Implementation of CRDTs with δ-mutators

Optimizing State-based CRDTs with Deltas and Composition

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Universidade do Minho

Where I Work

Portugal @ Europe

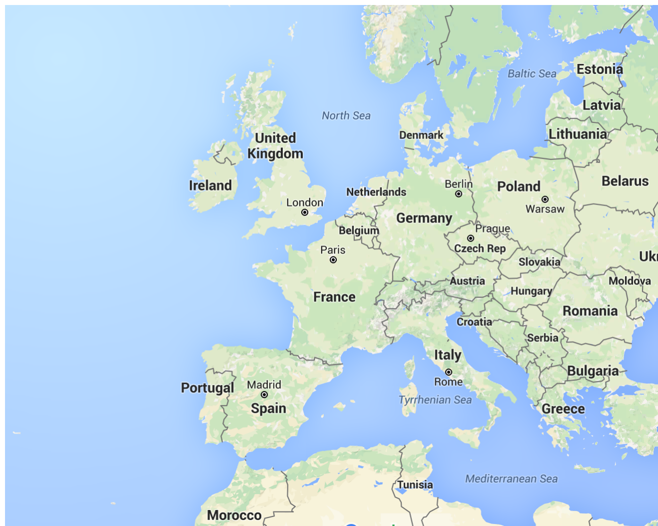

Image from Google Maps

Where I Work

HASLab @ Braga U.Minho Campus

Image from Google Maps

No Cats

But my kids pet is a kind of cat food

Why CRDTs?
Why Conflict-free Replicated Data Types?

- Synchronization requires connectivity and adds delays

Alexandre Duret-Lutz @ Flickr

Why CRDTs?
Why Conflict-free Replicated Data Types?

- Synchronization requires connectivity and adds delays
- Often a long queue can be replace by many small queues

$\Rightarrow$

Who cares if Alice buys bread, before or after, Bob buys a soda!

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Not Always

An Eiffel Tower with limited visitor capacity, needs synchronization.

But

Often Yes

Build as much as possible with CRDTs, synchronize the remaining.

Q.B. of Synchronization

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Trading Time for Space

- Less synchronization can lead to more bookkeeping
- Single checkout queue:
  - $0 \to 1 \to 2 \to 3 \to \ldots$
- Multiple checkout queues (three):
  - $[0, 0, 0] \to [0, 1, 0] \to [0, 1, 1] \to [0, 1, 2] \to \ldots$
  - More precisely: There is no global sequence!

$$[\mathbf{0}, 0, 0] \longrightarrow \ldots$$

$$[0, \mathbf{0}, 0] \longrightarrow [0, \mathbf{1}, 0] \longrightarrow \ldots$$

$\sqcup$ (join)

$$[0, 0, \mathbf{0}] \longrightarrow [0, 0, \mathbf{1}] \longrightarrow [0, 1, \mathbf{1}] \longrightarrow [0, 1, \mathbf{2}] \longrightarrow \ldots$$

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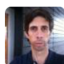
($[0,\mathbf{1},0]$ and $[0,0,\mathbf{1}]$ combine into $[0,1,\mathbf{1}]$ via $\sqcup$ (join))

Join derives a Least Upper Bound



Carlos Baquero @xmal · 20 Jun 2014

#seancribbsholdingthings Least Upper Bounds

FAVORITES

2

Why δs for state-based CRDTs?

(Joint work with Ali Shoker and Paulo Almeida)

- State-based CRDTs
  - ⊞ Simple middleware, Gossip
  - ⊟ Complex/Big state, with UIDs and concurrency info
- Replicas evolve by mutations, inflations in a lattice
  - $X' = m(X)$ e.g. GSet $\{a, b, c\} = add(b, \{a, c\})$
  - Updating other replicas $\Rightarrow$ shipping the big X'
- δ−mutations
  - $\delta = m^{\delta}(X)$ e.g. $\{b\} = add^{\delta}(b, \{a, c\})$
  - $X' = X \sqcup \delta$ $\{a, b, c\} = \{a, c\} \sqcup \{b\}$
  - Updating other replicas $\Rightarrow$ shipping δ, hoping $\delta \ll X'$
- δs can be merged in transit. Usually applied in causal order

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Math, lots of Math

$$
\begin{aligned}
\mathsf{CCounter} &= \mathsf{DotKernel}\langle\mathbb{N}\rangle \\
\mathsf{val}_i(j,(s,c)) &= \begin{cases} v & \text{if } (j,n,v) \in s \\ 0 & \text{otherwise} \end{cases} \\
&\quad \text{with } n = \mathsf{max}(\{k \mid (j,k) \in c\} \cup \{0\}) \\
\mathsf{inc}_i^\delta((s,c)) &= (\bot,(i,n)) \sqcup \mathsf{add}_i^\delta(\mathsf{val}_i(i,(s,c)) + 1,(s,c)) \\
&\quad \text{with } n = \mathsf{maximal}_i(c) \\
\mathsf{dec}_i^\delta((s,c)) &= (\bot,(i,n)) \sqcup \mathsf{add}_i^\delta(\mathsf{val}_i(i,(s,c)) - 1,(s,c)) \\
&\quad \text{with } n = \mathsf{maximal}_i(c) \\
\mathsf{value}_i(dk) &= \sum_{j \in \mathbb{I}} \mathsf{val}_i(j,dk) \\
\mathsf{reset}_i^\delta(dk) &= \mathsf{reset}_i^\delta(dk)
\end{aligned}
$$

Fig. 16: δ-CRDT Causal Counter, replica i.

Reference library of data types

GitHub

https://github.com/CBaquero/delta-enabled-crdts

Why C++?

- Existing libraries: Python, Java, Erlang, Akka, (later Elixir)
- Strongly typed approach, no pointers and casts used.
- Good starting point from the Standard Template Library
- Efficiency . . . author already familiar with the language

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Delta Enabled CRDTs

16 data types and growing

README.md

delta-enabled-crdts

Reference implementations of state-based CRDTs that offer deltas for all mutations.

Datatypes

Current datatypes are:

- GSet: A grow only set
- 2PSet: A two phase set that supports removing an element for ever
- Pair: A pair of CRDTs, first and second.
- GCounter: A grow only counter
- PNCounter: A counter supporting increment and decrement
- LexCounter: A counter supporting increment and decrement (Cassandra inspired)
- DotKernel: (Auxiliary datatype for building causal based datatypes)
- CCounter: A (causal) counter for map embedding (Optimization over Riak EMCounter)
- AWORSet: A add-wins optimized observed-remove set that allows adds and removes
- RWORSet: A remove-wins optimized observed-remove set that allows adds and removes
- MVRegister: An optimized multi-value register (new unpublished datatype)
- EWFlag: Flag with enable/disable. Enable wins (Riak Flag inspired)
- DWFlag: Flag with enable/disable. Disable wins (Riak Flag inspired)
- ORMap: Map of keys to CRDTs. (spec in common with the Riak Map)
- RWLWWSet: Last-writer-wins set with remove wins bias (SoundCloud inspired)
- LWWReg: Last-writer-wins register

Primitive Types

A **join** template function was defined for taking **max** from ordered primitive types: char, int, float, bool, . . .

```
int a=2, b=0;
cout << join(a,b) << endl;  // Output is 2

char x='a', y='b';
x=join(x,y);
cout << x << endl;  // Output is b
```

Pair Composition

STL has a template pair composition. A point-wise join was defined

```
pair<int,char> a(1,'a'),b(0,'x');
cout << join(a,b) << endl;  // Output is pair (1,x)
```

While the point-wise version is default, a lexicographic join was also defined

```
cout << lexjoin(a,b) << endl;  // Output is pair (1,a)
```

Pairs can be nested and include non primitive types

```
pair<int,pair<gset<int>,char>> triplet;
```

GSet, a simple anonymous CRDT

Family: GSet, TwoPSet

Classic use

```
gset<string> a,b;

a.add("red"); b.add("blue");

a=b=join(a,b);

cout << a << endl; // GSet: ( blue red )
```

Obtaining deltas

```
gset<string> d = a.add("green");

b.join(d);

cout << a << endl; // GSet: ( blue green red )
cout << b << endl; // GSet: ( blue green red )
```

GSet, a simple anonymous CRDT

Family: GSet, TwoPSet

Accumulating deltas allows batching of mutations

```
gset<string> a,b;

// ... replica "a" sees many adds ...

b.join(a);

auto acum = a.add("one");
acum.join(a.add("two"));
acum.join(a.add("three"));

b.join(acum);
```

Transmit information at a lower rate than replica mutation

PNCounter, a simple identified CRDT

Family: GCounter, PNCounter, LexCounter

Counters can be formed from any number type. Deltas can be anonymous but mutable instances must have a unique id.

```
pncounter<long,char> x('a'), y('b'),d;

x.inc(4); x.dec();
d=y.dec();

x.join(d);

cout << x.read() << endl; // Output is 2
```

Default template types are **int** for counter and **string** for id

```
pncounter<> z("syncfree"); z.inc();
cout << z.read() << endl; // Output is 1
```

Dot Kernel for Causal CRDTs

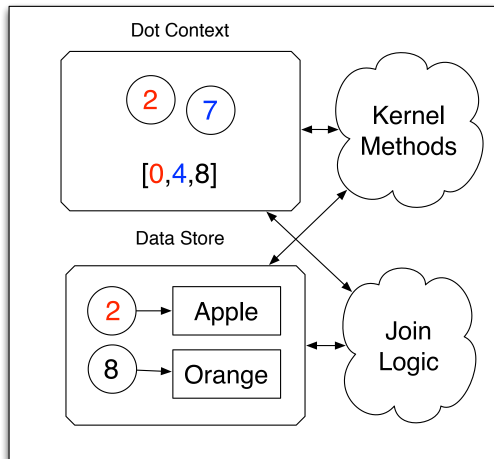
Family: CCounter, AWSet, RWSet, MVRegister, EWFlag, DWFlag

Causal CRDTs, implemented by a kernel type with a universal join.
All supported types are optimized (aka without tombstones)

Kernel Stucture

- DotContext: A version vector plus a sparse dot cloud
- DataStore: Mapping dots to chosen payload values

Dot Kernel



Looking at the causal Dot Contexts compare Data Stores. Check the dot key for each mapping to payloads, under the rules:

- If we both have the mapping, keep the mapping.
- If only me has a mapping
  - If the other didn't see it before, keep it
  - If the other saw it before, drop it
- Repeat last step vice-versa

Universal Causal Join

$$(s, c) \sqcup (s', c') = ((s \cap s') \cup \{(i, n, e) \in s \mid (i, n) \notin c'\} \cup \{(i, n, e) \in s' \mid (i, n) \notin c\}, c \sqcup c')$$

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Dot Kernel for Causal CRDTs

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Kernel Stucture

- DotContext: A version vector plus a sparse dot cloud
- DataStore: Mapping dots to chosen payload values

- Causal CRDTs hold an instance of a kernel
- Used to add new dot to value pairs, remove pairs, join
- Causal information is grow-only and compacted when possible
- Data Store can grow and shrink
- Possible to share a DotContext among instances, in maps

Add-Wins Observed-Remove Set

Family: CCounter, AWSet, RWSet, MVRegister, EWFlag, DWFlag

Classic use

```
aworset<float> x("uid-x"), y("uid-y"), d;

float pi=3.14, e=2.718;

x.add(pi); x.add(e); x.rmv(pi);
d=y.add(pi); // Concurrent add to above remove

x.join(d);

cout << x.read() << endl; // Output is ( 2.718 3.14 )
```

All kernel types support an *observed reset*

```
x.reset(); x.join(y);

cout << x.read() << endl; // Output is ( )
```

(Optimized) Multi-Value Register

Family: CCounter, AWSet, RWSet, MVRegister, EWFlag, DWFlag

Collecting and merging deltas on site x

```
mvreg<string> x("uid-x"),y("uid-y"),d;

d=x.write("hello"); d.join(x.write("world"));

y.write("world"); y.write("hello");

y.join(d);

cout << y.read() << endl; // Output is ( hello world )
```

(Optimized) Multi-Value Register

Reducing siblings, (joint design with Marek, Nuno, Annette, Marc)

Concurrent values related in an order can be reduced.

Total order example

```
mvreg<int> x("uid-x"), y("uid-y");

x.write(0); y.write(3);
x.join(y); x.resolve();

cout << x.read() << endl; // Output is ( 3 )

x.write(1); // Value can go up and down
```

(Optimized) Multi-Value Register

Reducing siblings, (joint design with Marek, Nuno, Annette, Marc)

Partial order example

```
mvreg<pair<int,int>> x("uid-x"),y("uid-y"),z("uid-z");

x.write(pair<int,int>(0,0));
y.write(pair<int,int>(1,0));
z.write(pair<int,int>(0,1));

x.join(y); x.join(z); x.resolve();

cout << x.read() << endl; // Output is ( (0,1) (1,0) )
```

Observed-Remove Map (joint design Paulo, Russell, . . .)

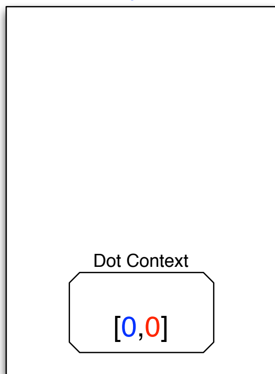
Embeds: CCounter, AWSet, RWSet, MVRegister, EWFlag, DWFlag, ORMap

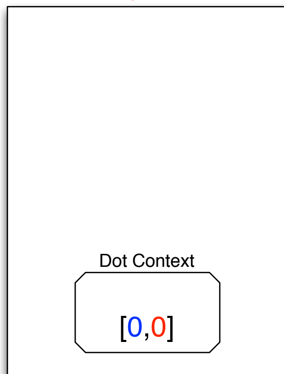
Embedded map objects share a common causal context

```
ormap<string,aworset<string>> mx("x"),my("y");
```

Observed-Remove Map

String mapping to an AWSet





Observed-Remove Map

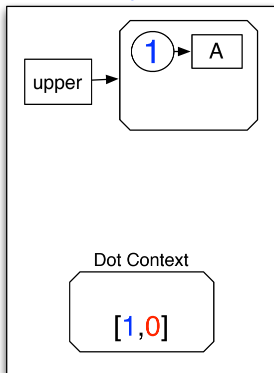
String mapping to an AWSet

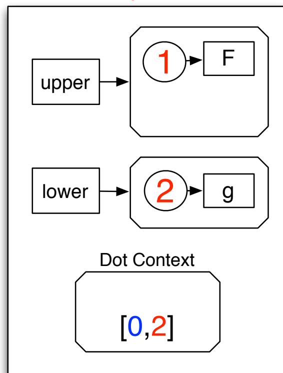
Embedded map objects share a common causal context

```
ormap<string,aworset<string>> mx("x"),my("y");

mx["upper"].add("A");
my["upper"].add("F");
my["lower"].add("g");
```

Observed-Remove Map

String mapping to an AWSet






```
mx["upper"].add("A");
```

```
my["upper"].add("F");
my["lower"].add("g");
```

Observed-Remove Map

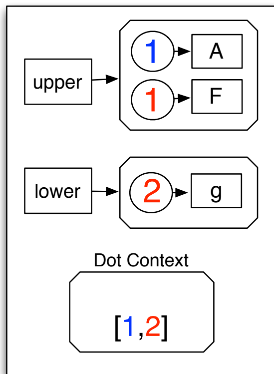
String mapping to an AWSet

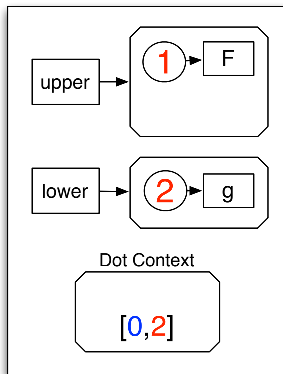
Embedded map objects share a common causal context

```
ormap<string,aworset<string>> mx("x"),my("y");

mx["upper"].add("A");
my["upper"].add("F");
my["lower"].add("g");

mx.join(my);
```

Observed-Remove Map

String mapping to an AWSet





mx.join(my);

Observed-Remove Map

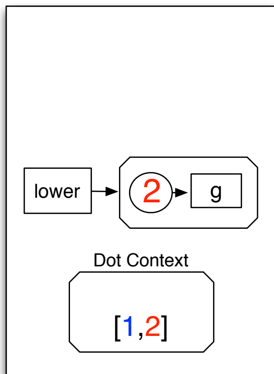
String mapping to an AWSet

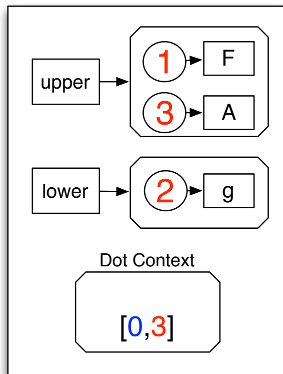
Removing/erasing entries leads to a reset on the value

```
ormap<string,aworset<string>> mx("x"),my("y");

mx["upper"].add("A");
my["upper"].add("F");
my["lower"].add("g");


mx.join(my);

mx.erase("upper");
my["upper"].add("A");
```

Observed-Remove Map

String mapping to an AWSet





mx.erase("upper");

my["upper"].add("A");

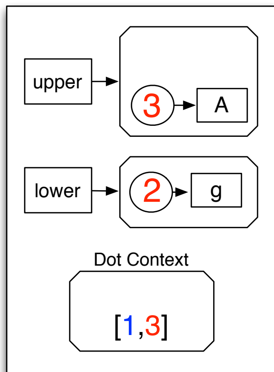
Reseted state does not come back

```
ormap<string,aworset<string>> mx("x"),my("y");

mx["upper"].add("A");
my["upper"].add("F");
my["lower"].add("g");


mx.join(my);

mx.erase("upper");
my["upper"].add("A");

mx.join(my);
```

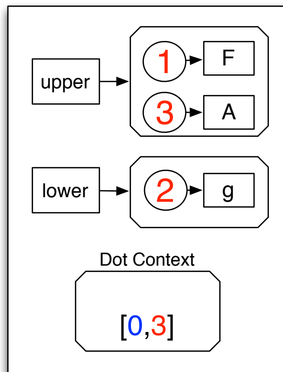
Observed-Remove Map

String mapping to an AWSet

Map X



Map Y



mx.join(my);

Observed-Remove Map

Integer mapping to String mapping to an AWSet

Maps can be nested

```
ormap<int,ormap<string,aworset<string>>> ma("alice");

ma[23]["color"].add("red at 23");
ma[44]["sound"].add("loud at 44");
```

Different key types at different nesting levels

C++, nice error messages at compile time

```
delta-enabled-crdts — bash — 80×24
MacBook-Pro:delta-enabled-crdts cbm$ make
g++ -std=c++11 -ferror-limit=2 delta-crdts.cc delta-tests.cc -o delta-tests
In file included from delta-tests.cc:38:
./delta-crdts.cc:47:9: error: no member named 'join' in
      'std::__1::basic_string<char>'
    res.join(r);
    ~~~ ^
./delta-crdts.cc:68:52: note: in instantiation of function template
      specialization 'join_selector<false>::join<std::__1::basic_string<char> >'
      requested here
  return join_selector< is_arithmetic<T>::value >::join(l,r);
                                                   ^
./delta-crdts.cc:967:15: note: in instantiation of function template
      specialization 'join<std::__1::basic_string<char> >' requested here
            ::join(dsa.second,dsb.second) == dsb.second ) // < based on join
              ^
delta-tests.cc:805:3: note: in instantiation of member function
      'mvreg<std::__1::basic_string<char>, std::__1::basic_string<char>
      >::resolve' requested here
y.resolve();
  ^
1 error generated.
make: *** [delta-tests] Error 1
MacBook-Pro:delta-enabled-crdts cbm$
```

Future Work

- Add more data types: Sequences, Graphs, ...
- MSc thesis starting
  - Choose serialization format
  - Spread deltas over gossip. E.g. Plumtree
  - Recover from failed nodes and link breaks
- Compare delta state based, with causal shipping of operations
- (Hypothesis: Less synchronous networks favor state based)
- Replace use of in-memory STL Sets, and Maps, by a local DB.

Questions?

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