Specification of shared objects in wait-free distributed systems

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UNIVERSITÉ DE NANTES

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UNIVERSITE BRETAGNE LOIRE

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JURY

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Introduction – Motivation

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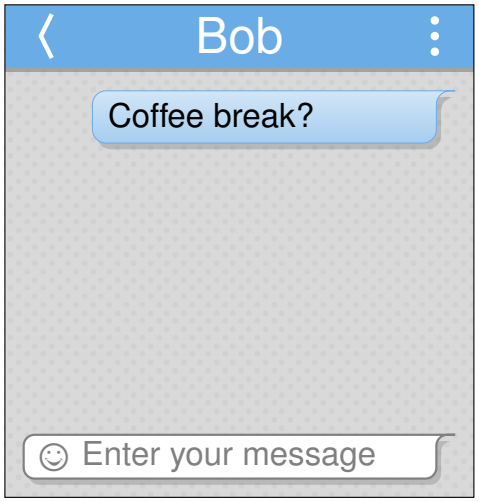

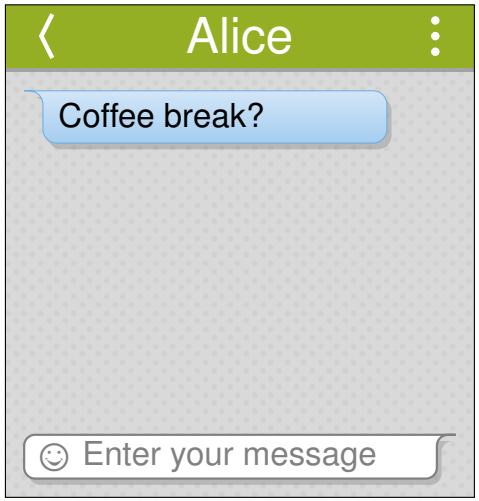

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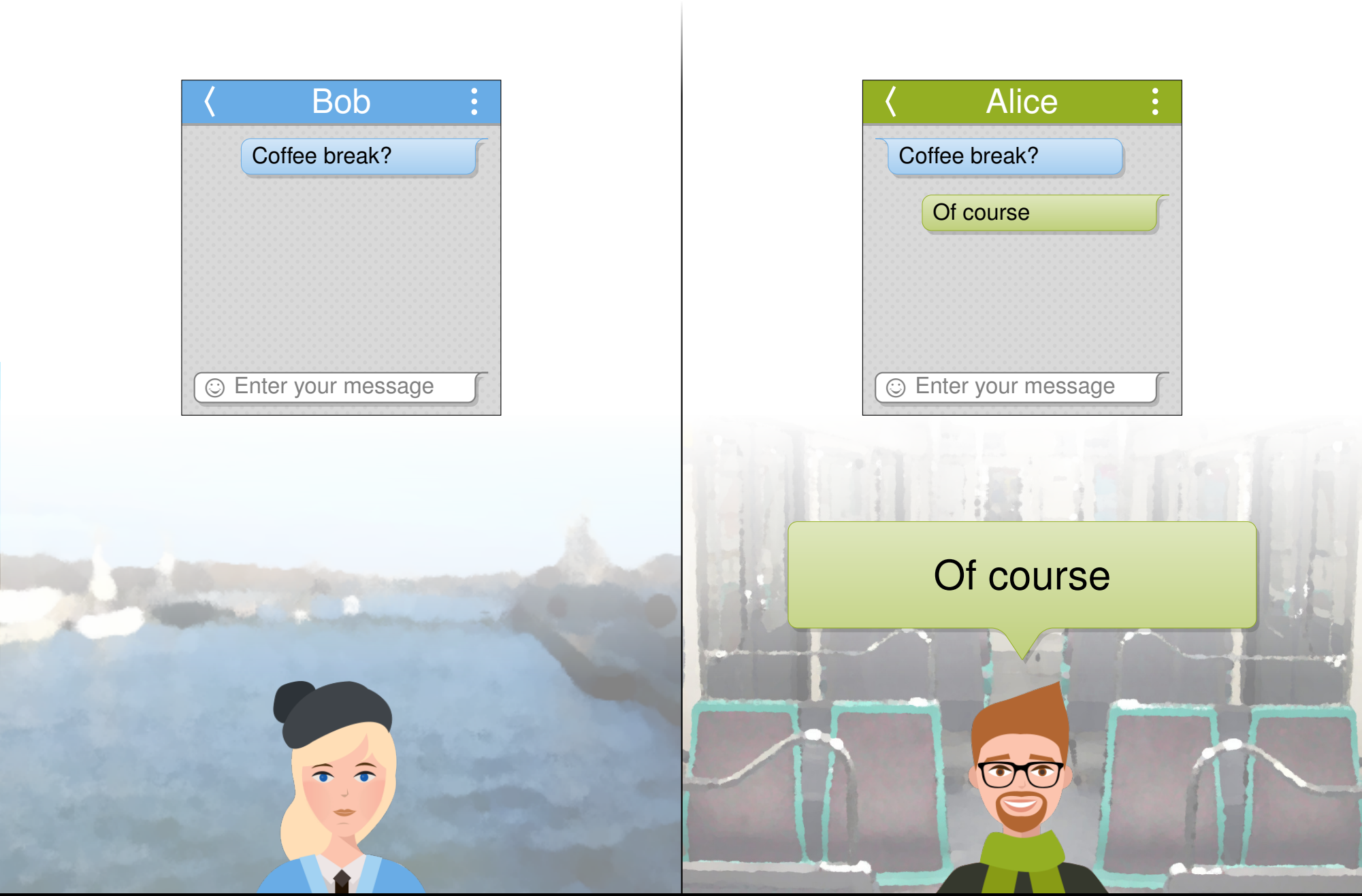

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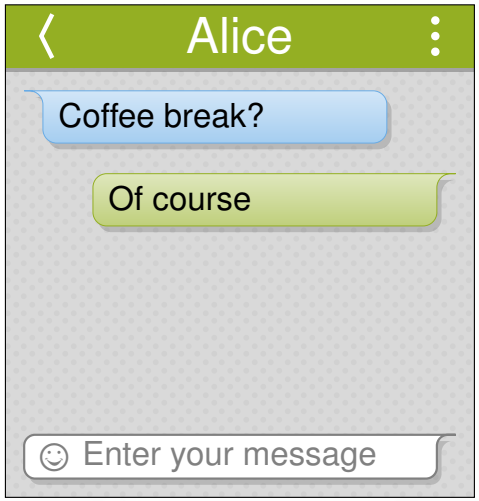

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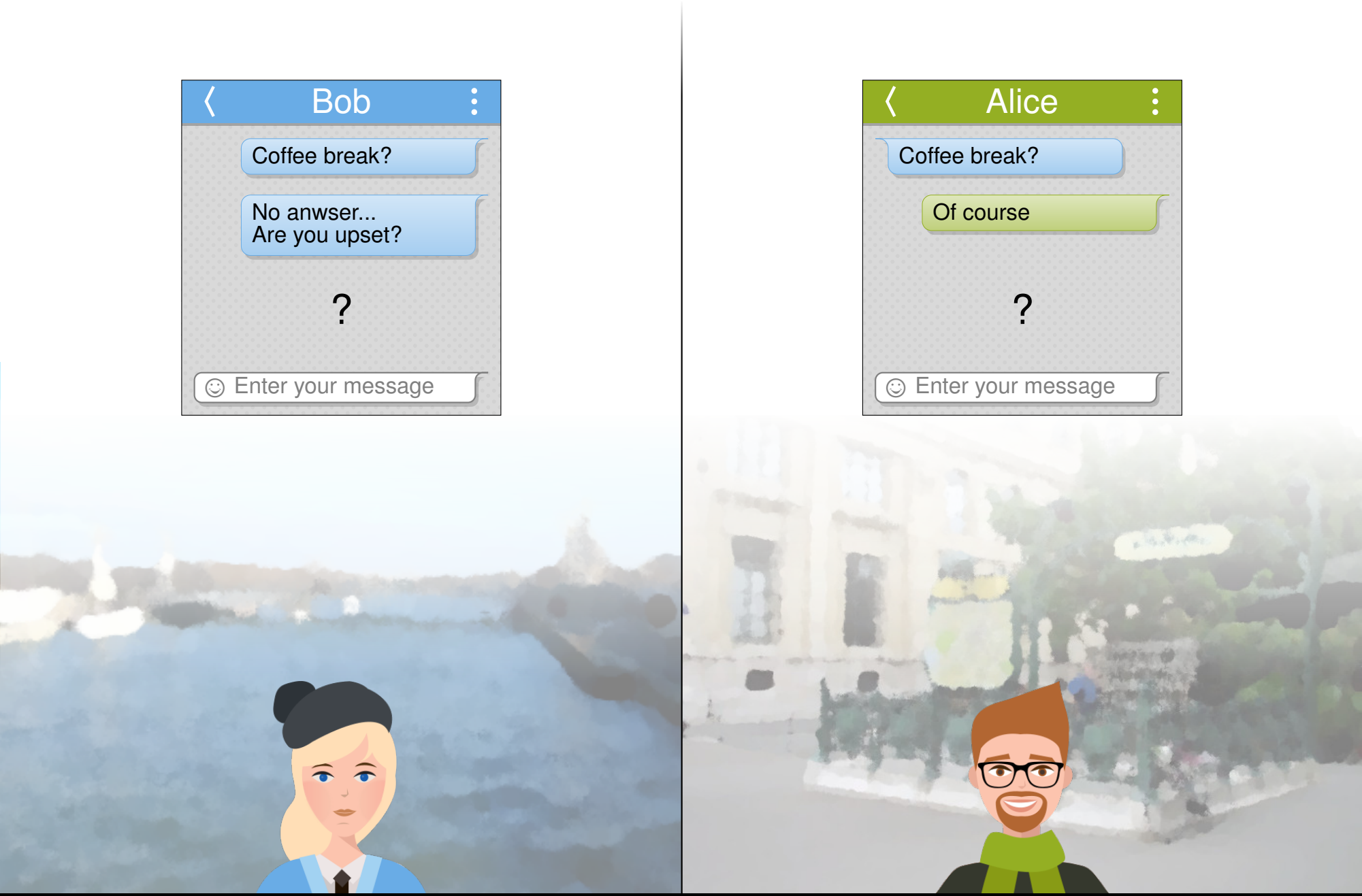

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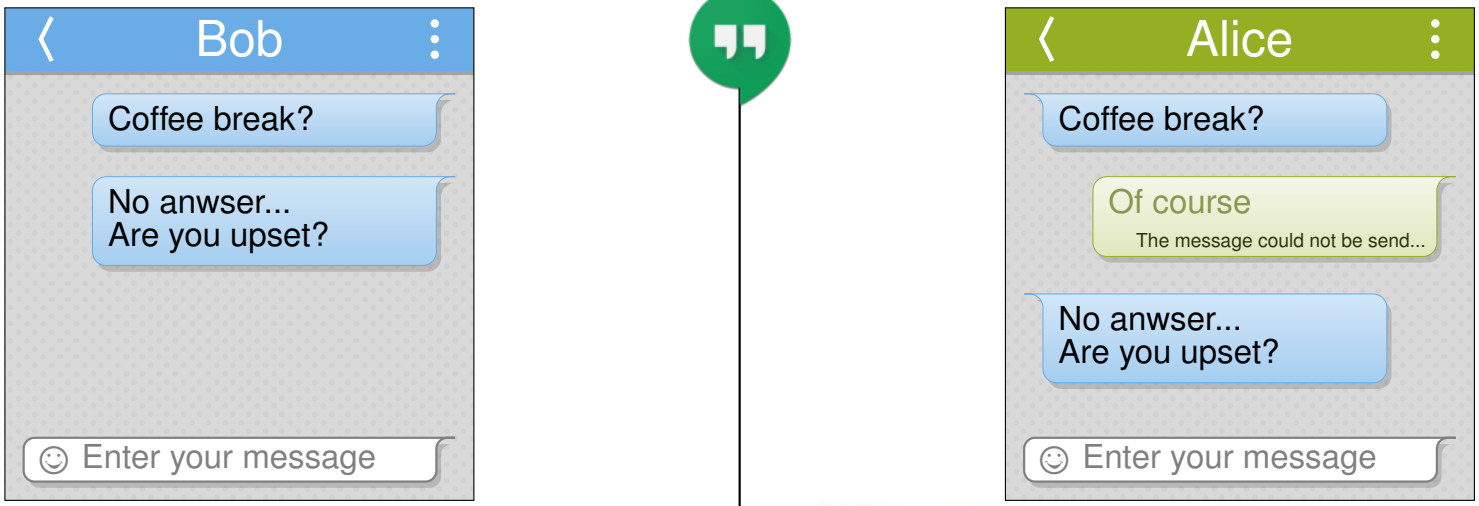

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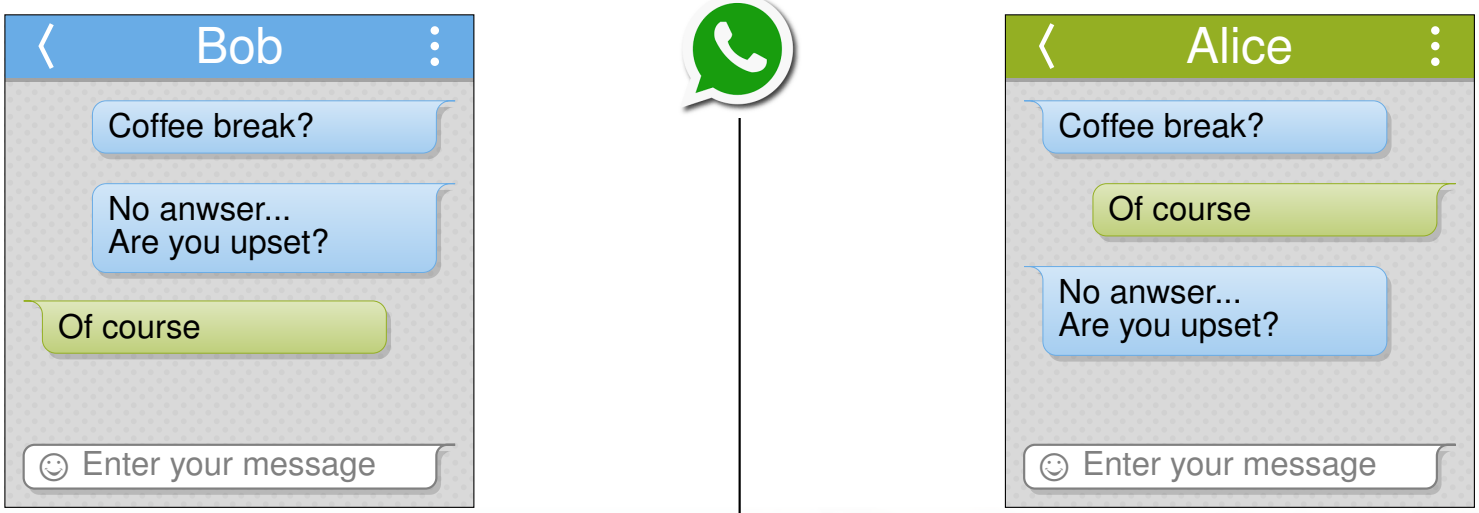

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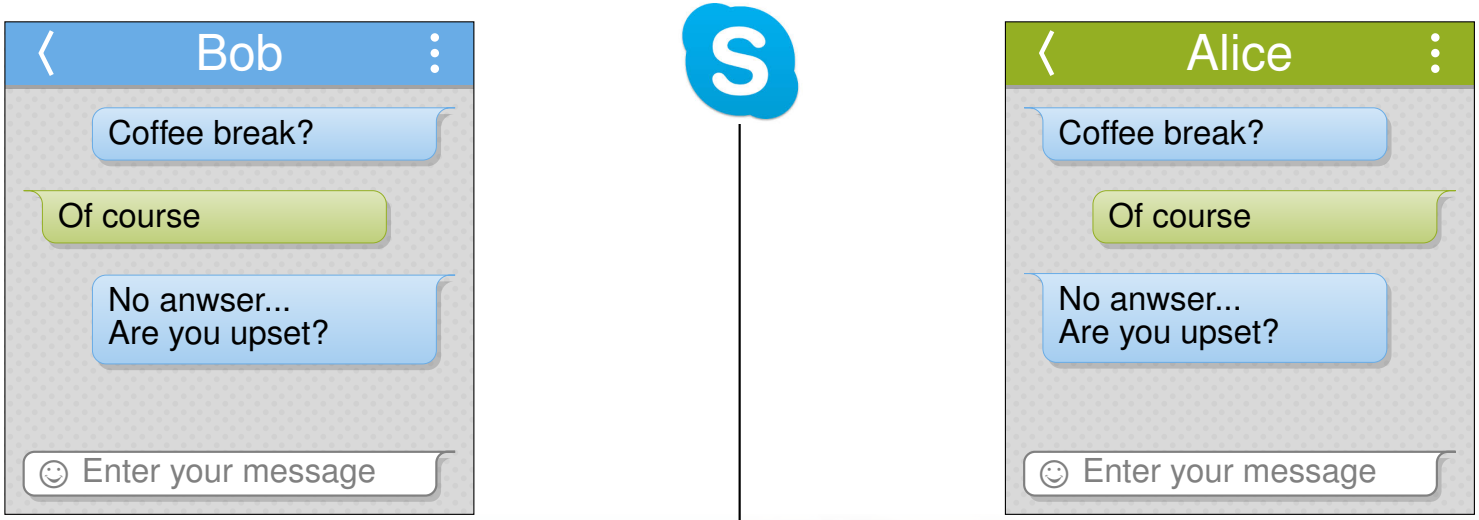

Concurrency

Several *processes* interact with the same *shared object*

- Alice and Bob
- Computers
- Threads...

- Instant messaging service
- Collaborative application
- Shared memory...

Wait-free asynchronous message passing distributed systems

- Fixed and known number of processes
- Message send and receive primitives
- Unbounded communication delays
- Operations return instantly
  - Impossible to implement strong consistency[1]

Problem statement

How to specify shared objects
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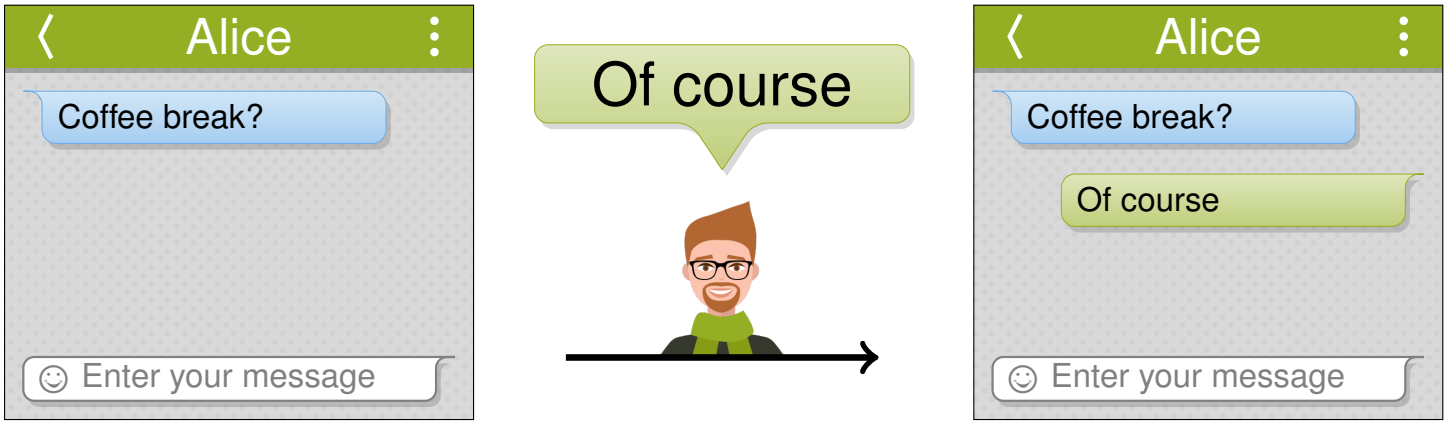

Consistency criterion

`shared Messenger m = new Messenger();`

- Concurrent behaviour?
- Consistency criterion

Sequential specification

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class Messenger {
   string[] received;
   void send(string message) {
     received.length ++ ;
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Data bases and transactional memory

Transactions

Serializability

Concurrent systems

Eventual consistency

CRDT

Strong eventual consistency

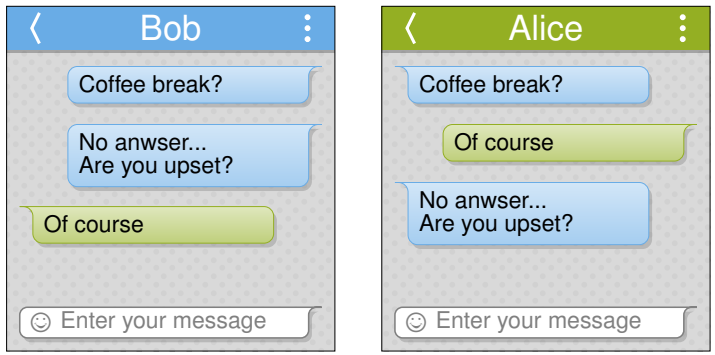
Parallel programming

Memory models

PRAM

Causal memory

Cache consistency



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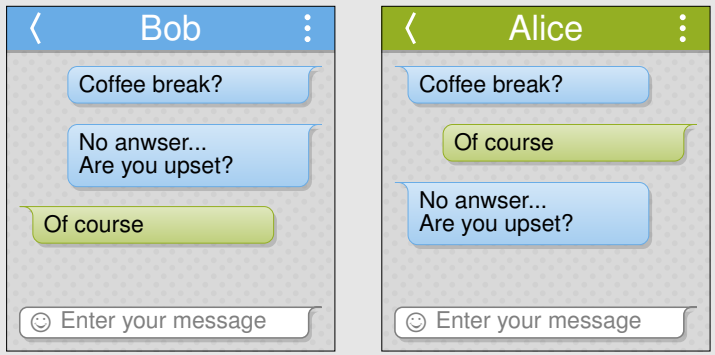

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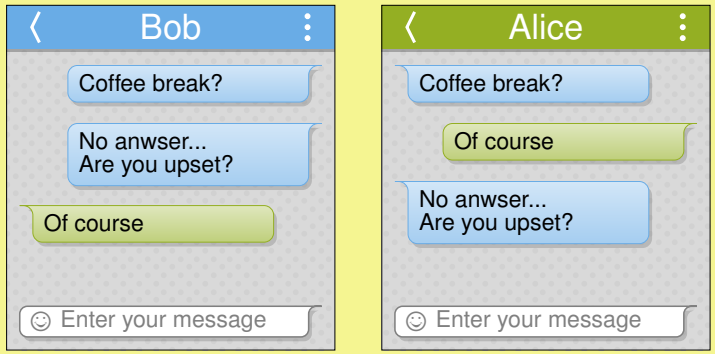

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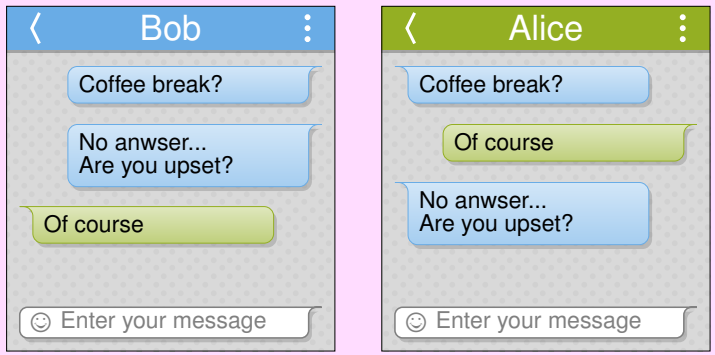

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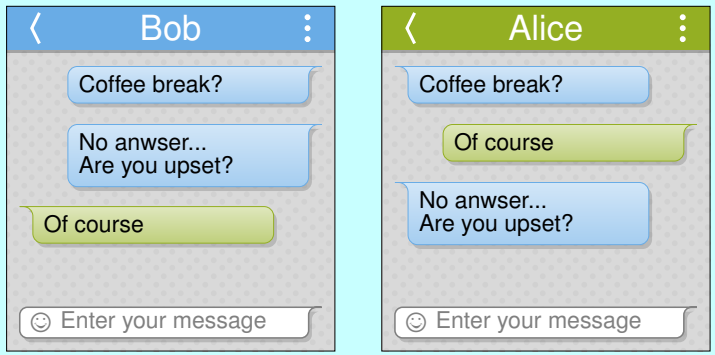

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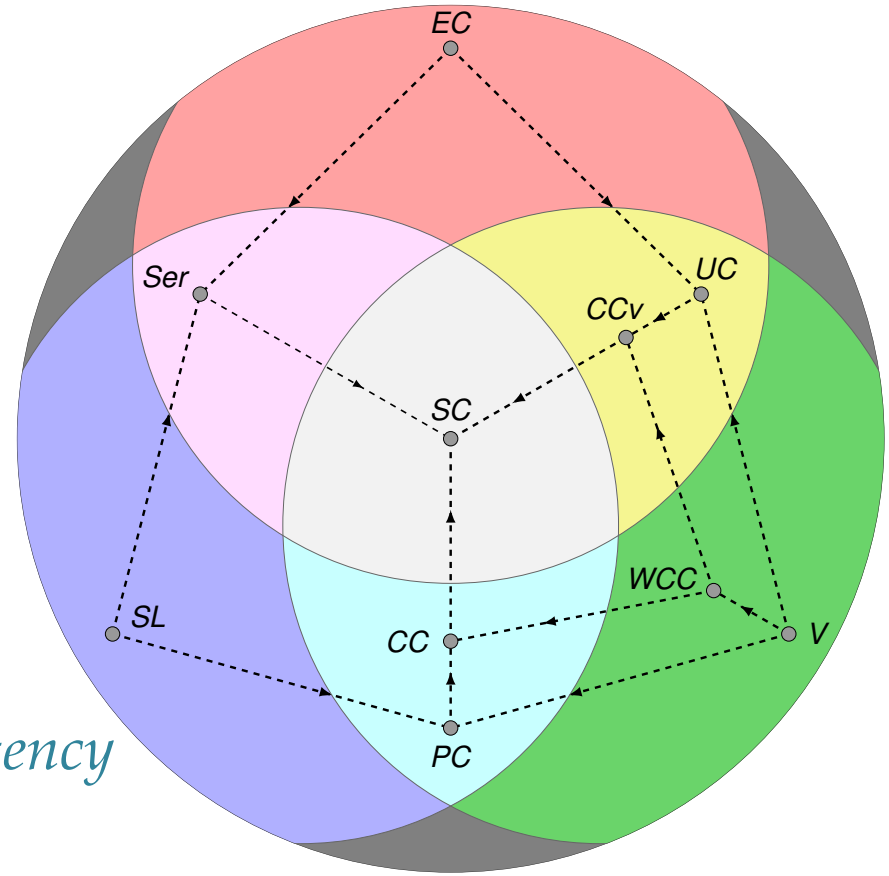

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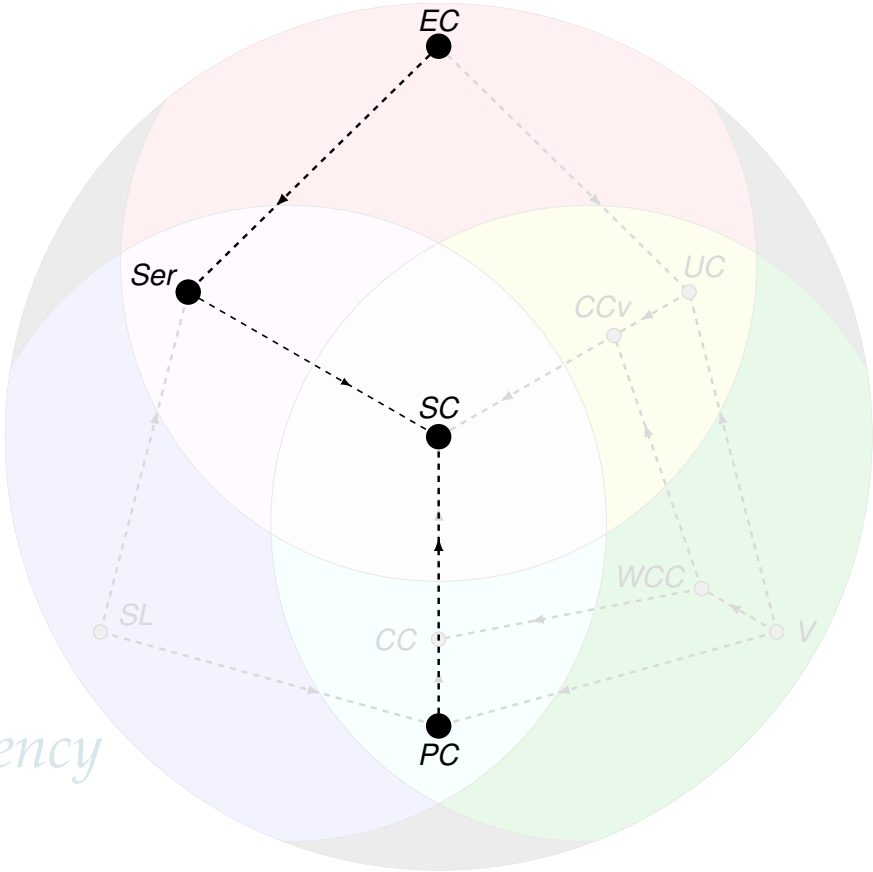

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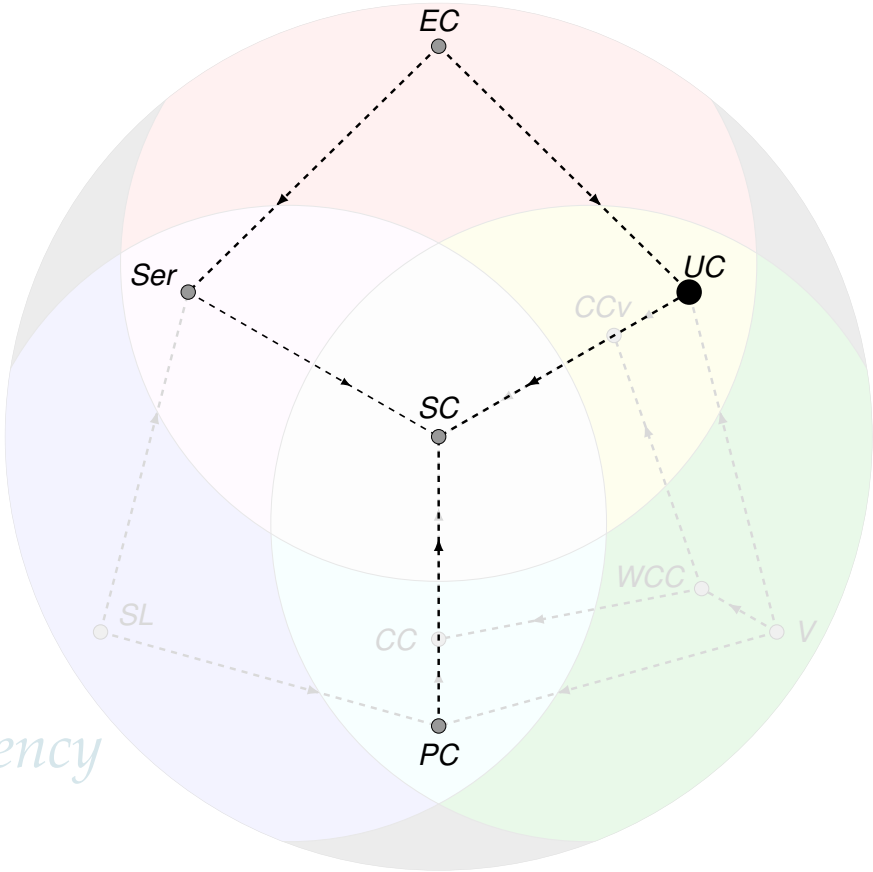

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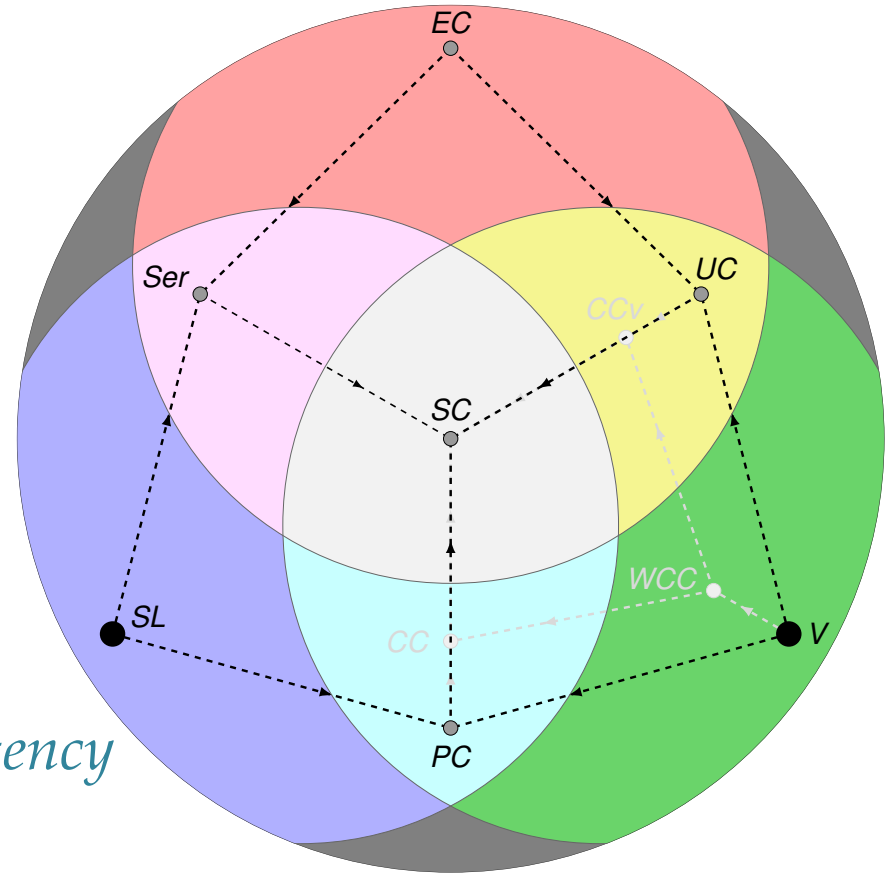

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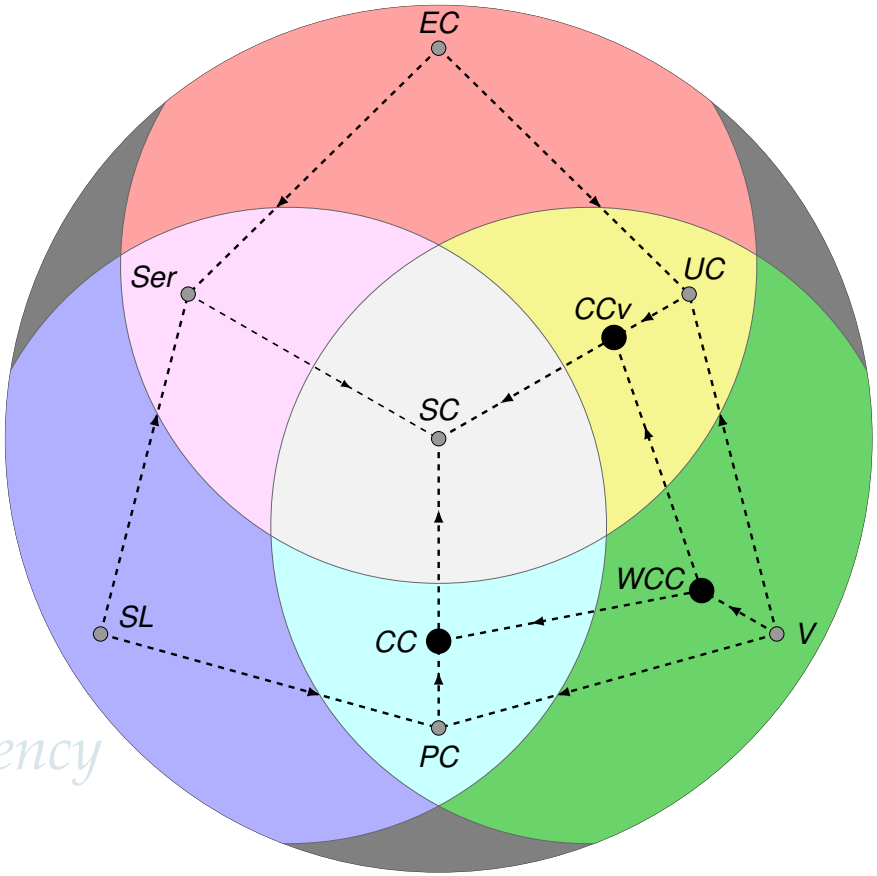
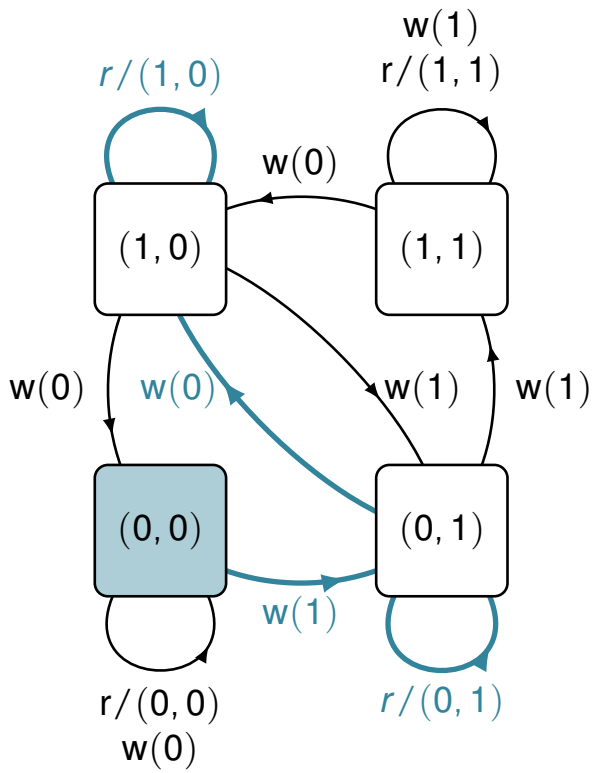


1. Model – *Window streams of size k*

Abstract data type (ADT)



Two kinds of operations

Writes

- $v \in \mathbb{N}$: message
- $\mathrm{w}(v)$: sending of v

Reads

- $\mathrm{r}/(v_1, \ldots, v_k)$: refresh
- ordered k last values written
- k : size of the screen

General case

Read part : return value

Write part : state transition

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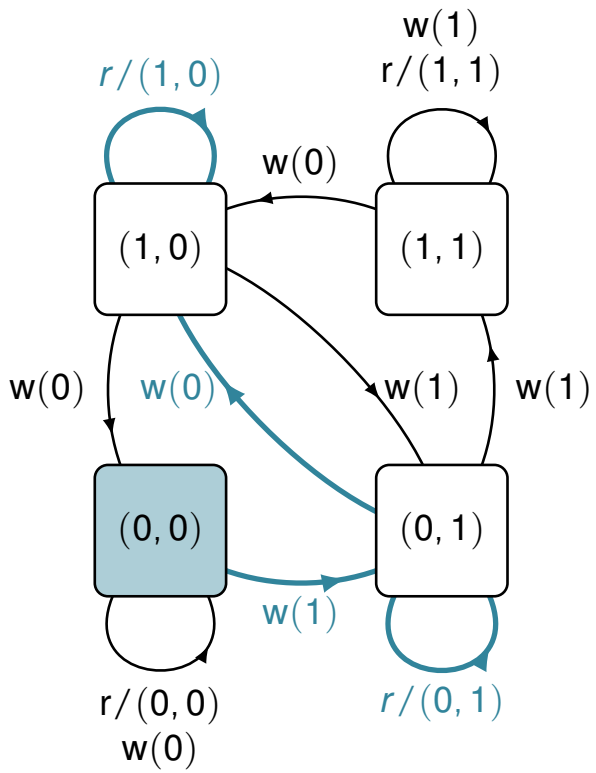

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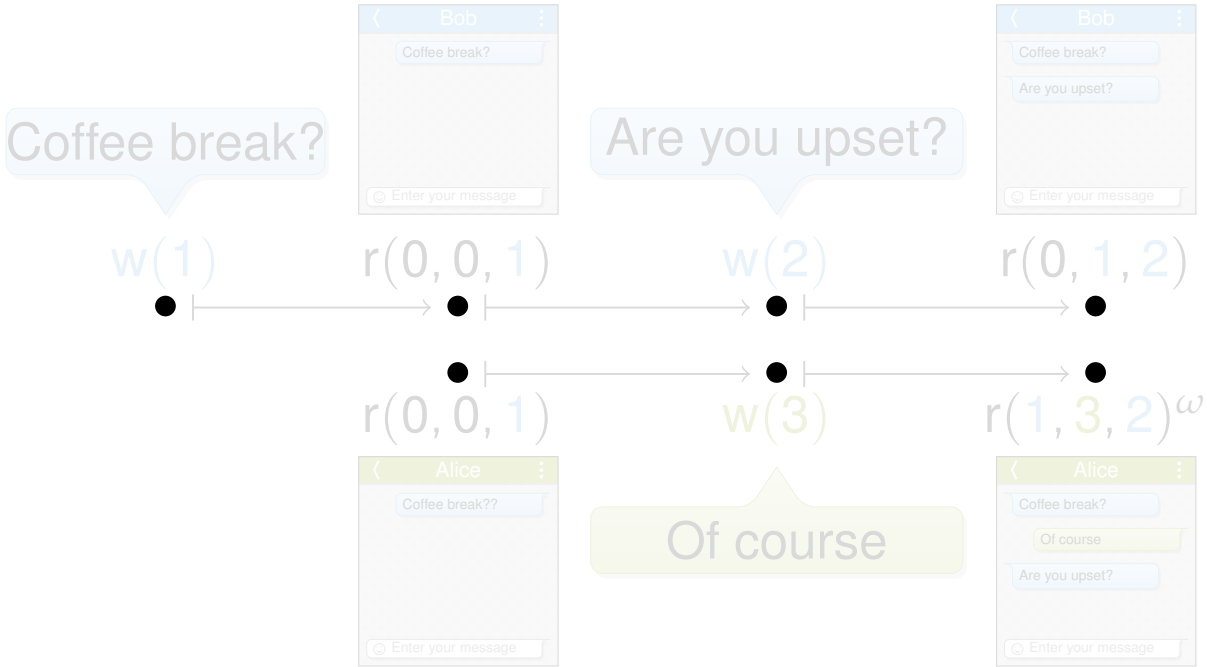
Sequential specification

- Set of path from the initial state
- Example : $\mathrm{w}(1) \cdot \mathrm{r}/(0,1) \cdot \mathrm{w}(0) \cdot \mathrm{r}/(1,0)^\omega$

1. Model – Concurrent history



Modelisation of an execution

- Events
- Operations
- Process order

General case

- Creation of threads at runtime
- Possibility of preemption

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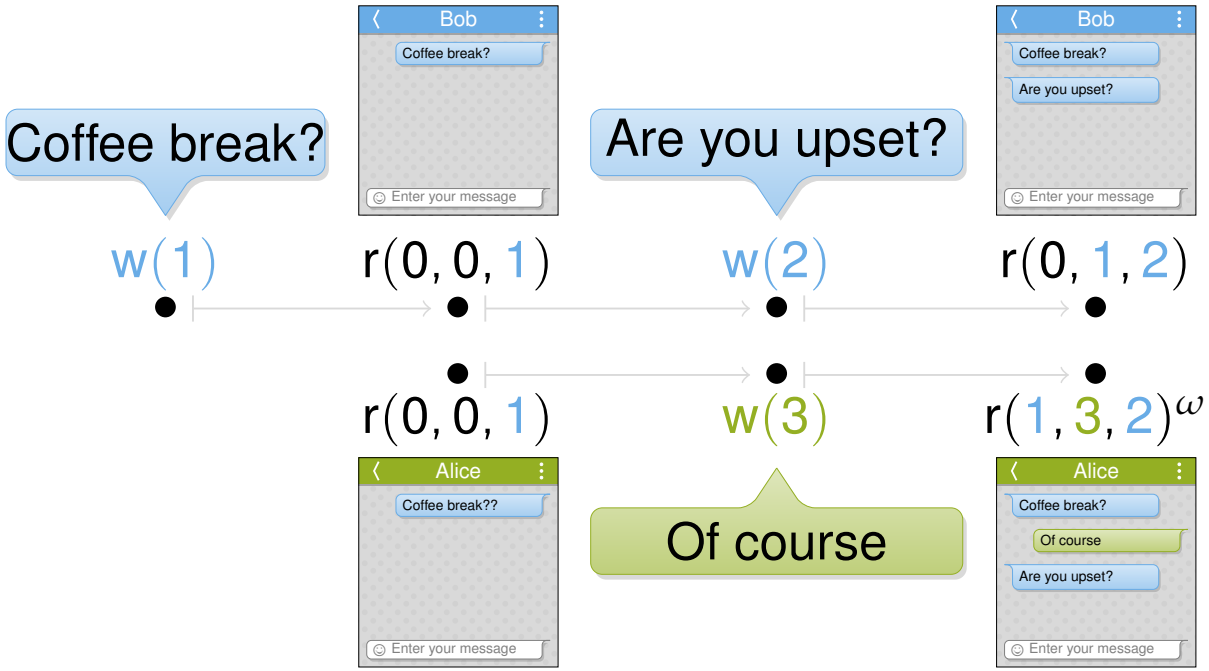

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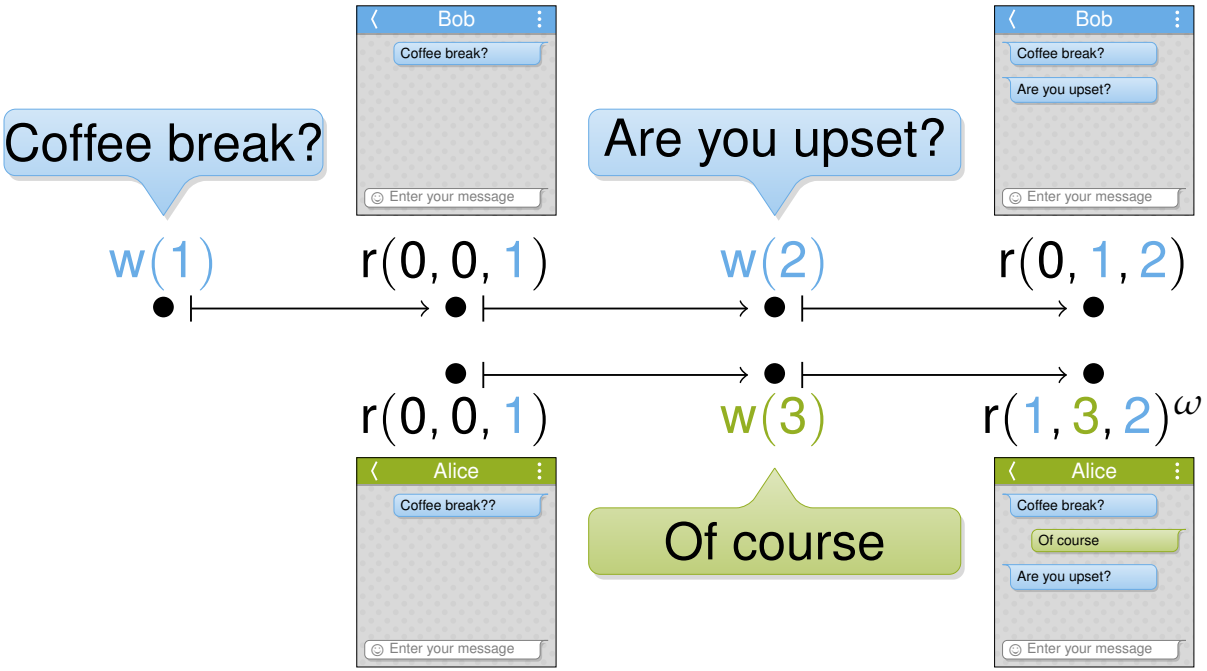

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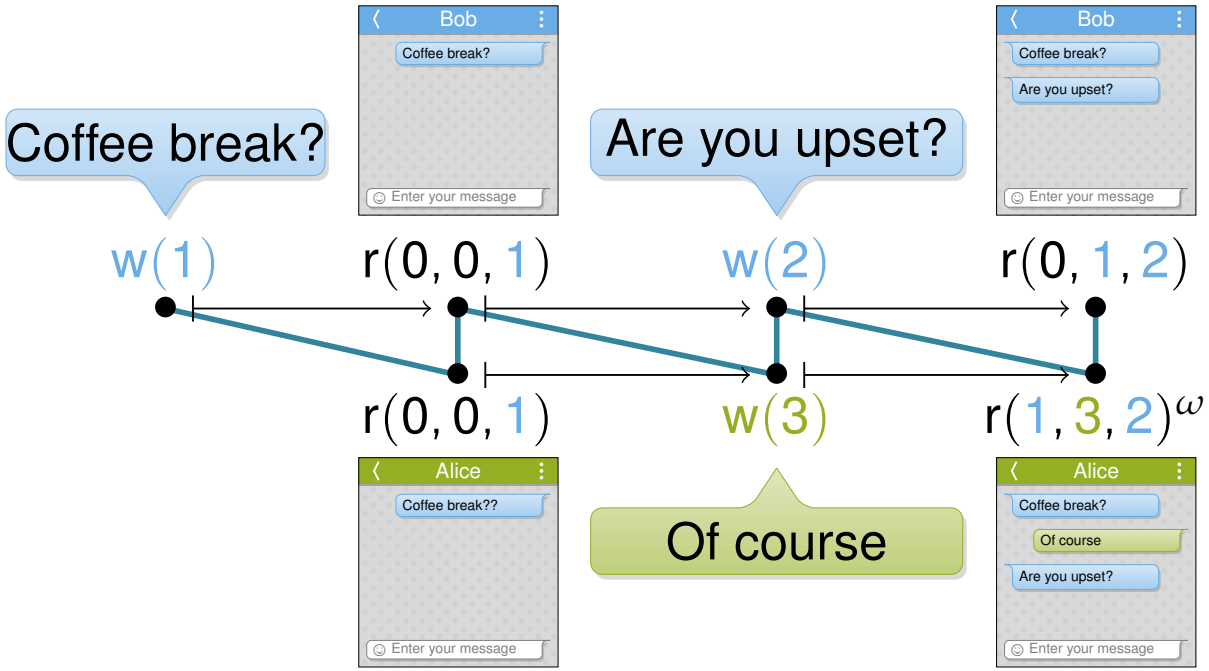


Linearization

- Sequence of operations
- Total order on the events
- Respects the process order

Définition

- C : ADT $\to$ set of concurrent histories

Lattice structure

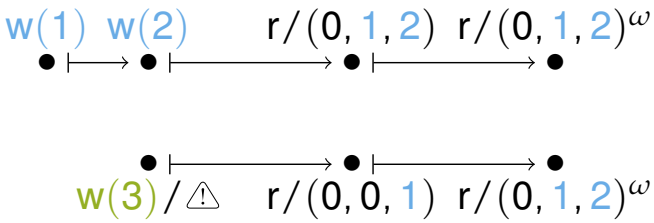
- C_1 stronger than C_2 $\qquad \forall T, C_1(T) \subset C_2(T)$
  - C_1 admits fewer histories than C_2
- Conjonction $\qquad (C_1 + C_2)(T) = C_1(T) \cap C_2(T)$
  - $C_1 + C_2$ stronger than C_1 and C_2

Example : sequential consistency

$H \in SC(T)$: there exists a linearization of H admitted by T

1. Model – Three messaging services

Hangouts



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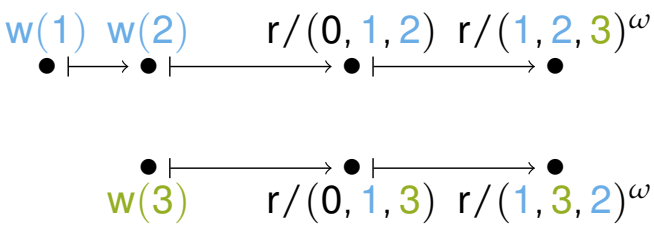

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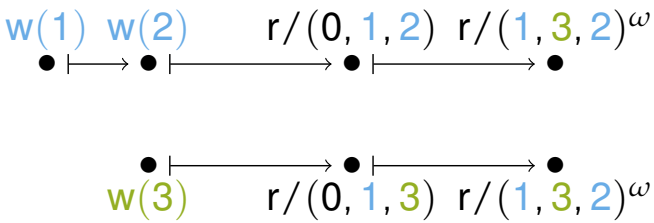

Serializability (Ser)[1]

- *Aborted* writes : error ⚠
- Other events in a linearization admitted by T

Pipelined consistency (PC)[2]

A linearization per process contains

- All the reads of H
- All the writes from the process

Eventual consistency (EC)[3]

- Eventually, all reads are done in the same state

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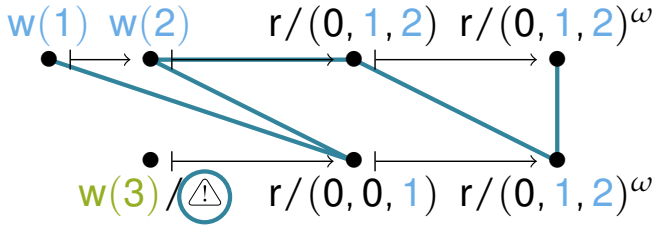

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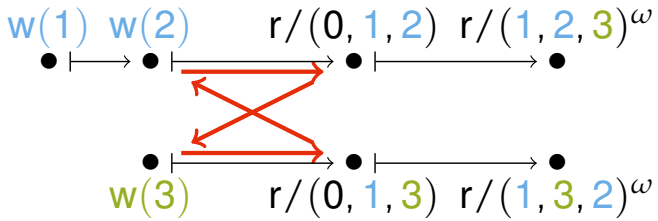

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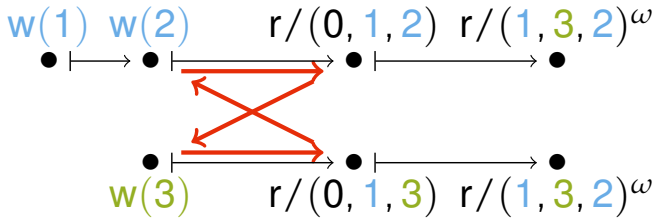

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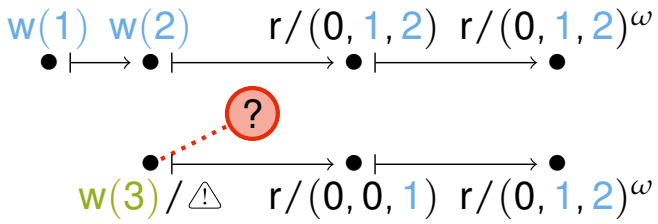

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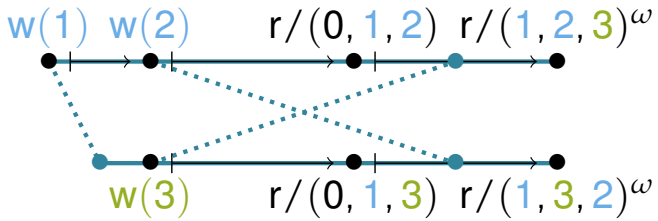

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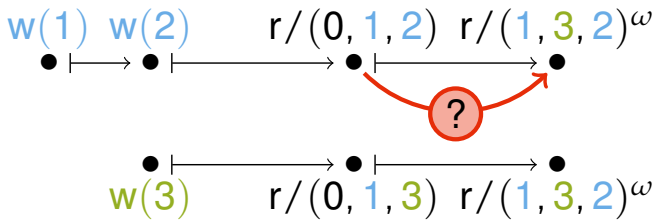

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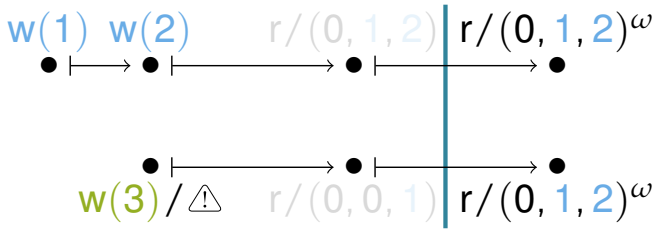

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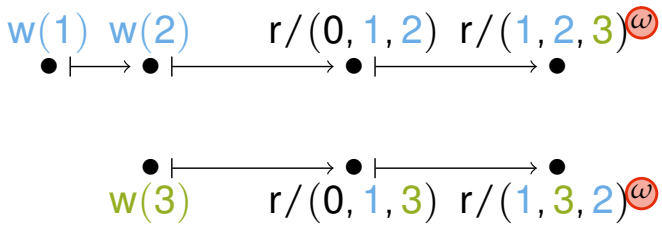

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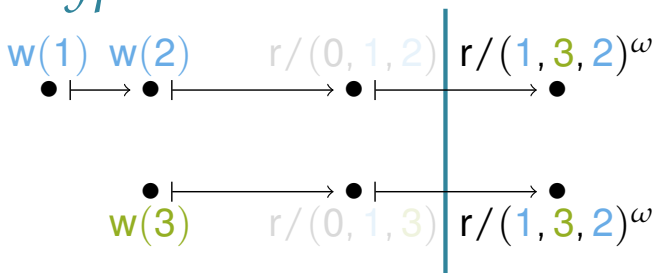

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- *Aborted* writes : error ⚠
- Other events in a linearization admitted by T

Pipelined consistency (*PC*)[2]

A linearization per process contains

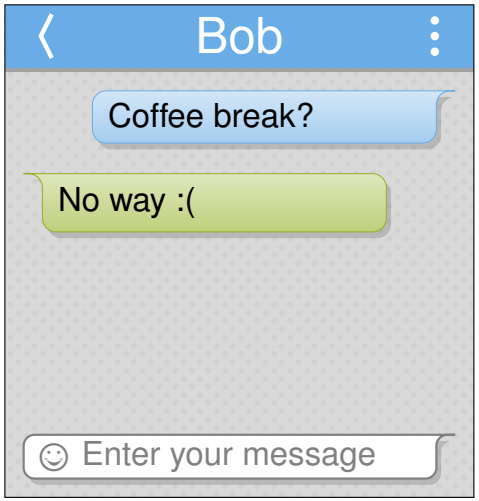
- All the reads of H
- All the writes from the process

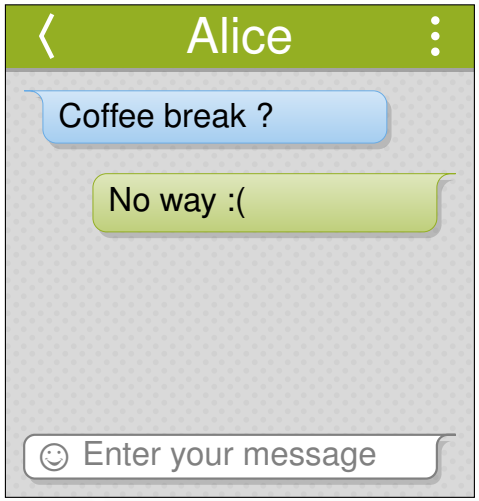
Eventual consistency (*EC*)[3]

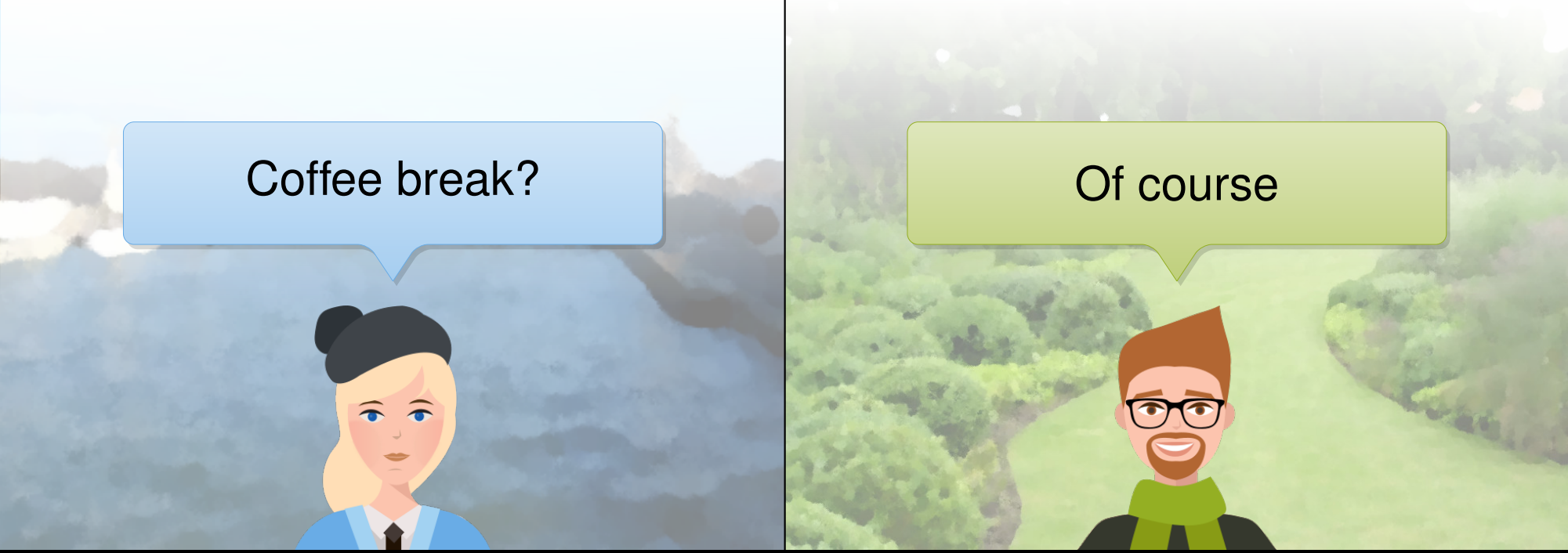
- Eventually, all reads are done in the same state

[1] Papadimitriou. *The serializability of concurrent database updates*. 1979
[2] Lipton, Sandberg. *PRAM: A Scalable Shared Memory.* 1988
[3] Vogels. *Eventually consistent*. 2009

2. Update consistency – Motivation







Strong eventual consistency[1]

EC :	eventually	$\Rightarrow$	same state
SEC :	same *visible* operations	$\Rightarrow$	same state

Concurrent specification[2]

$$\text{visible Operations} \to \text{State}$$

Limits

- No modularity in the specification
- Strong connexions with the computing model
- Restricted to a specific type of implementation

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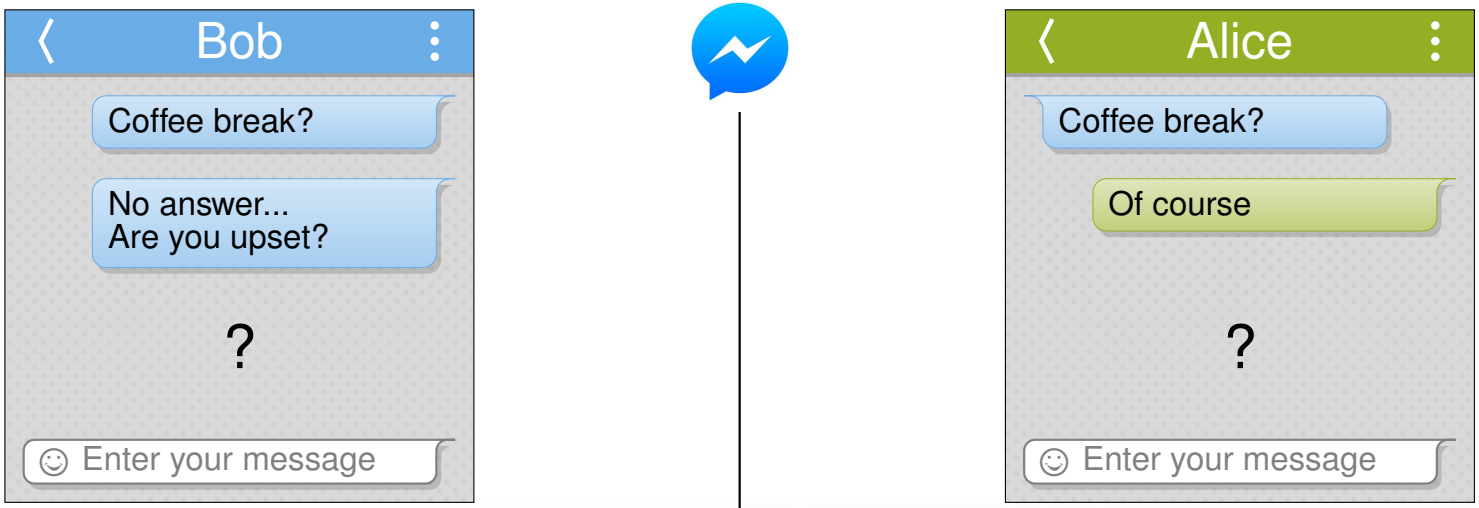

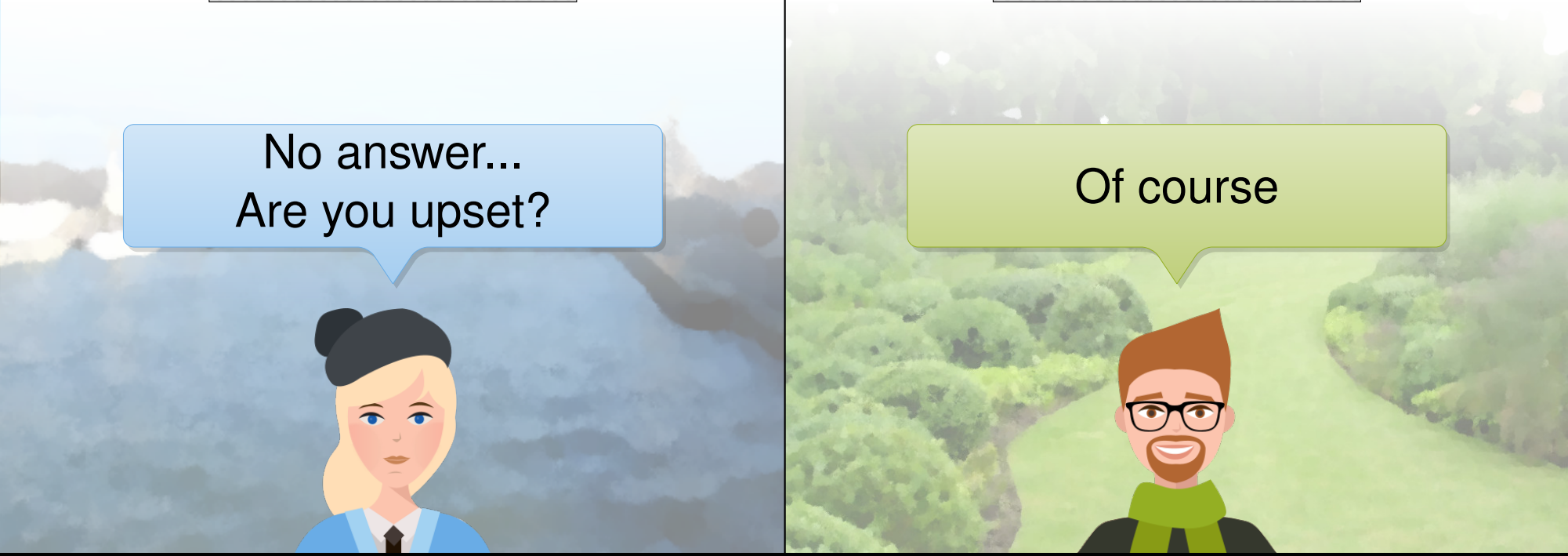

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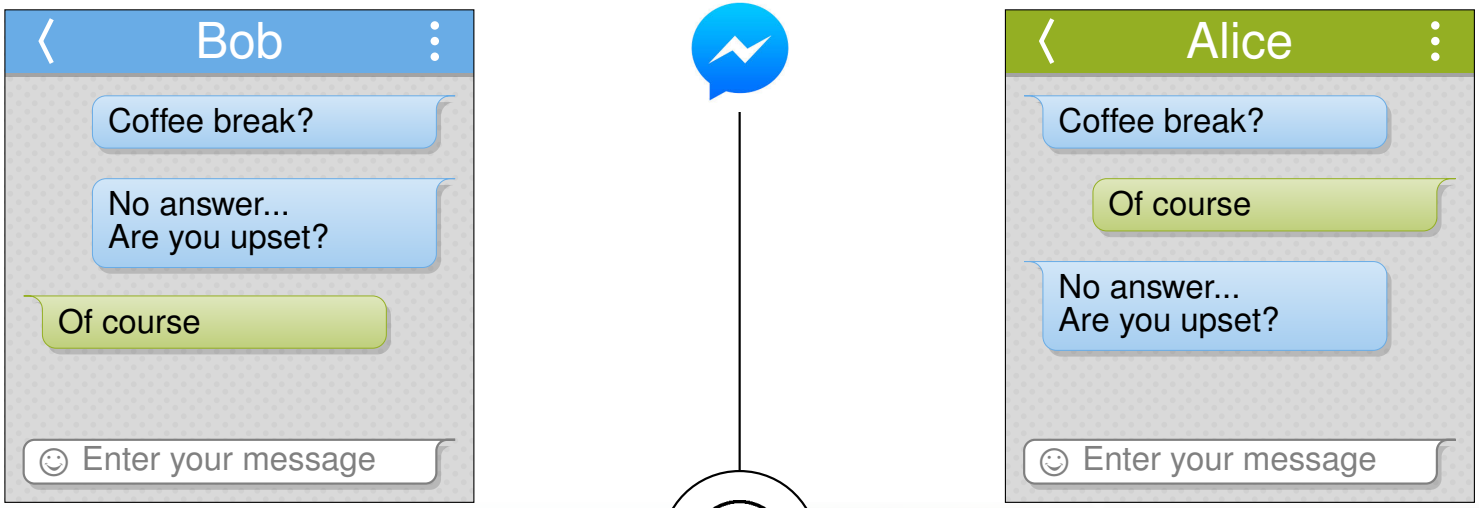

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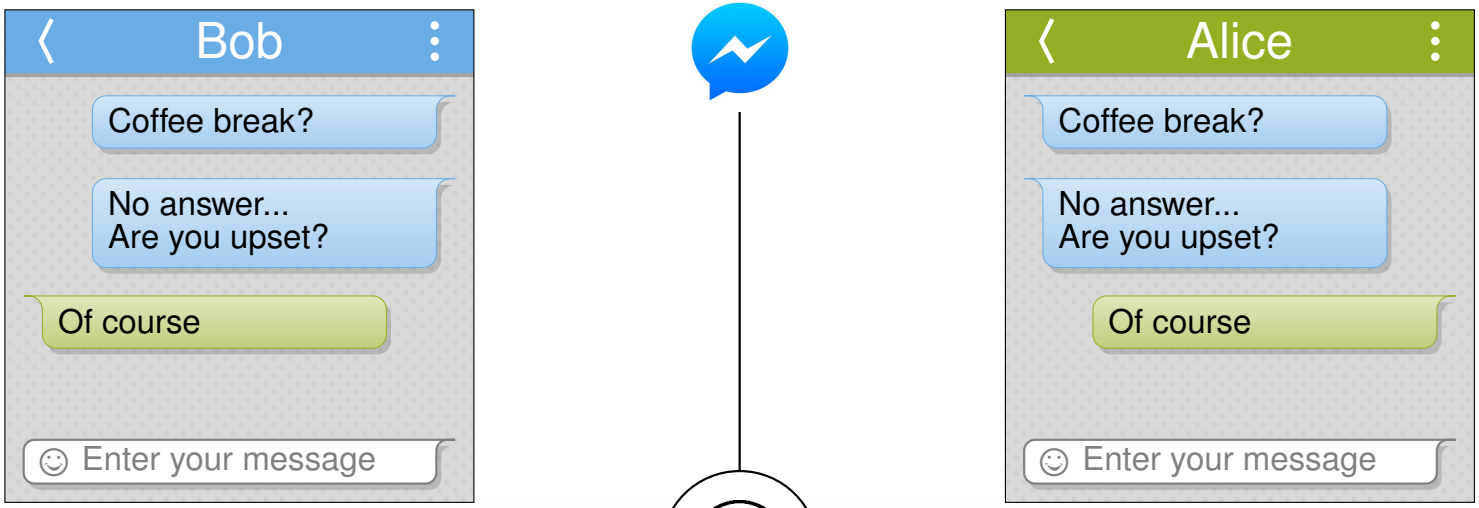

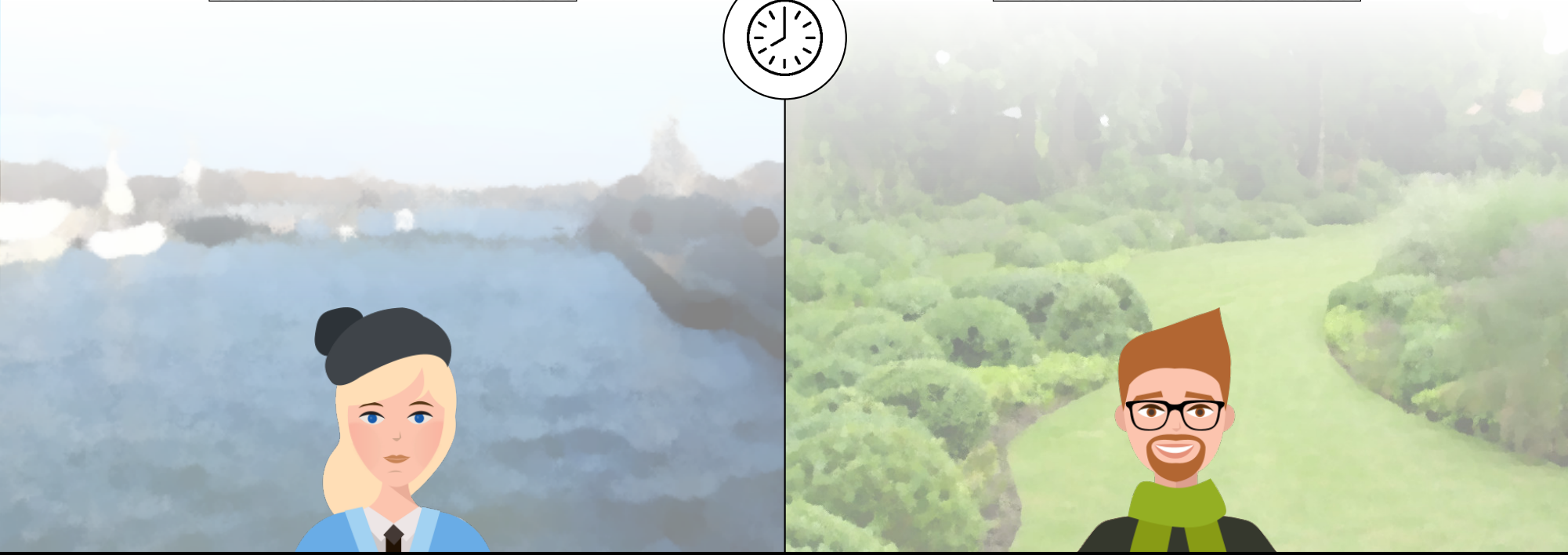

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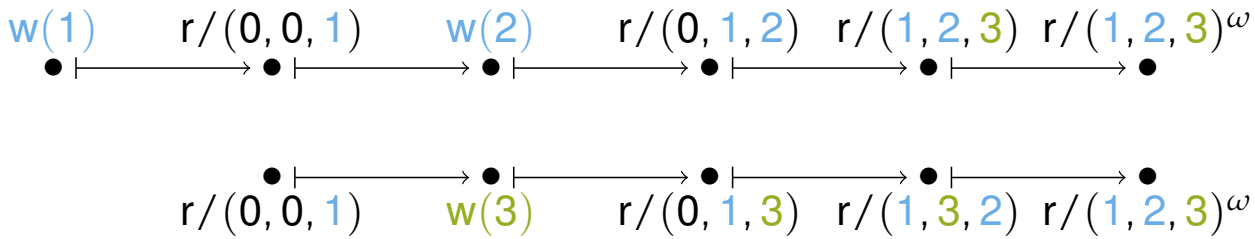

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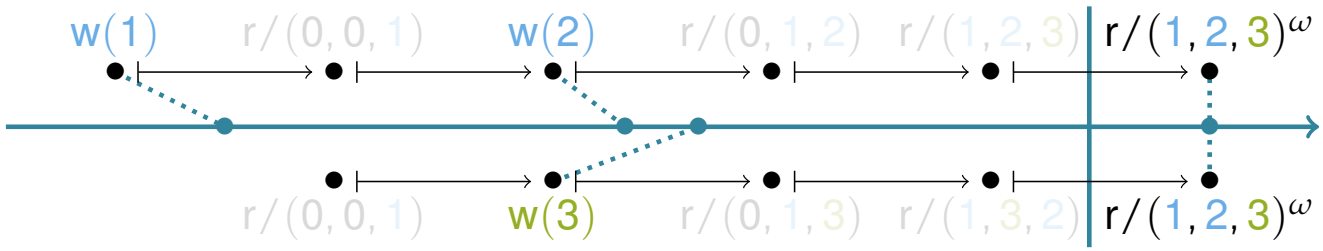

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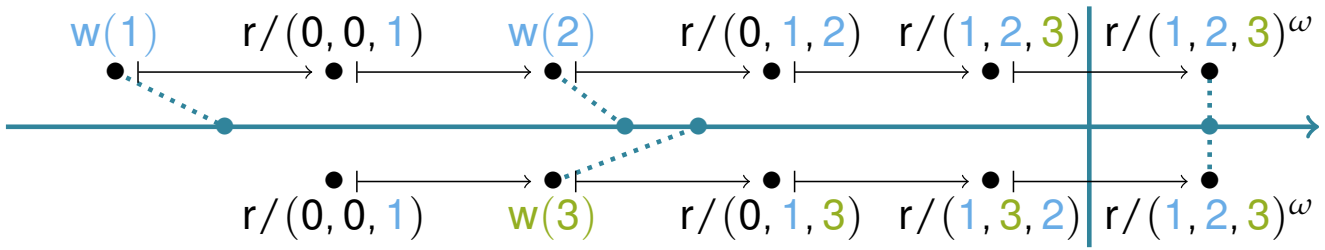

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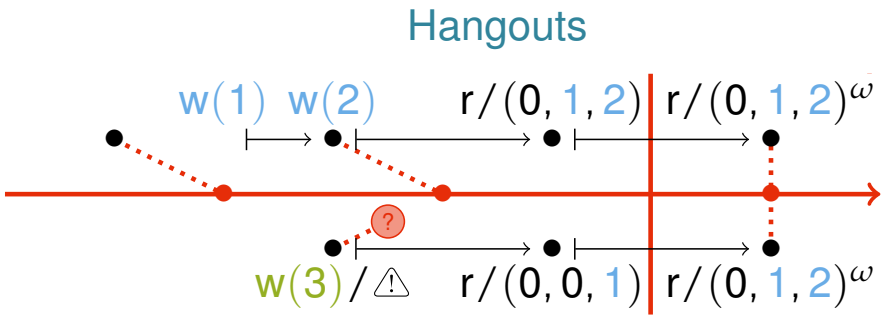

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Idea

- Build a total order *a priori*
- Write: send a message
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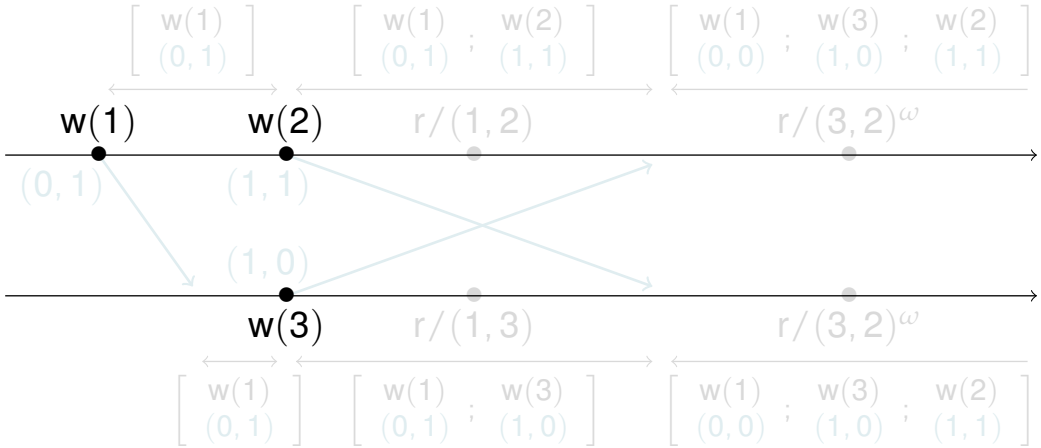
Example



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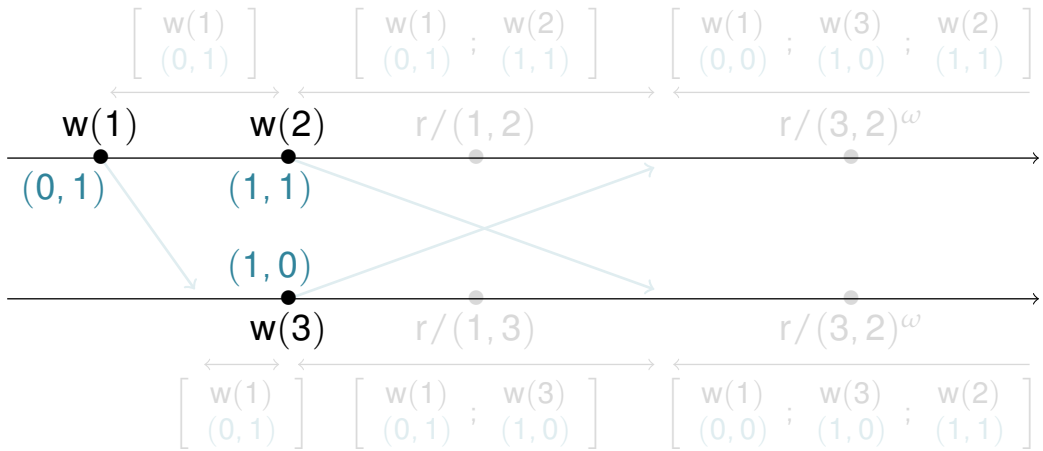

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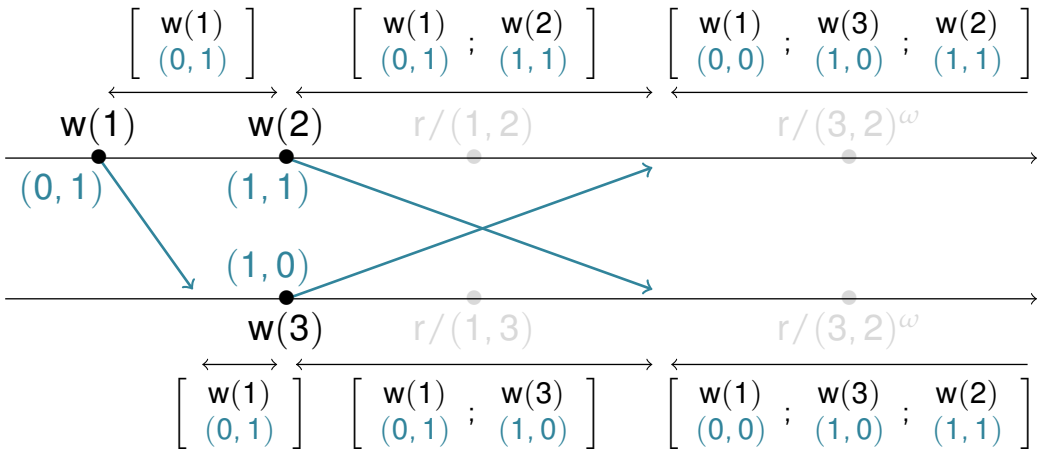

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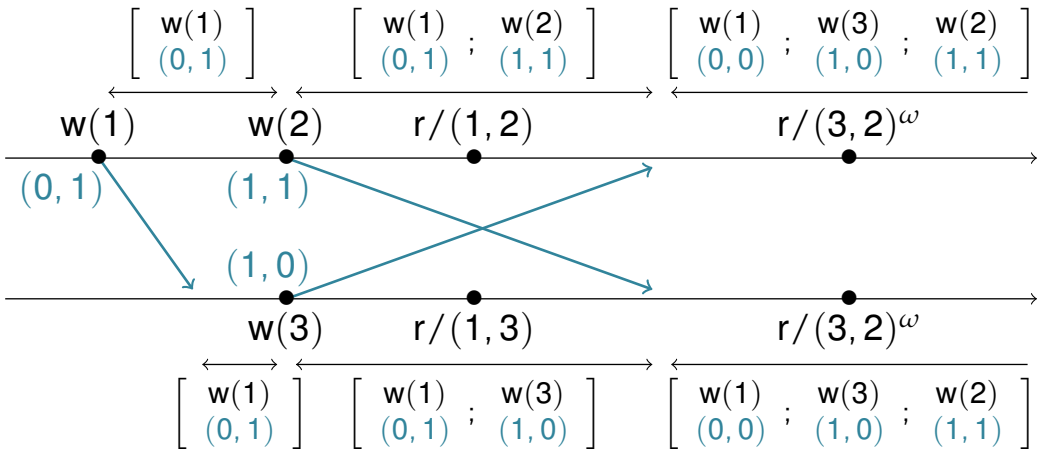

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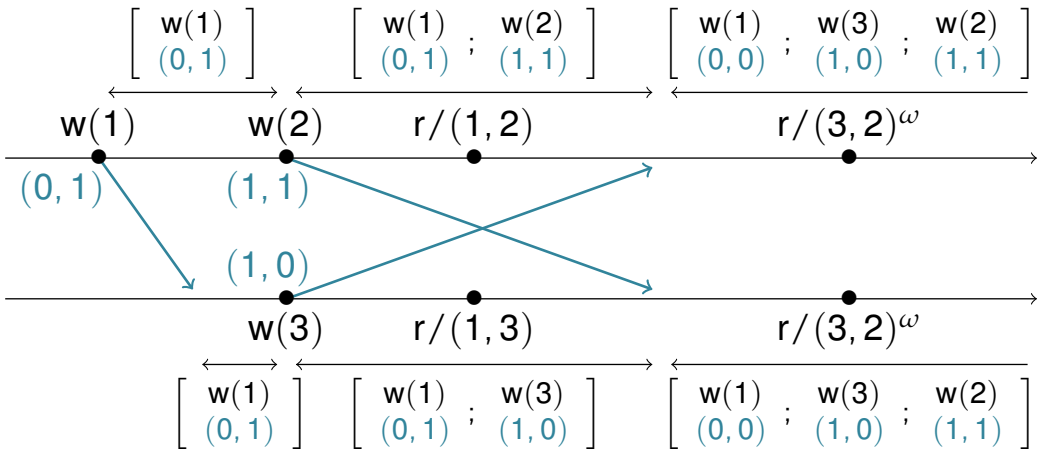

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Weak criterion

- Weaker than sequential consistency
- All objects have a wait-free implementation

Examples

- Sequential consistency
  - CAP theorem
- Update consistency
- Serializability
  - All writes abort
- Pipelined consistency
  - FIFO broadcast of a message and local execution

Primary criteria

Eventual consistency (EC)

- All processes reach a common state

Validity (V)

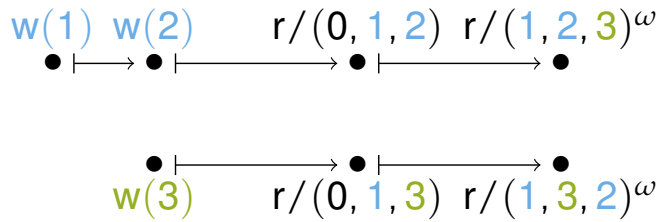
- Each process reaches a state that reflects all the writes

State locality (SL)

- A change of state corresponds to the execution of a write

Complementary criteria

Pipelined consistency (PC)



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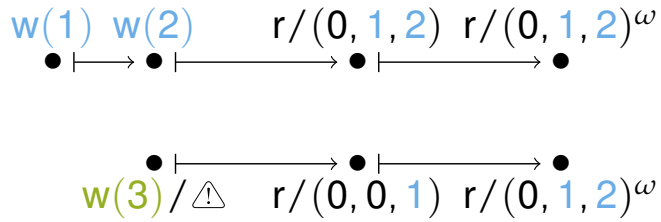
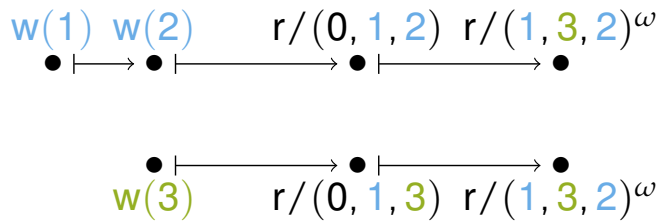


Update consistency (UC)



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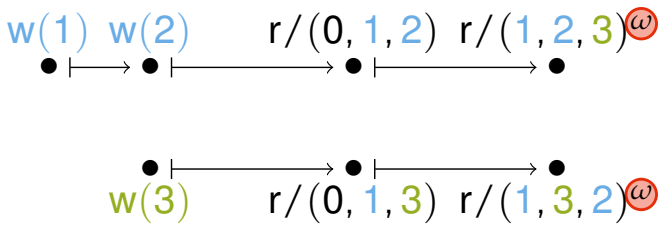

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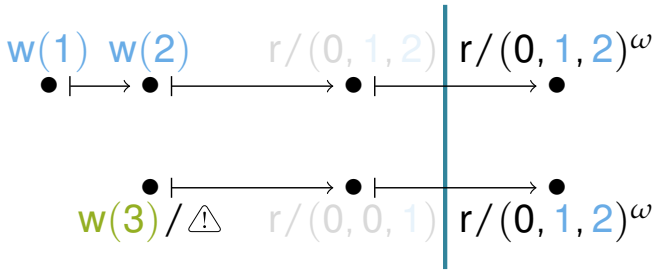

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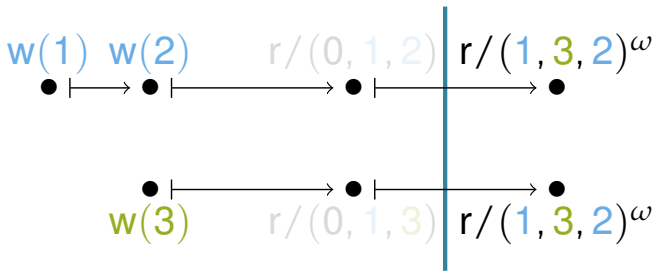

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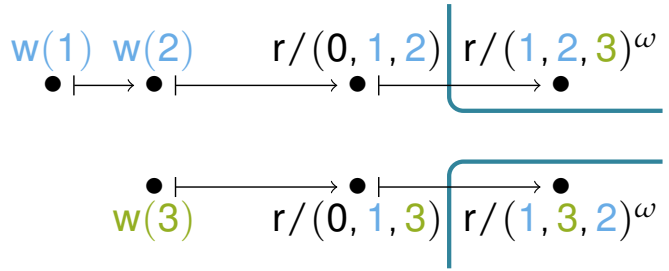

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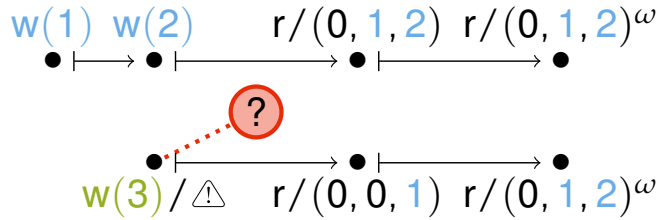

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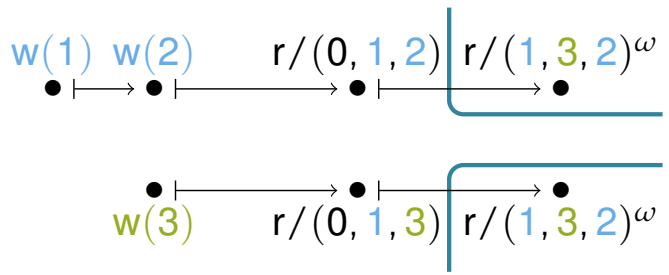

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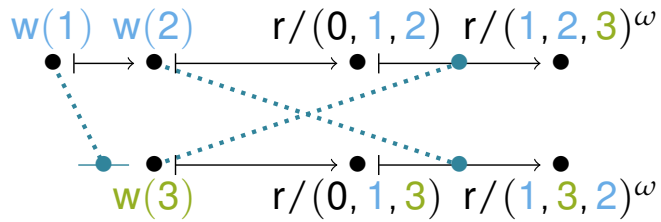

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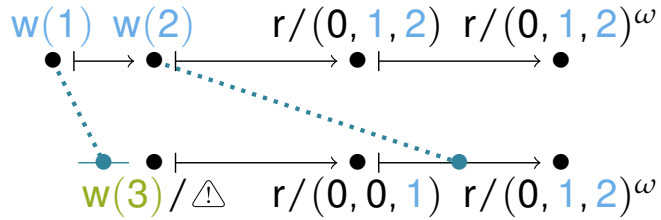

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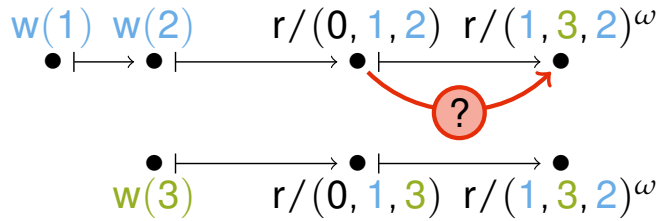

3. Calculability – $EC + V + SL$

Proposition

- $EC + V + SL$ is a strong criterion

Proof

- ($EC + V + SL$)-consistent window stream
- Consensus

Consensus

Termination : each correct process returns a value
- State locality

Agreement : all returned values are the same
- Eventual consistency

Validité : all returned values have been proposed
- Validity

Impossible to implément Consensus in wait-free systems[1]

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Primary criteria

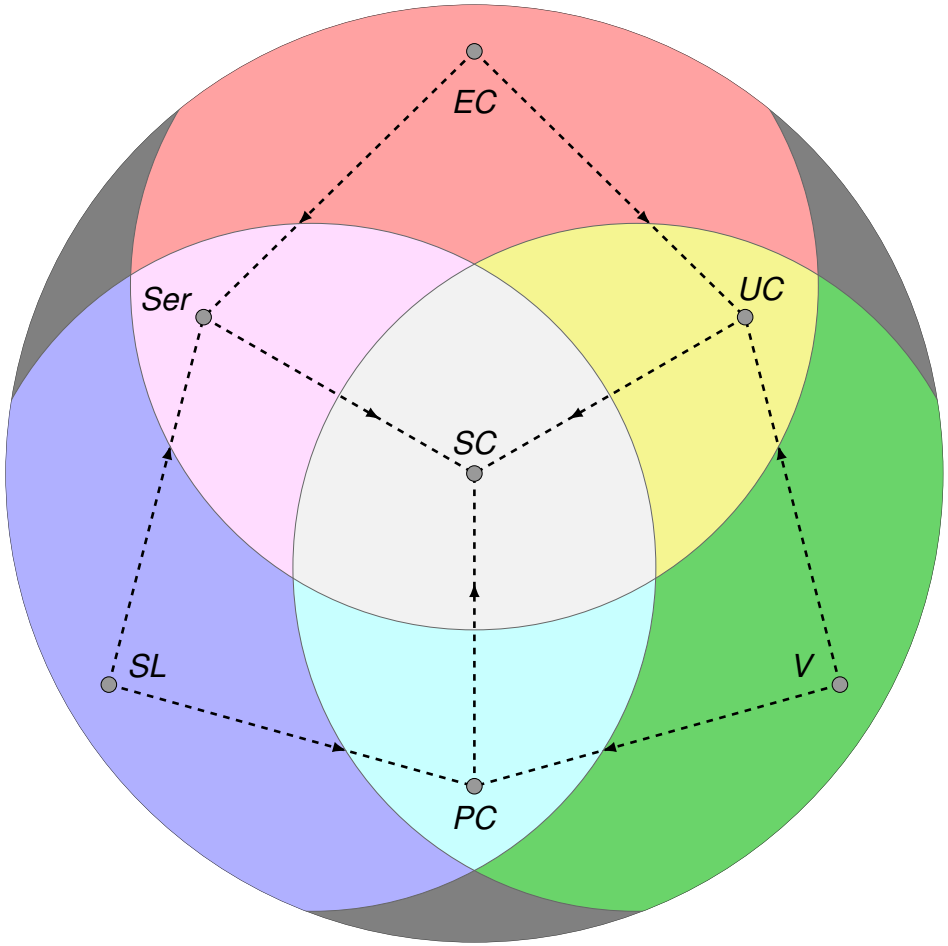
- State locality
- Eventual consistency
- Validity

Secondary criteria

- Update consistency
- Pipelined consistency
- Serializability

Conjonction of complementary criteria

- Strong consistency



3. Calculability – Which one shall you use?

Serializability → substitute to strong consistency

- Maximal security
- Easy to implement in client-server models
- The user take care of the faults

Update consistency → collaborative applications, data

- Close to autostabilization
- More expensive
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Pipelined consistency → parallel algorithms

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I am in New-York all the week
Enter your message
Alice, Carole
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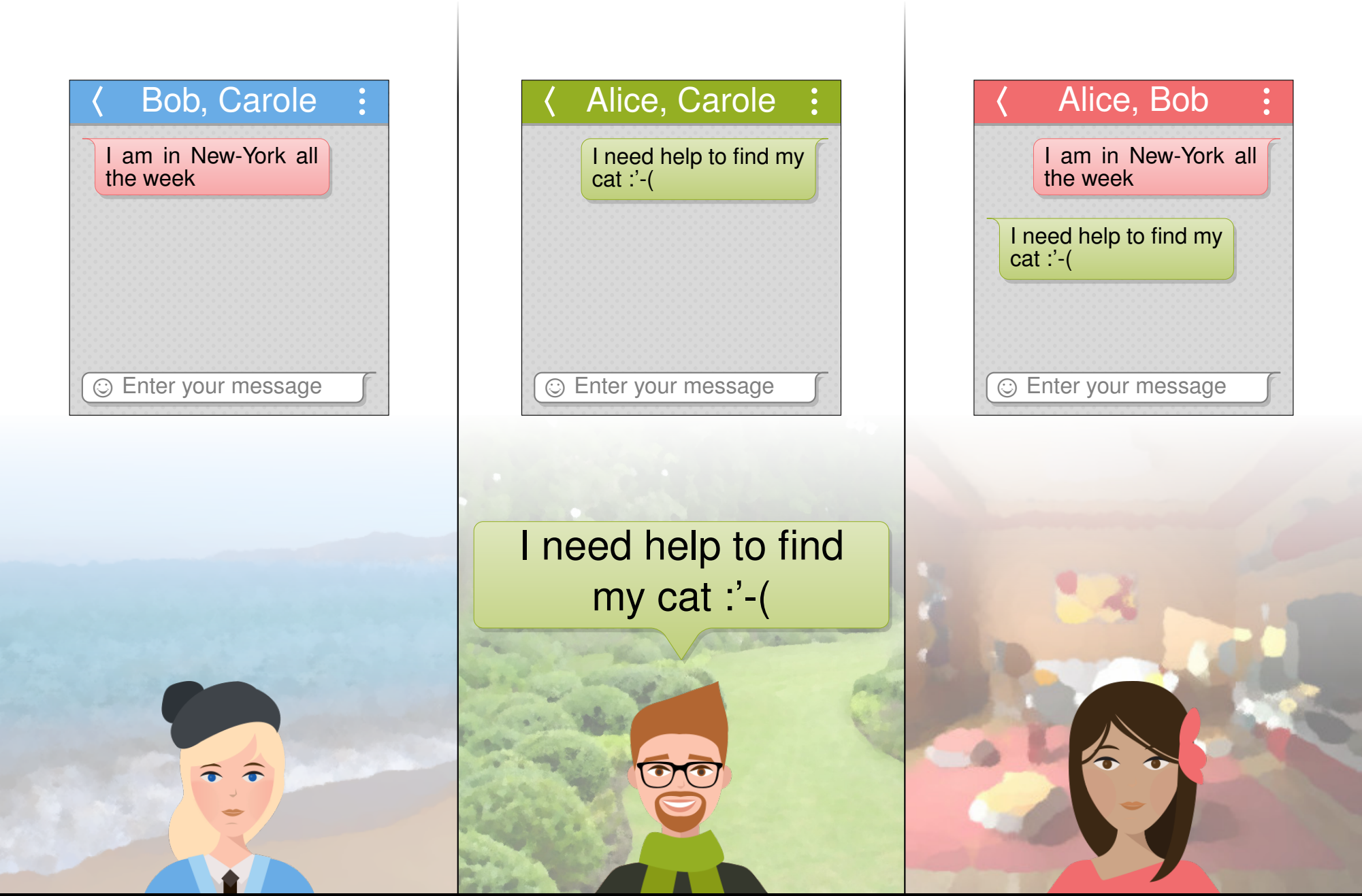
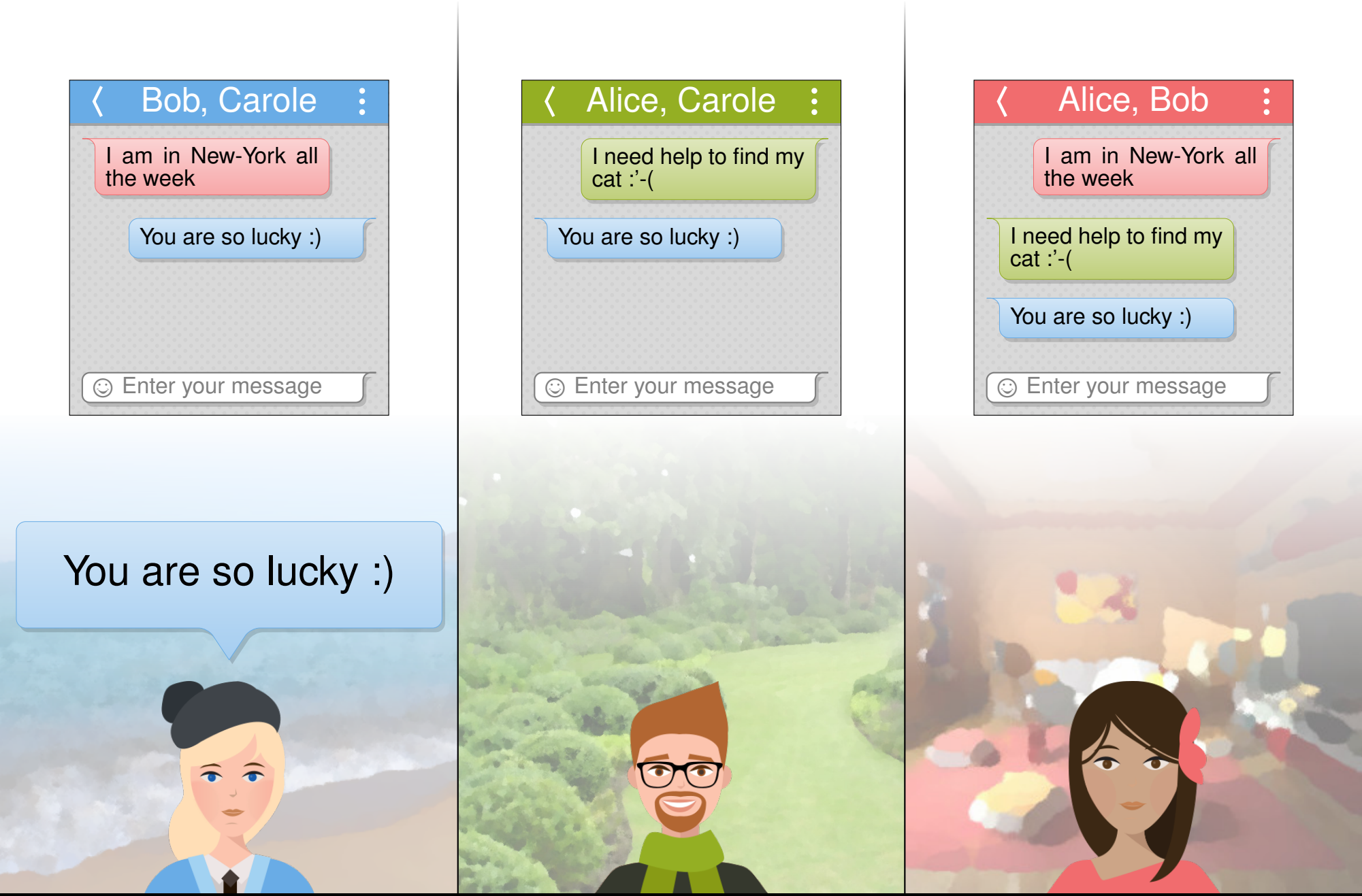
4. Causality – Motivation

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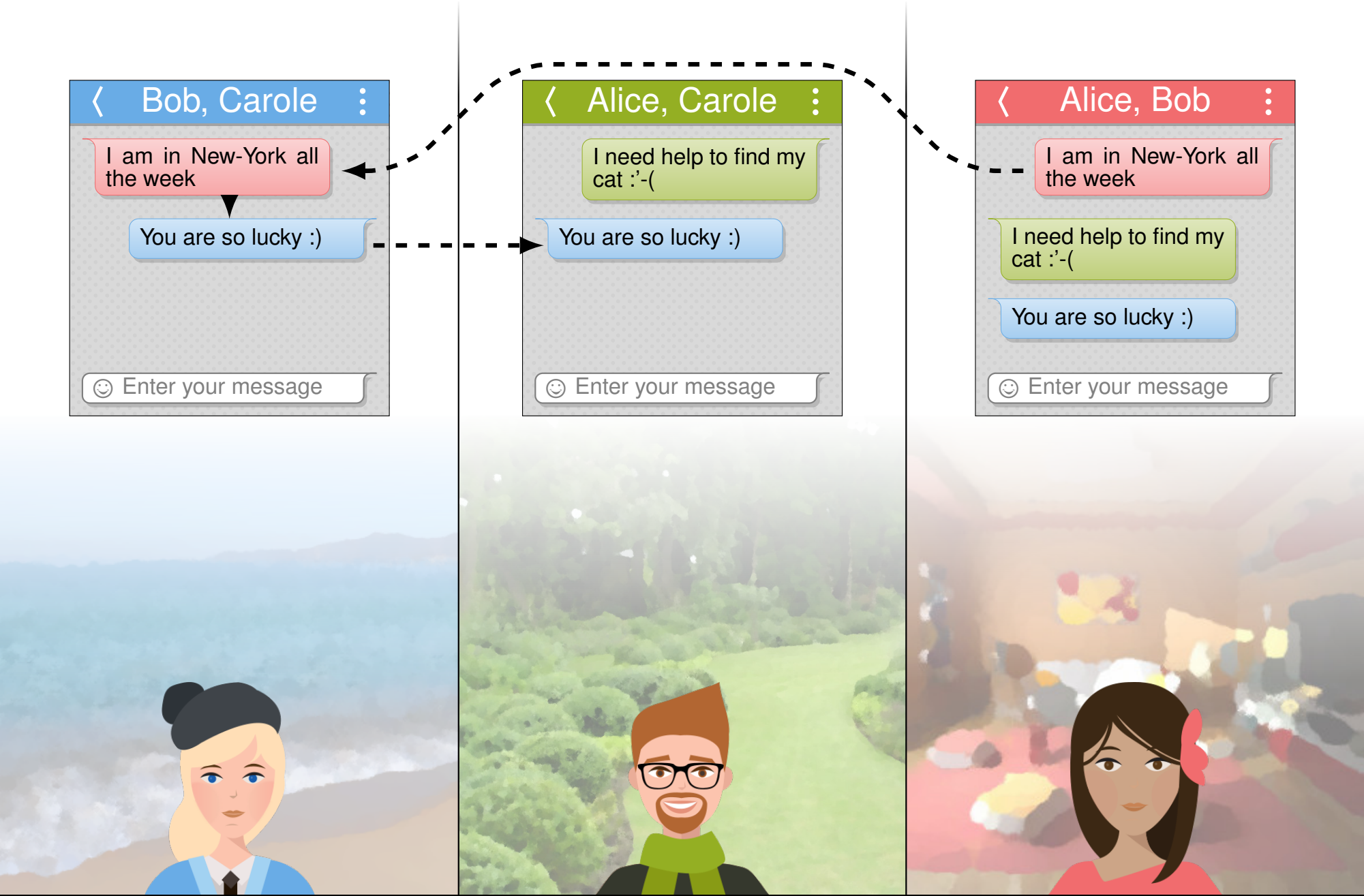
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4. Causality – Causal memory[1]

Read-from relation

- Relation $\mathrm{w}_x(n) \multimap \mathrm{r}_x/n$
- At most one predecessor per read
- reads without predecessor retourn 0

$\rightarrow$ semantic dependances

Causal memory

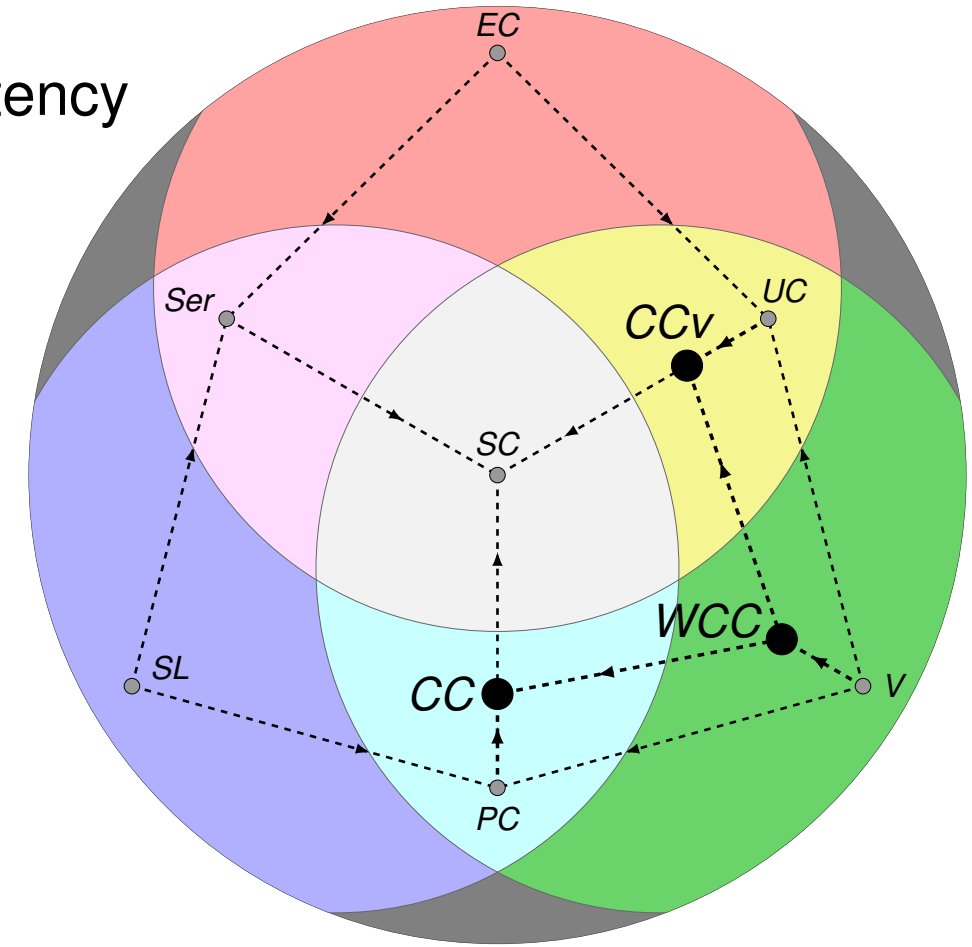
There exists $\multimap$ such that

- there is a partial order $\rightarrow$ that contains $\multimap$ and $\mapsto$
- the linearizations of PRAM respect $\rightarrow$

[1] Ahamad *et. al. Causal Memory: Definition, Implementation and Programming.* DISC 1995

Three new criteria

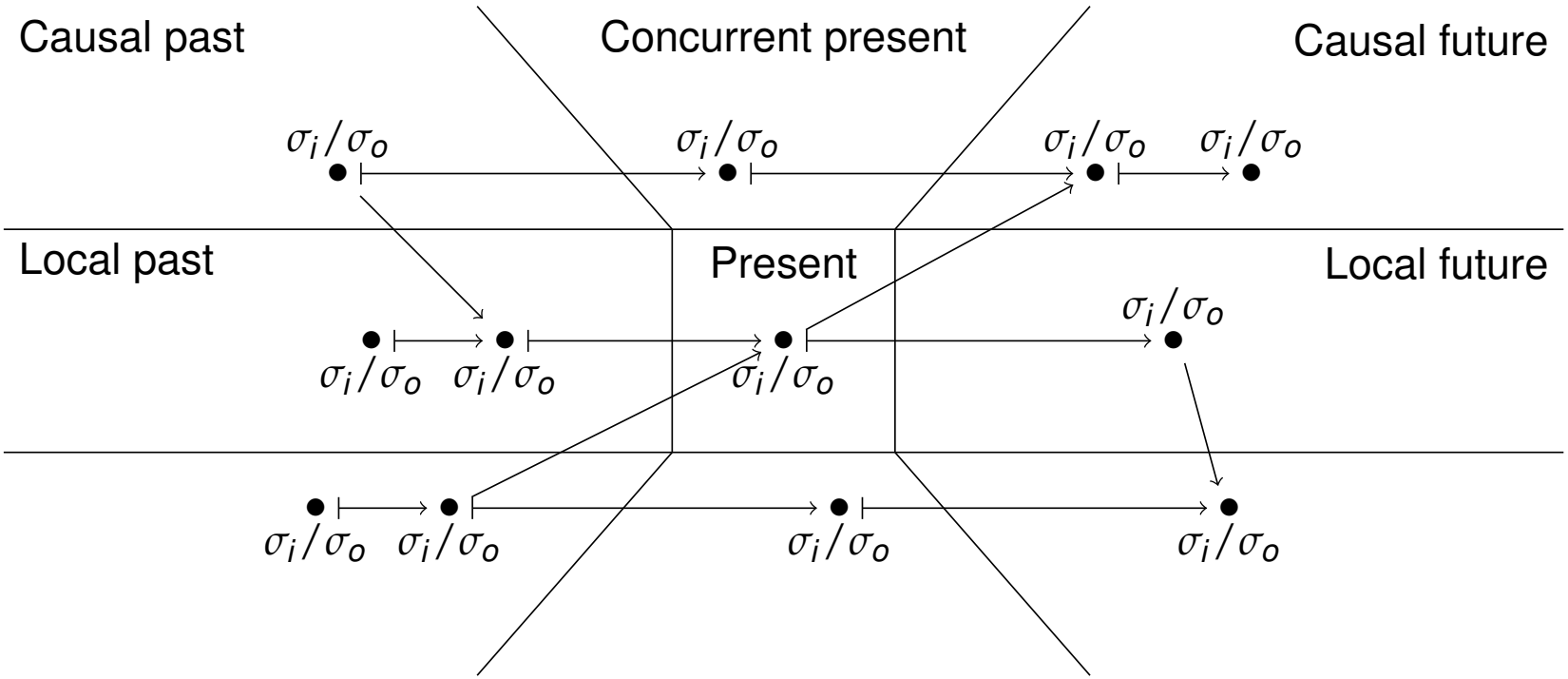
- Causal consistency
  - $CC \geq PC$
- Weak causal consistency
  - $WCC \geq V$
- Causal convergence
  - $CCv \geq UC$



Causal order

- Partial order on the events
- Contains the process order

6 temporal zones per event



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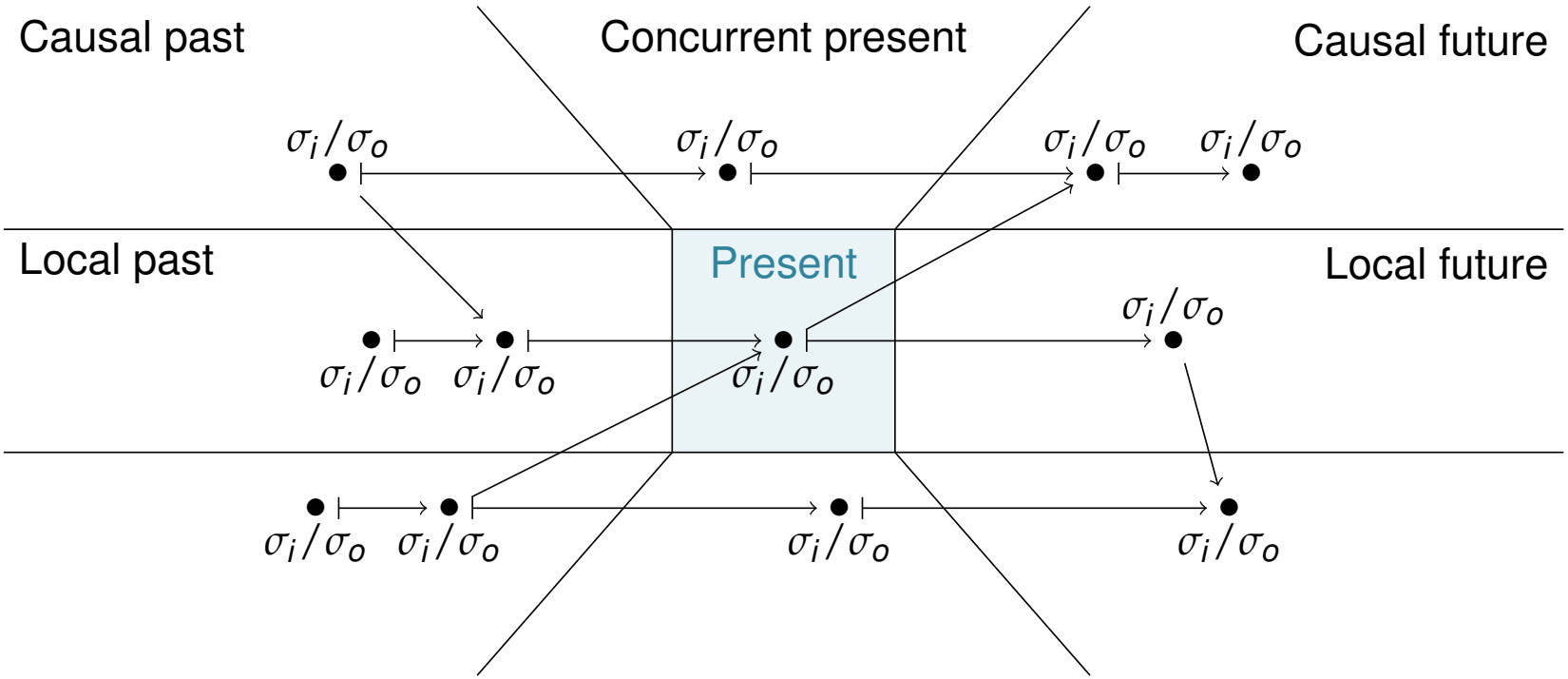

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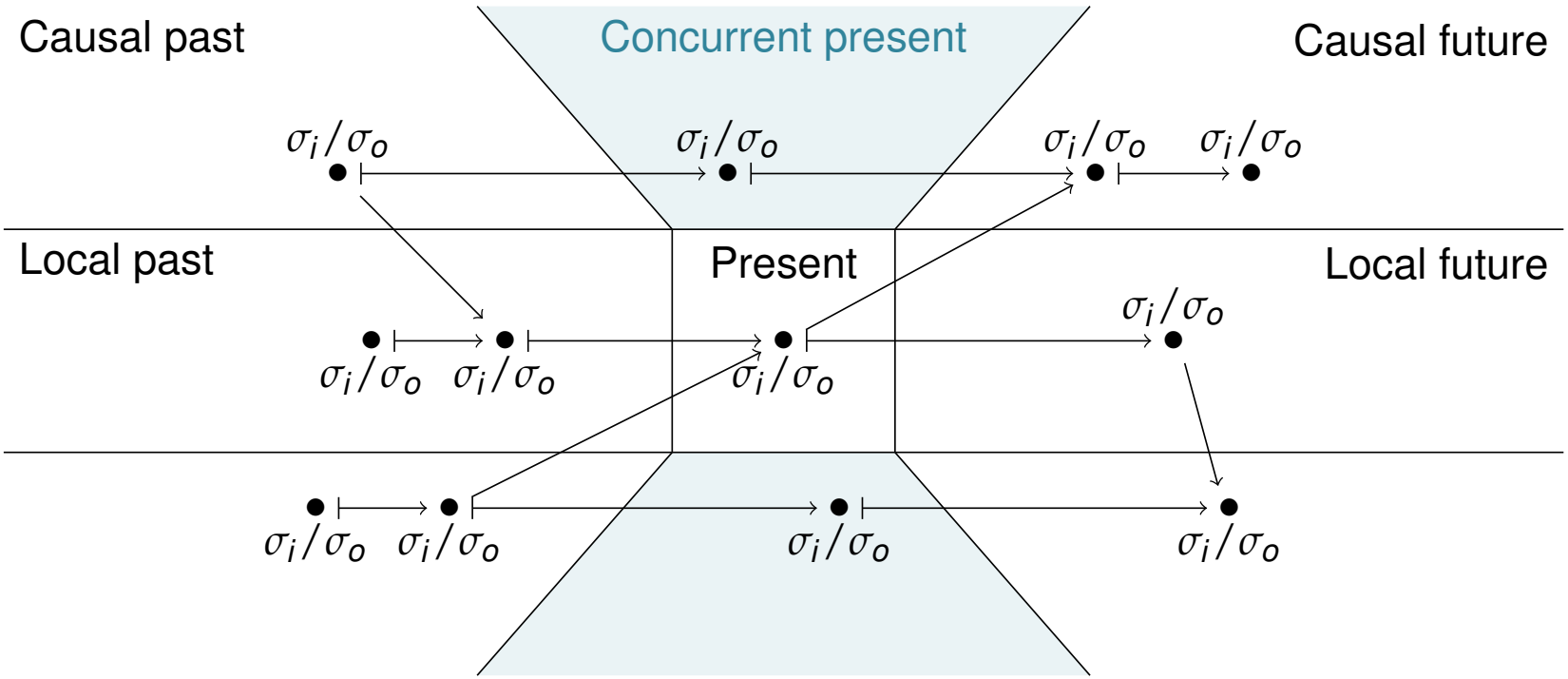
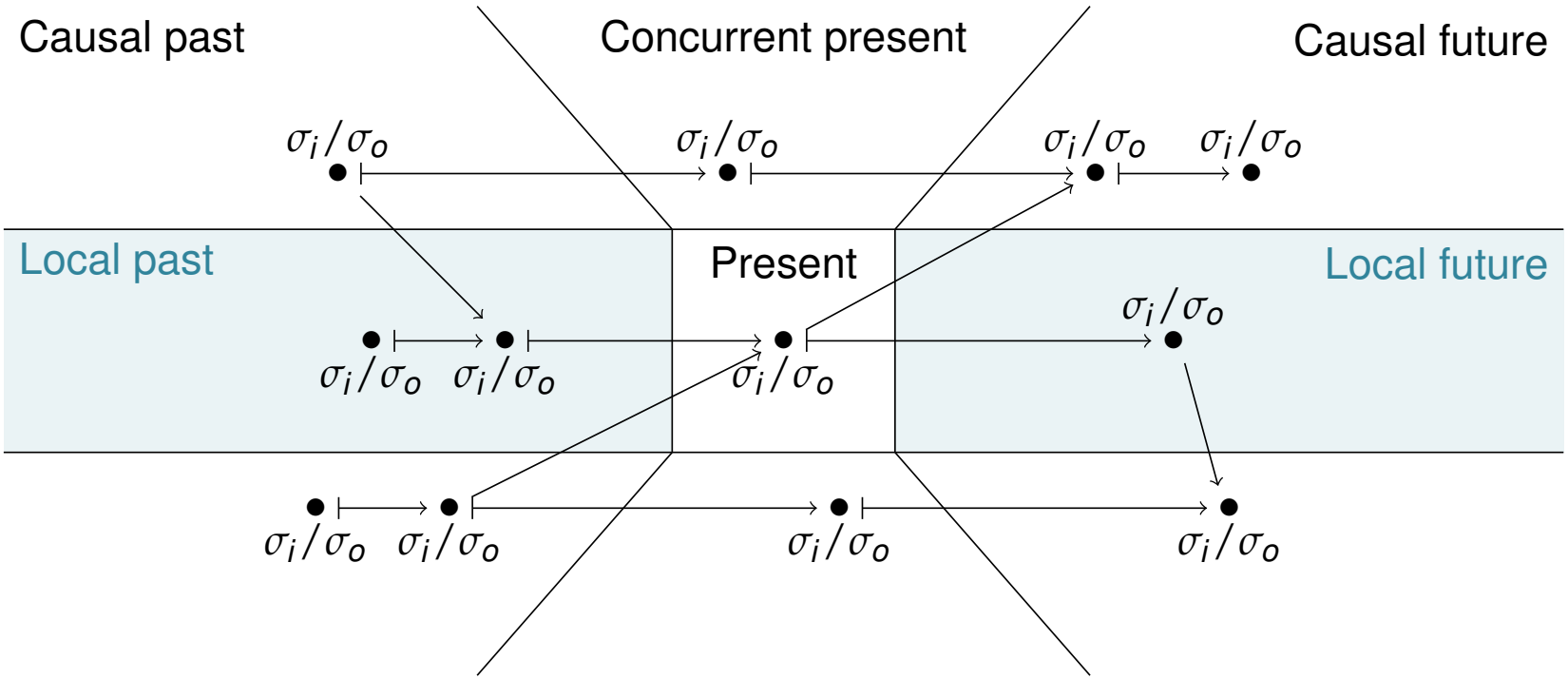


Causal order

- Partial order on the events
- Contains the process order

6 temporal zones per event



Causal order

- Partial order on the events
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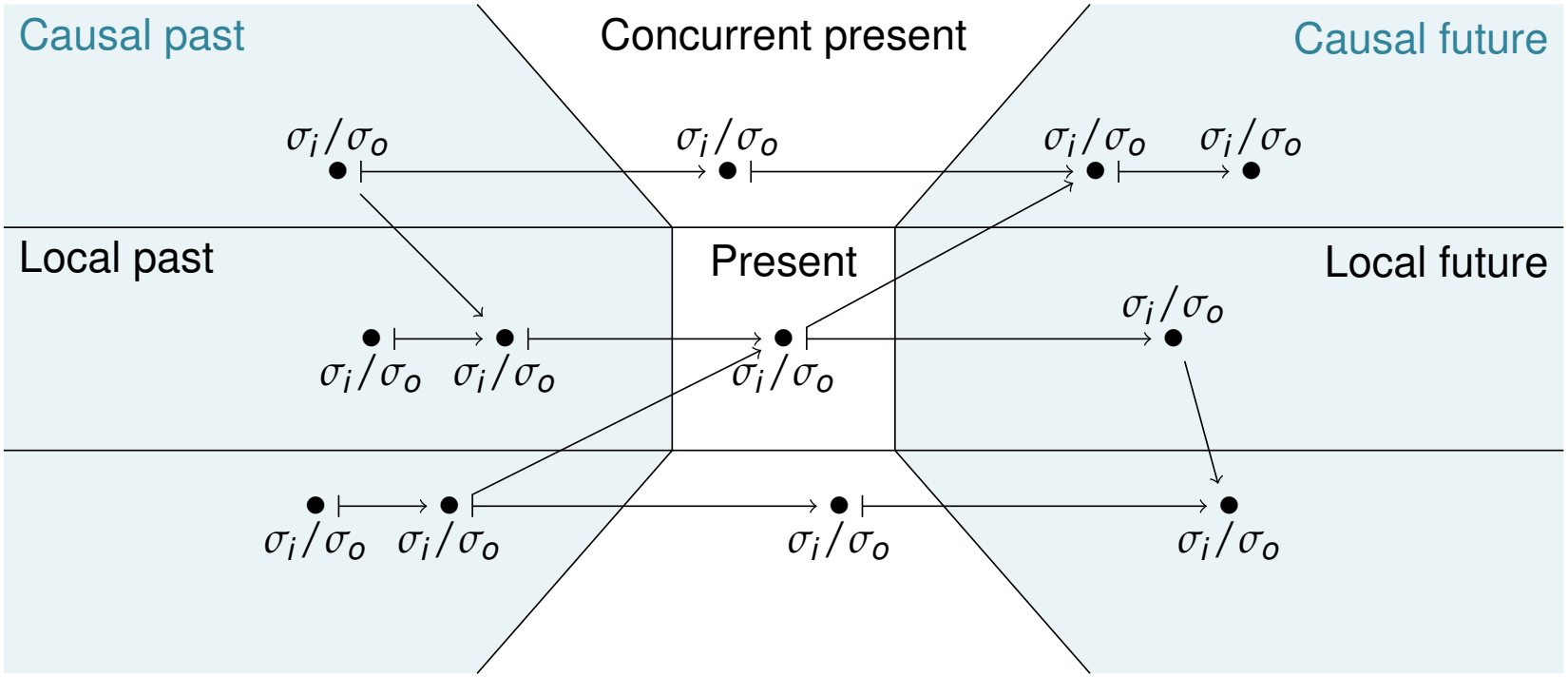
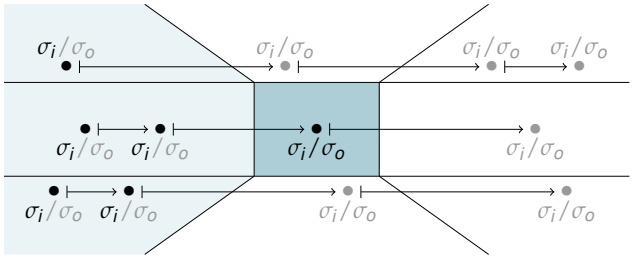


Weak causal consistency

There exists :

- A causal order
- A linearization per event
  - that respects the causal order
  - that contains the present
  - that contains the writes of the causal past
  - admitted by the sequential specification



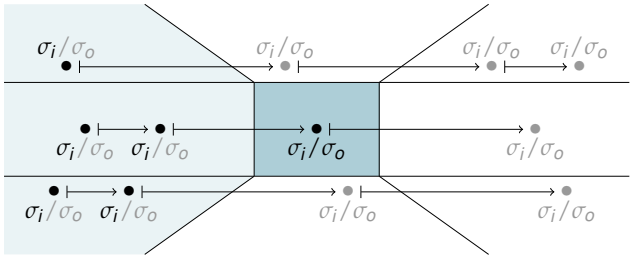
Causal consistency

- The linearizations contain the local past

Weak causal consistency

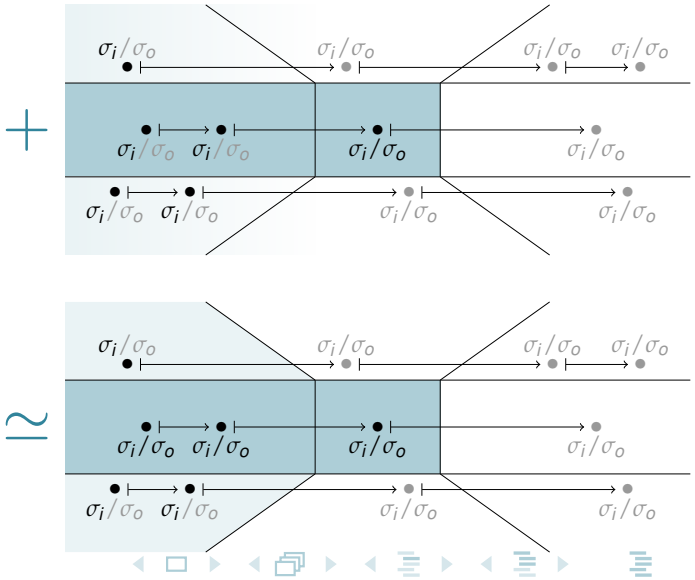
There exists :

- A causal order
- A linearization per event
  - that respects the causal order
  - that contains the present
  - that contains the writes of the causal past
  - admitted by the sequential specification



Causal consistency

- The linearizations contain the local past



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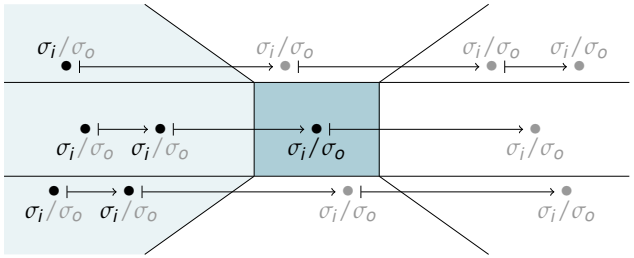
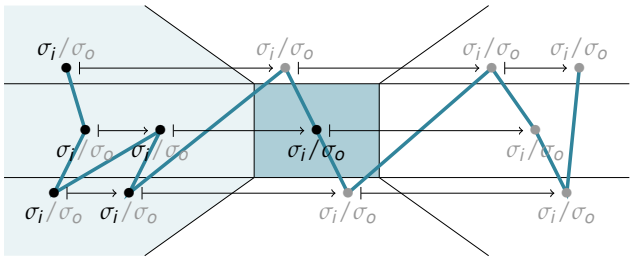
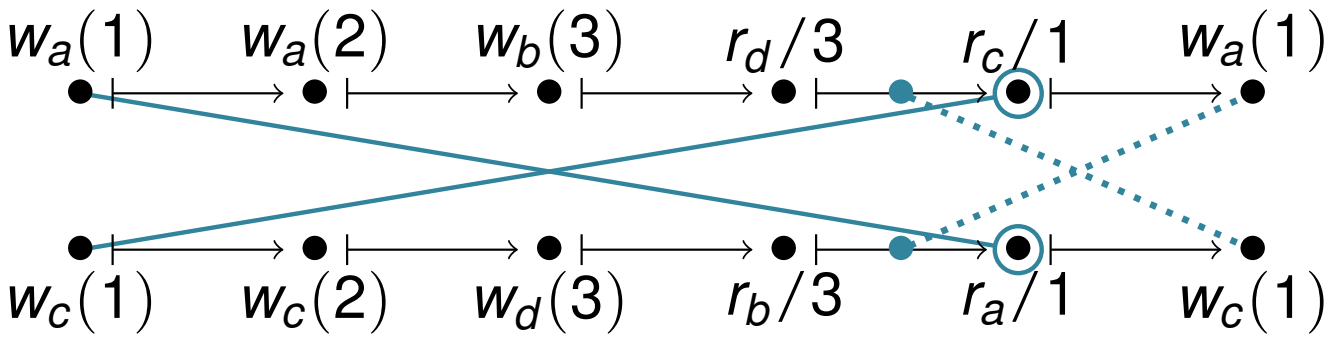


Causal convergence

- The linearizations respect a common total order



Causal memory ✓ Causal consistency X



Proposition

- H causally consistent for memory
- H admitted by causal memory

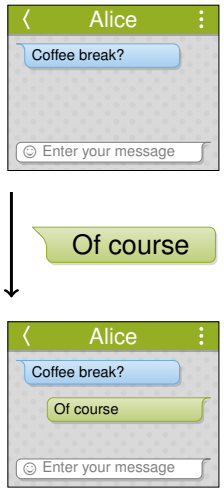
Converse

- All the writes of H are different [1]
- H admitted by causal memory
- H causally consistent for memory

[1] Misra. *Axioms for Memory Access in Asynchronous Hardware Systems.* TOPLAS 1986

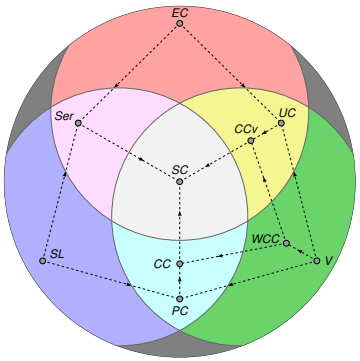
Conclusion – Proposition

Sequential specification




```
class Messenger {
   string[] received;
   void send(string message) {
     received.length ++ ;
     received[received.length - 1] = message ;
   }
}
```

Consistency criterion




```
void main () {
   Messenger m = UC.connect!Messenger("AliceBob");
         ⋮
}
```

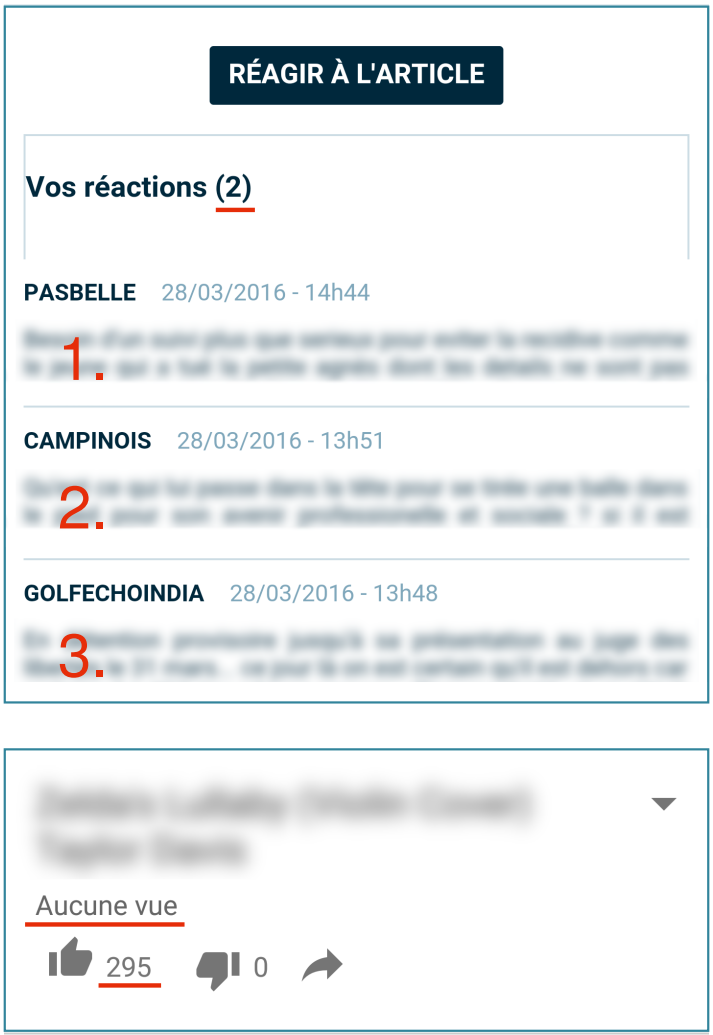
Calculability

- Identification of objects impossible to implement
- Generic implementations

Future work

- Implementations adapted to the objects
  - Study the complexity
- Generation of optimal code
  - In the framework of CODS
- Get closer to strong consistency in practice
  - Quantitative metrics for consistency

Conclusion – Programs composed of several objects



Composability

- Very rare property

Future work

- Composition of objects
- Composition de criteria
- Integrity constraints[1]
  - Connexion with data bases

[1] Maussion. *Update Consistency for Data Integrity in Distributed Data Bases*. Internship report, 2015

Conclusion – Publications

PPoPP'16 : P. M. J. *Causal Consistency: Beyond Memory*. 21st ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming, 2016

IPDPS'15 : P. M. J. *Update Consistency for Wait-free Concurrent Objects*. 29th IEEE International Parallel and Distributed Processing Symposium, 2015

NETYS'15 : P. J. M. *Tracking Causal Dependencies in Web Services Orchestrations Defined in ORC*. 3rd International Conference on NETwork sYStems, 2015

DISC'14 : P. M. J. *Brief Announcement: Update Consistency in Partitionable Systems*. 28th International Symposium on Distributed Computing, 2014

MSR'13 : P. J. M. *Construction d'une sémantique concurrente par instrumentation d'une sémantique opérationelle structurelle*. Modélisation des Systèmes Réactifs, 2013

IJFCS : B. P. T. *On the Complexity of Concurrent Multiset Rewriting*. International Journal of Foundations of Computer Sciences, 2015