Developer's Responsibility or Database's Responsibility? Rethinking Concurrency Control in Databases

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Ideal World vs. Reality

- Ideal world: Serializable transactions
  - Developers don’t need to worry about concurrency issues
- Reality: Most applications don’t use serializable transactions
  - Many use weaker isolation levels (READ COMMITTED, etc.)
  - Some use ad-hoc transactions (i.e., individual SQL statements + external concurrency control mechanisms)

Ideal World vs. Reality

“Buy One Item” transaction

```
1.  If (quantity > 0):
2.    Update (quantity = quantity – 1)
```

“The unit test always passes but in my production database `quantity` is sometimes -1, please investigate.”

Ideal World vs. Reality

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Under Read Committed:

#	TX1	TX2
1	Reads 1	
2		Reads 1
3	Updates to 0	
4	Commits	
5		Updates to -1
6		Commits

Overview

- A study of real-world concurrency bugs
  - Looked at 93 bugs from 46 open-source applications
  - Understand their <u>consequences</u>, <u>root causes</u>, and their <u>fixes</u>

- What can we do?

A Study of Real-world Concurrency Bugs

Questions

- Do weakly isolated or ad-hoc transactions actually cause anomalies in real-world applications?
- How much effort does it require to handle these anomalies?
- Why aren’t people more eager to use Serializable transactions?
  - Maybe the contention level is low and correctness issues don’t arise?
  - Maybe the occasional data inconsistency is OK and can be manually fixed?
  - Maybe fixing correctness issues in an application is easy for its developers?

A Study of Real-world Concurrency Bugs

Methodology

- Investigated active, open-source database applications
  - Domains: e-commerce, gaming, chatting, ORM tools
- Inspected bug reports, discussions and code commit history
  - No specific keyword or phrase
  - Started from broad search: “SQL”, “transaction”, “red committed”, “race condition”, “concurrent”, “for update”, “duplicate”, …
  - Manually inspected each bug
  - Ignored deadlock-related issues, unless related to isolation level

A Study of Real-world Concurrency Bugs

Outcome

- Found 93 isolation bugs in 46 different applications
- Identified consequence, root cause, and fix for each bug

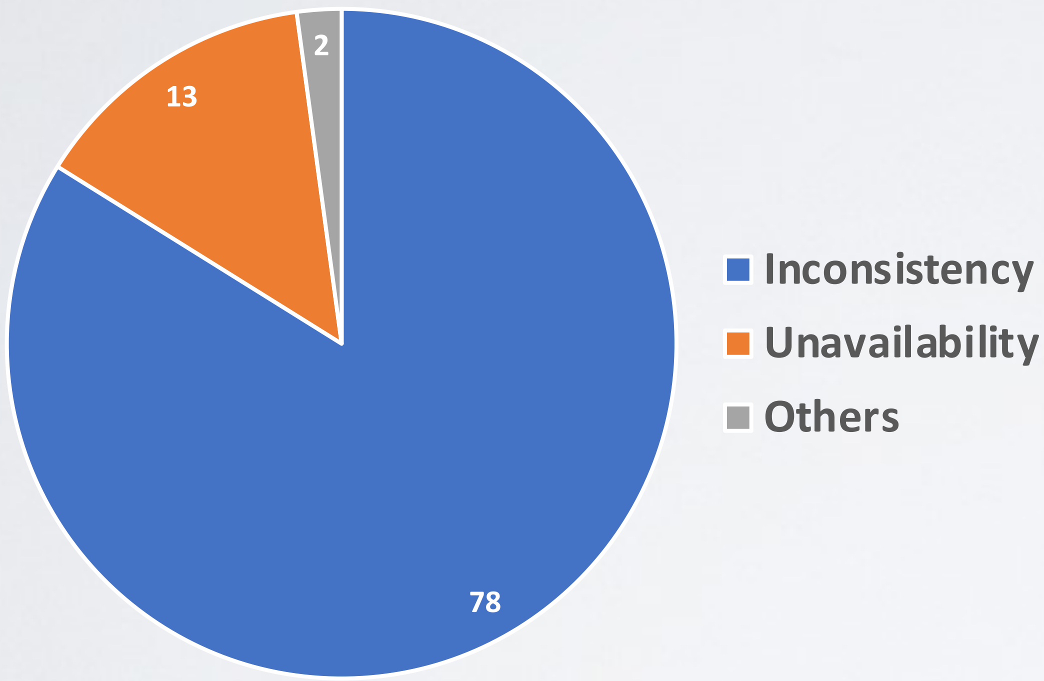
- Full bug list: http://go.osu.edu/isolation-bug-study

A Study of Real-world Concurrency Bugs

Limitation: selection bias

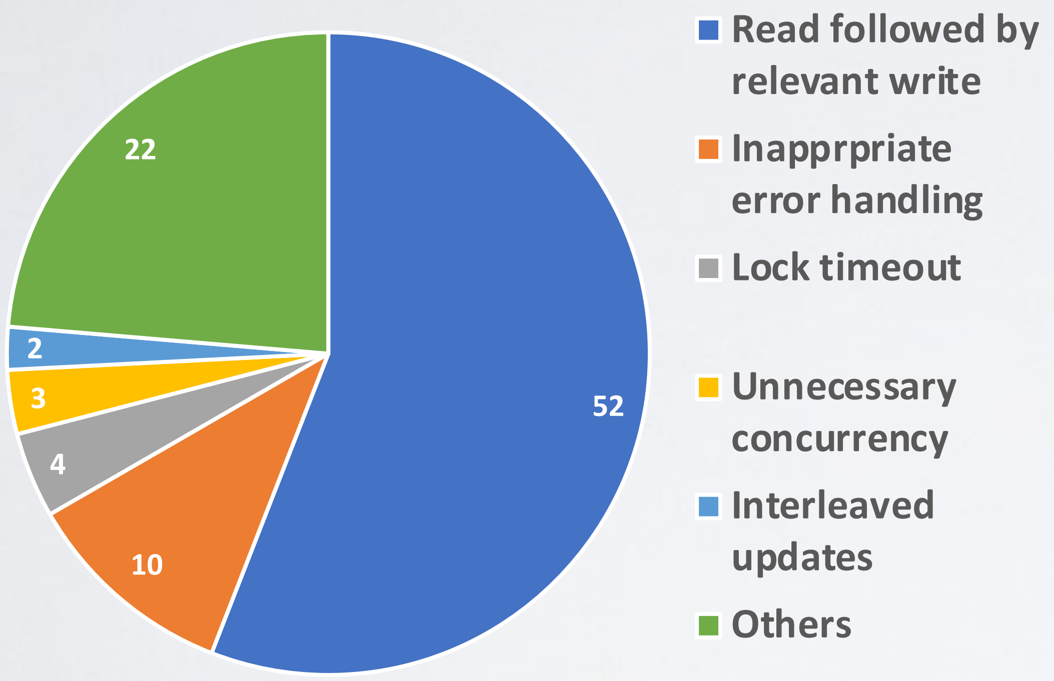
- Looked at open-source applications only
  - Corollary: most bug reports on open-source database systems
- Keyword search limitation
  - May have over-represented behaviors that can be described succinctly
  - May have missed bugs that are described only in domain-specific terms
- We cannot answer what percentage of applications experience concurrency issues
  - But we know that it affects many applications

Consequences of concurrency bugs



- Most common inconsistencies:
  - Wrong count (30)
  - Duplicate IDs (16) ← big problem!
- New insight: Mostly idle applications are also impacted!
  - “About 2-5% chance this happens. I have about 100 orders per day.”
  - “It is rare, but it has happened 5 times over the past few months in a set of 10,000 orders”.

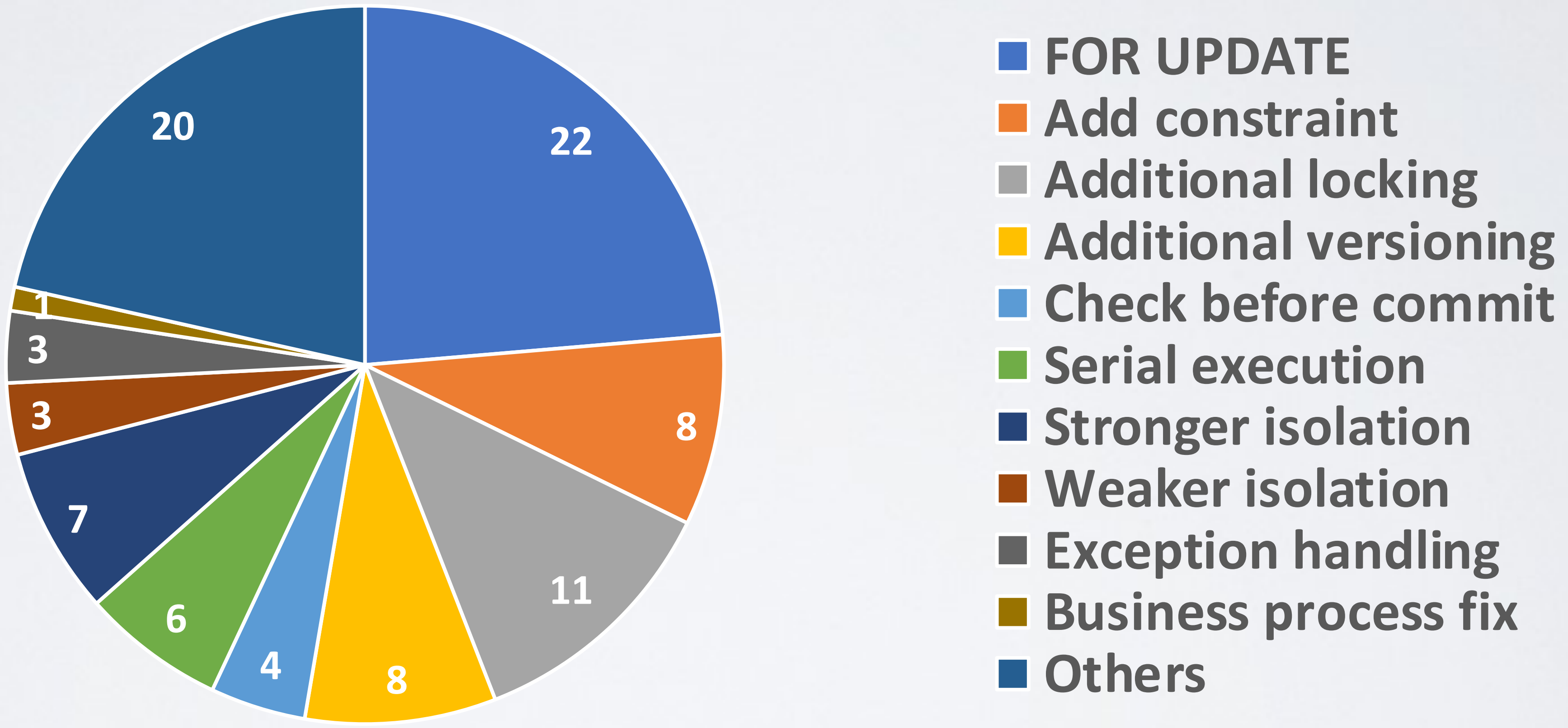
Root causes of concurrency bugs



- Read followed by relevant write:
  - Single row check-then-update (42)
    - `If (quantity > 0), then`
      `Update (quantity = quantity – 1)`
  - Multi-row check-then-update (10)
    - `INSERT (SELECT MAX(id) + 1)`
- Inappropriate error handling:
  - None/insufficient exception handling (9)
  - Exception over-handling (1)
- Unnecessary concurrency:
  - TXs don’t commit in order issued (3)
    - No isolation level provides this guarantee!

How developers fix concurrency bugs

No universally acceptable solution!



Answering the questions

- Do weakly isolated or ad-hoc transactions actually cause anomalies in real-world applications? **Yes.**

Answering the questions

- How much effort does it require to handle these anomalies? **A lot.**

1. Reproduction effort: **Moderate.**
    - Most bugs involve very few transactions.
    - Nondeterministic bugs, so “luck” and patience needed to hit.
        - Common tricks to increase conflict rate: increase concurrency, slow transactions down
2. Diagnosis effort: **Low.**
    - Very little discussion or uncertainty on the cause.
3. Fix and verify effort: **Very high.**
    - Lengthy discussions debating possible fixes and pros/cons of each.
    - First suggestions are often flawed or introduce more issues.

Answering the questions

- Why not Serializable transactions? **Long locking.**

- Common concern is performance
  - Reasons of poor performance not a focus of our study
- Error cases are very important too
  - Failures do not propagate through layers → wasted resources
- Deadlock detection is very sensitive to timeout parameter
  - One application implemented a queue-based solution (serial execution) to eliminate guessing of deadlock timeouts in deployment

What can we do?

- Short-term solutions
- How much can automatic analysis help?
- How can we incorporate developer effort to fixing concurrency bugs?
- Closing thought: the role of developer education

Short-term solutions

- Point to database systems that implement:
  - Snapshot Isolation
  - Unique/auto-incremented IDs
  - Optimistic concurrency control
- Likely a non-starter for the open-source applications we studied
- But stronger isolation will not address all problematic behaviors:
  - Duplicate inserts/deletes
  - Transaction ordering assumption

Can automatic analysis help?

- Consider two transactions on rows A, B, C:

  T1: Write(A), Read(B)

  T2: Write(A), Read(C)
- Lock-based CC will block on write lock for A
- Optimistic CC will abort one transaction, due to write conflict on A

- Automatic analysis can easily determine that execution is serializable, no matter how operations interleave
  - Theoretically possible to run with no concurrency control*

*latching still needed

Can automatic analysis help?

- Can source code analysis identify such “no concurrency control necessary” phases in actual executions?
  - Essentially: identify when isolation is guaranteed by query semantics
- Challenges:
  - Sound static analysis struggles to be precise
  - Dynamically-typed languages are harder to analyze precisely, tools are not as advanced
  - Extracting query predicates from SQL is non-trivial
  - Tension between abstract CC model and vendor-specific CC implementation
    - Problematic behaviors on an abstract model may not occur in practice, and vice versa
- Opportunities:
  - Application logic is often very simple, does not stress scalability of static analysis
  - No data sharing in application logic, avoids imprecise analysis due to shared objects

How can we incorporate developer effort?

- Developers can convey application-specific constraints and invariants that automatic analysis will never reliably extract
- Examples:
  - Transaction is for reporting purposes and does not need serializable results
  - No concurrent transactions from same client
  - Which tables or records are likely to be hot
- Challenges:
  - How are we presenting concurrency bugs in an understandable way?
    - How can we reliably track executions through software layers?
  - How do we incorporate user feedback and allow user control of concurrency?
  - Can we automatically suggest modifications to SQL in application code?

Closing thought: developer education

- Application developers are much more comfortable at the programming language level rather than the database level.
  - Noted widespread use of the term “race condition” for weak isolation errors.
- First developer reaction is: “let’s add a lock somewhere”
  - Locking is undergraduate concept. Easy to understand, hard to get right.
- Challenges in introducing isolation earlier in the curriculum:
  1. Early definitions of isolation are operational: they dictate how to implement using locks
  2. Dependency graph-based definitions of isolation are hard to grasp, even harder to use to analyze real transactions

Conclusion

- A study of real-world concurrency bugs
  - Looked at 93 bugs from 46 open-source applications
  - Understand their consequences, root causes, and their fixes:
    - Consequence: Most bugs manifest as <u>data inconsistencies</u>
    - Root cause: Mainly the assumption of <u>atomic read-then-write</u>
    - Fix: <u>No universally acceptable solution</u>
- What can research do?
  - Automatic analysis is a very promising path
  - New abstractions to convey concurrency bugs and incorporate user input