Coordination Avoidance
in Distributed Databases

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Outline

- Coordination avoidance and Invariant Confluence principle
- Examples of Invariant Confluence principle application
- Read-atomic multi-partition transactions
- Conclusions

Transaction serializability

- Transactions - groups of multiple operations over multiple data items
- Traditional way to deal with concurrent transactions - serializability: a database providing serializability guarantees that the result of executing the transactions is equivalent to some serial execution of the transactions
    - Convenient for programmers - no need to reason about concurrency
    - Inconvenient for databases - serializability requires coordination
- Reasons to avoid coordination - allows for greater availability of a distributed database, lower access latency and greater scalability

Thesis statement

- Key question posed by Bailis - when is it necessary to use coordination to achieve conflict-free parallel execution, and when is it possible to forego coordination without compromising the safety of parallel transactions

- *Thesis Statement: Many semantic requirements of database-backed applications can be efficiently enforced without coordination, thus improving scalability, latency, and availability.*

Application side: data invariants

- Bailis proposal: instead of reasoning about data consistency on the level of read and write operations (transactions), **consider what coordination is actually required by a given application**
- Make applications define data invariants and explicitly specify what correctness means to these applications
- Example: “each employee record is linked to a department record”
- Consider if **application requires coordination**, by **taking into account both** application invariants **and** the nature of data transformation in transaction

Invariant confluence test

- Invariant confluence determines whether the result of executing operations on independent copies of data can be combined (or "merged") into a single, coherent (i.e., convergent) copy of database state.
- Given **a set of operations**, **a safety property** that we wish to maintain over all copies of database state, **and a merge function**, invariant confluence tells us **whether coordination-free execution is possible**.

Application of Invariant Confluence principle

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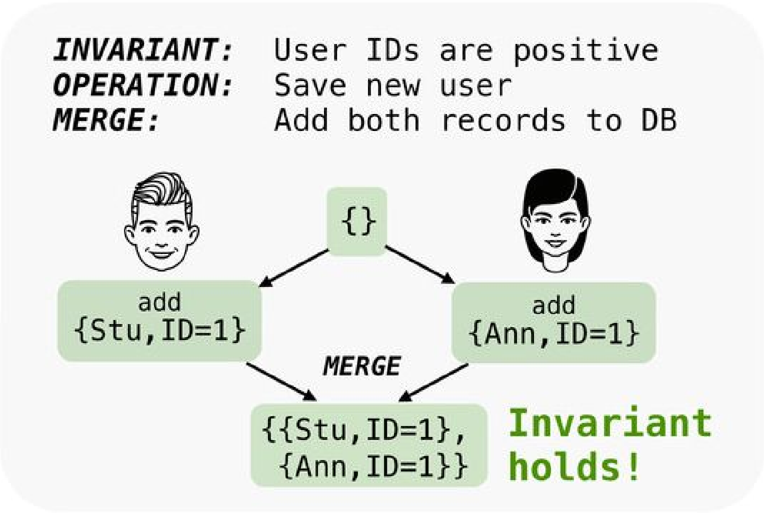
I-Confluence proof construction

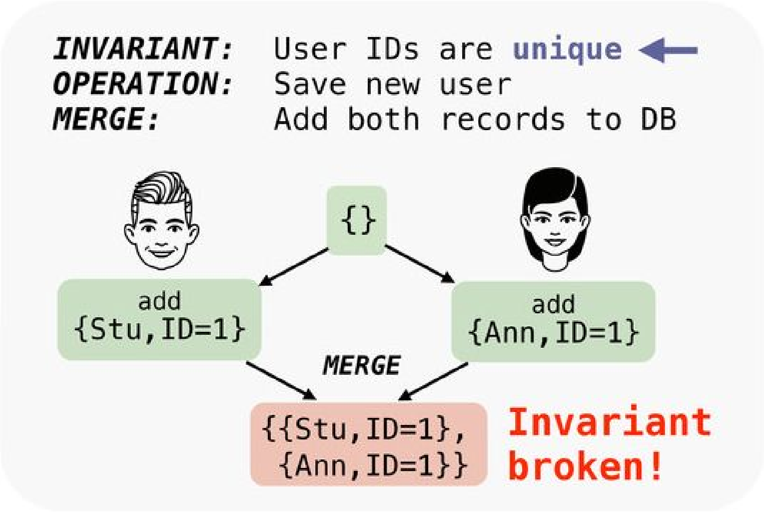
- To show a set of transactions **are not invariant confluent** with respect to an invariant I - **use proof by counterexample:** present two I-T-reachable states with a common ancestor that, when merged, are not I-valid.

- To show a set of transactions **are invariant confluent** with respect to an invariant I **use proof by contradiction**: show that if a state S is not I-valid, merging two I-T-reachable states S1 and S2 with a common ancestor state to produce S implies either one or both of S1 or S2 must not be I-valid.

Invariant confluence test example

- Key question: can invariants be violated by merging independent operations?





I-Confluence applied to common SQL operations

Invariant	Operation	invariant confluent?	Proof #
Attribute Equality	Any	Yes	1
Attribute Inequality	Any	Yes	2
Uniqueness	Choose specific value	No	3
Uniqueness	Choose some value	Yes	4
AUTO_INCREMENT	Insert	No	5
Foreign Key	Insert	Yes	6
Foreign Key	Delete	No	7
Foreign Key	Cascading Delete	Yes	8
Secondary Indexing	Update	Yes	9
Materialized Views	Update	Yes	10
>	Increment [Counter]	Yes	11
<	Increment [Counter]	No	12
>	Decrement [Counter]	No	13
<	Decrement [Counter]	Yes	14
[NOT] CONTAINS	Any [Set, List, Map]	Yes	15, 16
SIZE=	Mutation [Set, List, Map]	No	17

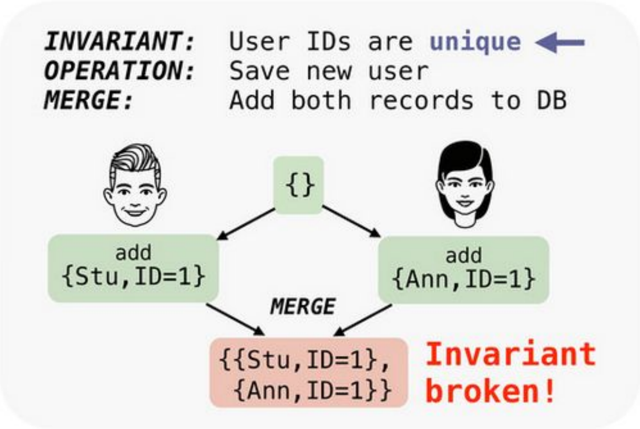
Table 6.1: Example SQL (top) and ADT invariant confluence along with references to formal proofs in Section 6.2.

I-Confluence example 1

Invariant	Operation	invariant confluent?	Proof #
Uniqueness	Choose specific value	No	3
Uniqueness	Choose some value	Yes	4

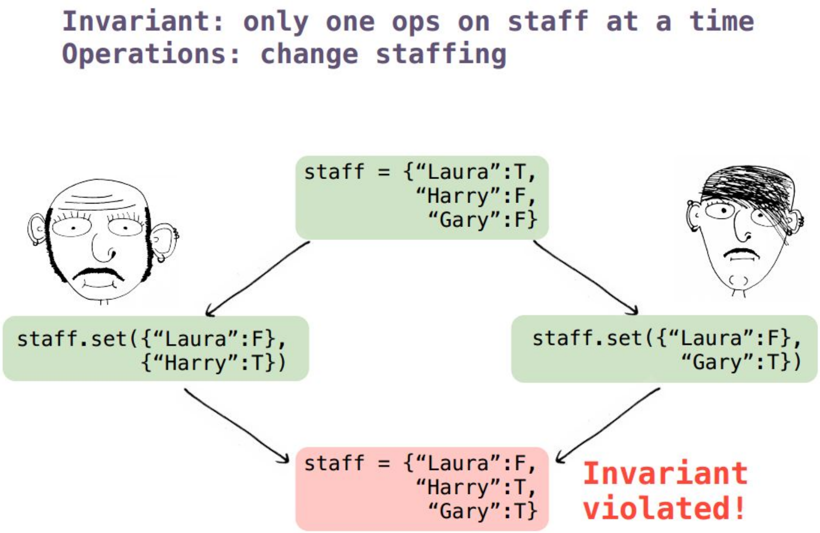
- Claim: **common uniqueness invariants aren't I-Confluent** (e.g., PRIMARY KEY and UNIQUE constraints).
- Example invariant: user IDs must be unique
- However, **reads and deletions are both invariant confluent** under uniqueness invariants: **reading and removing items cannot introduce duplicates**
- Case 2: the database chooses unique values on behalf of users. **If replicas assign unique IDs within their respective portion of the ID namespace, then merging locally valid states will also be globally valid**

Proof by counterexample:



I-Confluence example 2

- Claim 9: writing arbitrary values is not invariant confluent with respect to multi-item uniqueness constraints.
- Proof: by counterexample



I-Confluence example 3

Invariant	Operation	invariant confluent?	Proof #
Attribute Equality	Any	Yes	1
Attribute Inequality	Any	Yes	2

- Claim: Attributed equality invariants are i-confluent for any operations
- Example: **every user must have a last name assigned**, marking the LNAME column with a NOT NULL constraint
- **Proof by contradiction**: assume two database states S1 and S2 are each I-T-reachable under per-record inequality invariant I but that I(S1 U S2) is false. Then there must be a **r** ∈ S1 U S2 that violates I (i.e., r has the forbidden value) and such **r** must appear in S1, S2, or both. But, that would imply that one of S1 or S2 is not I-valid under I, a contradiction.

I-Confluence example 4

Invariant	Operation	invariant confluent?	Proof #
AUTO_INCREMENT	Insert	No	5

- Claim 11: Writing arbitrary values are not invariant confluent with respect to sequentiality constraints.
- Proof: by counterexample

Consider the following transactions:

$$T_{1s} := w(x_a = 1);\ \mathtt{commit}$$
$$T_{2s} := w(x_b = 3);\ \mathtt{commit}$$

and the sequentiality constraint on records:

$$I_s(D) = \{\max(r \in D) - \min(r \in D) = |D| + 1\} \vee \{|D| = 0\}$$

Now, I_s *holds over the empty database* ($I_s(\{\}) \rightarrow \mathtt{true}$)*, while inserting sequential new records into independent, empty replicas is also valid:*

$$T_{1s}(\{\}) = \{x_a = 1\},\ I_u(\{x_a = 1\}) \rightarrow \mathtt{true}$$
$$T_{2s}(\{\}) = \{x_b = 3\},\ I_u(\{x_b = 3\}) \rightarrow \mathtt{true}$$

However, merging these states results in invalid state:

$$I_s(\{x_a = 1\} \sqcup \{x_b = 3\} = \{x_a = 1, x_b = 3\}) \rightarrow \mathtt{false}$$

Therefore, $\{T_{1s}, T_{2s}\}$ *is not invariant confluent under* I_s.

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I-Confluence example 5

Invariant	Operation	invariant confluent?	Proof #
>	Increment [Counter]	Yes	11
<	Increment [Counter]	No	12
>	Decrement [Counter]	No	13
<	Decrement [Counter]	Yes	14

Claim 17 Counter ADT increments are invariant confluent with respect to greater-than constraints .

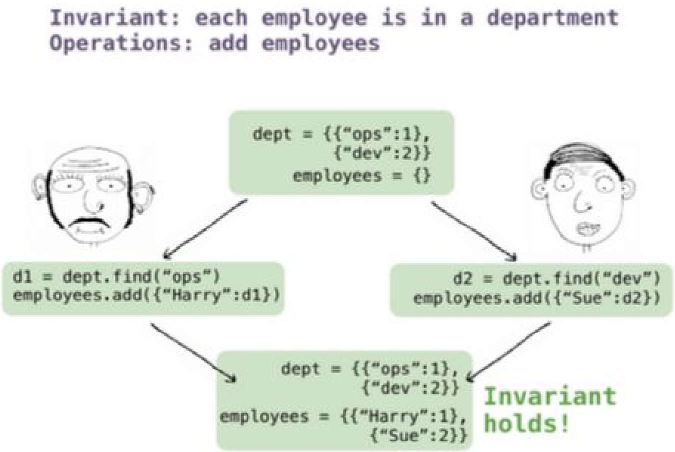
Claim 18 Counter ADT increments are not invariant confluent with respect to less-than constraints .

Claim 19 Counter ADT decrements are not invariant confluent with respect to greater-than constraints .

Claim 20 Counter ADT decrements are invariant confluent with respect to less-than constraints .

I-Confluence example 6: foreign keys

- Claim: **Insertions under foreign key constraints are invariant confluent**
- Proof by contradiction:
  - Invalid state: a record missing a corresponding record on the opposite side of the association
  - *S1* and *S2* - correct states before the merge (no invalid records)
  - *r* - invalid record in merged state S
  - As S1 and S2 are both valid, *r* must have a corresponding foreign key record (f) that “disappeared” during merge. Merge (in the current model) does not remove versions, so this is impossible.
- Arbitrary **deletion/modification** of records **is unsafe**: a user might be added to a department that was concurrently deleted



Read-atomic multi-partition transactions

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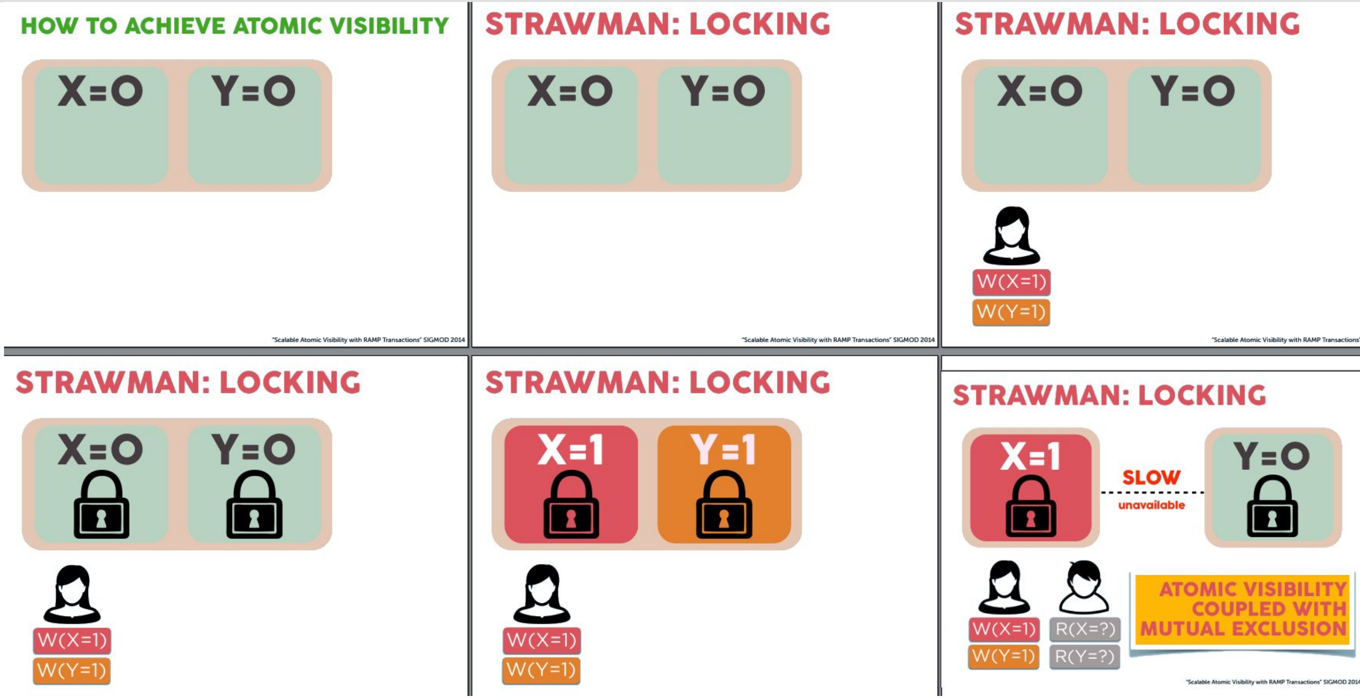
Foreign keys updates

FOREIGN KEY DEPENDENCIES
NEED
ATOMIC VISIBILITY
SEE ALL OF A TXN'S UPDATES, OR NONE OF THEM

I.e. in Facebook graph:
either we're both friends,
or neither of us is



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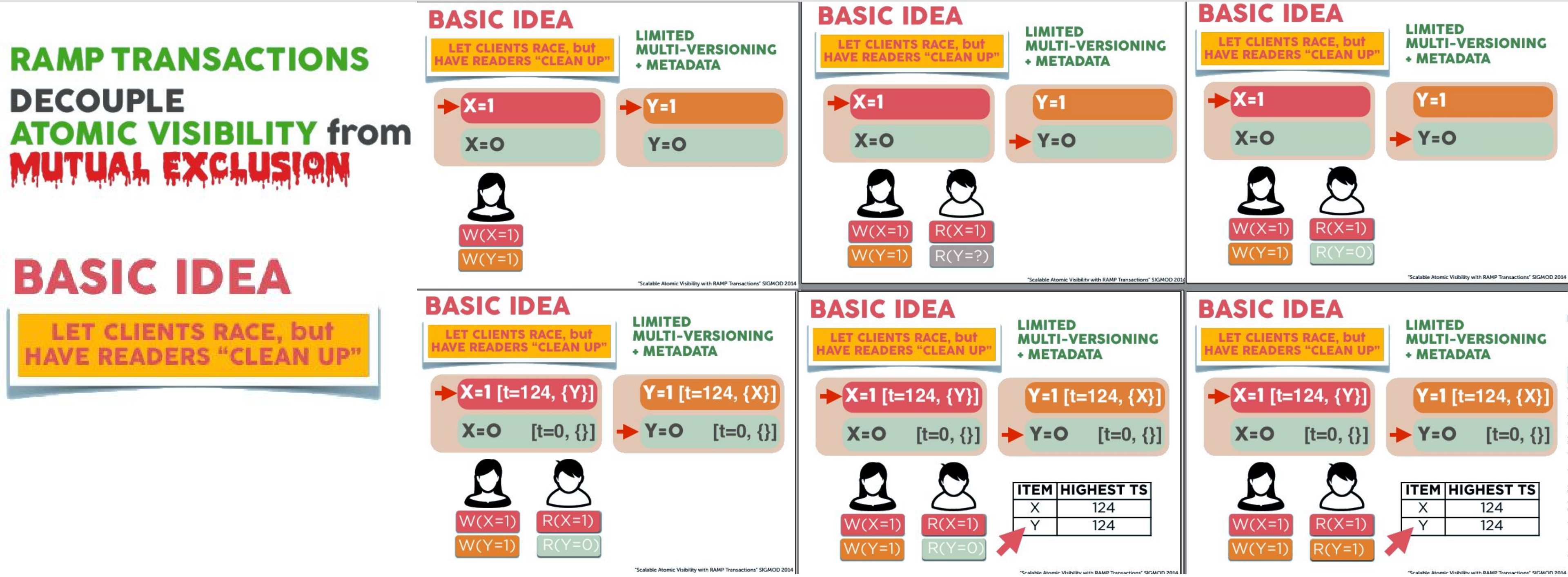
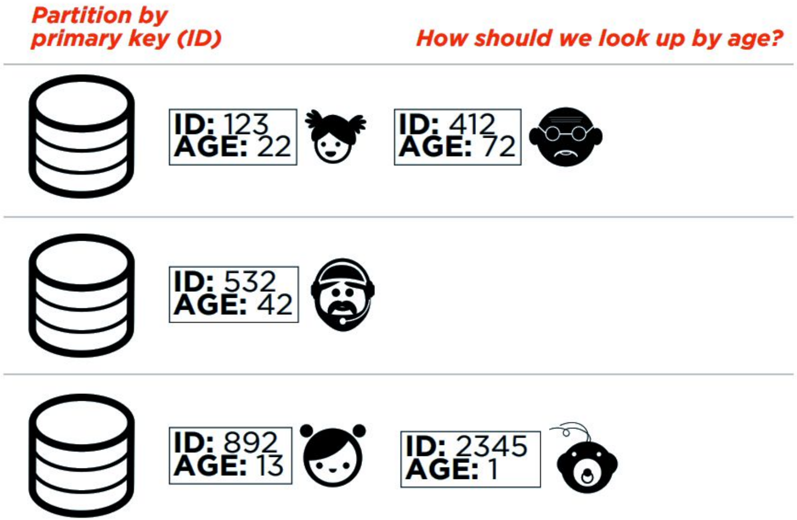
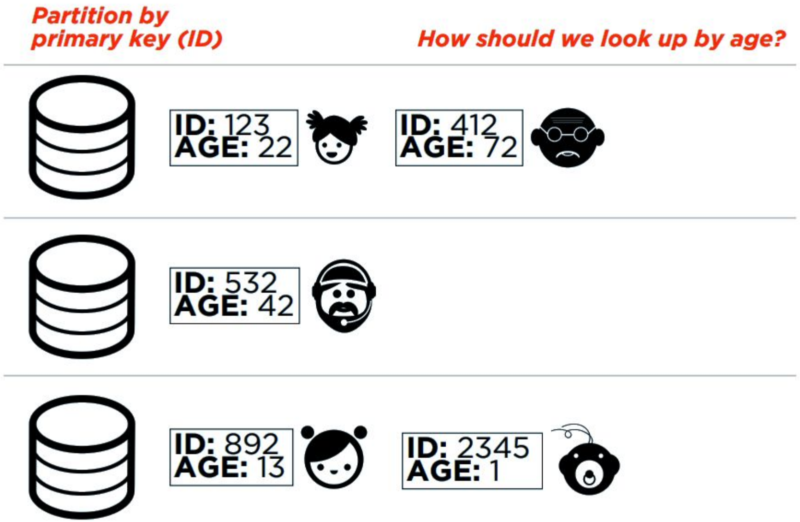
Read-atomic multi-partition transactions

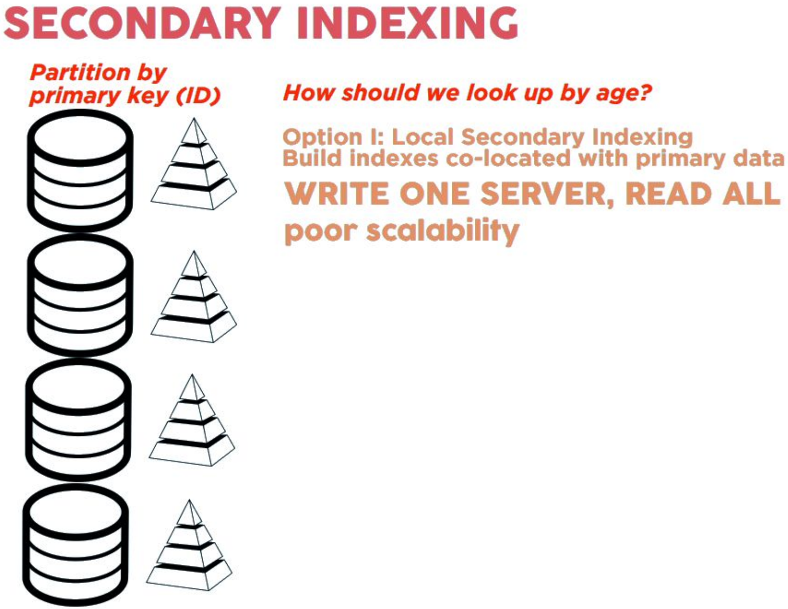


Another problem solved with RAMP transactions

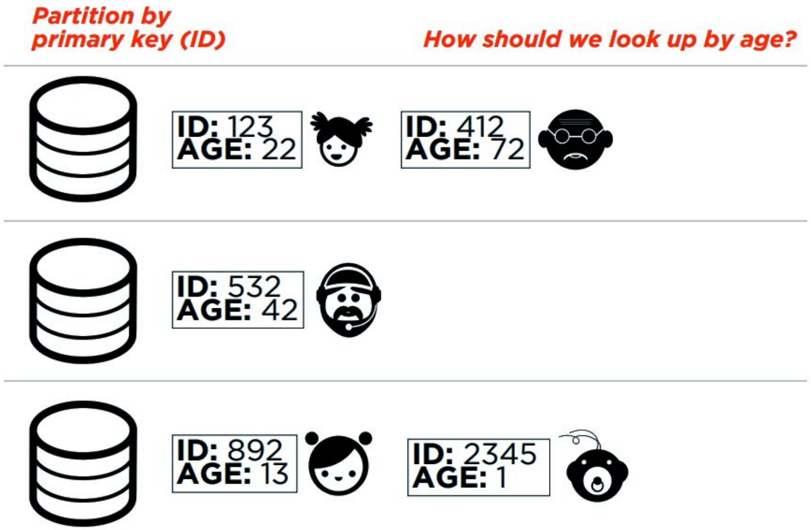


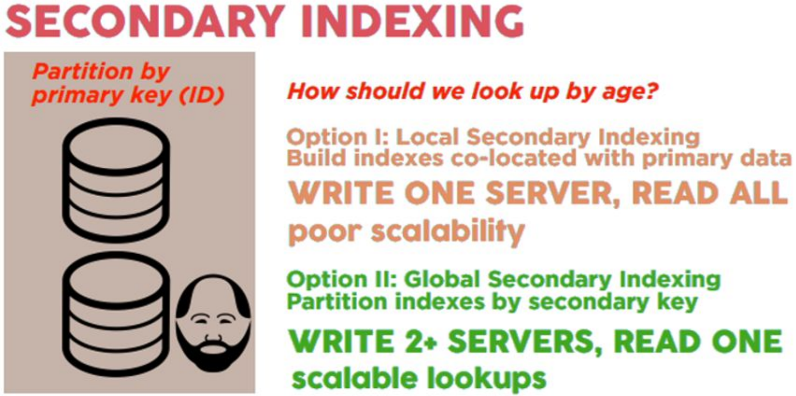
Secondary indexing

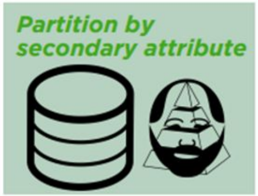




Secondary indexing







Real-world services employ either local secondary indexing (e.g., Espresso [38], Cassandra, and Google Megastore's local indexes [7]) or non-atomic (incorrect) global secondary indexing (e.g., Espresso and Megastore's global indexes, Yahoo! PNUTS's proposed secondary indexes [15]). The former is non-scalable but correct, while the latter is scalable but incorrect.

Conclusions

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Conclusions

Traditional database systems suffer from coordination bottlenecks

By understanding application requirements, we can avoid coordination unless *necessary*

We can build systems that actually scale while providing correct behavior

Use of validations (DB constraints) in Rails web-apps:

Name	Occurrences	I-Confluent?
validates_presence_of	1762	Depends
validates_uniqueness_of	440	No
validates_length_of	438	Yes
validates_inclusion_of	201	Yes
validates_numericality_of	133	Yes
validates_associated	39	Depends
validates_email	34	Yes
validates_attachment_content_type	29	Yes
validates_attachment_size	29	Yes
validates_confirmation_of	19	Yes
Other	321	Mixed

Table 6.4: Use of and invariant confluence of built-in validations.

Thank you!

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