Rx-CML: Migrating MultiMLton to the Cloud

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MultiMLton

Introduction

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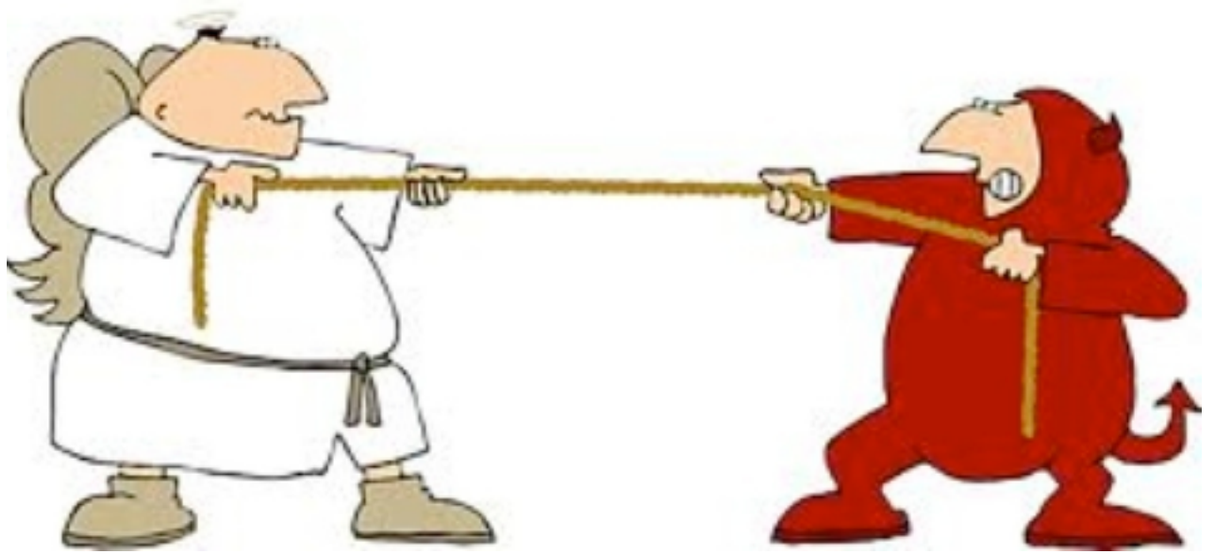

Simplicity
Safety

Performance
Functionality

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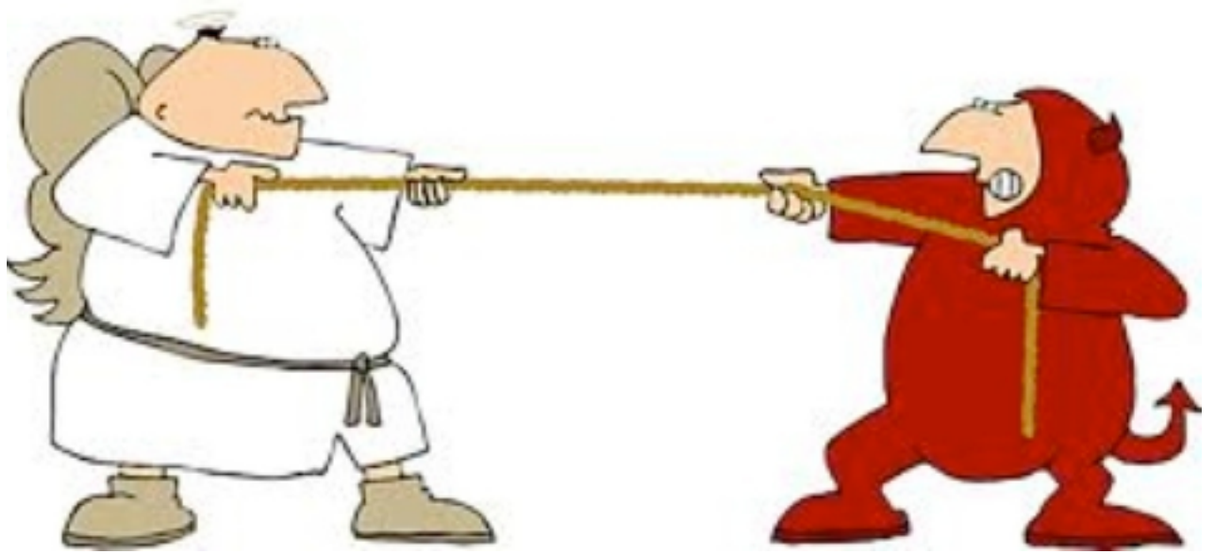

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Always desirable to marry the two whenever possible

Big Picture

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- Functional language + Synchronous message passing
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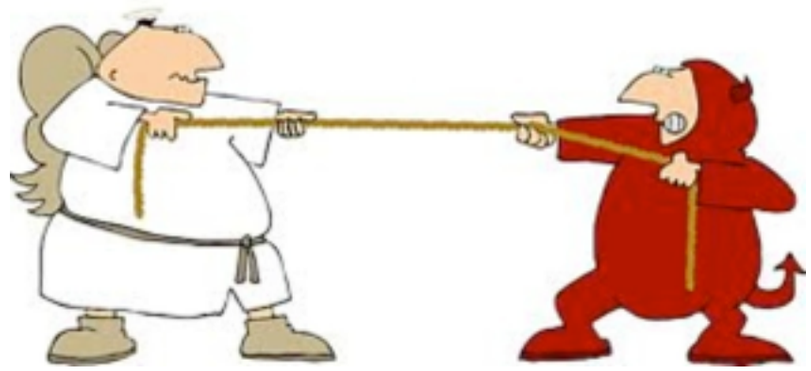

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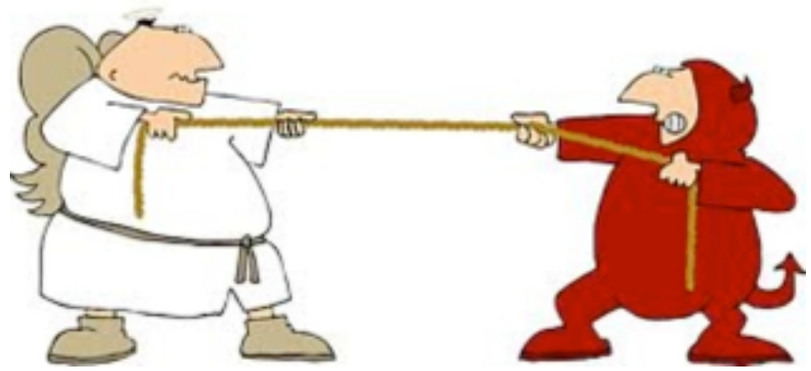

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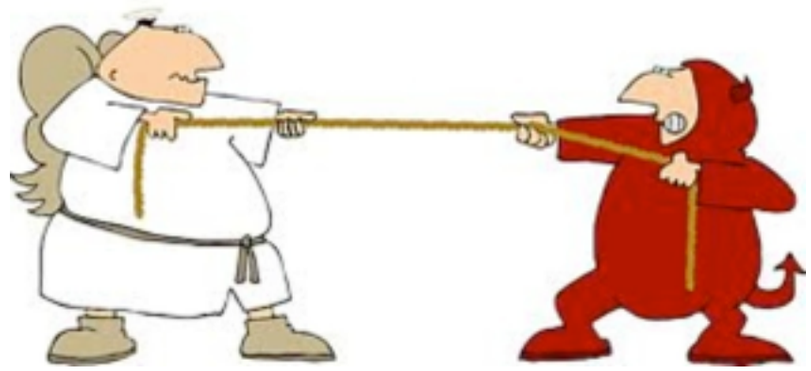

Synchrony *latency*

  - ★ Explicit asynchrony complicates reasoning

Can we discharge synchronous communications ***asynchronously*** *while ensuring* ***observable equivalence****?*

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2. A cloud infrastructure + speculative execution framework

   a. discharges synchronous sends asynchronously

   b. detects when the equivalence fails, and

   c. repairs failed executions

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- Concurrent ML
  - ★ Dynamic lightweight threads
  - ★ *Synchronous* message passing
  - ★ First-class events
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- A distributed extension of MultiMLton - MLton for scalable architectures
- Concurrent ML
  - ★ Dynamic lightweight threads
  - ★ *Synchronous* message passing
  - ★ First-class events
    - ✦ *Composable synchronous protocols*

```
val channel : unit -> ‘a chan
val spawn   : (unit -> unit) -> thread_id
val send    : ‘a chan * ‘a -> unit
val recv    : ‘a chan -> ‘a
val sendEvt : ‘a chan * ‘a -> unit event
val recvEvt : ‘a chan -> ‘a event
val sync    : ‘a event -> ‘a
```

```
val never     : ‘a event
val alwaysEvt : ‘a -> ‘a event
val wrap  : ‘a event -> (‘a -> ‘b) ->
            ‘b event
val guard : (unit -> ‘a event) -> ‘a event
val choose : ‘a event list -> ‘a event
...
```

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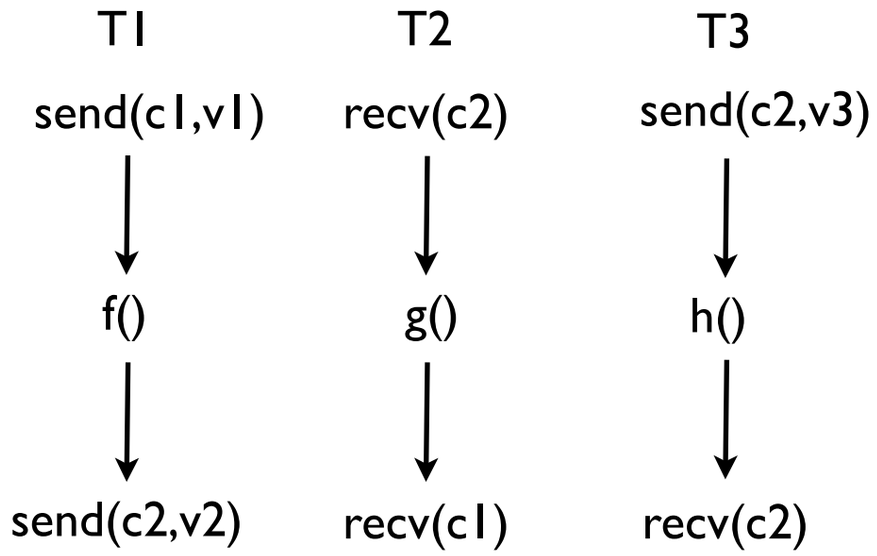
MultiMLton

Basic Idea (1)

T1	T2	T3
send(c1,v1) f() send(c2,v2)	recv(c2) g() recv(c1)	send(c2,v3) h() recv(c2)

Synchronous Execution



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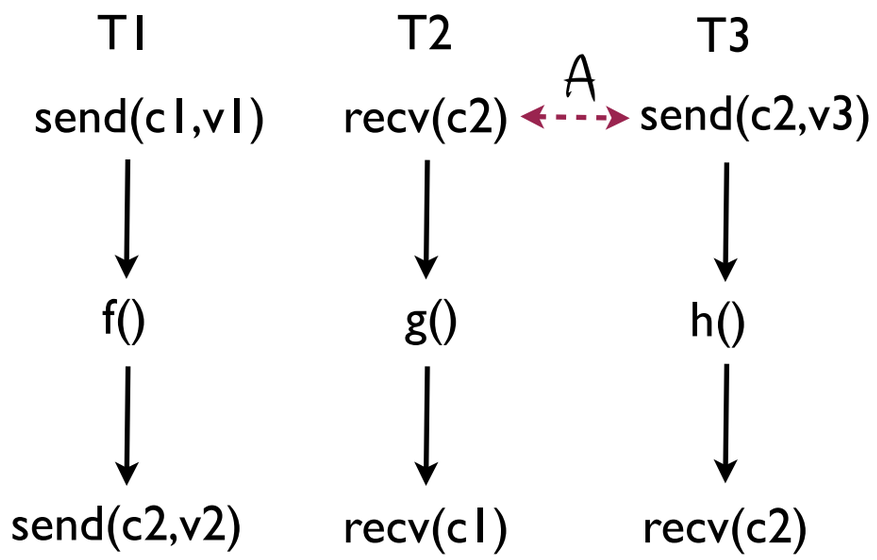

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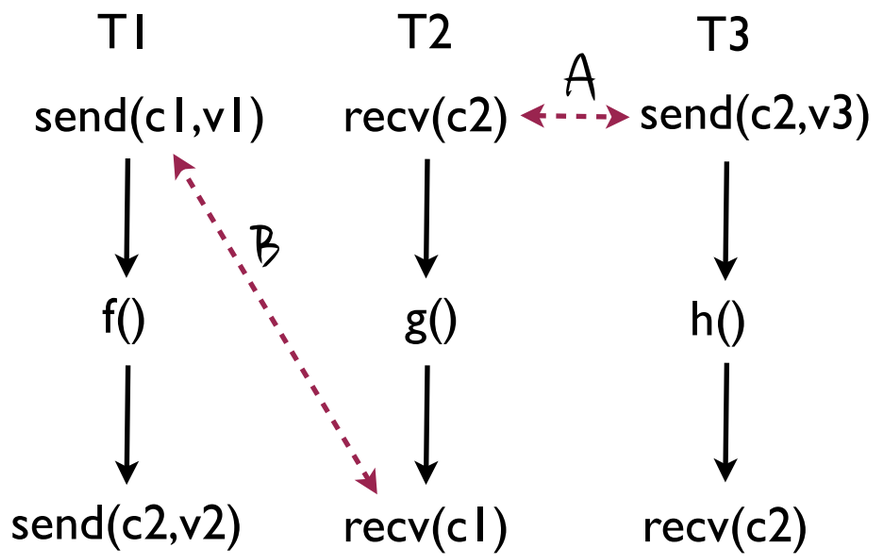

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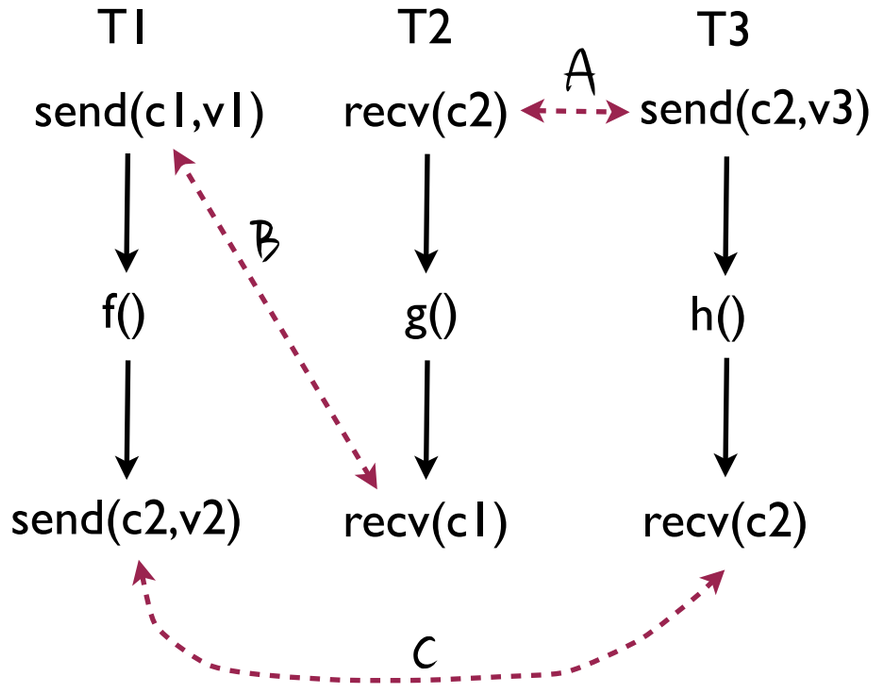

Basic Idea (2)

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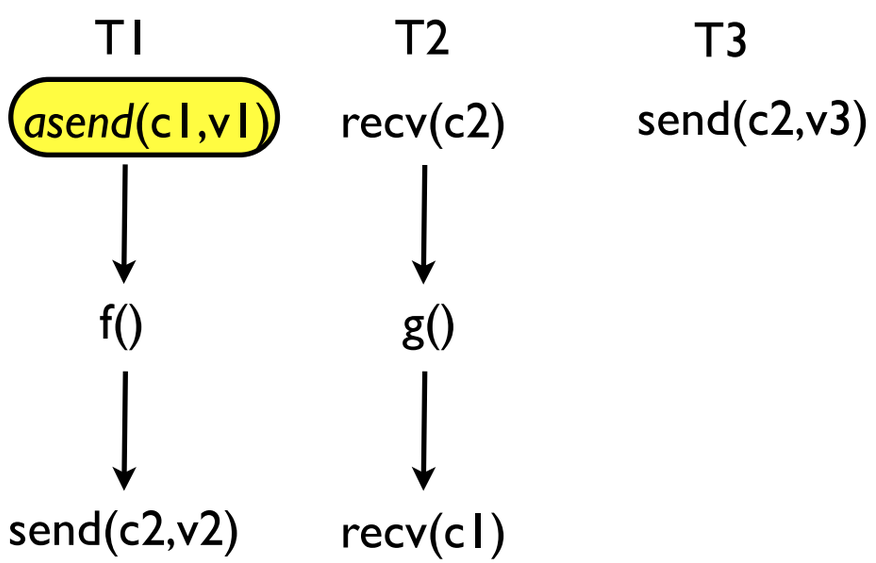

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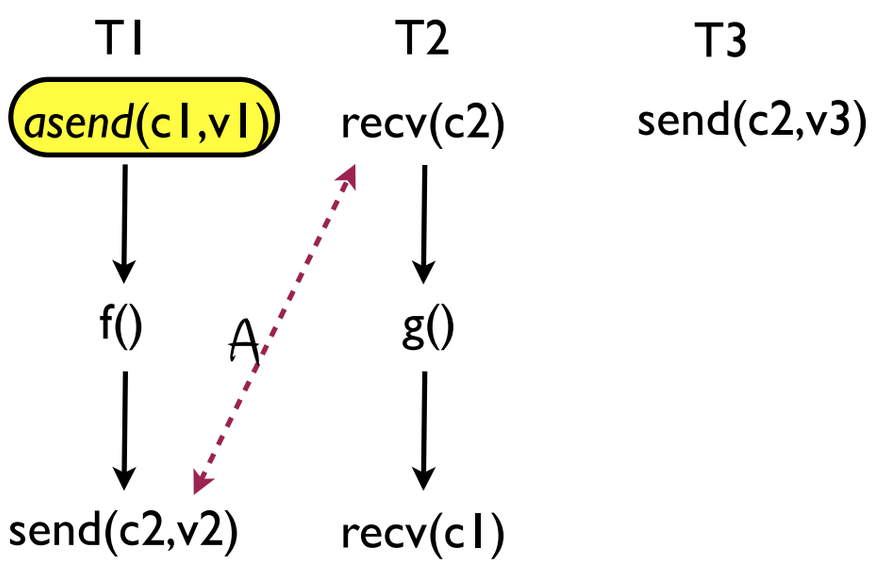

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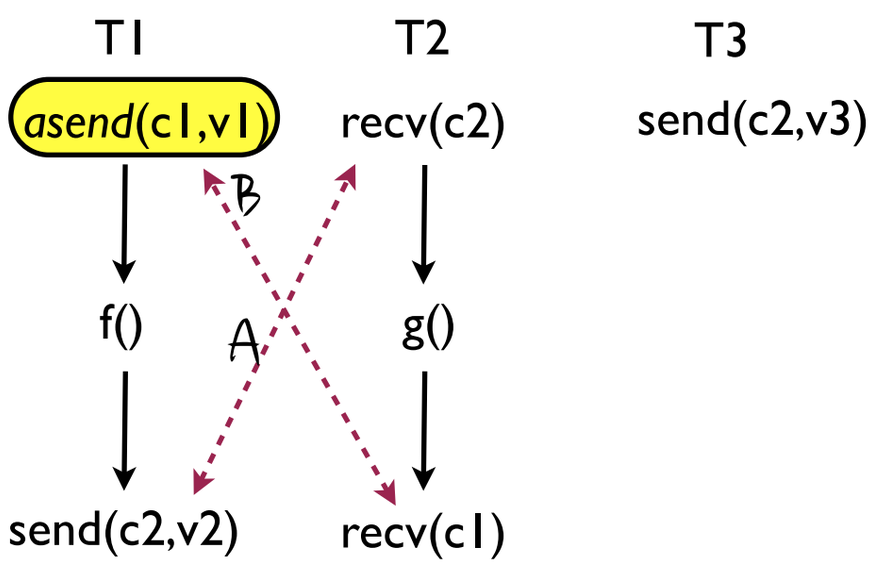

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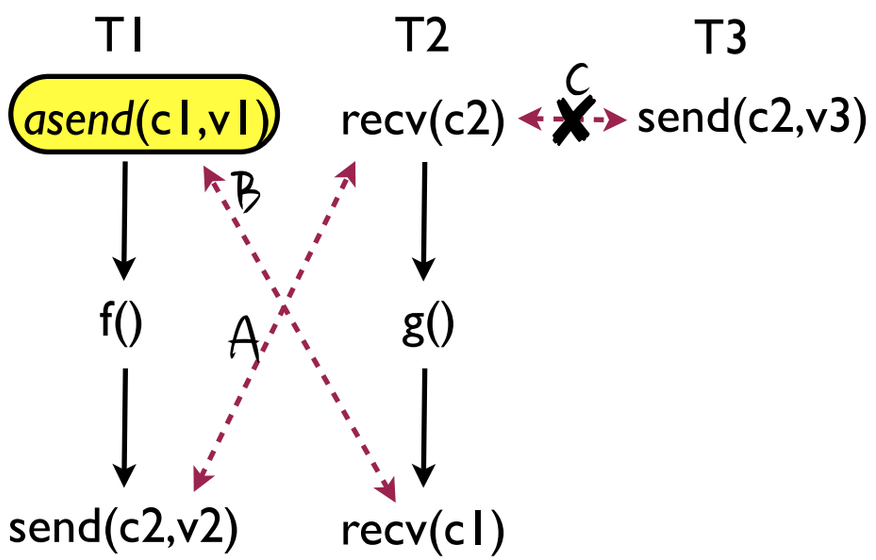

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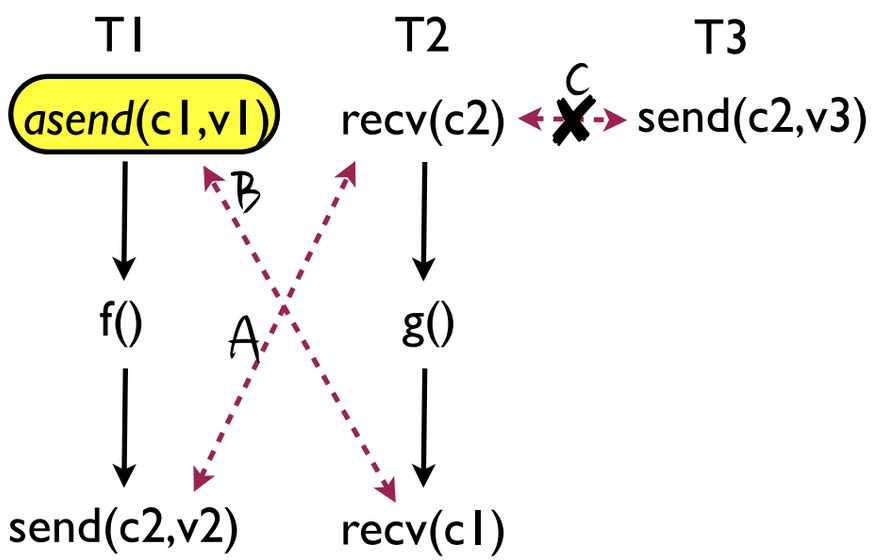

- Synchronous evaluation does not result in cyclic dependence
  - ★ Cyclic dependence => divergent behavior w.r.t synchronous evaluation

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fun bsend (BCHAN (vcList, acList), v: 'a, id: int) : unit =
let
  val _ = map (fn vc => if (vc = nth (vcList, id)) then () else send (vc, v))
              vcList (* phase 1 -- Value distribution *)
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synchronously send values

prevent receivers from proceeding until all members have received the value

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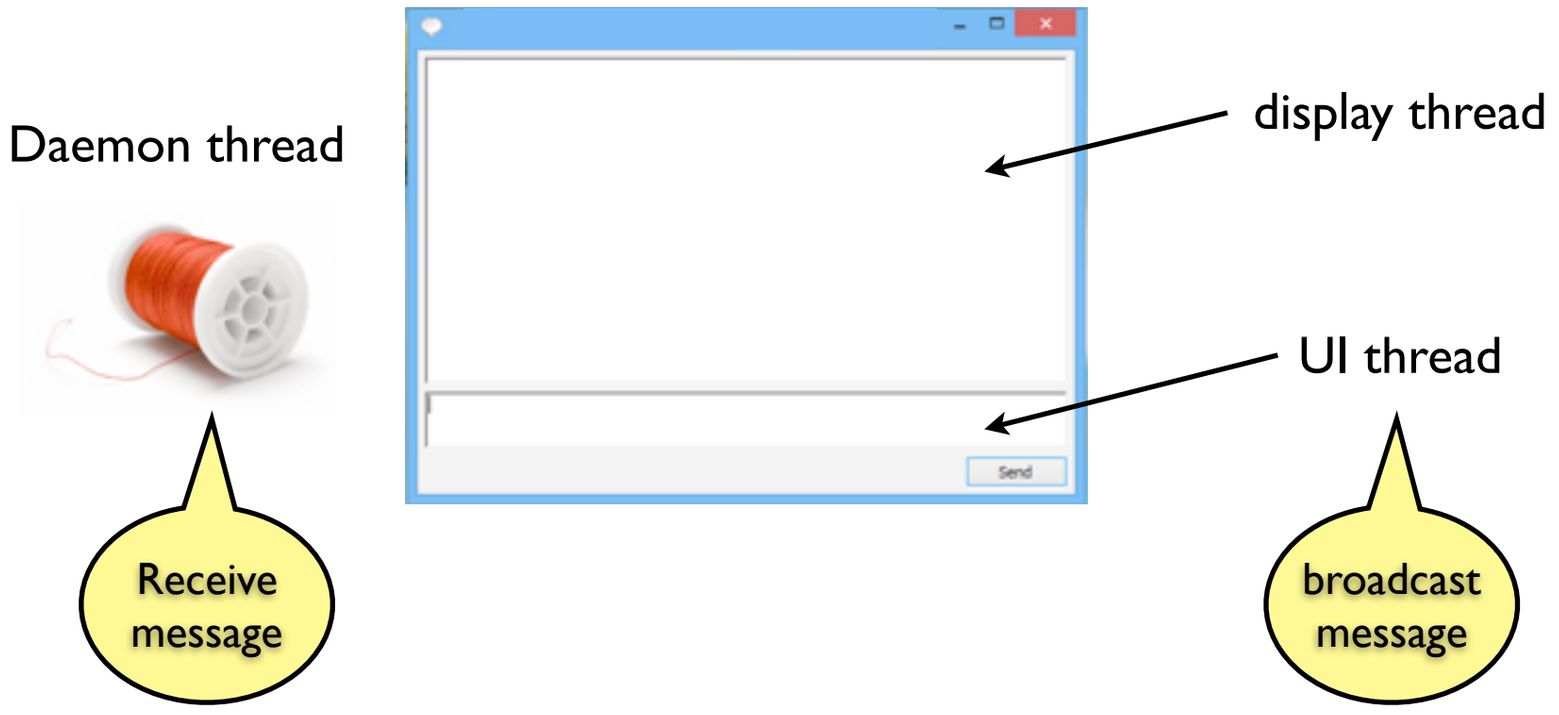
  - ★ Discharging asynchronously breaks causal ordering
  - ★ *Our idea: program synchronously, discharge asynchronously, detect and remediate causal ordering violations*

Example: Distributed Group Chat

- A distributed group chat program = {Node}
- Node = MultiMLton process = {CML threads}



Distributed Group Chat - Run 1

Display	UI	Daemon

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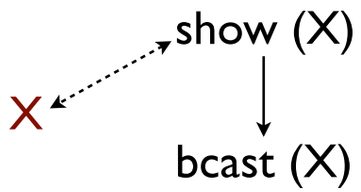

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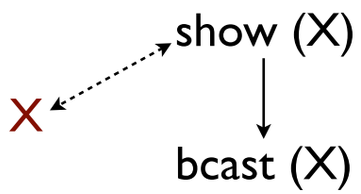

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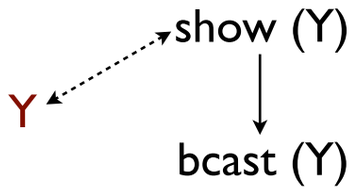

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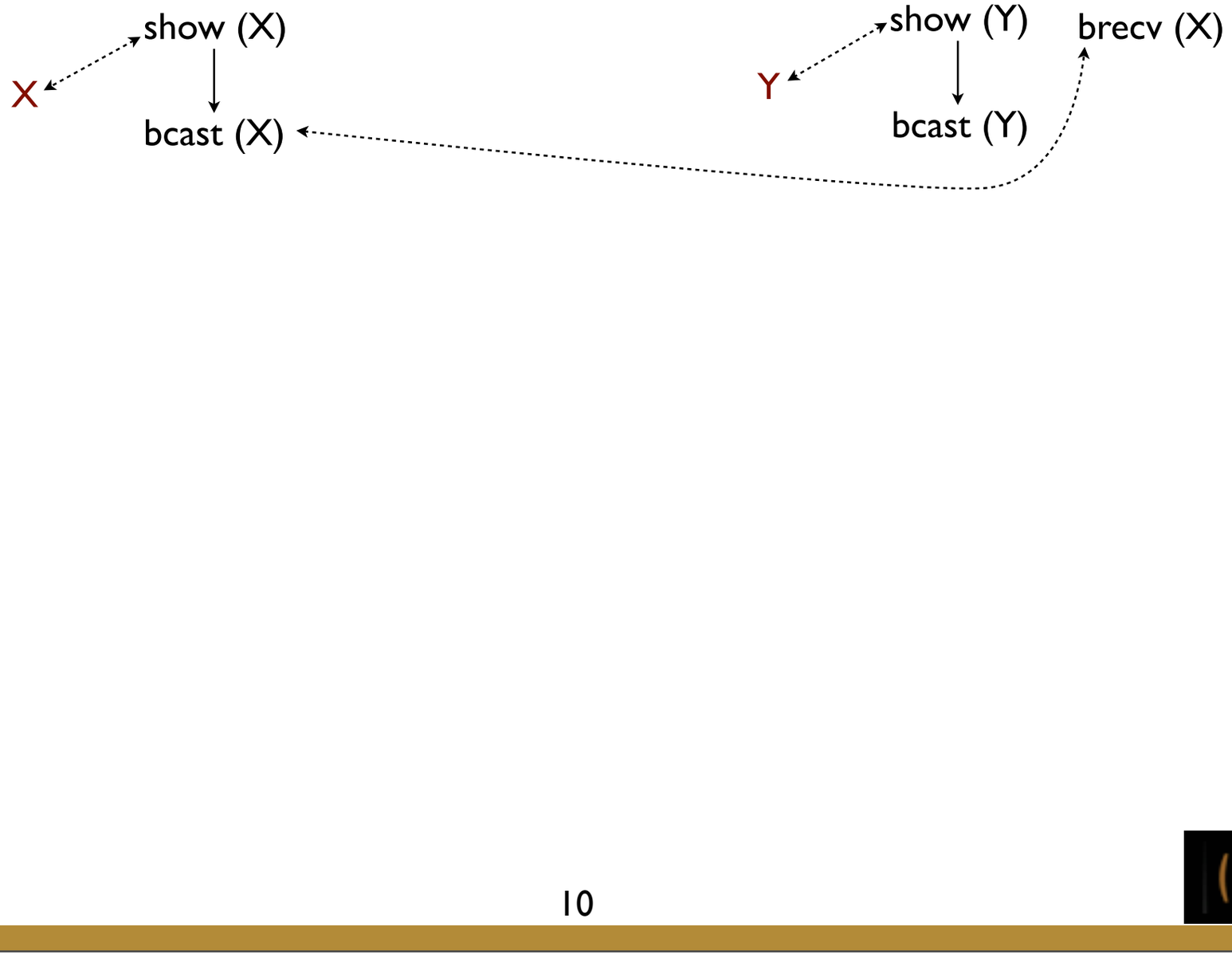

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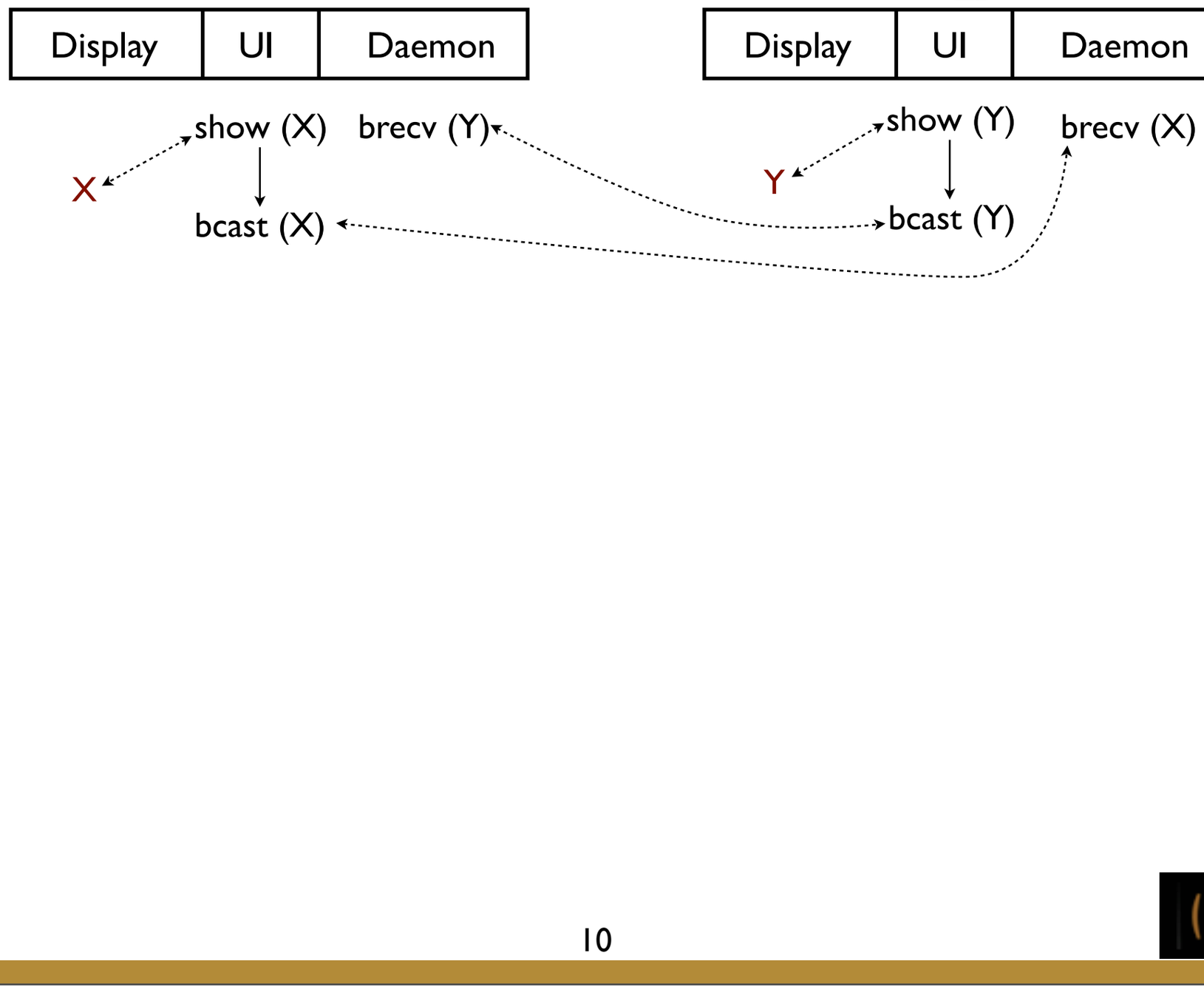

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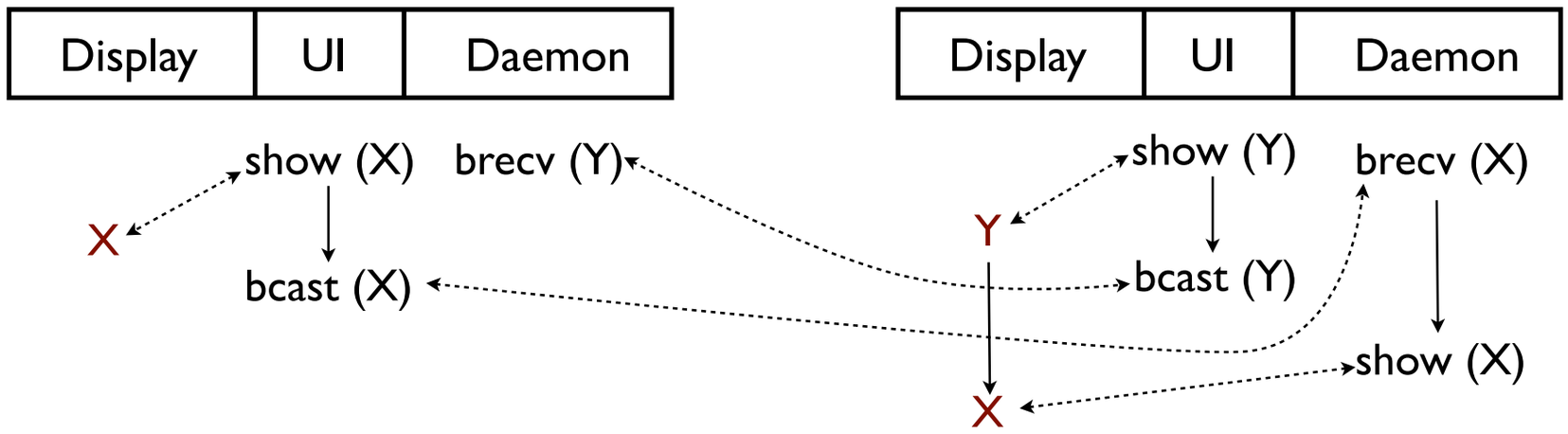

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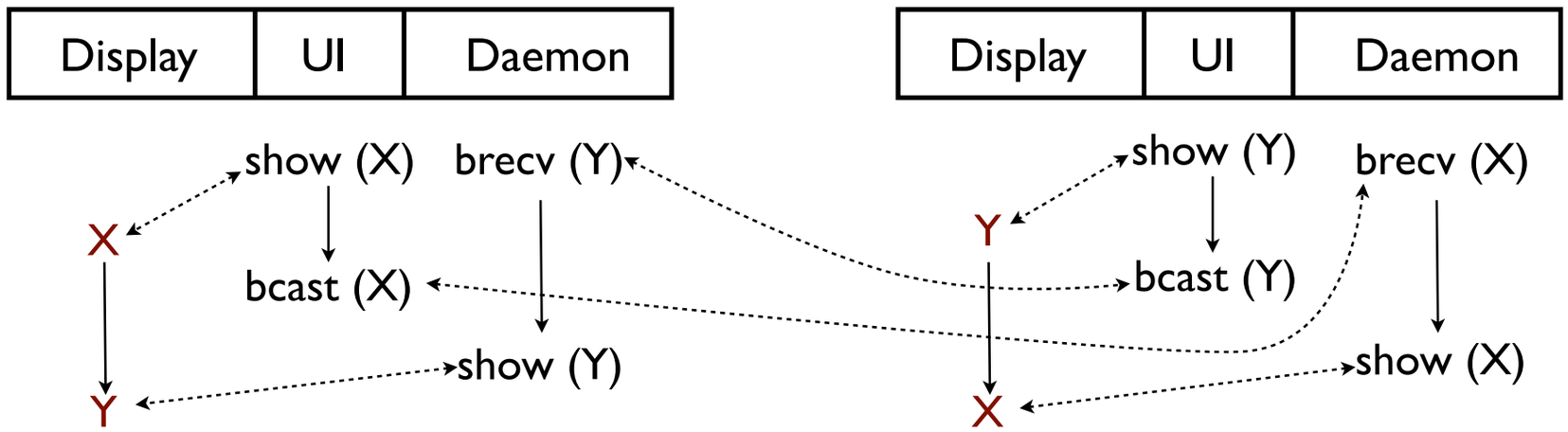

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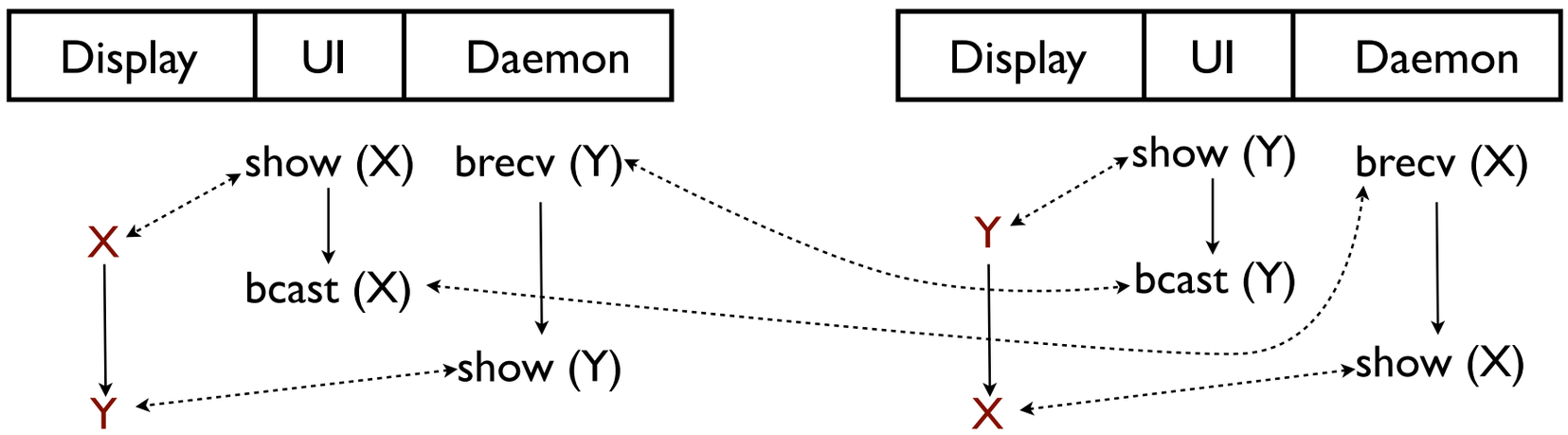

- Observations
  - ★ X and Y independently generated => No causal dependence between bcast (X) and bcast (Y)
- No Cycles => Correct execution!

Distributed Group Chat - Run 2

Display	UI	Daemon

Display	UI	Daemon

Display	UI	Daemon

Distributed Group Chat - Run 2

Display	UI	Daemon

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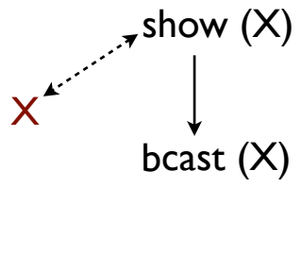

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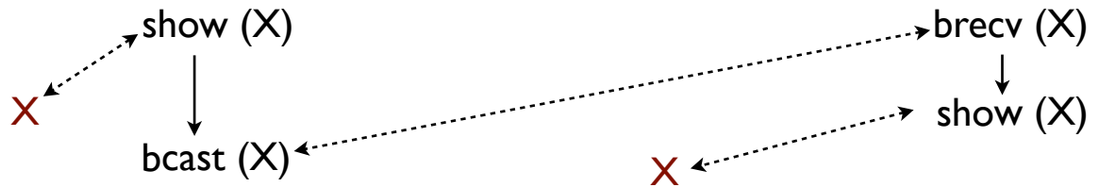

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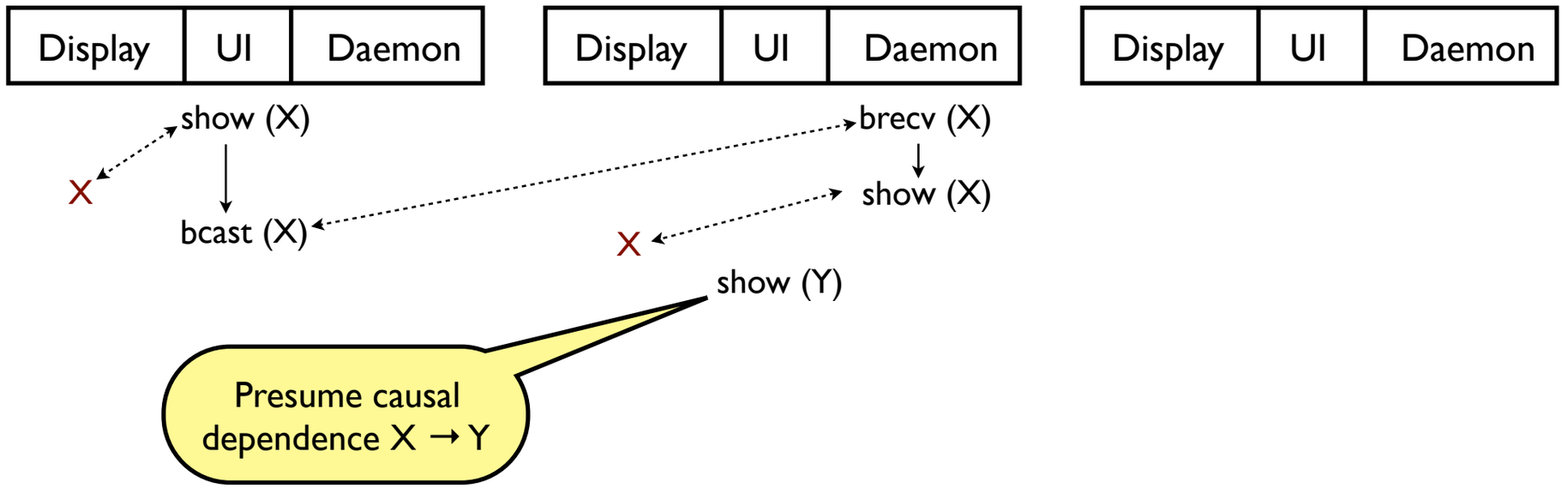

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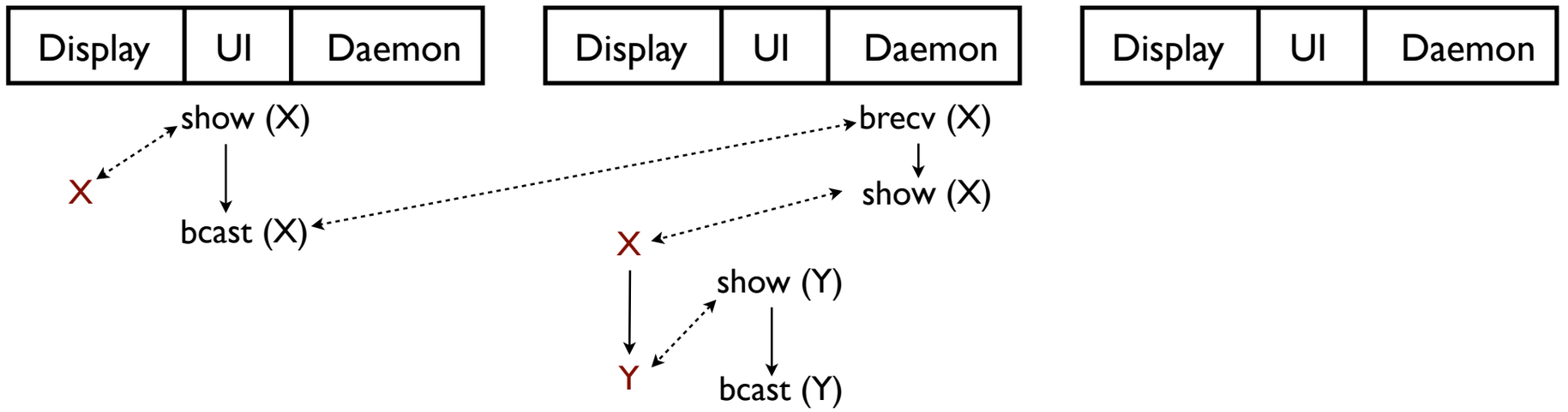

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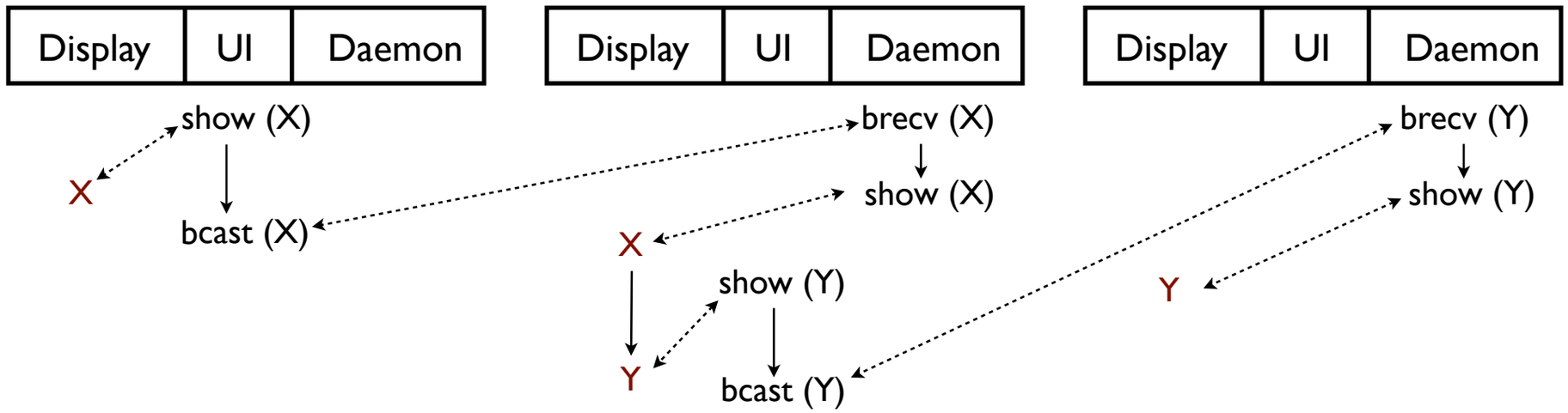

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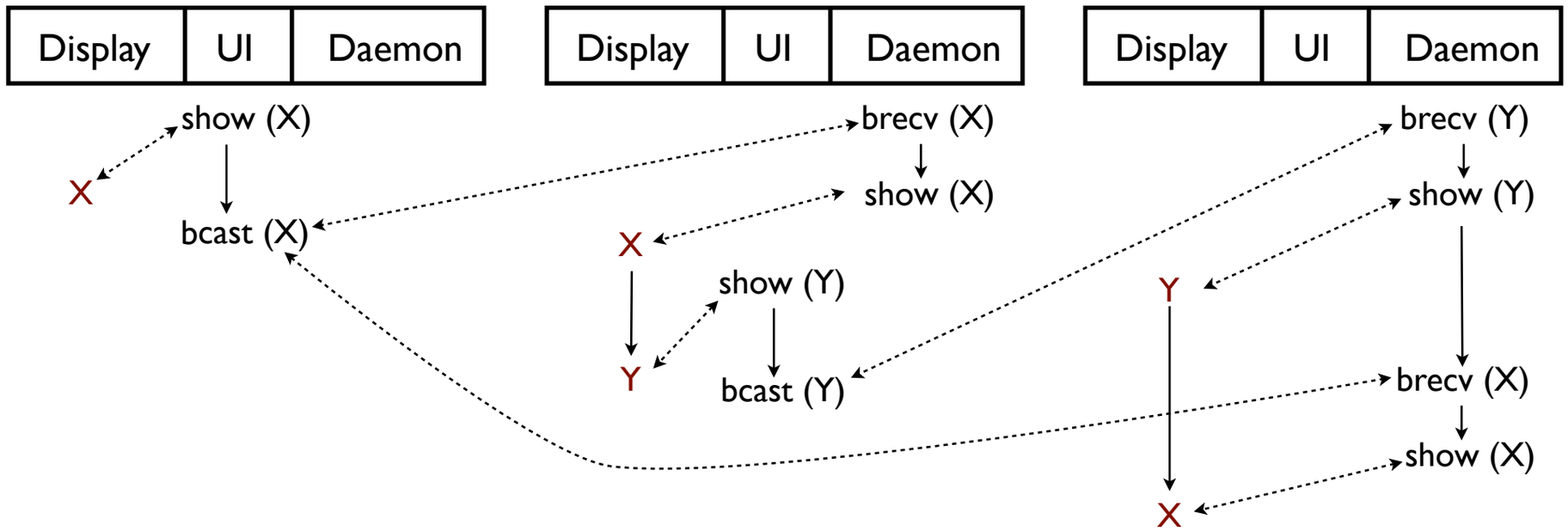

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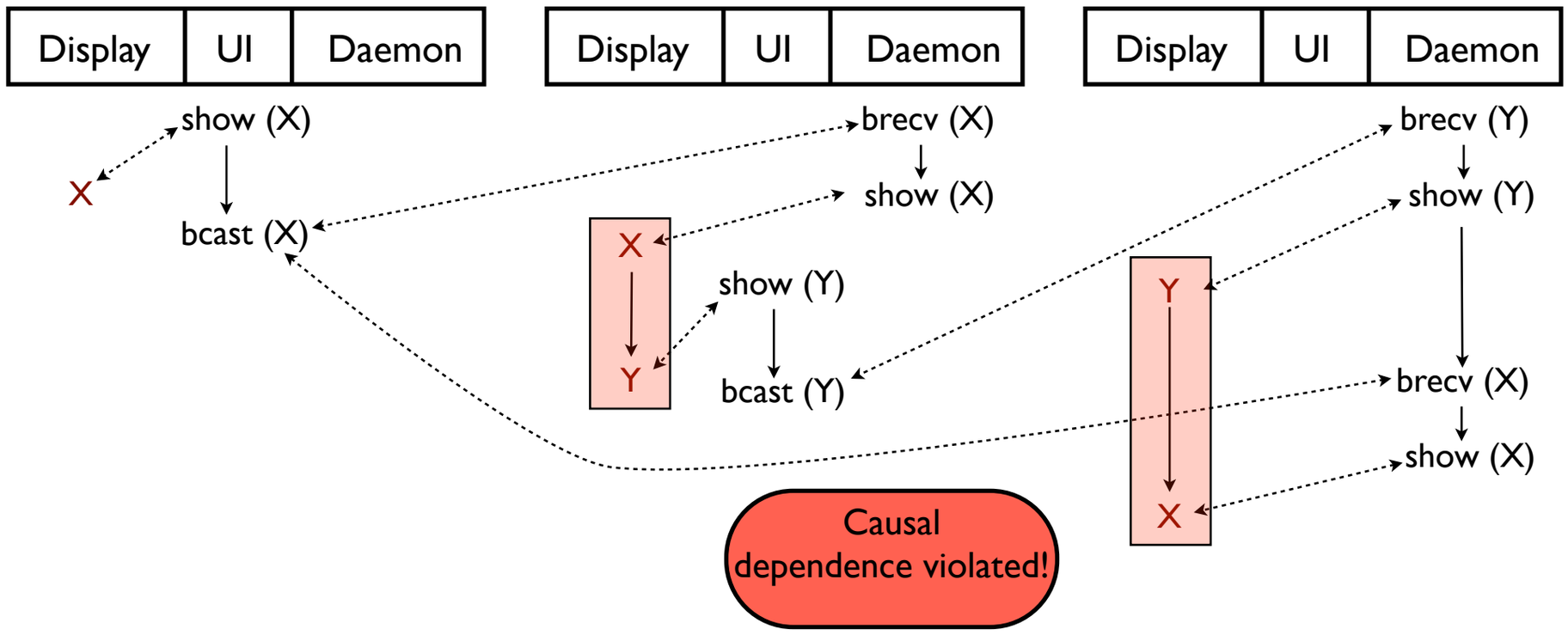

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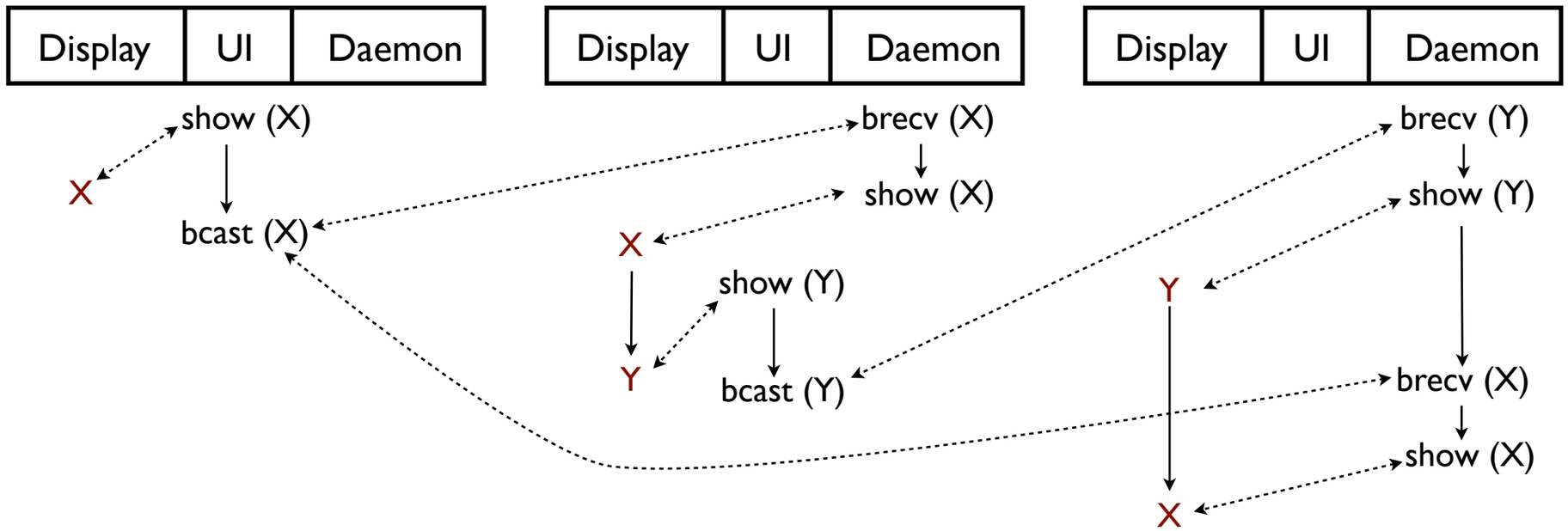
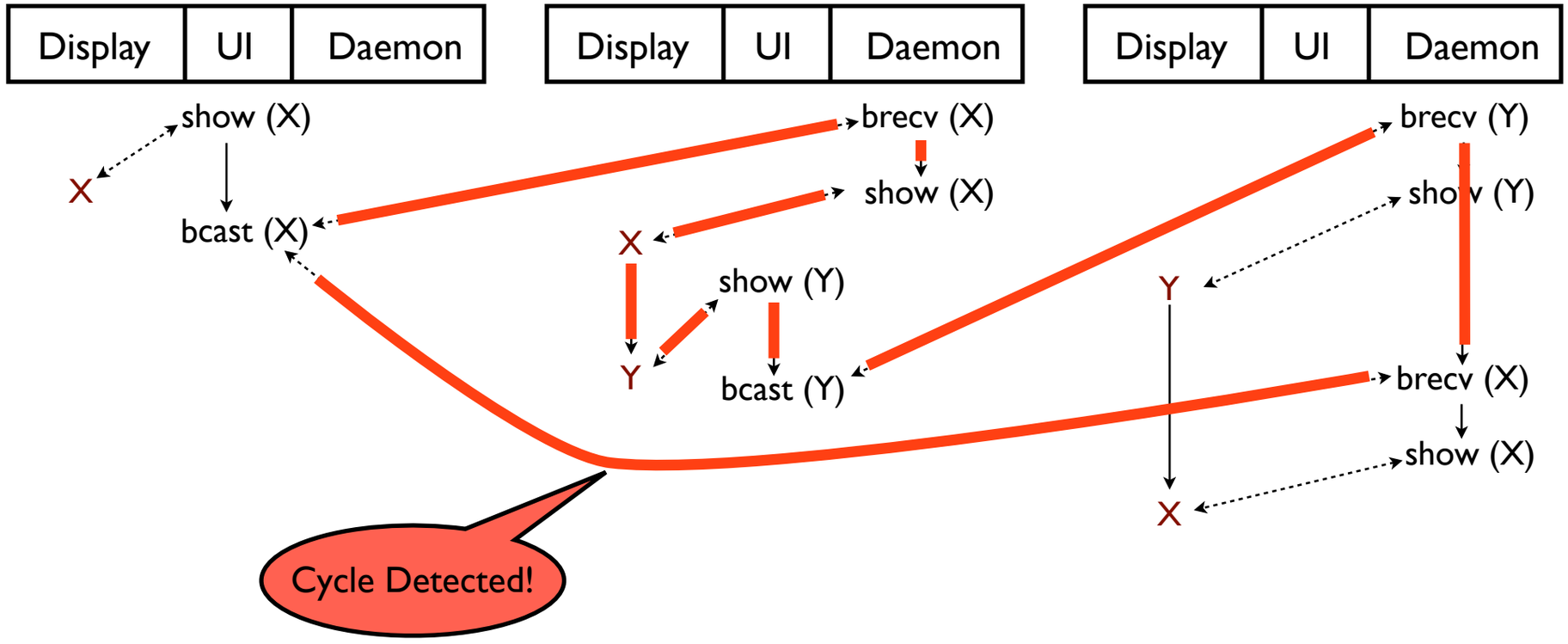


Distributed Group Chat - Run 2



Distributed Group Chat - Results

- Simulation on 3 geo-distributed Amazon EC2 instances
- Measure time between message initiation and receipt by all parties over 1000 iterations

Execution	*Avg.time (ms)*	*Errors*
Sync	1540	0
Unsafe Async	520	7
Safe Async ($\mathbb{R}x^{\mathrm{CML}}$)	533	0

Formalization Overview

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- ***Actions + happens-before relation***
  - ★ Captures visibility and dependence properties
- Happens-before is intentionally *relaxed*: may define more behaviors than possible in CML
  - ★ Strengthen the relation with ***well-formedness*** conditions

Actions and Execution

- Actions:

$$
\begin{array}{lcll}
\mathbb{A} & := & b_t & \text{(thread t starts)} \\
 & | & e_t & \text{(thread t ends)} \\
 & | & j_t^m t' & \text{(thread t detects thread t' has terminated)} \\
 & | & f_t^m t' & \text{(thread t creates a new thread t')} \\
 & | & s_t^m c, v & \text{(thread t sends value v on channel c} \\
 & | & r_t^m c & \text{(thread t receives a value on channel c)} \\
 & | & p_t^m v & \text{(thread t outputs an observable value v)}
\end{array}
$$

$$c \in \mathbb{C} \quad t, t' \in \mathbb{T} \quad v \in \mathbb{V} \quad m, n \in \mathbb{N}$$

- Execution:

$$\mathsf{E} := \langle \mathsf{P}, \mathsf{A}, \rightarrow_{po}, \mathsf{M} \rangle$$

program

a set of actions

program order: sequential actions of a thread

communication match: relates sends and receives

Communication and Thread Dependence

- A communication order exists between matching communication actions:

$$\alpha \rightarrow_{co} \beta \text{ and } \beta \rightarrow_{co} \alpha \text{ if } M(\alpha) = \beta$$

- Thread dependence order:

$$\alpha \rightarrow_{td} \beta \text{ if:}$$
$$(1)\ \alpha = f_t^m t' \text{ and } \beta = b_{t'} \text{ or}$$
$$(2)\ \alpha = e_t \text{ and } \beta = j_{t'}^m t$$

Happens-before Relation

- Establishes both intra- and inter-thread dependences:

$$
\begin{aligned}
\rightarrow_{hb} \quad = \quad & (\rightarrow_{po} \cup \rightarrow_{td} \cup \\
& \{(\alpha, \beta) \mid \alpha \rightarrow_{co} \alpha' \wedge \alpha' \rightarrow_{po} \beta\} \cup \\
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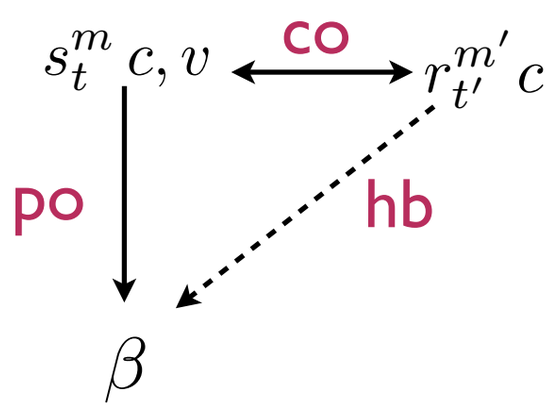

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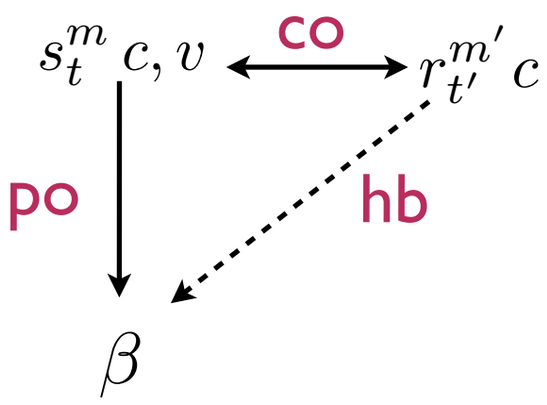
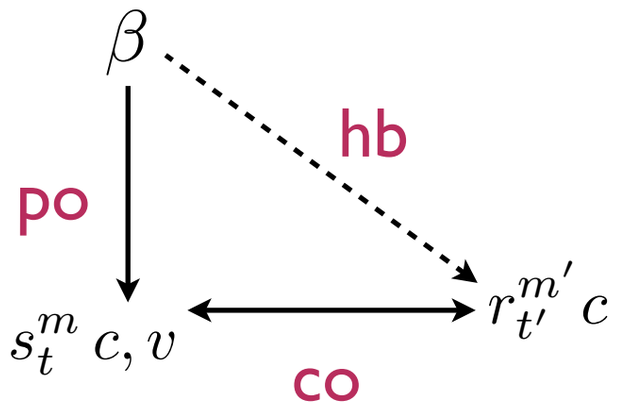




Example

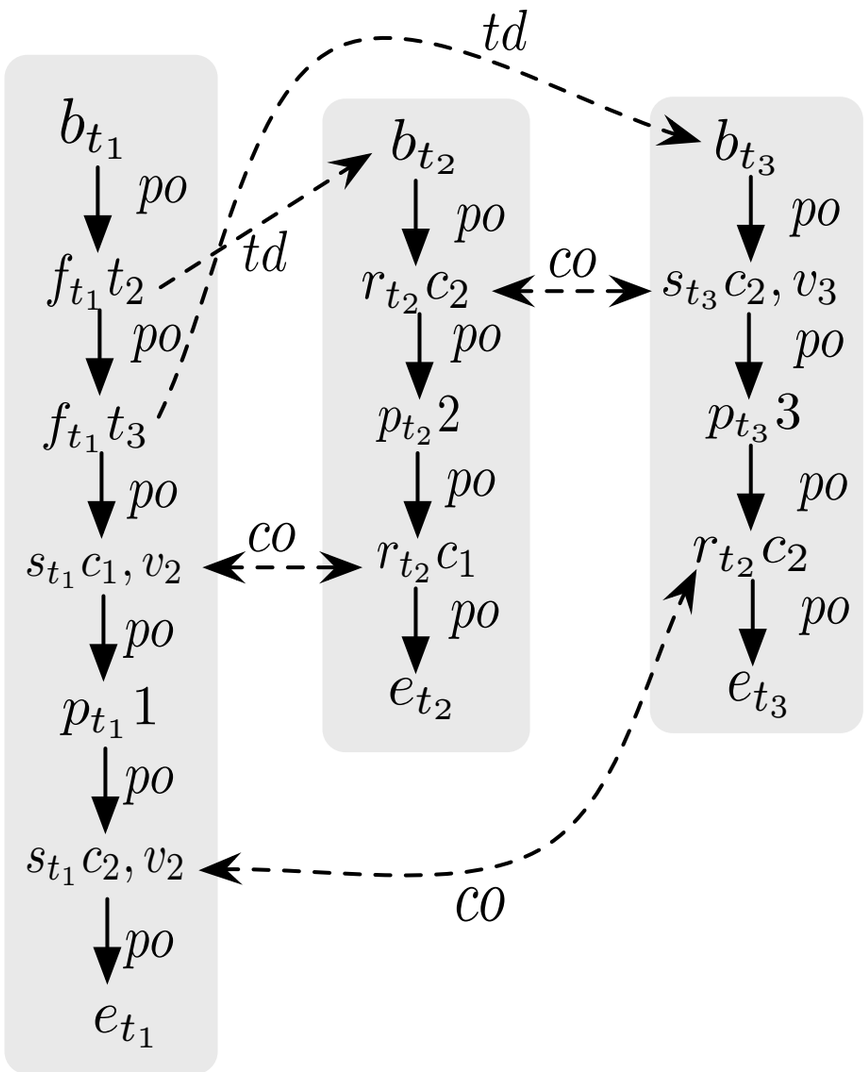
T1	T2	T3

`send(c1,v1)`
`f()`
`send(c2,v2)`
	`recv(c2)`
	`g()`
	`recv(c1)`
		`send(c2,v3)`
		`h()`
		`recv(c2)`

- Assume T1 spawns T2 and T3
- Let f, g, h = print 1, print 2, print 3

Example

T1	T2	T3
send(c1,v1) f() send(c2,v2)	recv(c2) g() recv(c1)	send(c2,v3) h() recv(c2)



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Example

```
T1              T2              T3
send(c1,v1)  ||  recv(c2)     ||  send(c2,v3)
f()          ||  g()          ||  h()
send(c2,v2)  ||  recv(c1)     ||  recv(c2)
```

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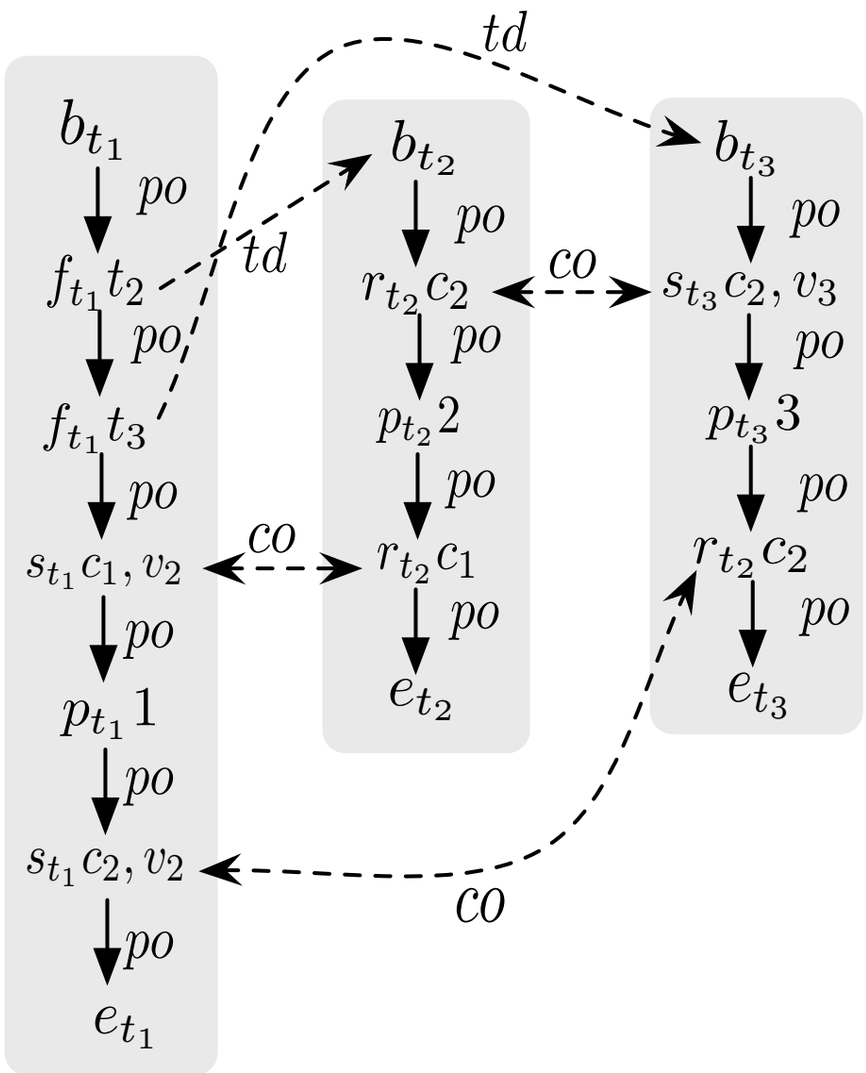
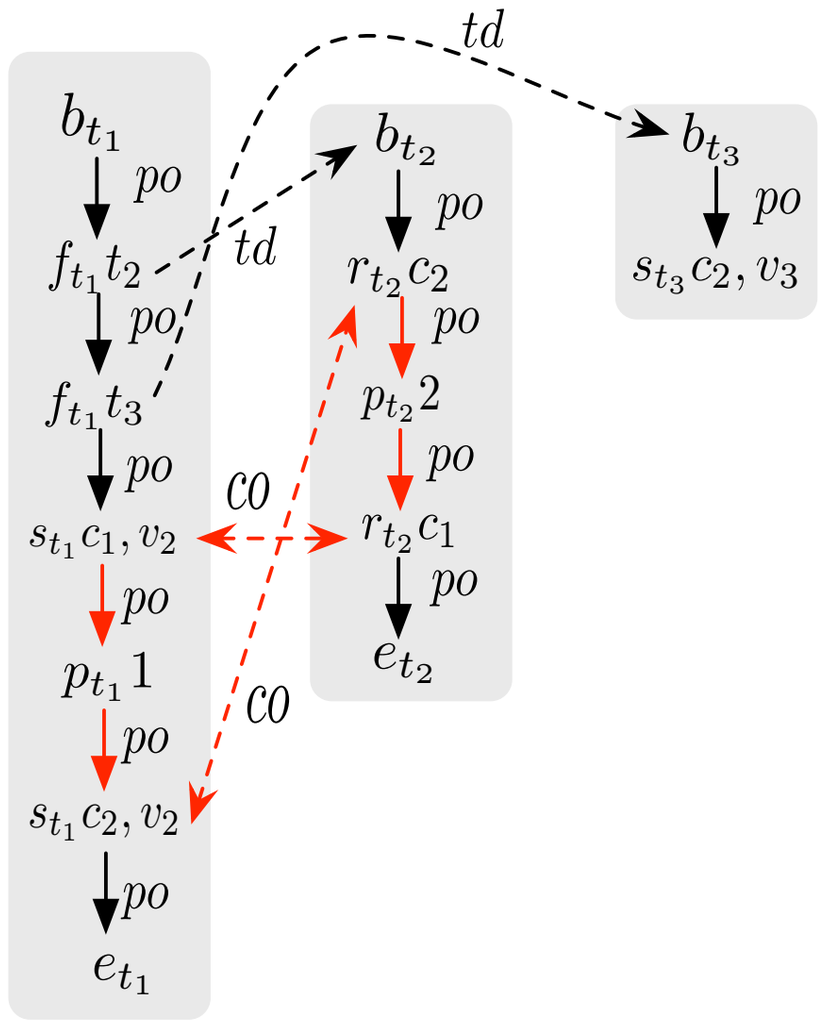
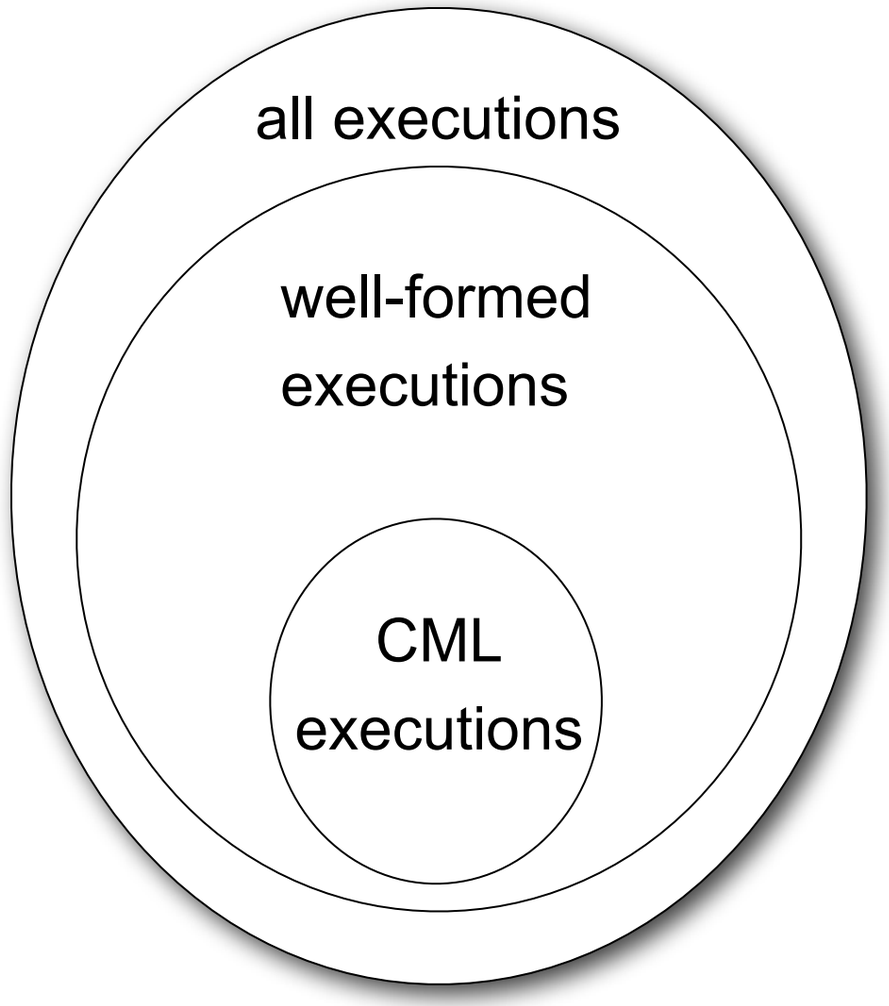




Well-formed Executions

Obs (Well-formed Execution of P) ∈ {Obs (CML Execution of P)}



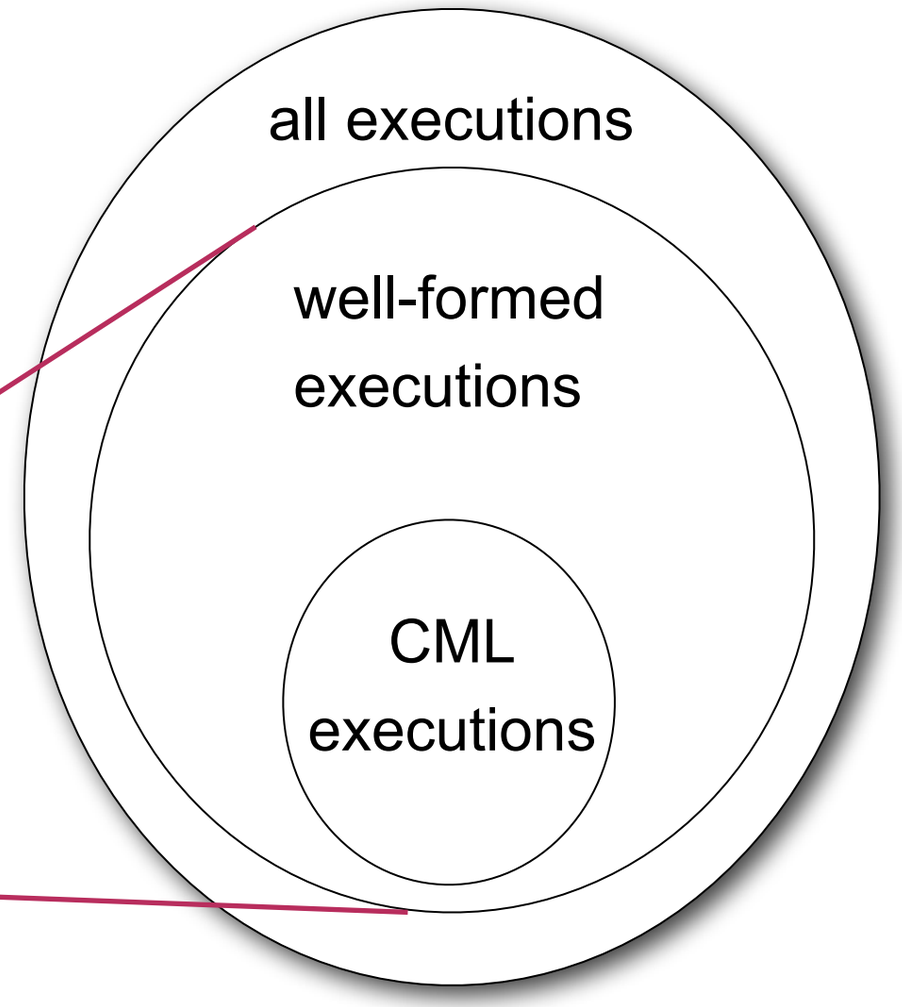
PURDUE UNIVERSITY

MultiMLton

Well-formed Executions

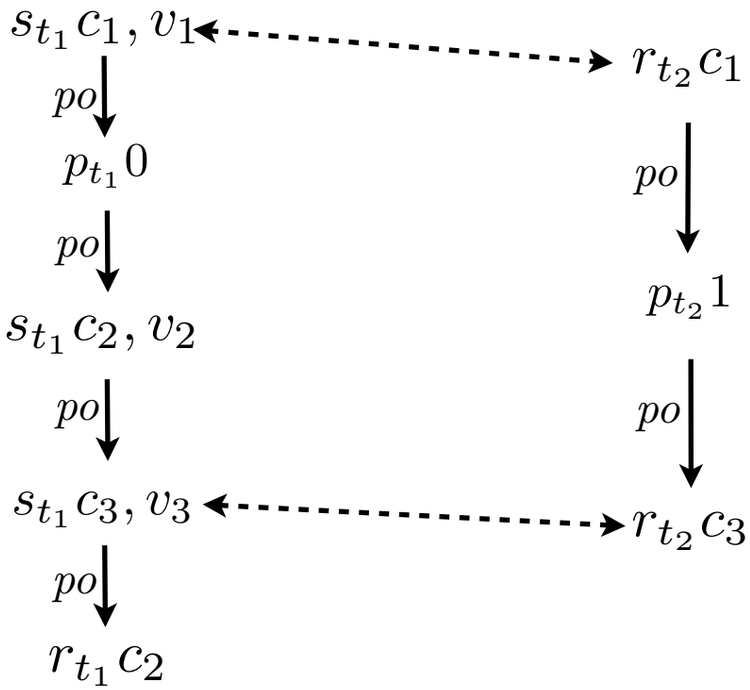
Obs (Well-formed Execution of P) ∈ {Obs (CML Execution of P)}

1. Sensible intra-thread semantics
2. Acyclic happens-before relation
3. No outstanding communication action preceding an observable action



Well-formedness -> Speculation

Track executions to see if they become
ill-formed (rollback) or turn into CML executions (commit)



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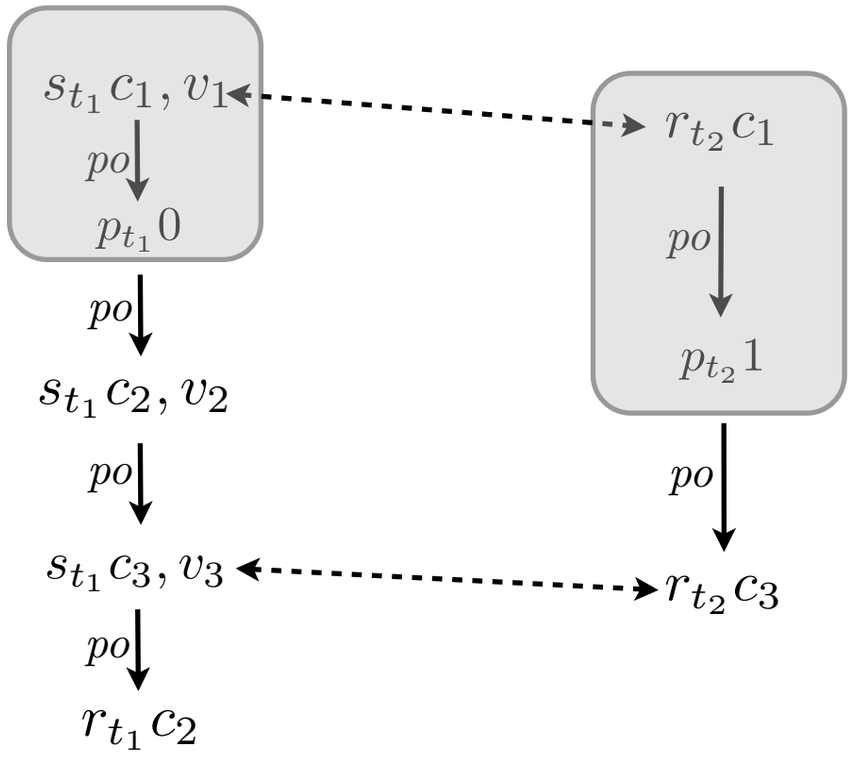

A CML execution

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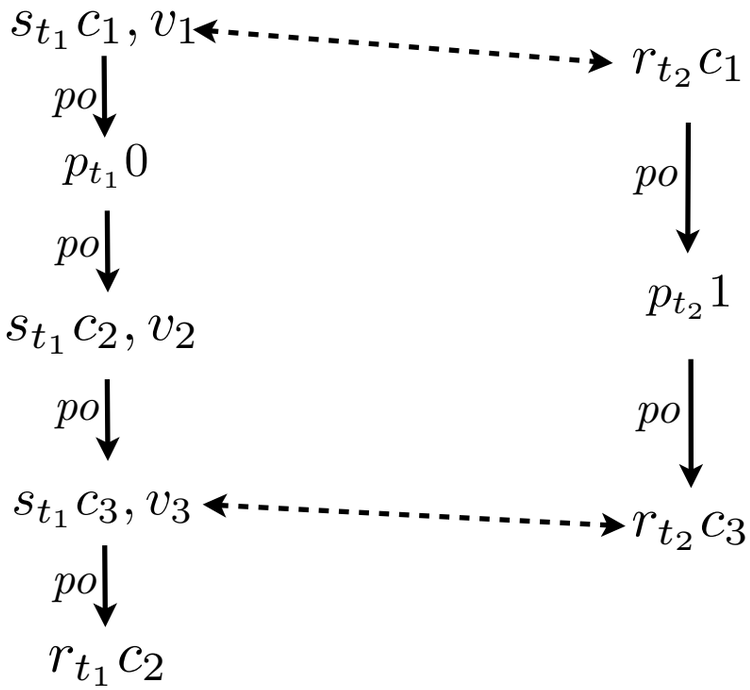

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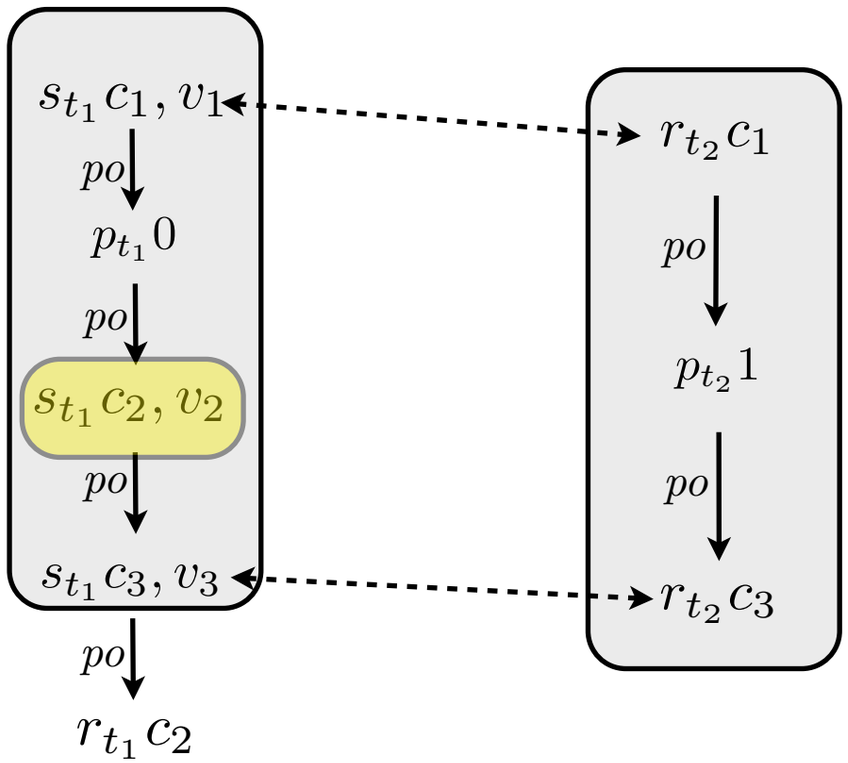

A well-formed execution that *can lead* to a CML execution

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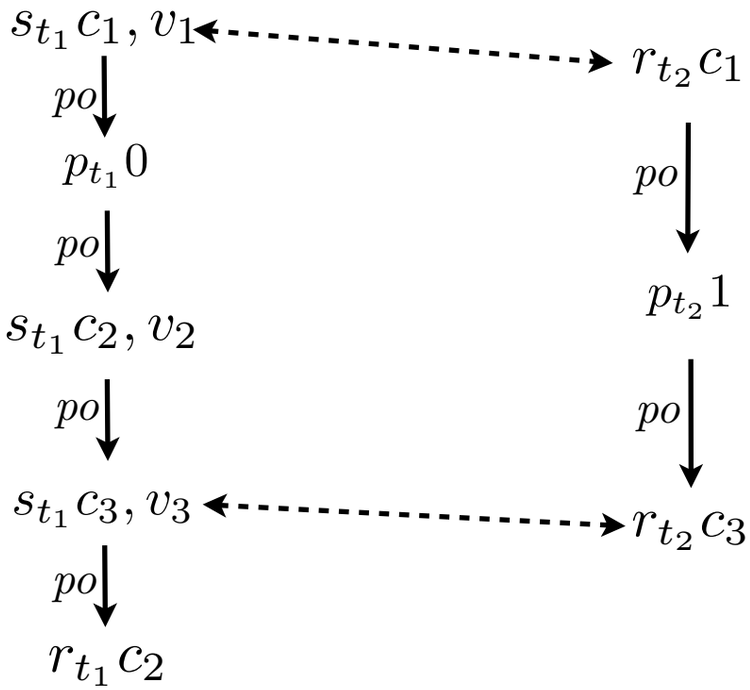

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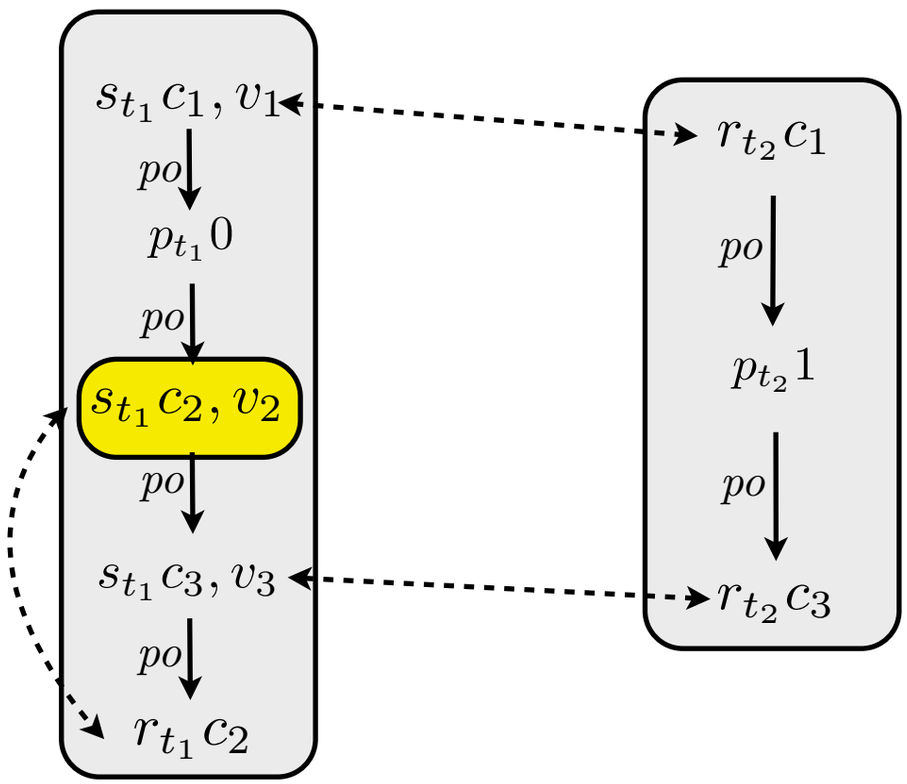

Not a well-formed execution

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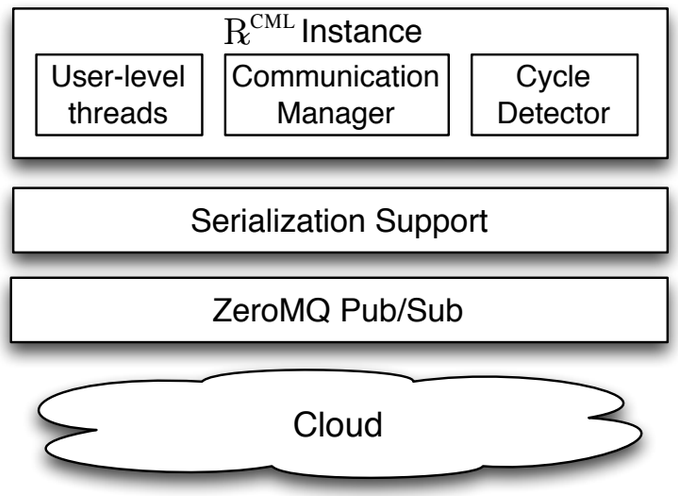

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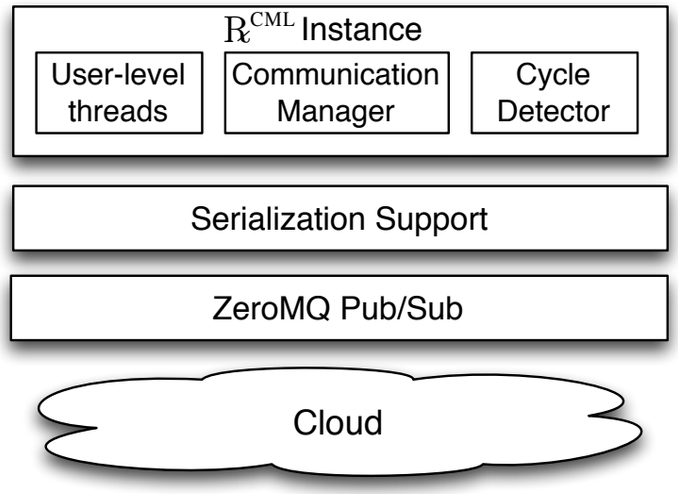

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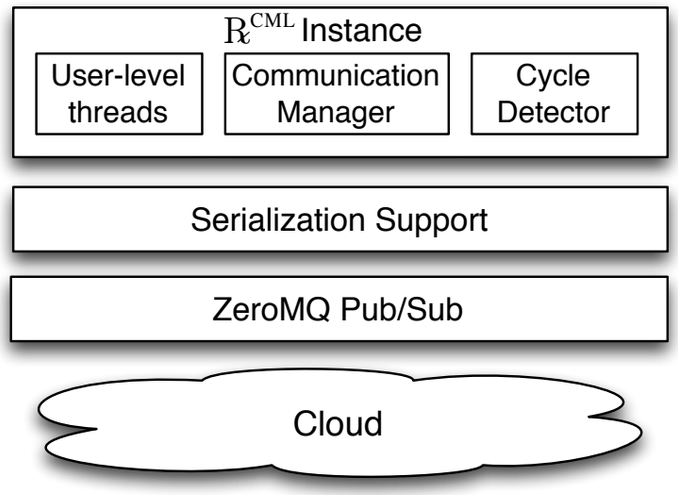

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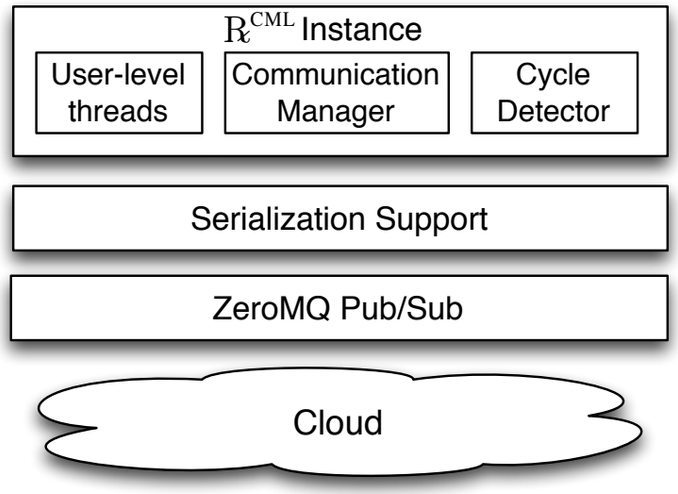

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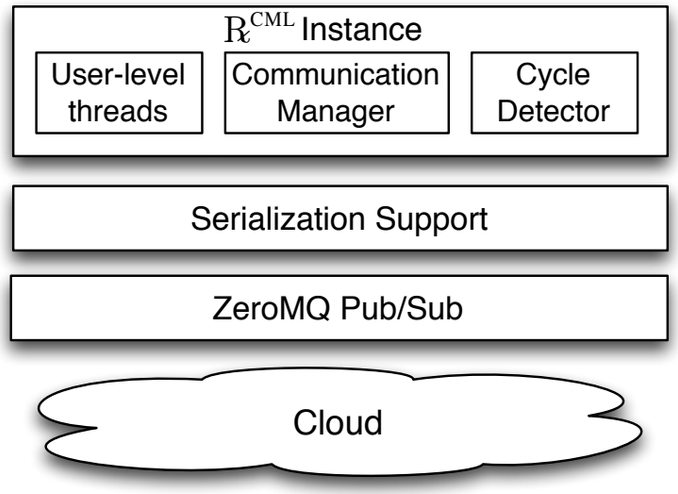

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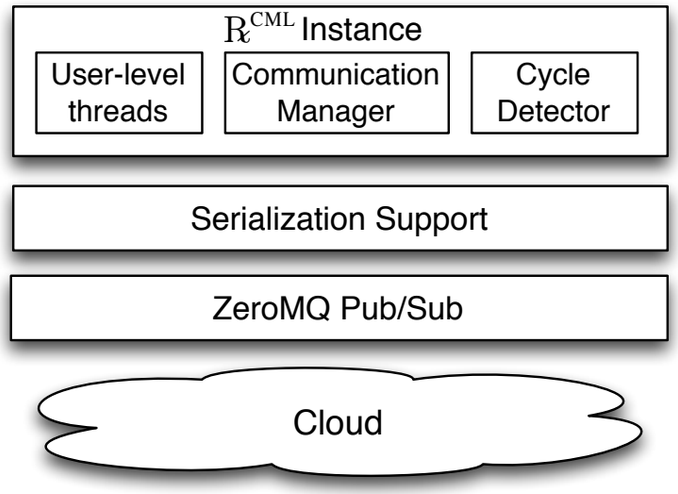
  - ★ Roll-back ill-formed executions, re-execute non-speculatively



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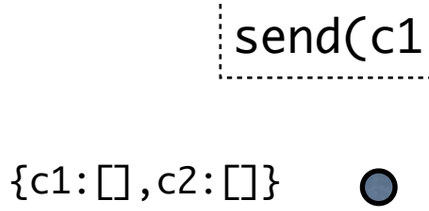
Instance 1

```
send(c1,0);
```

Instance 2

```
recv(c1);
```

Instance 3



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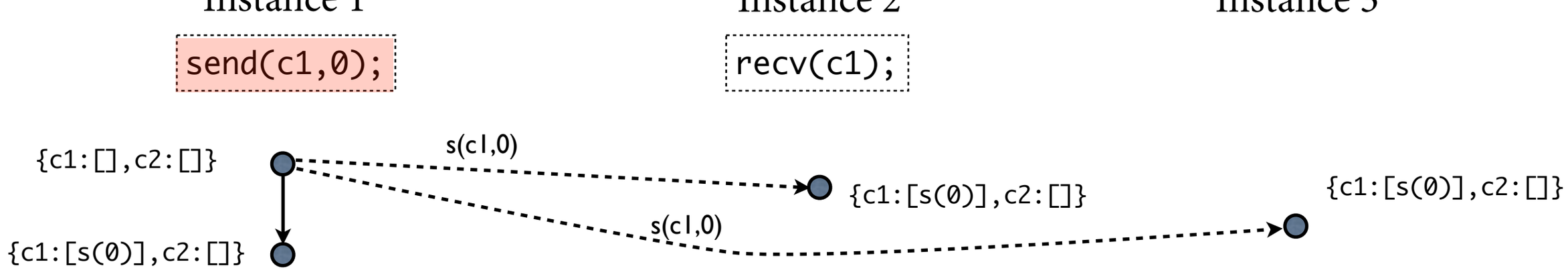

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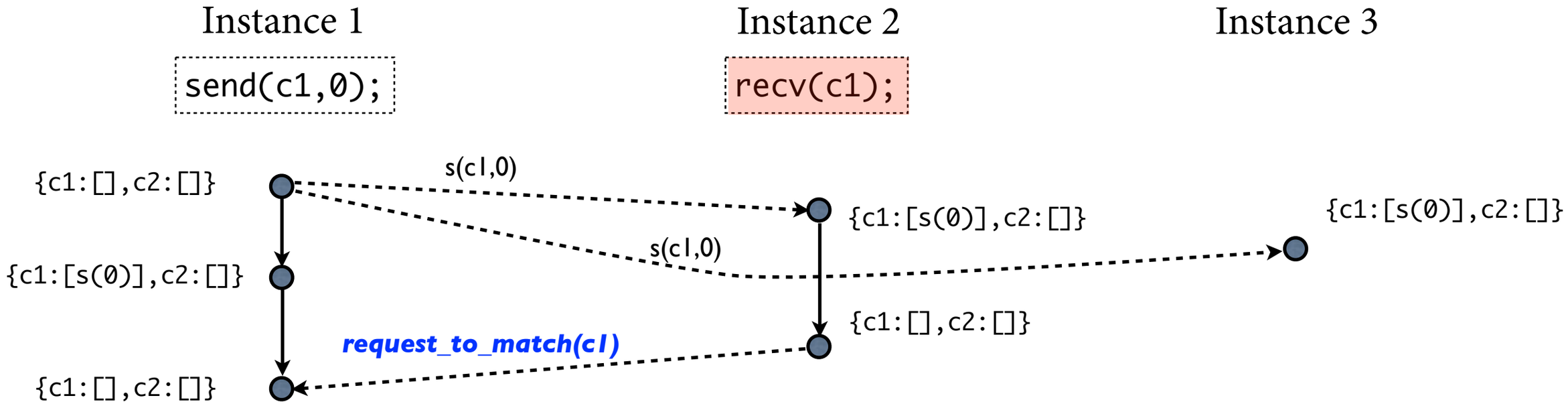

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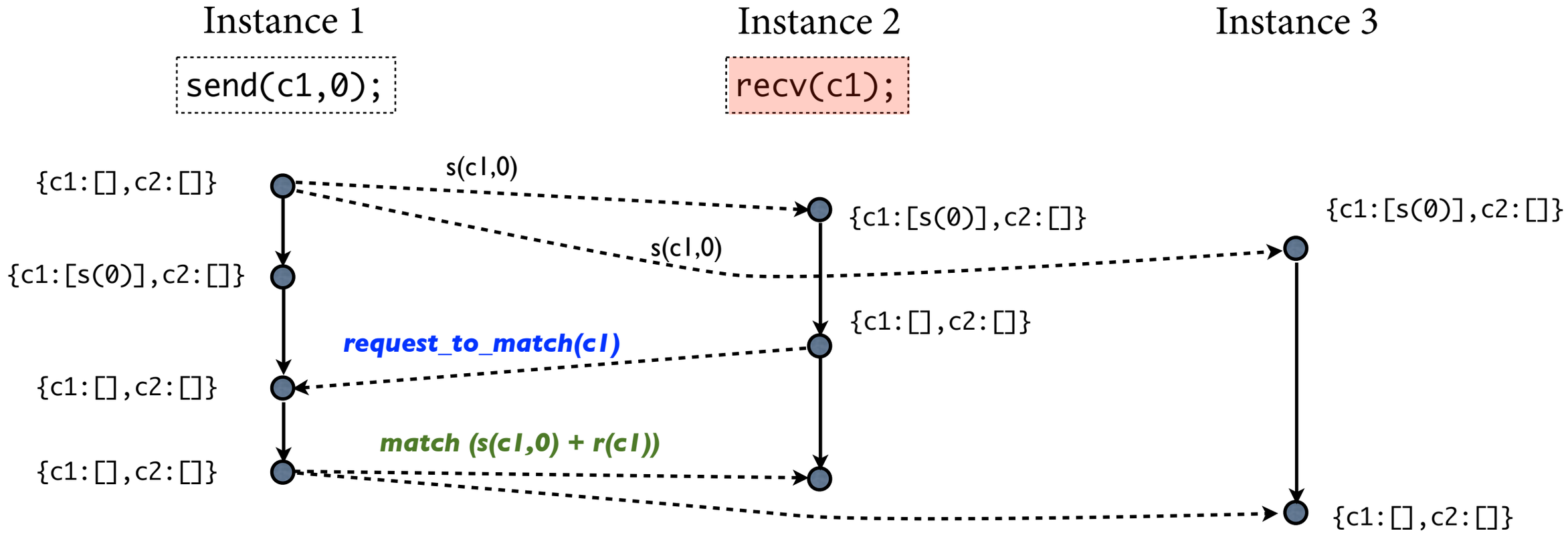

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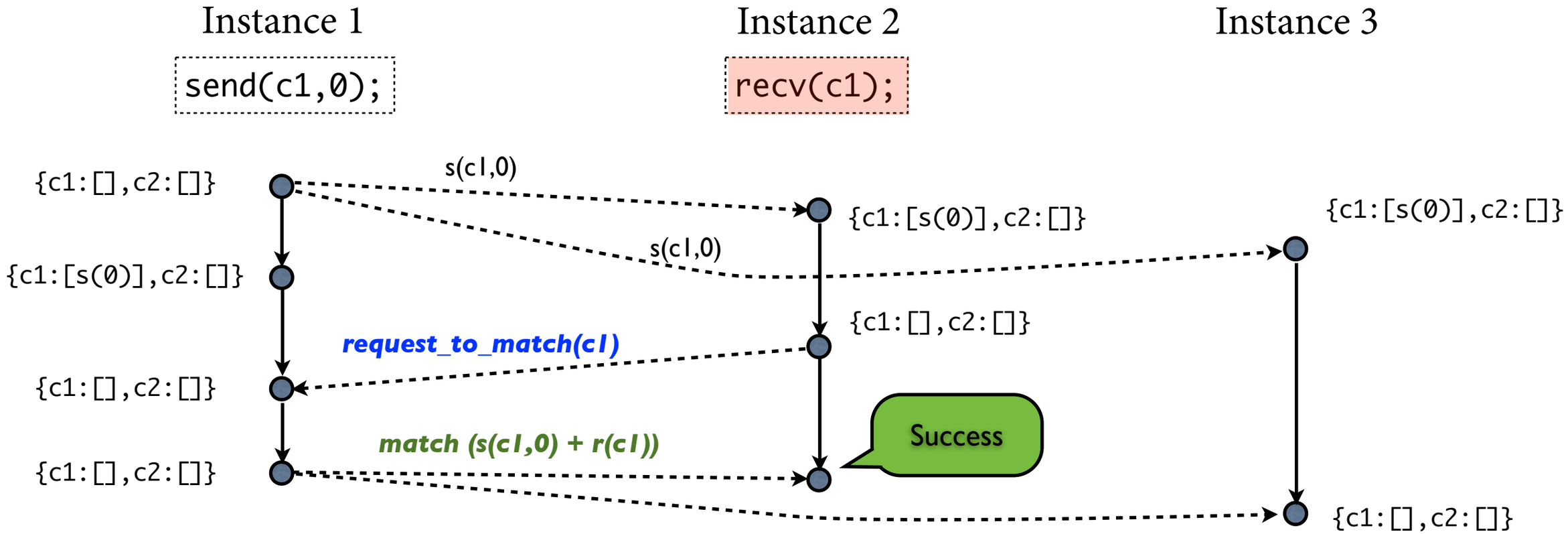

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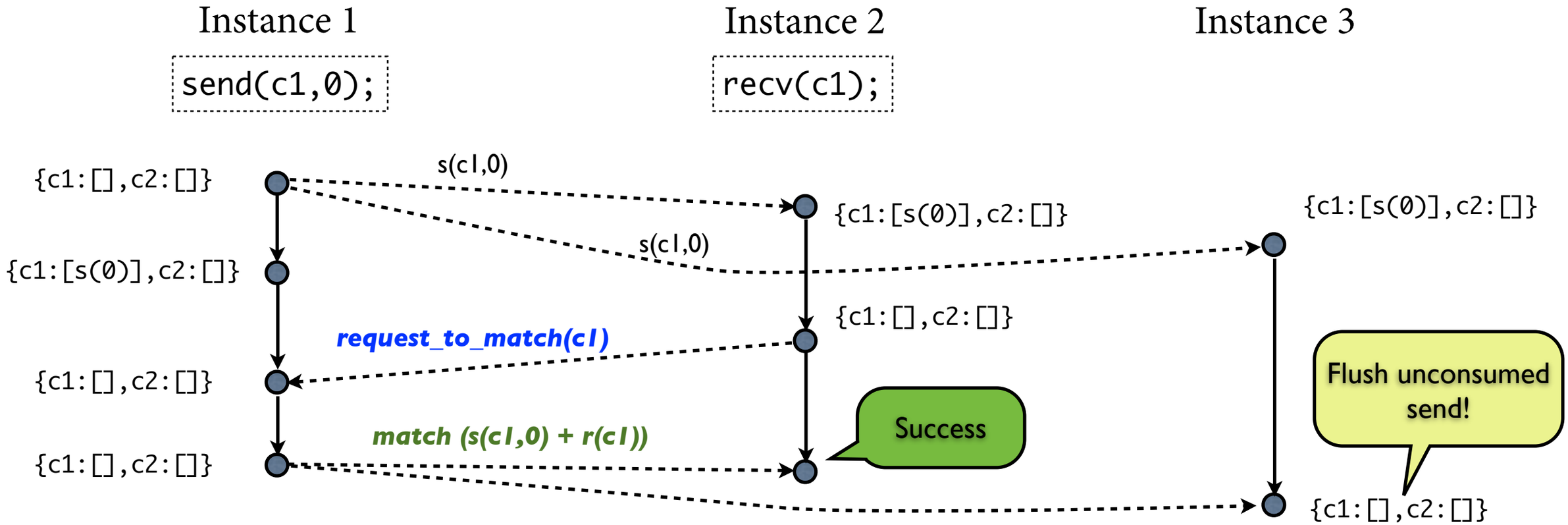
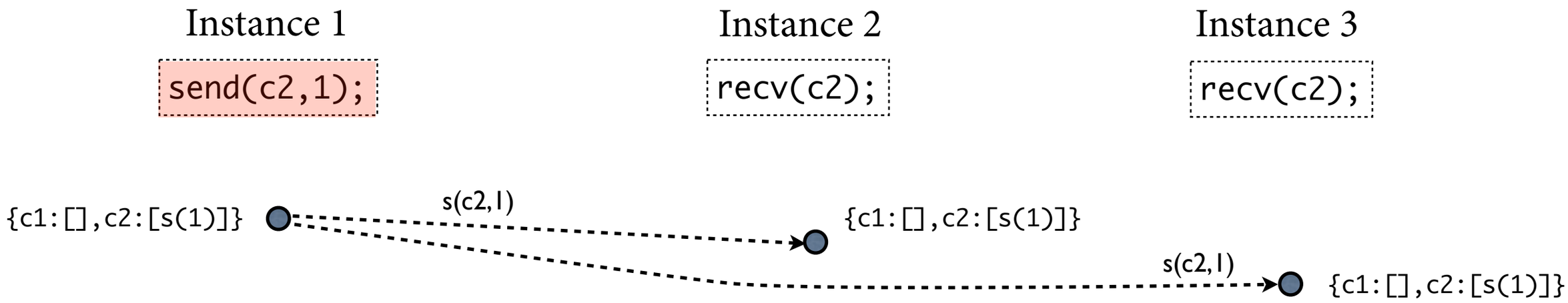


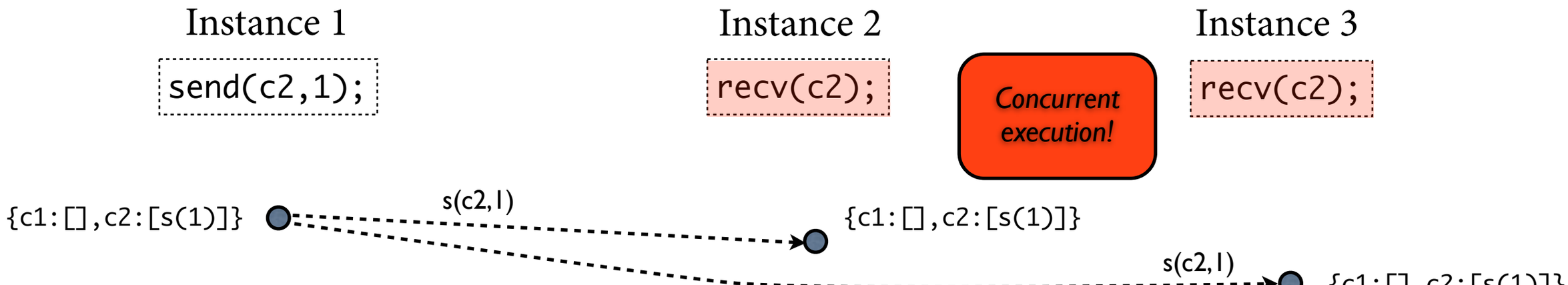
Channel Consistency (2)

Instance 1	Instance 2	Instance 3
`send(c2,1);`	`recv(c2);`	`recv(c2);`

Channel Consistency (2)



Channel Consistency (2)



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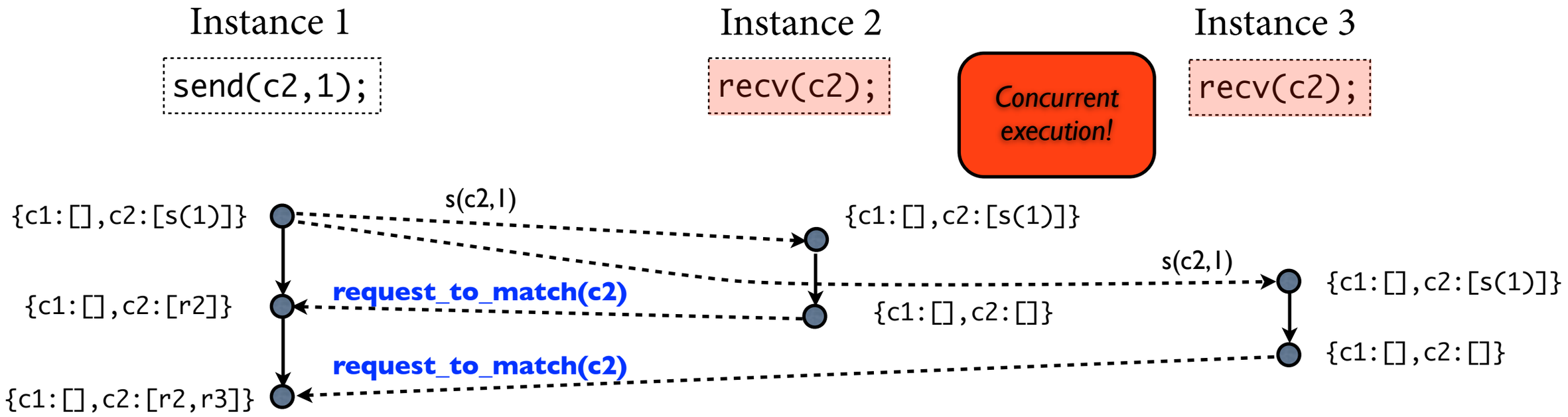

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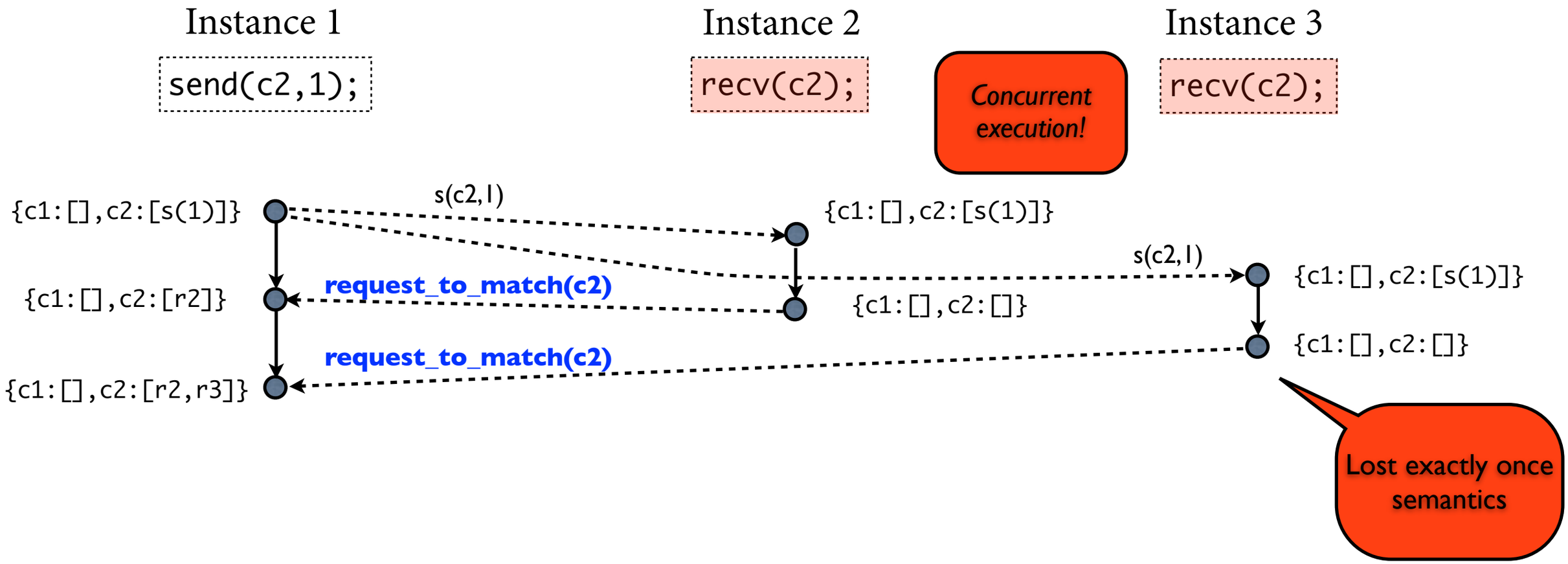

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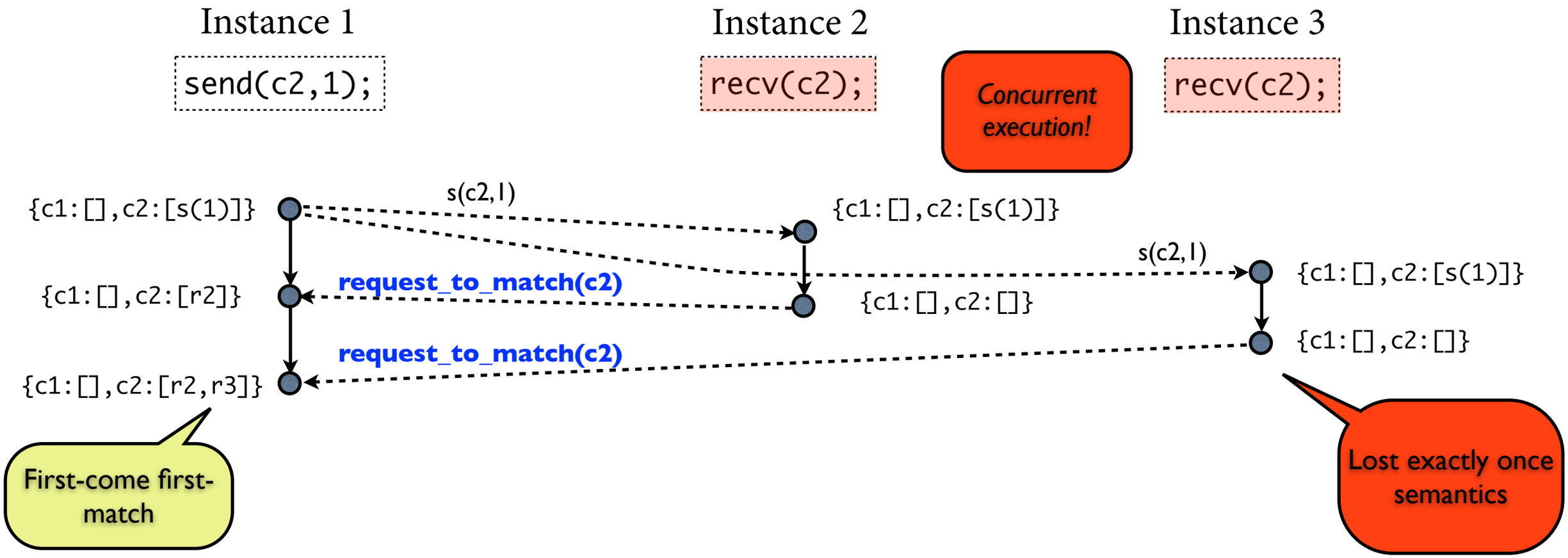

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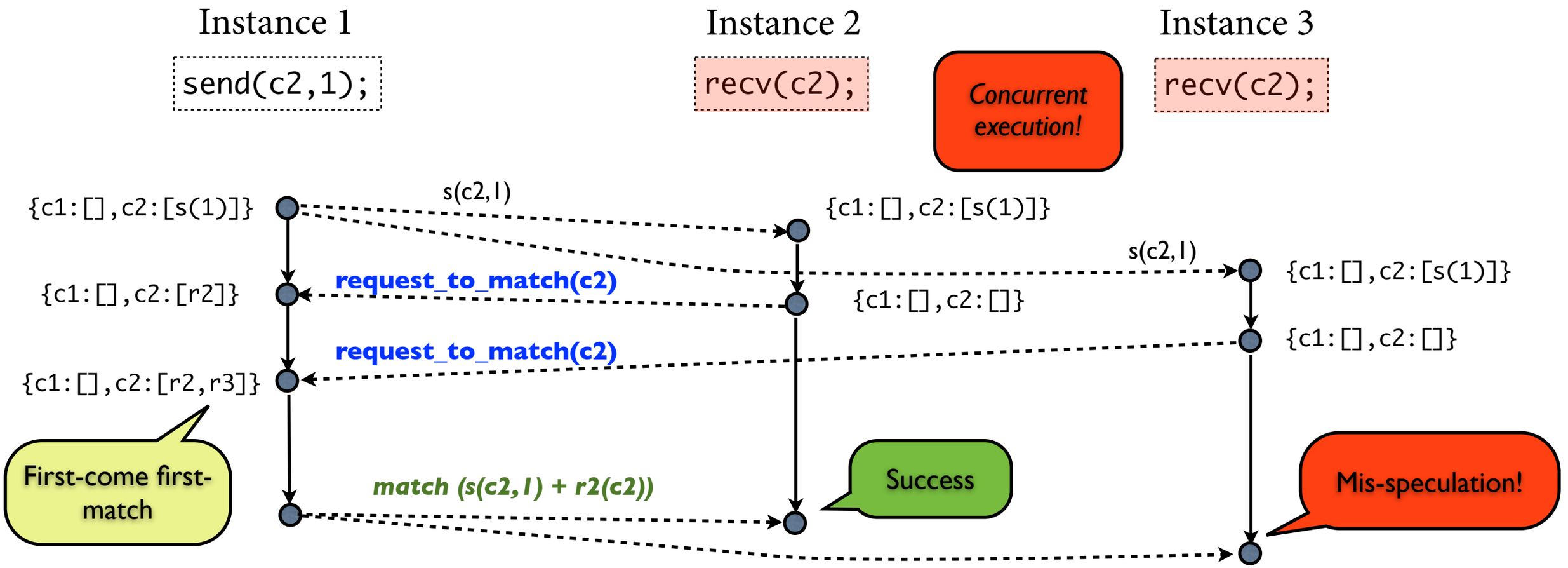

Speculative Execution

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- Remediation
  - ★ *Uncoordinated!* - Transitively inform each mis-speculated thread to rollback
  - ★ *Check-point (Continuation) + Log-based (Dependence graph)* recovery
  - ★ Rollback to last checkpoint, replay correct speculative actions
  - ★ Continues non-speculatively until next observable action = Progress

Results

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- Optimistic OLTP
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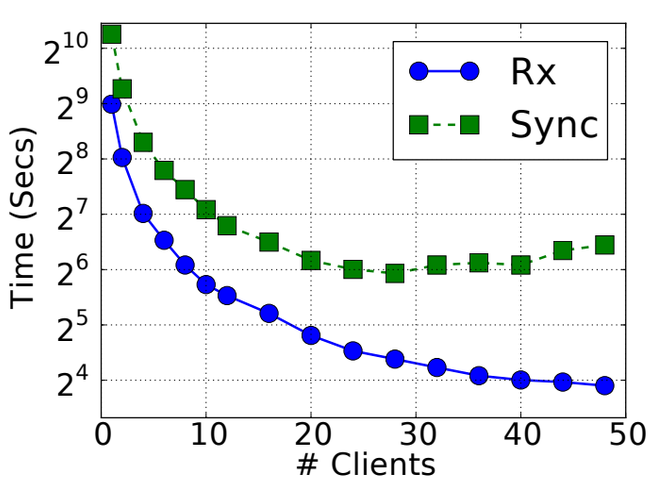
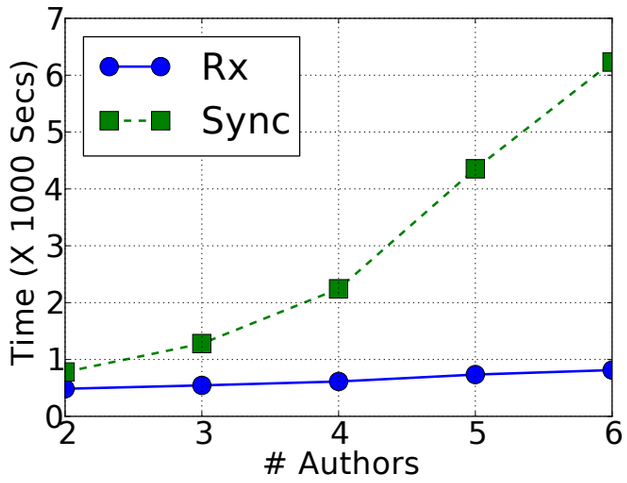


OLTP



Collaborative Editing

- Rx-CML was 5.8X to 7.6X faster than the synchronous version
  - ★ 9-17% of communications were mis-speculated.

Conclusion

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- Composable synchronous events vs. the Cloud

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MultiMLton

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  - ★ reason synchronously, but implement asynchronously
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- Distributed implementation of MultiMLton
  - ★ Case studies demonstrate effectiveness of the approach
- Future Work - Fault tolerance
  - ★ Make checkpoints and dependence graph resilient
  - ★ Treat failures as mis-speculations -> rollback to last saved checkpoint

Questions?

http://multimlton.cs.purdue.edu