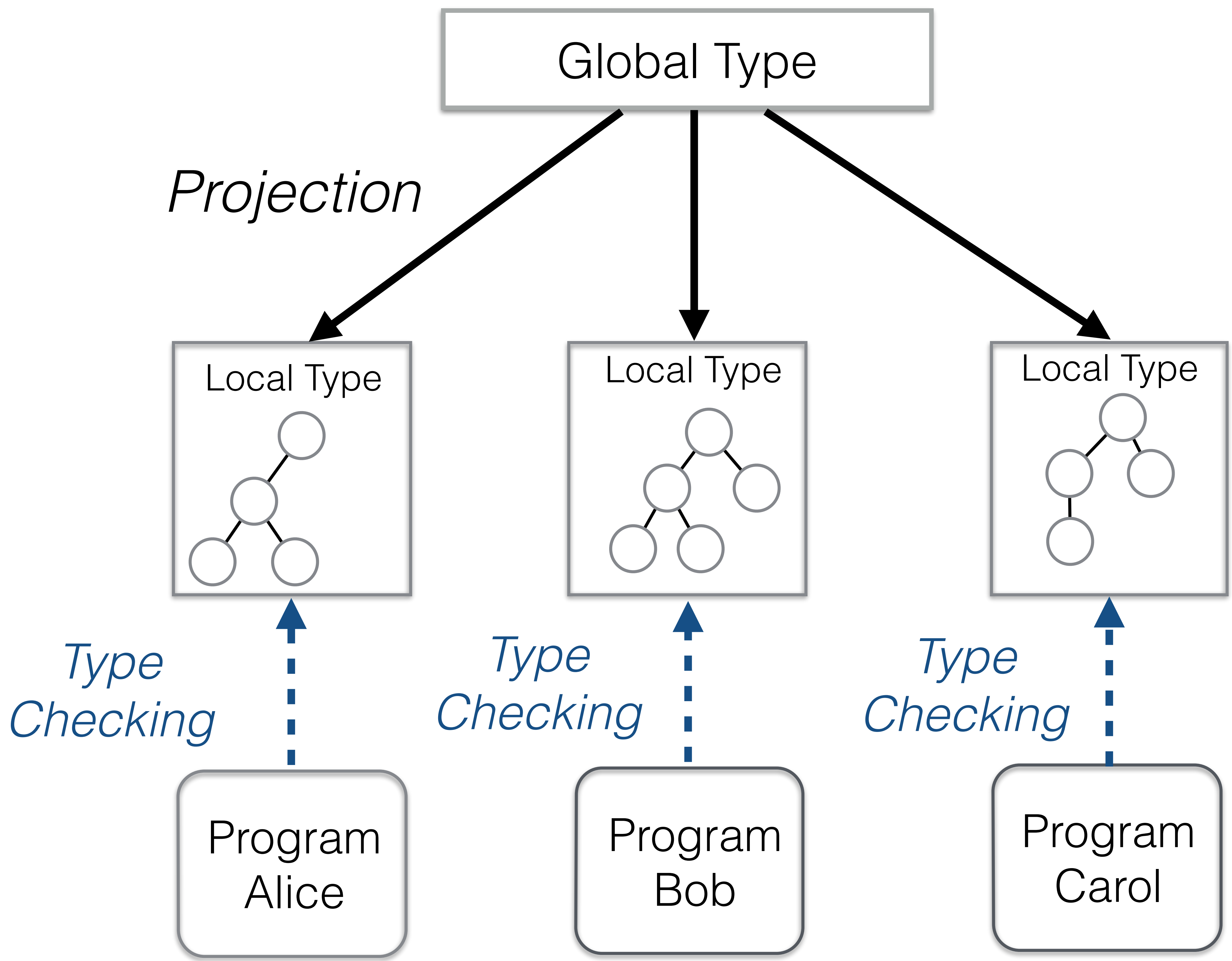
MPI code generations



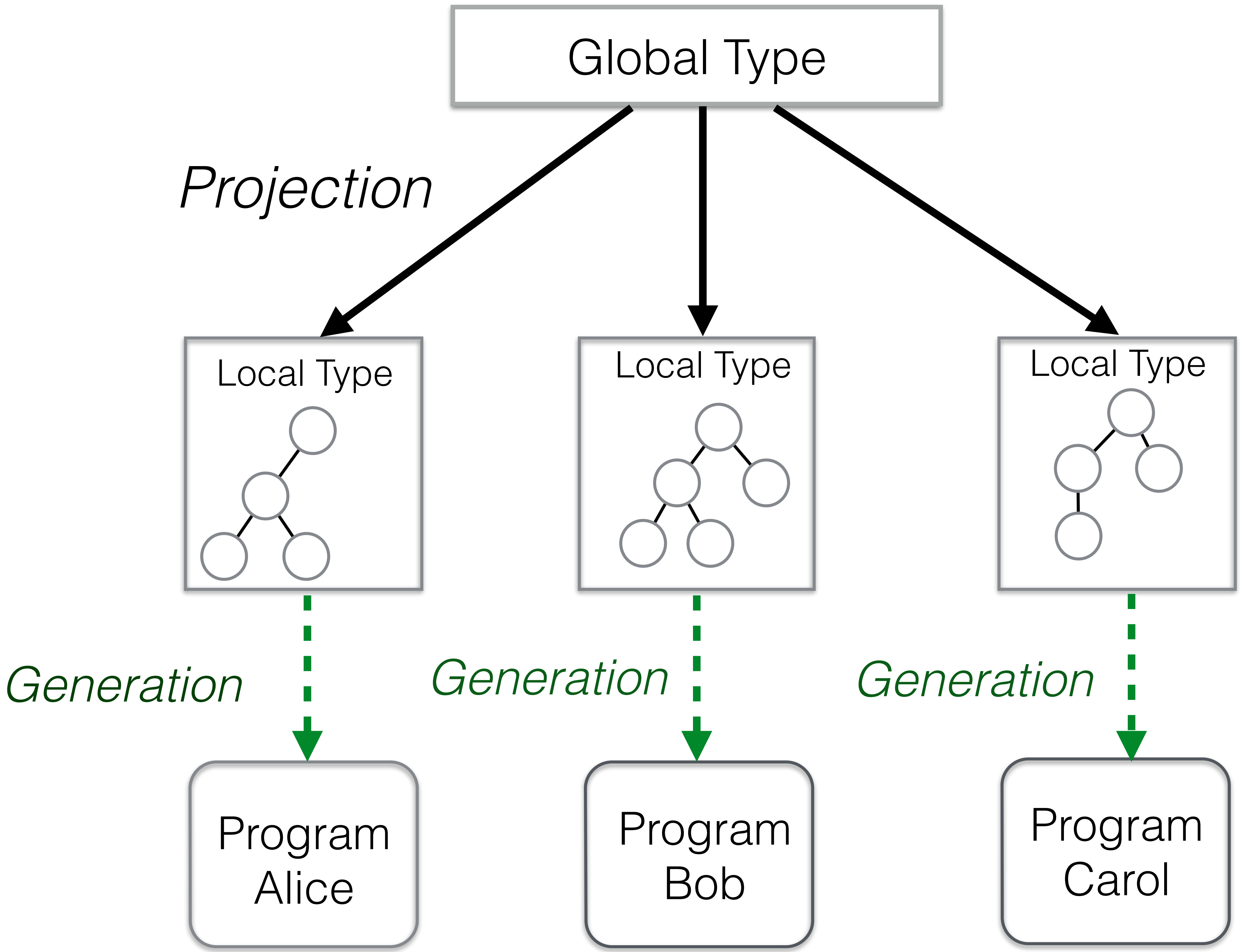
Dynamic Monitoring
[RV'13, COORDINATION'14, FMSD'15]



Type Checking [OOPSLA'15, POPL'16]

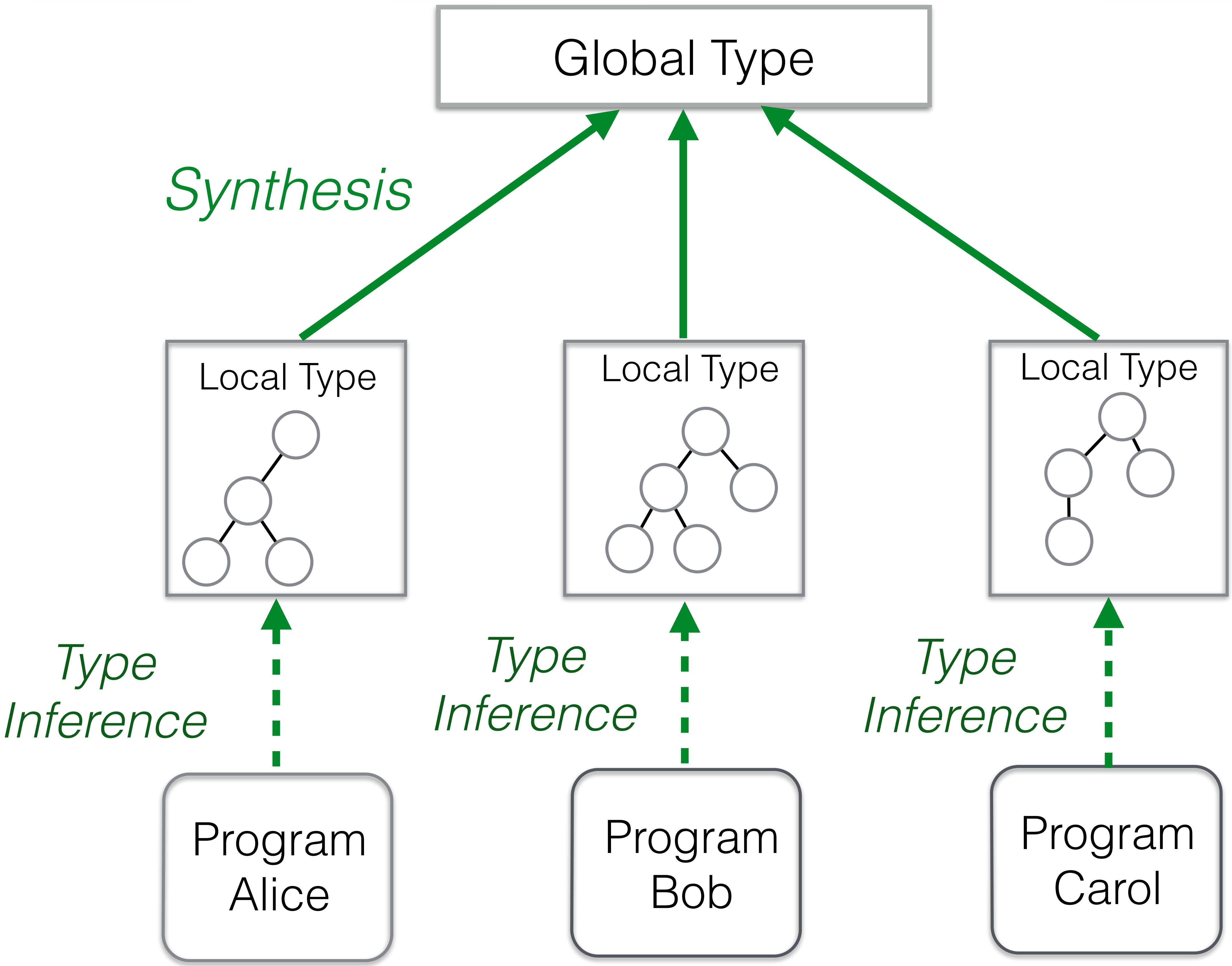


Code Generation [CC'15, FASE'16]



Synthesis

[ICALP'13, POPL'15, CONCUR'15, TACAS'16]



Scribble SMTP

RFC 821 August 1982
Simple Mail Transfer Protocol

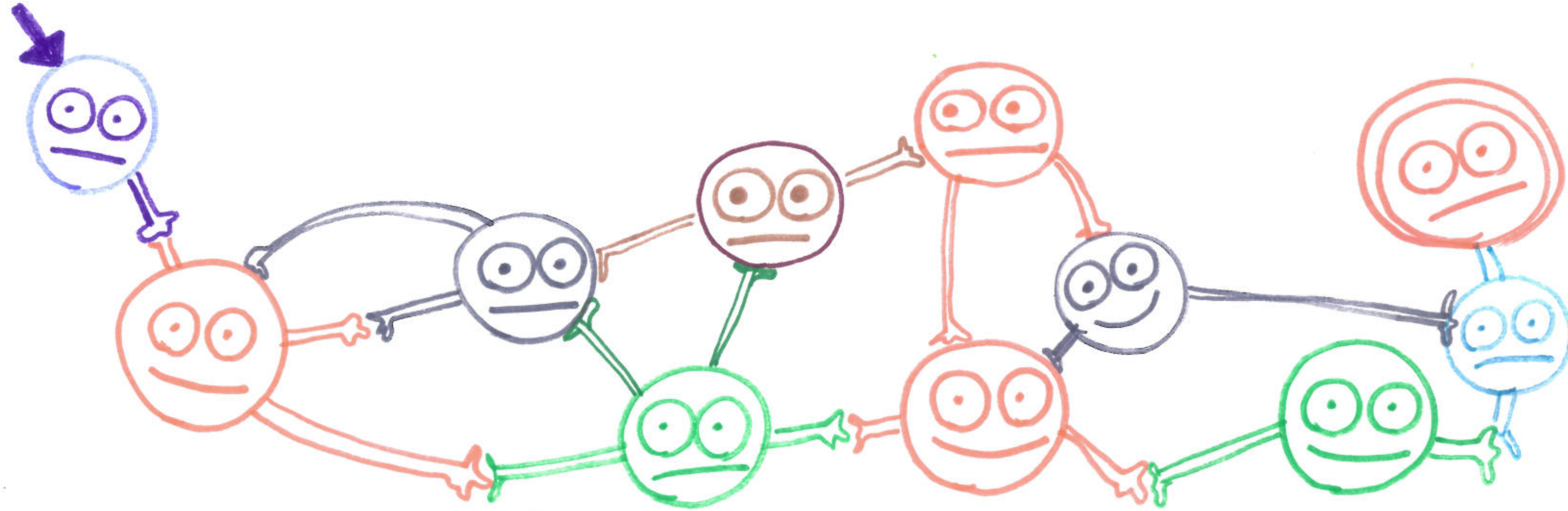
TABLE OF CONTENTS

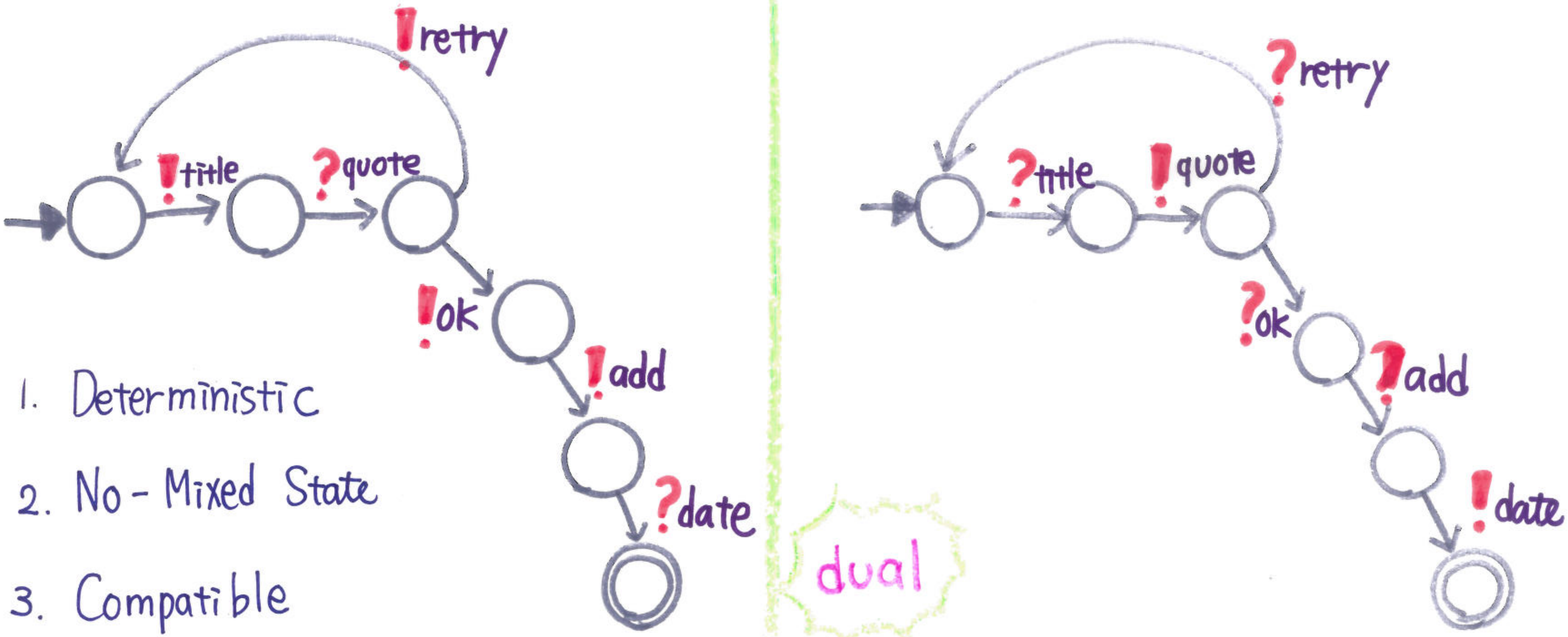
Multiparty Compatibility in Communicating Automata

Synthesis and Characterisation of Multiparty Session Types

Nobuko Yoshida Pierre-Malo Deniélou

ICALP'13



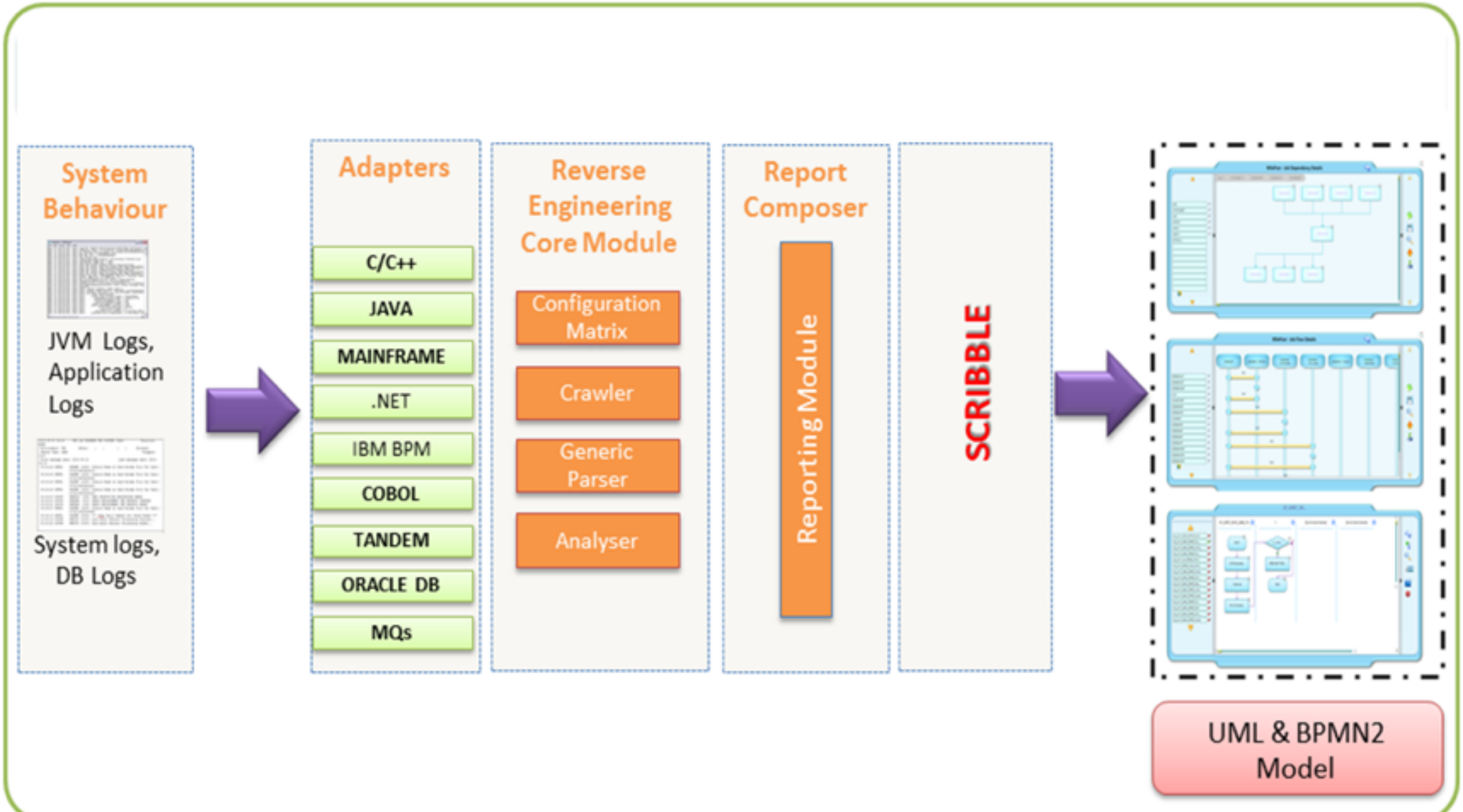


1. Deterministic
2. No-Mixed State
3. Compatible

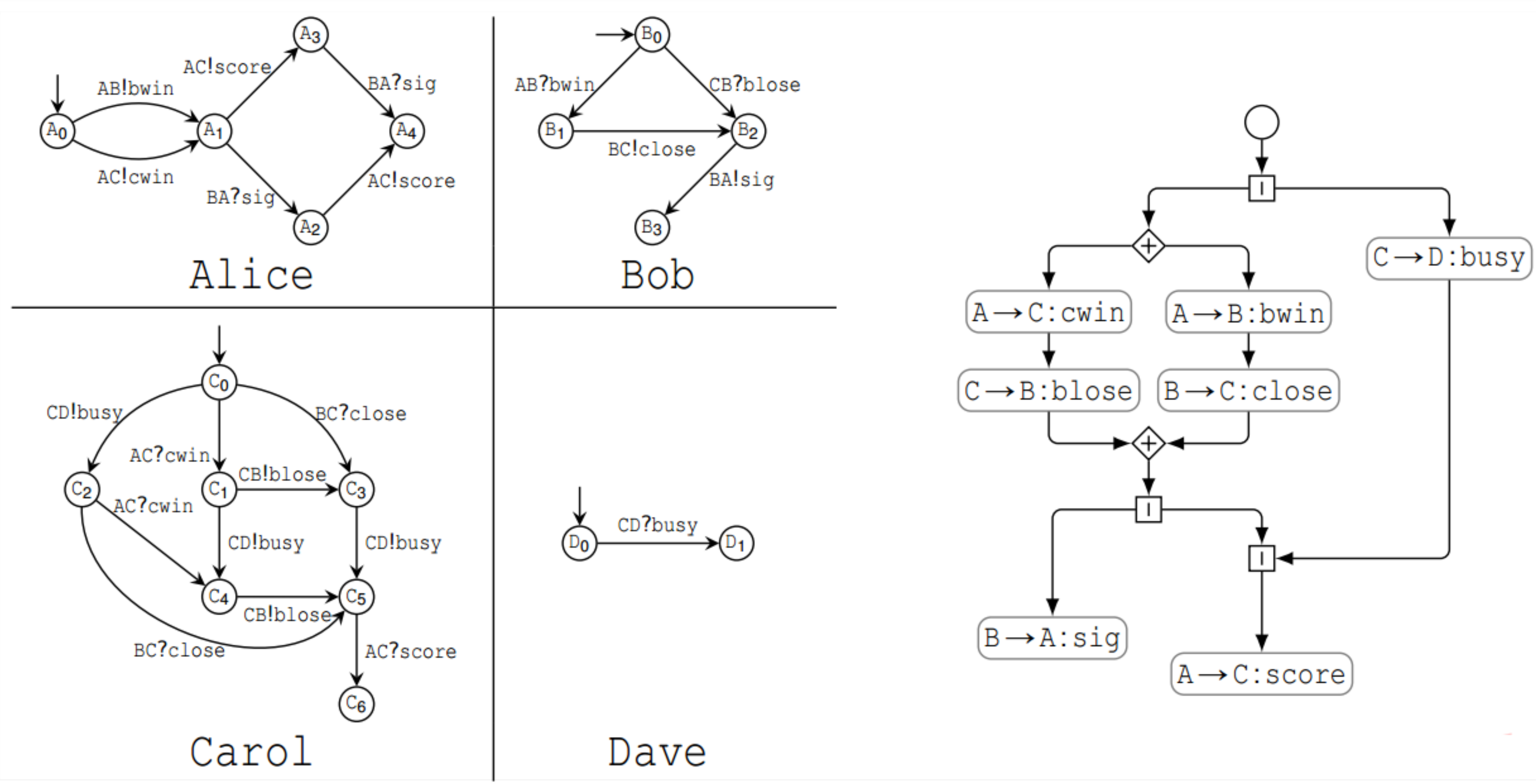
[Gouda et al 1986] Two compatible machines without mixed states which are deterministic satisfy deadlock-freedom.

http://www.zdlc.co/faq/

Zero Deviation Life Cycle Platform



From Communicating Machines to Graphical Choreographies [POPL'15, CONCUR'15]

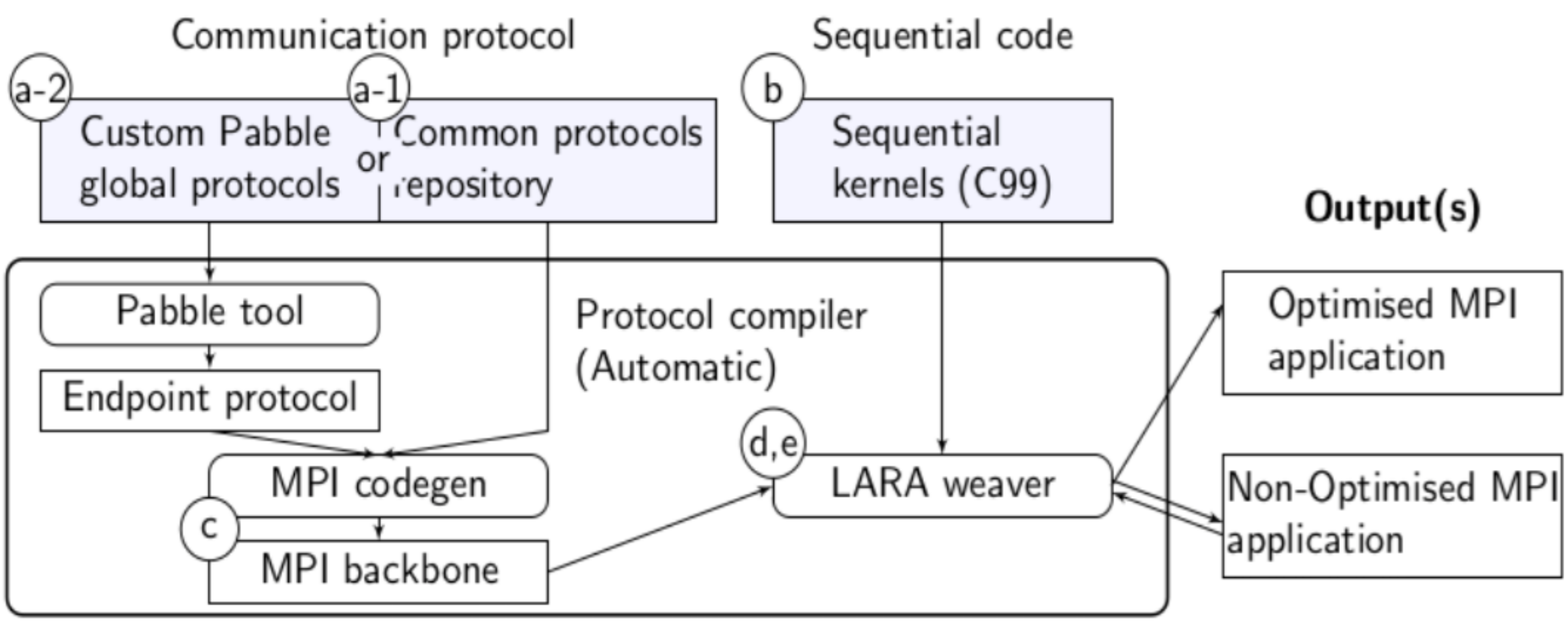


[ESOP'10,ESOP'12,CONCUR'12,CONCUR'14]

Message Passing Programming [CC’15, OOPSLA’15]

A complete parallel programming workflow

- Captures **parallel interaction patterns** by Pabble language
- Combines with **sequential computation kernels** in C
- Generates **communication safe & deadlock free** MPI programs
- Optimisation as part of merging technique

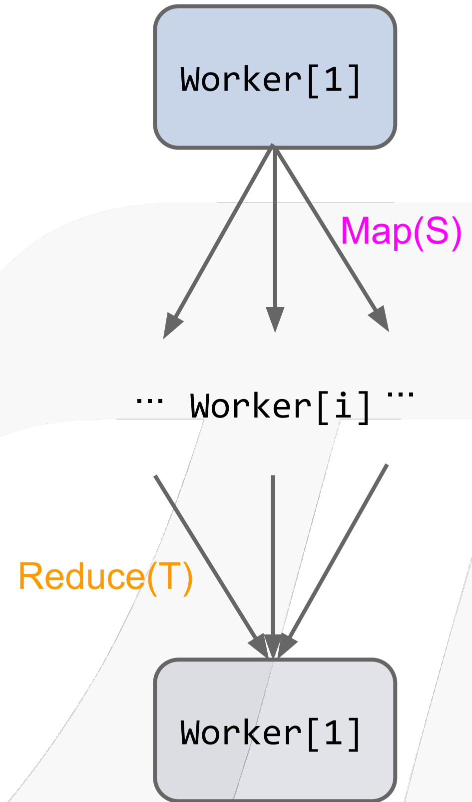


Example: Simple search engine

Scatter-Gather protocol

- Distribute query to all nodes
- Nodes collect relevant records
- Results gathered and merged
- Display results to user

```
const N = 2..max;
global protocol ScatterGather(role Worker[1..N])
{
  Init()     from __self    to __self;

  Map(S)     from Worker[1] to __All;
  Reduce(T)  from __All     to Worker[1];

  Finish()   from __self    to __self;
}
```



Scatter-Gather protocol

Example: search engine

Merging backbone with kernels

```
#pragma pabble type S
  typedef void S; MPI_Datatype MPI_S = MPI_BYTE;
#pragma pabble type T
  typedef void T; MPI_Datatype MPI_T = MPI_BYTE;
#pragma pabble Init
  bufMap0_r = calloc(meta.buflen(Map), sizeof(S));
#pragma pabble Map
  bufMap0_s = pabble_sendq_dequeue();
  MPI_Scatter( …, MPI_S, Worker_RANK(1), … );
  free(bufMap0_s);
  pabble_recvq_enqueue(Map, bufMap0_r);
#pragma pabble Map
  bufReduce1_r = calloc(meta.buflen(Reduce)*meta.
nprocs, sizeof(T));
#pragma pabble Reduce
  bufReduce1_s = pabble_sendq_dequeue();
  MPI_Gather( … , MPI_T, Worker_RANK(1) …);
  free(bufReduce1_s);
  pabble_recvq_enqueue(Reduce, bufReduce1_r);
#pragma pabble Reduce
#pragma pabble Finish
```

```
  typedef char *S; MPI_Datatype MPI_S = MPI_CHAR;

  typedef char *T; MPI_Datatype MPI_T = MPI_CHAR;
  load_data();
  bufMap0_r = calloc(meta.buflen(Map), sizeof(S));
  distribute_data();
  bufMap0_s = pabble_sendq_dequeue();
  MPI_Scatter( …, MPI_S, Worker_RANK(1), … );
  free(bufMap0_s);
  pabble_recvq_enqueue(Map, bufMap0_r);
  distribute_data();
  bufReduce1_r = calloc(meta.buflen(Reduce)*meta.
nprocs, sizeof(T));
  collect_records();
  bufReduce1_s = pabble_sendq_dequeue();
  MPI_Gather( … , MPI_T, Worker_RANK(1) …);
  free(bufReduce1_s);
  pabble_recvq_enqueue(Reduce, bufReduce1_r);
  collect_records();
  display_cleanup();
```

Evaluation

Productivity: Flexibility

Reusable protocols

- e.g. scatter-gather
- e.g. stencil

Berkeley Dwarfs [CACM'09]

- Representative parallel computing patterns
- 4 of 5 HPC patterns

		Repository	Berkeley HPC Dwarfs
heateq	stencil*	Yes	Structured Grid
nbody	ring*	Yes	Particle Methods
wordcount	scatter-gather*	Yes	
adpredictor	scatter-gather*	Yes	
montecarlo	scatter-gather*	Yes	
montecarlo-mw	master-worker*	Yes	
LEsolver	wraparound mesh		Structured Grid
matvec	custom		Dense Matrix
fft64	6-step butterfly		Spectral (FFT)

Evaluation

Productivity: Effort

Protocols in repository

- Use backbone directly
- Write kernel
- Effort = K / B+K

Custom protocols

- Write Pabble protocol
- Tool generate backbone
- Write kernel
- Effort = P+K / B+K

Effort ratio

- LOC savings

		Pabble LOC(P)	Backbone LOC (B)	Kernel LOC(K)	Effort
heateq	stencil*	15	154	335	0.69
nbody	ring*	15	93	228	0.71
wordcount	scatter-gather*	8	76	176	0.70
adpredictor	scatter-gather*	8	76	182	0.71
montecarlo	scatter-gather*	8	76	70	0.48
montecarlo-mw	master-worker*	10	82	70	0.46
LEsolver	wraparound mesh	15	132	208	0.66
matvec	custom	15	130	117	0.41
fft64	6-step butterfly	11	64	134	0.68

Language and Implementations

- Carrying out large-scale experiences with OOI, VMWare, Red Hat, Congnizant, Pivotal, Amazon, AMQP, RabbitMQ
  - JBoss SCRIBBLE [ICDCIT'10,COB'12,TGC'13] and ZDLC projects
- High-performance computing
  Session Java [ECOOP'08,ECOOP'10,Coordination'11]
  $\Longrightarrow$ Multiparty Session C and MPI
  [TOOLS'12,Hearts'12,EuroMPI'12,PDP'14,CC'15,OOPSLA'15]
- Multiparty session languages Ocaml, Java, C, MPI, Python, Scala, Jolie, Haskell, Erlang
  - Effect and Concurrent Haskell [POPL'16]
  - Practical interruptible conversations: Distributed dynamic verification with session types and Python [RV'13,FMCD'15]
  - Multiparty Session Actors [COORDINATION'14]

Multiparty Session Type Theory

- Multiparty Asynchronous Session Types [POPL'08,JACM]
- Progress
  - Global Progress in Dynamically Interleaved Multiparty Sessions [CONCUR'08], [Math. Struct. Comp. Sci.]
  - Inference of Progress Typing [Coordination'13]
- Asynchronous Optimisations and Resource Analysis
  - Global Principal Typing in Partially Commutative Asynchronous Sessions [ESOP'09]
  - Higher-Order Pi-Calculus [TLCA'07,TLCA'09,Info.&Comp]
  - Buffered Communication Analysis in Distributed Multiparty Sessions [CONCUR'10]

- Extensions of Multiparty Session Types
  - Multiparty Symmetric Sum Types [Express'10]
  - Trustworthy Pervasive Healthcare Services via Multi-party Session Types [FHIES'12]
  - Parameterised Multiparty Session Types [FoSSaCs'10, LMCS, SPLASH'15]
  - Global Escape in Multiparty Sessions [FSTTCS'10] [Math. Struct. Comp. Sci.]
  - Dynamic Multirole Session Types [POPL'11]
  - Nested Multiparty Sessions [CONCUR'12]
  - Timed Multiparty Session Types [CONCUR'14]
- Dynamic Monitoring
  - Monitoring Networks through Multiparty Sessions [TGC'11] [FORTE'13]

- Automata Theories
  - Multiparty Session Automata [ESOP'12]
  - Synthesis in Communicating Automata [ICALP'13]
  - From communicating machines to graphical choreographies [POPL'15]
  - Meeting Deadlines Together [CONCUR'15]
- Denotational and Trace Semantics
  - Expressiveness of Multiparty Session Types [FSTTCS'15]
- Petri Nets
  - Multiparty Session Nets [TGC'14]
- Typed Behavioural Theories
  - On Asynchronous Eventful Session Semantics [FORTE'11] [Math. Struct. Comp. Sci.]
  - Governed Session Semantics [CONCUR'13]
  - Characteristic Bisimulations for Higher-Order Session Processes [CONCUR'15]

- Choreography Languages
  - Compositional Choreographies [CONCUR'13]
- Logics
  - Design-by-Contract for Distributed Multiparty Interactions [CONCUR'10]
  - Specifying Stateful Asynchronous Properties [CONCUR'12]
  - Multiparty, Multi-session Logic [TGC'12]
  - Multiparty Session Types as Coherence Proofs [CONCUR'15]

Session Type Reading List

- Home Page http://mrg.doc.ic.ac.uk/
- [ESOP'98] Language Primitives and Type Disciplines for Structured Communication-based Programming, Honda, Vasconcelos and Kubo
- [SecRet'06] Language Primitives and Type Disciplines for Structured Communication-based Programming Revisited, Yoshida and Vasconcelos, ENTCS.
- [SFM'15] Gentle Introduction to Multiparty Asynchronous Session Types, Coppo et al.
- [POPL'15] From communicating machines to graphical choreographies, Lange, Tuosto and Yoshida.

- [COB'14,TGC'13] The Scribble Protocol Language, Honda et al.
- [ECOOP'08] Session-Based Distributed Programming in Java, Hu, Yoshida and Honda.
- [FMSD'15] Practical interruptible conversations: Distributed dynamic verification with multiparty session types and Python, Demangeon, Honda, Hu, Neykova and Yoshida.
- [CC'15] Protocols by Default: Safe MPI Code Generation based on Session Types, Ng, Coutinho and Yoshida.

A rare cluster of qualities

From the team of OOI CI:

Kohei has lead us deep into the nature of communication and processing. His esthetics, precision and enthusiasm for our mutual pursuit of formal Session (Conversation) Types and specifically for our OOI collaboration to realize this vision in very concrete terms were, as penned by Henry James, lessons in seeing the nuances of both beauty and craft, through a rare cluster of qualities - curiosity, patience and perception; all at the perfect pitch of passion and expression.