Understanding Eventual Consistency

MSI Presentation SS2014

Horst Schneider, Patrick Beedgen
Hochschule Mannheim

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Introduction

" ...the storage system guarantees that if no new updates are made to the object, eventually all accesses will return the last updated value"
–W. Vogels (2009)

Interpretation 1

"When you read data[...], the response might not reflect the results of a recently completed write operation. The response might include some stale data. Consistency across all copies of the data is usually reached within a second; so if you repeat your read request after a short time, the response returns the latest data."

Interpretation 2

"This sort of system we term "single writer eventual consistency". So what are its properties?
(1) A client could read stale data.
(2) The client could see out-of-order write operations. [...] So this is our weakest form of consistency - eventually consistent with out of order reads in the short term."

DynamoDB Documentation

"When you read data[...], the response might not reflect the results of a recently completed write operation. The response might include **some stale data**. *Consistency across all copies of the data is* **usually reached within a second**; *so if you repeat your read request after a short time, the response returns the latest data."*

MongoDB Documentation

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So this is our weakest form of consistency - eventually consistent with **out of order reads** *in the short term."*

The Problem

- Disparate and low-level formalisms
  consistency model is tied to system implementation
- Weak guarantees
  in realistic scenarios updates **never** *stop*
- Conflict resolution policies
  resolution of conflicts in multiple replicas
- Combinations of different consistency levels
  strong consistency may be needed at certain times

$\Rightarrow$ Some sort of formalism is needed to define semantics of Eventual Consistency

Agenda

1. Replicated Data Types
2. Axiomatic Specification Framework
3. Consistency Strengthening Interfaces
4. Conclusion / Discussion

Replicated Data Types

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  - a **value** $\in \mathrm{Val}$
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- Two examples: Int Register **intreg**, Counter **ctr**

$$\mathrm{Op}_{\mathrm{ctr}} = \{\mathrm{rd}, \mathrm{inc}\}$$
$$\mathrm{Op}_{\mathrm{intreg}} = \{\mathrm{rd}, \mathrm{wr}(k) | k \in \mathbb{Z}\}$$

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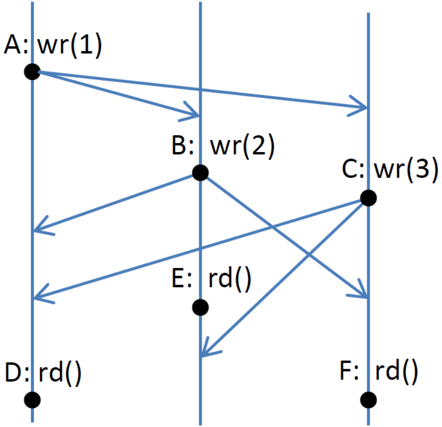
Replicated Data Types

Semantics of Eventual Consistency

- semantics of eventually consistent systems are harder to formalize
- concurrent operations on the same object happen on multiple replicas
- each replica executes operations immediately, updating other replicas later
- different implementation strategies for replicated data types

Replicated Data Types

Conflict Resolution Strategies



Replicated Data Types

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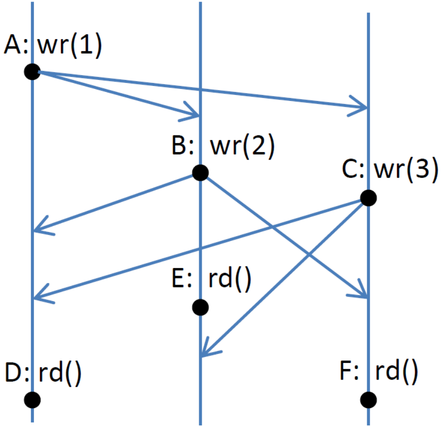

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Replicated Data Types

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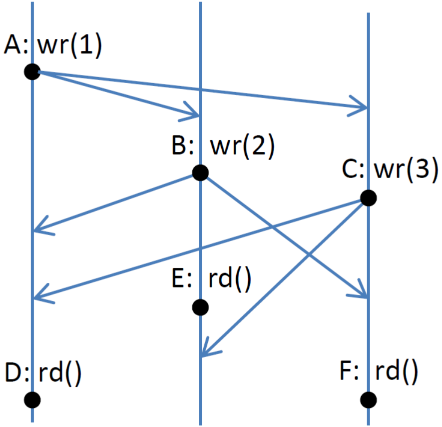

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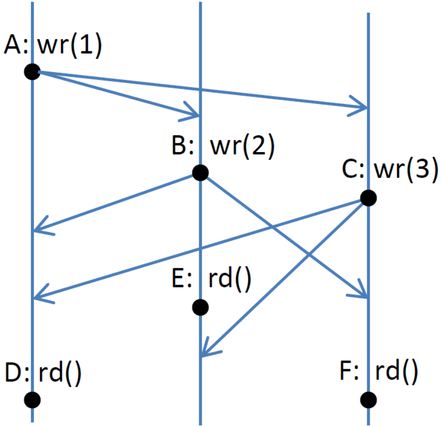

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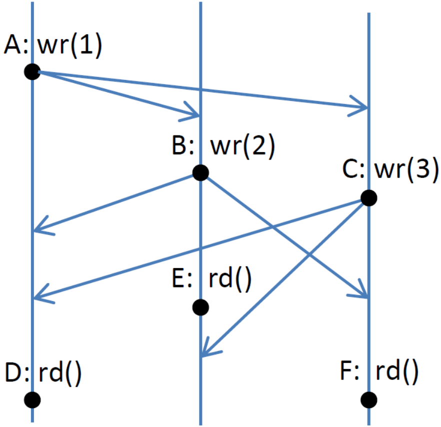

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2. Order concurrent operations
3. Flag conflicts (let the user decide)
4. Resolve conflicts semantically

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- visibility and order of preceding operations have to be included

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Example: Strategy **Make Concurrent Calls Commutative**

$$F_{\mathrm{ctr}}(\mathrm{inc}, V, \mathrm{vis}, \mathrm{ar}) = \bot;$$
$$F_{\mathrm{ctr}}(\mathrm{rd}, V, \mathrm{vis}, \mathrm{ar}) = (\text{the number of inc operations in } V);$$

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Example: Strategy **Order Concurrent Operations**

$$F_{\mathrm{intreg}}(\mathrm{inc}, V, \mathrm{vis}, \mathrm{ar}) = S_{\mathrm{intreg}}(V^{\mathrm{ar}} f)$$

- clients wish to perform operations in a common context
- **sessions** provide a way to track client identity for operations
- an **action** is a tuple $(e, s, [x.f : k])$
  - e: unique identifier
  - s: session id $\in \mathrm{SId}$
  - $[x.f : k]$: object, operation and return value

Axiomatic Specification Framework

Session and Action

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Example:

$$a = (1af3c, 17, [x.rd : k]);\ \mathrm{type}(x) = \mathrm{intreg}$$

Axiomatic Specification Framework

History and Execution

- the set of all actions that happen in a database is denoted as Act
- a **history** (A, so) is a set of actions $A \subseteq \mathrm{Act}$ and a **session order** relation $\mathrm{so} \subseteq A \times A$
- an **execution** $X = (A, \mathrm{so}, \mathrm{vis}, \mathrm{ar})$ enhances the history with visibility and arbitration relations
- we can now extract an operation context for any action in any session, providing a deterministic return value

Axiomatic Specification Framework

Levels of Eventual Consistency

- With these replicated data types we can define multiple forms of Eventual Consistency
  - Basic Eventual Eonsistency
  - Session Guarantees
  - Causality axioms
- Every form contains multiple axioms
- More axioms means stronger consistency

Axiomatic Specification Framework

- Axioms a database implementation has to enforce to offer **basic eventual consistency**
- Well Formedness Axioms
  - SOwf: *so is the union of transitive, irreflexive and total orders on actions by each session*
  - VISwf: $\forall a, b.\ a \xrightarrow{\text{vis}} b \Rightarrow obj(a) = obj(b)$
  - ARwf: $\forall a, b.\ a \xrightarrow{\text{ar}} b \Rightarrow obj(a) = obj(b)$

Axiomatic Specification Framework

Basic Eventual Consistency Axioms

- Data Type Axiom:
  $\forall a \in A.\ \mathrm{rval}(a) = F_{\mathrm{type(a)}}(\mathrm{ctxt}(a))$
- Basic Eventual Consistency axioms:
  - THINAIR:
    $\mathrm{so} \cup \mathrm{vis}$ is anticyclic
  - EVENTUAL:
    $\forall a \in A.\ \neg(\exists \text{infinitely many } b \in A.\ \mathrm{same}(a, b)) \wedge \neg(a \xrightarrow{\text{vis}} b))$

Axiomatic Specification Framework

Problem with basic eventual consistency

TODO: Image explaining photo/noboss example from paper

Axiomatic Specification Framework

Session guarantees

- With basic eventual consistency we still might be reading values out of order
- Axioms that formalise that all operation within a session keep the current context consistent
- Read Your Writes: *An operation sees all previous operations by the same session*
- Writes Follow Reads in Visibility: *Arbitration orders an operation after other operations previously seen by the same session*
- ... etc.

Axiomatic Specification Framework

Causality Axioms

- Per-object-causal-visibility: *POCV guarantees that an operation sees all operations on the same object that causally affect it*
- Per-object-causal-arbitration: *POCA correspondingly restricts the arbitration relation*

Consistency Strengthening Interfaces

On-Demand Consistency Strengthening

- Amazon Shopping Cart Example from Paper
- Explain the need for "Consistency on Demand" in certain business cases

Consistency Strengthening Interfaces

Consistency Annotations

- Every **action** accepted by the database has to annotaed with a **consistency annotation**

$$(e, s, [x.f_{\mu} : k])\mu \in \{ORD, CSL\}$$

- Either **ordinary** or **causal**
- Ordinary actions behave like we defined previously
- Causal actions make all operations performed before the annotations visible to all previous actions

Consistency Strengthening Interfaces

Fences

- Instead of annotating every single action, a **fence** could be used
- A *fence* is an **action** where the executing replica forces all its updates on every other replica in the cluster

$$\text{action a} = (e, s, \mathrm{fence})$$

- The execution of other actions is halted until all replicas acknowledge the receipt
- this violates the **A** in **CAP**

Conclusion

- The paper provides a way to **precisely specify eventually consistent systems** in a common notation
- **Every aspect of a system is covered**, from data types to client interaction
- Specifications are **independent of implementation details**
- Still **very theoretical**, no tools available to map between specifications and implementation
- The framework is **not suitable for programmers**, as it is very abstract and not easily understandable and applicable
- The Paper is still "work in progress"

Discussion