hochschule mannheim

# 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)*

# Introduction

## Interpretations of Eventual Consistency

### 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."*

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### DynamoDB Documentation

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### MongoDB Documentation

> *"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."*

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⇒ 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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- two examples: Int Register **intreg**, Counter **ctr**

$$\mathrm{Op}_{\mathrm{ctr}} = \{\mathrm{rd}, \mathrm{inc}\}$$

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

# Replicated Data Types

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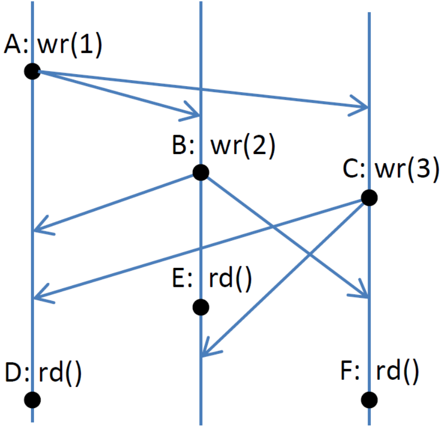
# Replicated Data Types

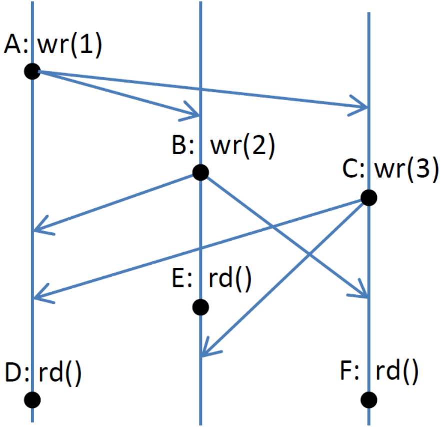
## Semantics of Eventual Consistency

- 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 → **conflicts**
- different conflict resolution 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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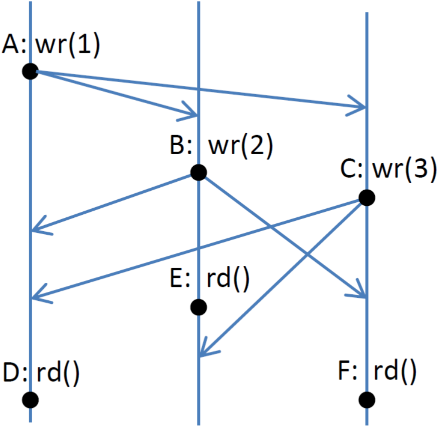

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2. order concurrent operations

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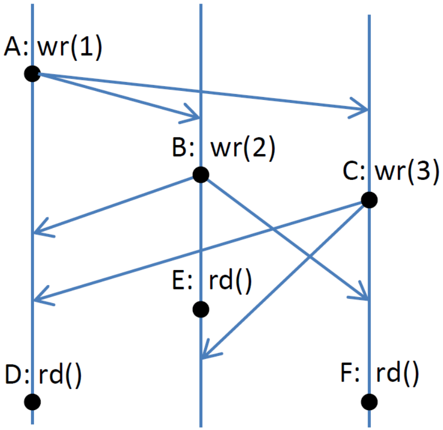

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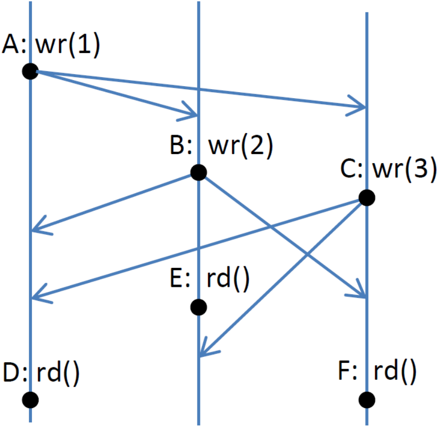

1. make concurrent operations commutative
2. order concurrent operations
3. flag conflicts (let the user decide)
4. resolve conflicts semantically

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

example: Strategy **Make Concurrent Calls Commutative**

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

example: Strategy **Make Concurrent Calls Commutative**

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

example: Strategy **Order Concurrent Operations**

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

# 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 $\mathrm{Act}$
- a **history** $(A, \mathrm{so})$ 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
    - Session Guarantees
    - Causality
- every form contains multiple axioms
- more axioms mean stronger consistency

# Axiomatic Specification Framework

## Basic Eventual Consistency Axioms

- 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: $\forall a, b.\ a \xrightarrow{\mathsf{vis}} b \Rightarrow obj(a) = obj(b)$
  - ARwf: $\forall a, b.\ a \xrightarrow{\mathsf{ar}} b \Rightarrow obj(a) = obj(b)$

# Axiomatic Specification Framework

## Basic Eventual Consistency Axioms

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

# 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

## Online Shopping

- almost everybody does online shopping
  - we put items in our shopping cart
  - we pay them
  - we continue shopping.. or not

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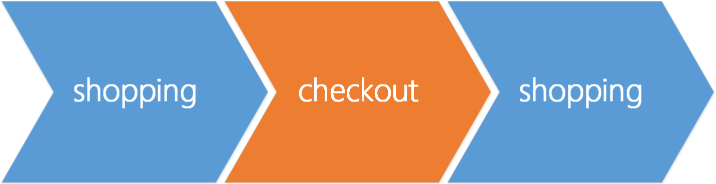

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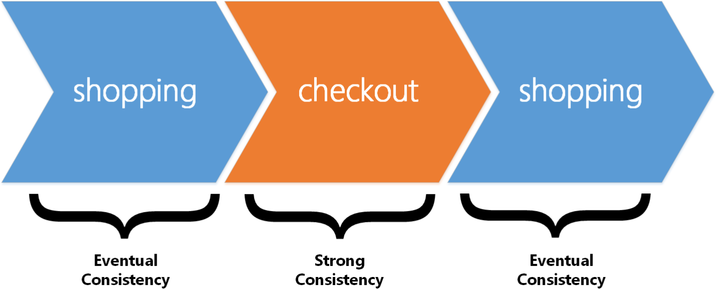

# Consistency Strengthening Interfaces

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

# 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