Replicated Data, From Practice to Theory

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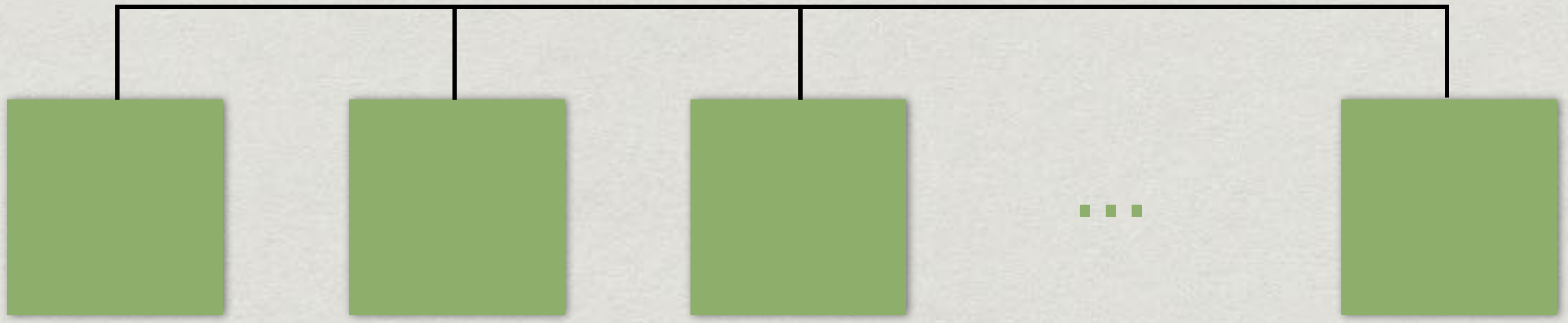
Distributed systems

Distributed systems

- N nodes connected by asynchronous network



Distributed systems

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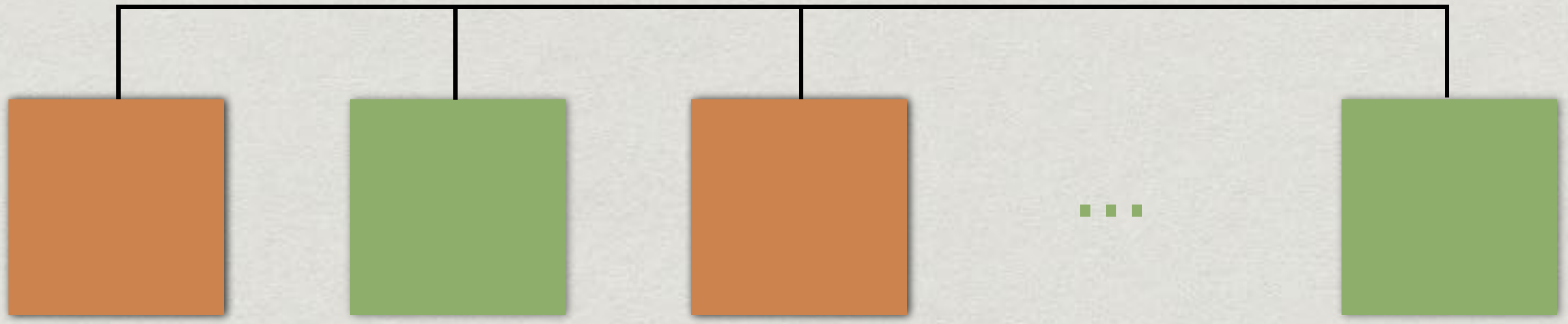
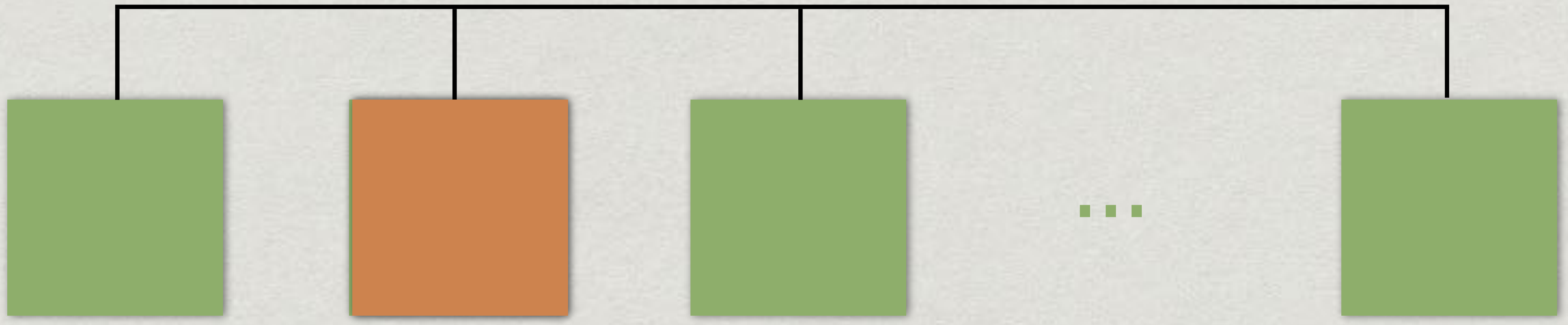
- Nodes may fail and recover infinitely often



Distributed systems

- N nodes connected by asynchronous network
- Nodes may fail and recover infinitely often
- Nodes resume from safe state before failure



Replicated datatypes

Replicated datatypes

- Each node replicates the data structure

Replicated datatypes

- Each node replicates the data structure
- Queries / updates addressed to any replica
  - Queries are side-effect free
  - Updates change the state of the data structure

Replicated datatypes …

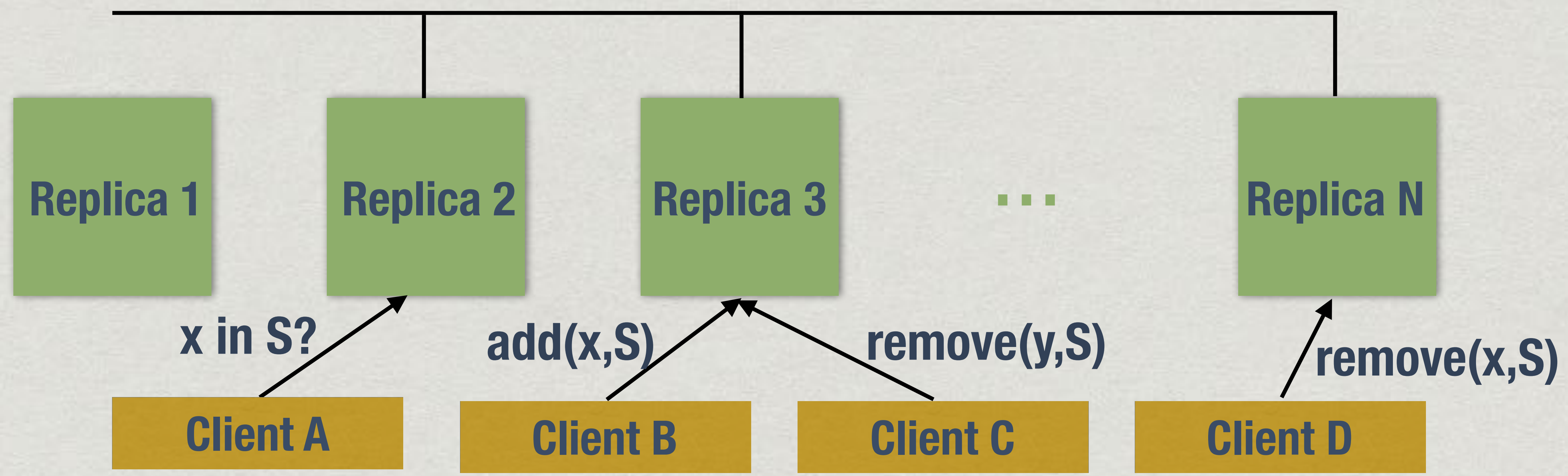
- Typical applications
  - Amazon shopping carts
  - Google docs
  - Facebook “like” counters

Replicated datatypes …

- Typical data structure — Sets
  - Query : is x a member of S?
  - Updates : add x to S, remove x from S

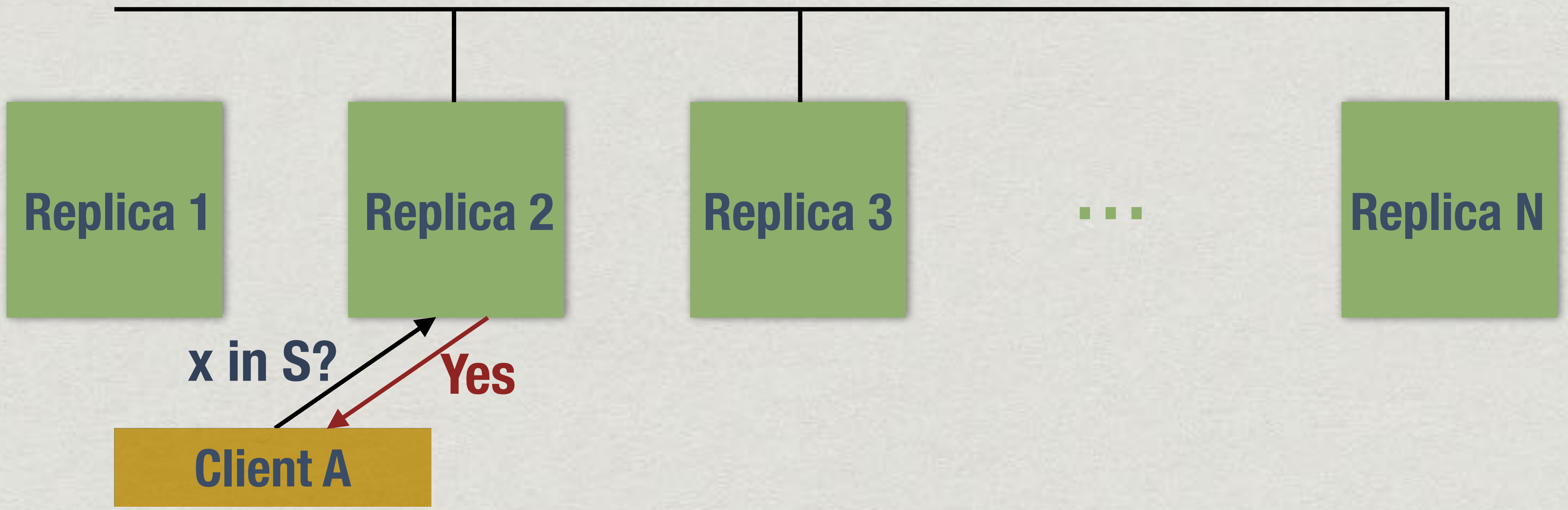
Clients and replicas

- Clients issue query/update requests
- Each request is fielded by an individual source replica

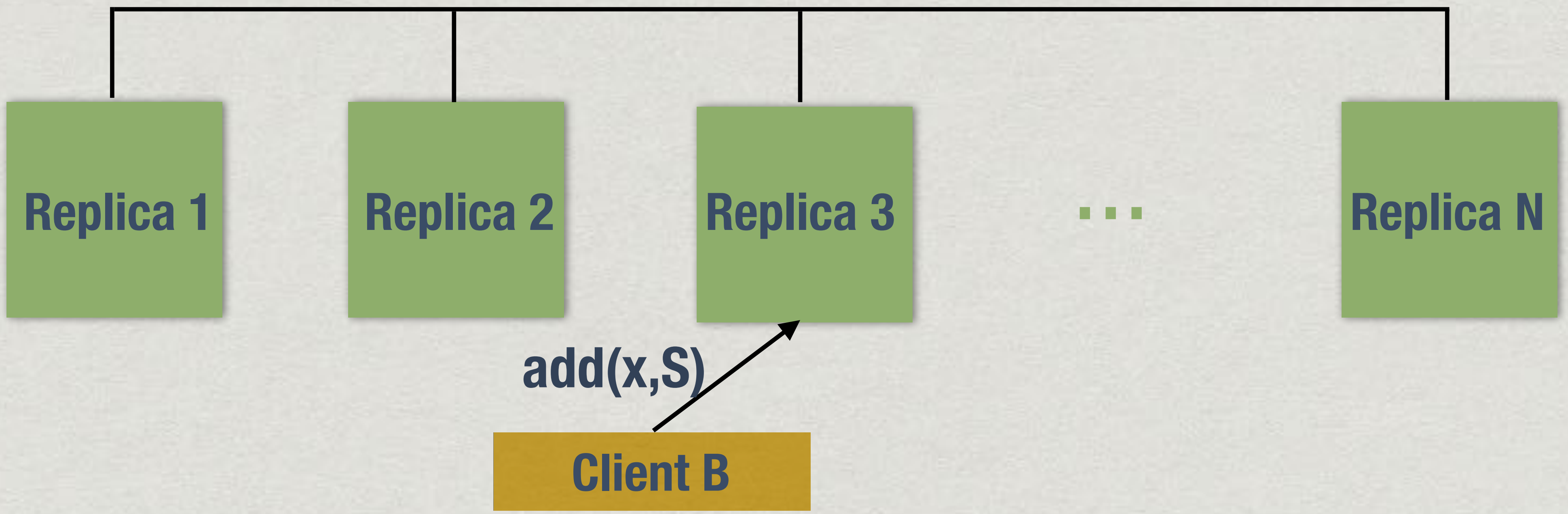


Processing query requests

- Queries are answered directly by source replica, using local state

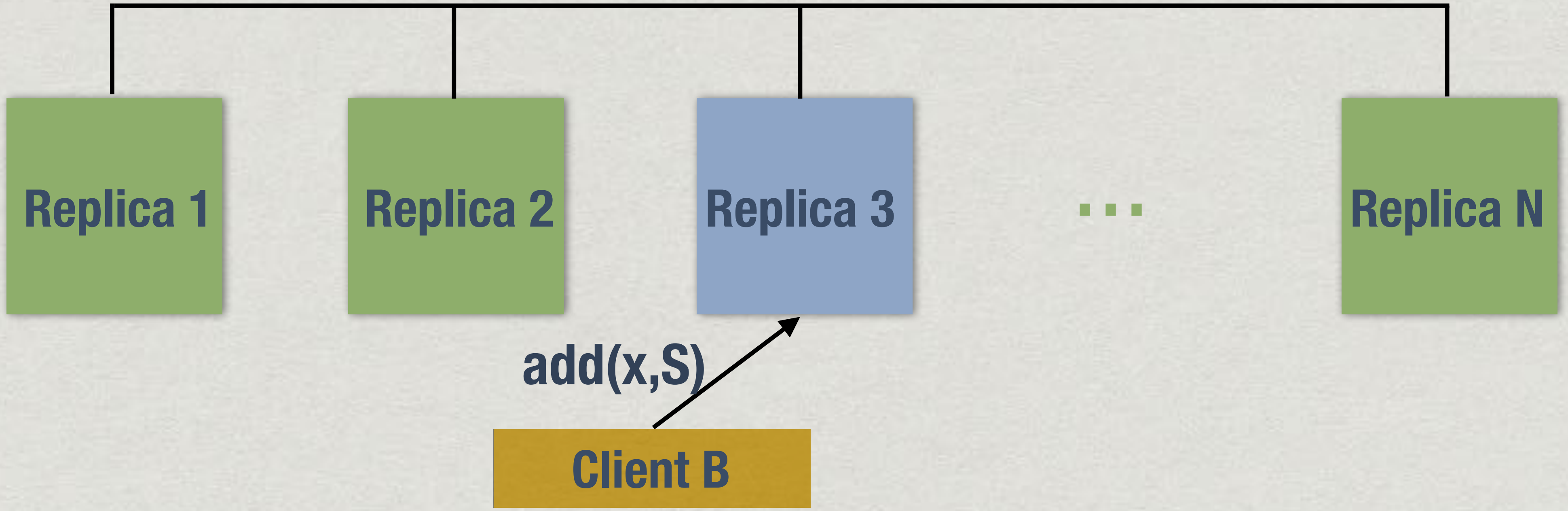


Processing updates



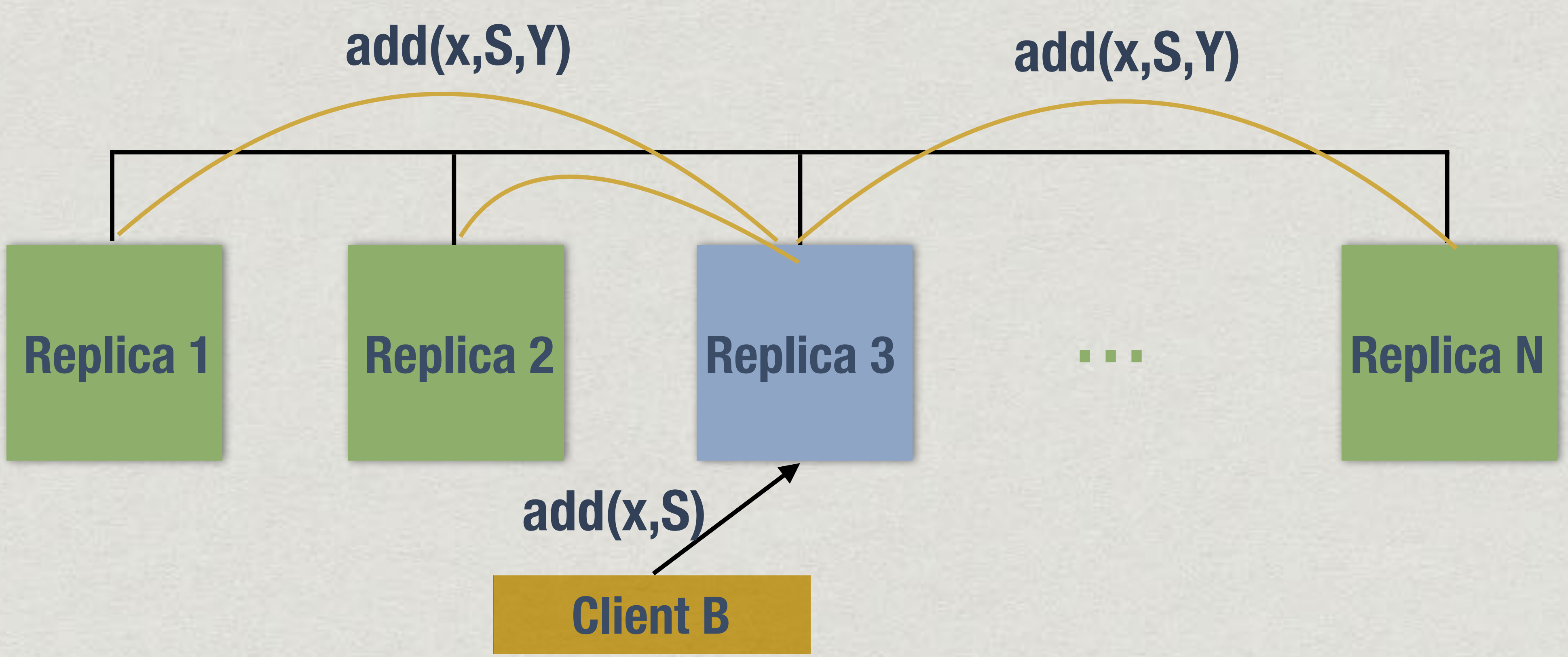
Processing updates

- Source replica first updates its own state



Processing updates

- Source replica first updates its own state
- Propagates update message to other replicas
  - With auxiliary metadata (timestamps etc)



Consistency

* Queries answered by replicas based on local data
* What guarantees can we provide about consistency?

The CAP bottleneck

- Consistency All the nodes see the same data at the same time
- Availability Every request receives a status response—success or failure
- Partition Tolerance Resilient to (transient or permanent) failures in connectivity
- CAP Theorem [Brewer 2000, Gilbert+Lynch 2002]
  A distributed system can satisfy at most 2 out of 3

The CAP tradeoff

- Network failures are unavoidable, require partition tolerance
- Give up consistency or availability
- Traditional distributed databases: maintain consistency
- Web services require high availability
- What is a suitable weakening of consistency?

Strong eventual consistency

- Replicas may diverge while updates propagate
  - All messages are reliably delivered
- Replicas that receive the same set of updates are query equivalent
  - Concurrent updates need not arrive same order
- After a period of quiescence, all replicas converge
  - Does not specify what value they converge to!

Facebook example (2012)

http://markcathcart.com/2012/03/06/eventually-consistent/

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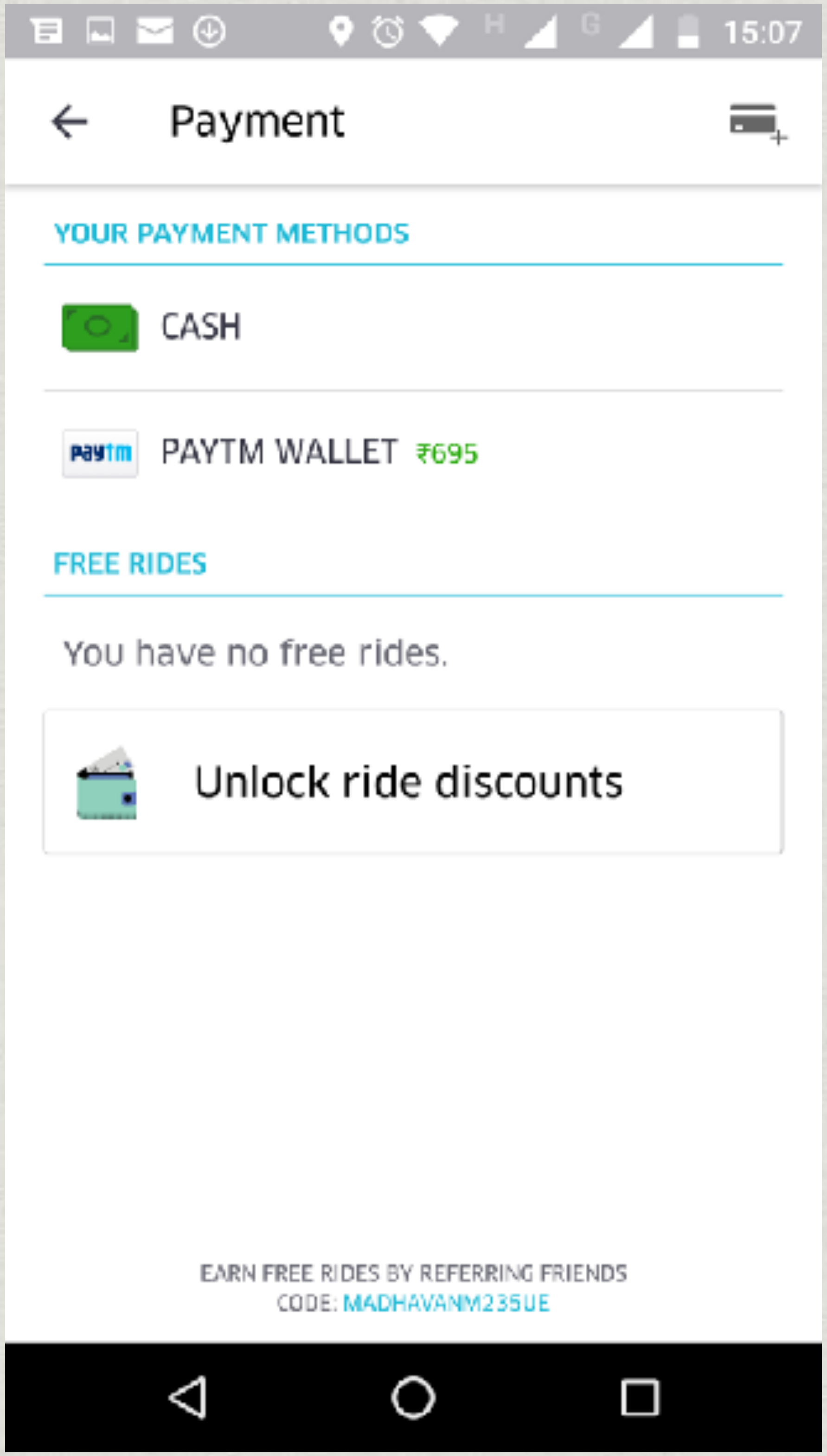
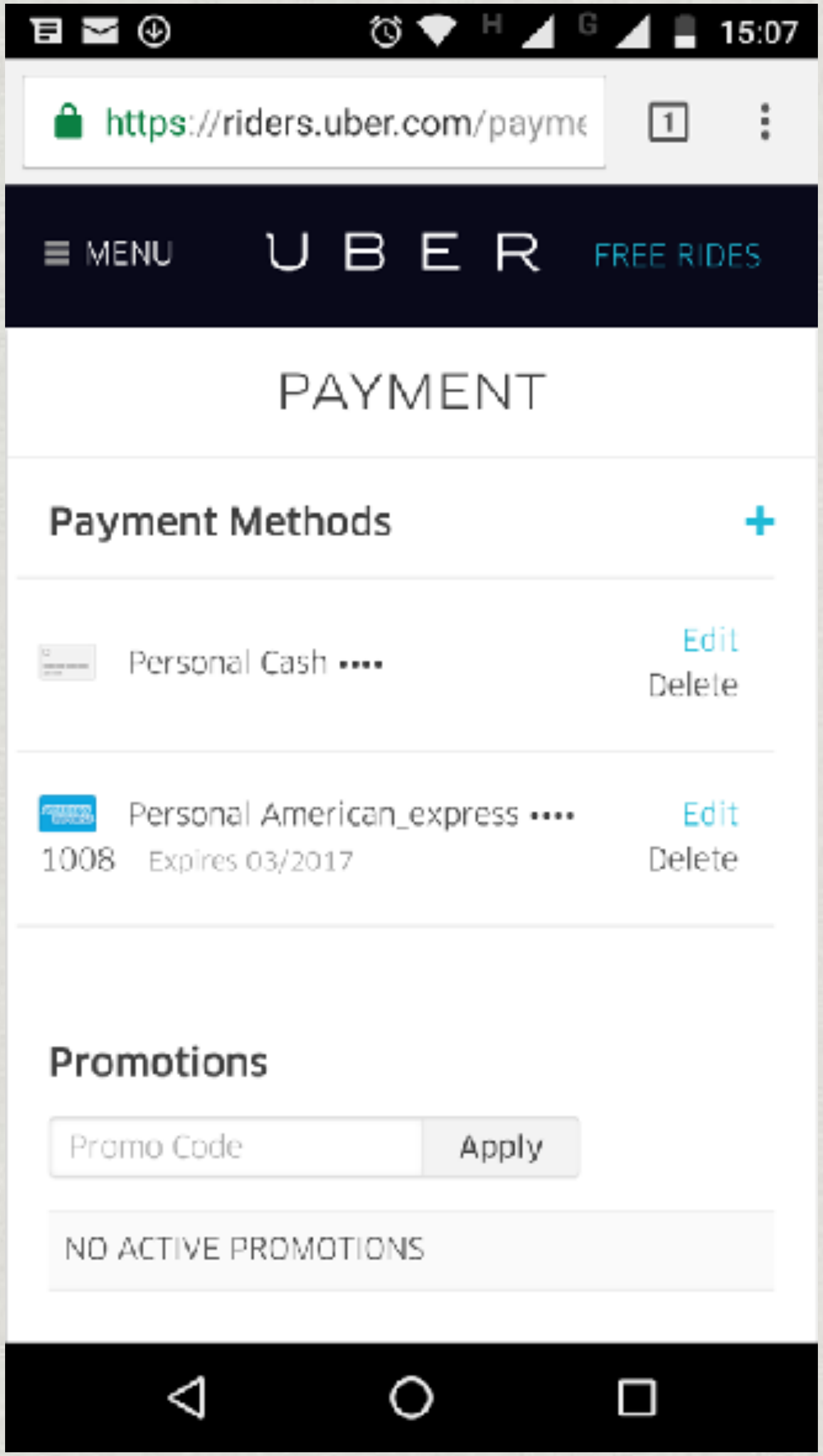
Uber: App vs Webpage





CRDT: Conflict Free Data Types

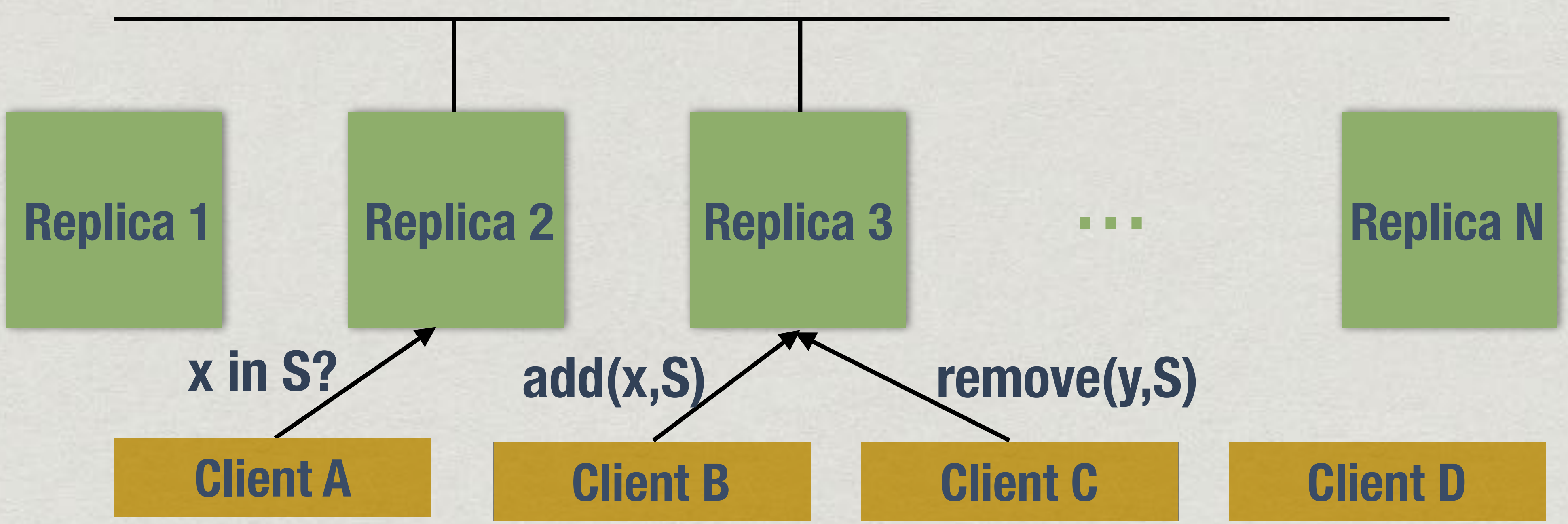
- Introduced by Shapiro et al 2011
- Implementations of counters, sets, graphs, … that satisfy strong eventual consistency by design
- Maintain auxiliary metadata at each replica
- Use metadata to reconcile updates
  - State based: merge entire state
  - Op based: send summary of operation

A distributed counter

- N replicas, each maintains a vector C_i of counters
  - $C_i[k]$ — i's info about increments received by k
- Increment at i — update $C_i[i]$
- Merge j's info at i: take max of $C_i[k]$ and $C_j[k]$
- Query counter value at i — sum of all entries in C_i
- All updates are monotonic

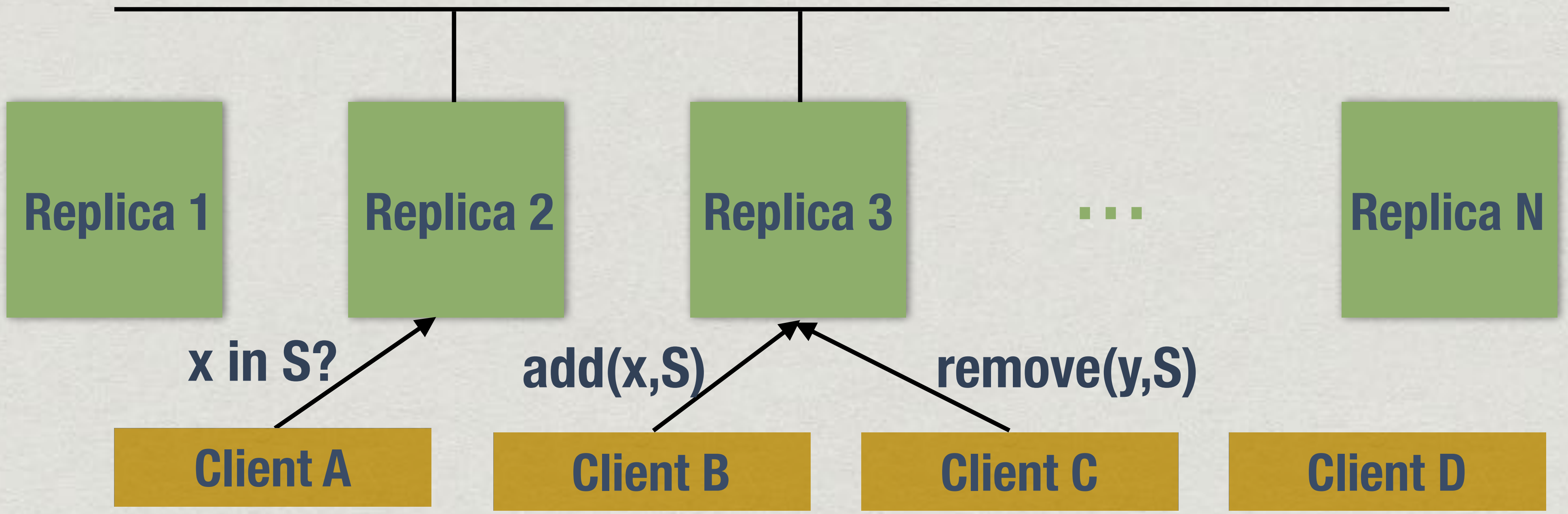
A distributed set

- add(x), remove(x), member(x)
- add(x) and remove(x) are conflicting
  - What is the effect of concurrent operations



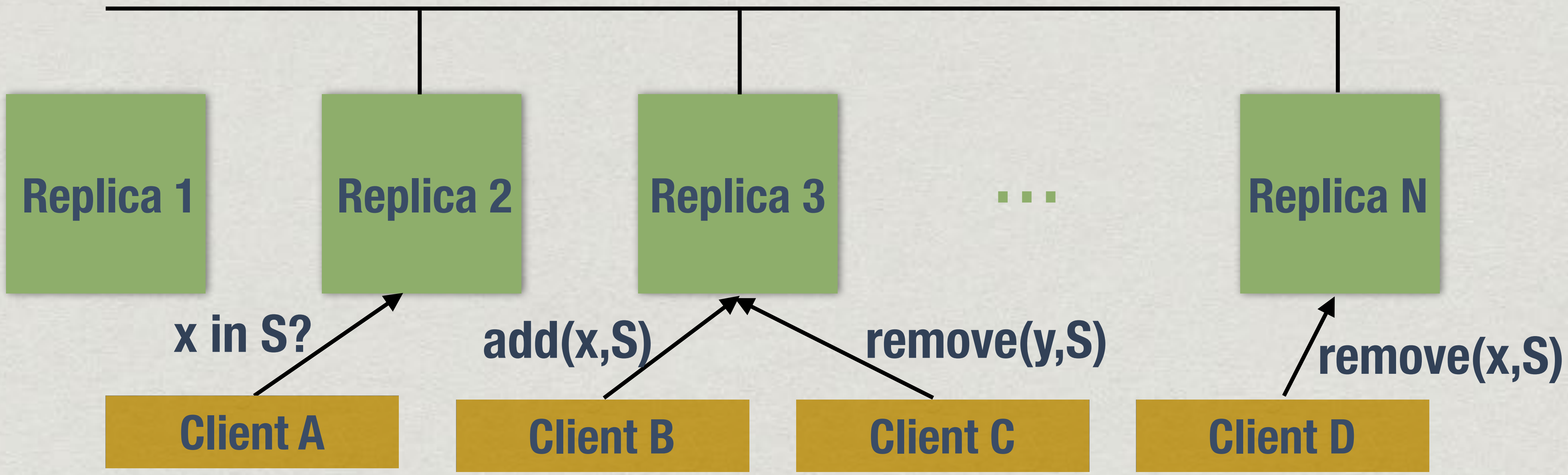
A distributed set

- Define a conflict resolution policy
  - Add wins — “Observed-Remove” (OR) set
  - Question is of consistency, not “correctness”



“Operational” specifications

- My implementation uses timestamps, … to detect causality and concurrency
- If my replica received <add(x,S),t> and <remove(x,S),t’> and t and t’ are related by …, then answer Yes to “x in S?”, otherwise No

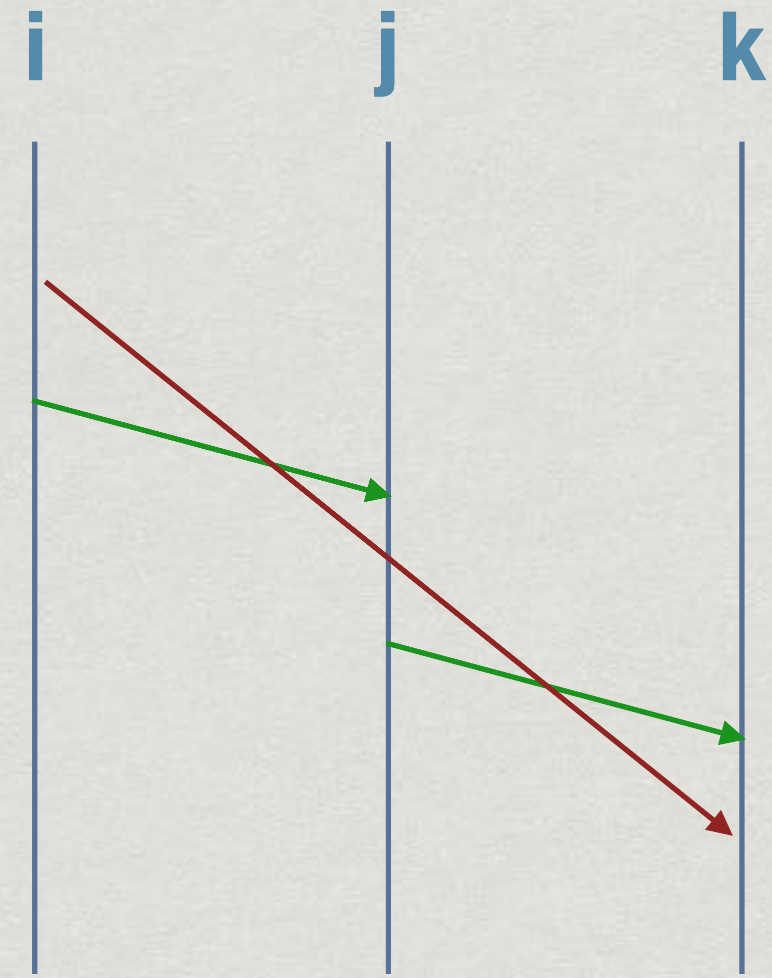


Declarative specification

- Represent a concurrent computation canonically
  - Say a labelled partial order
- Describe effect of a query based on this abstract representation
  - Reordering of concurrent updates does not matter
  - Strong eventual consistency is guaranteed

Declarative specification

- A fully general declarative model is very complicated [Burckhardt et al, POPL 2014]
- Message delivery relation, visibility relation for updates, ...
- Simplify — assume causal delivery of messages
- Can then use partial orders



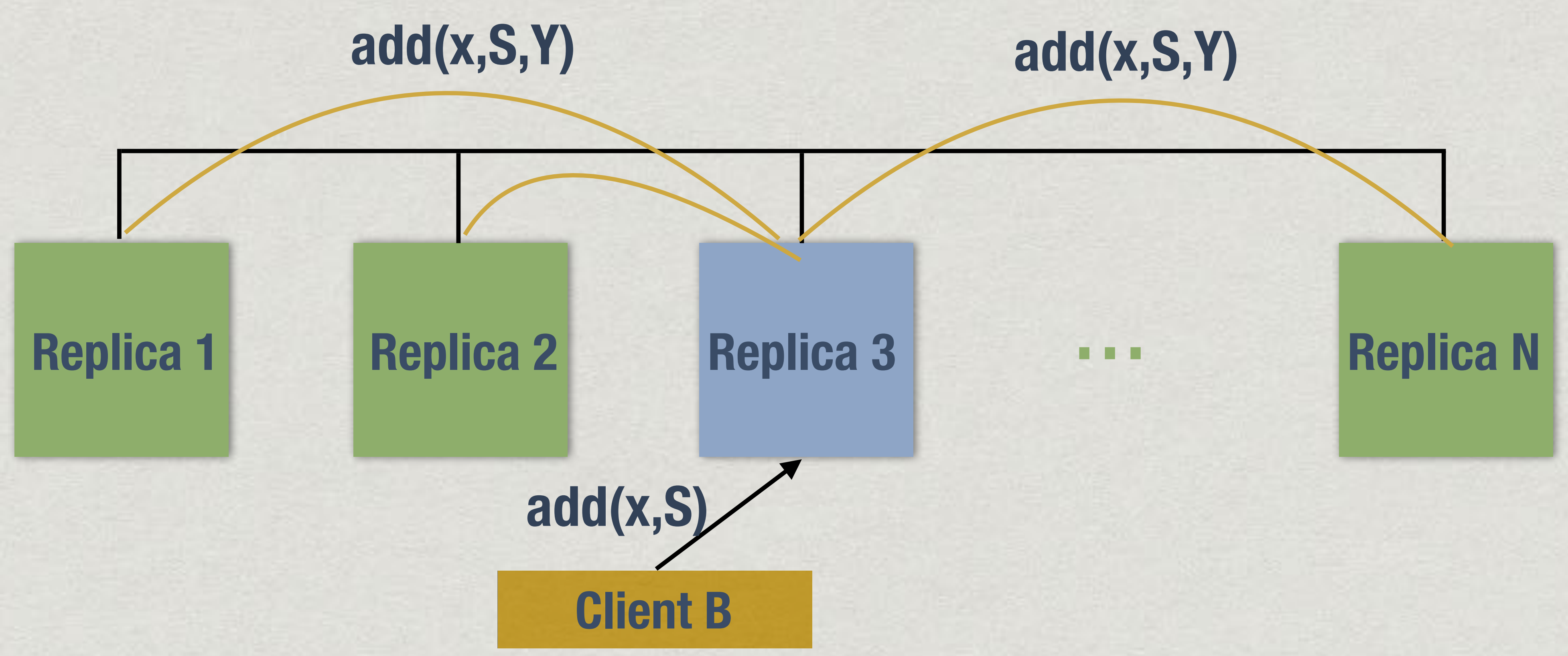
Violation of causal delivery

CRDTs

- Conflict-free Replicated Data Type: D = (V,Q,U)
  - V — underlying universe of values
  - Q — query operations
  - U — update operations
- For instance, for OR-sets,
  Q = {member-of}, U = {add, remove}

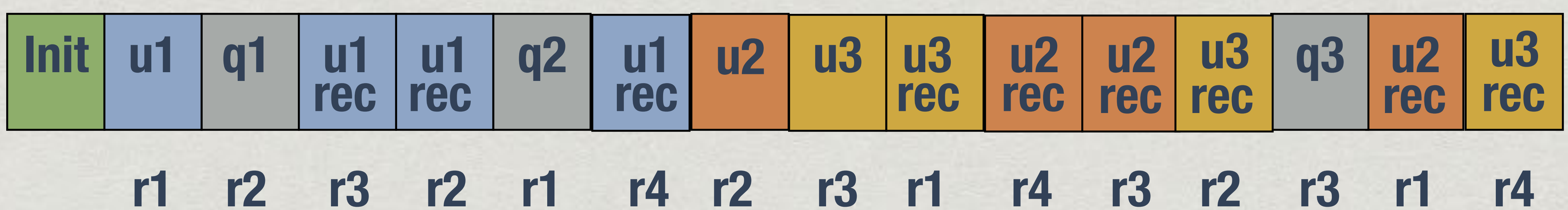
Runs of CRDTs

- Recall that each update is
  - locally applied at source replica,
  - followed by N-1 messages to other replicas



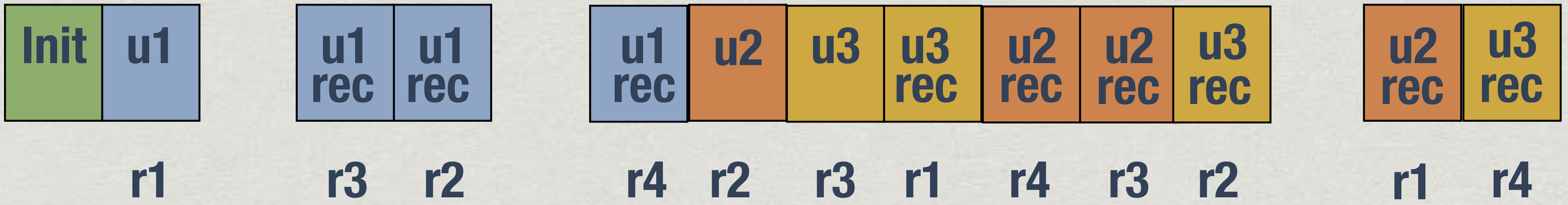
Runs of CRDTs …

- Sequence of query, update and receive operations



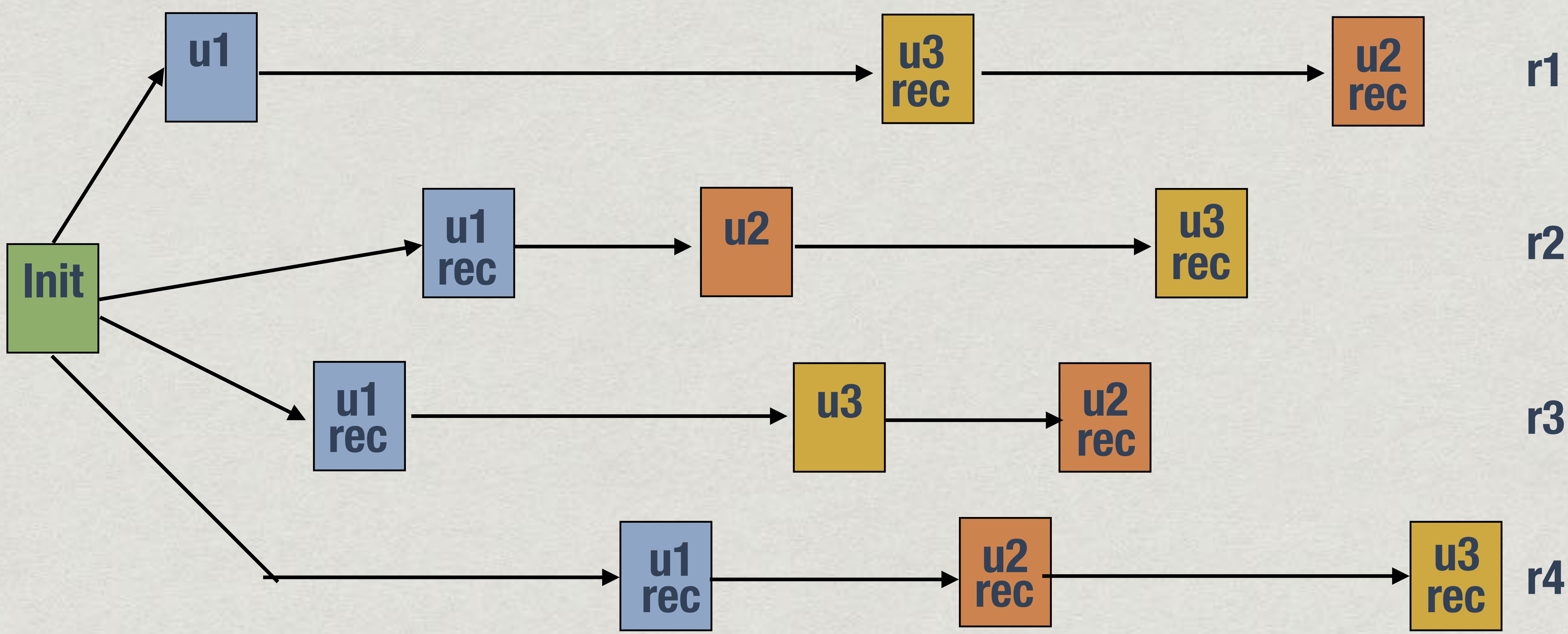
Runs of CRDTs …

- Ignore query operations
- Associate a unique event with each update and receive operation



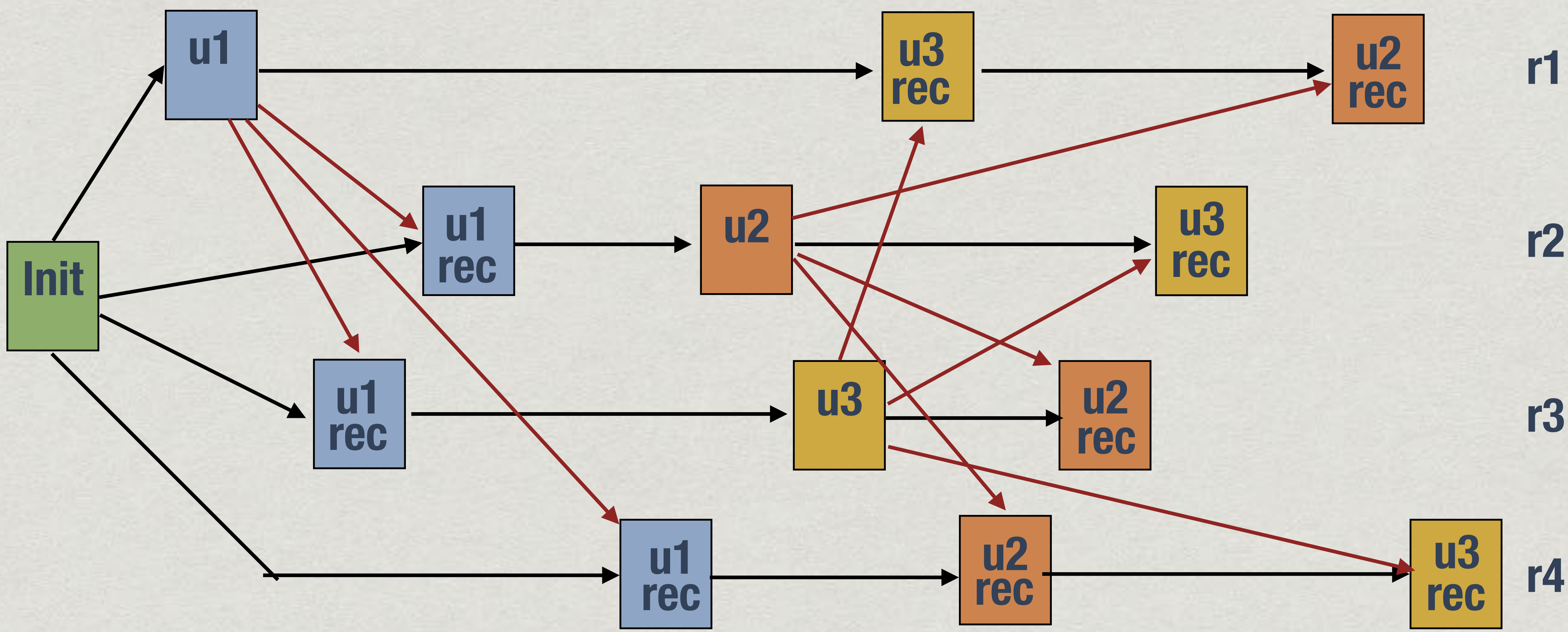
Runs of CRDTs ...

- Replica order: total order of each replica's events



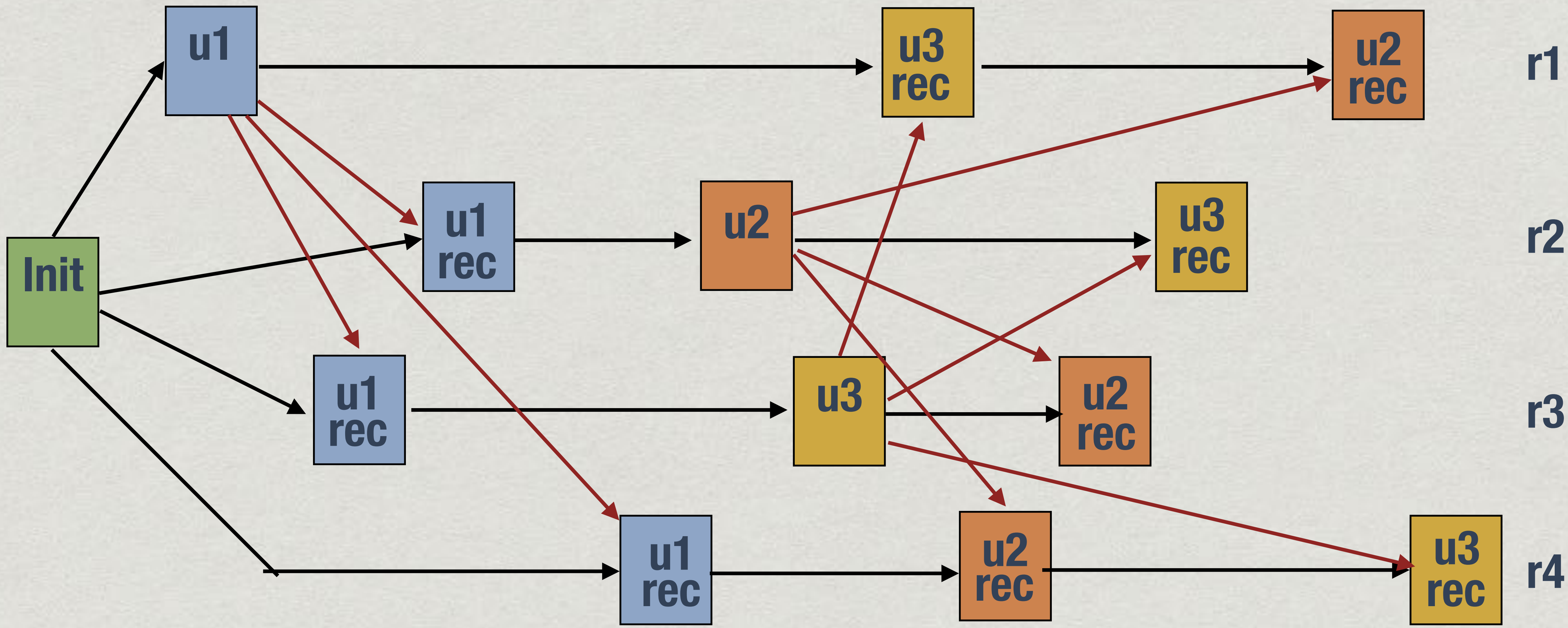
Runs of CRDTs ...

- Delivery order: match receives to updates



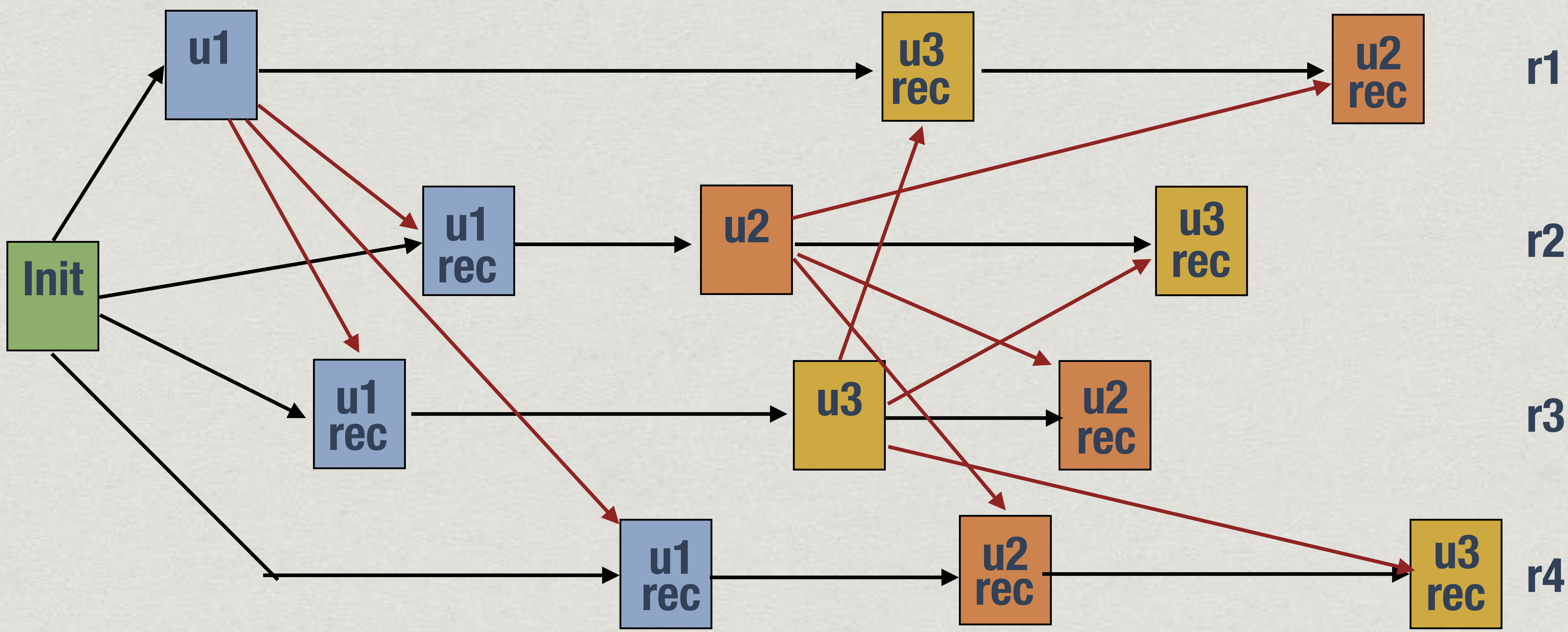
Runs of CRDTs …

- Happened before order on updates: Replica + Delivery
  - Need not be transitive
  - Causal delivery of messages makes it transitive



Runs of CRDTs …

- Local view of a replica
  - Whatever is visible below its maximal event



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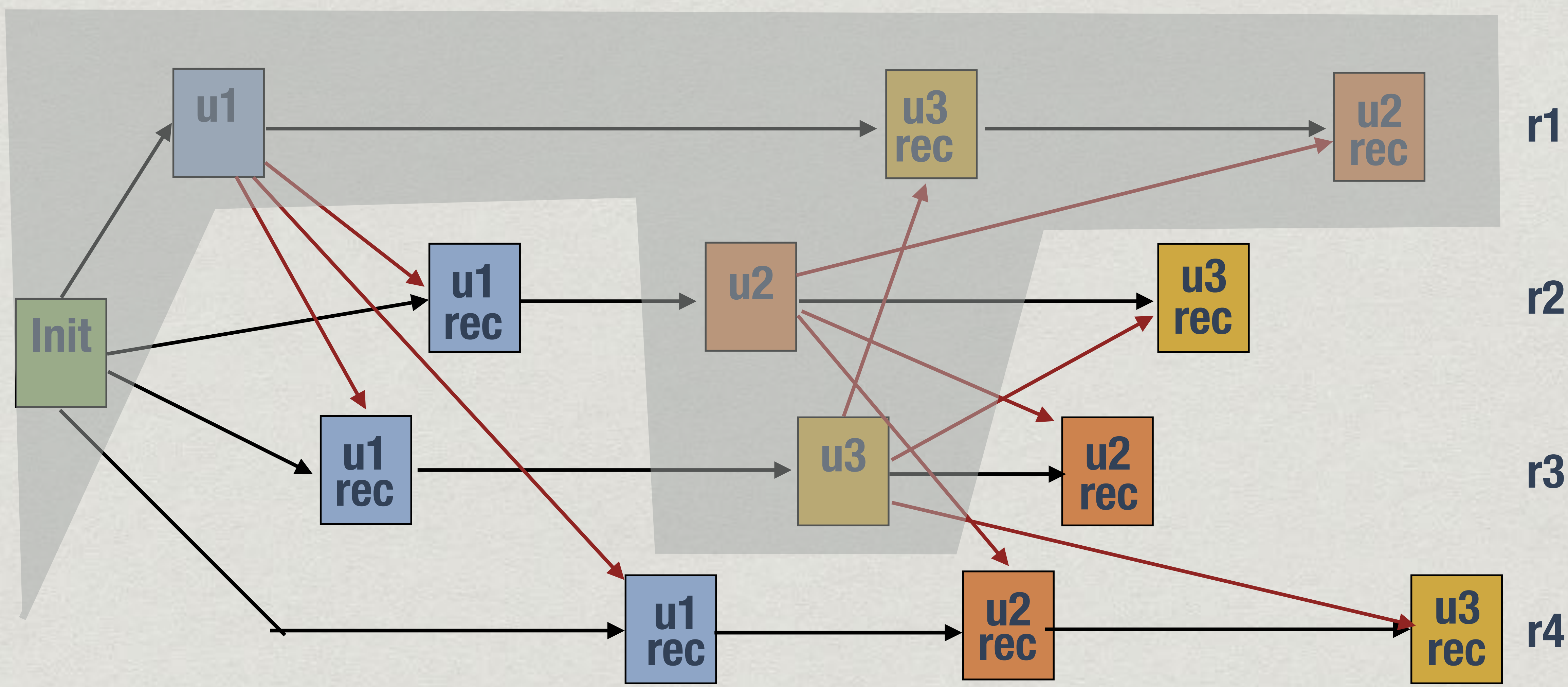

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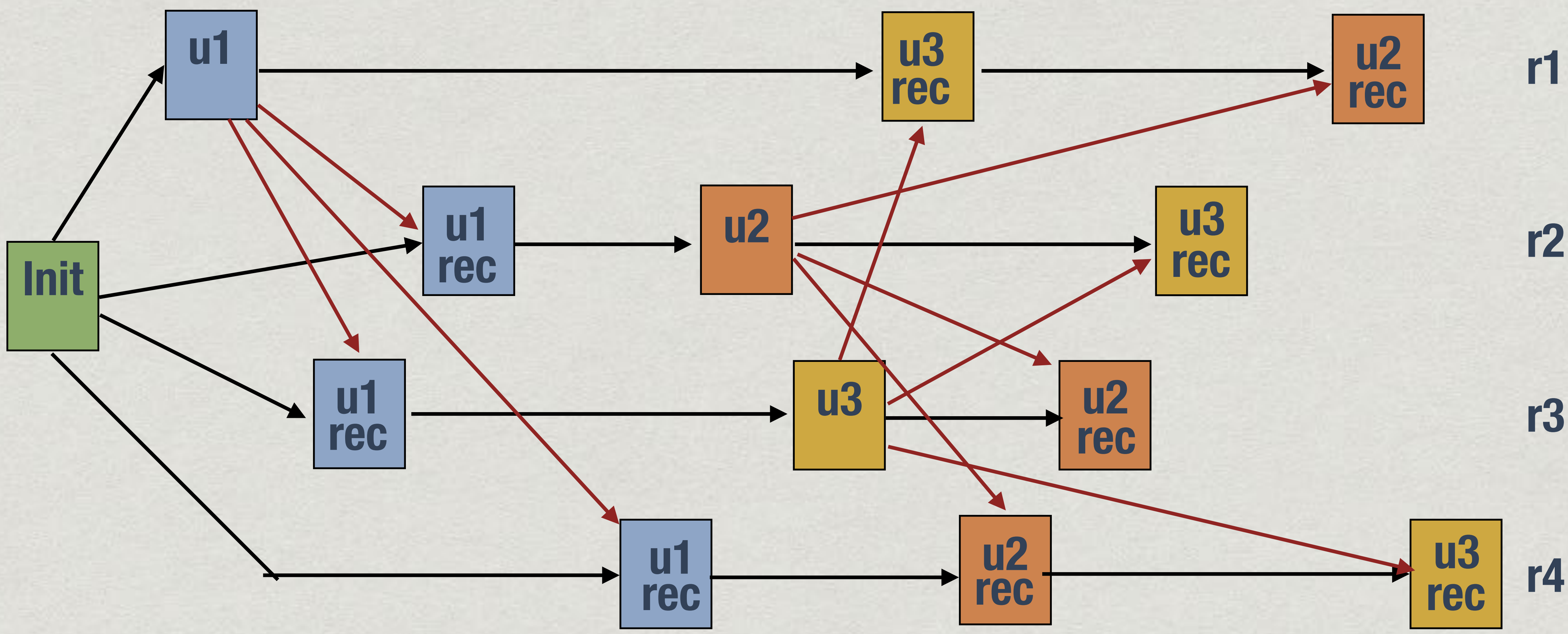

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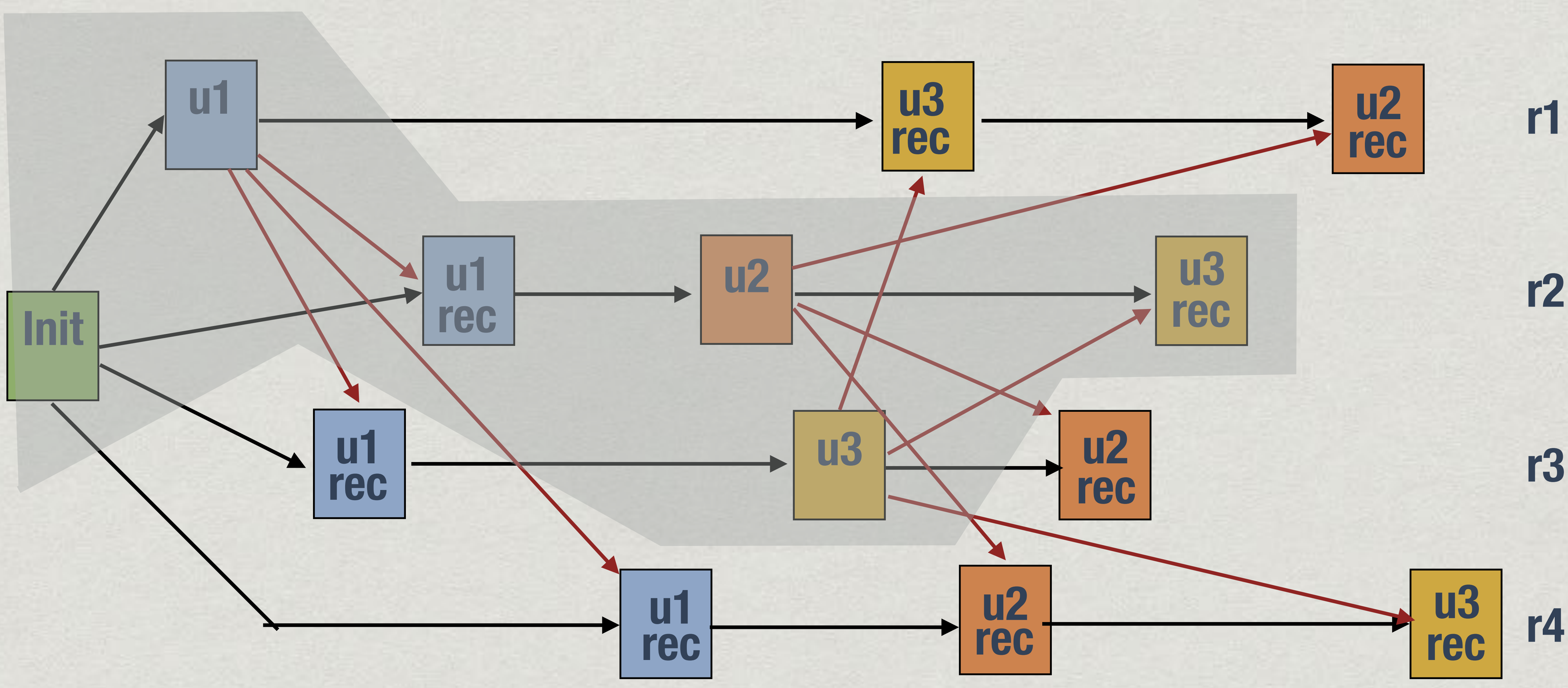

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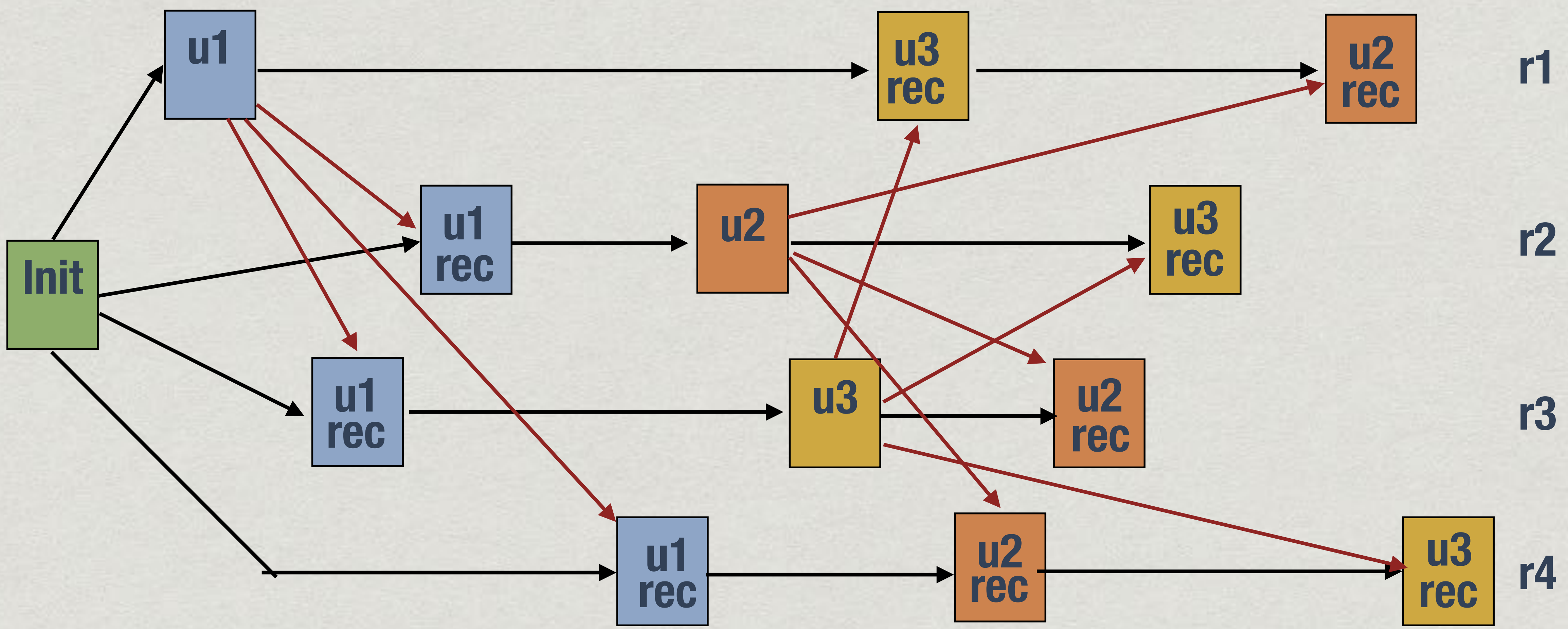
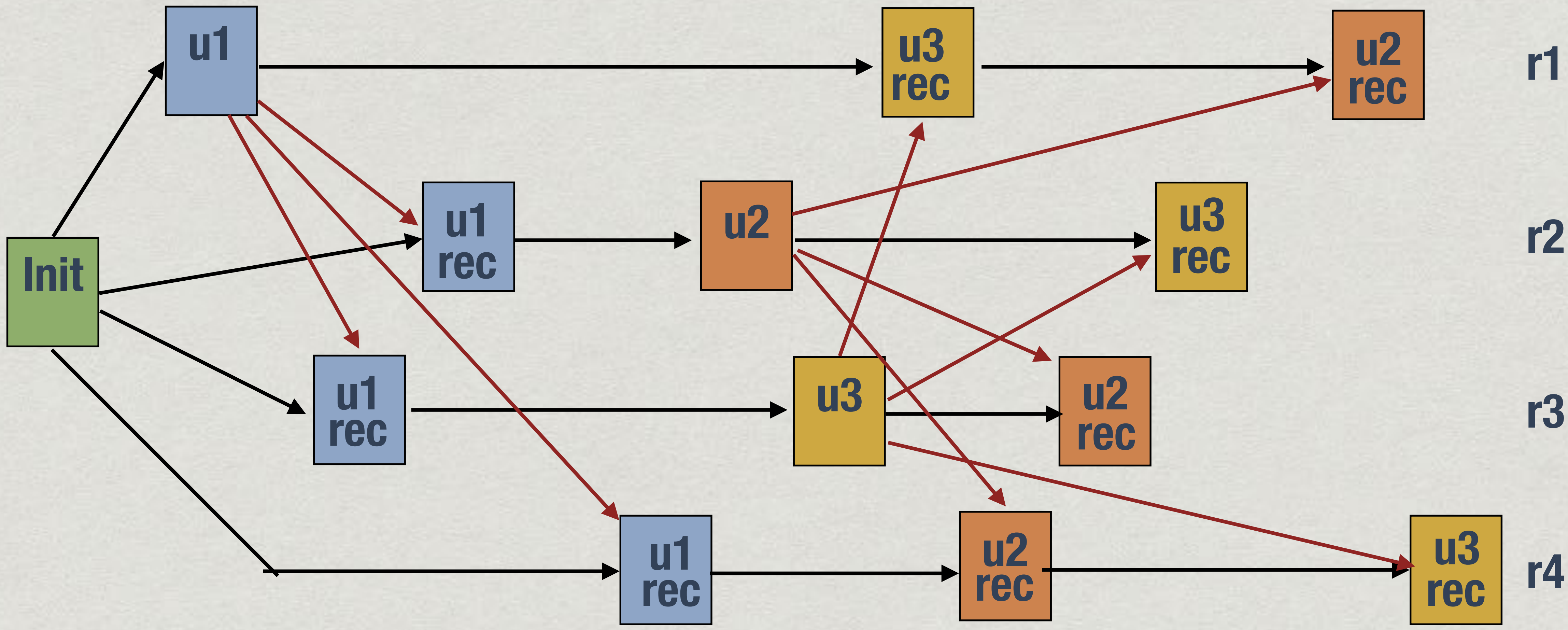


Runs of CRDTs …

- Even if updates are received locally in different orders, “happened before” on updates is the same



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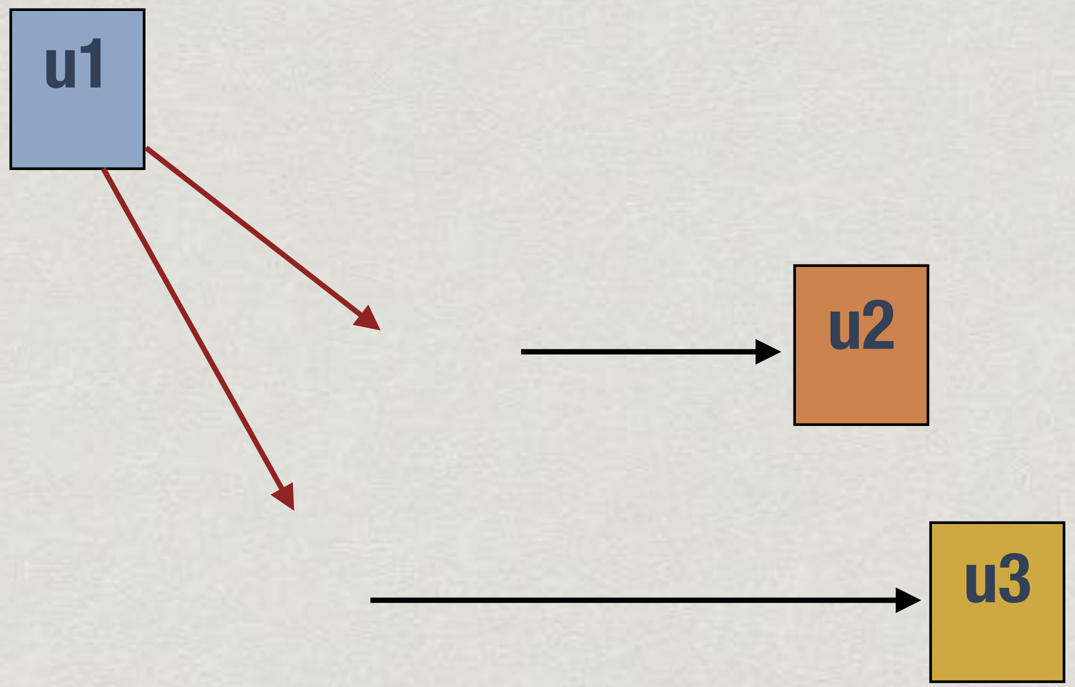

Declarative specification

- Define queries in terms of partial order of updates in local view
- For example: add wins in an OR-set
  - Report “x in S” to be true if some maximal update is add(x,S)
  - Concurrent add(x,S), remove(x,S) will both be maximal

Bounded past

- Typically do not need entire local view to answer a query
- Membership in OR-sets requires only maximal update for each element
  - N events per element

Verification

- Given a CRDT D = (V,Q,U), does every run of D agree with the declarative specification?
- Strategy
  - Build a reference implementation from declarative specification
  - Compare the behaviour of D with reference implementation

Finite-state implementations

- Assume universe is bounded
- Can use distributed timestamping to build a sophisticated distributed reference implementation [VMCAI 2015]
  - Asynchronous automata theory
  - Requires bounded concurrency for timestamps to be bounded

Global implementation

- A simpler global implementation suffices for verification [ATVA 2015]
- Each update event is labelled by the source replica with an integer (will be bounded later)
- Maintain sequence of updates applied at each replica
  - either local update from client
  - or remote update received from another replica

Later Appearance Record

- Each replica's history is an LAR of updates
  - (u_1,l_1) (u_2,l_2) … (u_k,l_k)
    - u_j has details about update: source replica, arguments
    - l_j is label tagged to u_j by source replica
- Labels are consistent across LARs — (u_i,l) in r1 and (u_j,l) in r2 denote same update event
- Maintain LAR for each replica

Causality and concurrency

- Suppose r3 receives (u,l) from r1 and (u’,l’) from r2
  - If (u,l) is causally before (u’,l’), (u,l) must appear in r2’s LAR before (u’,l’)
  - If (u,l) is not causally before (u’,l’) and (u’,l’) is not causally before (u,l), they must have been concurrent
- Can recover partial order and answer queries according to declarative specification

Pruning LARs

- Only need to keep latest updates in each local view
- If (u,l) generated by r is not latest for any other replica, remove all copies of (u,l)
- To prune LARs, maintain a global table keeping track of which updates are pending (not yet delivered to all replicas)
- Labels of pruned events can be safely reused

Outcome

- Simple global reference implementation that conforms to declarative specification of CRDT
- Reference implementation is bounded if we make suitable assumptions about operating environment
  - Bounded universe
  - Bounded message delivery delays

Verification strategy

- Counter Example Guided Abstraction Refinement (CEGAR)
  - Build a finite-state abstraction of given CRDT
  - Compute synchronous product with reference implementation
  - If an incompatible state is reached, trace out corresponding bad run in CRDT
    - If we find a bad run, we have found a bug
    - If not, refine abstraction and repeat

One size does not fit all

* Traditional strong consistency requires coordination across replicas
* Eventual consistency provides very weak guarantees

A football match

- Goals for A and B are recorded separately
- Strong consistency: 3-4
- Eventual consistency: 2-0, 2-3, 3-2, …
- Prefix: 1-0, 1-1,1-2, 2-2, 3-2, 3-3, 3-4
- Monotonic: Can’t read 1-2 after 3-2

Multiple requirements

- Shopping cart can be eventually consistent
- Checkout requires synchronisation
- Mobile wallet requires read-my-own writes
- Same data store may support different consistency models across operations

An abstract model

- Causal consistency plus Petri net like tokens [Gotsman et al, POPL 2016]
- Tokens model conflict, force synchronization
- Proof rule to check correctness of a specification
- Extend to an effective verification procedure?

The nature of replicas

* Should all replicas service all operations?
* Synchronized operations propagated via “core” servers
* How to model an underground data vault?

In practice …

- Publicly available libraries like Riak for eventually consistent data structures
    - Useful for high scores in online games etc
    - Difficult to program “critical” operations
- Distributed data stores like Redis
    - No clear consistency guarantees

Speculation and apologies

- “Sorry, the price for your booking has changed”
- Systems speculate and then apologise
- What is a good formal model?

Summary

* Distributed data stores are increasingly in use
* We have formal models for CRDTs, eventual consistency
* The real world is more complicated
  * Technology remains far ahead of theory
* Good theoretical foundations can validate and clarify empirical advances