Programming Distributed Systems

06 Replicated Data Types

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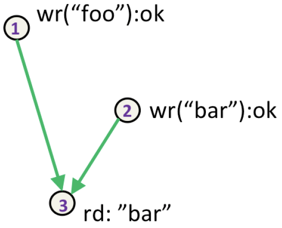
Motivation

So far, we resolved conflicting updates (i.e. non-commutative) updates simply by sequencing operations using arbitration order (ar).

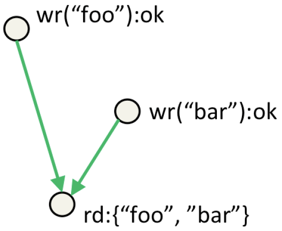
But sometimes, applications

- do not want to depend on a global order such as ar
- want to be made aware of conflicts
- want to resolve conflicts in a specific way

Example: Multi-value register



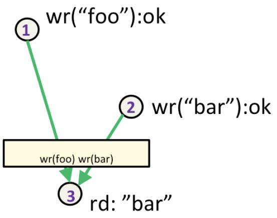
Standard Register (Last Writer Wins)



Multi-Value Register (Amazon Dynamo)

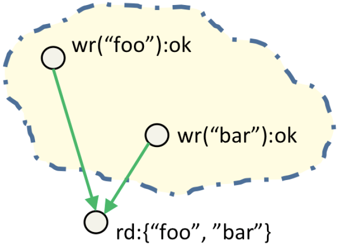
How can we determine the state?

Sequence-based conflict resolution



visible state = **sequence** of visible operations, sorted by arbitration oder

GENERAL CONFLICT RESOLUTION



visible state = **subgraph** of visible operations

Formal model

- Before: $S: Op \times Op^{*} \longrightarrow Val$

  The operation we are performing

  “Current state” = Sequence of all Prior operations

  Returned Value

- Now: $F: Op \times C \longrightarrow Val$

  The operation we are performing

  Operation Context= Event Graph of visible operations

  Returned Value

Sequential semantics for registers

$$S : Op \times Op^* \rightarrow Val$$

$S(rd(), wr(2) \cdot wr(8)) = 8$ (read returns last value written)

$S(rd(), \epsilon) = undef$

$S(wr(3), rd() \cdot wr(2) \cdot wr(8)) = ok$ (write always returns ok)

Operation Context

An operation context is a finite event graph $C = (E, op, vis, ar)$.

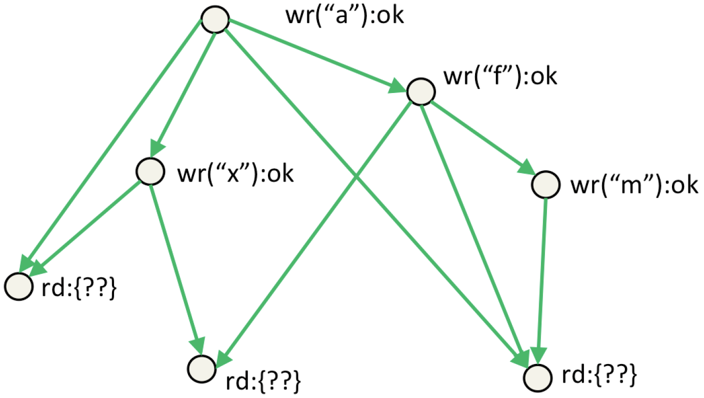
- Events in E capture what prior operations are visible to the operation that is to be performed.
- Models the situation at a single replica

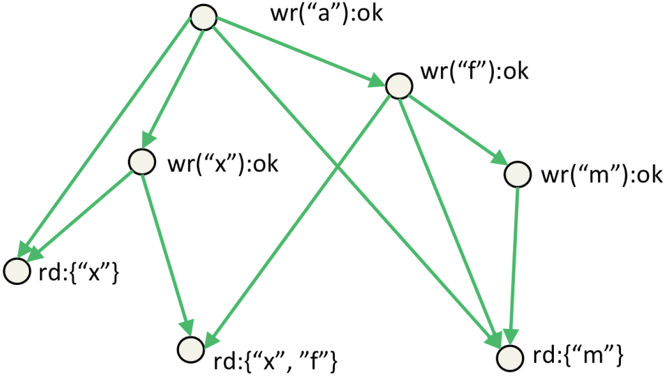
Concurrent semantics for Multi-Value Register

$$F : Op \times C \to Val$$

$$\begin{array}{rcl} F_{mvr}(wr(x), C) & = & ok \\ F_{mvr}(rd(), C) & = & \{x | \text{ exists e in C such that } op(e) = wr(x) \\ & & \quad \text{and e is vis-maximal in C}\} \end{array}$$

Quizz: What do the read ops return?




wr("a"):ok
wr("f"):ok
wr("x"):ok
wr("m"):ok
rd:{"x"}
rd:{"x", "f"}
rd:{"m"}

Return values in Abstract Executions revisited

- Previous lecture:

An abstract execution $(E, op, rval, rb, ss, vis, ar)$ satisfies a sequential semantics S if

$$rval(e) = S(op(e), vis^{-1}.sort(ar))$$

- Read-value consistency can also be defined wrt concurrency semantics

An abstract execution $A = (E, op, rval, rb, ss, vis, ar)$ satisfies a concurrent semantics F if

$$rval(e) = F(op(e), A \mid_{vis^{-1}(e), op, vis, ar}$$

Conflict-free Replicated Data Types (CRDTs) [3]

- Same API as sequential abstract data type, but with concurrency semantics
- Catalogue of CRDTs
  - Register (Laster-writer wins, Multi-value)
  - Set (Grow-Only, Add-Wins, Remove-Wins)
  - Flags
  - Counter (unlimited, restricted/bounded)
  - Graph (directed, monotone DAG)
  - Sequence / List
  - Map, JSON
- If operations are commutative, same semantics as in sequential execution
- Otherwise, need arbitration to resolve conflict

Specification: Replicated counter

- Operation inc commutes $\Rightarrow$ No conflict resolution policy is needed
- Value returned depends only on E and op, but not on vis and ar

$$F_{ctr}(rd(), (E, op, vis, ar)) = |\{e' \in E \mid op(e') = inc\}|$$

Semantics of a replicated Set or How to design a CRDT

- Sequential specification of abstract data type Set S:

$$\begin{array}{lll} \{\text{true}\} & \text{add(e)} & \{e \in S\} \\ \{\text{true}\} & \text{rmv(e)} & \{e \notin S\} \end{array}$$

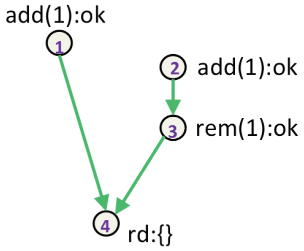
- The following pairs of operations are commutative (for two elements e, f and $e \neq f$):
  - {true} add(e); add(e) $\{e \in S\}$
  - {true} add(e); add(f) $\{e, f \in S\}$
  - {true} rmv(e); rmv(e) $\{e \notin S\}$
  - {true} rmv(e); rmv(f) $\{e, f \notin S\}$
  - {true} add(e); rmv(f) $\{e \in S, f \notin S\}$

$\Rightarrow$ For these ops, the concurrent execution should yield the same result as executing the ops in any order.

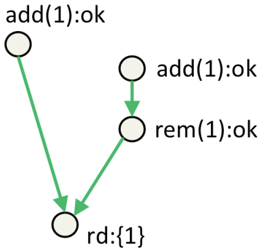
What are the options regarding a concurrency semantics for add(e) and rmv(e)?

- The operations add(e) and rmv(e) are *not* commutative
  - $\{\text{true}\}$ add(e); rmv(e) $\{e \notin S\}$
  - $\{\text{true}\}$ rmv(e); add(e) $\{e \in S\}$
- Options for conflict-resolution strategy when *concurrently* executing add(e) and rmv(e)
  - add-wins: $e \in S$
  - remove-wins: $e \notin S$
  - erroneous state (i.e. escalate the conflict to the user)
  - last-writer wins (i.e. define arbitration order through total order, e.g., by adding totally- ordered timestamps)

Set Semantics



Standard Set



Add-Wins Set

Formal Semantics for the Add-Wins Set

$$\begin{aligned}
F_{aws}(add(x), C) &= ok \\
F_{aws}(rmv(x), C) &= ok \\
F_{aws}(rd(), C) &= \{x \mid \text{exists e in C such that } op(e) = add(x) \\
&\quad \text{and there exists no e' in C such that} \\
&\quad op(e') = rmv(x) \text{ and } e \xrightarrow{vis} e'\}
\end{aligned}$$

Sets with “interesting” semantics

- Grow-only set
  - Convergence by union on element set
  - No remove operation
- 2P-Set (Wuu & Bernstein PODC 1984)
  - Set of added elements + set of tombstones (= removed elements)
  - Add/remove each element once
  - Problem: Violates sequential spec
- c-set (Sovran et al., SOSP 2011)
  - Count for each element how often it was added and removed
  - Problem: Violates sequential spec

Take a break!

A Mathematician, a Biologist and a Physicist are sitting in a street cafe watching people going in and coming out of the house on the other side of the street. First they see two people going into the house. Time passes. After a while they notice three persons coming out of the house.

The Physicist: “The measurement wasn’t accurate.”.

The Biologist: “They have reproduced”.

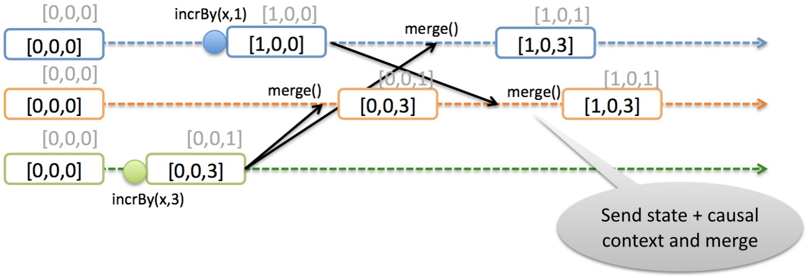
The Mathematician: “If now exactly one person enters the house then it will be empty again.”

CRDTs: Strong Eventual Consistency

- *Eventual delivery:* Every update is eventually applied at all correct replicas
- *Termination:* Update operation terminates
- *Strong convergence:* Correct replicas that have **applied the same update** have equivalent state

How to implement CRDTs

State-based CRDTs: Counter



- Synchronization by propagating replica state
- Updates must inflate the state
- State must form a join semi-lattice wrt merge

$\Rightarrow$ Merge must be idempotent, commutative, associative

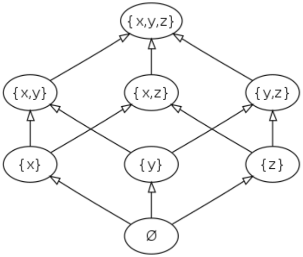
Join-semilattice

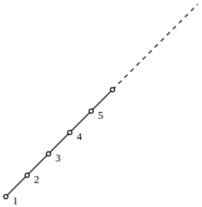
- A join-semilattice S is a set that has a join (i.e. a least upper bound) for any non-empty finite subset:

For all elements $x, y \in S$, the least upper bound (LUB) $x \sqcup y$ exists.

- A semilattice is commutative, idempotent and associative.
- A partial order on the elements of S is induced by setting $x \leq y$ iff $x \sqcup y = y$.

Examples



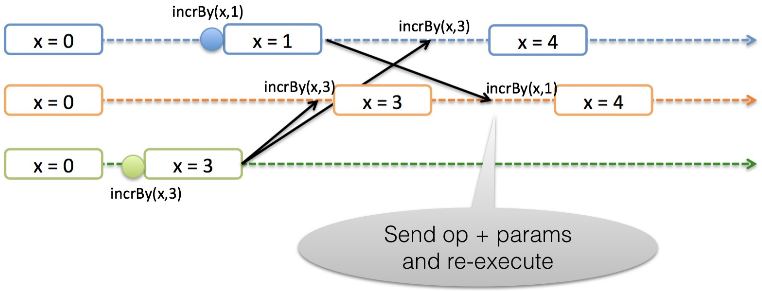


Example: Counter

Specification 6 State-based increment-only counter (vector version)

```
1:  payload integer[$n$] $P$                          ▷ One entry per replica
2:      initial $[0, 0, \ldots, 0]$
3:  update *increment* ()
4:      let $g = myID()$                              ▷ $g$: source replica
5:      $P[g] := P[g] + 1$
6:  query *value* () : integer $v$
7:      let $v = \sum_i P[i]$
8:  compare (X, Y) : boolean $b$
9:      let $b = (\forall i \in [0, n-1] : X.P[i] \leq Y.P[i])$
10: merge $(X, Y)$ : payload $Z$
11:     let $\forall i \in [0, n-1] : Z.P[i] = \max(X.P[i], Y.P[i])$
```

Operation-based CRDTs



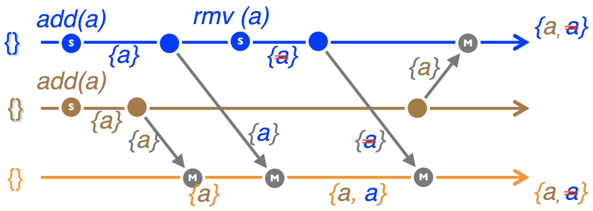
- *Concurrent* updates must commute
- Requires reliable causal delivery for CRDTs with non-commutative operations

Example: Counter

Specification 5 op-based Counter

```
payload integer $i$
    initial 0
query $value$ () : integer $j$
    let $j = i$
update $increment$ ()
    downstream ()                          ▷ No precond: delivery order is empty
        $i := i + 1$
update $decrement$ ()
    downstream ()                          ▷ No precond: delivery order is empty
        $i := i - 1$
```

Example: Add-wins Set (Observed-remove Set)



{a}.add(a) = {a, a} — *unique*

{a, b}.rmv(a) = {~~a~~, b} — *mark visible instances of a*

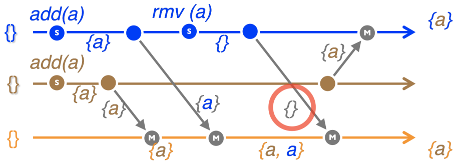
{~~a~~, a}.contains(a) | true — *∃ non-marked instance of a*

{a, b}.merge({~~a~~, c}) = {~~a~~, b, c} — *union + marker*

Example: Add-wins Set (Observed-remove Set)

```
payload set $E$, set $T$                                  -- $E$: elements; $T$: tombstones
                                 -- sets of pairs { (element $e$, unique-tag $n$), ... }
initial $\varnothing, \varnothing$
query contains (element $e$) : boolean b
    let $b = (\exists n : (e, n) \in E)$
query elements () : set $S$
    let $S = \{e | \exists n : (e, n) \in E\}$
update add (element $e$)
    prepare ($e$)
        let $n = unique()$                        -- $unique()$ returns a unique tag
    effect ($e, n$)
        $E := E \cup \{(e, n)\} \setminus T$                       -- $e$ + unique tag
update remove (element $e$)
    prepare ($e$)                                 -- Collect pairs containing $e$
        let $R = \{(e, n) | \exists n : (e, n) \in E\}$
    effect ($R$)                                  -- Remove pairs observed at source
        $E := E \setminus R$
        $T := T \cup R$
```

Optimized version of Add-wins Set



- Possible to garbage-collect the tombstone after remove
- Trick: Assuming causal delivery, a removed element will never be re-introduced (with the same id)[2]

Optimized version of Add-wins Set

```
payload set $E$, vect $v$              -- $E$: *elements, set of triples* (element $e$, timestamp $c$, replica $i$)
                                       -- $v$: *summary (vector) of received triples*

initial $\varnothing, [0, \ldots, 0]$
query *contains* (element $e$) : boolean b
    let $b = (\exists c, i : (e, c, i) \in E)$
query *elements* () : set $S$
    let $S = \{e | \exists c, i : (e, c, i) \in E\}$
update *add* (element $e$)
    prepare ($e$)
        let $r = myID()$                 -- $r$ = *source replica*
        let $c = v[r] + 1$
    effect ($e, c, r$)
        pre causal delivery
        **if** $c > v[r]$ **then**
            let $O = \{(e, c', r) \in E | c' < c\}$
            $v[r] := c$
            $E := E \cup \{(e, c, r)\} \setminus O$
update *remove* (element $e$)
    prepare ($e$)                        -- *Collect all unique triples containing* $e$
        let $R = \{(e, c, i) \in E\}$
    effect ($R$)                         -- *Remove triples observed at source*
        pre causal delivery
        $E := E \setminus R$
```

Challenges with CRDTs

- Meta-data overhead for CRDTs that require causal contexts
  - Version vectors track concurrent modifications
  - Problematic under churn (i.e. when nodes come and go)
- Monotonically growing state with state-based approach
  - Infeasible for inherently growing data types such as sets, maps, lists with prevalent add
  - When removing elements, often tombstones are required for conflict resolution that relies on concurrency information
  - Requires garbage collection of tombstones when updates become causally stable
- Composability
  - CRDTs can be recursively nested (e.g. Maps, Sequences) or atomically updated in transactions
  - Which type of composability is preferable? What is the semantics of the composed entity?

Delta-based CRDTs

- State-based CRDTs suffer from monotonically growing state (lattice!)
- Op-based CRDTs require reliable causal delivery

Delta-based CRDTs[1]

- Small message comprising a set of incremental updates
- Works over unreliable communication channels (because idem-potent and commutative)

A delta-mutator m^δ is a function, corresponding to an update operation, which takes a state X in a join-semilattice S as parameter and returns a delta-mutation $m^\delta(X)$, also in S.

$$X' = X \sqcup m^\delta(X)$$

Adoption of CRDTs in industry

basho

bet365

ROVIO

SCALITY

Riot GAMES

LEAGUE of LEGENDS

riak

TOMTOM

TRIFORK.
...think software

Tapjoy

SOUNDCLOUD

HELIUM

akka

PROJECTFIFO

facebook

redis

Conclusion

- CRDTs provide Strong Eventual Consistency (sometimes even more)
- Properties of good conflict resolution
  - Don't loose updates/information!
  - Deterministic (independent of local update order)
  - Semantics close to sequential version
- Meta-data overhead can be substantial

Further reading I

[1] Paulo Sérgio Almeida, Ali Shoker und Carlos Baquero. "Delta state replicated data types". In: *J. Parallel Distrib. Comput.* 111 (2018), S. 162–173. DOI: 10.1016/j.jpdc.2017.08.003. URL: https://doi.org/10.1016/j.jpdc.2017.08.003.

[2] Annette Bieniusa u. a. "An optimized conflict-free replicated set". In: *CoRR* abs/1210.3368 (2012). arXiv: 1210.3368. URL: http://arxiv.org/abs/1210.3368.

[3] Nuno Preguiça, Carlos Baquero und Marc Shapiro. "Conflict-Free Replicated Data Types (CRDTs)". In: *Encyclopedia of Big Data Technologies*. Hrsg. von Sherif Sakr und Albert Zomaya. Cham: Springer International Publishing, 2018, S. 1–10. ISBN: 978-3-319-63962-8. DOI: 10.1007/978-3-319-63962-8_185-1. URL: https://doi.org/10.1007/978-3-319-63962-8_185-1.