Borrowing an Identity for a Distributed Counter

[Work in progress report]

Vitor Enes Carlos Baquero Paulo Sérgio Almeida João Leitão

Sunday 23rd April, 2017

MSc Student at University of Minho
PaPoC '17, Belgrade

Outline

1. Distributed Counters
2. Building CRDTs
3. Borrow-Counter

Distributed Counters

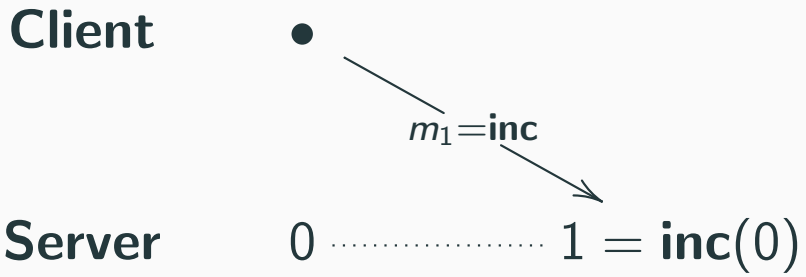
Distributed Counters

Client

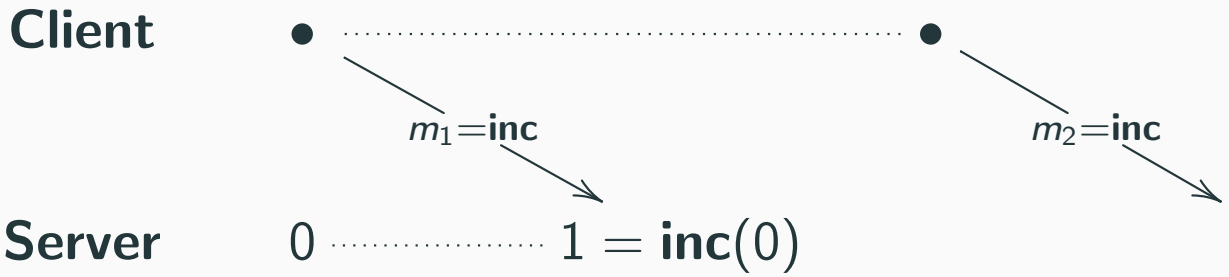
Server 0

Distributed Counters

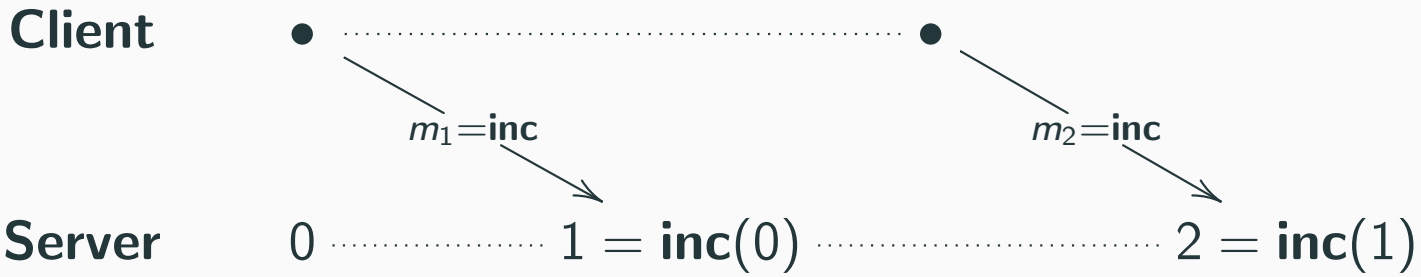
Distributed Counters



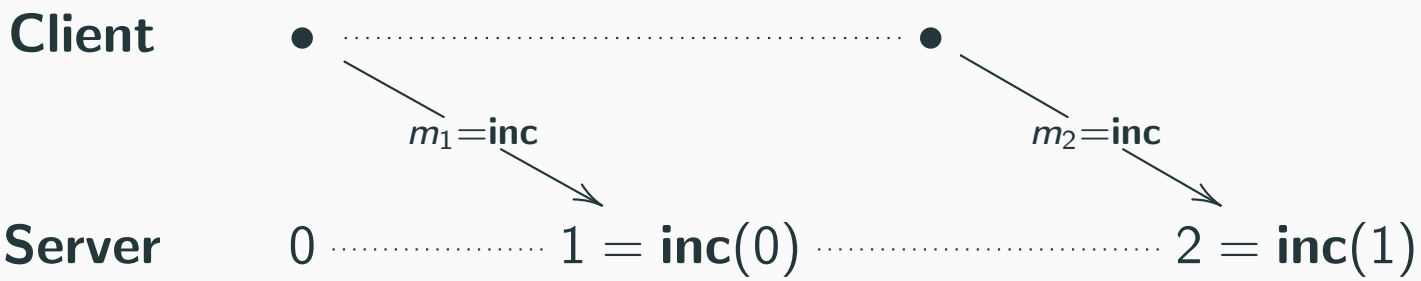
Distributed Counters



Distributed Counters

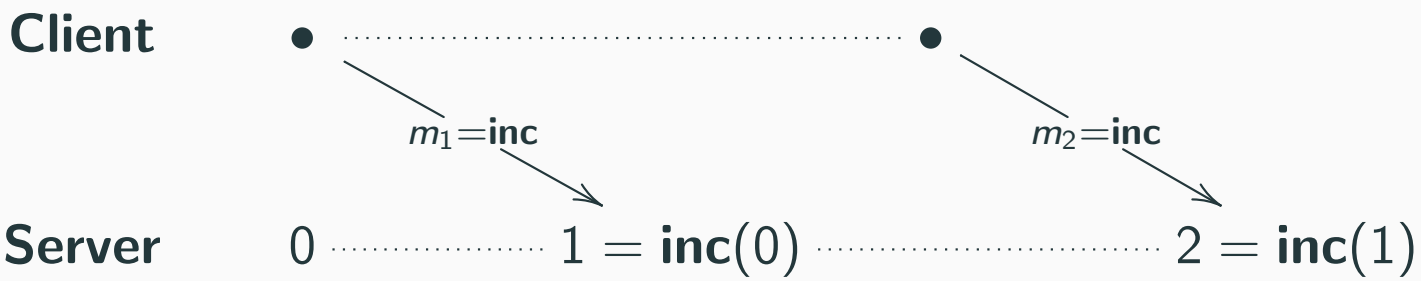


Distributed Counters



What if m_1 is lost?

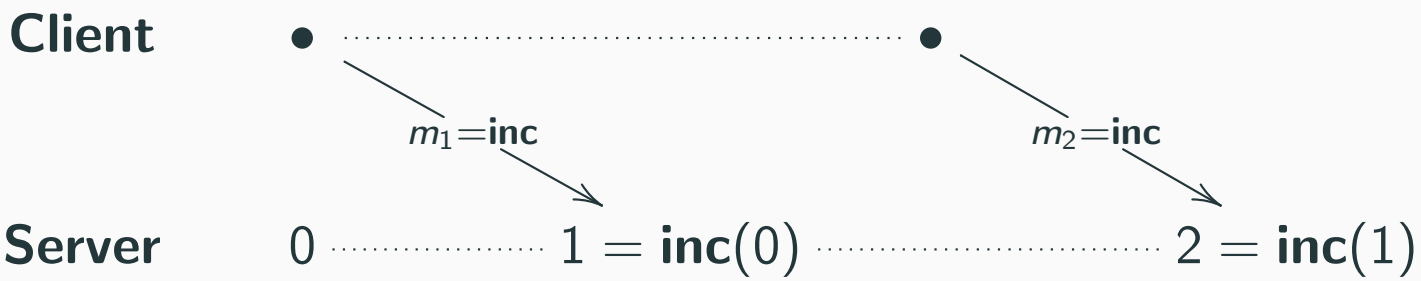
Distributed Counters



What if m_1 is lost?

What if m_2 is duplicated?

Distributed Counters

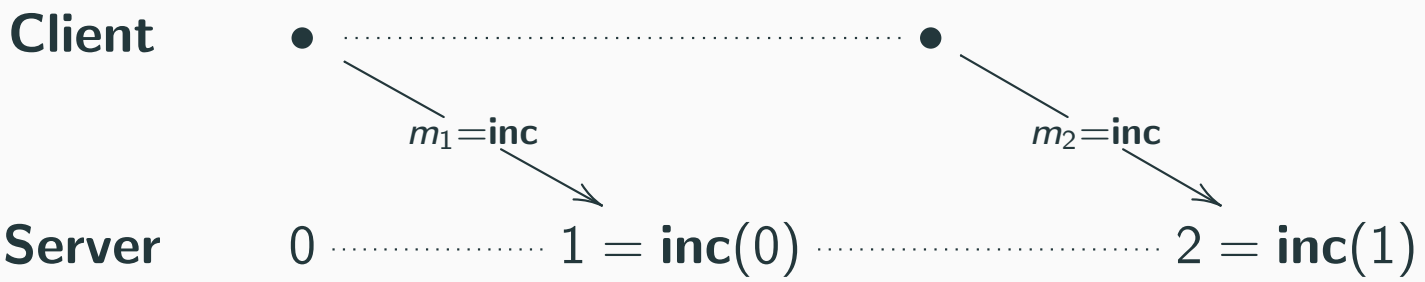


What if m_1 is lost?

What if m_2 is duplicated?

(See **CASSANDRA-2495**: Add a proper retry mechanism for counters in case of failed request)

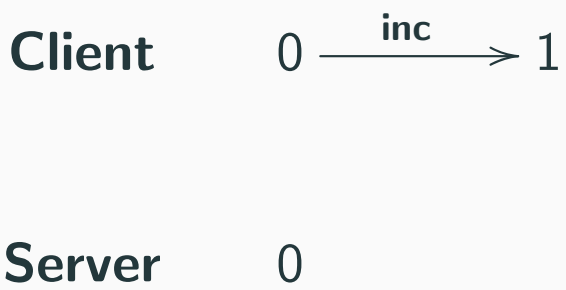
Distributed Counters



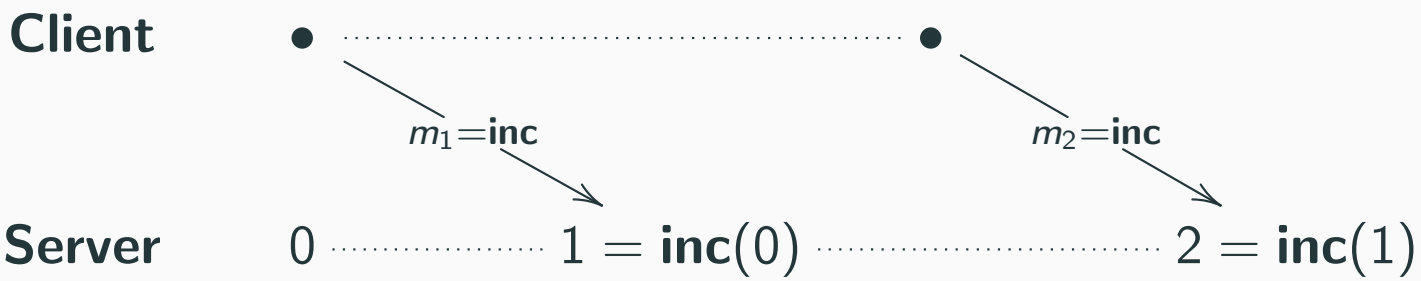
What if m_1 is lost?

What if m_2 is duplicated?

(See **CASSANDRA-2495**: Add a proper retry mechanism for counters in case of failed request)



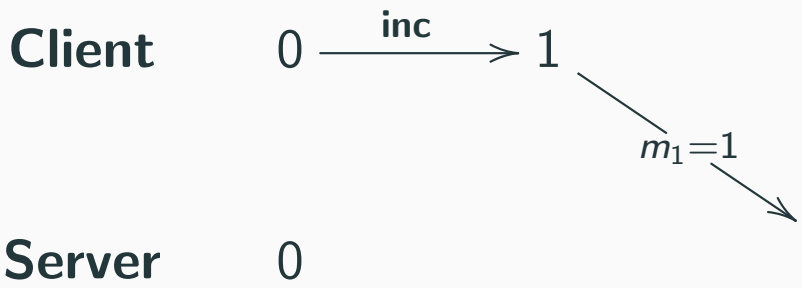
Distributed Counters



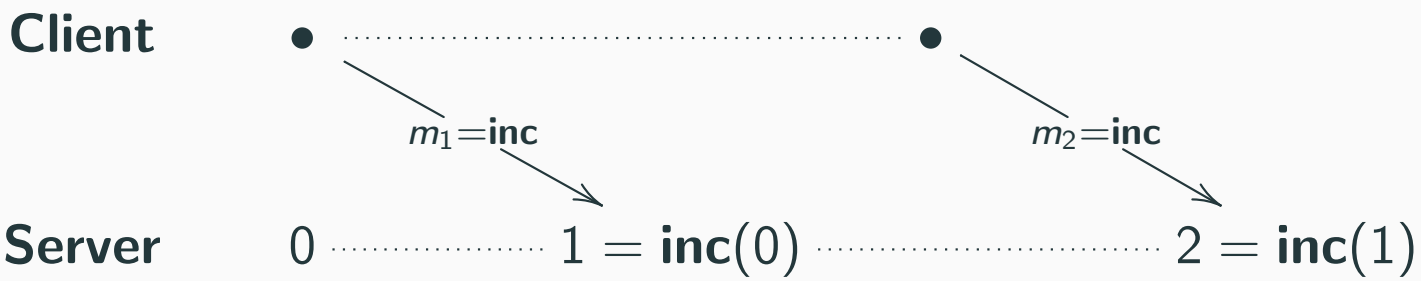
What if m_1 is lost?

What if m_2 is duplicated?

(See **CASSANDRA-2495**: Add a proper retry mechanism for counters in case of failed request)



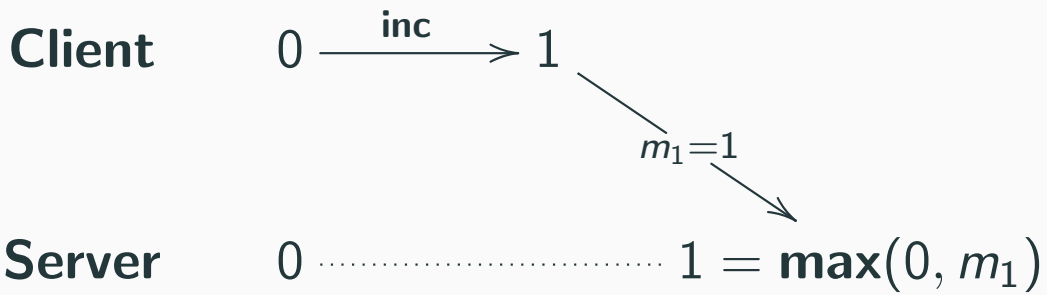
Distributed Counters



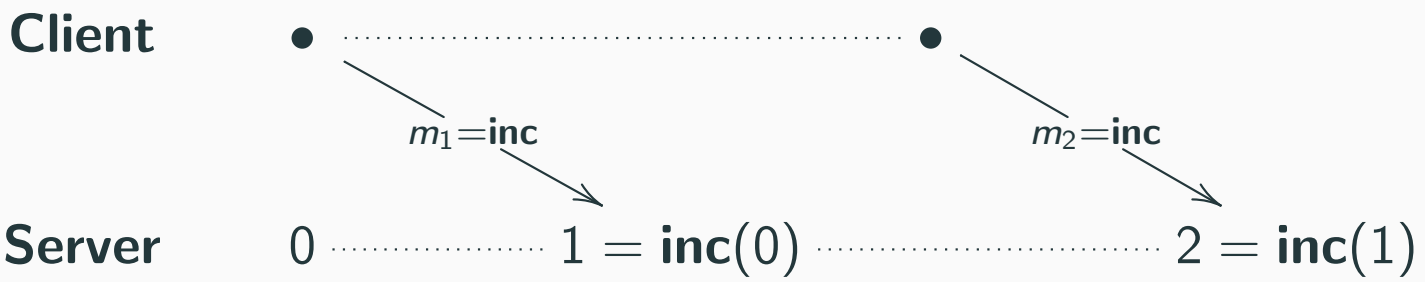
What if m_1 is lost?

What if m_2 is duplicated?

(See **CASSANDRA-2495**: Add a proper retry mechanism for counters in case of failed request)



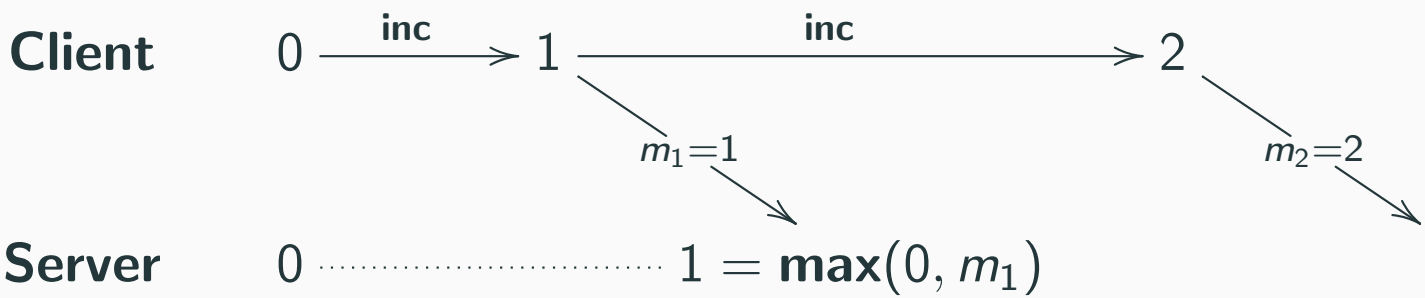
Distributed Counters



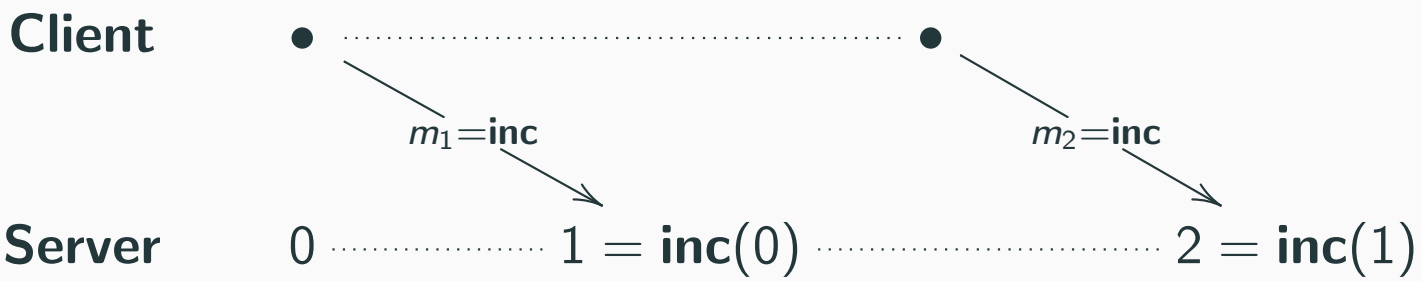
What if m_1 is lost?

What if m_2 is duplicated?

(See **CASSANDRA-2495**: Add a proper retry mechanism for counters in case of failed request)



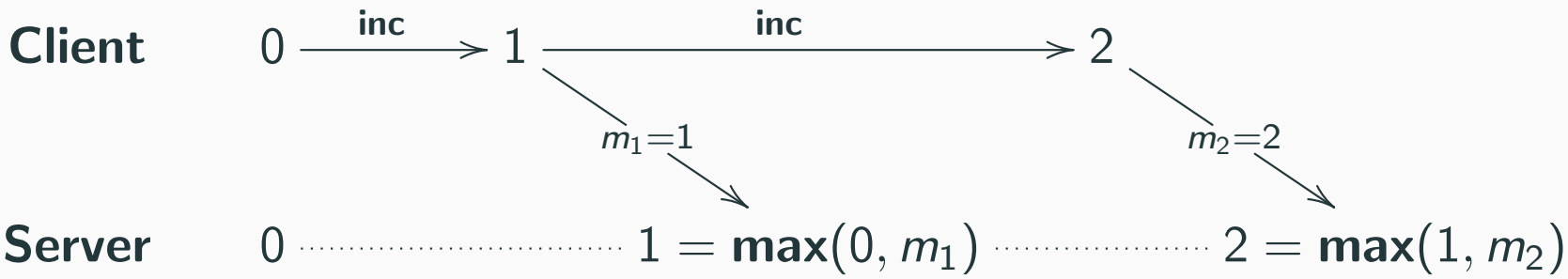
Distributed Counters



What if m_1 is lost?

What if m_2 is duplicated?

(See **CASSANDRA-2495**: Add a proper retry mechanism for counters in case of failed request)



MaxInt - State-based CRDT

MaxInt

$$\textbf{MaxInt} = \mathbb{N}$$

$$\bot = 0$$

MaxInt - State-based CRDT

MaxInt

$$\textbf{MaxInt} = \mathbb{N}$$

$$\bot = 0$$

$$\textbf{inc}(s) = s + 1$$

$$\textbf{value}(s) = s$$

MaxInt - State-based CRDT

MaxInt

$$\begin{aligned}
\textbf{MaxInt} &= \mathbb{N} \\
\bot &= 0 \\
\textbf{inc}(s) &= s + 1 \\
\textbf{value}(s) &= s \\
s \sqcup s' &= \textbf{max}(s, s')
\end{aligned}$$

MaxInt - State-based CRDT

MaxInt

$$\begin{aligned} \textbf{MaxInt} &= \mathbb{N} \\ \bot &= 0 \\ \textbf{inc}(s) &= s + 1 \\ \textbf{value}(s) &= s \\ s \sqcup s' &= \textbf{max}(s, s') \end{aligned}$$

Is it solved? Can I leave?

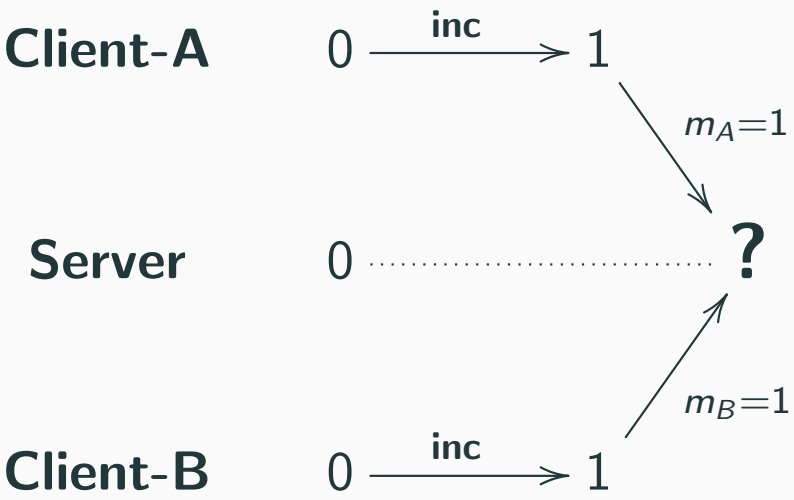
Let's make it more interesting

Client-A $0 \xrightarrow{\textbf{inc}} 1$

Server 0

Client-B $0 \xrightarrow{\textbf{inc}} 1$

Let's make it more interesting



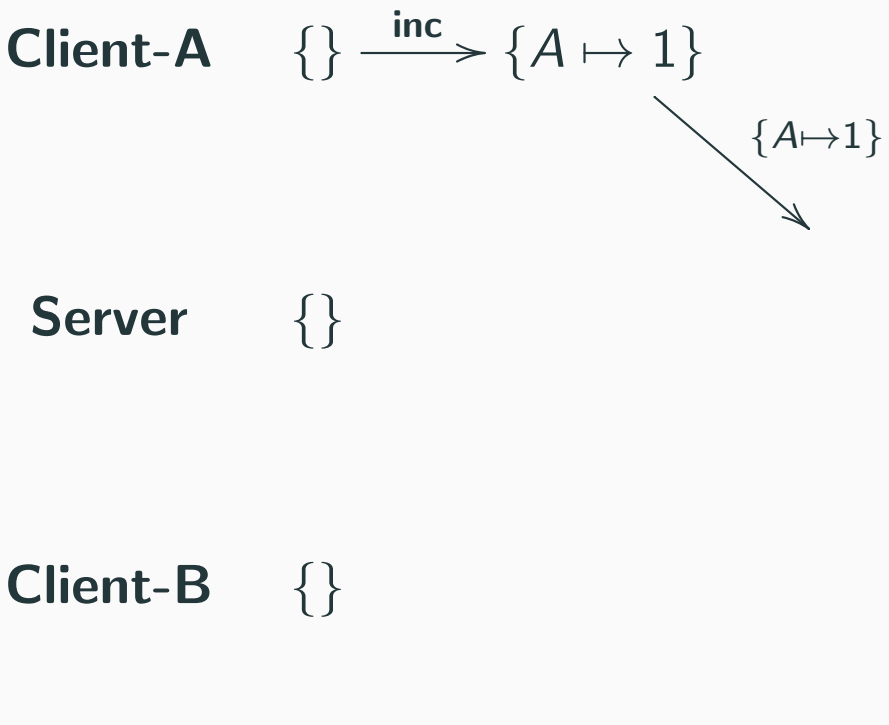
Naming CRDTs: GCounter

Client-A {}

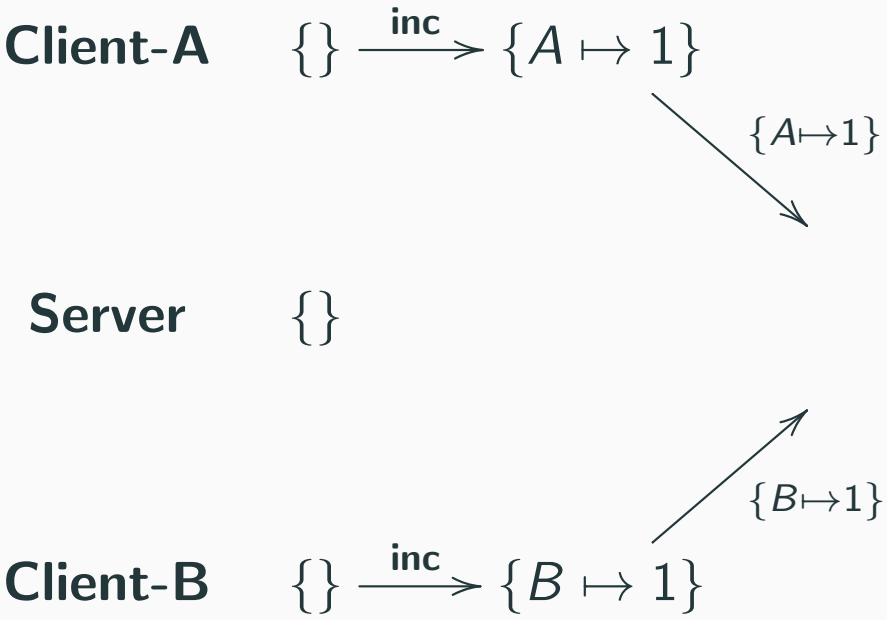
Server {}

Client-B {}

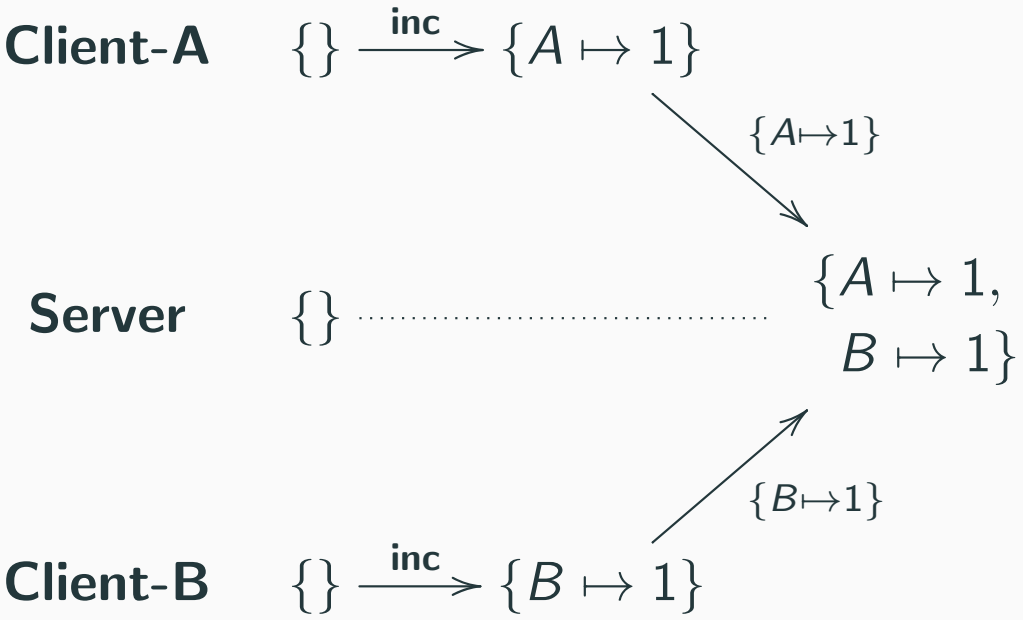
Naming CRDTs: GCounter



Naming CRDTs: GCounter



Naming CRDTs: GCounter



The Identity Explosion Problem

Problem

- It doens't scale!
- State size **linear** with the number nodes that **ever** incremented the counter
- Even if some nodes leave the system

The Identity Explosion Problem

Problem

- It doens't scale!
- State size **linear** with the number nodes that **ever** incremented the counter
- Even if some nodes leave the system

Our solution: Borrow-Counter

- Distinguish **transient** and **permanent** nodes

The Identity Explosion Problem

Problem

- It doens't scale!
- State size **linear** with the number nodes that **ever** incremented the counter
- Even if some nodes leave the system

Our solution: Borrow-Counter

- Distinguish **transient** and **permanent** nodes
- Allow transient nodes to use (borrow) the **identity** of a permanent node to increment a counter

The Identity Explosion Problem

Problem

- It doens't scale!
- State size **linear** with the number nodes that **ever** incremented the counter
- Even if some nodes leave the system

Our solution: Borrow-Counter

- Distinguish **transient** and **permanent** nodes
- Allow transient nodes to use (borrow) the **identity** of a permanent node to increment a counter
- Safe **retirement** transient of nodes, incorporating their increments in a permanent node

Building CRDTs

Some notation first!

- **Maps**, *e.g.* **GCounter** $= \mathbb{I} \hookrightarrow \mathbb{N}$
  - ✓ $\{\}$
  - ✓ $\{A \mapsto 2, B \mapsto 1\}$

Some notation first!

- **Maps**, *e.g.* **GCounter** $= \mathbb{I} \hookrightarrow \mathbb{N}$
  - ✓ $\{\}$
  - ✓ $\{A \mapsto 2, B \mapsto 1\}$
- **Sets**, *e.g.* **GSet**$\langle\mathbb{N}\rangle = \mathcal{P}(\mathbb{N})$
  - $\{\}$
  - $\{2, 3, 5, 7, 11\}$

Some notation first!

- **Maps**, *e.g.* **GCounter** $= \mathbb{I} \hookrightarrow \mathbb{N}$
  - ✓ $\{\}$
  - ✓ $\{A \mapsto 2, B \mapsto 1\}$
- **Sets**, *e.g.* **GSet**$\langle\mathbb{N}\rangle = \mathcal{P}(\mathbb{N})$
  - $\{\}$
  - $\{2, 3, 5, 7, 11\}$
- **Pairs**
  - $\mathbb{I} \times \mathbb{N}$
    - $(A, 2) \equiv A_2$

Some notation first!

- **Maps**, *e.g.* **GCounter** $= \mathbb{I} \hookrightarrow \mathbb{N}$
  - ✓ $\{\}$
  - ✓ $\{A \mapsto 2, B \mapsto 1\}$
- **Sets**, *e.g.* **GSet**$\langle\mathbb{N}\rangle = \mathcal{P}(\mathbb{N})$
  - $\{\}$
  - $\{2, 3, 5, 7, 11\}$
- **Pairs**
  - $\mathbb{I} \times \mathbb{N}$
    - $(A, 2) \equiv A_2$
  - $\mathbb{I} \times \mathbb{B}$
    - $(A, \mathsf{False}) \equiv \underline{A}$
    - $(A, \mathsf{True}) \equiv \overline{A}$

Some notation first!

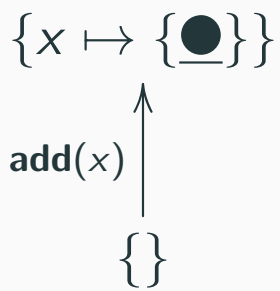
- **Maps**, *e.g.* **GCounter** $= \mathbb{I} \hookrightarrow \mathbb{N}$
  - ✓ $\{\}$
  - ✓ $\{A \mapsto 2, B \mapsto 1\}$
- **Sets**, *e.g.* **GSet**$\langle\mathbb{N}\rangle = \mathcal{P}(\mathbb{N})$
  - $\{\}$
  - $\{2, 3, 5, 7, 11\}$
- **Pairs**
  - $\mathbb{I} \times \mathbb{N}$
    - $(A, 2) \equiv A_2$
  - $\mathbb{I} \times \mathbb{B}$
    - $(A, \mathsf{False}) \equiv \underline{A}$
    - $(A, \mathsf{True}) \equiv \overline{A}$
- $\mathcal{D} = \{\bullet, \blacktriangle, \blacksquare\}$ (for now)

$$\textbf{AWSet}\langle\mathcal{E}\rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$$

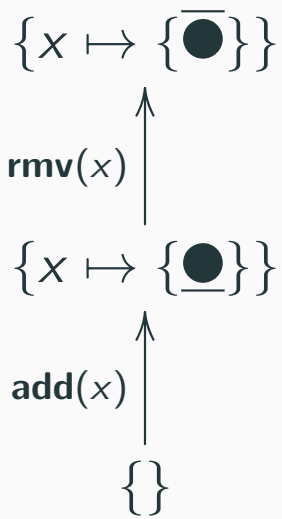
(with tombstones)

$\{\}$

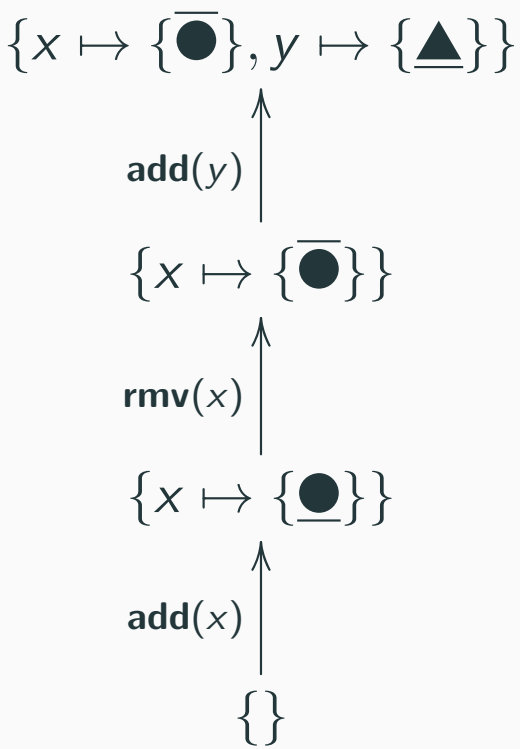
AWSet$\langle \mathcal{E} \rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$
(with tombstones)



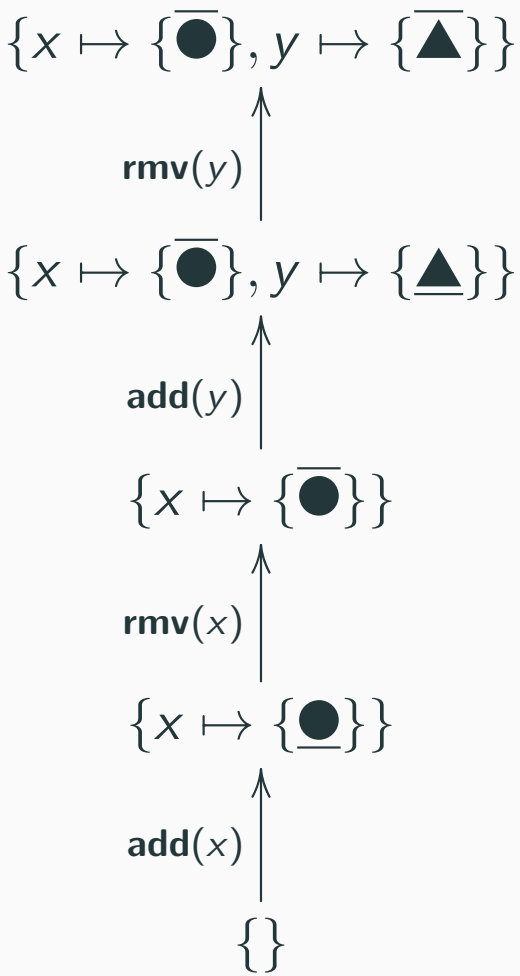
AWSet$\langle \mathcal{E} \rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$
(with tombstones)



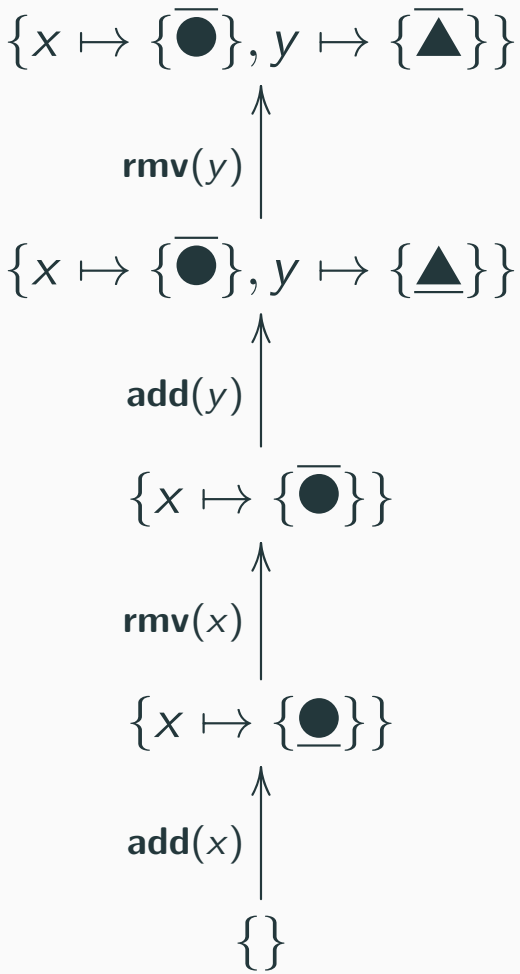
AWSet$\langle \mathcal{E} \rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$
(with tombstones)



AWSet$\langle \mathcal{E} \rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$
(with tombstones)

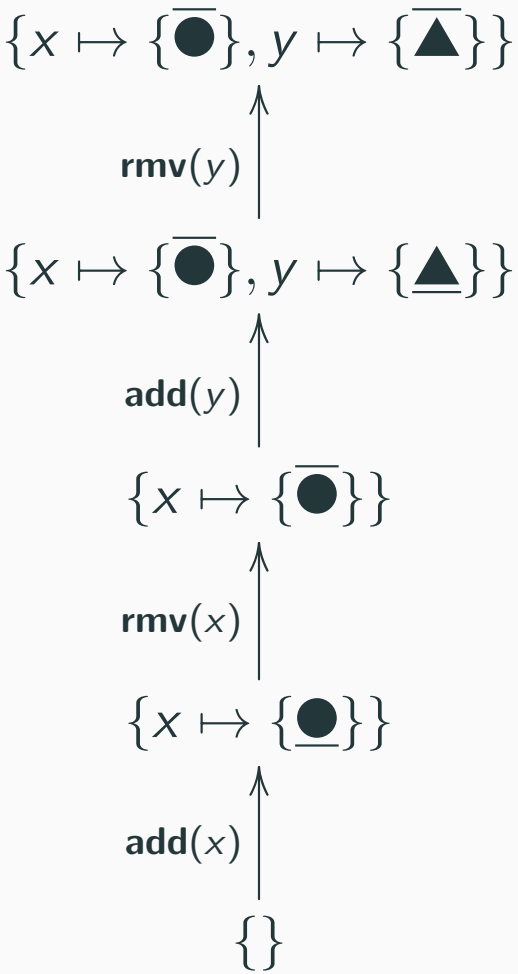


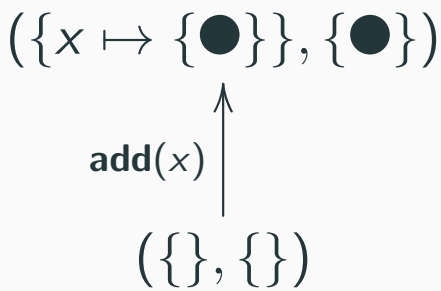
$\mathbf{AWSet}\langle\mathcal{E}\rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$ (with tombstones)	$\mathbf{AWSet}\langle\mathcal{E}\rangle = (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D})$ (without tombstones)



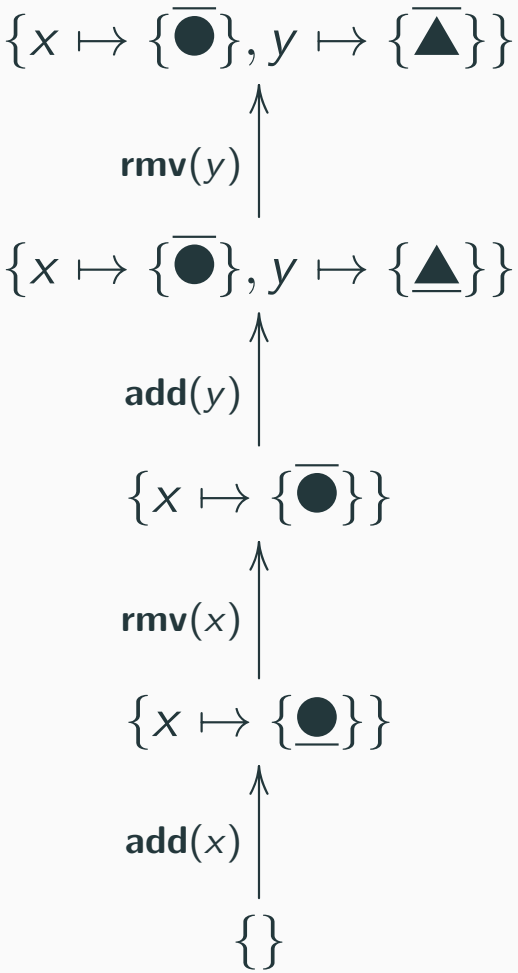
$(\{\}, \{\})$

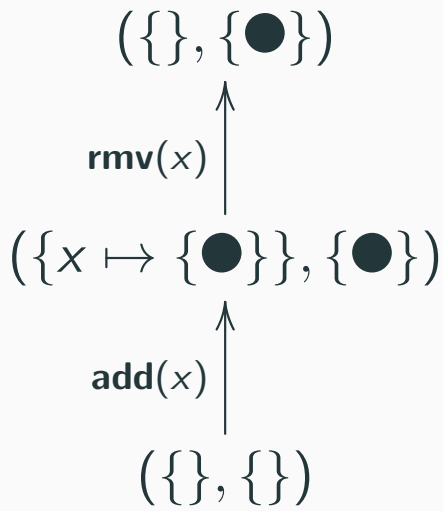
$\mathbf{AWSet}\langle\mathcal{E}\rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$ (with tombstones)	$\mathbf{AWSet}\langle\mathcal{E}\rangle = (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D})$ (without tombstones)



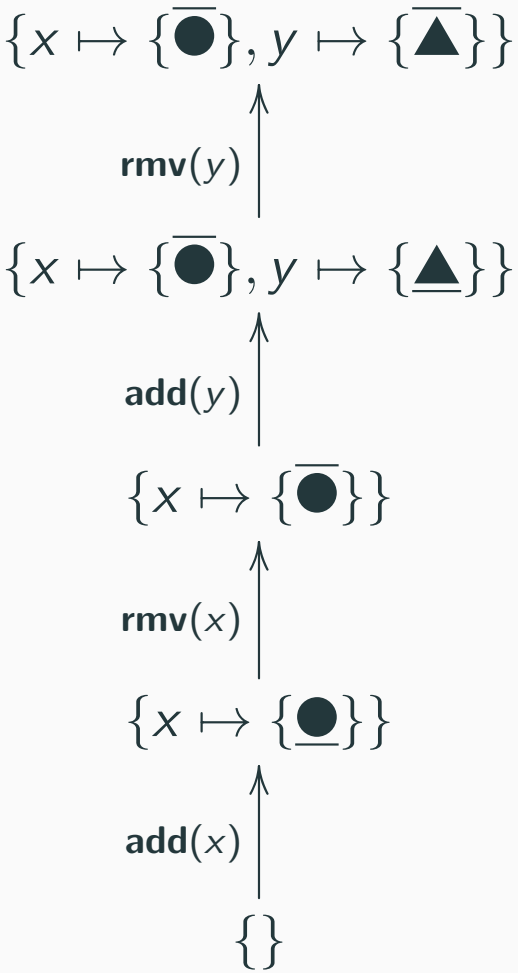


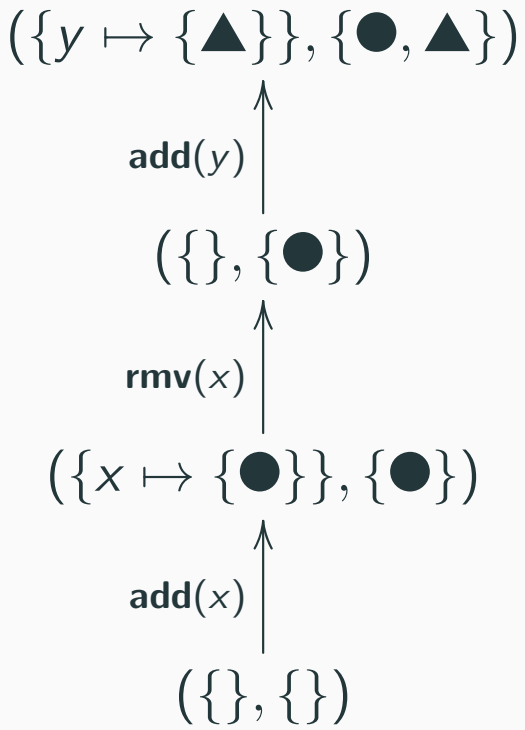
$\mathbf{AWSet}\langle\mathcal{E}\rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$ (with tombstones)	$\mathbf{AWSet}\langle\mathcal{E}\rangle = (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D})$ (without tombstones)



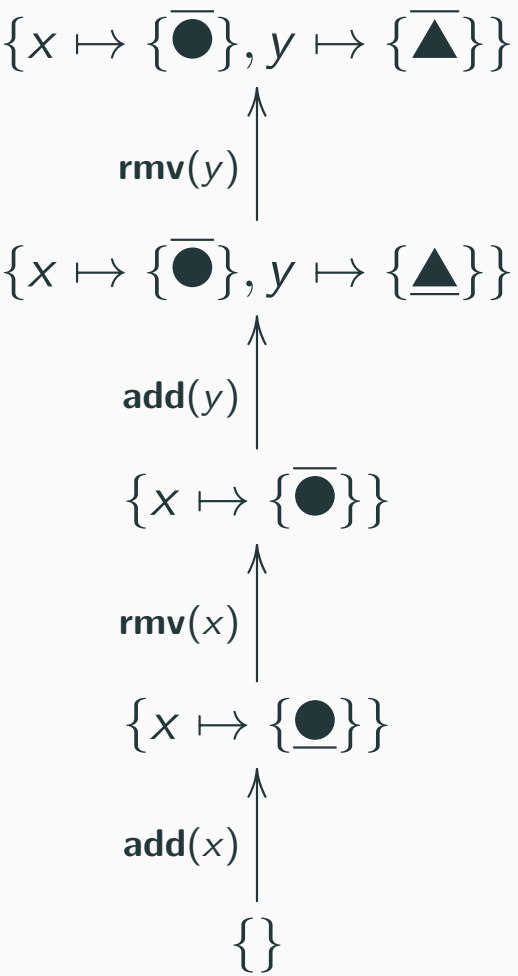


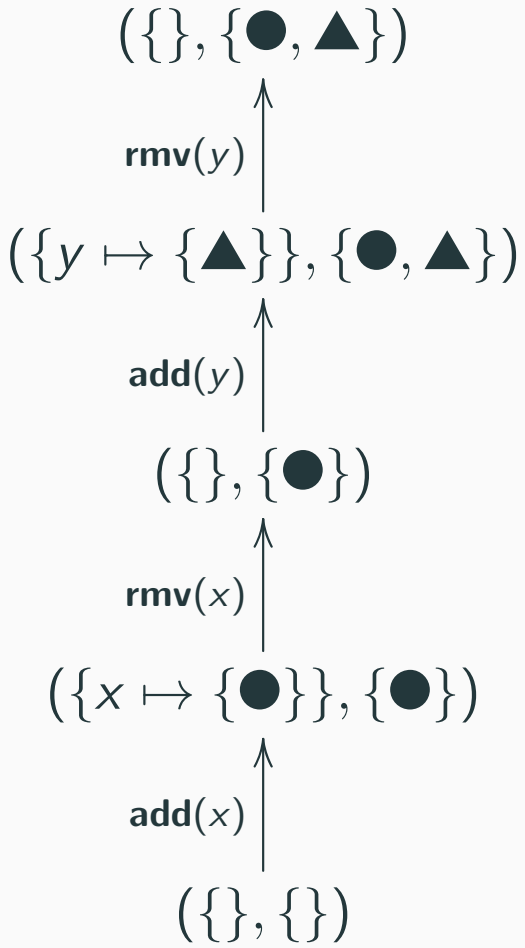
$\mathbf{AWSet}\langle\mathcal{E}\rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$ (with tombstones)	$\mathbf{AWSet}\langle\mathcal{E}\rangle = (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D})$ (without tombstones)





$\mathbf{AWSet}\langle\mathcal{E}\rangle = \mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D} \times \mathbb{B})$ (with tombstones)	$\mathbf{AWSet}\langle\mathcal{E}\rangle = (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D})$ (without tombstones)





Dot Stores and Causal Context

$$\mathbf{AWSet}\langle\mathcal{E}\rangle = (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D})$$

Dot Stores and Causal Context

$$\begin{aligned}\mathbf{AWSet}\langle\mathcal{E}\rangle &= (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D}) \\ &= \mathbf{DotMap}\langle\mathcal{E}, \mathbf{DotSet}\rangle \times \mathbf{CausalContext}\end{aligned}$$

Dot Stores and Causal Context

$$\begin{aligned}\textbf{AWSet}\langle\mathcal{E}\rangle &= (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle\mathcal{E}, \textbf{DotSet}\rangle \times \textbf{CausalContext}\end{aligned}$$

- **DotStore**
  - $\textbf{DotMap}\langle\mathcal{K}, \mathcal{V} : \textbf{DotStore}\rangle = \mathcal{K} \hookrightarrow \mathcal{V}$
  - $\textbf{DotSet} = \mathcal{P}(\mathcal{D})$
  - $\textbf{DotFun}\langle\mathcal{L} : \textbf{Lattice}\rangle = \mathcal{D} \hookrightarrow \mathcal{L}$

Dot Stores and Causal Context

$$\begin{aligned}\textbf{AWSet}\langle\mathcal{E}\rangle &= (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle\mathcal{E}, \textbf{DotSet}\rangle \times \textbf{CausalContext}\end{aligned}$$

- **DotStore**
  - $\textbf{DotMap}\langle\mathcal{K}, \mathcal{V} : \textbf{DotStore}\rangle = \mathcal{K} \hookrightarrow \mathcal{V}$
  - $\textbf{DotSet} = \mathcal{P}(\mathcal{D})$
  - $\textbf{DotFun}\langle\mathcal{L} : \textbf{Lattice}\rangle = \mathcal{D} \hookrightarrow \mathcal{L}$
- $\textbf{CausalContext} = \mathcal{P}(\mathcal{D})$

Dot Stores and Causal Context

$$\begin{aligned}\textbf{AWSet}\langle\mathcal{E}\rangle &= (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle\mathcal{E}, \textbf{DotSet}\rangle \times \textbf{CausalContext}\end{aligned}$$

- **DotStore**
  - $\textbf{DotMap}\langle\mathcal{K}, \mathcal{V} : \textbf{DotStore}\rangle = \mathcal{K} \hookrightarrow \mathcal{V}$
  - $\textbf{DotSet} = \mathcal{P}(\mathcal{D})$
  - $\textbf{DotFun}\langle\mathcal{L} : \textbf{Lattice}\rangle = \mathcal{D} \hookrightarrow \mathcal{L}$
- $\textbf{CausalContext} = \mathcal{P}(\mathcal{D})$

In practice

- Dots are not geometric figures: $\mathcal{D} = \mathbb{I} \times \mathbb{N}$

Dot Stores and Causal Context

$$\begin{aligned}\textbf{AWSet}\langle\mathcal{E}\rangle &= (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle\mathcal{E}, \textbf{DotSet}\rangle \times \textbf{CausalContext}\end{aligned}$$

- **DotStore**
  - $\textbf{DotMap}\langle\mathcal{K}, \mathcal{V} : \textbf{DotStore}\rangle = \mathcal{K} \hookrightarrow \mathcal{V}$
  - $\textbf{DotSet} = \mathcal{P}(\mathcal{D})$
  - $\textbf{DotFun}\langle\mathcal{L} : \textbf{Lattice}\rangle = \mathcal{D} \hookrightarrow \mathcal{L}$
- $\textbf{CausalContext} = \mathcal{P}(\mathcal{D})$

In practice

- Dots are not geometric figures: $\mathcal{D} = \mathbb{I} \times \mathbb{N}$
- And under **causal** anti-entropy, the Causal Context can be efficiently encoded as: $\mathbb{I} \hookrightarrow \mathbb{N}$
  - $\{\mathbf{A_1}, \mathbf{A_2}, \mathbf{A_3}, \mathbf{A_4}\} \equiv \{\mathbf{A} \mapsto 4\}$

Dot Stores and Causal Context

$$\begin{aligned}\textbf{AWSet}\langle\mathcal{E}\rangle &= (\mathcal{E} \hookrightarrow \mathcal{P}(\mathcal{D})) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle\mathcal{E}, \textbf{DotSet}\rangle \times \textbf{CausalContext}\end{aligned}$$

- **DotStore**
  - $\textbf{DotMap}\langle\mathcal{K}, \mathcal{V} : \textbf{DotStore}\rangle = \mathcal{K} \hookrightarrow \mathcal{V}$
  - $\textbf{DotSet} = \mathcal{P}(\mathcal{D})$
  - $\textbf{DotFun}\langle\mathcal{L} : \textbf{Lattice}\rangle = \mathcal{D} \hookrightarrow \mathcal{L}$
- $\textbf{CausalContext} = \mathcal{P}(\mathcal{D})$

In practice

- Dots are not geometric figures: $\mathcal{D} = \mathbb{I} \times \mathbb{N}$
- And under **causal** anti-entropy, the Causal Context can be efficiently encoded as: $\mathbb{I} \hookrightarrow \mathbb{N}$
  - $\{\mathbf{A_1}, \mathbf{A_2}, \mathbf{A_3}, \mathbf{A_4}\} \equiv \{\mathbf{A} \mapsto 4\}$
- If under **non-causal** anti-entropy: $(\mathbb{I} \hookrightarrow \mathbb{N}) \times \mathcal{P}(\mathcal{D})$
  - $\{\mathbf{A_1}, \mathbf{A_2}, \mathbf{A_4}\} \equiv (\{\mathbf{A} \mapsto 2\}, \{\mathbf{A_4}\})$

$$\begin{aligned}\textbf{MVRegister}\langle\mathcal{V}\rangle &= (\mathcal{D} \hookrightarrow \mathcal{V}) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotFun}\langle\mathcal{V}\rangle \times \textbf{CausalContext}\end{aligned}$$

$$(\{\}, \{\})$$

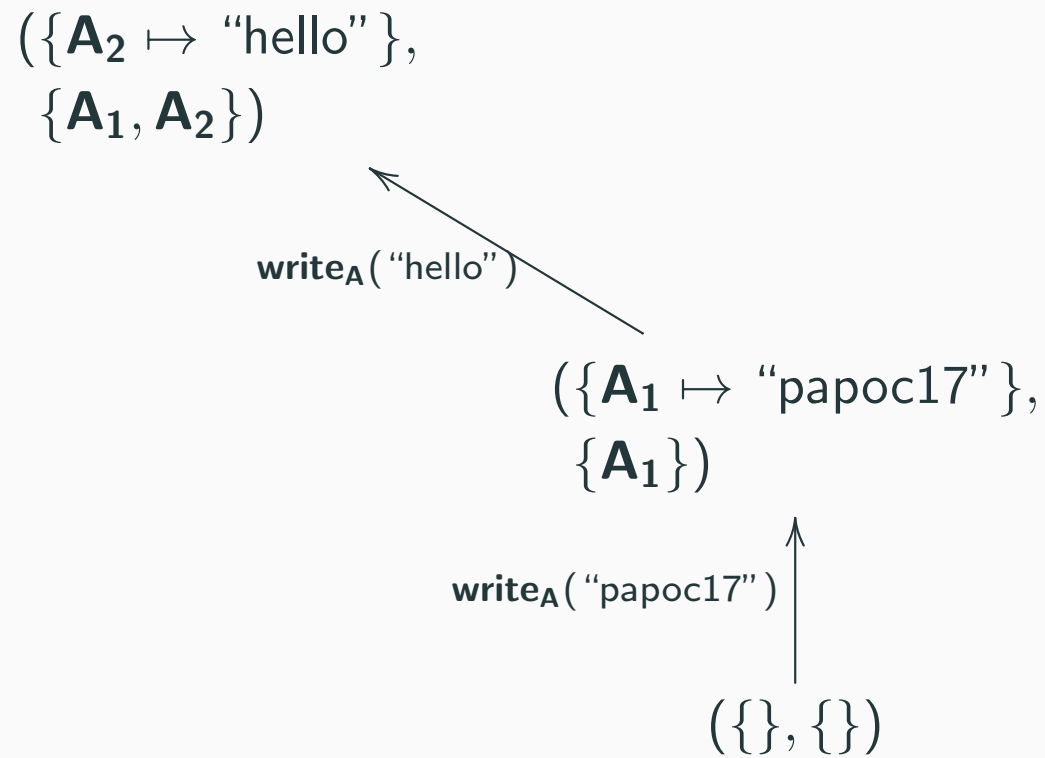
$$\textbf{MVRegister}\langle\mathcal{V}\rangle = (\mathcal{D} \hookrightarrow \mathcal{V}) \times \mathcal{P}(\mathcal{D})$$
$$= \textbf{DotFun}\langle\mathcal{V}\rangle \times \textbf{CausalContext}$$

$$(\{\mathbf{A_1} \mapsto \text{“papoc17”}\},\ \{\mathbf{A_1}\})$$

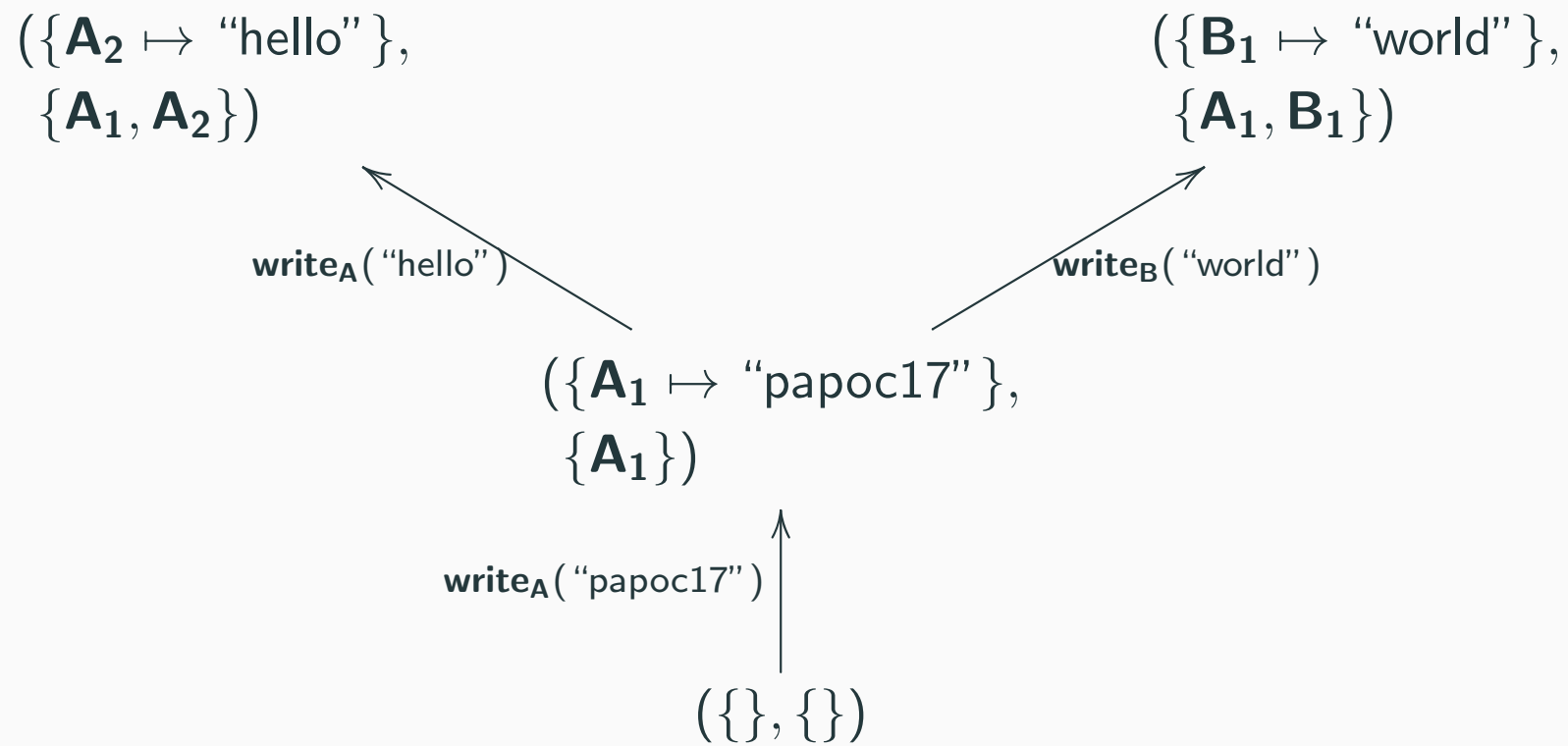
$$\uparrow \textbf{write}_{\mathbf{A}}(\text{“papoc17”})$$

$$(\{\}, \{\})$$

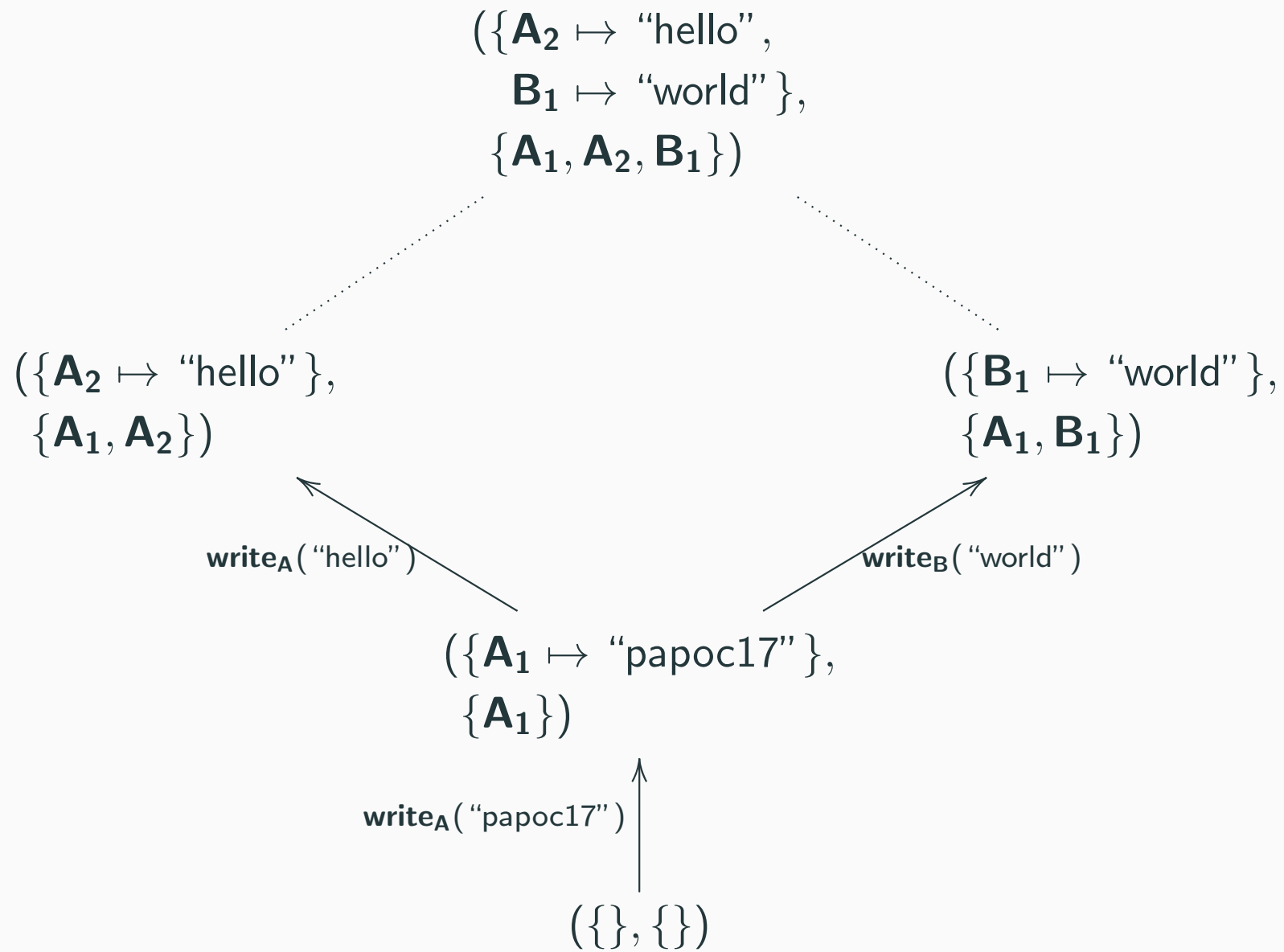
$$\mathbf{MVRegister}\langle\mathcal{V}\rangle = (\mathcal{D} \hookrightarrow \mathcal{V}) \times \mathcal{P}(\mathcal{D})$$
$$= \mathbf{DotFun}\langle\mathcal{V}\rangle \times \mathbf{CausalContext}$$



$$\mathbf{MVRegister}\langle\mathcal{V}\rangle = (\mathcal{D} \hookrightarrow \mathcal{V}) \times \mathcal{P}(\mathcal{D})$$
$$= \mathbf{DotFun}\langle\mathcal{V}\rangle \times \mathbf{CausalContext}$$



$$\mathbf{MVRegister}\langle\mathcal{V}\rangle = (\mathcal{D} \hookrightarrow \mathcal{V}) \times \mathcal{P}(\mathcal{D})$$
$$= \mathbf{DotFun}\langle\mathcal{V}\rangle \times \mathbf{CausalContext}$$



Borrow-Counter

Borrowing an Identity

- Transient nodes borrow an **identity** (in form of a **dot**) from permanent nodes
- Transient nodes increment the counter using that **dot**

Borrowing an Identity

- Transient nodes borrow an **identity** (in form of a **dot**) from permanent nodes
- Transient nodes increment the counter using that **dot**

$$(\mathcal{D} \hookrightarrow \mathbb{N}) \times \mathcal{P}(\mathcal{D}) = \textbf{DotFun}\langle\mathbb{N}\rangle \times \textbf{CausalContext}$$

Borrowing an Identity

- Transient nodes borrow an **identity** (in form of a **dot**) from permanent nodes
- Transient nodes increment the counter using that **dot**

$$(\mathcal{D} \hookrightarrow \mathbb{N}) \times \mathcal{P}(\mathcal{D}) = \textbf{DotFun}\langle\mathbb{N}\rangle \times \textbf{CausalContext}$$

$$(\{\mathbf{A_1} \mapsto 0\}, \{\mathbf{A_1}\}) \xrightarrow{\textbf{inc}}$$

Borrowing an Identity

- Transient nodes borrow an **identity** (in form of a **dot**) from permanent nodes
- Transient nodes increment the counter using that **dot**

$$(\mathcal{D} \hookrightarrow \mathbb{N}) \times \mathcal{P}(\mathcal{D}) = \textbf{DotFun}\langle\mathbb{N}\rangle \times \textbf{CausalContext}$$

$$(\{\mathbf{A_1} \mapsto 0\}, \{\mathbf{A_1}\}) \xrightarrow{\textbf{inc}} (\{\mathbf{A_1} \mapsto 1\}, \{\mathbf{A_1}\})$$

Borrowing an Identity

- What about dot ownership?

Borrowing an Identity

- What about dot ownership?

$$(\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow \mathbb{N})) \times \mathcal{P}(\mathcal{D}) = \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \rangle \rangle \times \textbf{CausalContext}$$

Borrowing an Identity

- What about dot ownership?

$$(\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow \mathbb{N})) \times \mathcal{P}(\mathcal{D}) = \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \rangle \rangle \times \textbf{CausalContext}$$

$$(\{\}, \{\})$$

Borrowing an Identity

- What about dot ownership?

$$(\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow \mathbb{N})) \times \mathcal{P}(\mathcal{D}) = \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \rangle \rangle \times \textbf{CausalContext}$$

$$(\{\}, \{\}) \xrightarrow{\textbf{create}_{A,A}}$$

Borrowing an Identity

- What about dot ownership?

$$(\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow \mathbb{N})) \times \mathcal{P}(\mathcal{D}) = \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \rangle \rangle \times \textbf{CausalContext}$$

$$(\{\}, \{\}) \xrightarrow{\textbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, \{\mathbf{A_1}\})$$

Borrowing an Identity

- What about dot ownership?

$$(\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow \mathbb{N})) \times \mathcal{P}(\mathcal{D}) = \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \rangle \rangle \times \textbf{CausalContext}$$

$$(\{\}, \{\}) \xrightarrow{\textbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, \{\mathbf{A_1}\}) \xrightarrow{\textbf{create}_{A,T}}$$

Borrowing an Identity

- What about dot ownership?

$$(\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow \mathbb{N})) \times \mathcal{P}(\mathcal{D}) = \mathbf{DotMap}\langle \mathbb{I}, \mathbf{DotFun}\langle \mathbb{N} \rangle \rangle \times \mathbf{CausalContext}$$

$$(\{\}, \{\}) \xrightarrow{\mathbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, \{\mathbf{A_1}\}) \xrightarrow{\mathbf{create}_{A,T}} (\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, T \mapsto \{\mathbf{A_2} \mapsto 0\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

$$\downarrow \mathbf{inc}_{T,17}$$

Borrowing an Identity

- What about dot ownership?

$$(\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow \mathbb{N})) \times \mathcal{P}(\mathcal{D}) = \mathbf{DotMap}\langle \mathbb{I}, \mathbf{DotFun}\langle \mathbb{N} \rangle \rangle \times \mathbf{CausalContext}$$

$$(\{\}, \{\}) \xrightarrow{\mathbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, \{\mathbf{A_1}\}) \xrightarrow{\mathbf{create}_{A,T}} (\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, T \mapsto \{\mathbf{A_2} \mapsto 0\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

$$\downarrow \mathbf{inc}_{T,17}$$

$$(\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, T \mapsto \{\mathbf{A_2} \mapsto 17\}\}, \{\mathbf{A_1}, \mathbf{A_2}\}) \xleftarrow{\mathbf{retire}_T}$$

Borrowing an Identity

- What about dot ownership?

$$(\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow \mathbb{N})) \times \mathcal{P}(\mathcal{D}) = \mathbf{DotMap}\langle \mathbb{I}, \mathbf{DotFun}\langle \mathbb{N} \rangle \rangle \times \mathbf{CausalContext}$$

$$(\{\}, \{\}) \xrightarrow{\mathbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, \{\mathbf{A_1}\}) \xrightarrow{\mathbf{create}_{A,T}} (\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, T \mapsto \{\mathbf{A_2} \mapsto 0\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

$$\downarrow \mathbf{inc}_{T,17}$$

$$(\{A \mapsto \{\mathbf{A_1} \mapsto 0\}\}, T \mapsto \{\mathbf{A_2} \mapsto 17\}\}, \{\mathbf{A_1}, \mathbf{A_2}\}) \xrightarrow{\mathbf{retire}_T} \mathbf{?}$$

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

$$\begin{aligned}\textbf{BorrowCounter} &= (\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow (\mathbb{N} \times \mathbb{B}))) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \times \mathbb{B} \rangle \rangle \times \textbf{CausalContext}\end{aligned}$$

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

$$\begin{aligned}\textbf{BorrowCounter} &= (\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow (\mathbb{N} \times \mathbb{B}))) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \times \mathbb{B} \rangle \rangle \times \textbf{CausalContext}\end{aligned}$$

$$(\{\}, \{\})$$

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

$$\begin{aligned}\textbf{BorrowCounter} &= (\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow (\mathbb{N} \times \mathbb{B}))) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \times \mathbb{B} \rangle \rangle \times \textbf{CausalContext}\end{aligned}$$

$$(\{\}, \{\}) \xrightarrow{\textbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, \{\mathbf{A_1}\})$$

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

$$\begin{aligned}\textbf{BorrowCounter} &= (\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow (\mathbb{N} \times \mathbb{B}))) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \times \mathbb{B} \rangle \rangle \times \textbf{CausalContext}\end{aligned}$$

$$(\{\}, \{\}) \xrightarrow{\textbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, \{\mathbf{A_1}\}) \xrightarrow{\textbf{create}_{A,T}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}, T \mapsto \{\mathbf{A_2} \mapsto \underline{0}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

$$\begin{aligned}\textbf{BorrowCounter} &= (\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow (\mathbb{N} \times \mathbb{B}))) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \times \mathbb{B} \rangle \rangle \times \textbf{CausalContext}\end{aligned}$$

$$(\{\}, \{\}) \xrightarrow{\textbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, \{\mathbf{A_1}\}) \xrightarrow{\textbf{create}_{A,T}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}, T \mapsto \{\mathbf{A_2} \mapsto \underline{0}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

$$\downarrow \textbf{inc}_{T,17}$$

$$(\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}, T \mapsto \{\mathbf{A_2} \mapsto \underline{17}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

$$\begin{aligned}\textbf{BorrowCounter} &= (\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow (\mathbb{N} \times \mathbb{B}))) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \times \mathbb{B} \rangle \rangle \times \textbf{CausalContext}\end{aligned}$$

$$(\{\}, \{\}) \xrightarrow{\textbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, \{\mathbf{A_1}\}) \xrightarrow{\textbf{create}_{A,T}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}, T \mapsto \{\mathbf{A_2} \mapsto \underline{0}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

$$\downarrow \textbf{inc}_{T,17}$$

$$(\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, T \mapsto \{\mathbf{A_2} \mapsto \underline{17}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\}) \xleftarrow{\textbf{retire}_T} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, T \mapsto \{\mathbf{A_2} \mapsto \underline{17}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

$$\begin{aligned}\textbf{BorrowCounter} &= (\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow (\mathbb{N} \times \mathbb{B}))) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \times \mathbb{B} \rangle \rangle \times \textbf{CausalContext}\end{aligned}$$

$$(\{\}, \{\}) \xrightarrow{\textbf{create}_{A,A}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, \{\mathbf{A_1}\}) \xrightarrow{\textbf{create}_{A,T}} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}, T \mapsto \{\mathbf{A_2} \mapsto \underline{0}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\})$$

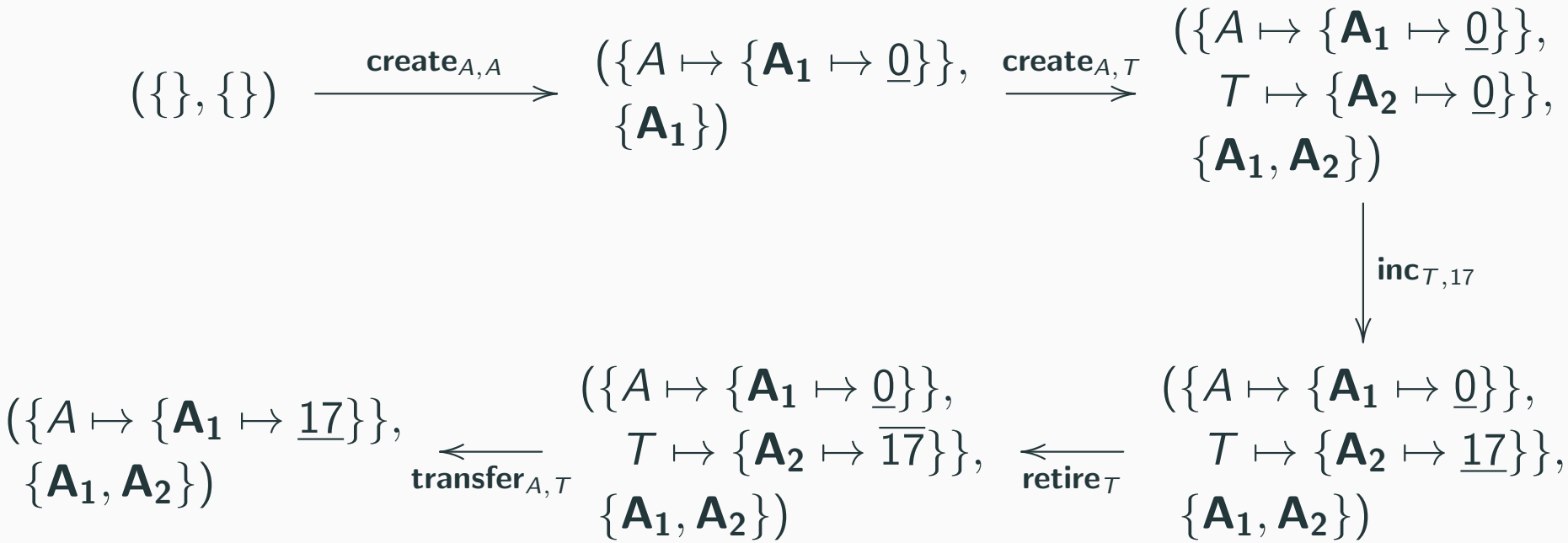
$$\downarrow \textbf{inc}_{T,17}$$

$$(\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, T \mapsto \{\mathbf{A_2} \mapsto \underline{17}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\}) \xleftarrow{\textbf{retire}_T} (\{A \mapsto \{\mathbf{A_1} \mapsto \underline{0}\}\}, T \mapsto \{\mathbf{A_2} \mapsto \overline{17}\}\}, \{\mathbf{A_1}, \mathbf{A_2}\}) \xleftarrow{\textbf{transfer}_{A,T}}$$

Safe Retirement

- Transient nodes **should** mark dots as **inactive**

$$\begin{aligned}\textbf{BorrowCounter} &= (\mathbb{I} \hookrightarrow (\mathcal{D} \hookrightarrow (\mathbb{N} \times \mathbb{B}))) \times \mathcal{P}(\mathcal{D}) \\ &= \textbf{DotMap}\langle \mathbb{I}, \textbf{DotFun}\langle \mathbb{N} \times \mathbb{B} \rangle \rangle \times \textbf{CausalContext}\end{aligned}$$



What we covered

- The Identity Explosion Problem
- CRDT building techniques
- **Borrow-Counter**: a new design for CRDT counters that allows retirement of transient nodes
    - (We focused on increment-only counters)

Questions?

bit.ly/borrow-papoc