Graceful Degradation through Time Travel

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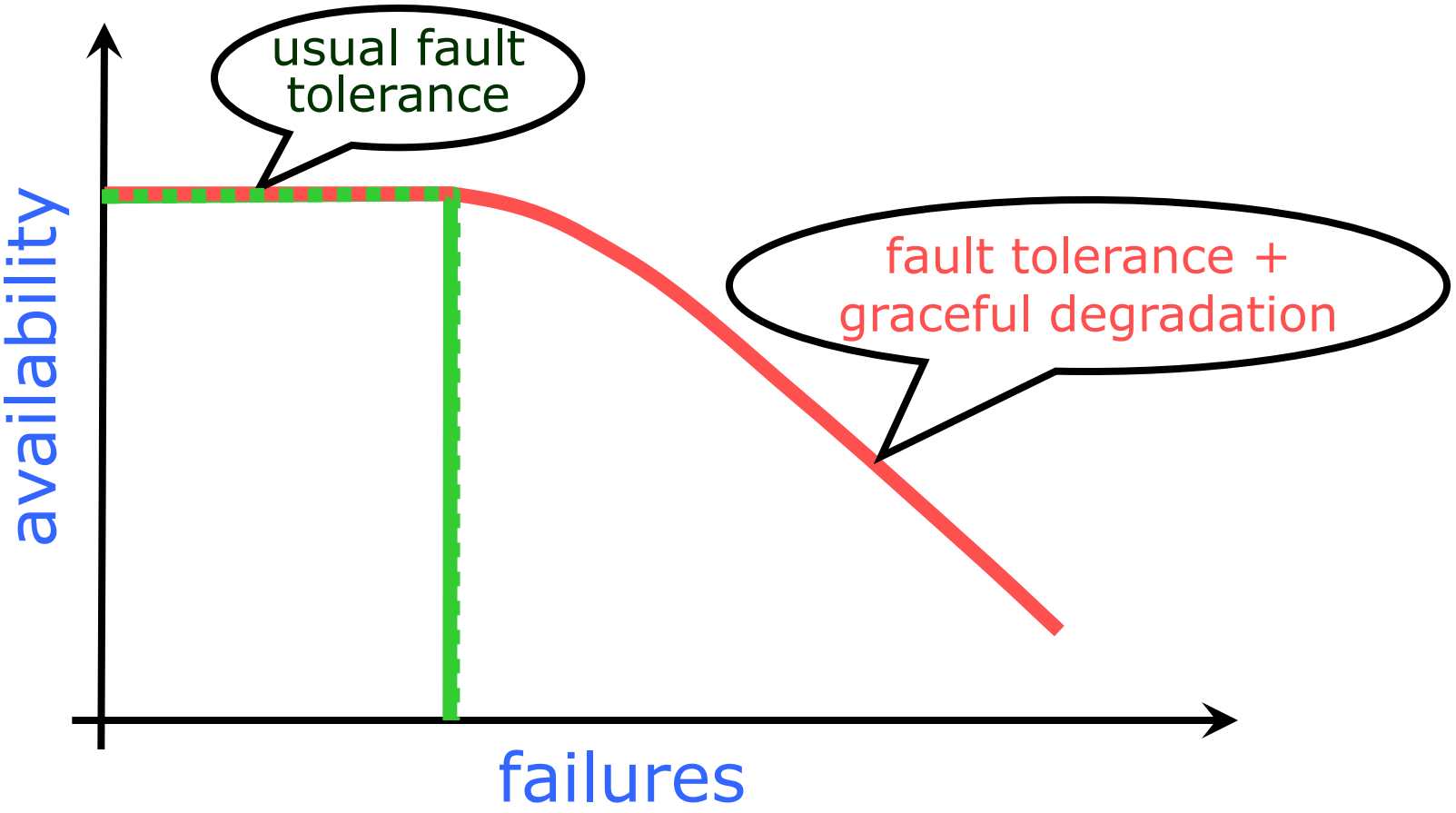
Fault Tolerance vs. Graceful Degradation



Graceful Degradation via Time Travel

- critical to maintain "correctness"
- time travel
- coherent state from the past

  - **coherent degraded state**
    - **already used for failure recovery, archival systems, historical databases**

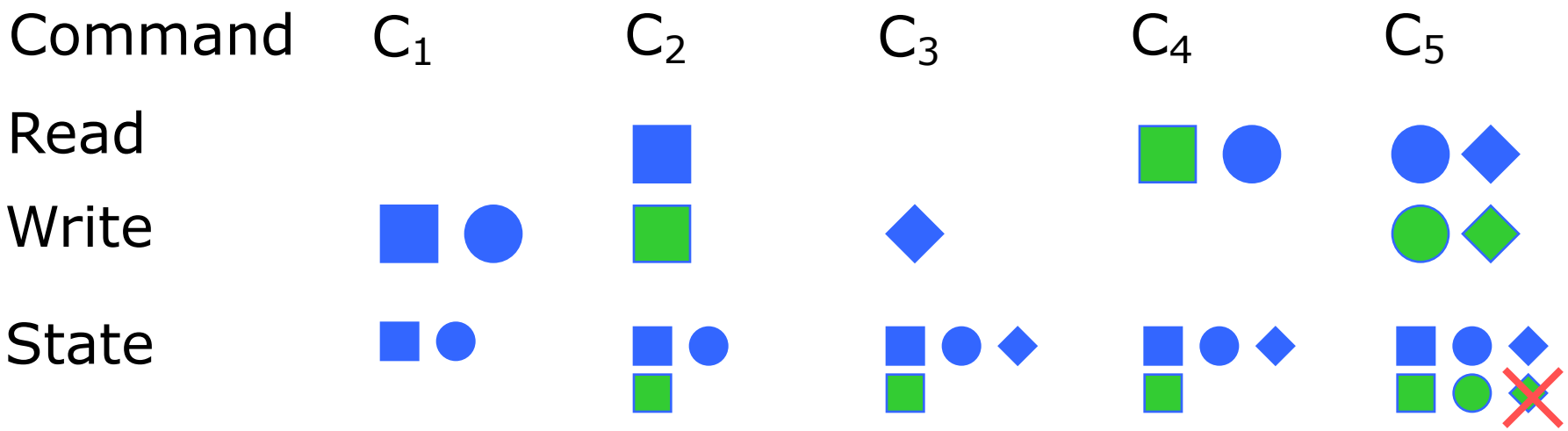
Contributions

- three “correctness” specs for graceful degradation
- mechanisms to implement the specs in a versioned storage system
- discussion of tradeoffs between the three specs

Notations and Definitions

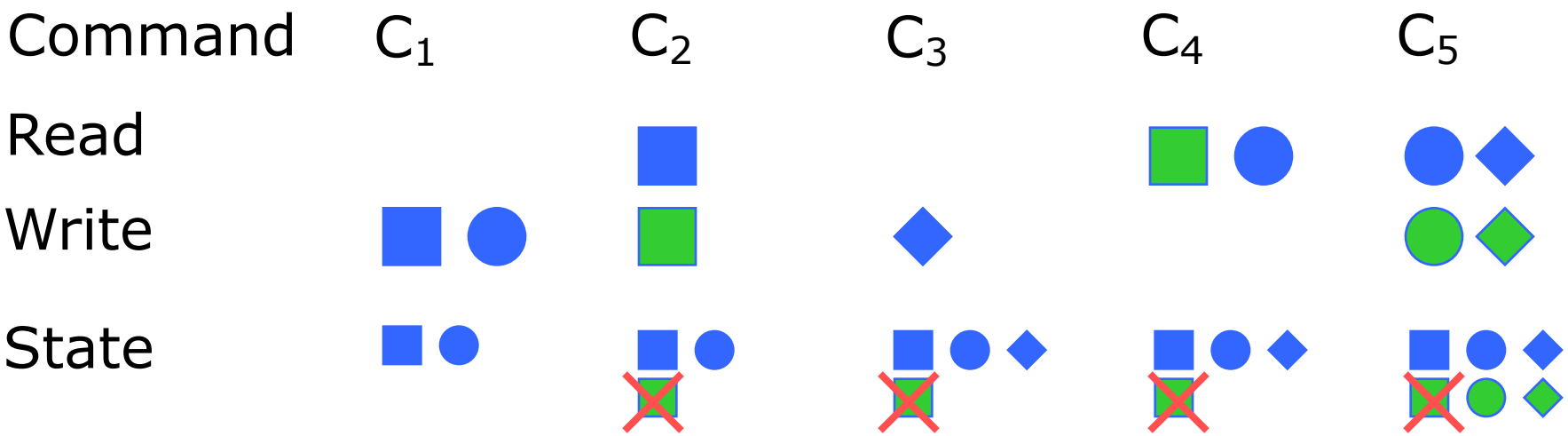
- State Machine (M)
  - State M(c_1, c_2, ..., c_n)
- Command (c)
  - Query: does not change state
  - Update: changes state
  - Read Set (c.rs): set of objects read
  - Write Set (c.ws): set of objects written
- Serialization
- Linearization

Naïve Approach and Problem



- Versioned storage system: objects, versions
- Time travel: go back in time before failure
  - may lead to invalid state!

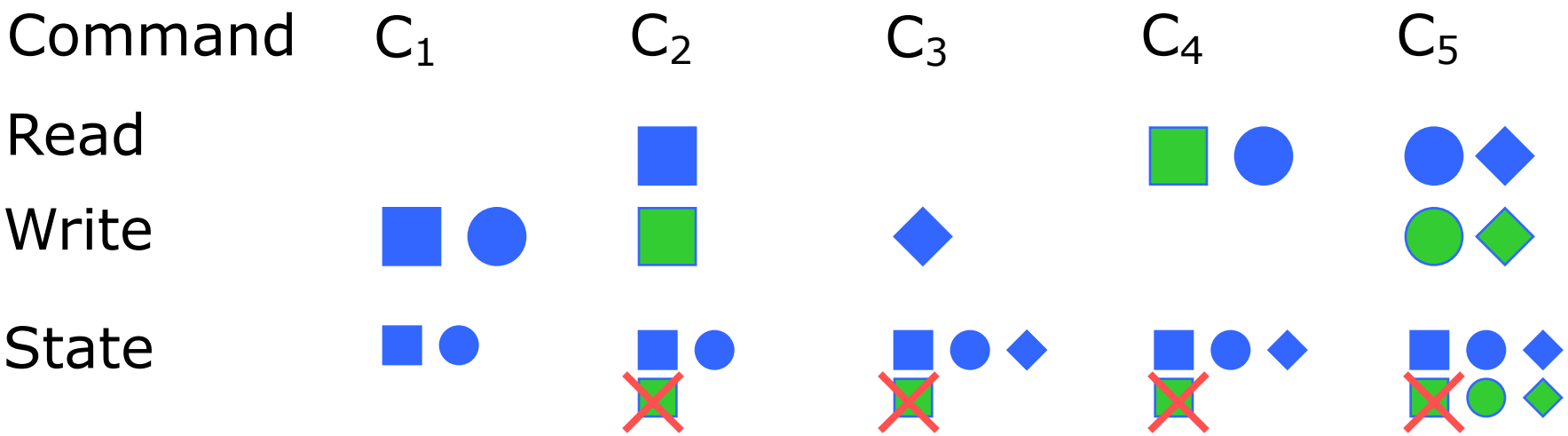
Spec 1: Prefix Linearizability



- **Coherent Degraded State 1:** ■●

  any state $M(c_1, c_2, \ldots, c_k)$ for $1 \leq k \leq n$
  for a given execution $(c_1, c_2, \ldots, c_n)$

Spec 2: Prefix Serializability



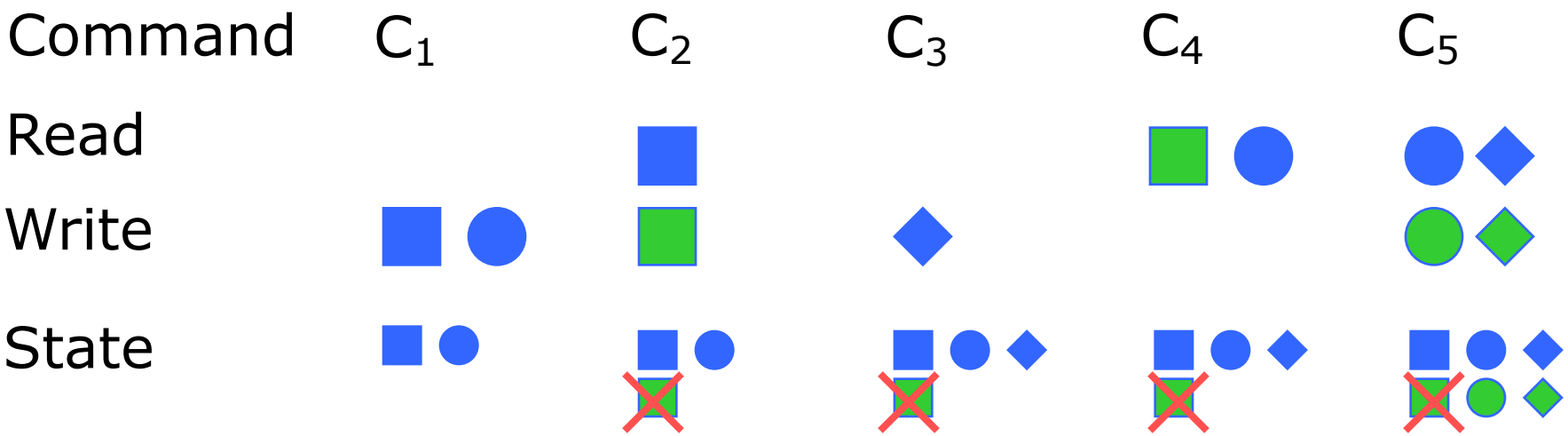
- **Coherent Degraded State 2:** ■●◆

  any state $M(c_{i1}, c_{i2}, \ldots, c_{ik})$ for $1 \leq k \leq n$

  for a valid serialization $(c_{i1}, c_{i2}, \ldots, c_{in})$

  of a given execution $(c_1, c_2, \ldots, c_n)$

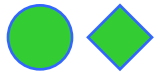
Spec 3: Subsequence Linearizability



- **Coherent Sub-Sequence:**

  a sub-sequence $c_{j1}, c_{j2}, \ldots, c_{jk}$ for $1 \leq j_1 < j_2 < \ldots < j_k \leq n$, where value of each object $o \in c_{ji}.rs \cup c_{ji}.ws$ is same before execution of c_{ji} in sub-sequence and the given sequence $(c_1, c_2, \ldots, c_n)$

Spec 3: Subsequence Linearizability

Command	C_1	C_3	C_5
Read			
Write			
State			

- **Coherent Degraded State 3:** 

  any state $M(c_{j1}, c_{j2}, \ldots, c_{jk})$ for $1 \leq j_1 < j_2 < \ldots < j_k \leq n$

  for a coherent sub-sequence $(c_{j1}, c_{j2}, \ldots, c_{jk})$

  of a given execution $(c_1, c_2, \ldots, c_n)$

Degree of Degradation

- n – k:
  - n is the total number of commands
  - k is the number of commands reflected in the degraded state
- Examples:
  - Prefix linearizability: 4 (c_1)
  - Prefix serializability: 3 (c_1,c_3)
  - Subsequence linearizability: 2 (c_1,c_3,c_5)

Putting it Together

- Normal Mode
  - all required objects are available!
  - command executed atomically (transaction style)
- Degraded Mode (excessive failures)
  - one or more required objects is not available!
  - find a **most recent coherent degraded state** based on a chosen spec
  - execute query on the coherent degraded state
  - abort updates in the degraded mode!

Most Recent Coherent Degraded State

- State:
  - a set of versions one for each object
- Coherent Degraded State:
  - valid degraded state defined by one of the specs
- More Recent Coherent Degraded State:
  - S_1 is more recent than S_2 if for each object o and versions $<o,v_1> \in S_1$ and $<o,v_2> \in S_2$, $v_1 \geq v_2$
- Most Recent Coherent Degraded State:

Spec 1: Timestamp-Based Mechanism

- Timestamps with each version:
  - Write timestamp: <o,v>.wt
    - timestamps are transactional!
- Timestamp-Based Coherent Set S:
  - iff there is a timestamp t such that:

    for each <o,v> $\in$ S,

    <o,v>.wt $\leq$ t < <o,v>.succ.wt

Spec 1: Timestamp-Based Mechanism

- Finding the most recent coherent set:
  - Start with a set S of most recent available versions
  - Let <o,v> $\in$ S have the highest timestamp t
  - If $\exists$ <o',v'> $\in$ S with t $\geq$ (o',v').succ.wt:

    Replace <o,v> with highest available version of o and timestamp < t

Spec 3: Weaker Dependency-Based Mechanism

- Dependencies with each version:

  $\forall$ <o,v> $\in$ c.ws, <o,v>.wdep := c.ws

  $\cup$ <ro,v>.wdep $\forall$ <ro,v> $\in$ c.rs

  $\cup$ <wo,v>.prev.wdep $\forall$ <wo,v> $\in$ c.ws

- Weak-Dependency-Based Coherent Set S:
  - iff $<o_1,v_1>$ and $<o_2,v_2>$ in S:

    if $<o_1,v> \in <o_2,v_2>.wdep \Rightarrow v \leq v_1$,

    $<o_2,v> \in <o_1,v_1>.wdep \Rightarrow v \leq v_2$

Spec 3: Weaker Dependency-Based Mechanism

- Finding the most recent coherent set:
  - Start with a set S of most recent available versions
  - If $\exists$ $<o_1,v_1> \in S$, $<o_2,v_2> \in S$, and $<o_1,v> \in <o_2,v_2>.wdep$ with $v > v_1$:

    Replace $<o_2,v_2>$ with the highest available version of $o_2 < v_2$

Spec 2: Dependency-Based Mechanism

- Dependencies with each version:

  $\forall$ <o,v> $\in$ c.ws, <o,v>.dep := c.ws
  $\cup$ <ro,v>.dep $\forall$ <ro,v> $\in$ c.rs
  $\cup$ <wo,v>.prev.dep $\forall$ <wo,v> $\in$ c.ws
  $\cup$ <wo,v>.prev.equiv $\forall$ <wo,v> $\in$ c.ws

  $\forall$ <o,v> $\in$ c.rs, <o,v>.equiv := <o,v>.equiv
  $\cup$ <ro,v>.dep $\forall$ <ro,v> $\in$ c.rs
  $\cup$ <wo,v>.prev.dep $\forall$ <wo,v> $\in$ c.ws

Mechanisms vs. Specs

- Timestamp-based mechanism $\Leftrightarrow$
  prefix linearizability (spec 1)
- Dependency-based mechanism $\Leftrightarrow$
  prefix serializability (spec 2)
- Weak-Dependency-based mechanism $\Leftrightarrow$
  subsequence linearizability (spec 3)
- Proofs in the paper!

Implications

- Timestamp-Based Coherency:
  - accurate time travel to consistent past state
  - Similar to Immortal Databases [LBMSWZ05, SIGMOD]
- Dependency-Based Coherency:
  - virtual time travel
  - degraded state may not have really existed!
- Weaker Dependency-Based Coherency:
  - undo the effects of some commands

Example:

Source-Code tree with independent packages

- Jan 07:
  - Perl, Python
- Feb 07:
  - Python Update
- Mar 07:
  - Perl Update
- Apr 07:
  - Stats Query
- May 07:
  - Python Update

Tradeoffs

- Strength:
  - Spec 1 (PL) ≥ Spec 2 (PS) ≥ Spec 3 (SL)
- Degree of Degradation:
  - Spec 1 (PL) ≥ Spec 2 (PS) ≥ Spec 3 (SL)
- Overhead:
  - Spec 1 (PL) ≤ Spec 3 (SL) ≤ Spec 2 (PS)

Graceful Degradation for Updates

- Degraded updates are hard!
- Permanent failures:
  - perform updates on the degraded state
- Transient failures:
  - branched versions
    - pick latest branch as valid and proceed
    - use a merge operation to combine branches

Summary and Conclusions

- graceful degradation improves availability in the face of excessive failures
- coherency needs to be preserved during degradation
- time travel helps coherent degradation
  - definitions, mechanisms, analysis