Conflict-free Replicated Data Types – A principled approach to Eventual Consistency

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Replication 101

Replicated data

Share data ⇒ Replicate at many locations

- Performance: local reads
- Availability: immune from network failure
- Fault-tolerance: replicate computation
- Scalability: load balancing

Updates

- Push to all replicas:
  - Asynchronous: Reliable Multicast
  - Synchronous: Atomic Multicast
- Consistency?

Strong consistency

State Machine Replication

- Arbitrary sequential, deterministic object
- Globally: total order of updates
- All replicas execute updates in same order

Consensus

- Simultaneous N-way agreement
- Fault-tolerance: *cf* FLP85
- Doesn't scale
- ≡ Atomic Multicast
- building block for Commitment, etc.

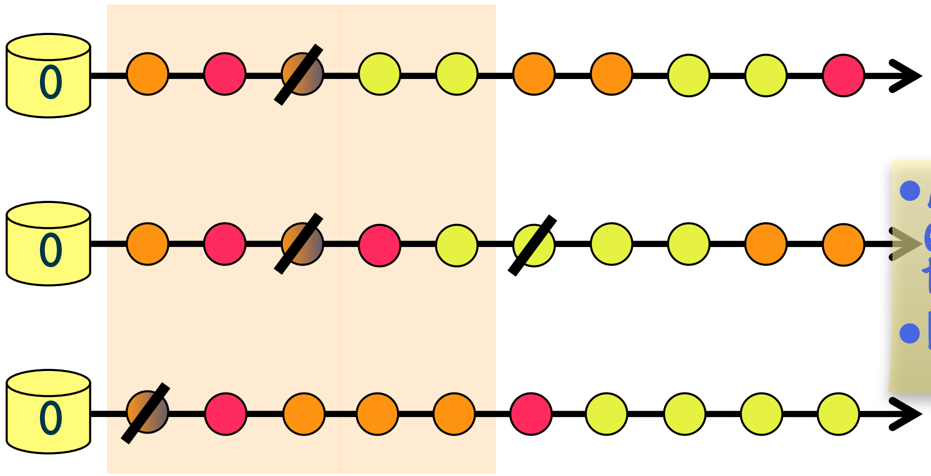
Eventual consistency

Optimistic approach

- Avoid (foreground) synchronisation
- Speculate: replicas diverge
- Reliable broadcast (scalable)
- If no conflicts, merge
- Otherwise, reconcile;
  - arbitrate, merge
  - roll back inconsistent replicas, roll forward

Consistent when all replicas have received all operations & arbitrations

Convergence



- All operations eventually reach the common prefix
- Equivalence across

- Prefixes equivalent (not necessarily equal)
- orange-grey: aborted
- red/orange: commute

Consensus on next extension of prefix

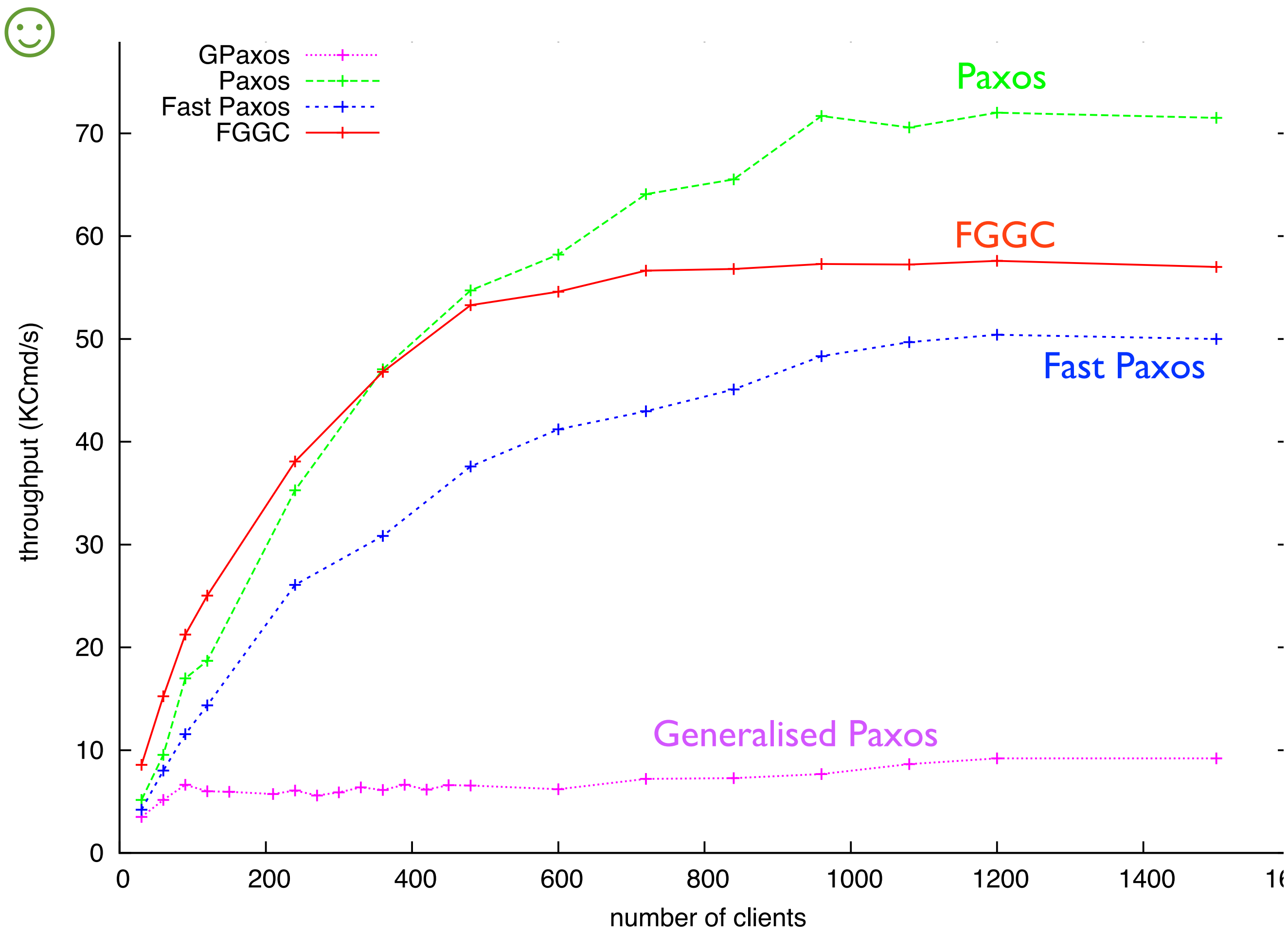
- In the background
- Local progress not blocked
- Conflict ⇒ rollback

Improve consensus:

- Leverage future, semantics
- Genuine partial replication

- Minimise rollbacks
- Choose most promising schedule
- Commutativity

Fast Gen.lised Genuine Paxos

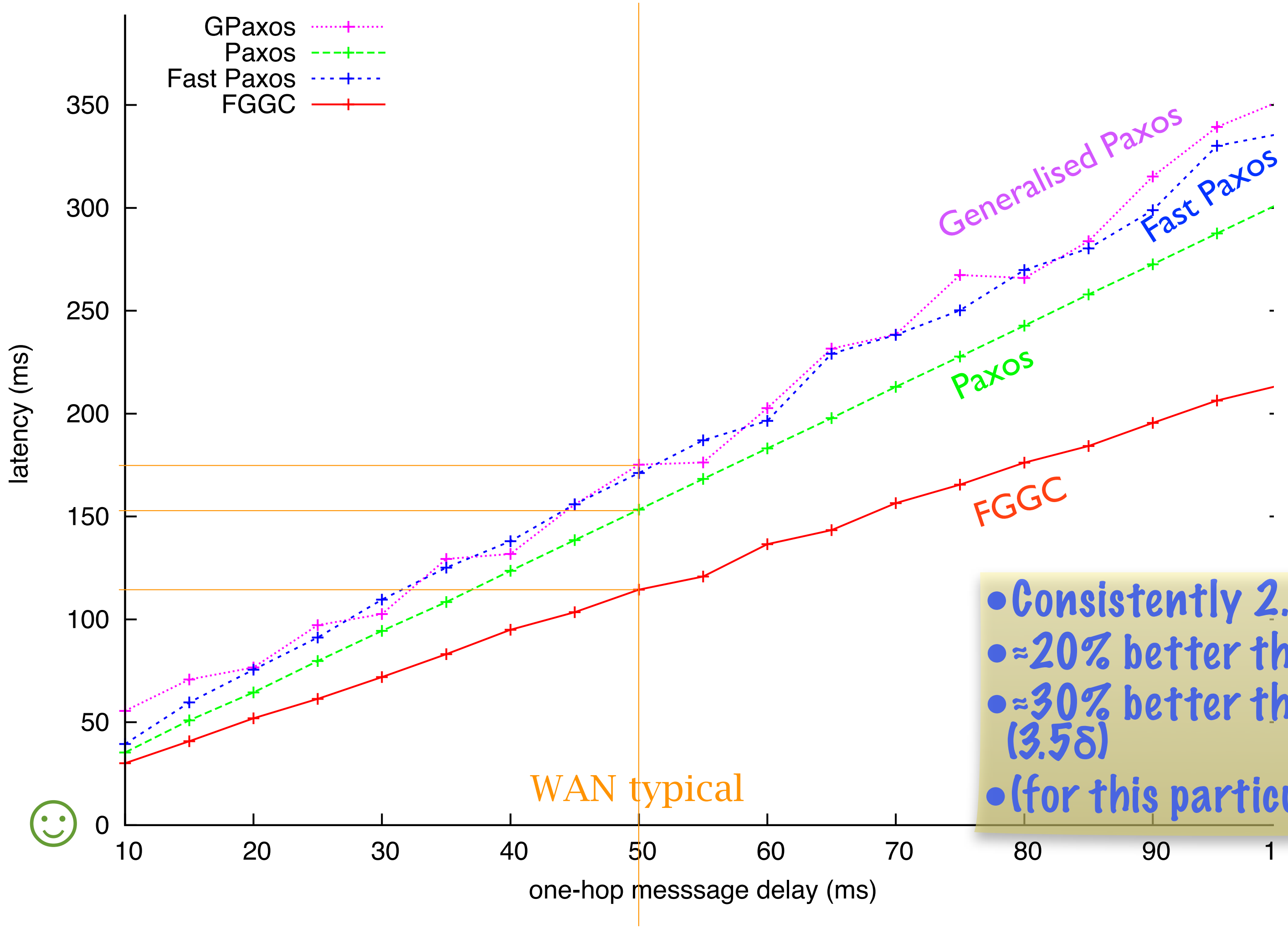


- On a LAN Paxos is fastest (because simplest?)

Throughput on LAN *(1024 regs.)* [Sutra 2010]

- Collision recovery has high cost in Generalised Paxos

Fast Gen.lised Genuine Paxos



- Consistently 2.2δ
- ≈20% better than Paxos (3δ)
- ≈30% better than Gen. Paxos (3.5δ)
- (for this particular benchmark)

Varying message delay *(1024 regs., 360 clients)* [Sutra 2010]

Eventual Consistency so far

- Availability ++
- Latency --

- Complexity ++
- Scalability???

Eventual consistency
- Moved consensus to background
- Optimistic, speculation
  $\Rightarrow$ more available, responsive
- High-level operations: leverage semantics
- Knowledge of "future"

Arbitration/merge on conflict
- Surprisingly complex
- Mostly ad-hoc, error-prone

Improved consensus
- Very complex

Scalability?

Conflict-free Replicated Data Types (CRDTs)

Intuition:

- *Conflicts* are the problem
- Design data types with no conflicts

CRDTs

- Available, fast
- Reconcile scalability + consistency

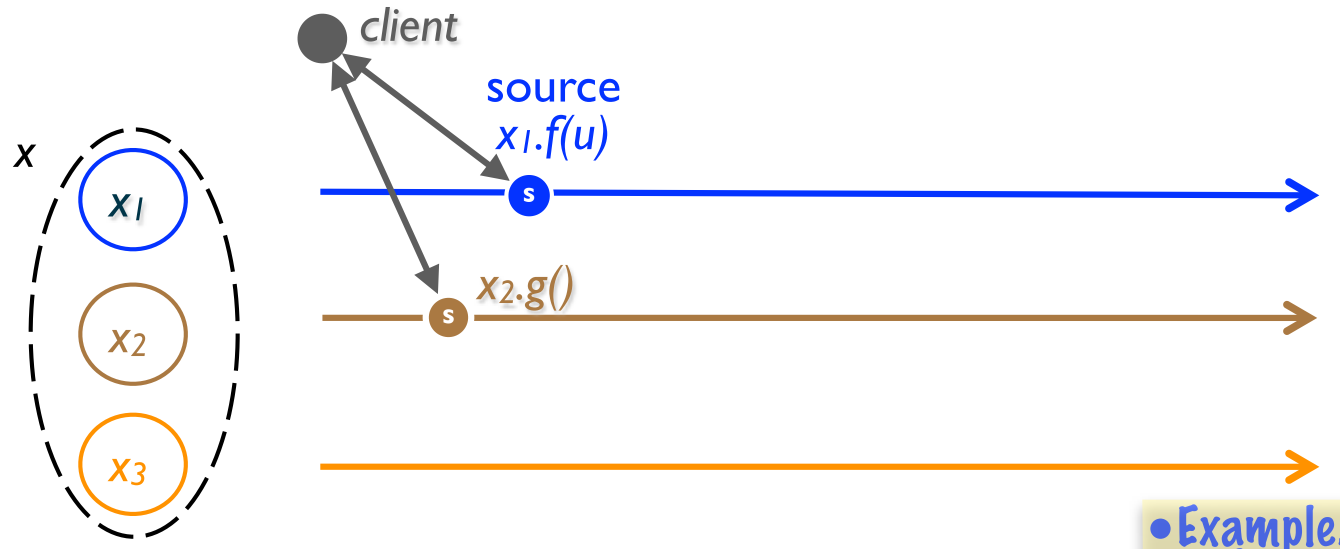
Simple sufficient conditions

- Principled, correct

CRDTs: The theory

Sufficient conditions for correctness without synchronisation

Query

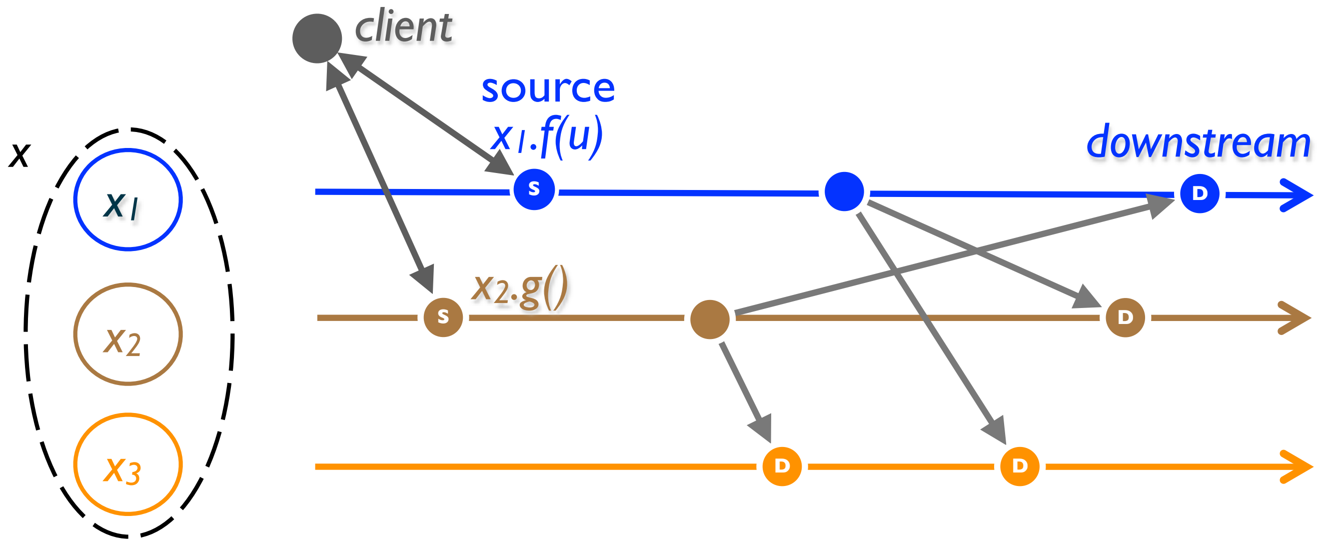


- Example: Amazon shopping cart is replicated
- unspecified client, e.g., Web front-end
- One or more
- load-balancer, failures may direct client to different replicas

Local at *source* replica

- Client's choice

Update



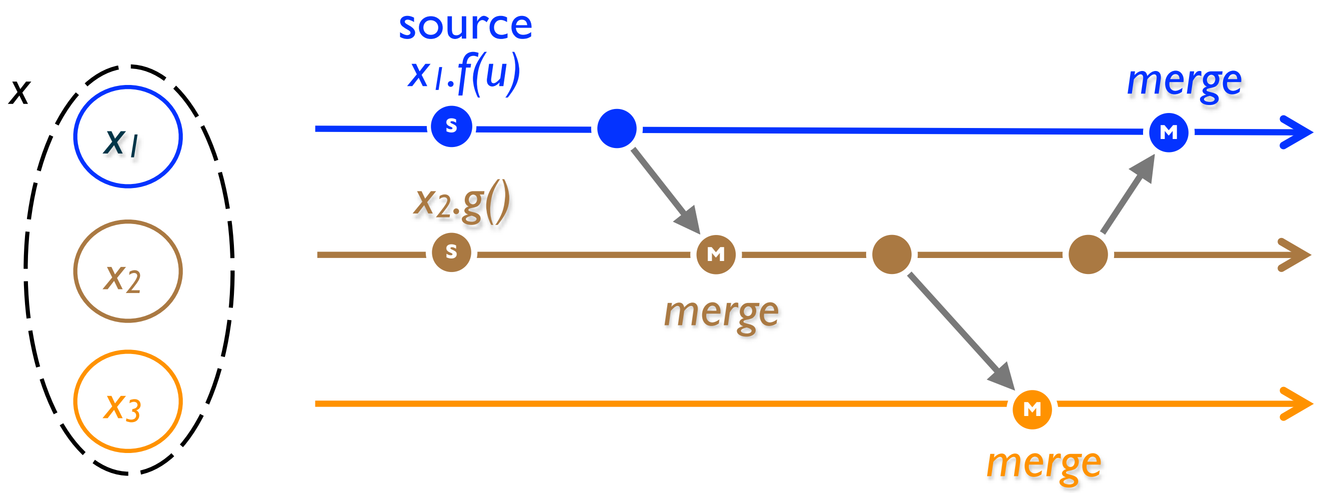
- source: client's choice
- Downstream: all replicas (including source)
- Eventual

- Queries are local

Two-phase updates

- At source:
  - Synchronous
  - Atomic
- Downstream:
  - Asynchronous
  - Atomic

State-based replication



Update at source $x_1.f(u)$, $x_2.g()$, …

- Precondition, compute
- Assign payload

Convergence:

- Episodically: send x_i payload
- On delivery: *merge* payloads

- merge two valid states
- produce valid state
- no historical info available

State-based specification

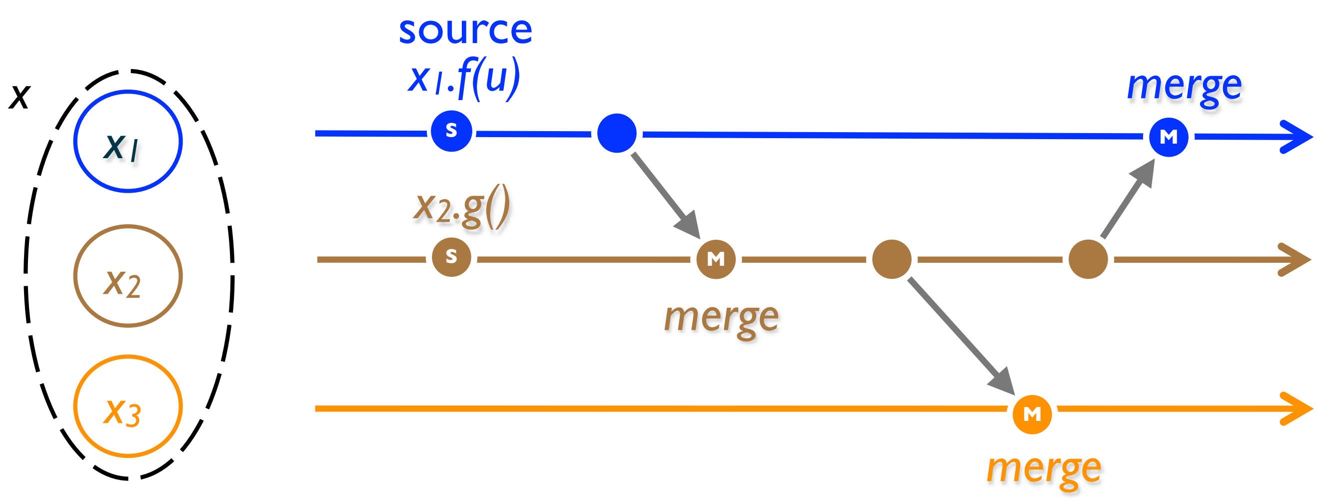
payload *Payload type; instantiated at all replicas*
  initial *Initial value*
query *Query* (*arguments*) : *returns*
  pre *Precondition*
  let *Evaluate synchronously, no side effects*

update *Source-local operation* (*arguments*) : *returns*
  pre *Precondition*
  let *Evaluate at source, synchronously*
  Side-effects at source to execute synchronously

compare (value1, value2) : boolean b
  Is value1 $\leq$ value2 in semilattice?

merge (value1, value2) : payload mergedValue
  LUB merge of value1 and value2, at any replica

State-based convergent objects: CvRDT



- □ = Least Upper Bound
LUB = merge

If

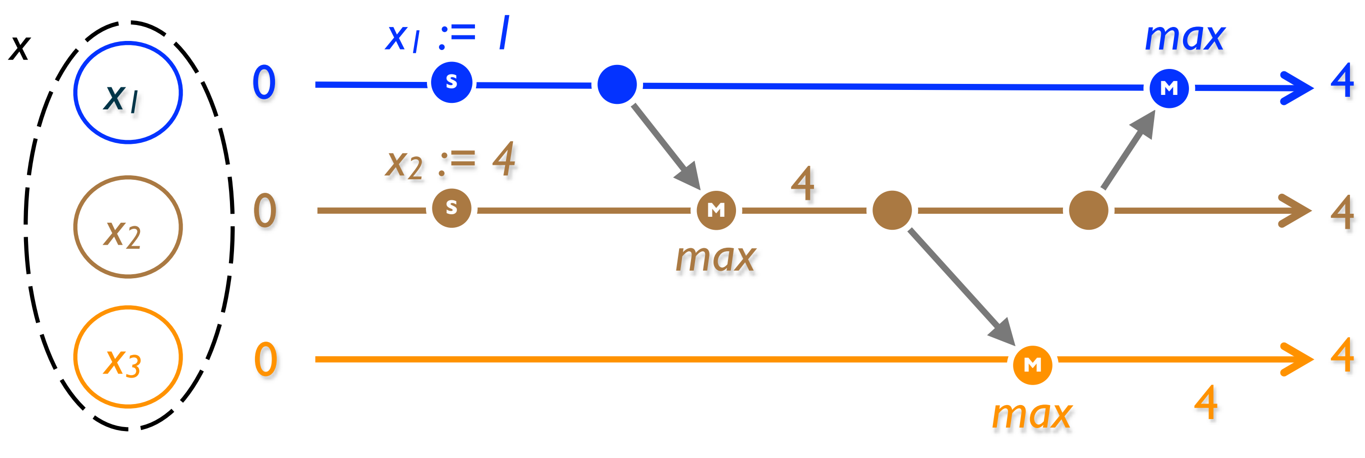
- payload type forms a <u>semi-lattice</u>
- updates are increasing
- *merge* computes Least Upper Bound ⊔

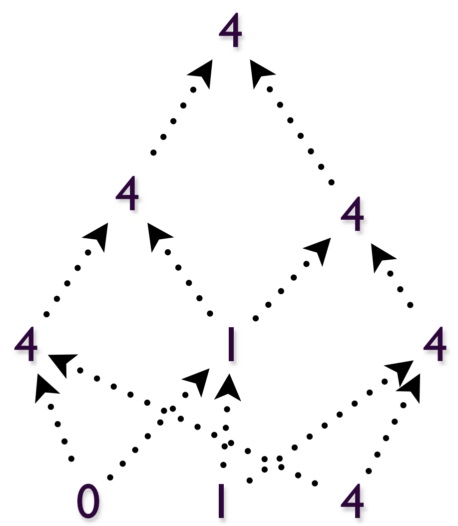
then replicas converge to LUB of last values

- no reference to history

Example: Payload = int, *merge* = *max*

Example CvRDT





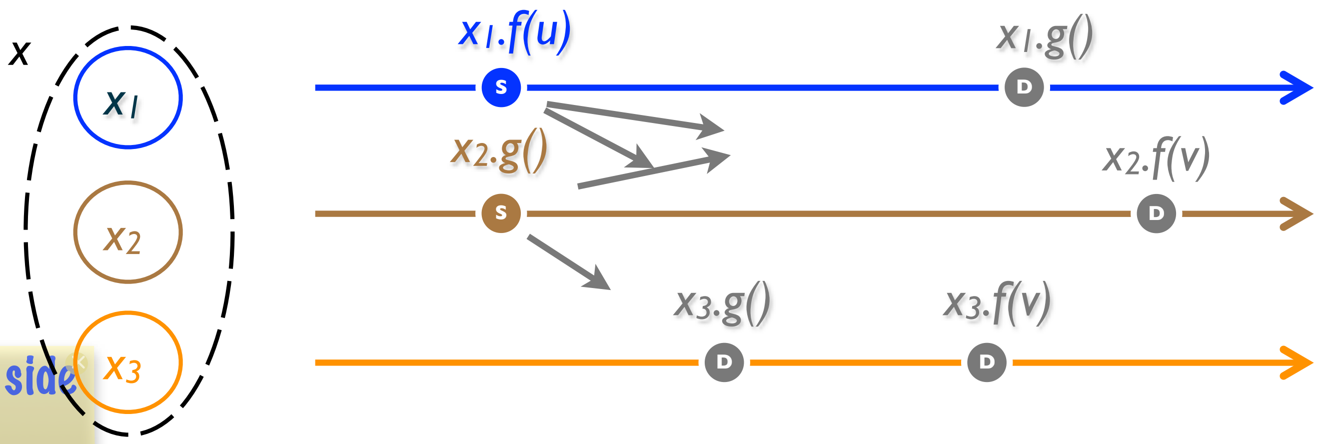
If

- payload type forms a semi-lattice
- updates are increasing
- *merge computes Least Upper Bound* ⊔

then replicas converge to LUB of last values

Example: *f* = assign, *merge* = max

Operation-based replication



- source: no side effects
- source +downstream atomic

- downstream atomic
- at all replicas eventually

At source:

- source precondition, computation
- broadcast to all replicas

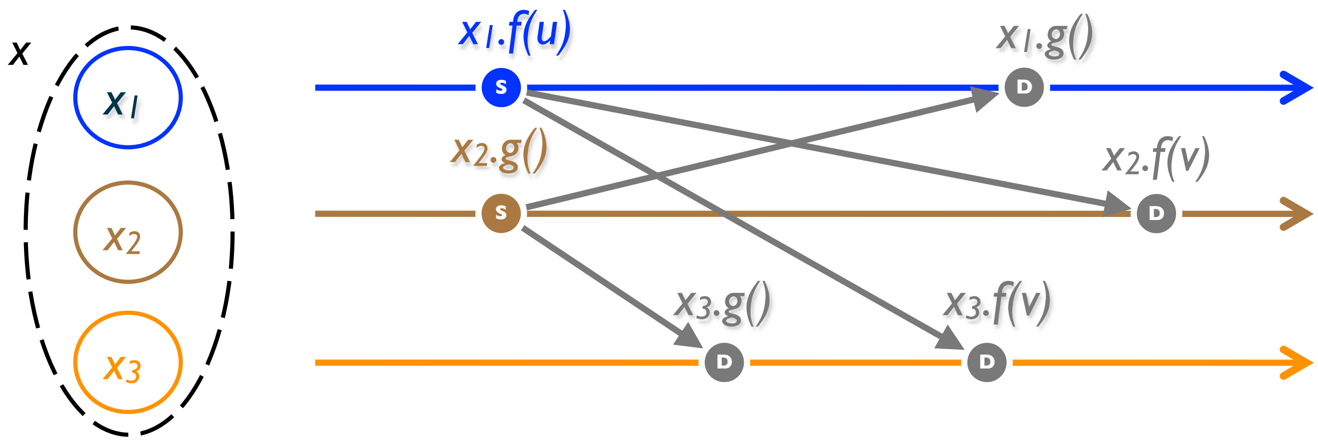
Eventually, at all replicas:

- downstream precondition
- Assign local replica

Operation-based specification

payload *Payload type; instantiated at all replicas*
    initial *Initial value*
query *Source-local operation* (*arguments*) : *returns*
    pre *Precondition*
    let *Execute at source, synchronously, no side effects*
update *Global update* (*arguments*) : *returns*
    atSource (*arguments*) : *returns*
        pre *Precondition at source*
        let *1st phase: synchronous, at source, no side effects*
    downstream (*arguments passed downstream*)
        pre *Precondition against downstream state*
        2nd phase, asynchronous, side-effects to downstream state

Commutative-operation-based objects: CmRDTs



- Delivery order ≃ ensures downstream precondition
- happened-before or weaker

If:
- (*Liveness*) all replicas execute all dowstreams in precondition order
- (*Safety*) concurrent operations all commute

Then: replicas converge

CvRDT ≡ CmRDT

Operation-based emulation of state-based object

- At source: apply state-based update
- Downstream: apply state-based *merge*
- Monotonic semi-lattice ⇒ commute

State-based emulation of op-based object

- Update: at-source, add op to set of messages
- Merge: union of message sets
- Execute when *dpre* = true
- Live: eventual delivery, eventual execute
- Commute ⇒ semi-lattice

- Use state or operations
- as convenient

CRDTs: The challenge

What interesting objects can we design with no synchronisation whatsoever?

Counter

Increment / decrement

- Payload: P = [int, int, …],
  N = [int, int, …]
- $value() = \sum_i P[i] - \sum_i N[i]$
- $increment\ () = P[MyID]{+}{+}$
- $decrement\ () = N[MyID]{+}{+}$
- $merge(x,y) =$
  $x \sqcup y = ([\ldots, max(x.P[i], y.P[i]), \ldots]_i,$
  $[\ldots, max(x.N[i], y.N[i]), \ldots]_i)$
- Positive or negative

- like vector clock

Counter

- N masters
- vector of single-master counters
- like vector clock

Increment / decrement

- Payload: P = [int, int, …],
  N = [int, int, …]
- *value*() = $\sum_i P[i] - \sum_i N[i]$
- *increment* () = $P[MyID()]$++
- *decrement* () = $N[MyID()]$++
- *merge*(x,y) =
  $x \sqcup y = ([\ldots, max(x.P[i], y.P[i]), \ldots]_i, [\ldots, max(x.N[i], y.N[i]), \ldots]_i)$
- Positive or negative

- can't maintain global invariant such as x>0

Register

Container for a single atom

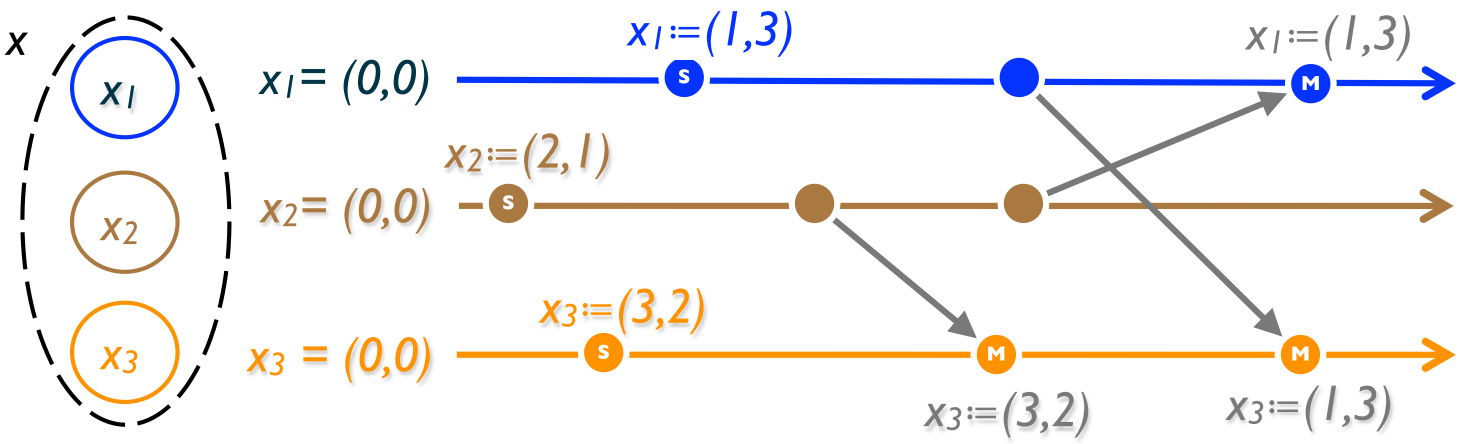
Operations:

- *read: val*
- *assign (val)*
  - Overwrites preceding value

Concurrent *assign*

- Single value, arbitrary choice?
- All concurrent values?

Last Writer Wins Register



- Examples:
- NFS
- shared memory?

CvRDT payload: *(atom value, timestamp ts)*

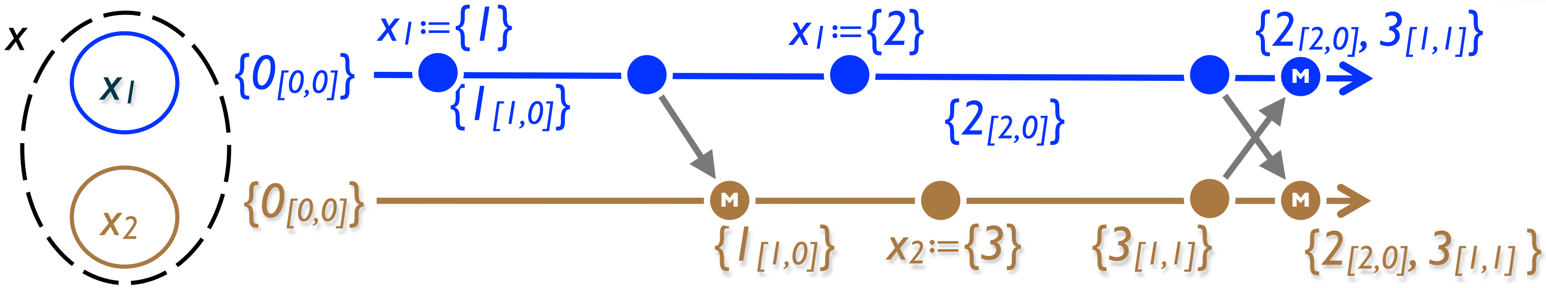
- *assign*: overwrite *value*, increment *ts*
- Merge takes *value* with highest timestamp; other is lost
- $x \leq y \stackrel{\text{def}}{=} x.ts \leq y.ts$
- $merge\ (x,y) = x.t < y.t\ ?\ y : x$

- spec: state-based
- values form a semi-lattice
- no reference to history fi

- Timestamps implement a *total order*
- Generally ≈real time but could be any total order

MV-Register

- Examples:
- Unison
- CVS, SVN
- Dynamo shopping cart



- A more recent assignment overwrites an older one
- Concurrent assignments are merged by union
- Standard VC merge

$\approx$ LWW-Set Register

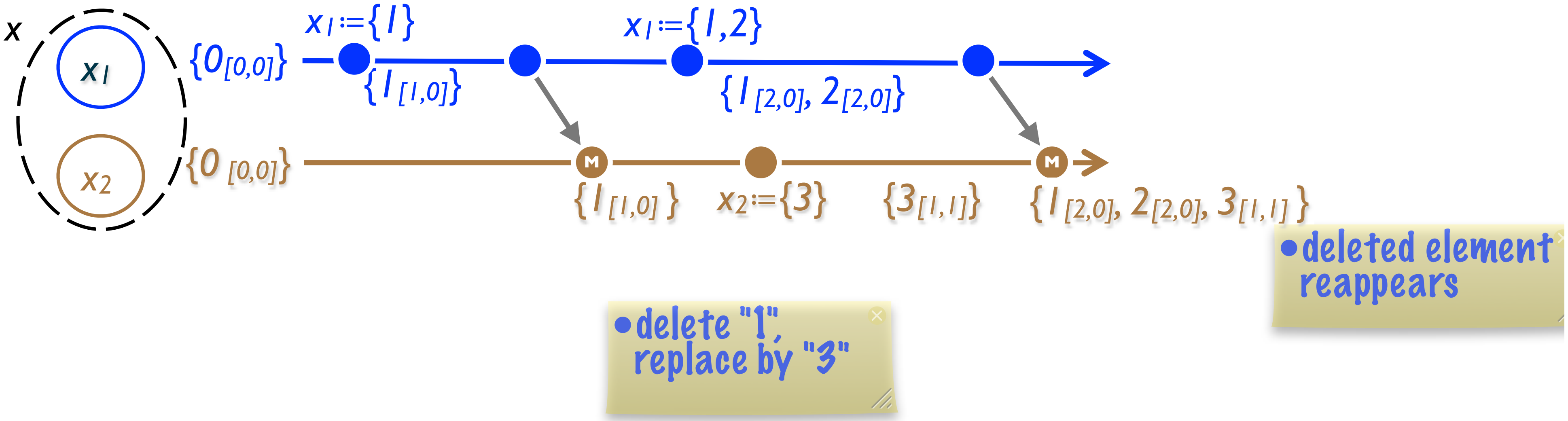
- Payload = { (*value*, VT *vv*) }
- *assign:* overwrite *value*, *vv*++

Concurrent updates unioned (no lost updates)

- *merge* (*X*,*Y*) =

$$\{ x \in X \mid \nexists\, y \in Y: x.vv < y.vv \} \cup$$
$$\{ y \in Y \mid \nexists\, x \in X: x.vv > y.vv \}$$

Bookstore anomalies



"An add operation is never lost. However, deleted items can resurface." [Dynamo, SOSP 2007]

Preferred approach: Set CRDT

Set

Operations:

- *add* (atom *a*)
- *remove* (atom *a*)
- *lookup* (atom *a*) : boolean

No duplicates

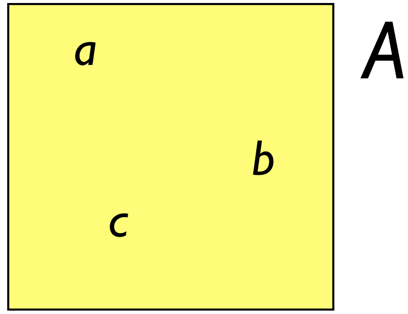
The prototypical CRDT?

- *remove* does not commute with *add*
- Approximations: modify semantics

- union and intersection commute
- not set difference

Grow-only Set, state-based

- Build intuition
- Simple examples
- What state do I ned to store and transmit?



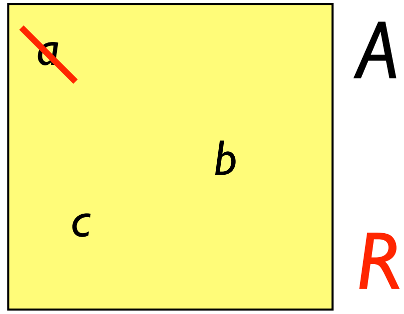
add (a)
add (b)
add (c)
add (b)

Payload = set *A*
add (atom a)
merge (x,y) = $x \cup y$

- Assume: state eventuelly delivered
- Why not remove()?
- Trial and error...
- Hmm, let's move on to something else

2P-Set (state)

- A=added
- R= removed (tombstones)
- Once removed, an element cannot be added again
- Remove has precedence over add (absorbing)



add (a)
add (b)
remove (a)
add (c)
add (b)
add (a)

Add, remove: 2P-set

- Payload = (*Grow-Set A*, *Grow-Set R*)
- *add (atom a)*
  remove (atom a) [spre: $a \in A$]
  lookup (a) = $a \in A \wedge a \notin R$
- $x \leq y \stackrel{\text{def}}{=} x.A \subseteq y.A \wedge x.R \subseteq y.R$
- *merge (x,y)* = $(x.A \cup y.A, x.R \cup y.R)$

- In many distr. sys., uses of Set, add creates a unique element, so this is not a limitation

U-Set = no tombstones

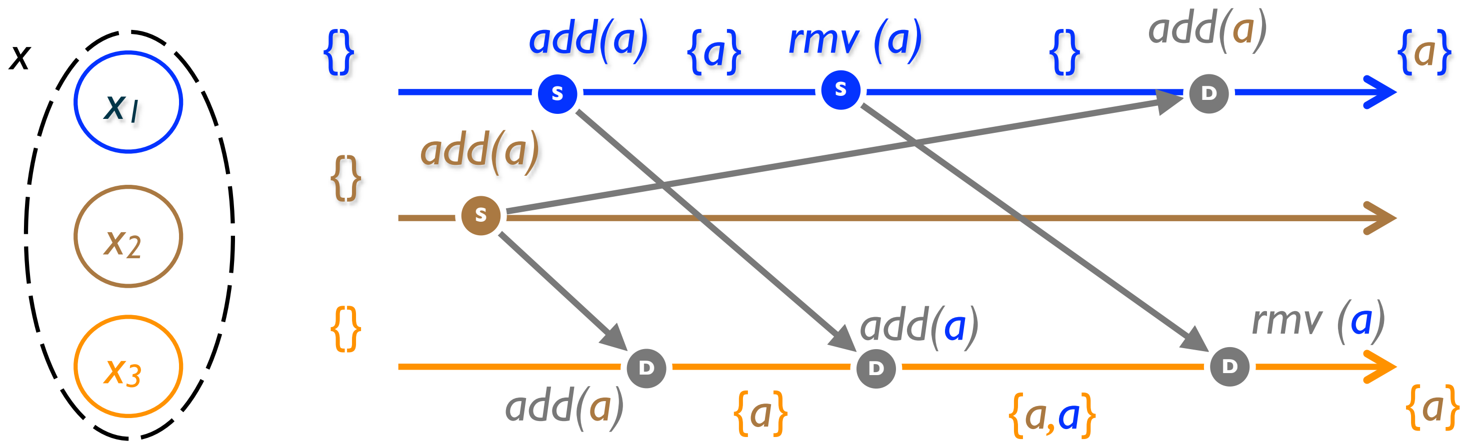
2P-Set

Special, common case: *a* unique

- Never add again
- No tombstones

Correct shopping cart

Observed-Remove Set (state)



- Can never remove more tokens than exist
- Op order ⇒ removed tokens have been previously added

- Payload: Map *M*: *element* to 2P-Set of *tokens*
- Make *add* unique:
  add(a) = M.add (a, unique-token)
- Remove the unique elements observed
  remove(a) = M.removeAll (a)
- *lookup(a)* = $a \in M \wedge$ *a.tokens* not empty
- *merge (x,y)* = merge token sets

- Better shopping cart
- What anomalies?

Map

Set of (key, value) pairs

Payload: $S = \{ (k, v), \ldots \}$

- *lookup* $(k) = \{ v: (k, v) \in S \}$
- *add* $(k, v) = S \coloneqq S \cup \{ (k,v) \}$
- *remove* $(k, v) = S \coloneqq S \setminus \{ (k,v) \}$
- *removeAll* $(k) = S \coloneqq S \setminus \{ (k, \_) \}$

CRDT approximations

- 2P-Map
- PN-Map
- LWW Map
- Observed-Remove Map

Graph

Graph = (V, E)
  where V = set of atoms
    $E \subseteq V \times V$

addVertex (v) → *addEdge* (v, w)
  → *removeEdge* (v, w) → *removeVertex* (v)

- and similarly for w

- delay concurrent removes

Any of the set-like CRDTs is OK

- e.g. 2P-Set ⇒ 2P-Graph

In the general case, cannot enforce global property, e.g. acyclic

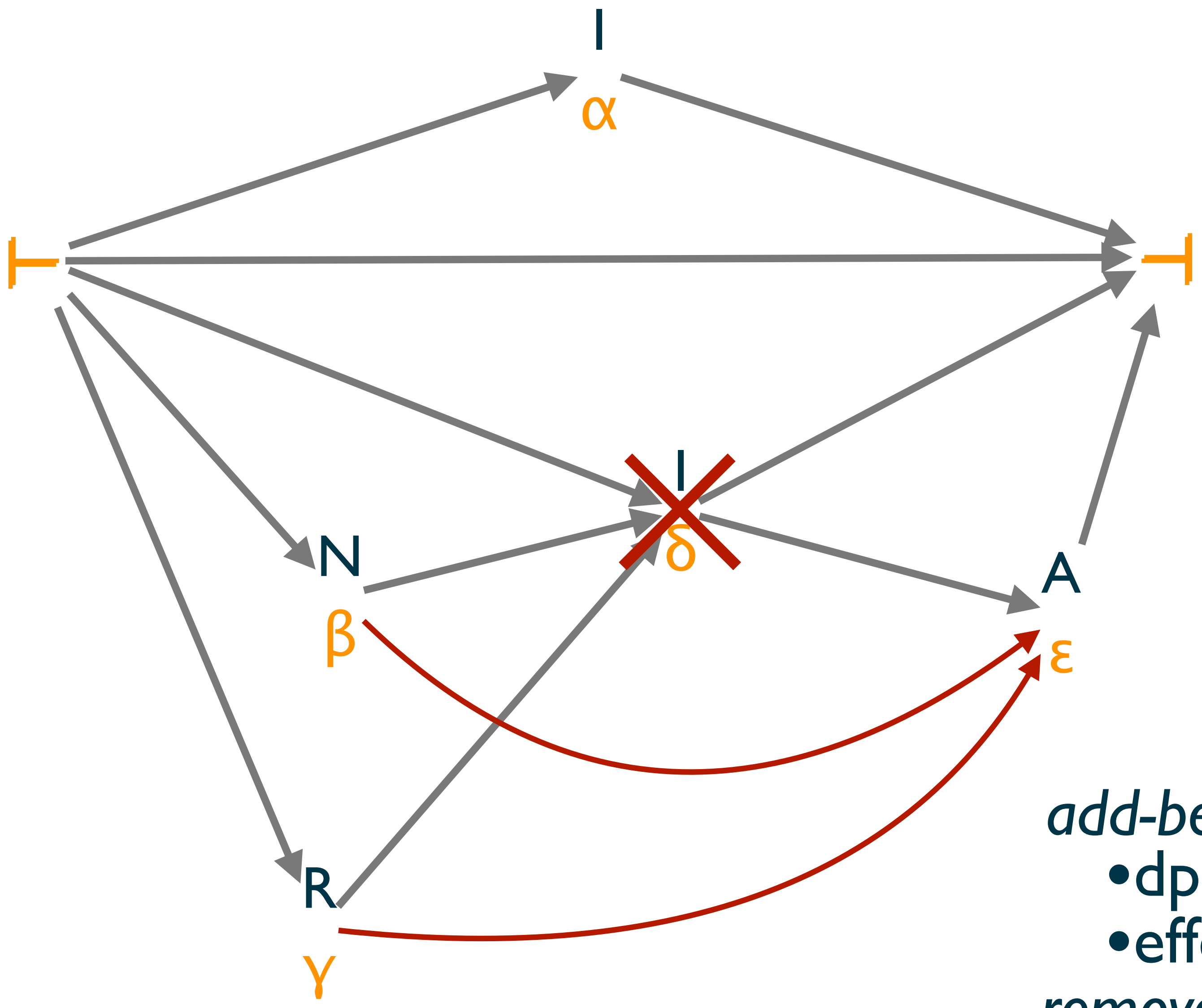
- Counter-examples next

GC

Tombstone

- 2P-Set: forbid *add-remove-add*
- Graph: *addEdge(u,v)* || *removeVertex(u)*
- Discard when all concurrent *addEdge* delivered
  - i.e. when *removeVertex* stable
  - Wuu, Bernstein/Golding algorithm
- No consensus
- Not live in presence of crash

Monotonic DAG



- add: between already-ordered elements
- remove: preserves existing order
- Monotonic between remaining elements [restrictive meaning]
- Typical application: concurrent text editing

- Causal order too strong for add
- Too weak for delete

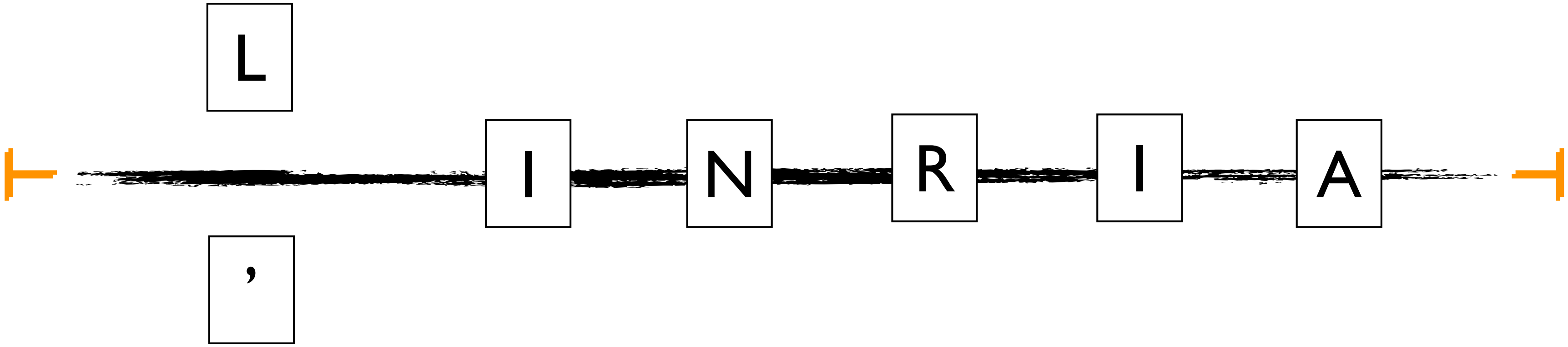
add-between (x, y, z)

- dpre: $x, z \in V \wedge x < z$
- effect: $y \in V \wedge x < y < z$

remove (y)

- effect: $y \notin V \wedge x < z$

Sequence



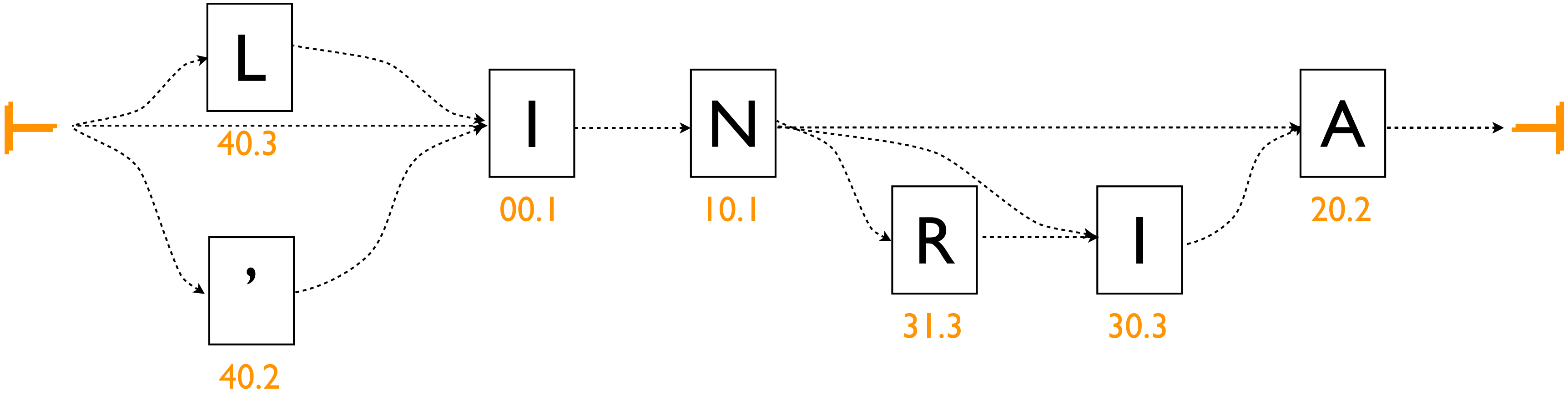
Sequence of elements of type *T*

- Co-operative edit buffer: sequence of atoms
- *add-at-location, remove*

Two approaches:

- Linked list
- Continuum

Roh's RGA



Elements of type *(atom v, LTS ts)*

- Explicit (total order) graph $x < y < z$

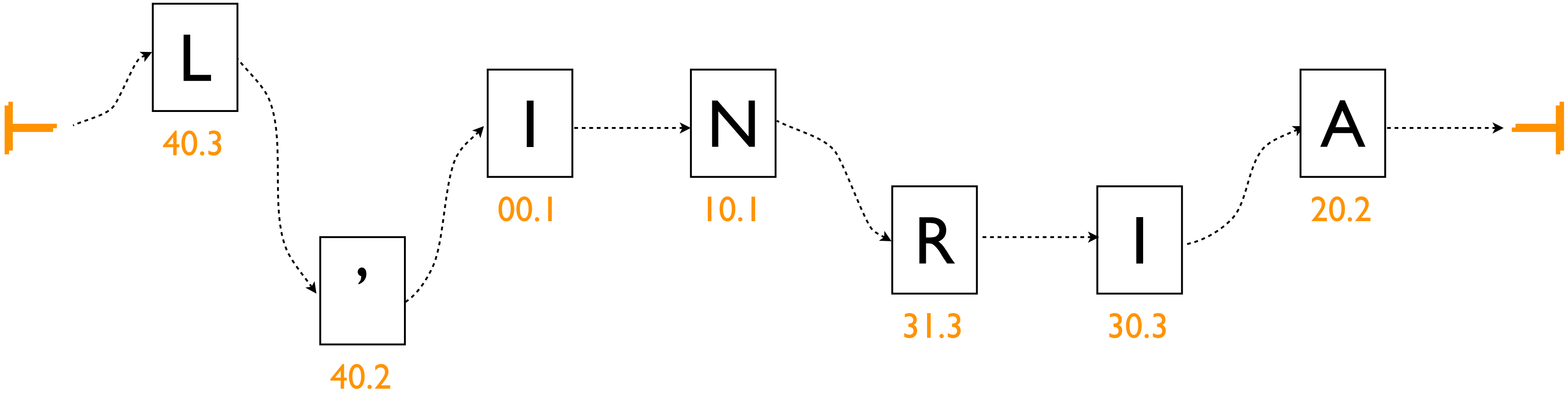
add-after (x, y):

- dpre: *add-after(..., x)* → *add-after (x, ...)*
- Sequential: *add-after (x,y)* → *add-after (x,z)* $\Rightarrow y.ts < z.ts \land x < z < y$
- Concurrent: *add-after (x,y)* || *add-after (x,z)* $\land\ y.lts < z.lts \Rightarrow x < z < y$

• Lamport timestamp

• Concurrent behaviour consistent

Roh's RGA



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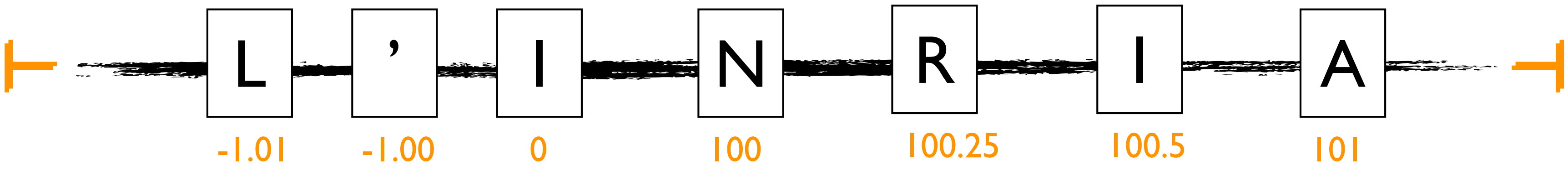
• Concurrent behaviour consistent

Continuum



Assign each element a unique real number

- *position*

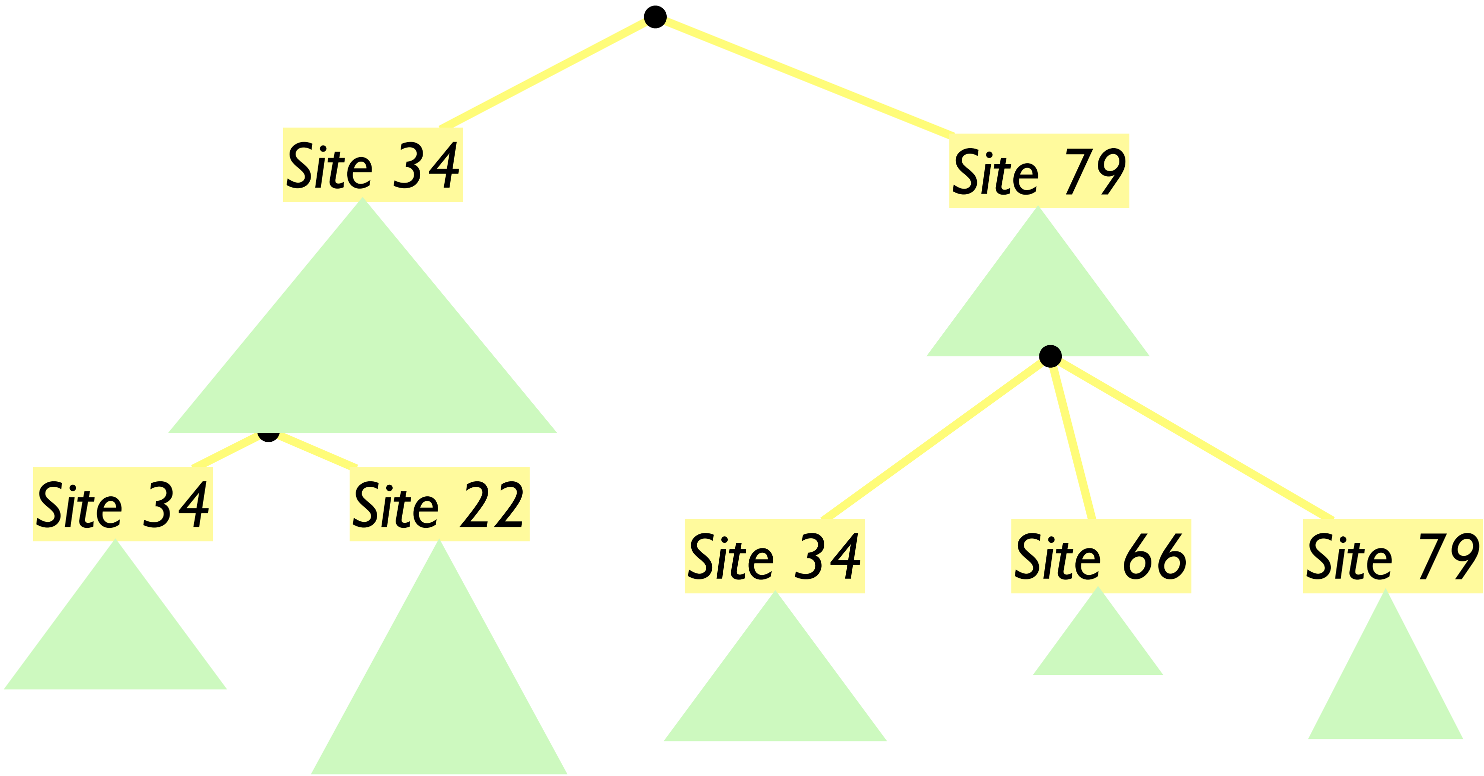
Real numbers not appropriate

- approximate by tree

Layered Treedoc

sparse 8^{64}-
-ary tree

binary tree



Edit: Binary tree

Concurrency: Sparse tree

Rebalance

• stronger form of GC

Tree has nice logarithmic properties

Wikipedia, CVS experiments:

- Lots of removes
- Unbalanced over time

Rebalancing changes IDs:

- Strong synchronisation (commitment)
- In the background
- Liveness not essential
- Core-Nebula: small-scale consensus

Take aways

Principled approach to eventual consistency

Two sufficient conditions:

- State: monotonic semi-lattice
- Operation: commutativity

Useful CRDTs

- Register: Last-Writer-Wins, Multi-Value
- ≈ Set: 2P (remove wins), OR (add wins)
- Map ≈ Set + Register
- Graph ≈ (Set, Set) + $E \subseteq V \times V$
- Monotonic DAG
- Sequence: list, continuum

Future work

CRDT-based cache for cloud

Strong invariants

- *counter* ≥ 0
- graph $\in$ DAG, tree, XML schema

Approaches:

- Restricted problems
- Consensus
- Eventual conformance: diverge + fix, probabilistic guarantees

•exponential backoff

Quasi-CRDTs

- Common operations commute
- Occasional consensus

CRDTs for cloud computing

ConcoRDanT: ANR 2010–2013

- Systematic study, explore design space
- Characterise invariants
- Library of data types: multilog, K-V store + composition

When consensus required:

- Mix commutative / non-commutative semantics
- Move off critical path, non-critical ops
- Speculation + conflict resolution