Verifying Transactional Consistency of MongoDB

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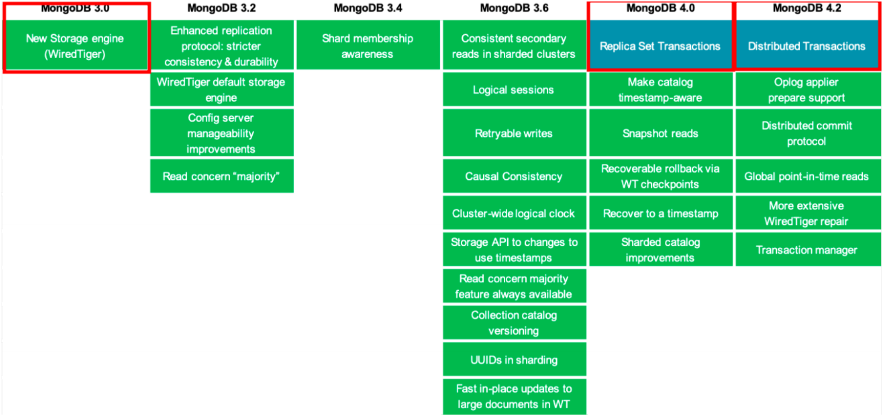
MongoDB 的三种经典部署架构



MongoDB 事务的三阶段发展过程

A Fundamental Question:

What transactional consistency guarantee do MongoDB transactions in each deployment provide?

挑战一：MongoDB 官方规约不清楚, SI 有多种变体

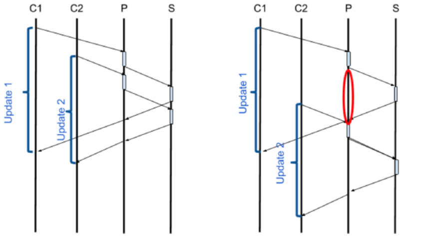
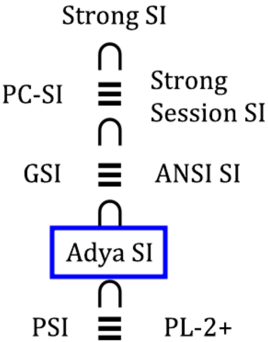
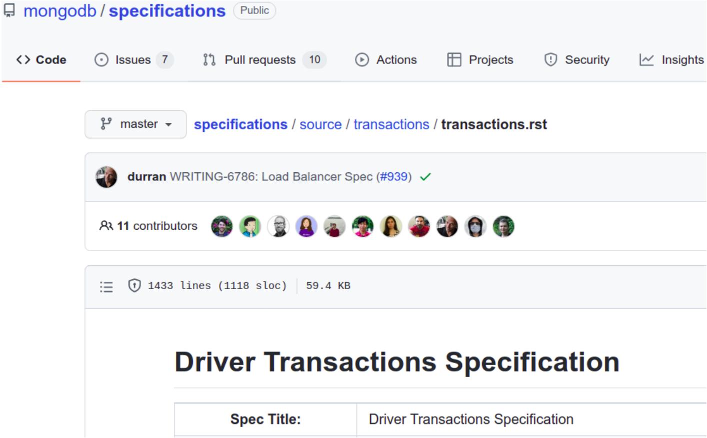


Figure 3: Back-to-Back Transactions with and without Speculative Snapshot Isolation



挑战二：MongoDB 缺少精简的事务协议描述，更没有严格证明

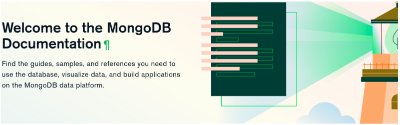


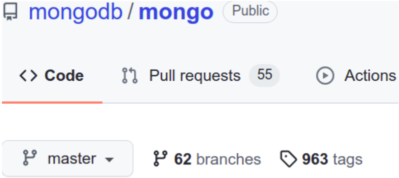
挑战三: SI 检测问题是 NP-complete 问题, 复杂度高

THEOREM 3.2. *For any criterion* $C \in \{$PREFIX CONSISTENCY, SNAPSHOT ISOLATION, SERIALIZABILITY$\}$ *the problem of checking whether a given history satisfies* C *is NP-complete.*

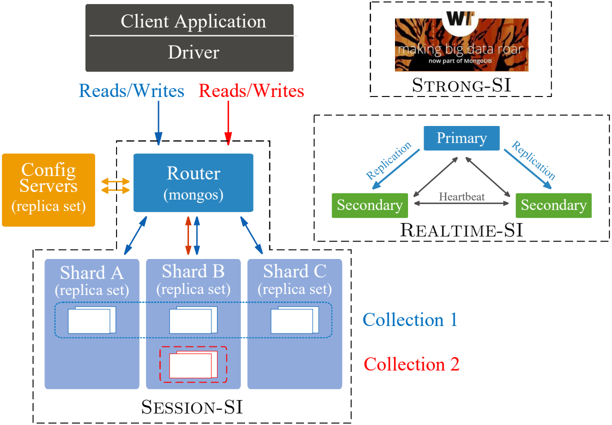
贡献一: 使用 (VIS, AR) 框架, 为多种 SI 变体提供形式化规约

贡献二：为 MongoDB 事务一致性协议提供精简的伪代码描述





贡献三：证明 WiredTiger、ReplicaSet、ShardedCluster 事务协议分别满足 StrongSI、RealtimeSI、SessionSI 变体



贡献四: 设计并评估了多项式时间 SI 变体白盒检测算法

JEPSEN

1. 事务 $T : (E, \mathsf{po})$
   - po : Program Order
   - $start(T)$: 事务开始时间
   - $commit(T)$: 事务提交时间

2. 历史 $\mathcal{H} : (\mathbb{T}, \textsc{so})$
   - $\mathbb{T}$: 已提交事务集合
   - $\textsc{so}$: Session Order

3. 执行 $\mathcal{A} : (\mathcal{H}, \textsc{vis}, \textsc{ar})$
   - $\textsc{vis}$: 可见性 (Visibility) 偏序关系
   - $\textsc{ar}$: 仲裁 (Arbitration) 全序关系
   - $\textsc{vis} \subseteq \textsc{ar}$

一个事务一致性模型可定义为一组一致性公理的集合 Φ。

历史 $\mathcal{H}$ 满足事务一致性模型 Φ, 如果存在 $\textsc{vis}$ 与 $\textsc{ar}$ 使得

$$\exists \textsc{vis}, \textsc{ar}.\ (\mathcal{H}, \textsc{vis}, \textsc{ar}) \models \Phi。$$

$\forall (E, \mathsf{po}) \in \mathcal{H}.\ \forall e \in \mathsf{Event}.\ \forall key, val.\ \big(\mathsf{op}(e) = \mathsf{read}(key, val) \land \{f \mid (\mathsf{op}(f) = \_(key, \_) \land f \xrightarrow{\mathsf{po}} e\} \neq \emptyset\big) \implies \mathsf{op}(\max_{\mathsf{po}}\{f \mid \mathsf{op}(f) = \_(key, \_) \land f \xrightarrow{\mathsf{po}} e\}) = \_(key, val)$	(INT)
$\forall T \in \mathcal{H}.\ \forall key, val.\ T \vdash \mathsf{read}(key, val) \implies \max_{\mathrm{AR}}(\mathrm{VIS}^{-1}(T) \cap \mathsf{WriteTx}_{key}) \vdash \mathsf{write}(key, val)$	(EXT)

$\mathrm{SO} \subseteq \mathrm{VIS}$	(SESSION)	$\mathrm{AR} \,;\, \mathrm{VIS} \subseteq \mathrm{VIS}$	(PREFIX)
$\mathrm{RB} \subseteq \mathrm{VIS}$	(RETURNBEFORE)	$\mathrm{CB} \subseteq \mathrm{AR}$	(COMMITBEFORE)
$\mathrm{VIS} \subseteq \mathrm{RB}$	(REALTIMESNAPSHOT)	$\forall S, T \in \mathcal{H}.\ S \bowtie T \implies (S \xrightarrow{\mathrm{VIS}} T \lor T \xrightarrow{\mathrm{VIS}} S)$	(NOCONFLICT)

$$\mathrm{SI} = \textsc{Int} \land \textsc{Ext} \land \textsc{Prefix} \land \textsc{NoConflict}$$

$$\textsc{SessionSI} = \text{SI} \land \textsc{Session}$$

$$\textsc{SessionSI} = \text{SI} \wedge \textsc{Session}$$

$$\textsc{RealtimeSI} = \text{SI} \wedge \textsc{ReturnBefore} \wedge \textsc{CommitBefore}$$

$$\textsc{SessionSI} = \text{SI} \land \textsc{Session}$$

$$\textsc{RealtimeSI} = \text{SI} \land \textsc{ReturnBefore} \land \textsc{CommitBefore}$$

$$\text{GSI} = \text{SI} \land \textsc{RealtimeSI} \land \textsc{CommitBefore}$$

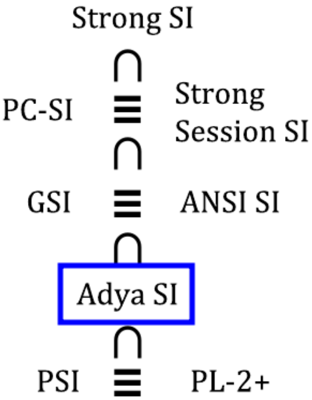
$$\textsc{SessionSI} = \text{SI} \land \textsc{Session}$$

$$\textsc{RealtimeSI} = \text{SI} \land \textsc{ReturnBefore} \land \textsc{CommitBefore}$$

$$\text{GSI} = \text{SI} \land \textsc{RealtimeSI} \land \textsc{CommitBefore}$$

$$\textsc{StrongSI} = \text{GSI} \land \textsc{ReturnBefore}$$

- ANSI-SI
- SI
- GSI
- StrongSI
- StrongSessionSI
- PSI
- WriteSI
- NMSI
- PCSI



Conclusion

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