Understanding Eventual Consistency

MSI Presentation SS2014

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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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(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."*

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

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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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(e.g. $\sigma = \{\mathrm{rd}\ \mathrm{rd}\ \mathrm{wr}(5)\ \mathrm{wr}(6)\ \mathrm{rd}\}$ or $\sigma = \{\mathrm{rd}\ \mathrm{rd}\ \mathrm{inc}\ \mathrm{inc}\ \mathrm{rd}\}$)

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S_{\mathrm{intreg}}(\sigma\ \mathrm{wr}(k)) &= S_{\mathrm{ctr}}(\sigma\ \mathrm{inc}) = \bot;
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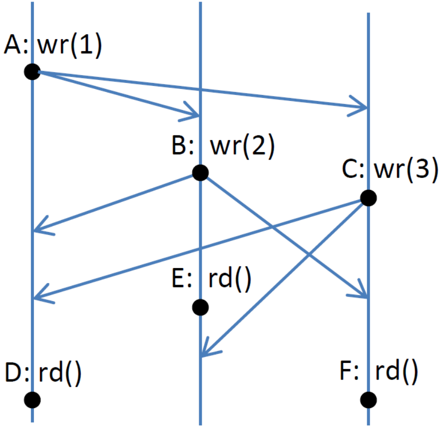
Replicated Data Types

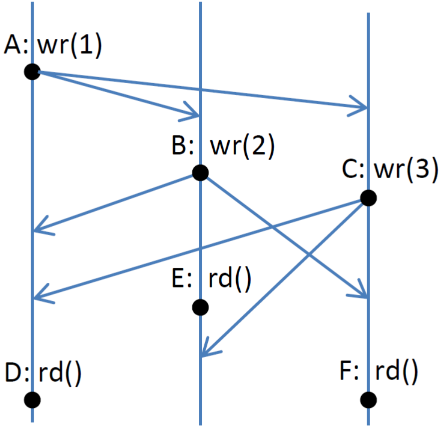
Semantics of Eventual Consistency

- 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


A: wr(1)
B: wr(2)
C: wr(3)
E: rd()
D: rd()
F: rd()

Replicated Data Types

Conflict Resolution Strategies



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Replicated Data Types

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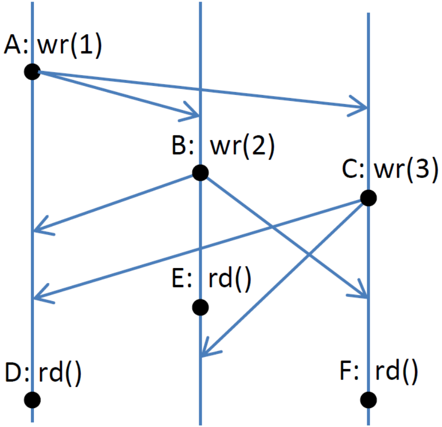

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2. Order concurrent operations

Replicated Data Types

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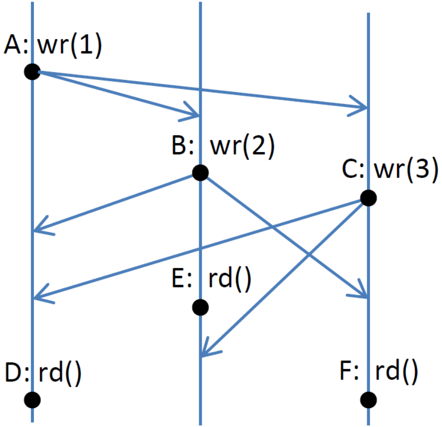

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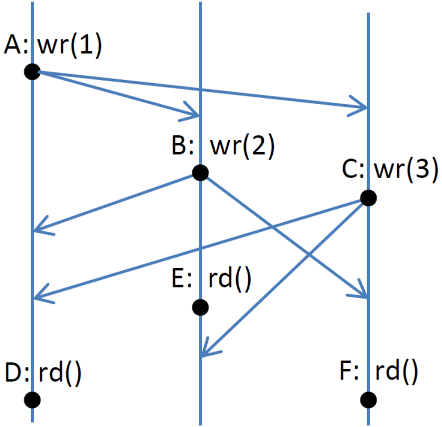

1. Make concurrent operations commutative
2. Order concurrent operations
3. Flag conflicts (let the user decide)
4. Resolve conflicts semantically

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- visibility and order of preceding operations have to be included

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Example: Strategy **Make Concurrent Calls Commutative**

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

Example: Strategy **Make Concurrent Calls Commutative**

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

Example: Strategy **Order Concurrent Operations**

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

Axiomatic Specification Framework

Session and Action

- 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

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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 consistency
  - Ordering guarantees
  - On-demand consistency strengthening
- Every form contains multiple axioms

Axiomatic Specification Framework

Basic Eventual Consistency Axioms

- Axioms a database implementation has to apply to offer basic eventual consistency
- Well-Formedness Axioms
  - SOwf, ARwf, VISwf
- Data Type Axiom
  - RVAL
- Basic Eventual Consistency axioms
  - EVENTUAL
  - THINAIR

Axiomatic Specification Framework

Session guarantees

- Axioms that ensure that databases stay consistent within a single session with a client
- !RYW!, MR, !WYRV!, WFRA, MWV, MWA

Axiomatic Specification Framework

Causal Consistency Axioms

- POCV, POCA

Axiomatic Specification Framework

On-Demand Consistency Strengthening

- Amazon Shopping Cart Example
- Explain Need for Consistency on Demand in certain business cases

Axiomatic Specification Framework

Consistency Annotations

- every operation accepted by the db has to annotaed with a "consistency annotation"
- either ordinary or causal
- ordinary actions behave like we defined previously
- causal actions make all operations performed before the annotations visible to other actions

Axiomatic Specification Framework

Fences

- instead of annotation every single action we put them into a fence
- a fence is a set of actions where the db node forces all other replica to execute the actions in the fence and send a receipt
- Essentially turns the cluster into an array of 'CP' databasesCP)

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

Discussion