Choreographic Quick Changes: First-Class Location (Set) Polymorphism

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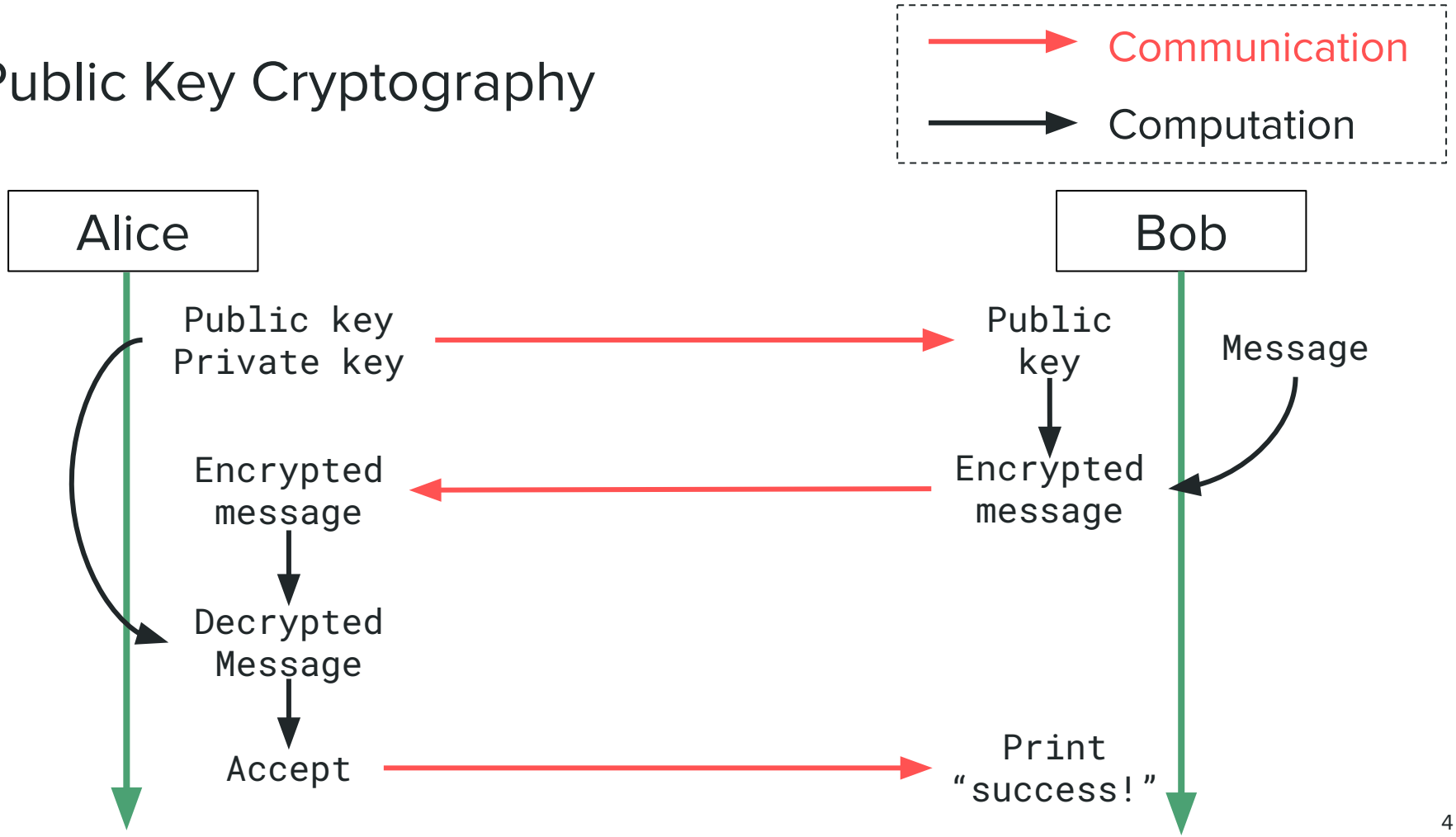
OOPSLA'25

Choreographic Programming

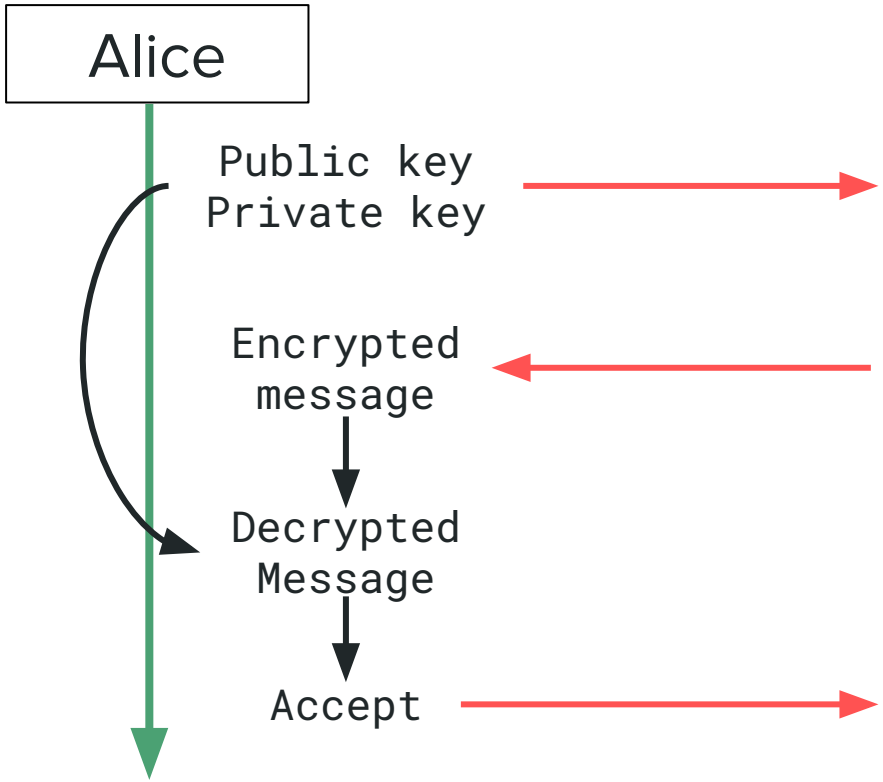
An emerging paradigm for safe concurrent programming

What does concurrent programming typically look like?

Public Key Cryptography



Typically a **separate program** is used to describe the actions of **each participant** in a concurrent computation



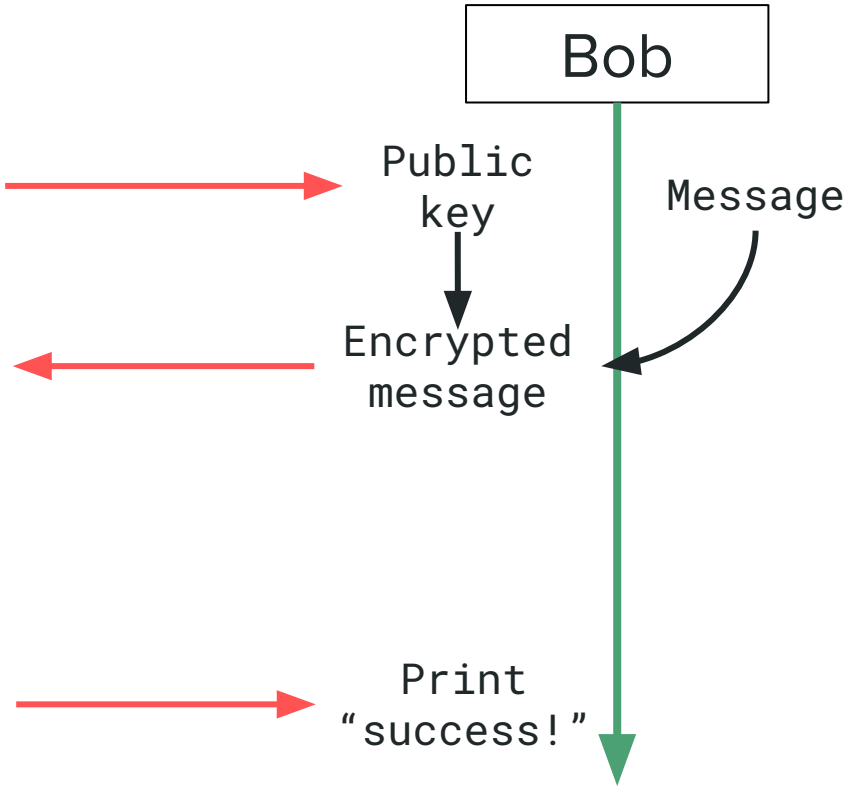
Alice

```
Generate public and secret keys
Send public key to Bob
Receive message from Bob
Decrypt message
Verify message:
    If accept send True to Bob
    Else send False to Bob
```

Typically a **separate program** is used to describe the actions of **each participant** in a concurrent computation

Bob

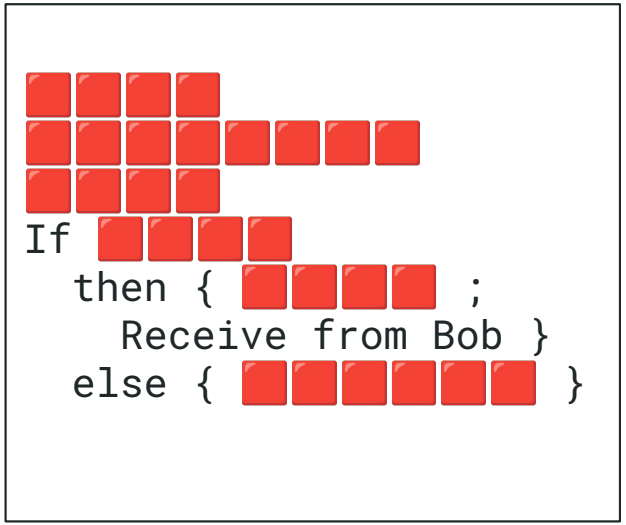
```
Receive public key from Alice
Encrypt message
Send encrypted message to Alice
Receive choice from Alice
    If True print “success”
    Else print “failure”
```



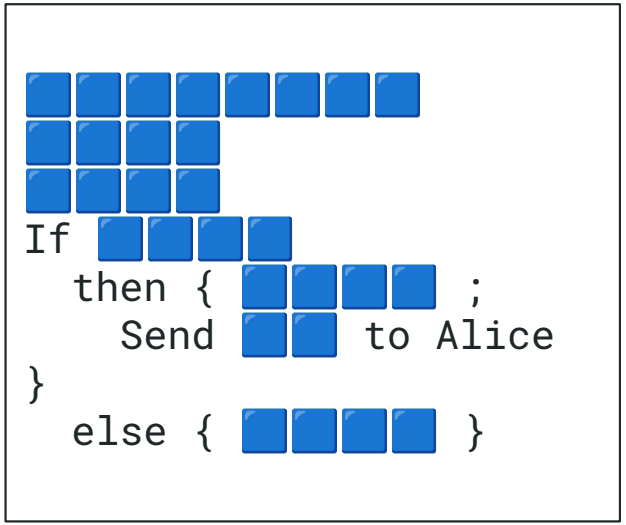
Why is concurrent programming difficult?

Changes to **one participant's code** must be **reflected in** the code of **other participants**

Alice

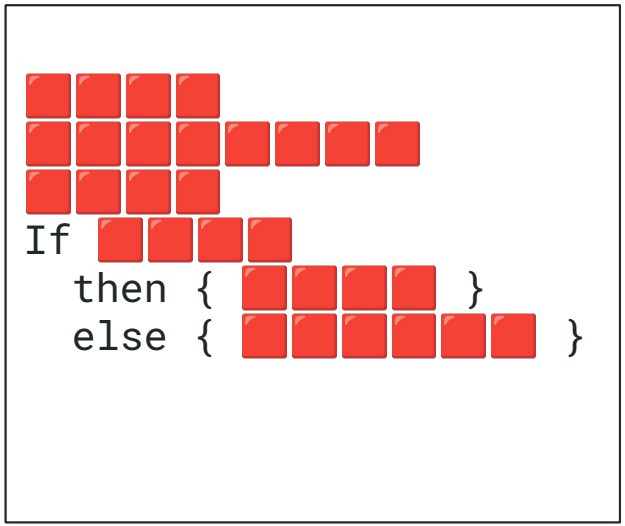


Bob

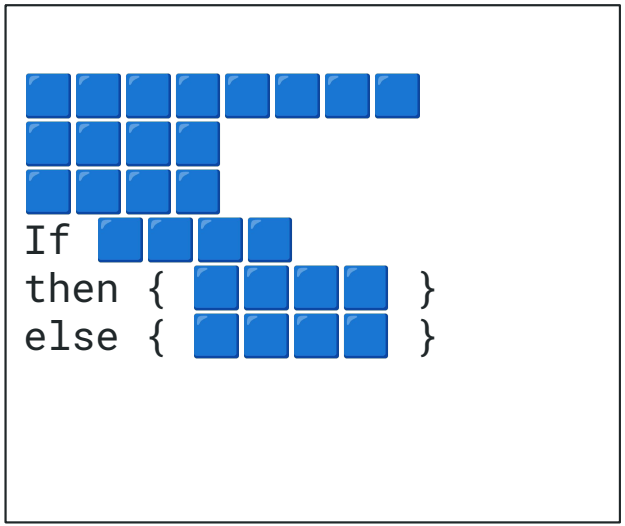


It can be easy to mistakenly introduce **deadlocks**

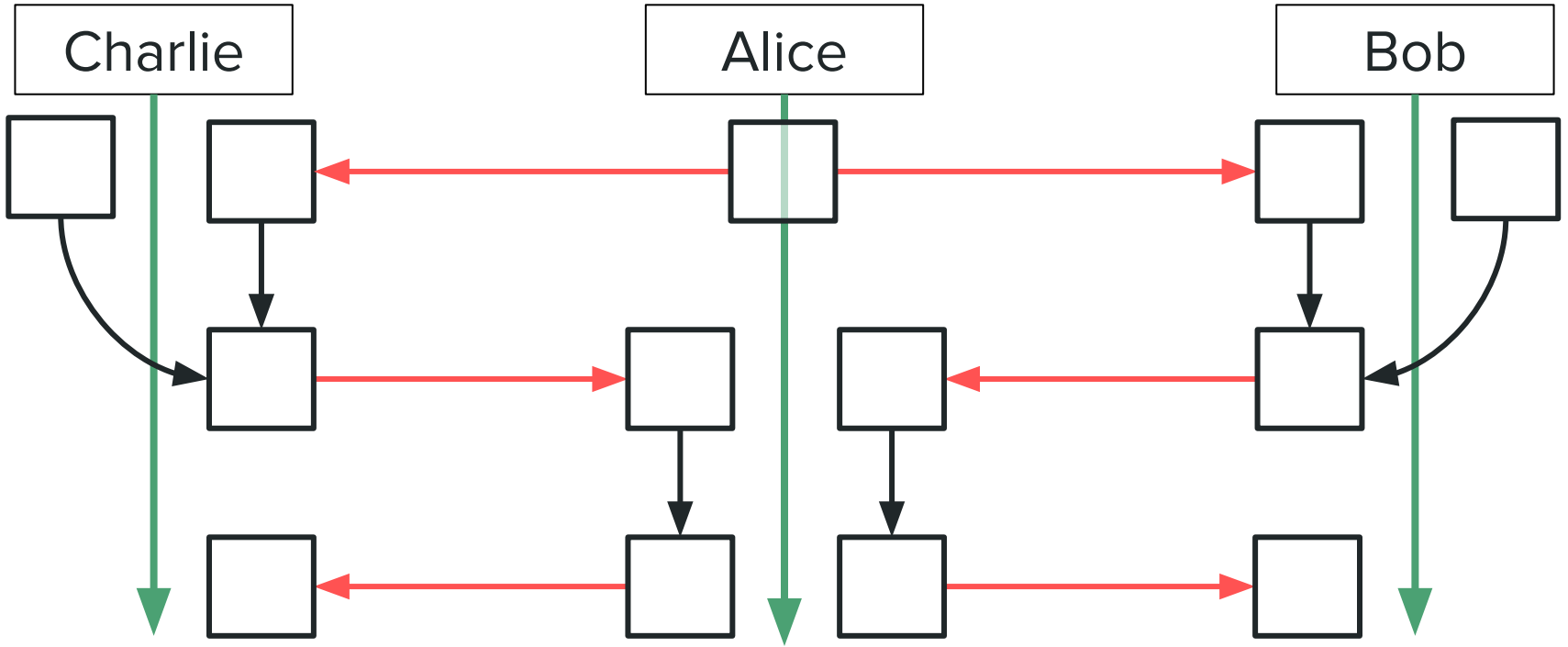
Alice ⏱️ 🤔



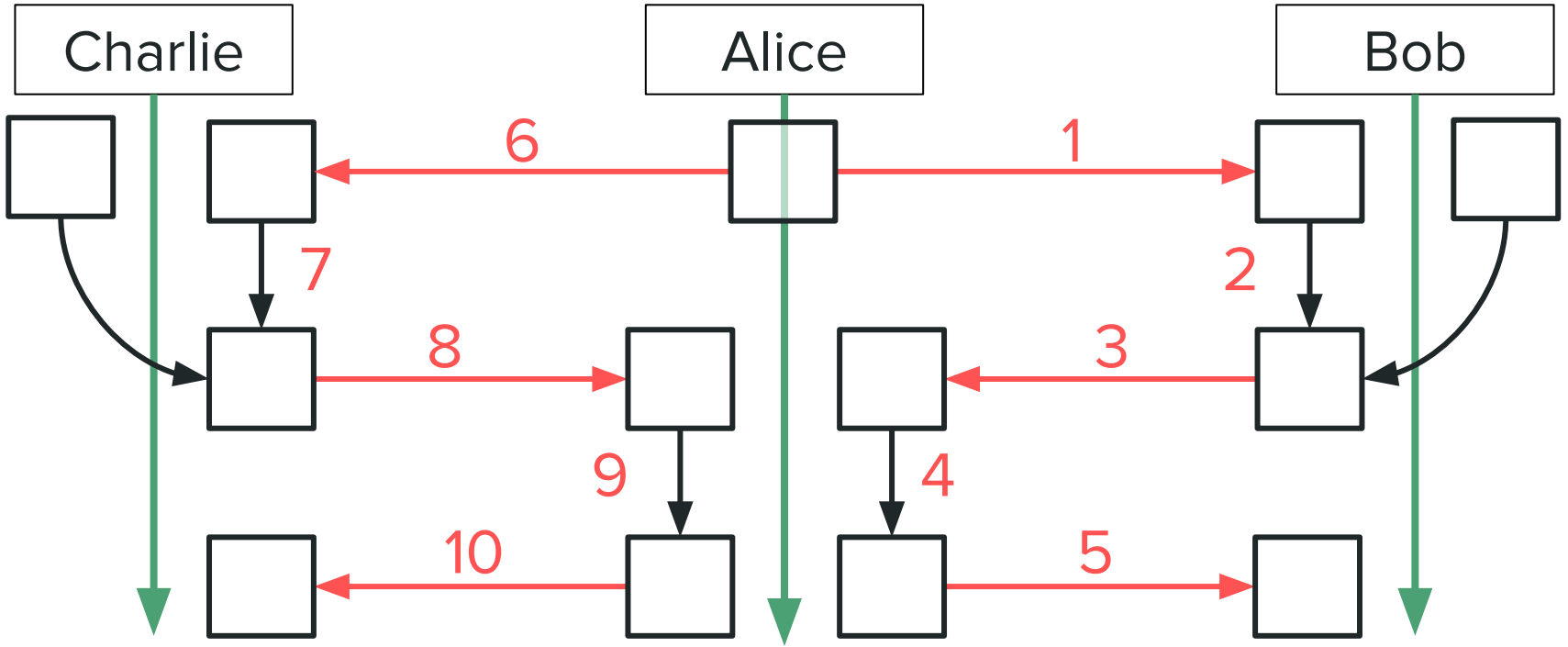
Bob 😕



More participants makes analysis more **complex**



To prevent issues like **deadlocks**, we need to be able to reason about **all possible event orders**



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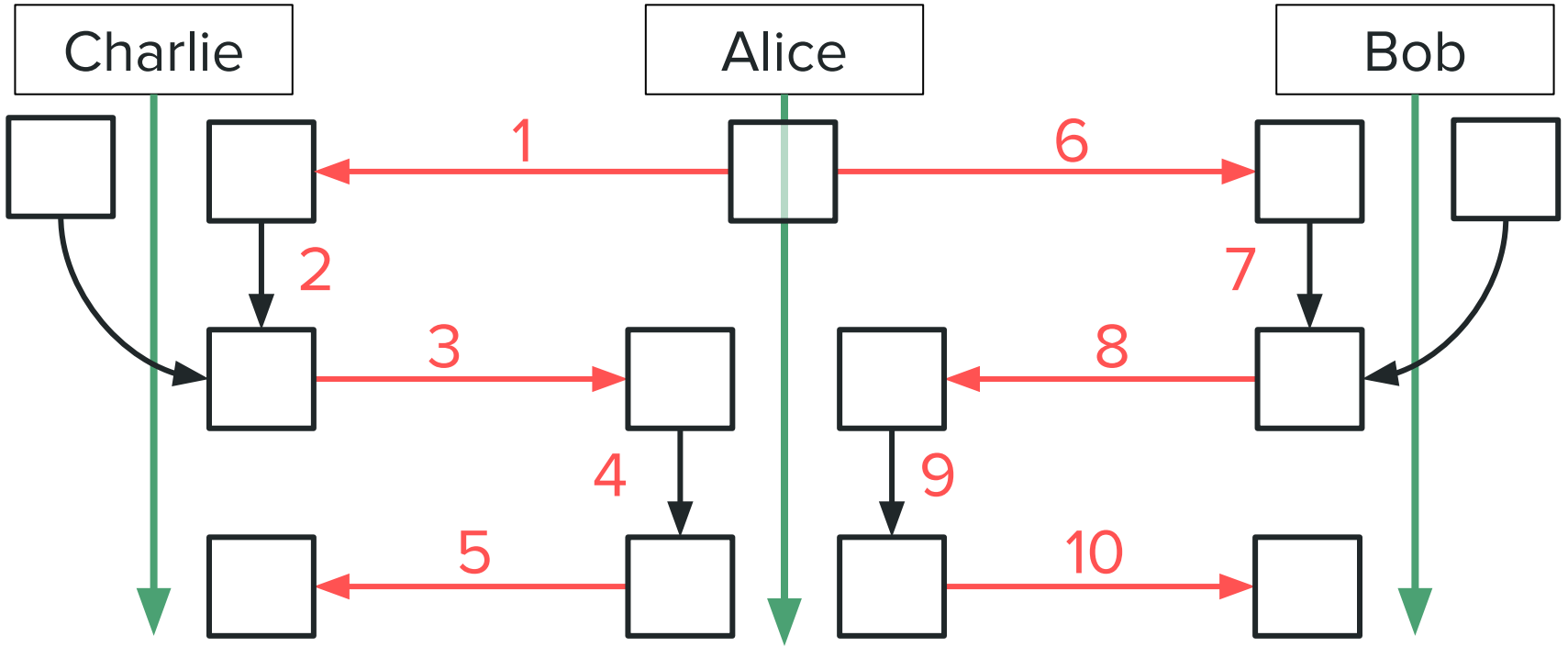
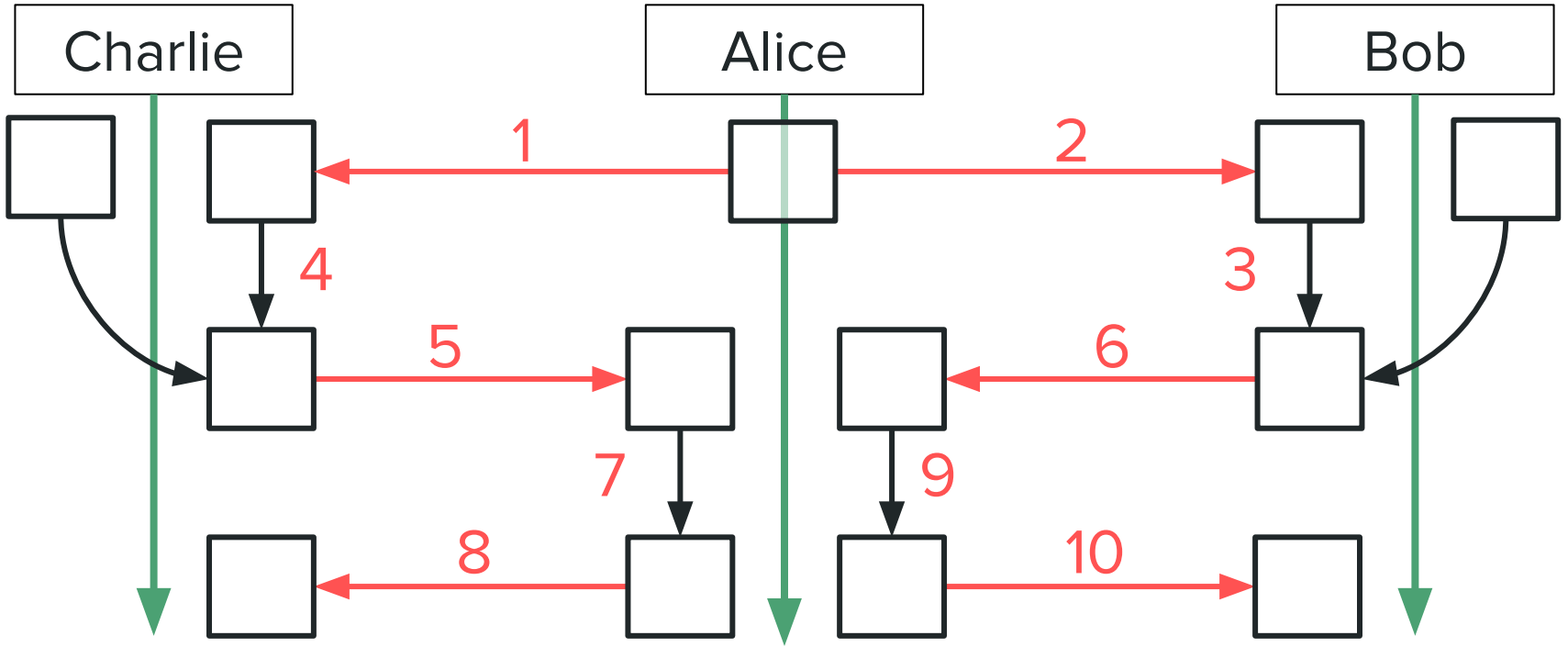
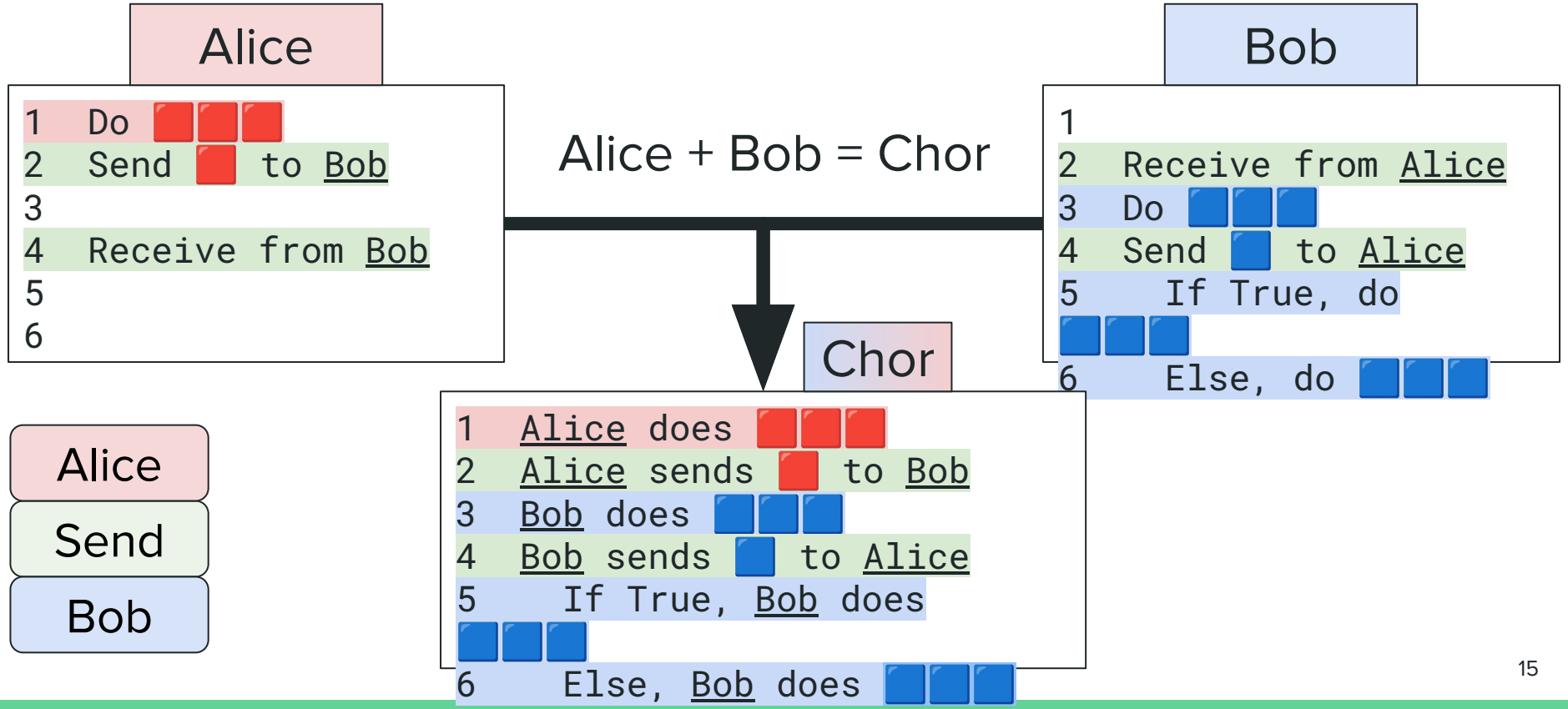


To prevent issues like **deadlocks**, we need to be able to reason about **all possible event orders**

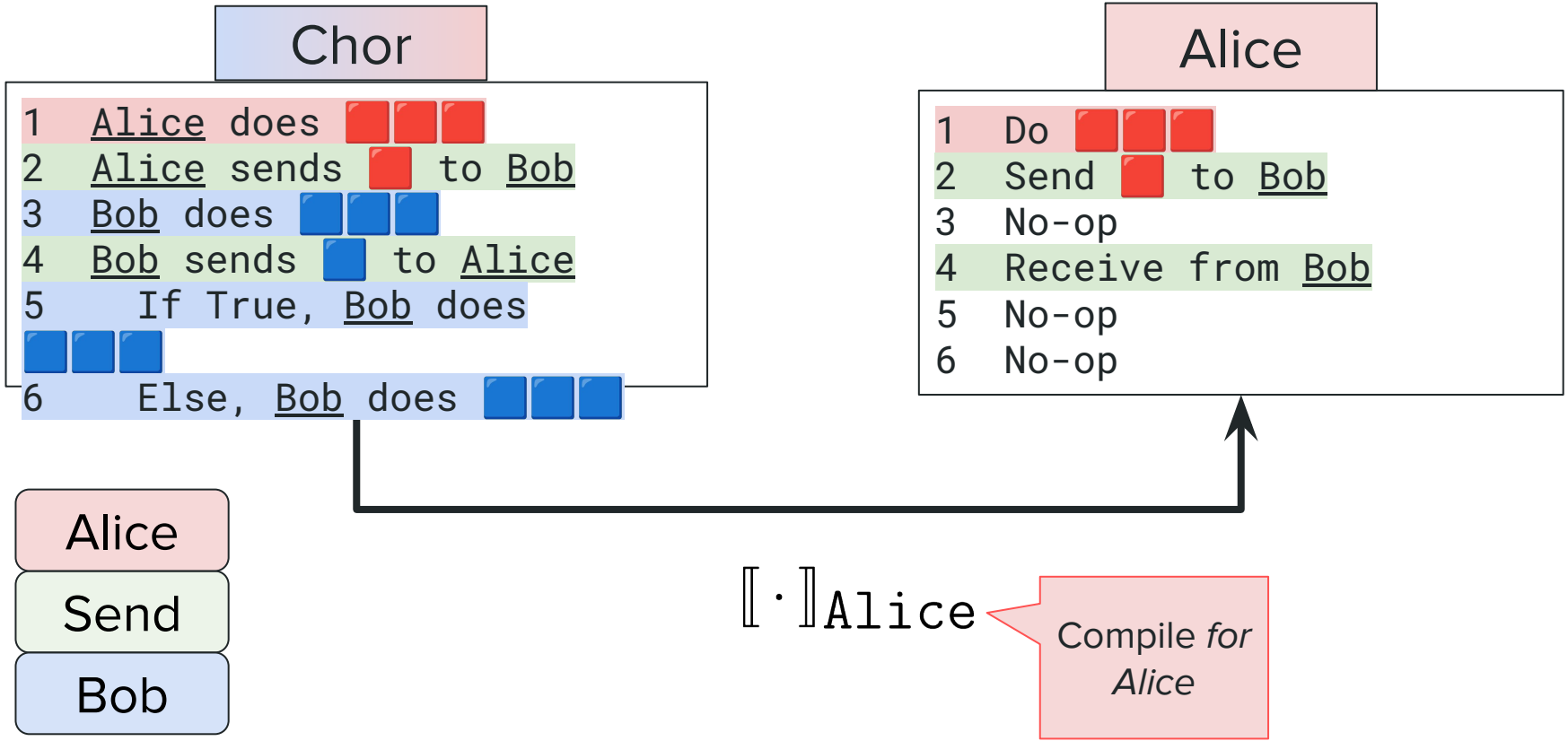


How does choreographic programming solve this?

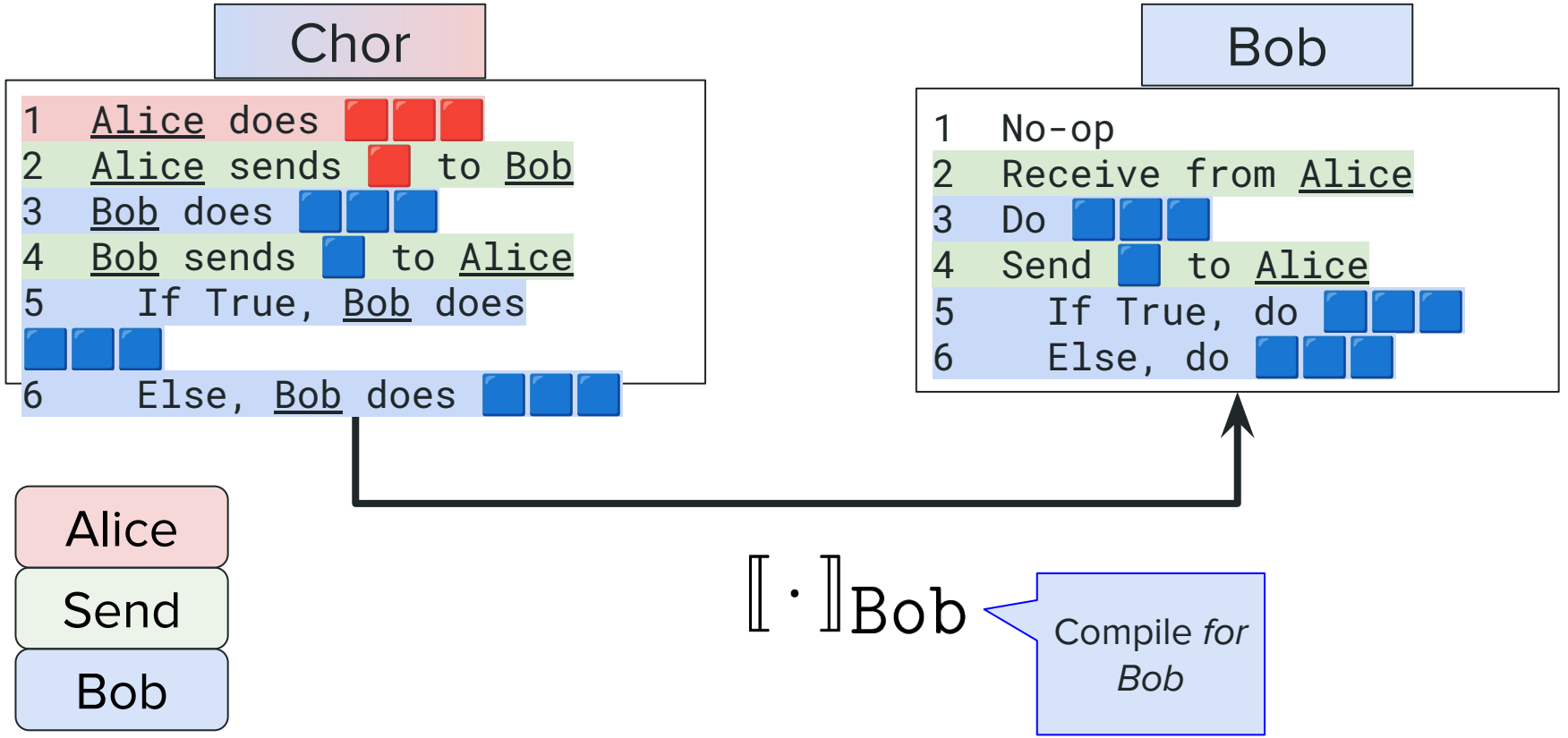
Choreographies are a **single program** which specifies the actions of **all participants**



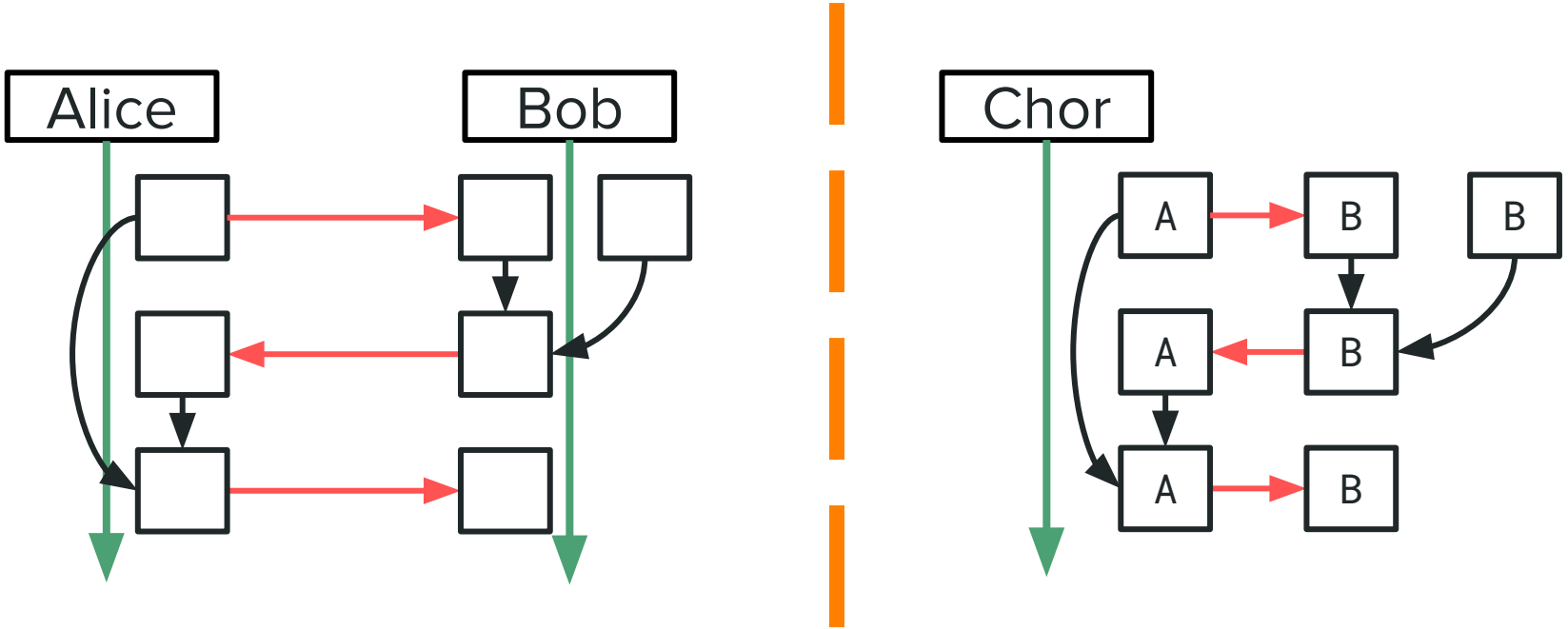
We can determine the actions of each participant with a **compilation procedure** called **endpoint projection**



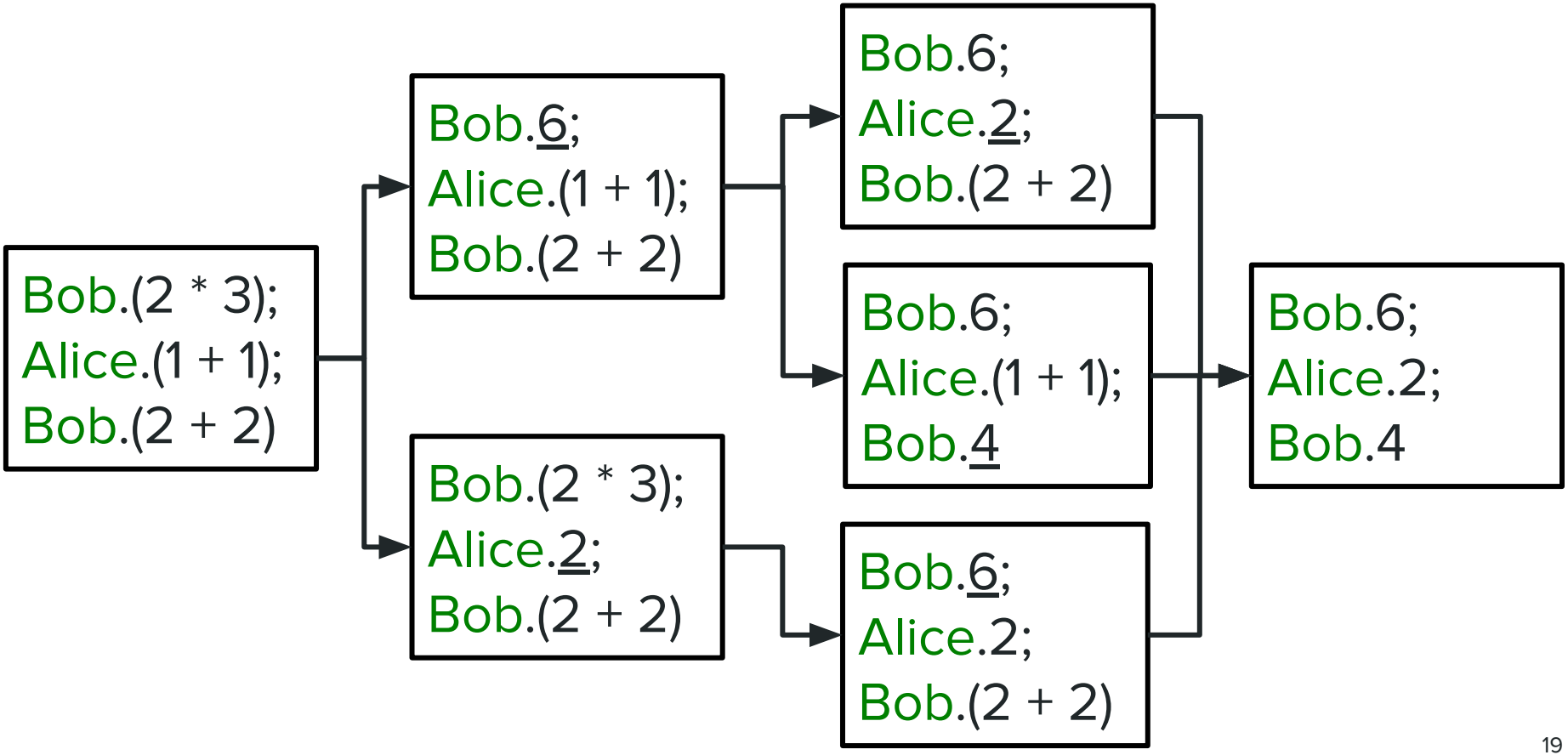
We can determine the actions of each participant with a **compilation procedure** called **endpoint projection**



We can define a **semantics for choreographies** which **simulates the behavior** of a **concurrent system** and **captures all possible event orders**

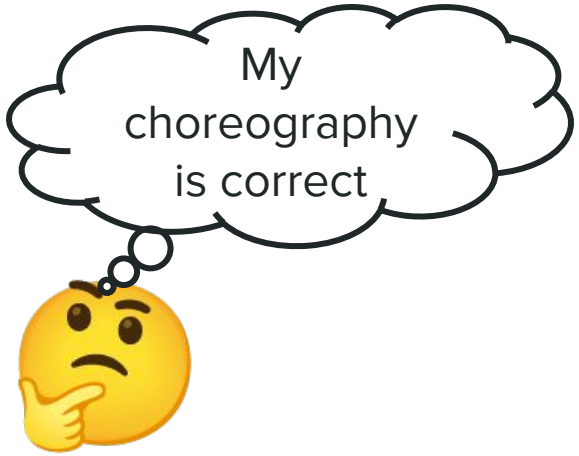


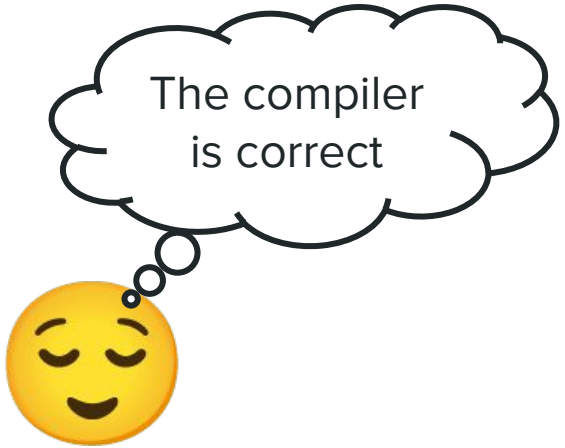
How can we capture all possible event orders?

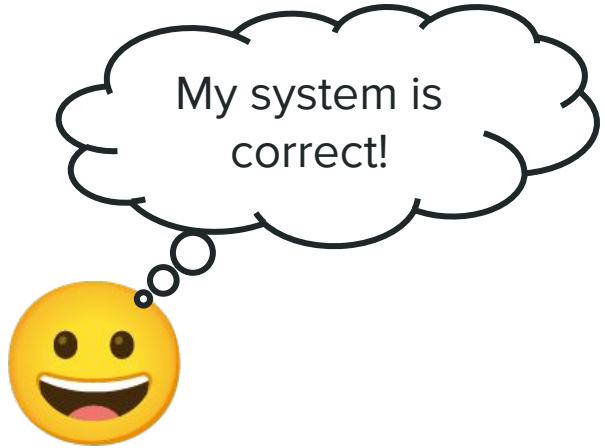


Using a separate **choreographic semantics** allows us to **analyze the behavior** of **concurrent systems**

$$\{\varphi\}C\{\psi\} \quad + \quad C \sim [\![C]\!] \quad = \quad \{\varphi\}[\![C]\!]\{\psi\}$$

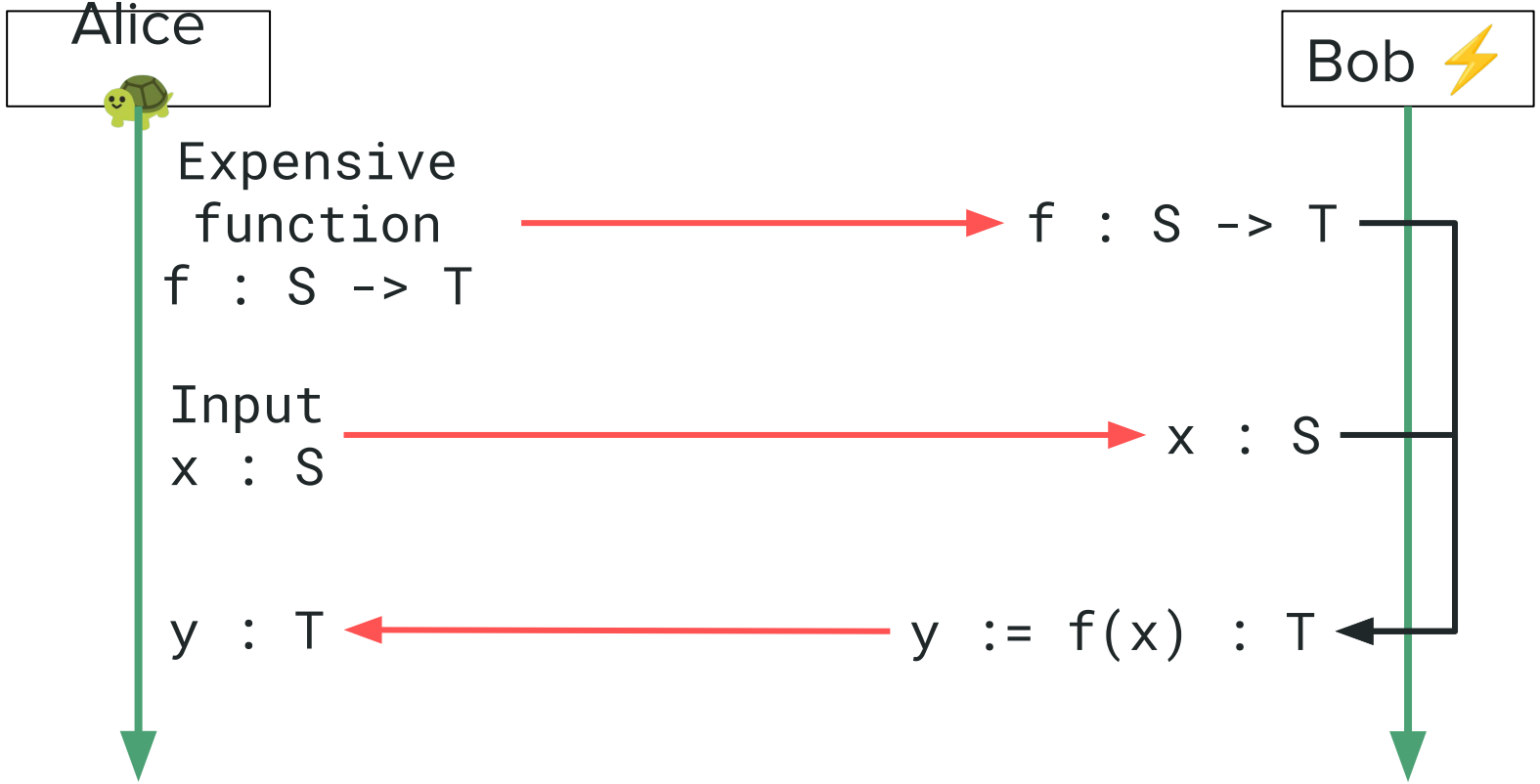






First-Class Location Names

Prior choreographies can handle a **static client-worker pattern**



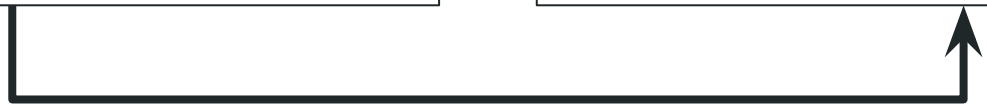
Prior choreographies can handle a **static client-worker pattern**

Chor

```
fun runAtWorker(
  F : (T1 → T2) @ Alice,
  X : T1 @ Alice) :=
 let Bob.f := F ~> Bob
     Bob.x := X ~> Bob
 in Bob.f(x) ~> Alice
```

Alice

```
fun runAtWorker(
  F : T1 → T2,
  X : T1) :=
 send F to Bob;
 send X to Bob;
 recv from Bob
```



$[\![\cdot]\!]_{\mathtt{Alice}}$

Prior choreographies can handle a **static client-worker pattern**

Chor

```
fun runAtWorker(
  F : (T1 → T2) @ Alice,
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 let Bob.f := F ~> Bob
     Bob.x := X ~> Bob
 in Bob.f(x) ~> Alice
```
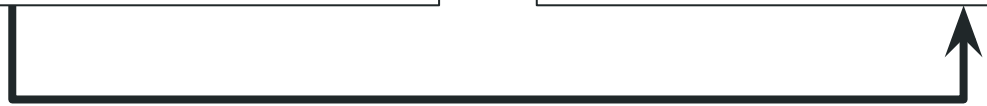
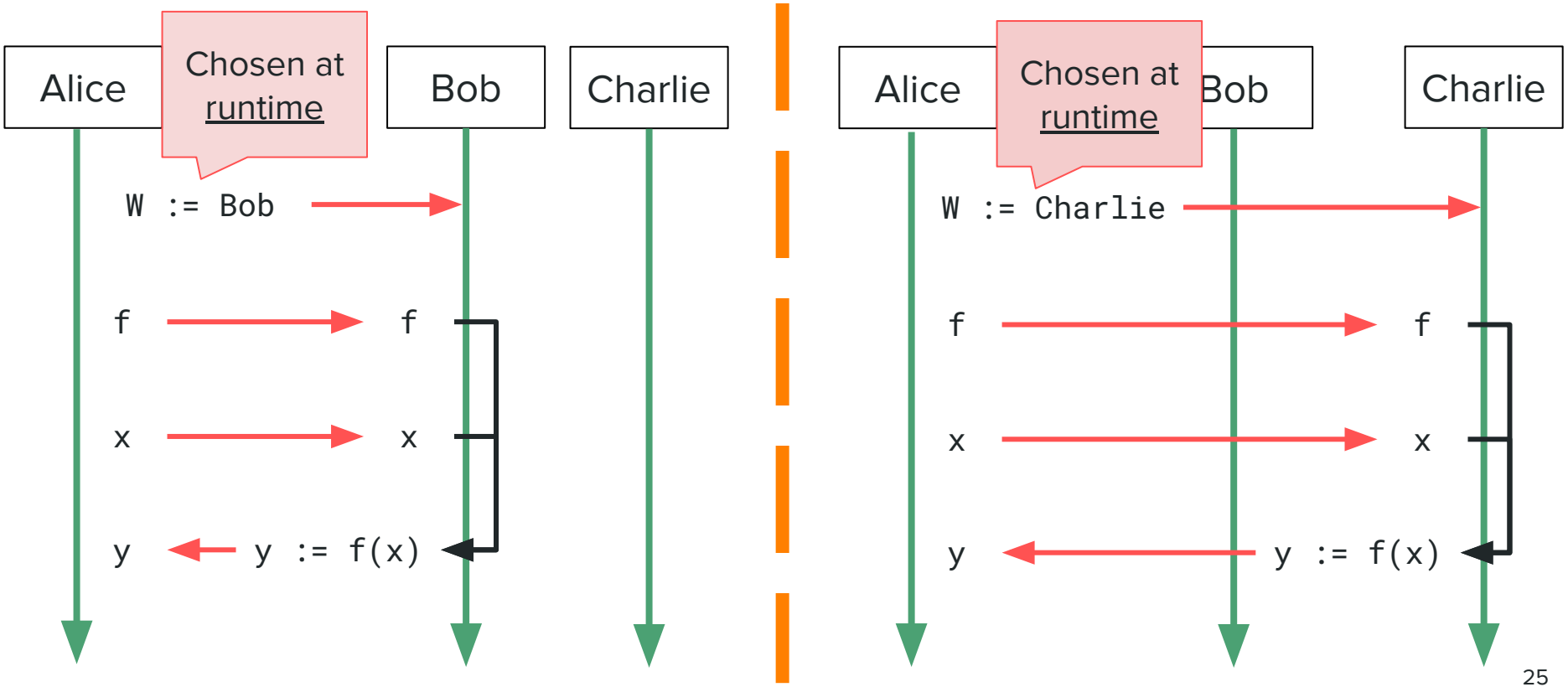

Bob

```
fun runAtWorker(

  ) :=
 let f := recv from Alice
     x := recv from Alice
 in send f(x) to Alice
```



$[\![\cdot]\!]_{\text{Bob}}$

But what if we want to **dynamically select a worker**?



Location names need to be **first-class** to accomplish this

This means that we can:

- Generate and inspect them at runtime
- Send them as messages
- Use them as type-level values

```
Alice computes W = select();
W     computes f(x) : T @ W
```

How do we enable **first-class location names** in a **type-safe manner**?

Chor

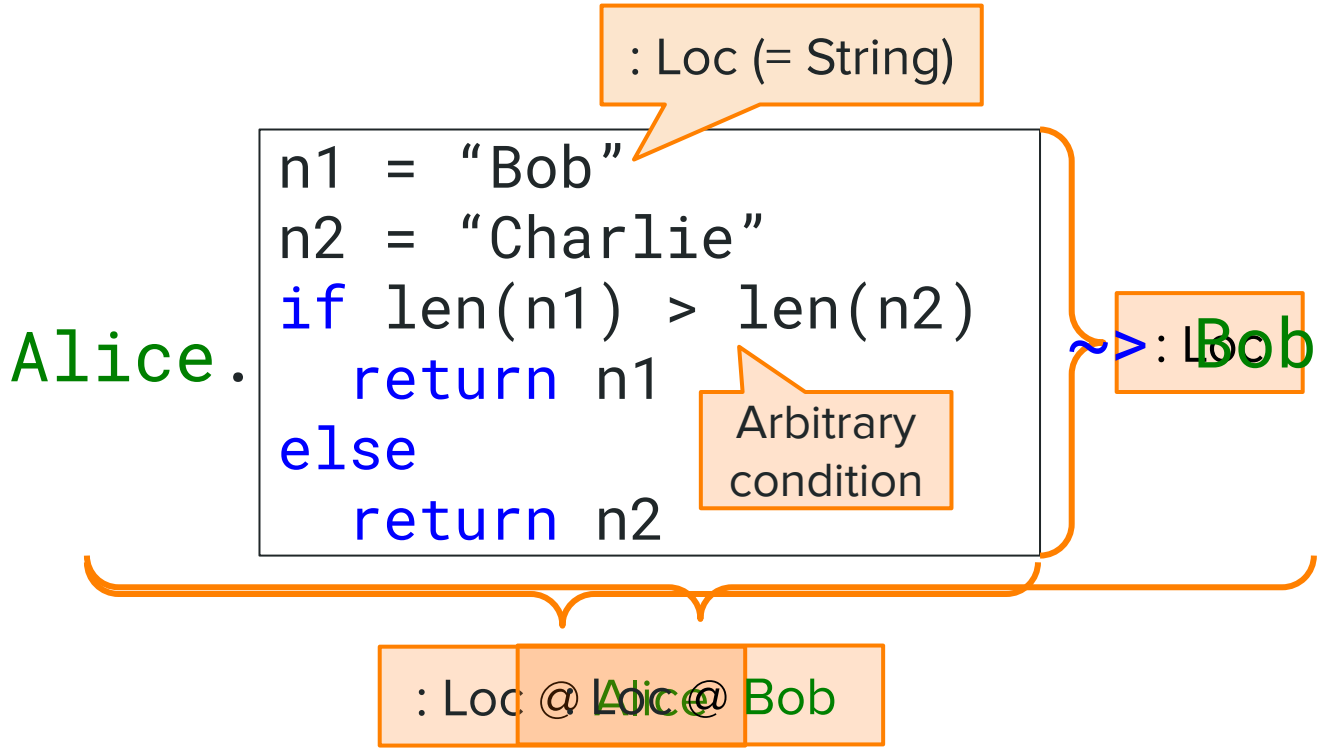
```
let W := Alice.choose()
    W.f := F ~> W
    W.x := X ~> W
in W.f(x) ~> Alice
```

Alice

```
let W := choose()
in send F to W;
   send X to W;
   recv from W
```

$[\![\cdot]\!]_{\texttt{Alice}}$

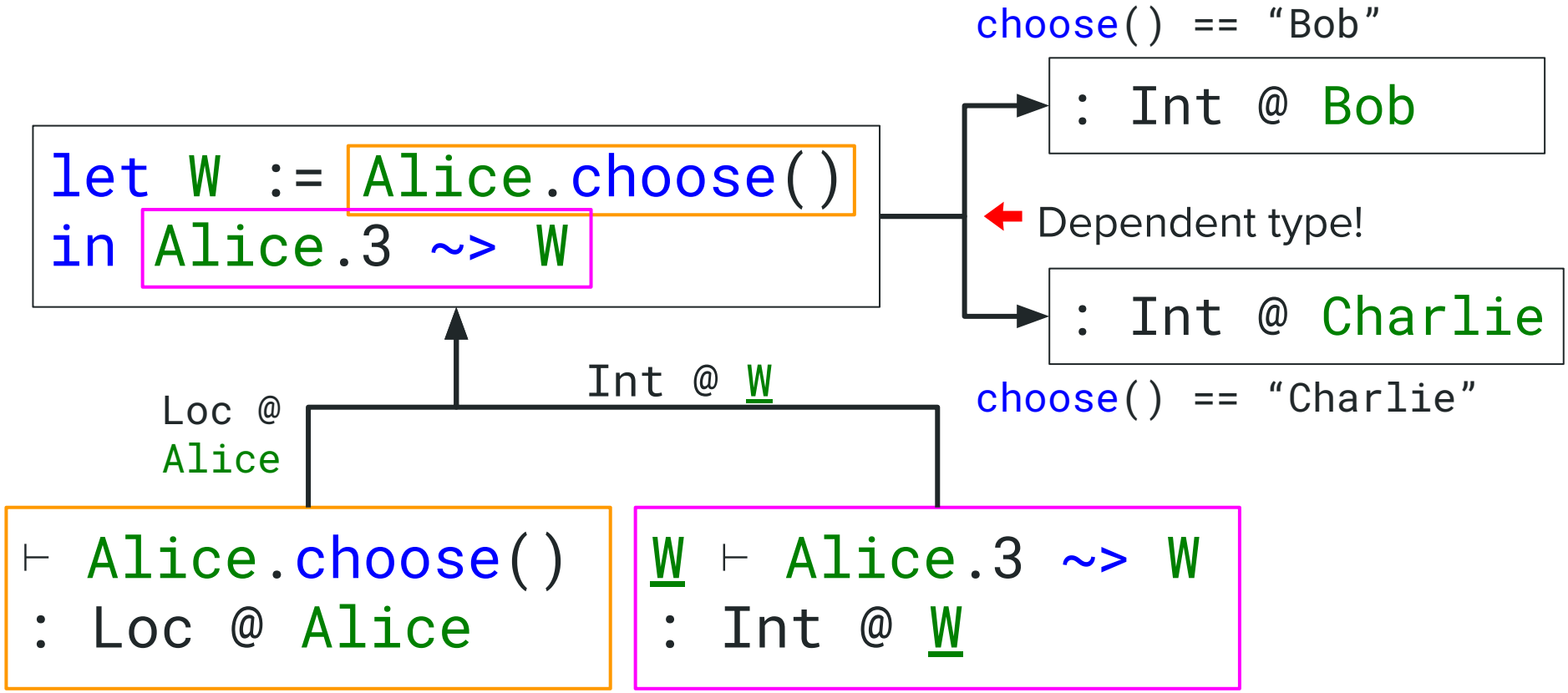
Solution Part 1: Have some way of **representing location names** in a first-class manner



Solution Part 2: Allow for **reifying** a “representation” to a **real location** using a **let-expression**

```
let
    Bob.f := F ~> Bob
    Bob.x := X ~> Bob
in Bob.f(x) ~> Alice
```

Problem: We might introduce **dependent types**



What's wrong with using dependent types?

- Slower and possibly undecidable type-checking
  - Can implement a semi-decision procedure
- Complex for programmers to understand
- Other issues related to their use in choreographies:

```
T1, T2 : Type @ Alice

Alice.x = Alice.(if b then e1 else e2)
  : (if b then T1 else T2) @ Alice

Alice.x ~> Bob : ??? @ Bob
```

Some programs **don't have dependency**...

Chor

```
let W := Alice.choose()
    W.f := F ~> W
    W.x := X ~> W
in W.f(x) ~> Alice
```

: T2 @ Alice

😔 Intermediate types depend on W

```
W        : Loc @ Alice
W.f      : (T1 → T2) @ W
W.x      : T1 @ W
W.f(x)   : T2 @ W

W.f(x) ~> Alice : T2 @ Alice
```

🤔 💡 But the output type does not depend on W!

Limit ourselves: Ensure the **type** of a **let's body does not depend** on the **chosen location**

```
let W := Alice.choose()
    W.f := F ~> W
    W.x := X ~> W
in W.f(x) ~> Alice
```

T2 @ Alice ✅

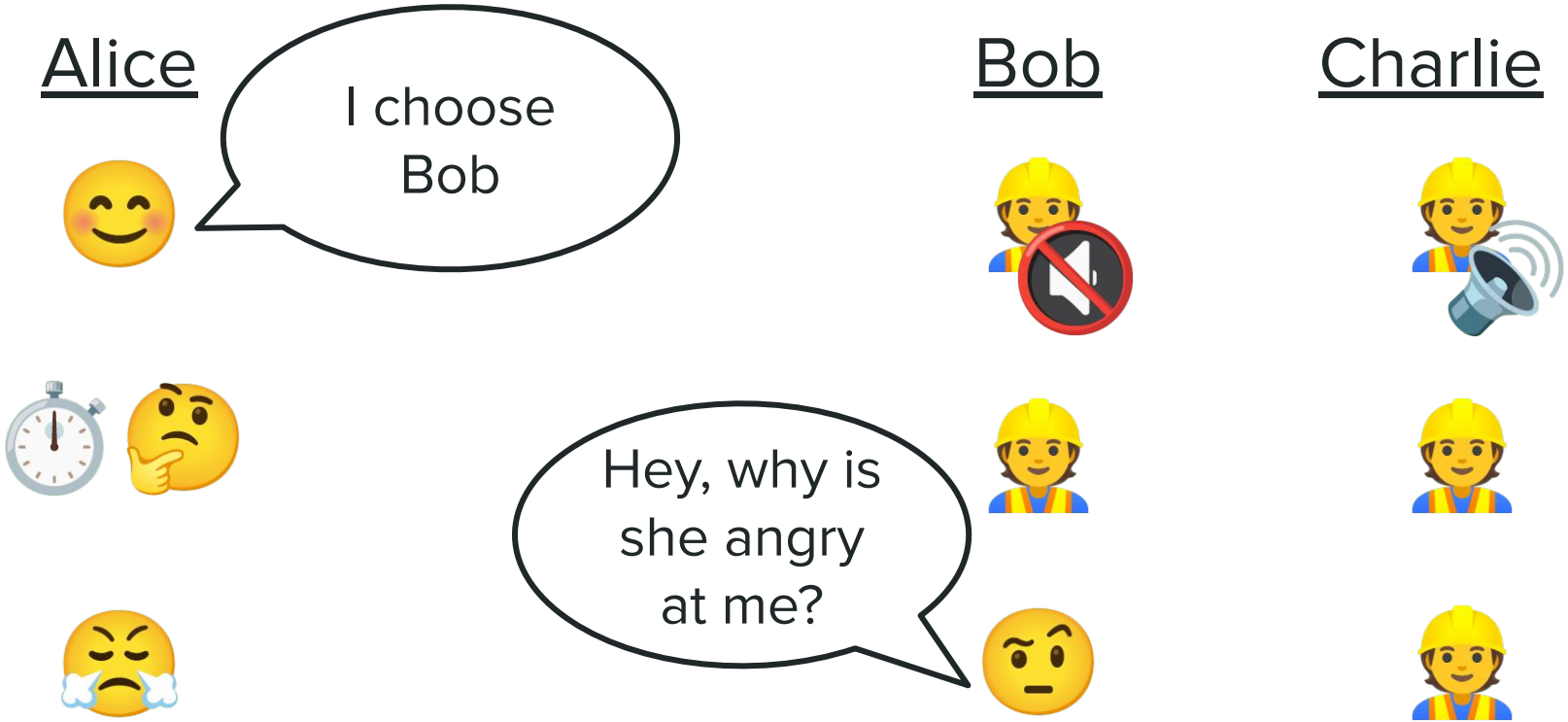
```
let W := Alice.choose()
in Alice.3 ~> W
```

Int @ W ❌

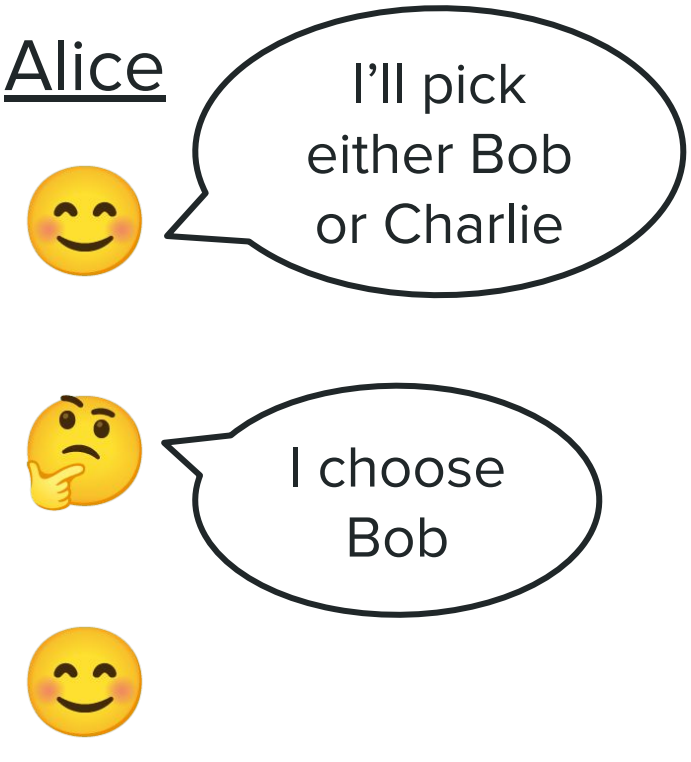
```
let W := Alice.choose()
in λ(Y : Int @ Alice).
      Y ~> W
```

Int @ Alice → Int @ W ❌

Problem: Dynamically chosen locations can **cause deadlocks when a worker doesn't know that they've been selected**



Solution Part 3: **Bound the set of possible workers** and **ensure that they are all aware of the selected worker**

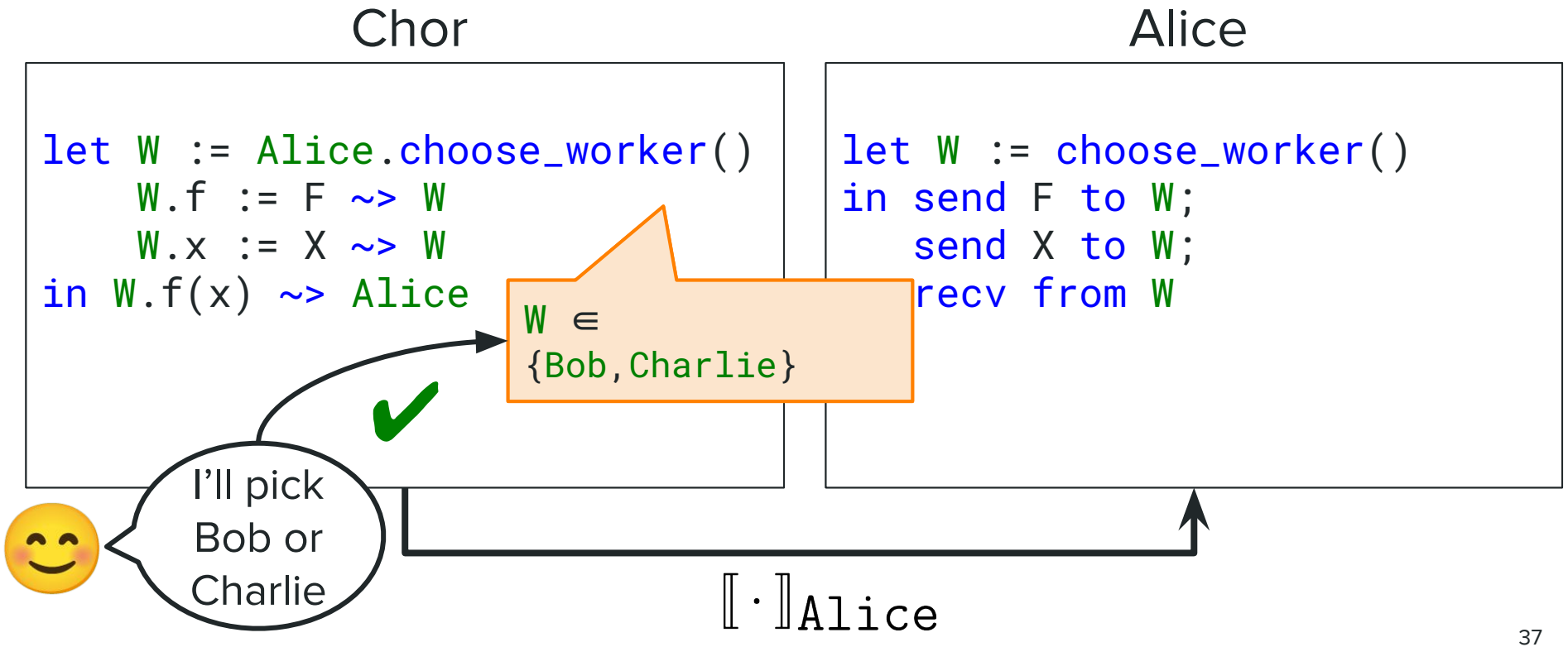


We bound the set of workers **with the local type system**

```
n1 = “Bob”
   : Loc{Bob} <: Loc{Bob,Charlie}
n2 = “Charlie”
   : Loc{Charlie} <: Loc{Bob,Charlie}
if len(n1) > len(n2)
  return n1 : Loc{Bob,Charlie}
else
  return n2 : Loc{Bob,Charlie}
```

Loc{Bob,Charlie}

We then require the **chosen worker to be shared with the entire worker pool** before reifying it



We then require the **chosen worker to be shared with the entire worker pool** before reifying it

Chor

```
let W := Alice.choose_worker()
         ~> {Bob,Charlie}
    W.f := F ~> W
    W.x := X ~> W
in W.f(x) ~> Alice
```

Bob

```
let W := recv from Alice in
  if (W == Bob) then
    let f := recv from Alice
        x := recv from Alice
    in send f(x) to Alice
  else return
```

$[\![\cdot]\!]_{\text{Bob}}$

Comparison: Session Types/Concurrent λ-calculus

Alice

```
let W := Alice.choose_worker()
in choose W for {Bob,Charlie}
   | “Bob” =>
     send F to Bob;
     send X to Bob;
     recv from Bob
   | “Charlie” =>
     send F to Charlie;
     send X to Charlie;
     recv from Charlie
   | else => Fail
end
```

Bob

```
choice from Alice of
   | “Bob” =>
     let f := recv from Alice;
         x := recv from Alice;
     in send (f x) to Alice
   | “Charlie” => return
   | else => Fail
end
```

Choreography Type

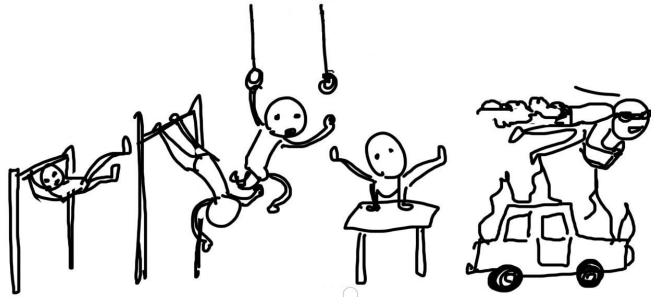
```
runAtWorker :
  (T1 → T2) @ Alice →
  T1 @ Alice →
  T2 @ Alice
```

Session Types

```
Alice.runAtWorker :
  choose for {Bob,Charlie}
   | “Bob” =>
     send (T1 → T2) to Bob;
     send T1 to Bob;
     recv T2 from Bob
   | “Charlie” =>
     send (T1 → T2) to Charlie;
     send T1 to Charlie;
     recv T2 from Charlie
   | else => done
  end
```

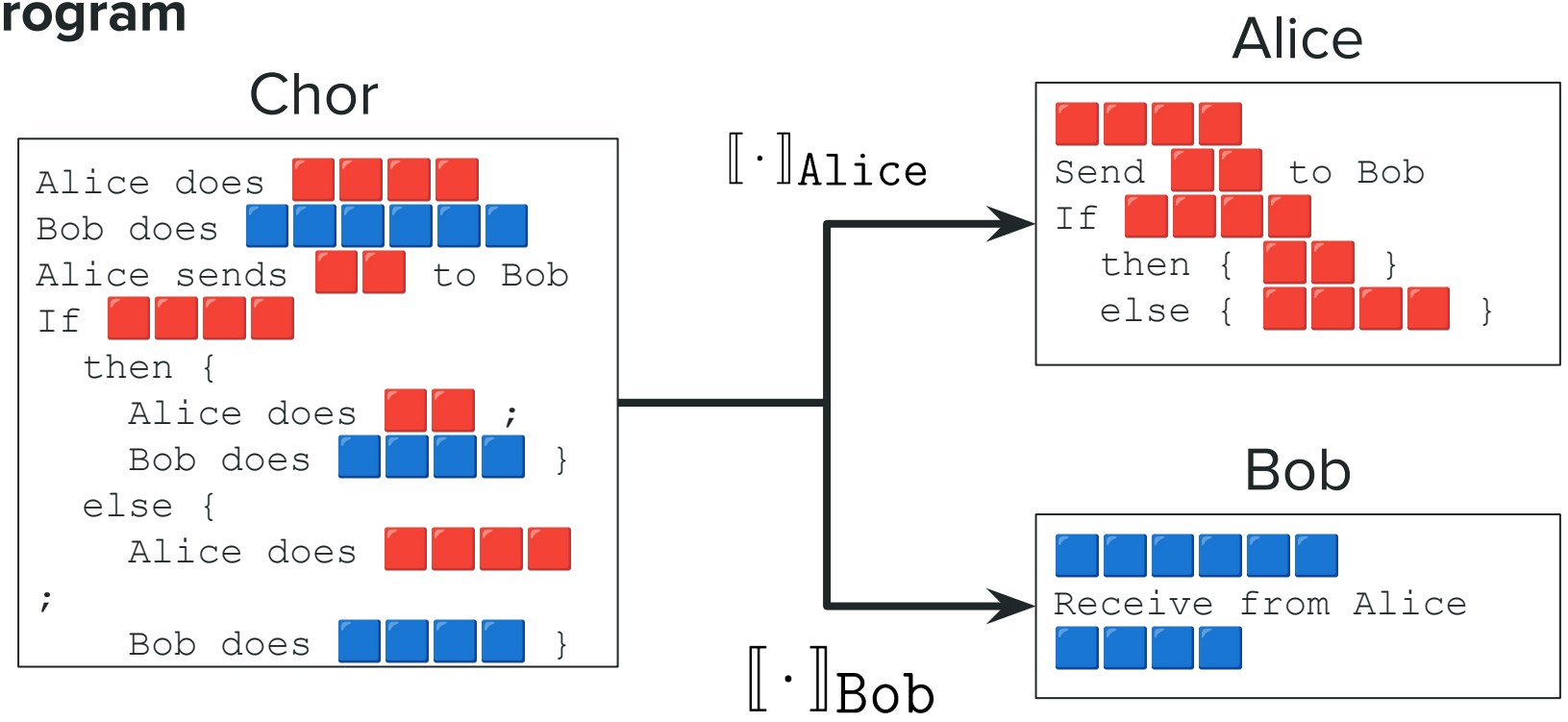
```
Bob.runAtWorker :
  choice from Alice
   | “Bob” =>
     recv (T1 → T2) Alice;
     recv T1 Bob;
     send T2 to Alice
   | “Charlie” => done
   | else => done
  end
```

This whole thing is a type 😨



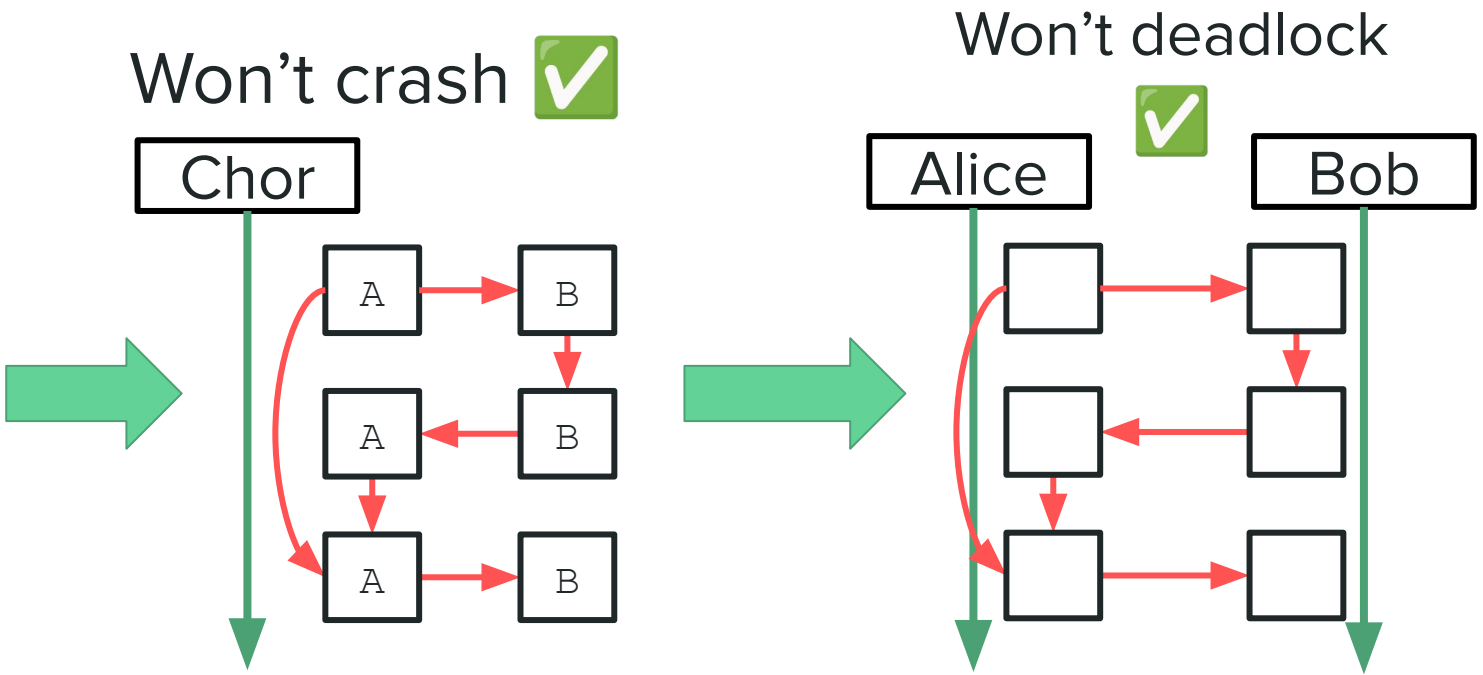
To summarize...

Choreographies are an **emerging paradigm** for **distributed programming** which combines the **actions of all nodes into one program**

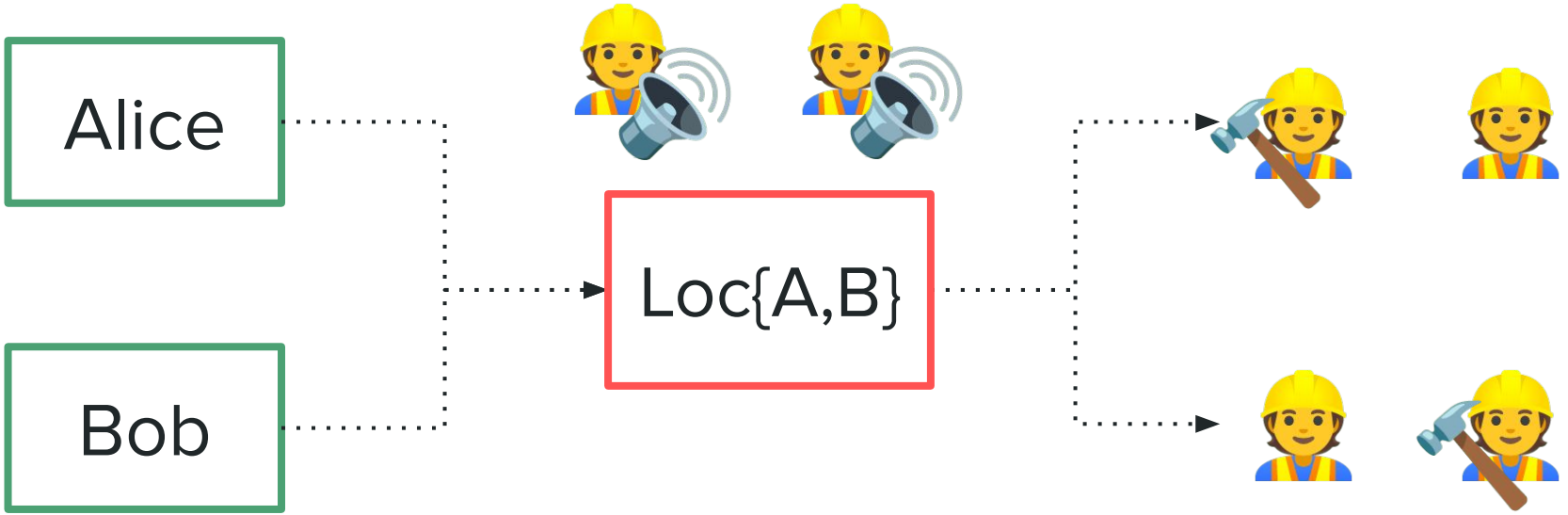


By using a **semantics** and **type system for choreographies**, we can guarantee that the **distributed system won't deadlock**

$\vdash C : T$



We allow for **well-typed, first-class location names** by **preventing type dependency** and ensuring that the **worker pool is notified of the worker selection**



Thanks for listening!