Modular Verification of Op-Based CRDTs in Separation Logic

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CAP Theorem

- Informally: no distributed data store can be all of the following: (strongly) *Consistent, Available, and Partition tolerant*.
- Often presented as “choose 2 out of 3”, but some pairs don’t make sense. Additionally, given enough time partitions are *unavoidable*.
- Better phrasing: given a network partition, your system can be (strongly) consistent or available, but not *both*.

(Strong) Eventual Consistency

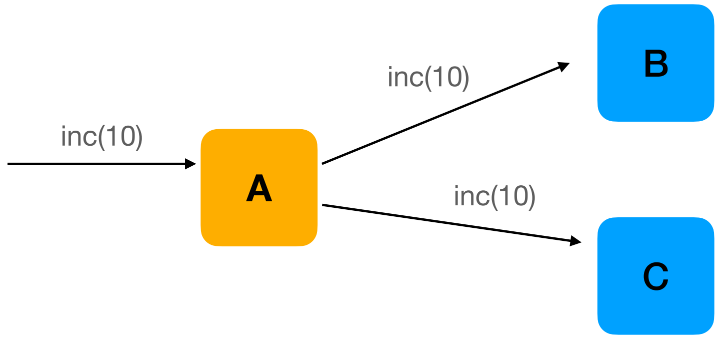
- SEC trades consistency in favour of availability.
- Replica states are allowed to diverge, but must eventually converge.
- Eventual delivery: updates eventually reach all correct replicas.
- Convergence: replicas that have delivered the same updates must be in equivalent states.
- CRDTs: a class of distributed data structures with SEC.

State-based CRDTs

- Updates communicated by sending entire state to other replicas.
- States taken from join semi-lattice, and “merging” states is taking their LUBs.
- Cons: encoding of data type semantics into lattice state can be tricky, inefficient if state is large (but there are pros too)

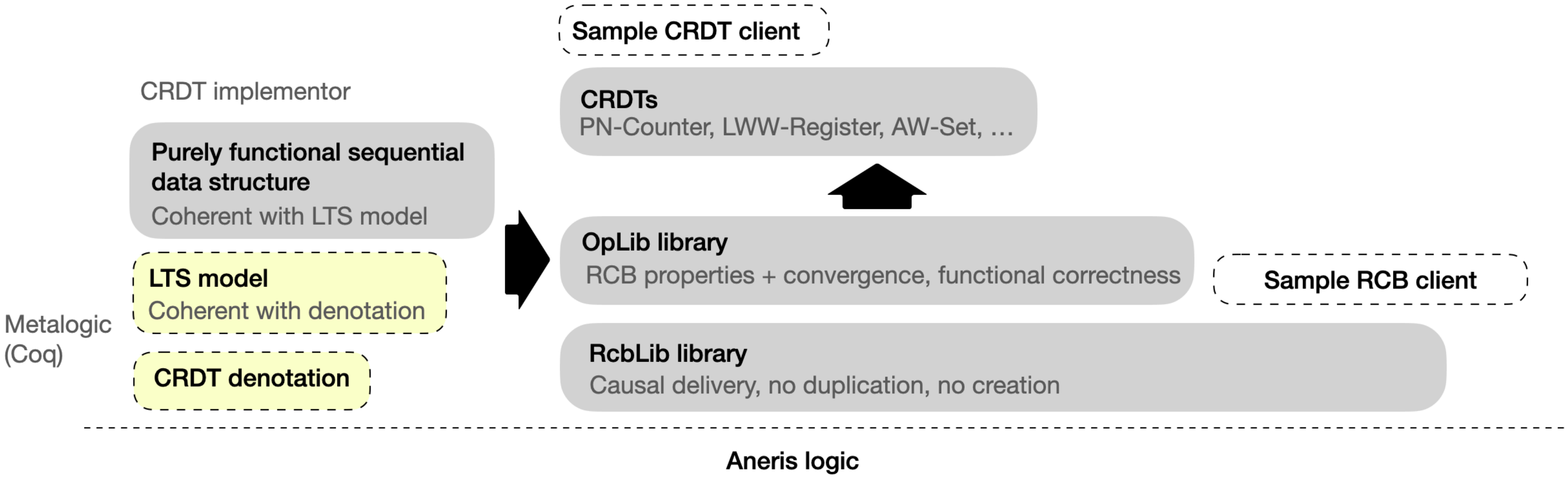
Op-based CRDTs

- Updates communicated by sending individual operations to other replicas
- Simpler design, but requires exactly-once delivery of operations
- Multiple things can go wrong: message dropped or duplicated, or replica dies



This Work

- We have implemented in OCaml and verified in Aneris a framework for building op-based CRDTs
- We used the framework to implement 12 example CRDTs, including higher-order combinators
- Our specifications are the first to be both *modular* and about *runnable implementations* (as opposed to protocols)
- For the first time, our formalisation of CRDTs includes a general-purpose library for Reliable Causal Broadcast (an exactly-once delivery protocol)



Sample CRDT client
CRDT implementor
CRDTs
PN-Counter, LWW-Register, AW-Set, …
Purely functional sequential data structure
Coherent with LTS model
OpLib library
RCB properties + convergence, functional correctness
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CRDT denotation
RcbLib library
Causal delivery, no duplication, no creation
Aneris logic

Causal Broadcast

- Interface: init(addrs), broadcast(msg), deliver()
- Guarantees: no duplication, no creation, and causal delivery
- Causal delivery: for any message m1 that potentially caused m2 (i.e. $m_1 \rightarrow m_2$) then every node delivers m1 before delivering m2

Resources for Causality

- Piggyback on Gondelman et al. (POPL'20): a causally-consistent key-value store
- Locally, track set of messages delivered at replica i: OwnLocal(i, s)
- Globally, track set of all messages ever sent: OwnGlobal(h)
- We can then prove resource laws: e.g. causality

$$\boxed{\text{GlobalInv}}^{\mathcal{N}_{\text{GI}}} * \text{OwnLocal}(i, s) * \text{OwnGlobalSnapshot}(h) \vdash \Rrightarrow_{\mathcal{E}} \forall a \in s, w \in h.\ vc(w) < vc(a) \Rightarrow \exists a' \in s.\ \lfloor a' \rfloor = w$$

-

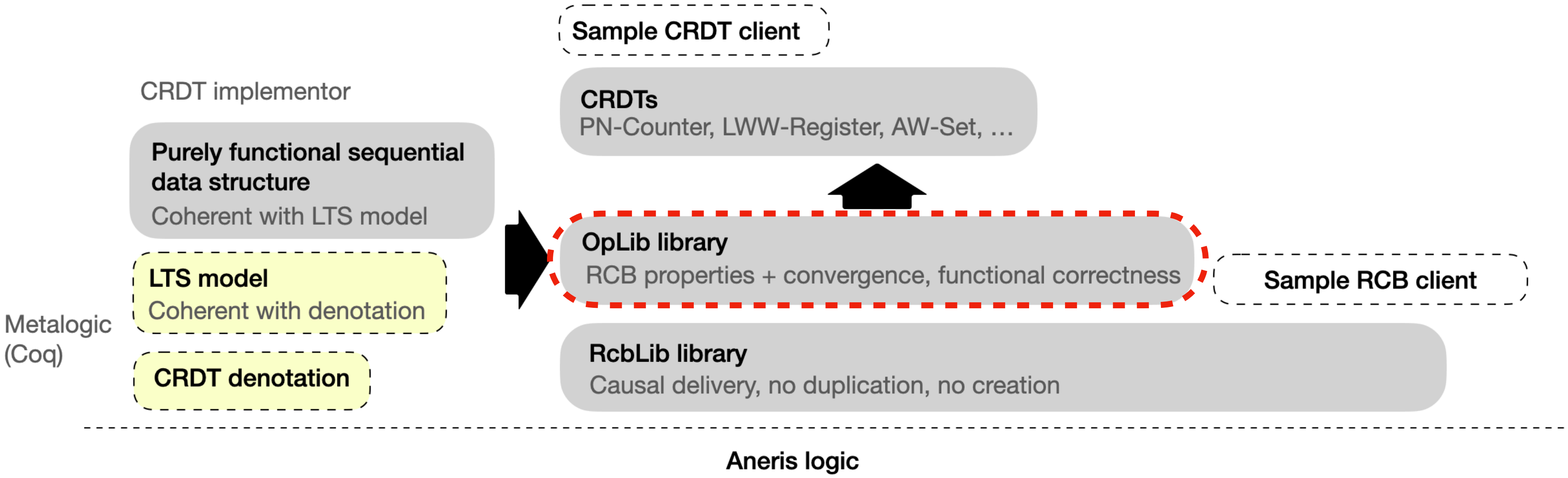
- The resources also allow us to give specifications to the broadcast and deliver functions

- Simplified broadcast spec:

$$\{\text{OwnGlobal}(h) * \text{OwnLocal}(i, s)\}$$

$$\langle ip_i; \text{broadcast}(p) \rangle$$

$$\{m.\ \mathit{payload}(m) = p * \text{OwnGlobal}(h \uplus \{m\}) * \text{OwnLocal}(i, s \uplus \{m\})\}$$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From Purely-Functional to CRDT

- We start with a purely-functional counter:
  an initial state (0) and
  a function to get from a state to the next (effect(c, n) = c + n)
- To turn it into a CRDT we need:
- A way to propagate operations (RCB).
- A way to (concurrently) apply remote operations.
- A way to manage mutable state (because of the above).

OpLib

- A library for implementing operation-based CRDTs
- User (CRDT implementor) provides initial state and effect function
- They get back a fully-fledged CRDT

```
let effect msg counter =
  let ((delta, _x), _y) = msg in
  counter + delta

let init_st () = 0

let crdt = fun () -> (init_st, effect)

let init addrs rid =
  let initRes = oplib_init int_ser int_deser addrs rid crdt in
  let (get_state, update) = initRes in
  (get_state, update)
```

Specifying OpLib

- Challenge: the CRDT's current state (e.g. the value of the counter) depends not just on local operations, but also remote ones.
- Tracking current state (Timany et al. 2021):

  IncrSpec

  $\{\mathsf{gcounter}(i, k)\}$

  $\langle ip_i;\ \texttt{incr()} \rangle$

  $\{(). \exists m. k < m * \mathsf{gcounter}(i, m)\}$

- Solution: don't track the current state. Instead, track local events *precisely* and a *lower bound* of remote events:
- $\mathrm{LocSt}(i, \bullet s, \circ h)$

Denotations

- In general, can specify CRDT with a *denotation*: partial function from set of events (including causality data) to CRDT state
- Example (multi-value register)
- $$[\![s]\!]_{\mathsf{mv-reg}} = \{(w, vc) | \exists o.(\mathrm{write}(w), vc, o) \in s \wedge vc \in \mathrm{Maximals}(s)\}$$
- Introduced in Burckhardt et al. [POPL'14] but now adapted to SL

OpLib specs

GetStateSpec

$$\langle \mathrm{LocSt}(i, \bullet\, s, \circ\, h) \rangle$$

$$\langle ip_i;\ \mathrm{get\_state}() \rangle$$

$$\left\langle \begin{array}{l} v.\ \exists h'\, w.\ h' \supseteq h * \mathrm{StCoh}(w, v) * \\ \quad \mathrm{LocSt}(i, \bullet\, s, \circ\, h') * [\![s \cup h']\!] = w \end{array} \right\rangle^{\mathcal{N}}$$

Convergence

UpdateSpec

$$\langle \mathrm{LocSt}(i, \bullet\, s, \circ\, r) * \mathrm{GlobSt}(h) \rangle$$

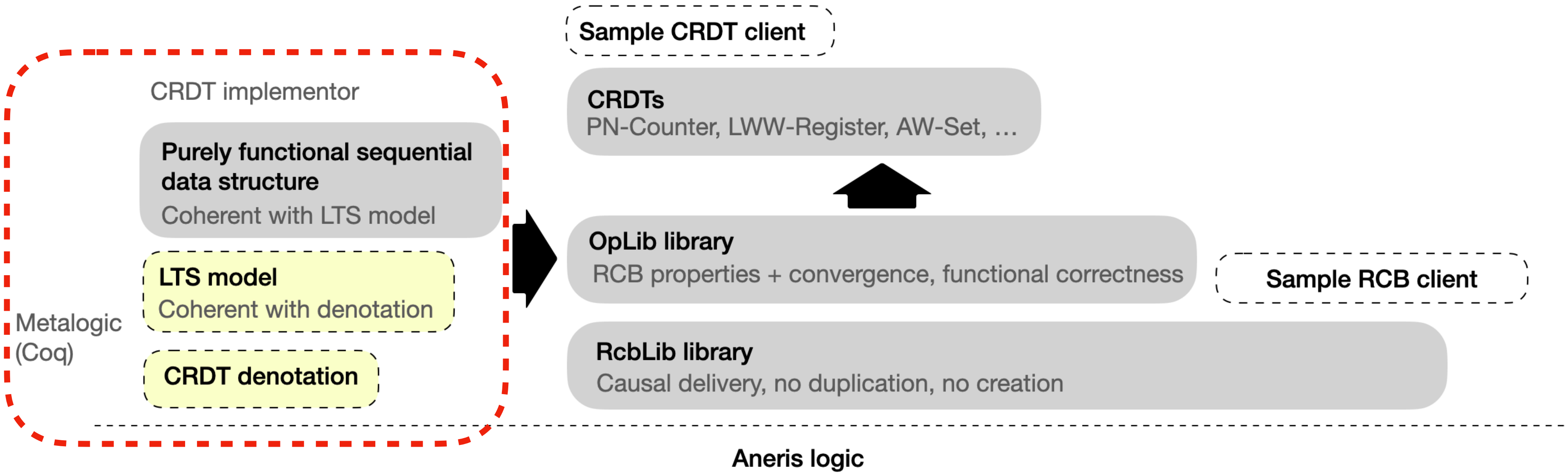
$$\langle ip_i;\ \mathrm{update}(v) \rangle$$

$$\left\langle \begin{array}{l} ().\ \exists a\, r'.\ r' \supseteq r * a \notin s * a \notin h * \mathit{payload}(a) = v * \\ \quad \mathit{origin}(a) = i * a \in \mathrm{Maximals}(h \cup \{a\}) * \\ \quad a \in \mathrm{Maximum}(s \cup r' \cup \{a\}) * \\ \quad \mathrm{LocSt}(i, \bullet\, s \cup \{a\}, \circ\, r') * \mathrm{GlobSt}(h \cup \{a\}) \end{array} \right\rangle^{\mathcal{N}}$$

Labelled Transition Systems

- Needed: a way to connect effect function to denotation
- Done via labelled transition system $(\text{St}, \text{Event}, \rightarrow, \sigma_0)$
- Coherence property:
- $[\![\emptyset]\!] = \sigma_0$
- $\forall s\, p\, e\, p'.\text{Valid}(s, e) \wedge [\![s]\!] = p \wedge p \xrightarrow{e} p' \implies [\![s \cup e]\!] = p'$
- Hoare triple for showing that effect() implements LTS

OpLib recap



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Implemented CRDTs

CRDT	# lines of OCaml	# lines of Coq	
Positive-Negative Counter	25	235	Simple CRDTs
Grown-only Counter	26	243	Simple CRDTs
Two-Part Set	25	182	Simple CRDTs
Add-Wins Set	34	371	Simple CRDTs
Remove-Wins Set	53	527	Simple CRDTs
Grow-Only Set	22	159	Simple CRDTs
Last-Writer-Wins Register	54	555	Simple CRDTs
Multi-Value Register	35	334	Simple CRDTs
Product Combinator	30	374	Combinators
Map Combinator	34	531	Combinators
Table of Positive-Negative Counters	22	74	Compound CRDTs
Table of Last-Writer-Wins Registers	22	74	Compound CRDTs
total	360	3585	

combined to make

combined to make

Library	# lines of OCaml	# lines of Coq
RcbLib	196	5019
OpLib	86	3595
total	282	8614

Conclusions

- We implemented in OCaml and verified in Aneris a framework for building op-based CRDTs, as well as many examples on top of it
- Ours is the first foundational proof of functional correctness and SEC for op-based CRDTs, as well as the first technique that is both modular and about implementations
- Future work: more complex CRDTs (collaborative text editing) and CRDTs with coordination
- Future work: state-based CRDTs

Thank you