Building correct-by-design highly available cloud applications

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Joint work with
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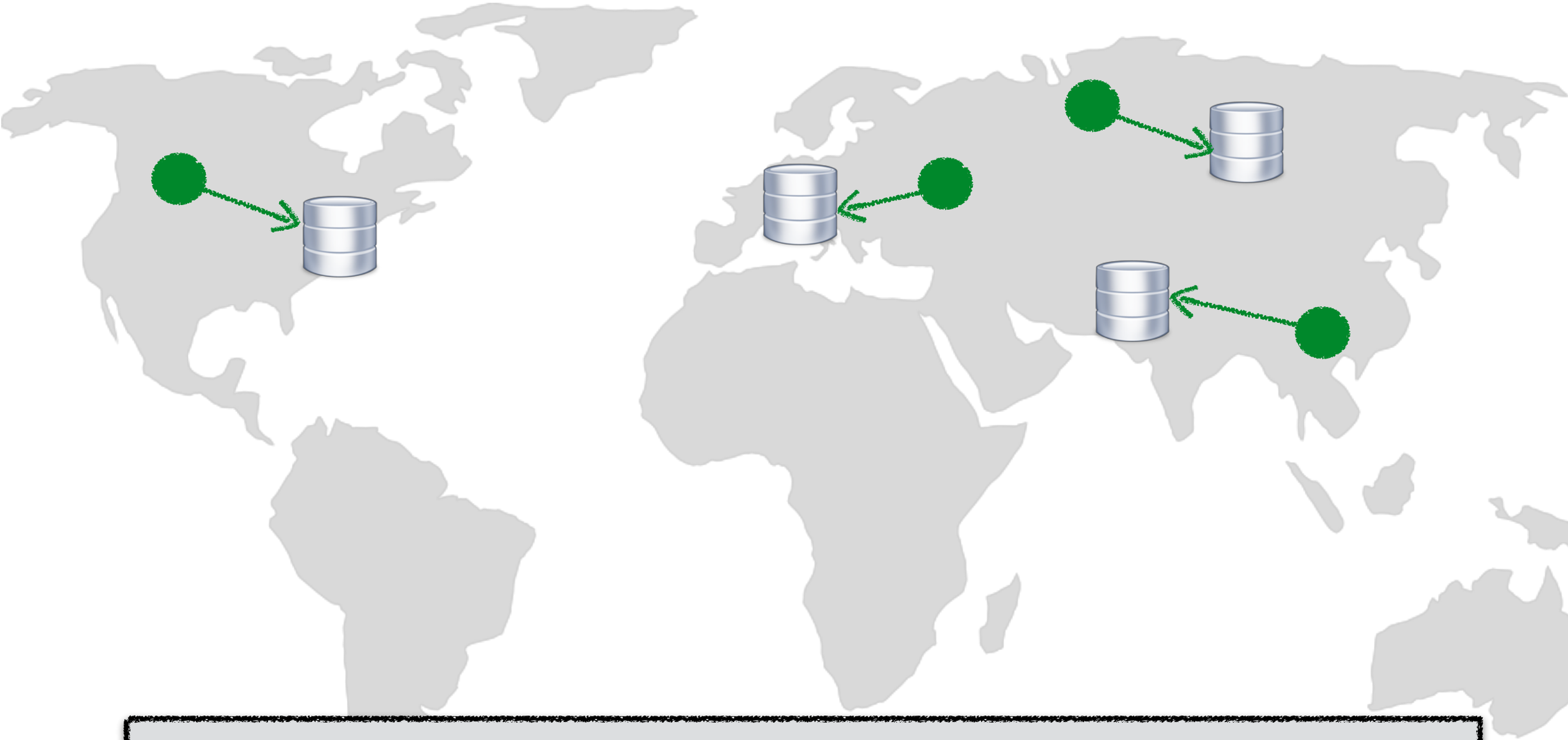
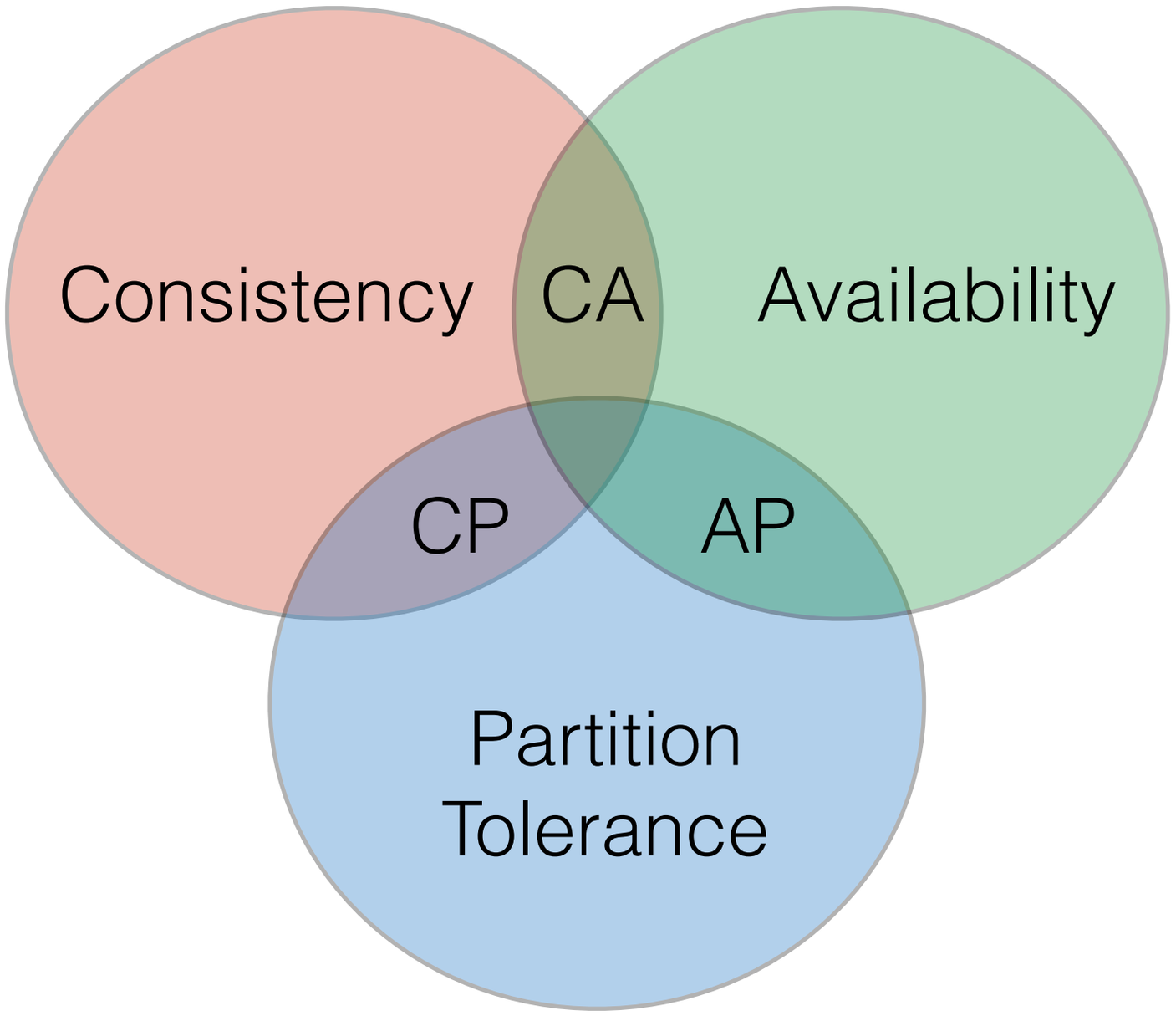
Shonan PL4DS Meeting, 27 - 30 May 2019

Geo-replication



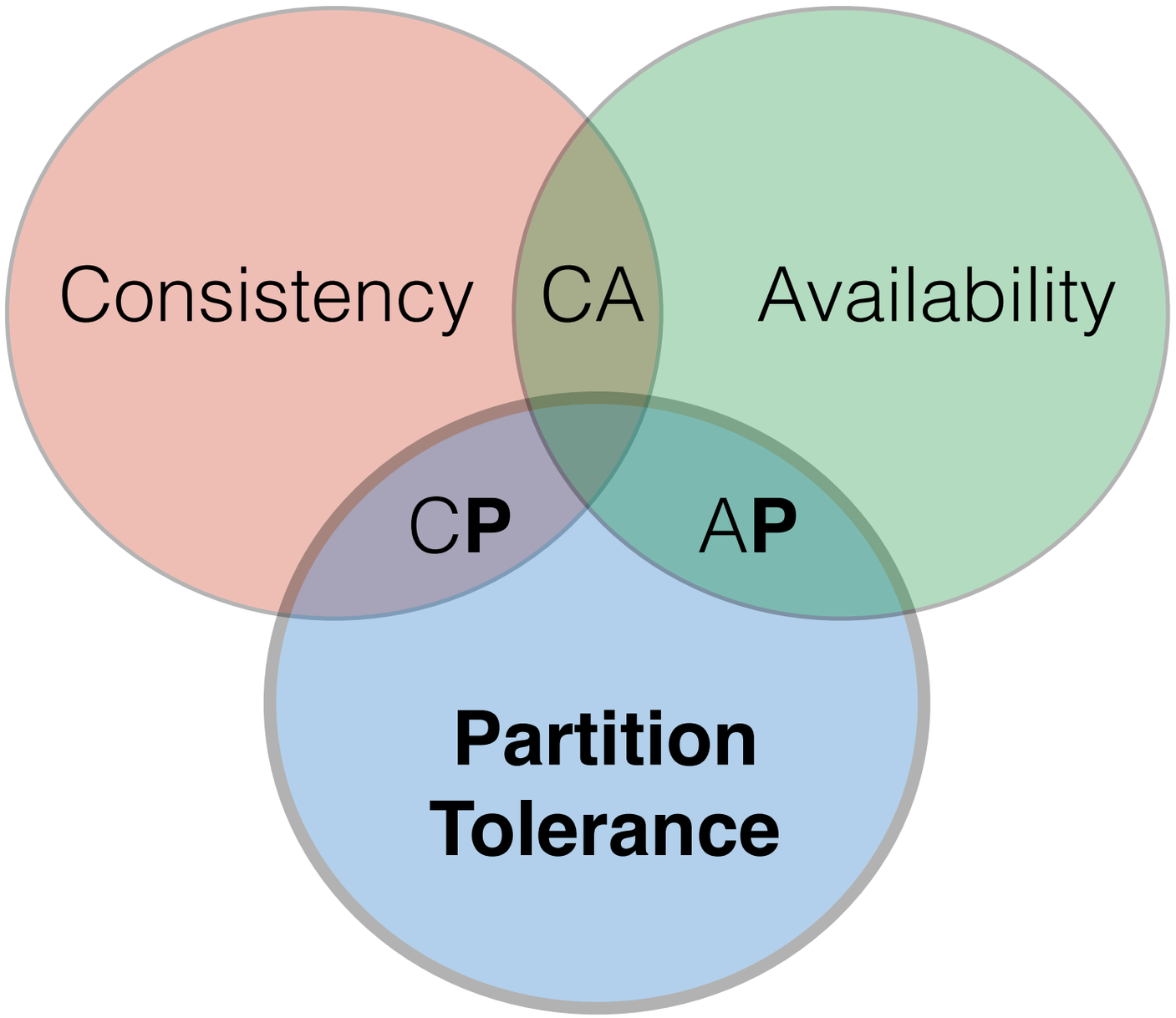
Provides fault tolerance and high availability.
Moving data closer to users improves response time.

CAP theorem



A distributed system can have only two out of the three guarantees [Brewer99]

CAP theorem



In distributed systems network partitions are unavoidable, so partition tolerance is mandatory.

Data consistency

Strong consistency

Eventual consistency

Weak consistency

- Reasoning about applications under weak consistency is fraught with technical subtleties
- Difficult to find the right balance between correctness, performance, and availability
- Requires a high-level of expertise from programmers

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- Difficult to find the right balance between correctness, performance, and availability
    - Requires a high-level of expertise from programmers

- **Goal:** To provide tools and techniques to build correct-by-design distributed programs from correct sequential programs

CRDTs: distributed set

- Sequential specification
  - {true} add(e) { e ∈ S }
  - {true} rmv(e) { e ∉ S }
- Commutative (e ≠ f):
  - {true} add(e) || add(e) { e ∈ S }
  - {true} rmv(e) || rmv(e) { e ∉ S }
  - {true} add(e) || add(f) { e,f ∈ S }
  - {true} rmv(e) || rmv(f) { e, f ∉ S }
  - {true} add(e) || rmv(f) { e ∈ S, f ∉ S }
- Deterministic conflict resolution policy:
  - {true} add(e) || rmv(e) { e ∈ S } **Add-wins**

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  - {true} add(e) || rmv(f) { e ∈ S, f ∉ S }
- Deterministic conflict resolution policy:
  - {true} add(e) || rmv(e) { e ∉ S } **Remove-wins**

CRDTs in the wild

Convergence is not enough to ensure application invariants

https://pages.lip6.fr/syncfree

e-games platform

player
alice
bob
eve

Set CRDT

enrolled
(alice,apex)
(bob,battle)
(alice,battle)

Set CRDT

tournament
apex
battle

Set CRDT

Invariant: A player may only enroll in an existing tournament (referential integrity)

Concurrent updates

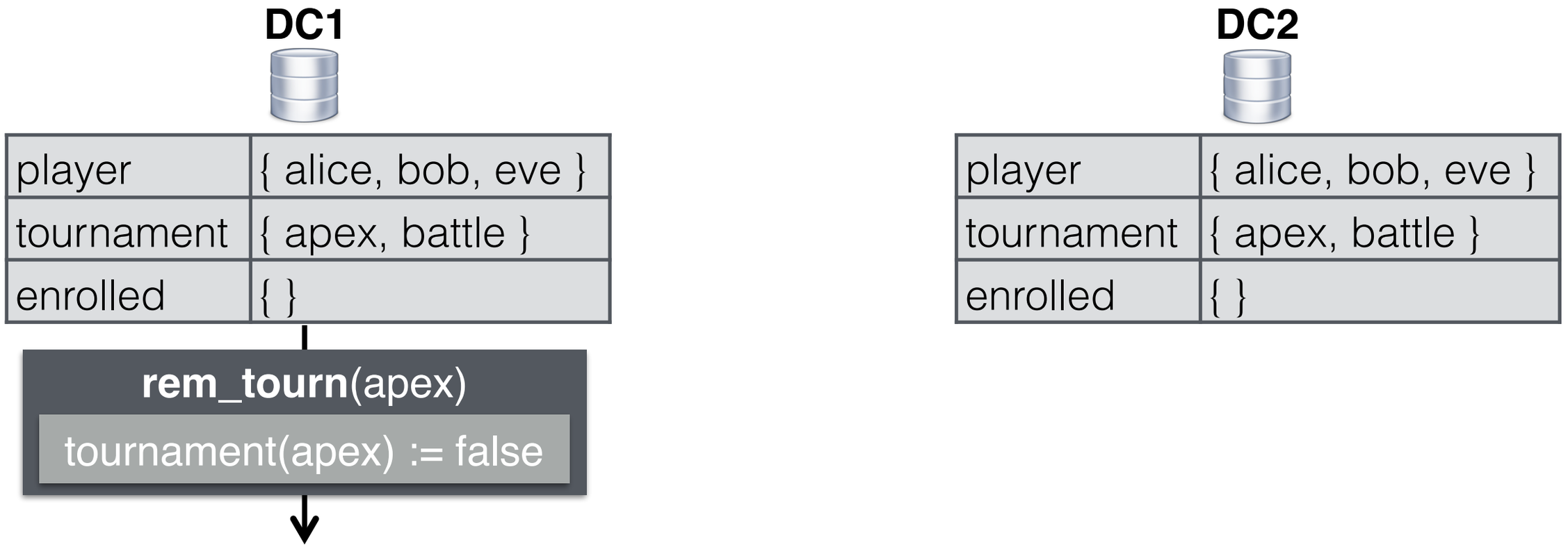
DC1

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ }

DC2

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ }

Concurrent updates



Concurrent updates

DC1

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ }

rem_tourn(apex)

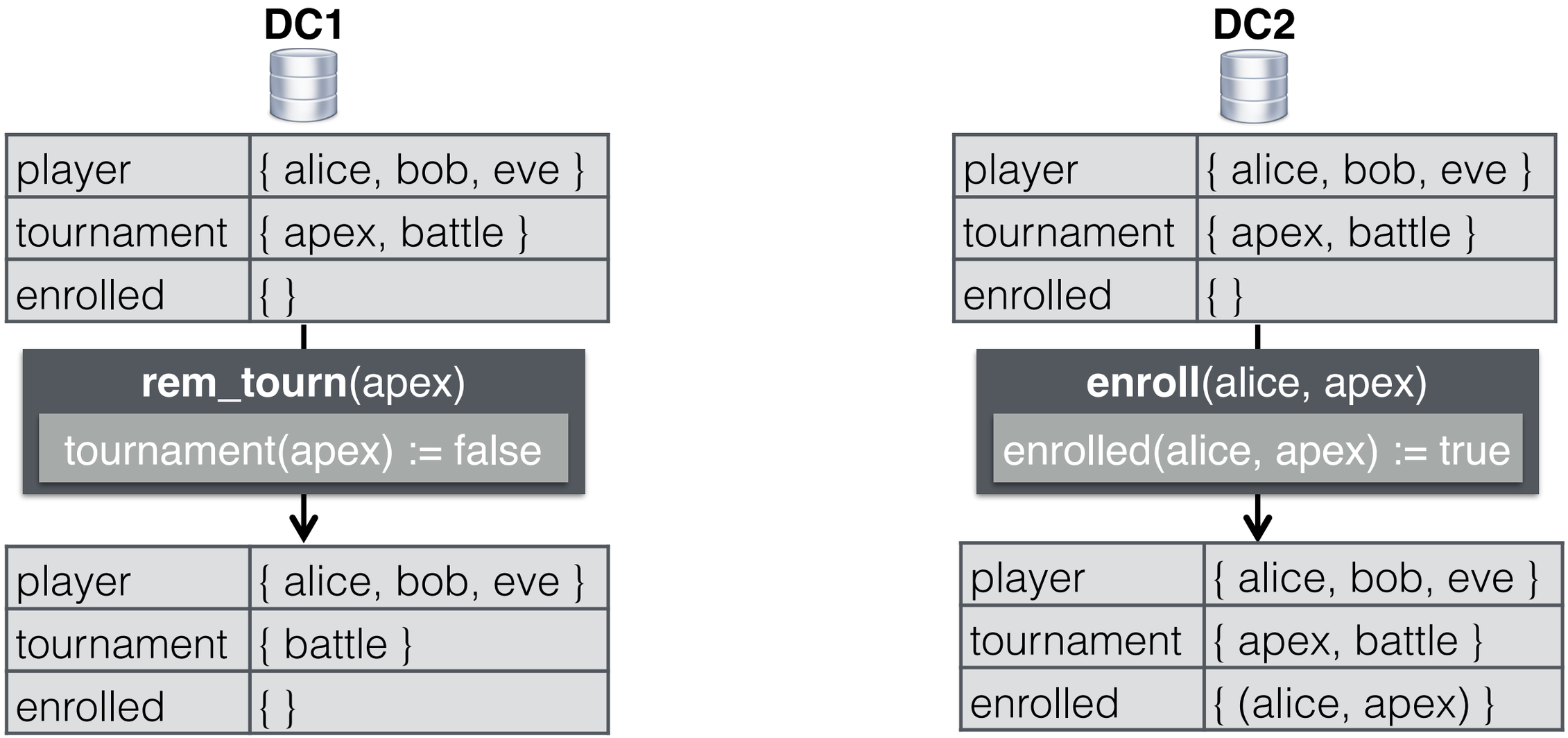
tournament(apex) := false

player	{ alice, bob, eve }
tournament	{ battle }
enrolled	{ }

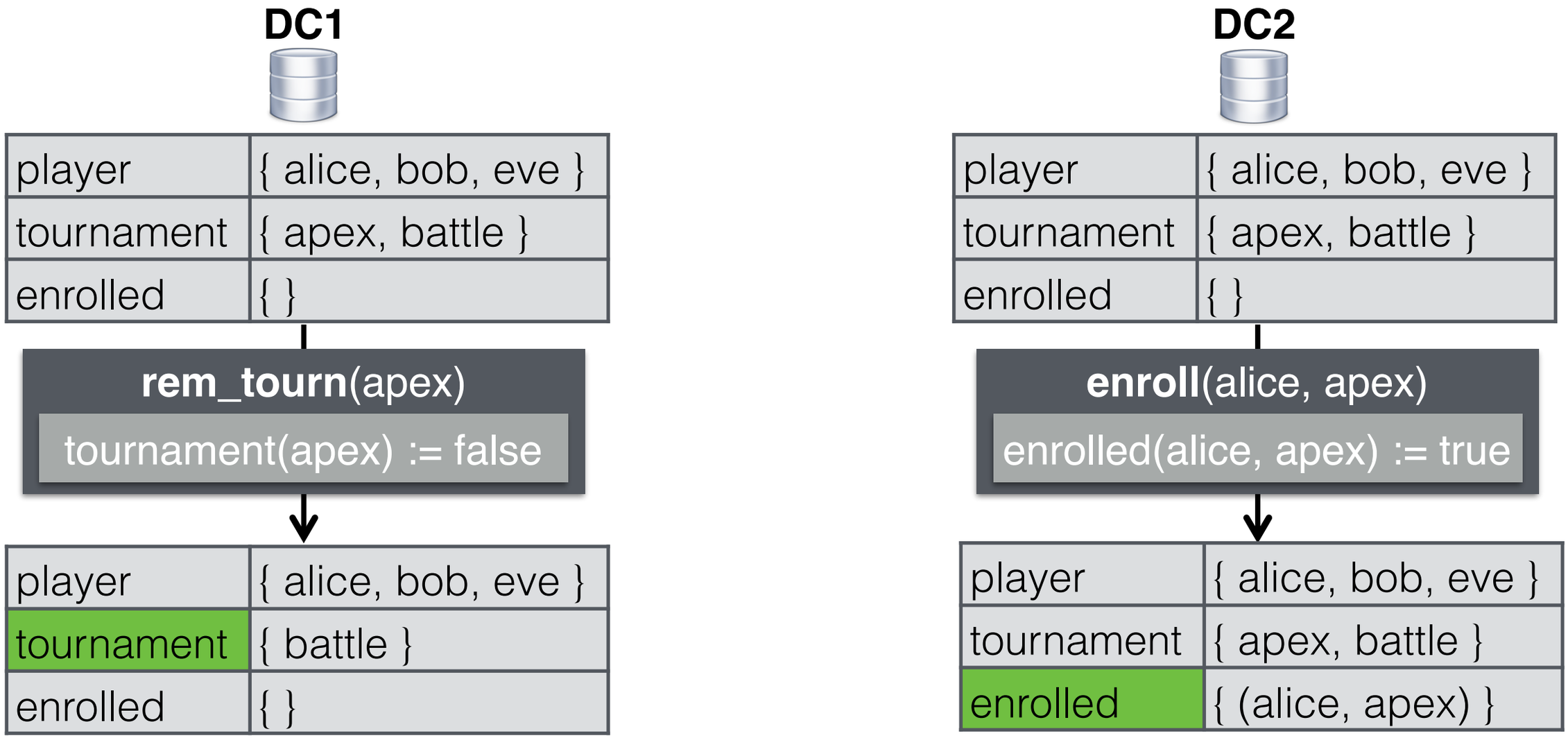
DC2

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ }

Concurrent updates



Concurrent updates



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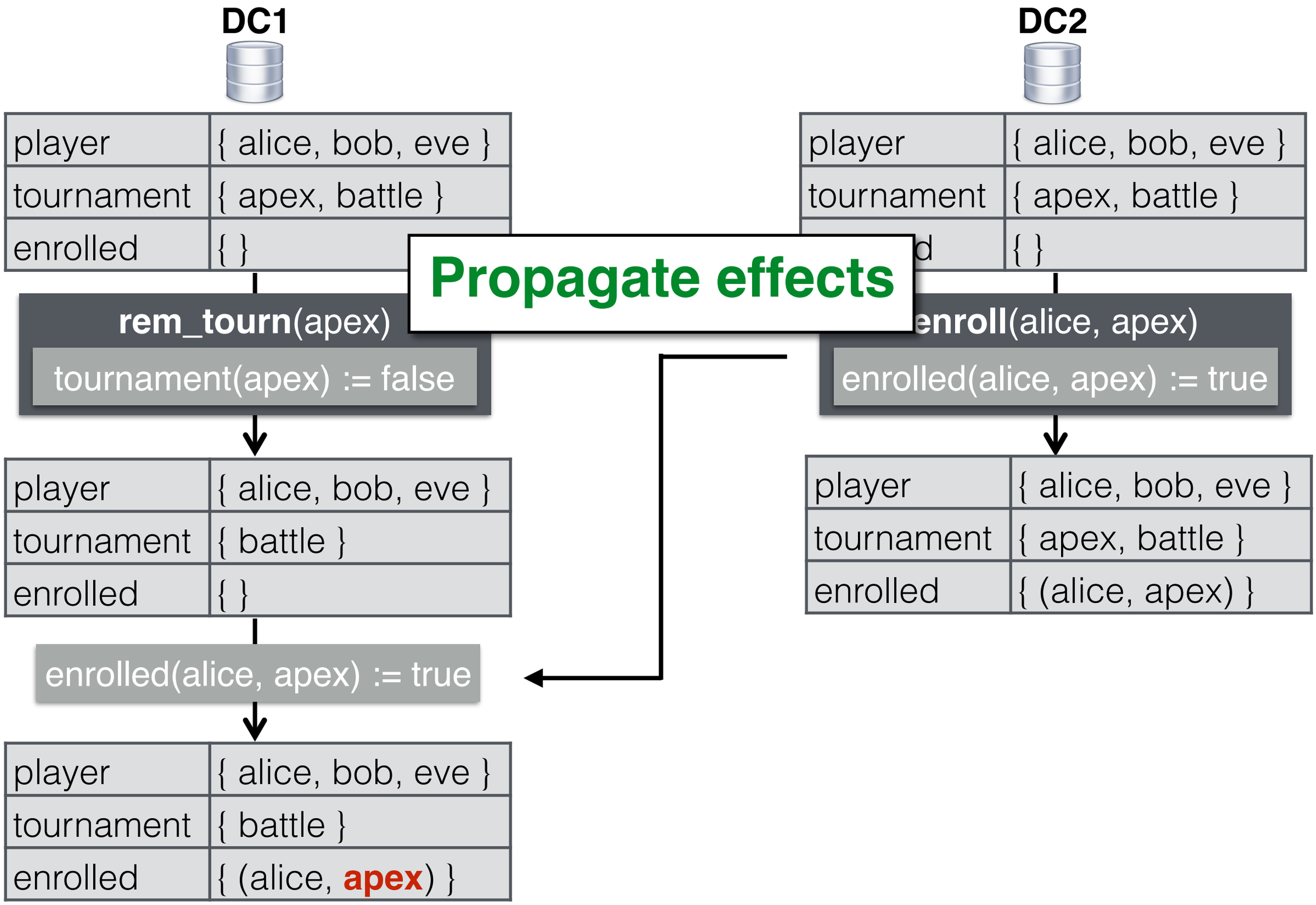

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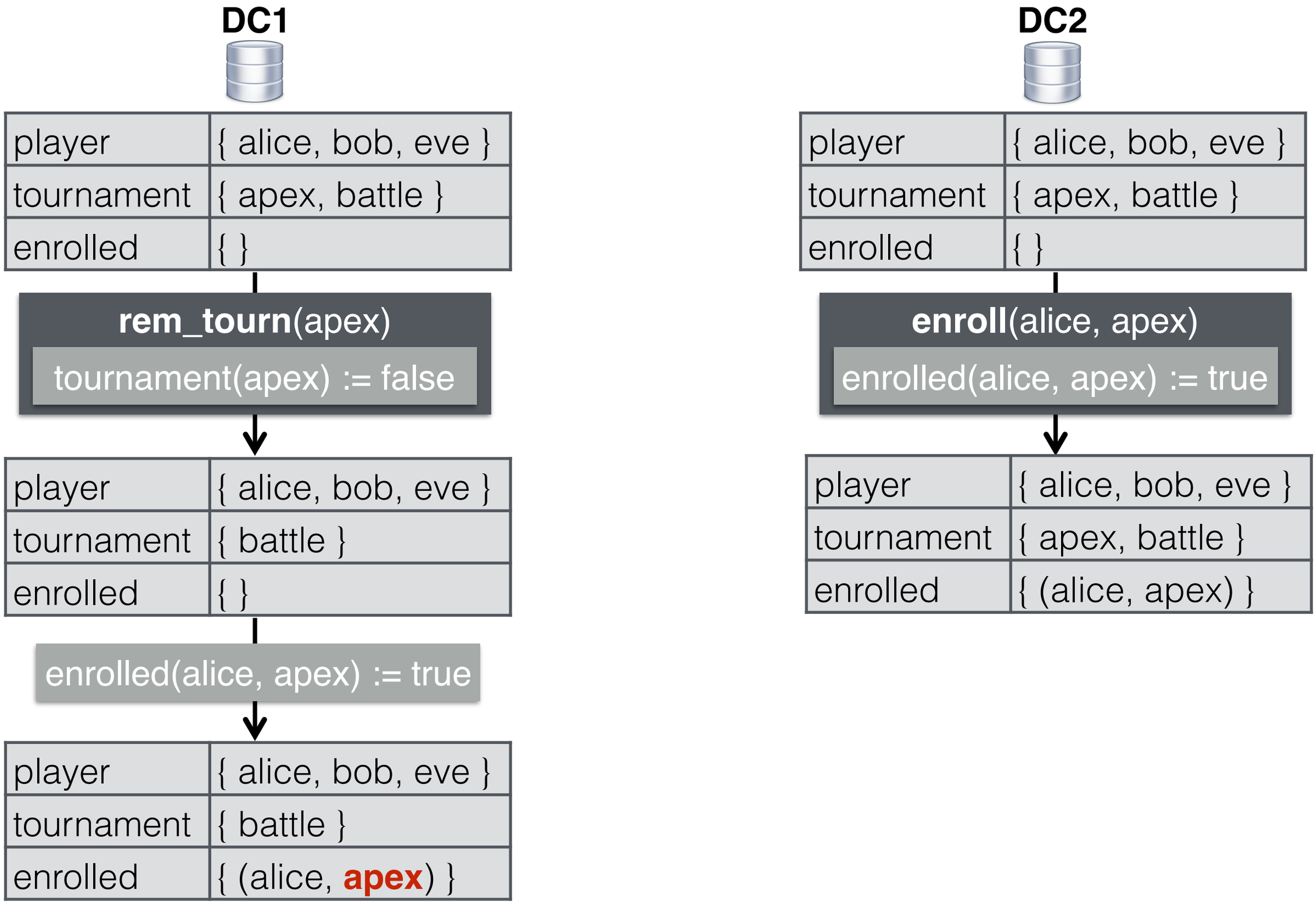
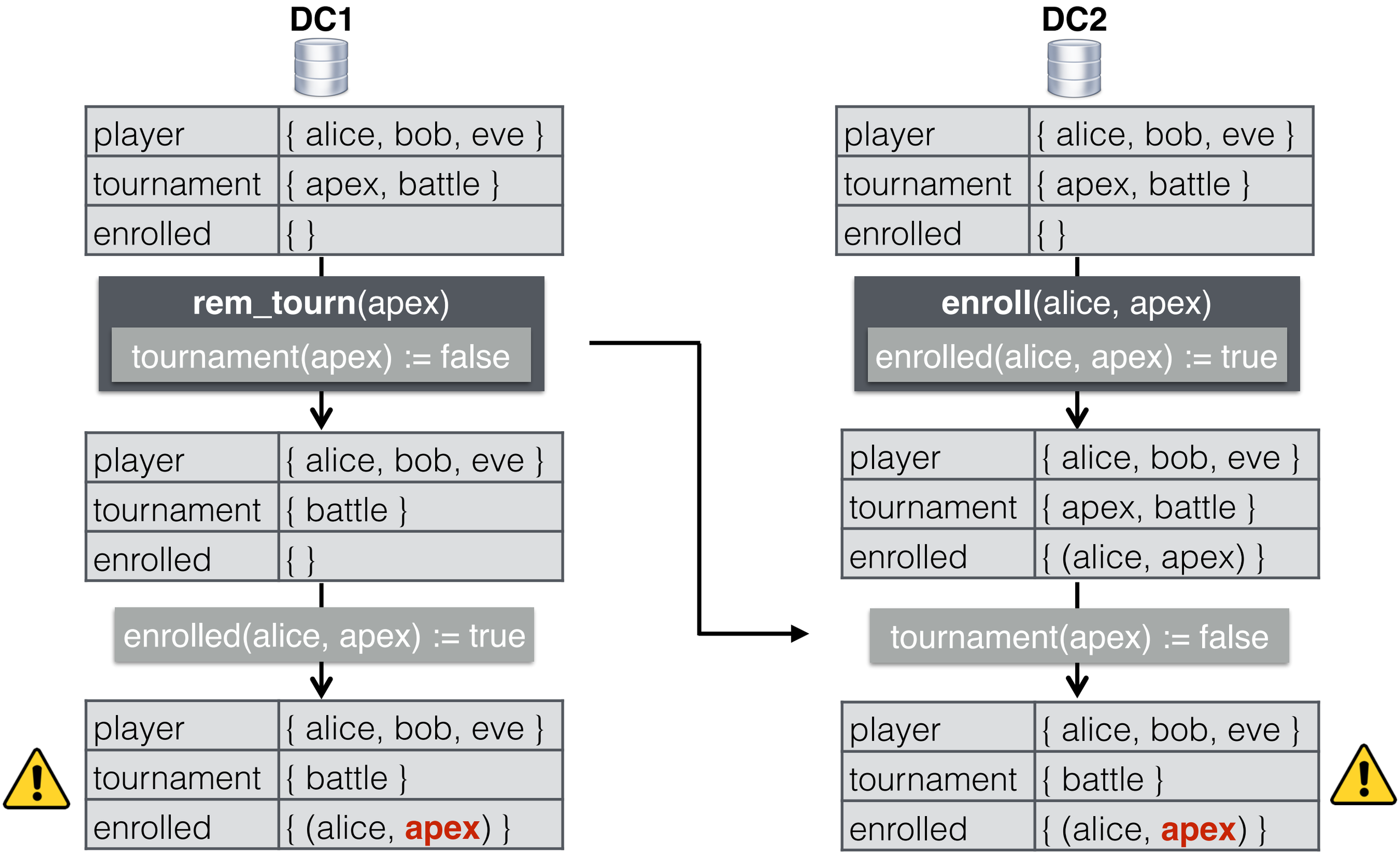


Concurrent updates



State converges,
but the invariant is broken

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player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ }

rem_tourn(apex)

tournament(apex) := false

player	{ alice, bob, eve }
tournament	{ battle }
enrolled	{ }

enrolled(alice, apex) := true

player	{ alice, bob, eve }
tournament	{ battle }
enrolled	{ (alice, **apex**) }

DC2

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ }

enroll(alice, apex)

enrolled(alice, apex) := true

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ (alice, apex) }

tournament(apex) := false

player	{ alice, bob, eve }
tournament	{ battle }
enrolled	{ (alice, **apex**) }

Invariants are global properties
replicas only have local information

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player	{ alice, bob, eve }
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player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ (alice, apex) }

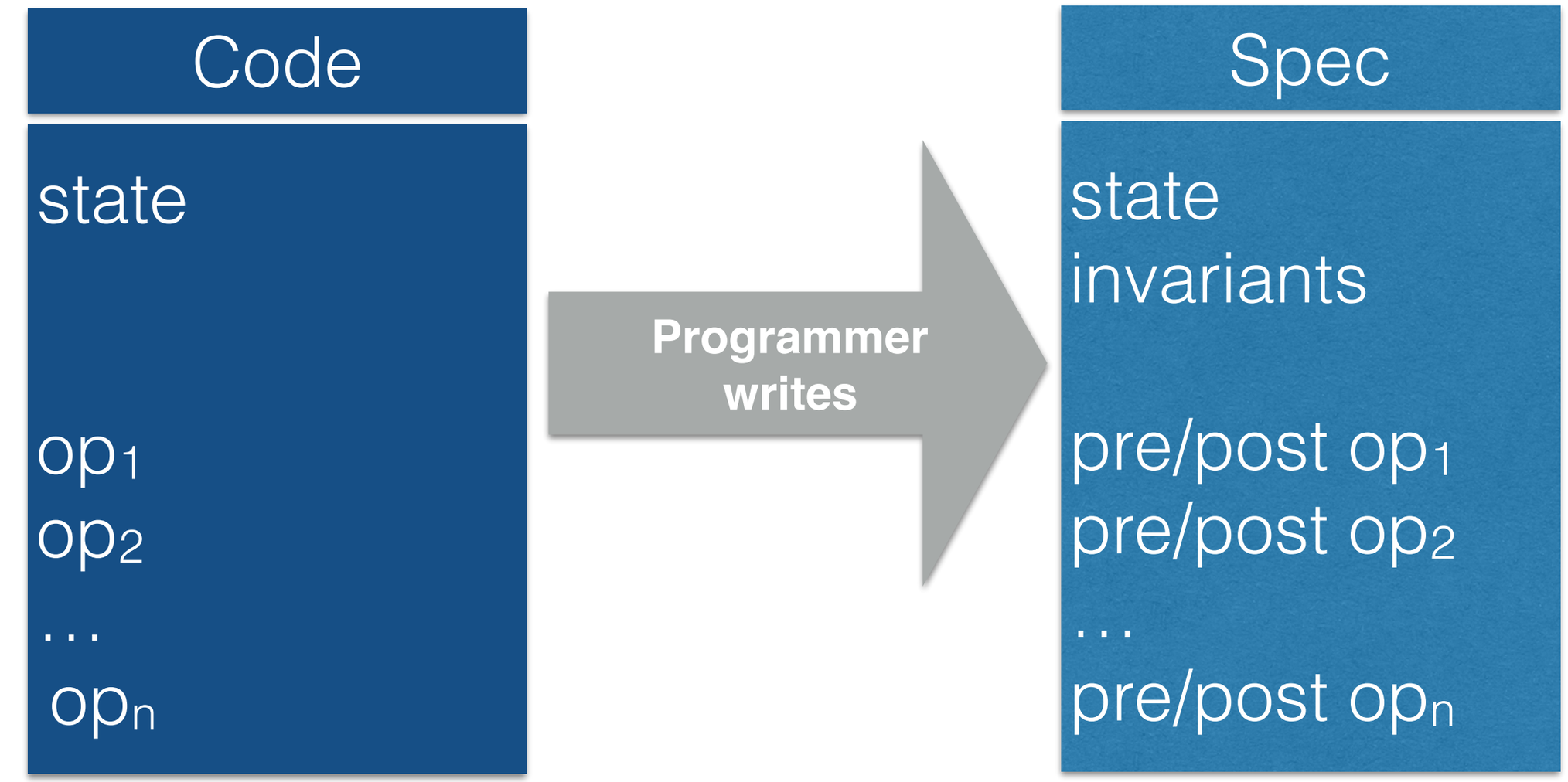
tournament(apex) := false

player	{ alice, bob, eve }
tournament	{ battle }
enrolled	{ (alice, **apex**) }

Techniques explored

- Invariant violation avoidance [EuroSys'15, POPL'16]
  - Prevent conflicting executions
  - Minimize synchronization
- Invariant preservation [VLDB'19]
  - Transform operations
  - Repair invariant when conflicting operations execute concurrently
  - Avoid synchronization altogether

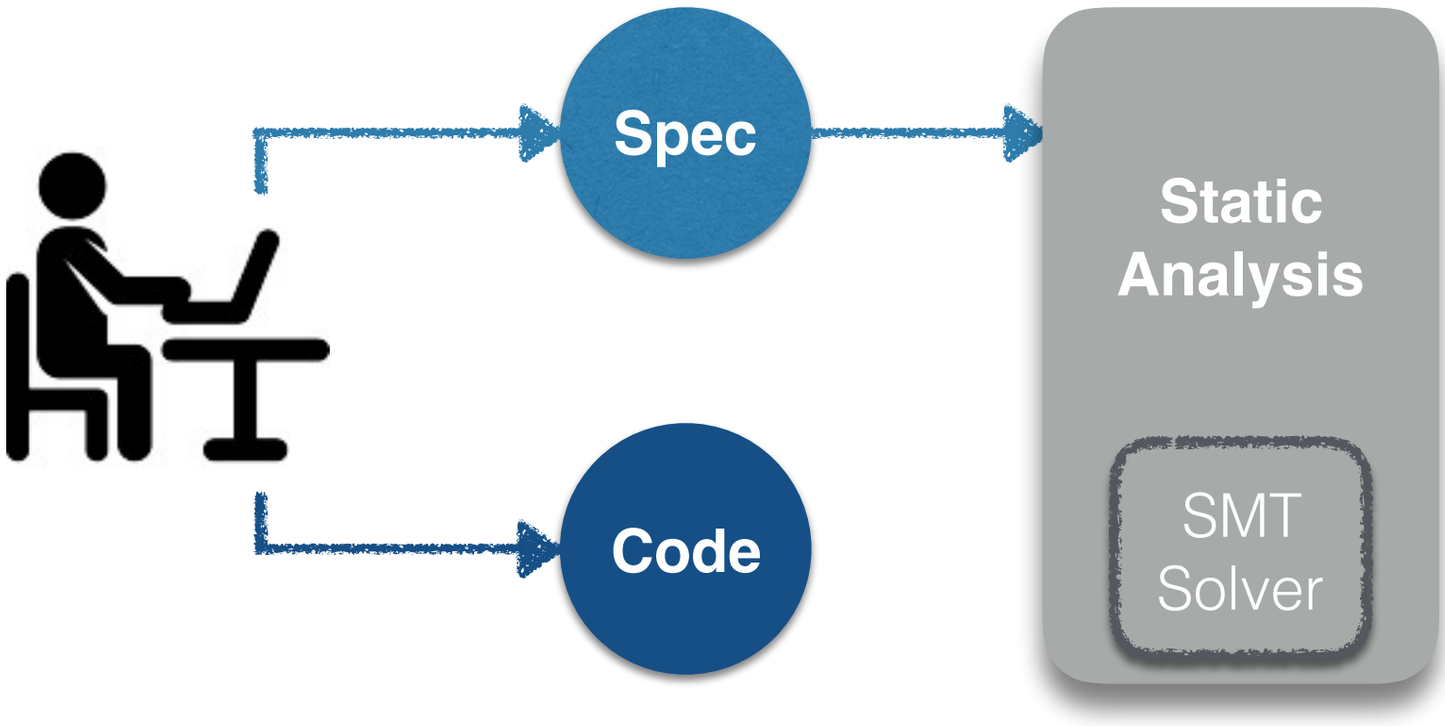
Methodology



Java, C, Ruby, …

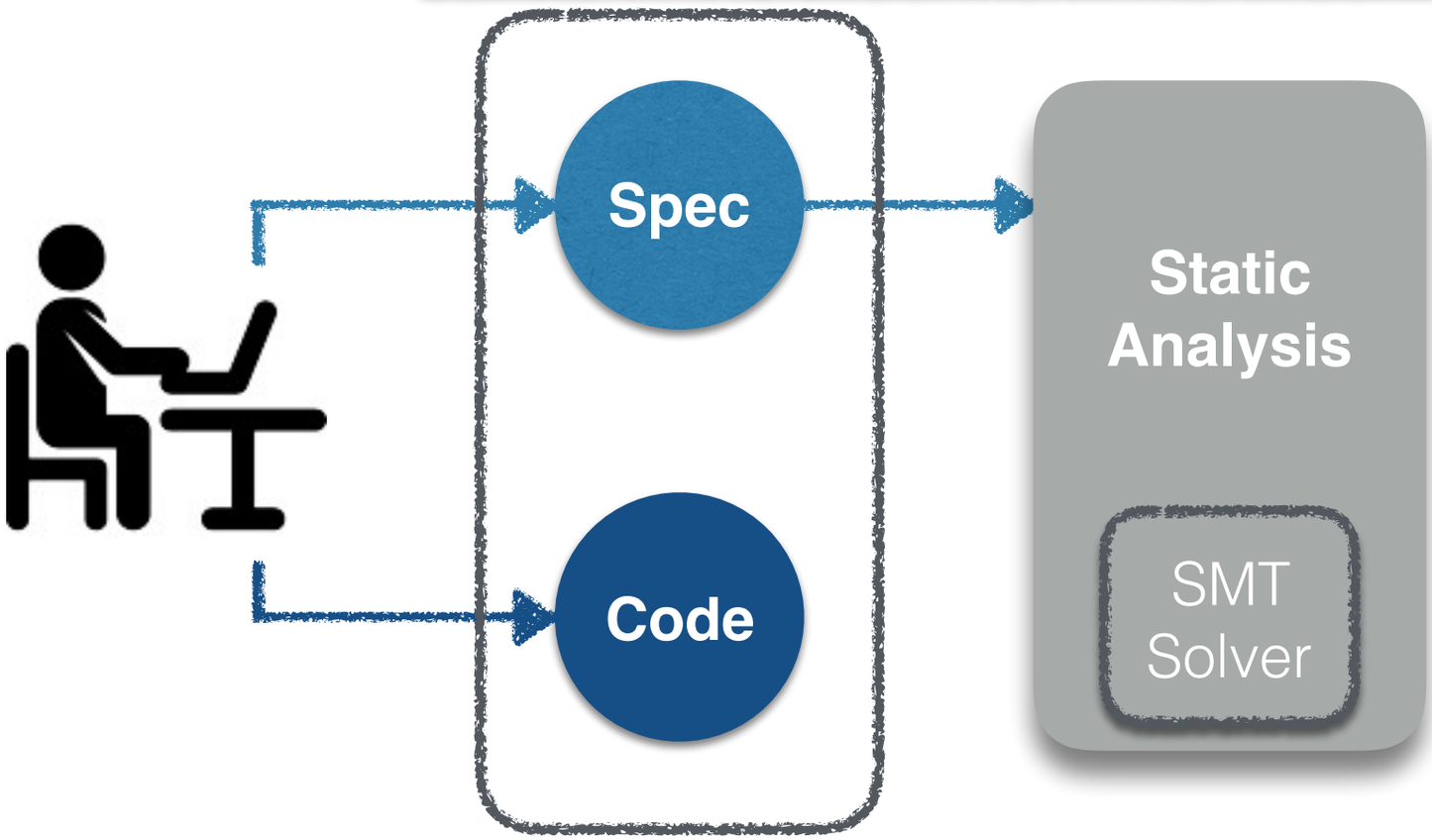
Boogie, Why3, …

Developer should focus on the application invariants



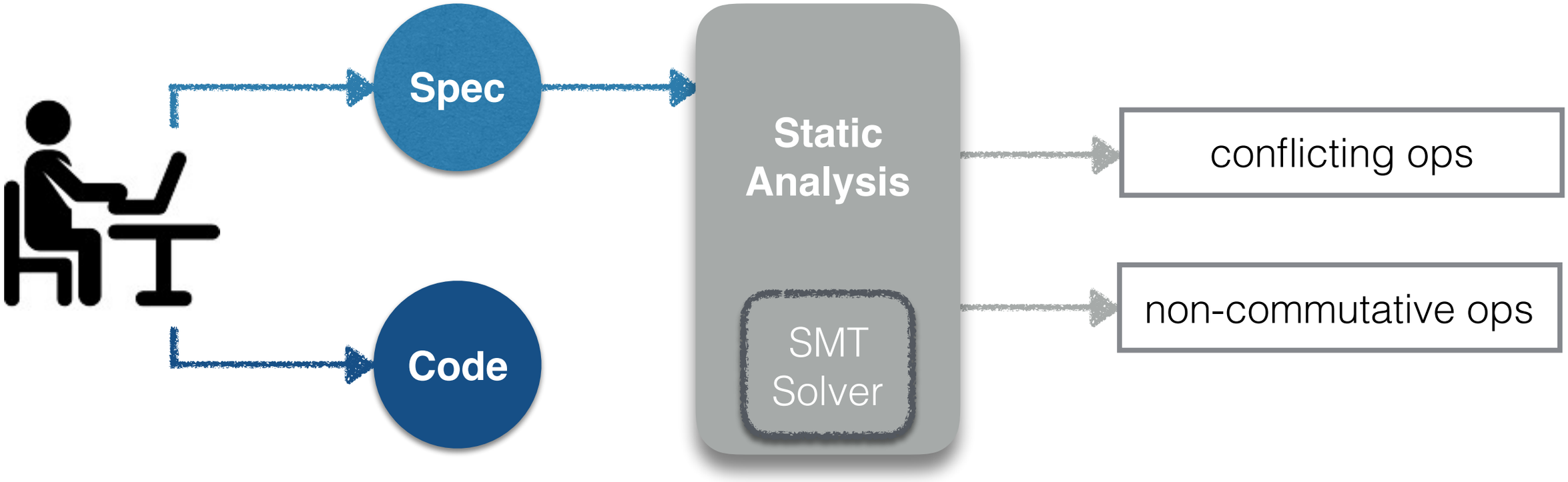
Developer should focus on the application invariants

Ignore concurrency problems raised by geo-replication



sequential code

Detect problematic concurrent operations



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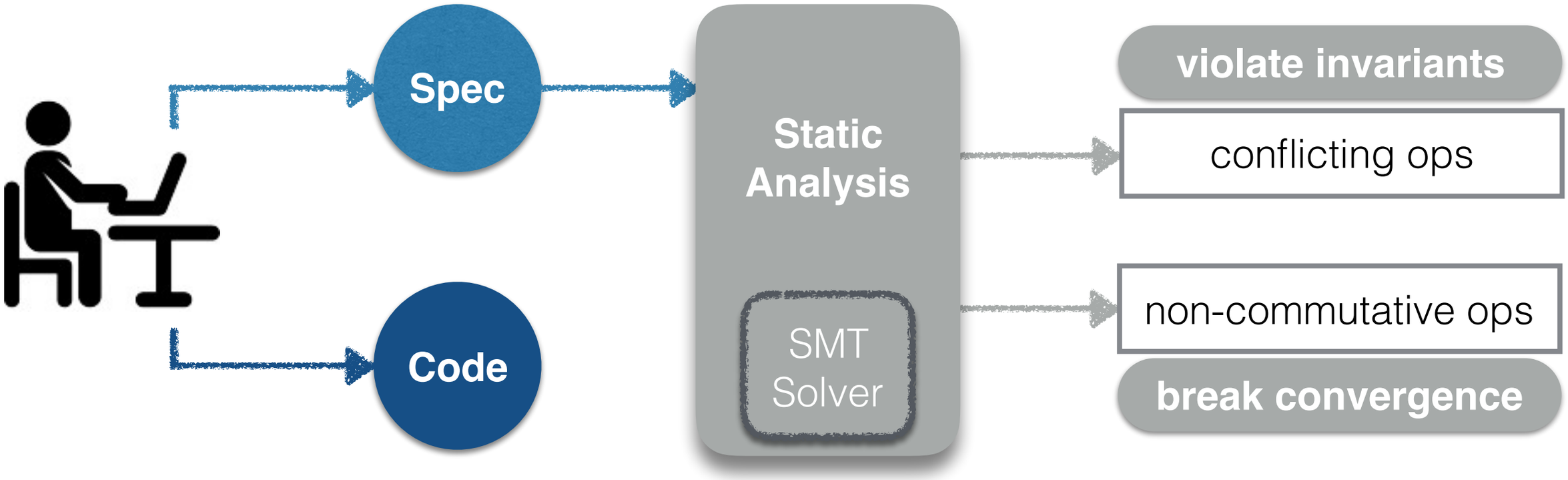
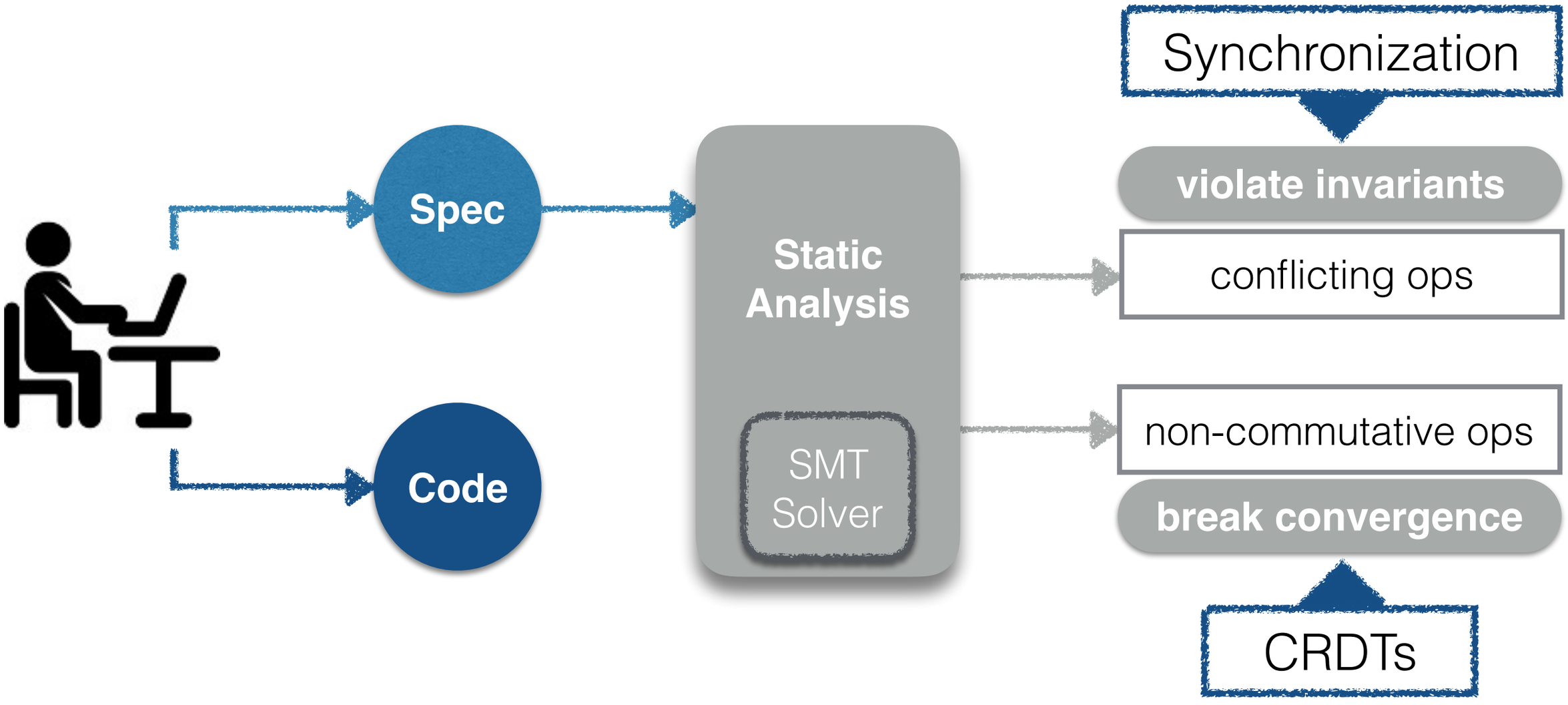


Select mechanisms to make problematic operations safe



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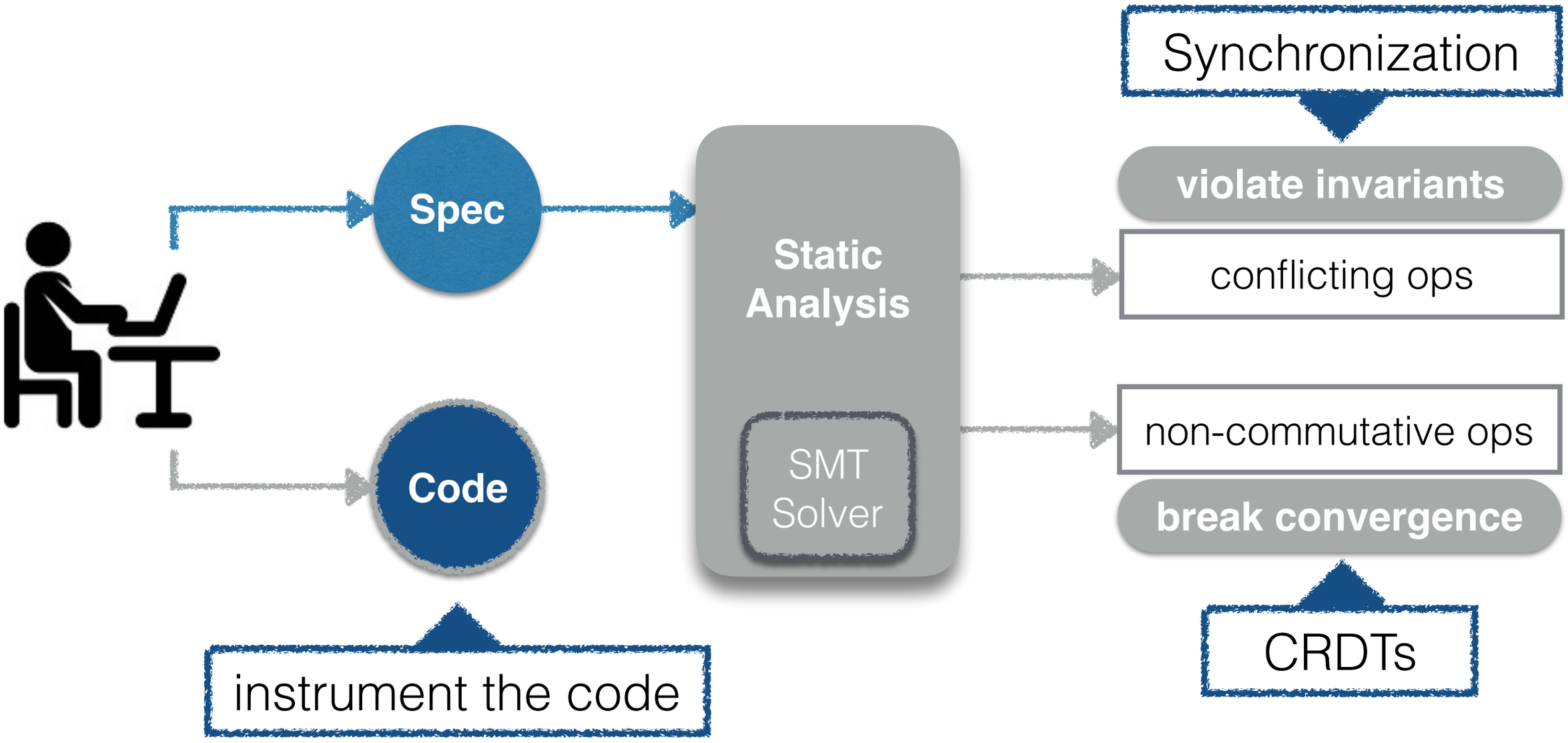
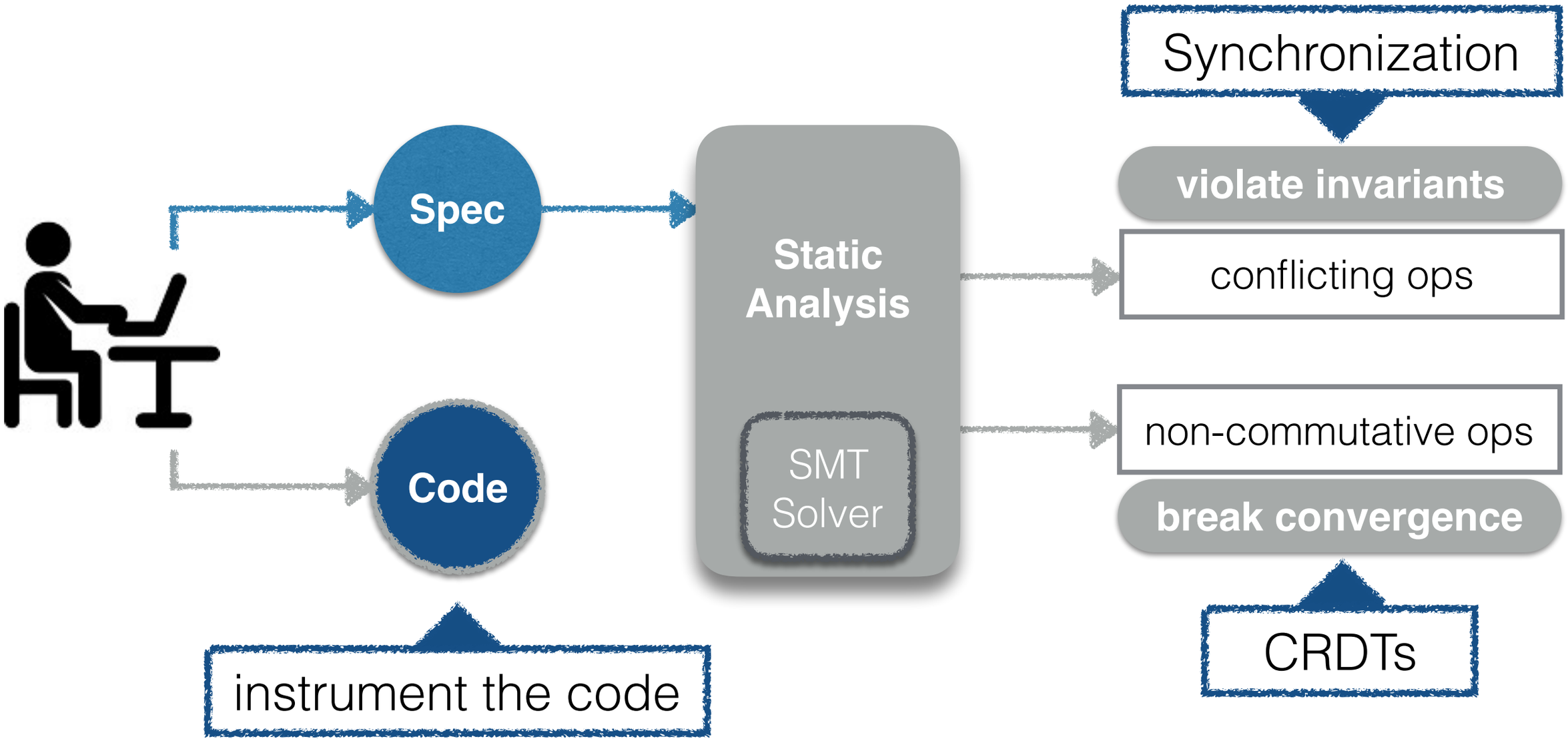
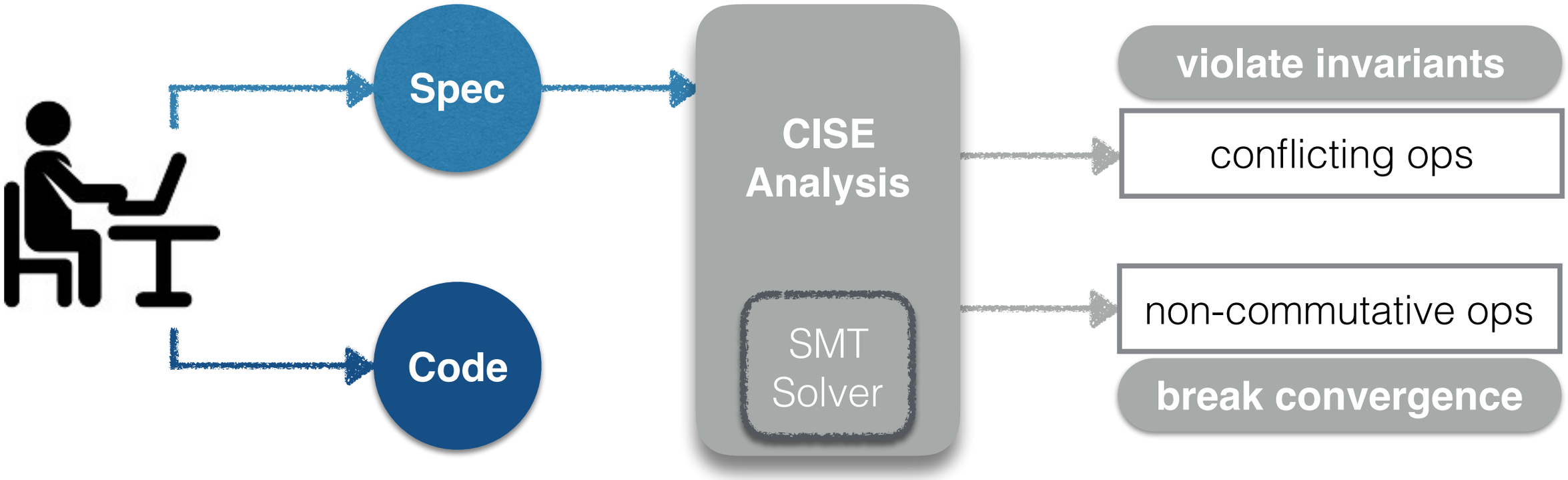


Select mechanisms

No insurance that the developer made the right choices



CISE: check the safety of synchronization choices



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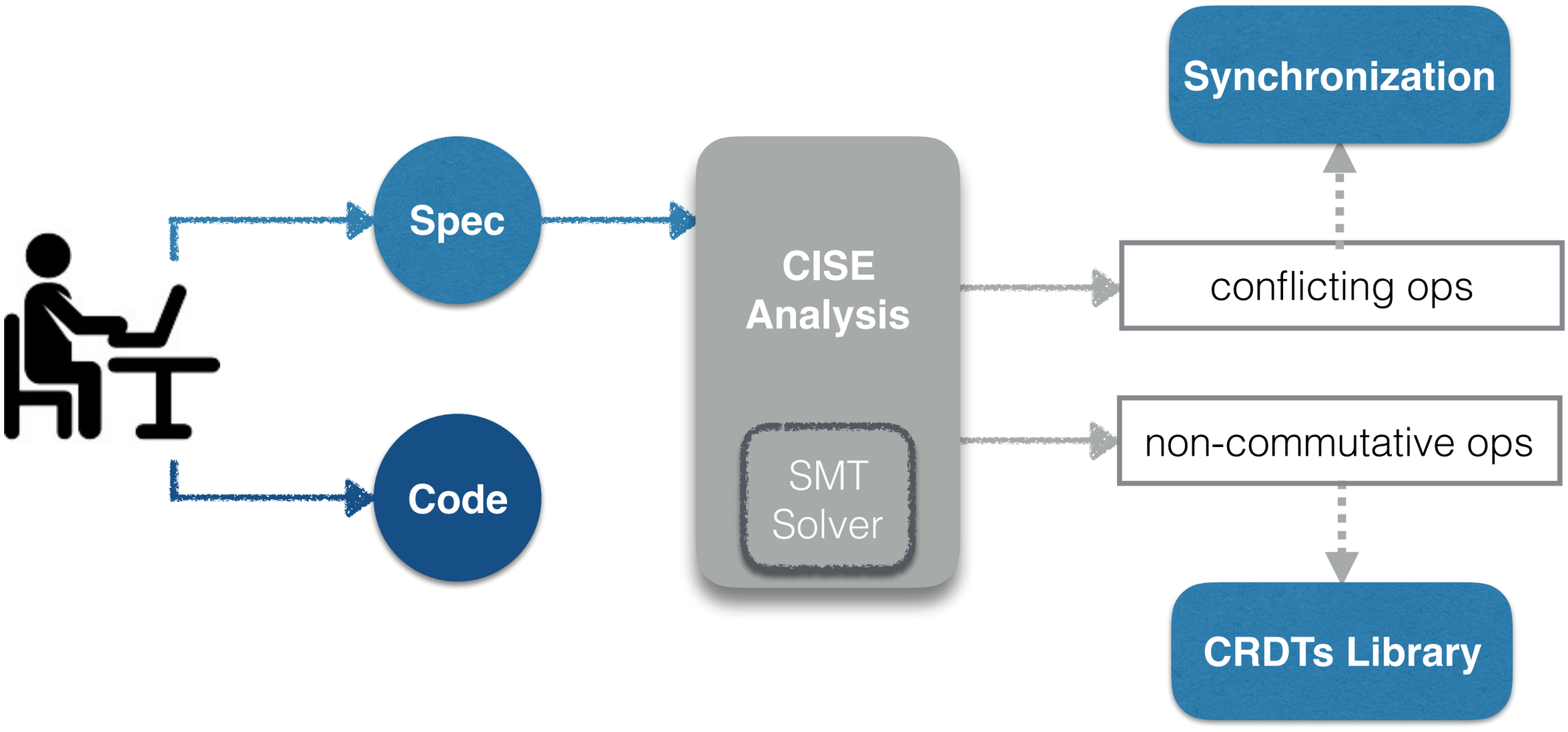

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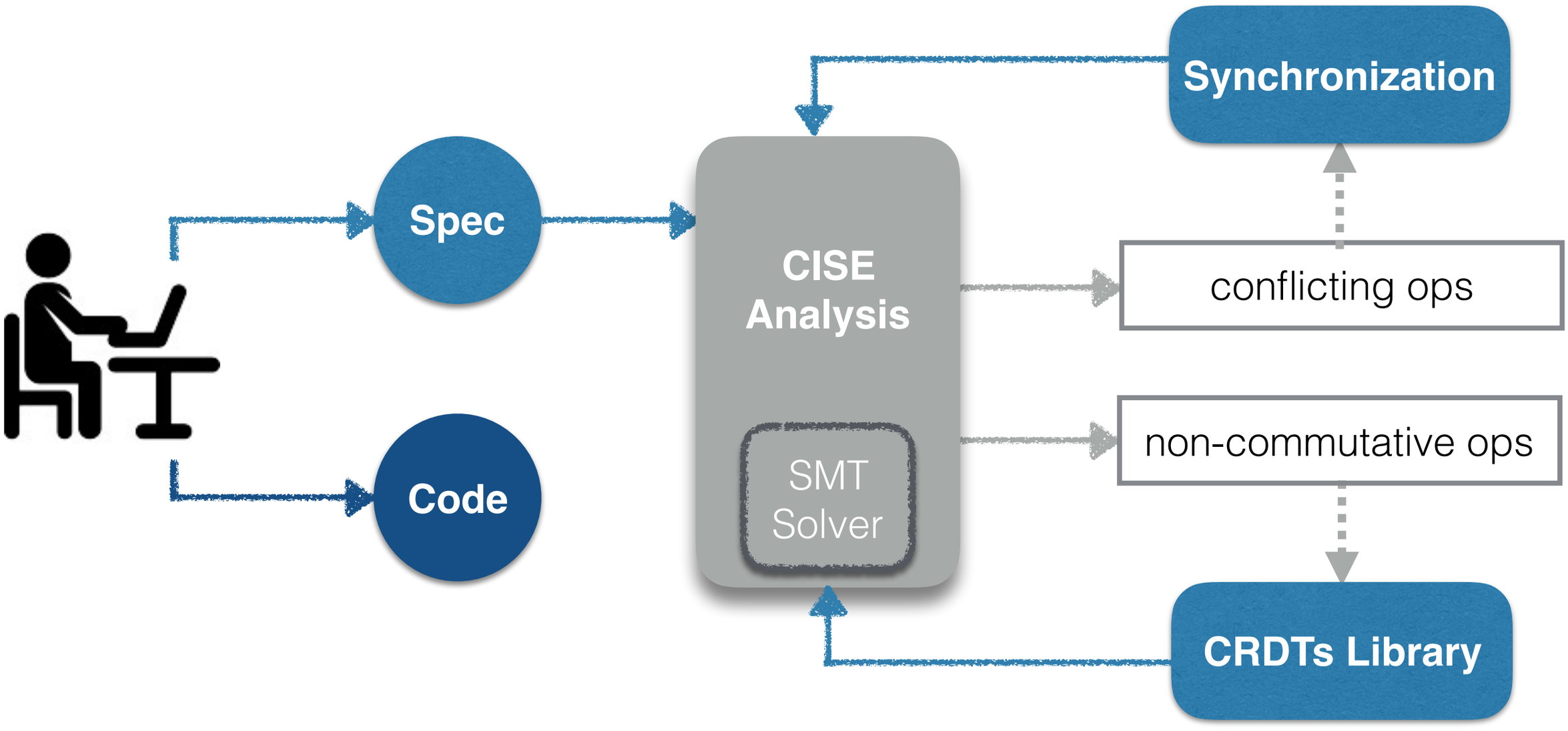
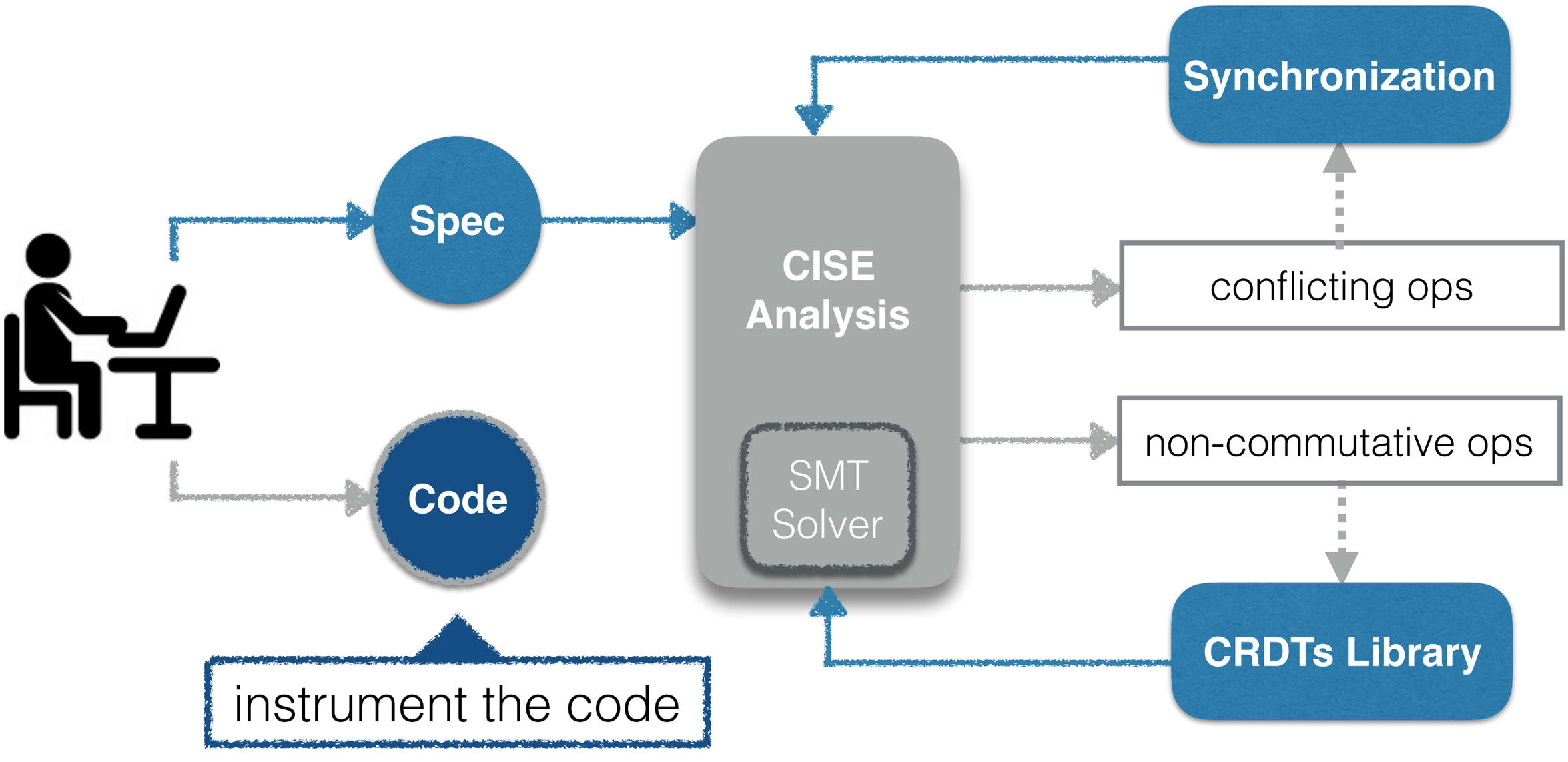
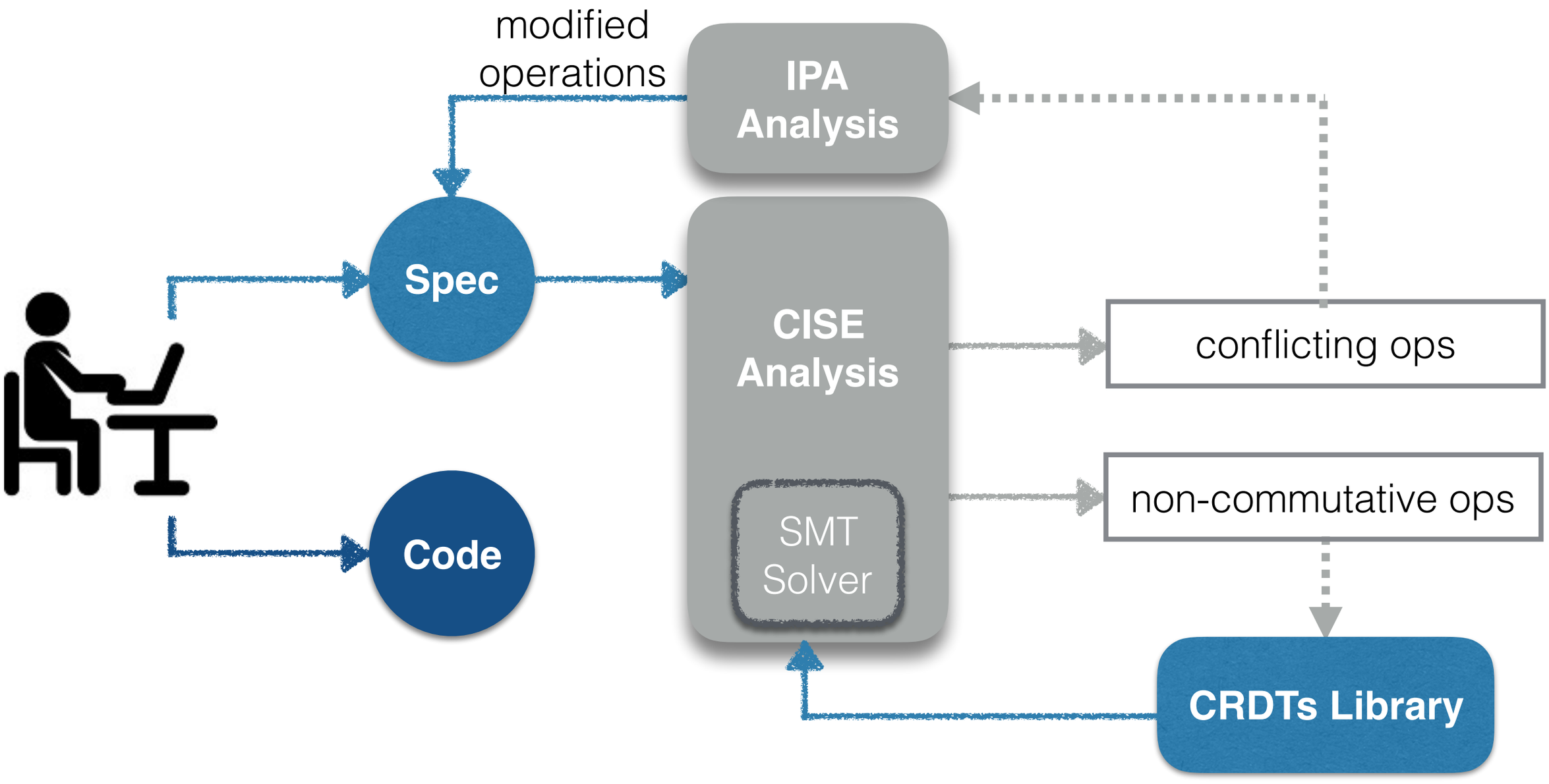


Correct-by-design* distributed application

*if the code satisfies the specification



Repairing invariants to avoid synchronization



DC1

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ }

rem_tourn(apex)

tournament(apex) := false

player	{ alice, bob, eve }
tournament	{ battle }
enrolled	{ }

DC2

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ }

enroll(alice, apex)

enrolled(alice, apex) := true

player	{ alice, bob, eve }
tournament	{ apex, battle }
enrolled	{ (alice, apex) }

Instead of repairing after the invariant violation preemptively add a repair to the operation

DC1

player	{ alice, bob, eve }
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tournament(apex) := true

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Instead of repairing after the invariant violation preemptively add a repair to the operation

Repair should have no observable effect, if no conflict occurs

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enroll(alice, apex)

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tournament(apex) := true

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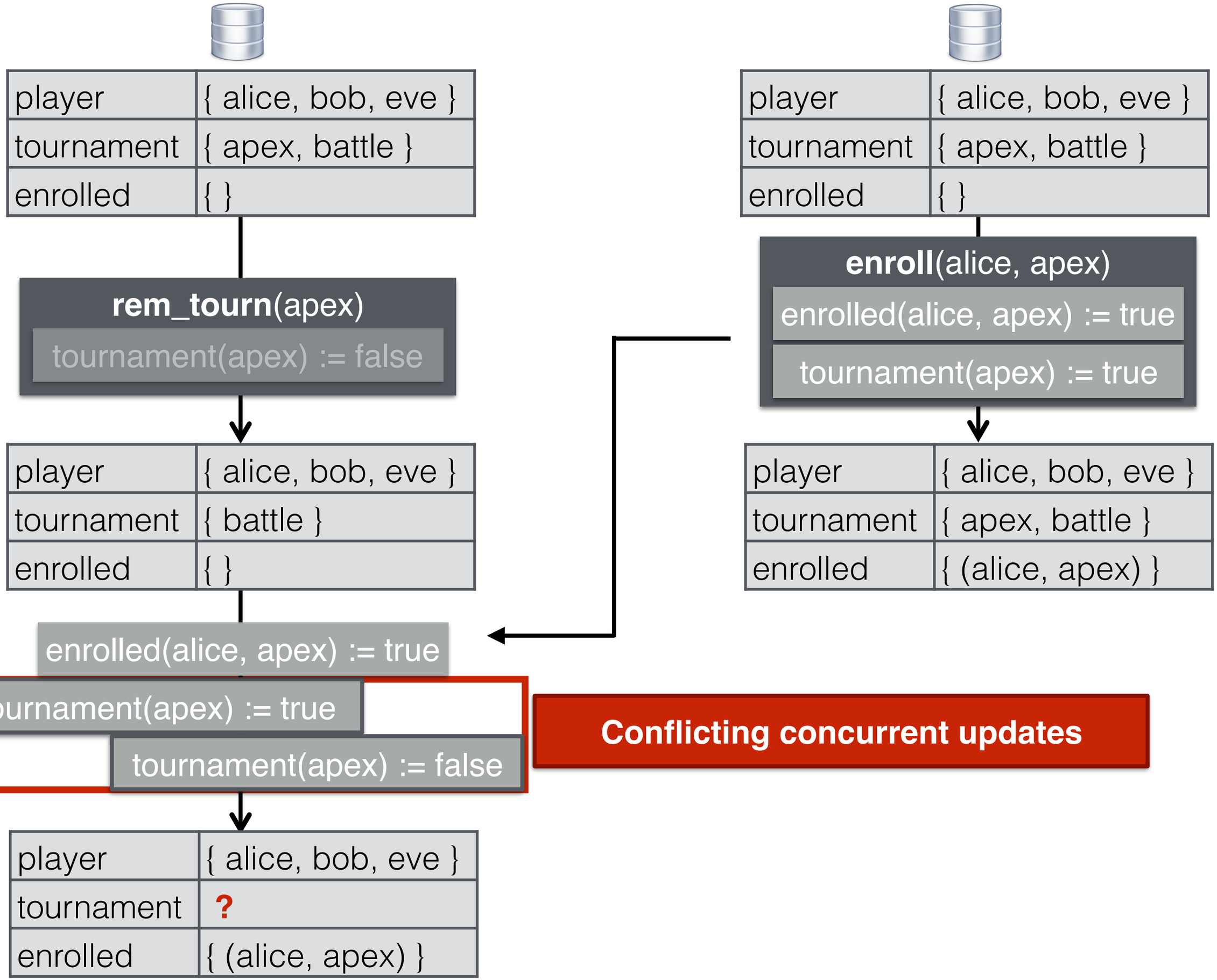
player
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tournament
{ apex, battle }
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tournament(apex) := false
player
{ alice, bob, eve }
tournament
{ battle }
enrolled
{ }
enrolled(alice, apex) := true
tournament(apex) := true
tournament(apex) := false
player
{ alice, bob, eve }
tournament
?
enrolled
{ (alice, apex) }
enroll(alice, apex)
enrolled(alice, apex) := true
tournament(apex) := true
player
{ alice, bob, eve }
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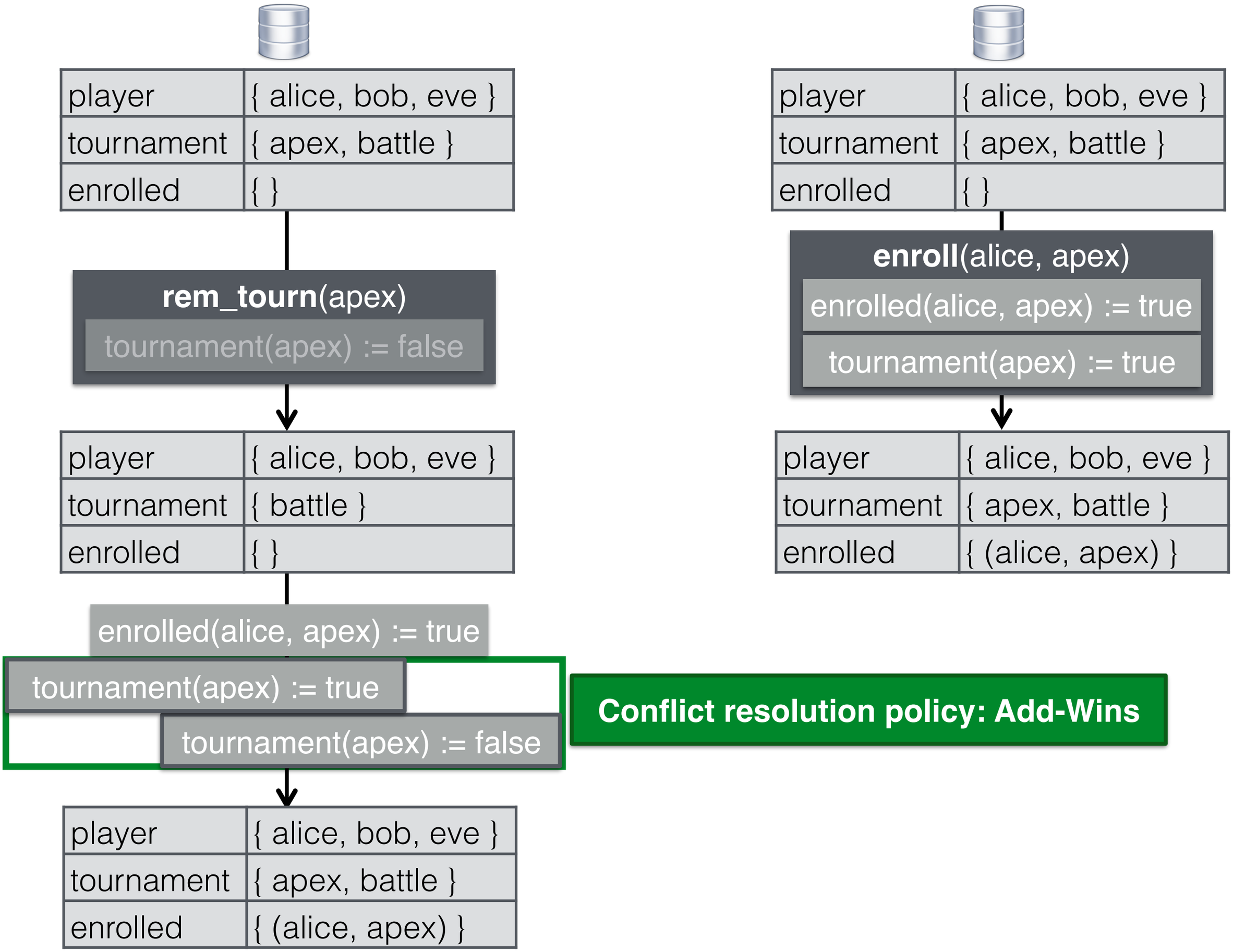
Conflicting concurrent updates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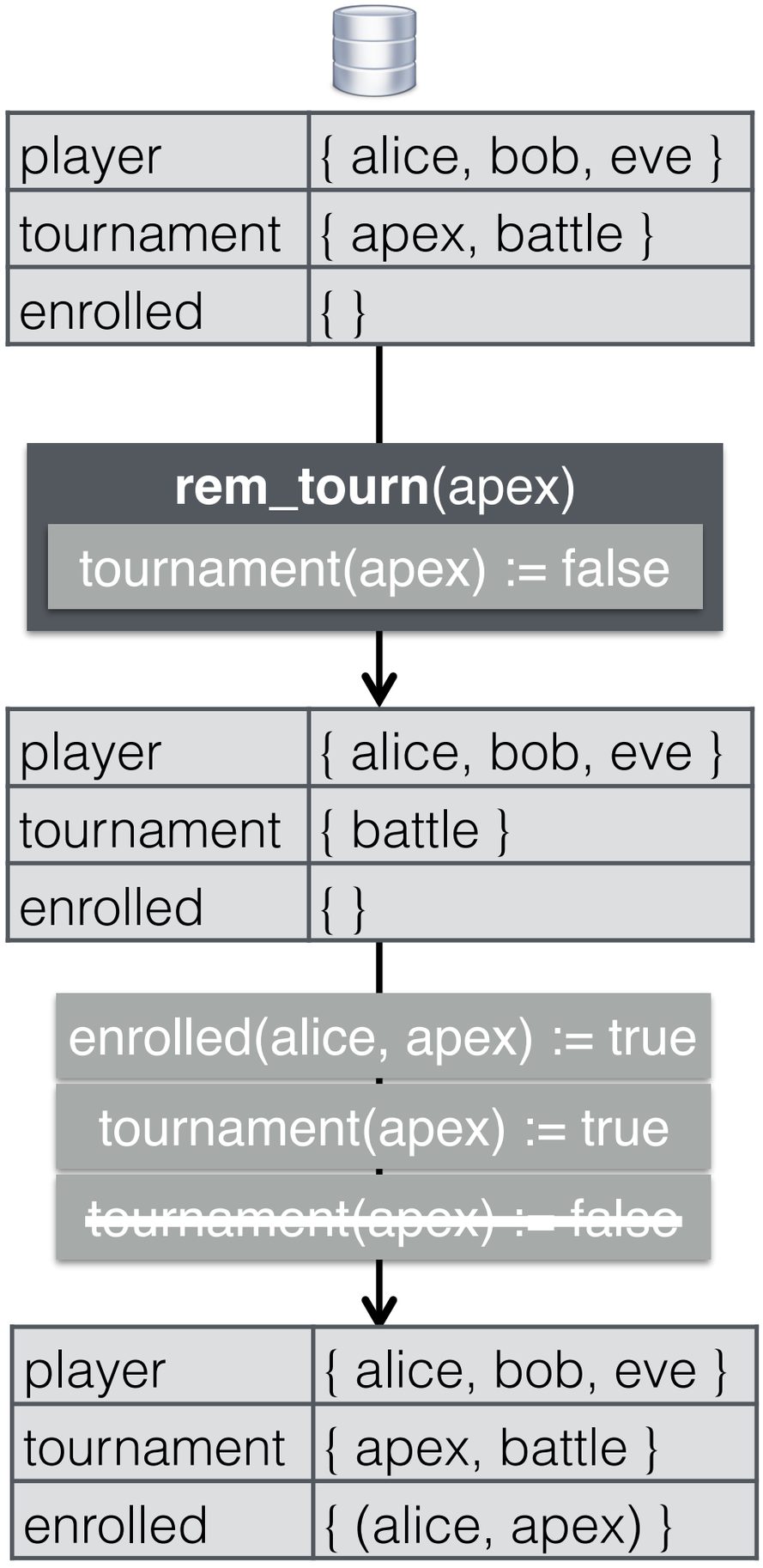
Conflict resolution policy: Add-Wins



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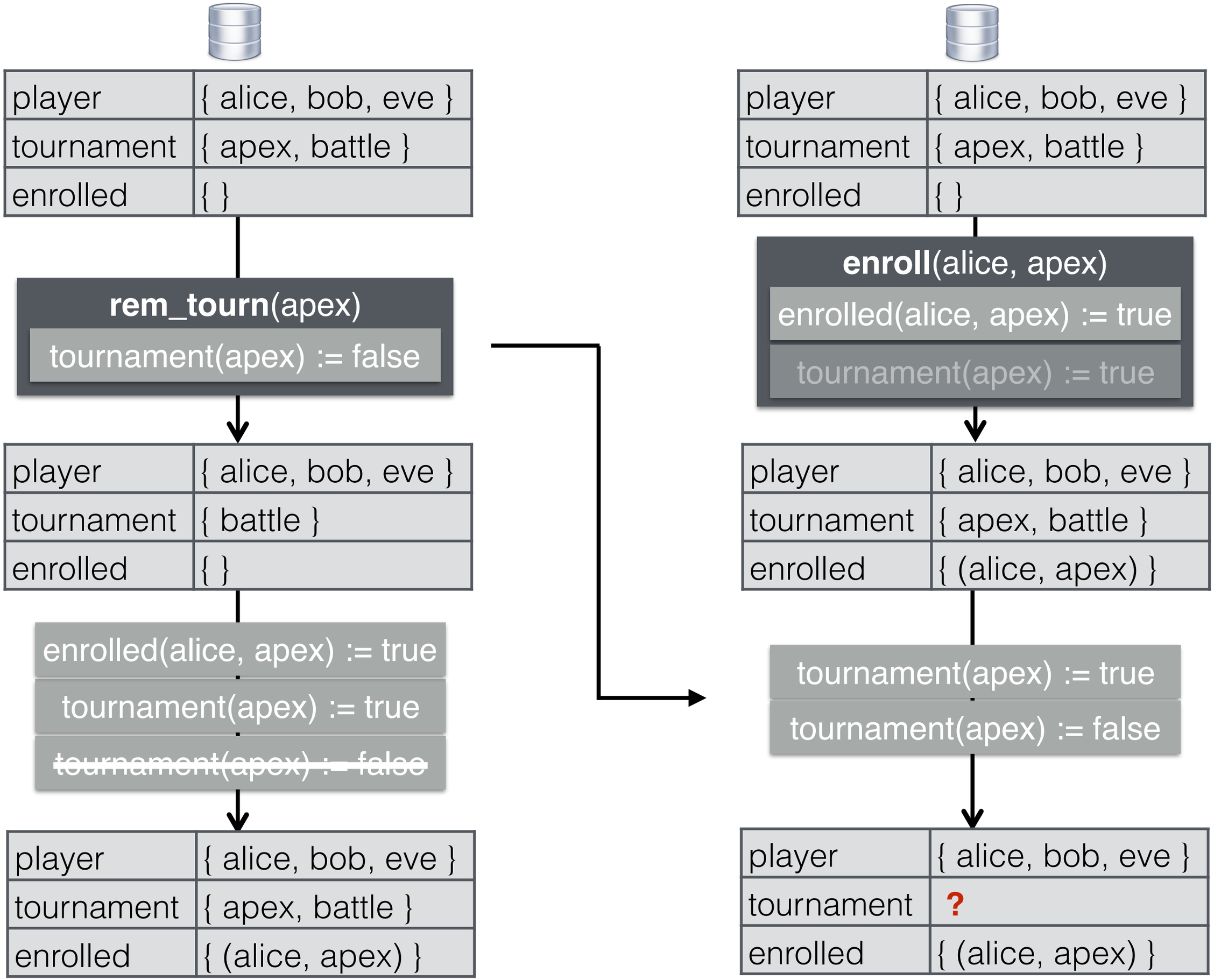
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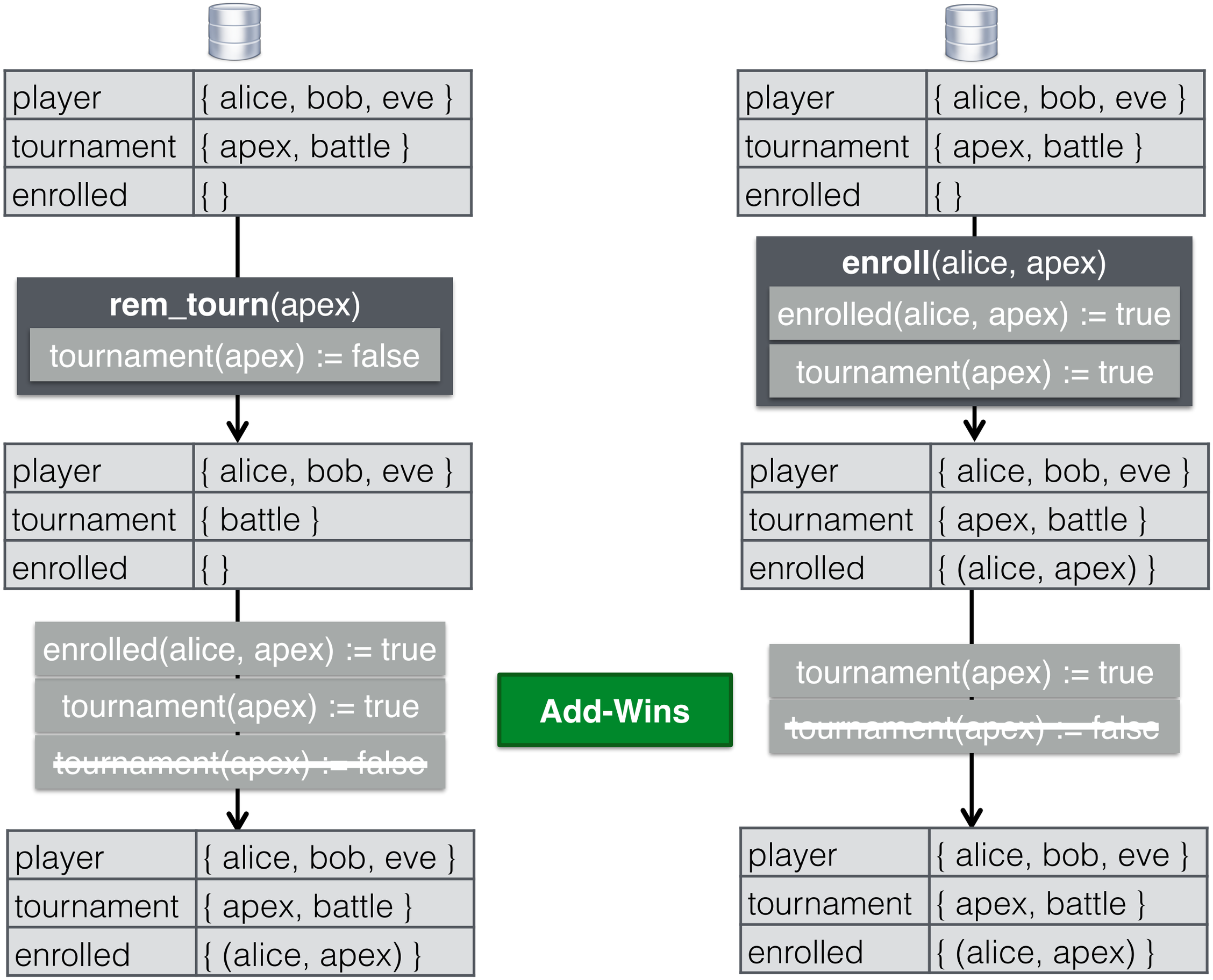
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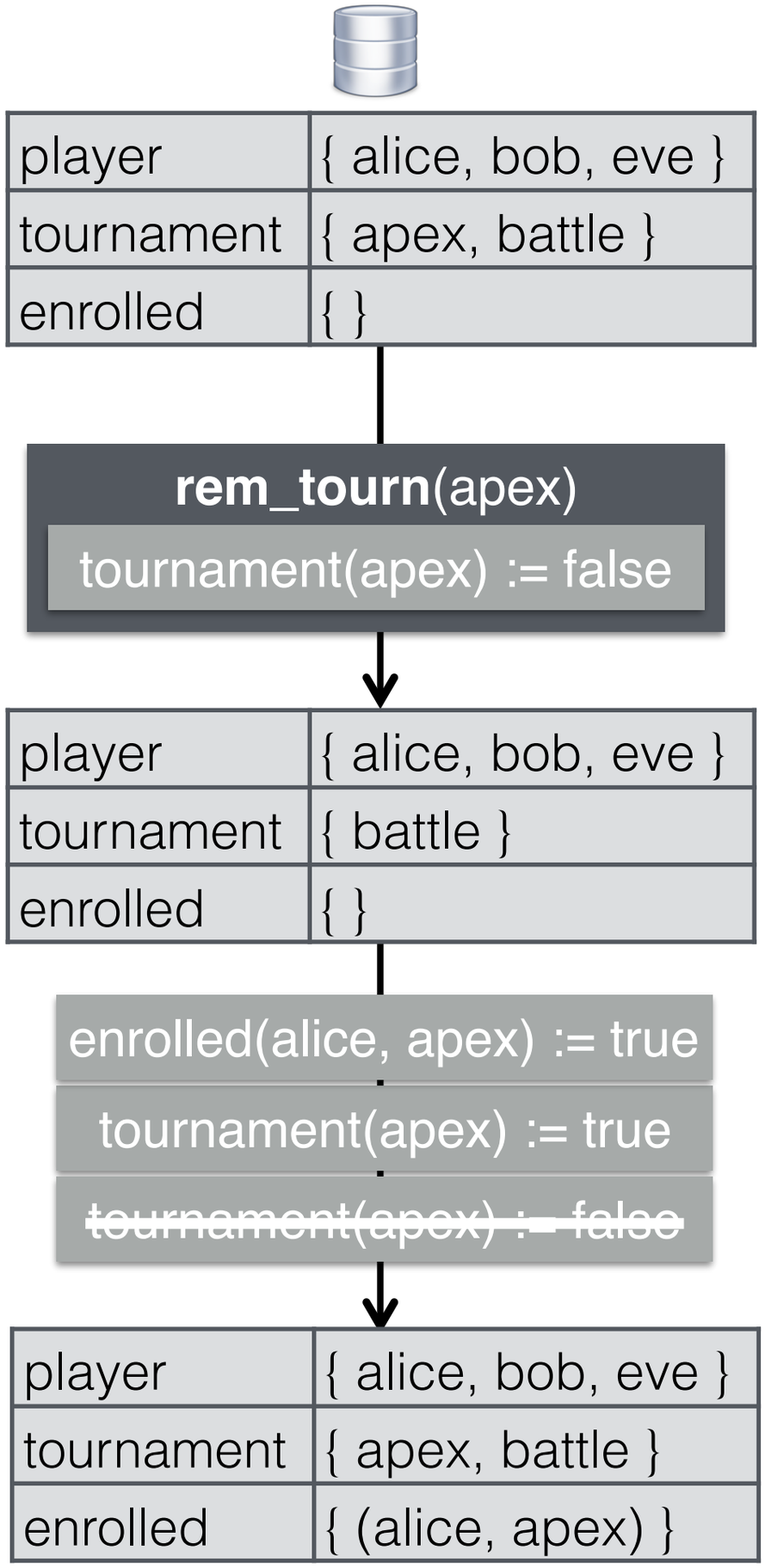
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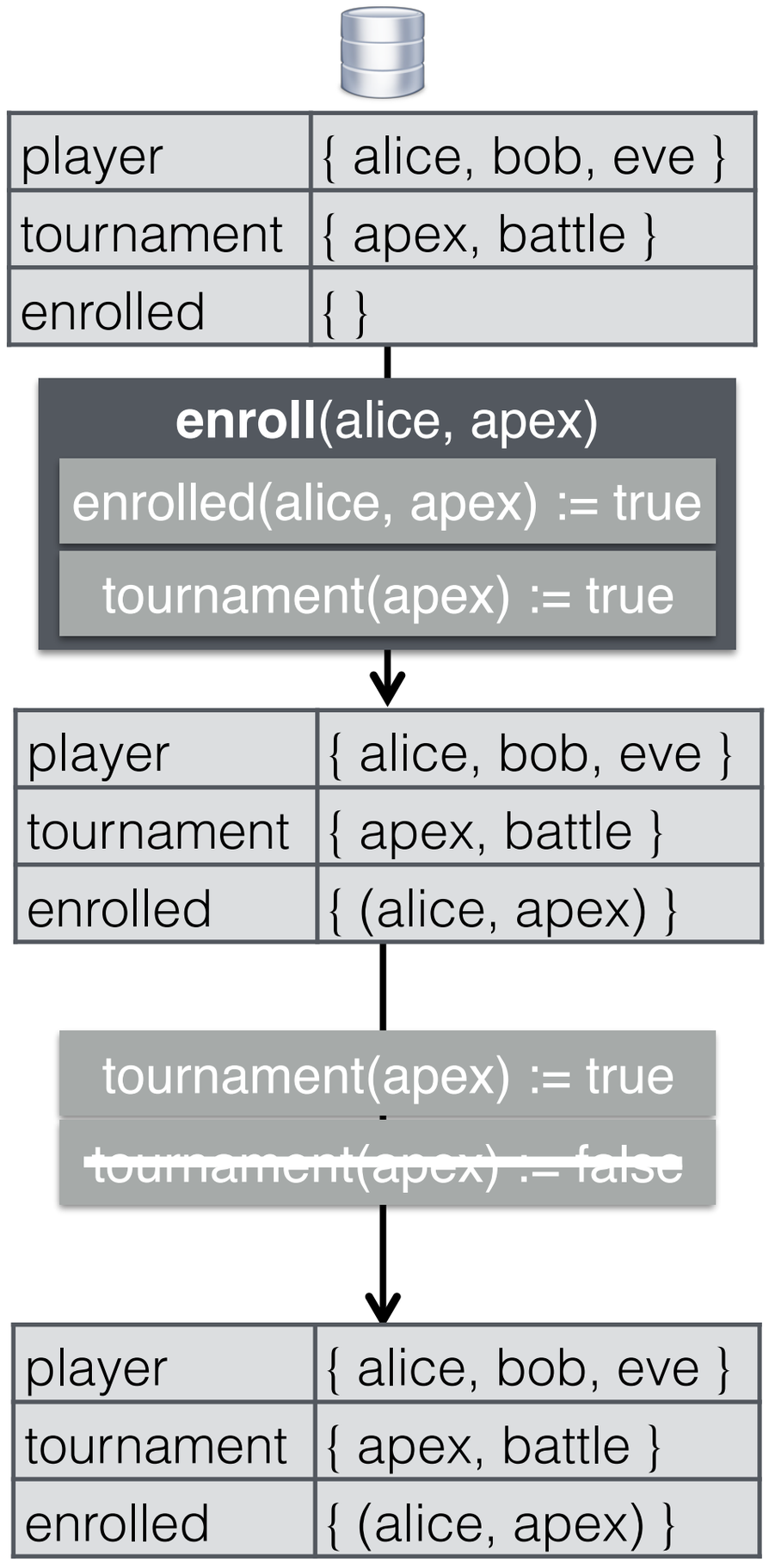
enrolled
{ (alice, apex) }


player
{ alice, bob, eve }
tournament
{ apex, battle }
enrolled
{ }
enroll(alice, apex)
enrolled(alice, apex) := true
tournament(apex) := true
player
{ alice, bob, eve }
tournament
{ apex, battle }
enrolled
{ (alice, apex) }
tournament(apex) := true
tournament(apex) := false
player
{ alice, bob, eve }
tournament
{ apex, battle }
enrolled
{ (alice, apex) }

Future work

- Applications are no longer monoliths, now we have loosely-coupled microservices
  - Each microservice might have its own database
  - Intra and inter-database invariants
  - Cross-service operations
  - Reasoning has to be compositional
- Push-button verification (no specification effort)
  - Extract spec from code
    - Good results for Ruby on Rails [Bocic+ ICSE'14, Bocic+ ICSE'17]

References

[Balegas+ VLDB'19]
IPA: invariant-preserving applications for weakly consistent replicated databases. Valter Balegas, Sérgio Duarte, Carla Ferreira, Rodrigo Rodrigues, Nuno Preguiça

[Gotsman+ POPL'16]
'Cause I'm strong enough: Reasoning about consistency choices in distributed systems. Alexey Gotsman, Hongseok Yang, Carla Ferreira, Mahsa Najafzadeh, Marc Shapiro

[Balegas+ EuroSys'15]
Putting consistency back into eventual consistency. Valter Balegas, Sérgio Duarte, Carla Ferreira, Rodrigo Rodrigues, Nuno Preguiça, Mahsa Najafzadeh, Marc Shapiro