Compositional Model-Driven Verification of Weakly Consistent Distributed Systems

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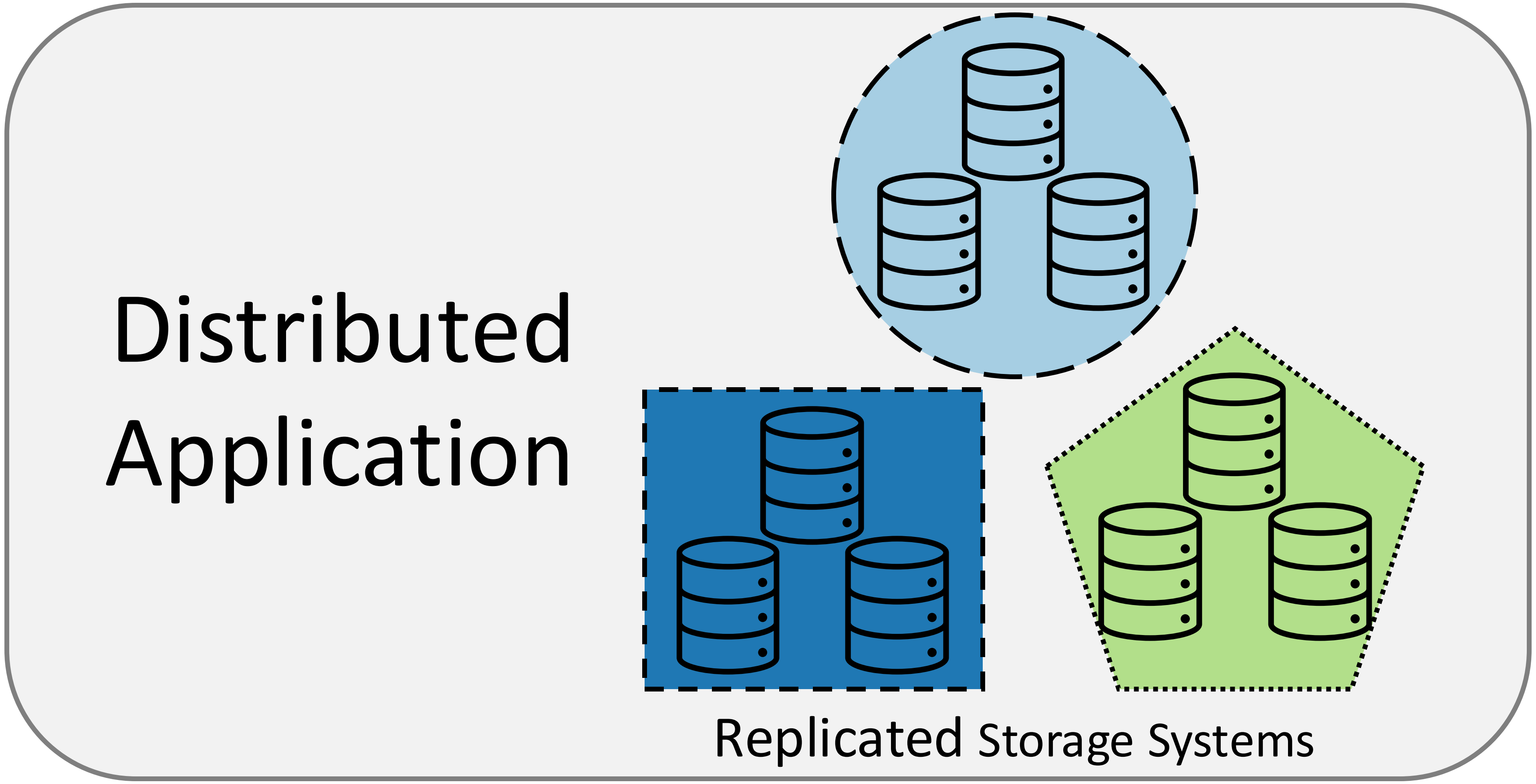
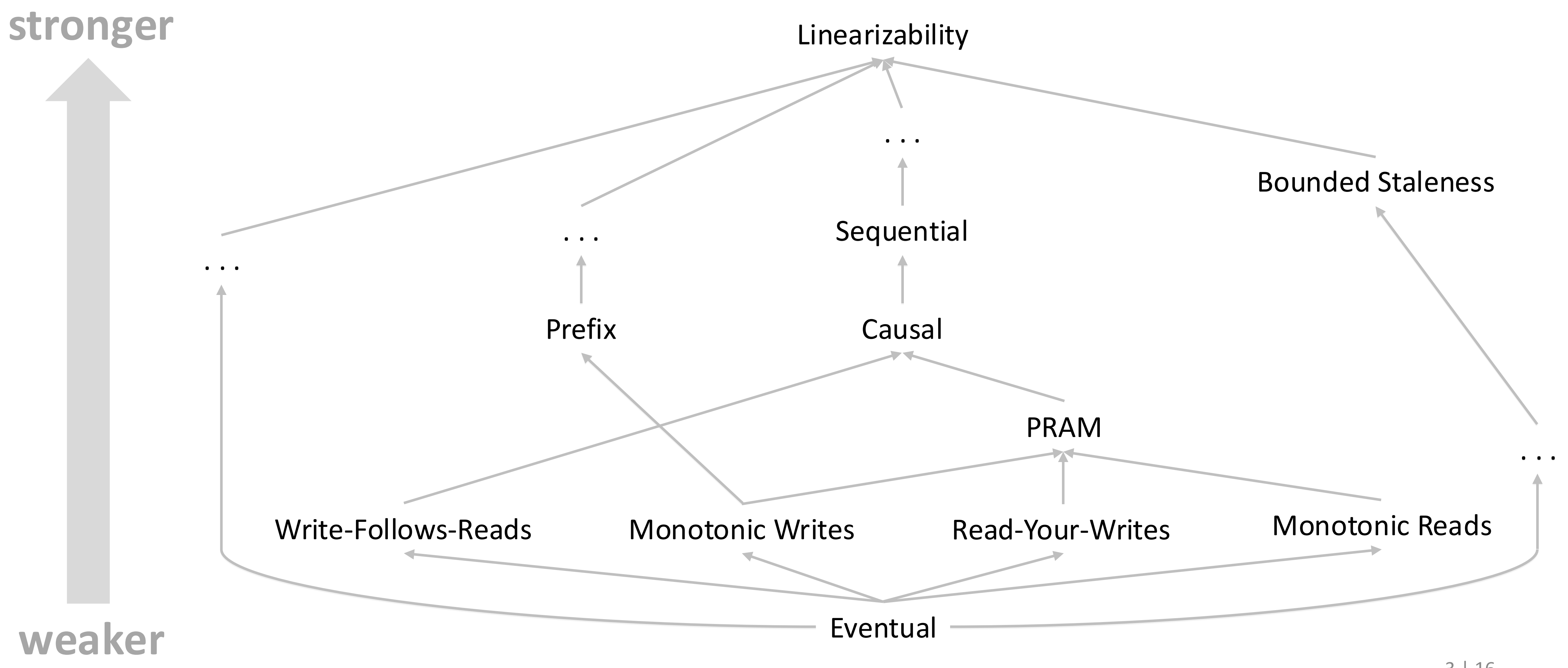
Northeastern University, *KAIST**, *Yonsei University*†, *FuriosaAI*‡

Weak Consistency Is Ubiquitous



Consistencies Are Ordered by Strength



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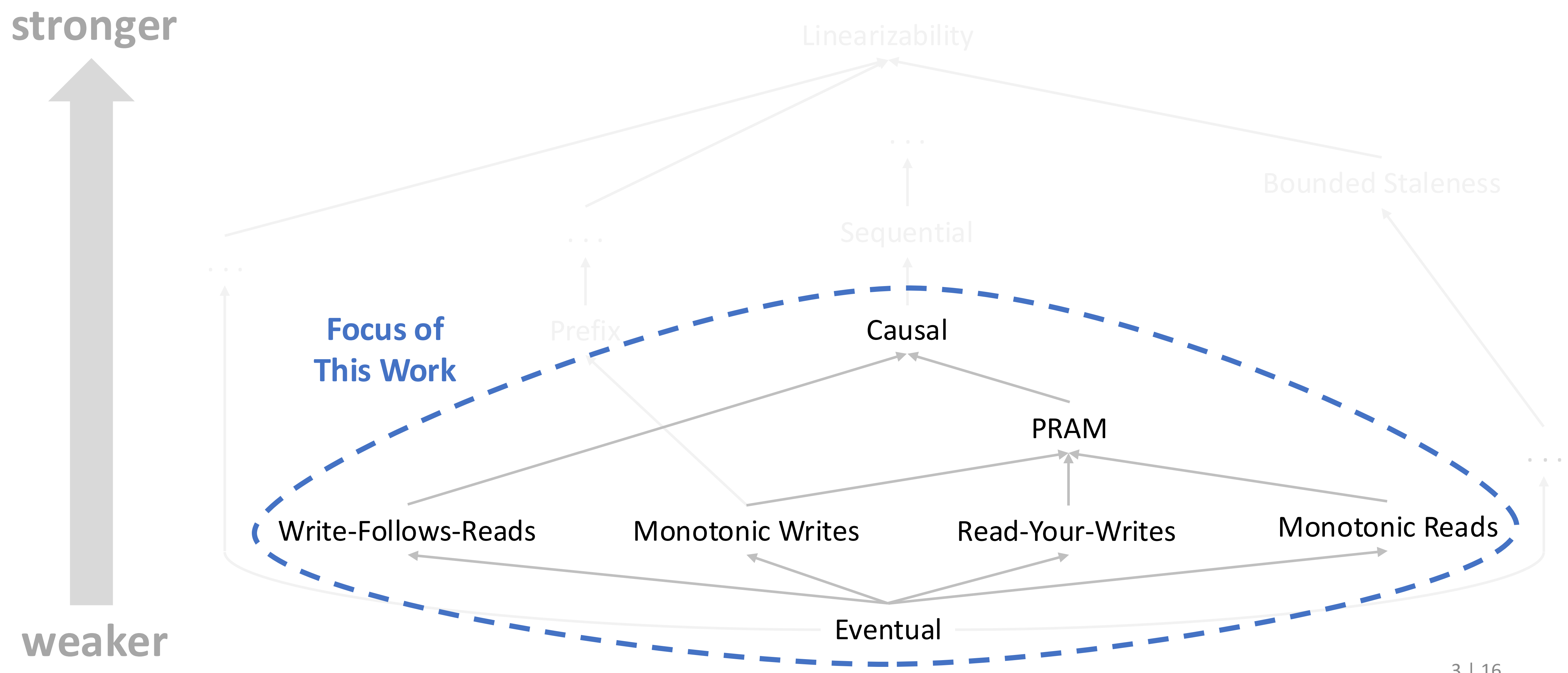

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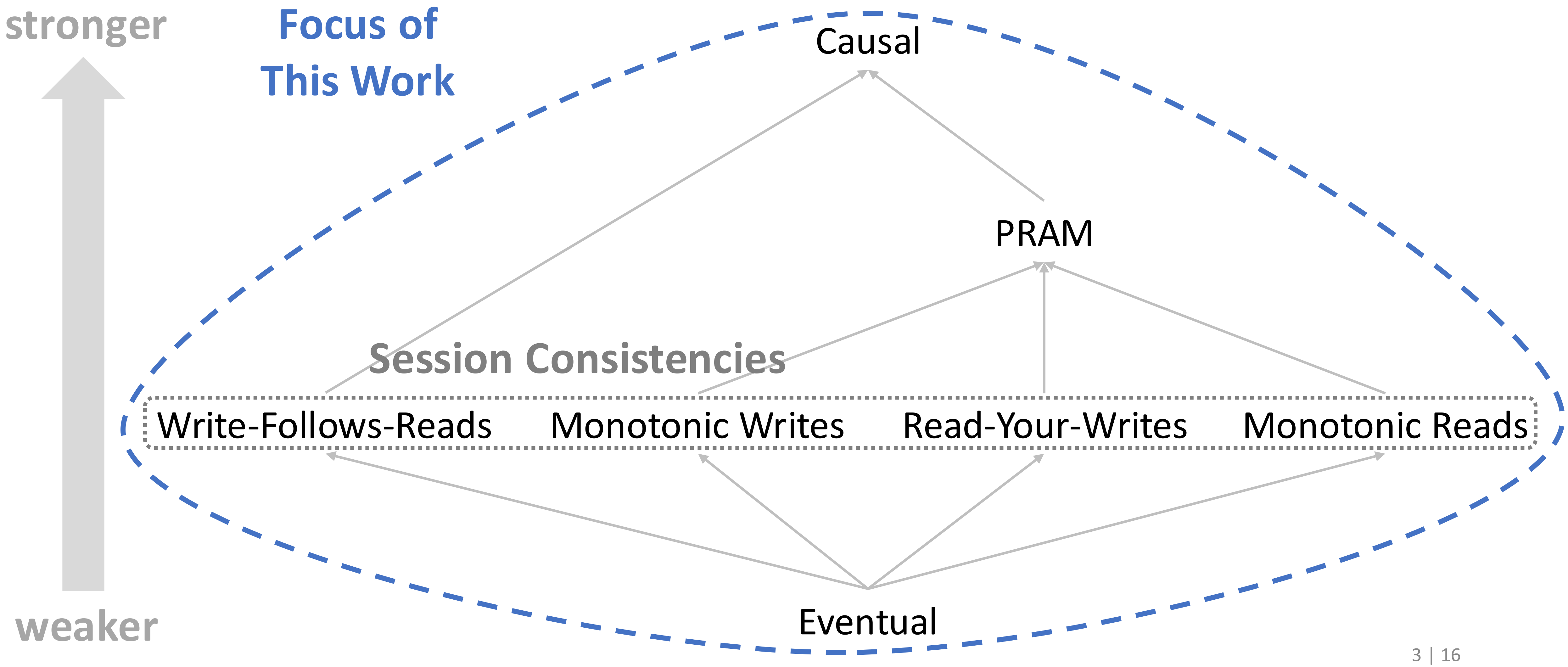

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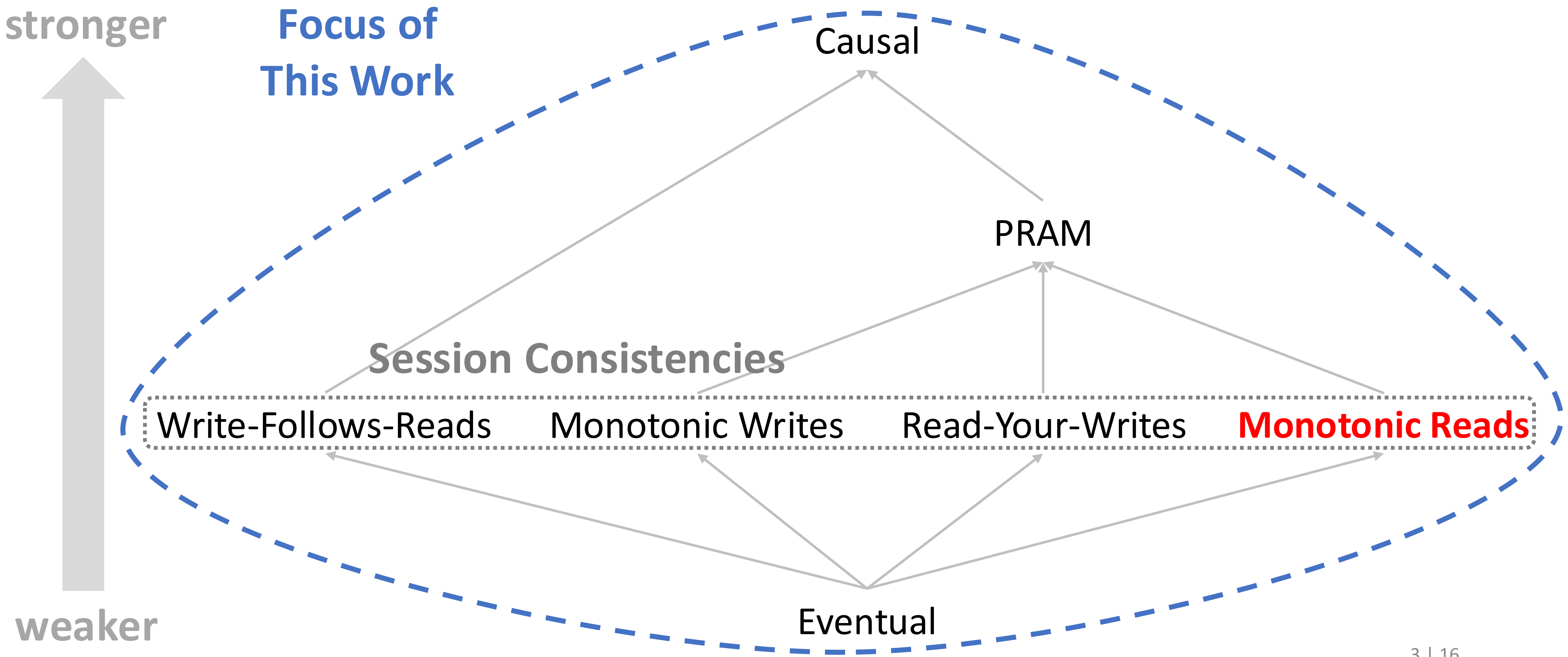

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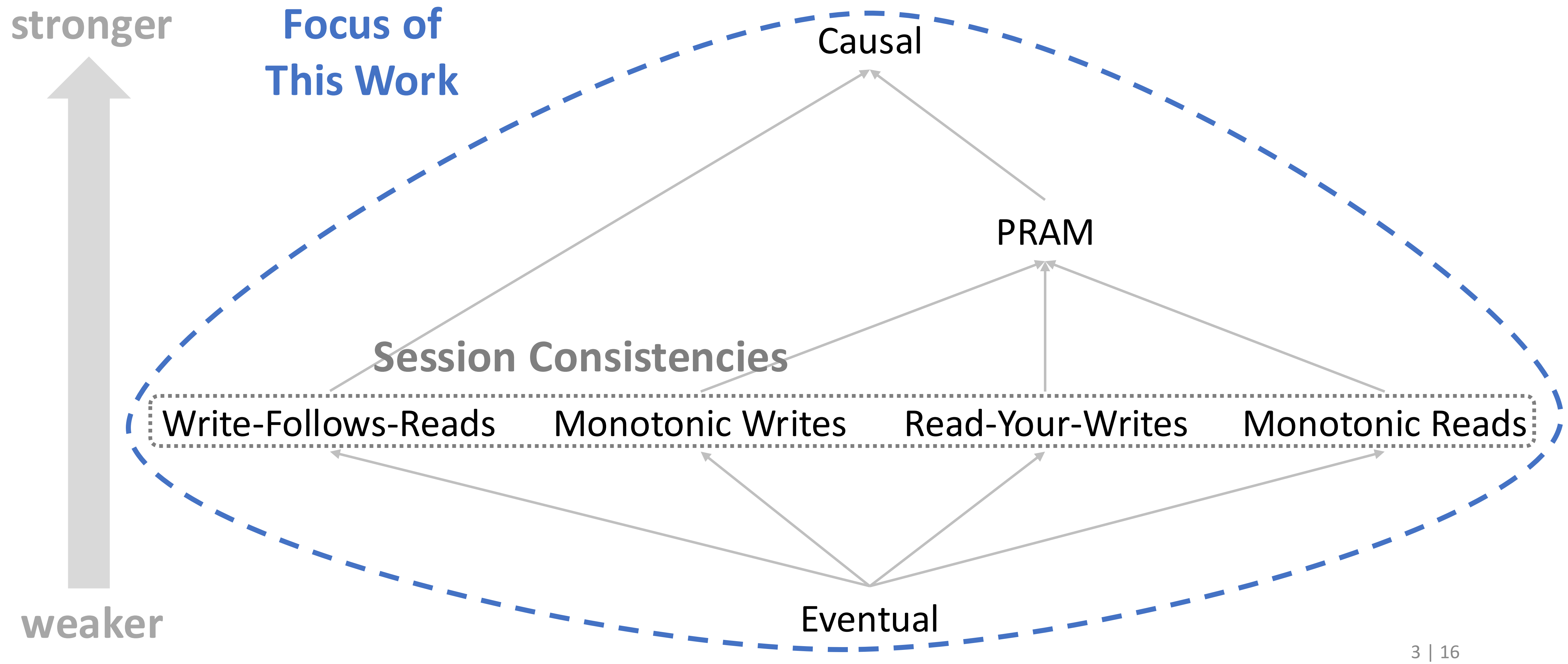

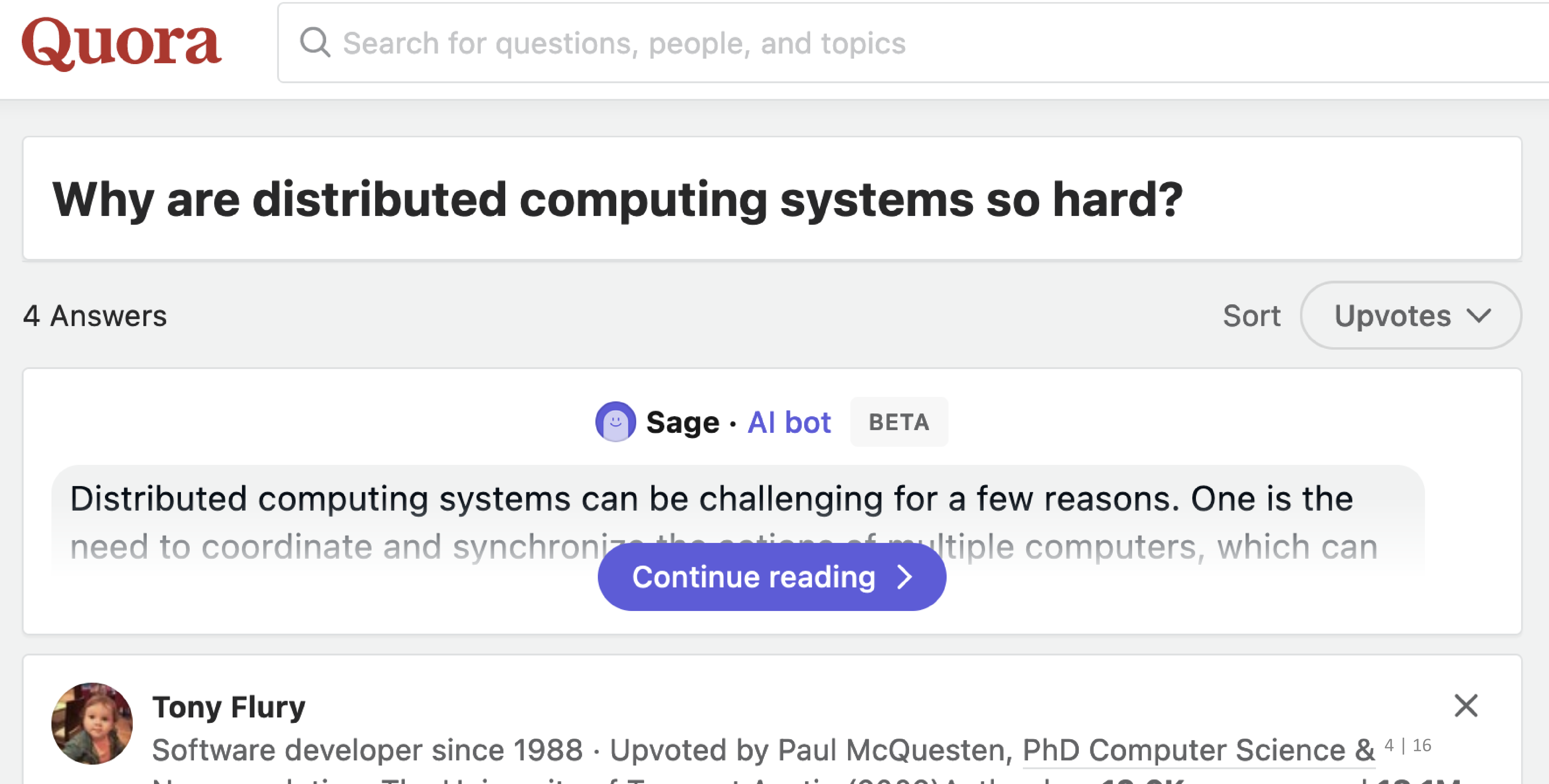

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Why are distributed computing systems so hard?

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Distributed computing systems can be challenging for a few reasons. One is the need to coordinate and synchroni

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Weak Consistencies Are Overlooked

Project	Code	Safety	Abstract Model	Model Composition	Verified Semantics
Chapar	Go				Causal
ADO	C		✓	✗	
LiDO	OCaml				
Verdi	OCaml	✓			Strong (Byz or Non-Byz)
IronFleet	C#				
Grove	Go		✗	N/A	
WormSpace	C				

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Weak Consistencies Are Overlooked

Project	Code	Safety	Abstract Model	Model Composition	Verified Semantics
Moveri	Go	✓	✓	✓	16 weak (Eventual, Causal, & more)
Chapar	Go				Causal
ADO	C		✓	✗	
LiDO	OCaml				
Verdi	OCaml	✓			Strong
IronFleet	C#		✗	N/A	(Byz or Non-Byz)
Grove	Go				
WormSpace	C				

Top-down Verification in 3 Layers

Semantic Models

Protocol Models

Impl. (Go)

Top-down Verification in 3 Layers

Semantic Models

- Compositional, implementation agnostic models.
- 16 consistency semantics.
- Satisfy existing consistency semantics definitions.

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- Configurable to 6 consistency semantics.

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refinement proofs ⊔|

Protocol Models <𝕋>

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Goose and bisimulaton proofs ⊔| ⊓|

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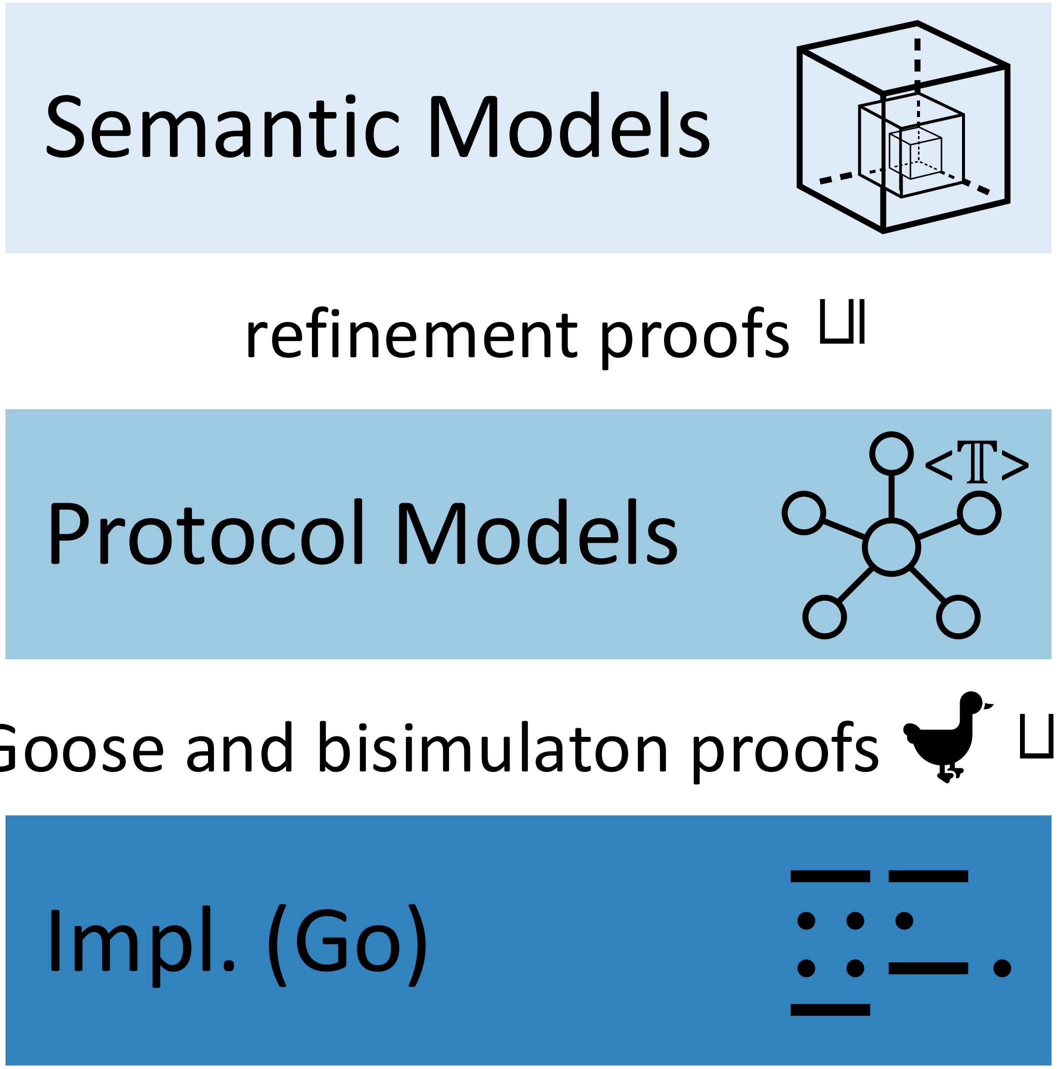
Top-down Verification in 3 Layers



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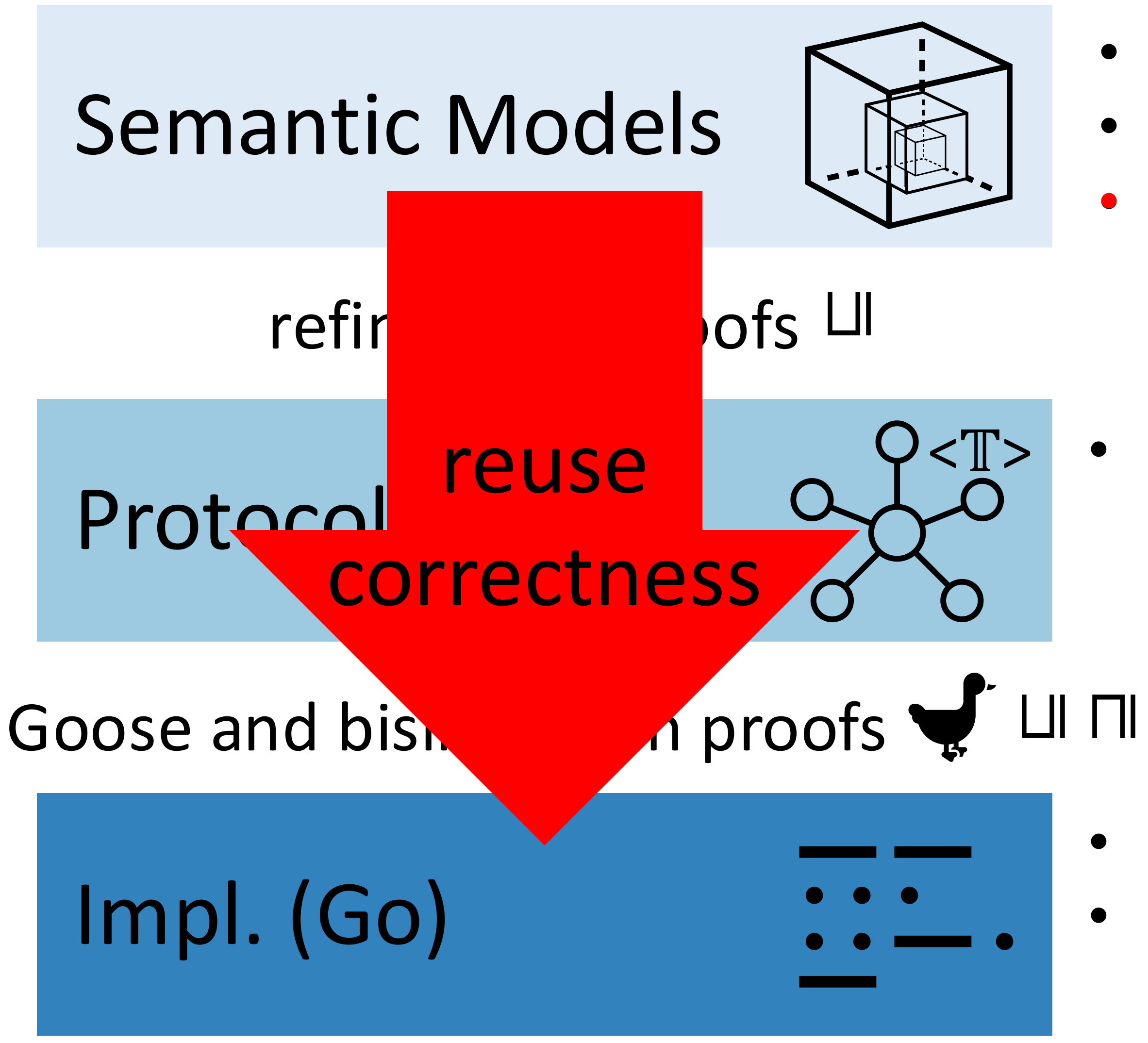

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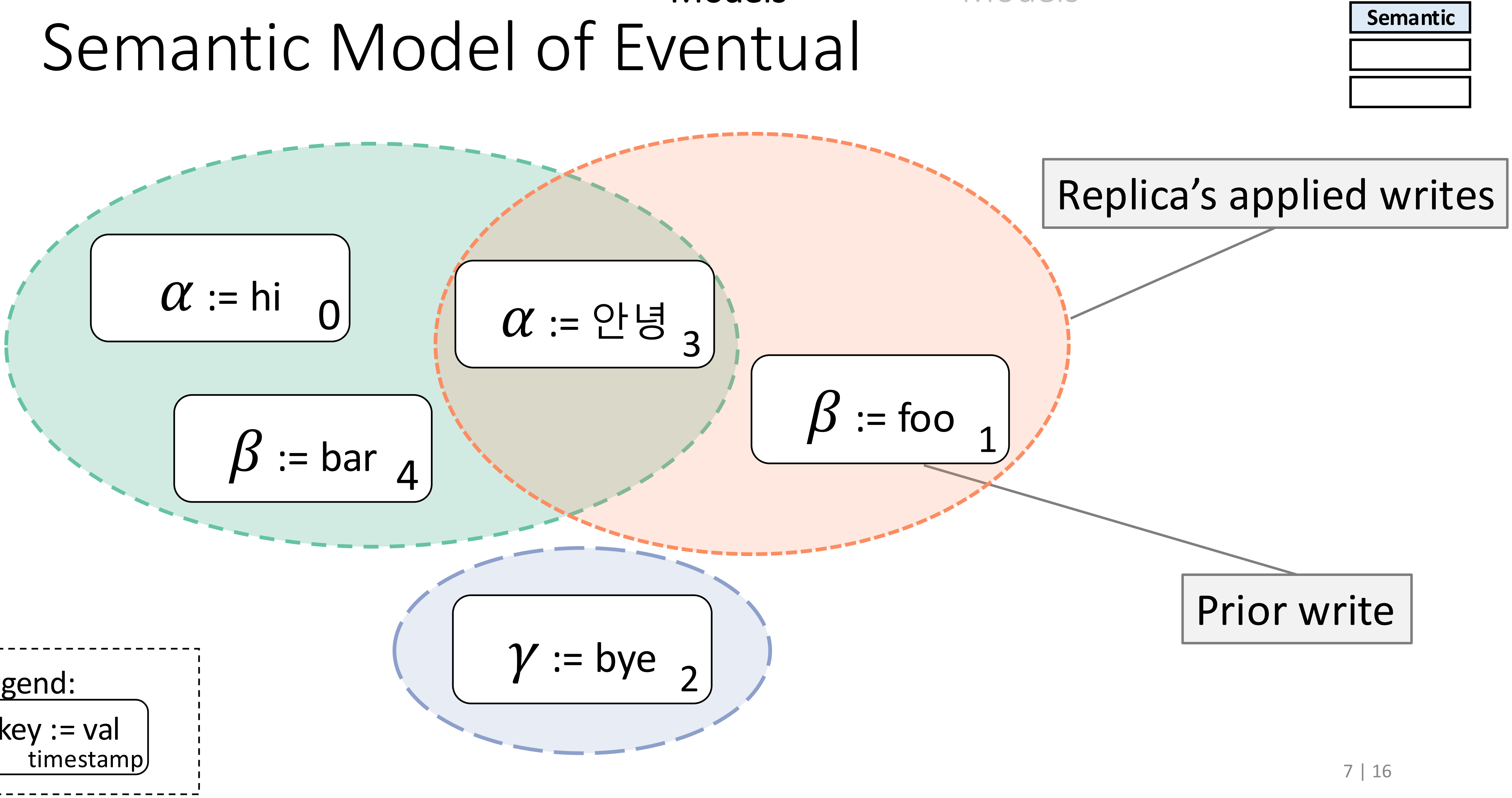
Semantic Model of Eventual



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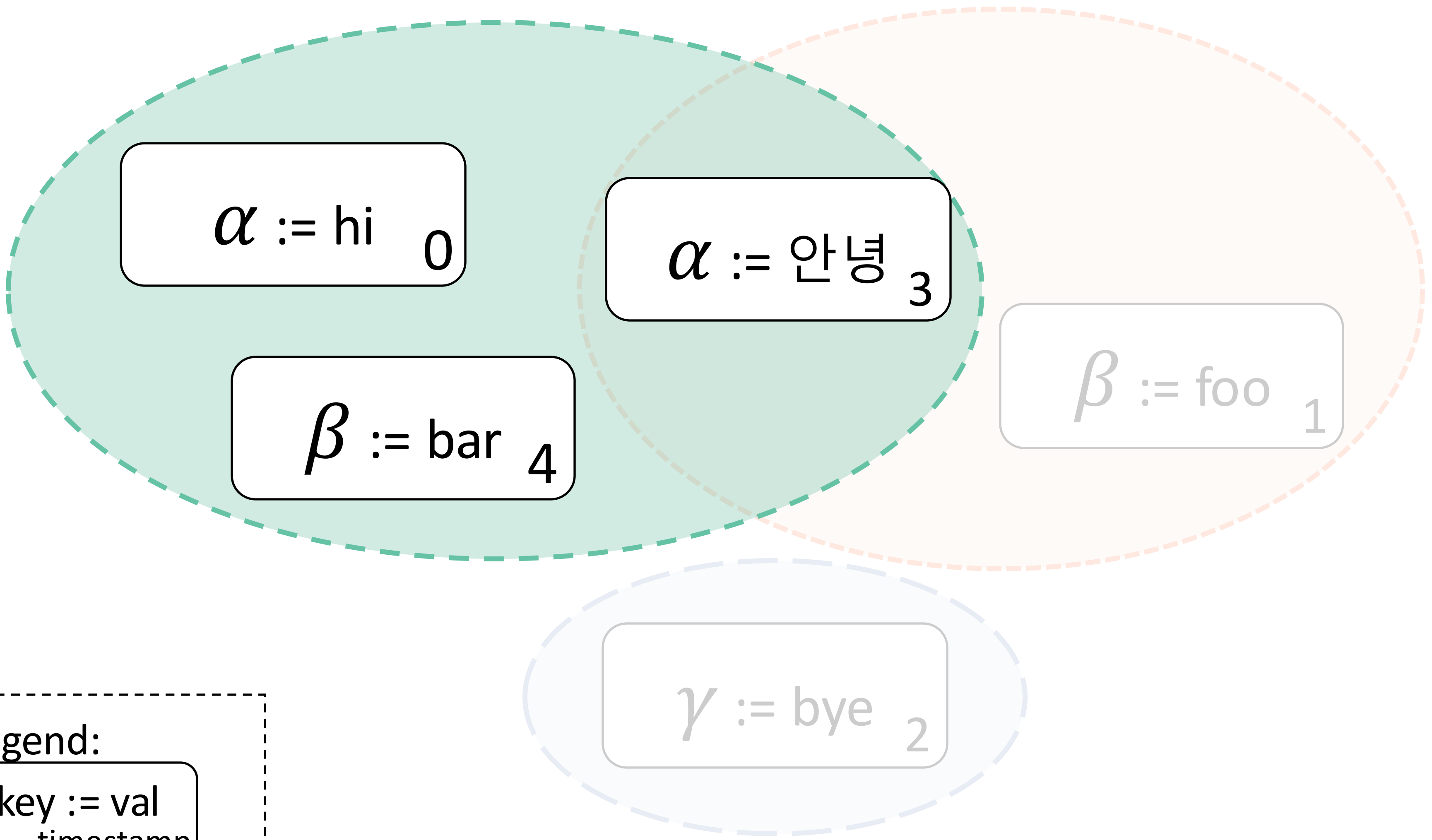
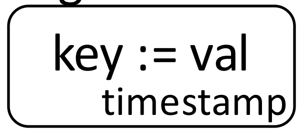


Legend:



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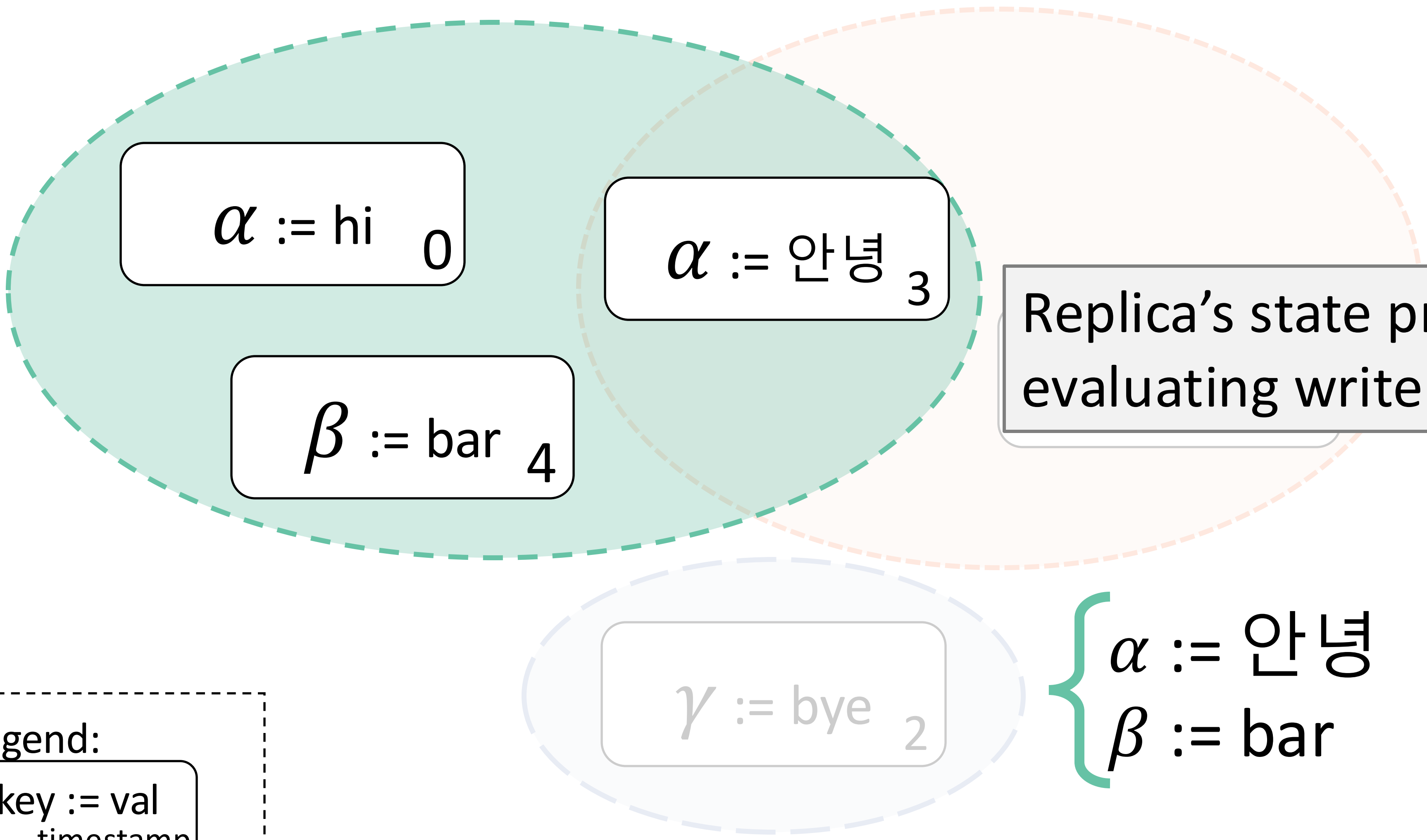


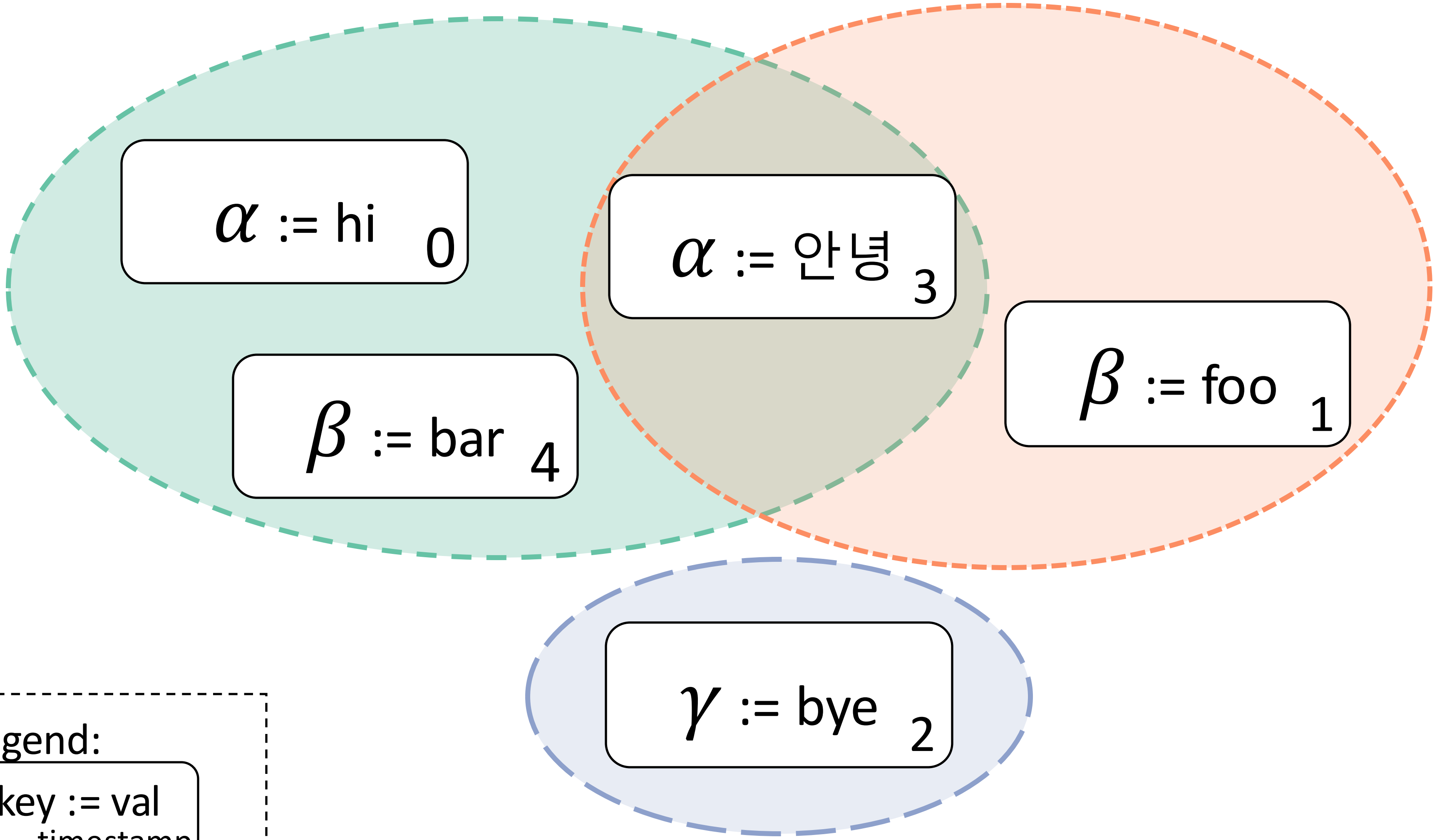
Replica's state produced by evaluating write subset in order.

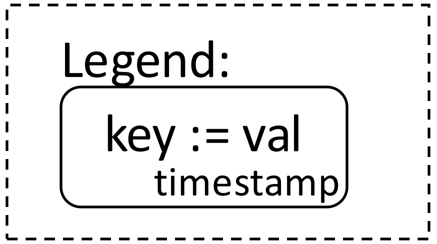
$$\begin{cases} \alpha := \text{안녕} \\ \beta := \text{bar} \end{cases}$$

Legend:

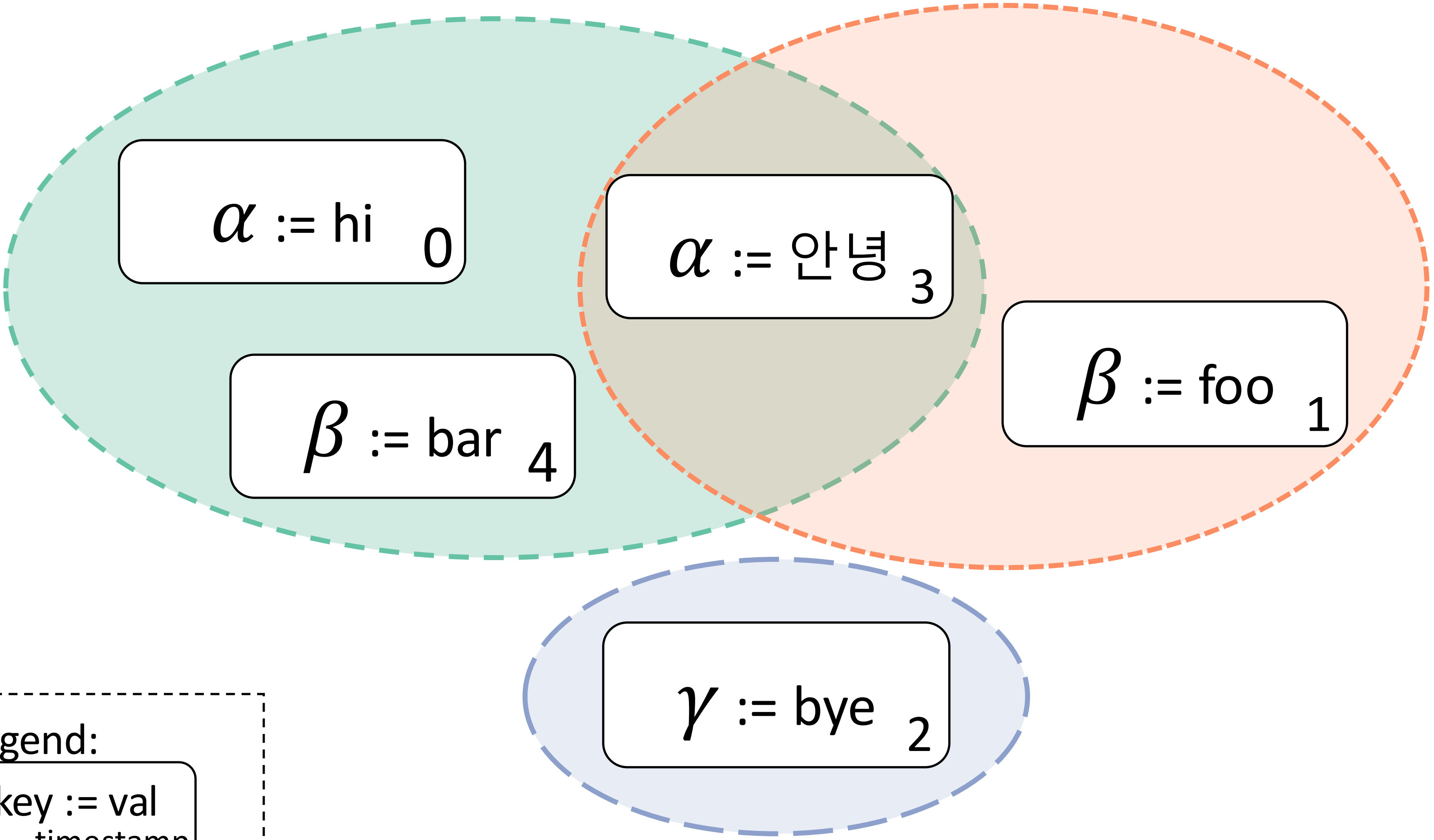
key := val timestamp

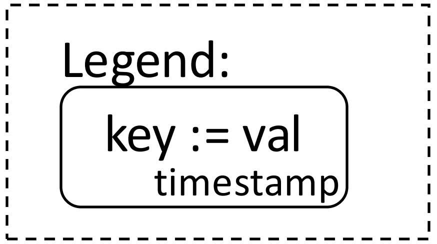
Semantic Model of Eventual





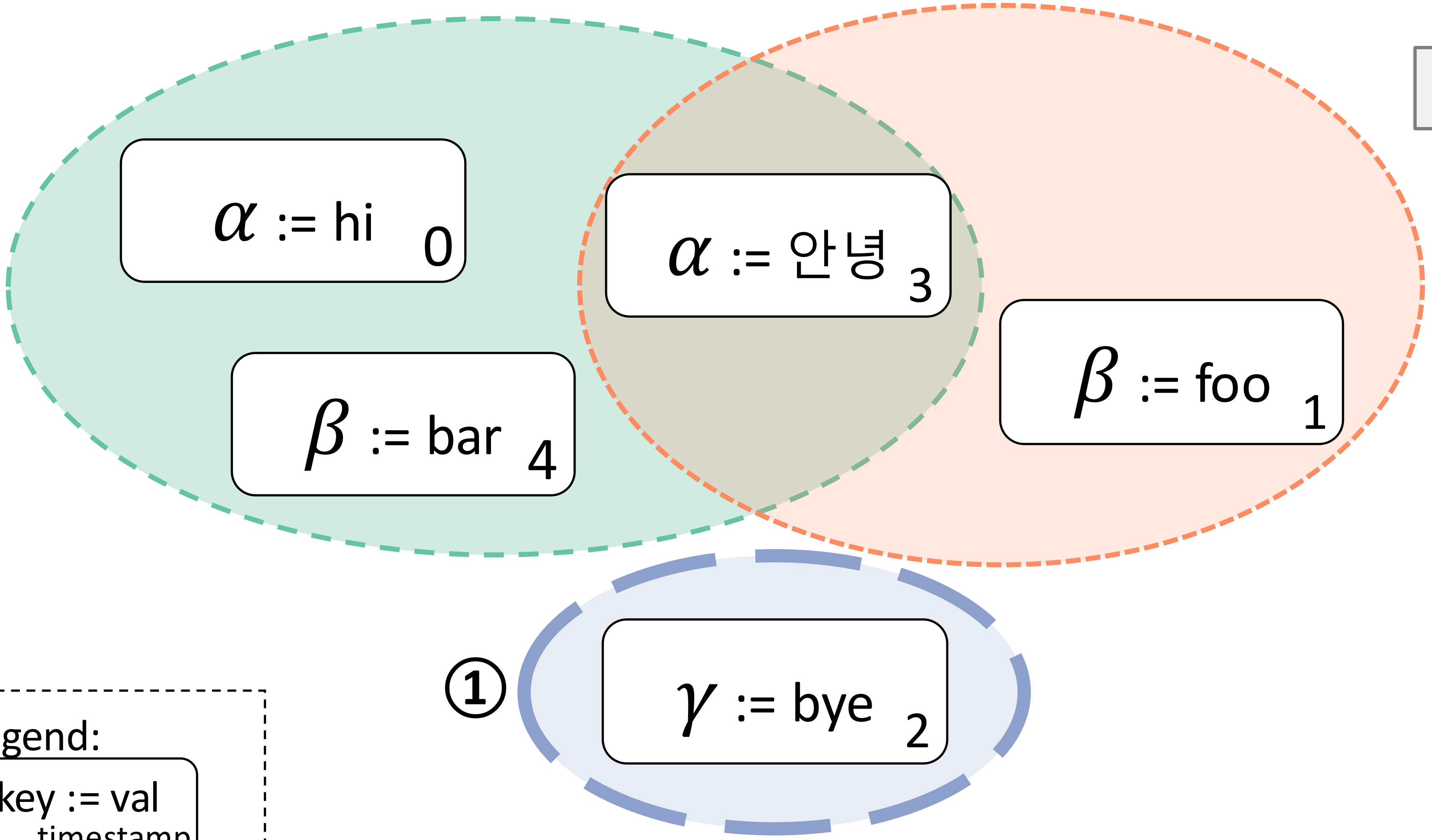
Semantic Model of Eventual: Write(β := baz)

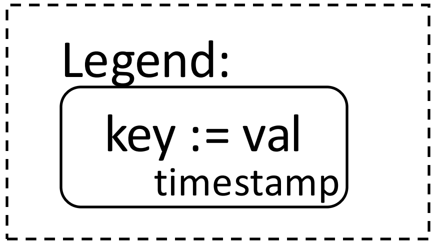




Semantic Model of Eventual: Write(β := baz)

① Pick replica subset





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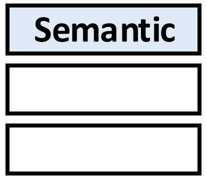
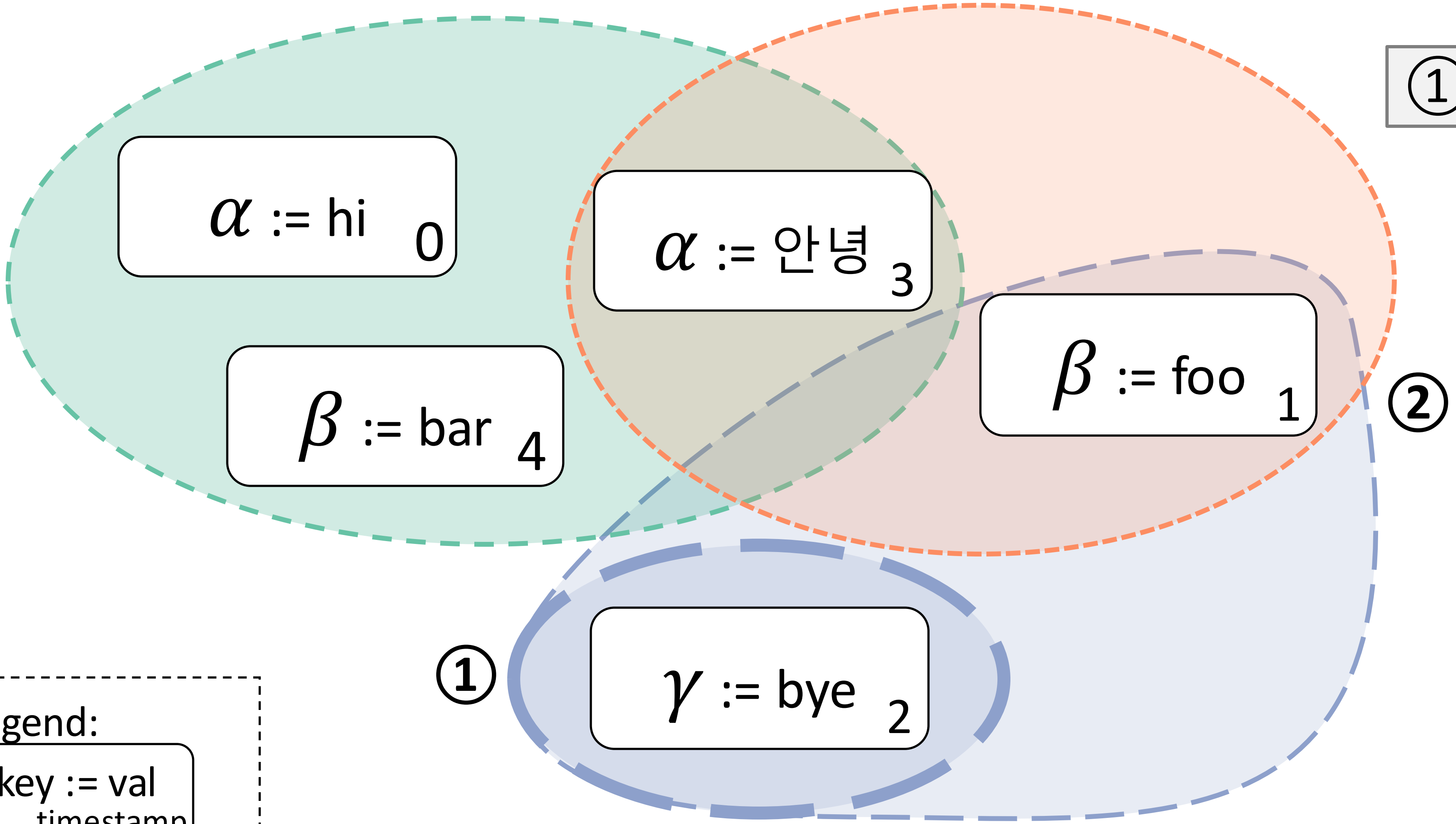




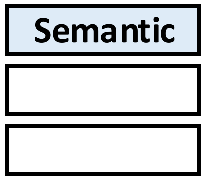
① Pick replica subset

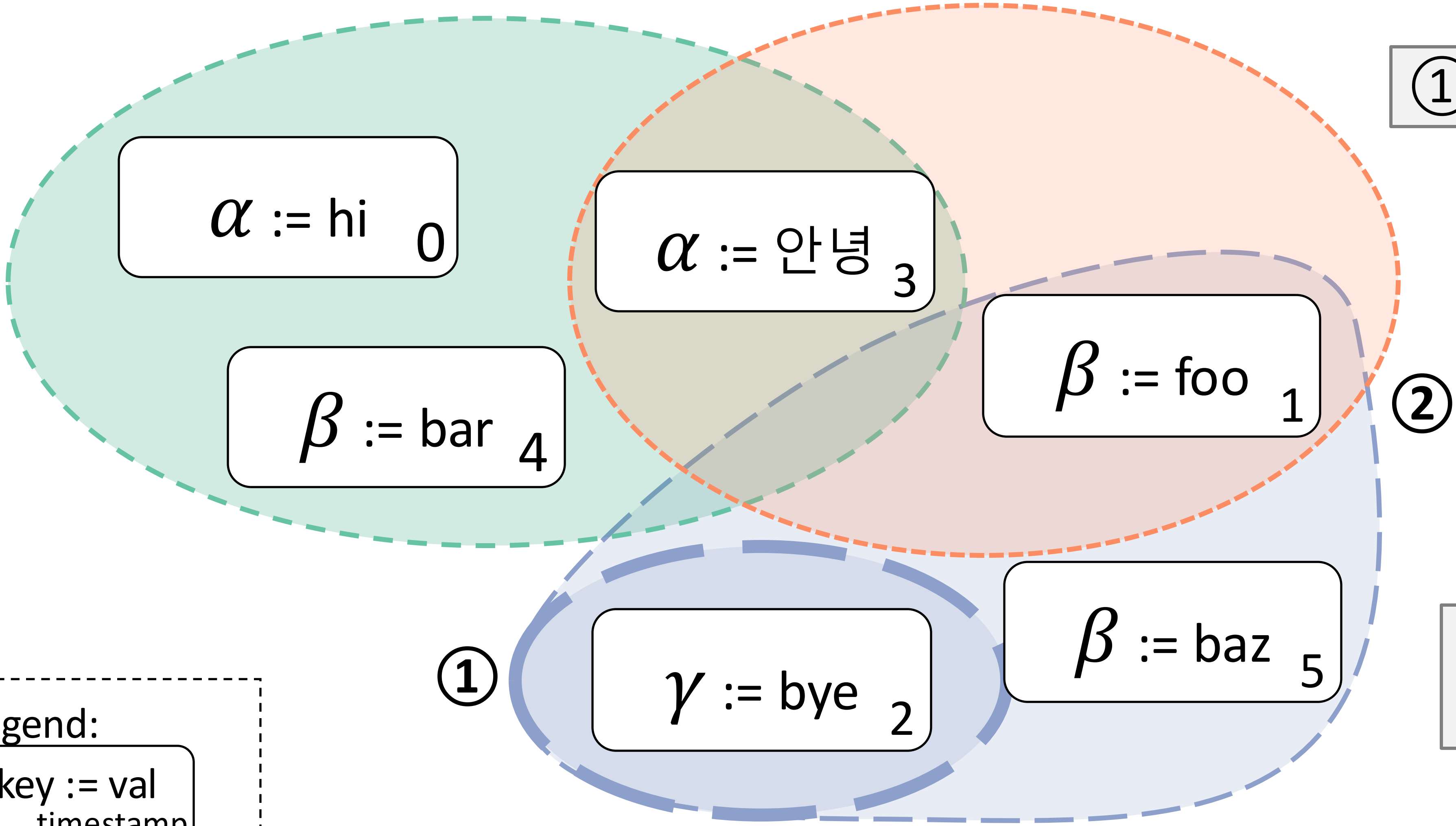
② Grow subset

Legend:

key := val timestamp

Semantic Model of Eventual: Write(β := baz)





① Pick replica subset

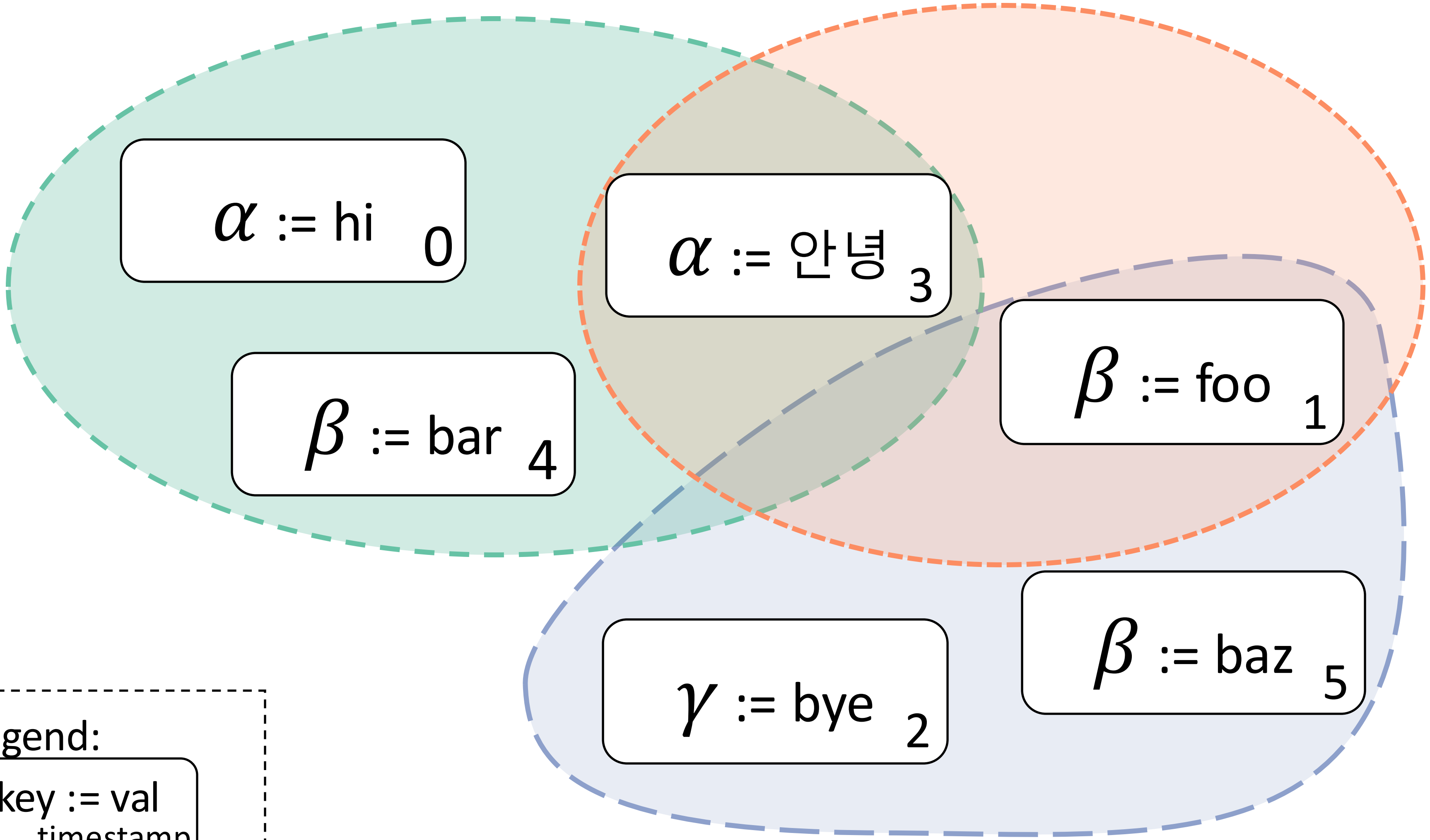
② Grow subset

③ Add new write with timestamp

Legend:

key := val
timestamp

Semantic Model of Eventual: Read(β)



Legend:
key := val
timestamp

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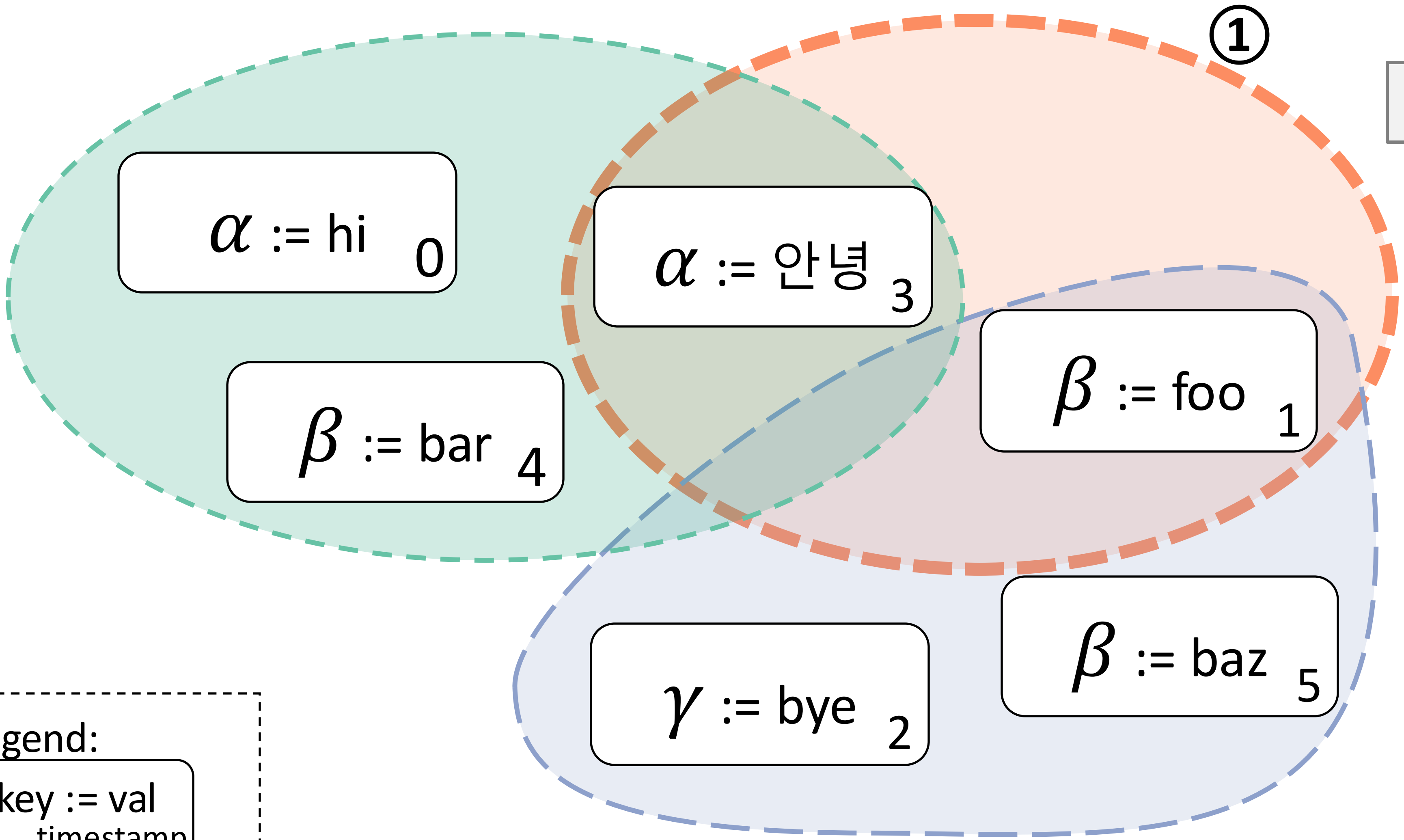

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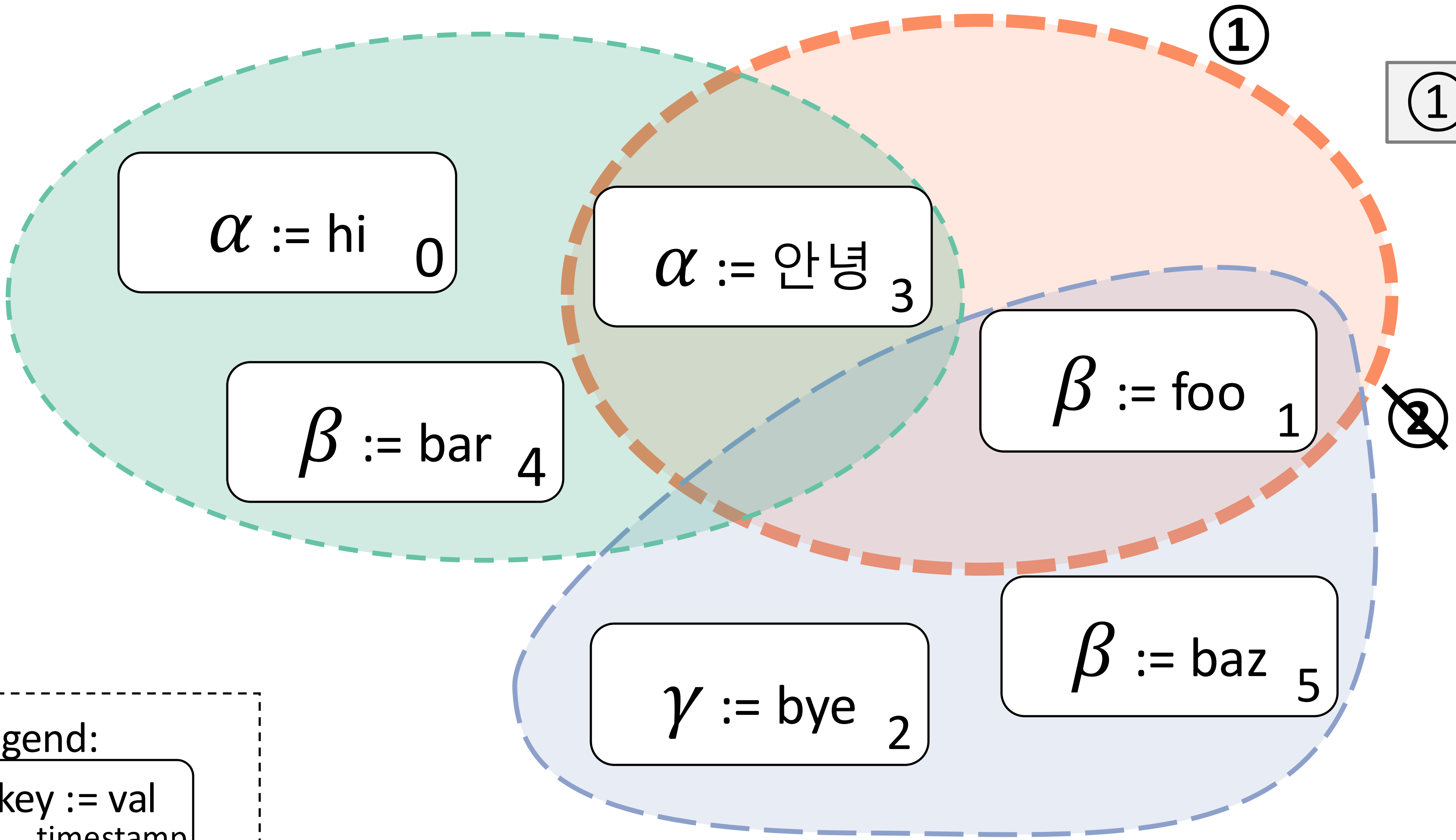

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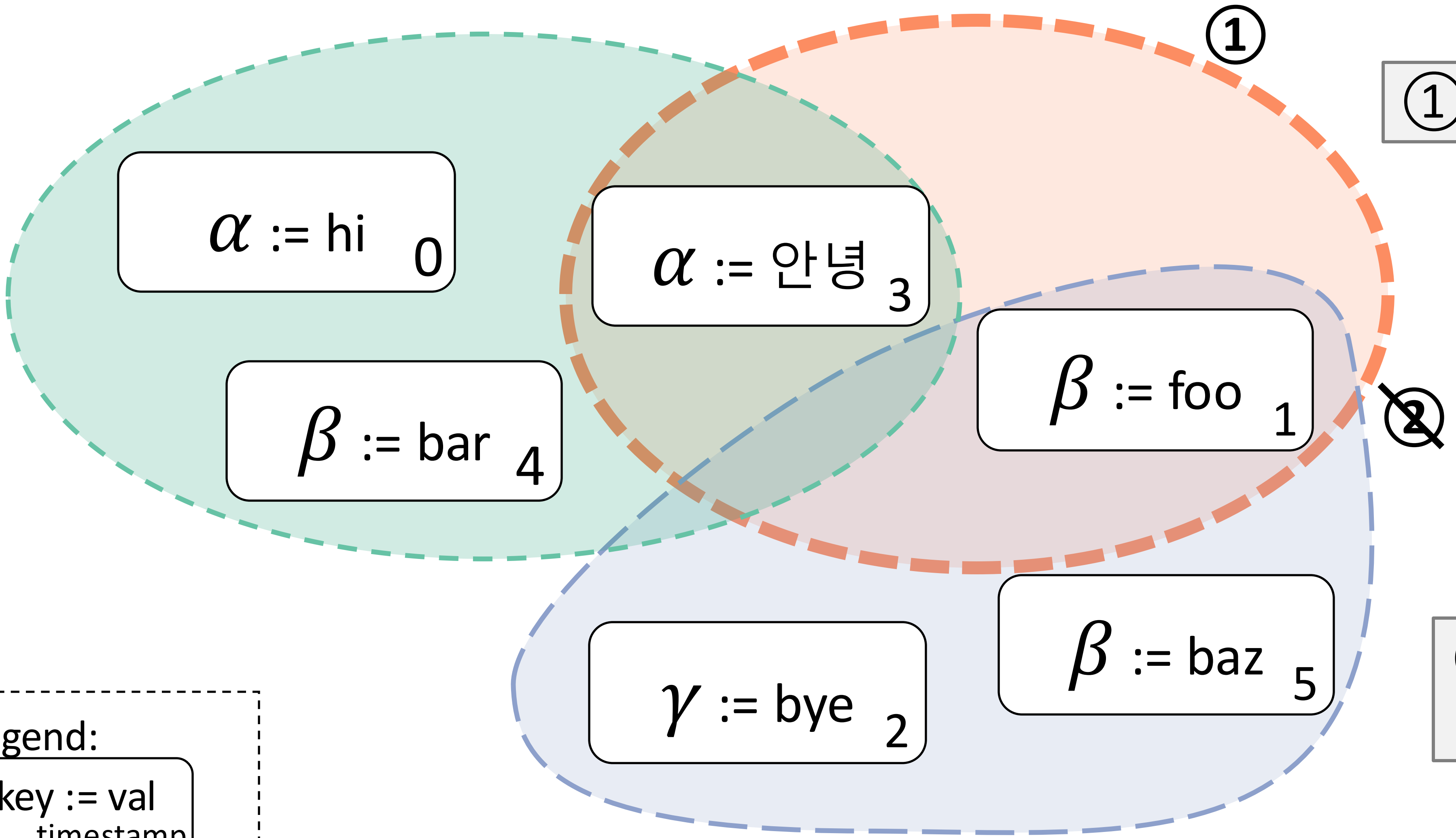


① Pick replica subset

② Grow subset

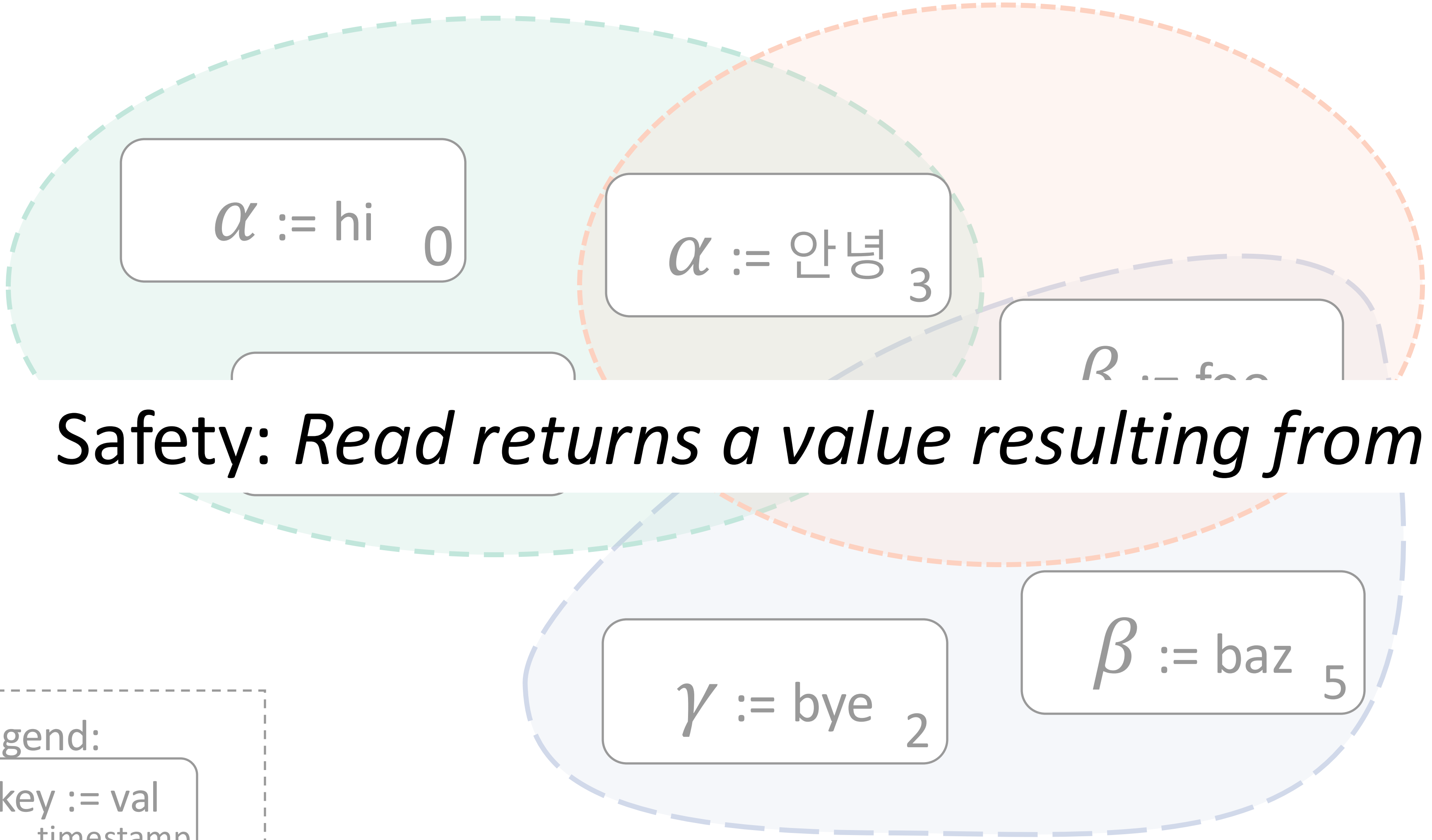
③ { β := foo $_1$ }

③ Return relevant write(s)

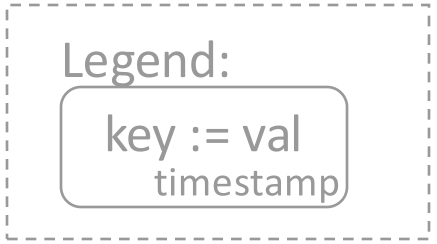
Legend:

key := val timestamp

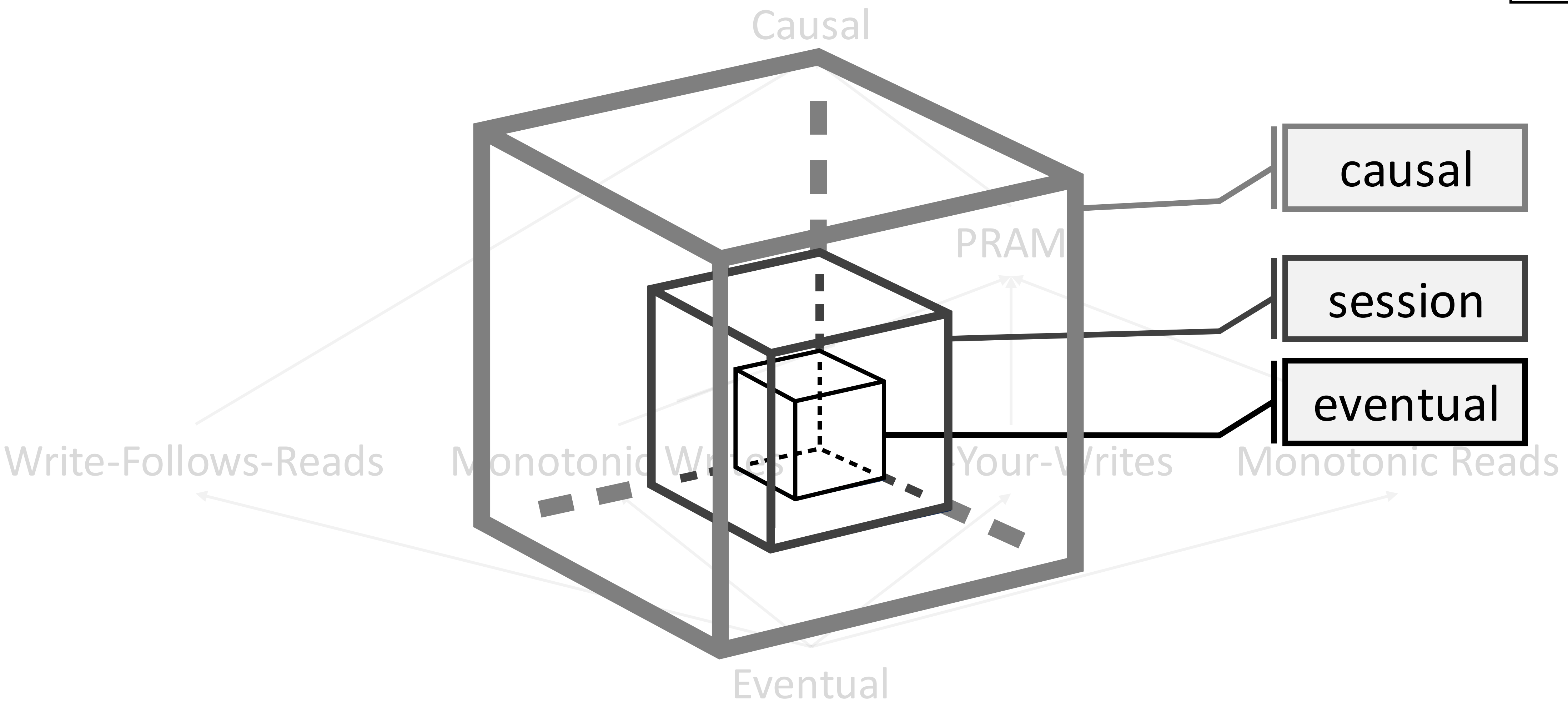
Semantic Model of Eventual: Read(β)



Safety: *Read returns a value resulting from* ***prior writes***.



Semantic Models Compose by Strength

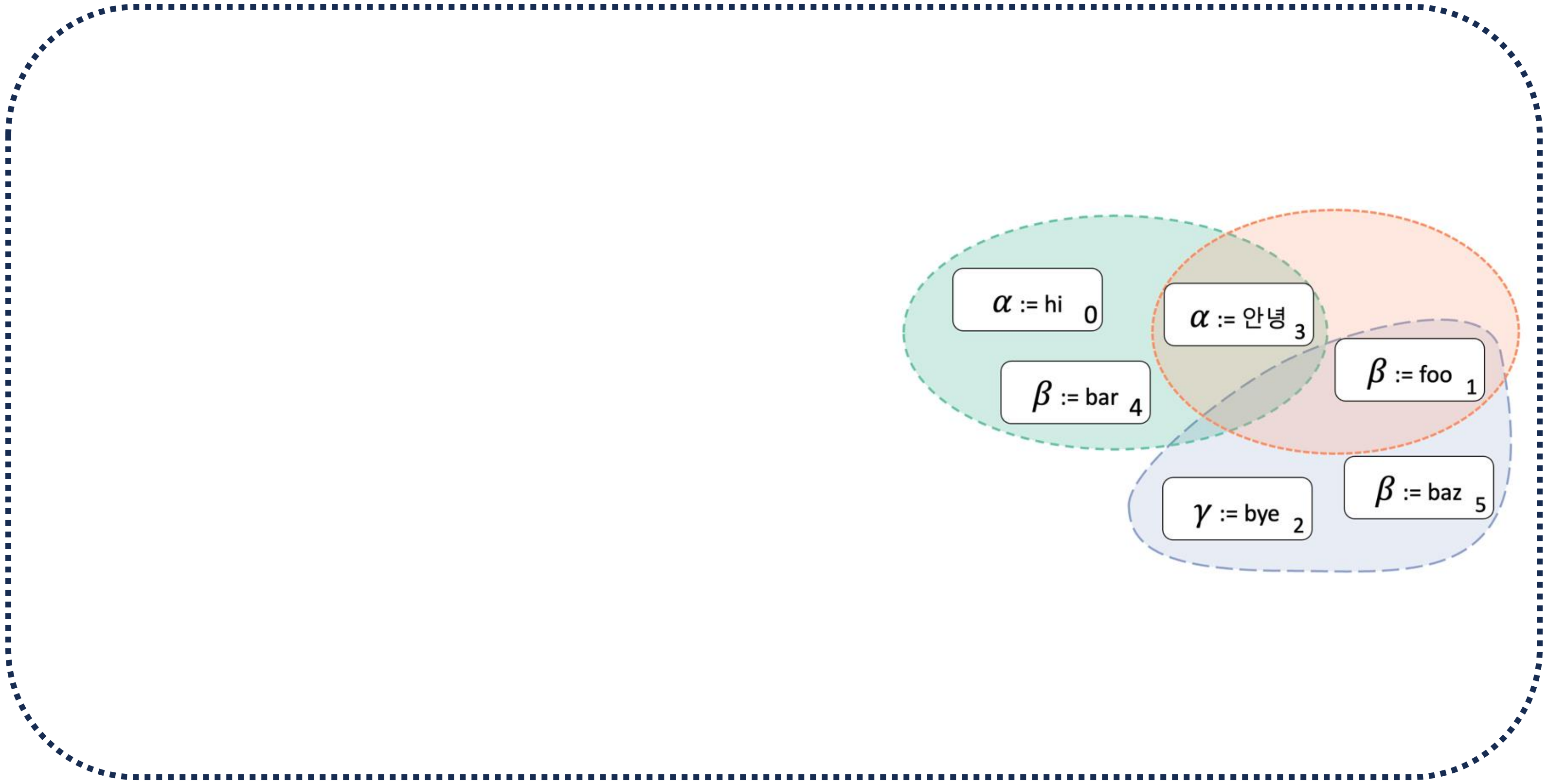


Semantic Model of Session (Using Eventual)

Legend:

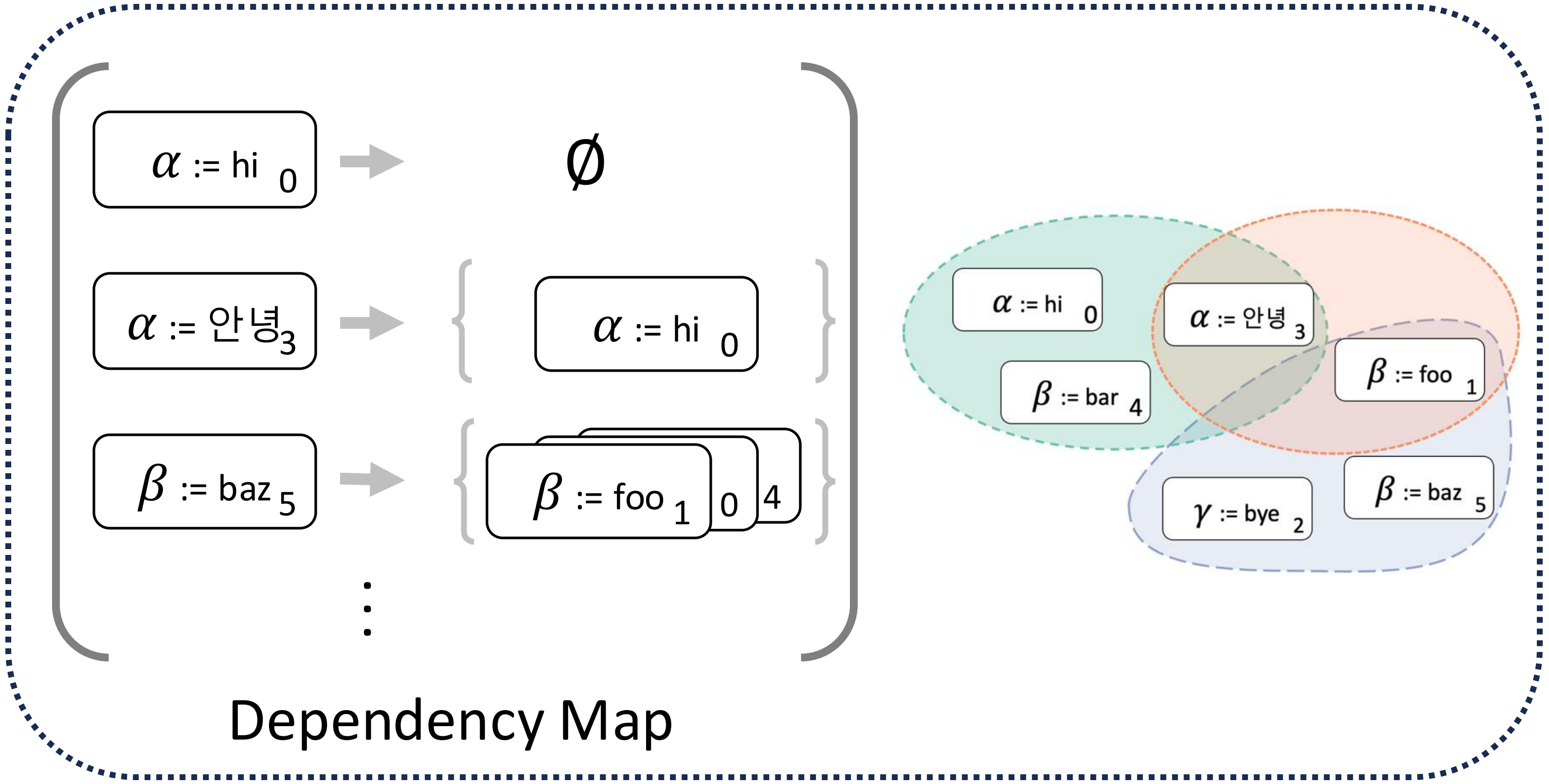
key := val
timestamp

Semantic Model of Session (Using Eventual)



Replicated Storage System

Semantic Model of Session (Using Eventual)



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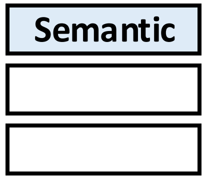
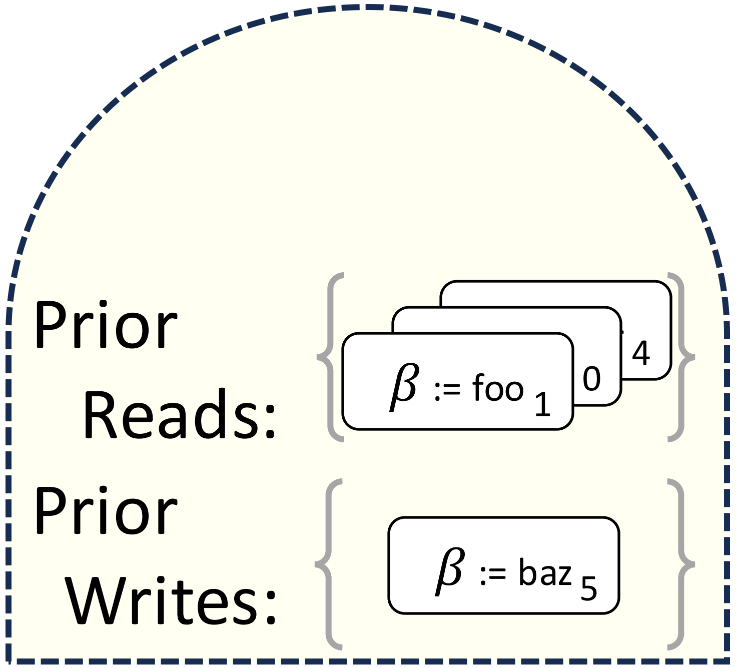
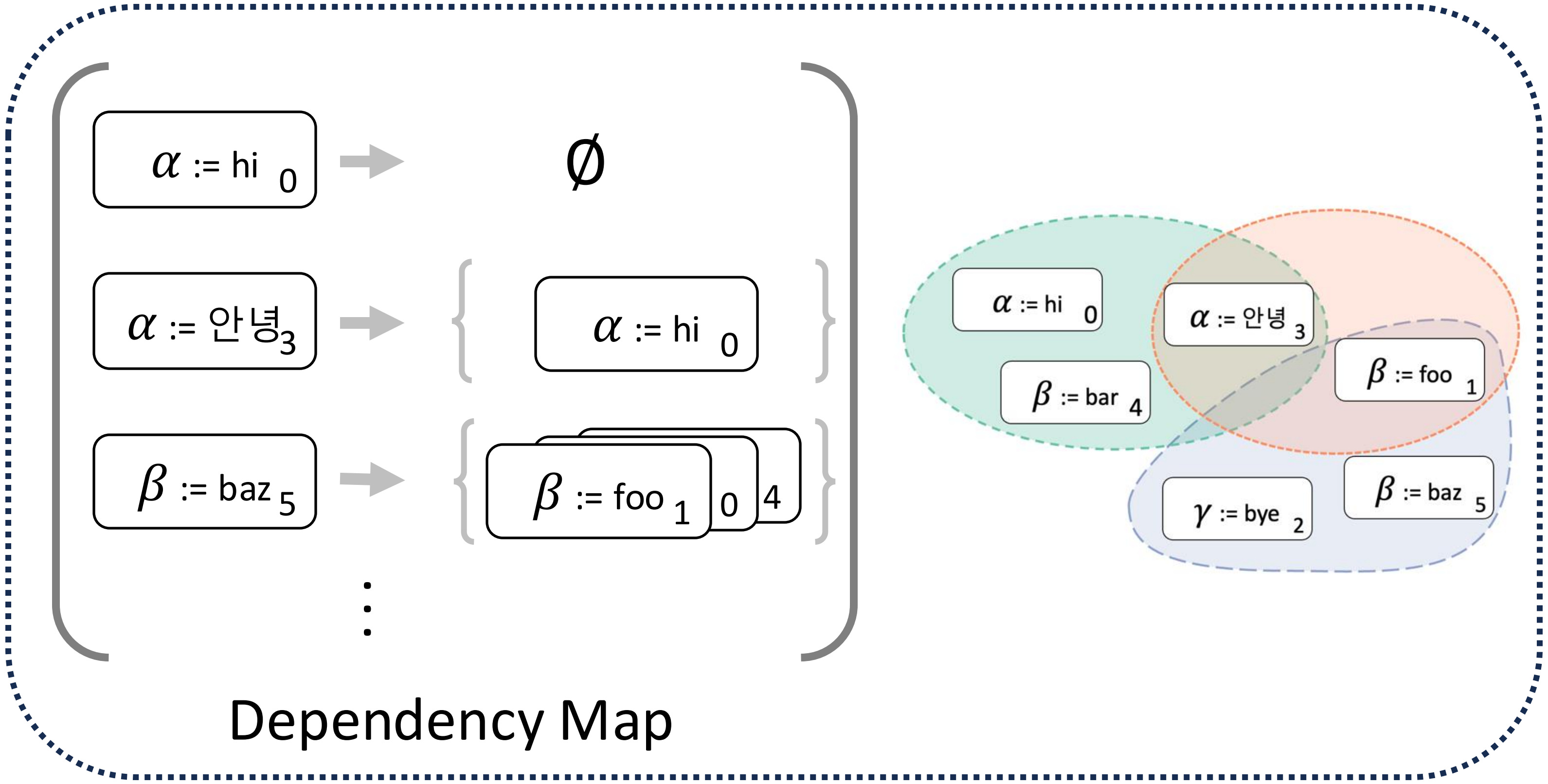


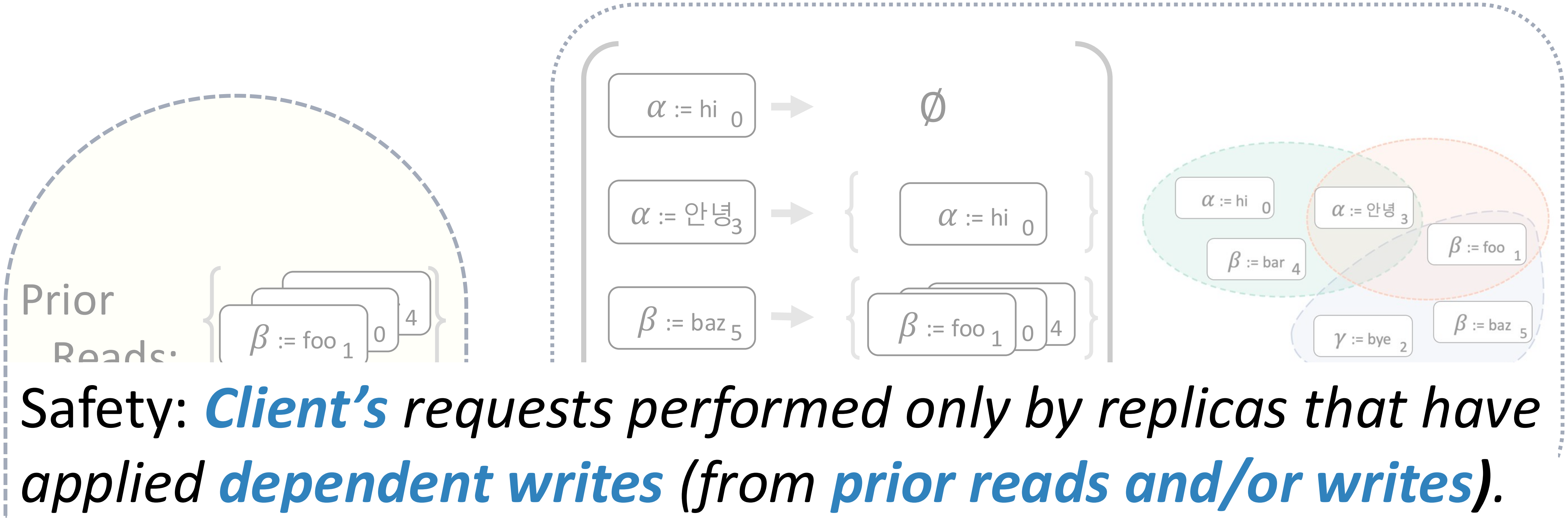




Client

Replicated Storage System

Semantic Model of Session (Using Eventual)

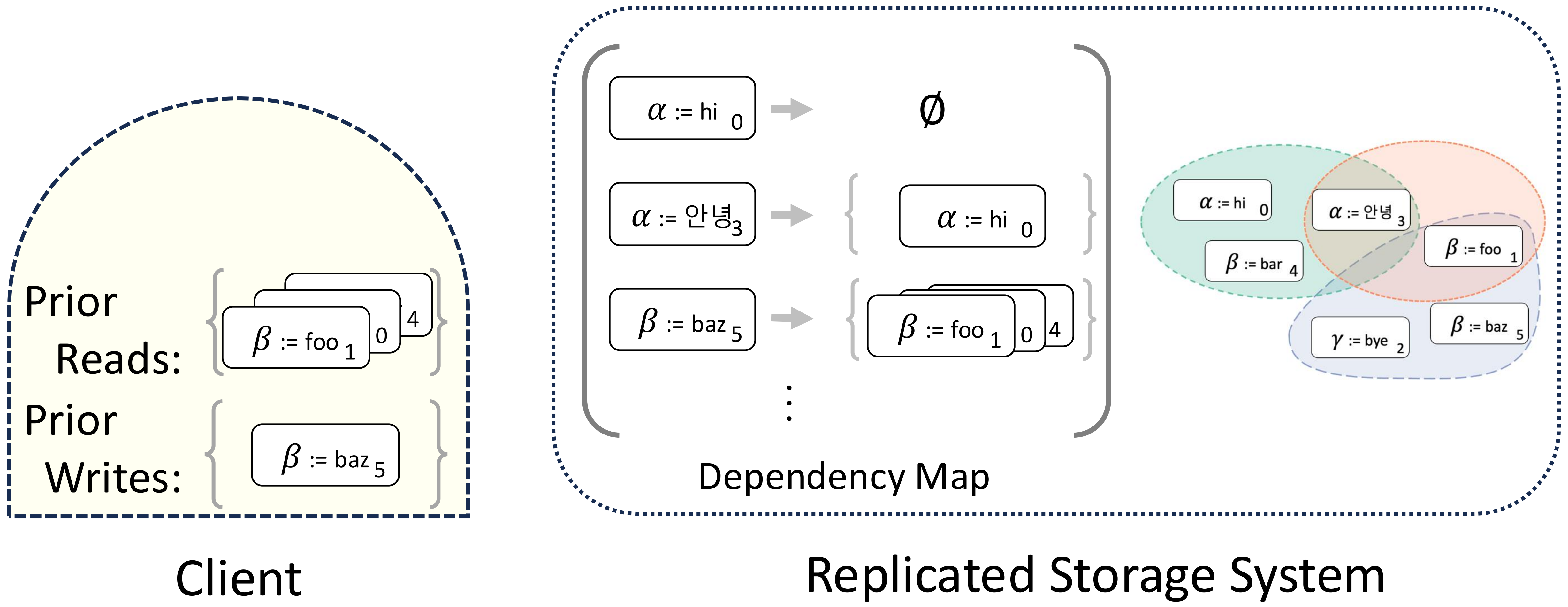


Safety: ***Client's*** *requests performed only by replicas that have applied* ***dependent writes*** *(from* ***prior reads and/or writes****)*.

Client

Replicated Storage System

Semantic Model of Causal (Using Session)



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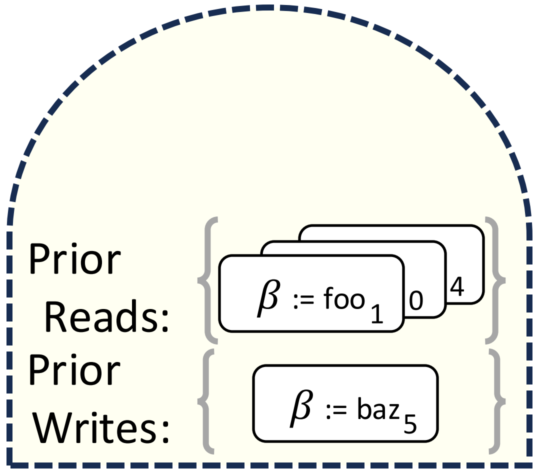

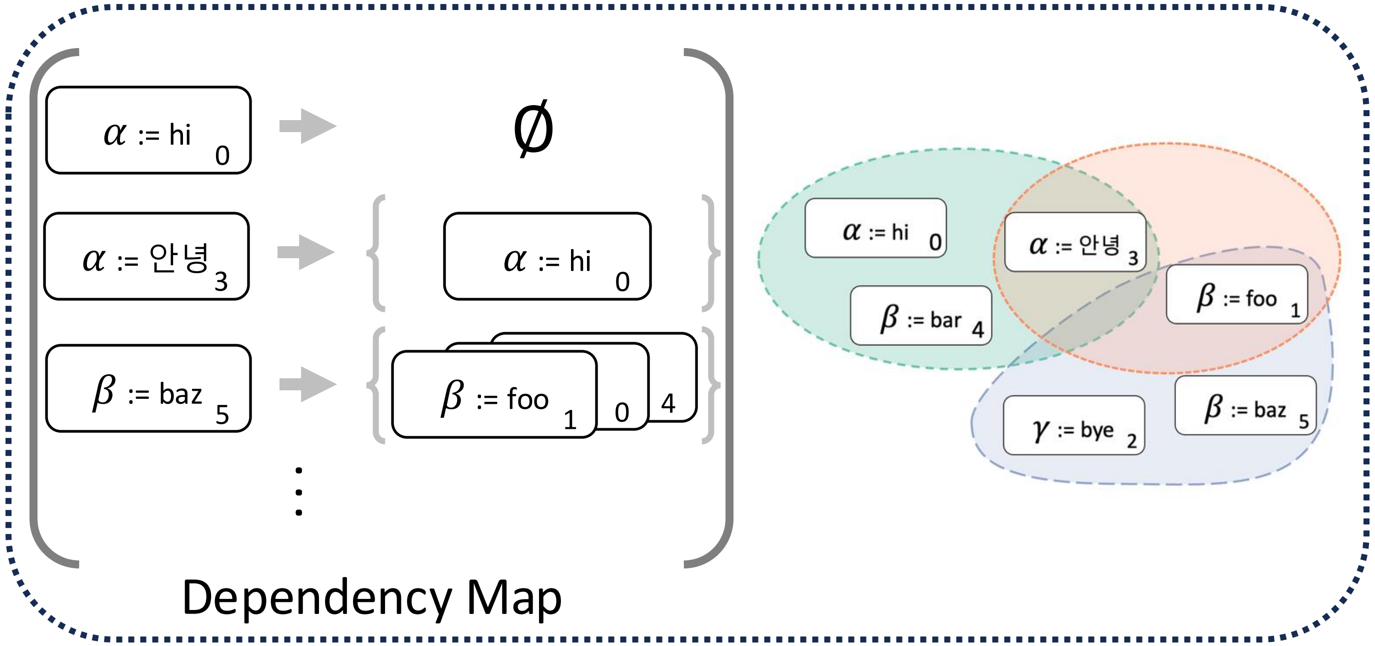

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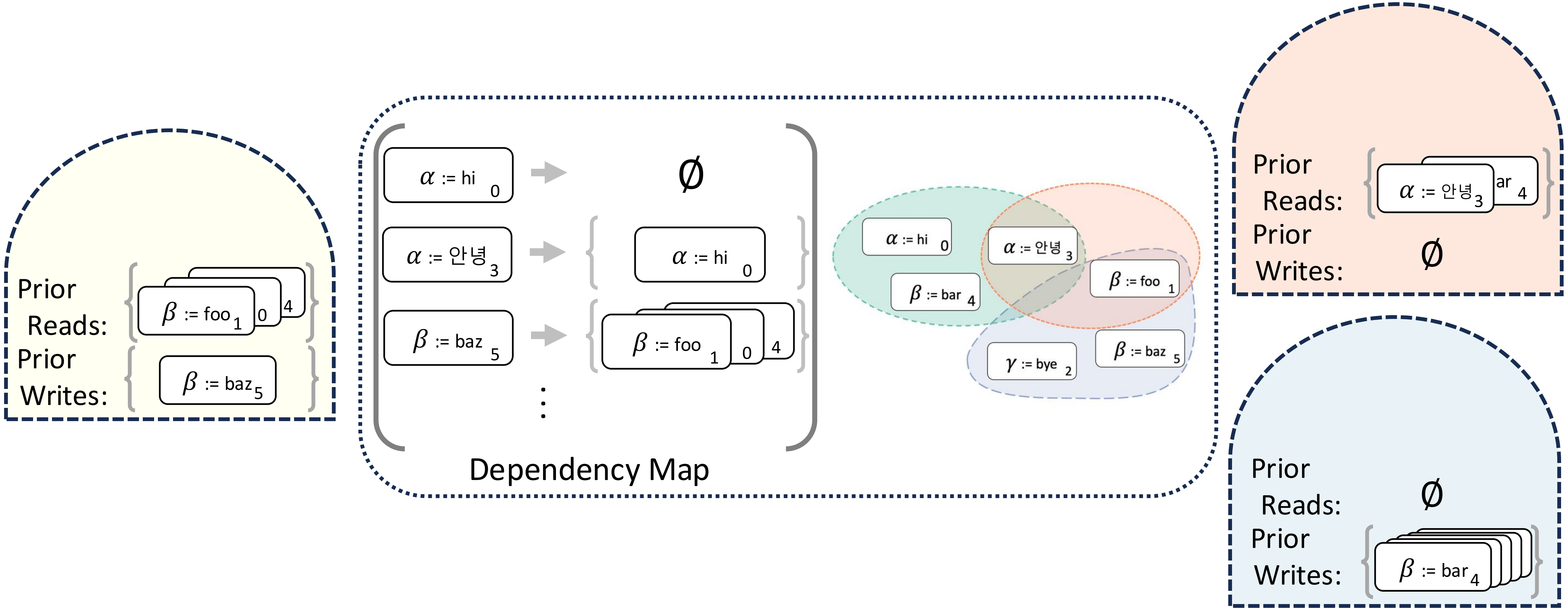

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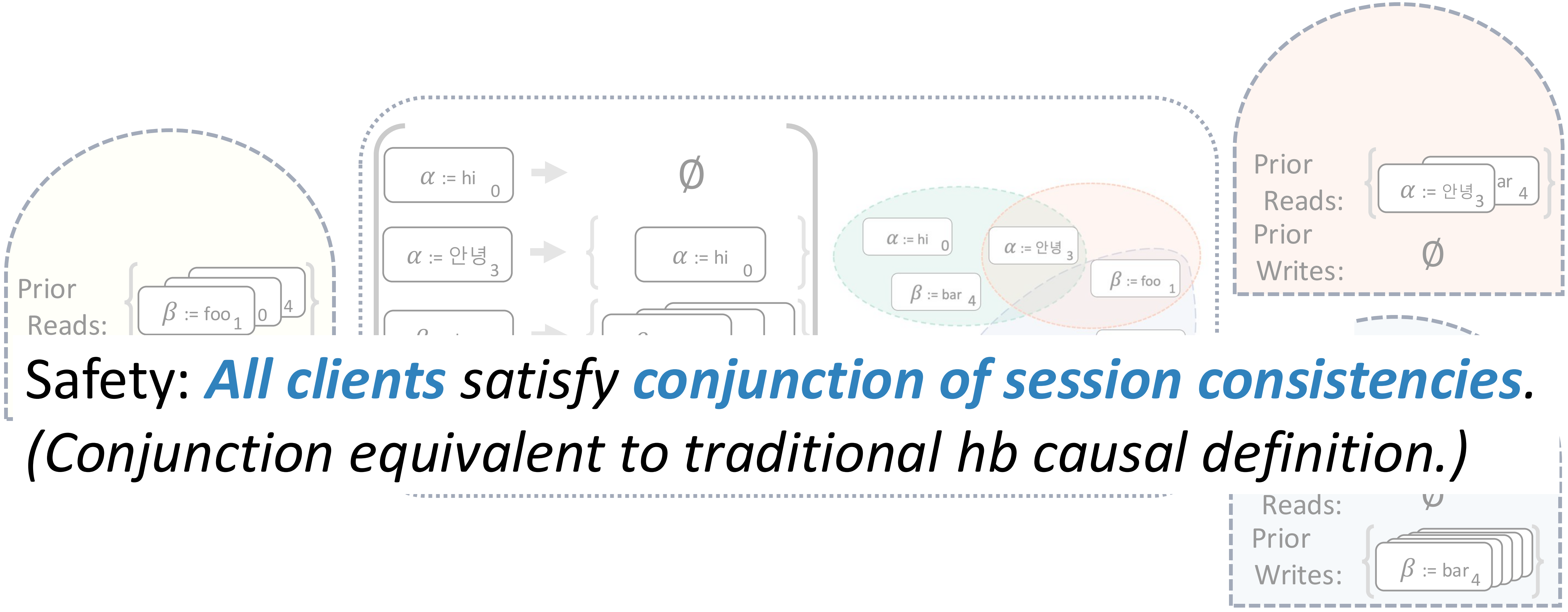
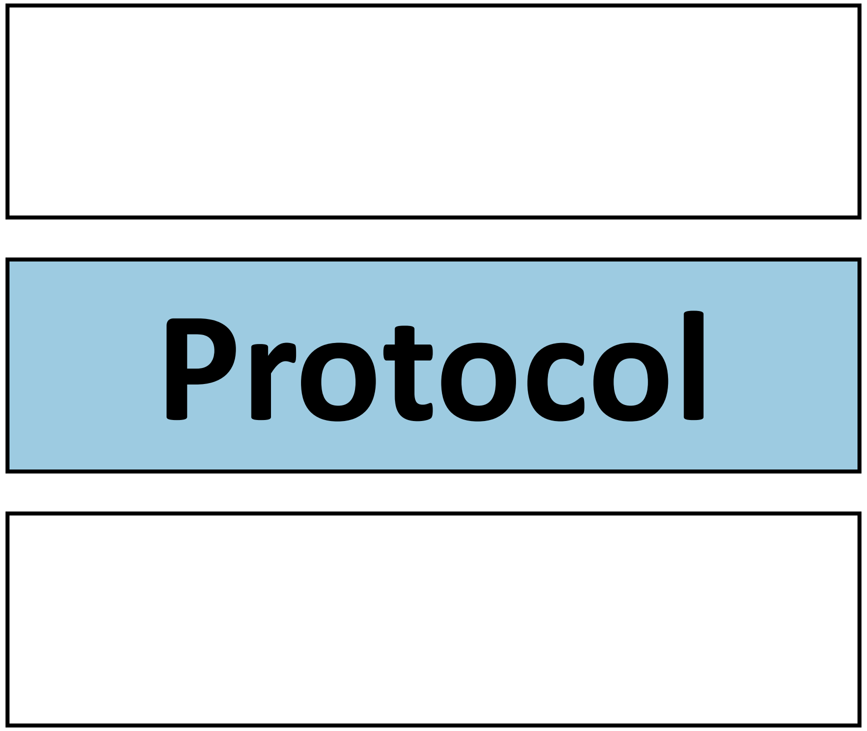
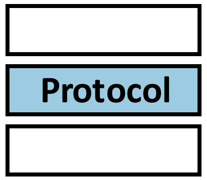


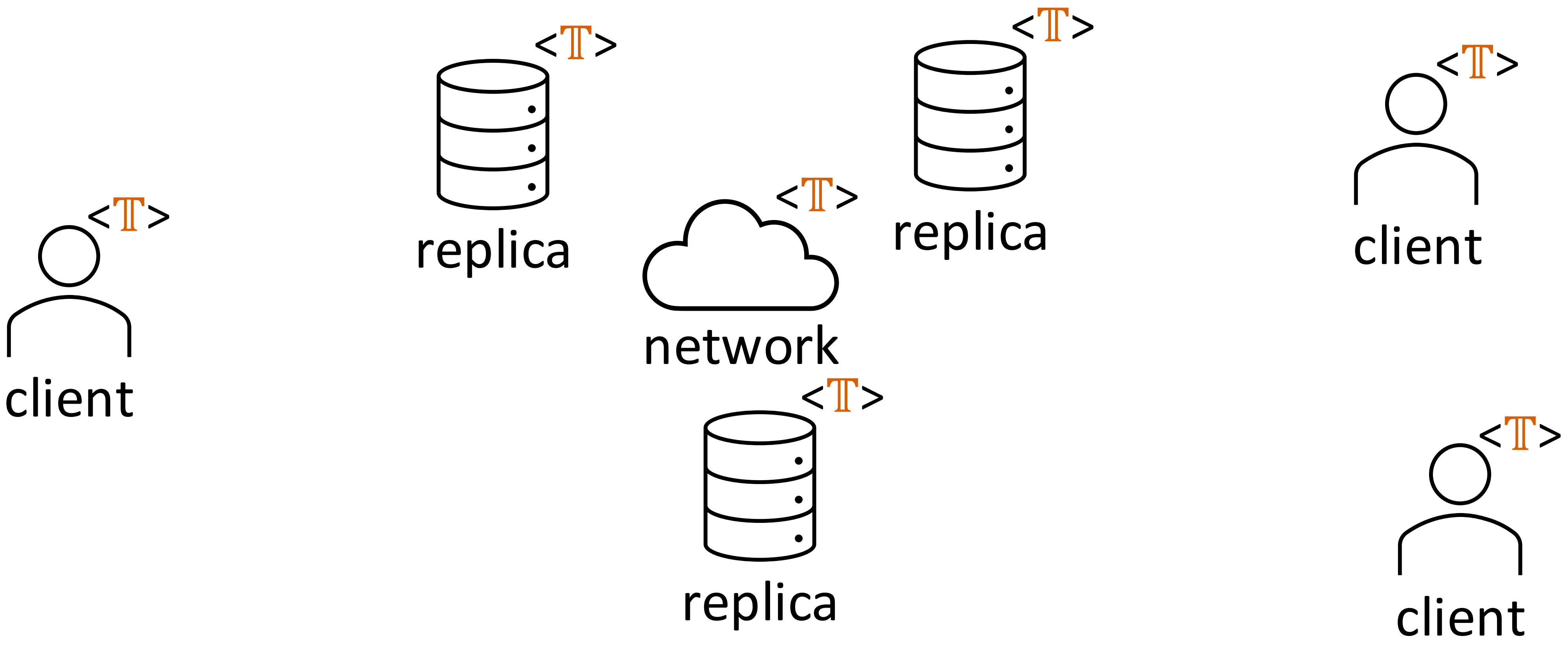
Safety: ***All clients*** *satisfy* ***conjunction of session consistencies***.

(Conjunction equivalent to traditional hb causal definition.)


Protocol

Templated Protocol Models Capture Detail





Protocol Model Replica’s Templated Behavior

```
Template 𝕋
{ Repl Inp Message : Type,
  inform           : Repl → Inp → Repl * list Message * bool,
  act              : Repl → Repl * list Message * bool,
  ... }

Func repl_step<𝕋>(repl :𝕋.Repl, inp :𝕋.Inp) :𝕋.Repl * list 𝕋.Message :=
  repl, msgs, cont := 𝕋.inform(repl, inp)
  while cont do
    repl, msgs', cont := 𝕋.act(repl)
    msgs := append(msgs, msgs')
  return repl, msgs
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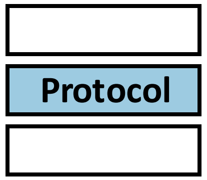

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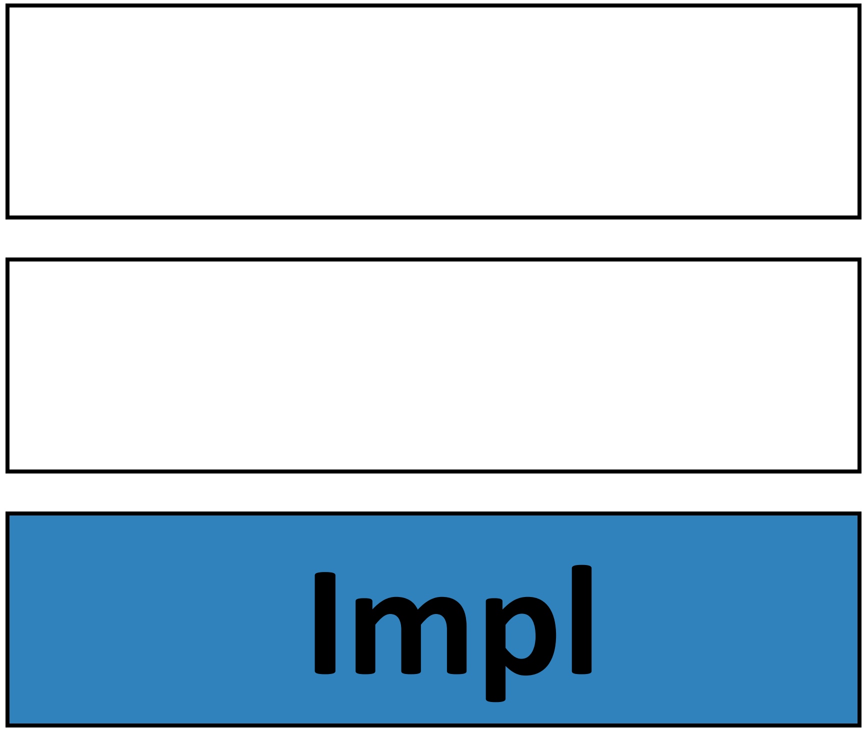
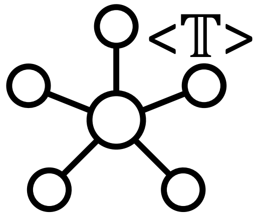

Impl

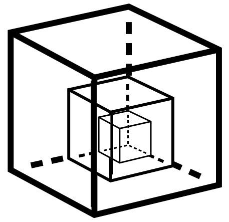
Reusing S-model Proofs for Go code

Impl. (Go)

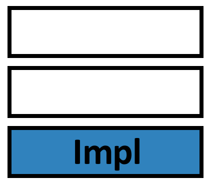


Protocol Models

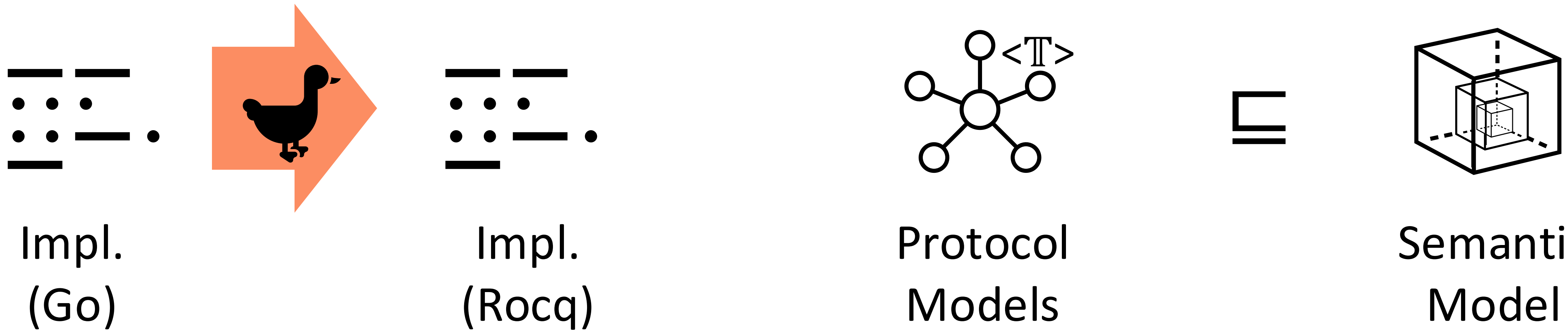
$\sqsubseteq$



Semantic Model

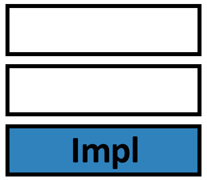


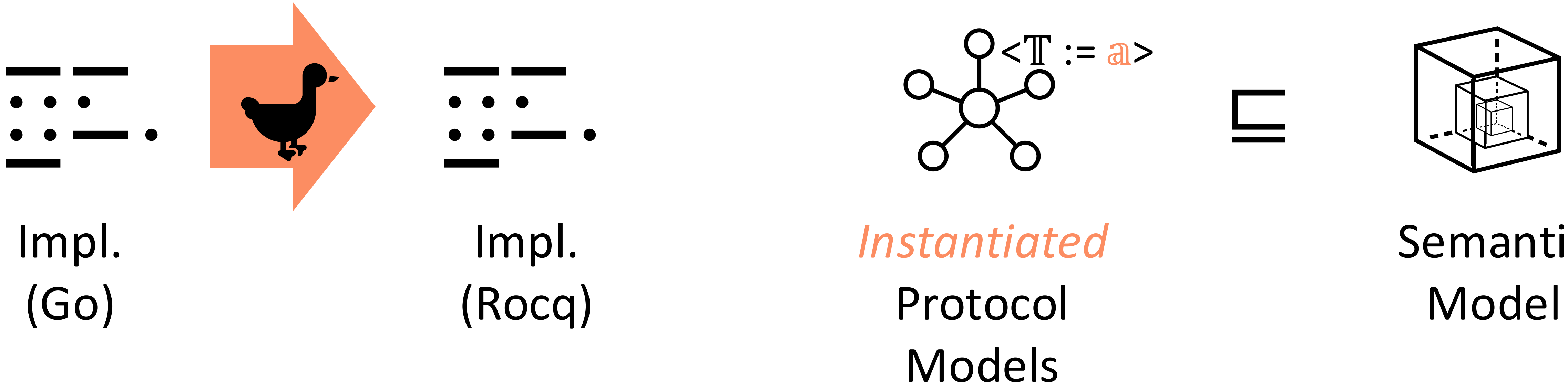
Reusing S-model Proofs for Go code



1. Use Goose to convert Go to Rocq.

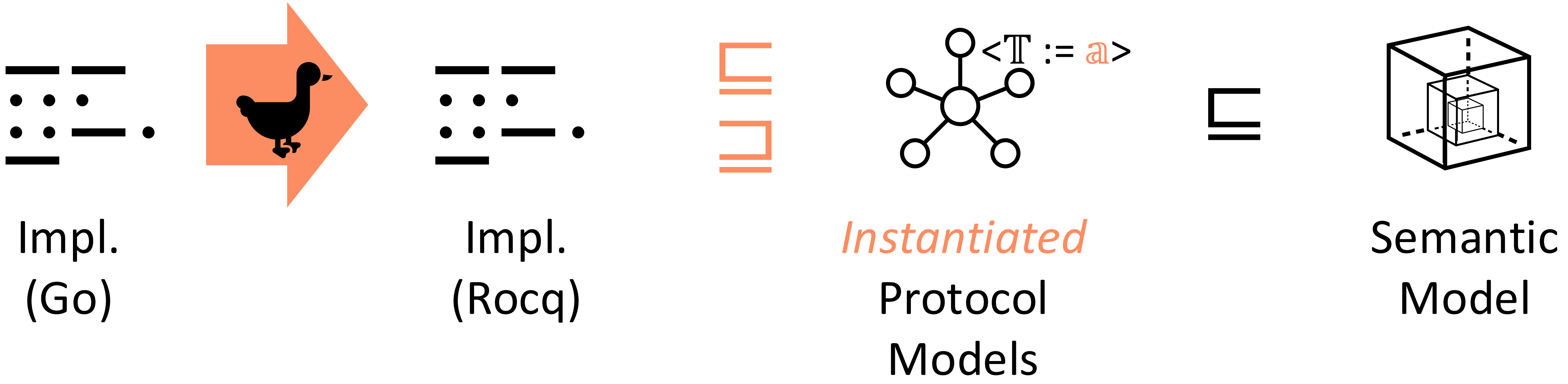
Reusing S-model Proofs for Go code





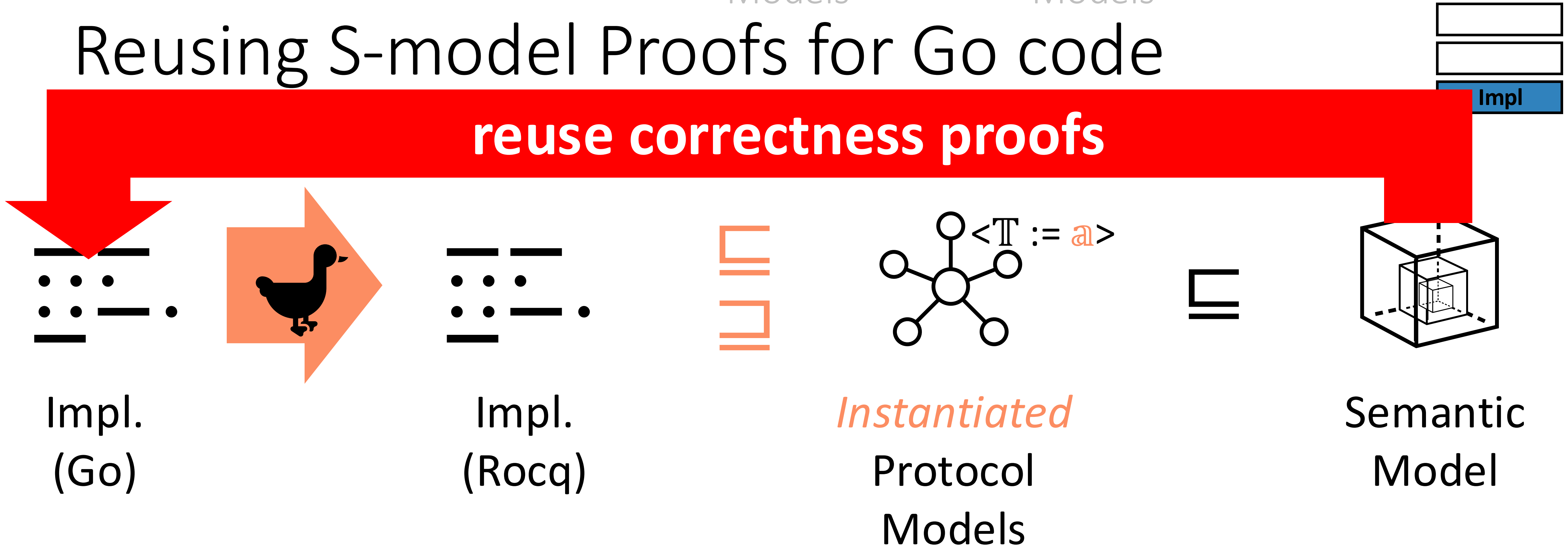
1. Use Goose to convert Go to Rocq.
2. Instantiate Protocol Models.

Reusing S-model Proofs for Go code



1. Use Goose to convert Go to Rocq.
2. Instantiate Protocol Models.
3. Prove bisimulation between Rocq and instantiated Protocol Models.

Reusing S-model Proofs for Go code



1. Use Goose to convert Go to Rocq.
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In summary, Moveri…

- Verification framework for weakly consistent systems.
- Leverages composition to model 16 consistencies.
- Used to verify Go implementations of
  - primary-replica style and gossip style

  systems exhibiting
  - eventual, session, and causal consistencies.

- ***Will support*** liveness and more consistencies.

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Questions?