℞-CML
: A Prescription for Safely Relaxing Synchrony

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(S³) MultiMLton

Introduction

Two often competing goals when ***designing*** and ***implementing*** concurrency abstractions

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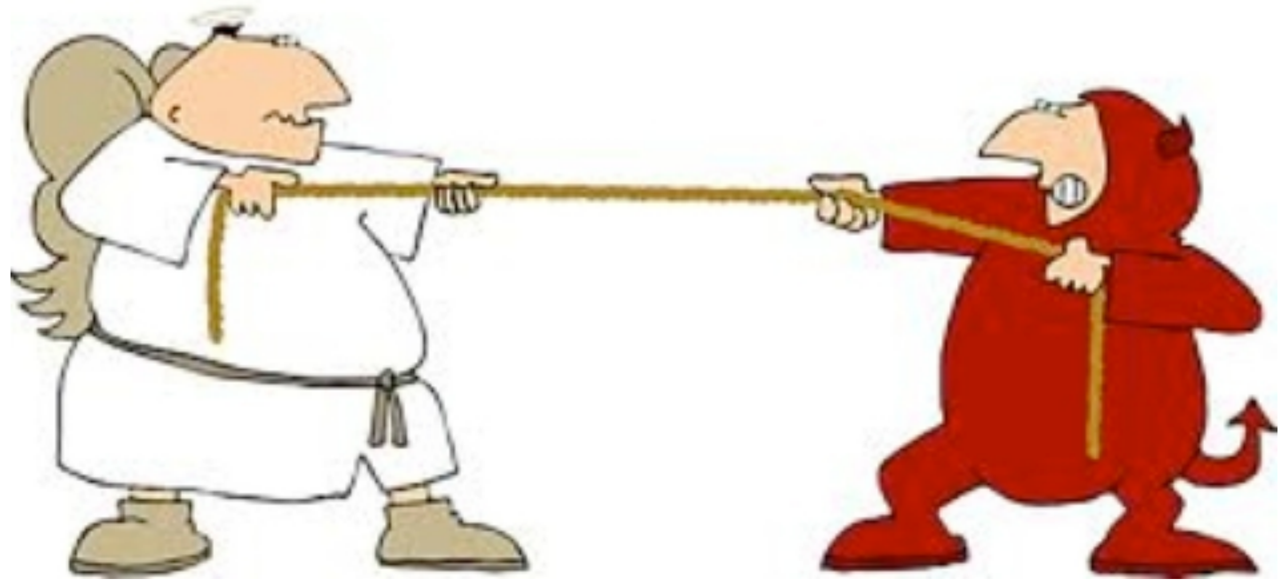

Simplicity
Safety

Performance
Functionality

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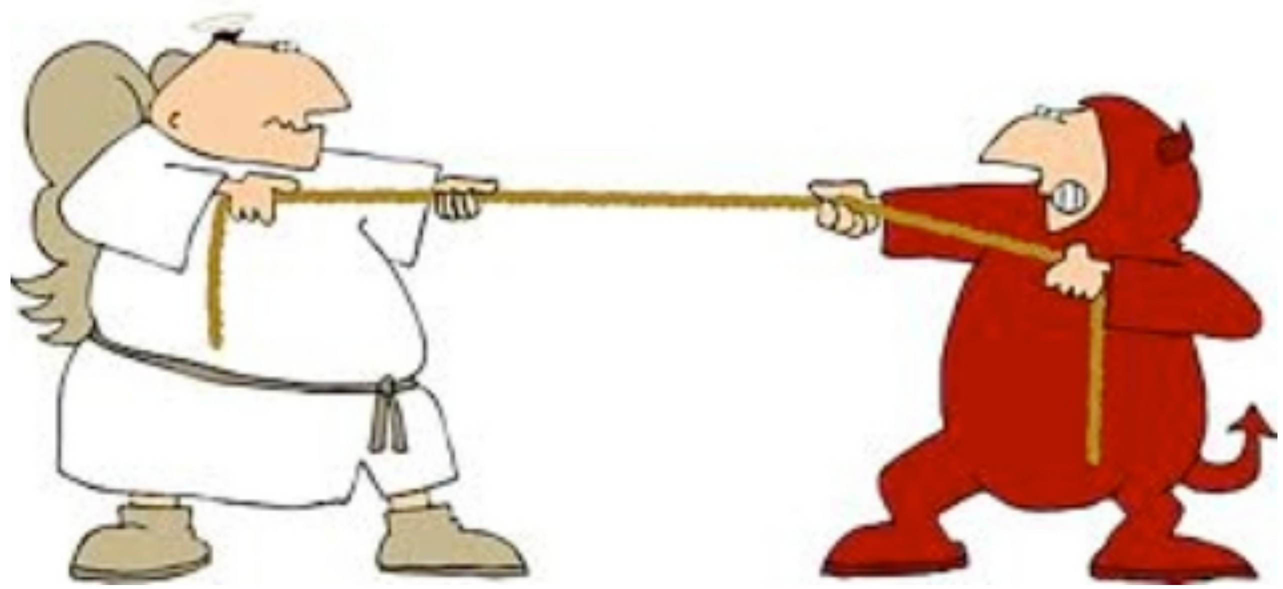

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Performance
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Always desirable to marry the two whenever possible

Big Picture

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- Functional language + Synchronous message passing
  - ★ Communication = Data transfer + Synchronization

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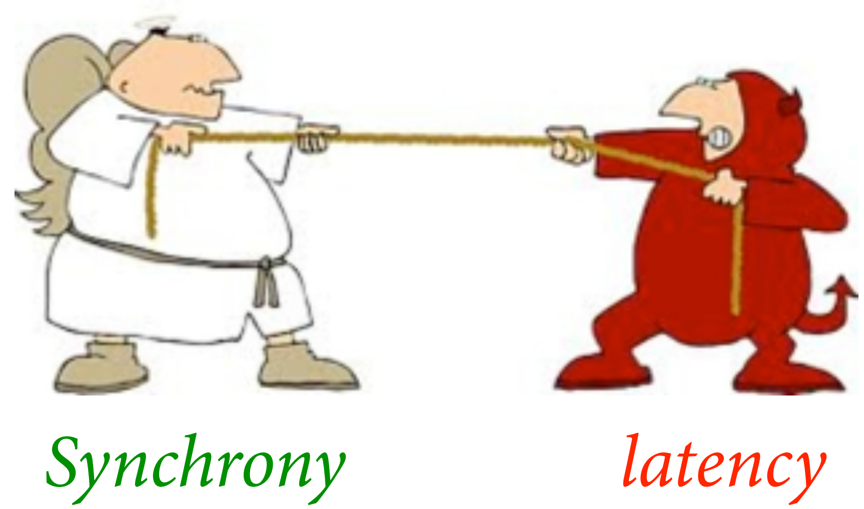

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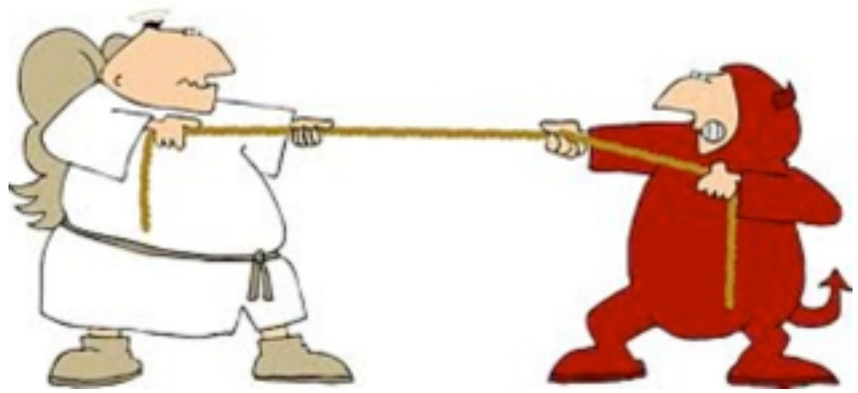

Synchrony *latency*

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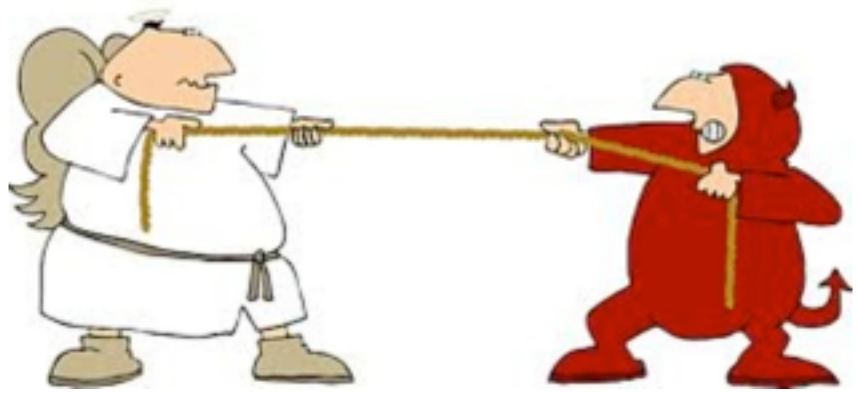

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Can we discharge synchronous communications ***asynchronously*** *while ensuring* ***observable equivalence****?*

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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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- Parallel extension of *Concurrent ML*
  - ★ Dynamic lightweight threads
  - ★ *Synchronous* message passing
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    - ✦ *Composable synchronous protocols*

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```
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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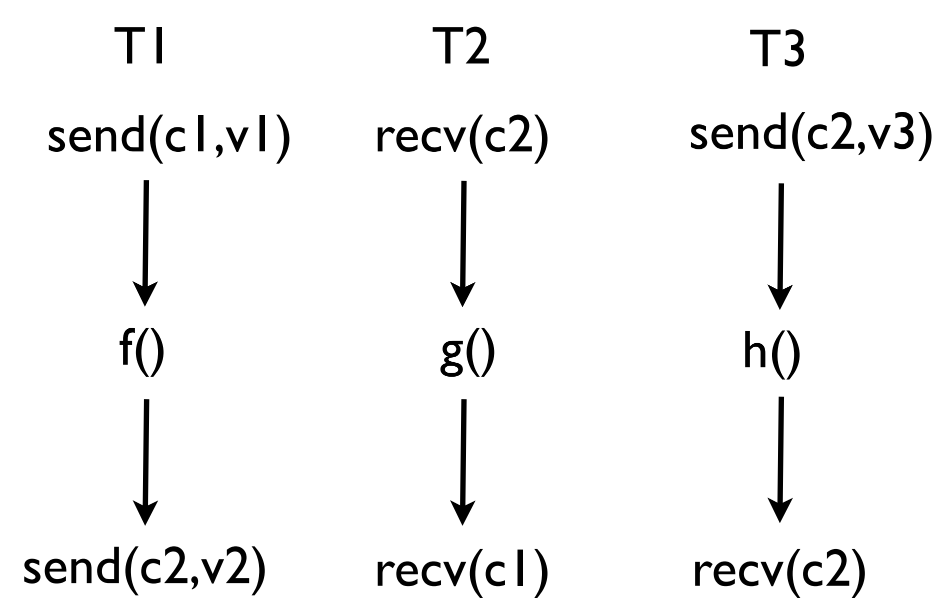
Basic Idea (1)

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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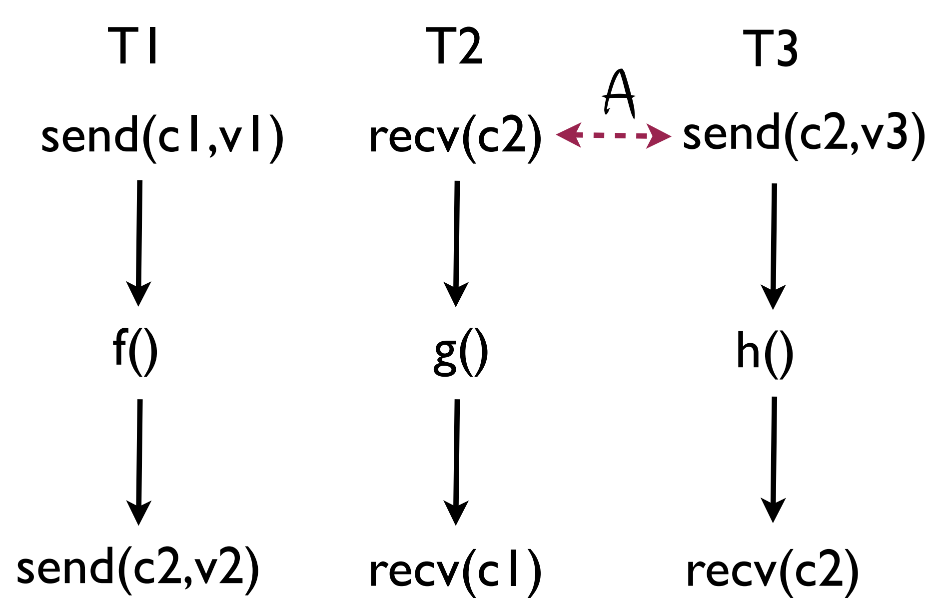

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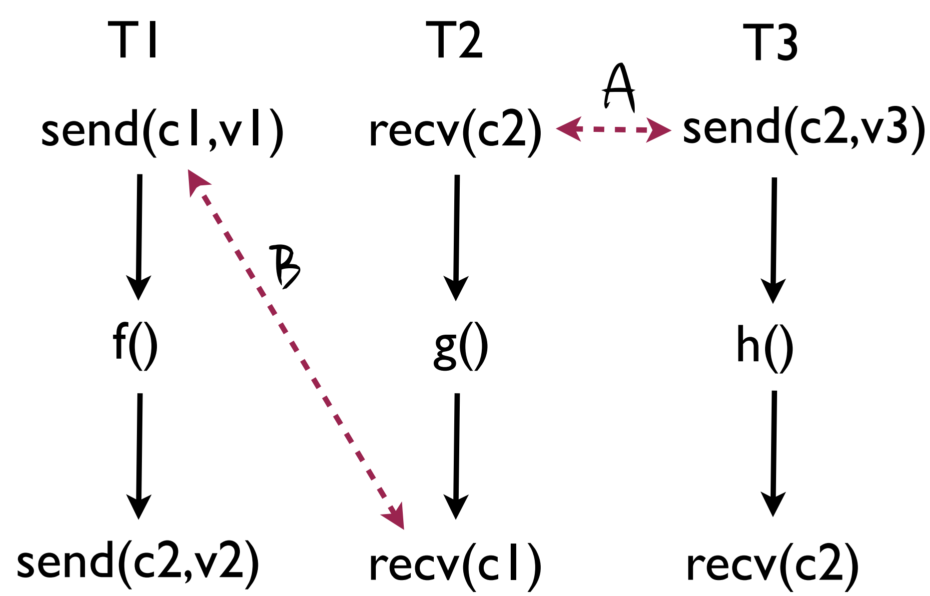

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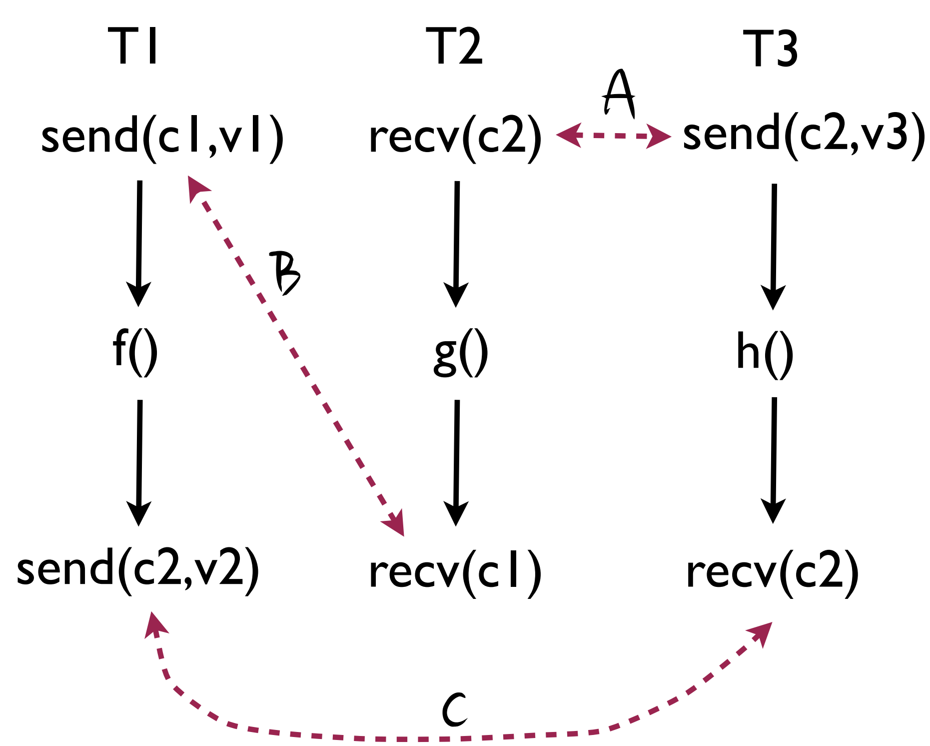

Basic Idea (2)

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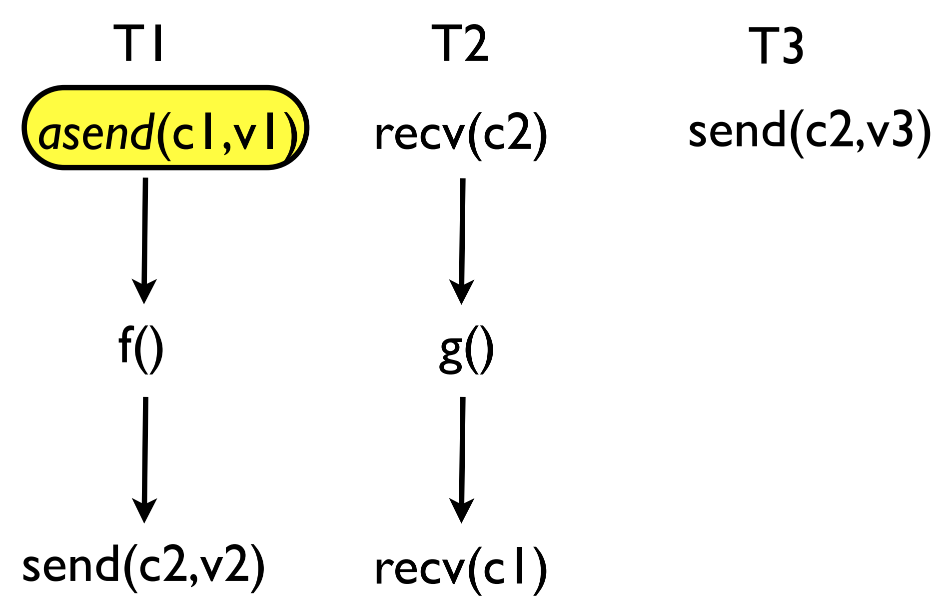

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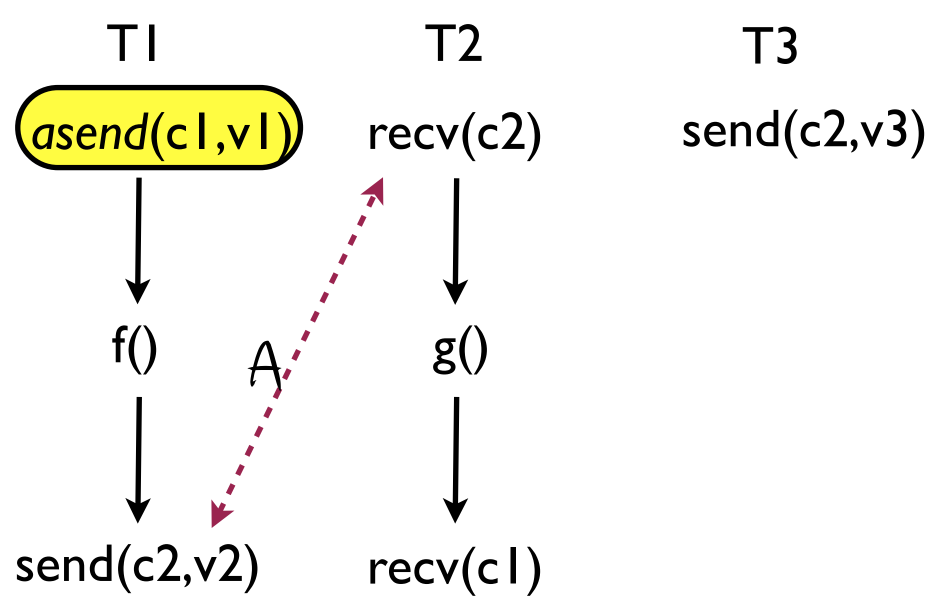

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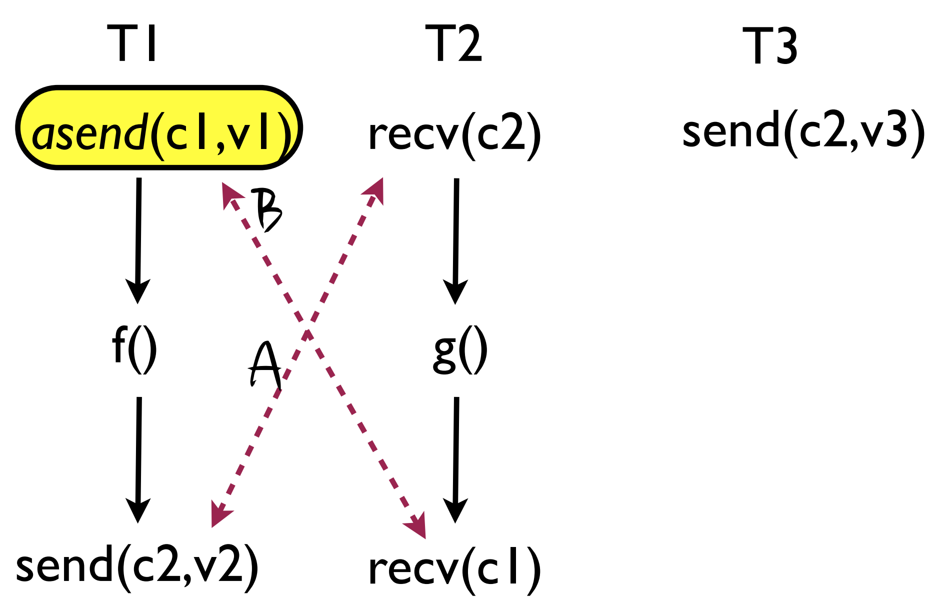

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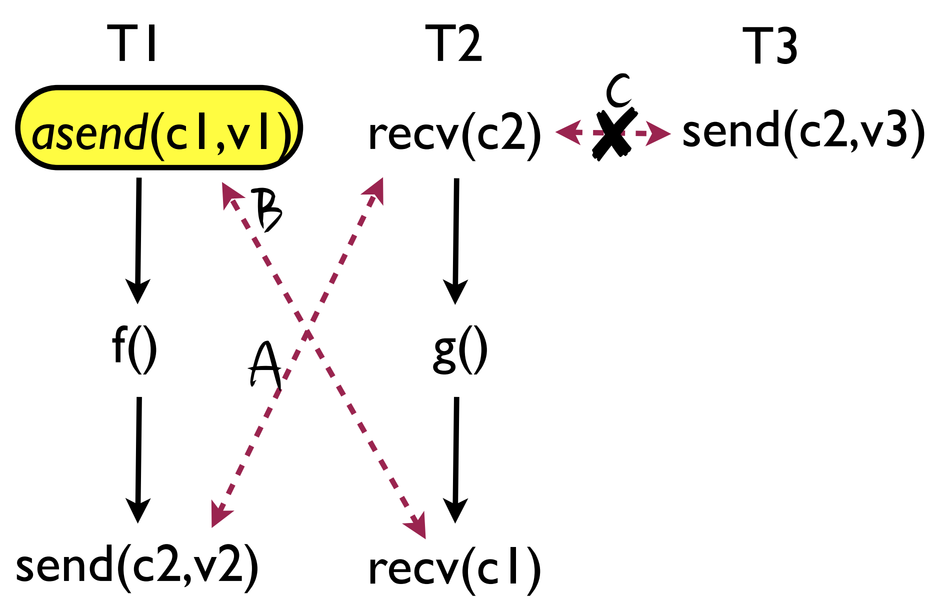

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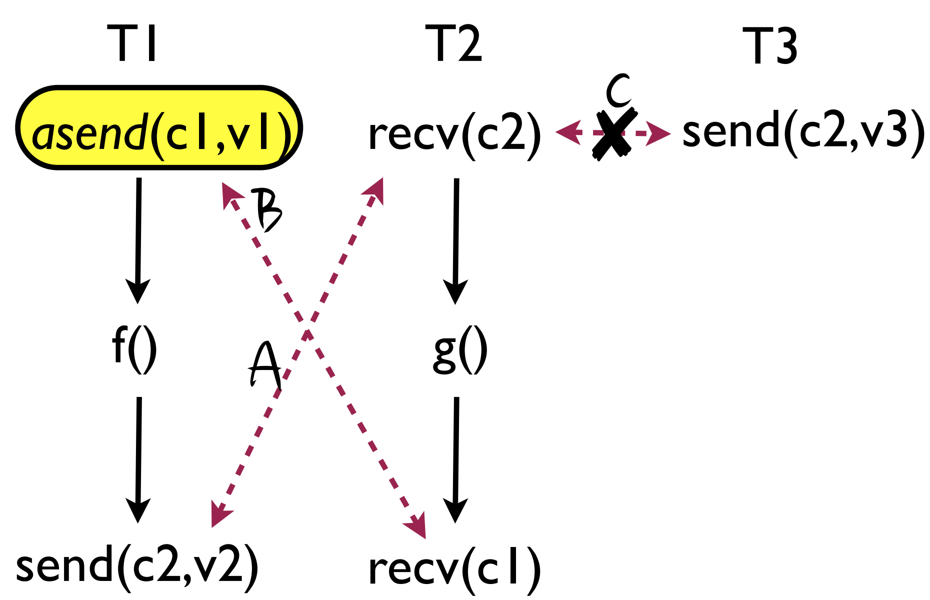

- Synchronous evaluation ***never*** results in cyclic dependence
  - ★ Cyclic dependence => divergent behavior w.r.t synchronous evaluation

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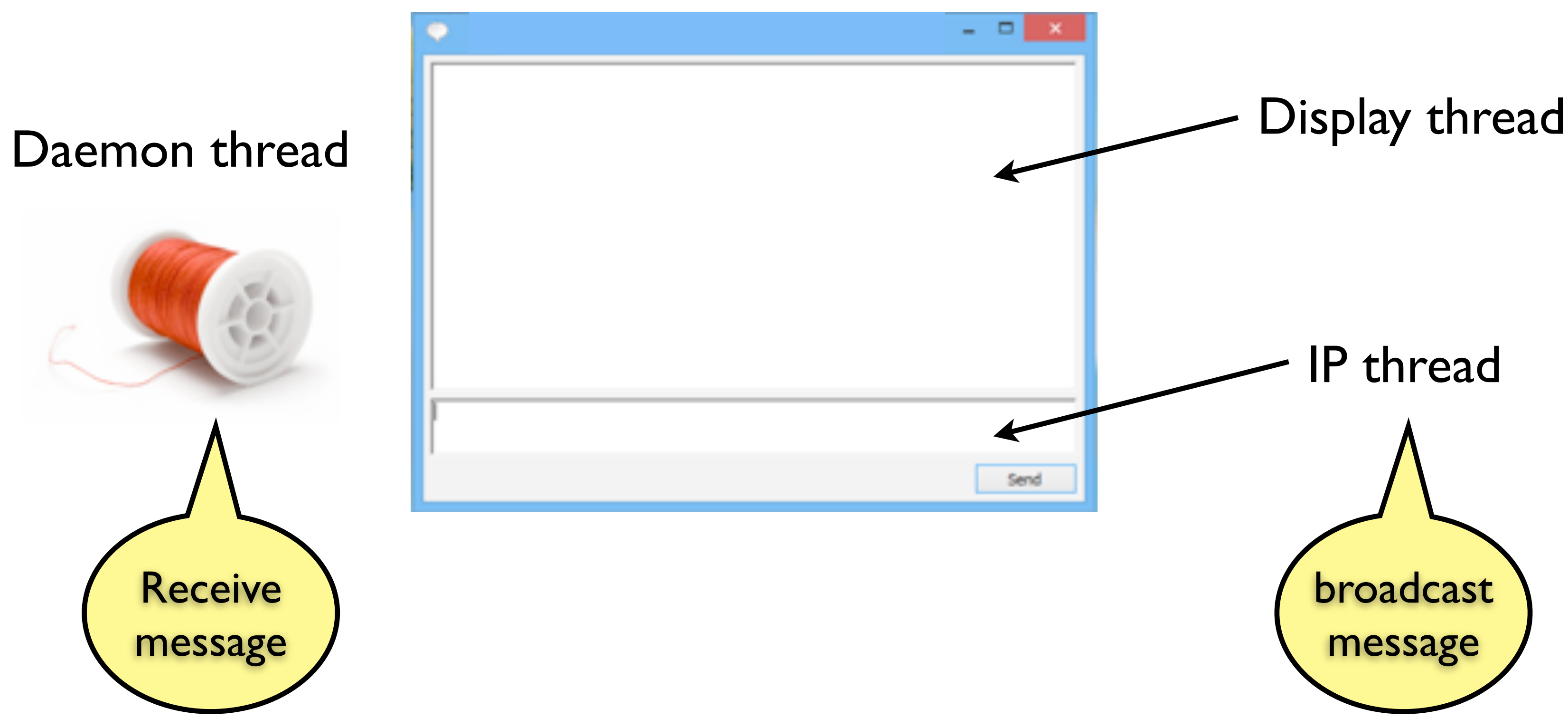
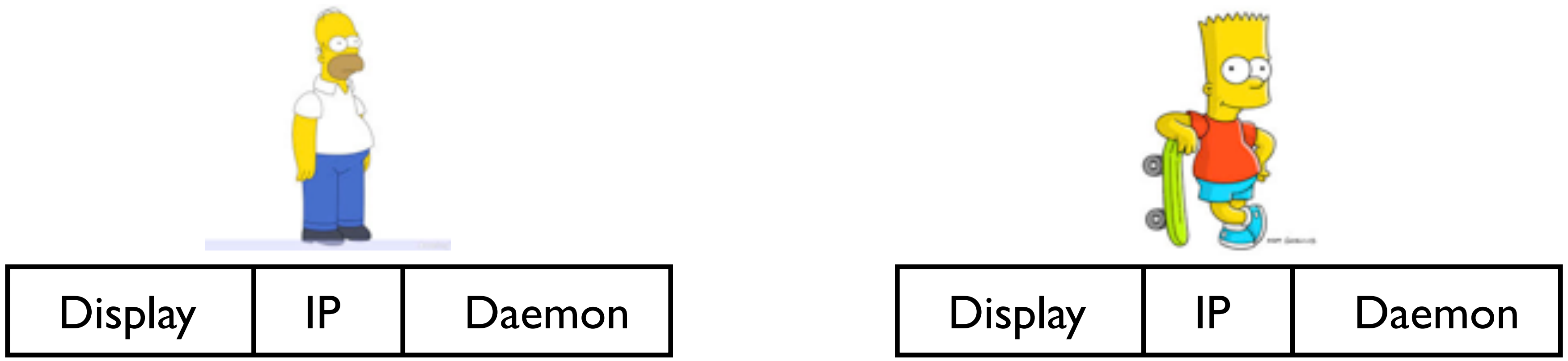
  - ★ Discharging asynchronously breaks causal ordering
  - ★ *Our idea: program synchronously, discharge asynchronously, detect and remediate causal ordering violations*

Example: Distributed Group Chat

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



Distributed Group Chat - Run 1



Distributed Group Chat - Run 1

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Display	IP	Daemon

show (X)

X

bcast (X)

Display	IP	Daemon

show (Y)

Y

bcast (Y)

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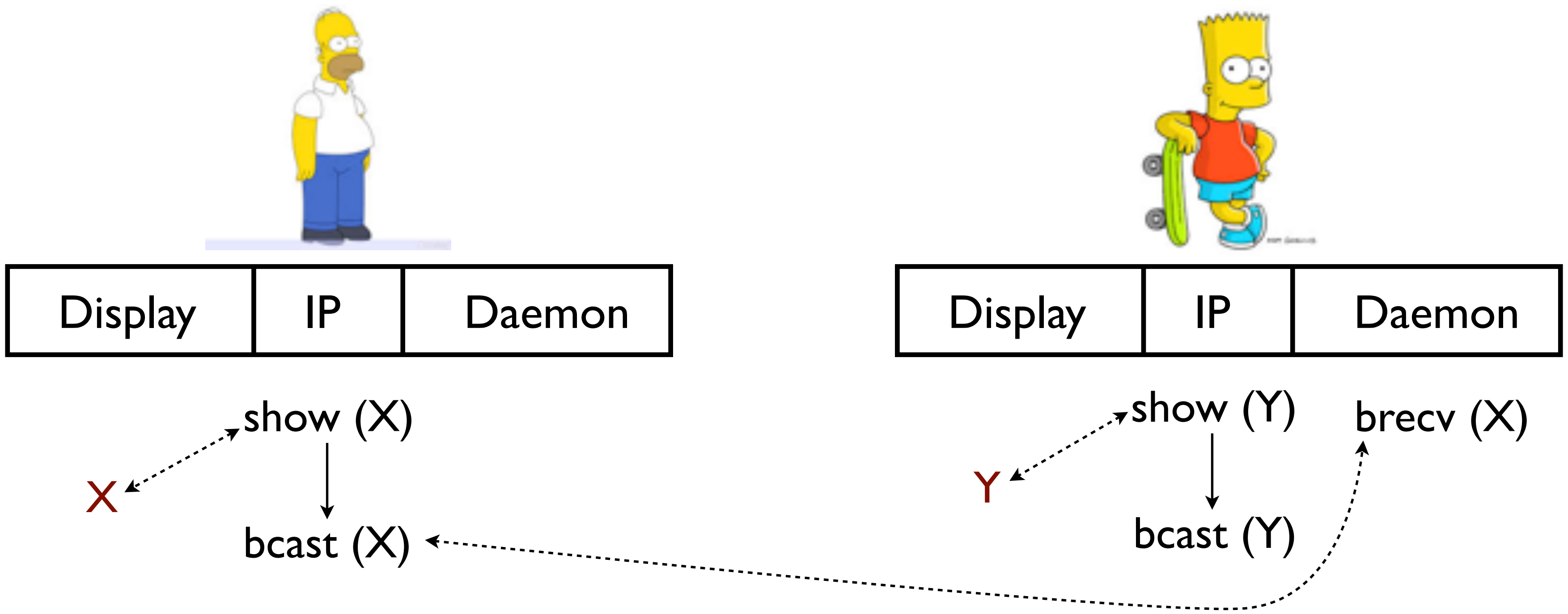

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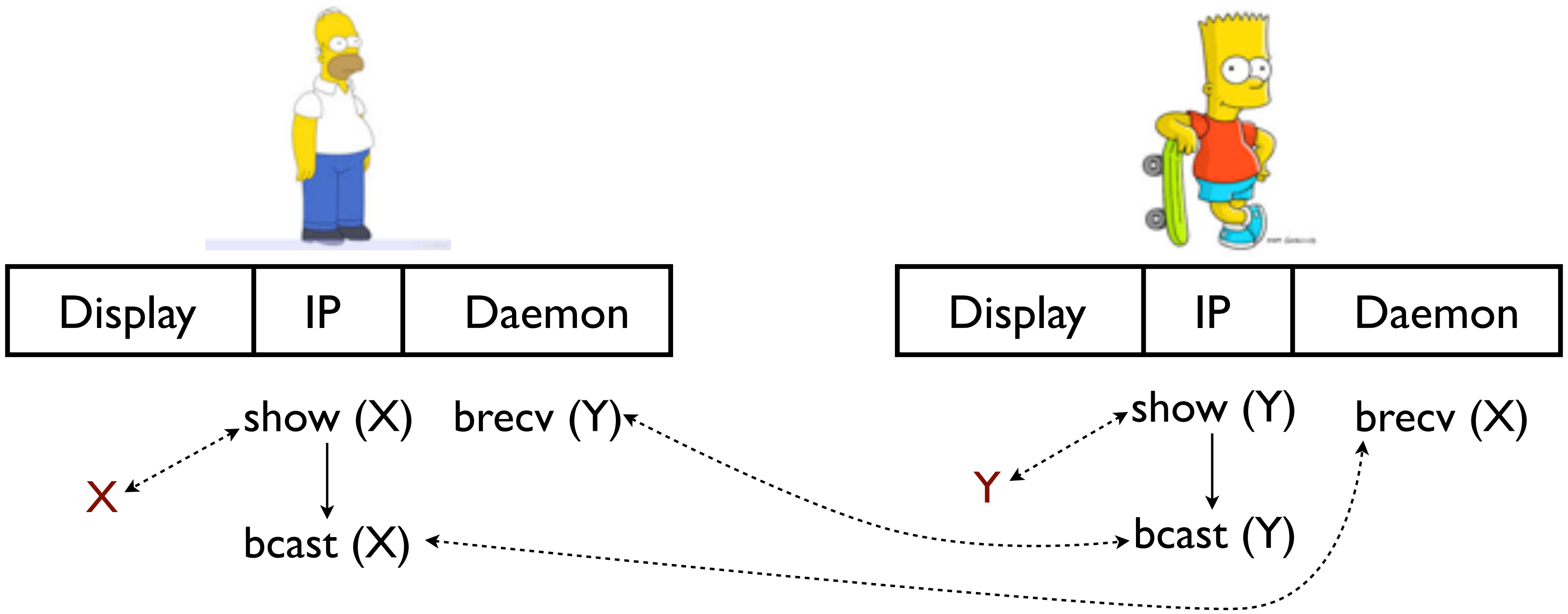

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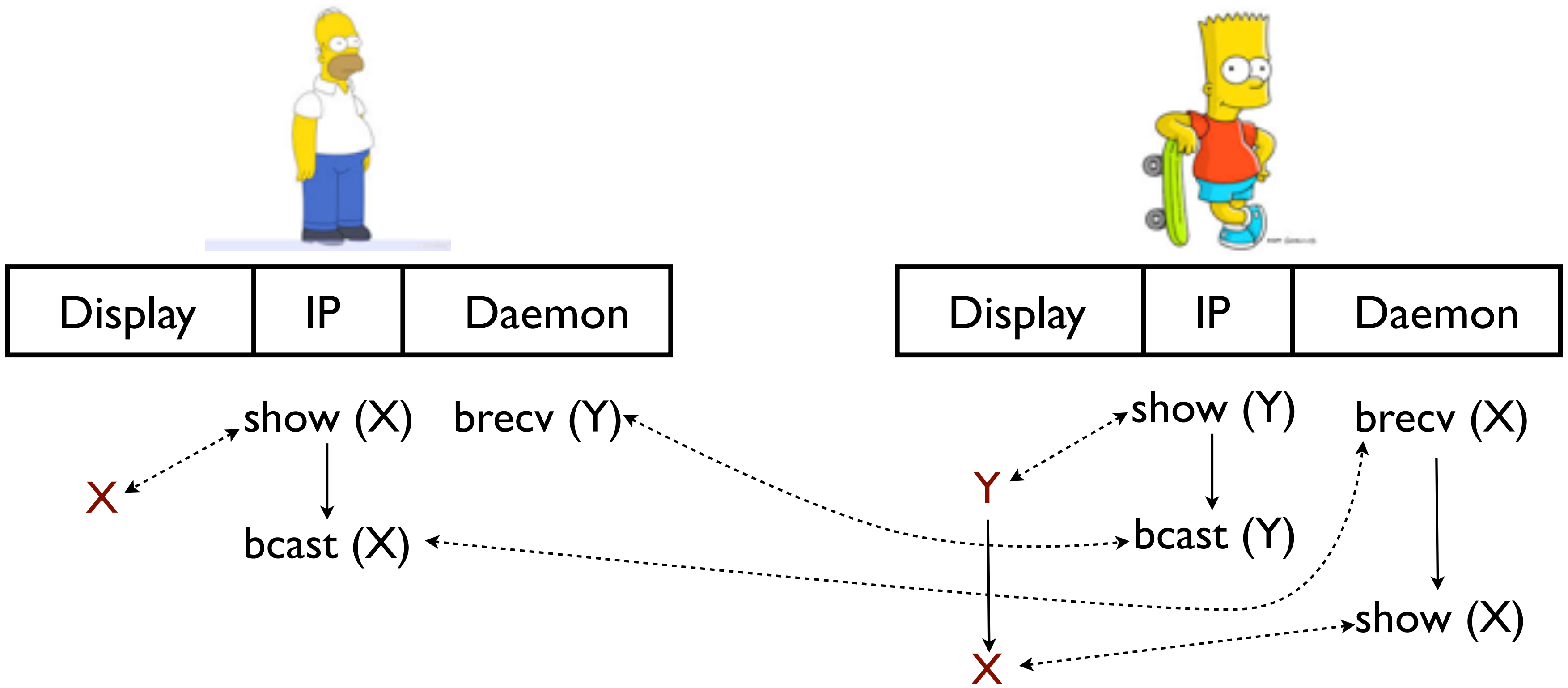

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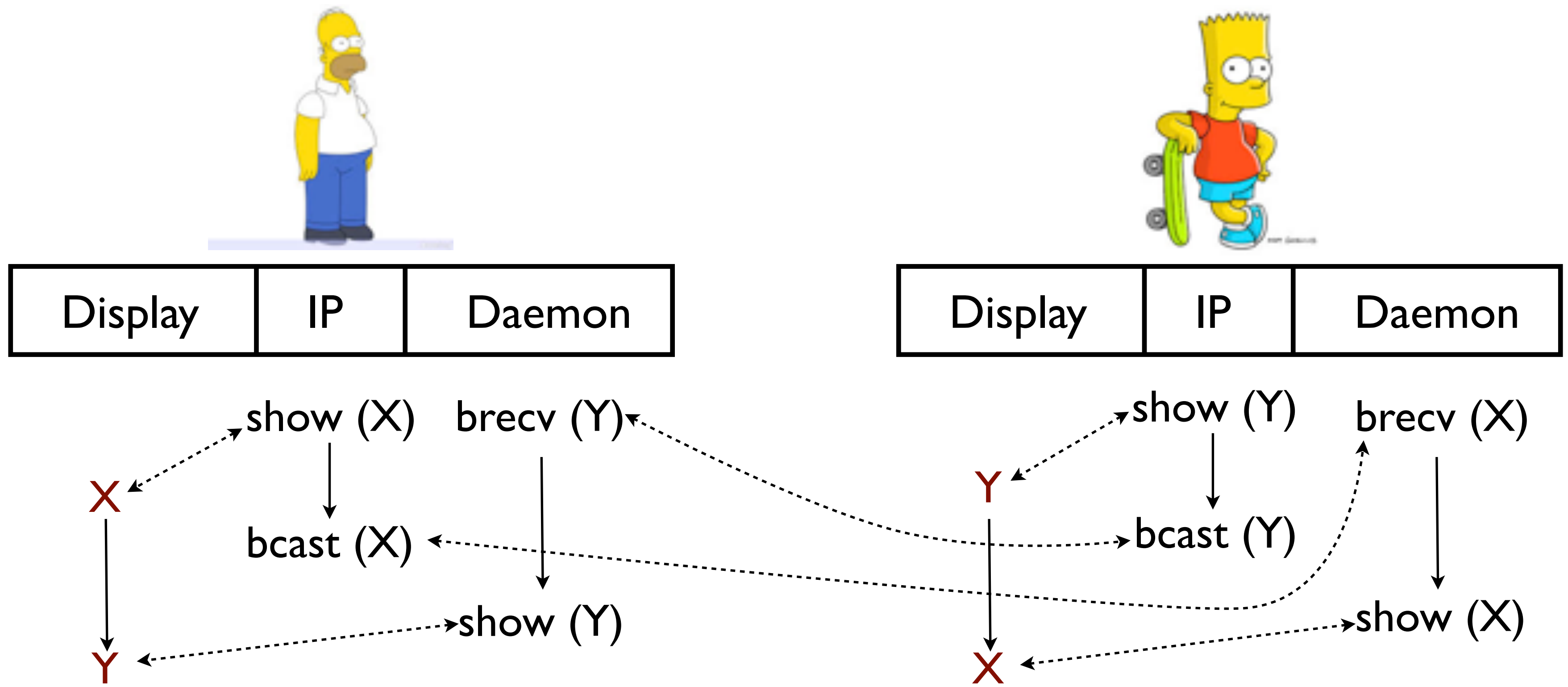

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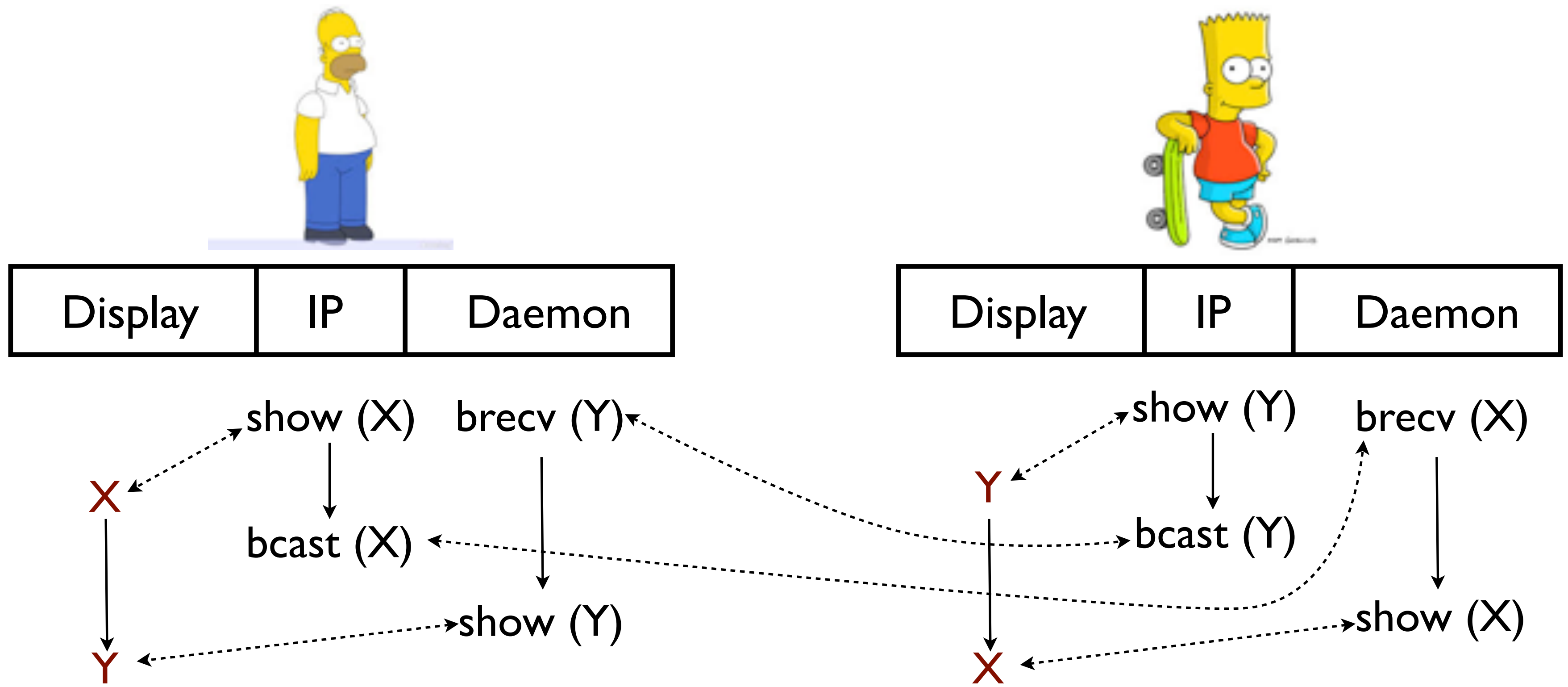


- Observations
  - ★ X and Y independently generated => No causal dependence between bcast (X) and bcast (Y)
- No Cycles => Correct execution!

Distributed Group Chat - Run 2

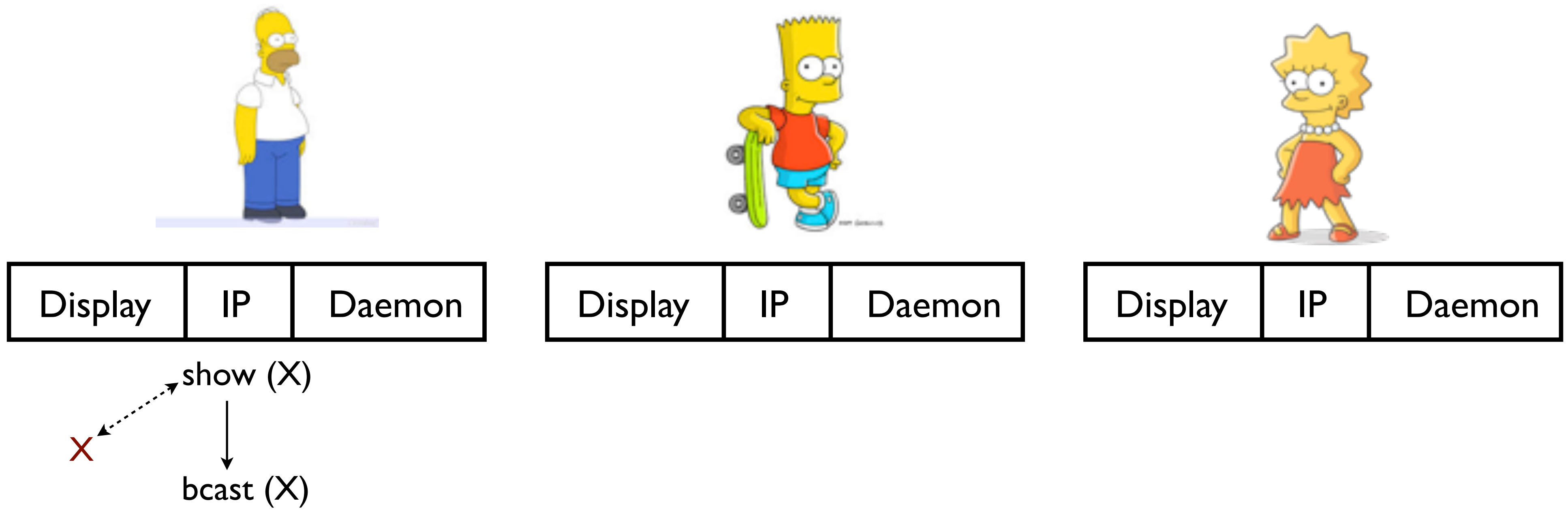


Display	IP	Daemon

Display	IP	Daemon

Display	IP	Daemon

Distributed Group Chat - Run 2



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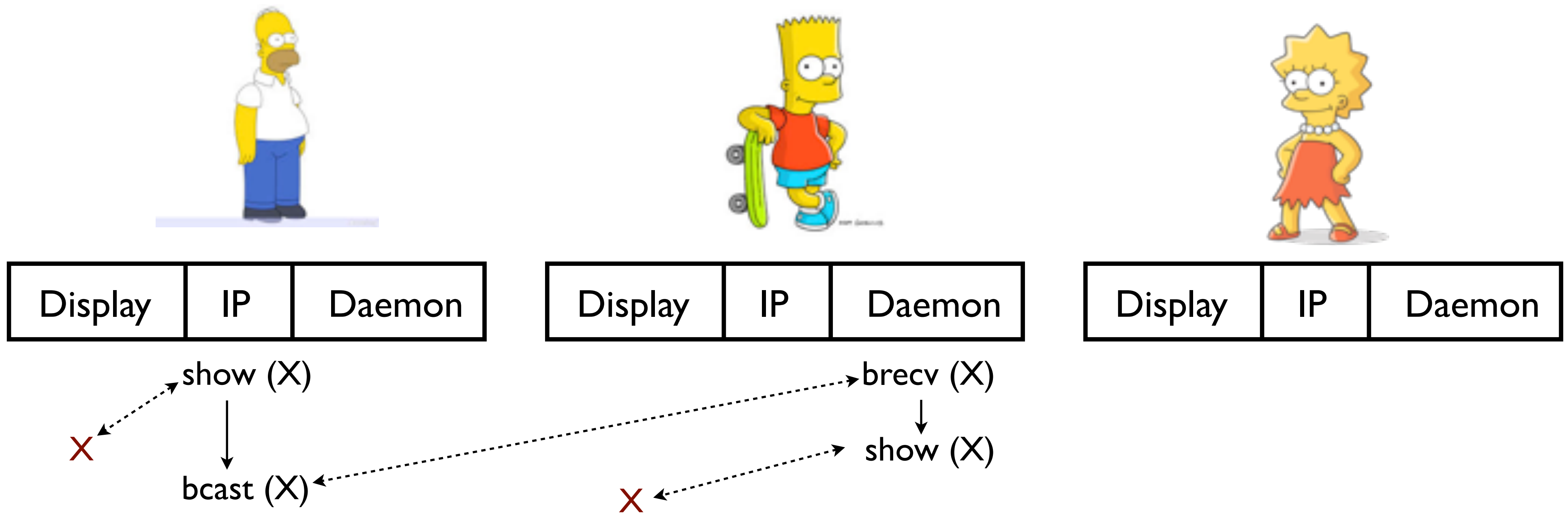

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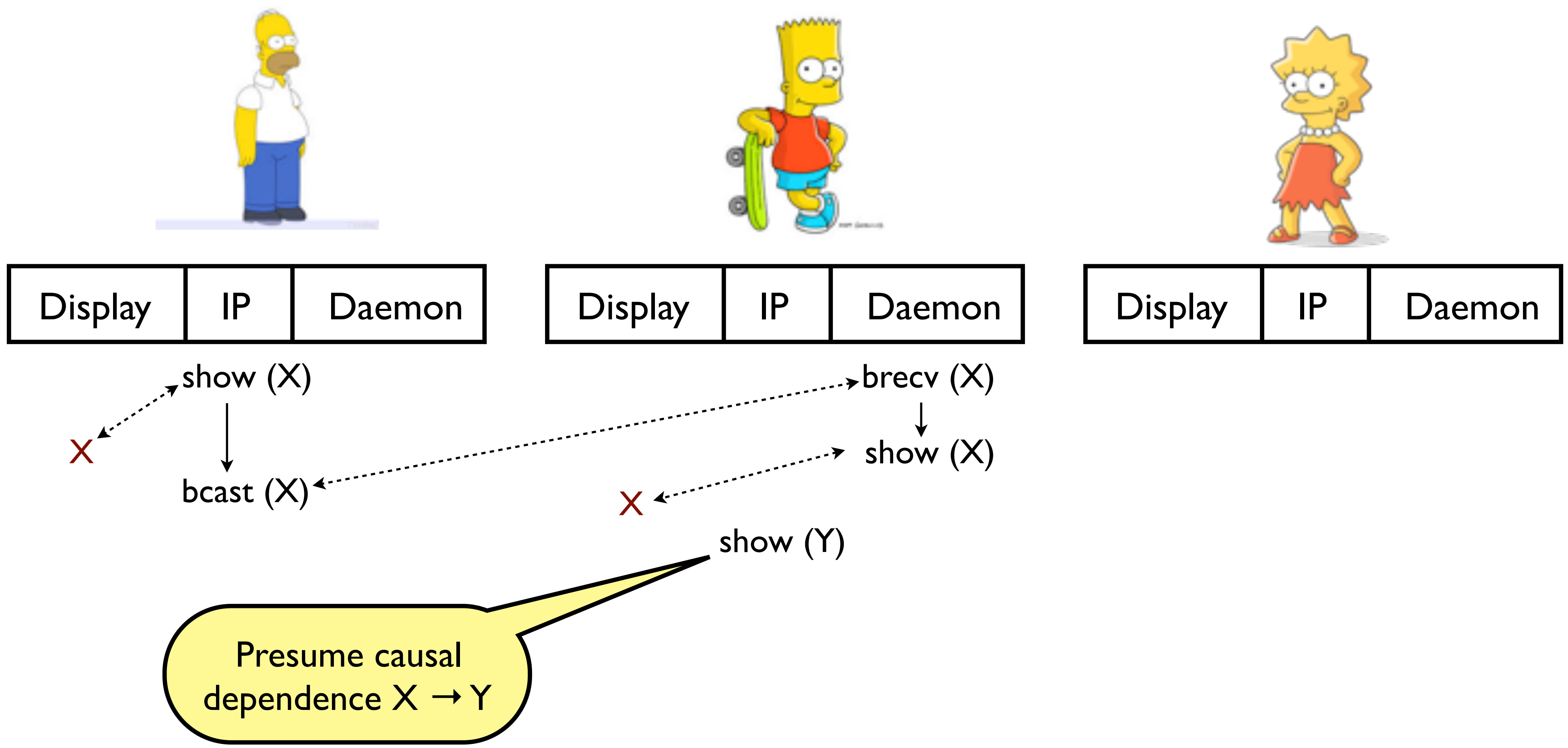

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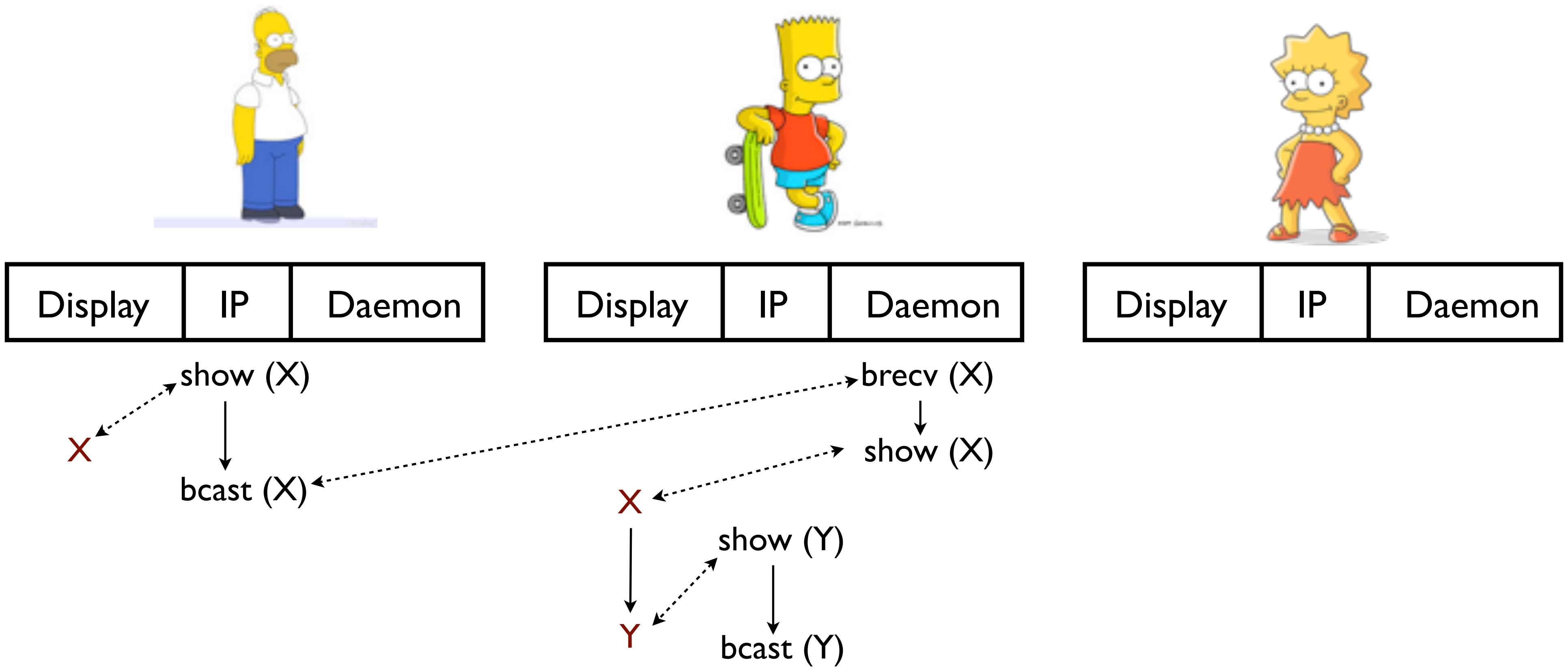

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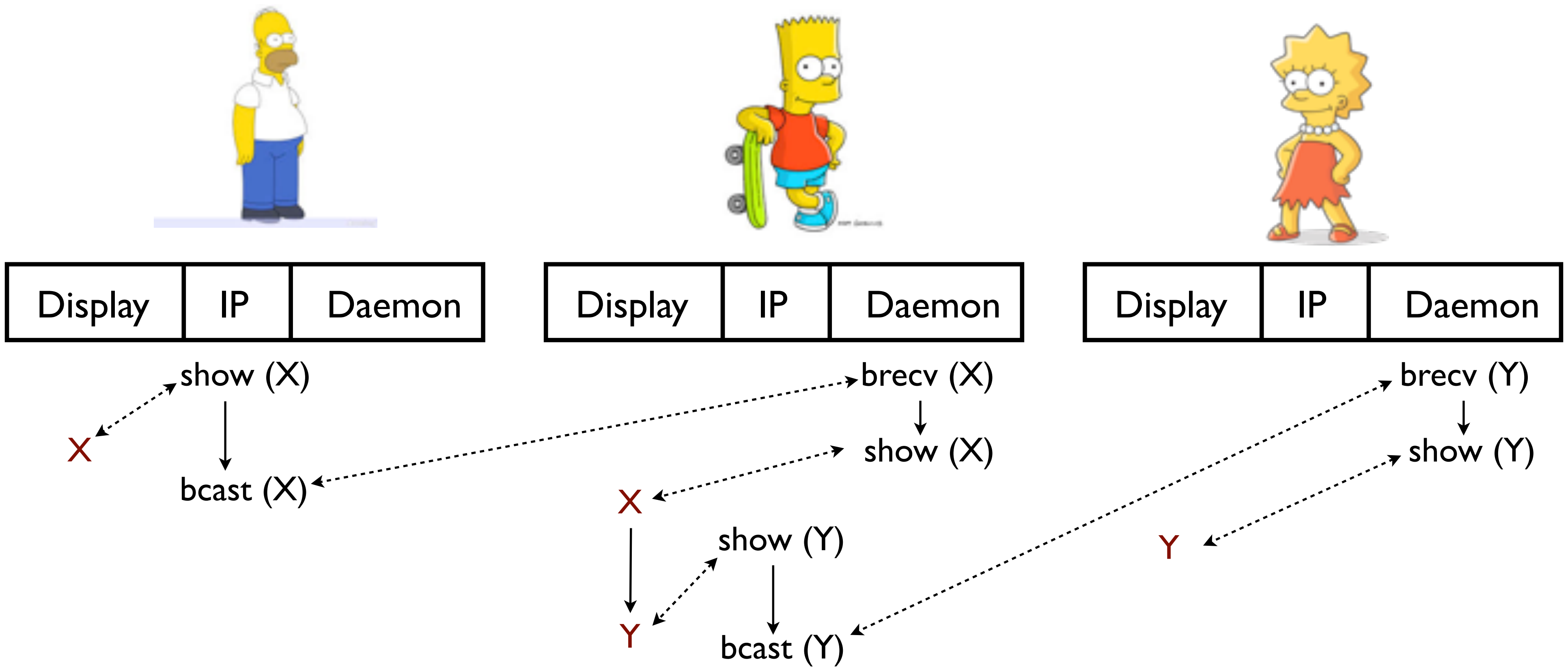

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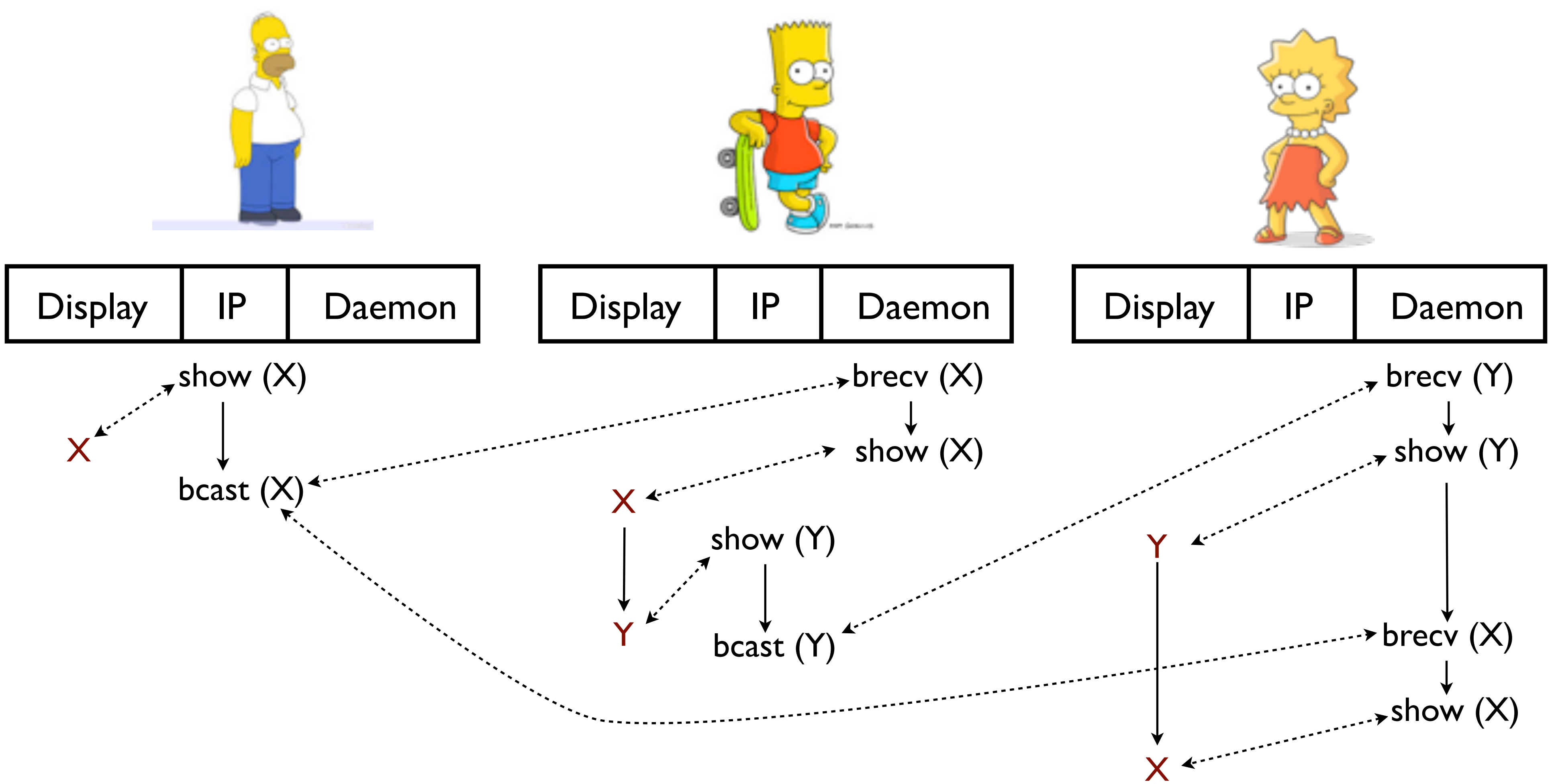

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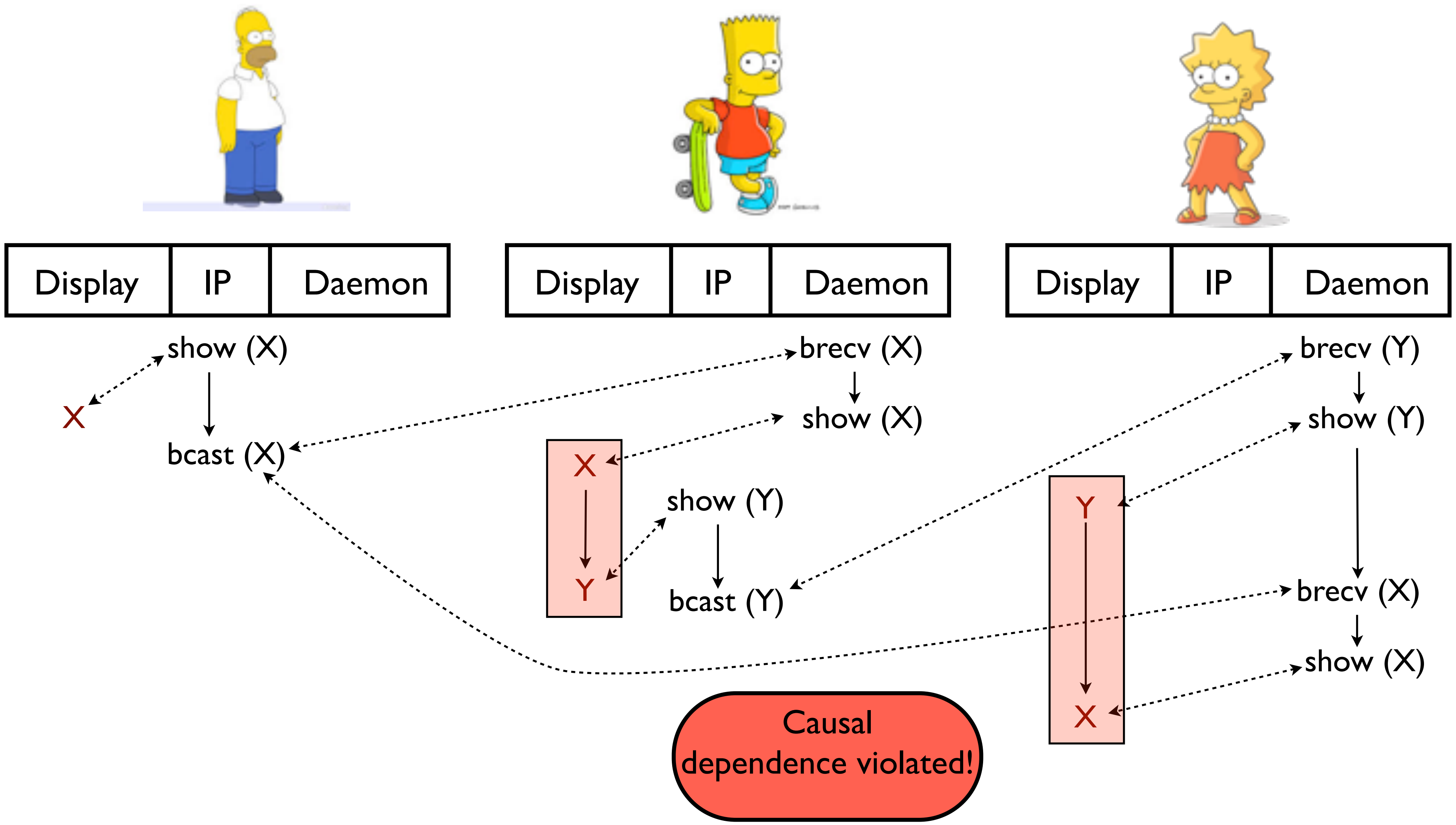

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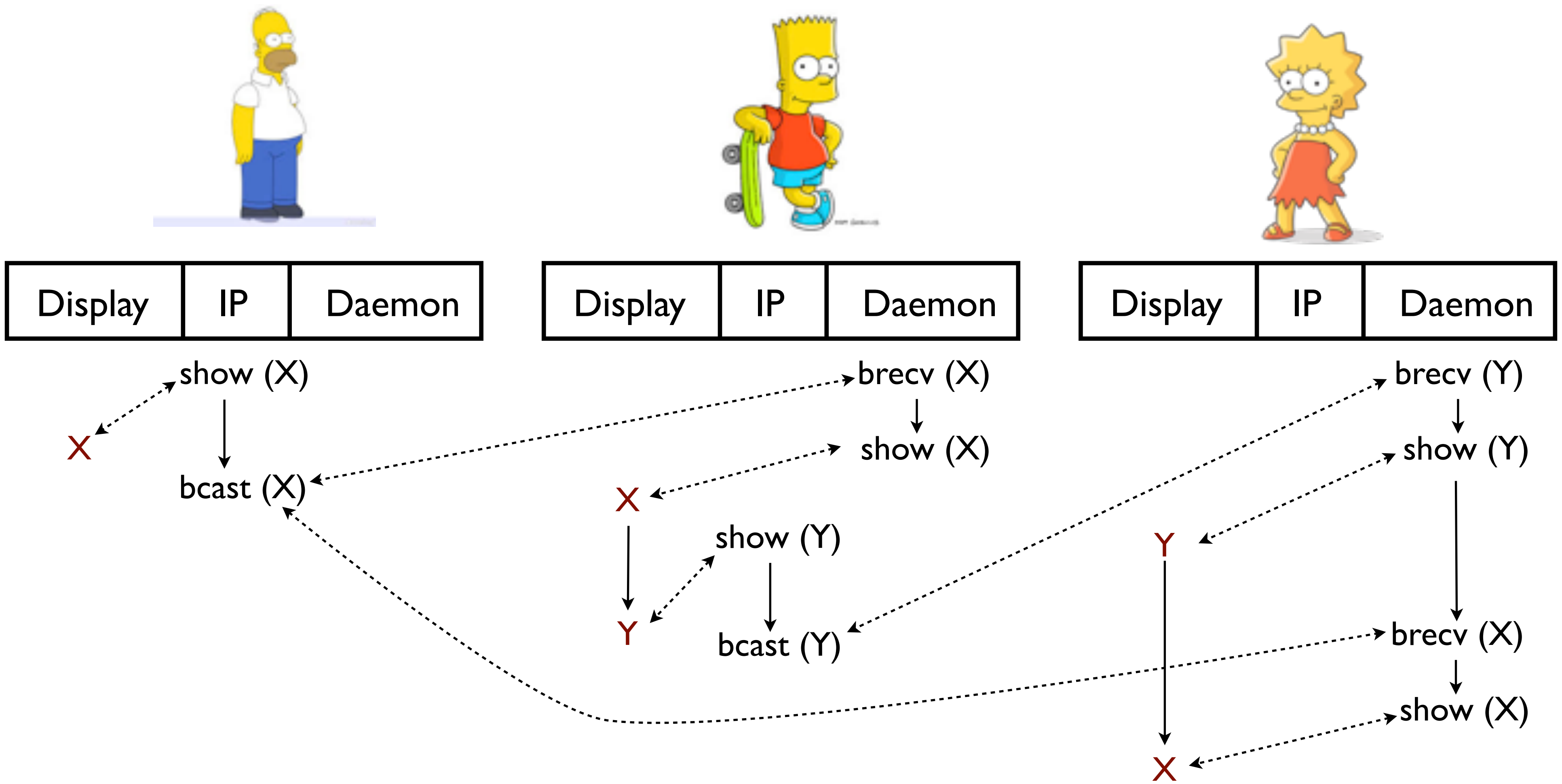

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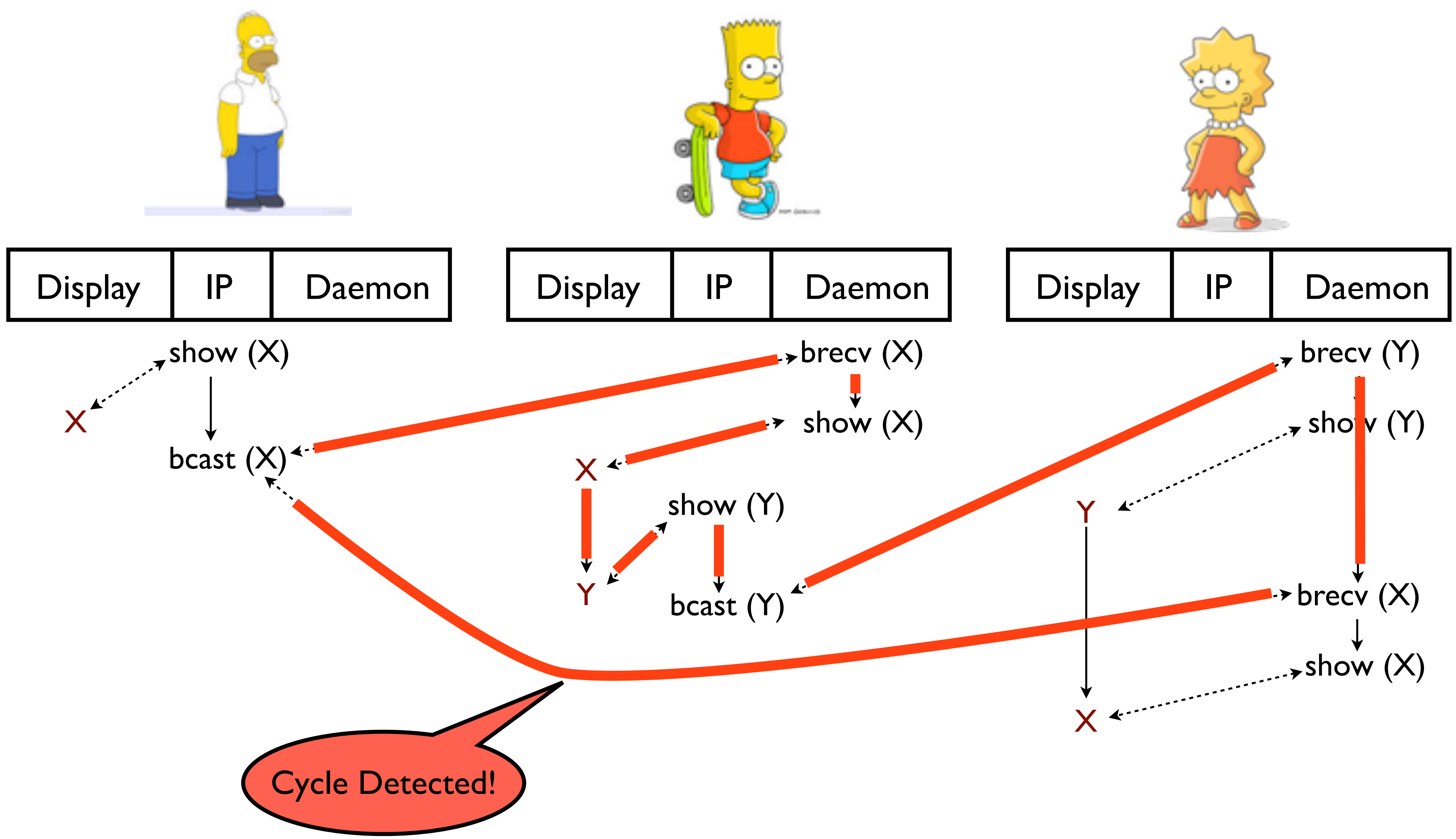

Distributed Group Chat - Results

- 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 ($\mathbb{R}^{\text{CML}}$)	533	0

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  - ★ Declarative characterization of (relaxed) CML behavior
- ***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:

$$\mathrm{E} := \langle \mathrm{P}, \mathrm{A}, \rightarrow_{po}, \rightarrow_{co} \rangle$$

program

a set of actions

program order: sequential actions of a thread

communication order: relates matching communication actions

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Communication and Thread Dependence

- Synchronous communication → communication order is symmetric:

$$a \rightarrow_{co} b \implies b \rightarrow_{co} a$$

- Thread dependence order:

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

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Happens-before Relation

- Establishes both intra- and inter-thread dependences:

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

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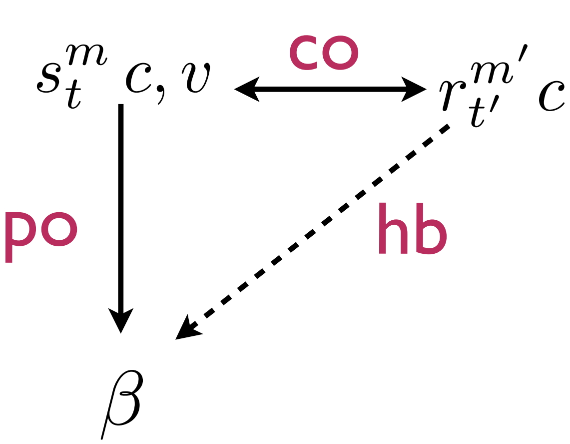

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MultiMLton

Happens-before Relation

- Establishes both intra- and inter-thread dependences:

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

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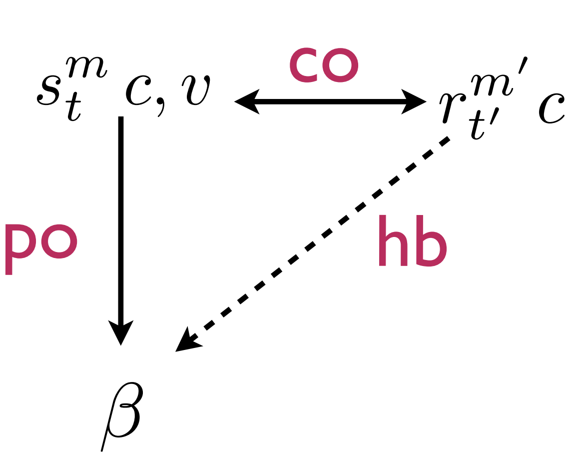

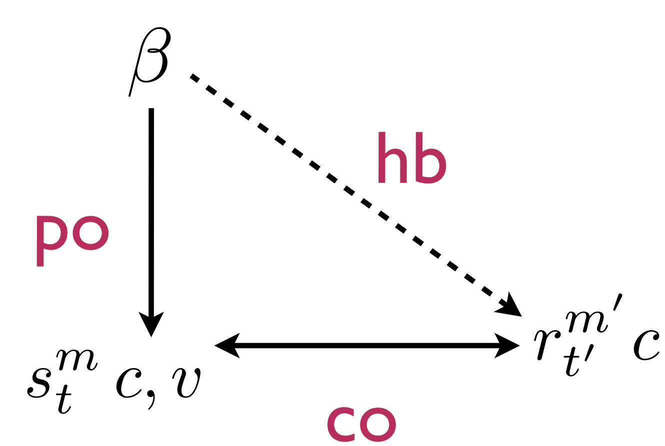

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MultiMLton

Example

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

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

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MultiMLton

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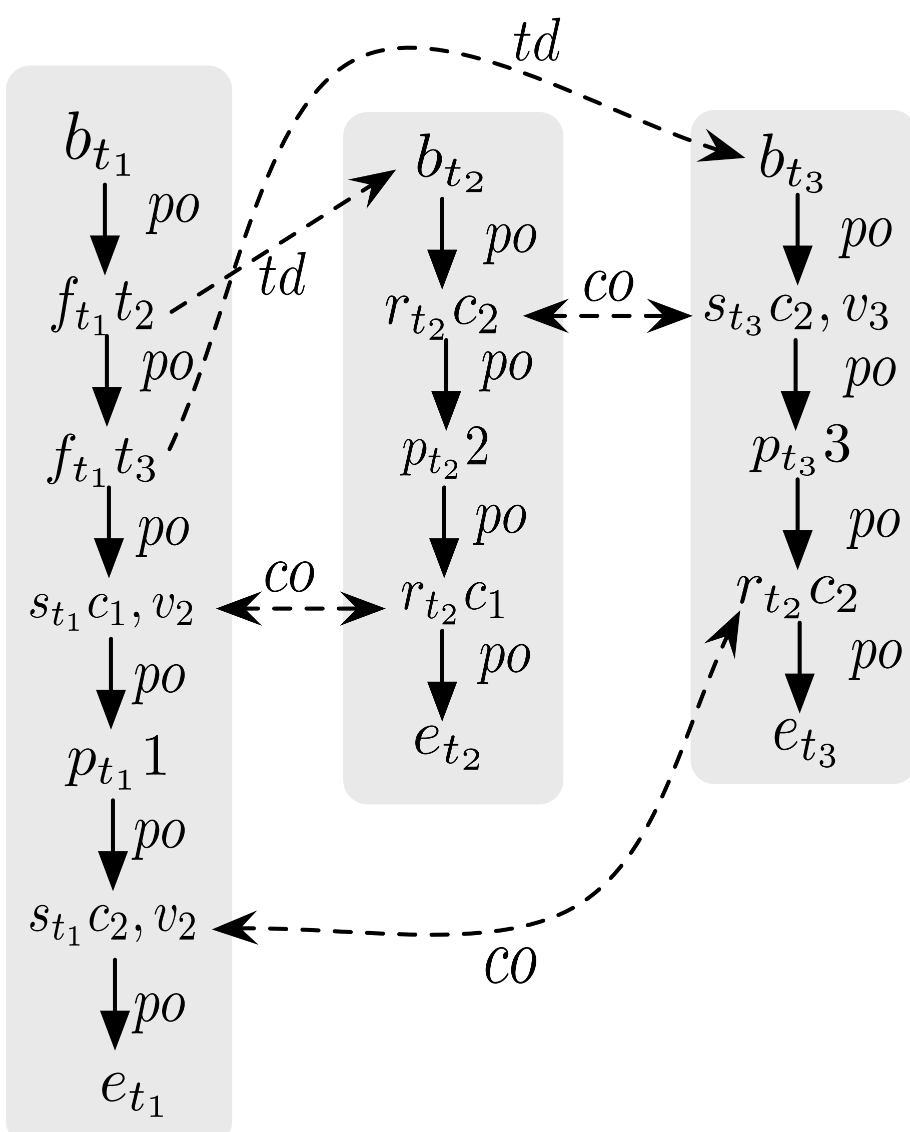

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MultiMLton

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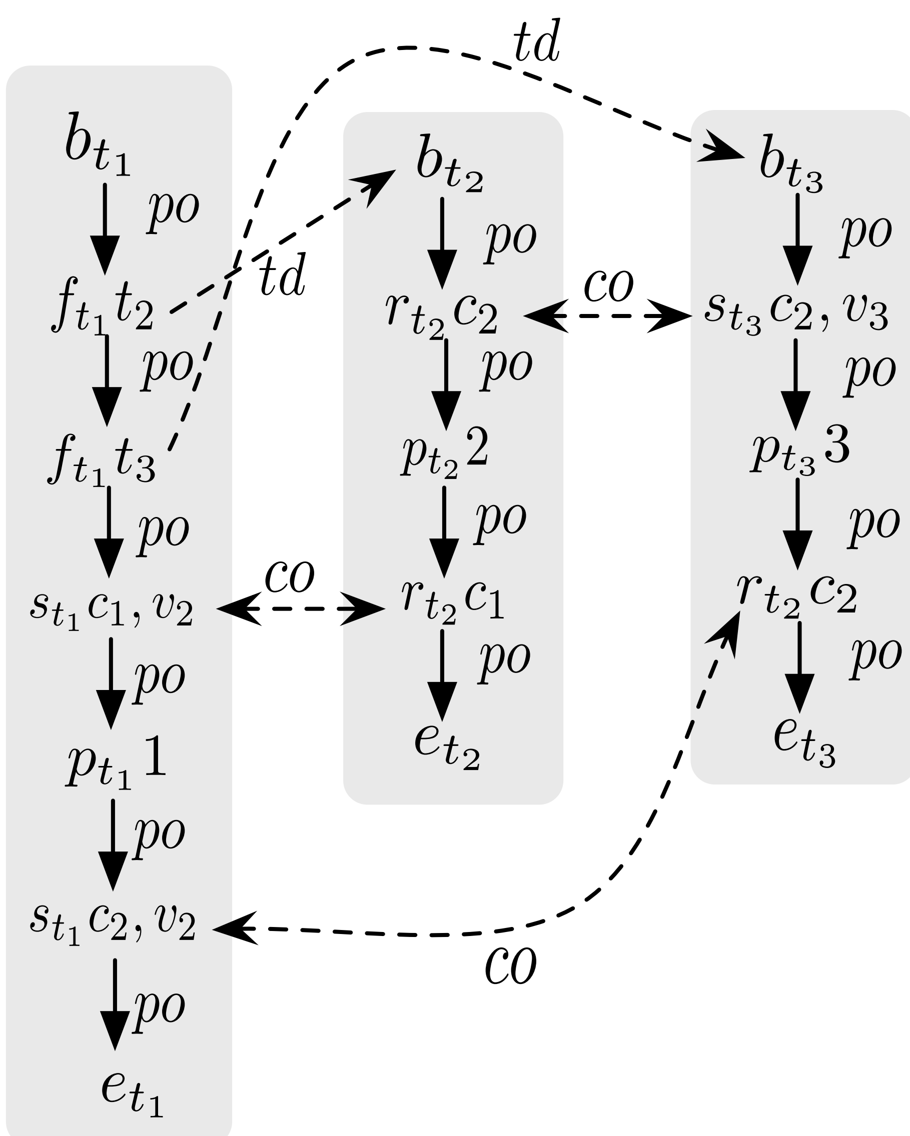

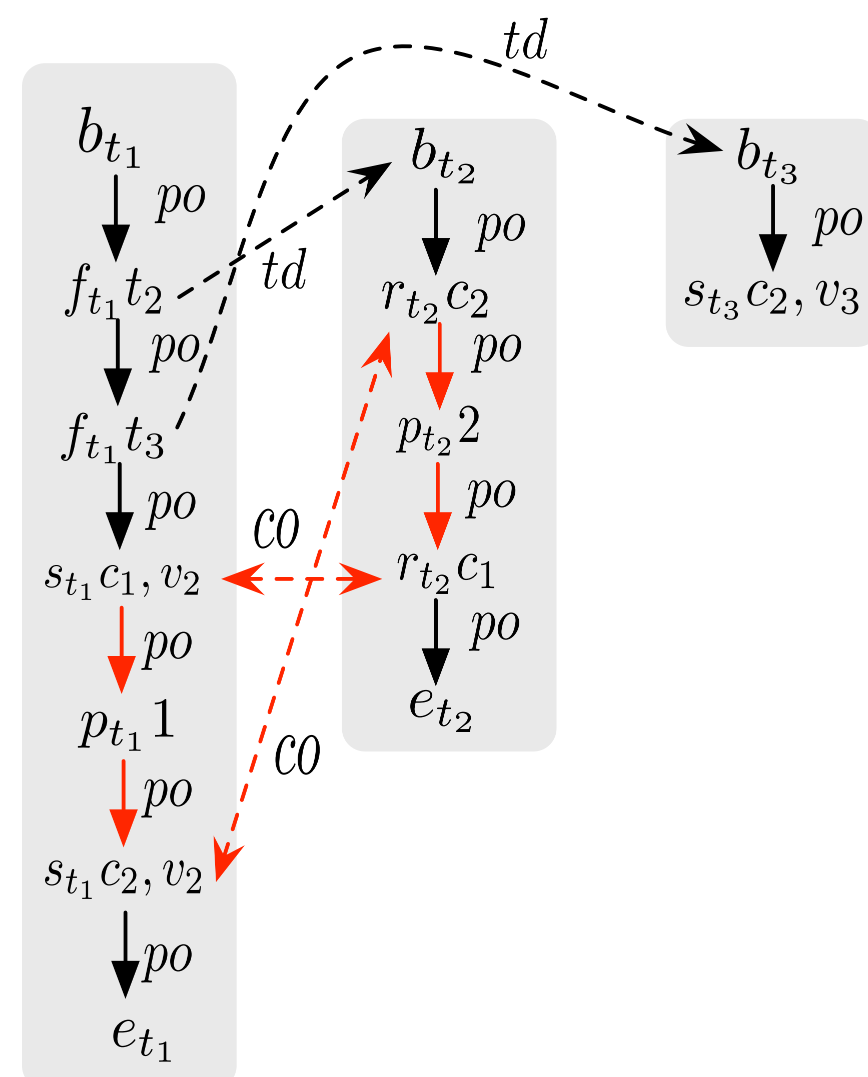

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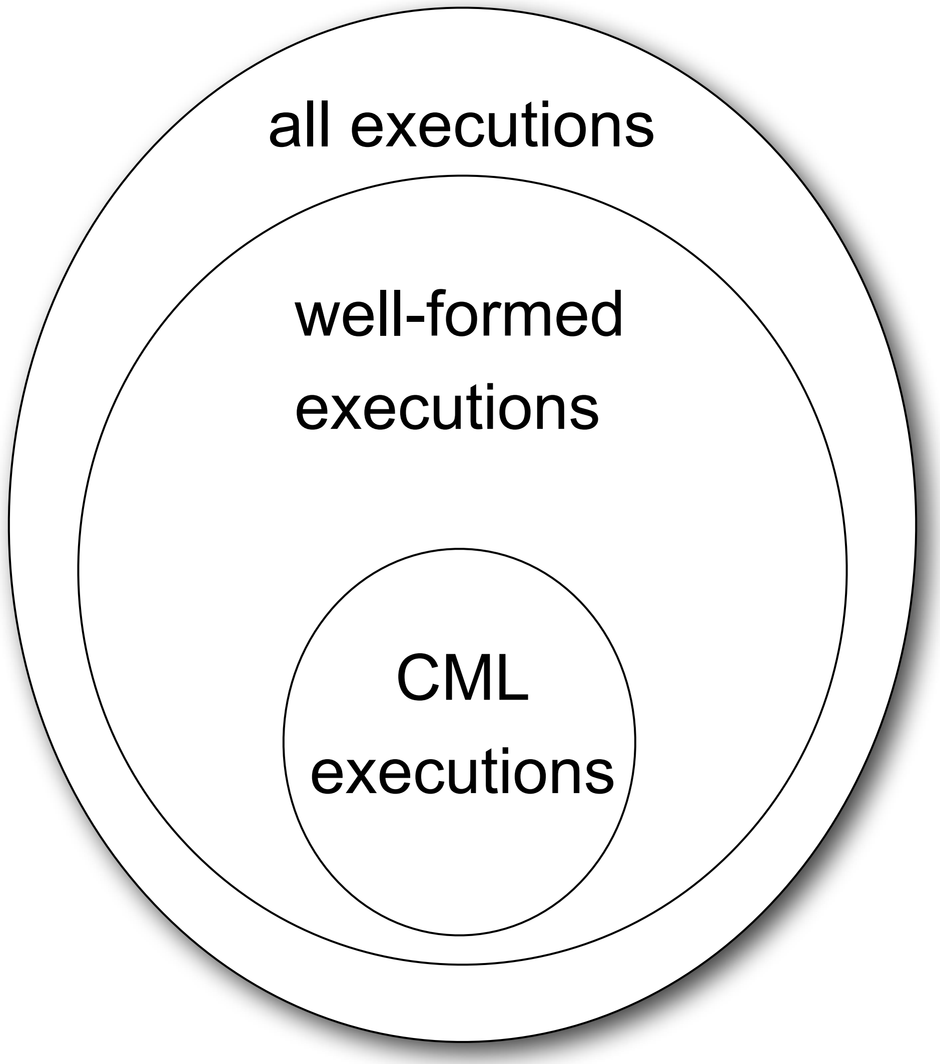
MultiMLton

Well-formed Executions

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



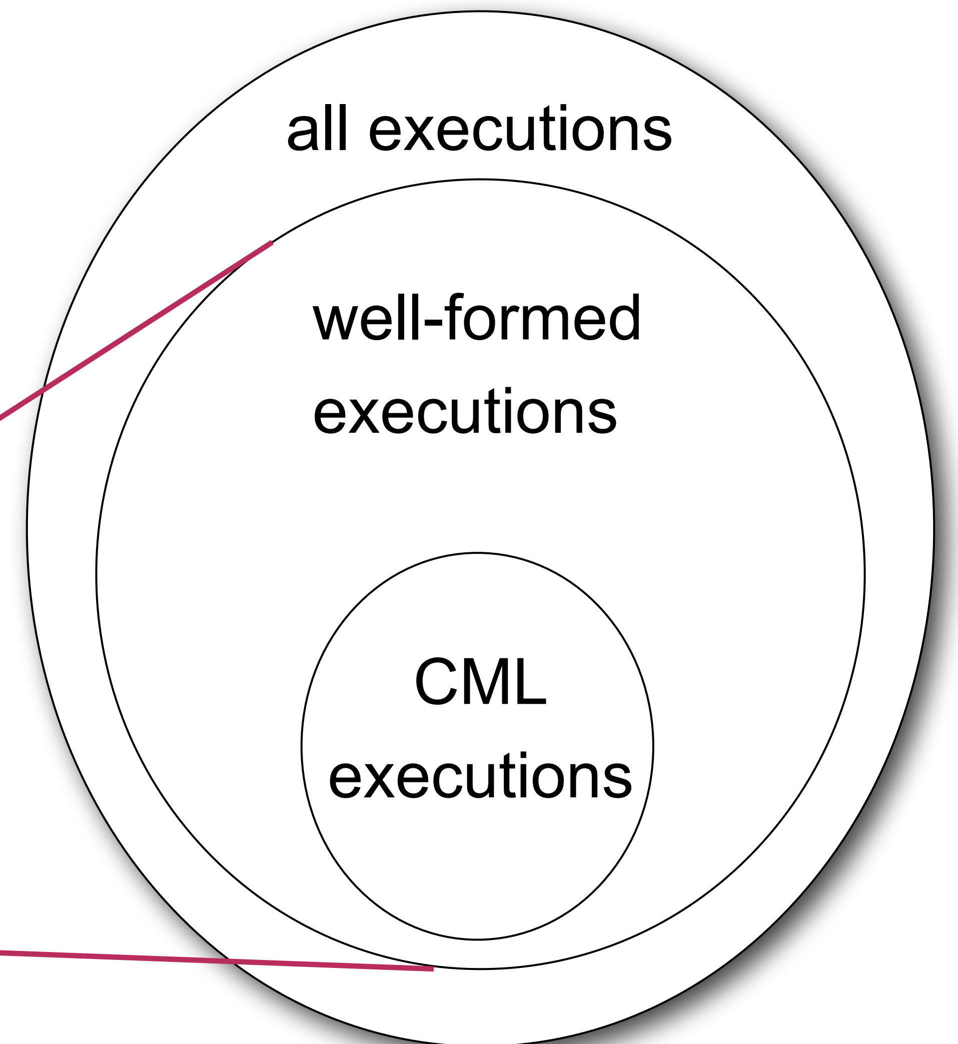
Well-formed Executions

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

1. Sensible intra-thread semantics

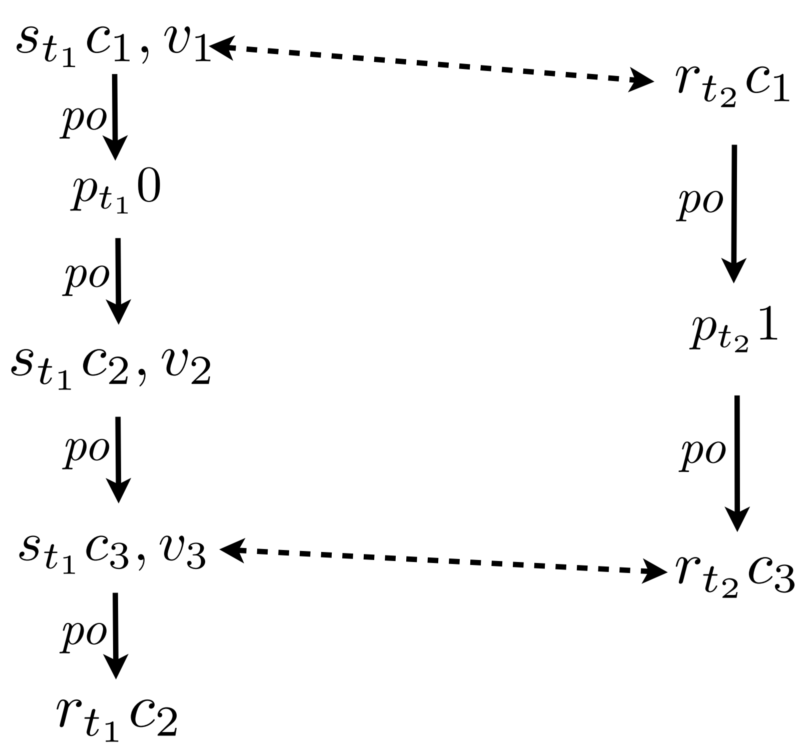
2. Acyclic happens-before relation

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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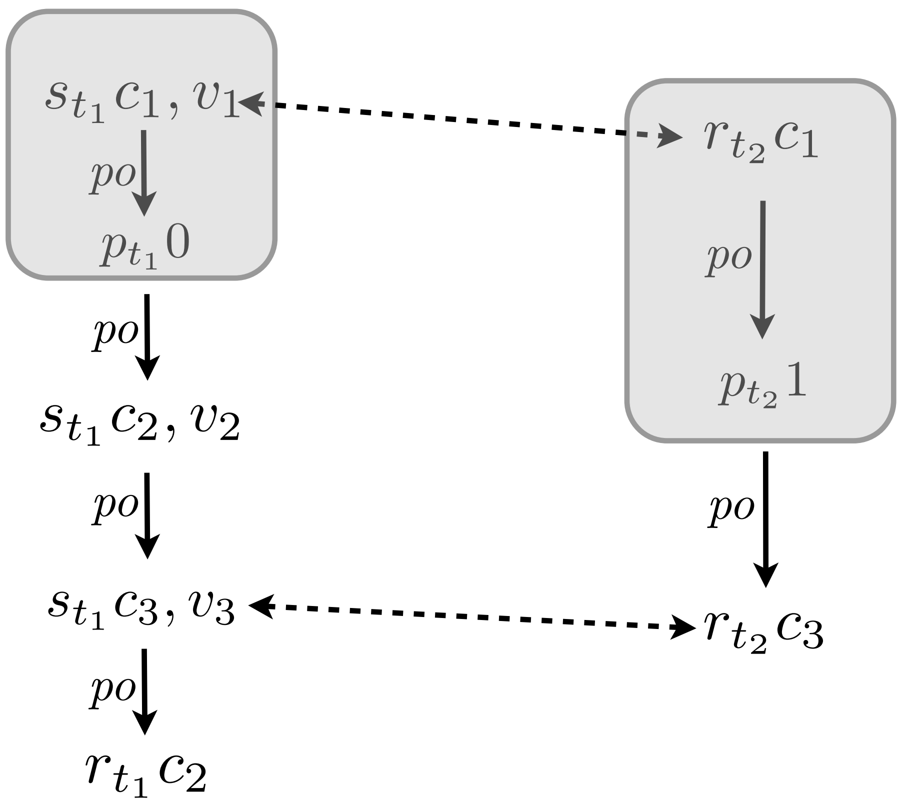

A CML execution

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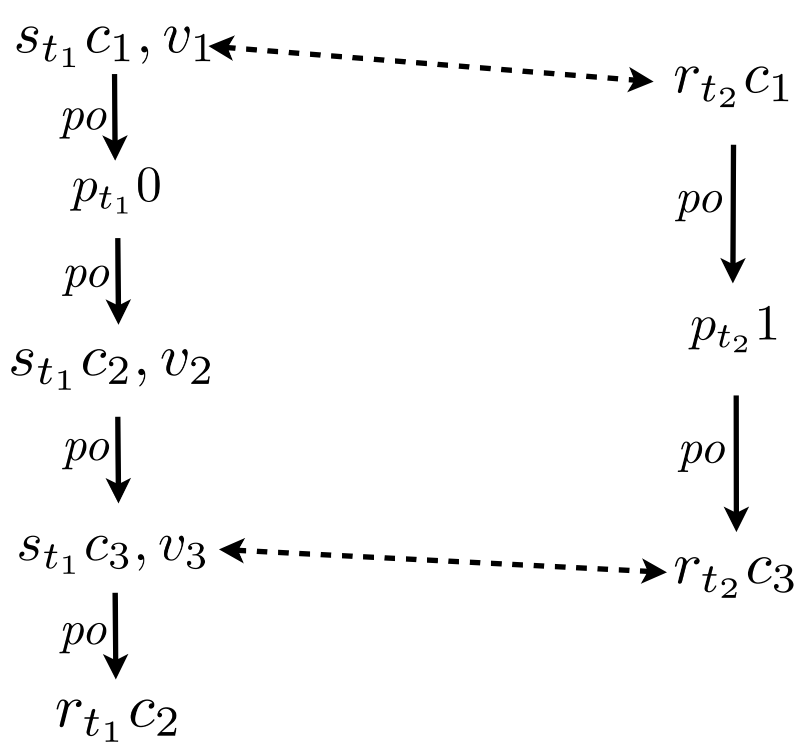

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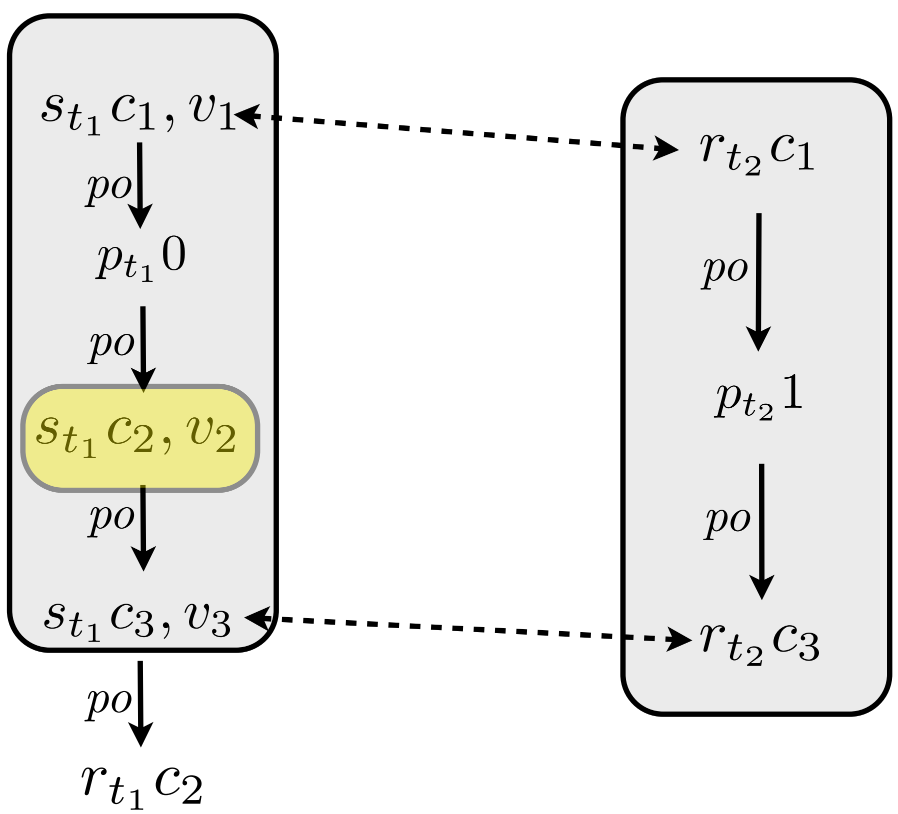

A well-formed execution that *can lead* to a CML execution

Well-formedness -> Speculation

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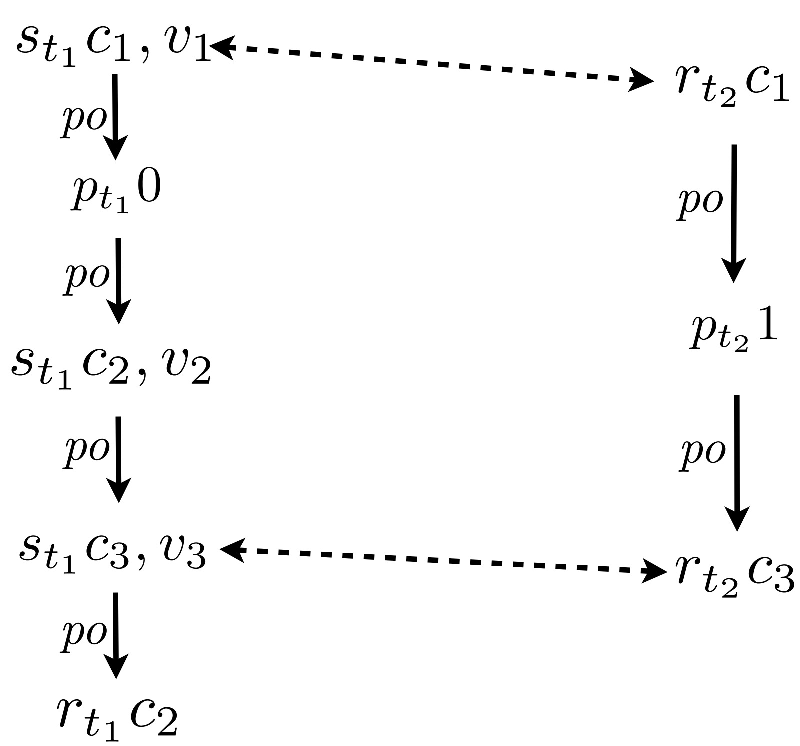

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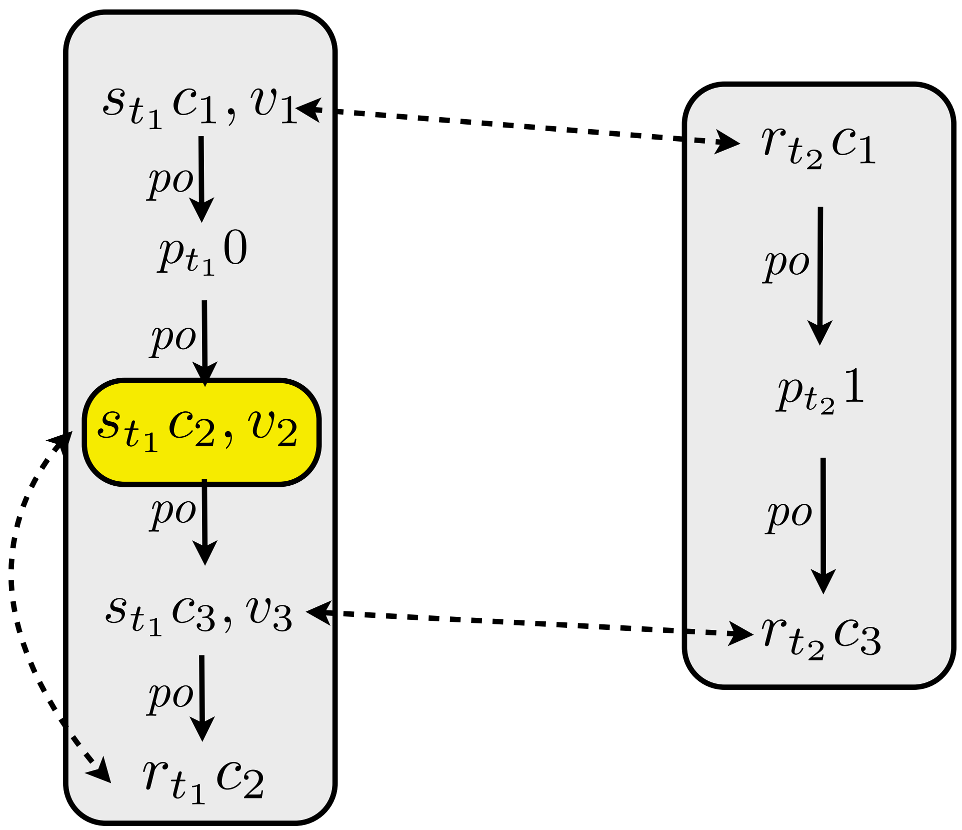

Not a well-formed execution

Implementation: Overview

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- ℞-CML: **RelaXed CML**
  - ★ MultiMLton with distribution support
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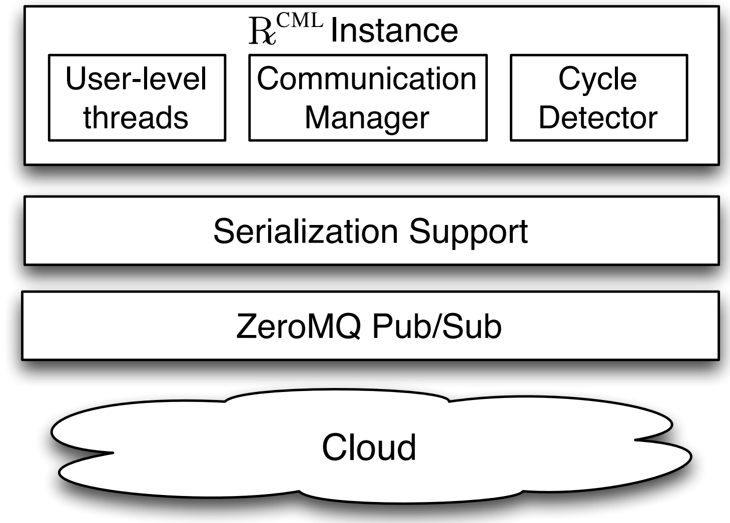

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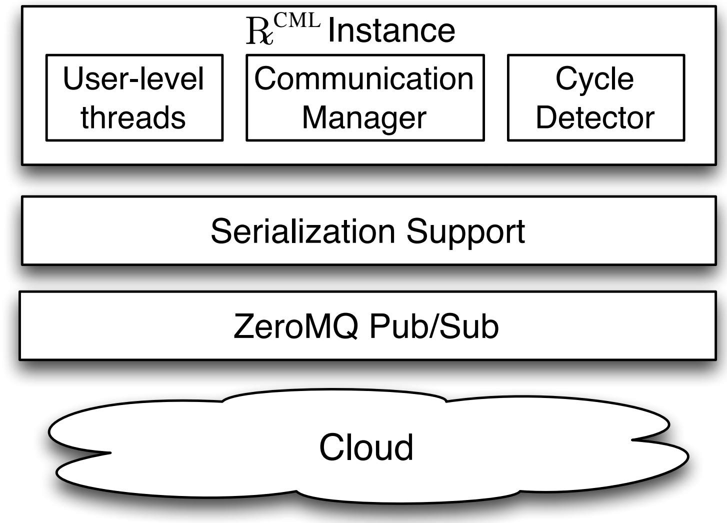

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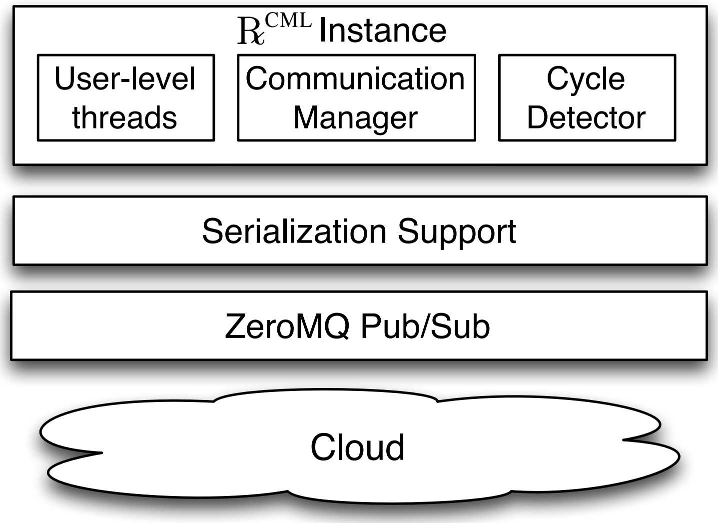

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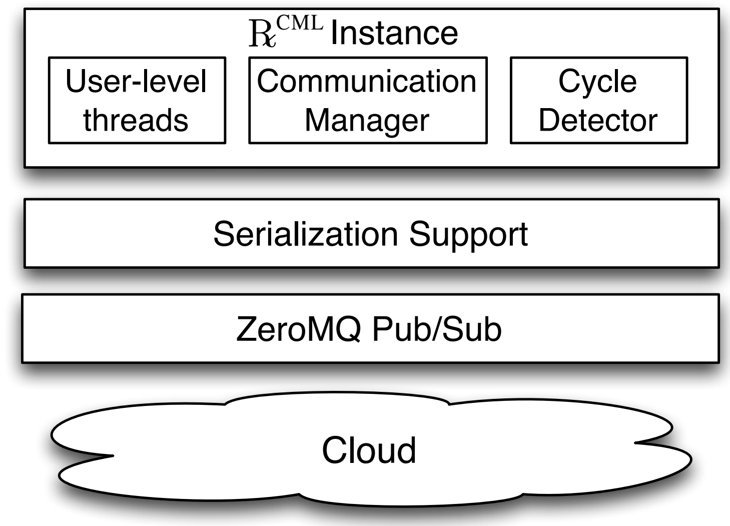

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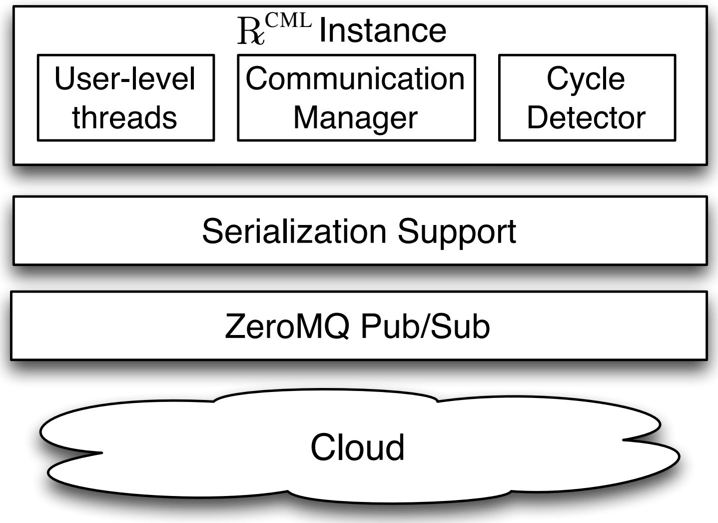

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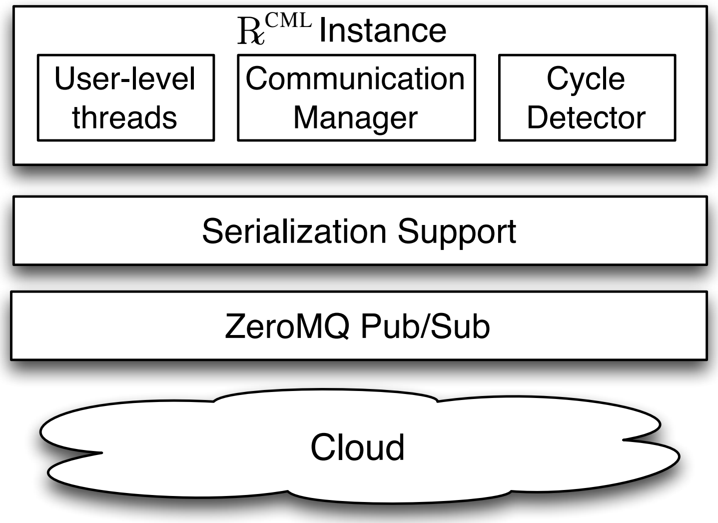

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  - ★ Roll-back ill-formed executions, re-execute non-speculatively

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(S³) MultiMLton

Channel Consistency (1)

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(ʃ³) MultiMLton

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Instance 1	Instance 2	Instance 3
`send(c1,0);`	`recv(c1);`	

`{c1:[],c2:[]}`

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MultiMLton

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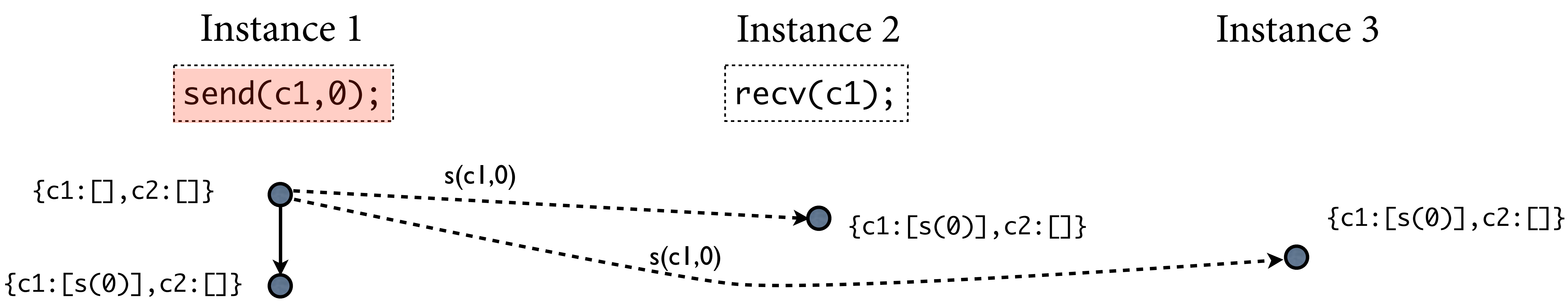

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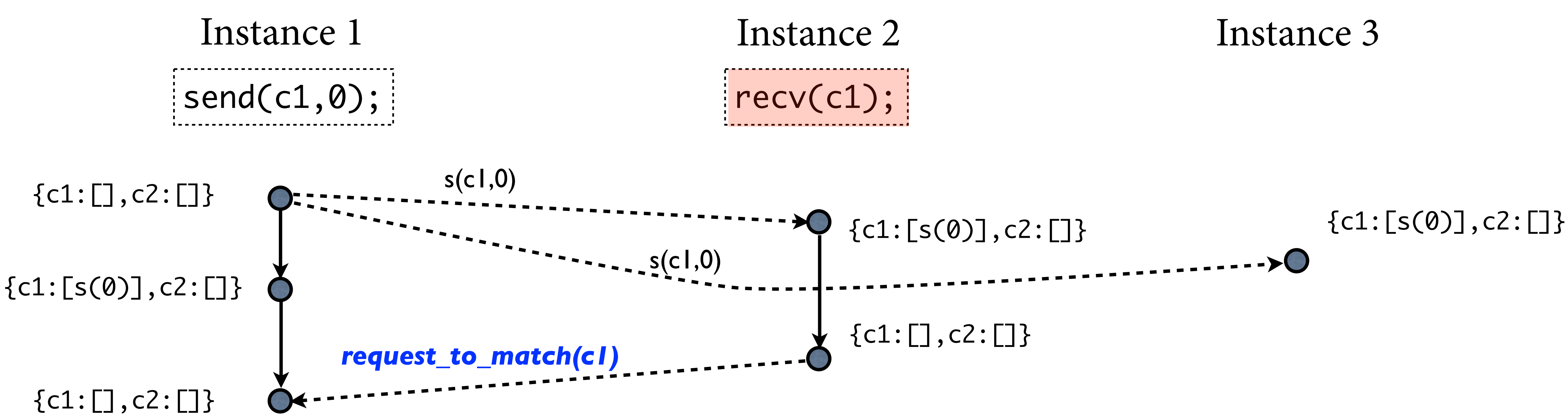

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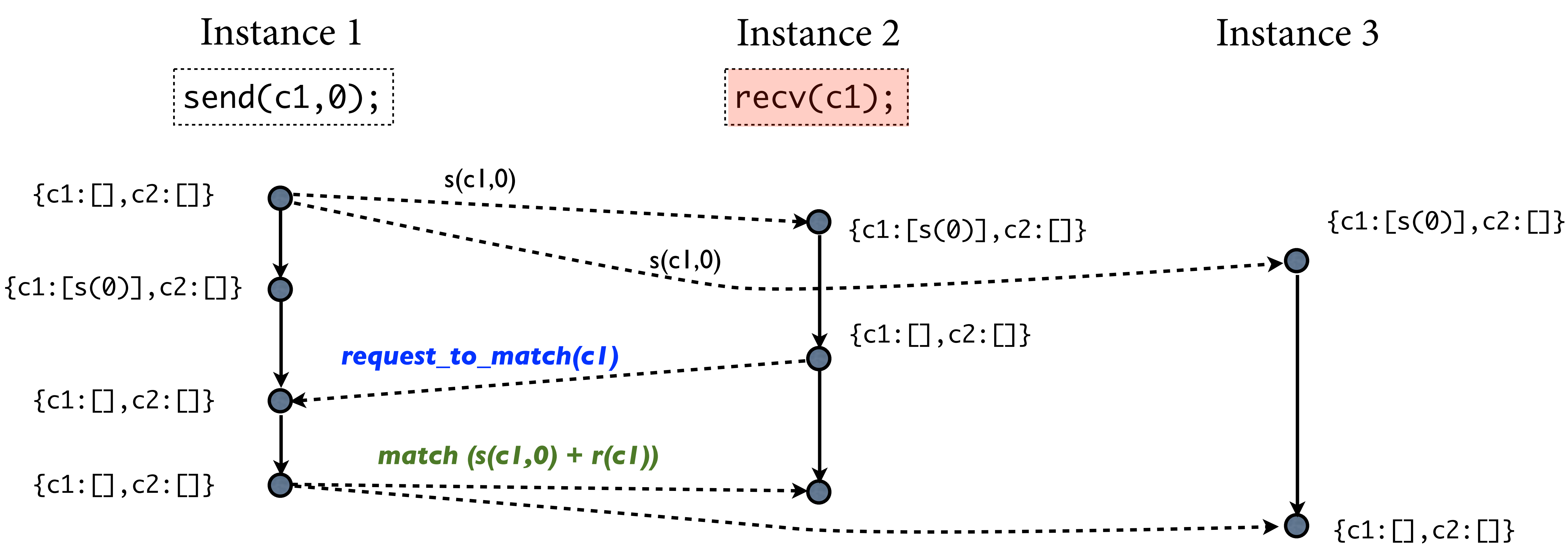

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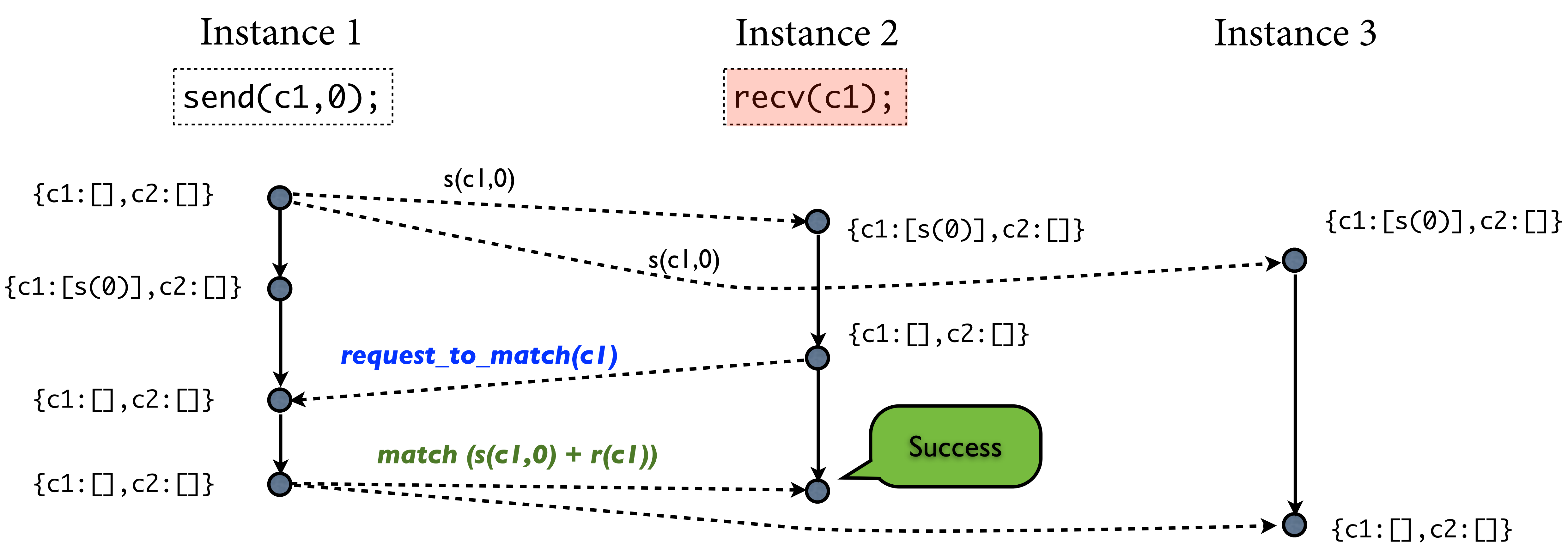

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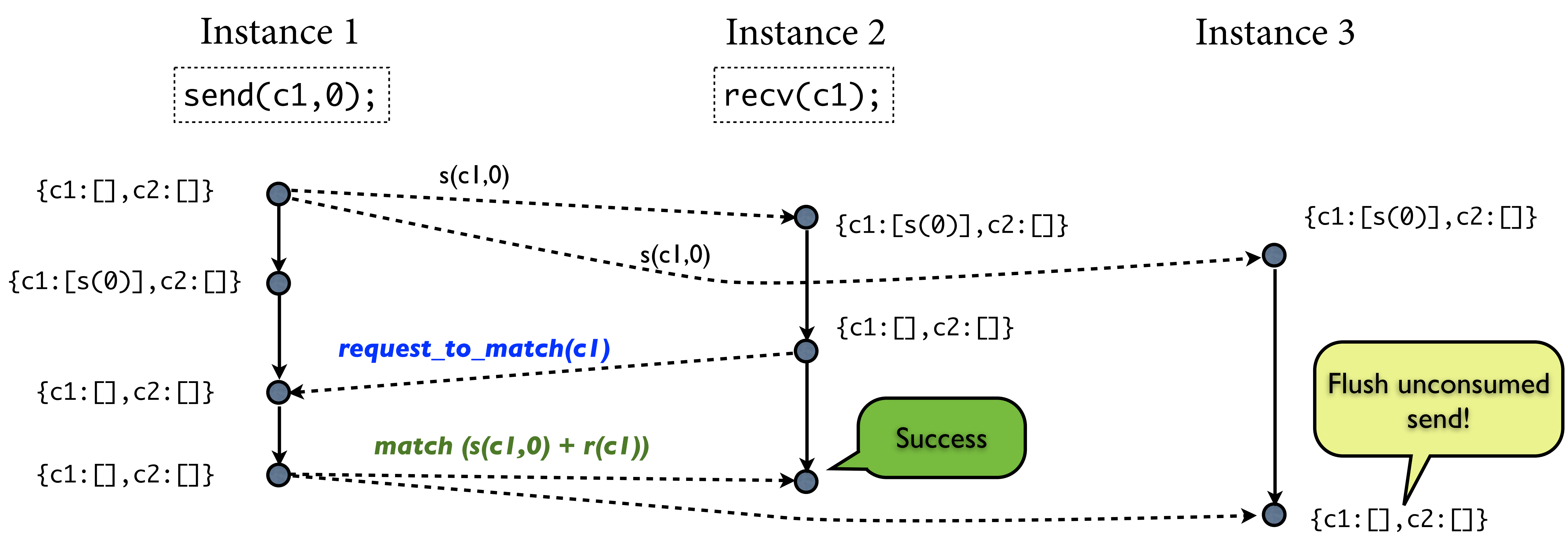

Channel Consistency (2)

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

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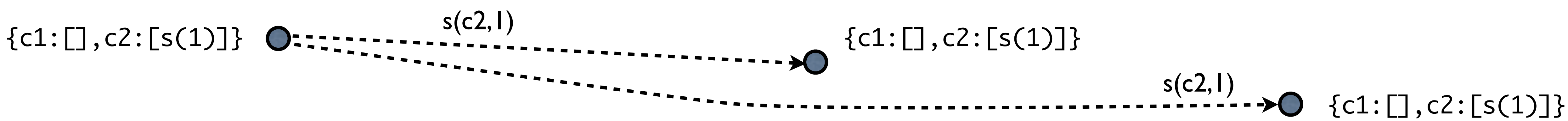

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(∫³) MultiMLton

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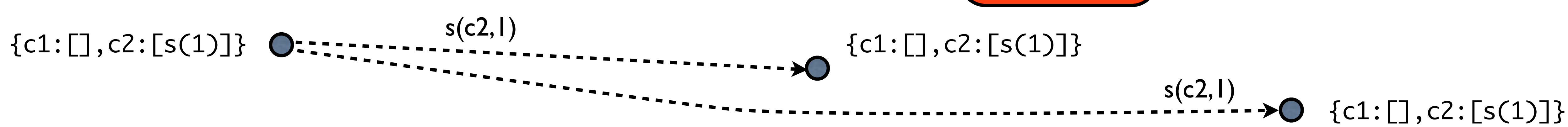
Instance 1	Instance 2		Instance 3
`send(c2,1);`	`recv(c2);`	*Concurrent execution!*	`recv(c2);`



Channel Consistency (2)

Instance 1

```
send(c2,1);
```

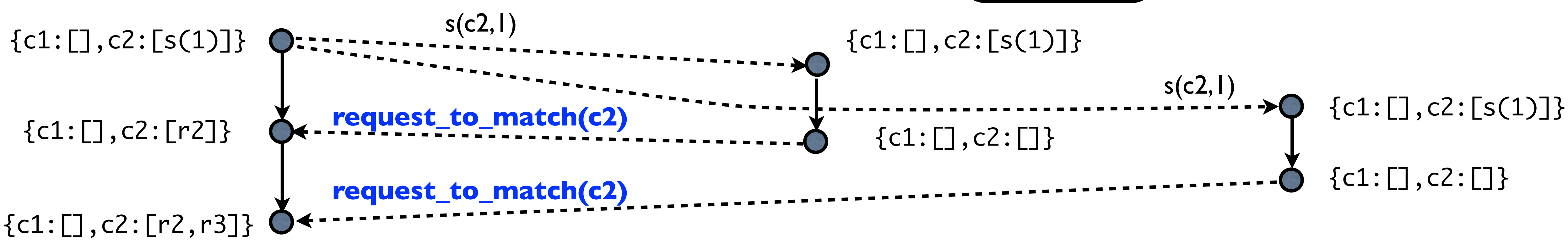
Instance 2

```
recv(c2);
```

Concurrent execution!

Instance 3

```
recv(c2);
```



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MultiMLton

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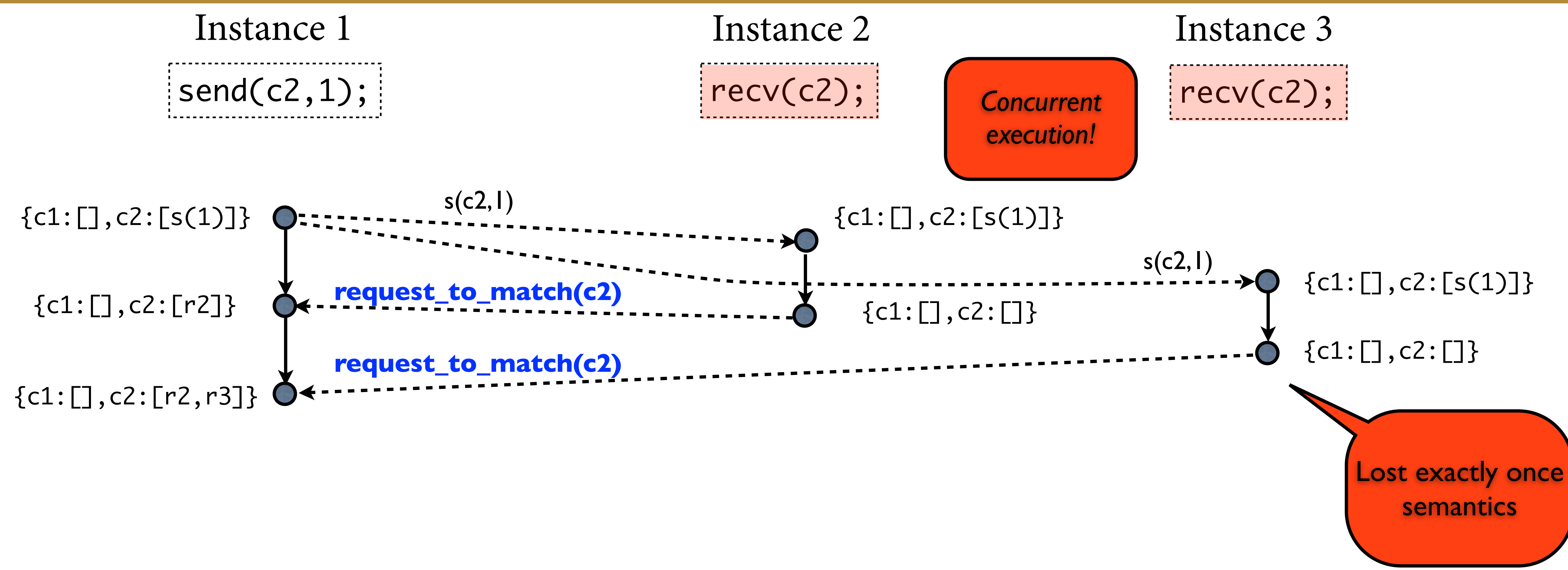

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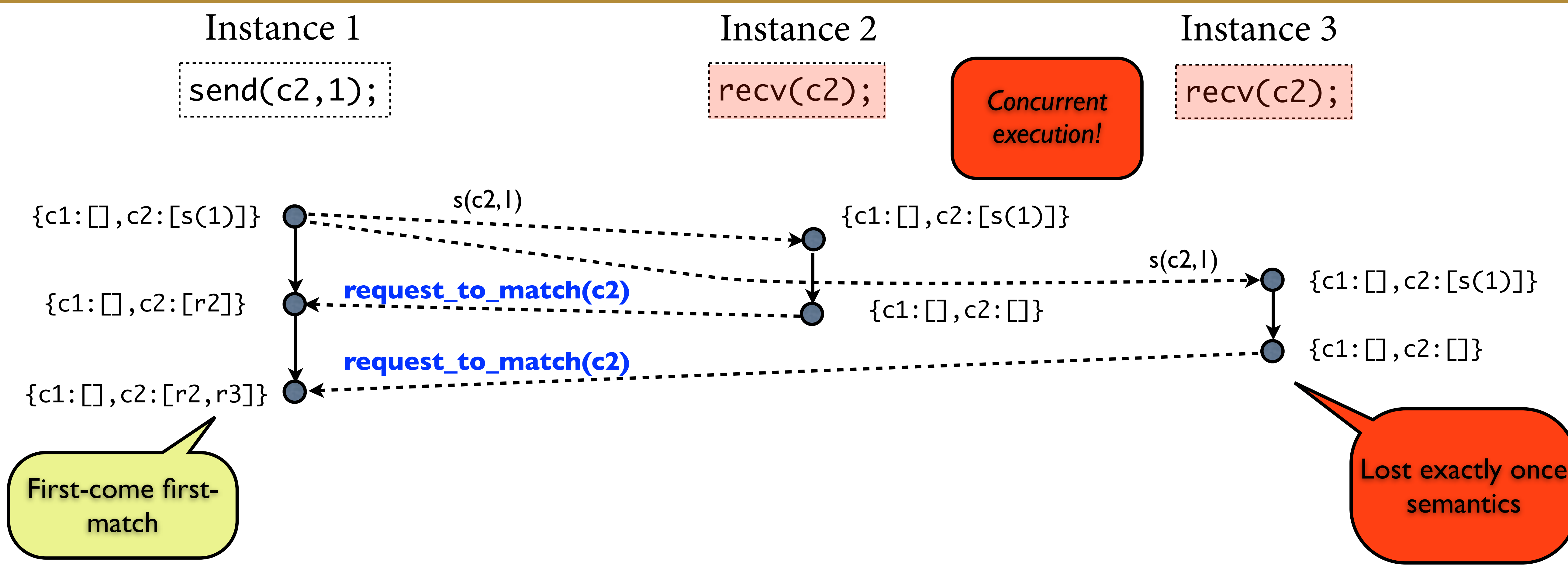

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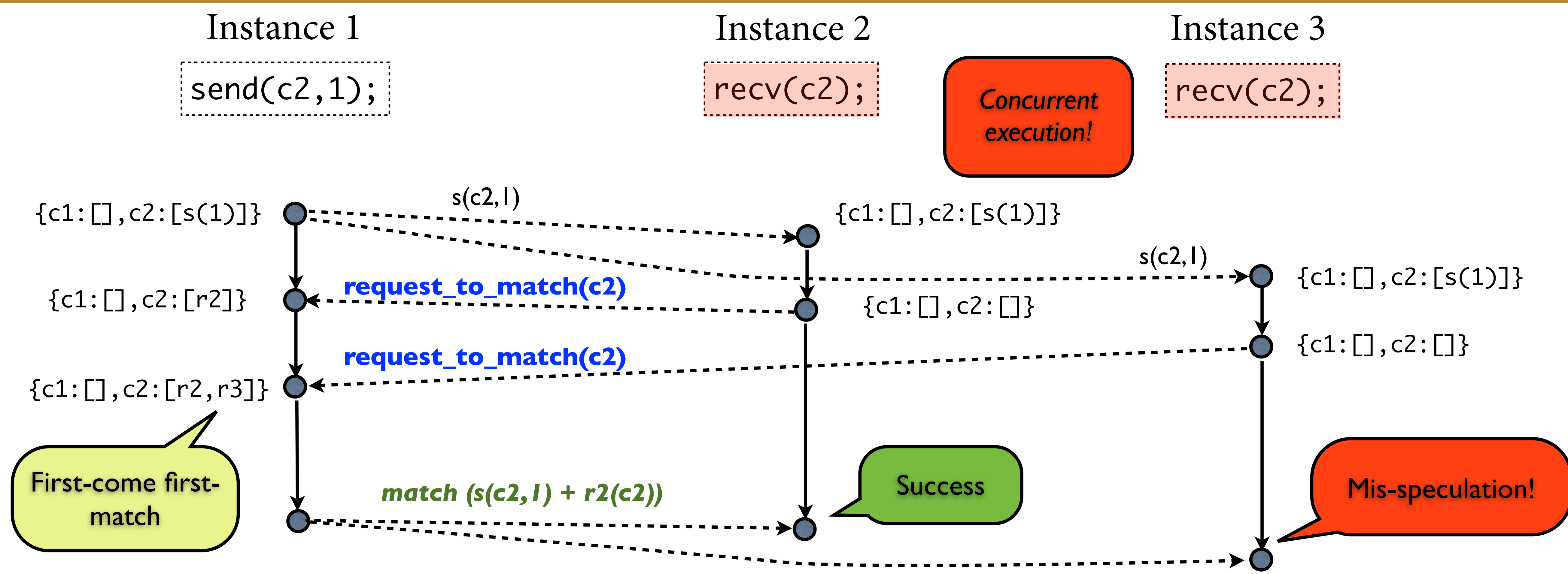

Speculative Execution

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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
  - ★ Distributed version of STAMP Vacation benchmark
  - ★ Database split into 64 shards, with concurrent transaction requests from geo-distributed clients
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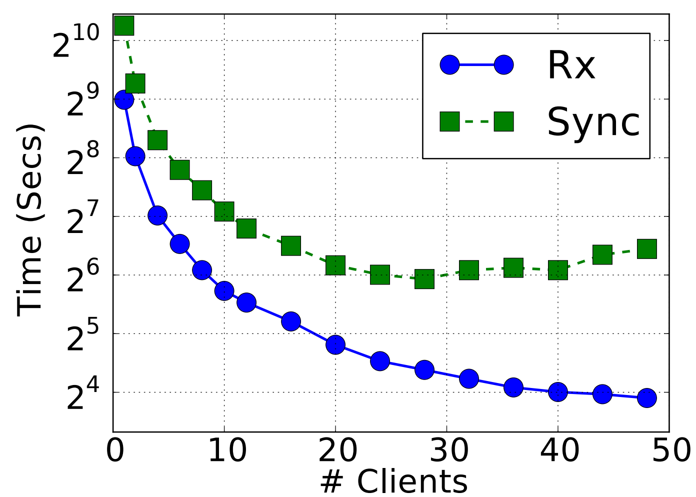
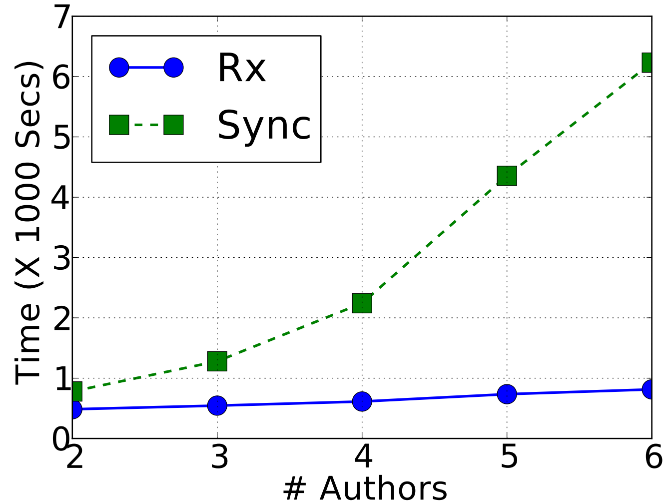


OLTP



Collaborative Editing

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

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MultiMLton

Conclusion

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- 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