efficient synchronization of state-based CRDTs

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9 Apr. 2019 @ ICDE'19

CRDTs

Conflict-free Replicated Data Types

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rich abstraction

- register, counter, set, map, ...

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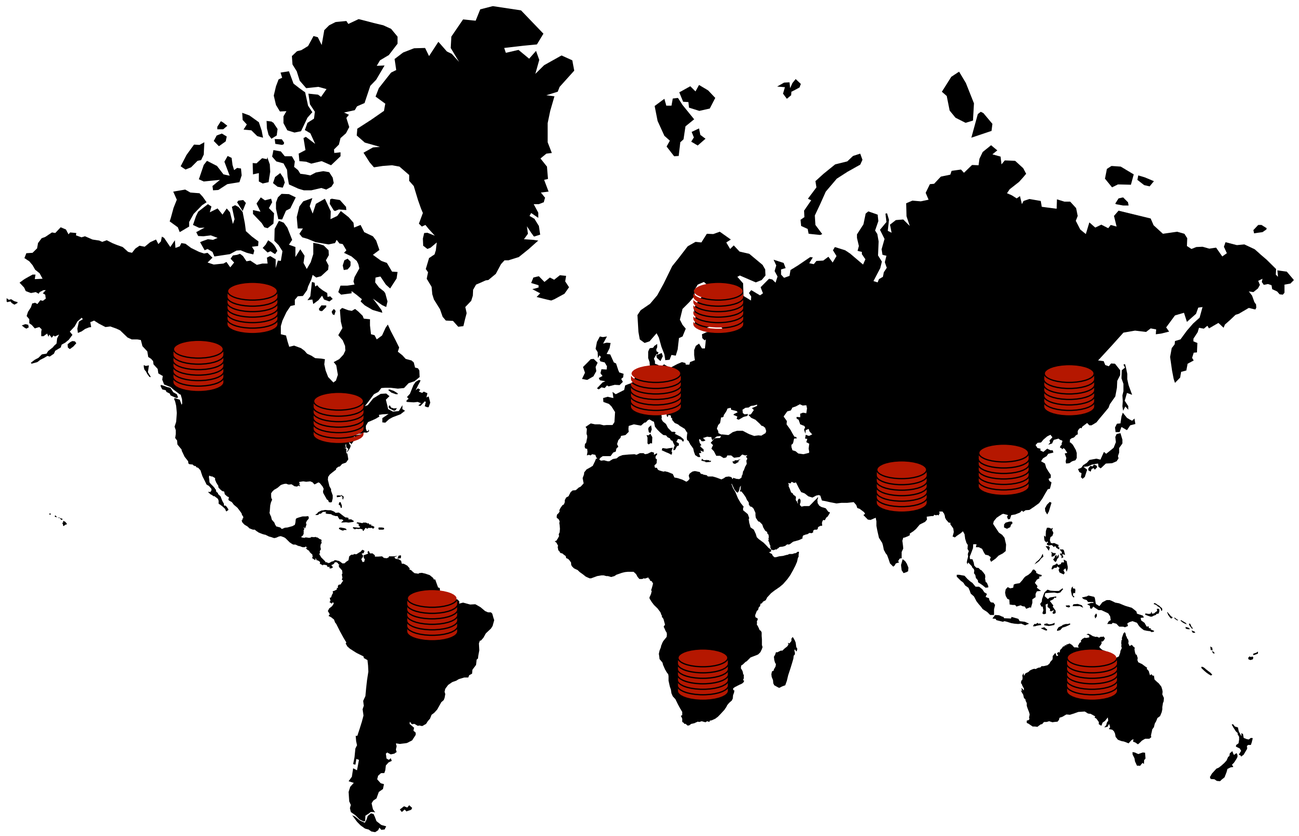

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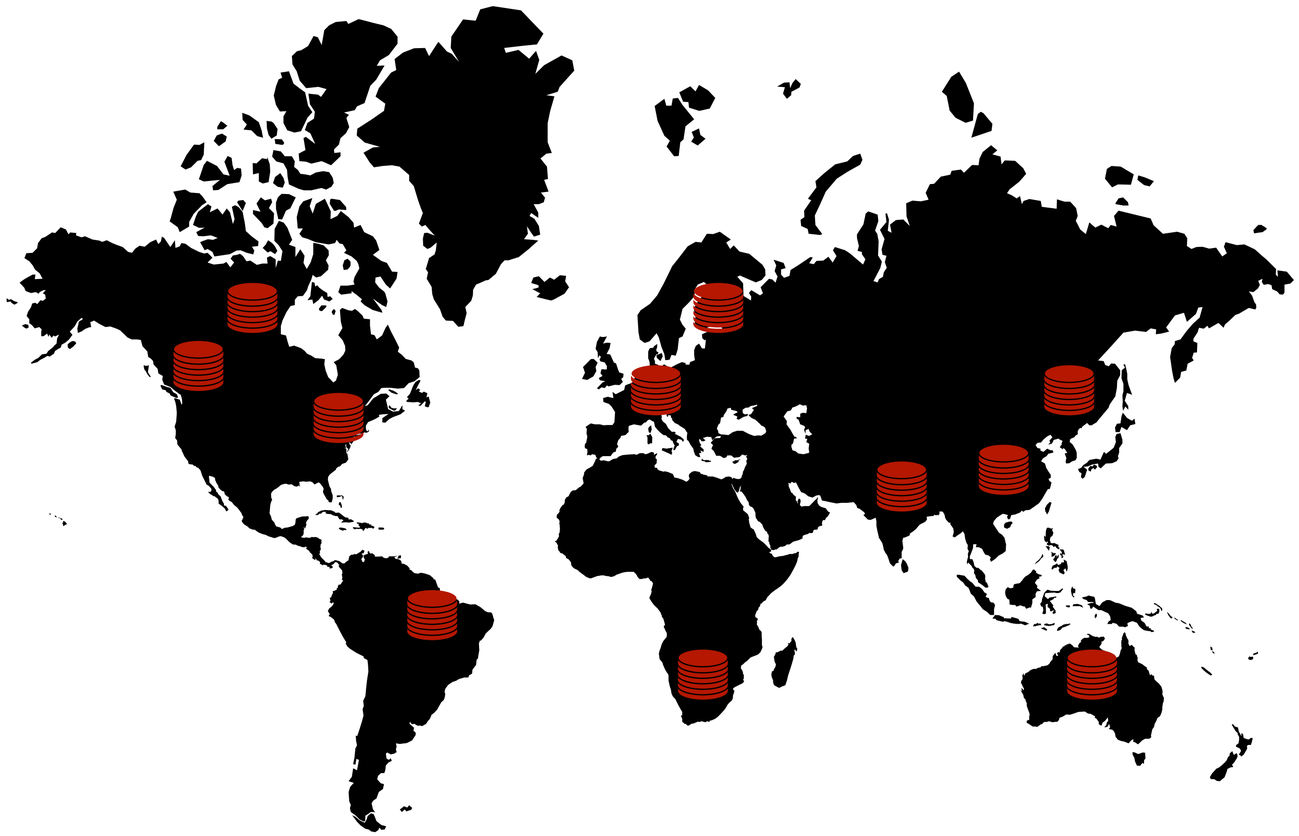

CRDTs

Conflict-free Replicated Data Types

rich abstraction
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why replicate?
- quality of service

no conflicts?!
- eventual consistency
- automatic conflict resolution

outline

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- **CRDT variants**
  - operation-based
  - state-based
    - delta-based

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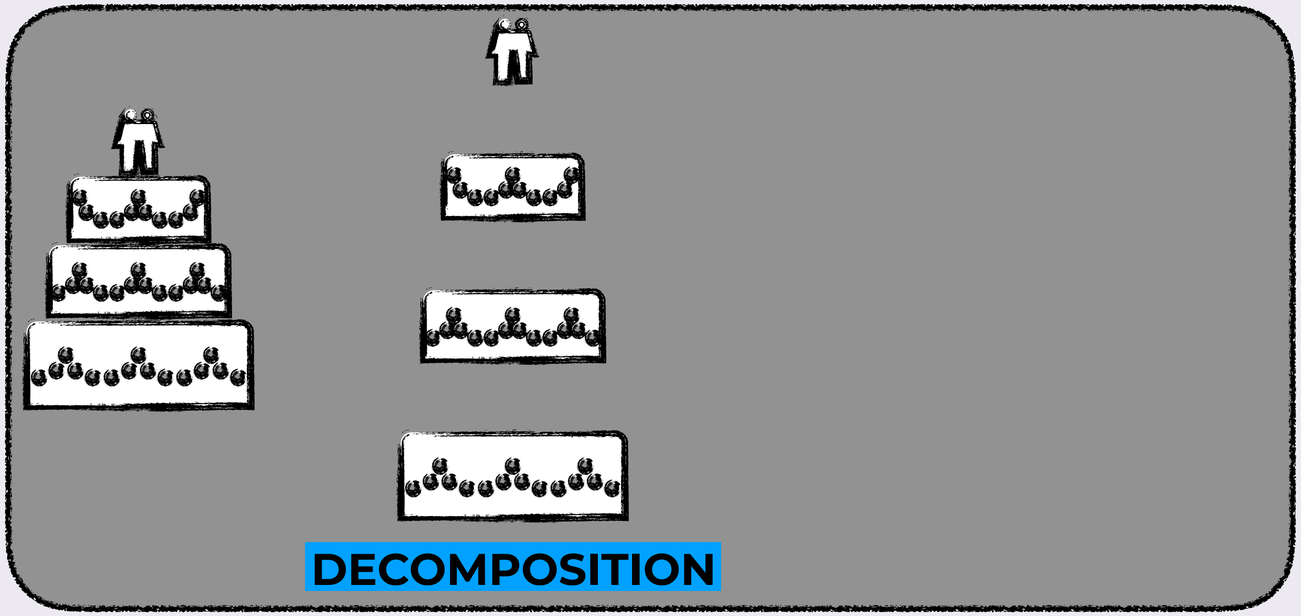

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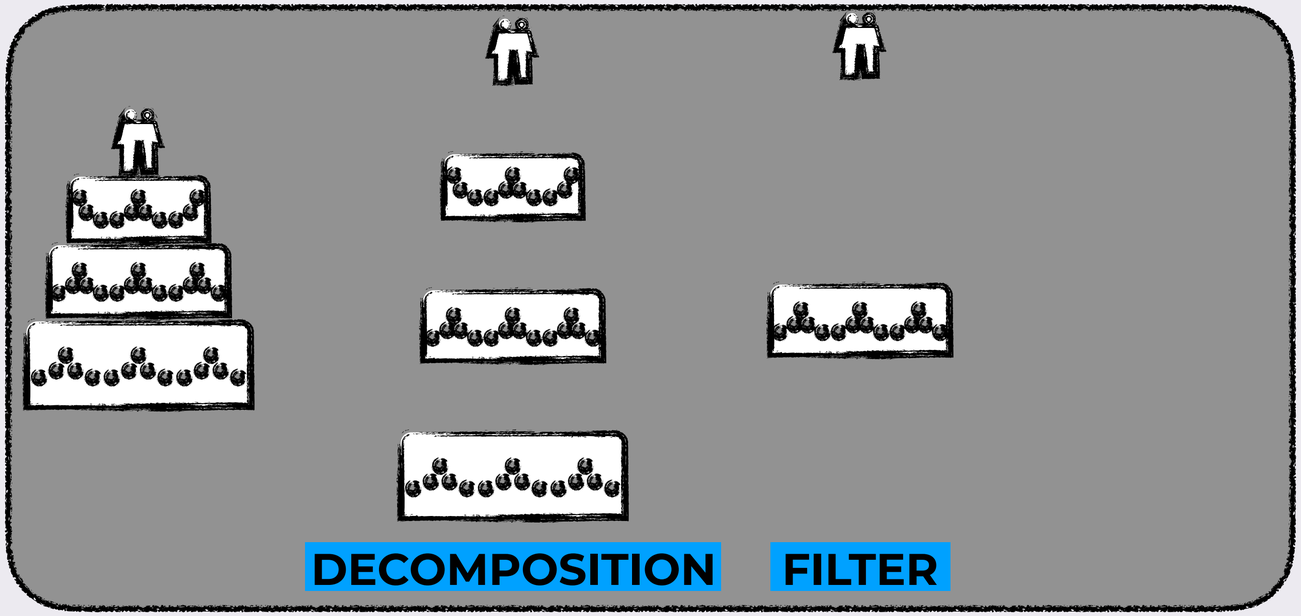

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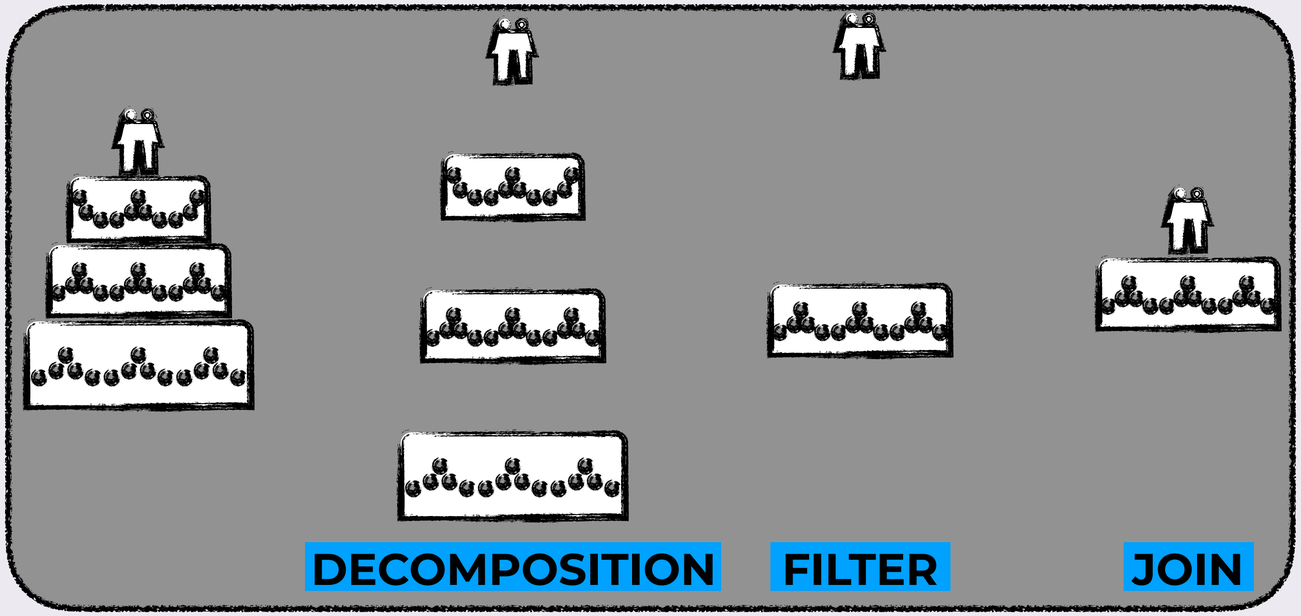

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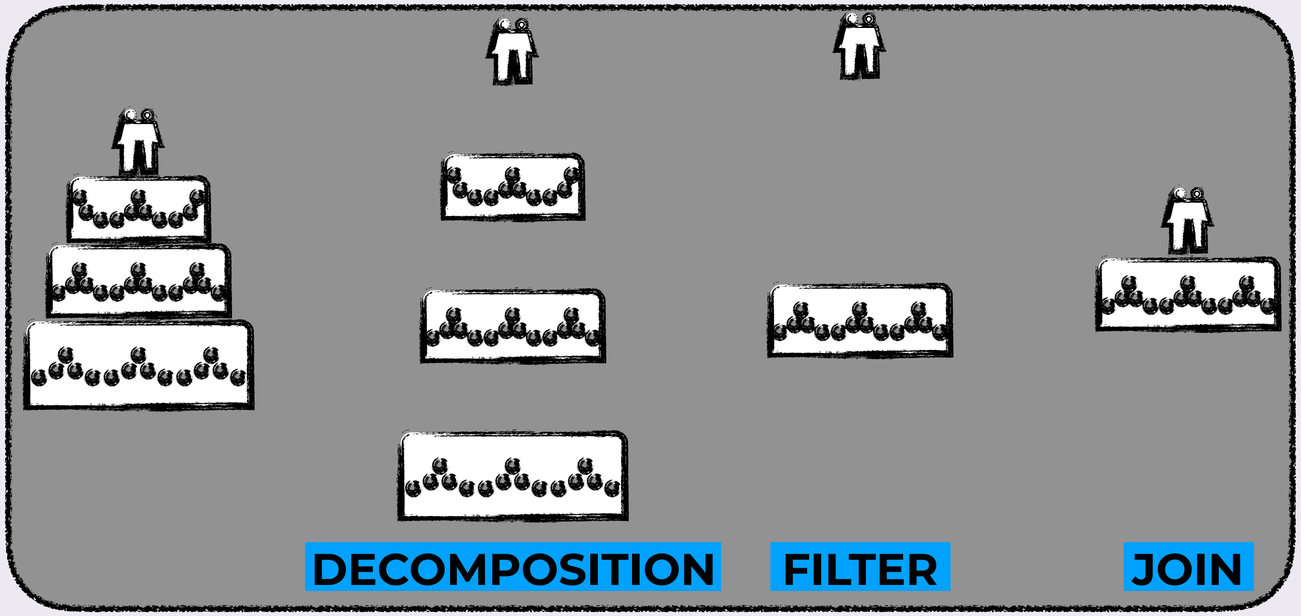

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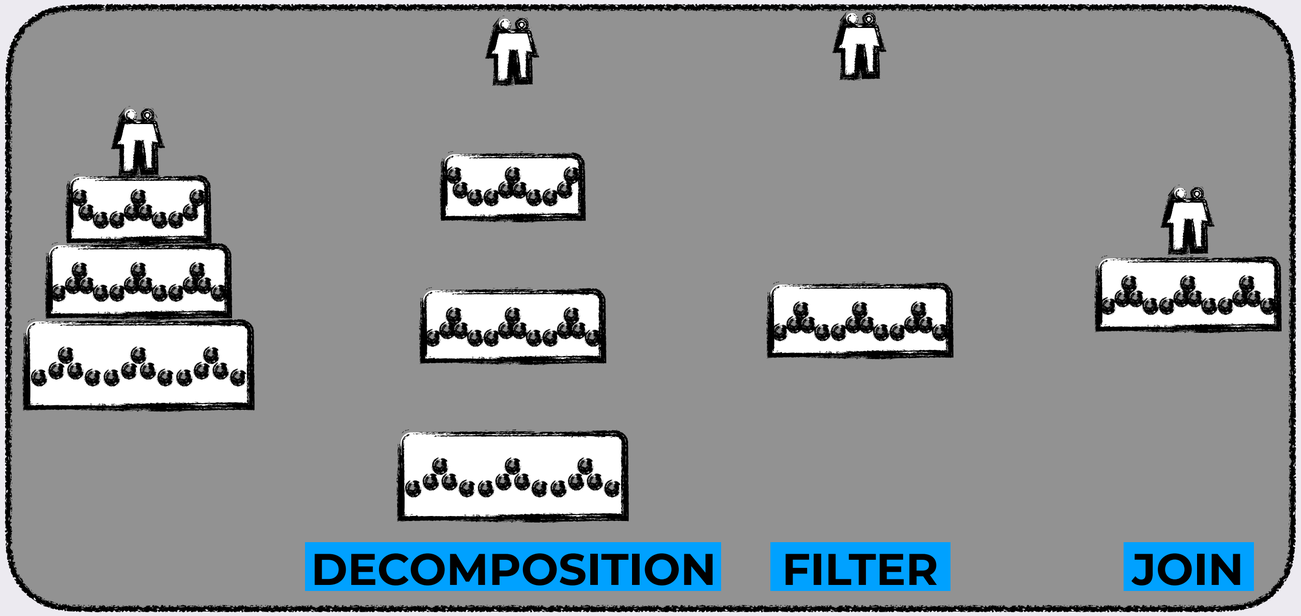

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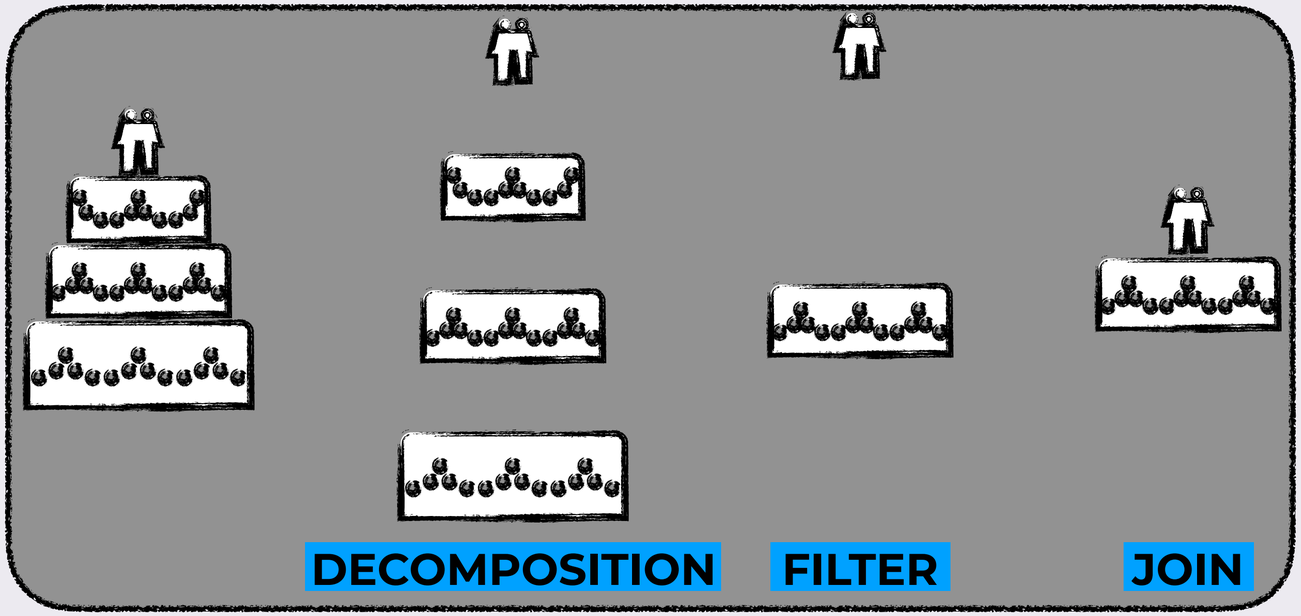

CRDT variants

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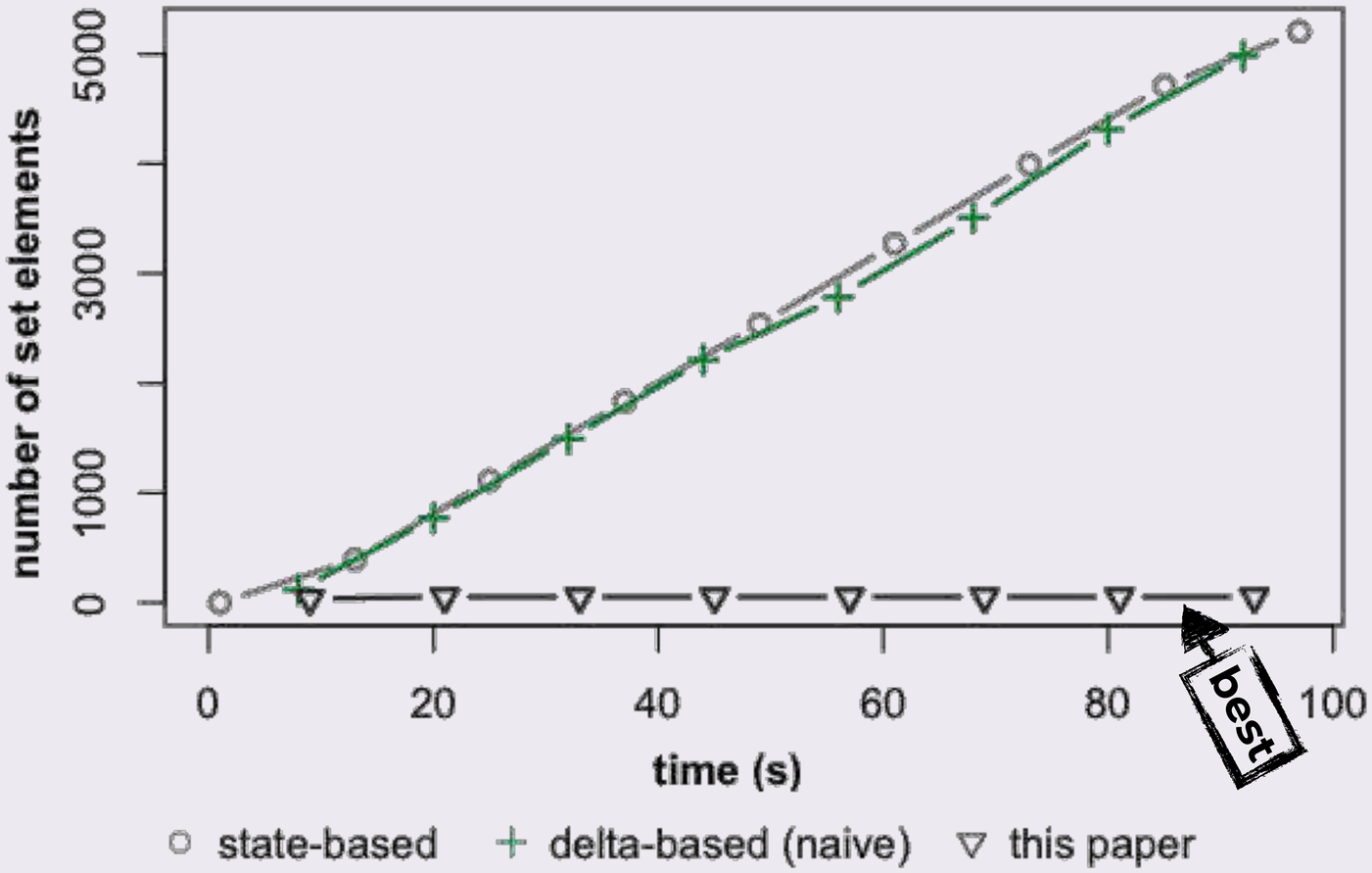
BEST OF BOTH WORLDS!

in reality...

BANDWIDTH
(as bad as state-based)



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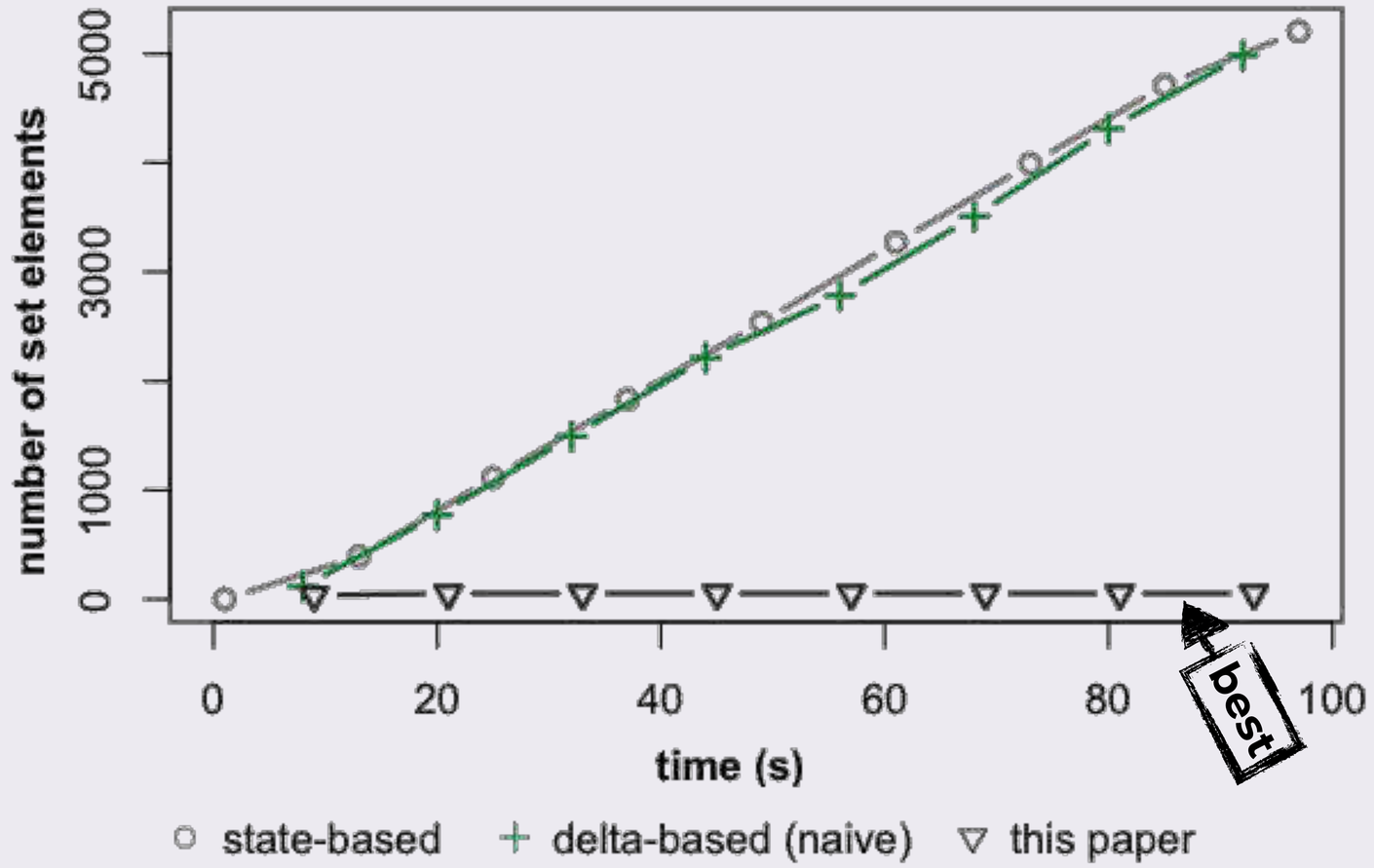
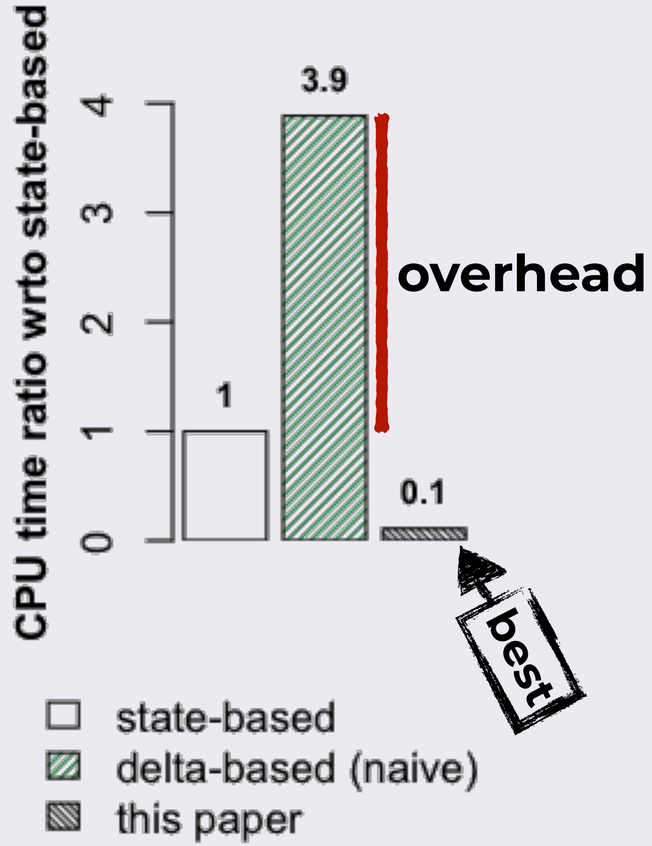


CPU
(worse than state-based)



main contribution

***achieve** delta-based **true potential** through careful delta propagation*

state-based CRDTs

- simplest example: **set**

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$$S, \subseteq, \cup$$

subset **set union**

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FILTER **JOIN**

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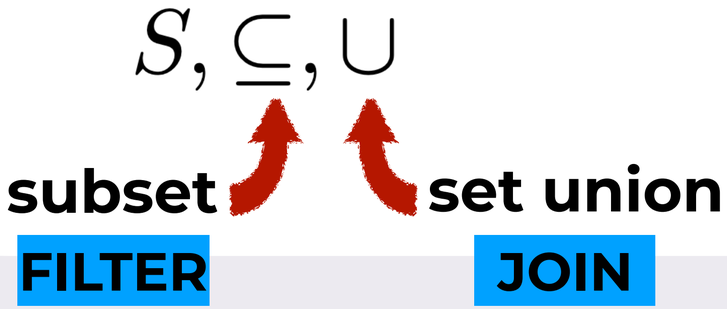

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- **delta-based:** delta-mutators (**dm**) return deltas

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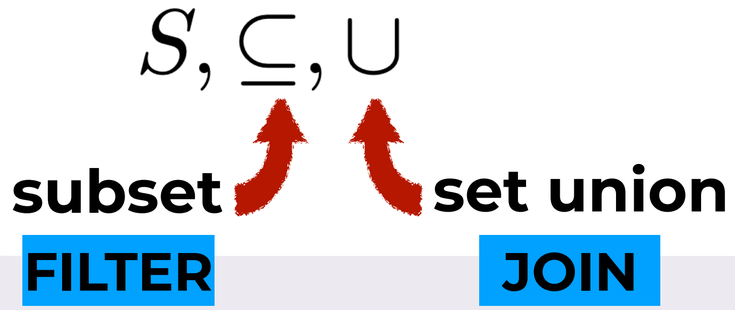

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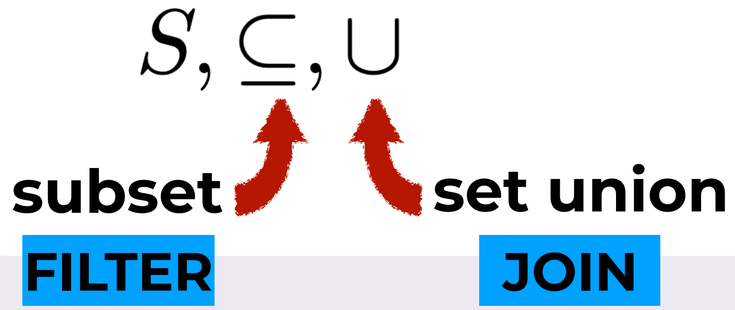

> ***add c to the set {a, b}***
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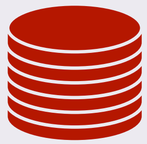
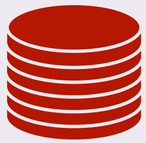
> **dm({a, b}) = {c}**

- **state-based:** mutators (**m**) inflate local state
- **delta-based:** delta-mutators (**dm**) return deltas
  1. **joined with local state**
  2. **added to a delta-buffer (to be propagated)**

delta-buffer notation





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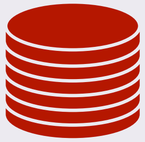

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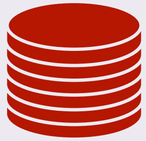

CRDT state

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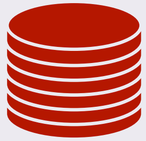

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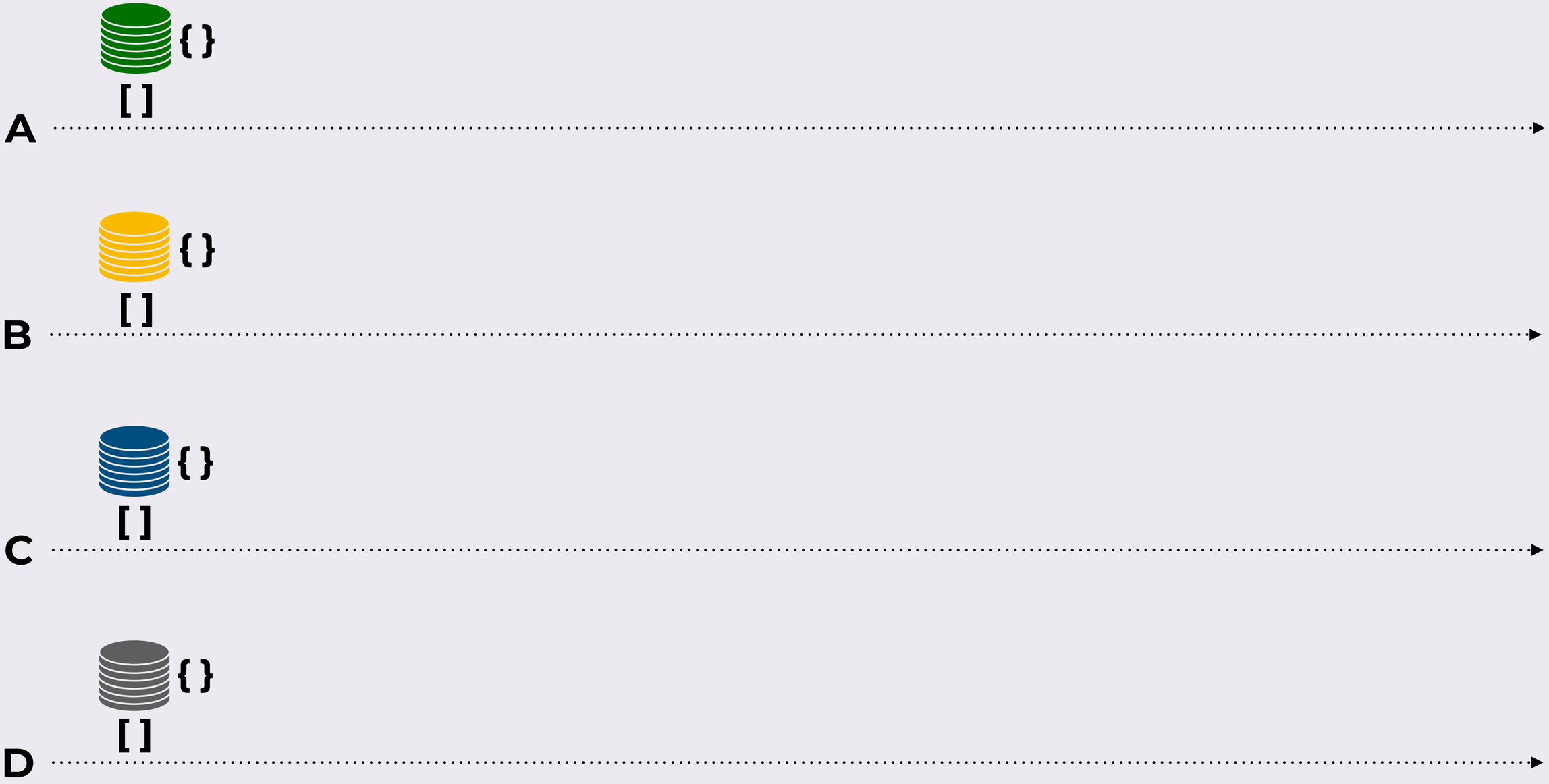

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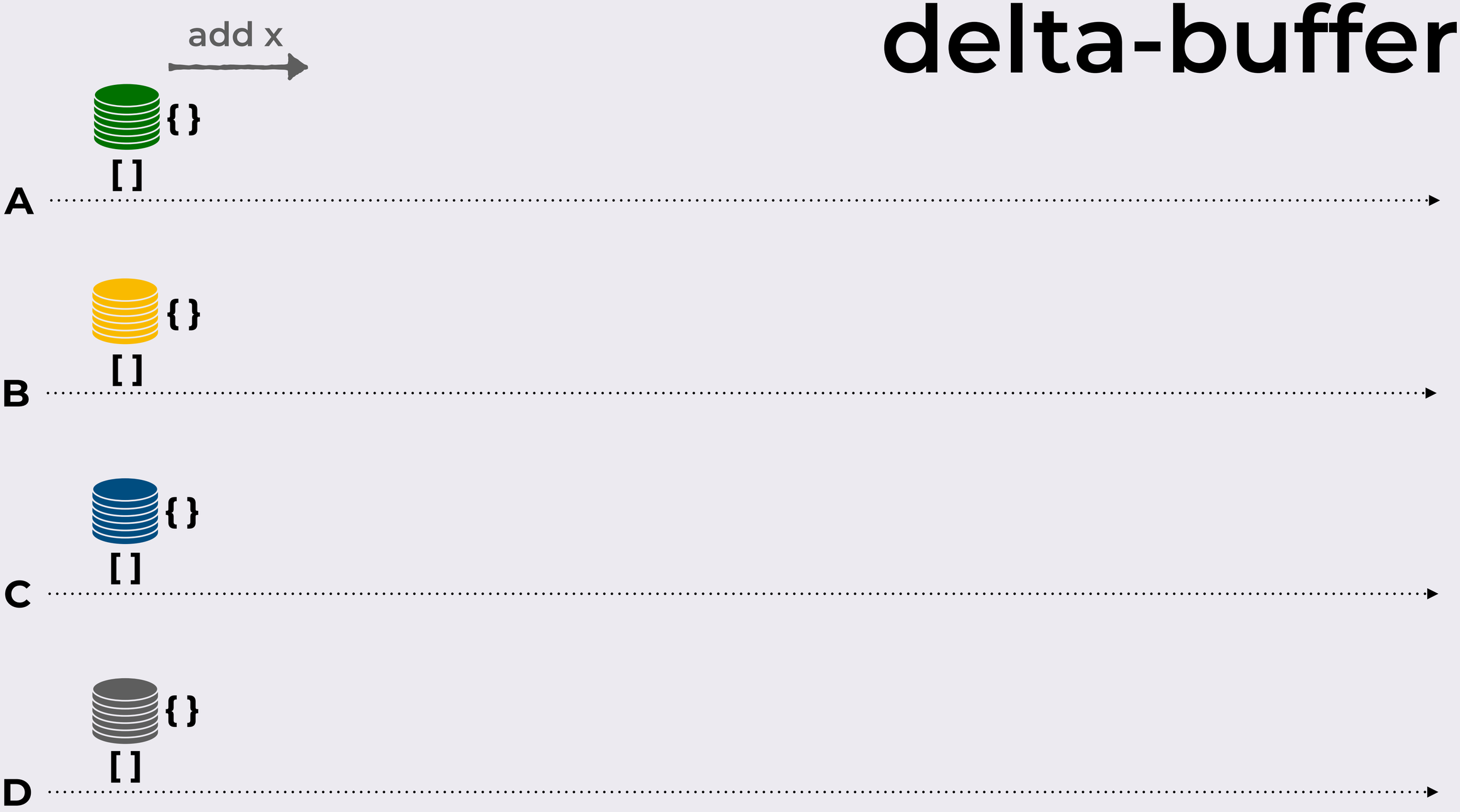

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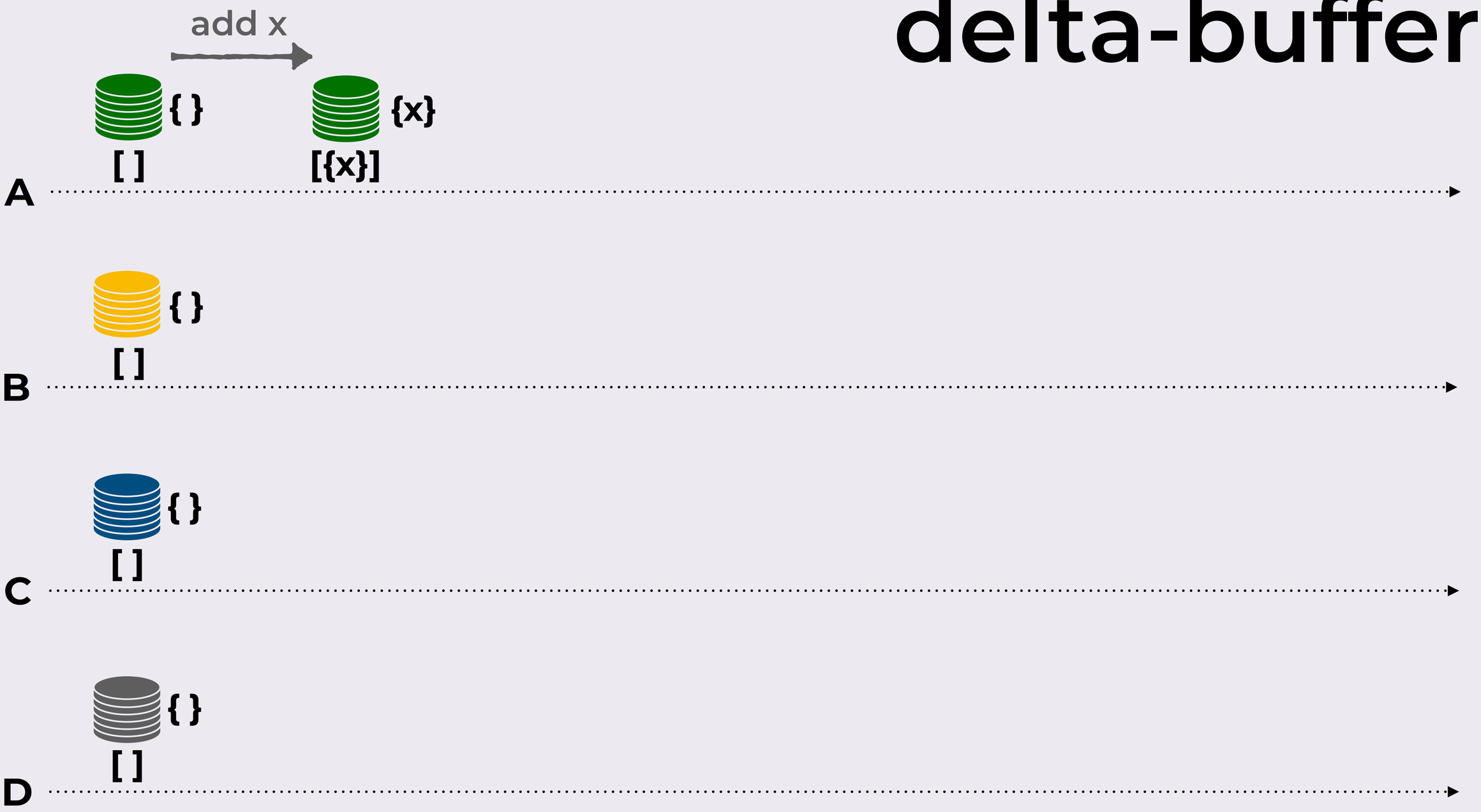

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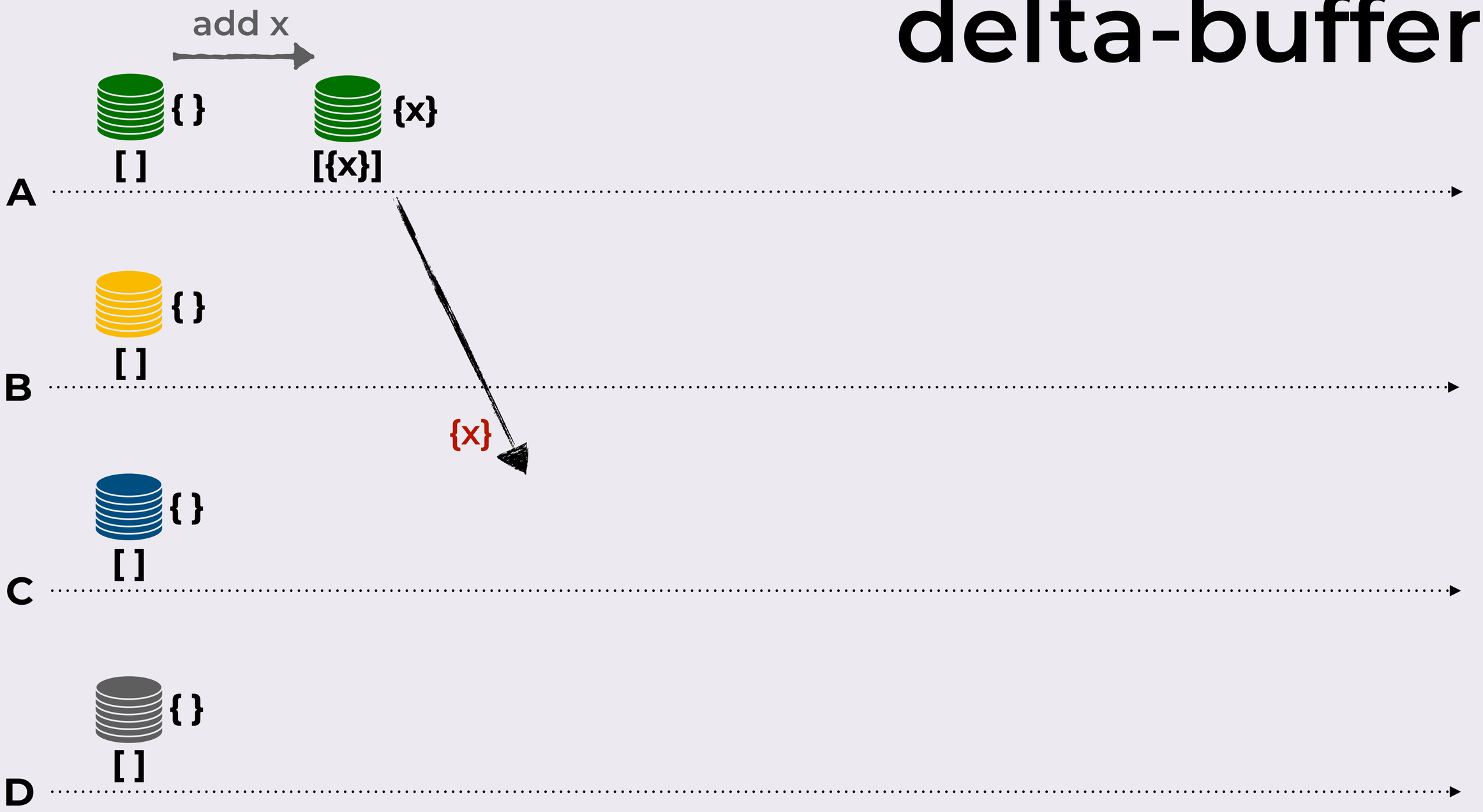

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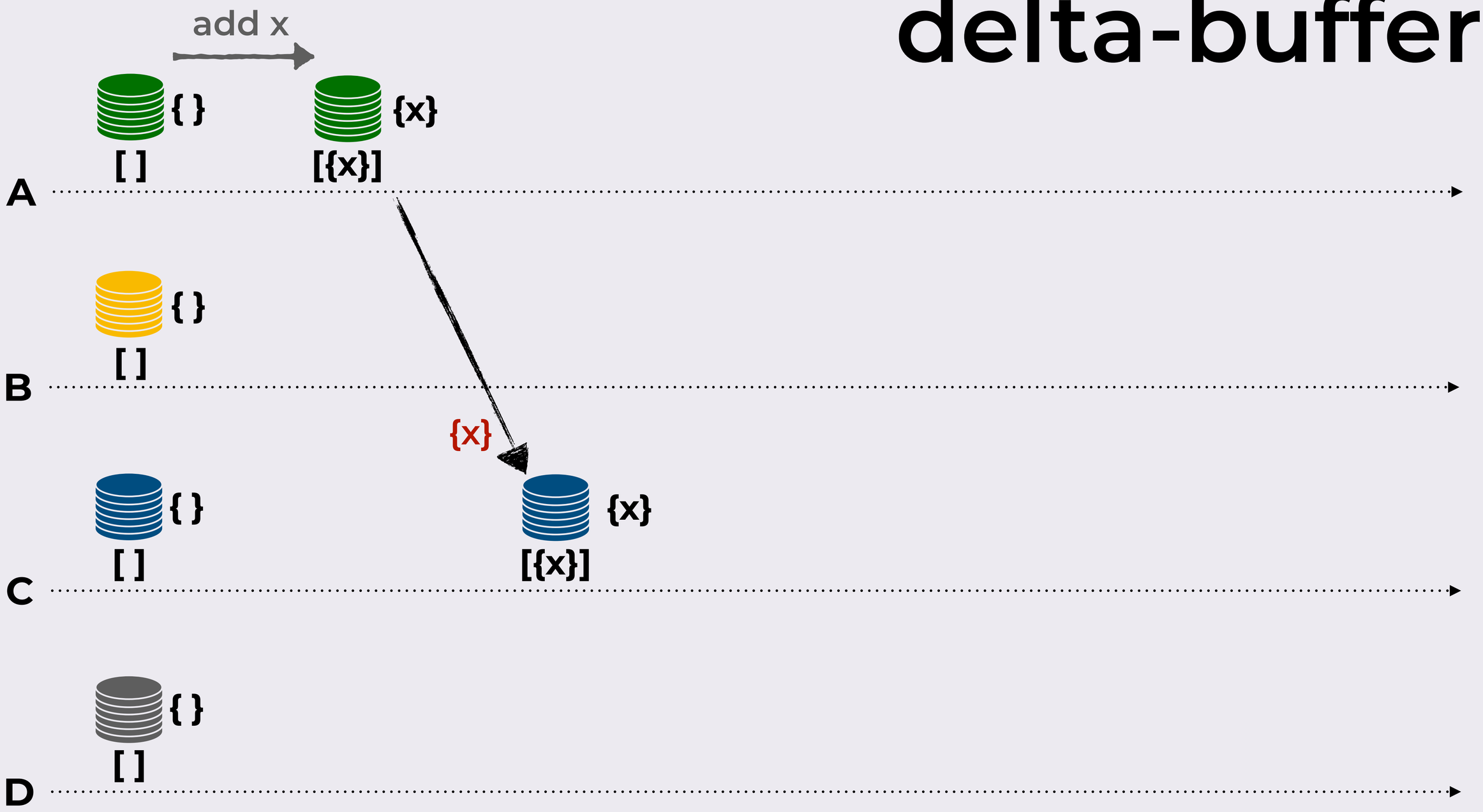

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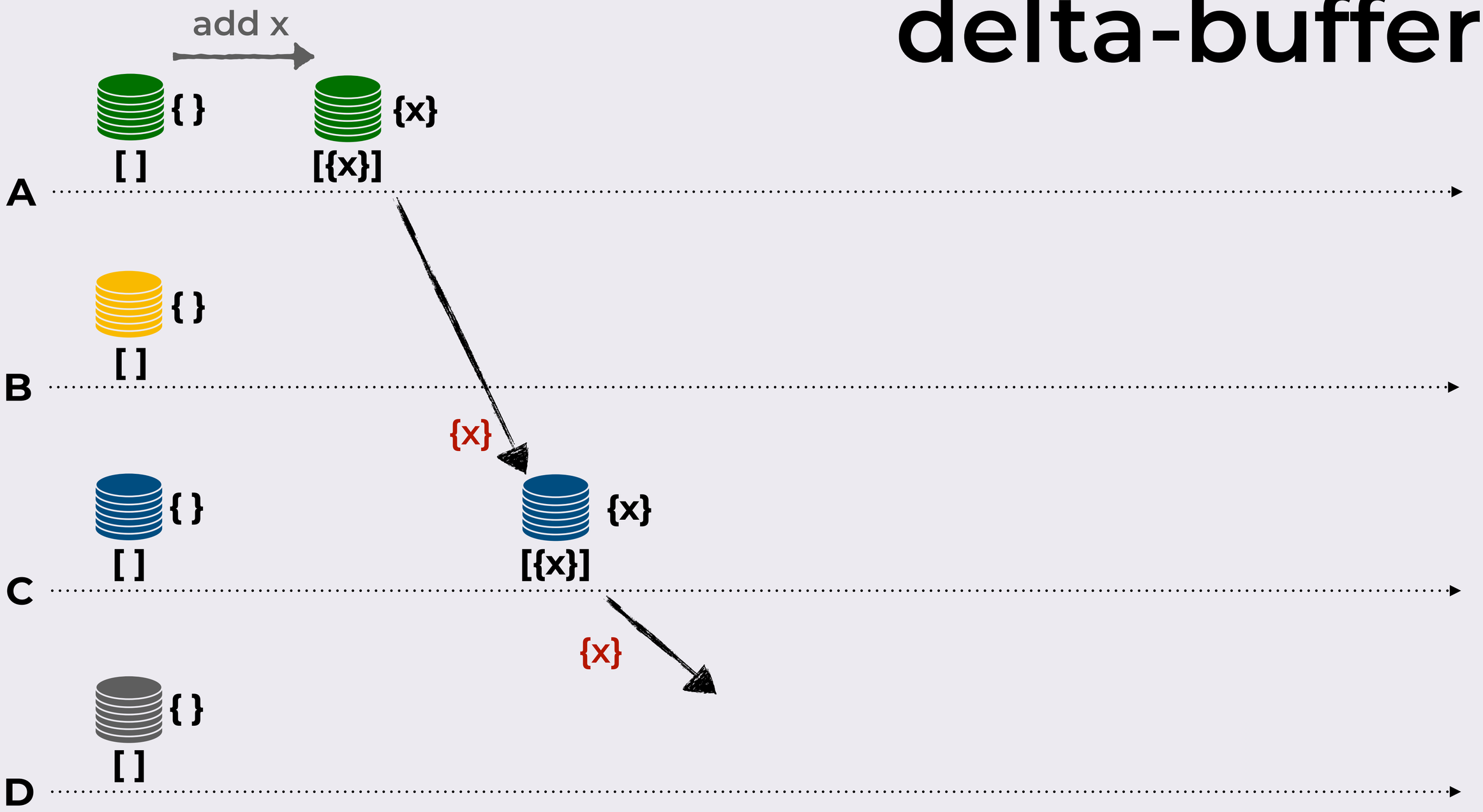

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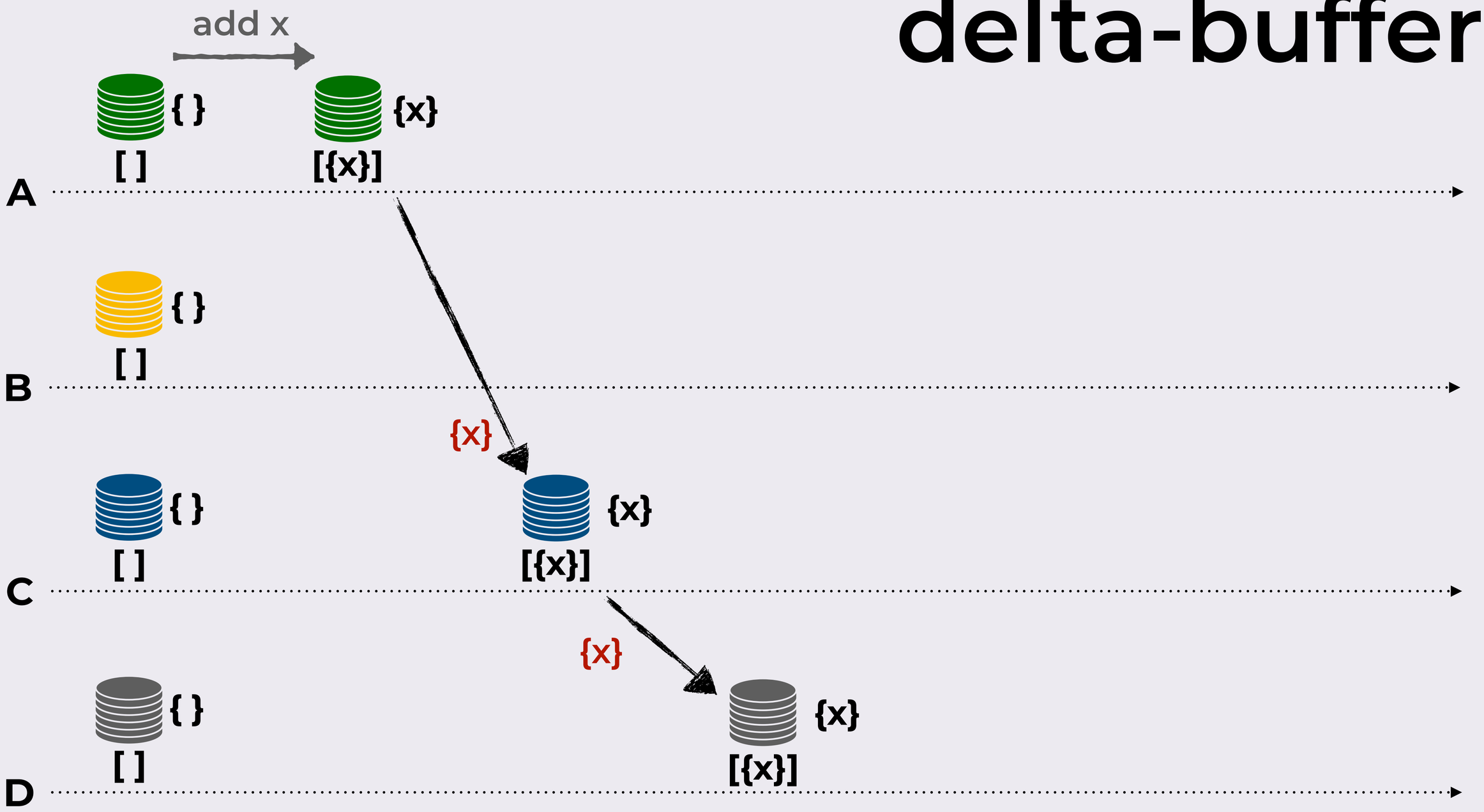

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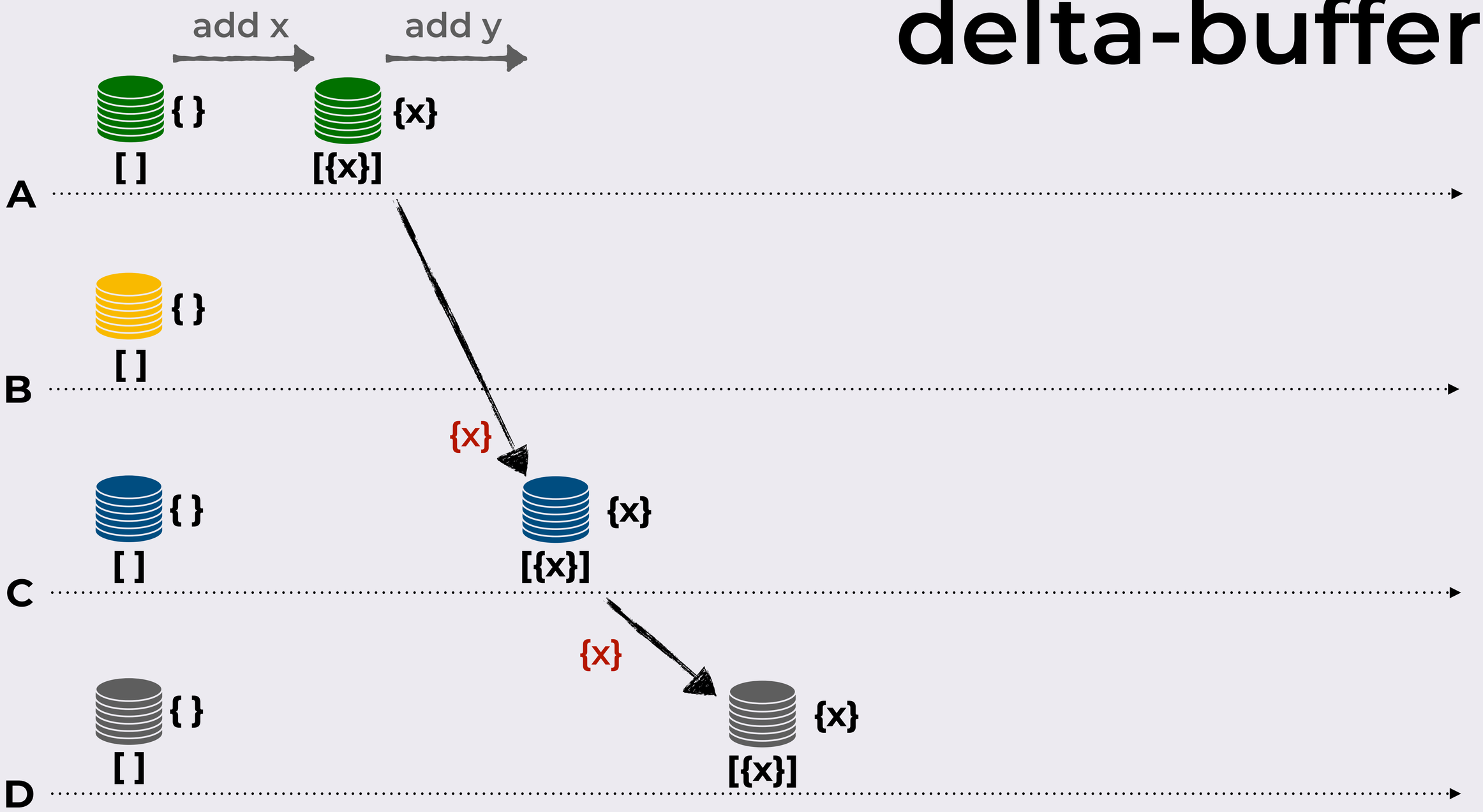

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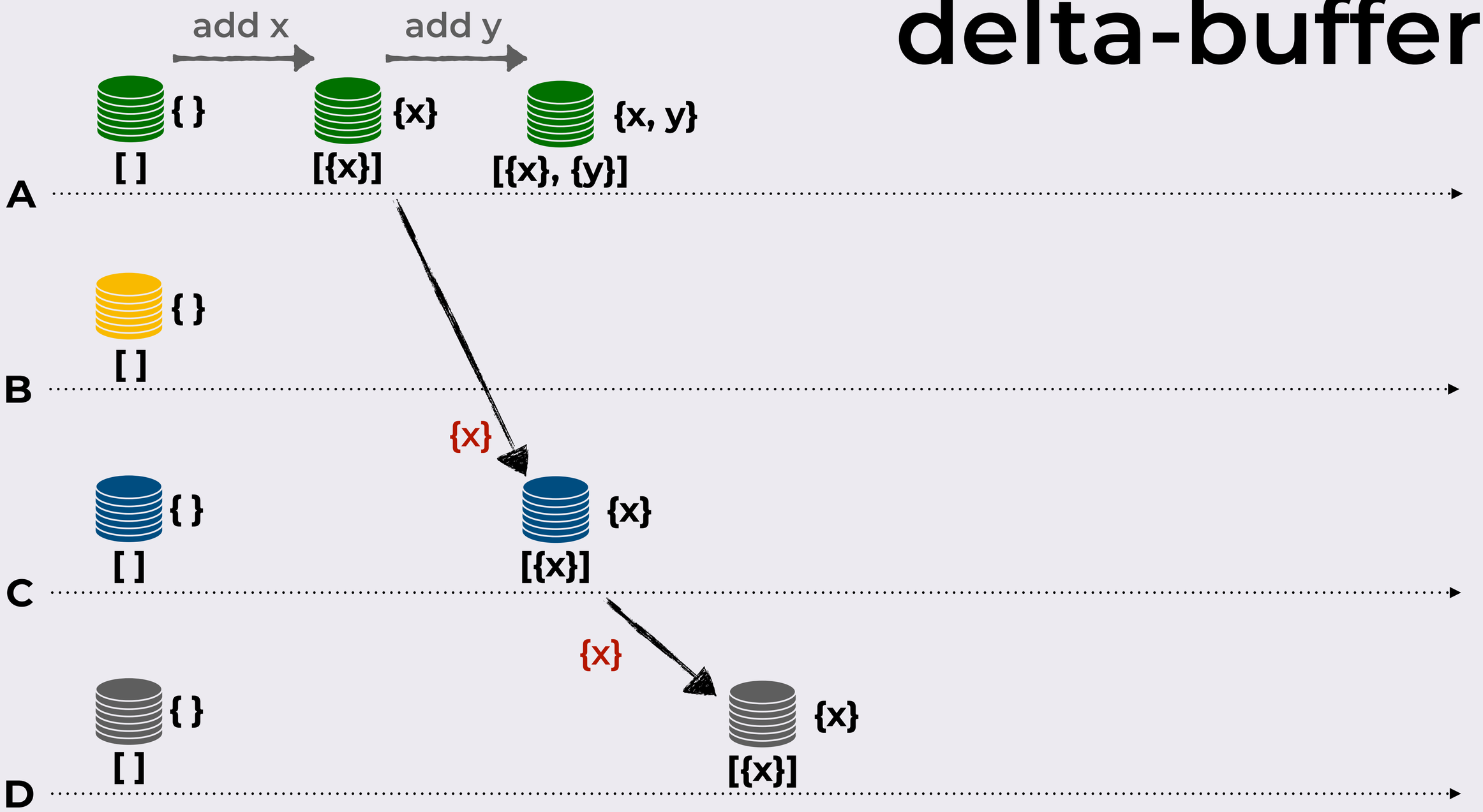

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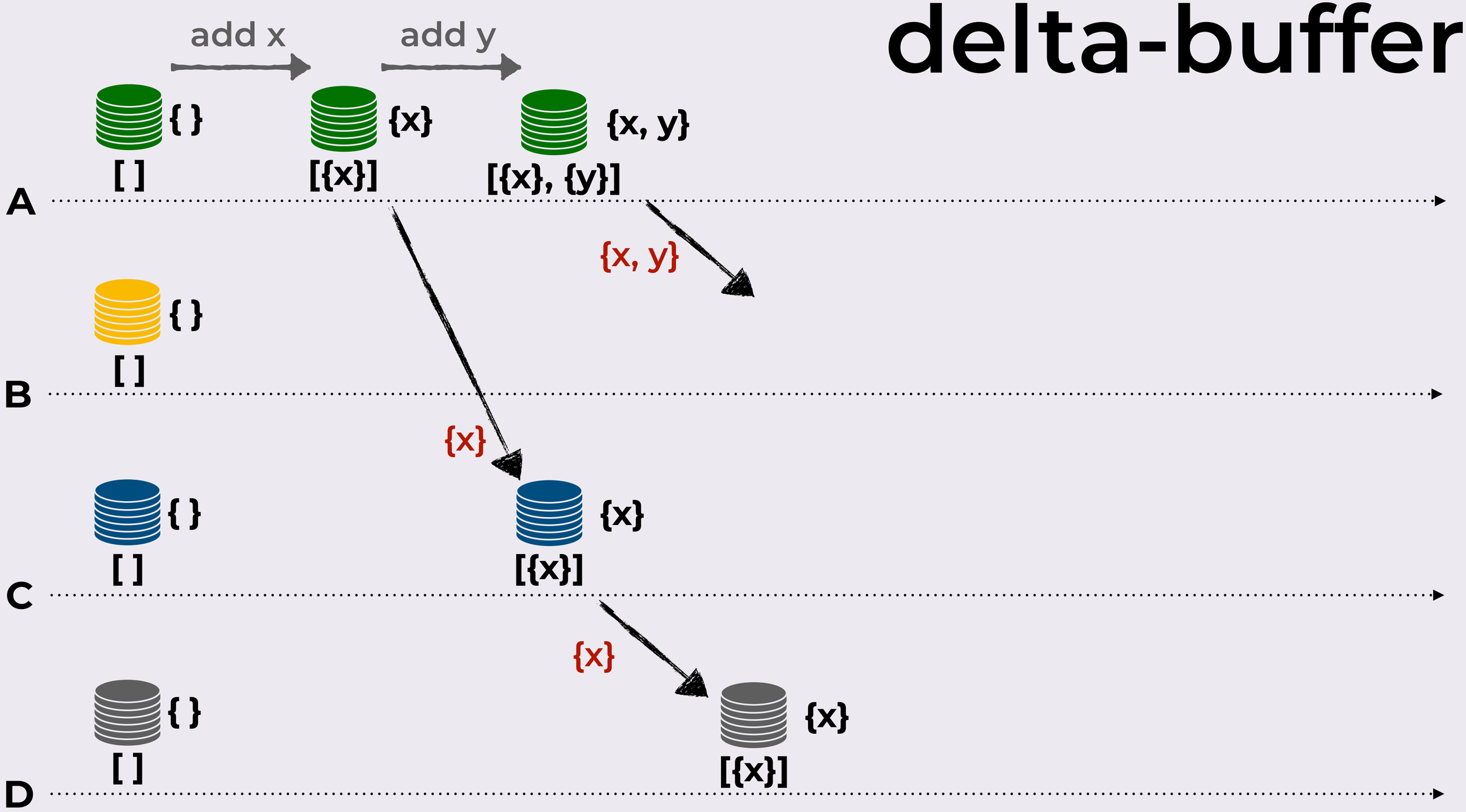

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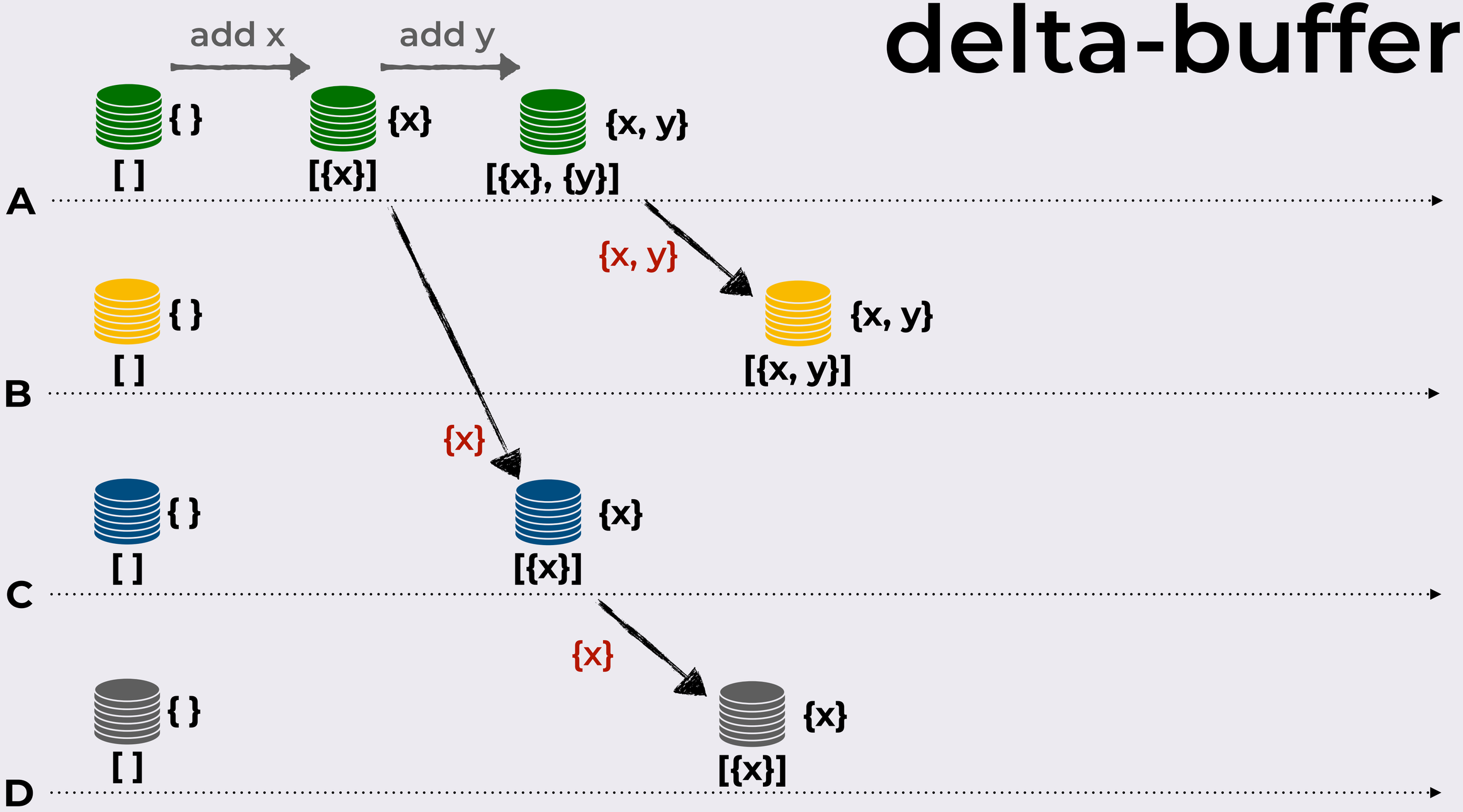

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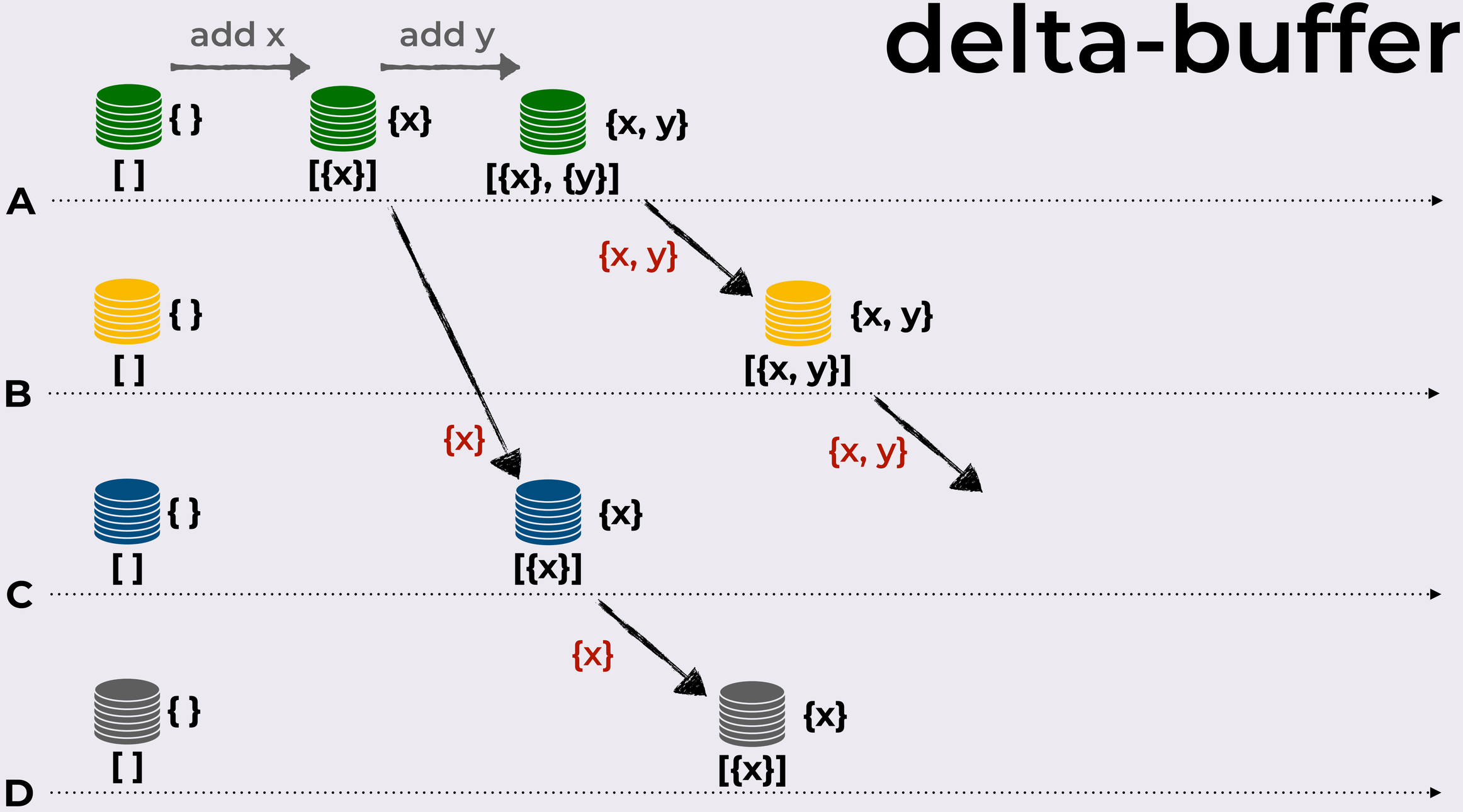

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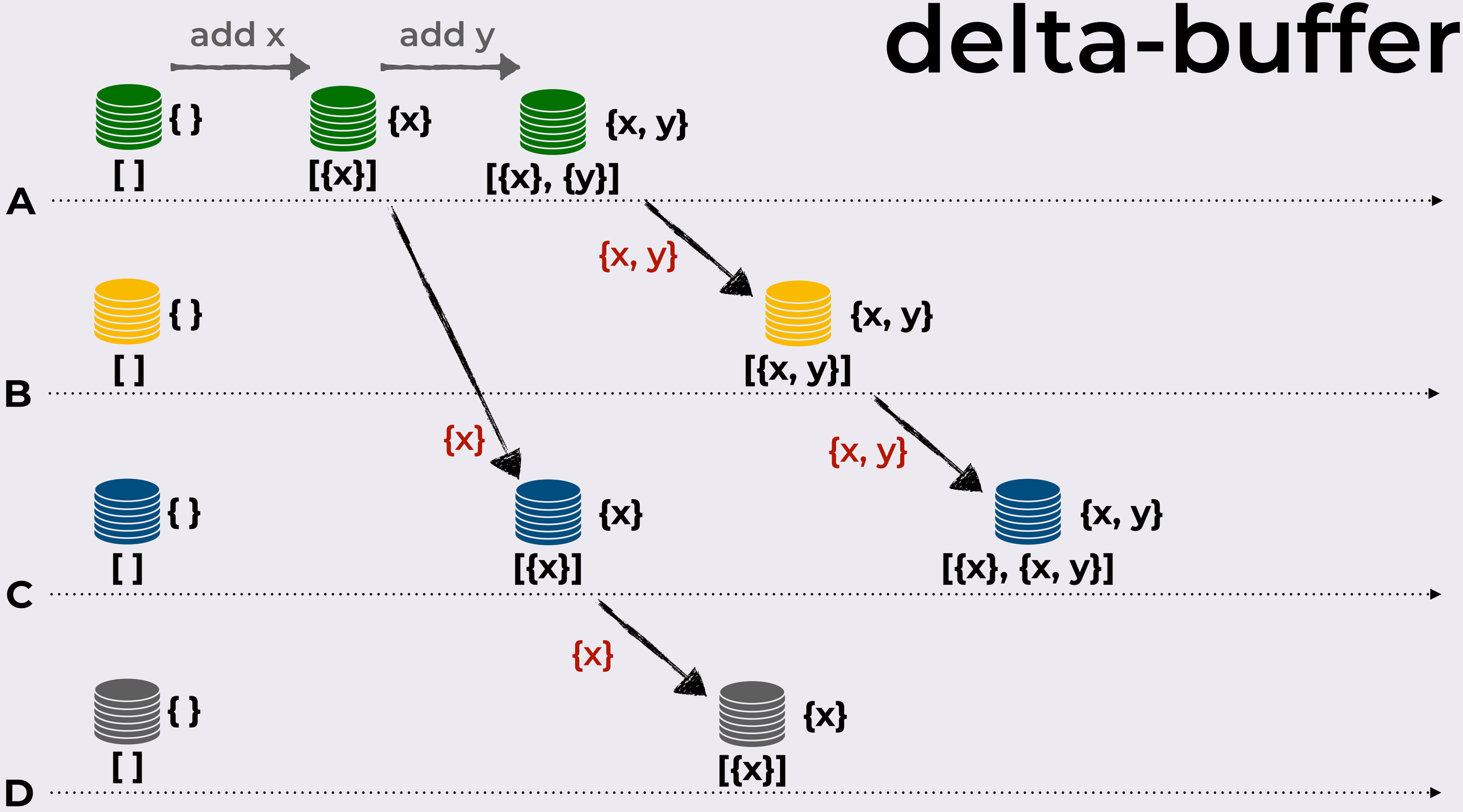

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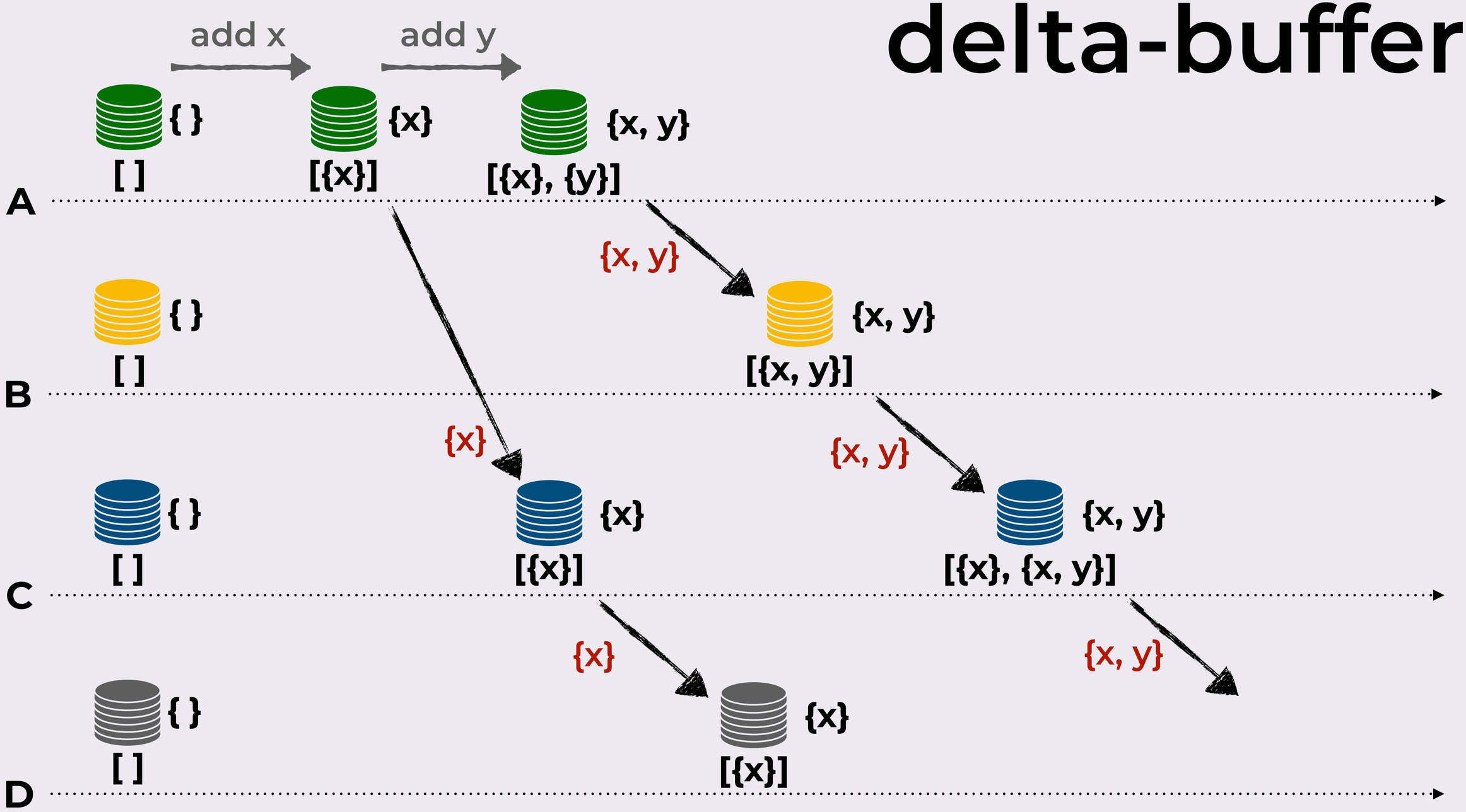

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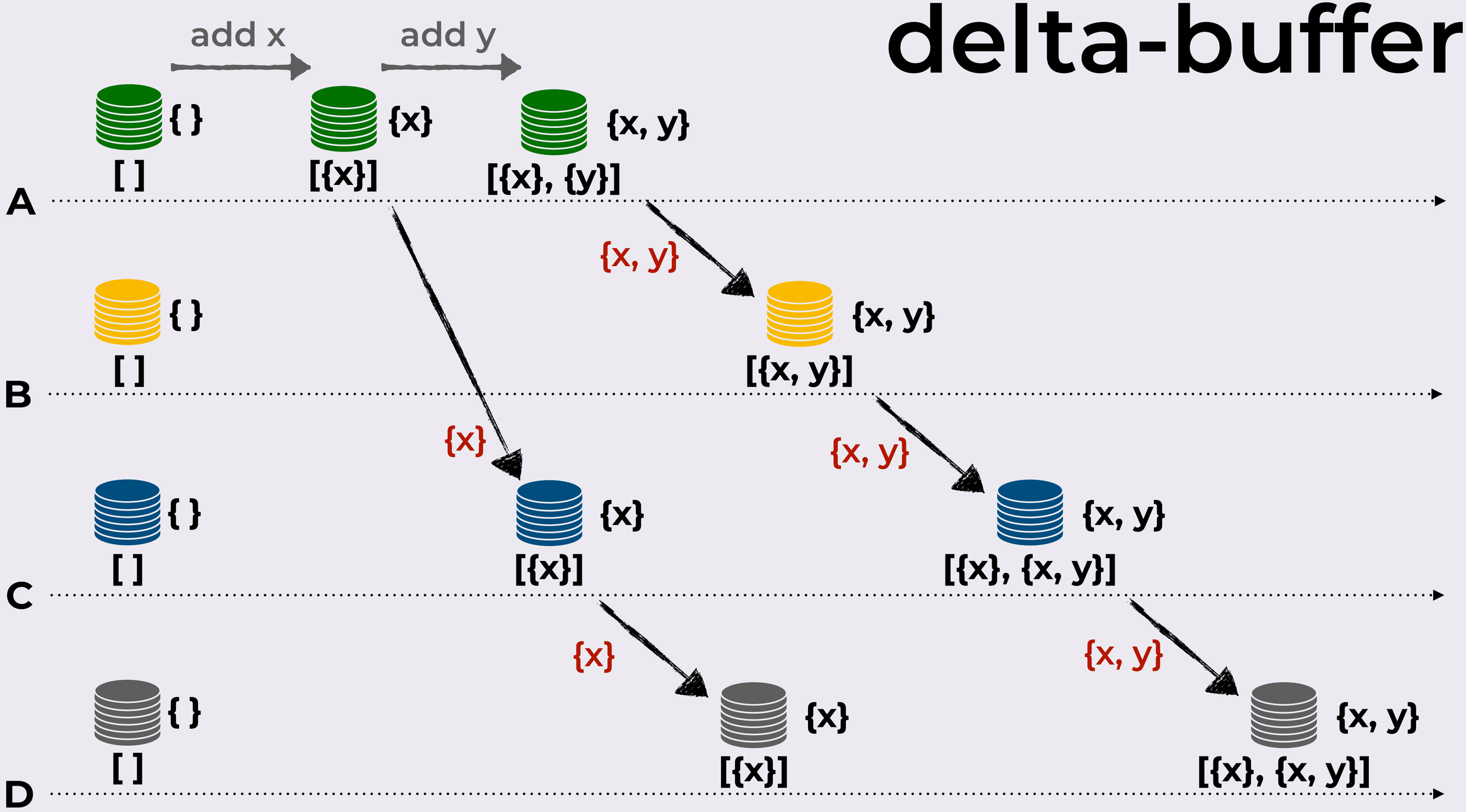

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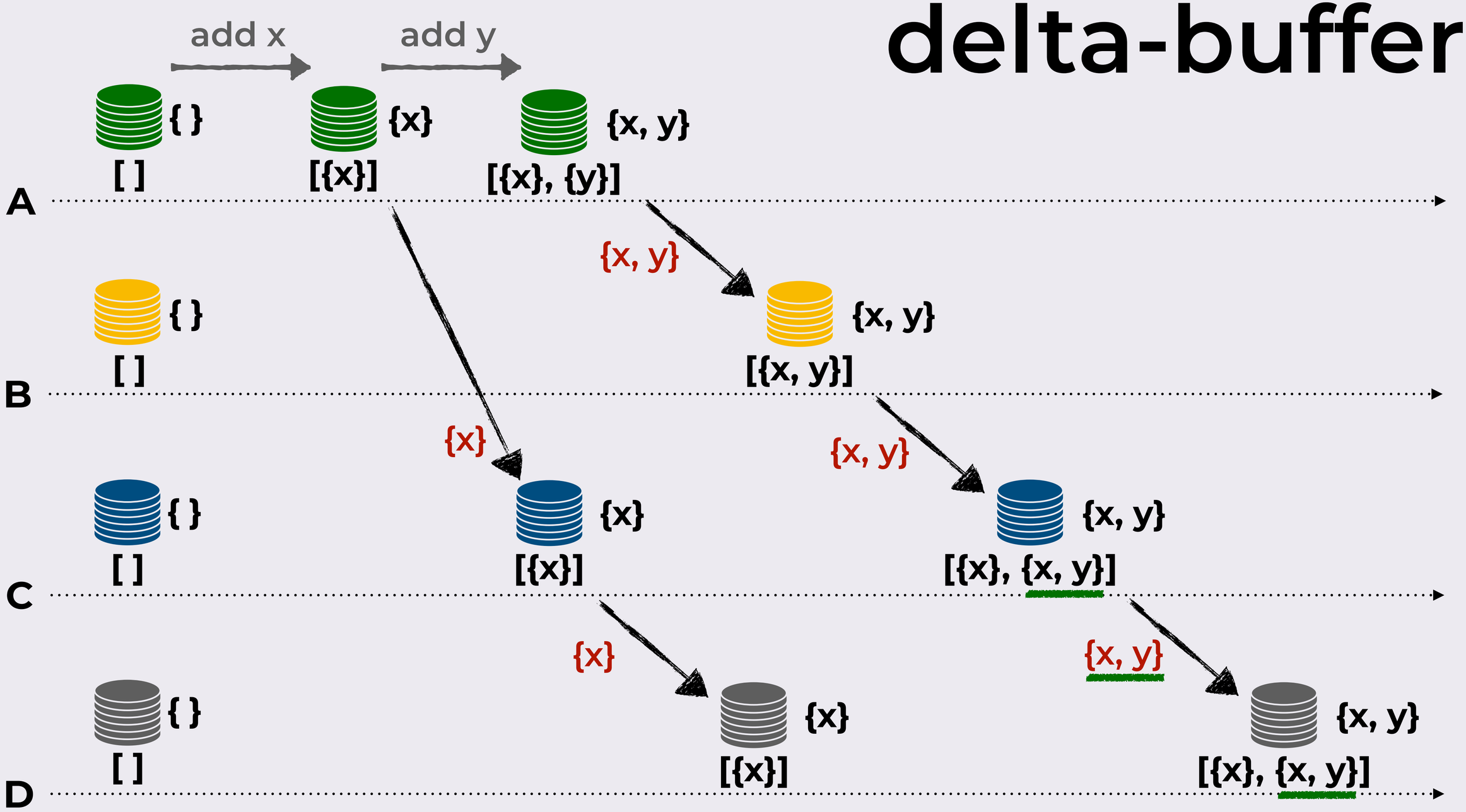

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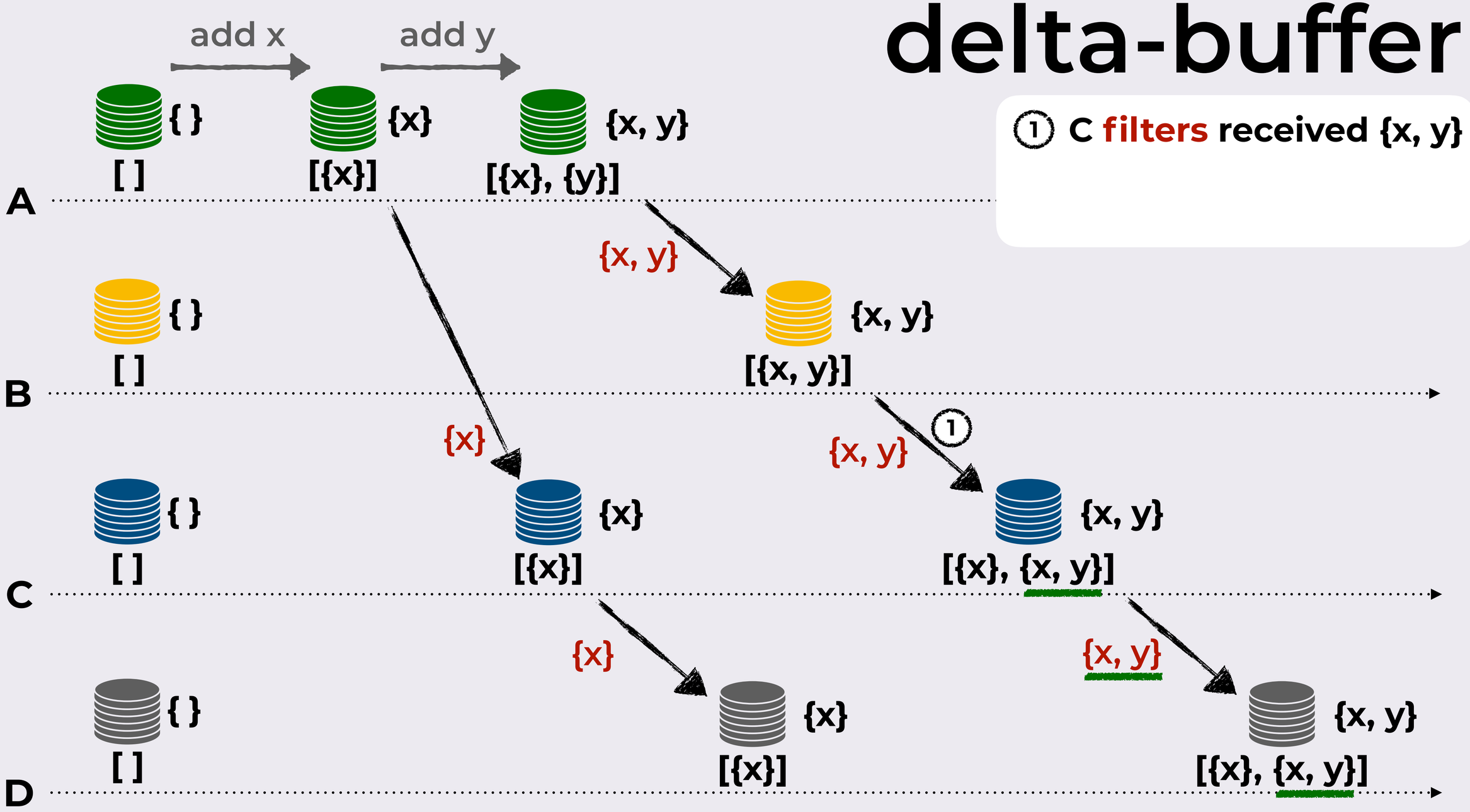
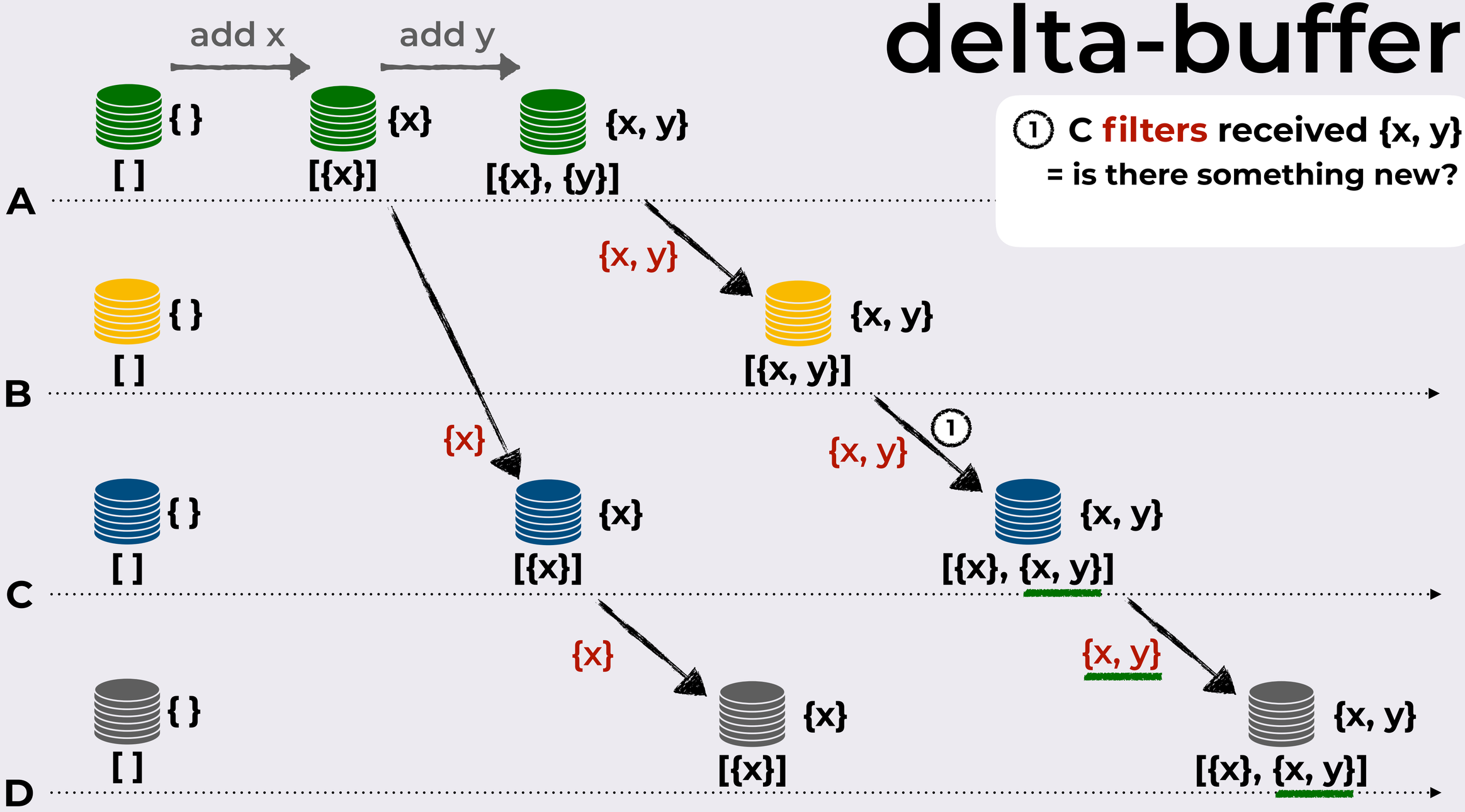


1 C **filters** received {x, y}

delta-buffer



① C **filters** received {x, y}
= is there something new?

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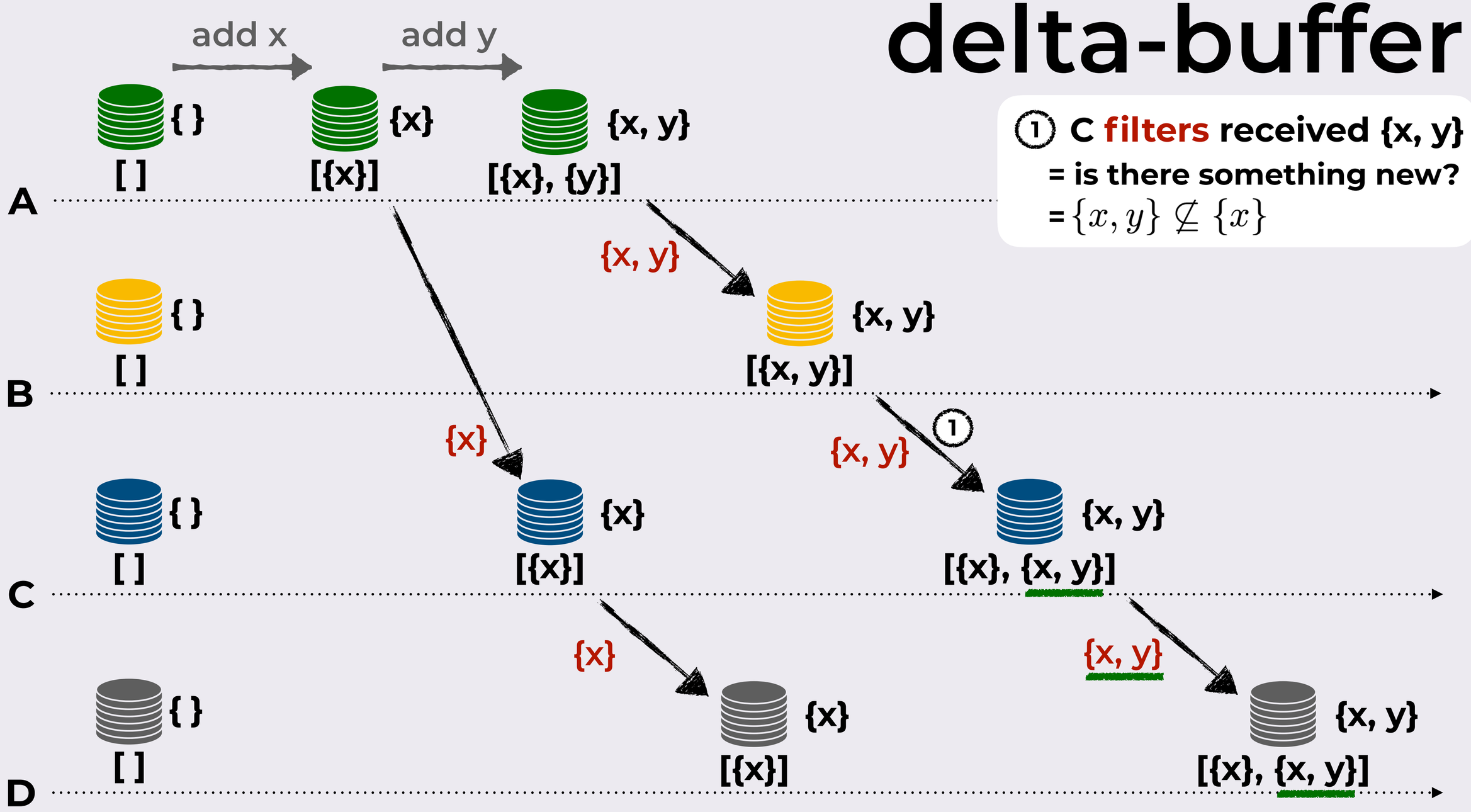

① C **filters** received {x, y}
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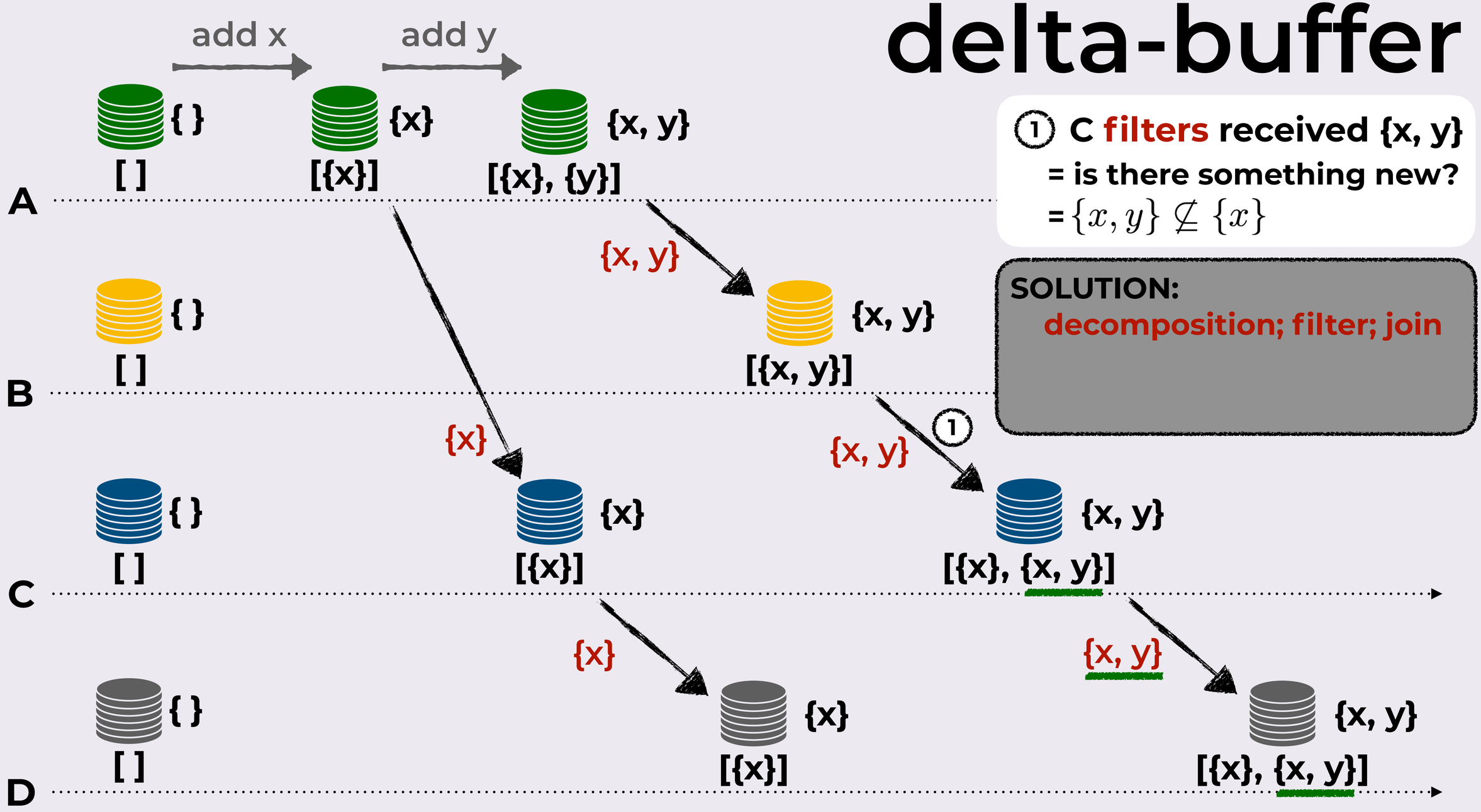

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SOLUTION:
decomposition; filter; join

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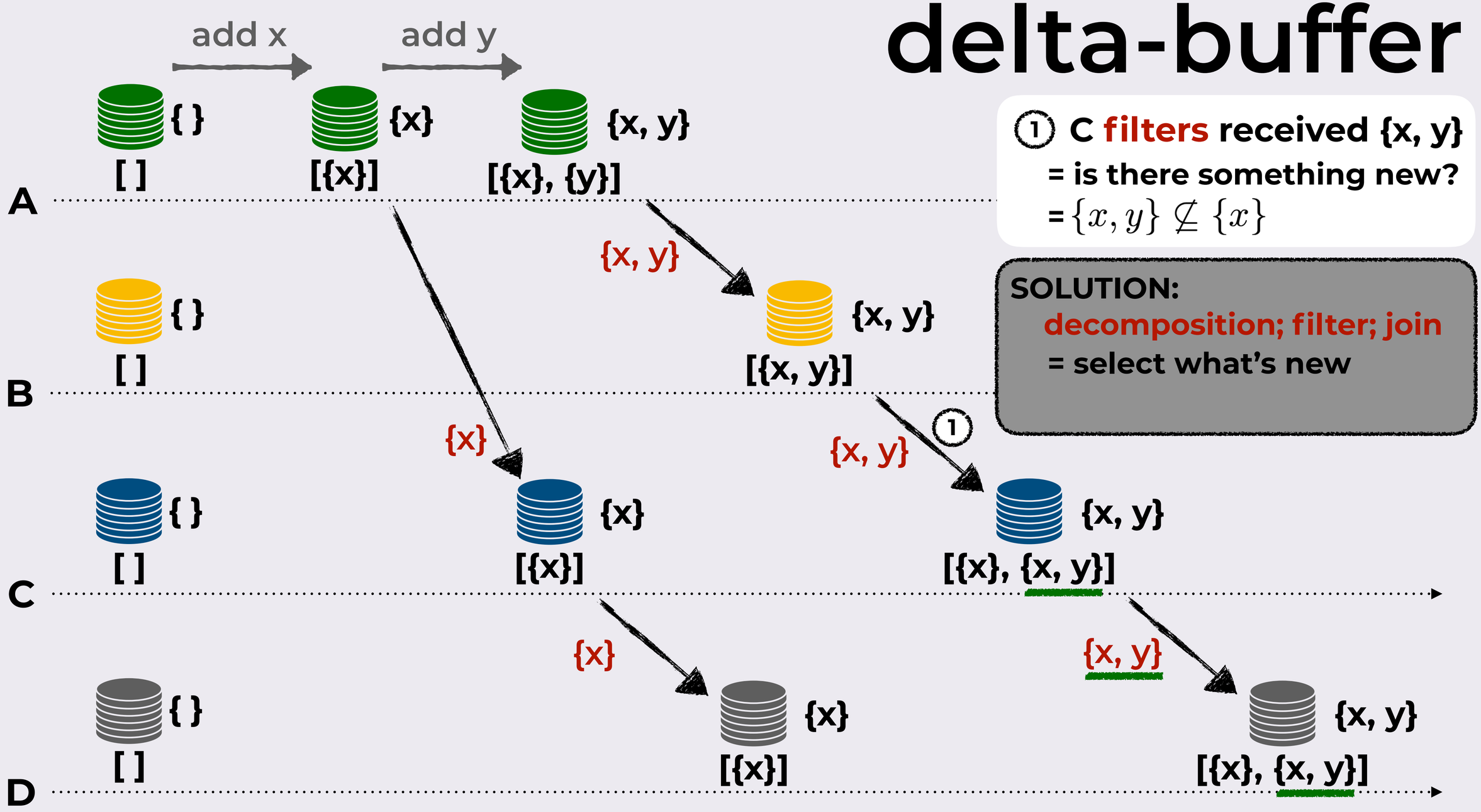

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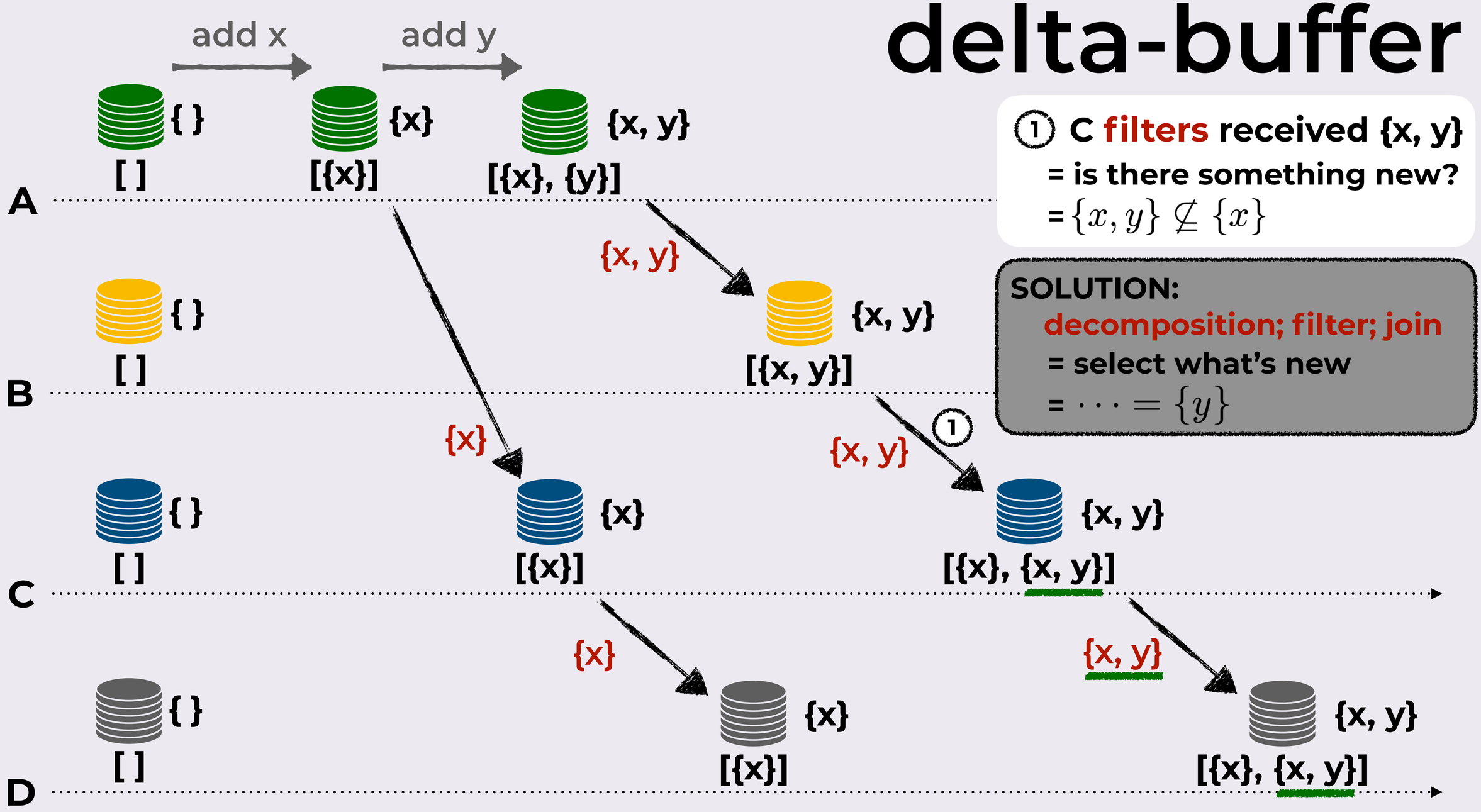

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= $\cdots = \{y\}$

decomposition

- **example:**

  decomposition$(\{a, b, c\}) = \{\{a\}, \{b\}, \{c\}\}$

decomposition

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  2. no element is redundant

✗ $S_1 = \{\{b\}, \{c\}\}$

✗ $S_2 = \{\{a, b\}, \{b\}, \{c\}\}$

decomposition

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- **S** is a **decomposition** of **x** if:

  1. join of S gives x
  2. no element is redundant
  3. every element is irreducible

✗ $S_1 = \{\{b\}, \{c\}\}$

✗ $S_2 = \{\{a, b\}, \{b\}, \{c\}\}$

✗ $S_3 = \{\{a, b\}, \{c\}\}$

decomposition

- **example:**
  $\text{decomposition}(\{a, b, c\}) = \{\{a\}, \{b\}, \{c\}\}$

- **S** is a **decomposition** of **x** if:

  1. join of S gives x
  2. no element is redundant
  3. every element is irreducible

✗ $S_1 = \{\{b\}, \{c\}\}$

✗ $S_2 = \{\{a, b\}, \{b\}, \{c\}\}$

✗ $S_3 = \{\{a, b\}, \{c\}\}$

✓ $S_4 = \{\{a\}, \{b\}, \{c\}\}$

decomposition

- **example:**

  $\text{decomposition}(\{a, b, c\}) = \{\{a\}, \{b\}, \{c\}\} = \Downarrow \{a, b, c\}$

- **S** is a **decomposition** of **x** if:

  1. join of S gives x
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✓ $S_4 = \{\{a\}, \{b\}, \{c\}\}$

decomposition; filter; join = difference

decomposition; filter; join = difference

- **example:**

decomposition; filter; join = difference

- **example:**

  difference$(\{x, y\}, \{x\}) = \{y\}$

decomposition; filter; join = difference

- **example:**

difference$(\{x, y\}, \{x\}) = \{y\} = \Delta(\{x, y\}, \{x\})$

decomposition; filter; join = difference

- **example:**

difference$(\{x, y\}, \{x\}) = \{y\} = \Delta(\{x, y\}, \{x\})$

$$\Delta(a, b) = \bigcup \{x \in \Downarrow a \mid x \not\subseteq b\}$$

decomposition; filter; join = difference

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DECOMPOSITION

decomposition; filter; join = difference

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DECOMPOSITION FILTER

decomposition; filter; join = difference

- **example:**

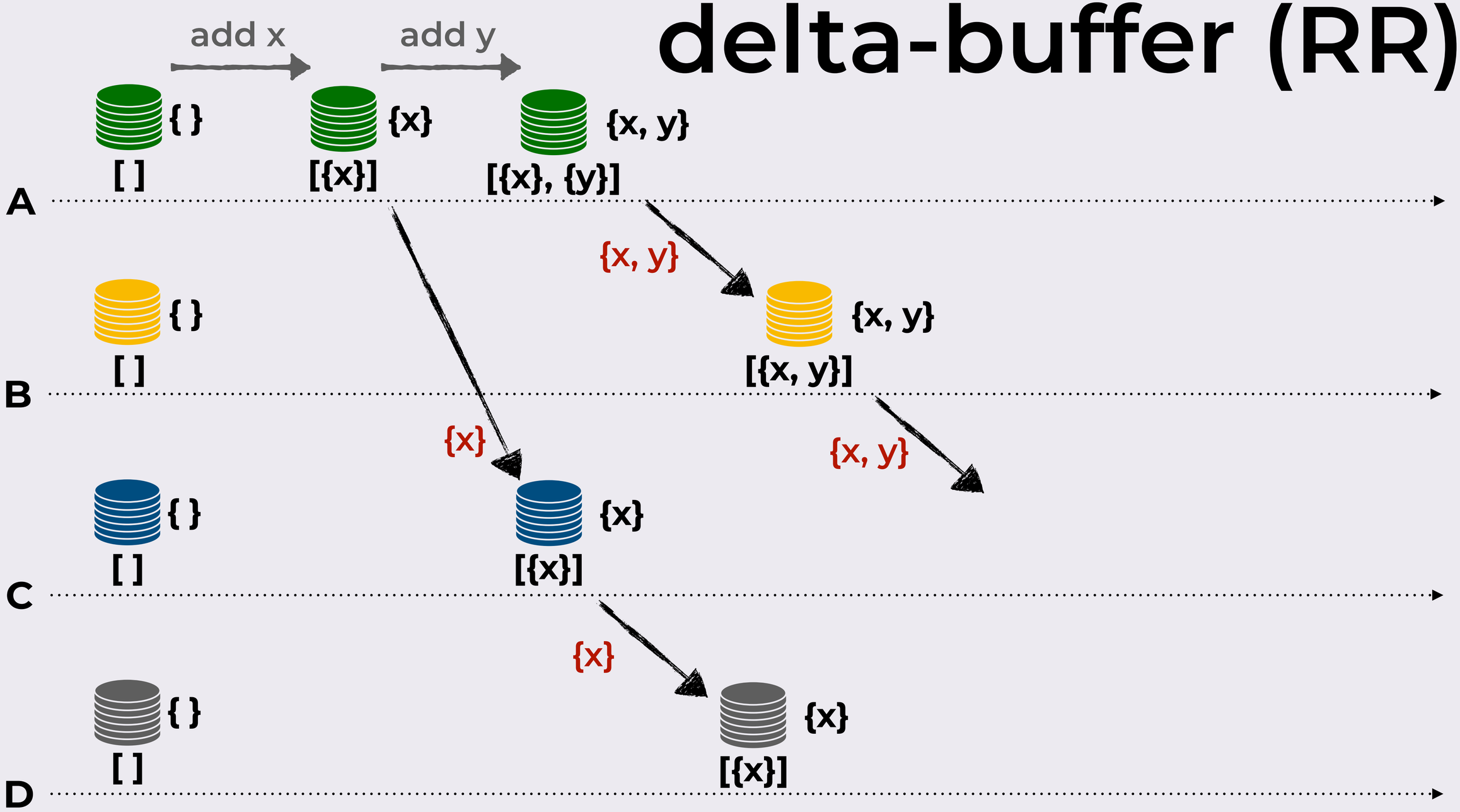
$\text{difference}(\{x, y\}, \{x\}) = \{y\} = \Delta(\{x, y\}, \{x\})$

JOIN

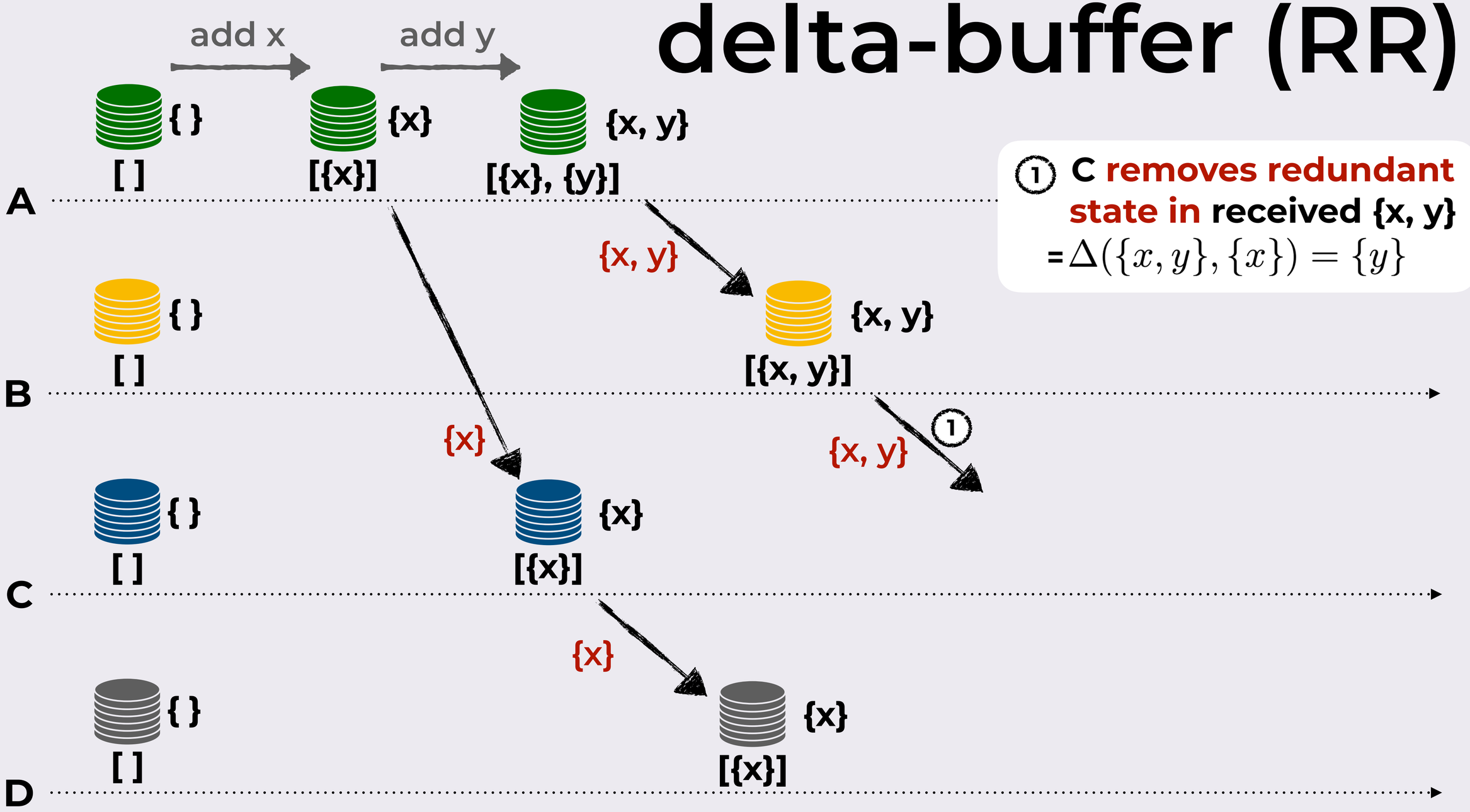
$$\Delta(a, b) = \bigcup \{x \in \Downarrow a \mid x \not\subseteq b\}$$

DECOMPOSITION FILTER

delta-buffer (RR)



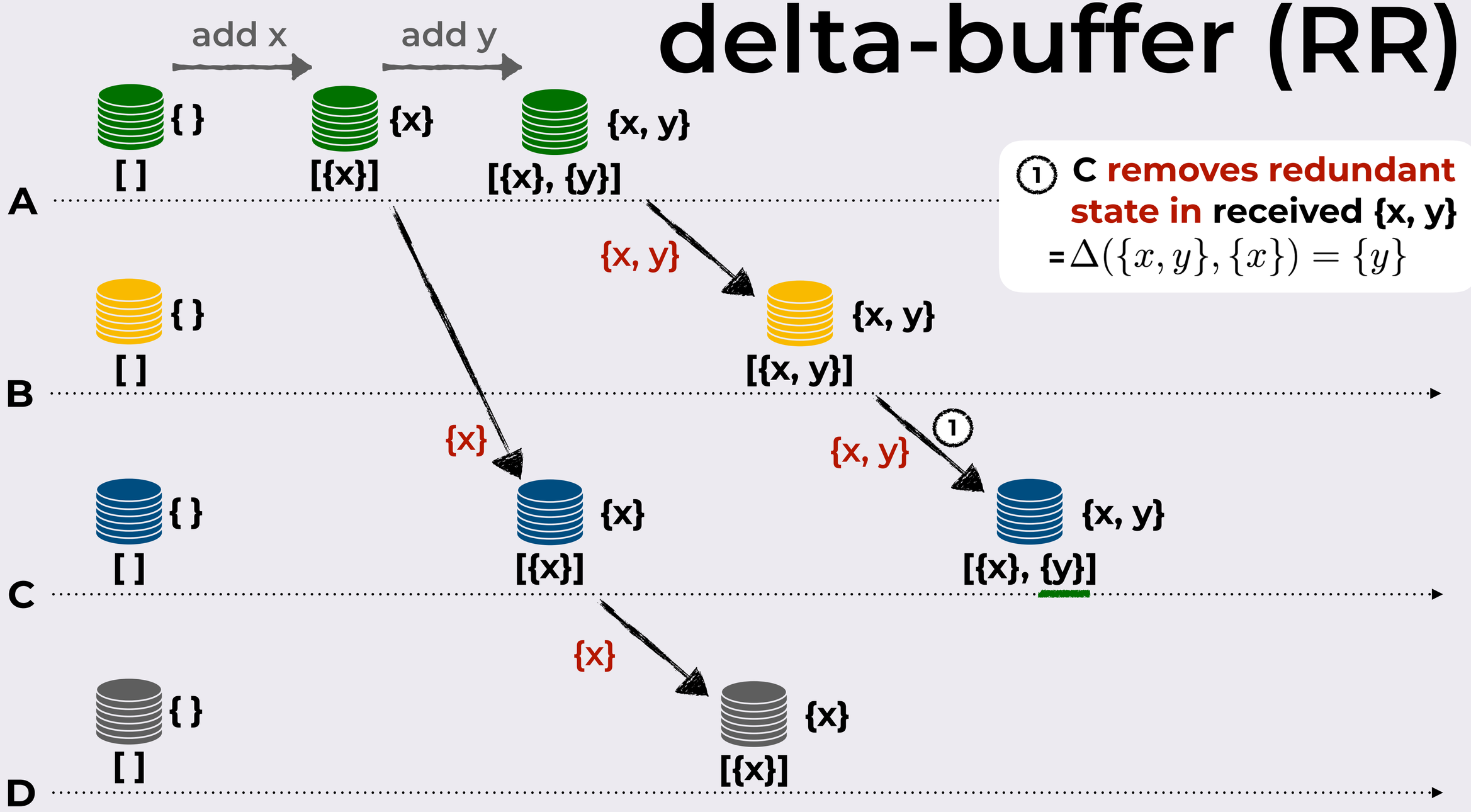
delta-buffer (RR)



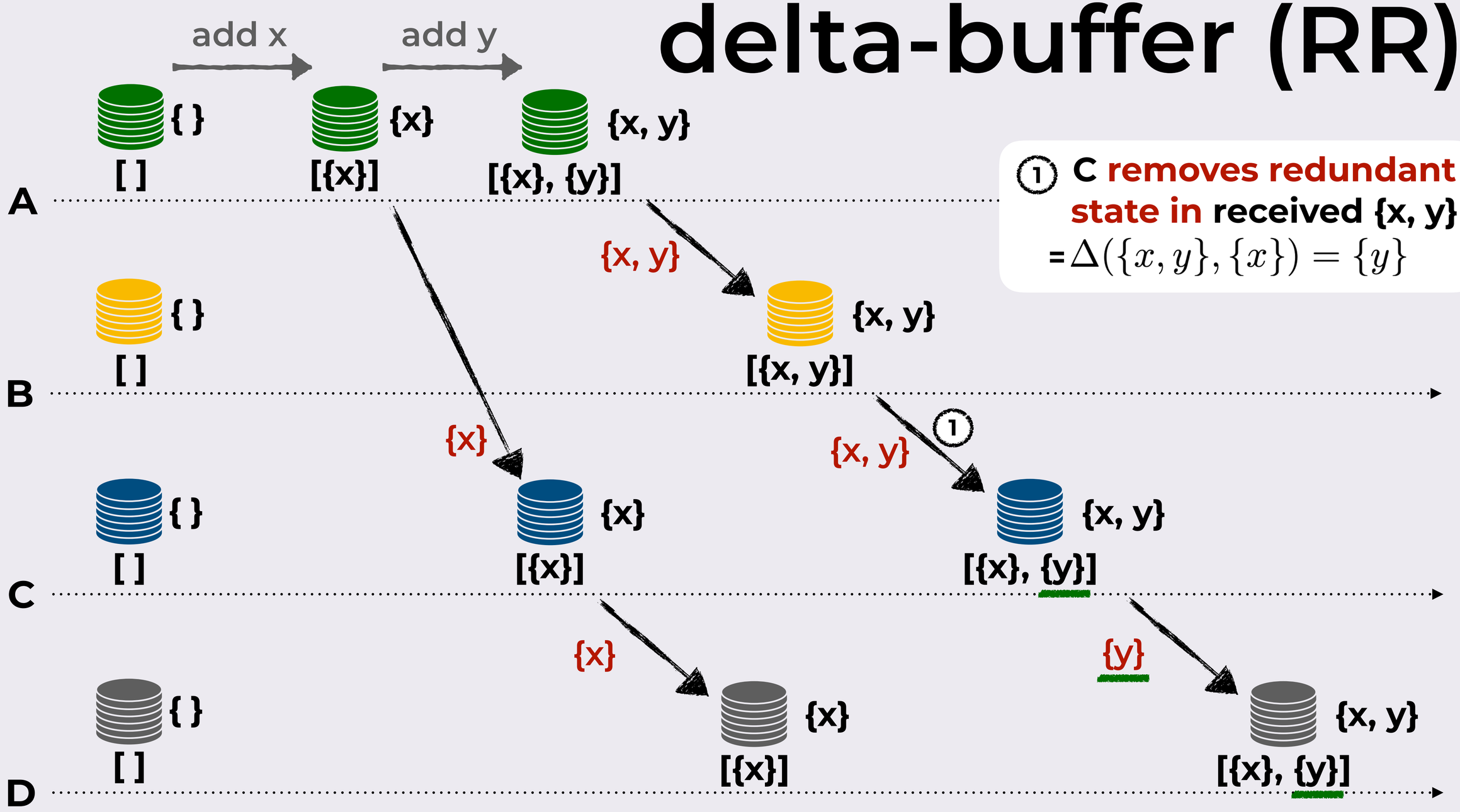
1 C removes redundant state in received {x, y}

$= \Delta(\{x, y\}, \{x\}) = \{y\}$

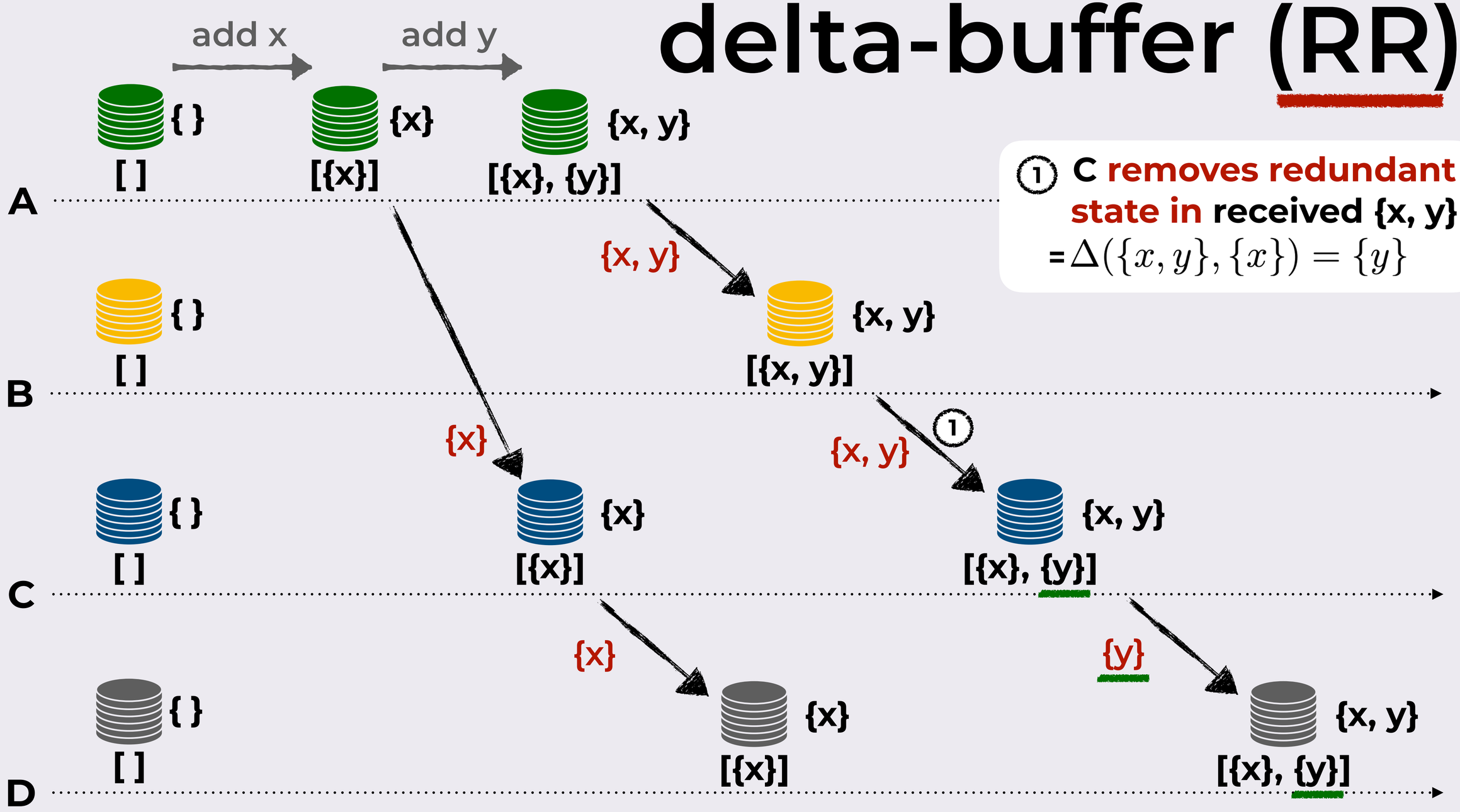
delta-buffer (RR)



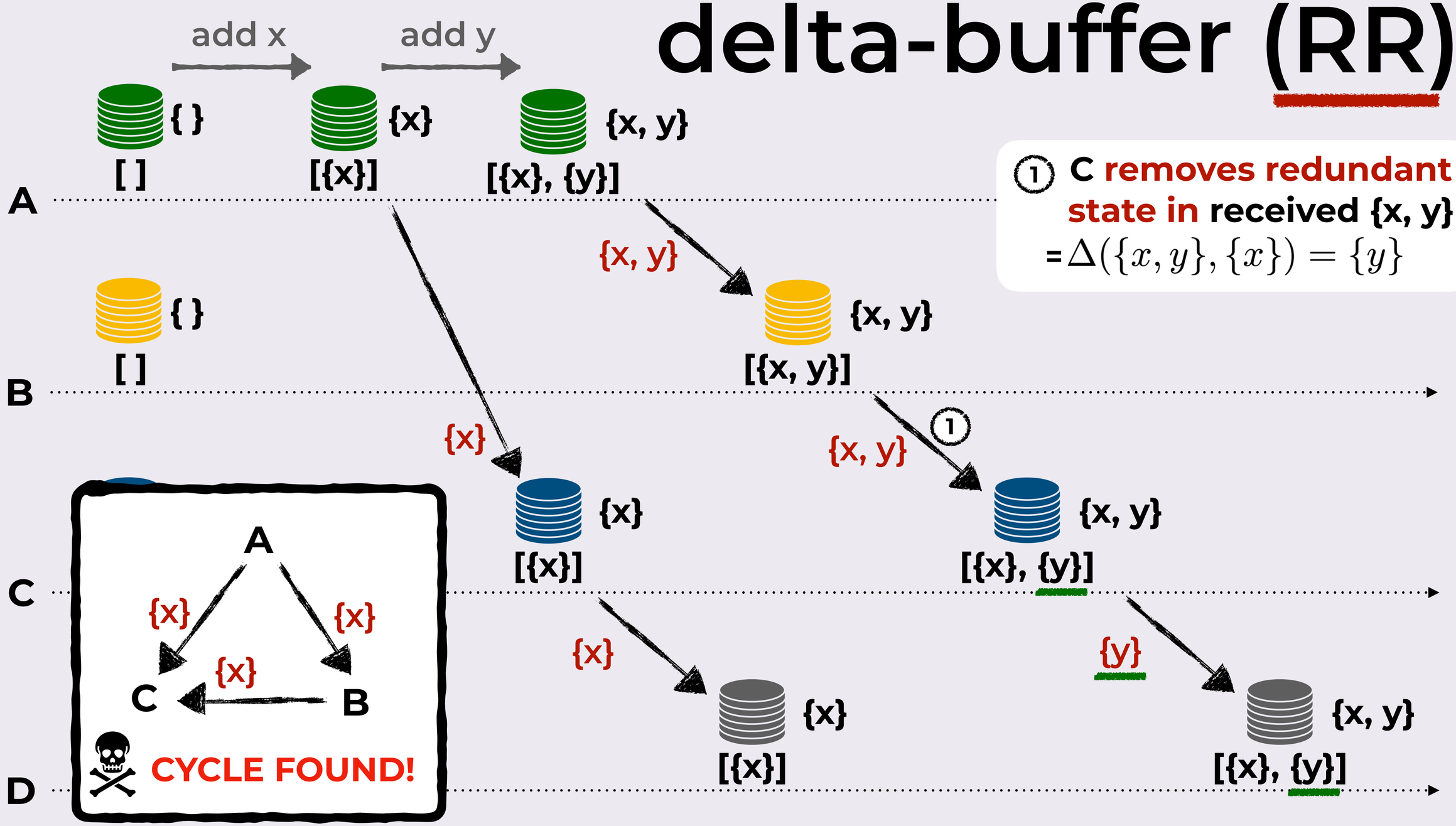
delta-buffer (RR)



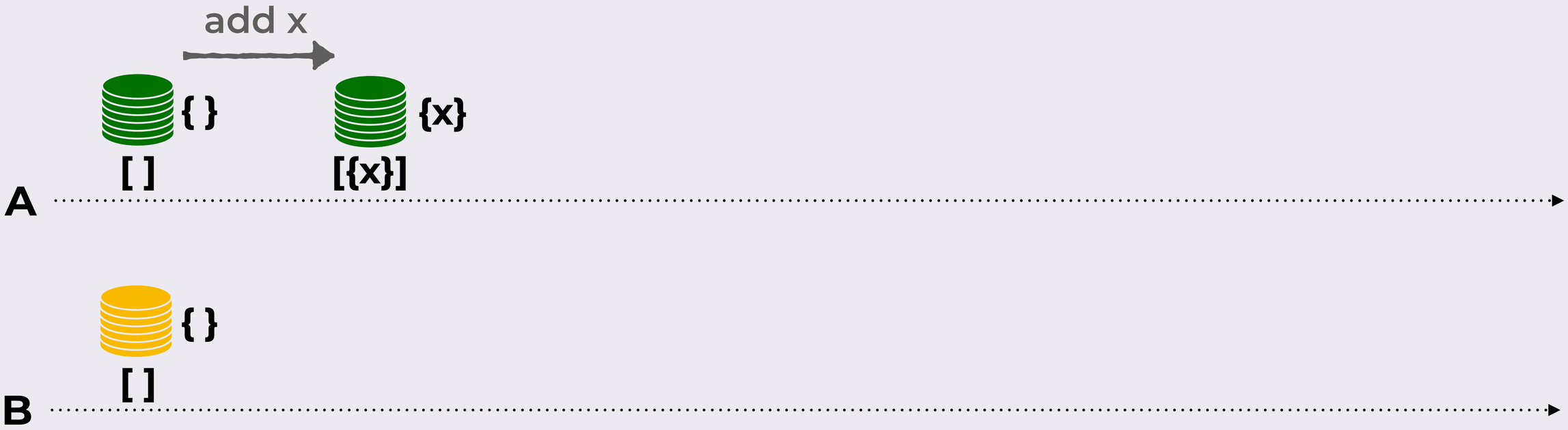
delta-buffer (RR)



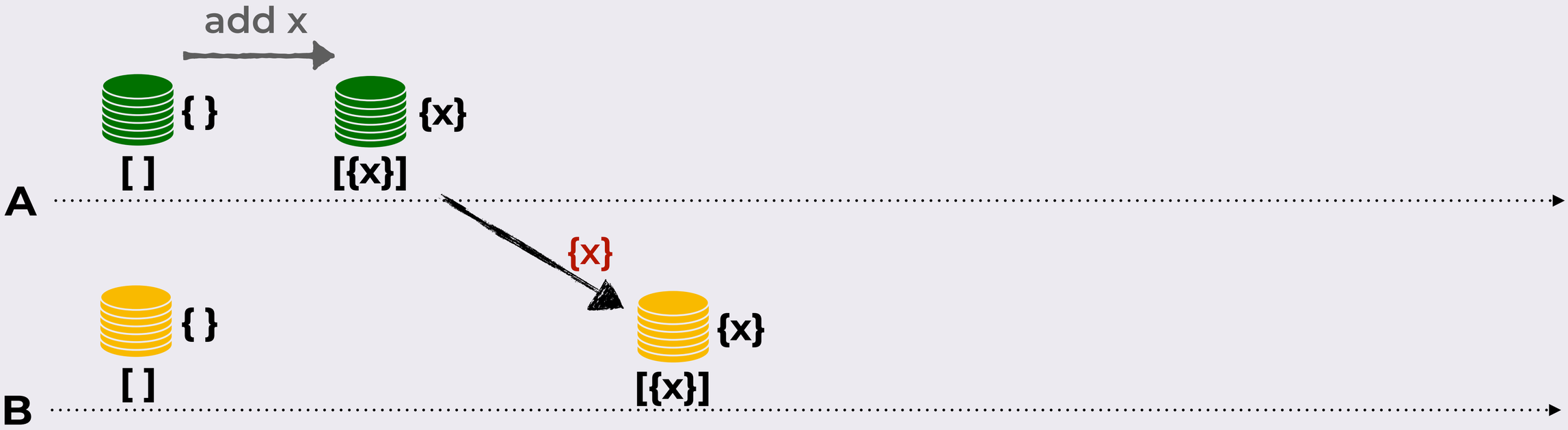
delta-buffer (RR)



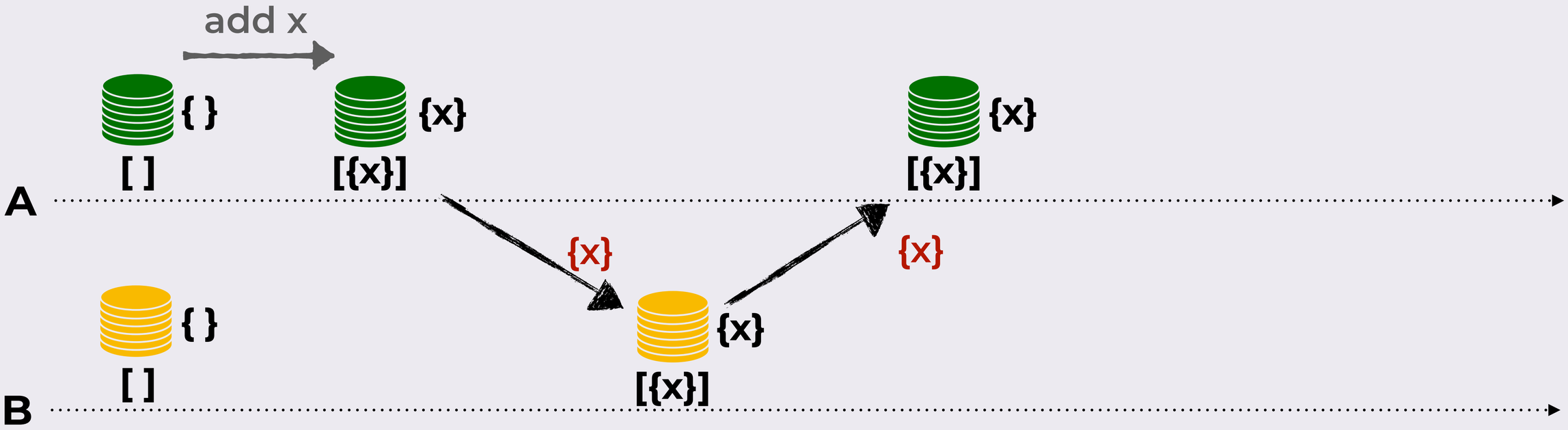
delta-buffer (BP)



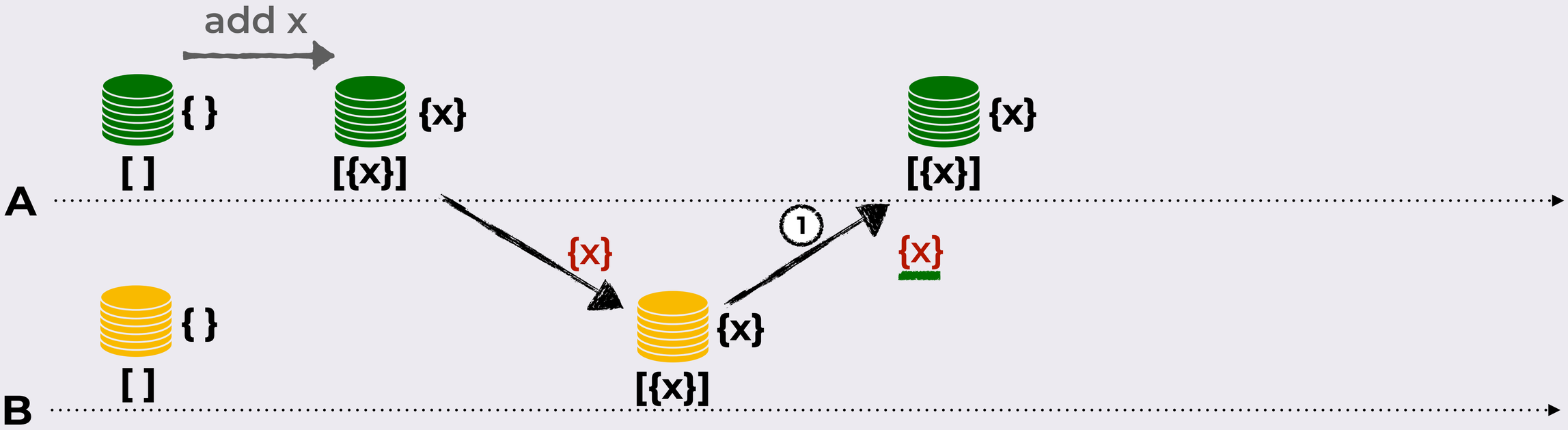
delta-buffer (BP)



delta-buffer (BP)

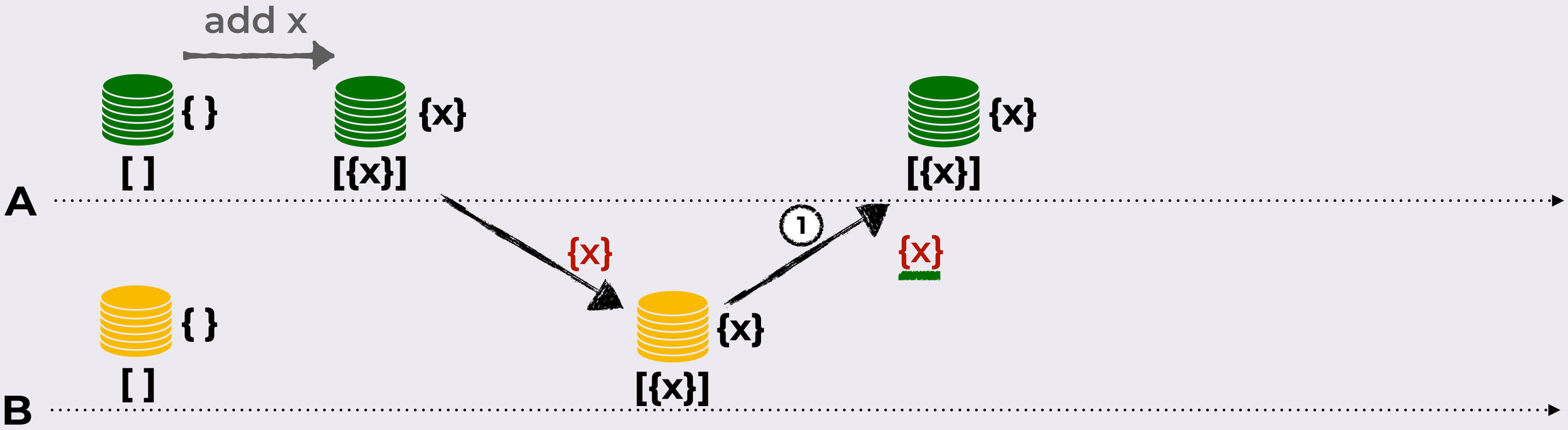


delta-buffer (BP)



① B should avoid back-propagation of {x}

delta-buffer (BP)



① B should avoid back-propagation of {x}

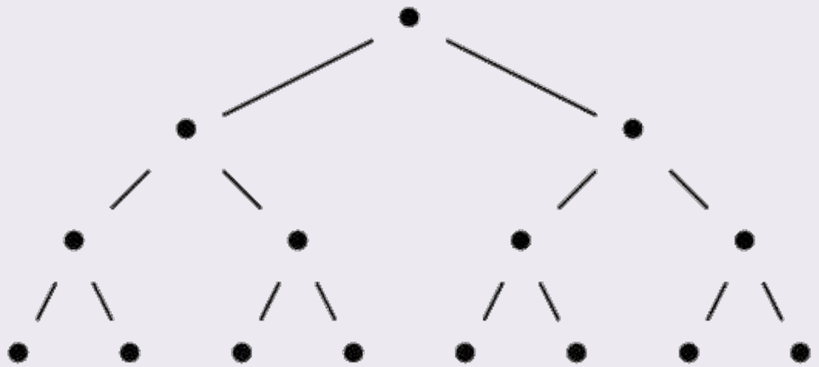
CRDT set micro-benchmark

- test the effect of **cycles** in the network topology:

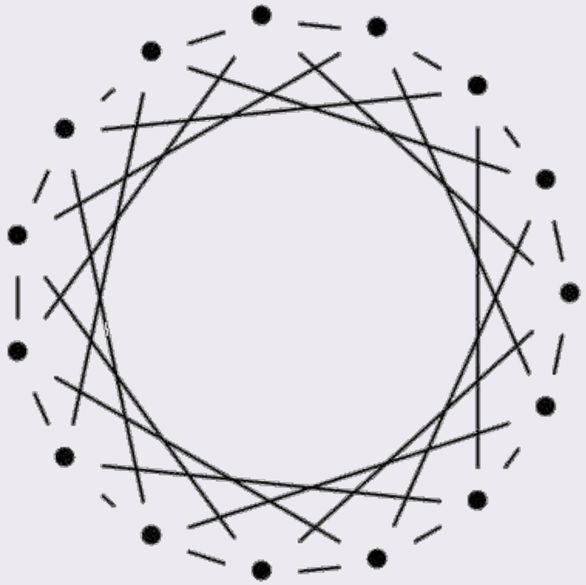
CRDT set micro-benchmark

- test the effect of **cycles** in the network topology:

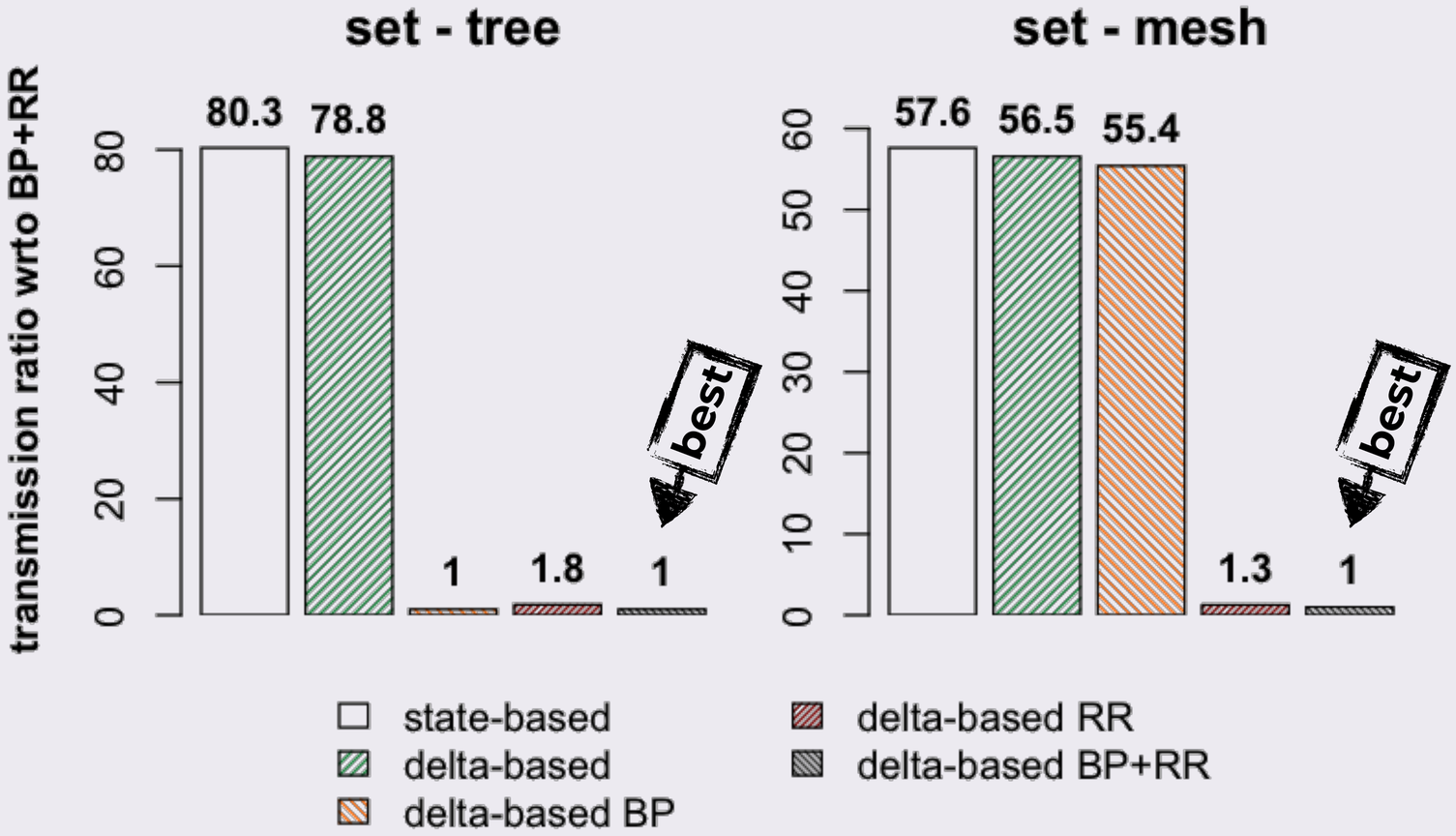
tree



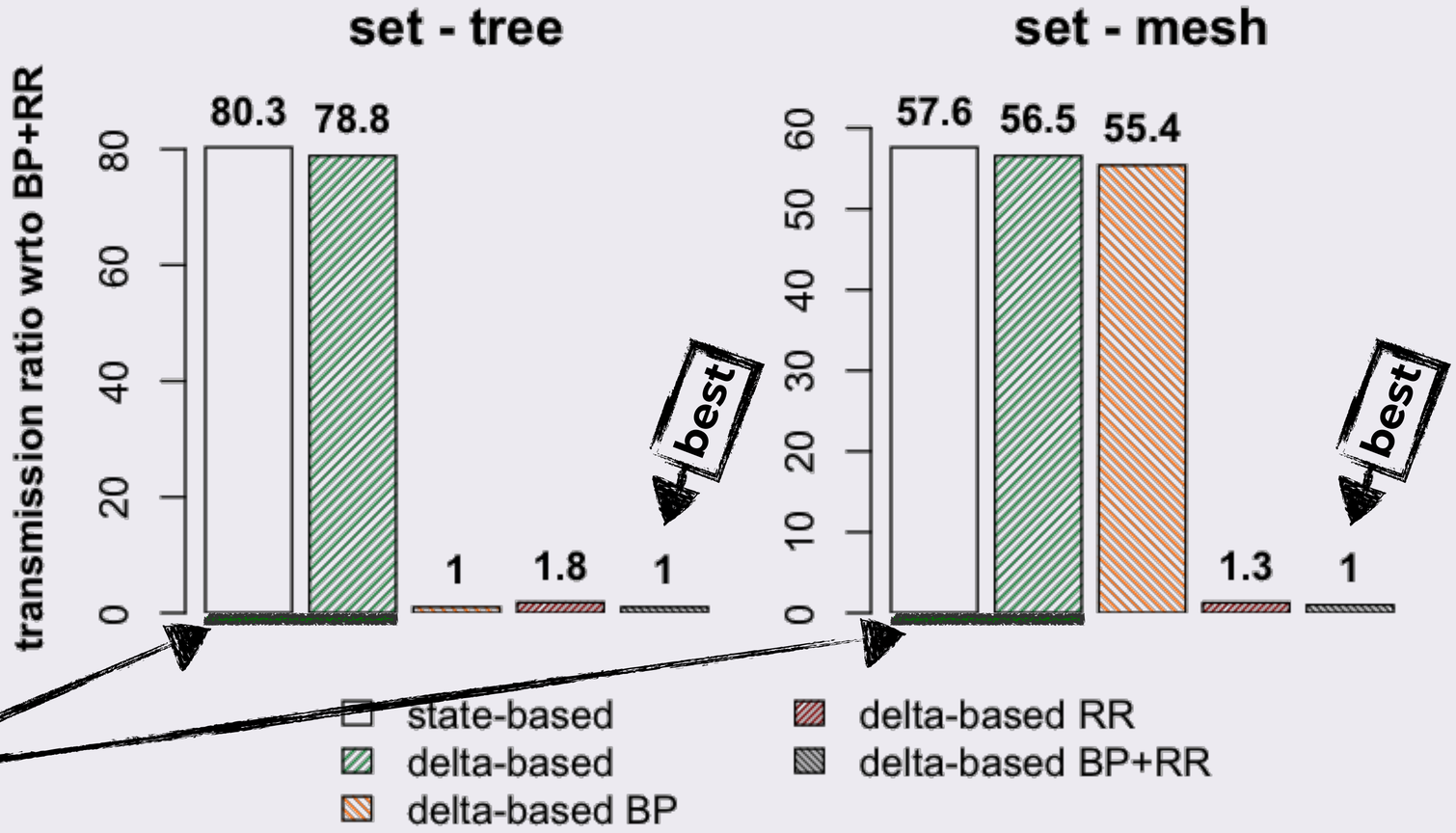
partial-mesh



CRDT set micro-benchmark



CRDT set micro-benchmark

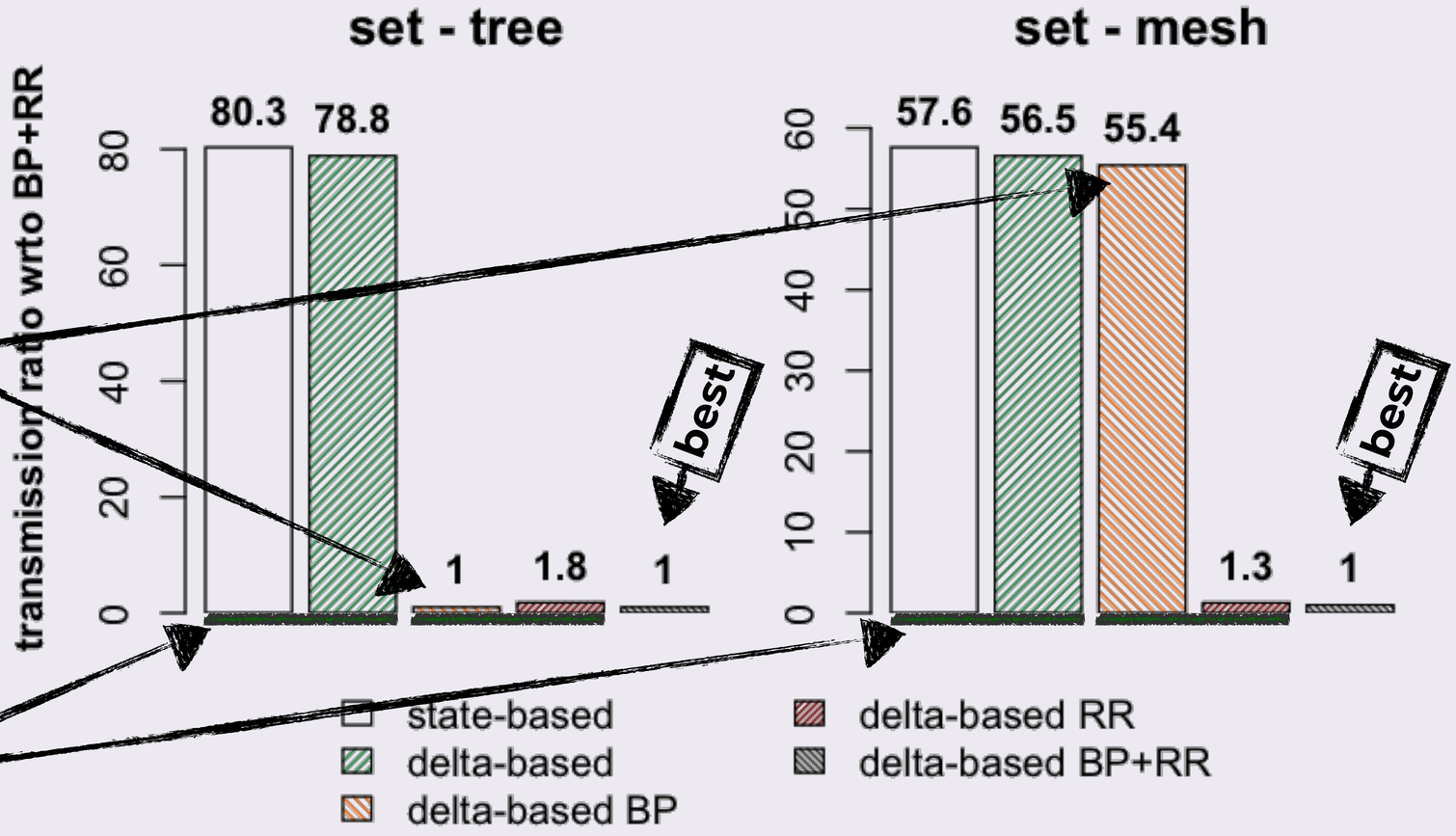


classic delta-based is as bad as state-based

CRDT set micro-benchmark

BP is enough if no cycles
RR needed in the general case

classic delta-based is as bad as state-based



but sets are easy...

but sets are easy...

for each CRDT composition technique,
there is a decomposition rule

but sets are easy...

$$
\begin{aligned}
c \in C: &\quad \Downarrow c = \{c\} \\
\langle a, b \rangle \in A \times B: &\quad \Downarrow \langle a, b \rangle = \Downarrow a \times \{\bot\} \cup \{\bot\} \times \Downarrow b \\
\langle c, a \rangle \in C \boxtimes A: &\quad \Downarrow \langle c, a \rangle = \Downarrow c \times \Downarrow a \\
\mathsf{Left}\, a \in A \oplus B: &\quad \Downarrow \mathsf{Left}\, a = \{\mathsf{Left}\, v \mid v \in \Downarrow a\} \\
\mathsf{Right}\, b \in A \oplus B: &\quad \Downarrow \mathsf{Right}\, b = \{\mathsf{Right}\, v \mid v \in \Downarrow b\} \\
f \in U \hookrightarrow A: &\quad \Downarrow f = \{k \mapsto v \mid k \in \mathsf{dom}(f) \wedge v \in \Downarrow f(v)\} \\
s \in \mathcal{P}(U): &\quad \Downarrow s = \{\{e\} \mid e \in s\}
\end{aligned}
$$

for each CRDT composition technique,
there is a decomposition rule

more results in the paper

- **counter** and **map** micro-benchmark
- comparison with:
  - **operation-based CRDTs**
  - **scuttlebutt and scuttlebutt variant**
- **retwis** benchmark

more results in the paper

- **counter** and **map** micro-benchmark
- comparison with:
  - **operation-based CRDTs**
  - **scuttlebutt and scuttlebutt variant**
- **retwis** benchmark

- **optimal** delta-mutators
- state-based CRDTs are **distributive lattices**
  - (not simply join-semilattices)

summary

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- identified **inefficiencies in delta propagation**

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- introduced concept of **decomposition** of state-based CRDTs
  - **difference** (Δ) between two states

summary

- identified **inefficiencies in delta propagation**
- introduced concept of **decomposition** of state-based CRDTs
  - **difference** (Δ) between two states
- proposed **BP** and **RR** optimizations
  - BP is enough in acyclic topologies
  - RR is needed in the more general case

efficient synchronization of state-based CRDTs

Vitor Enes, Paulo Sérgio Almeida, Carlos Baquero, João Leitão

9 Apr. 2019 @ ICDE'19

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