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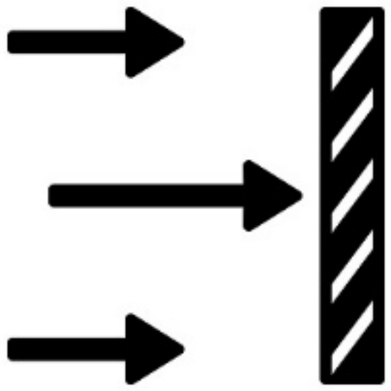
CRDT – CONFLICT-FREE REPLICATED DATA TYPES

CRDTs Units

- Eventual consistency, informally
- State-based objects
- Eventual consistency, more formally
- Conflict-free replicated data types



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EVENTUAL CONSISTENCY, INFORMALLY

Eventual Consistency

- Eventual consistency is desirable for **large-scale distributed systems** where **high availability** is important
- Tends to be cheap to implement (e.g., via gossip) but may serve stale data
- Constitutes a **challenge** for environments where **stronger consistency is important**

Handling Concurrent Writes

- Premise for eventual consistency **were scenarios with few** (no) **concurrent writes** to the same key (cf. client-centric consistency)
- However, we do need a mechanism to **handle concurrent writes** should they so happen
- **If there were** a way to **handle concurrent writes**, we could support **eventual consistency** more broadly
- Would "only" need to guarantee that **after processing all writes for a key**, **all replicas converge**, **no matter what order** the writes are processed (e.g., assuming gossip)

Examples

Growth-only counter (G-counter)

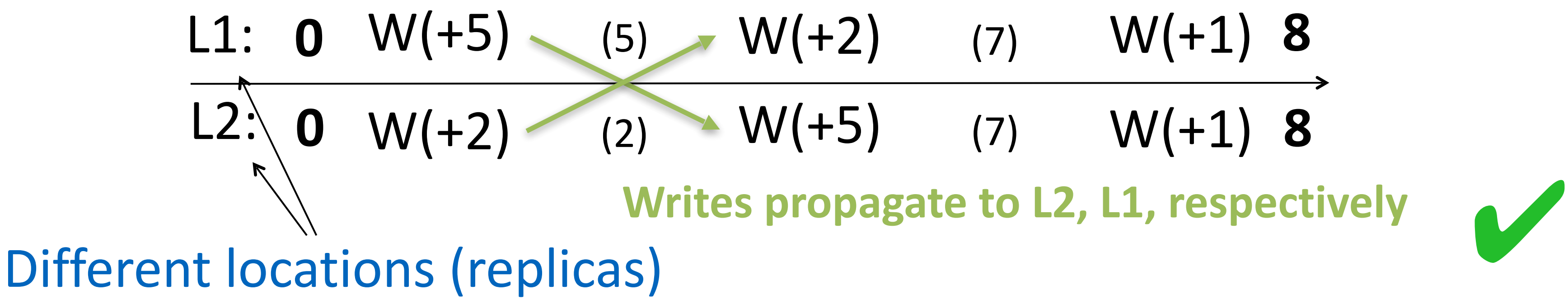
L1: **0** W(+5) (5) W(+2) (7) W(+1) **8**

L2: **0** W(+2) (2) W(+5) (7) W(+1) **8**

Different locations (replicas)

Examples

Growth-only counter (G-counter)



Examples

Growth-only counter (G-counter)

L1: **0** W(+5) (5) W(+2) (7) W(+1) **8**

L2: **0** W(+2) (2) W(+5) (7) W(+1) **8**

Writes propagate to L2, L1, respectively ✔

Different locations (replicas)

Max register

L1: **0** W(4) (4) W(2) (4) merge(5)

L2: **0** W(5) (5) W(3) (5) merge(4)

Examples

Growth-only counter (G-counter)

L1: **0** W(+5) (5) W(+2) (7) W(+1) **8**

L2: **0** W(+2) (2) W(+5) (7) W(+1) **8**

Writes propagate to L2, L1, respectively

Different locations (replicas)

Max register

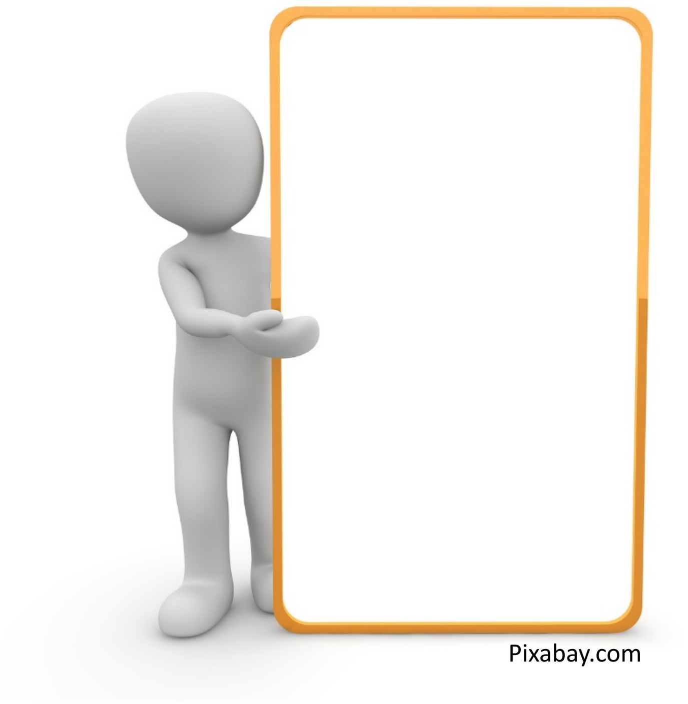
L1: **0** W(4) (4) W(2) (4) merge(5) **5**

L2: **0** W(5) (5) W(3) (5) merge(4) **5**

State propagate to L2, L1 via periodic merging

Self-study Questions

- Think of a few basic data structures, like lists, sets, counters, binary trees, heaps, maps, etc., and visualize for yourself what happens if replicated instances of these structures are updated via gossip.
- Does their state converge, no matter the update sequence?
- What happens if update operations are lost or duplicated?
- What mechanisms we know other than gossip could be used to keep these replicated structures updated without violating their convergence.
- What are pros and cons of these mechanisms?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CRDT – FROM STATE-BASED OBJECTS TO REPLICATED STATE-BASED OBJECTS

State-based objects

Mostly plain old objects

- Offer update and query requests to clients
- Maintain internal state
- Process client requests
- Perform merge requests amongst each other
- Periodically merge (support infrastructure)

State-based Object

- What we commonly know as object
- Comprised of
  - Internal state
  - One or more `query` methods
  - One or more `update` methods
  - A `merge` method

Class Average

Running Example

```
class Avg(object):
def __init__(self):
   self.sum = 0
   self.cnt = 0

def query(self):
   if self.cnt != 0:
       return
         self.sum /
           self.cnt
   else:
     return 0
```

```
def update(self, x):
   self.sum += x
   self.cnt += 1

def merge(self, avg):
   self.sum += avg.sum
   self.cnt += avg.cnt
```

Average

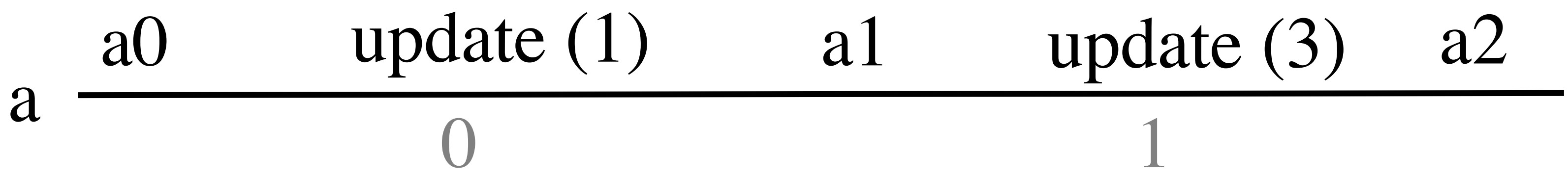
State-based object representing a running average

- Internal state
  - `self.sum` and `self.cnt`
- `Query` returns average
- `Update` updates average with a new value *x*
- `Merge` merges one `Avg` instance into another one

Replicated State-based Object

- State-based object replicated across multiple nodes
- E.g., replicate `Avg` across two nodes
- Both nodes have a copy of state-based object
- Clients send query and update to a single node
- Nodes periodically send their copy of state-based object to other nodes for merging

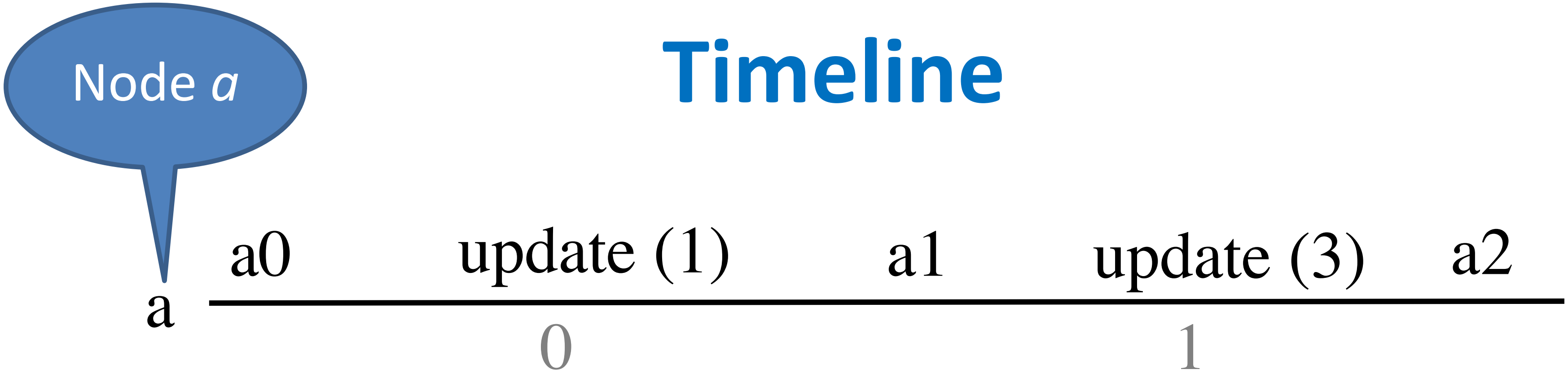
Timeline



Each state represents a snapshot of object in time that results from updates applied

	state		query ()	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:1,	cnt:1	1	{0}
a2	sum:4,	cnt:2	2	{0,1}

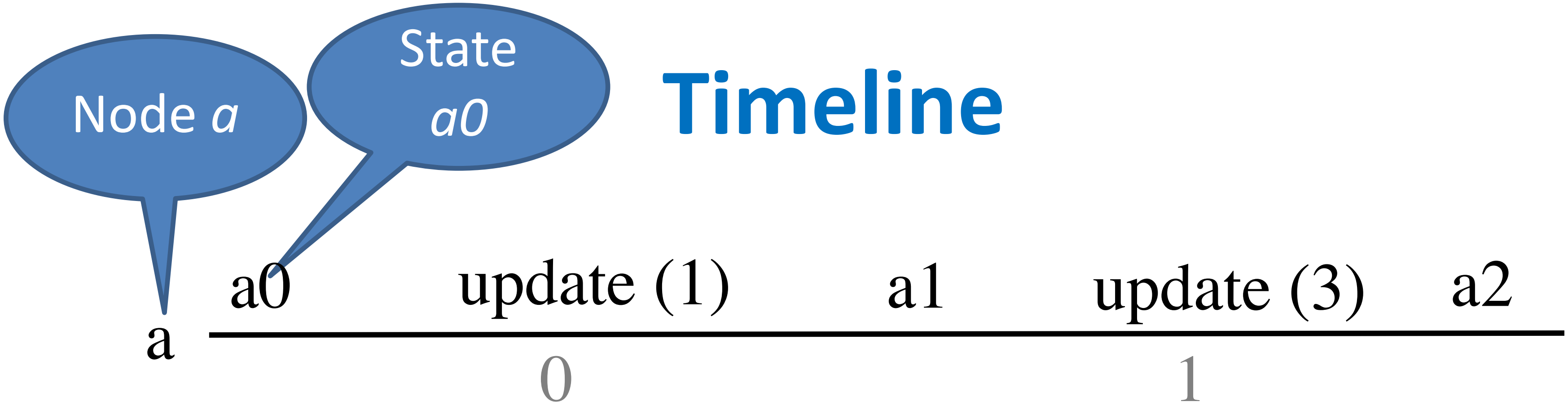
Timeline



Each state represents a snapshot of object in time that results from updates applied

	state		query ()	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:1,	cnt:1	1	{0}
a2	sum:4,	cnt:2	2	{0,1}

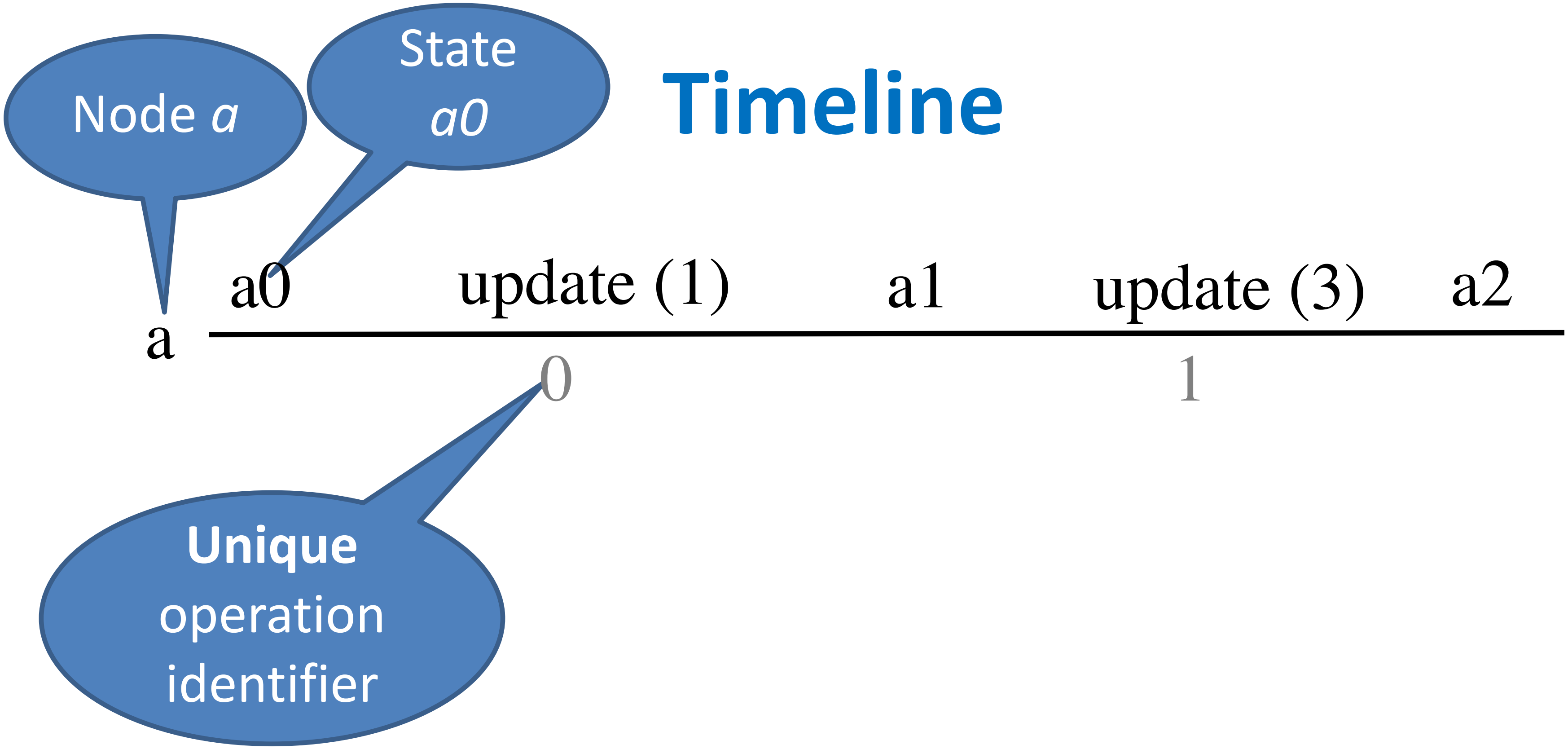
Timeline



Each state represents a snapshot of object in time that results from updates applied

	state		query ()	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:1,	cnt:1	1	{0}
a2	sum:4,	cnt:2	2	{0,1}

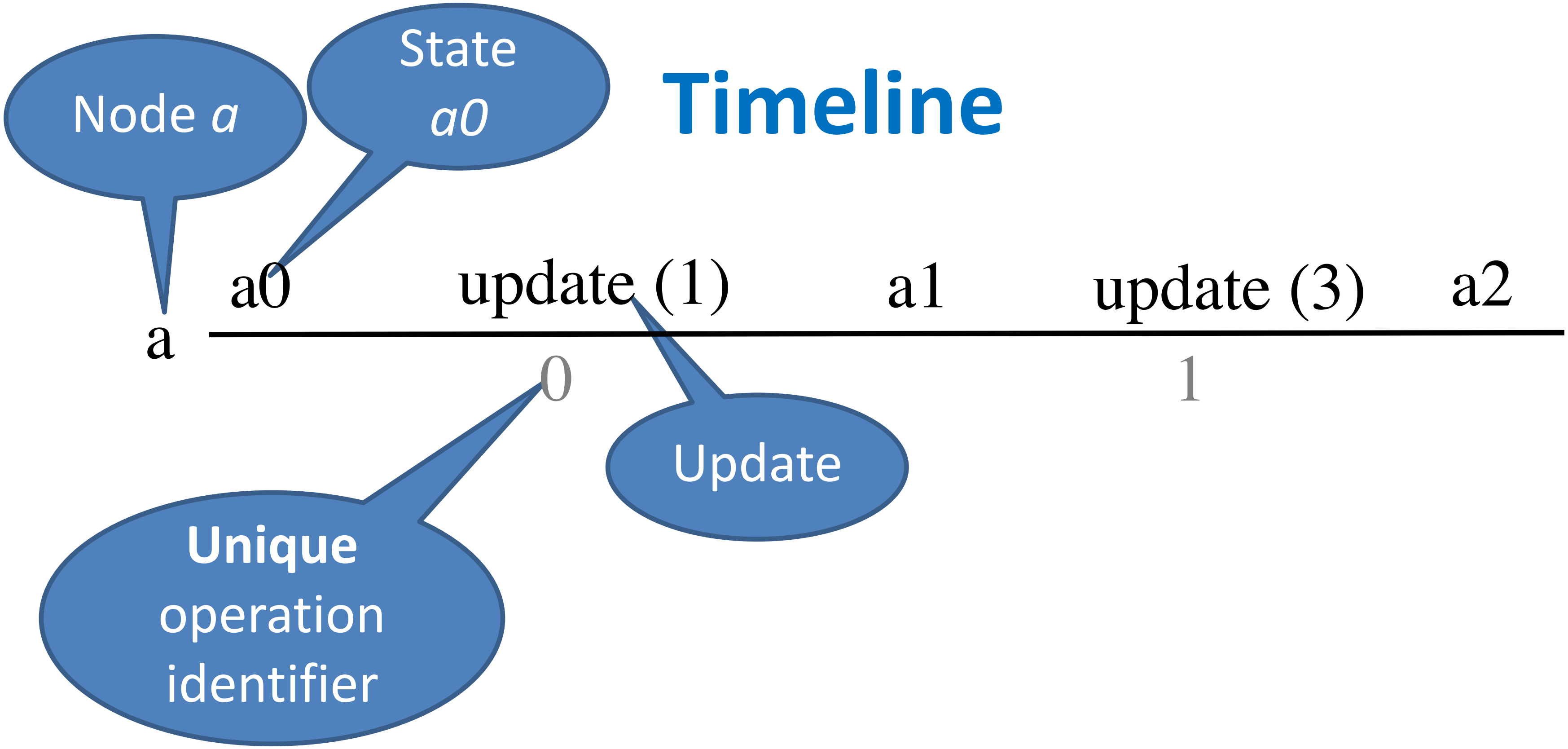
Timeline



Each state represents a snapshot of object in time that results from updates applied

	state		query ()	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:1,	cnt:1	1	{0}
a2	sum:4,	cnt:2	2	{0,1}

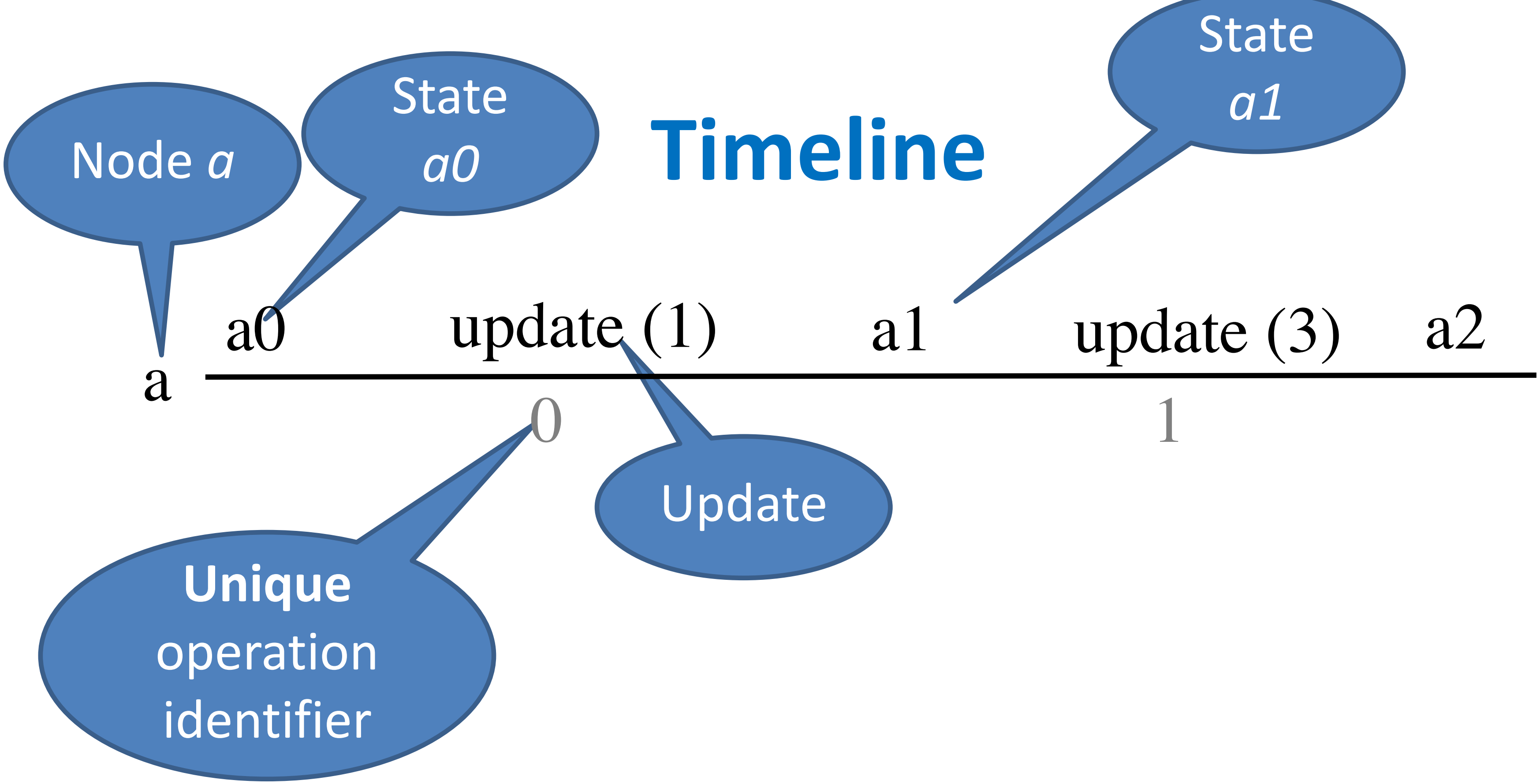
Timeline



Each state represents a snapshot of object in time that results from updates applied

	state	query ()	history
a0	sum:0, cnt:0	0	{ }
a1	sum:1, cnt:1	1	{0}
a2	sum:4, cnt:2	2	{0,1}

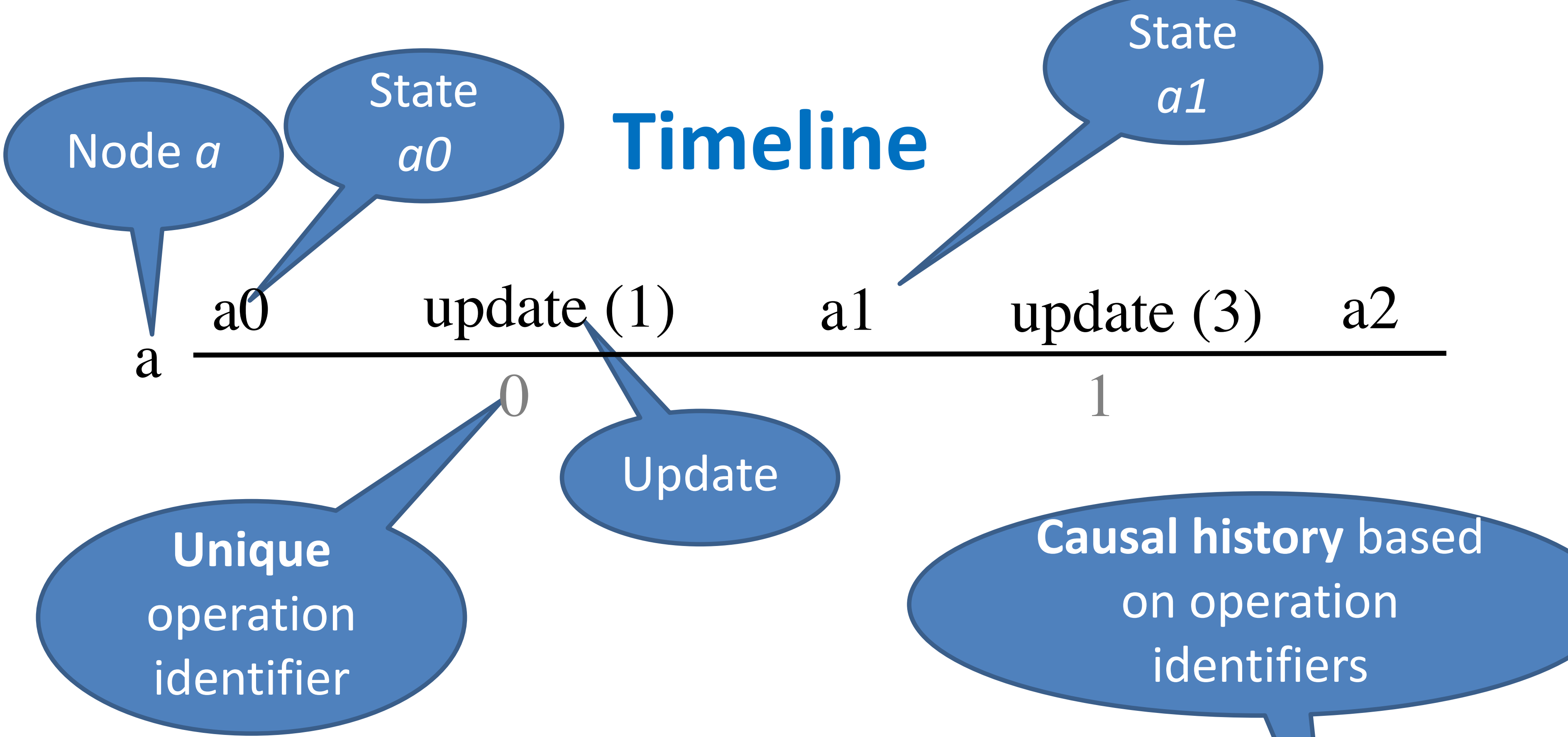
Timeline



Each state represents a snapshot of object in time that results from updates applied

	state		query ()	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:1,	cnt:1	1	{0}
a2	sum:4,	cnt:2	2	{0,1}

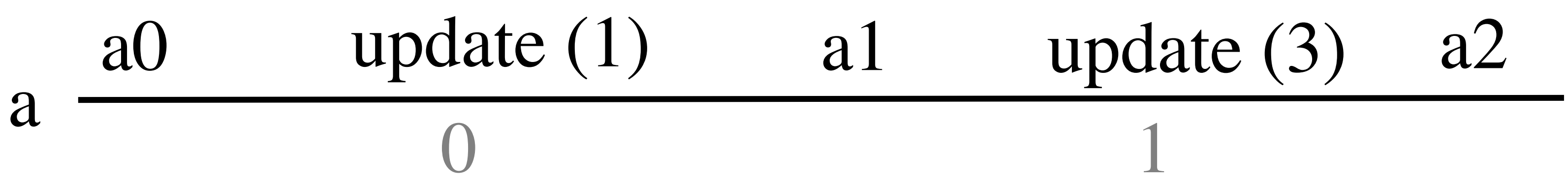
Timeline



Each state represents a snapshot of object in time that results from updates applied

	state		query ()	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:1,	cnt:1	1	{0}
a2	sum:4,	cnt:2	2	{0,1}

Timeline

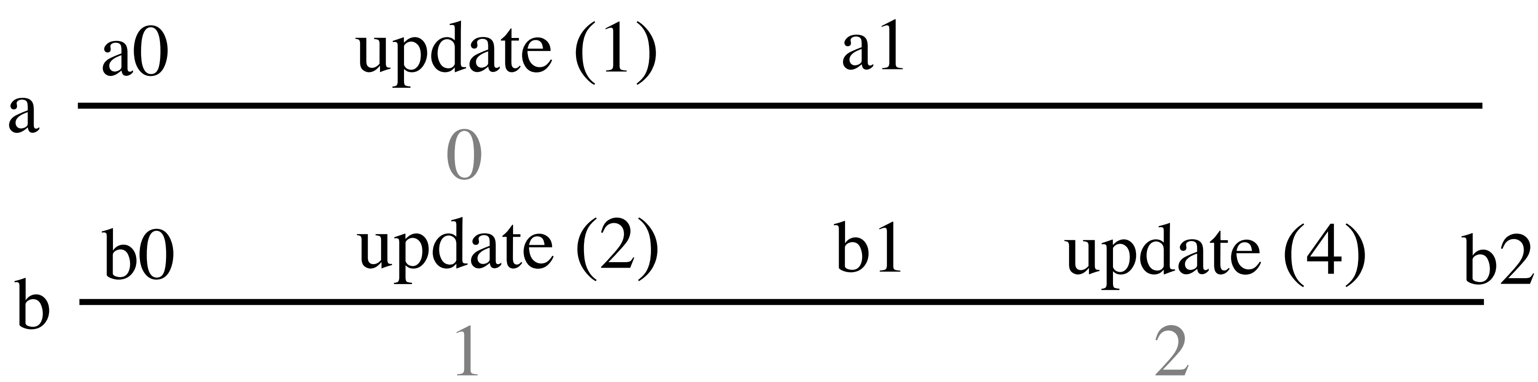


Operation identifier is unique across replicas

Each state represents a snapshot of object in time that results from updates applied

	state	query ()	history
a0	sum:0, cnt:0	0	{ }
a1	sum:1, cnt:1	1	{0}
a2	sum:4, cnt:2	2	{0,1}

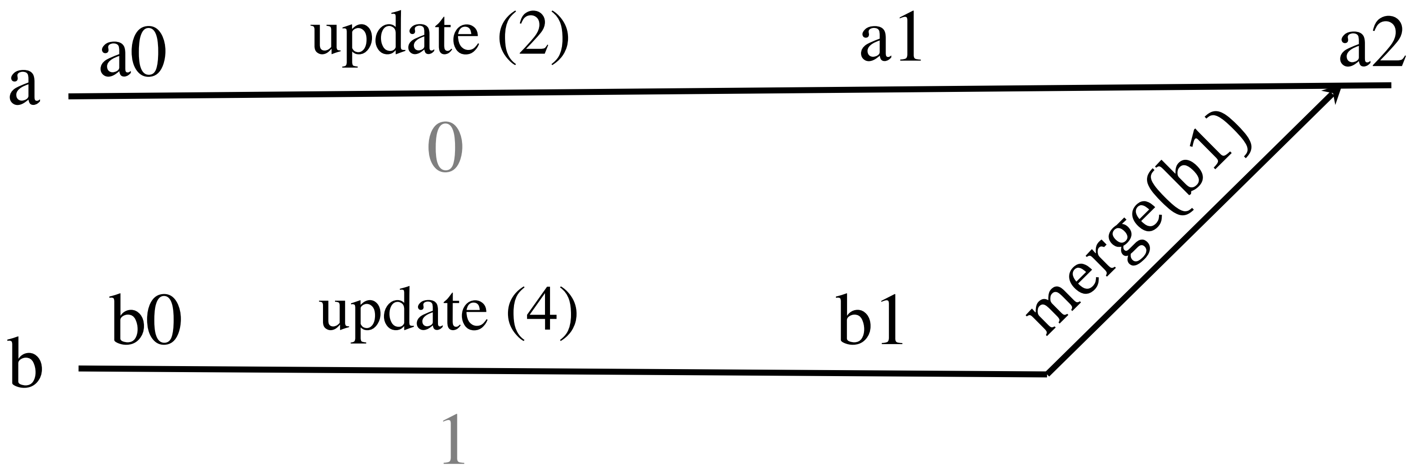
States and Causal Histories



If `y = x.update(…)` where the update has identifier *i*, then the causal history of *y* is the causal history of *x* union { *i* }.

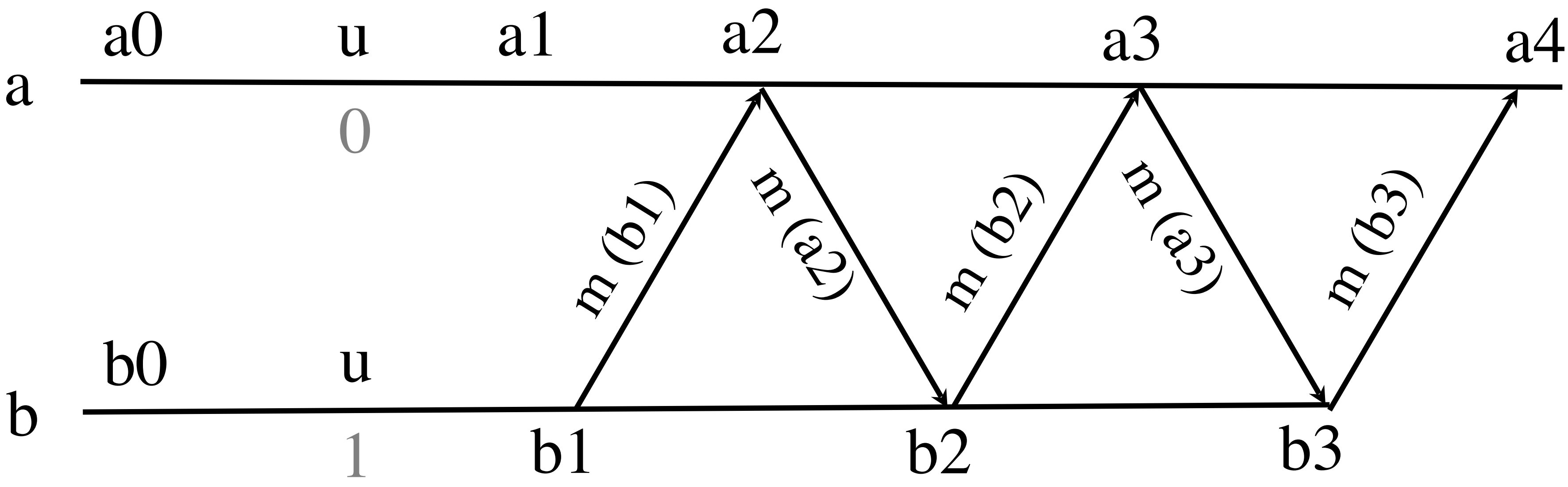
	state	query ()	history
a0	sum:0, cnt:0	0	{ }
a1	sum:1, cnt:1	1	{0}
b0	sum:0, cnt:0	0	{}
b1	sum:2, cnt:1	2	{1}
b2	sum:6, cnt:2	3	{1,2}

Merge



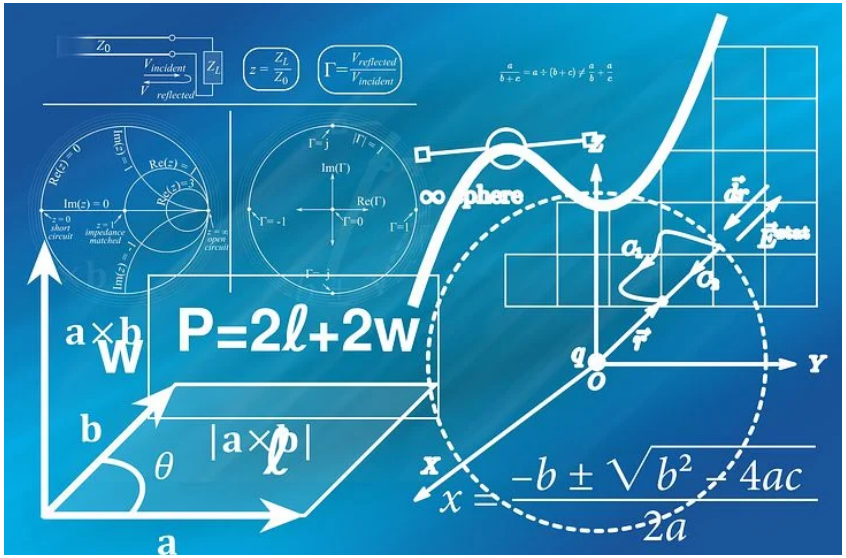
	state		query ()	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
a2	sum:6,	cnt:2	3	{0,1}

Nodes Periodically Propagate Their State



Self-study Questions

- Think of a few basic data structures, like lists, sets, counters, binary trees, heaps, maps, etc., and visualize for yourself what happens if replicated instances of these structures are updated via gossip.
- For the above data structures, specify merge operations that merge the state of two instances of a given structure.
- Assume merge happens periodically, does your replicated structures' state converge?



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CRDT –
EVENTUAL CONSISTENCY, MORE FORMALLY

Eventual Consistency

- A replicated state-based object is
  - **eventually consistent** if whenever two replicas of the state-based object have the same causal history, **they eventually** (not necessarily immediately) converge to the same internal state

Strong Eventual Consistency

- A replicated state-based object is
  - **strongly eventually consistent** if whenever two replicas of the state-based object have the same causal history, **they** (immediately) **have the same internal state**

- Strong eventual consistency implies eventual consistency

EC or SEC

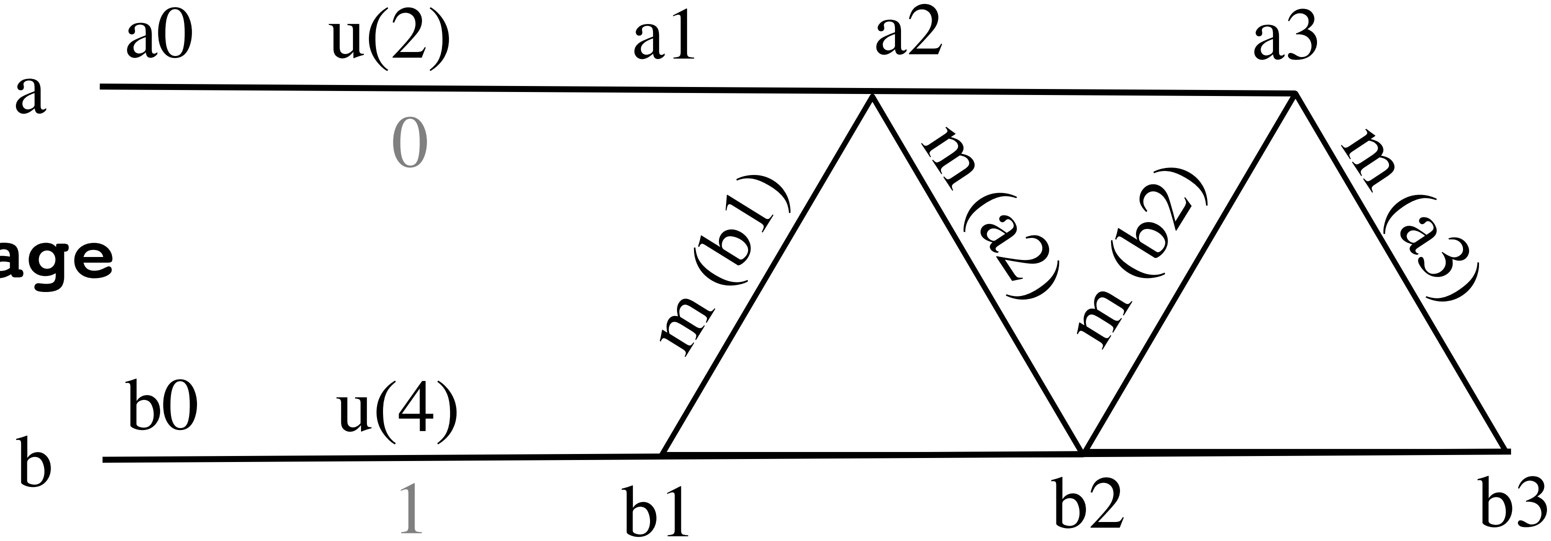
That is the question?

- Variants of our Average object, defined next
  - Average
  - NoMergeAverage
  - BMergeAverage
  - MaxAverage

- Note that some of these objects do not represent realistic functionality (i.e., needed functionality)

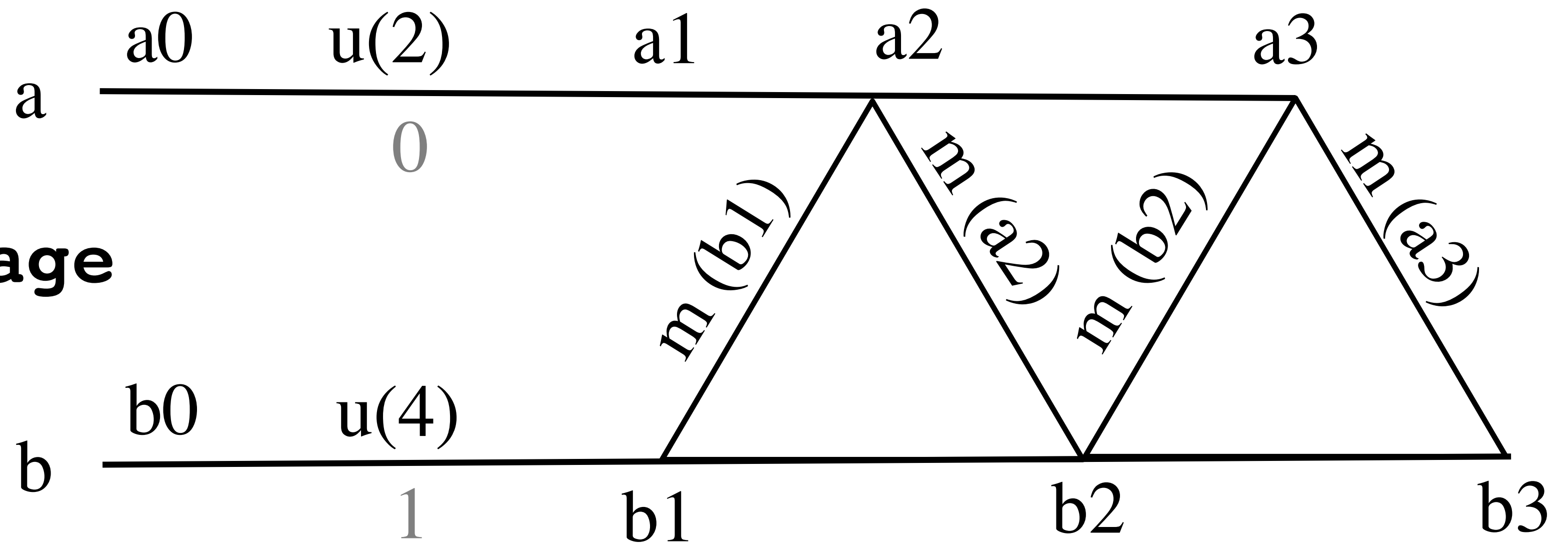
- These objects are meant to illustrate convergence concepts only

Average



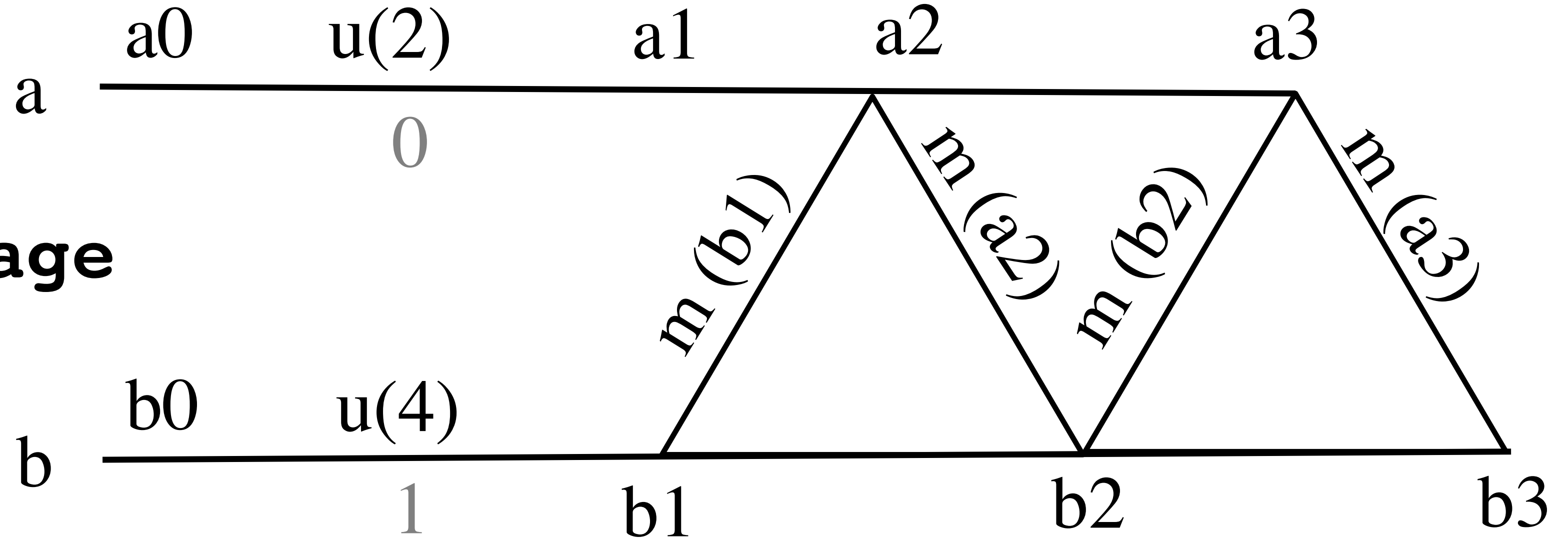
	state	query ( )	history
a0			
a1			
a2			
a3			
b0			
b1			
b2			
b3			

Average



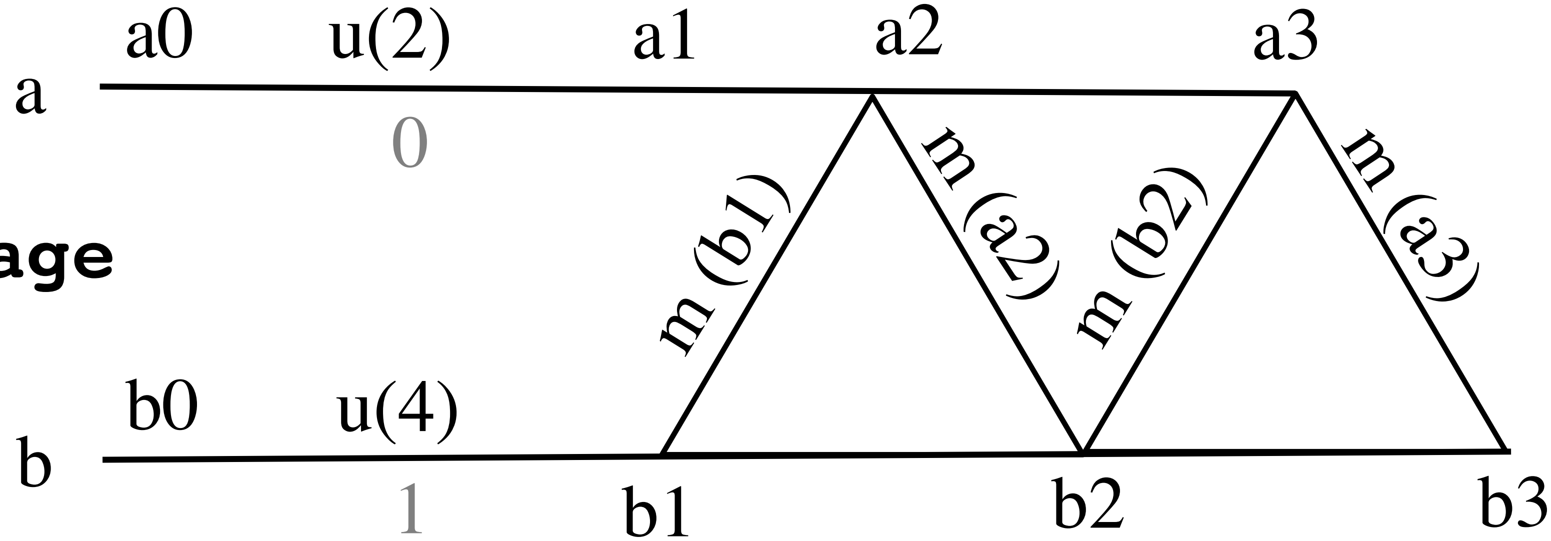
	state	query ( )	history
a0	sum:0, cnt:0	0	{ }
a1			
a2			
a3			
b0			
b1			
b2			
b3			

Average



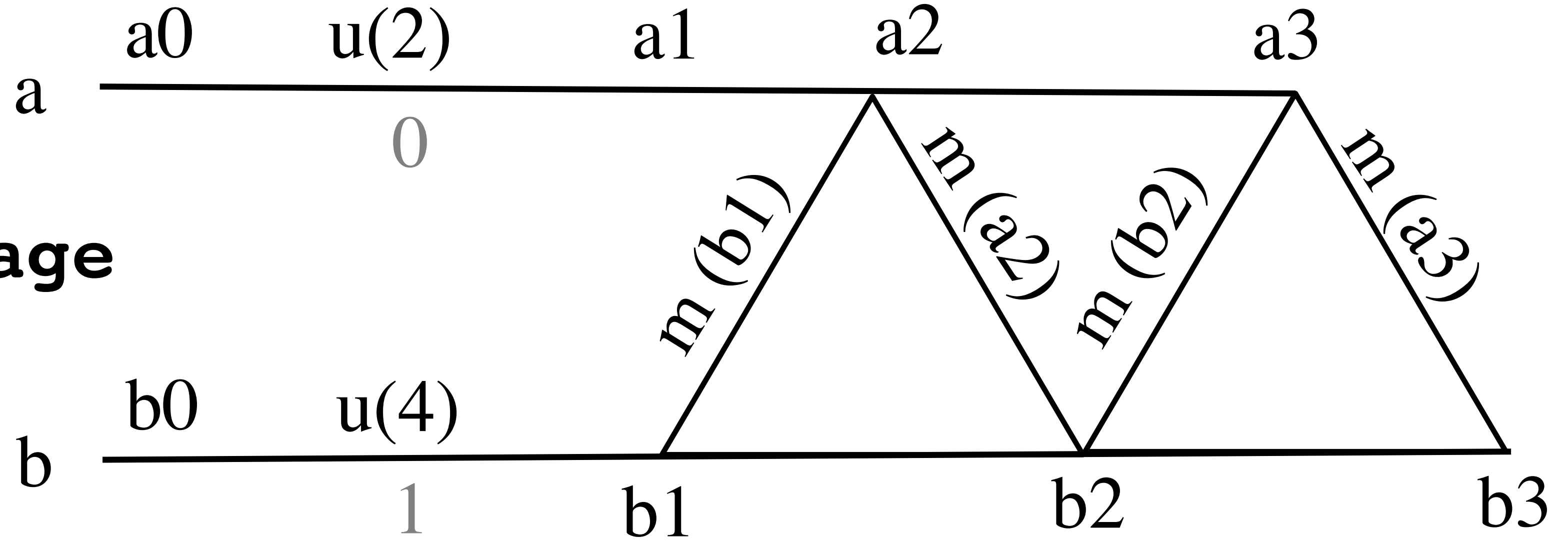
	state	query ( )	history
a0	sum:0, cnt:0	0	{ }
a1	sum:2, cnt:1	2	{0}
a2			
a3			
b0			
b1			
b2			
b3			

Average



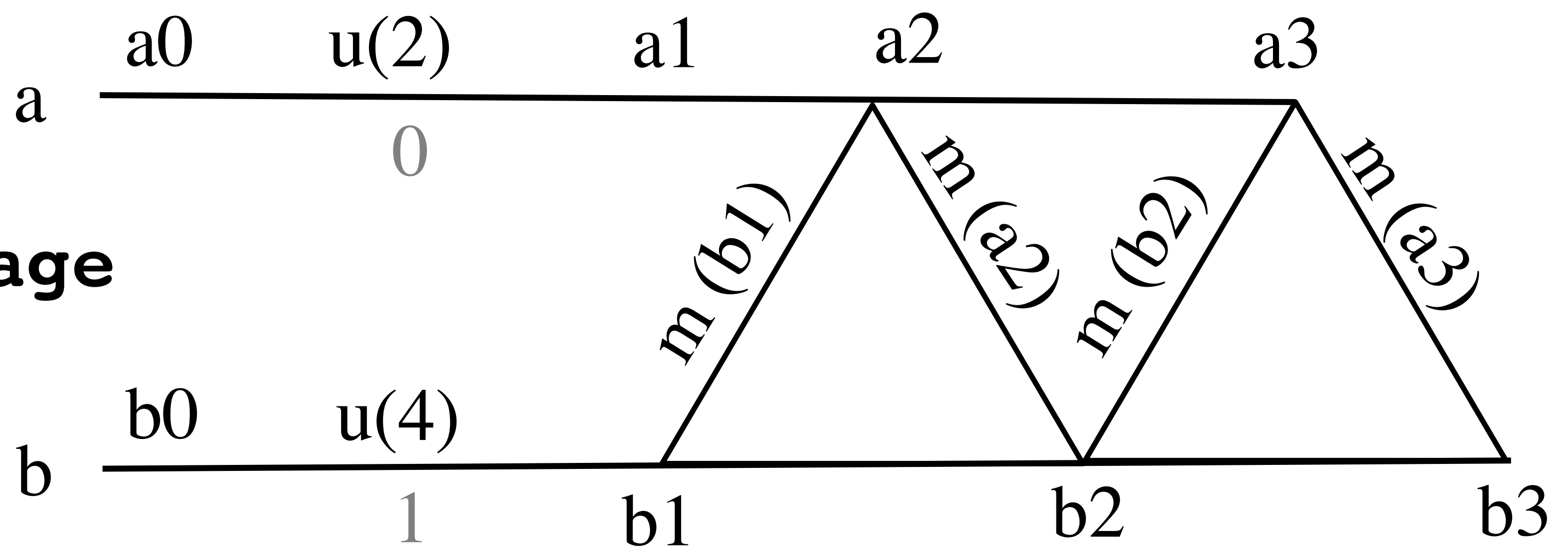
	state	query ( )	history
a0	sum:0, cnt:0	0	{ }
a1	sum:2, cnt:1	2	{0}
a2			
a3			
b0	sum:0, cnt:0	0	{}
b1			
b2			
b3			

Average



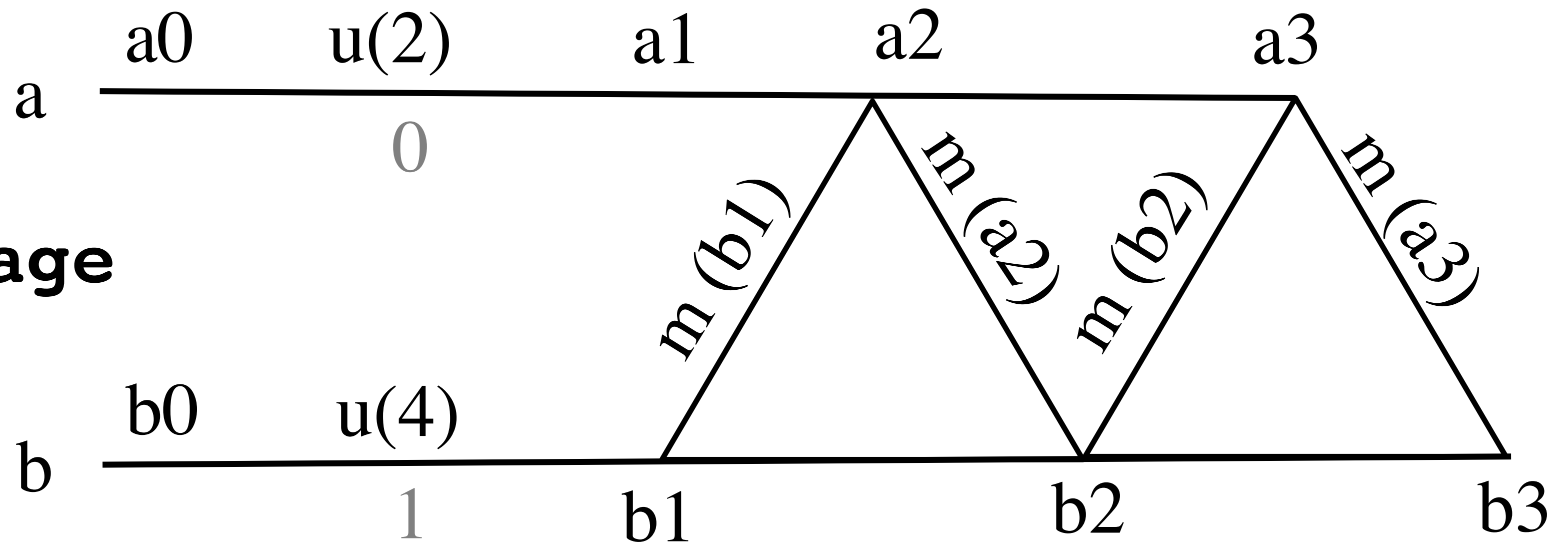
	state	query ( )	history
a0	sum:0, cnt:0	0	{ }
a1	sum:2, cnt:1	2	{0}
a2			
a3			
b0	sum:0, cnt:0	0	{}
b1	sum:4, cnt:1	4	{1}
b2			
b3			

Average



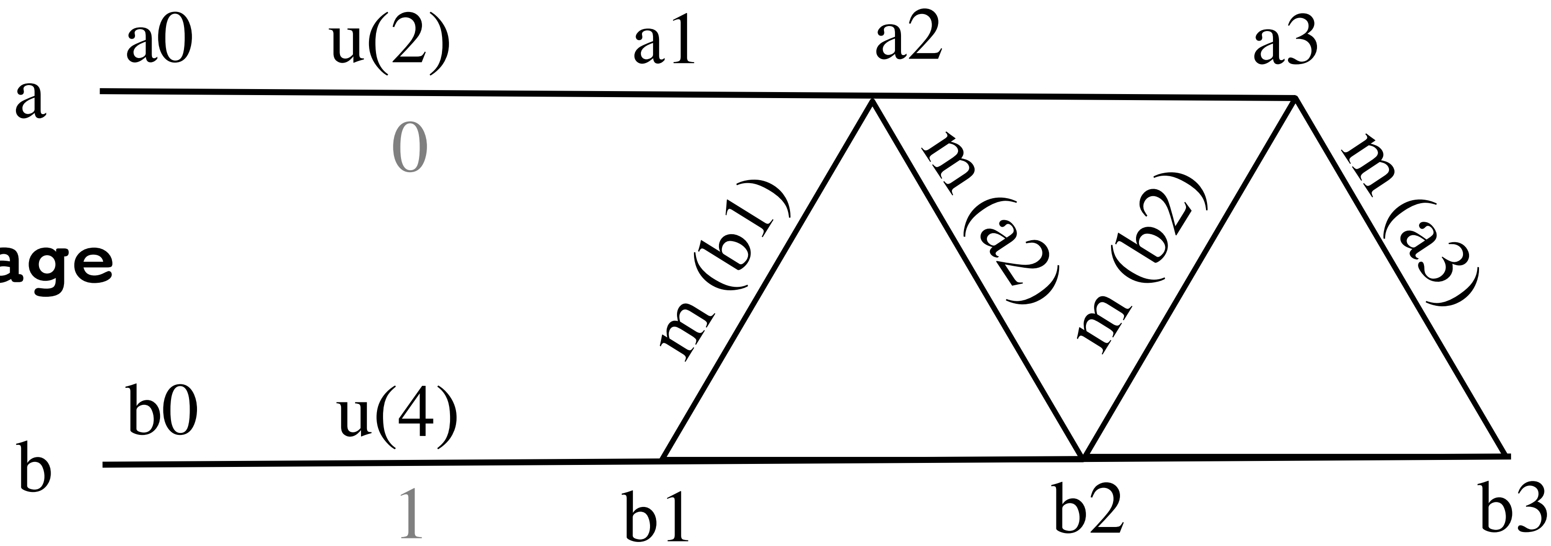
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:6,	cnt:2	3	{0,1}
a3				
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2				
b3				

Average



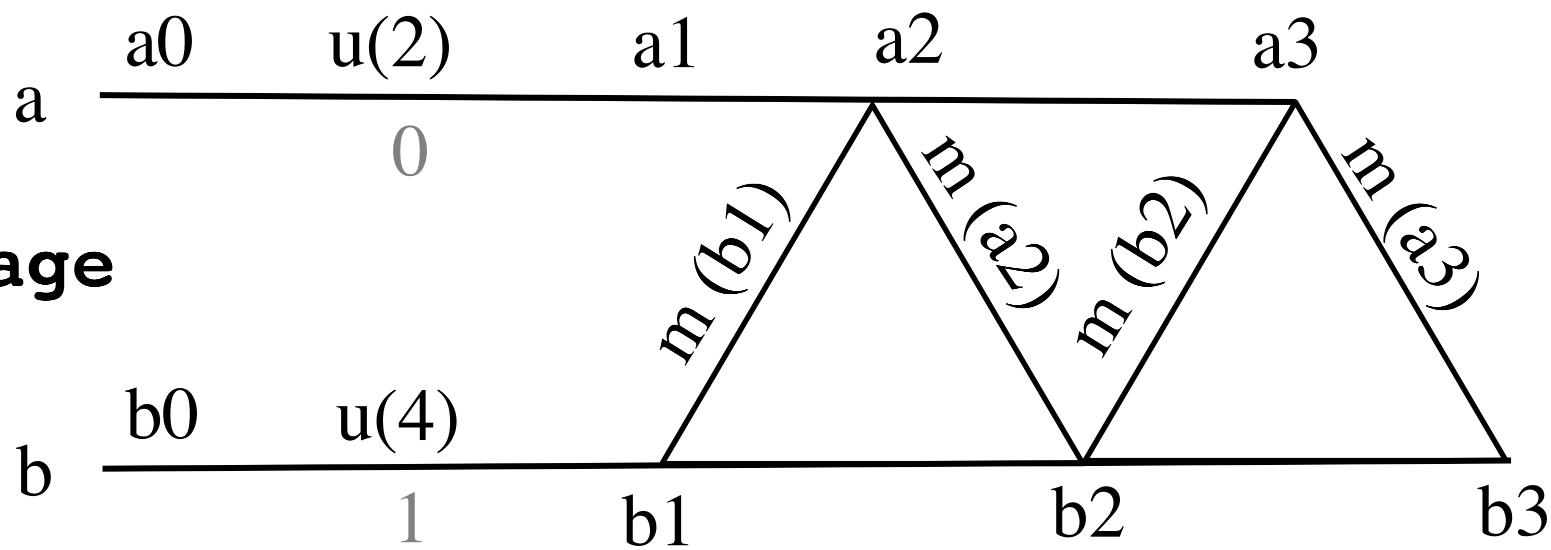
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:6,	cnt:2	3	{0,1}
a3				
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:10,	cnt:3	3.3	{0,1}
b3				

Average



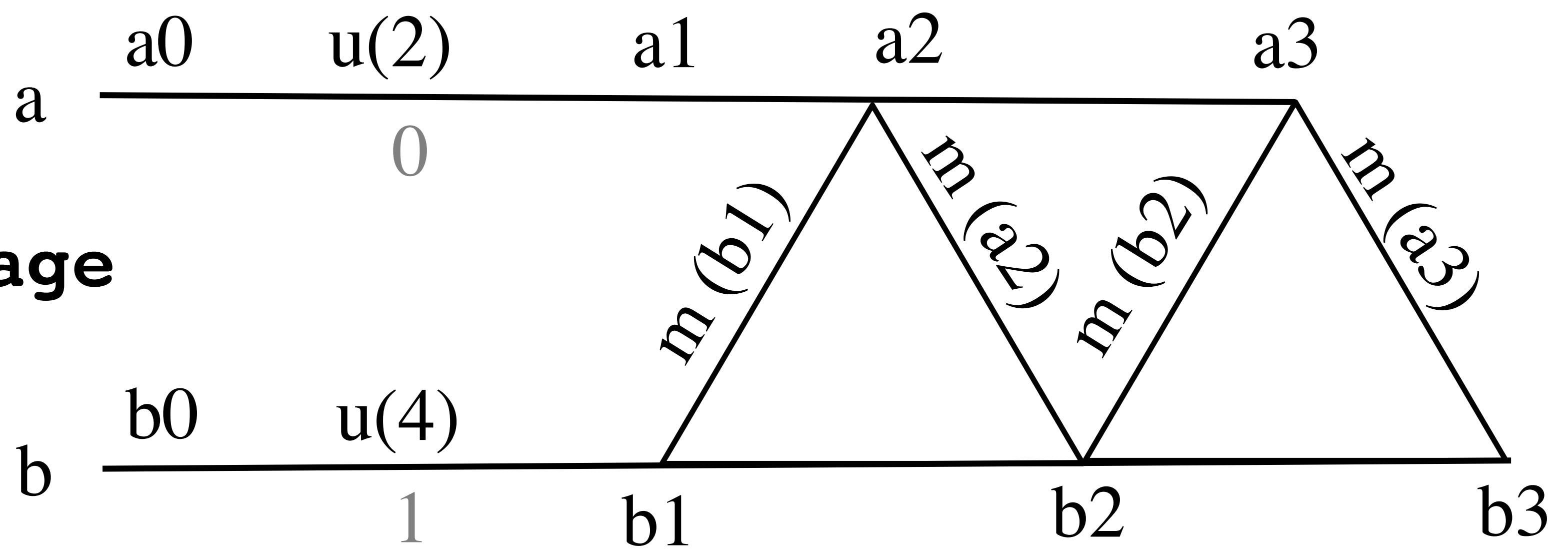
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:6,	cnt:2	3	{0,1}
a3	sum:16,	cnt:5	3.2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:10,	cnt:3	3.3	{0,1}
b3				

Average



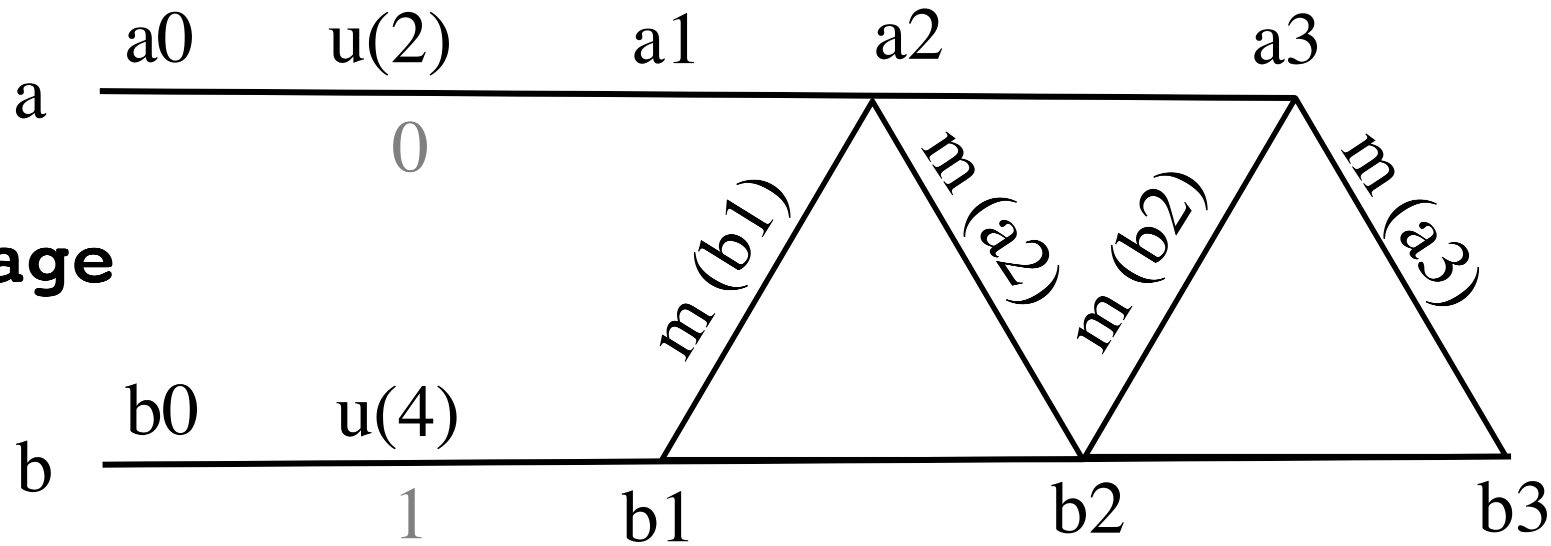
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:6,	cnt:2	3	{0,1}
a3	sum:16,	cnt:5	3.2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:10,	cnt:3	3.3	{0,1}
b3	sum:26,	cnt:8	3.25	{0,1}

Average



a, b attain the **same causal history** but **do not converge** to the **same internal state** – they **do not converge** at all**!**

	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:6,	cnt:2	3	{0,1}
a3	sum:16,	cnt:5	3.2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:10,	cnt:3	3.3	{0,1}
b3	sum:26,	cnt:8	3.25	{0,1}



Average

a, b attain the **same causal history** but **do not converge** to the **same internal state** – they **do not converge** at all**!**

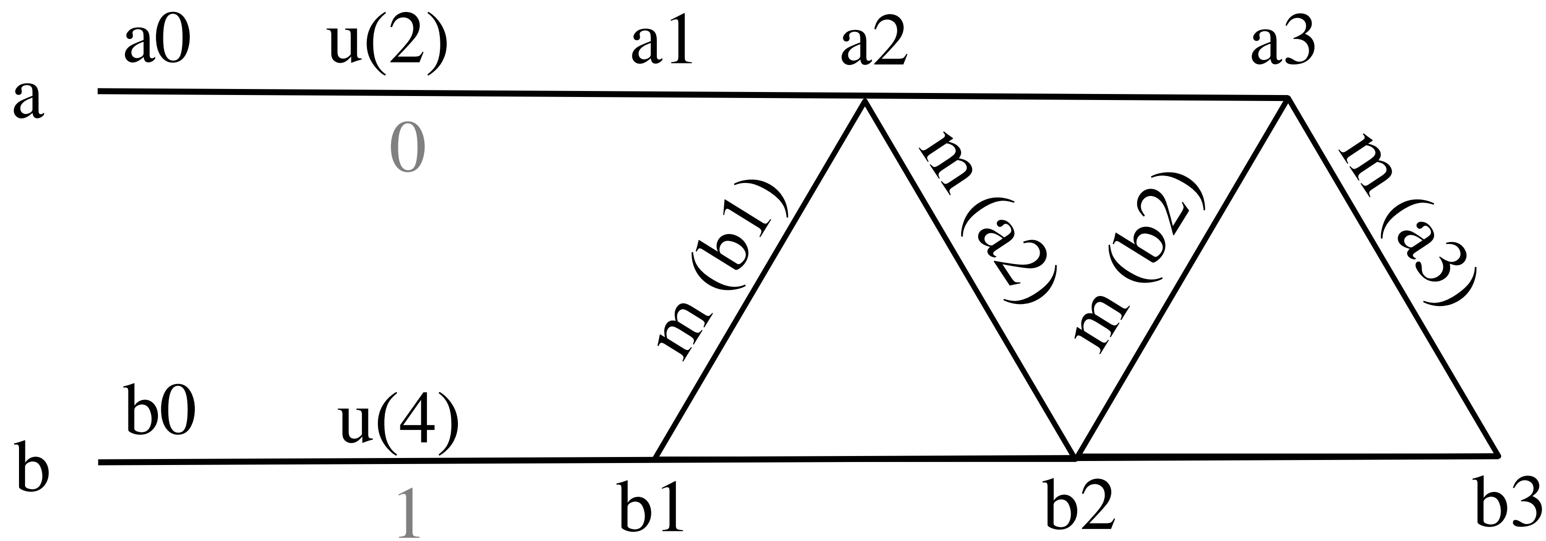
Neither eventually consistent, nor strongly eventually consistent

	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:6,	cnt:2	3	{0,1}
a3	sum:16,	cnt:5	3.2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:10,	cnt:3	3.3	{0,1}
b3	sum:26,	cnt:8	3.25	{0,1}

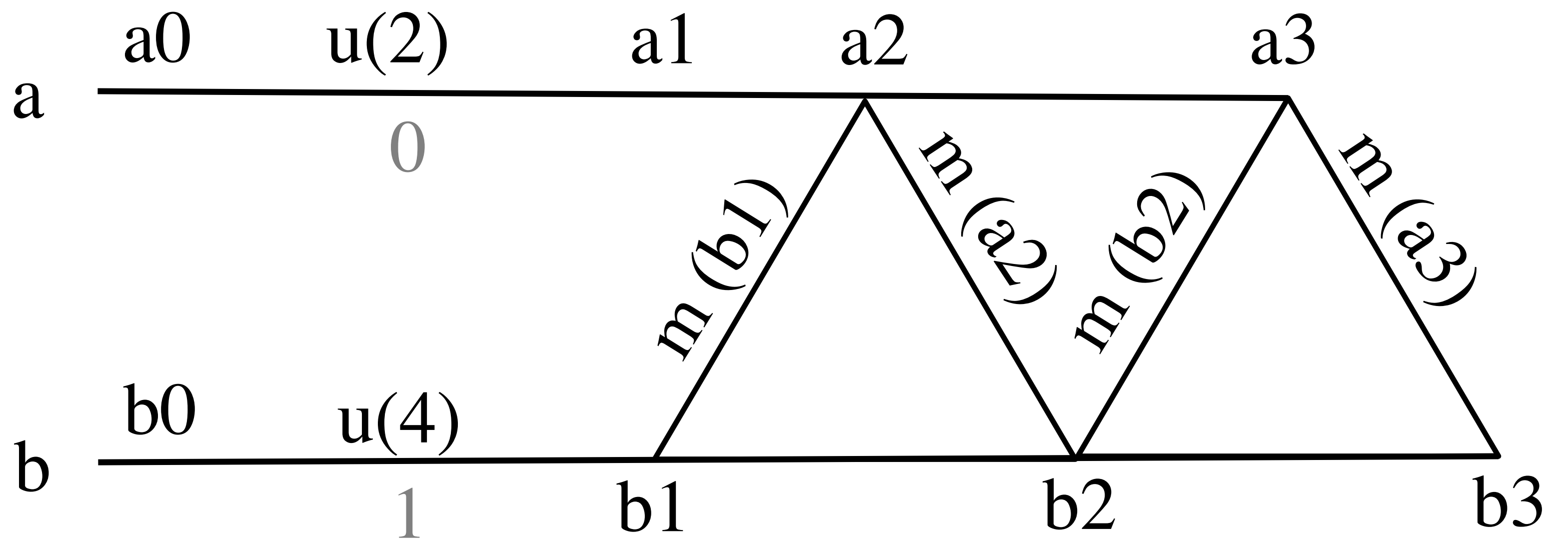
`NoMergeAverage`

- **Object's merge does nothing**

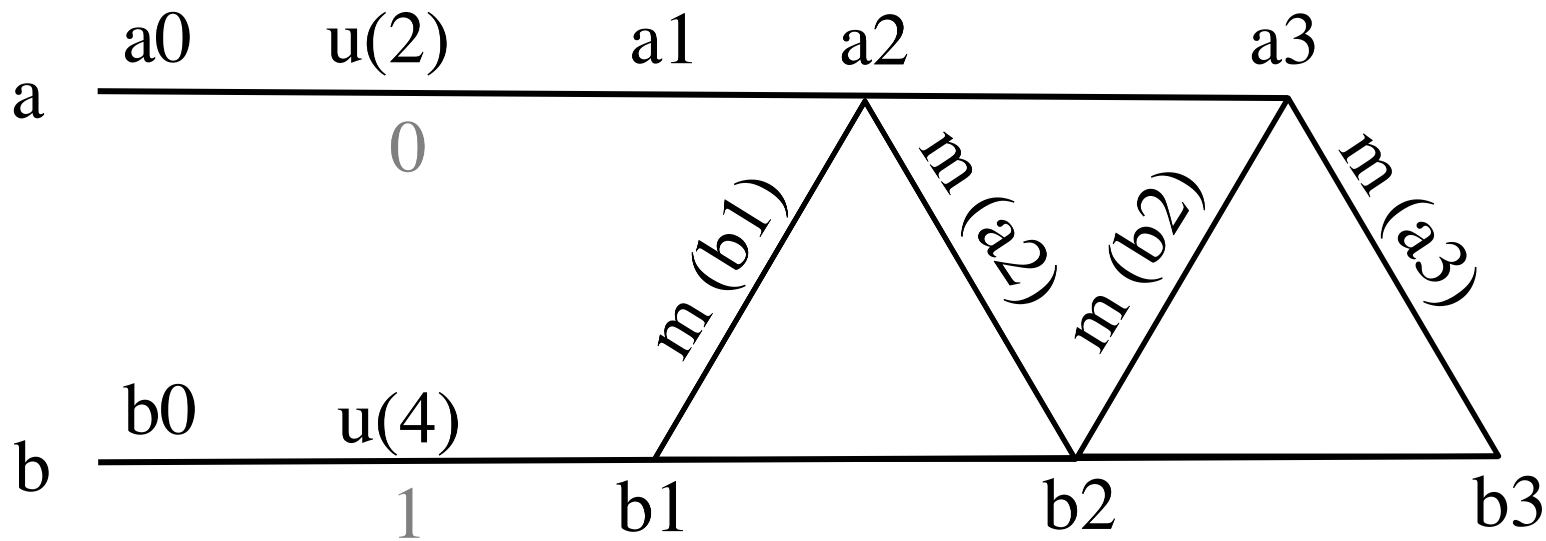
- All else is the same as for `Average`



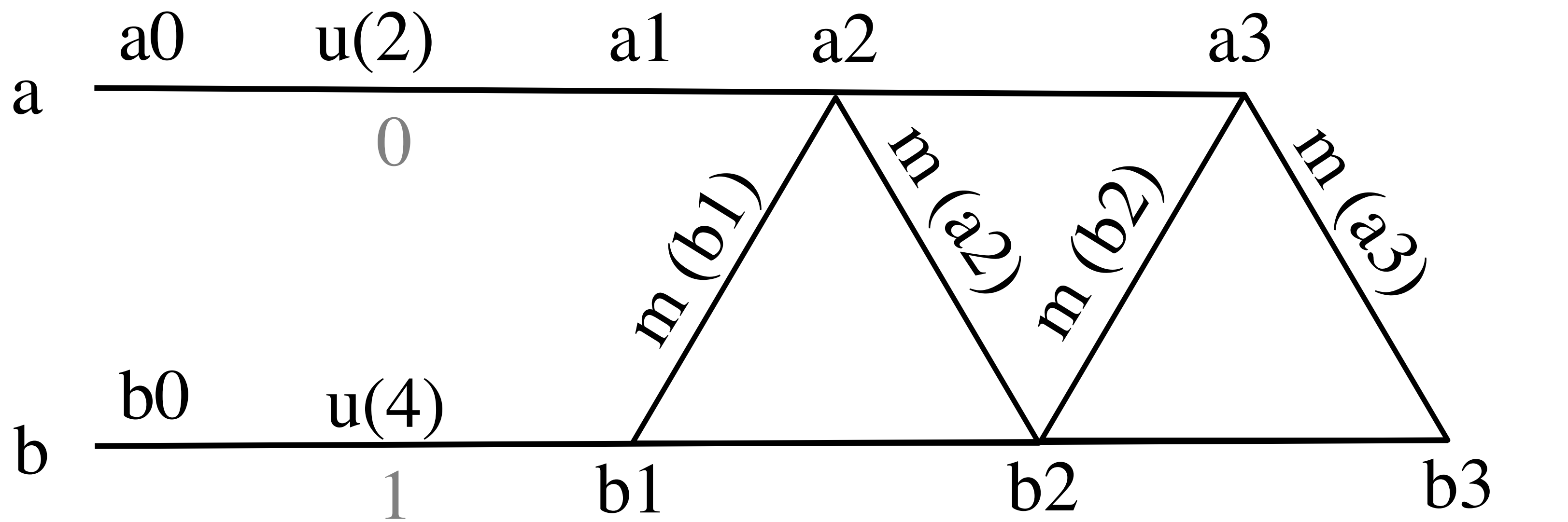
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



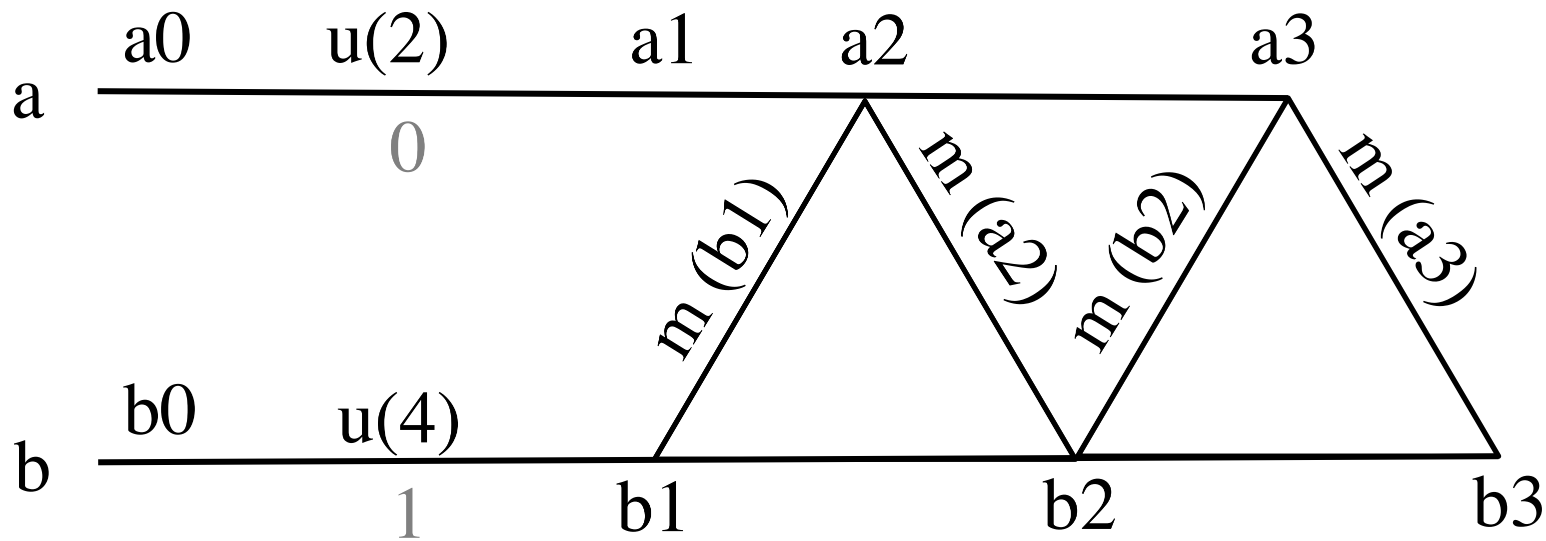
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



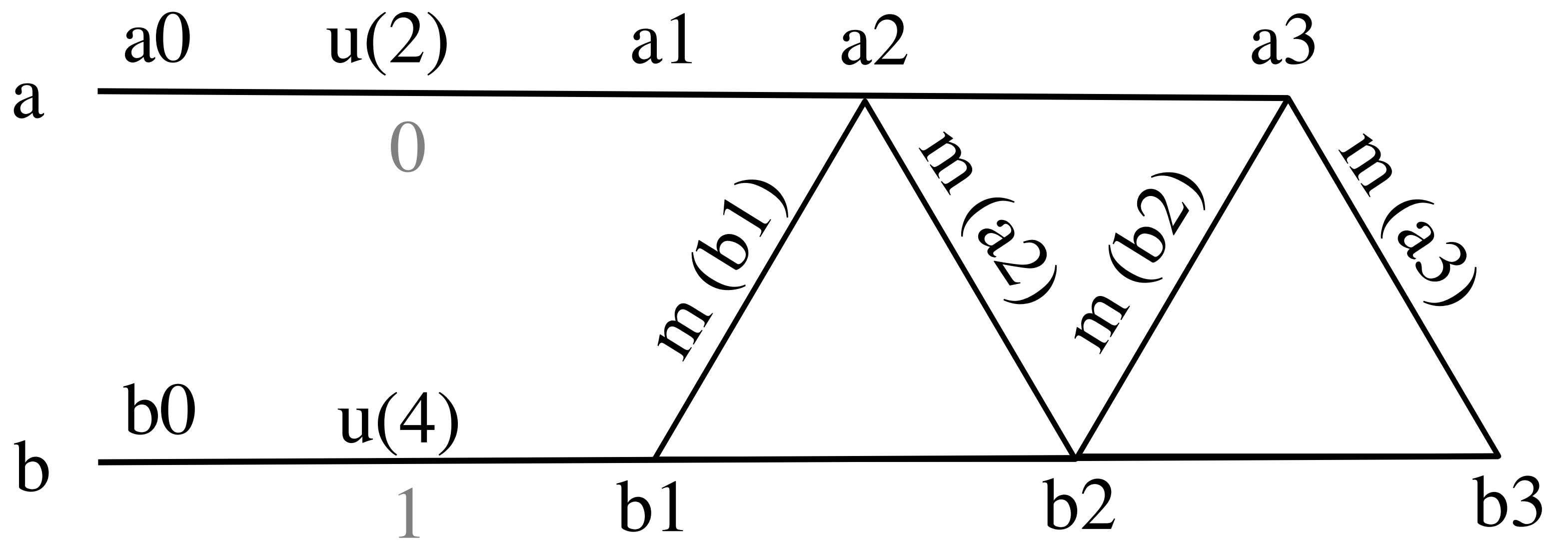
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



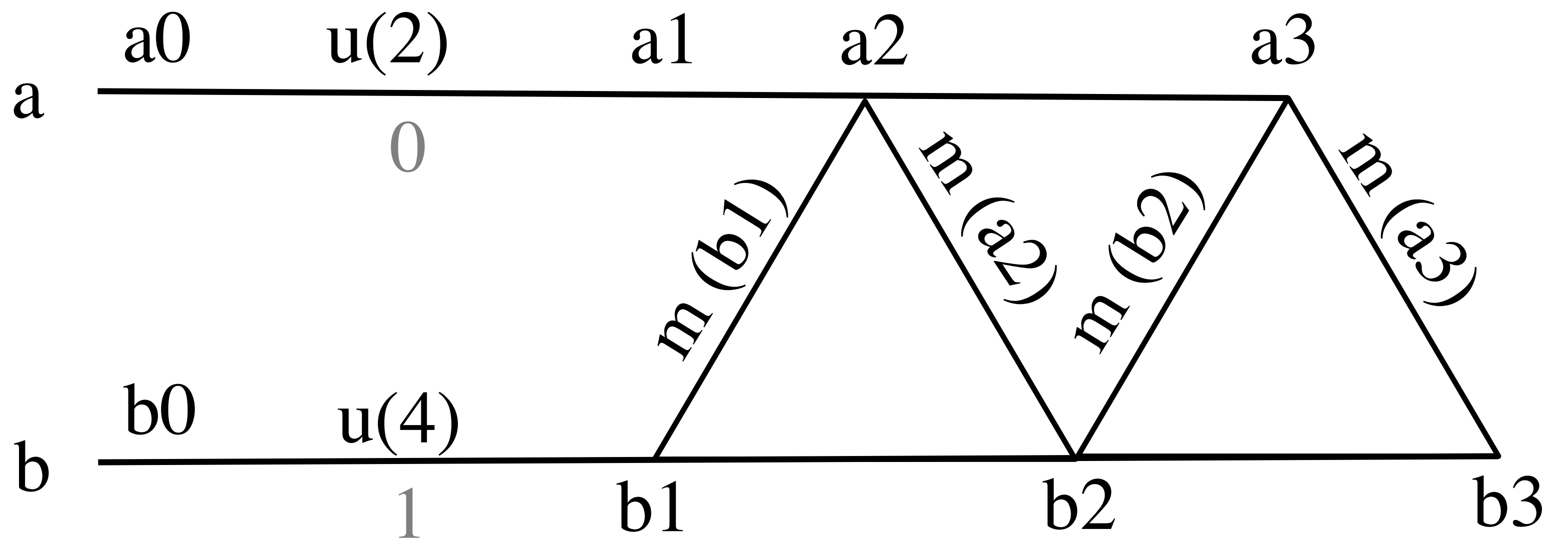
	state	query ( )	history
a0	sum:0, cnt:0	0	{ }
a1	sum:2, cnt:1	2	{0}
a2	sum:2, cnt:1	2	{0,1}
a3	sum:2, cnt:1	2	{0,1}
b0	sum:0, cnt:0	0	{}
b1	sum:4, cnt:1	4	{1}
b2	sum:4, cnt:1	4	{0,1}
b3	sum:4, cnt:1	4	{0,1}



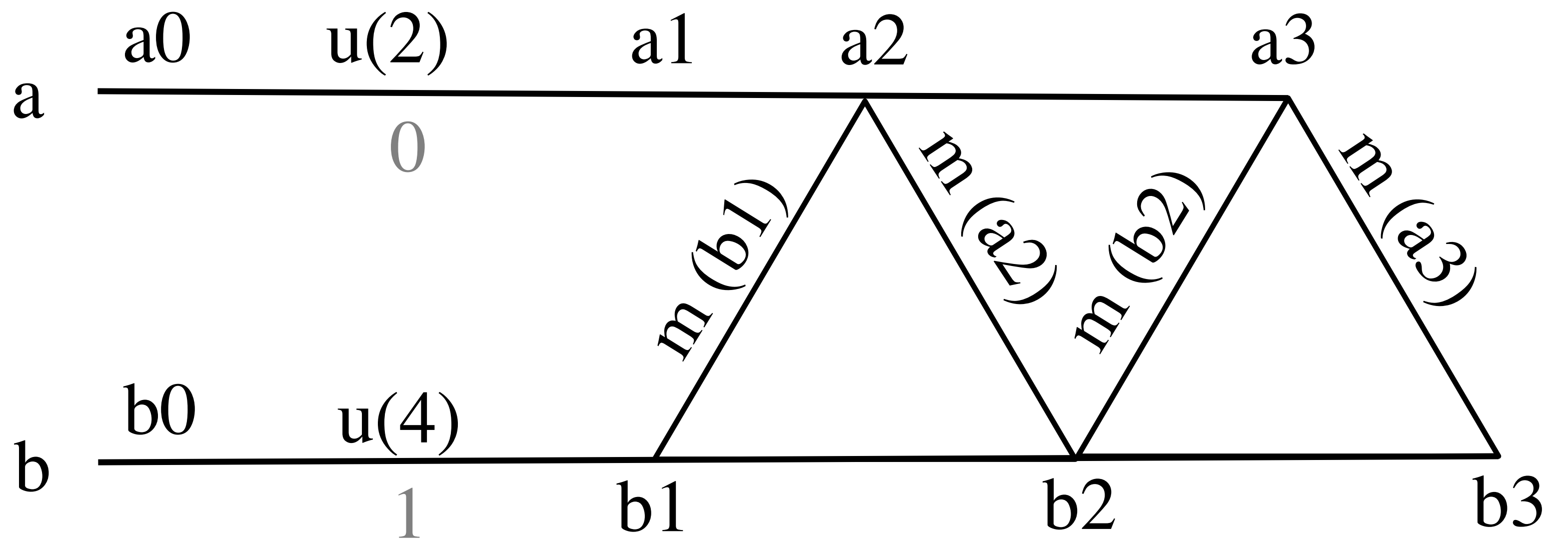
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



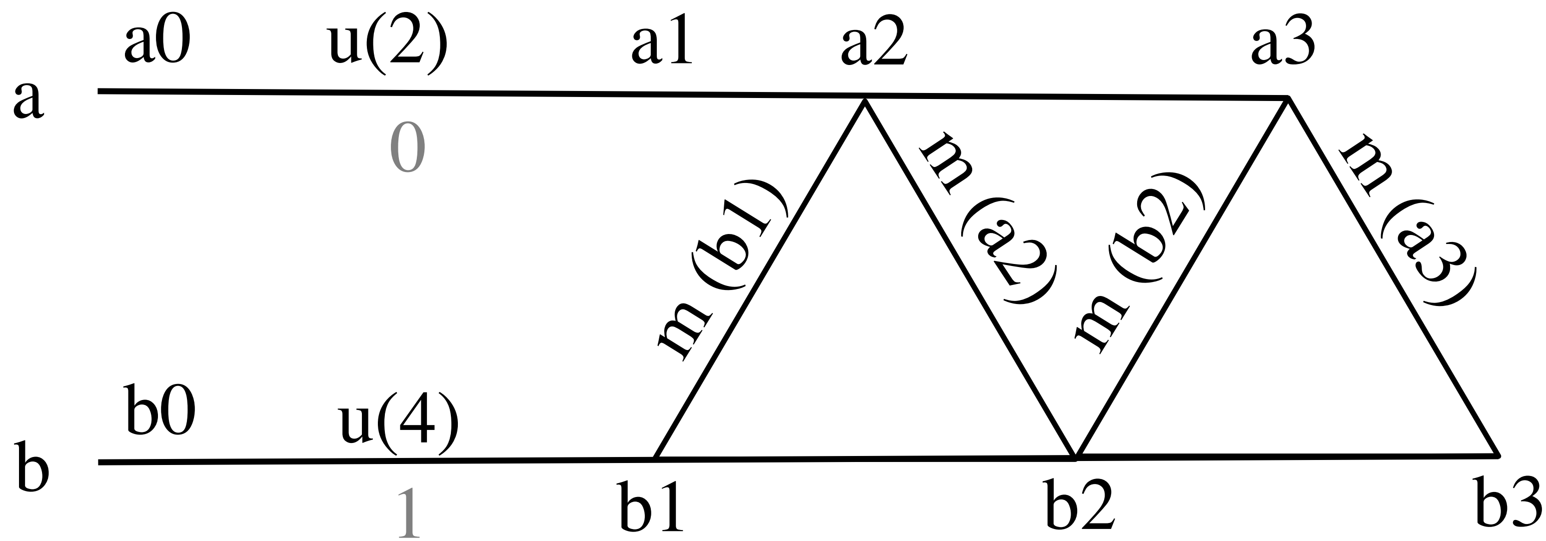
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



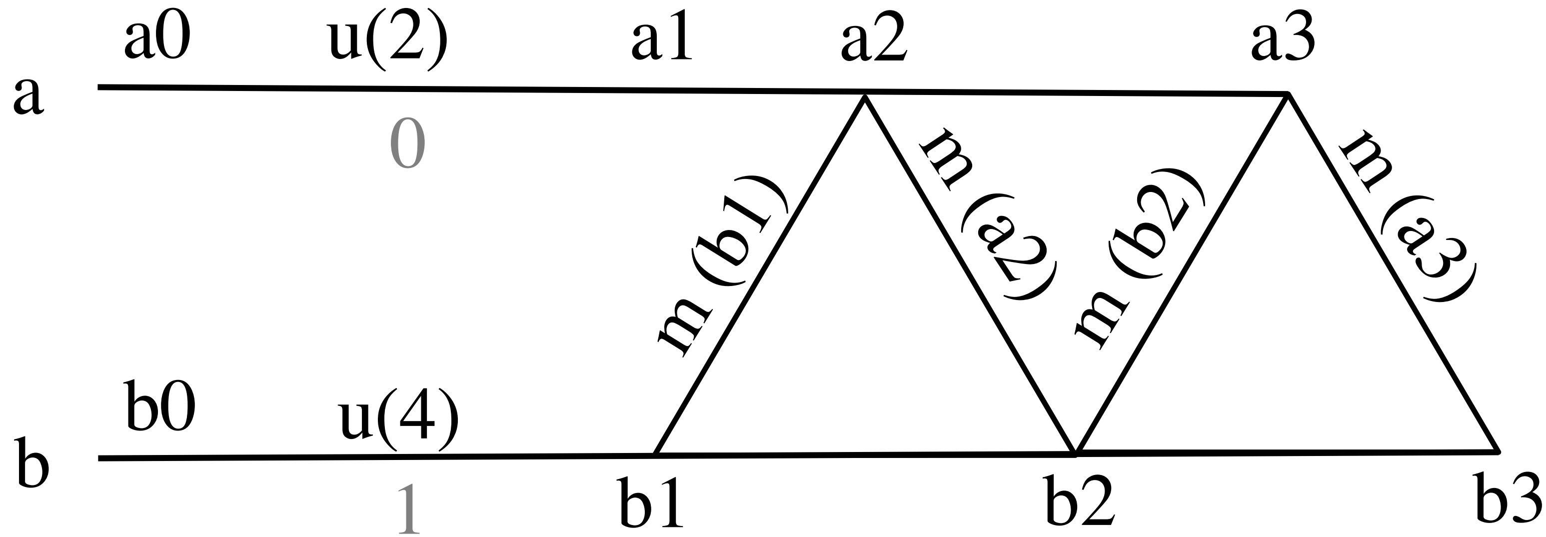
	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}

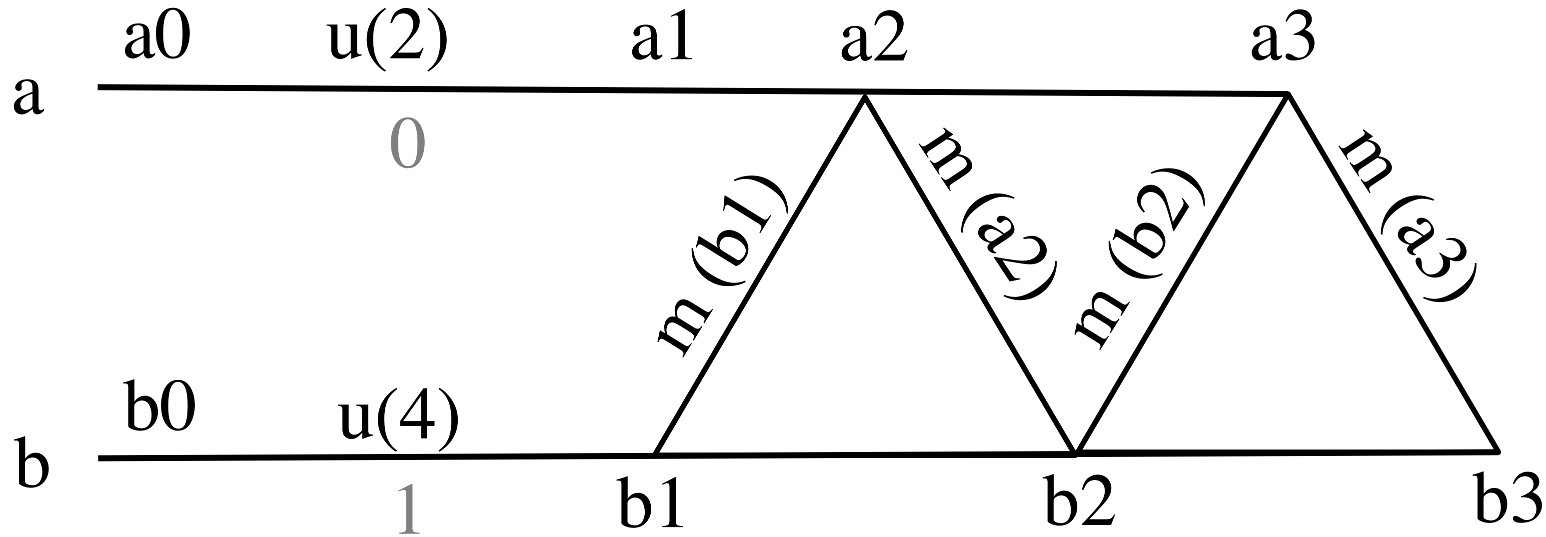


	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



a, b have **same causal history,** both **converge** to a stable but *different* **internal state**.

	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



a, b have **same causal history,** both **converge** to a stable but *different* **internal state**.

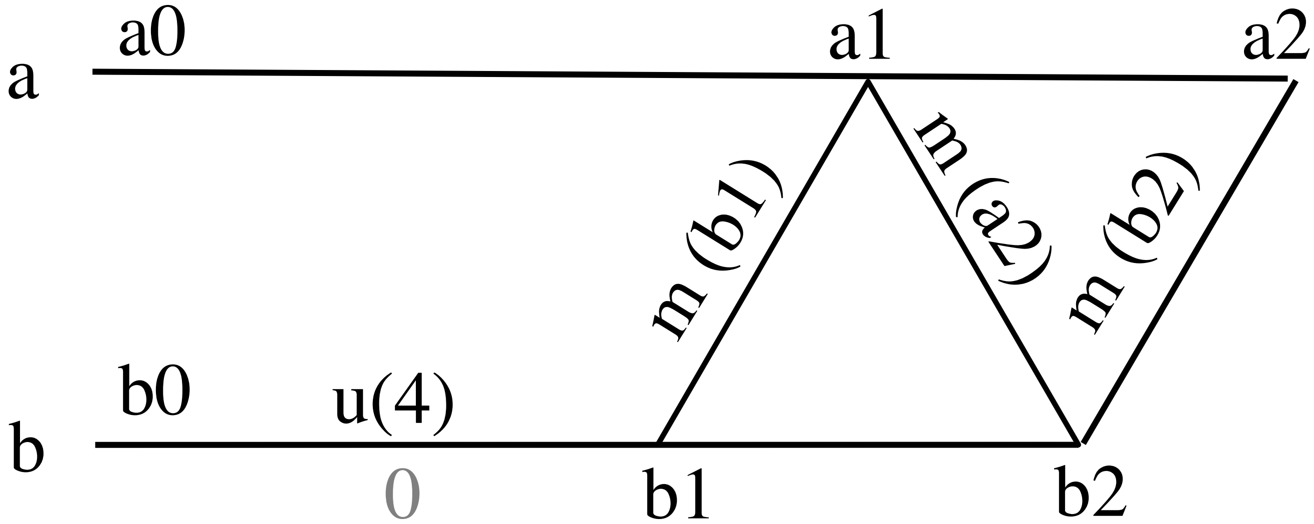
Neither eventually consistent, nor strongly eventually consistent.

	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:2,	cnt:1	2	{0,1}
a3	sum:2,	cnt:1	2	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}

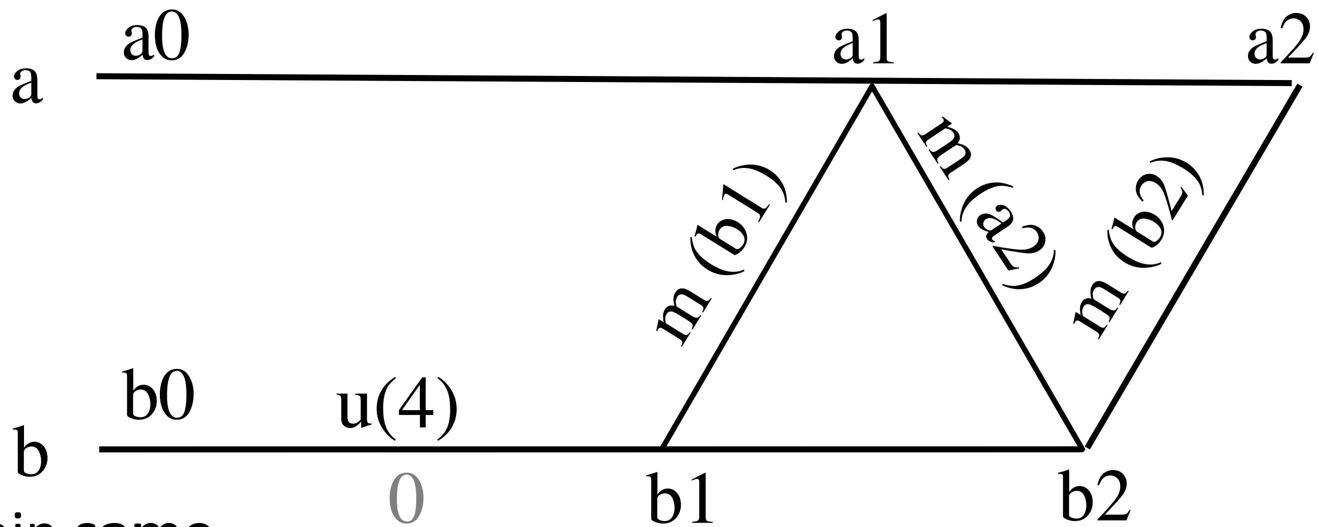
`BMergeAverage`

- Object’s merge
  - **At *b* – overwrite state with state at *a***
  - **At *a* – do nothing**

- All else is the same as for `Average`

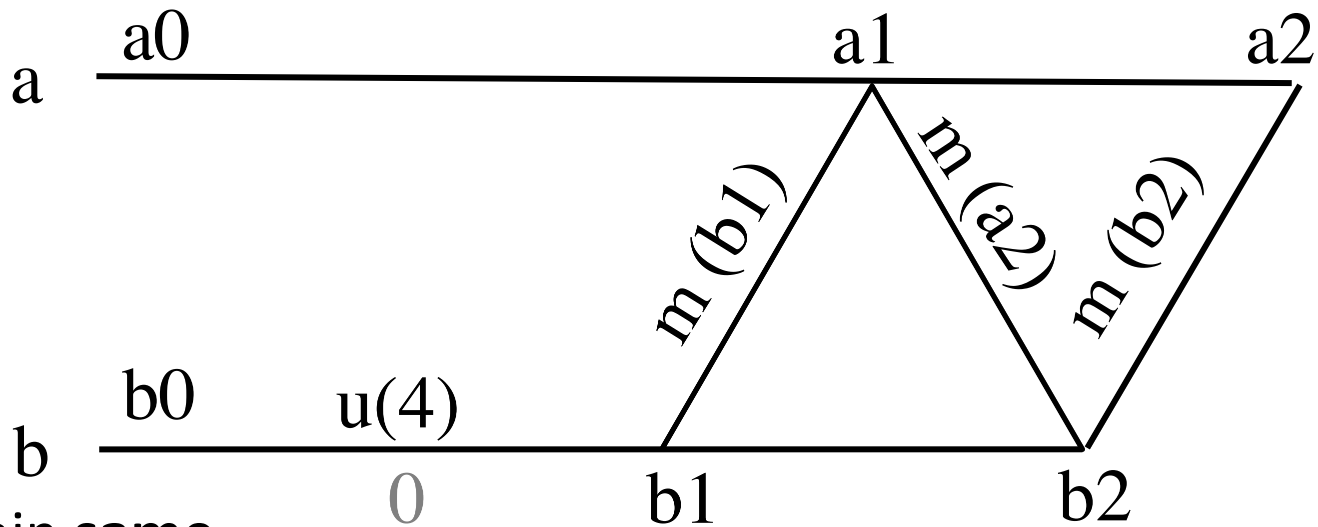


	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:0,	cnt:0	0	{0}
a2	sum:0,	cnt:0	0	{0}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{0}
b2	sum:0,	cnt:0	0	{0}



a, b attain **same causal history,** both eventually **converge** to the same **internal state** – **eventual consistent**.

	state	query ( )	history
a0	sum:0, cnt:0	0	{ }
a1	sum:0, cnt:0	0	{0}
a2	sum:0, cnt:0	0	{0}
b0	sum:0, cnt:0	0	{}
b1	sum:4, cnt:1	4	{0}
b2	sum:0, cnt:0	0	{0}



a, b attain **same causal history,** both eventually **converge** to the same **internal state – eventual consistent.**

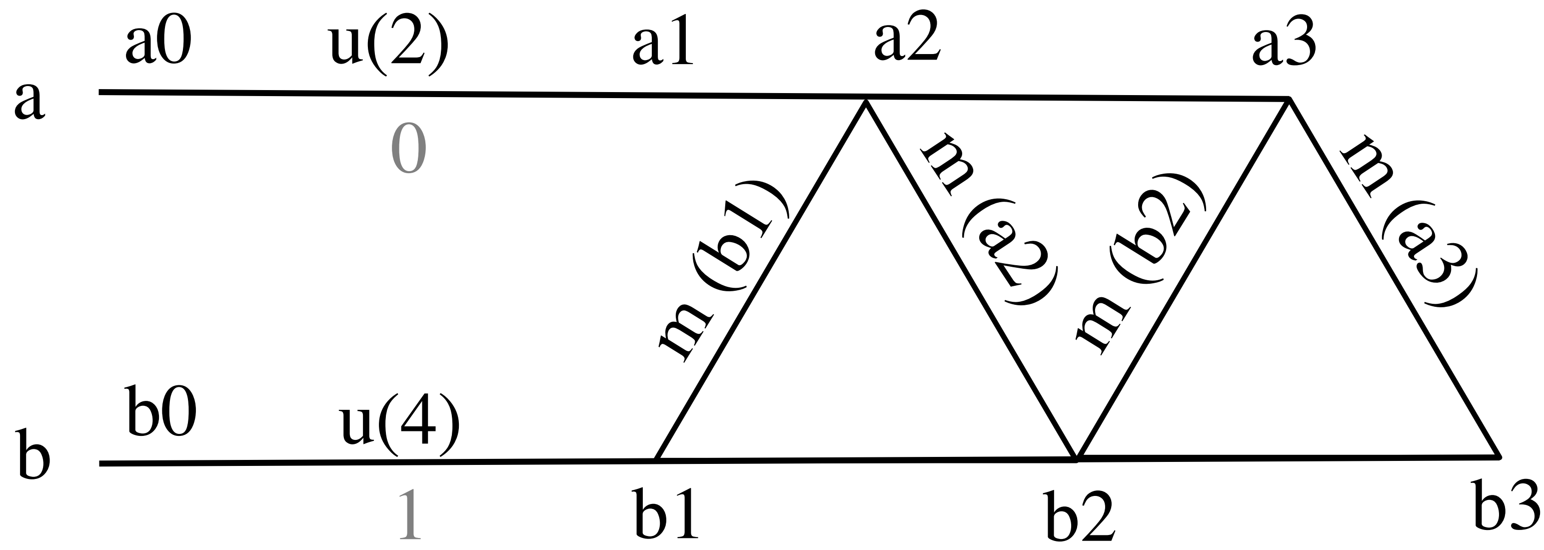
a1, b1 have same causal history but different internal state **– not strongly eventually consistent**

	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:0,	cnt:0	0	{0}
a2	sum:0,	cnt:0	0	{0}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{0}
b2	sum:0,	cnt:0	0	{0}

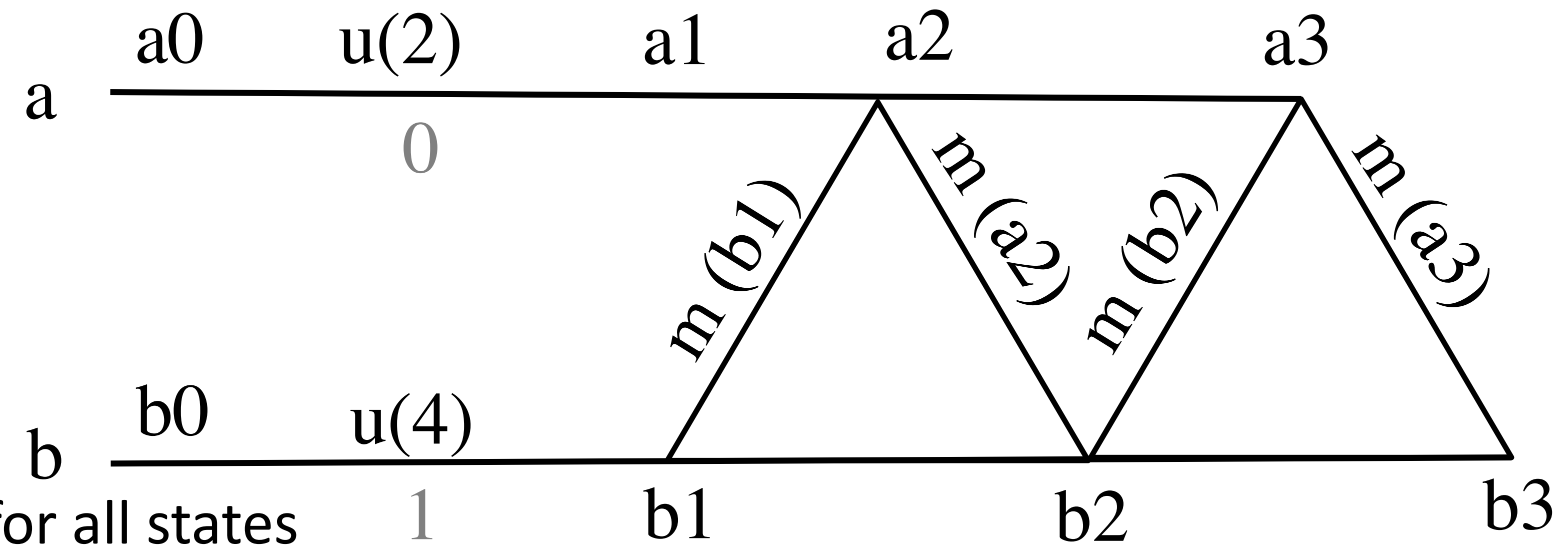
`MaxAverage`

- Object's merge
  - **Pair-wise max of `sum` and `cnt`**

- All else is the same as for `Average`

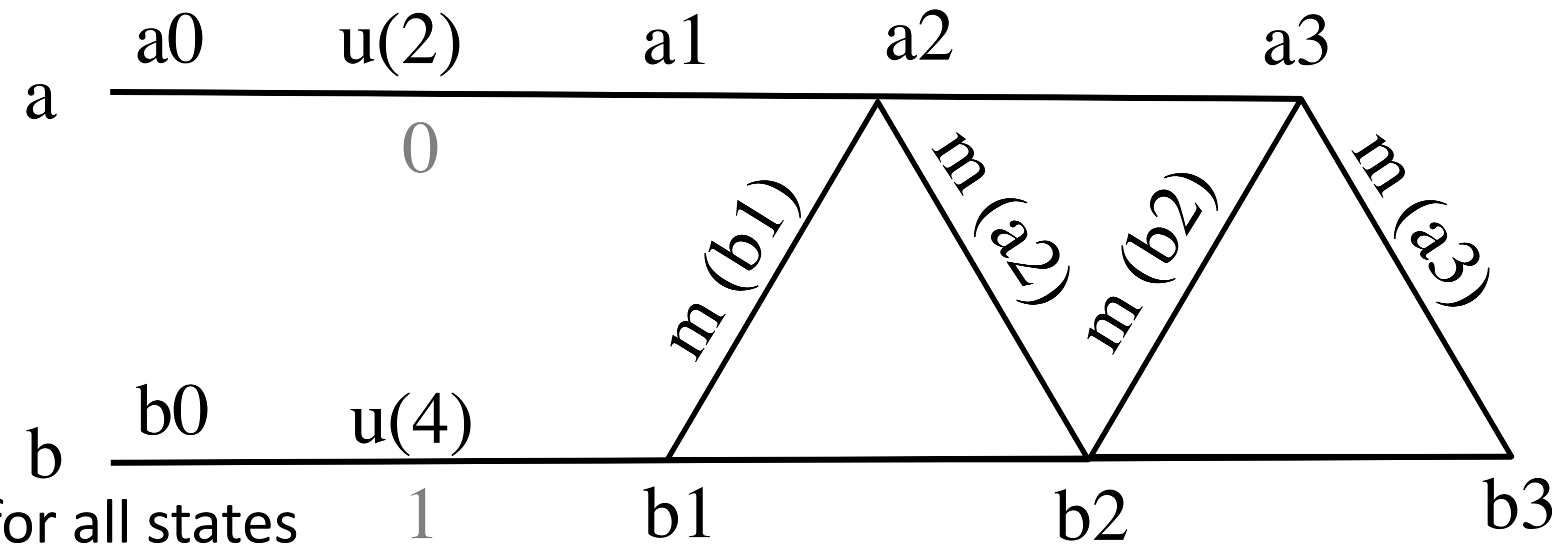


	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:4,	cnt:1	4	{0,1}
a3	sum:4,	cnt:1	4	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



At a, b for all states with the **same causal history,** they have the **same internal state – strongly eventually consistent**.

	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:4,	cnt:1	4	{0,1}
a3	sum:4,	cnt:1	4	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}



At a, b for all states with the **same causal history,** they have the **same internal state – strongly eventually consistent**.

Great!!! But, what does it actually compute? Here, update(2) overwritten by update(4)! ☹

	state		query ( )	history
a0	sum:0,	cnt:0	0	{ }
a1	sum:2,	cnt:1	2	{0}
a2	sum:4,	cnt:1	4	{0,1}
a3	sum:4,	cnt:1	4	{0,1}
b0	sum:0,	cnt:0	0	{}
b1	sum:4,	cnt:1	4	{1}
b2	sum:4,	cnt:1	4	{0,1}
b3	sum:4,	cnt:1	4	{0,1}

Lessons Learned I

- Same causal history, different internal state
- Same causal history, same stale state but different internal state
- Same causal history, eventually same internal state
- Same causal history, always same internal state – SEC

	C?	EC?	SEC?
Average	no	no	no
NoMergeAverage	yes	no	no
BMergeAverage	yes	yes	no
MaxAverage	yes	yes	yes

Designing a **strongly eventually consistent state-based object** with intuitive semantics is challenging!

Lessons Learned II

- Replicated state-based object
- No convergence
- Convergence
- Eventual consistency in this model
- Strong eventual consistency in this model

Self-study Questions

- Can you design Average such that it becomes EC or SEC as well as offers correct averaging semantics?
- Think of other data structures and design update, query, and merge operations with reasonable semantics.
- Always draw timelines and state diagrams for your designs and proof EC or SEC, if possible.
- Think of data structures that support multiple update operations and one or more query operations.

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CRDT –
CONFLICT-FREE REPLICATED DATA TYPES

Conflict-Free Replicated Data Types

- CRDT is a conflict-free replicated state-based object
- CRDT handles concurrent writes
- **Intuition**:
  - Do not allow writes with arbitrary values, limit to write operations which are **guaranteed not to conflict**
  - CRDTs are data structures with **special** write operations; they guarantee **strong eventual consistency** and are monotonic (no rollbacks)
- CRDTs are no panacea but a great solution when they apply!

Conflict-Free Replicated Data Types

- CRDTs can be **commutative / op-based (CmRDT)**:
  - **Example**: A growth-only counter, which can only process *increment* operations
  - Propagate operations among replicas (**duplicate-free, no-loss messaging**)
- CRDTs can be **convergent / state-based (CvRDT)**:
  - **Example**: A max register, which stores the maximum value written
  - Propagate and merge states (idempotent)
- Therefore, the value of a CRDT depends on **multiple write operations or states**, not just the latest one

State-based CRDTs

- A CRDT is a replicated state-based object
- Supports
  - Query
  - Update
  - Merge

CRDT Properties

A CRDT is a replicated state-based object that satisfies

- Merge is **associative** (e.g., (A + (B + C)) = ((A + B) + C))
  - For any three state-based objects x, y, and z, merge(merge(x, y), z) is equal to merge(x, merge(y, z))
- Merge is **commutative** (e.g., A + B = B + A)
  - For any two state-based objects, x and y, merge(x, y) is equal to merge(y, x)
- Merge is **idempotent**
  - For any state-based object x, merge(x, x) is equal to x
- Every **update is increasing**
  - Let *x* be a state-based object and let *y* = update(*x*, ...) be the result of applying an update to *x*
  - Then, update is increasing if merge(*x*, *y*) is equal to y

Max Register is a CRDT

The state-based object IntMax is a CRDT

- `IntMax` wraps an integer
- `Merge(a, b)` is the max of a, b
- `Update(x)` adds x to the wrapped integer
- Prove that `IntMax` is associative, commutative, idempotent, increasing

```
class IntMax(object):
  def __init__(self):
    self.x = 0
  def query(self):
    return self.x
  def update(self, x):
    assert x >= 0
    self.x += x
  def merge(self,
      other):
    self.x =
      max(self.x,
        other.x)
```

Establish Four Properties of CRDT

- Associativity

```
merge(merge(a, b), c)
= max(max(a.x, b.x), c.x)
= max(a.x, max(b.x, c.x))
= merge(a, merge(b, c))
```

- Impotence

```
merge(a, a)
= max(a.x, a.x)
= a.x
= a
```

- Commutativity

```
merge(a, b)
= max(a.x, b.x)
= max(b.x, a.x)
= merge(b, a)
```

- Update is increasing

```
merge(a, update(a, x))
= max(a.x, a.x + x)
= a.x + x
= update(a, x)
```

G-Counter CRDT

Replicated growth-only counter

- Internal state of a G-Counter replicated on *n* nodes is an *n*-length array of non-negative integers

- `query` returns sum of every element in *n*-length array
- `add(x)` when invoked on the i-th server, increments the i-th entry of the *n*-length array by x
  - E.g., Server 0 increments 0th entry, Server 1 increments 1st entry of array, and so on
- `merge` performs a pairwise maximum of the two arrays

PN-Counter CRDT

Replicated counter supporting addition & subtraction

- Internal state of a PN-Counter
  - pair of two G-Counters named *p* and *n*.
    - *p* represents total value added to PN-Counter
    - *n* represents total value subtracted from PN-Counter.

- query method returns difference `p.query() – n.query()`
- `add(x)` –first of two updates– invokes `p.add(x)`
- `sub(x)` –second of two updates– invokes `n.add(x)`
- `merge` performs a pairwise merge of *p* and *n*

G-Set CRDT

Replicated growth-only set

A G-Set CRDT represents a replicated set which can be added to but not removed from

- Internal state of a G-Set is just a set
- `query` returns the set
- `add(x)` adds *x* to the set
- `merge` performs a set union

2P-Set CRDT

Replicated set supporting addition and subtraction

- Internal state of a 2P-Set is a
  - pair of two G-Sets named *a* and *r*
    - *a* represents set of values added to the 2P-Set
    - *r* represents set of values removed from the 2P-Set
- `query` method returns the set difference `a.query() - r.query()`
- `add(x)` is the first of two updates
  - invokes a.add(x).
- `sub(x)` is the second of two updates
  - invokes `r.add(x)`
- `merge` performs a pairwise merge of *a* and *r*

Summary on CRDTs

- Formalized and introduced in 2014
- CmCRDTs and CvCRDTs are equivalent!
- Really neat solution if it applies
- Challenge is to design new CRDTs

Self-study Questions

- For the CRDTs introduced, establish its four properties.
- Create example executions for each CRDT and complete a timeline and a state table.
- Fine use cases where the introduced CRDTs apply and show how they are used.
- Think of new CRDTs and repeat the above.

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