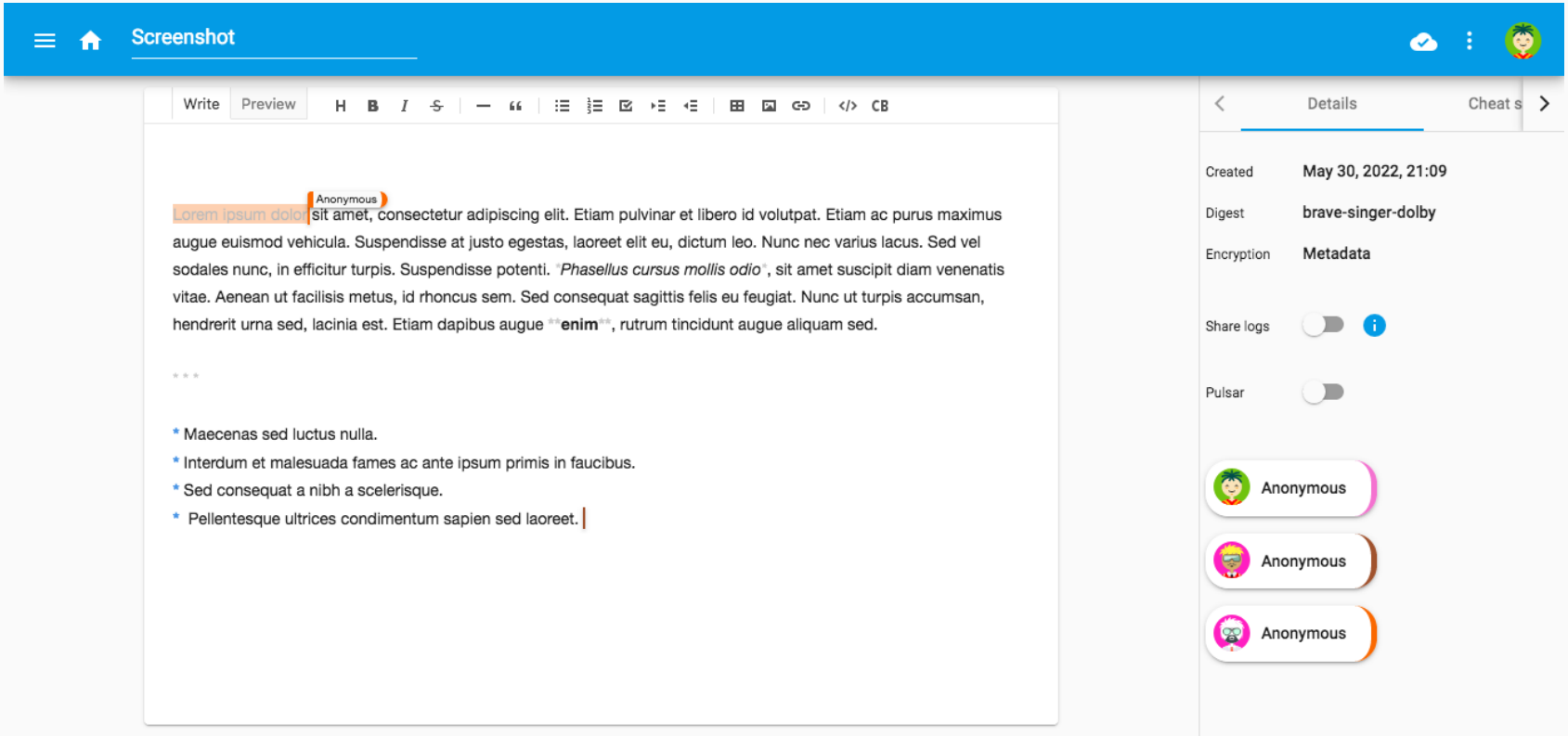
Conflict-free Replicated Data Types (CRDTs)

An Overview

Matthieu Nicolas (matthieu.nicolas@inria.fr)

02/05/2024

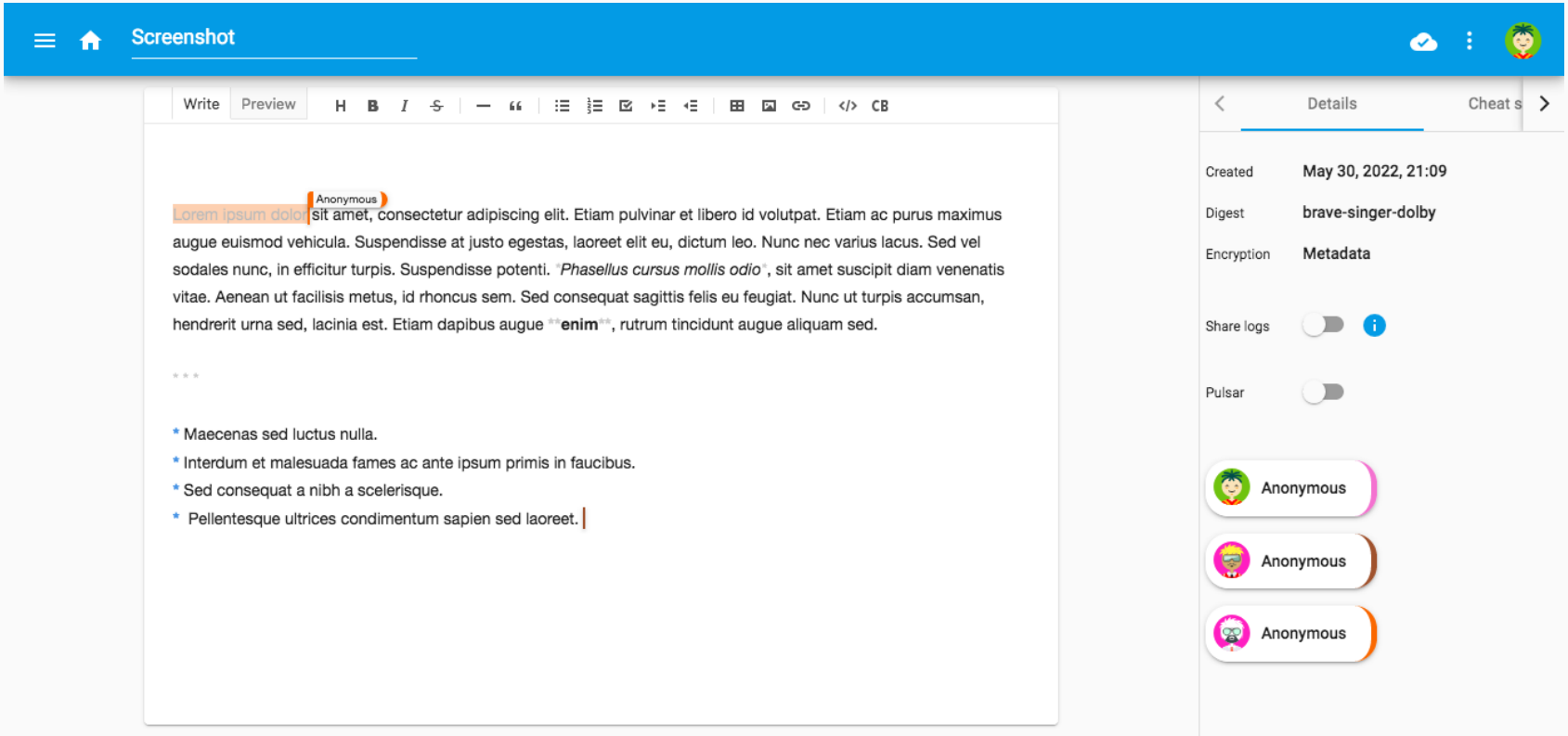
MUTE [Nic+17]



Local First Software [Kle+19]

- Peer-to-Peer (P2P) collaborative applications

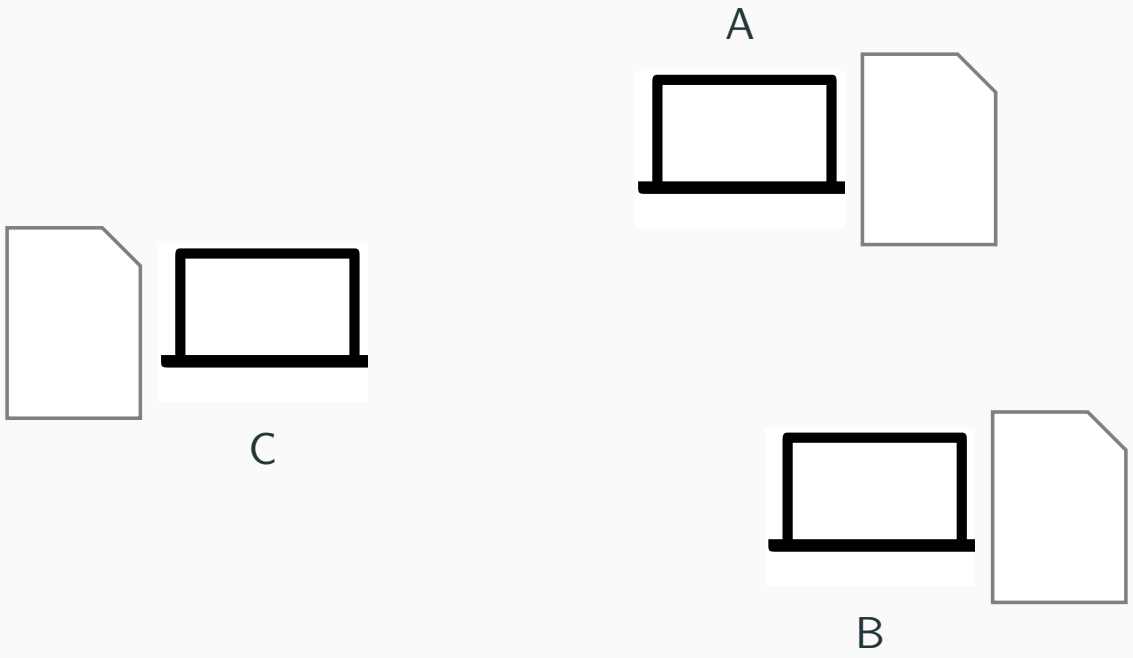
MUTE [Nic+17]



Local First Software [Kle+19]

- Peer-to-Peer (P2P) collaborative applications
- Always available
- Ensure ownership and privacy of data

Data replication in P2P systems



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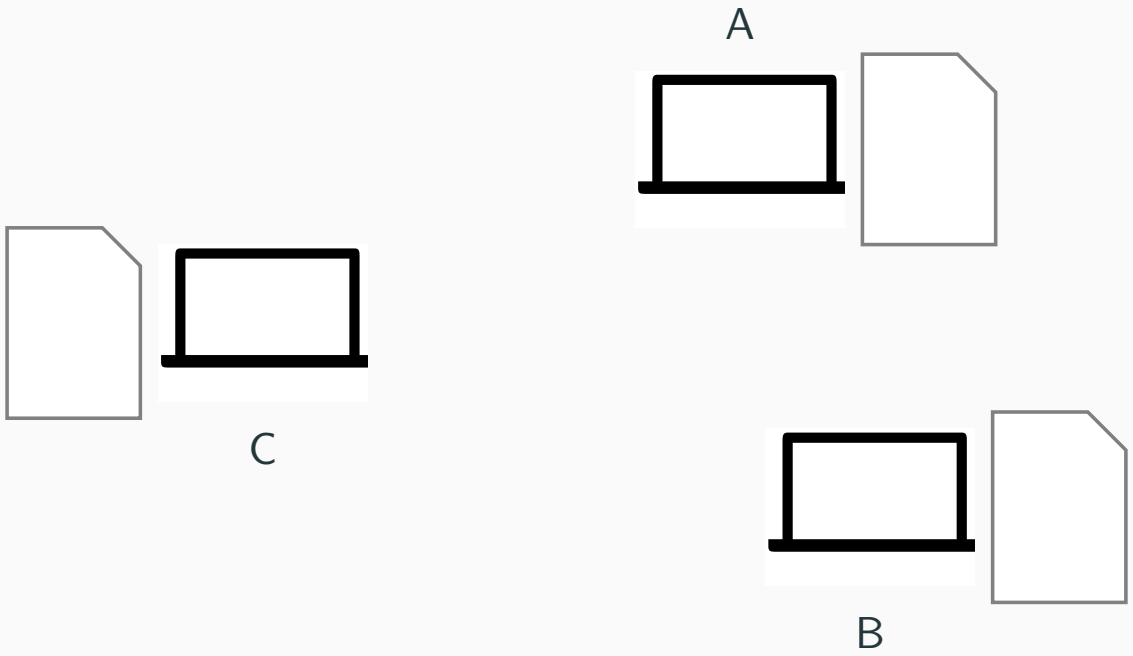

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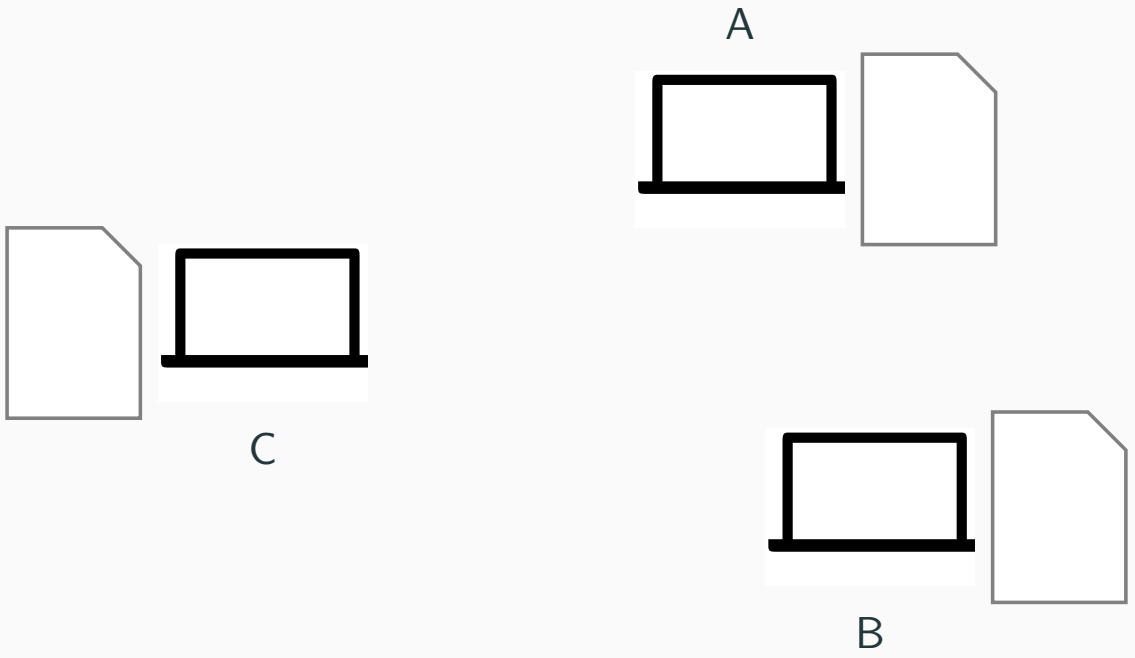

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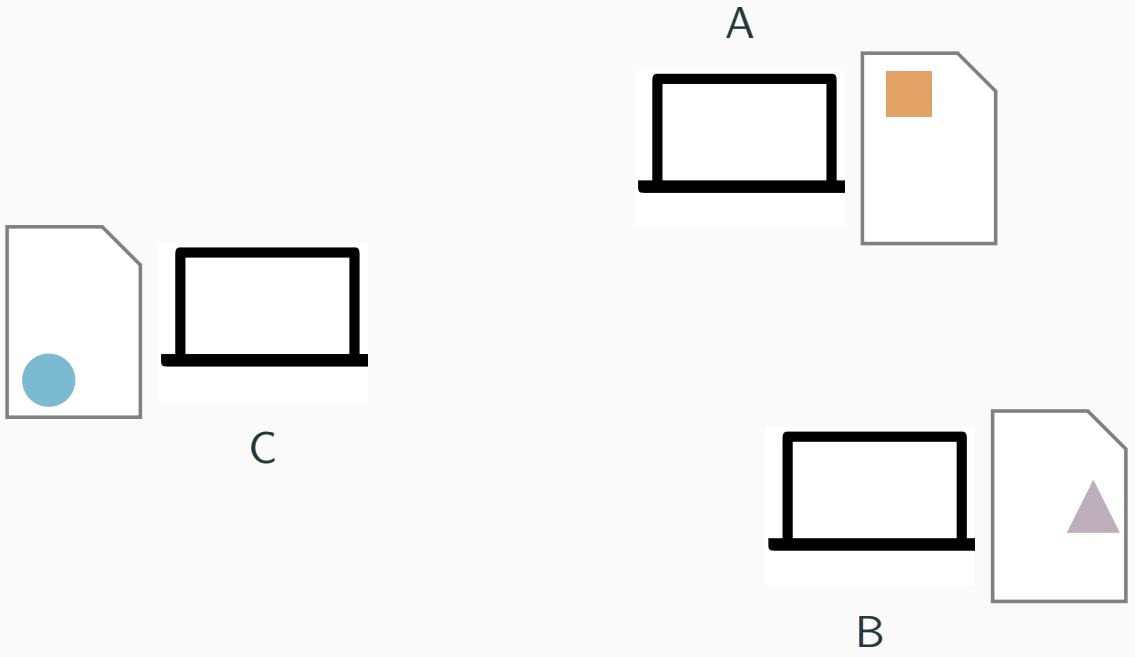

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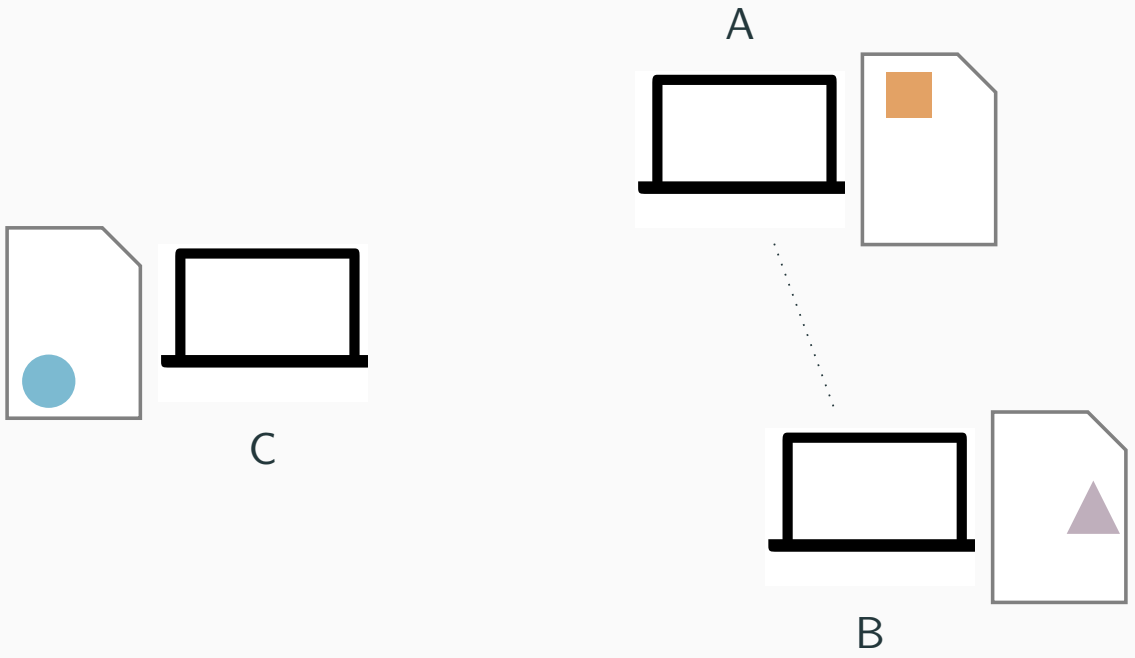

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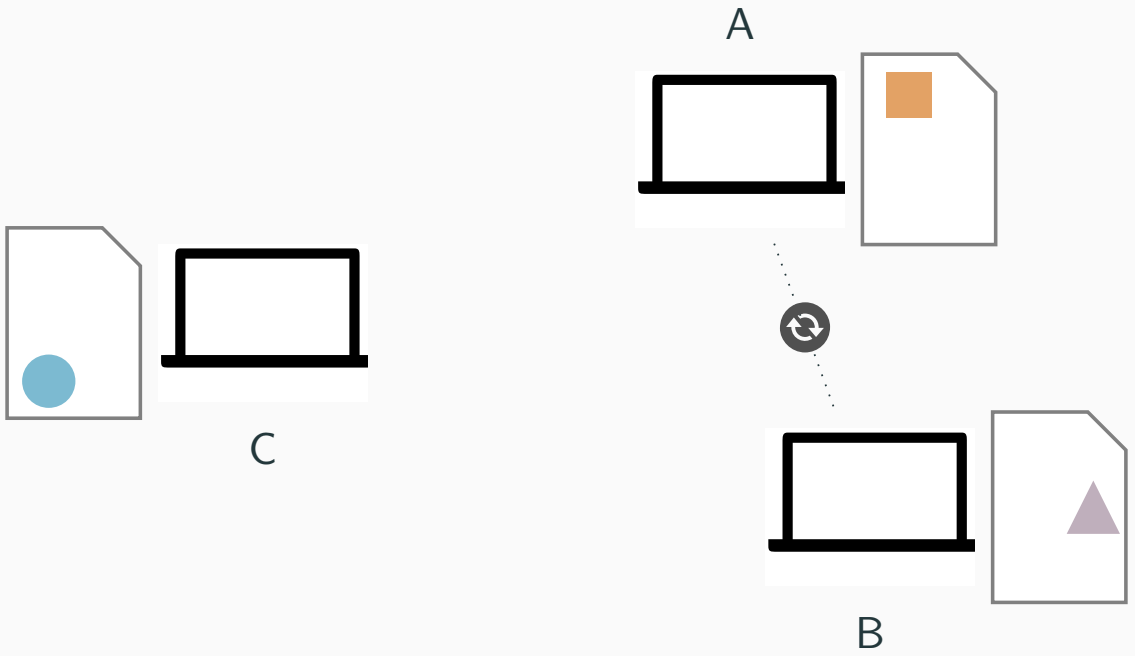

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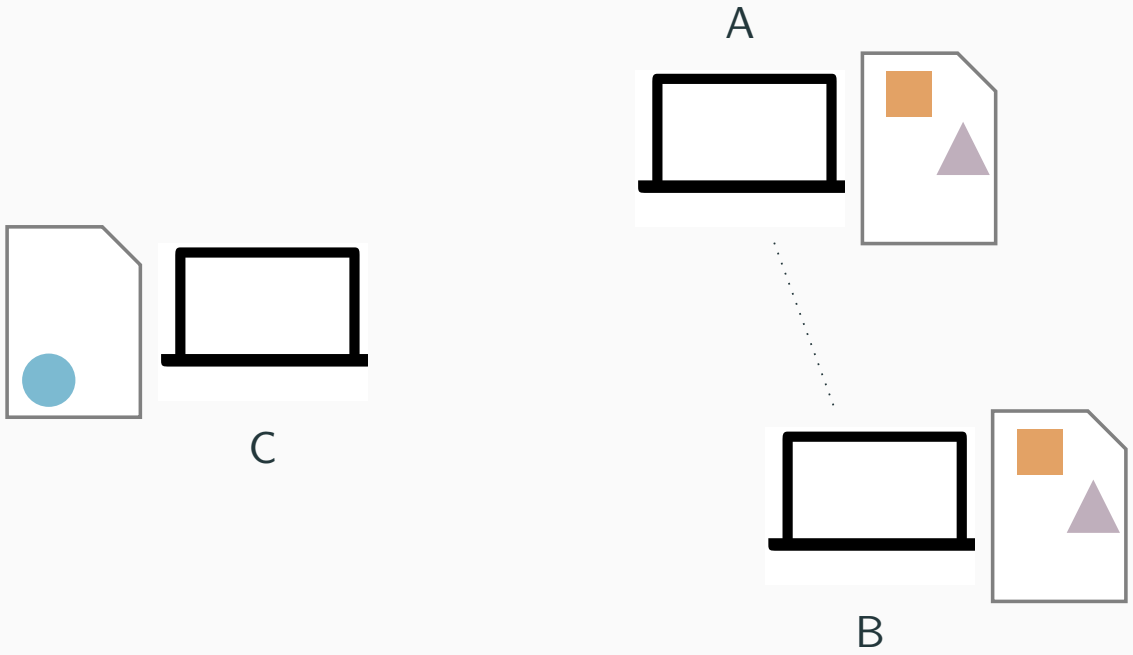

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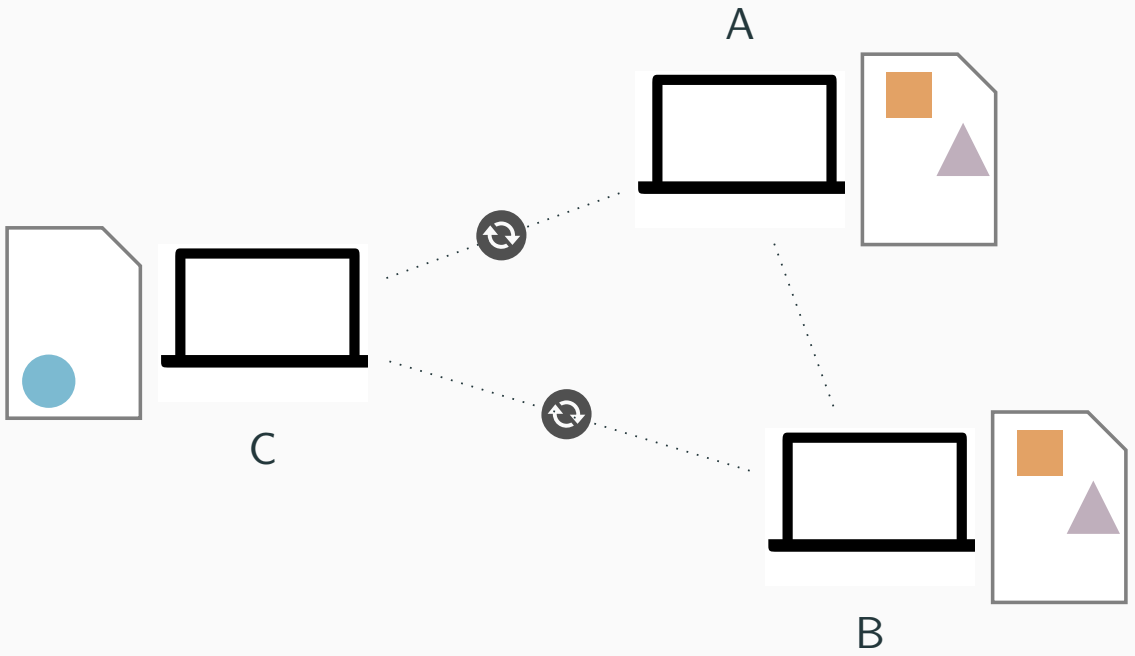

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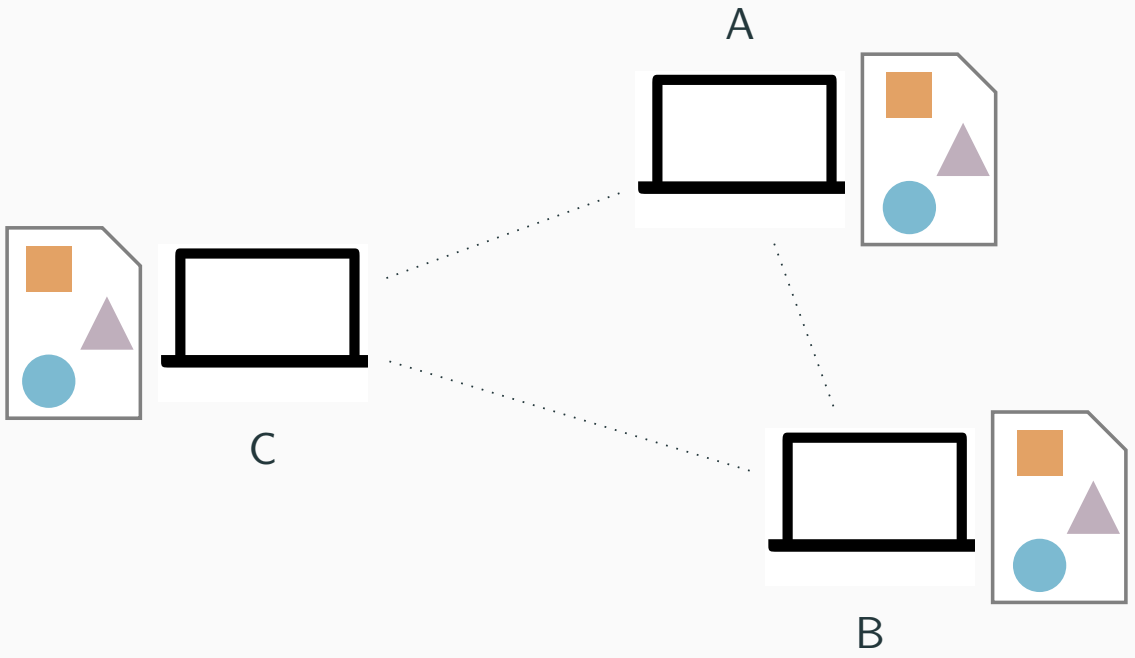

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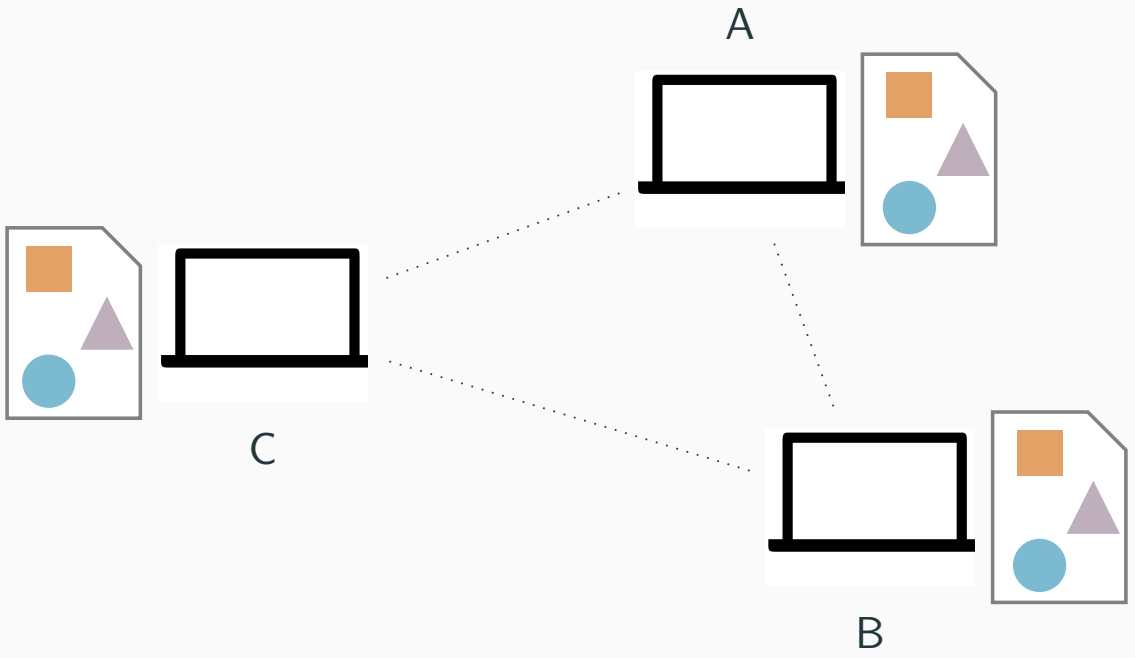

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Require *conflict resolution mechanisms*

Conflict-free Replicated Data Types (CRDTs)
are a family of conflict resolution mechanisms
for P2P systems

Conflict-free Replicated Data Types (CRDTs) [Sha+11]

- New specifications of existing Data Types, e.g. *Set* or *Sequence*
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- Rely on the lattice theory ...
- ... More specifically, CRDTs are join-semilattices

Lattice theory for CRDTs

Properties of join-semilattices

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- Exists a set of minimal states of the join-semilattice, the *irreducible elements*

Design of CRDTs

- Several CRDTs may be designed for a given data type . . .
- . . . Each offering different trade-offs

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What impact the design of a given CRDT [Pre18]

- Conflict Resolution Semantics
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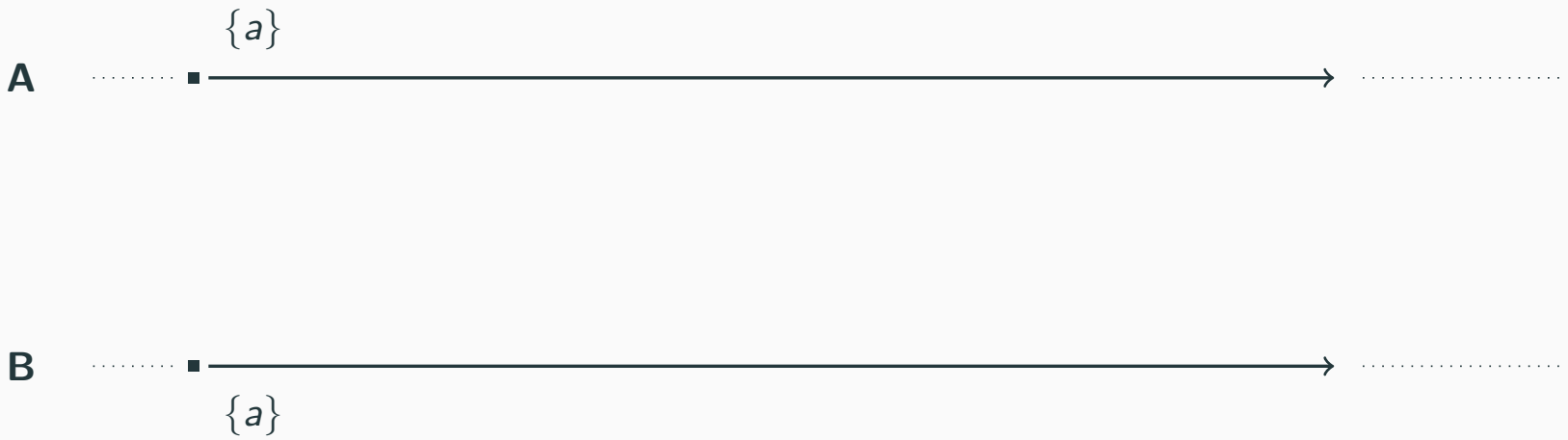
- Synchronisation Model

- Impact their overhead in terms of computation, memory and bandwidth

Conflict Resolution Semantics

- Distributed setting allows new scenarios



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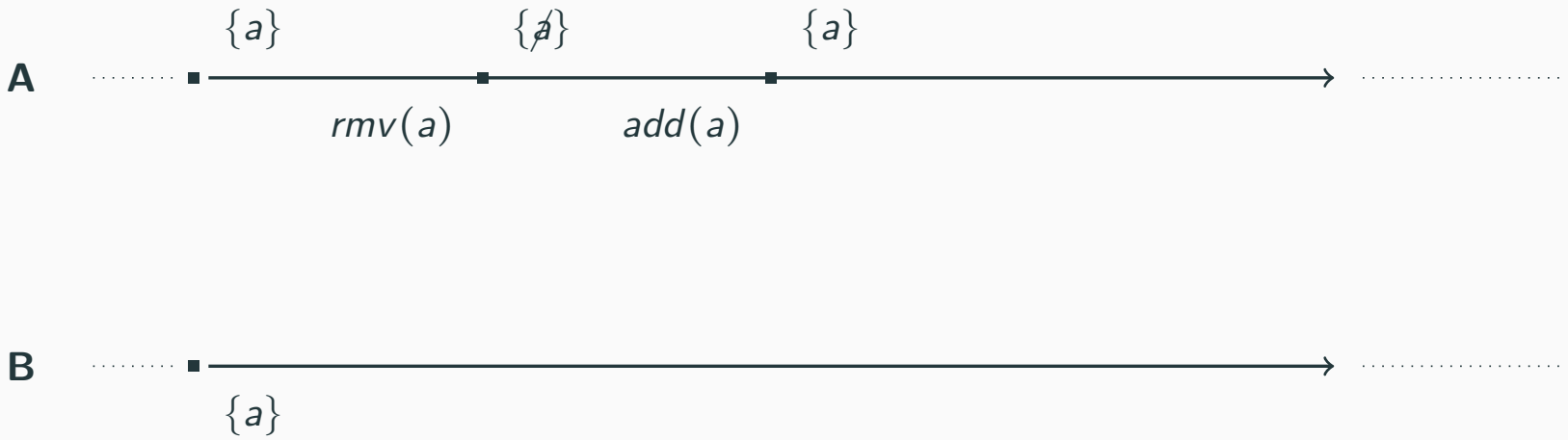

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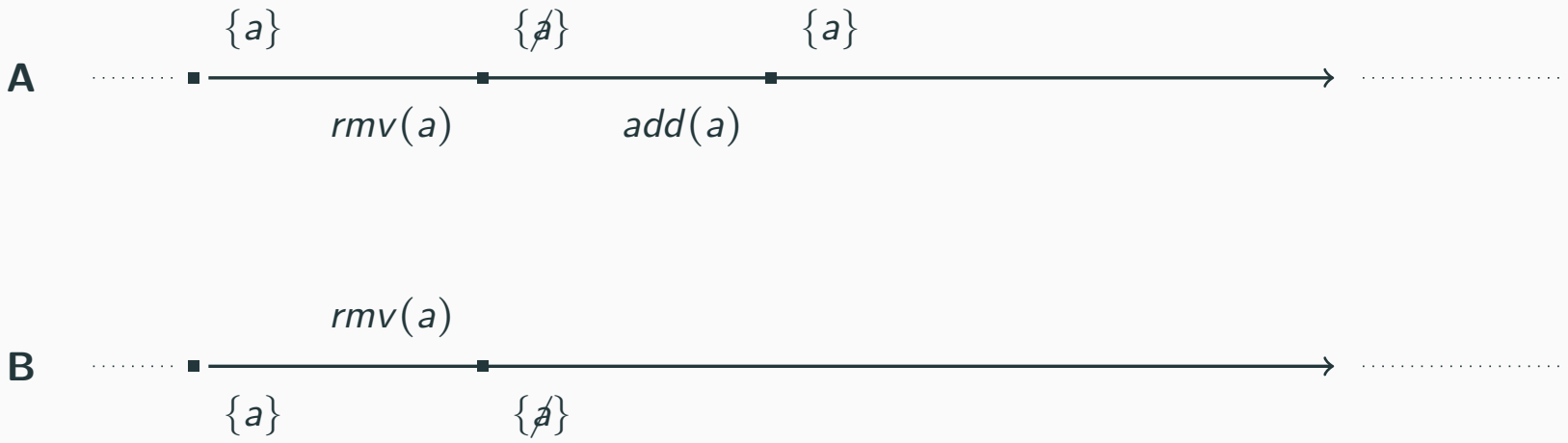

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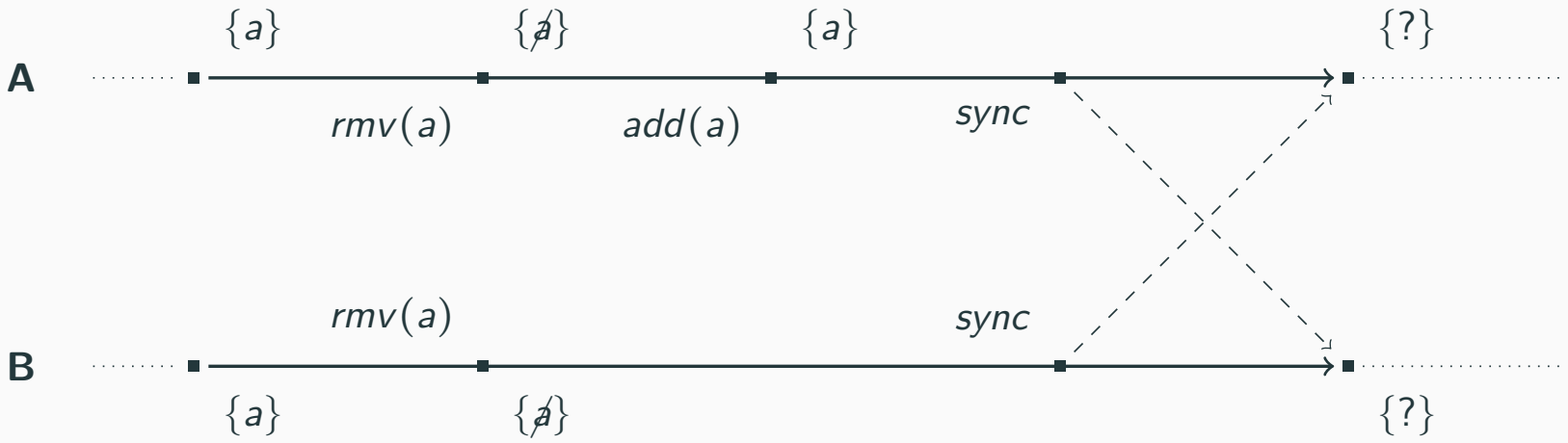

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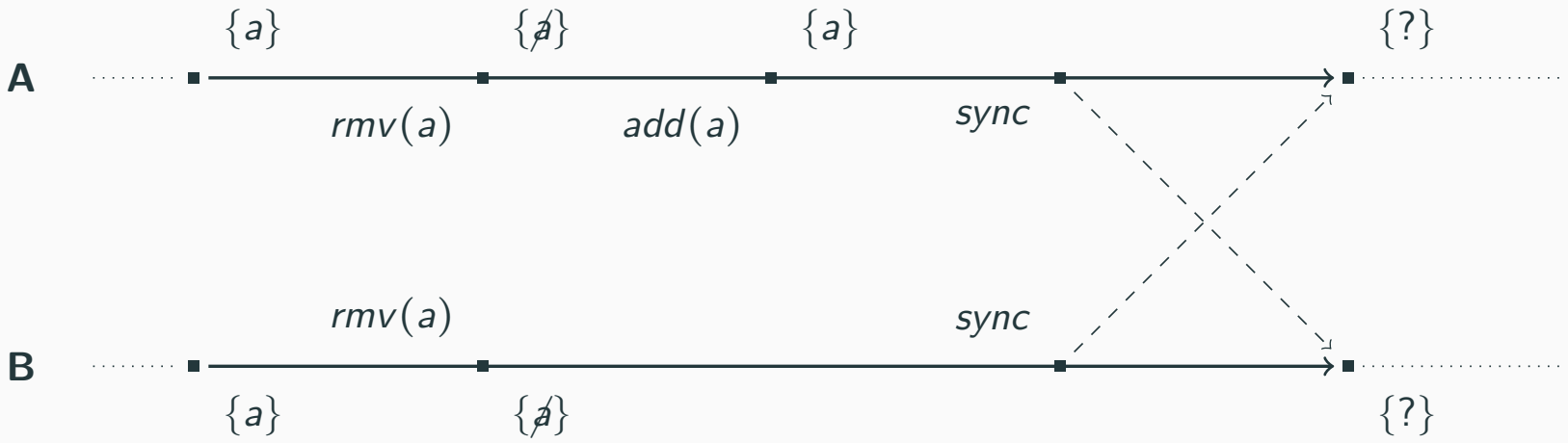
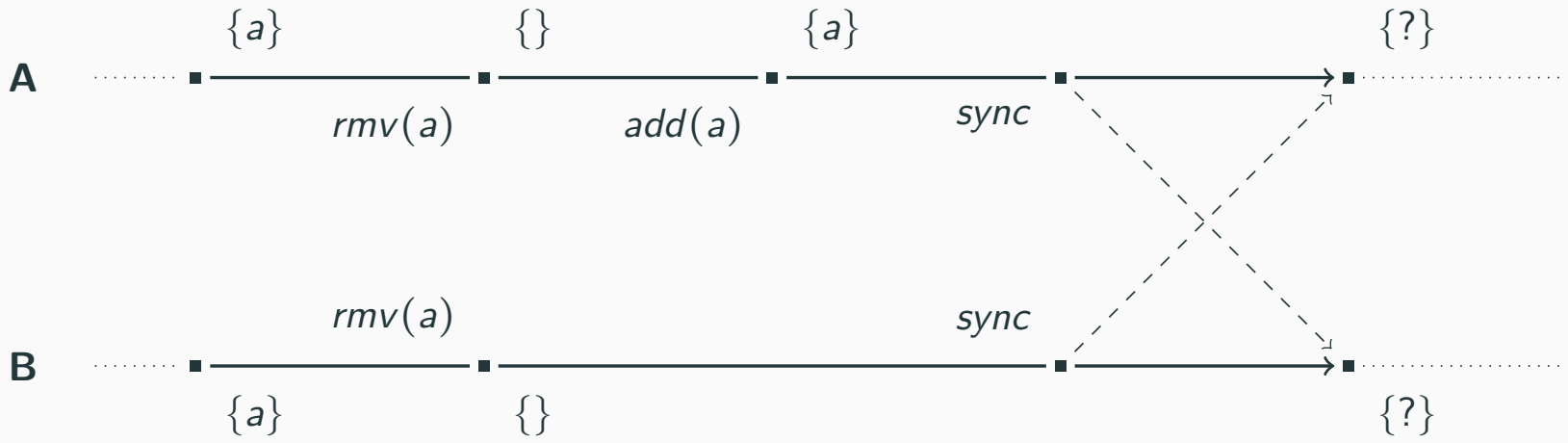


- What should be the final state in this scenario ?
- Designing a CRDT consists in defining its behaviour in such cases

Conflict Resolution Semantics - Case study of the Set



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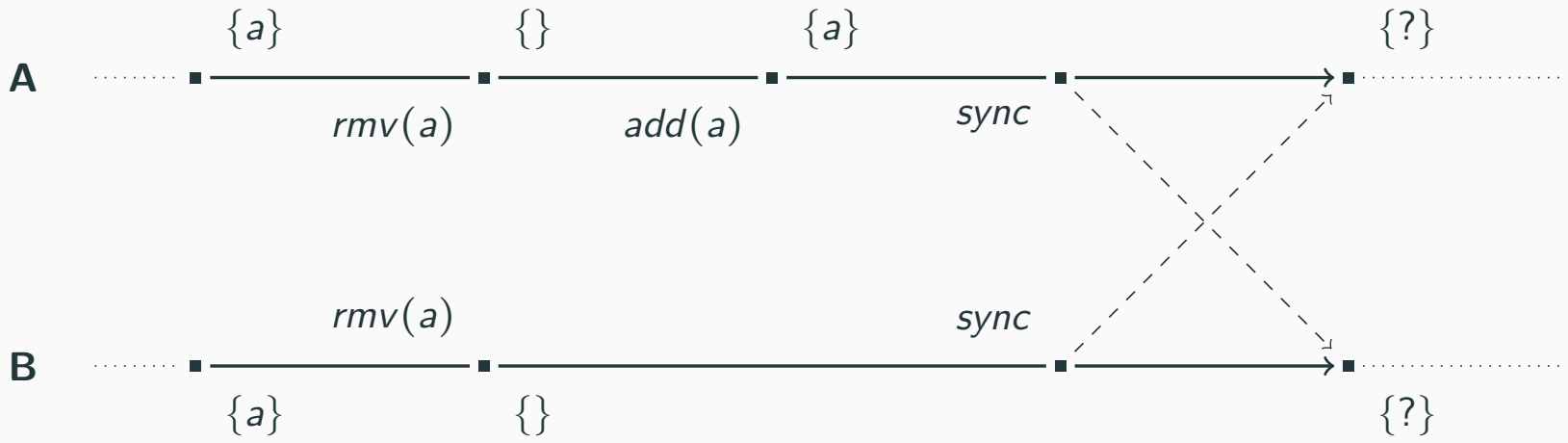

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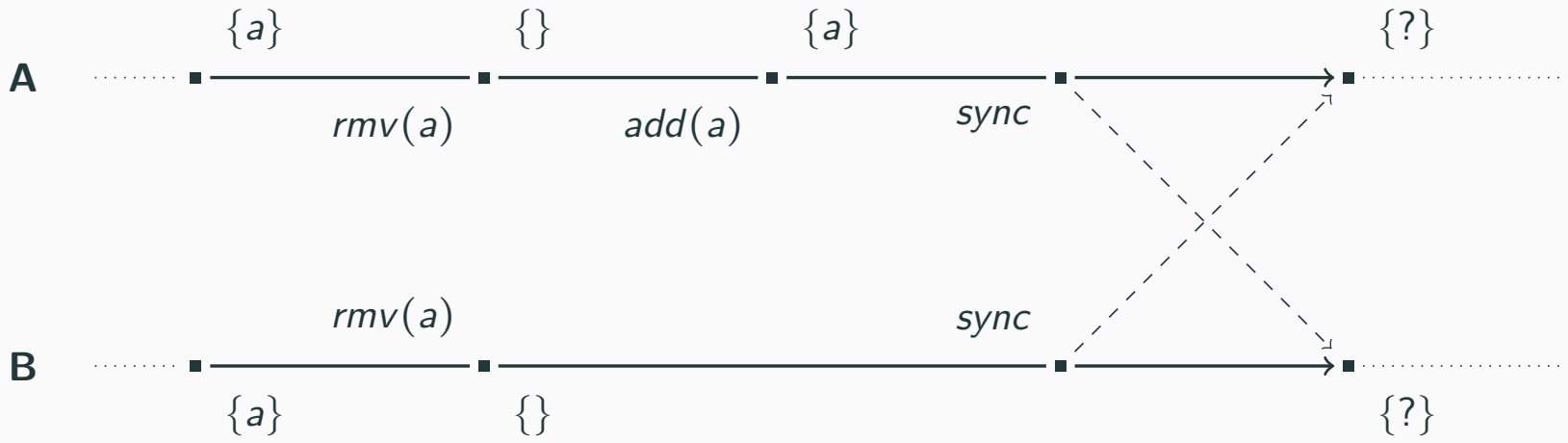

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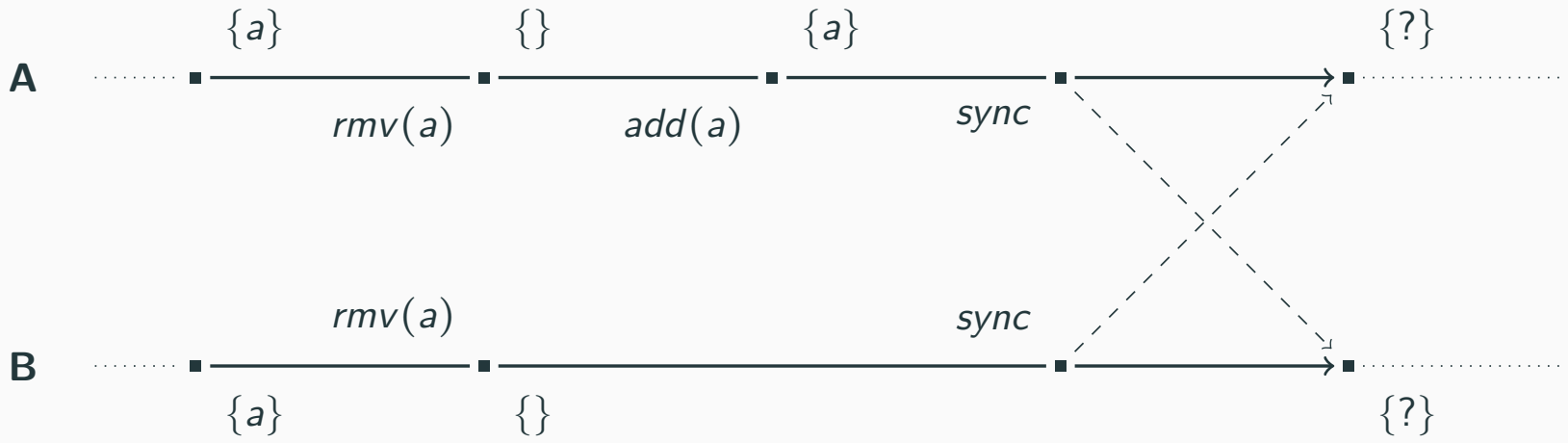

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- *Causal-Length* [YR20]: The last action of the longuest chain of updates determines the presence (or not) of the element $\Longrightarrow \{a\}$

Synchronisation Models

To converge

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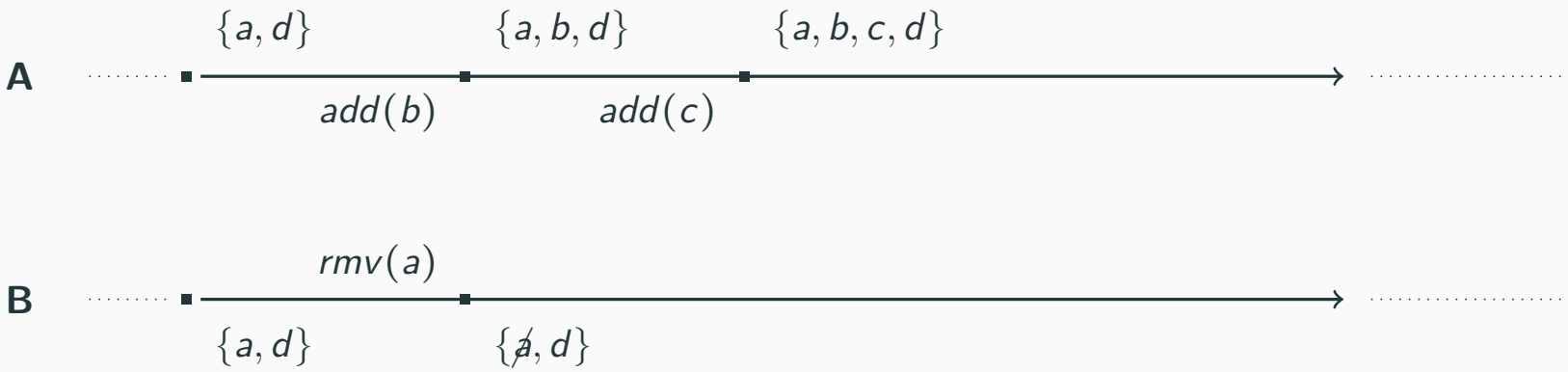

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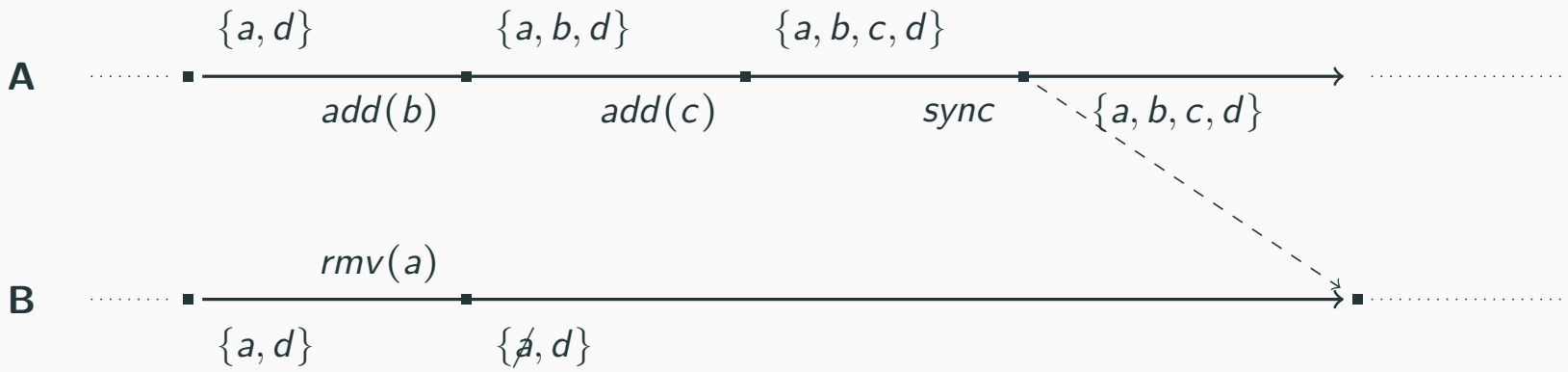

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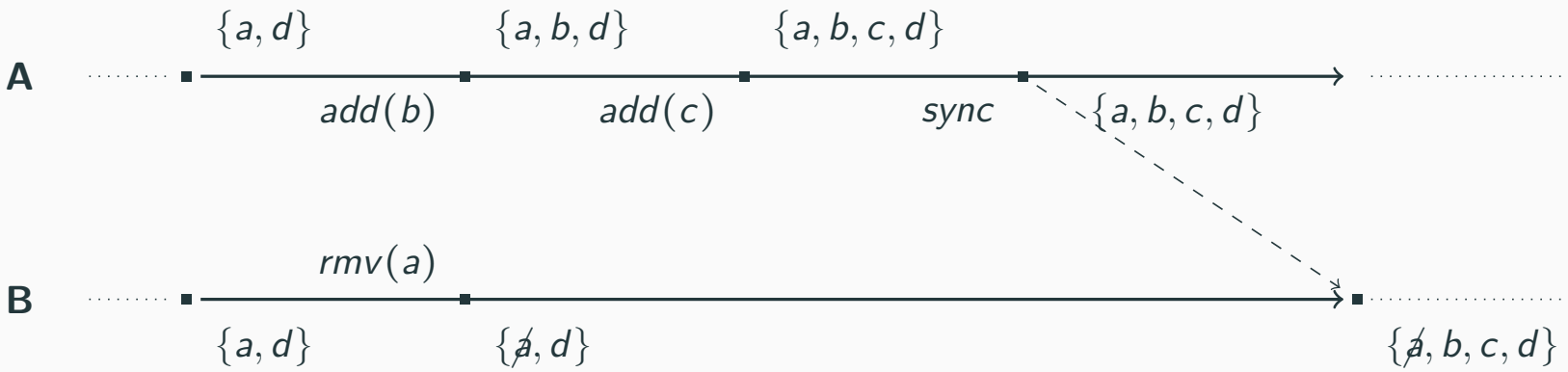

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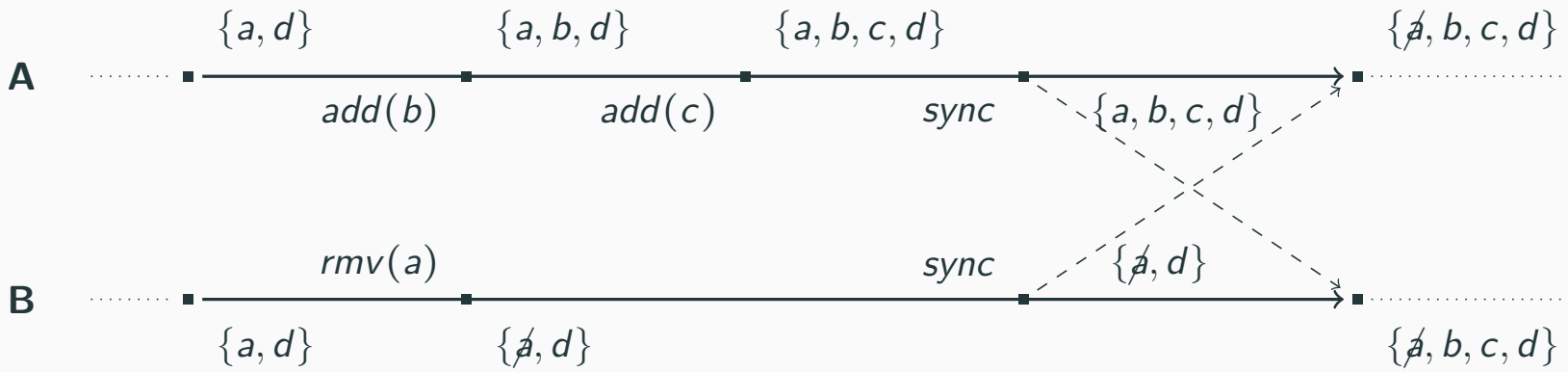

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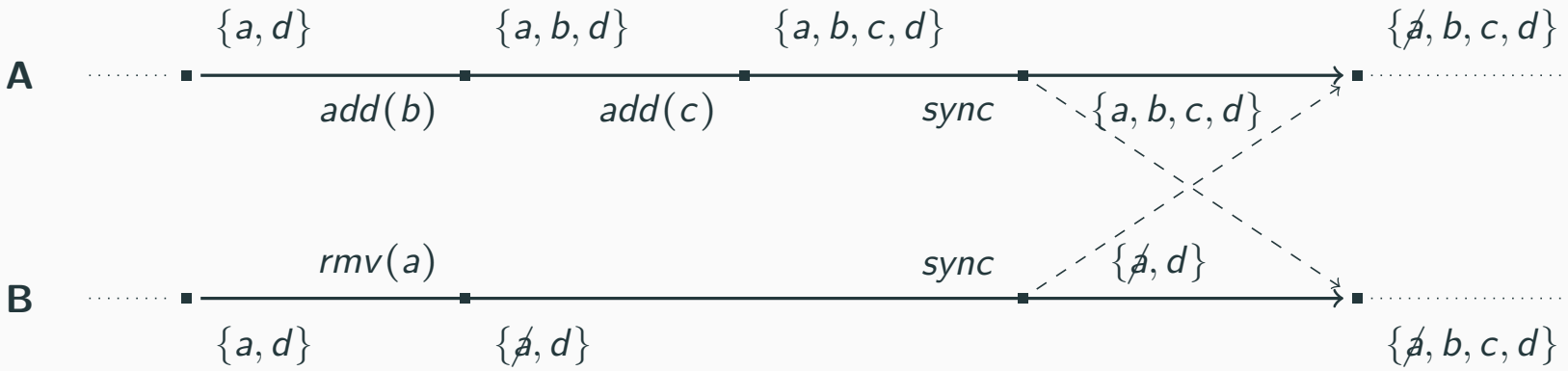

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- With `merge`, a commutative, associative and idempotent function

State-based synchronisation - Review

Strengths

- No assumptions on the network reliability
- i.e. messages may be lost, re-ordered or duplicated w/o impact

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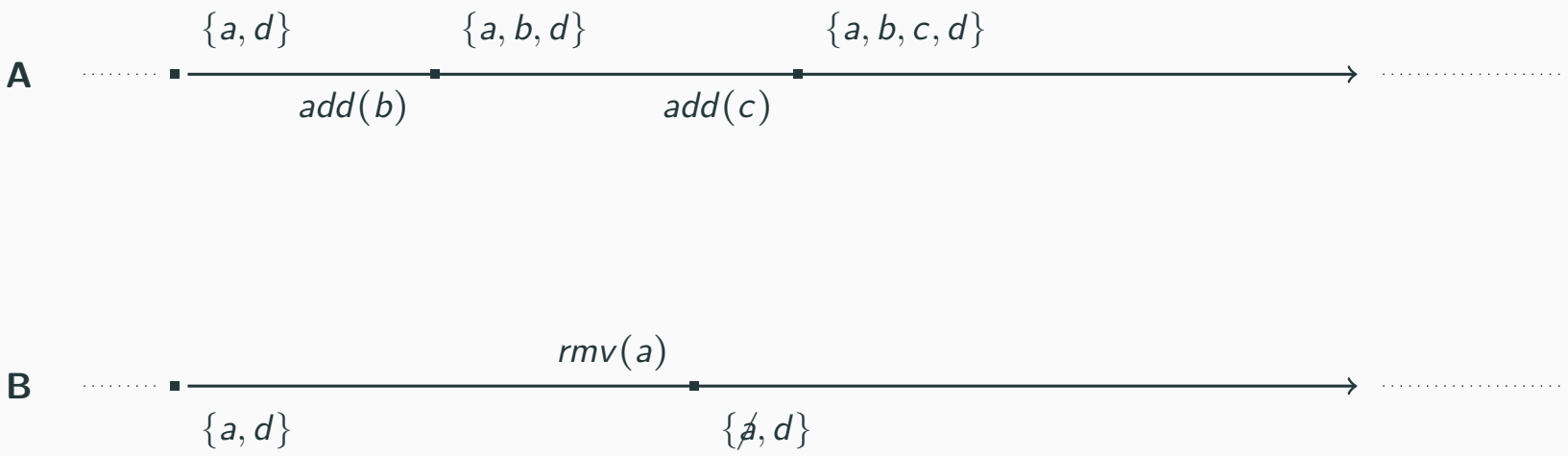
- Depending on data type, states expensive to broadcast...
- ...And `merge` expensive to execute

Operation-based synchronisation

- Encode updates as arbitrary messages, called *operations*
- An operation correponds to one or several *irreducible elements*



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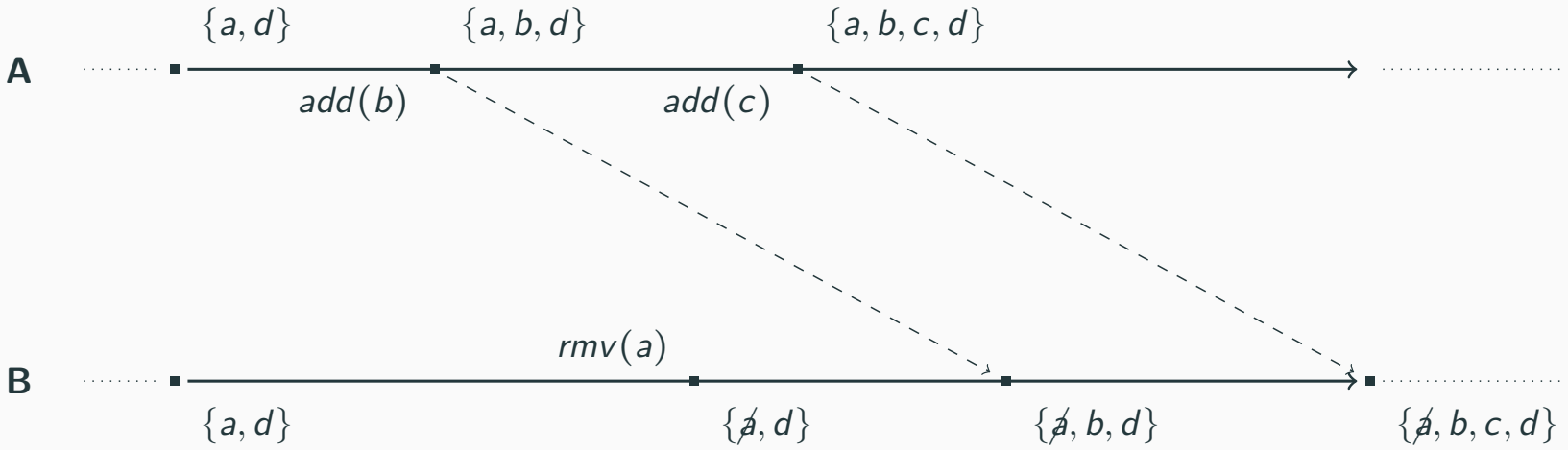

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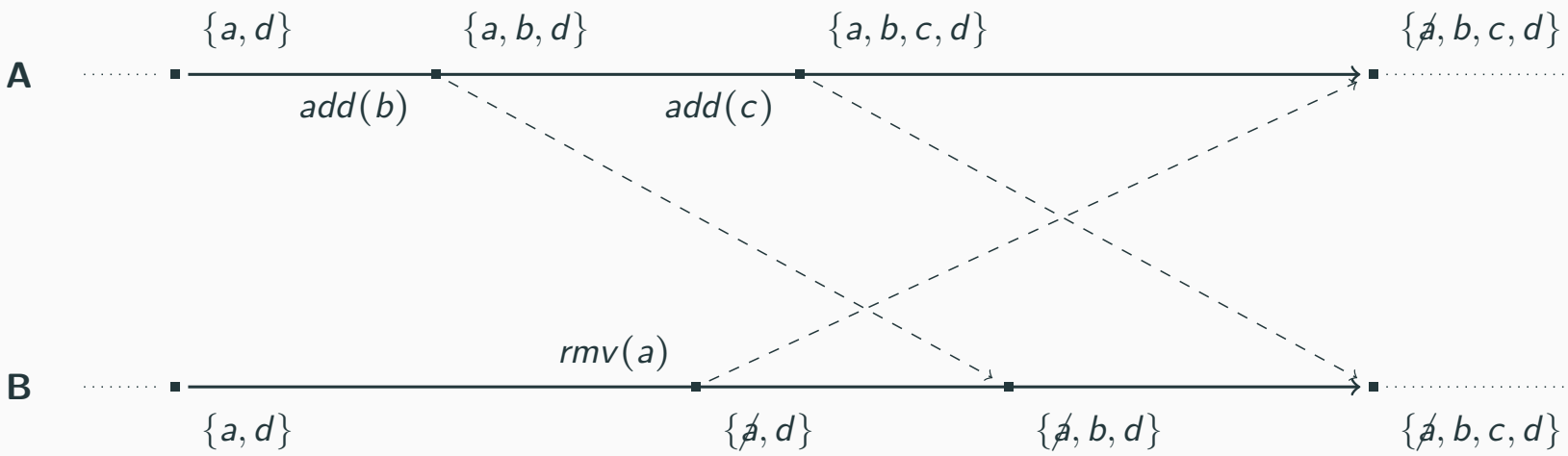

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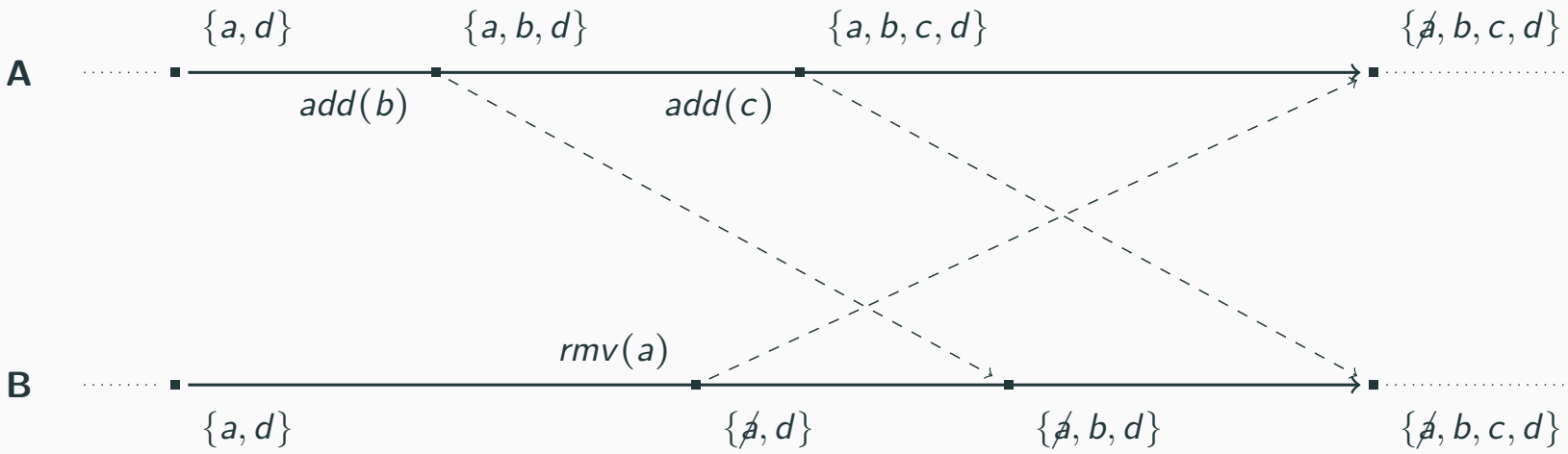

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- Concurrent operations must be commutative

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- Weak to network failures
- Have to pair Op-based CRDTs to a message delivery service
  - To re-order and/or de-duplicate operations
  - To retrieve lost operations using anti-entropy mechanisms

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- Enable nodes to collaboratively edit data w/o coordination
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Several CRDTs designed per data types

- With different behaviours in case of conflict...
- ...and different techniques to broadcast updates
- E.g. 10+ CRDTs for *Sequence*

State of the art

- CRDTs for many data types
  - *Register*, *Set* [Pre18], *Sequence* [Roh+11; WUM09], *JSON* [KB17], *Tree* [Kle+22] ...
- Libraries providing CRDTs to build new applications
  - Yjs [Yjs], Automerge [Aut]...

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- Libraries providing CRDTs to build new applications
  - Yjs [Yjs], Automerge [Aut]...
- Used in collaborative applications
  - Teletype (Atom's pair-programming feature), Apple Notes...
- Used in multi-master replication for distributed databases
  - Redis [Lab], Microsoft Azure CosmoDB [DB]...

Ongoing researchs

- Designing CRDTs for new use cases
  - Rich Text [Lit+22], Access Control [RIP23]

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- Designing CRDTs for systems with malicious nodes

Thanks for your attention, any questions?

Bibliographie i

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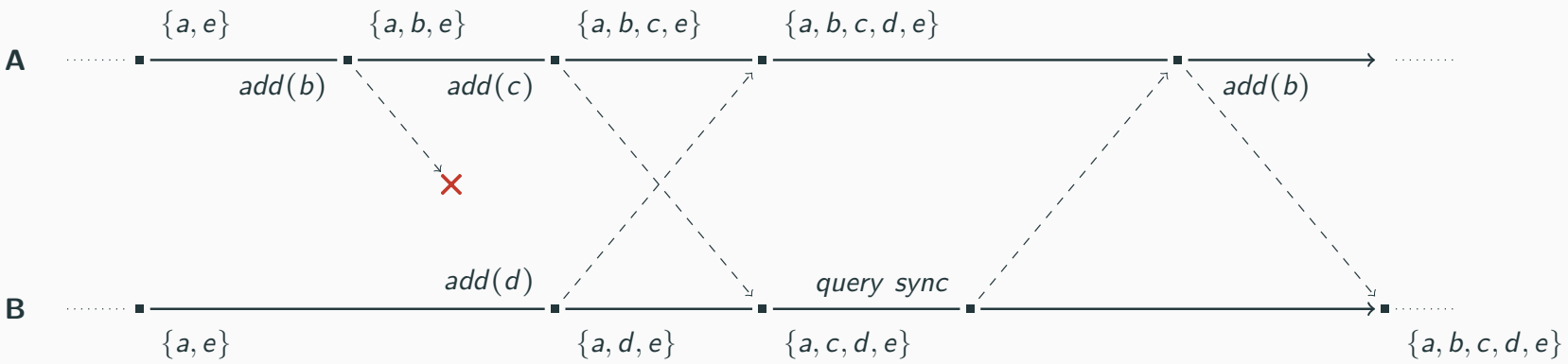
Back-up slides

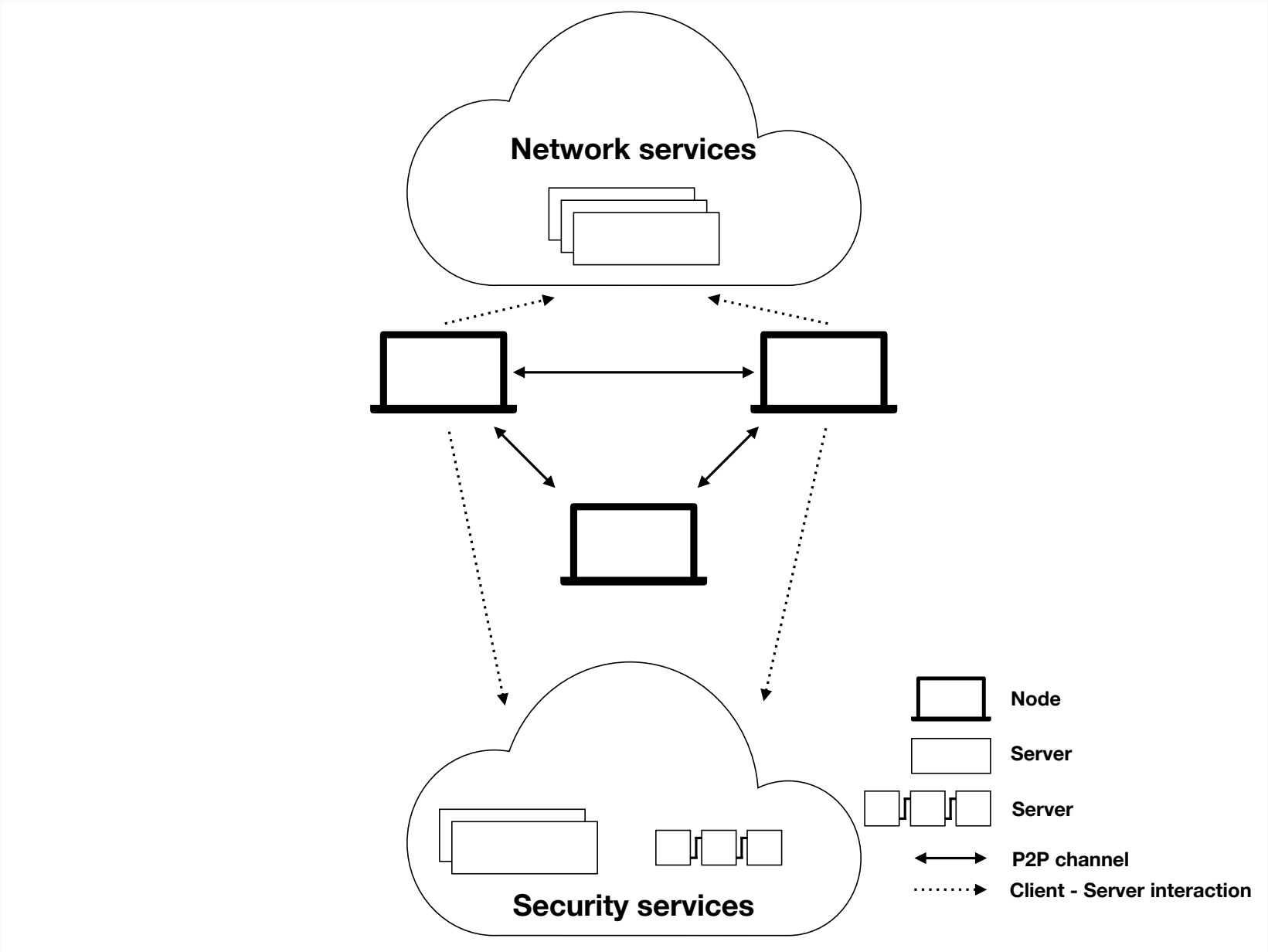
Operation-based synchronisation - network failure



Synchronisation Models - Summary

	State-based	Op-based	Delta-based
Integrate updates by merging states	✓	✗	✓
Integrate updates by irreducible elts	✗	✓	✓
Handle natively network failures	✓	✗	✓
Suited for real-time systems	✗	✓	✓

MUTE System Architecture



MUTE Software Architecture