A Session Type Provider

Compile-Time API Generation of Distributed Protocols with Refinements in F#

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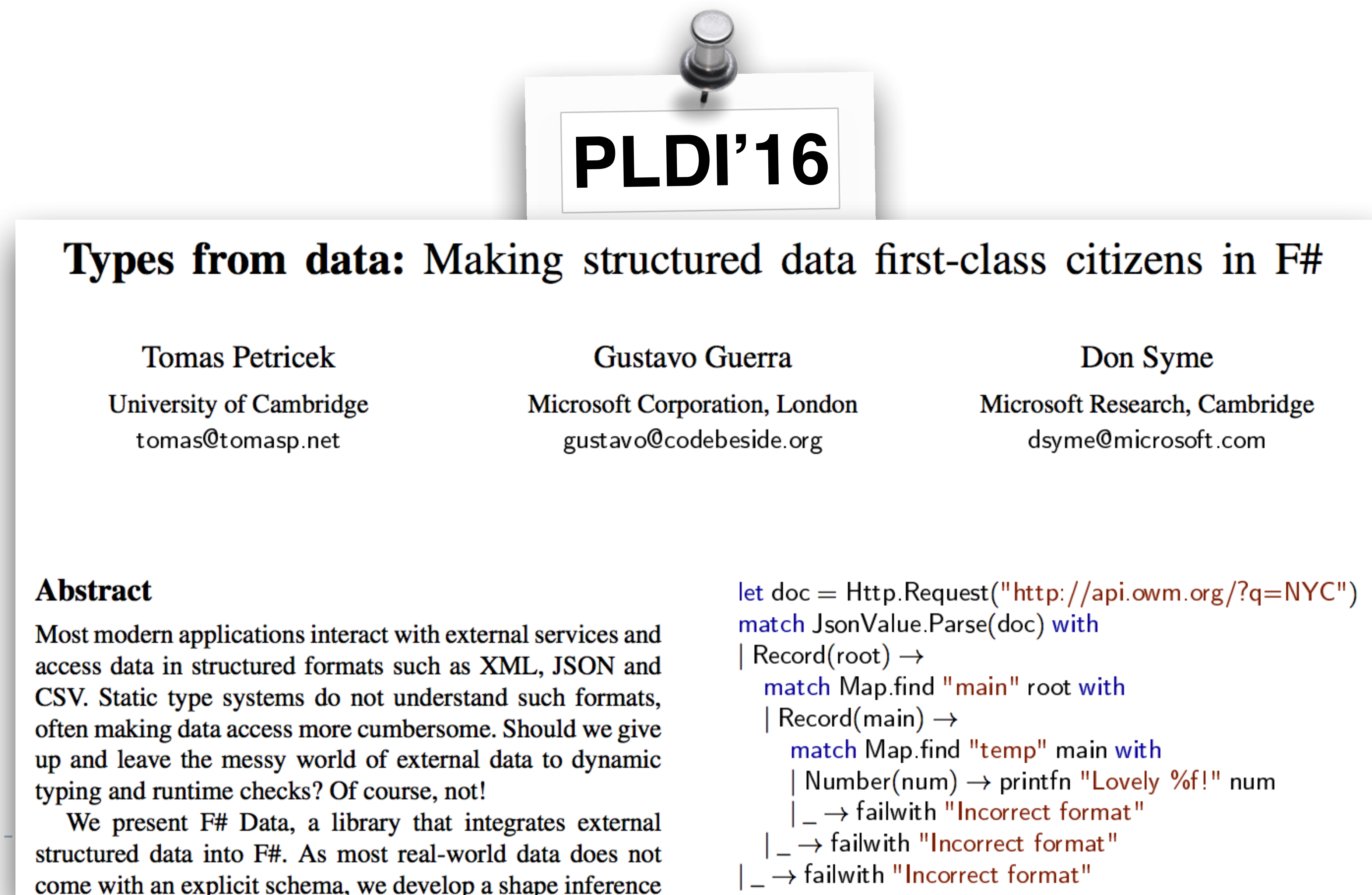
Part One
Type Providers

Type Providers

Problem: Languages do not integrate information

- We need to bring information into the language


PLDI'16

Types from data: Making structured data first-class citizens in F#

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Abstract

Most modern applications interact with external services and access data in structured formats such as XML, JSON and CSV. Static type systems do not understand such formats, often making data access more cumbersome. Should we give up and leave the messy world of external data to dynamic typing and runtime checks? Of course, not!

We present F# Data, a library that integrates external structured data into F#. As most real-world data does not come with an explicit schema, we develop a shape inference


```
let doc = Http.Request("http://api.owm.org/?q=NYC")
match JsonValue.Parse(doc) with
| Record(root) →
  match Map.find "main" root with
  | Record(main) →
    match Map.find "temp" main with
    | Number(num) → printfn "Lovely %f!" num
    | _ → failwith "Incorrect format"
  | _ → failwith "Incorrect format"
| _ → failwith "Incorrect format"
```

Before Type Providers

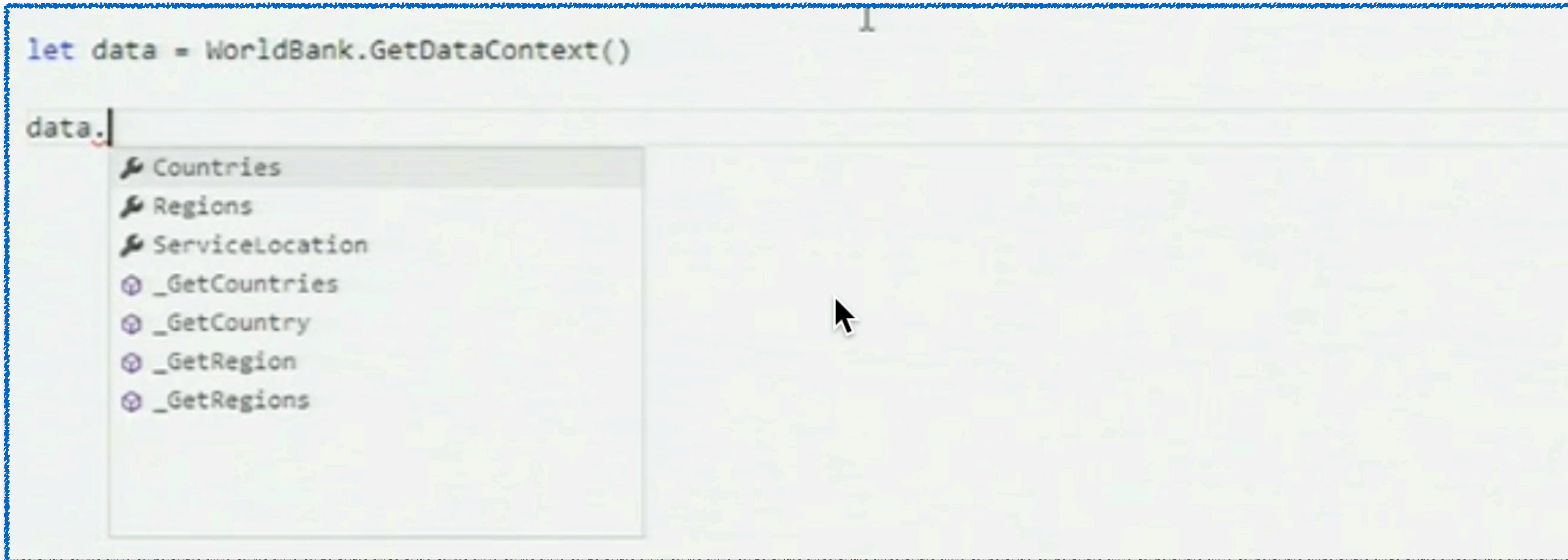
With Type Providers

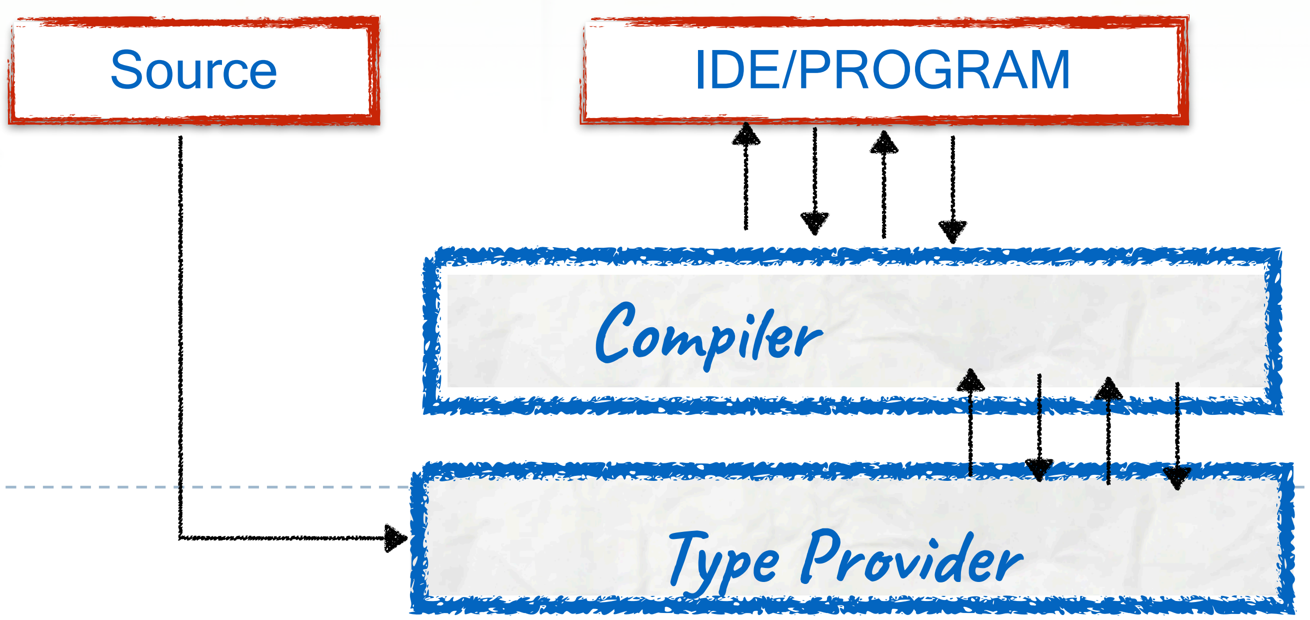
```
let doc = Http.Request("http://api.owm.org/?q=NYC")
match JsonValue.Parse(doc) with
| Record(root) →
  match Map.find "main" root with
  | Record(main) →
    match Map.find "temp" main with
    | Number(num) → printfn "Lovely %f!" num
    | _ → failwith "Incorrect format"
  | _ → failwith "Incorrect format"
| _ → failwith "Incorrect format"
```

```
type W = JsonProvider⟨"http://api.owm.org/?q=NYC"⟩
printfn "Lovely %f!" (W.GetSample().Main.Temp)
```

- ☑ all data is typed
- ☑ on-demand generation
- ☑ autocompletion
- ☑ background type-checking

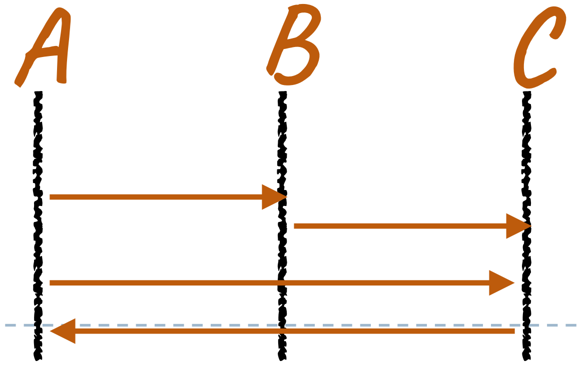
WorldBank Type Providers





Useful for structured data?

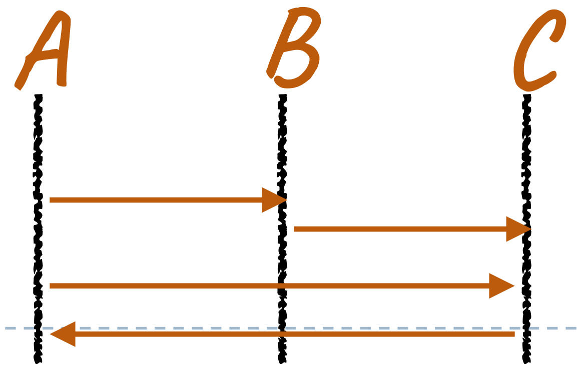
How about structured communication?



A generalisation to distributed protocols requires

- a notion of **schema for structured interactions** between services
- an understanding of how to extract the **localised behaviour** for each services

How about structured communication?



Part Two
Session Types

POPL'08

Multiparty Asynchronous Session Types

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Abstract

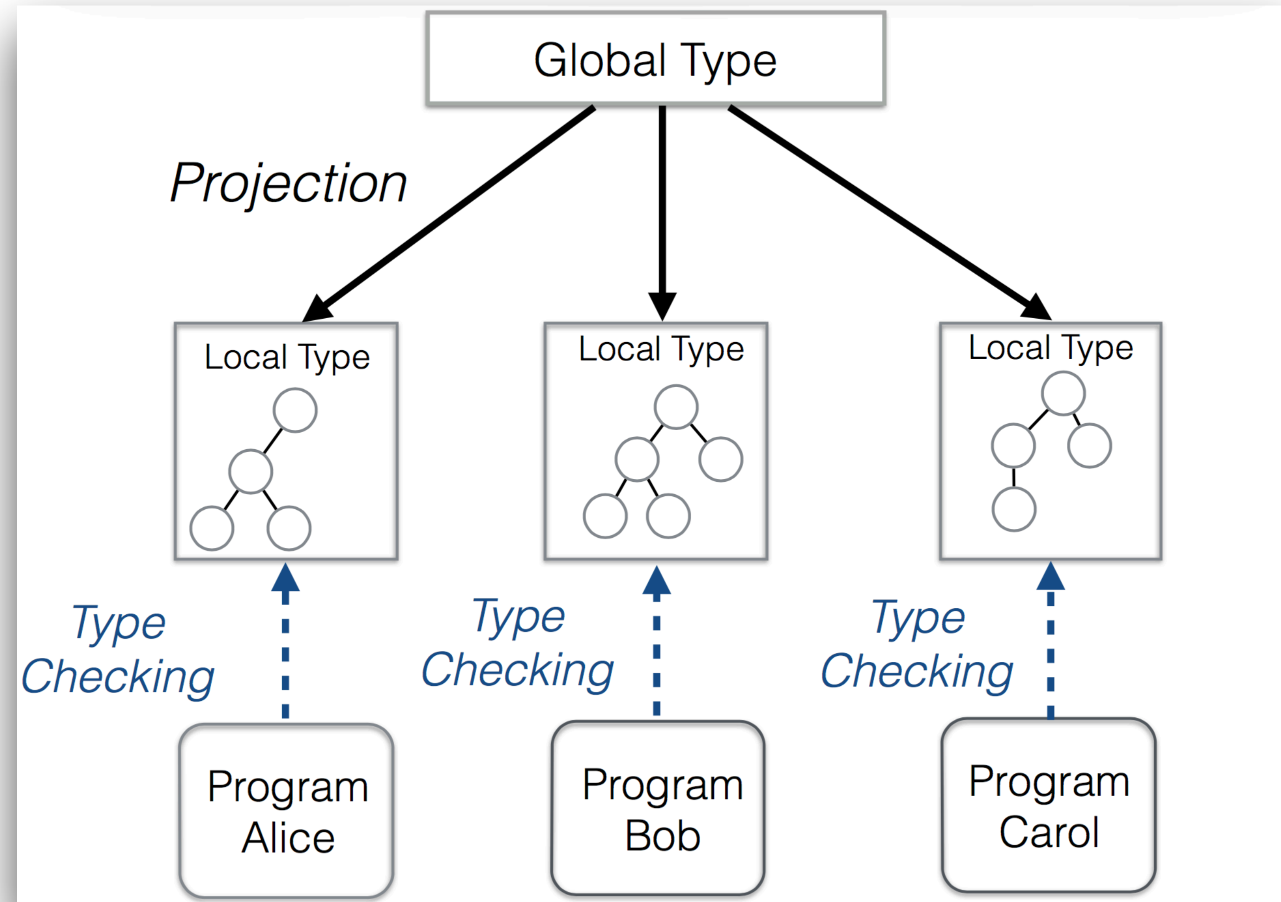
Communication is becoming one of the central elements in software development. As a potential typed foundation for structured communication-centred programming, session types have been studied over the last decade for a wide range of process calculi and programming languages, focussing on binary (two-party) sessions. This work extends the foregoing theories of binary session types to multiparty, asynchronous sessions, which often arise in practical communication-centred applications. Presented as a typed calculus for mobile processes, the theory introduces a new notion of types in which interactions involving multiple peers are directly abstracted as a global scenario. Global types retain a friendly type syntax of binary session types while capturing complex causal chains of multiparty asynchronous interactions. A global type plays the role of a shared agreement among communication peers, and is used as a basis of efficient type checking through its projection onto individual

vices (Carbone et al. 2006, 2007; WS-CDL; Sparkes 2006; Honda et al. 2007a). A basic observation underlying session types is that a communication-centred application often exhibits a highly structured sequence of interactions involving, for example, branching and recursion, which as a whole form a natural unit of conversation, or *session*. The structure of a conversation is abstracted as a type through an intuitive syntax, which is then used as a basis of validating programs through an associated type discipline.

As an example, the following session type describes a simple business protocol between Buyer and Seller from Buyer's viewpoint: Buyer sends the title of a book (a string), Seller sends a quote (an integer). If Buyer is satisfied by the quote, then sends his address (a string) and Seller sends back the delivery date (a date); otherwise it quits the conversation.

$$!\mathsf{string}; ?\mathsf{int}; \oplus\{\mathsf{ok} : !\mathsf{string}; ?\mathsf{date}; \mathsf{end}, \quad \mathsf{quit} : \mathsf{end}\} \qquad (1)$$

Session Types



- Protocol Validation

```
(int) from C to S;
(bool) from S to C;
```

✅

- Program Verification

```
runB c = let (x, c') =
receive c in send true c'
```

✅

A system of *well-behaved processes* is free from deadlocks, orphan messages and reception errors

Useful for structured data?

Data Type providers bring information into the language as strongly tooled, strongly typed

How about structured communication?

Session Type providers *bring* ***communication*** *into the language as strongly tooled, strongly typed*

Our Solution: Session Type Providers

```
Div(x:int, y:int) from C to S;
Res(z:float) from S to C;
```

```
type Prot = STP<"Prot.scr", C>
 let s = new Prot().Init()
   s.
```

Session Type Provider

Our Solution: Session Type Providers

```
Div(x:int, y:int) from C to S;
Res(z:float) from S to C;
```

```
type Prot = STP<“Prot.scr”, C>
 let s = new Prot().Init()
   s.
```

send

State2 State1.send(S Role, Div label, int x, int y)
Constraints: y!=0

Session Type Provider

Our Solution: Session Type Providers

```
Div(x:int, y:int) from C to S;
Res(z:float) from S to C;
```

```
type Prot = STP<"Prot.scr", C>
 let s = new Prot().Init()
   s.send(S, Div, 6, 3)
```

Session Type Provider

Our Solution: Session Type Providers

```
Div(x:int, y:int) from C to S;
Res(z:float) from S to C;
```

```
type Prot = STP<"Prot.scr", C>
 let s = new Prot().Init()
   s.send(S, Div, 6, 3)
    .
```

```
receive    State3 State1.receive(S Role, Res label, Buf<float> f)
```

Session Type Provider

Our Solution: Session Type Providers

```
Div(x:int, y:int) from C to S;
Res(z:float) from S to C;
```

```
type Prot = STP<"Prot.scr", C>
 let s = new Prot().Init()
   s.send(S, Div, 6, 3)
    .receive(S, Res, y)
```

Session Type Provider

Our Solution: Session Type Providers

```
Div(x:int, y:int) from S to C;
Res(z:float) from S to C;
```

```
type Prot = STP<"Prot.scr", C>
 let s = new Prot().Init()
   s.
```

Session Type Provider

Our Solution: Session Type Providers

```
Div(x:int, y:int) from C to S;
Res(z:float) from S to C;
```

```
type Prot = STP<“Prot.scr”, C>
 let s = new Prot().Init()
   s.send(S, Div, 6, “hello”)
```

Wrong **payload**

Session Type Provider

Our Solution: Session Type Providers

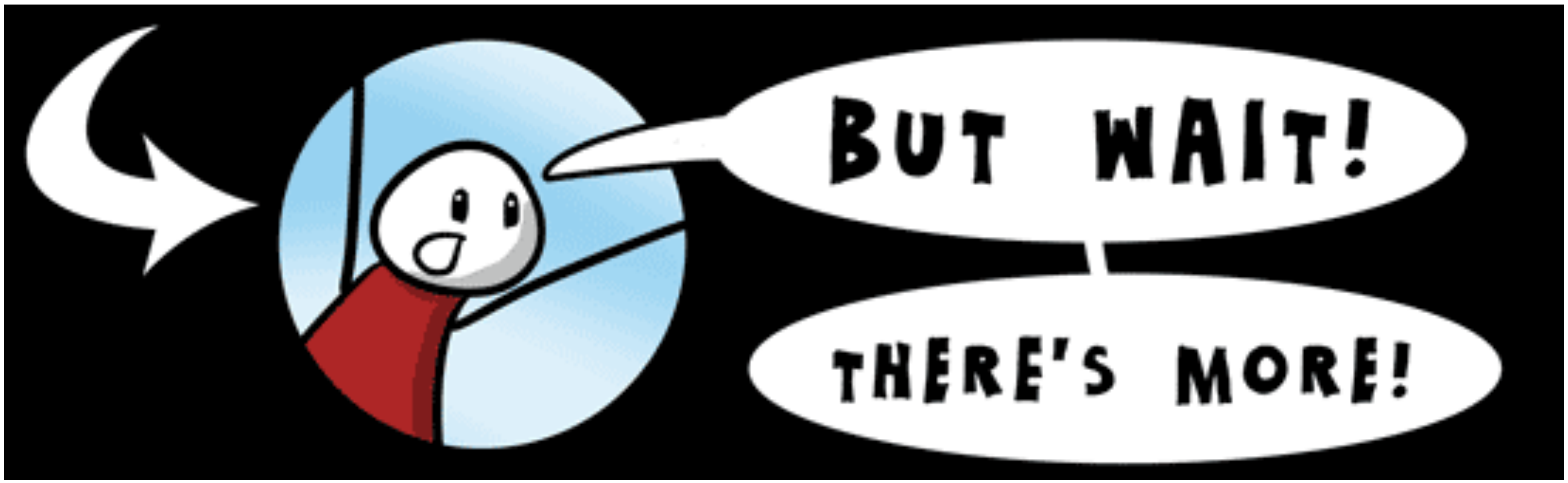
```
Div(x:int, y:int) from C to S;
Res(z:float) from S to C;
```

```
type Prot = STP<“Prot.scr”, A>
```

Wrong **protocol**

Session Type Provider

Session Type providers *bring* ***communication*** *into the language as strongly tooled, strongly typed*



Calculator Revisited!

y!=0

```
global protocol Ca    role S, role C){
 choice at C {
  Div(x:int, y:int) from C to S;
  Res(z:float) from C to S;
  do Calc(C, S);
 } or {
  Add(x:int, y:int) from C to S;
  Res(z:int) from S to C;
  do Calc(C, S);
 } or {
  Sqrt(x:float) from C to S;
  Res(y:floa ) from S to C;
  do Calc(C, S
 } or {
  Bye() fro
  Bye() from S
 }
}
```

x>0

Scribble with refinements

```
global protocol Calc(role S, role C){
 choice at C {
  Div(x:int, y:int) from C to S;@y!=0
  Res(z:float) from C to S;
  do Calc(C, S);
 } or {
  Add(x:int, y:int) from C to S;
  Res(z:int) from S to C;
  do Calc(C, S);
 } or {
  Sqrt(x:float) from C to S;@x>0
  Res(y:float) from S to C;
  do Calc(C, S);
 } or {
  Bye() from C to S;
  Bye() from S to C;
 }
}
```

interaction refinement

New

Part Three

A Session Type Provider

What do you get from a session type provider?

Session Types — **Safety**

- A statically well-typed endpoint program will never perform a non-compliant I/O action w.r.t. the source protocol.

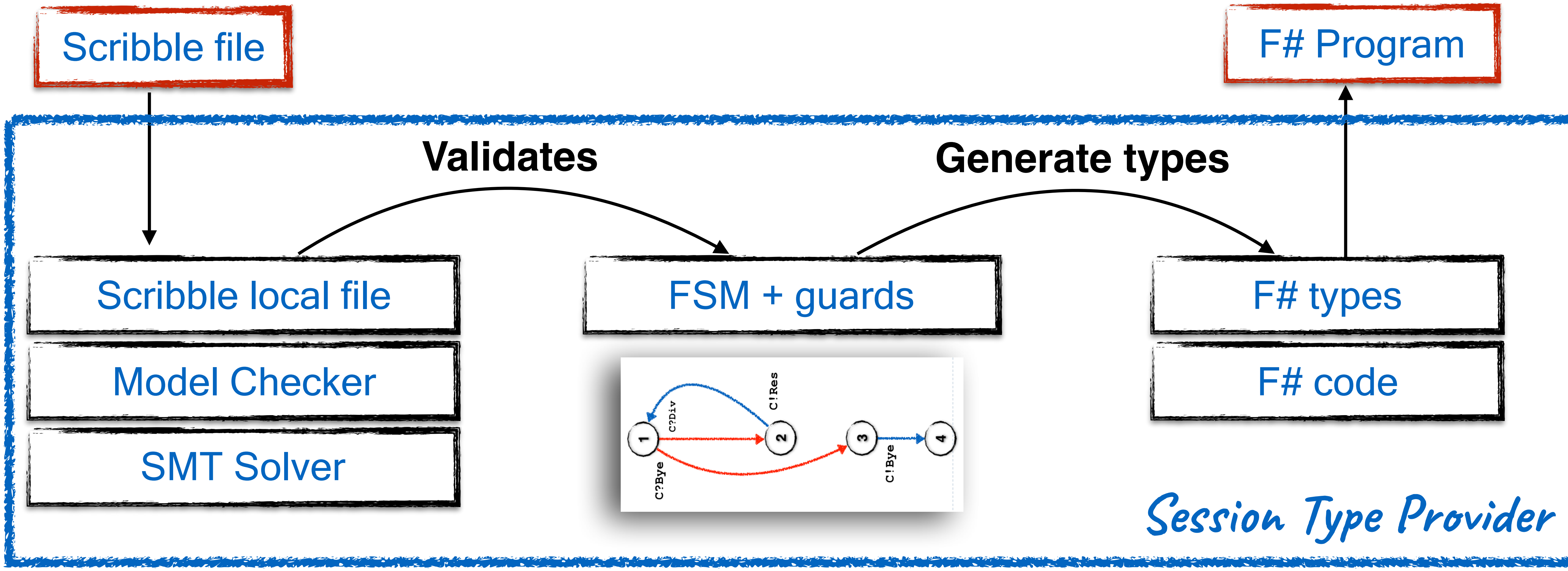
Type Providers — **Usability**

- compile-time generation
- background type checking & auto-completion
- a platform for tool integration (e.g. protocol validation)

Interaction refinements — **Reliability**

- runtime enforcement of constraint
- implicitly send values that can be inferred (safe by construction)
- do not send values that can be locally inferred

A Session Type Provider (Architecture)

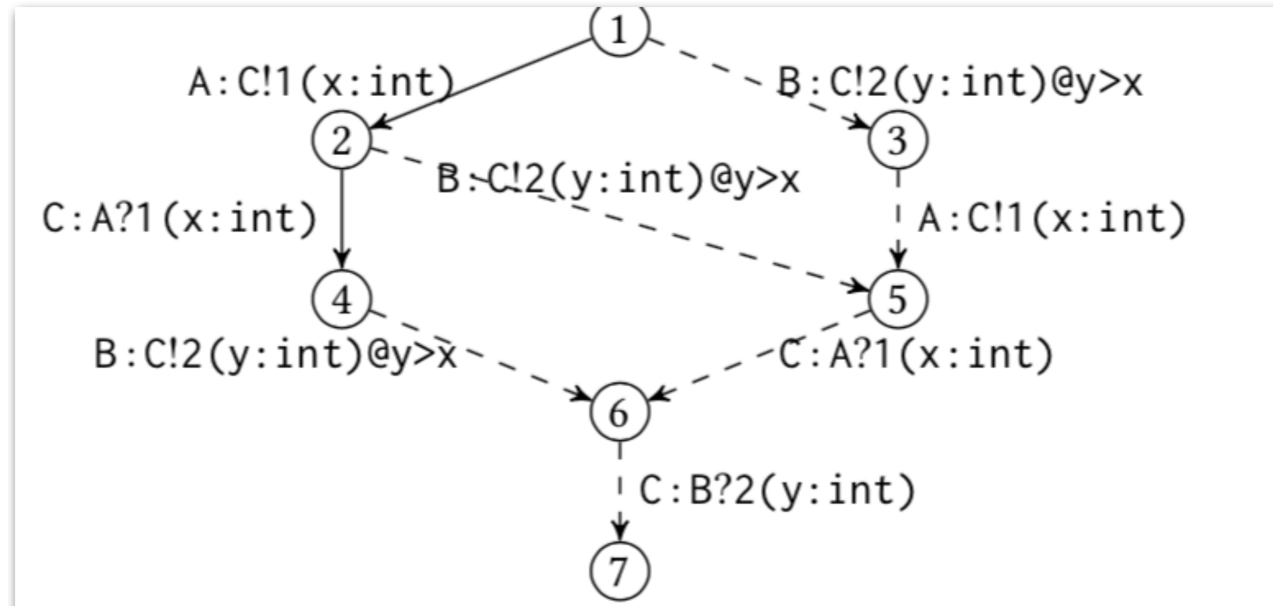


The type provider framework is used for tool integration

Model **Properties** **CFSM** **F# Type** **Code**

Model | **Properties** | **CFSM** | **F# Type** | **Code**

```
1(x:int) from A to C;
2(y:int) from B to C; @y>x
```



Bounded model checking as a validation methodology [FASE'16]

Safety Properties:

- ☑ reception-error freedom
- ☑ orphan-message freedom
- ☑ deadlock freedom

Refinement satisfiability

Refinement progress

Refinement satisfiability

- *check if the conjunction of all formulas is satisfiable*
  e.g. (and (> y (+ x 1))(< y 4)(> x 3))

```
1(x:int) from A to B; @x>3
choice at B {2() from B to A;}
         or {3(y:int) from B to A; @y>x+1 and y<4}
```

✗

Checks if all execution paths are reachable

```
1(x:int) from A to B; @x>3
choice at B {2() from B to A;}
         or {3(y:int) from B to A; @y>x+1 and y>4}
```

✓

Refinement satisfiability

- *check if the conjunction of all formulas is satisfiable*
  e.g. (and (> y (+ x 1))(< y 4)(> x 3))

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1(x:int) from A to B; @x>3
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```

✗

```
1(x:int) from A to B; @x>3
choice at B {2() from B to A;}
         or {3(y:int) from B to A; @y>x+1 and y>4}
```

✓

Model | **Properties** | CFSM | F# Type | Code

Refinement progress

- check if formula is satisfiable for all preceding solutions
  e.g.(forall ((x Int)(y Int))(=> (> x 3)(or (< x y)(> x y))))

```
1(x:int) from A to B; @x>3
2(y:int) from A to B;
choice at B {3() from B to A; @x>y}
```

```
1(x
2(y
cho
         or {4(y:int) from B to A; @x>y}
```

Ensures that at any output point in the protocol implementations there will be **always** some values for which the formula holds

```
1(x:int) from A to B; @x>3
2(y:int) from A to B; @y<=3
choice at B {3() from B to A; @x>=y}
         or {4(y:int) from B to A; @x<y}
```

Refinement progress

- check if formula is satisfiable for all preceding solutions
  e.g.(forall ((x Int)(y Int))(=> (> x 3)(or (< x y)(> x y))))

```
1(x:int) from A to B; @x>3
2(y:int) from A to B;
choice at B {3() from B to A; @x>y}
         or {4() from B to A; @x<y}
```

✗

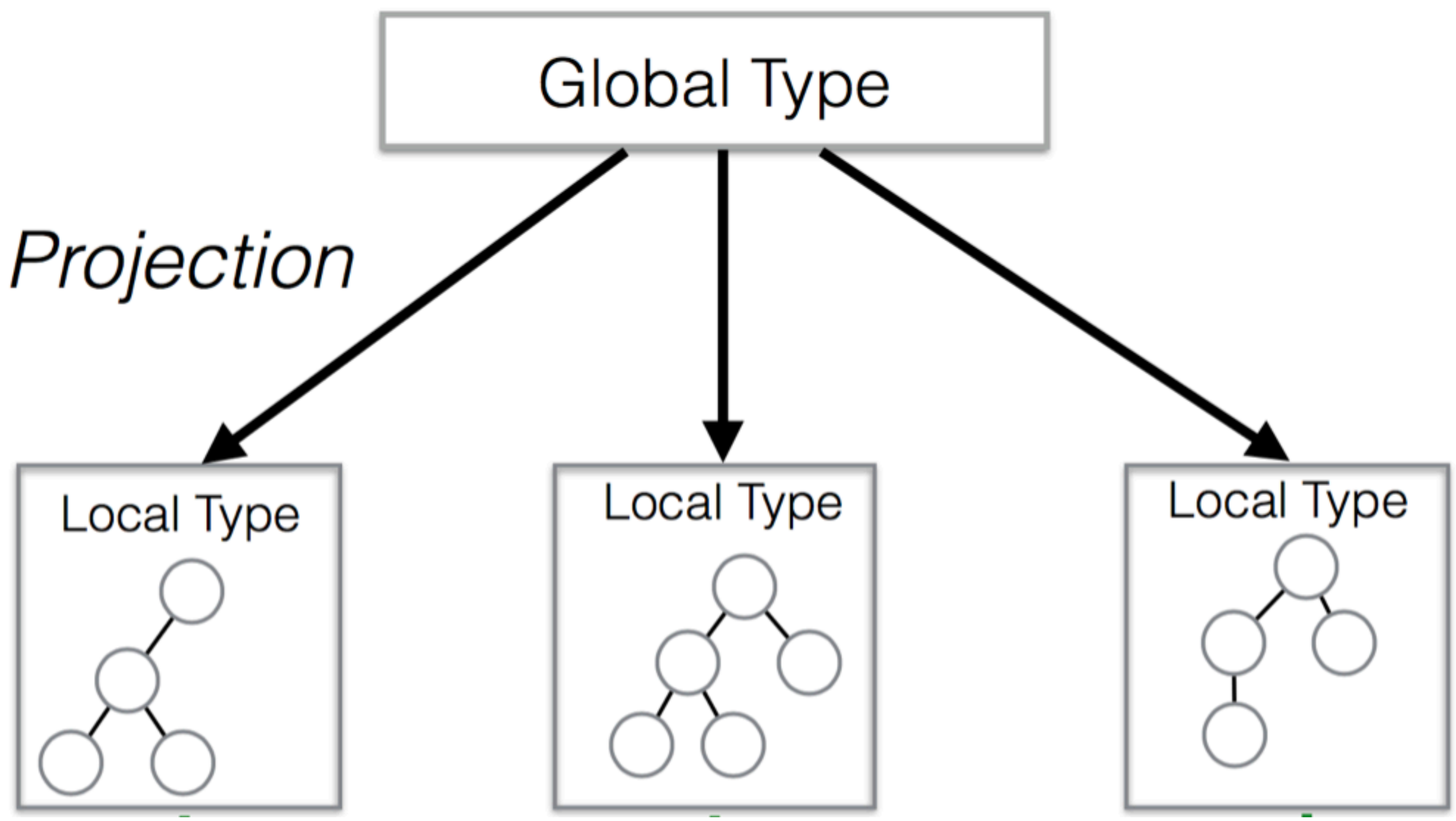
```
1(x:int) from A to B; @x>3
2(y:int) from A to B;
choice at B {3() from B to A; @x>=y}
         or {4() from B to A; @x<y}
```

✓

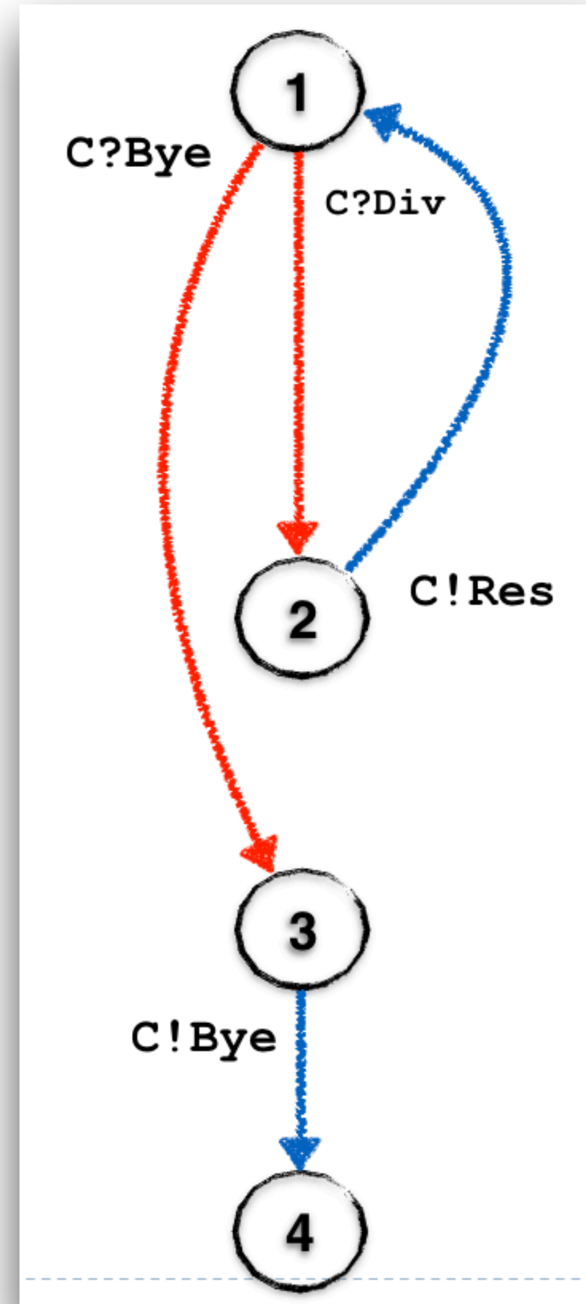
```
1(x:int) from A to B; @x>3
2(y:int) from A to B; @y<=3
choice at B {3() from B to A; @x>y}
         or {4() from B to A; @x<y}
```

✓ / ✗

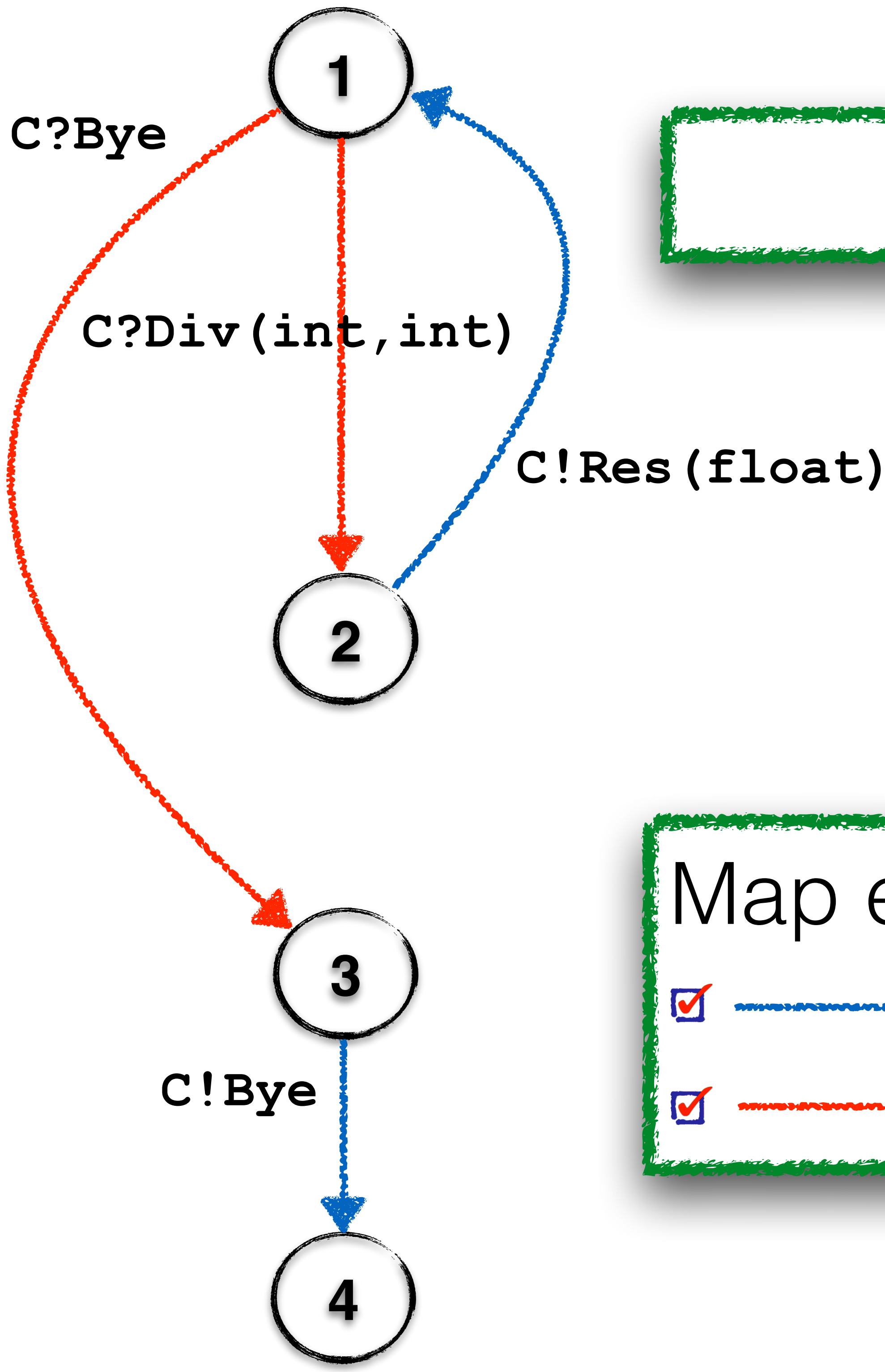
```
(x:T1) from A to B;   (y:T2) from B to C;  (z:T3) from C to A;
```



```
global protocol Calc(role S, role C){
choice at C {
 Div(x:int, y:int) from C to S; @y!=0
 Res(z:float) from C to S;
 do Calc(C, S);
 } or {
 Bye() from C to S;
 Bye() from S to C;
 }
}
```



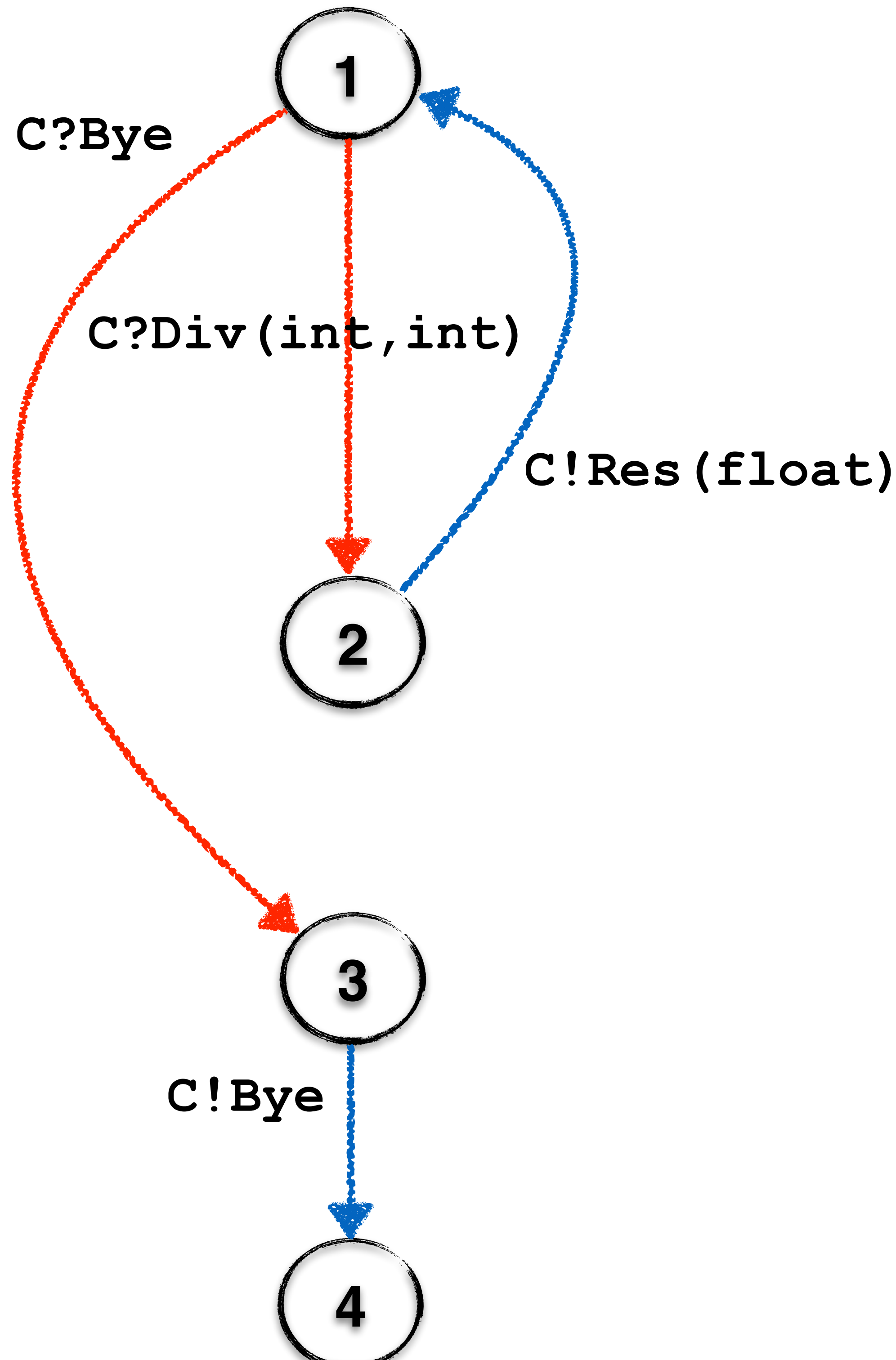
Model | Properties | CFSM | **F# Type** | Code



Map each state to a class

Map each transition to a method, e.g:

- ☑ → send method
- ☑ → receive method



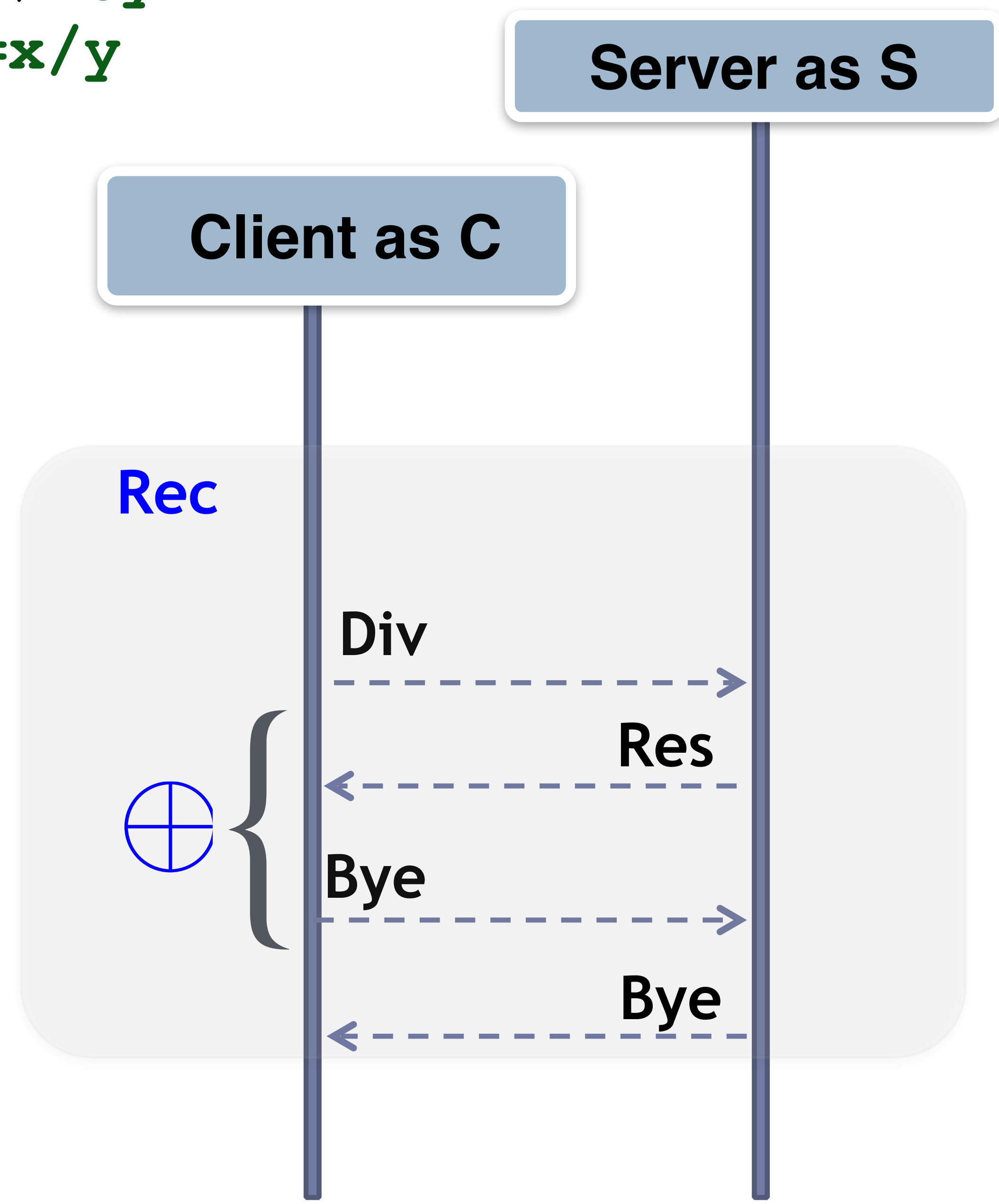

```
type State2 =
    member send: C*Res*float→ State1
```

```
type State3 =
    member send: C*Bye→ State4
```

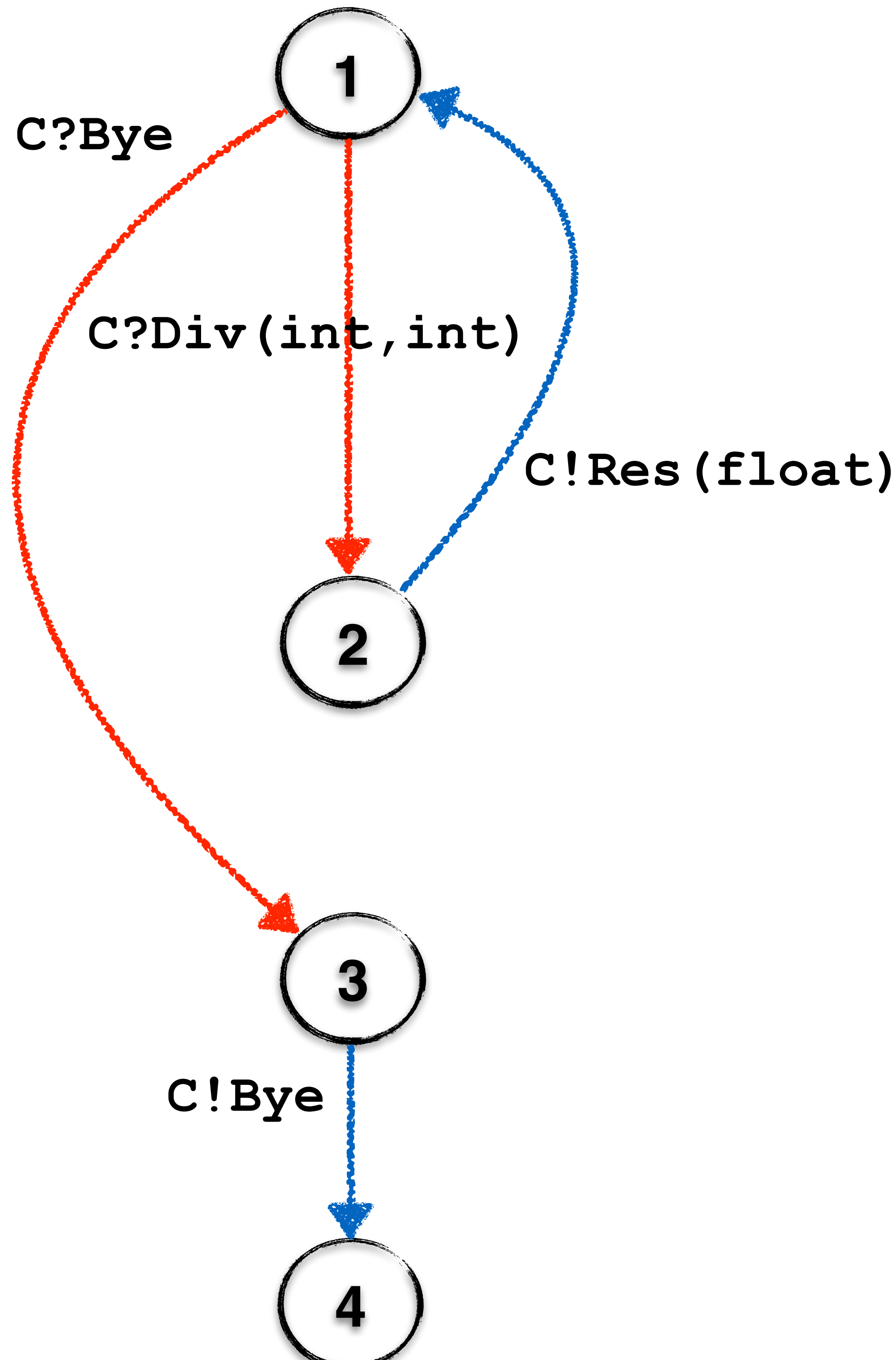
```
type State4 =
    member finish: unit→ End
```

Model | Properties | CFSM | **F# Type** | Code

```
global protocol Calc(role S, role C){
 choice at C {
   Div(x:int, y:int) from C to S; @y!=0
   Res(z:float) from C to S; @z=x/y
   do Addeer(C, S);
 } or {
   Bye() from C to S;
   Bye() from S to C;
 }
}
```



Model | Properties | CFSM | **F# Type** | Code



type State1 =
member branch: unit→ ChoiceS1

type Div = interface ChoiceS1
member receive: int*int→ State2

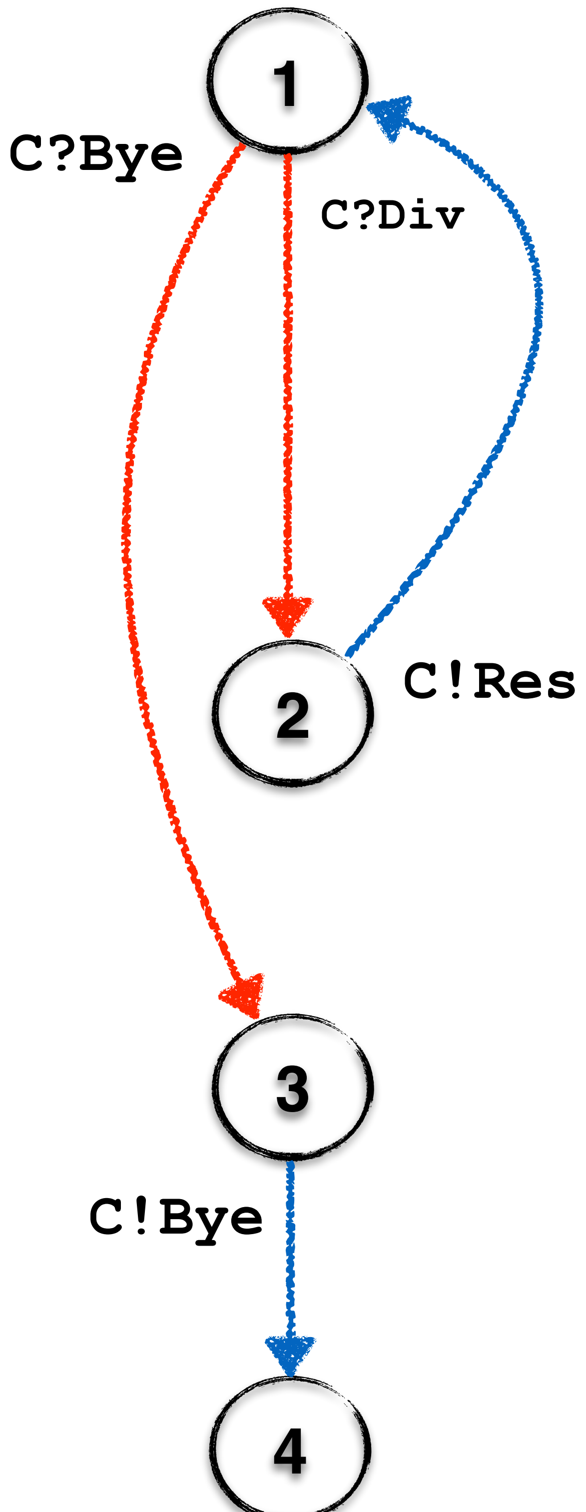
type Bye = interface ChoiceS1
member receive: → State3

type State2 =
member send: C*Res*~~float~~→ State1

type State3 =
member send: C*Bye→ State4

type State4 =
member finish: unit→ End

Model | Properties | CFSM | F# Type | **Code**




```
let rec calcServer (c:Calc.State1) =

  match c.branch() with
  |:? Calc.Bye as bye->

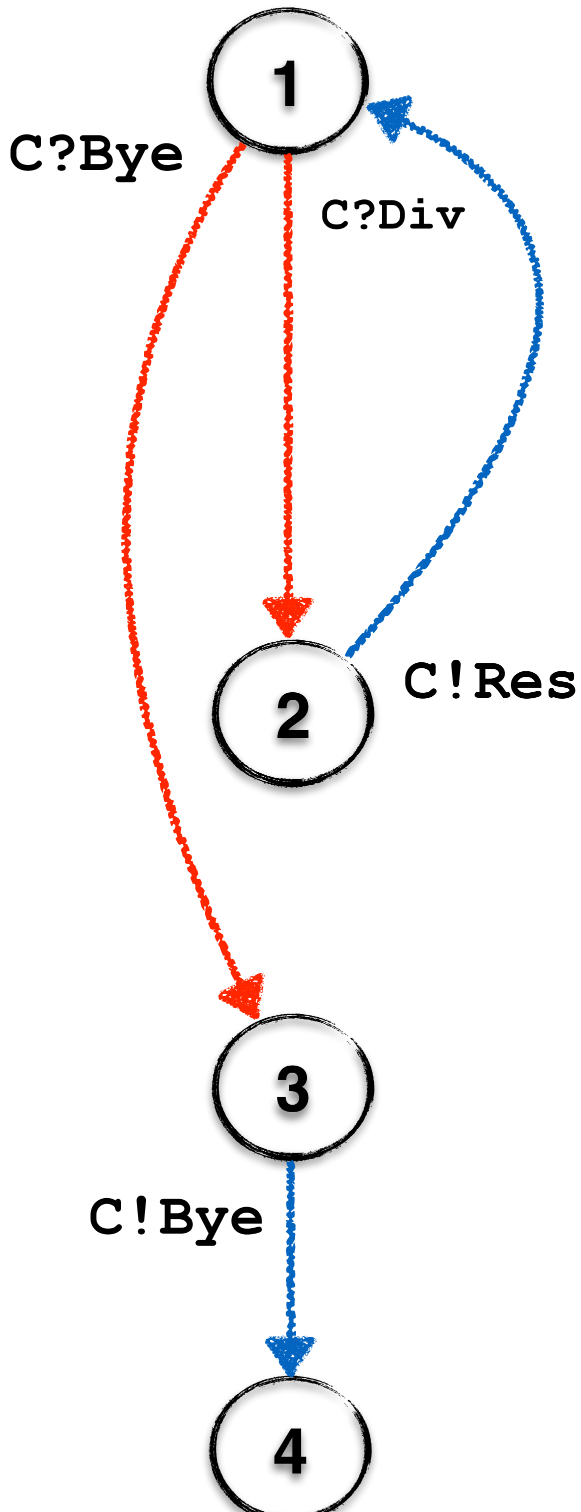


  |:? Calc.Div as div ->




calcServer c1
```

Model | Properties | CFSM | F# Type | **Code**




```
let rec calcServer (c:Calc.State1) =
 let x, y = new Buf<int>(),new Buf<int>()
  match c.branch() with
   |:? Calc.Bye as bye->
    bye.receive(C)
          .send(C, Bye).finish()

   |:? Calc.Div as div ->
    let c1 = div.receive(C, x, y)
                         .send(C, Res, x.Val/y.Val)

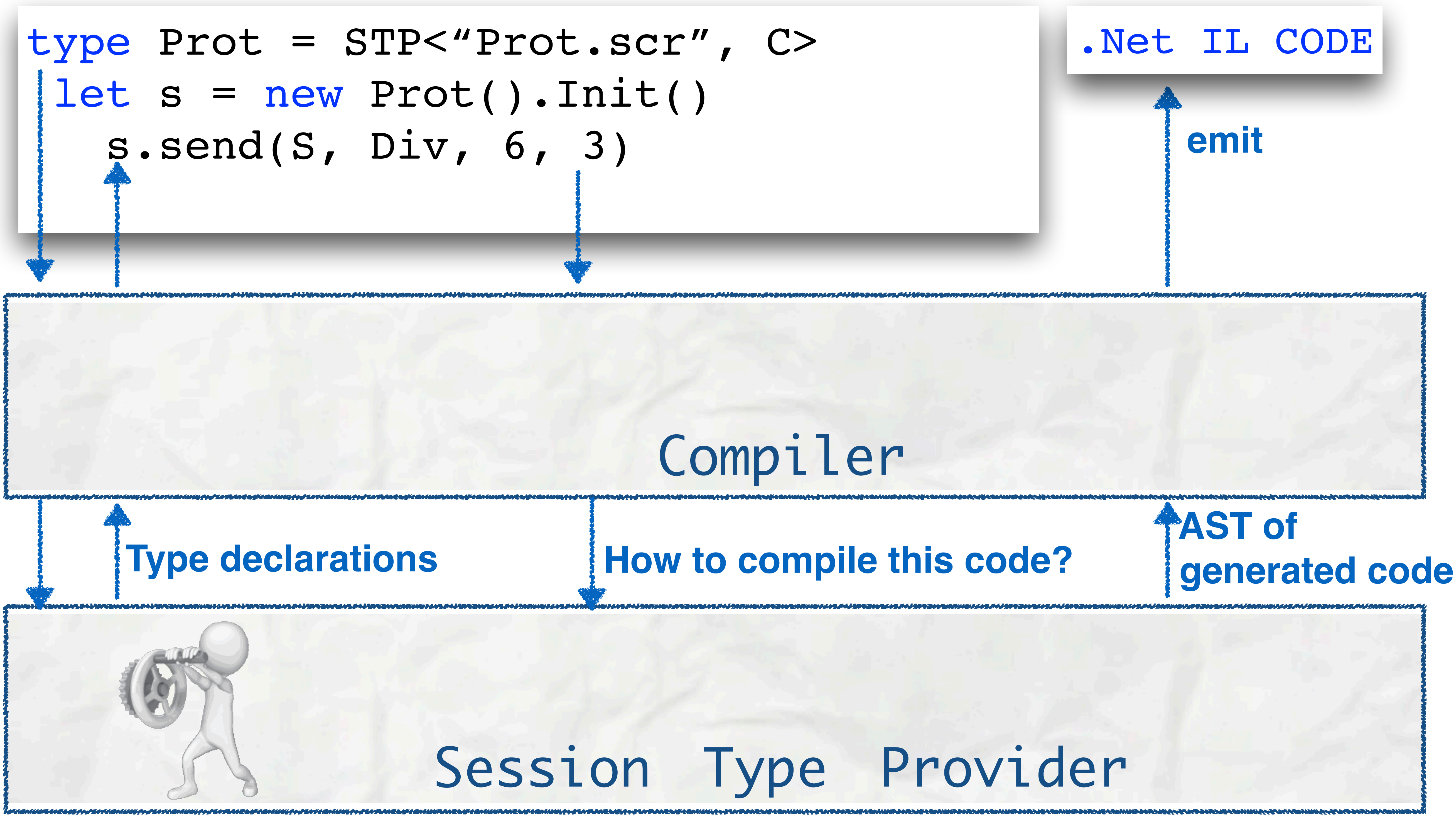
calcServer c1
```

send

- constraints as lambda functions
- serialise payload
- manage and use TCP sockets

- ☑ quotations
- ☑ splicing

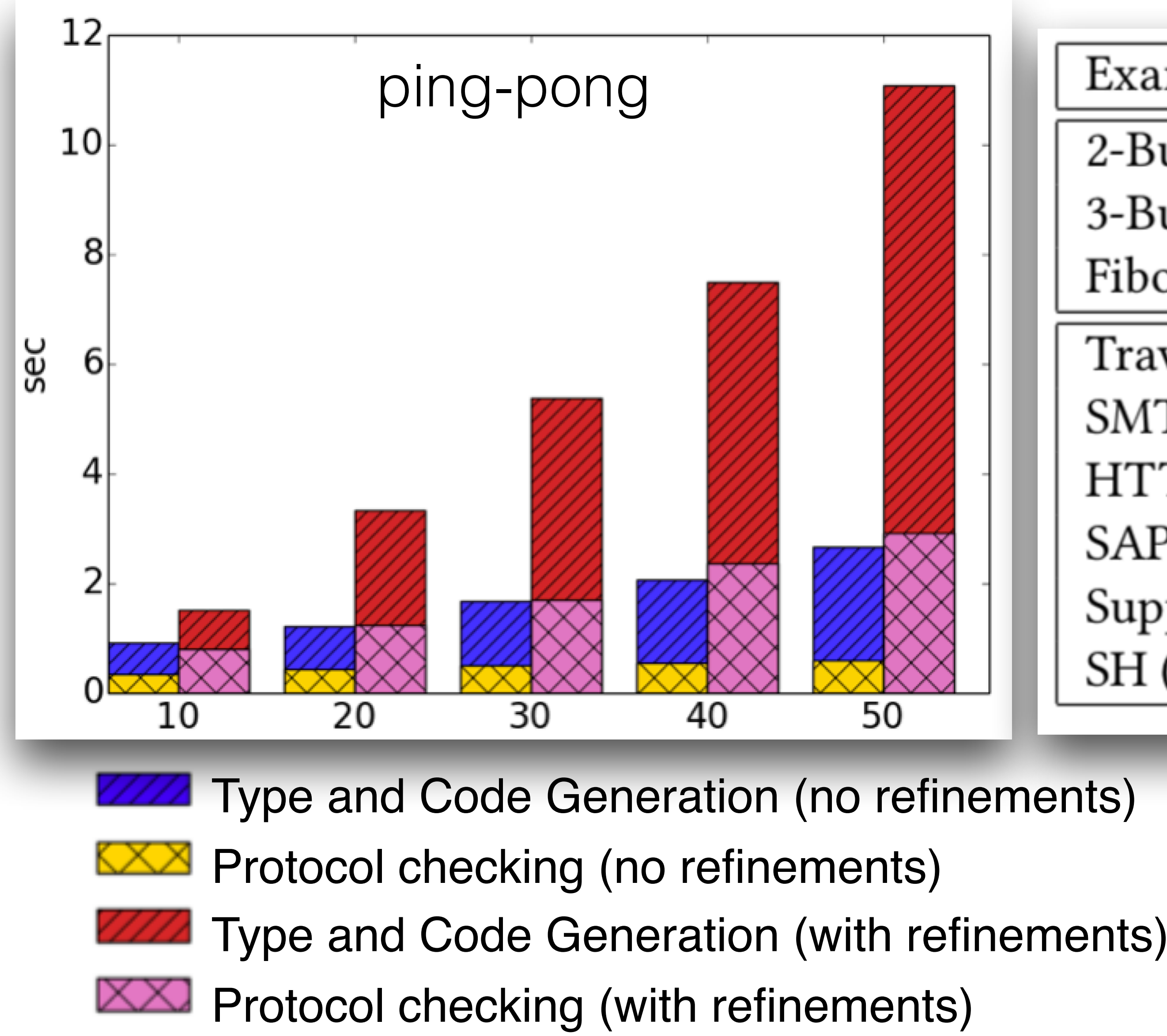
Model | Properties | CFSM | F# Type | **Code**



Safety guarantees

A statically well-typed STP-endpoint program **will never** perform a non-compliant I/O action w.r.t. the source protocol.

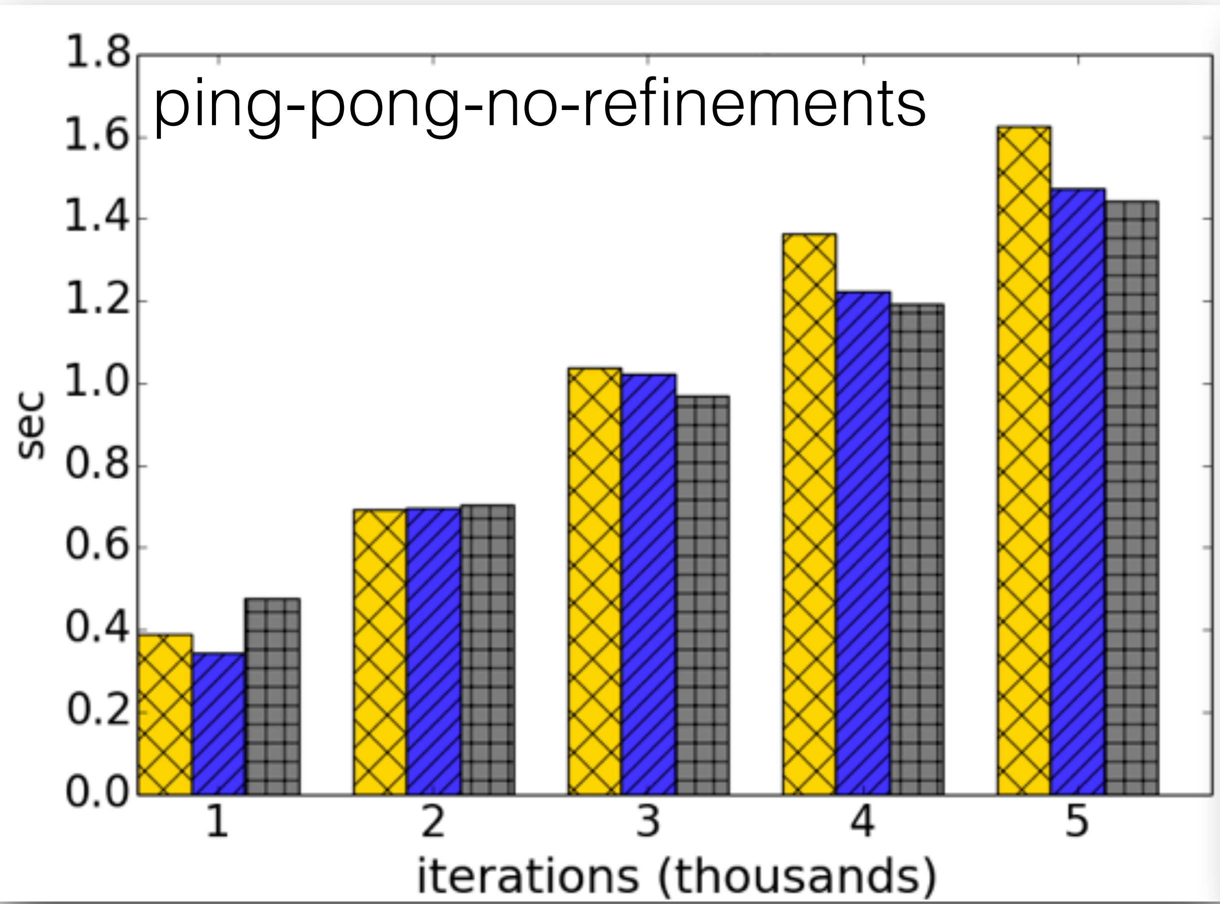
Compile-time performance

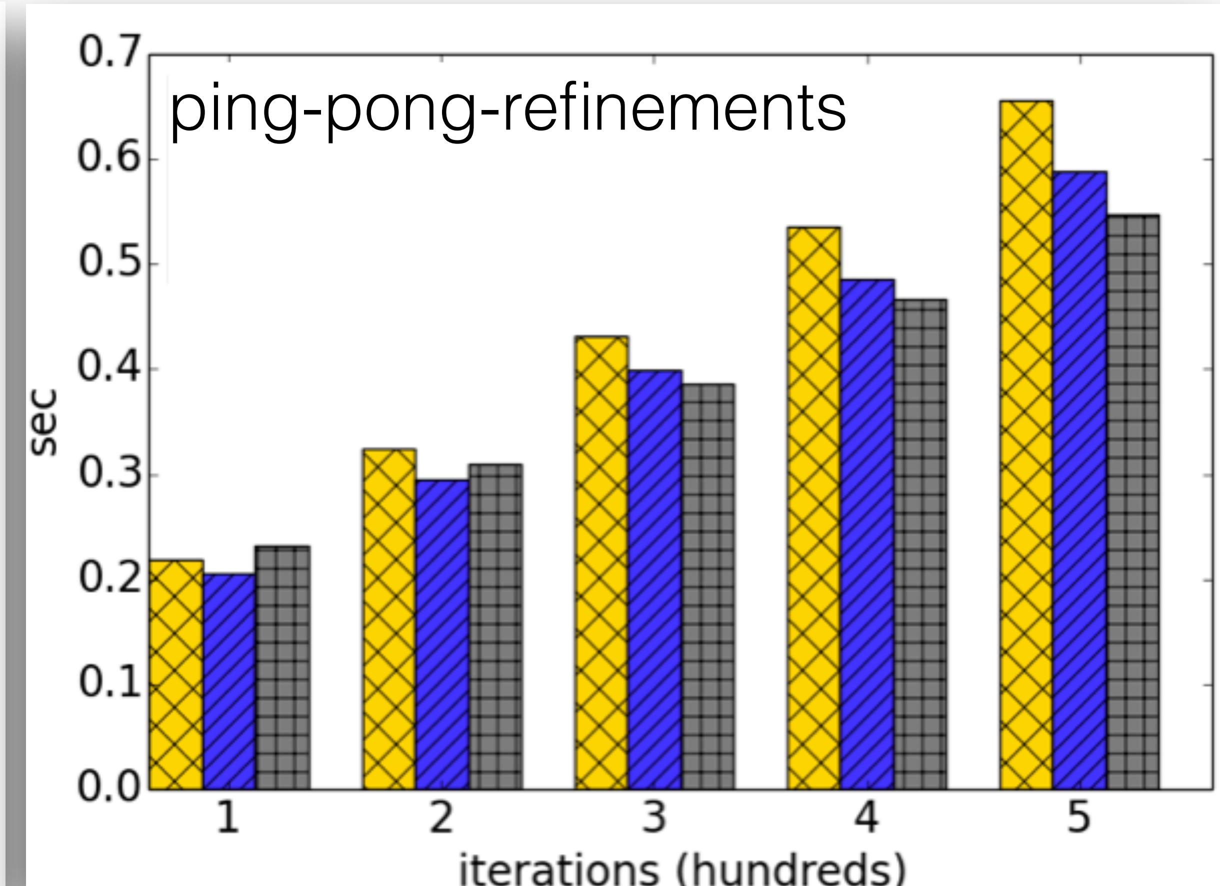


Example (role)	#LoC	#States	#Types	Gen (ms)
2-Buyer (B_1) [13]	16	7	7	280
3-Buyer (B_1) [5]	16	7	7	310
Fibonacci (S) [14]	17	5	7	300
Travel Agency (A) [24]	26	6	10	278
SMTP (C) [14]	165	18	29	902
HTTP (S) [3]	140	6	21	750
SAP-Negotiation (C) [18]	40	5	9	347
Supplier Info (Q) [24]	86	5	25	1582
SH (P)	30	12	15	440

API Generation does not impact the development time

Run-time performance





- Runtime overhead due to:
  - branching, runtime checks, serialisation
- The performance overhead of the library stays in 5%-7% range
- The performance overhead of run-time checks is up to 10%-12%

Future work and Resources

Framework Summary

- Type-driven development of distributed protocols
- Support for refinements on message interactions
- …ask me for more supported features

Future Work

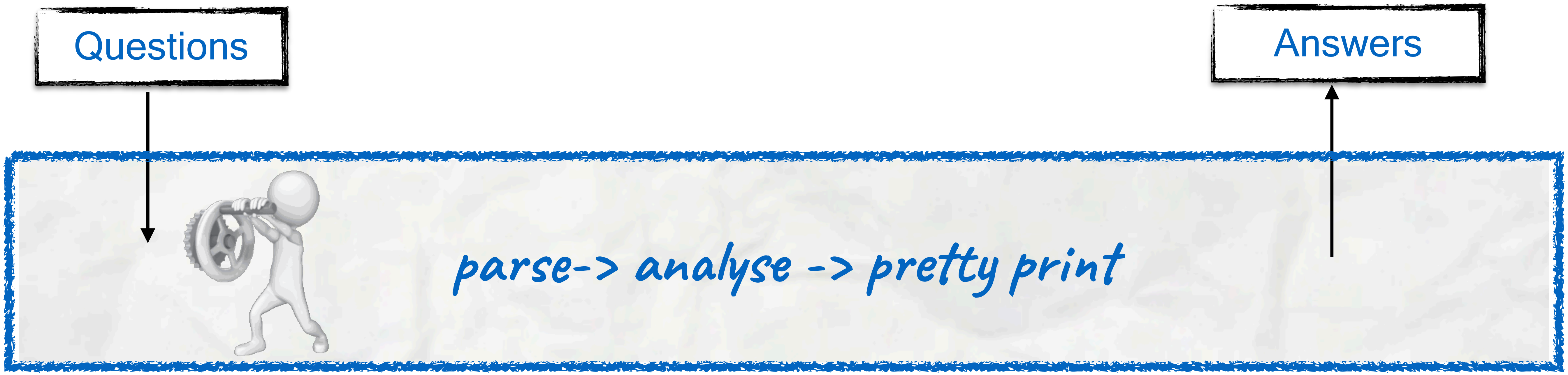
- Static verification of refinements
- Partial model checking
- Support for erased type providers (event-driven branching)

Resources:

- Session type provider: https://session-type-provider.github.io
- Scribble: http://scribble.doc.ic.ac.uk/
- MRG: mrg.doc.ic.ac.uk

Thank you!

Q & A



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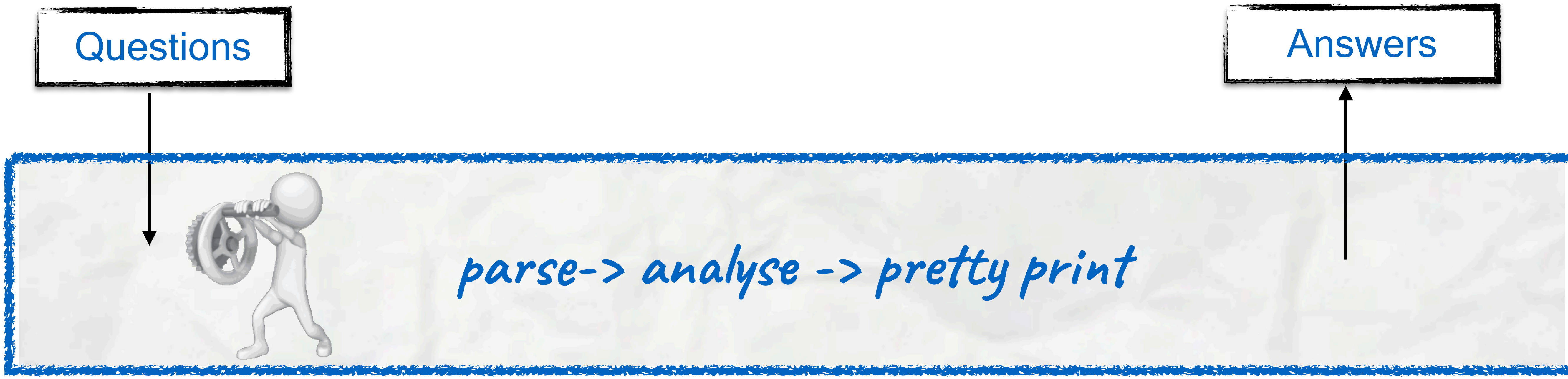
Q & A



Check the tool for more features:

- documentation on the fly
- non-blocking receive
- explicit connections
- recompilation on protocol change
- online vs offline mode
- support by any .Net language

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