Fluid Types

Statically Verified Distributed Protocols with Refinements

Fangyi Zhou Francisco Ferreira
Rumyana Neykova Nobuko Yoshida

Imperial College London

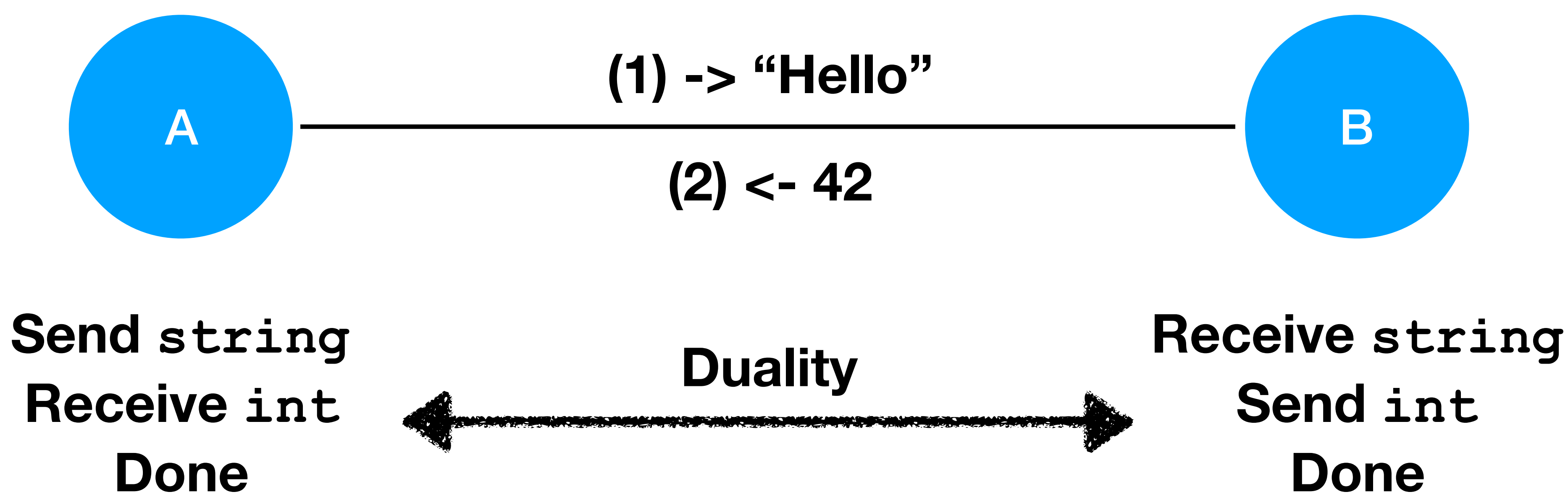
Brunel University London

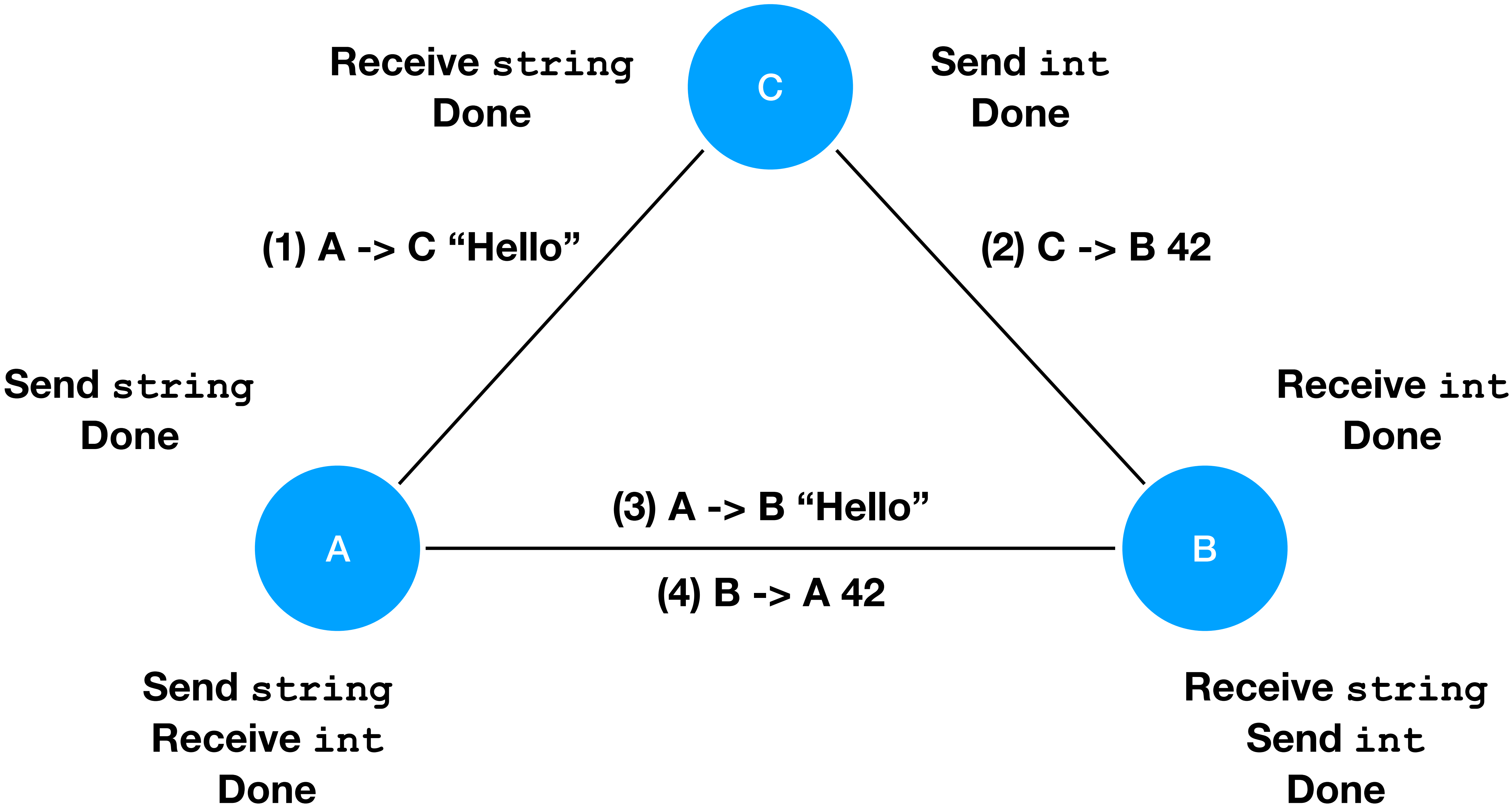
Quick Primer on Session Types

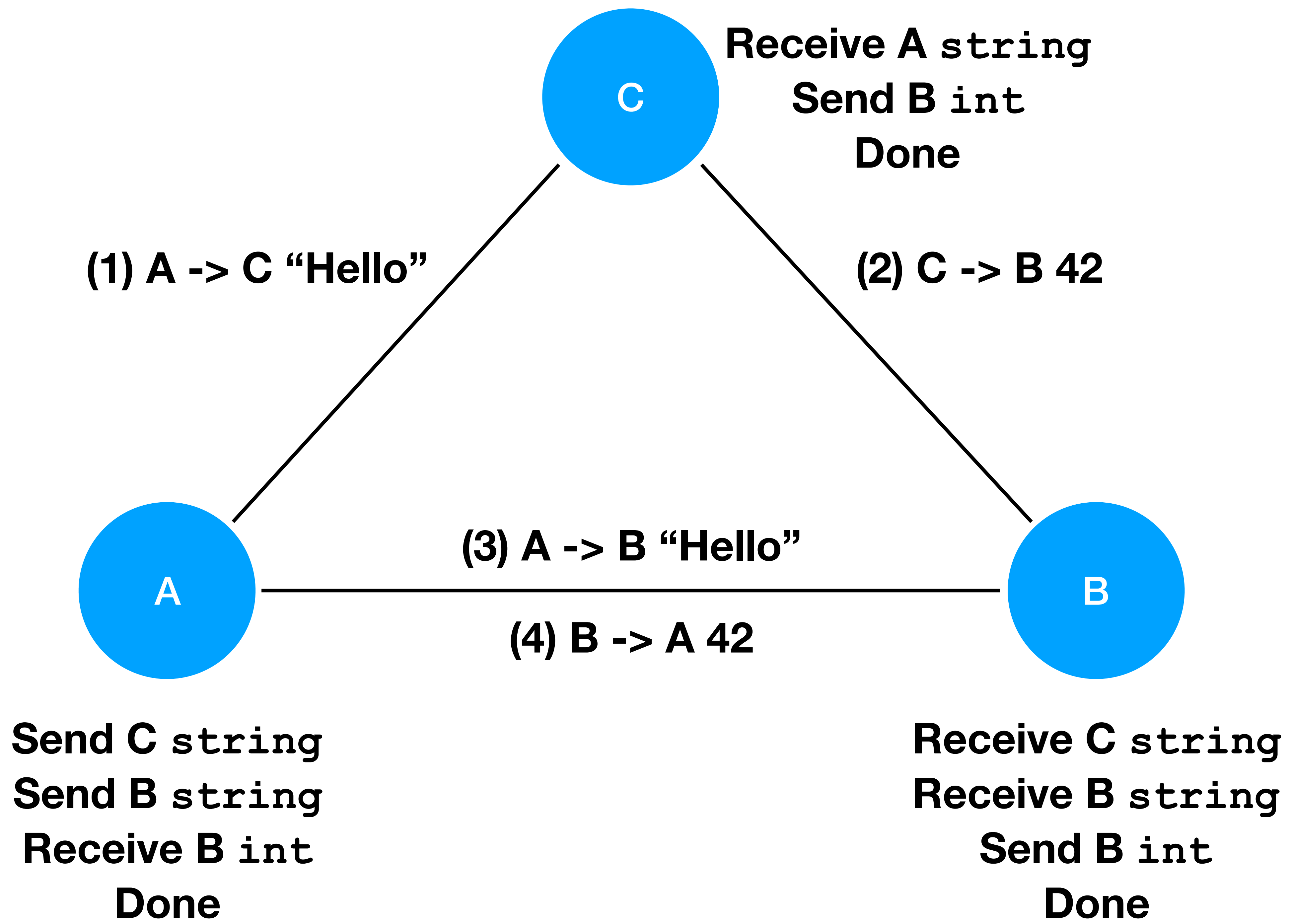
Concurrency

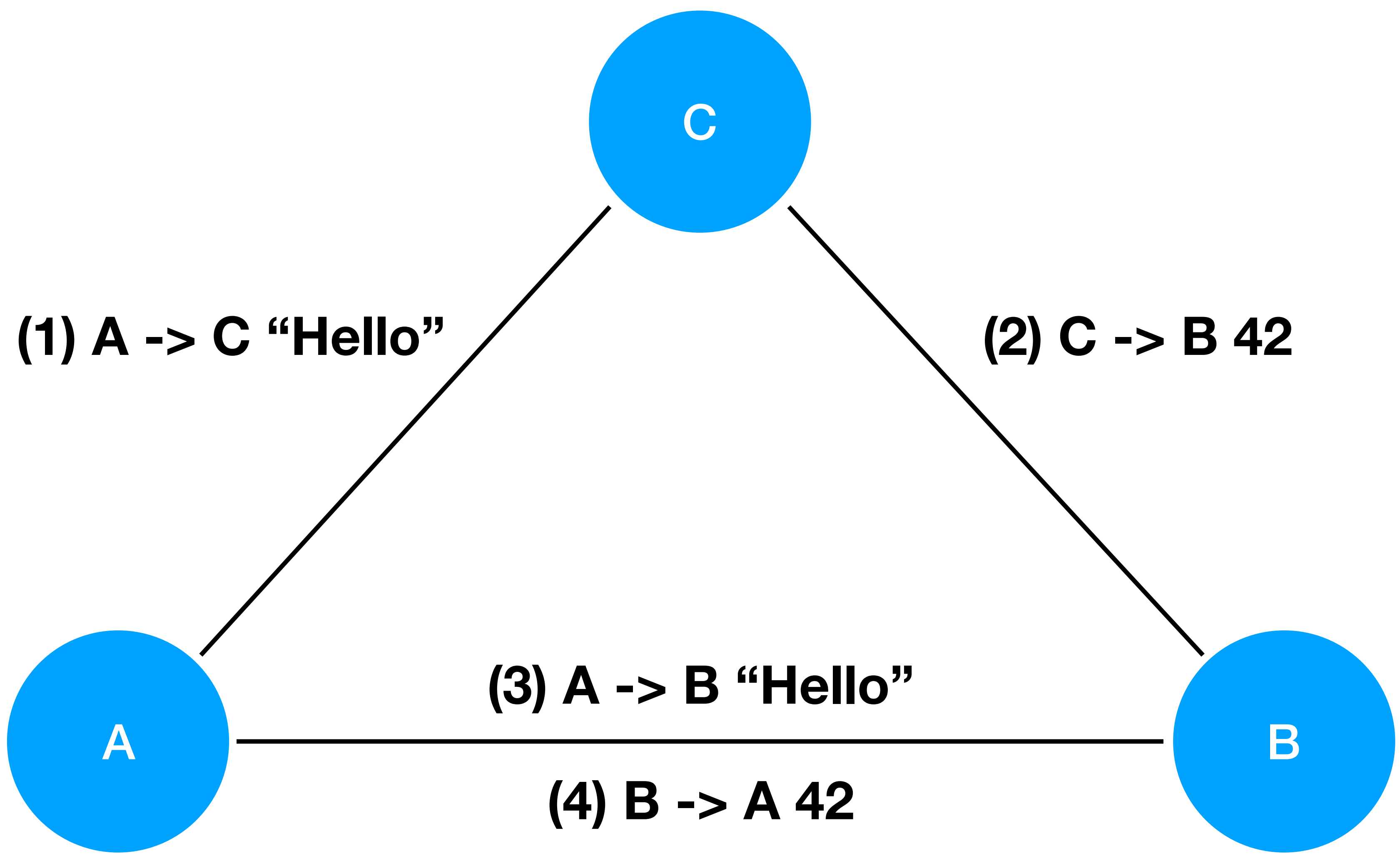
Shared Memory

Message Passing


A
B
(1) -> "Hello"
(2) <- 42
Send string
Receive int
Done
Duality
Receive string
Send int
Done


Receive string
Done
C
Send int
Done
(1) A -> C “Hello”
(2) C -> B 42
Send string
Done
Receive int
Done
A
(3) A -> B “Hello”
B
(4) B -> A 42
Send string
Receive int
Done
Receive string
Send int
Done


C
Receive A `string`
Send B `int`
Done
(1) A -> C "Hello"
(2) C -> B 42
A
(3) A -> B "Hello"
B
(4) B -> A 42
Send C `string`
Send B `string`
Receive B `int`
Done
Receive C `string`
Receive B `string`
Send B `int`
Done



Global Protocol

```
string from A to C;
int    from C to B;
string from A to B;
int    from B to A;
```

Motivation

Example: a simple protocol

- Two kids are playing a game on the playground
- **A** tells **B** a number
- **B** tries to find a larger number

```
protocol Playground (role A, role B) {
    initialGuess (int) from A to B;
    finalGuess (int) from B to A;
}
```

No guarantee whether this will be larger

Example: a simple protocol

- Two kids are playing a game on the playground
- **A** tells **B** a number
- **B** tries to find a larger number

```
protocol Playground (role A, role B) {
    initialGuess (x:int) from A to B @ x > 7;
    finalGuess (y:int) from B to A @ y > x;
}
```

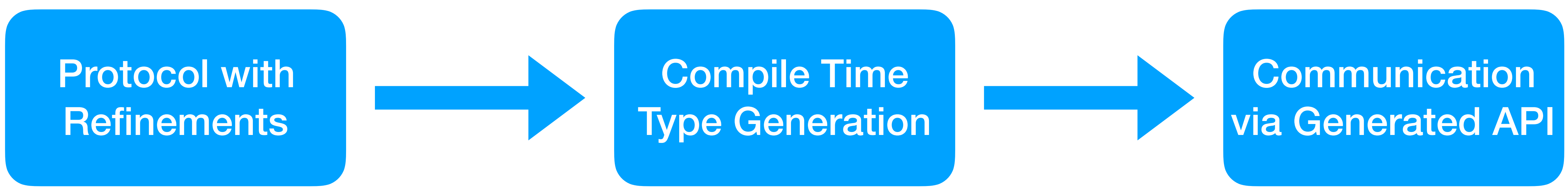
Named Parameters **Assertions**

Previously…

- Session Type Provider [Neykova et al. 2018]
  - Compile Time Type Generation in F#
  - Protocol validated during compilation
  - Refinements checked dynamically during execution

[Neykova et al. 2018]: Rumyana Neykova, Raymond Hu, Nobuko Yoshida, and Fahd Abdeljallal. 2018. A session type provider: compile-time API generation of distributed protocols with refinements in F#

Workflow (Previously)




```
protocol Playground
    (role A, role B) {
  initialGuess (x:int)
    from A to B @ x > 7;
  finalGuess (y:int)
    from B to A @ y > x;
}
```

```
type Protocol
  = SessionTypeProvider
    <“Playground.scr”, “A”>
```

```
let p =
  new Protocol().Init()
in
  p.send(B, initialGuess, 42)
   .receive(B, finalGuess, y)
   .finish()
```

Workflow (Now)

Protocol with Refinements → Compile Time **Refined** Type Generation → Communication via Generated **Refined** API → **Refinement Type Check**

Overview

- Add refinements to generated types
- Check refinements with a type system extension
    - Extract F# code into a refinement calculus
    - Check satisfiability using external solver

What are refinement types?

- Build upon an existing type system
- Allow base types to be refined via predicates
- Specify data dependencies
- Example: Liquid Haskell [Vazou et al. 2014]

[Vazou et al. 2014]: Niki Vazou, Eric L. Seidel, Ranjit Jhala, Dimitrios Vytiniotis, and Simon Peyton-Jones. 2014. Refinement types for Haskell.

Refinement Calculus: λ^H

- STLC with refinement types
- Terms can be encoded in SMT-LIB terms
- Establishes a subtyping relation via SMT solver

Types in λ^H

integers, booleans, …

- A base type

$$\{\nu : b \mid M\}$$

Base type b, value ν refined by term M

- A function type (dependent function)

$$(x : \tau_1) \to \tau_2$$

Variable x can occur in the type τ_2

c.f. Dependent Types $\prod_{x:\tau_1} \tau_2(x)$

Example

- The integer literal `1`
  - A possible type: $\{\nu : \textbf{int} \mid \nu = 1\}$
  - Another possible type: $\{\nu : \textbf{int} \mid \nu \geq 1\}$
  - Or more… $\{\nu : \textbf{int} \mid \textbf{true}\}$
- Solution: Bidirectional Typing

Bidirectional Typing

- Provides a more algorithmic approach
- Mutually inductive judgments
- Type Synthesis

$$\Gamma; \Delta \vdash M^{*} \Rightarrow \tau$$

Given Γ, Δ, M**, find the type** τ

***Not all terms are synthesisable**

- Type Check

$$\Gamma; \Delta \vdash M \Leftarrow \tau$$

Given Γ, Δ, M, τ**, determine if type is correct**

“Change of Direction” Rule

Subtyping Judgment **Well-formedness Judgment**

$$\frac{\Gamma;\Delta \vdash \tau <: \tau' \qquad \Gamma;\Delta \vdash M \Rightarrow \tau \qquad \Gamma;\Delta \vdash \tau'}{\Gamma;\Delta \vdash M \Leftarrow \tau'}$$

Subtyping with SMT

- Encode refinements term into SMT-LIB
- Use SMT solver to decide validity

$$\frac{\mathsf{Valid}(\llbracket\Gamma\rrbracket \wedge \llbracket\Delta\rrbracket \wedge \llbracket M_1\rrbracket \implies \llbracket M_2\rrbracket)}{\Gamma,\Delta \vdash \{v : b \mid M_1\} <: \{v : b \mid M_2\}}$$

Encoding in SMT-LIB

x **(A term Variable)** → x **(An SMT Variable)**

Encoding in SMT-LIB

(+) 1 2 → (+ 1 2)

Encoding in SMT-LIB

$x : \{\nu : \textbf{int} \mid \nu + 2 = 5\}$ $\longrightarrow$ $x + 2 = 5$

Encoding in SMT-LIB

$$\textbf{Valid}([\![\Gamma]\!] \wedge [\![\Delta]\!] \wedge [\![M_1]\!] \implies [\![M_2]\!])$$

$$\textbf{Unsat}([\![\Gamma]\!] \wedge [\![\Delta]\!] \wedge [\![M_1]\!] \wedge \neg [\![M_2]\!])$$

Subtyping with SMT

- Consider integer literal `1`
  - Synthesised type: $\{\nu : \textbf{int} \mid \nu = 1\}$
  - Check subtype: $\{\nu : \textbf{int} \mid \nu = 1\} <: \{\nu : \textbf{int} \mid \nu \geq 1\}$?
  - Encode into logic: $\textbf{SAT}((\nu = 1) \land \neg(\nu \geq 1))$?
  - Use SMT solver: **UNSAT**

Subtyping with SMT

- Consider term `x + 1` with context $x : \{\nu : \textbf{int} \mid \nu \geq 1\}$
  - Synthesised type: $\{\nu : \textbf{int} \mid \nu = x + 1\}$
  - Check subtype: $\{\nu : \textbf{int} \mid \nu = x + 1\} <: \{\nu : \textbf{int} \mid \nu \geq 2\}?$
  - Encode into logic: $\textbf{SAT}((x \geq 1) \wedge (v = x + 1) \wedge \neg(v \geq 2))?$
  - Use SMT solver: **UNSAT**

Generating Types

- Scribble validates protocol and generates CFSM
- Type Provider converts CFSM into F# code
- New: Adding refinements in types

From Protocol to CFSM (Scribble)

```
protocol Playground (role A, role B) {
    initialGuess (x:int) from A to B @ x > 7;
    finalGuess (y:int) from B to A @ y > x;
}
```

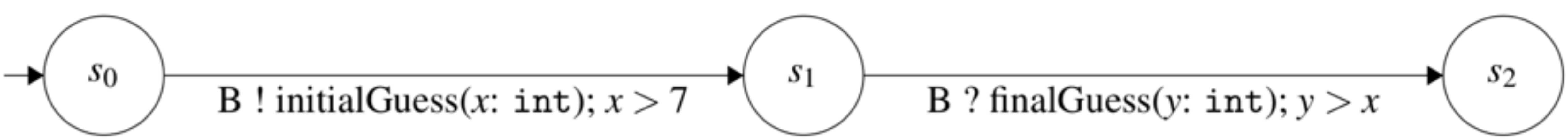
Projection to role A

`protocol Playground (role A, role B) {`
    `initialGuess (x:int)` ~~`from A`~~ `to B @ x > 7;`
    `finalGuess (y:int) from B` ~~`to A`~~ `@ y > x;`
`}`

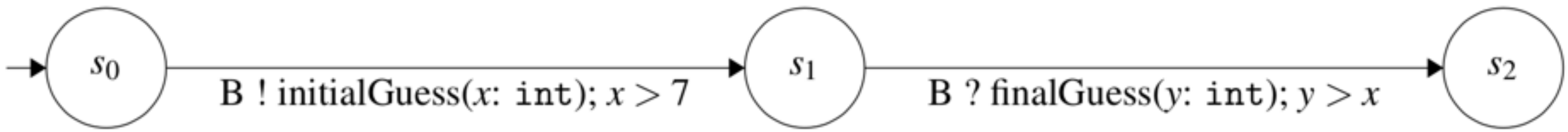
From Protocol to CFSM
(Scribble)

```
protocol Playground (role A, role B) {
     initialGuess (x:int) from A to B @ x > 7;
     finalGuess (y:int) from B to A @ y > x;
}
```

Projection to role `A`



From CFSM to λ^H (Type Provider)



$\emptyset$

$x : \{\nu : \textbf{int} \mid \nu > 7\}$

$x : \{\nu : \textbf{int} \mid \nu > 7\}$

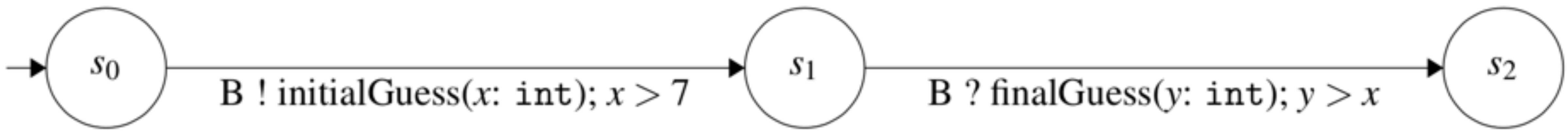
$y : \{\nu : \textbf{int} \mid \nu > x\}$

```
type State0 = {}
```

```
type State1 = {
  x: {v:int|v>7};
}
```

```
type State2 = {
  x: {v:int|v>7};
  y: {v:int|v>x};
}
```

From CFSM to λ^H
(Type Provider)



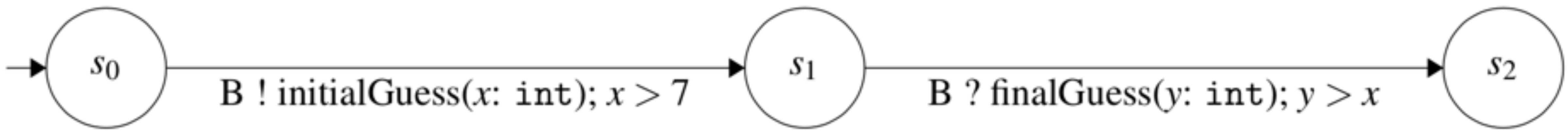

```
type State0 = {}
```

```
type State1 = {
  x: {v:int|v>7};
}
```

```
type State2 = {
  x: {v:int|v>7};
  y: {v:int|v>x};
}
```

```
initialGuess : (st: State0) -> (x: {v:int|v>7}) -> State1
```

From CFSM to λ^H (Type Provider)



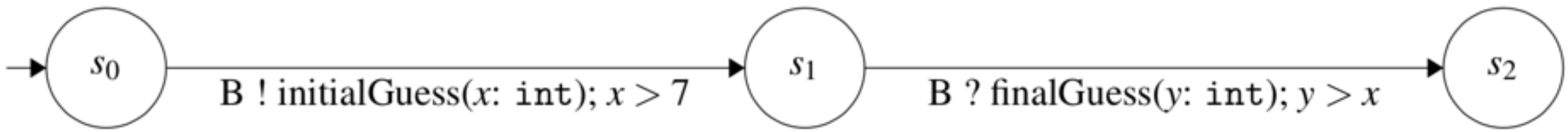

```
type State0 = {}
```

```
type State1 = {
  x: {v:int|v>7};
}
```

```
type State2 = {
  x: {v:int|v>7};
  y: {v:int|v>x};
}
```

```
finalGuess : (st: State1) -> (State2 * {v:int|v>st.x})
```

From CFSM to λ^H
(Type Provider)




```
type State0 = {}
```

```
type State1 = {
  x: {v:int|v>7};
}
```

```
type State2 = {
  x: {v:int|v>7};
  y: {v:int|v>x};
}
```

```
initialGuess : (st: State0) -> (x: {v:int|v>7}) -> State1
  finalGuess : (st: State1) -> (State2 * {v:int|v>st.x})
```

One Last Step…

- Typecheck the program with refined types
  - Extract F# expressions to terms in λ^H
  - Use F# Compiler Services to obtain AST
  - Check whether API usage is correct w.r.t. refinements

Future Work

- Support recursion in protocols
- Complete meta-theory for refinements in MPST
  - End to end meta-theory
- Support more features in refinement calculus

Thank you!