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

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MongoDB Documentation

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$\Rightarrow$ 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

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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
Sequential Data Type Specification

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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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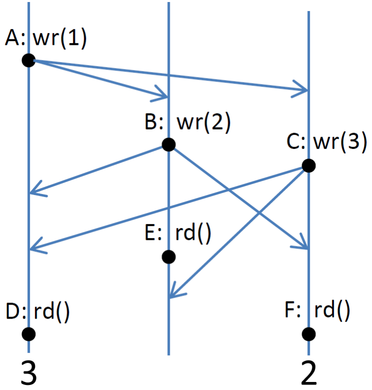
Replicated Data Types

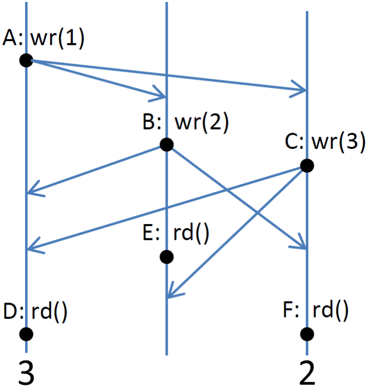
Semantics of Eventual Consistency

- 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 $\rightarrow$ **conflicts**
- different conflict resolution strategies for replicated data types

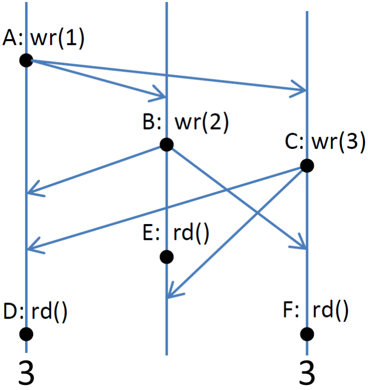
Replicated Data Types

Conflict Resolution Strategies





1. make concurrent operations commutative



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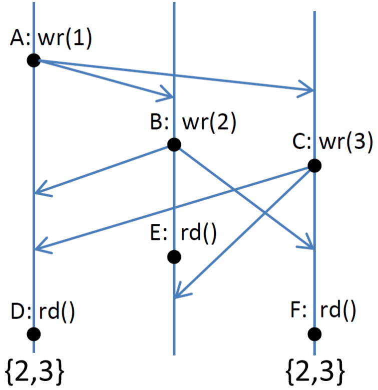

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Replicated Data Types

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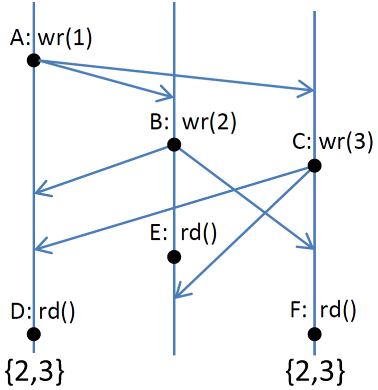

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4. resolve conflicts semantically

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$$u \xrightarrow{\mathrm{vis}} v, \mathrm{vis} \subseteq V \times V$$
$$u \xrightarrow{\mathrm{ar}} v, \mathrm{ar} \subseteq V \times V$$

example: Strategy **Make Concurrent Calls Commutative**

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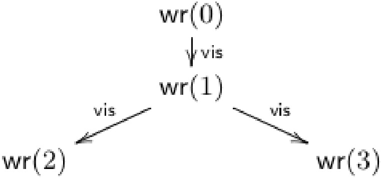
example: Strategy **Order Concurrent Operations**

$$F_{\mathrm{intreg}}(f, V, \mathrm{vis}, \mathrm{ar}) = S_{\mathrm{intreg}}(V^{\mathrm{ar}} f)$$
$$(S_\tau \;:\; \mathrm{Op}_\tau^+ \to \mathrm{Val})$$

example: Strategy **Flag Conflicts**



writes on a multi value register

Axiomatic Specification Framework

Session and Action

- a single client may do several changes to the same object
- **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 replicated data types we can define multiple forms of Eventual Consistency
  - Basic Eventual Consistency
  - Session Guarantees
  - Causality
- every form contains multiple axioms
- more axioms mean stronger consistency

- 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

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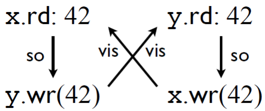

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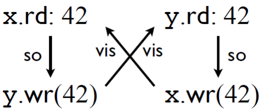
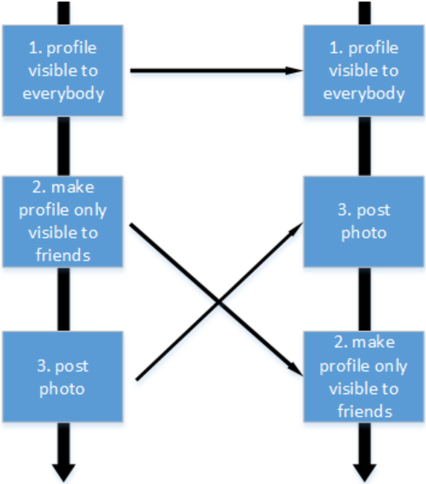
    

  - EVENTUAL:
    $\forall a \in A.\ \neg(\exists \text{infinitely many } b \in A.\ \mathrm{same}(a, b)) \wedge \neg(a \xrightarrow{\mathsf{vis}} b))$

Axiomatic Specification Framework

Problem with basic eventual consistency



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

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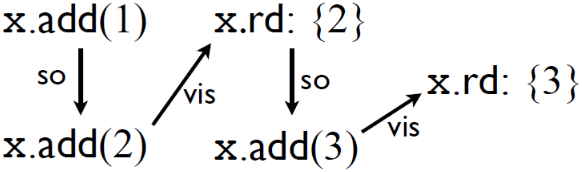

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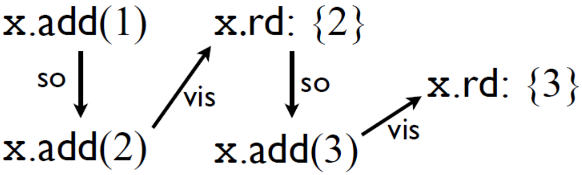

- Per-object-causal-arbitration: *POCA correspondingly restricts the arbitration relation*

Consistency Strengthening Interfaces

Online Shopping

- almost everybody does online shopping
    - we put items in our shopping cart
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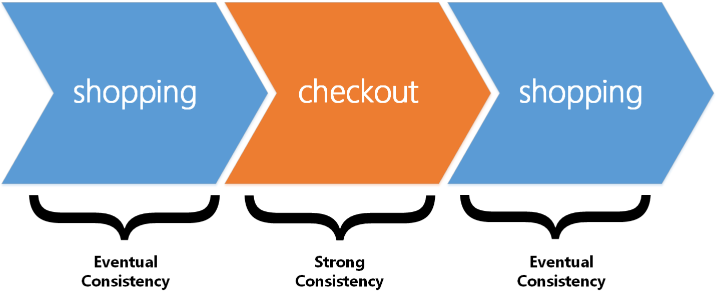

Consistency Strengthening Interfaces

Consistency Annotations

- every **action** accepted by the database has to marked 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** can 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

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- the database behaves like a **CP** database !

Conclusion

- the paper provides a formal way to **precisely specify eventually consistent systems**
- **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