Programming at Scale: Consistency

cs378h

Today

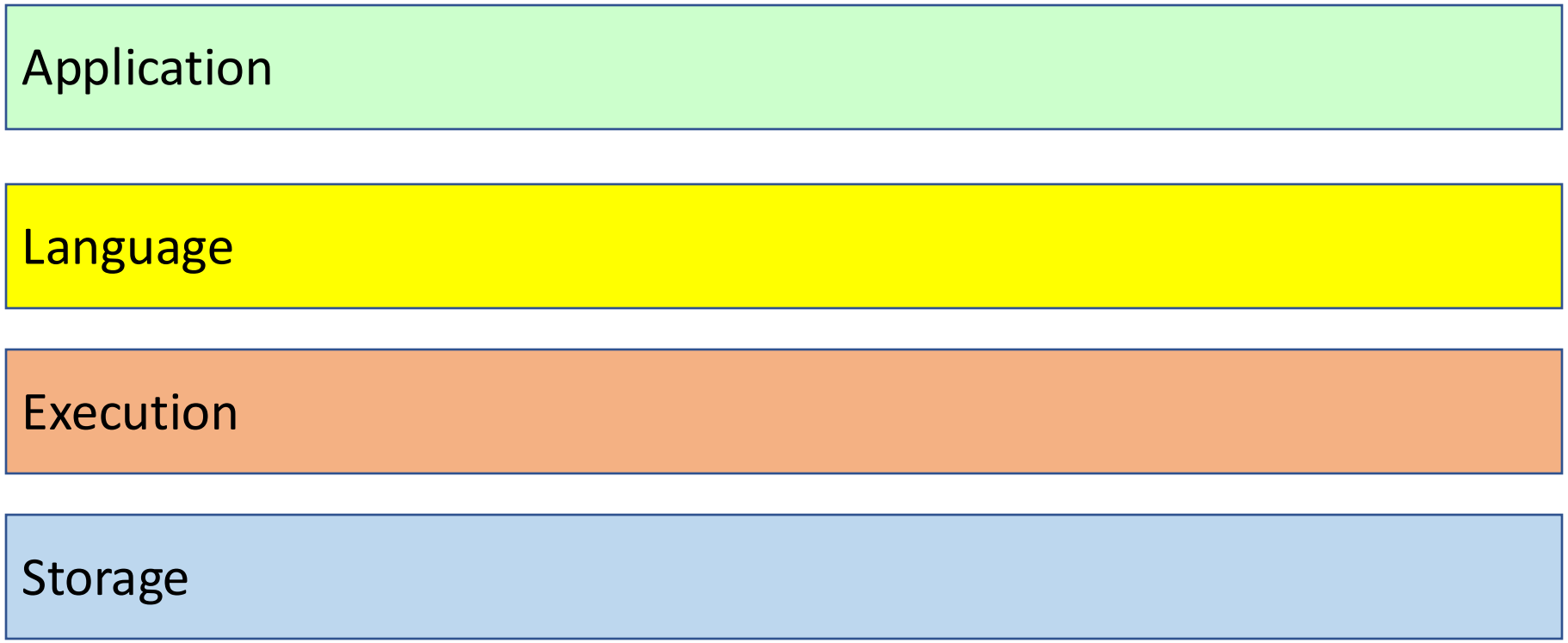
Questions?

Administrivia

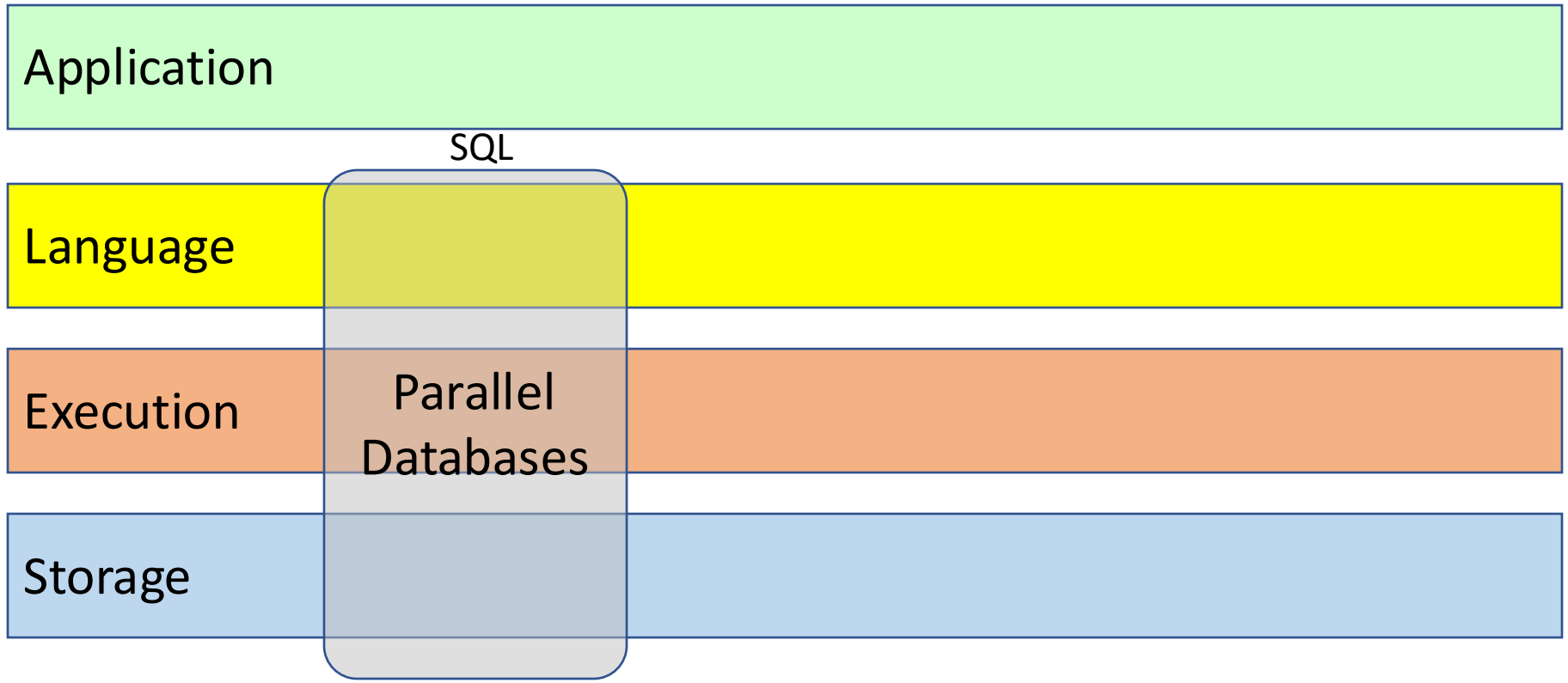
Agenda:

- Concurrency & Consistency at Scale

Data-Parallel Computation Systems



Data-Parallel Computation Systems



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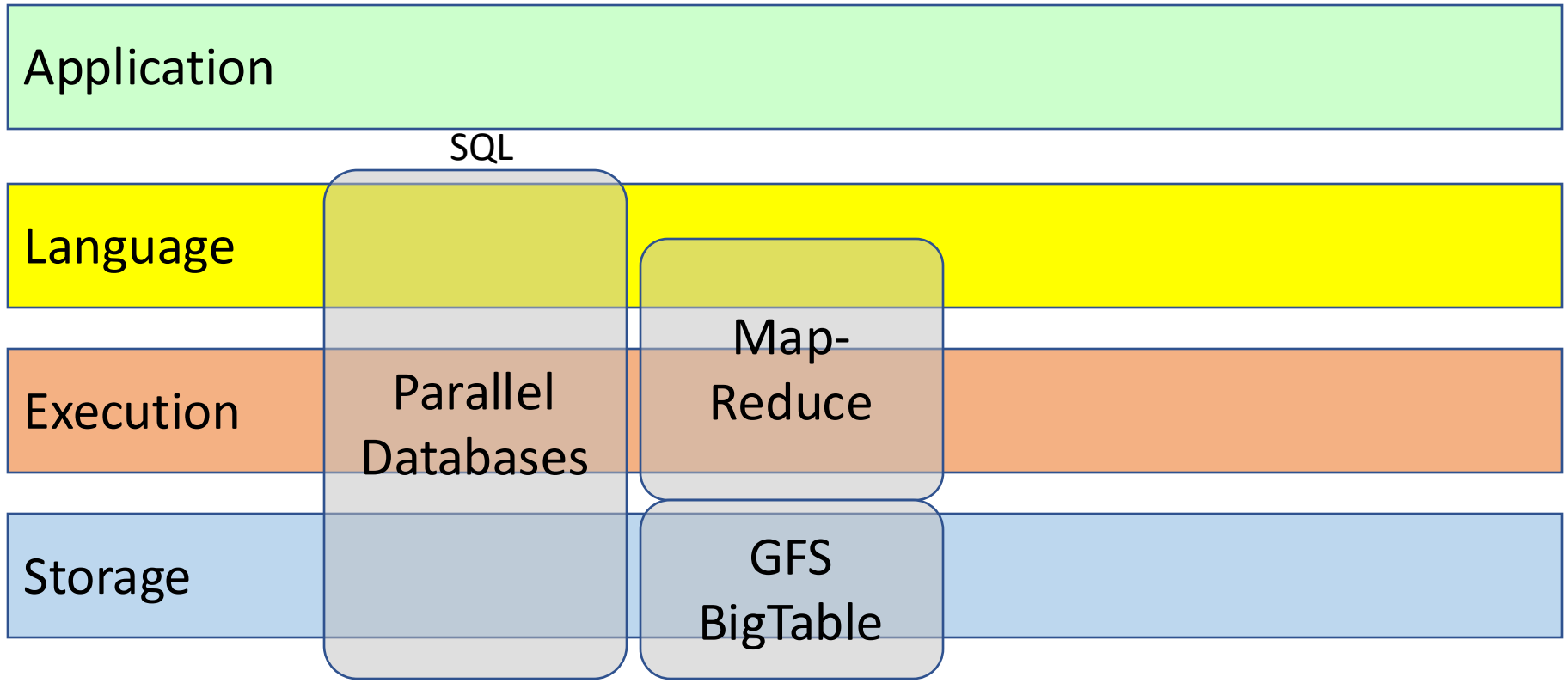

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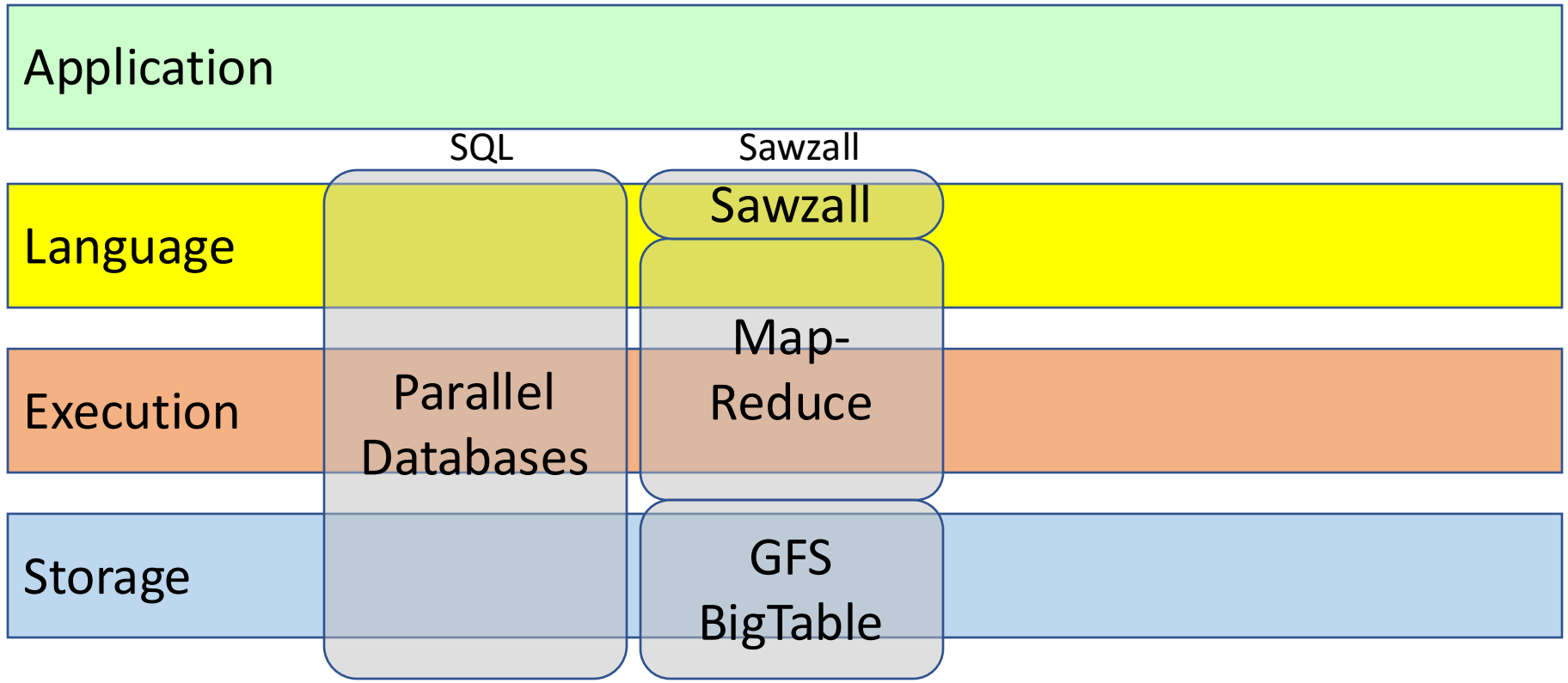

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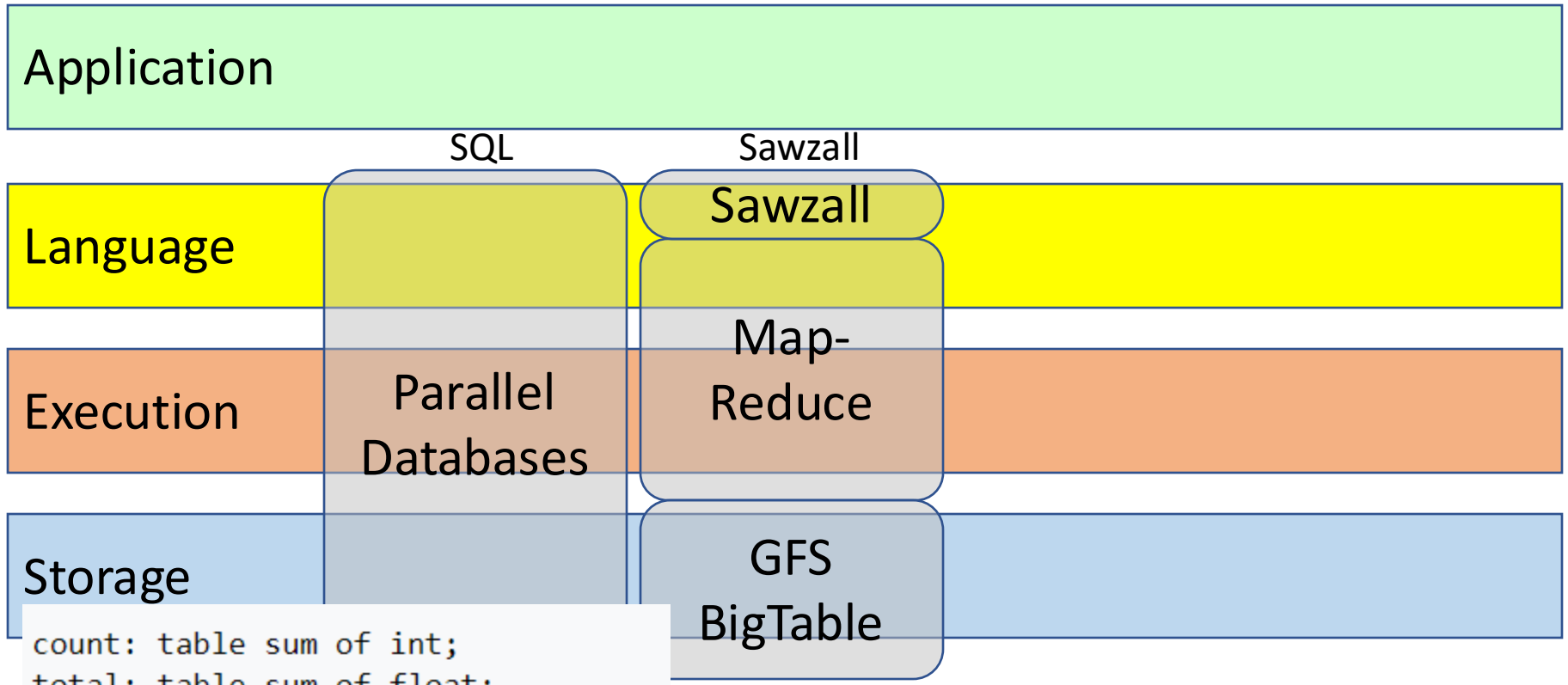
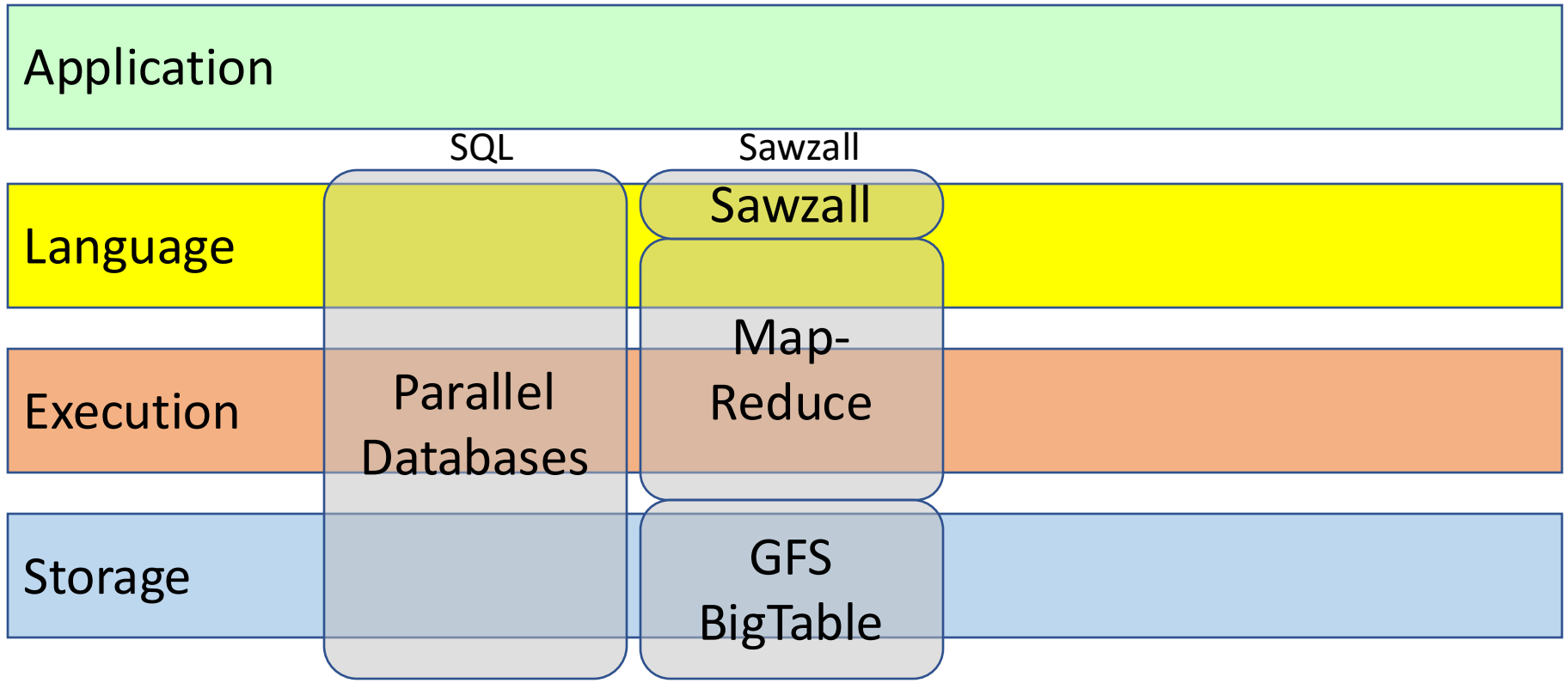



```
count: table sum of int;
total: table sum of float;
sum_of_squares: table sum of float;
x: float = input;
emit count <- 1;
emit total <- x;
emit sum_of_squares <- x * x;
```

Data-Parallel Computation Systems



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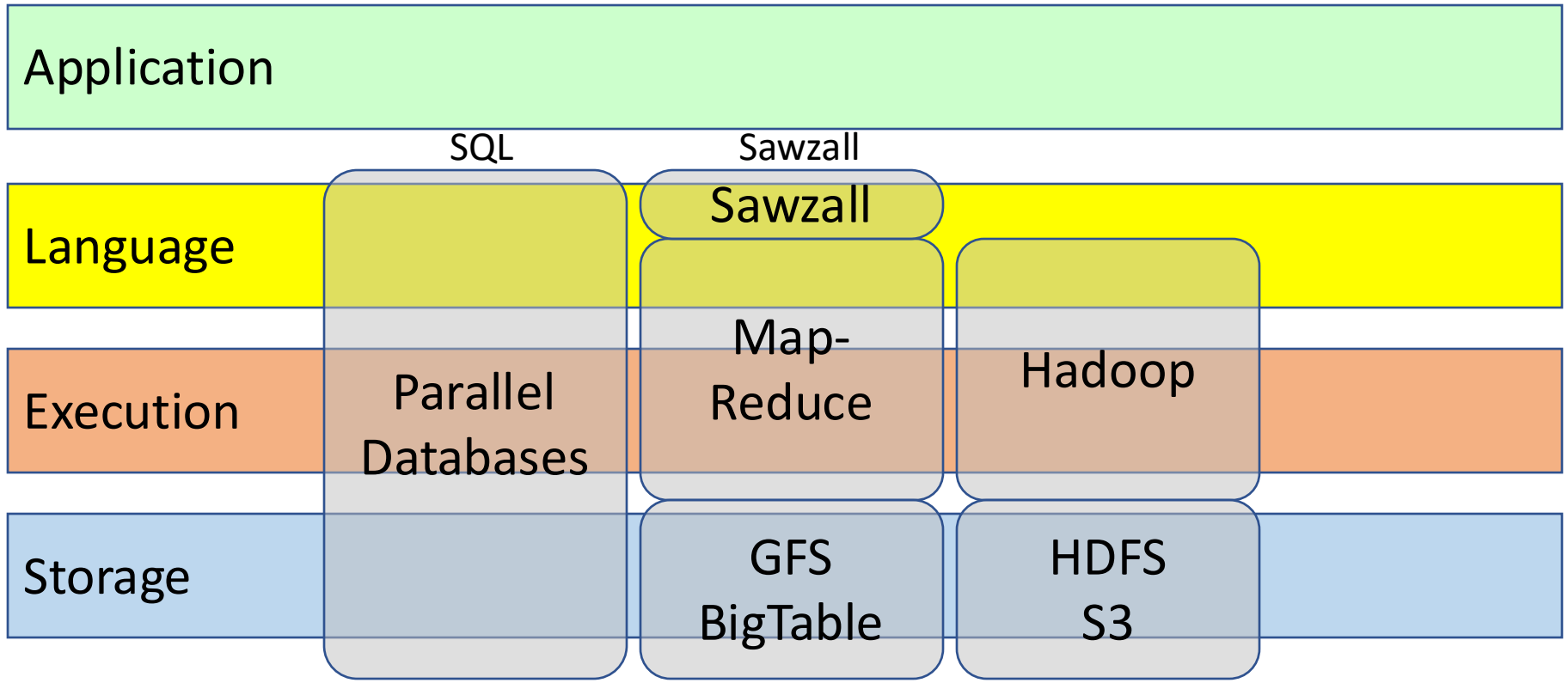

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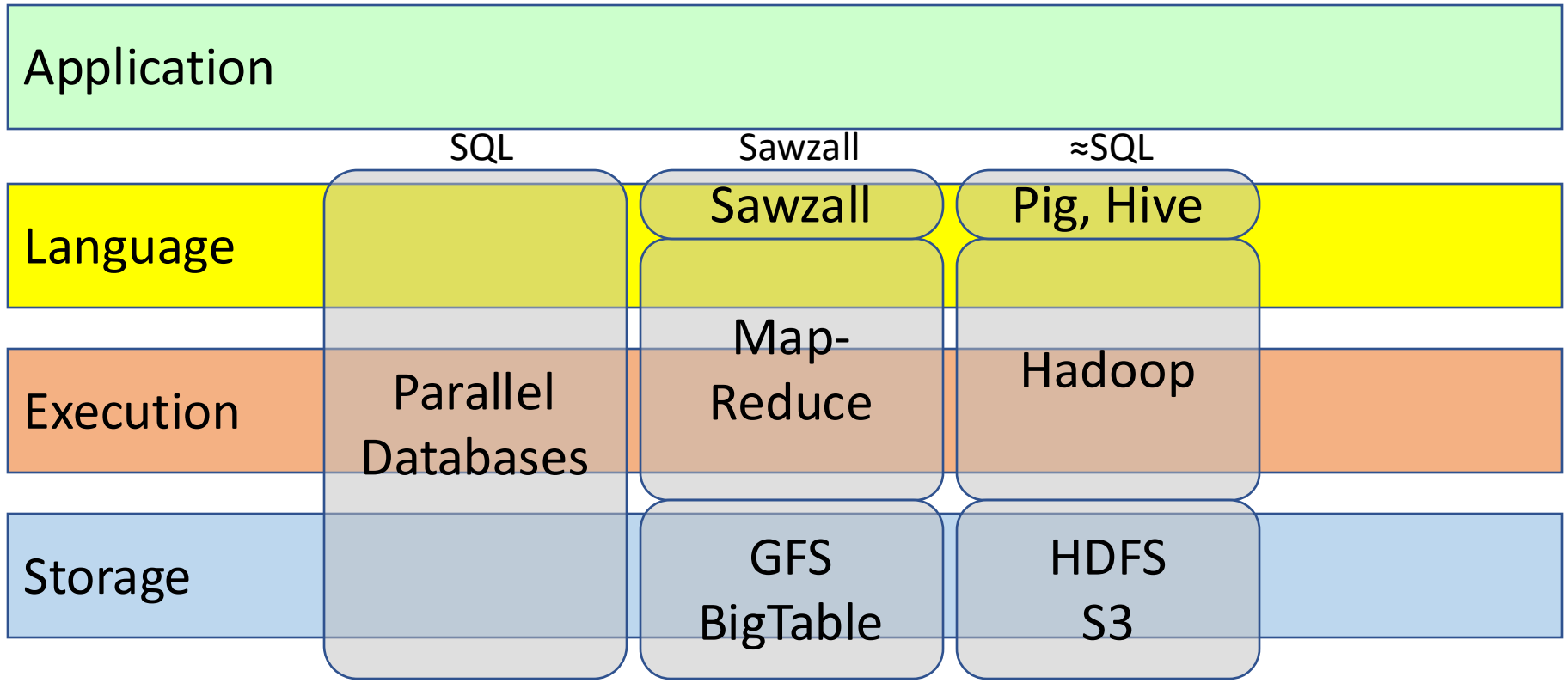
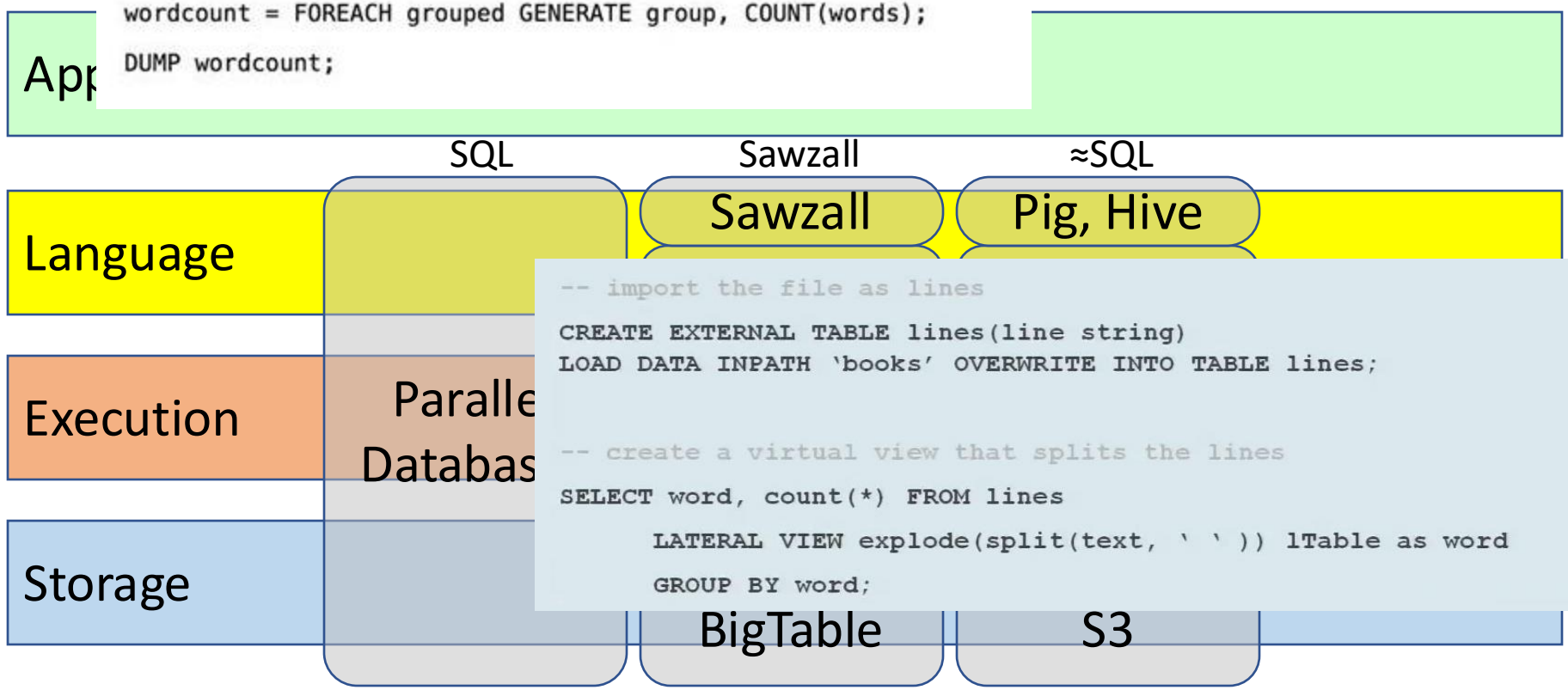


Systems

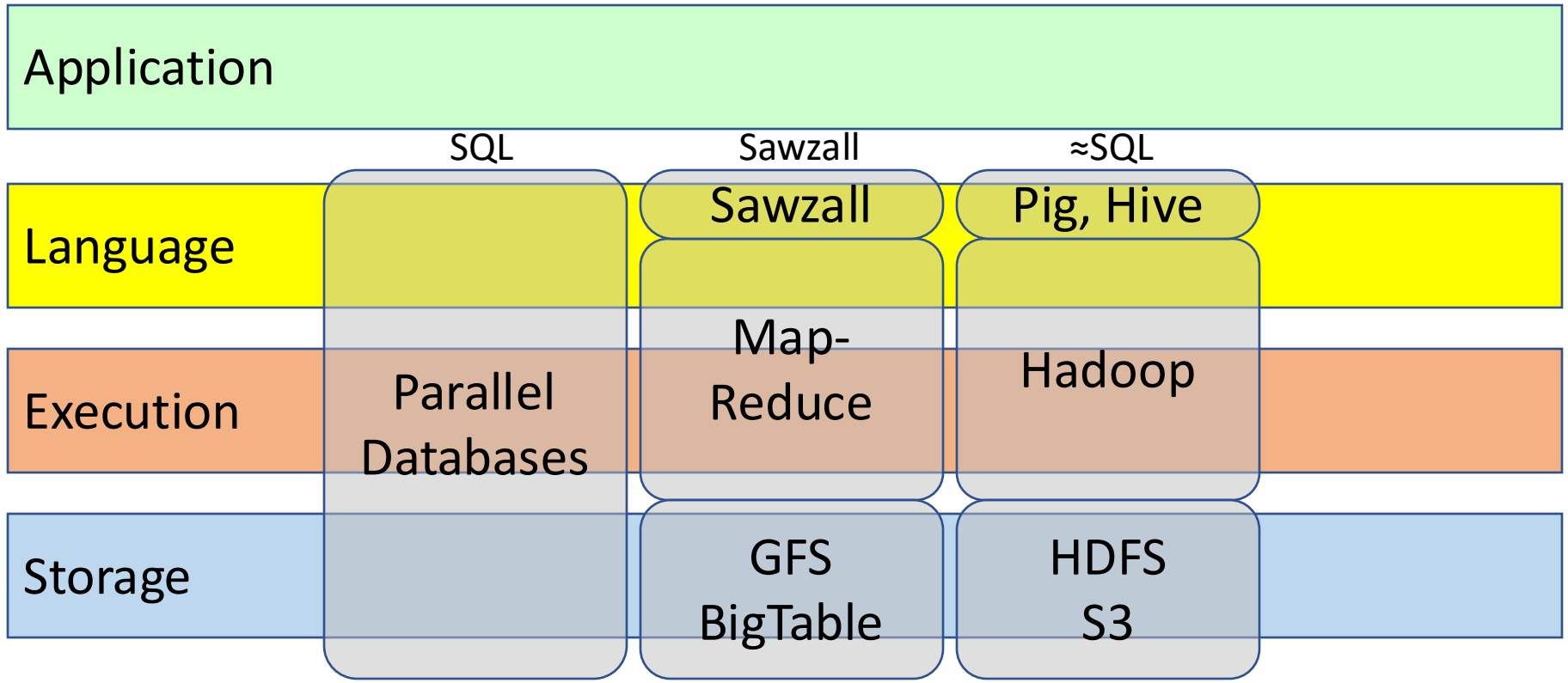
```
lines = LOAD '/user/hadoop/HDFS_File.txt' AS (line:chararray);
words = FOREACH lines GENERATE FLATTEN(TOKENIZE(line)) as word;
grouped = GROUP words BY word;
wordcount = FOREACH grouped GENERATE group, COUNT(words);
DUMP wordcount;
```




```
-- import the file as lines
CREATE EXTERNAL TABLE lines(line string)
LOAD DATA INPATH 'books' OVERWRITE INTO TABLE lines;

-- create a virtual view that splits the lines
SELECT word, count(*) FROM lines
      LATERAL VIEW explode(split(text, ' ' )) lTable as word
      GROUP BY word;
```

Data-Parallel Computation Systems



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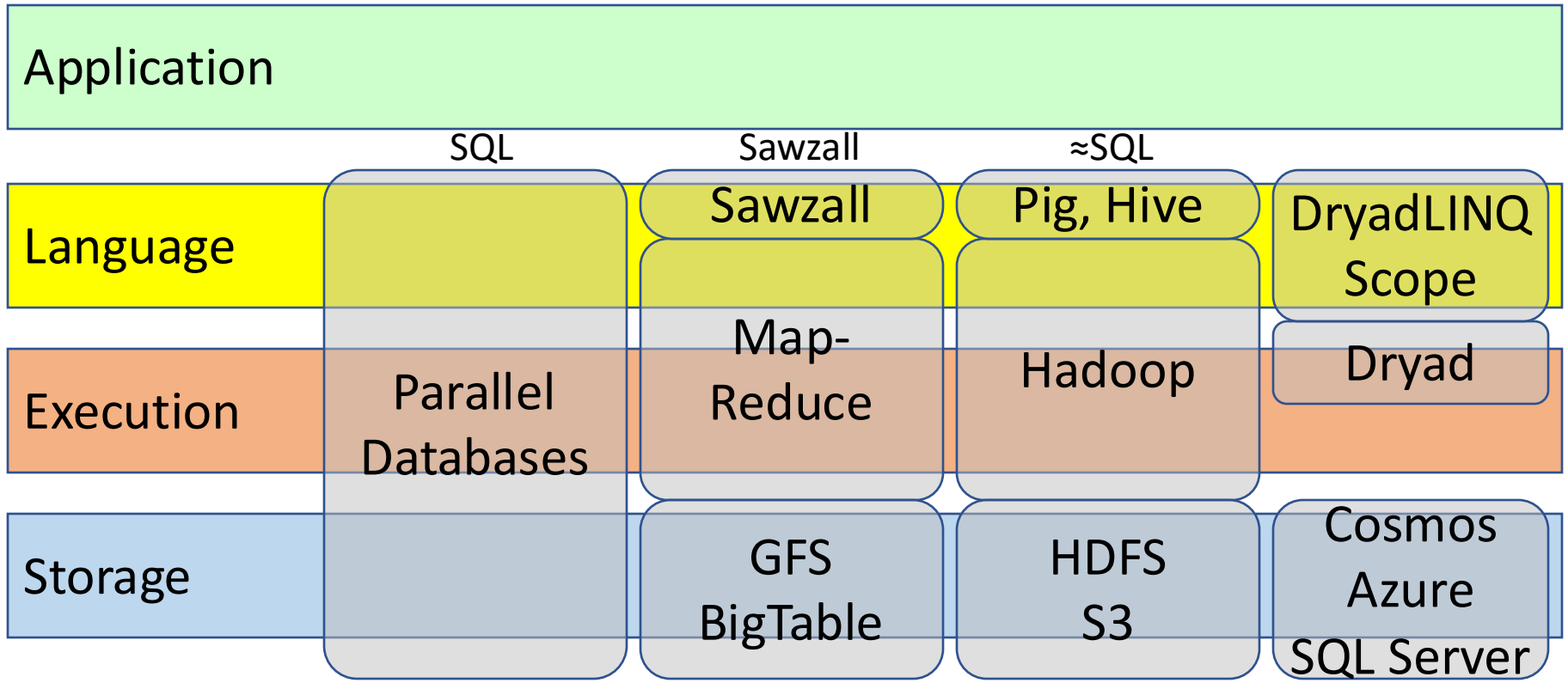

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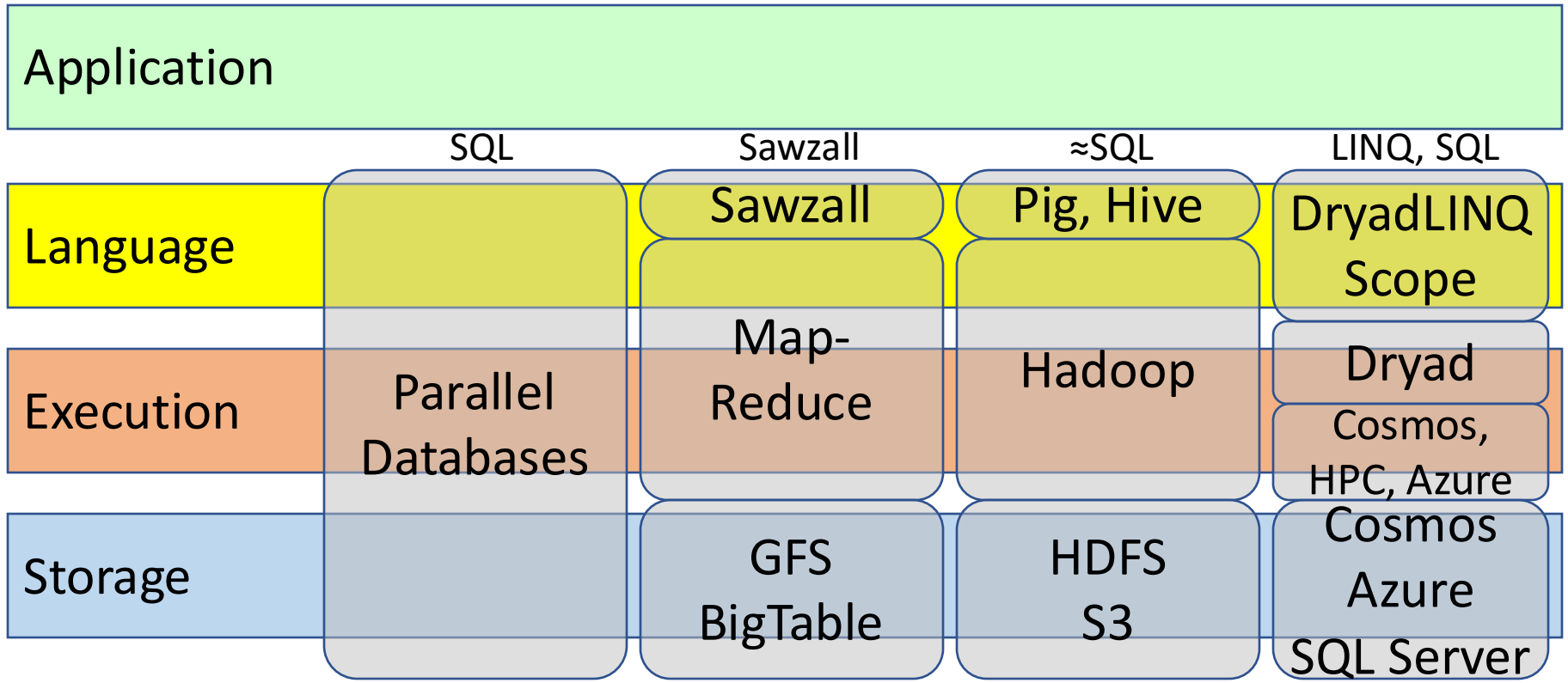

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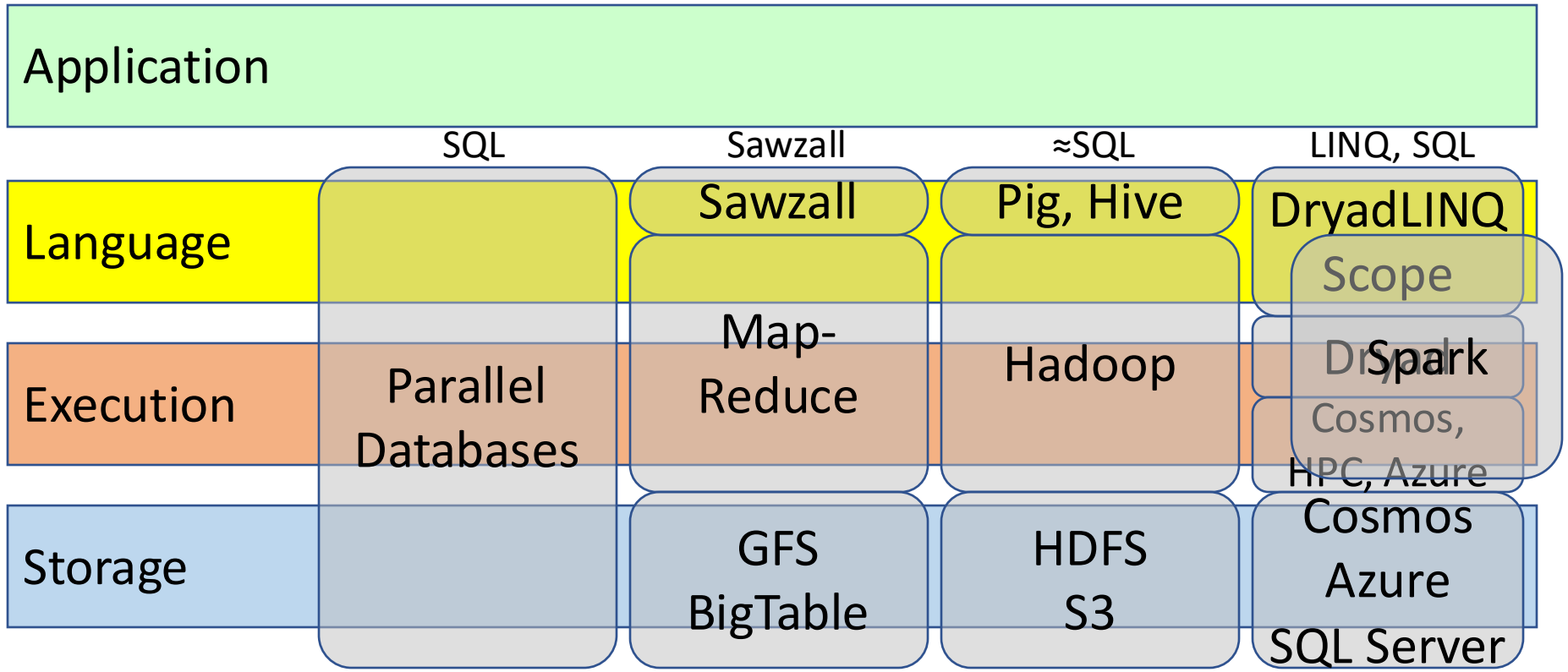
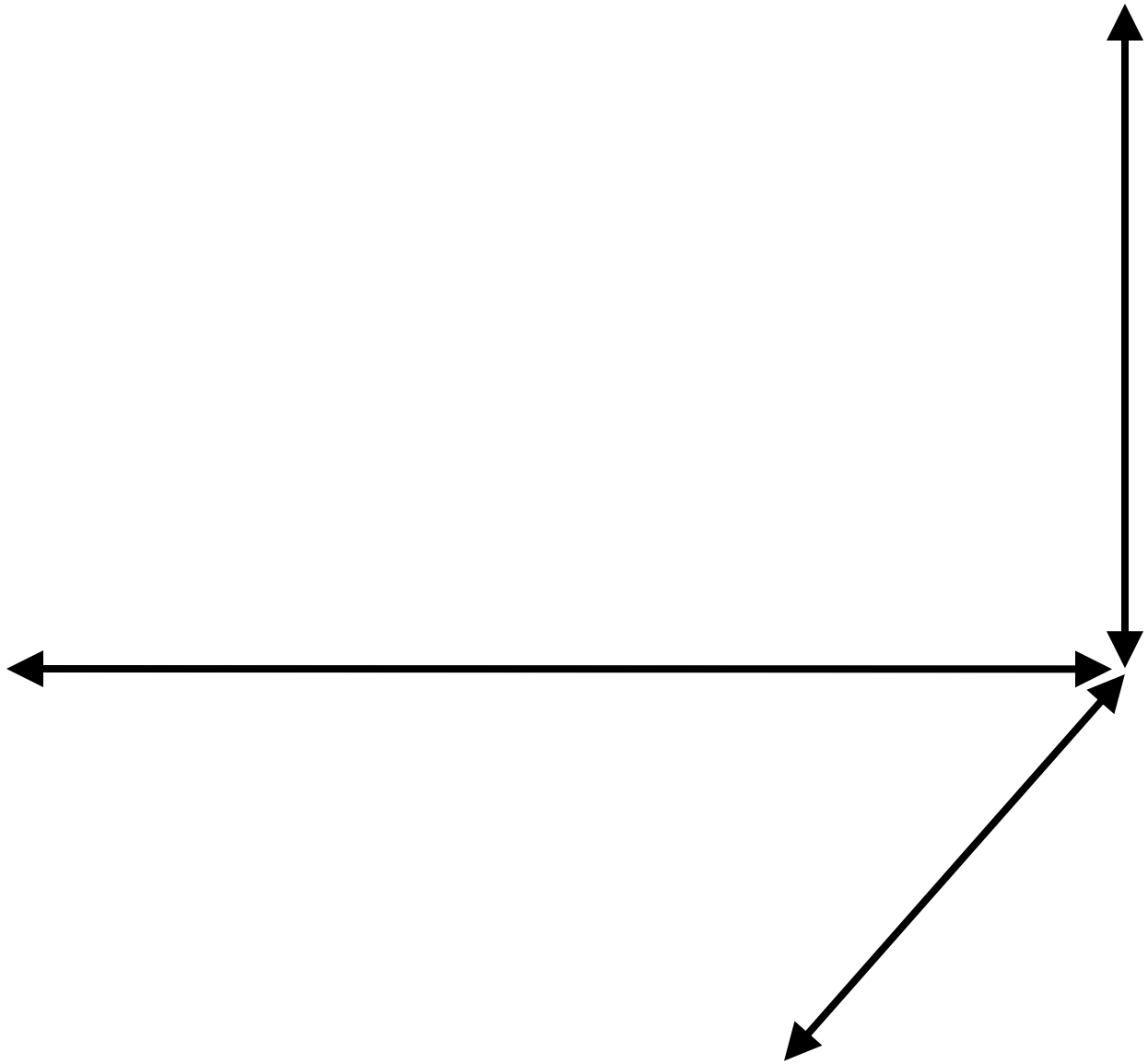


(Yet) Another Framework



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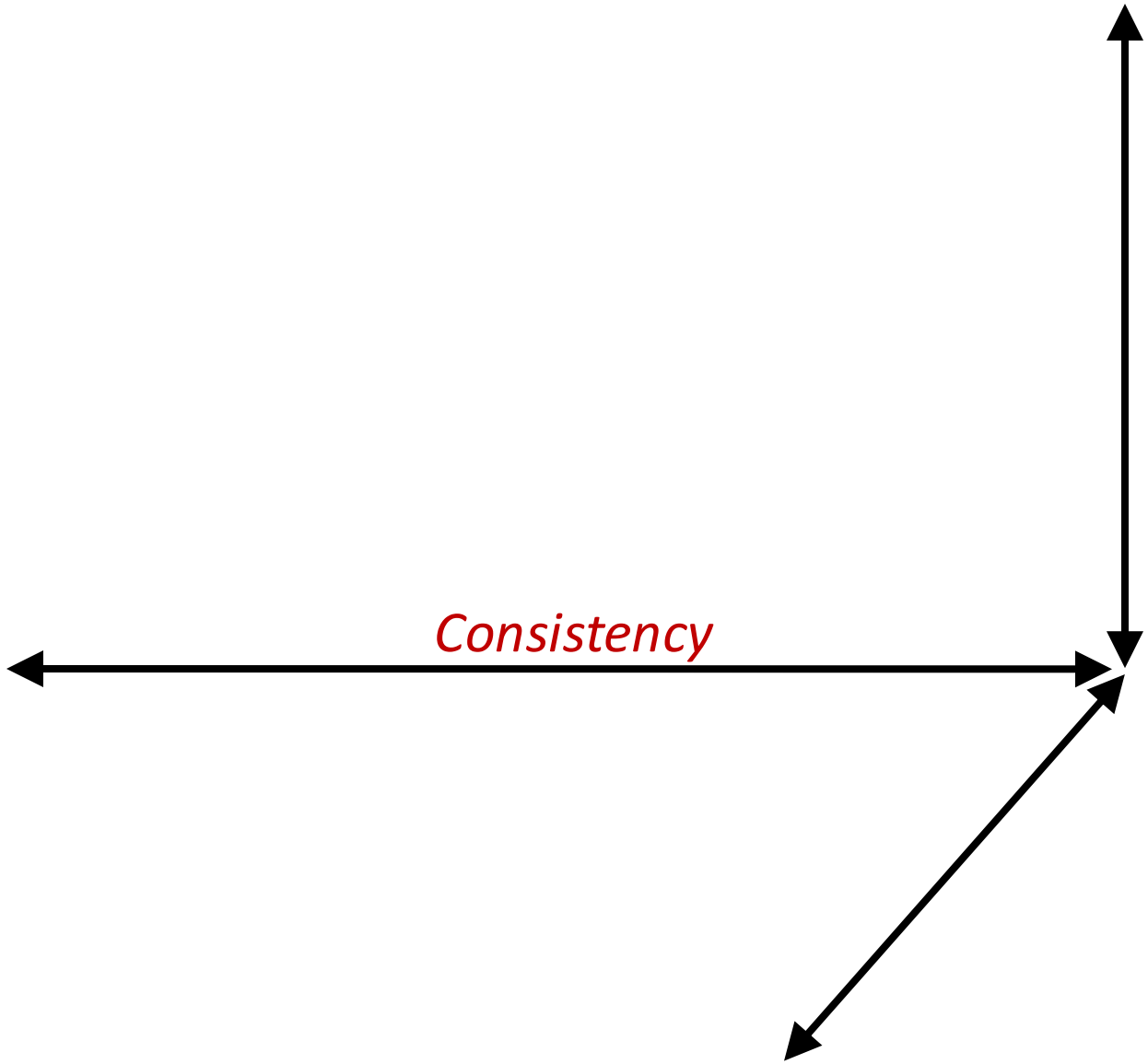

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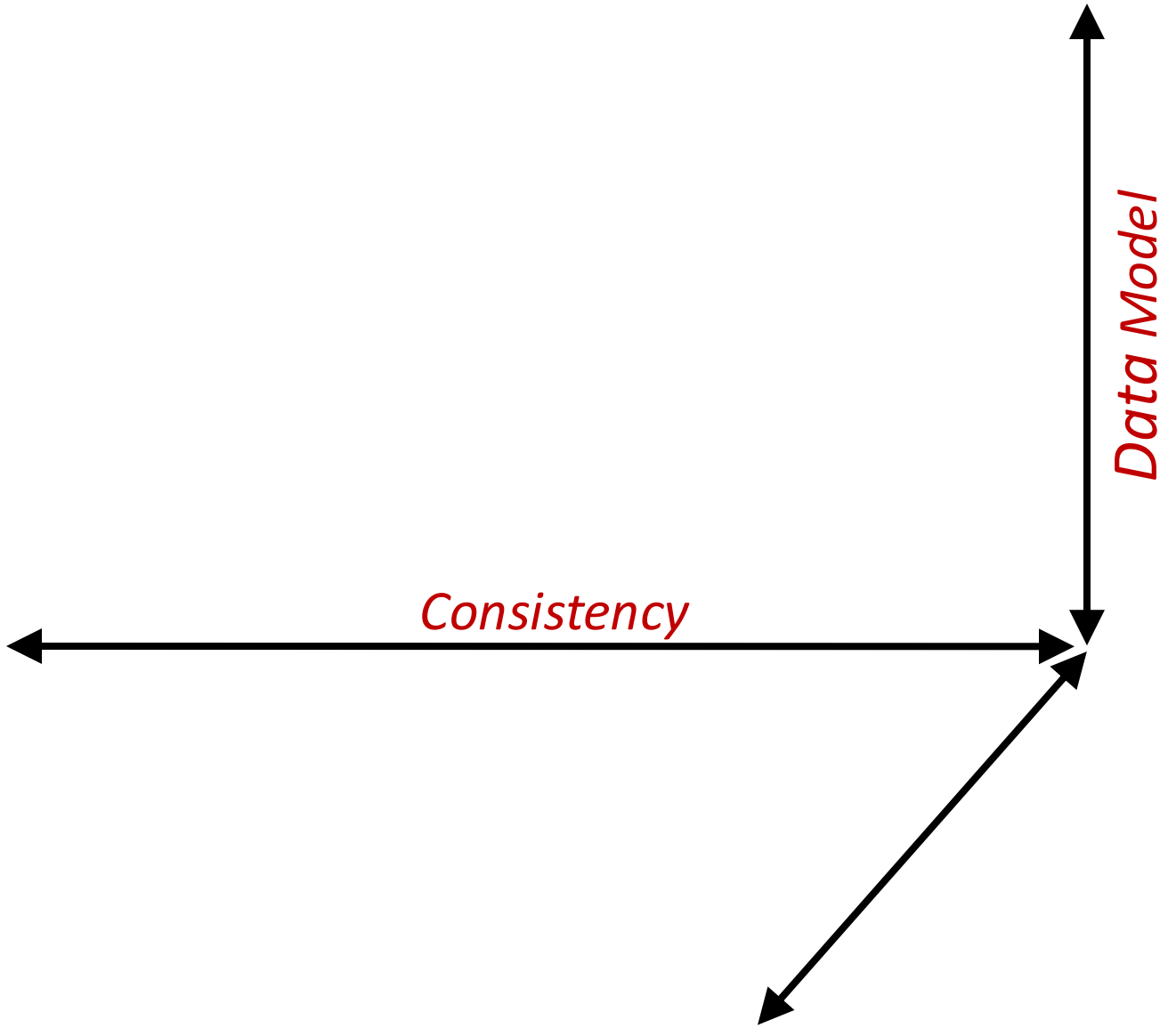

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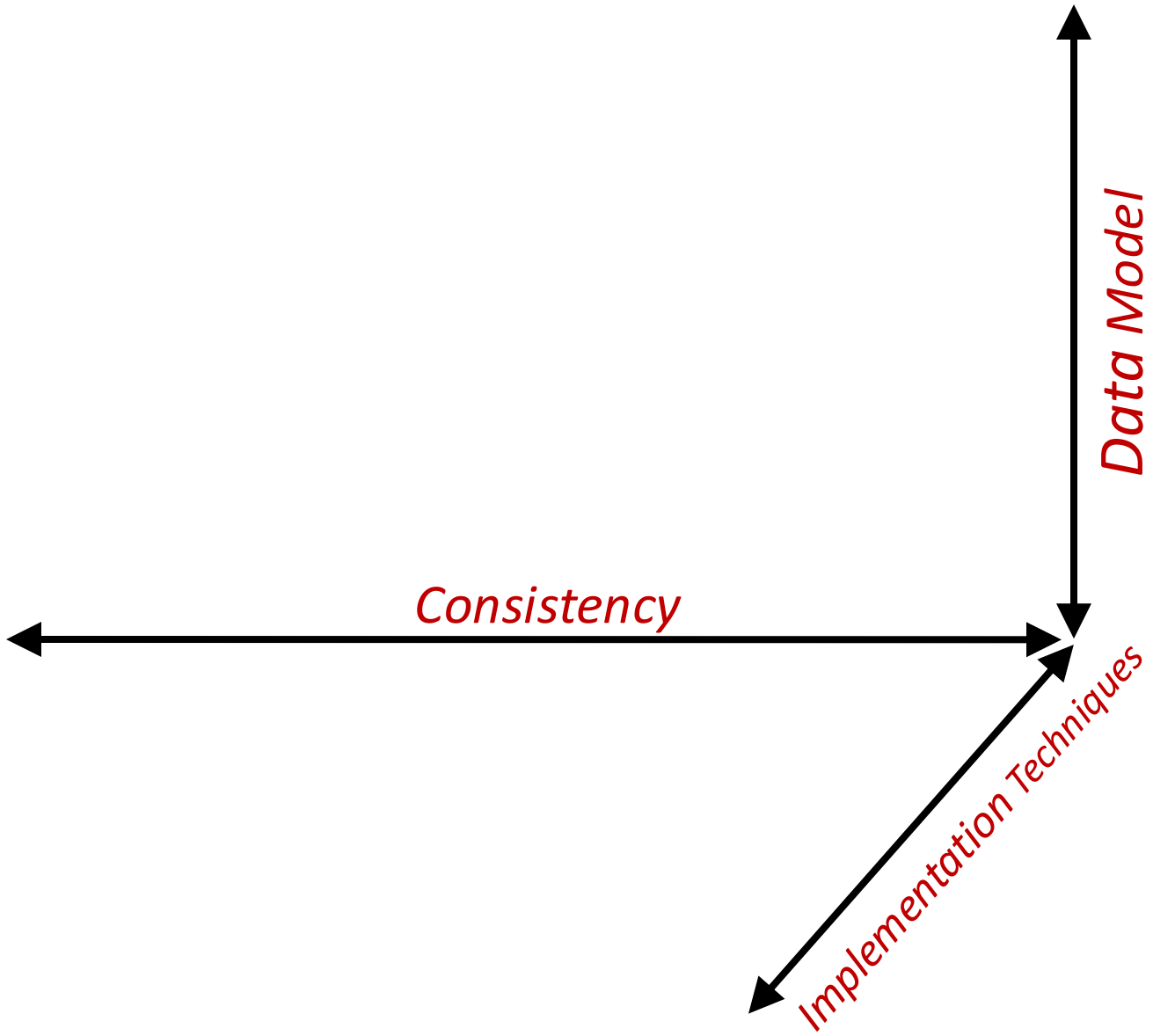

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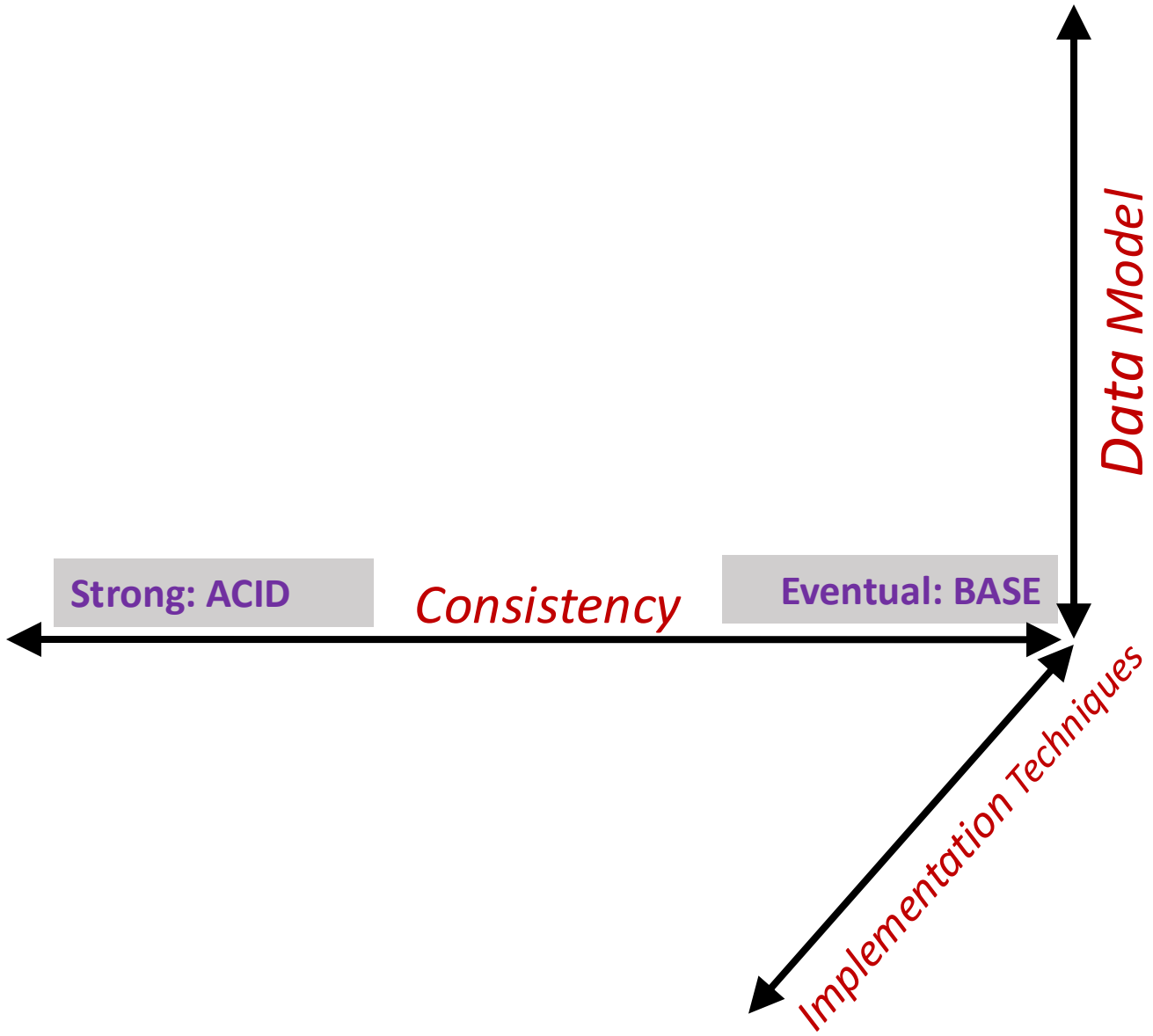

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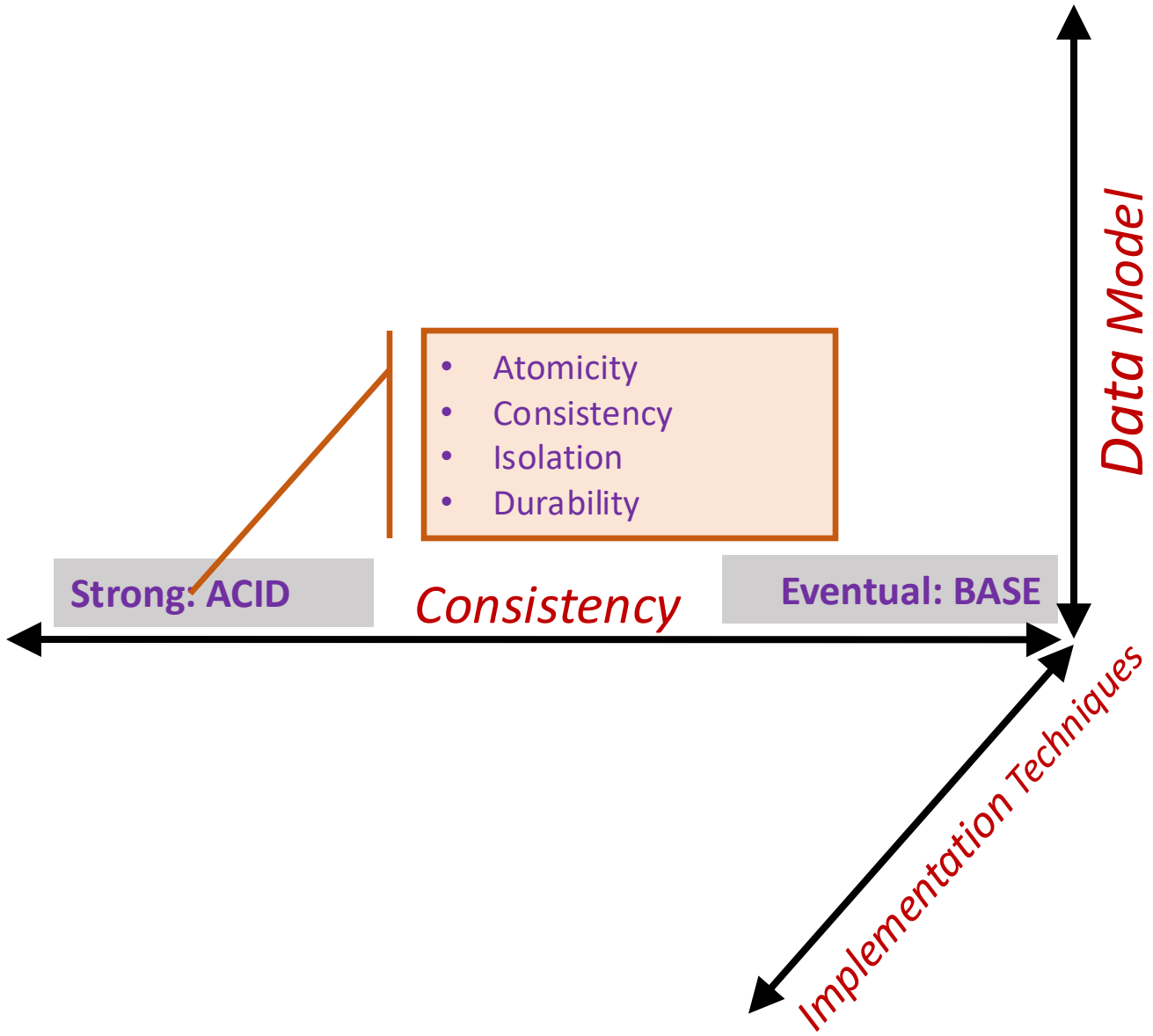

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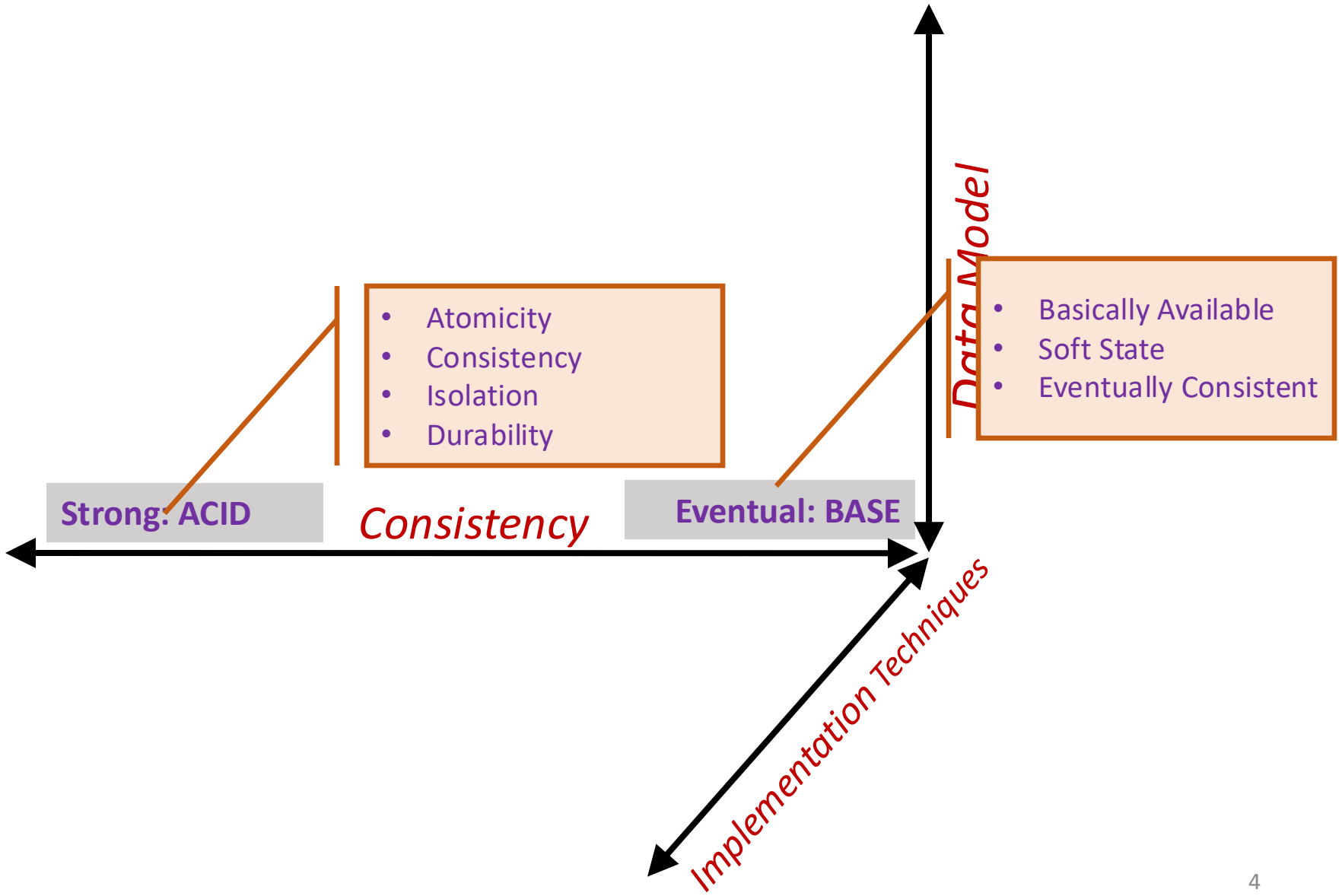

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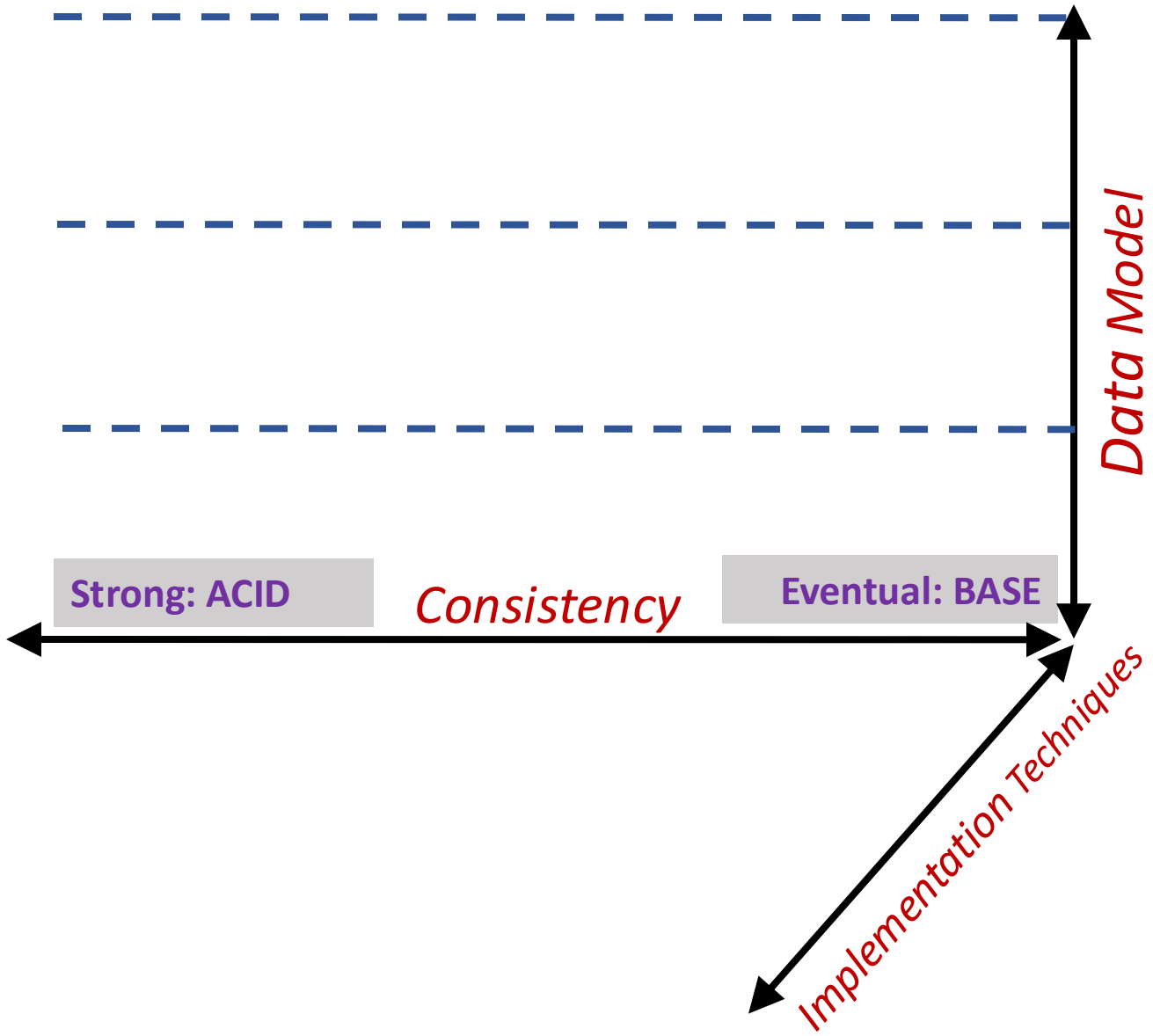

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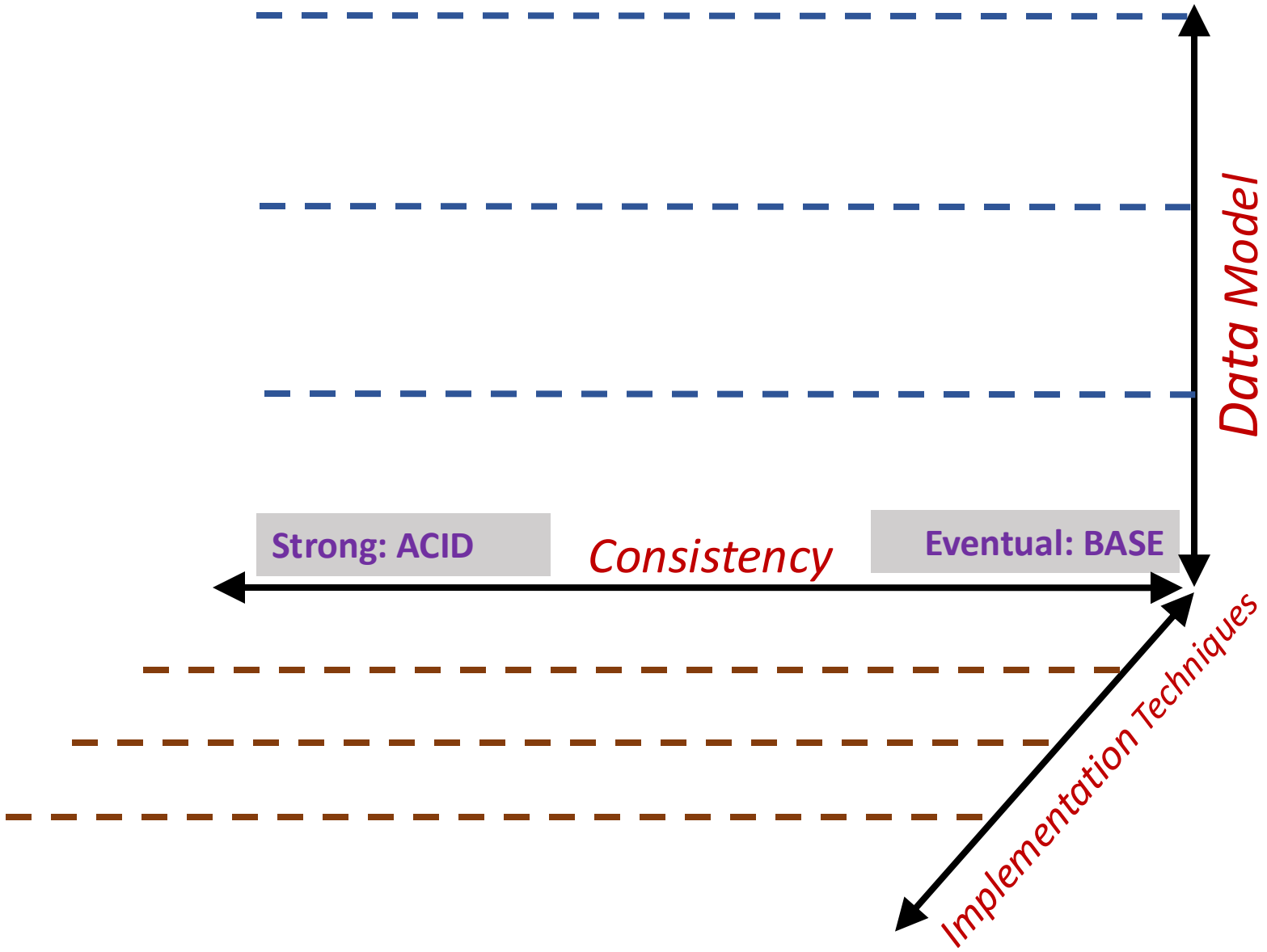

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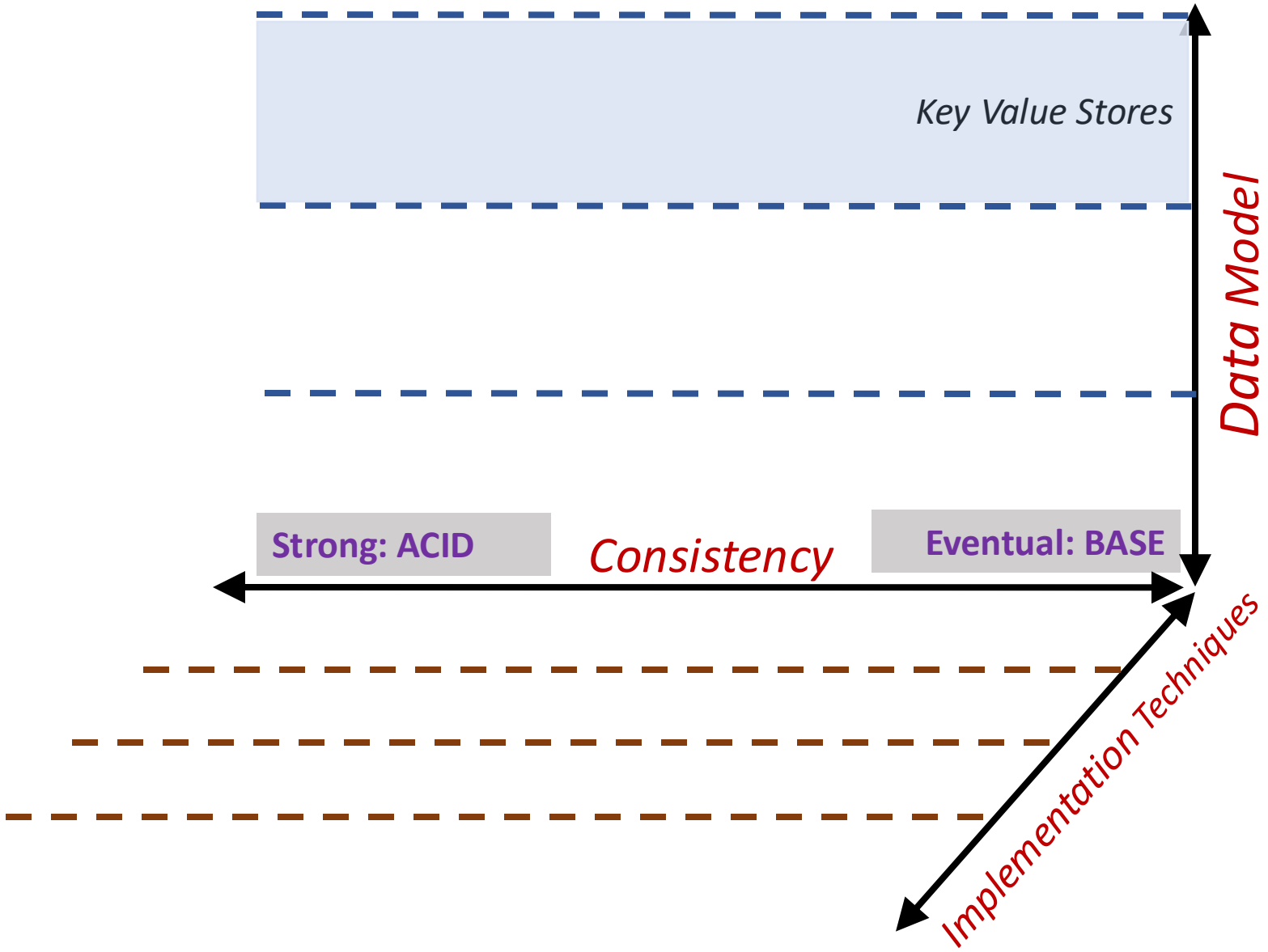

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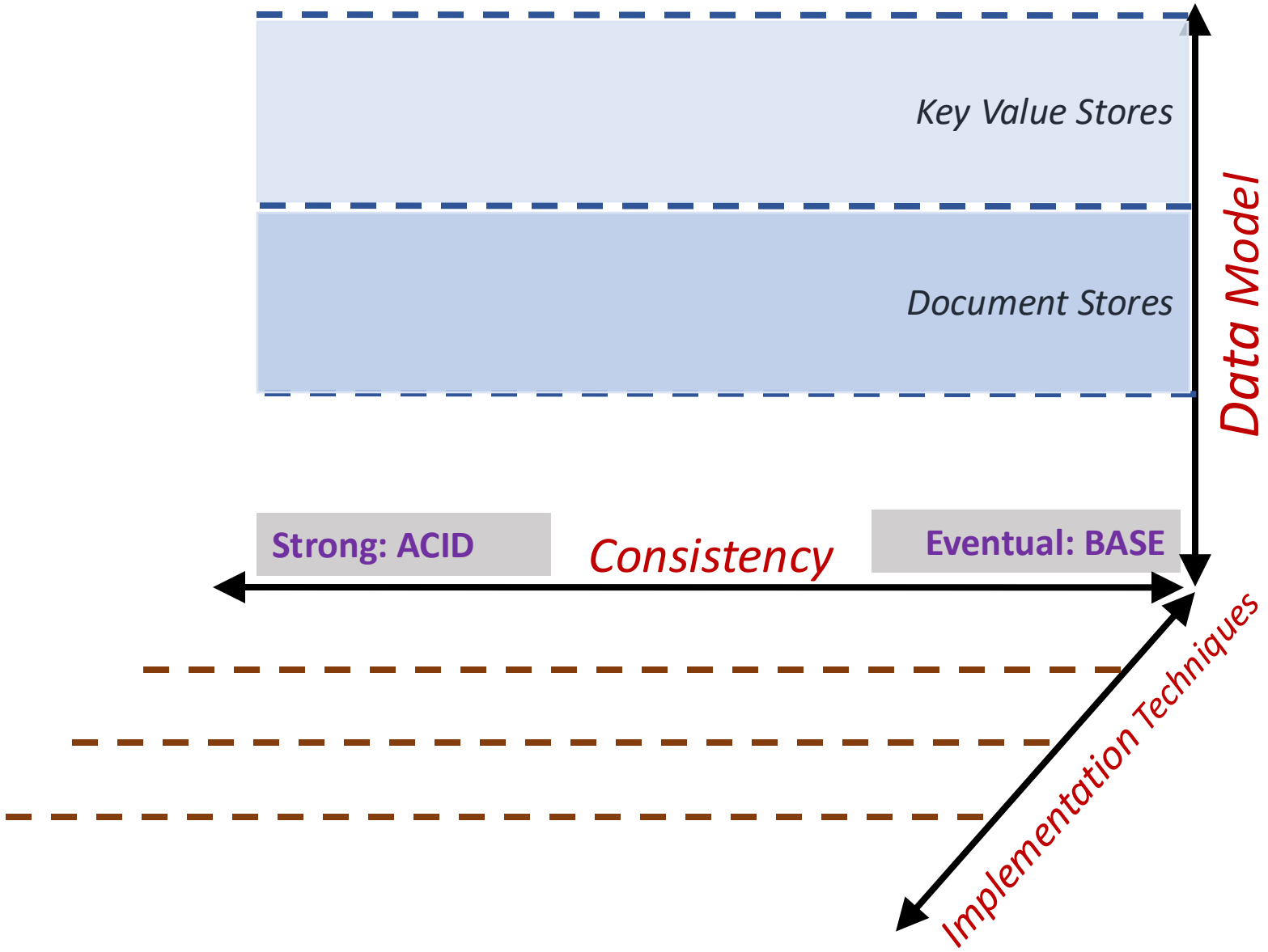

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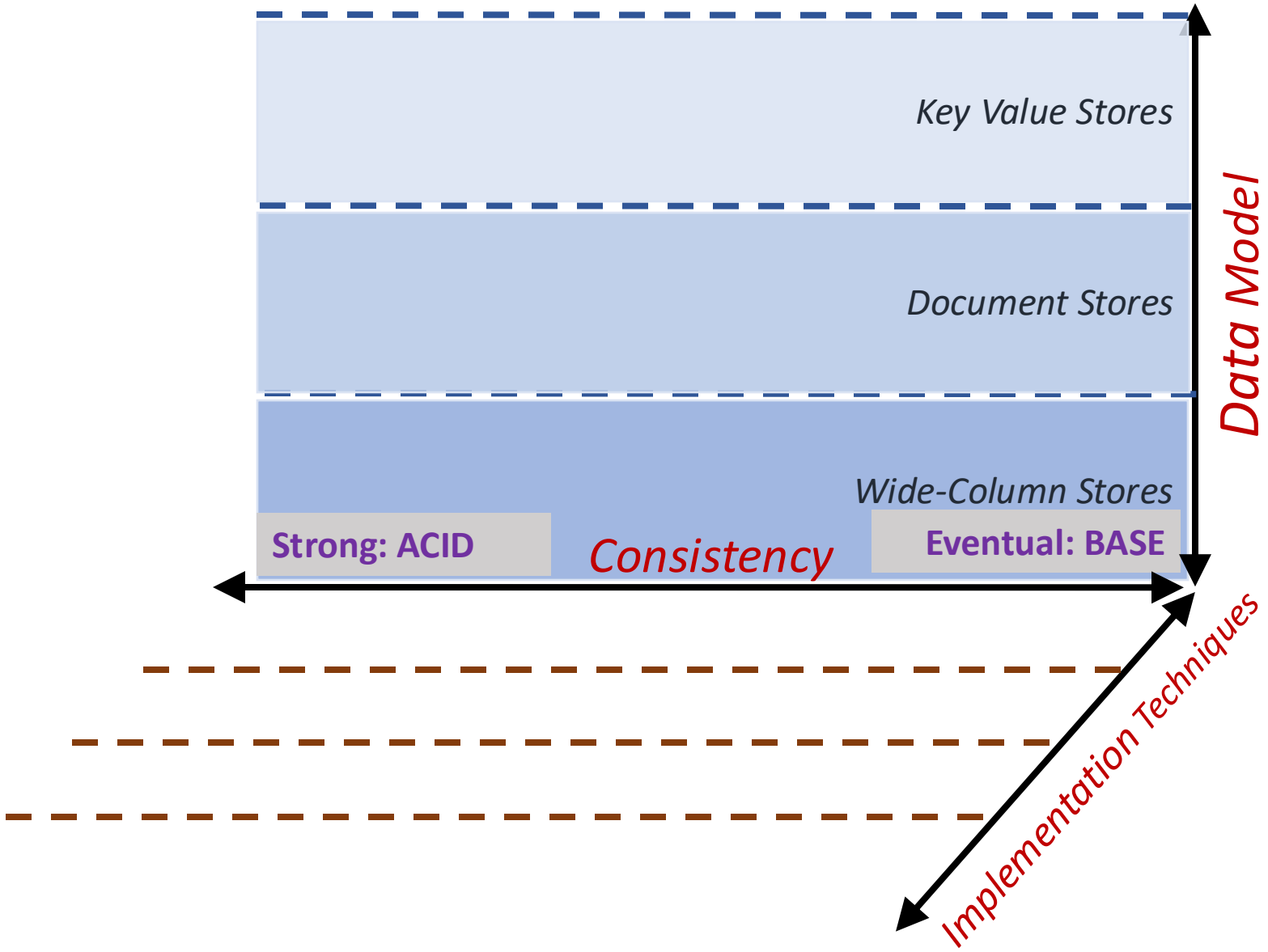

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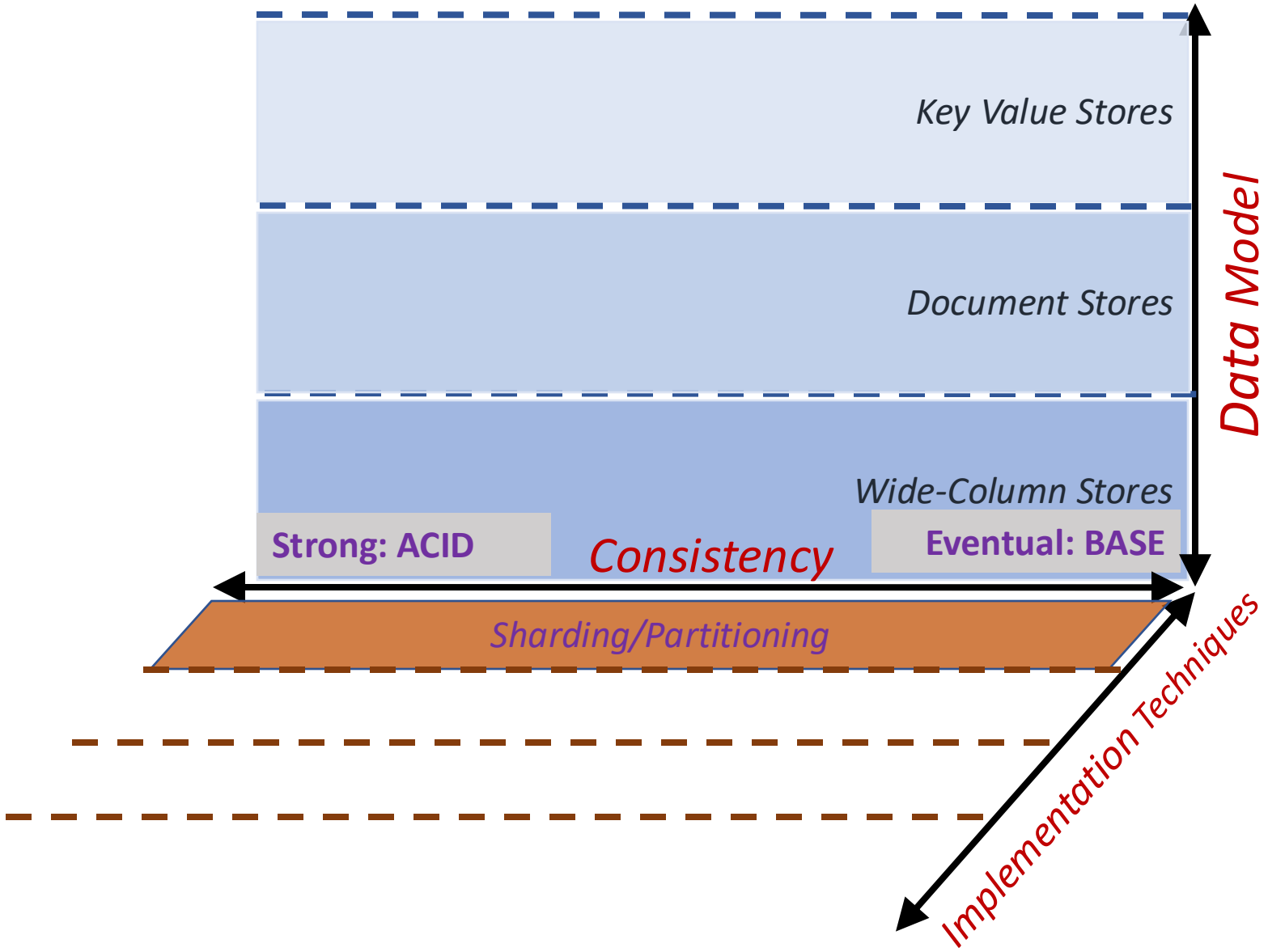

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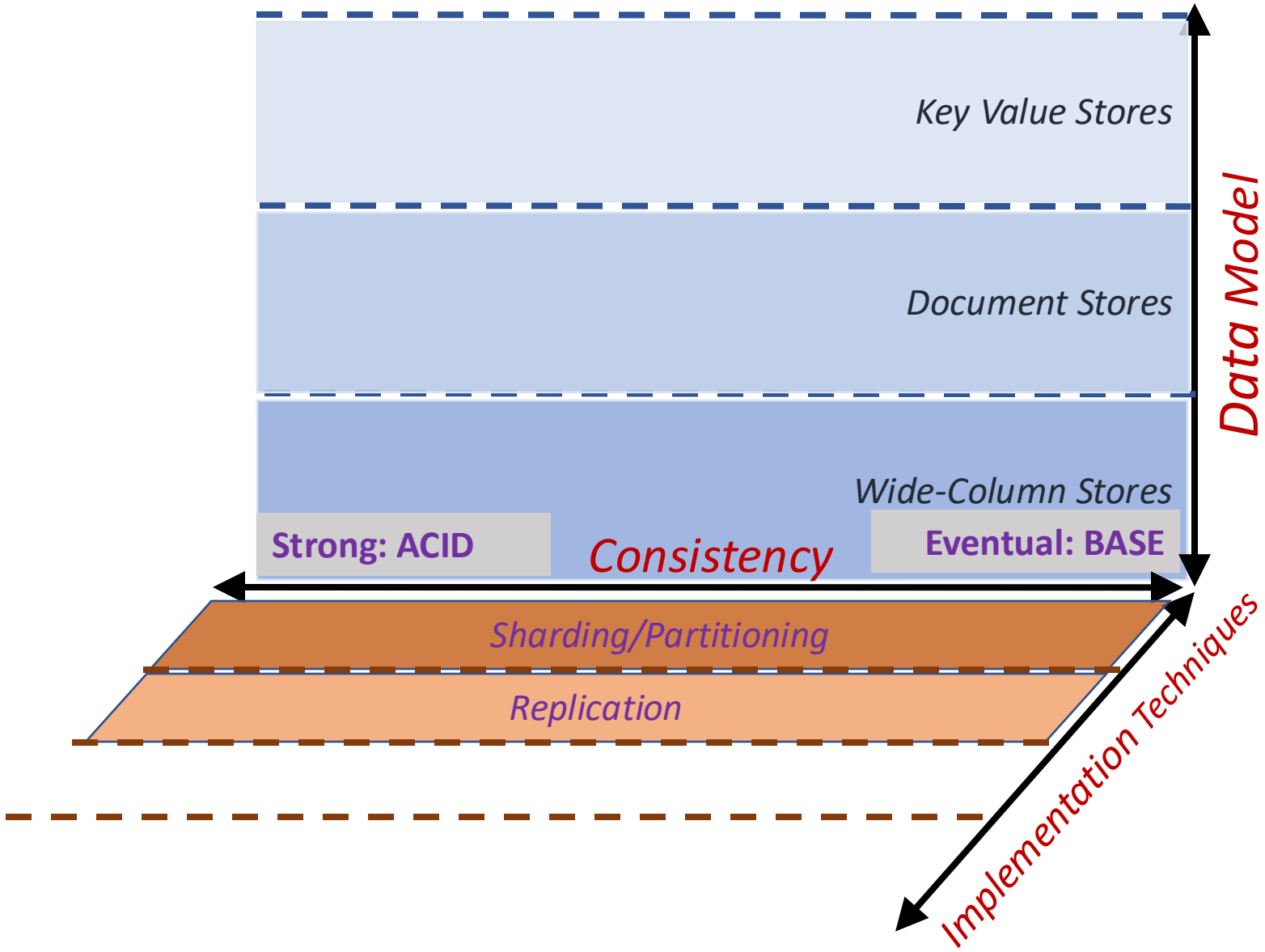

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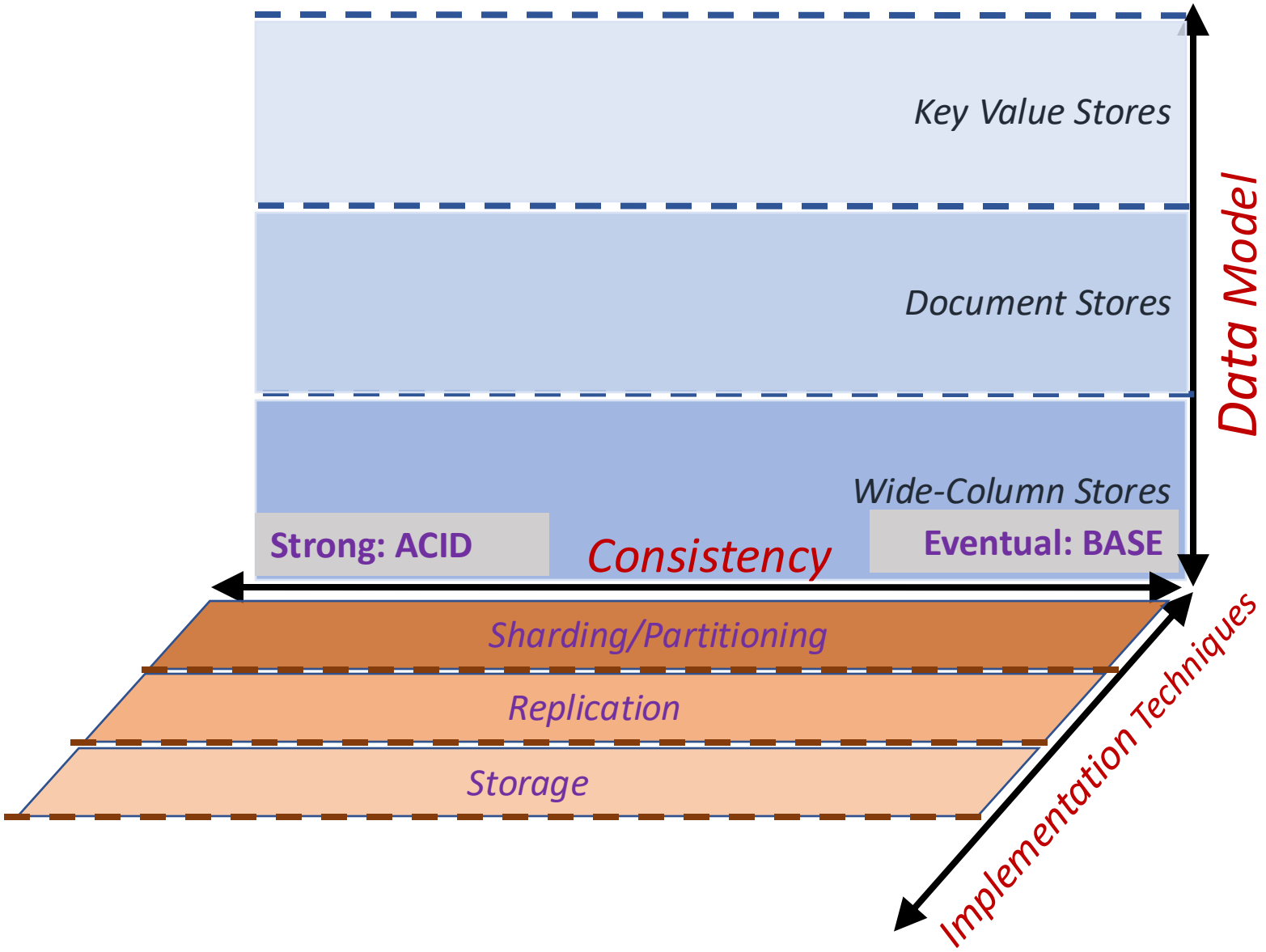

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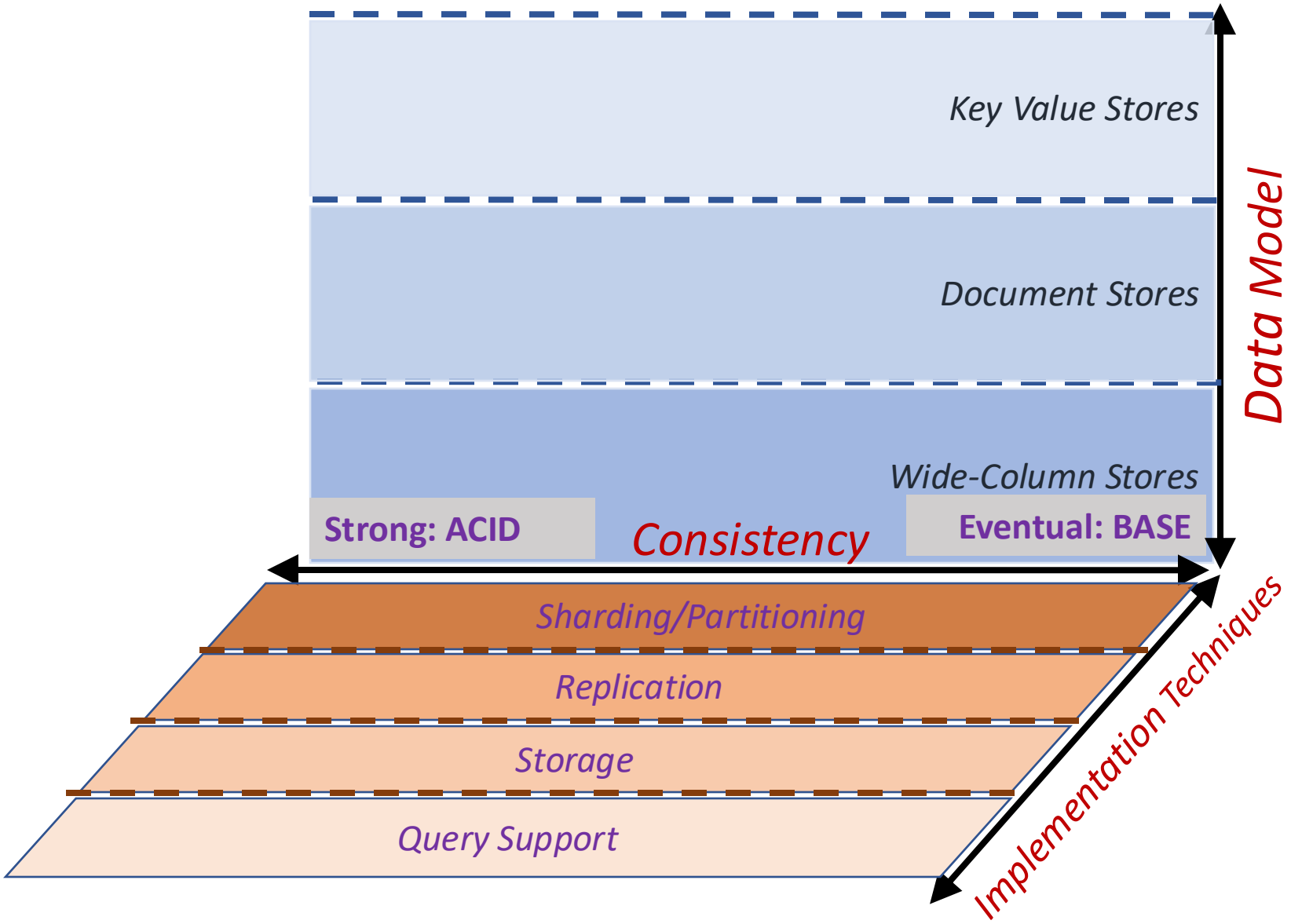

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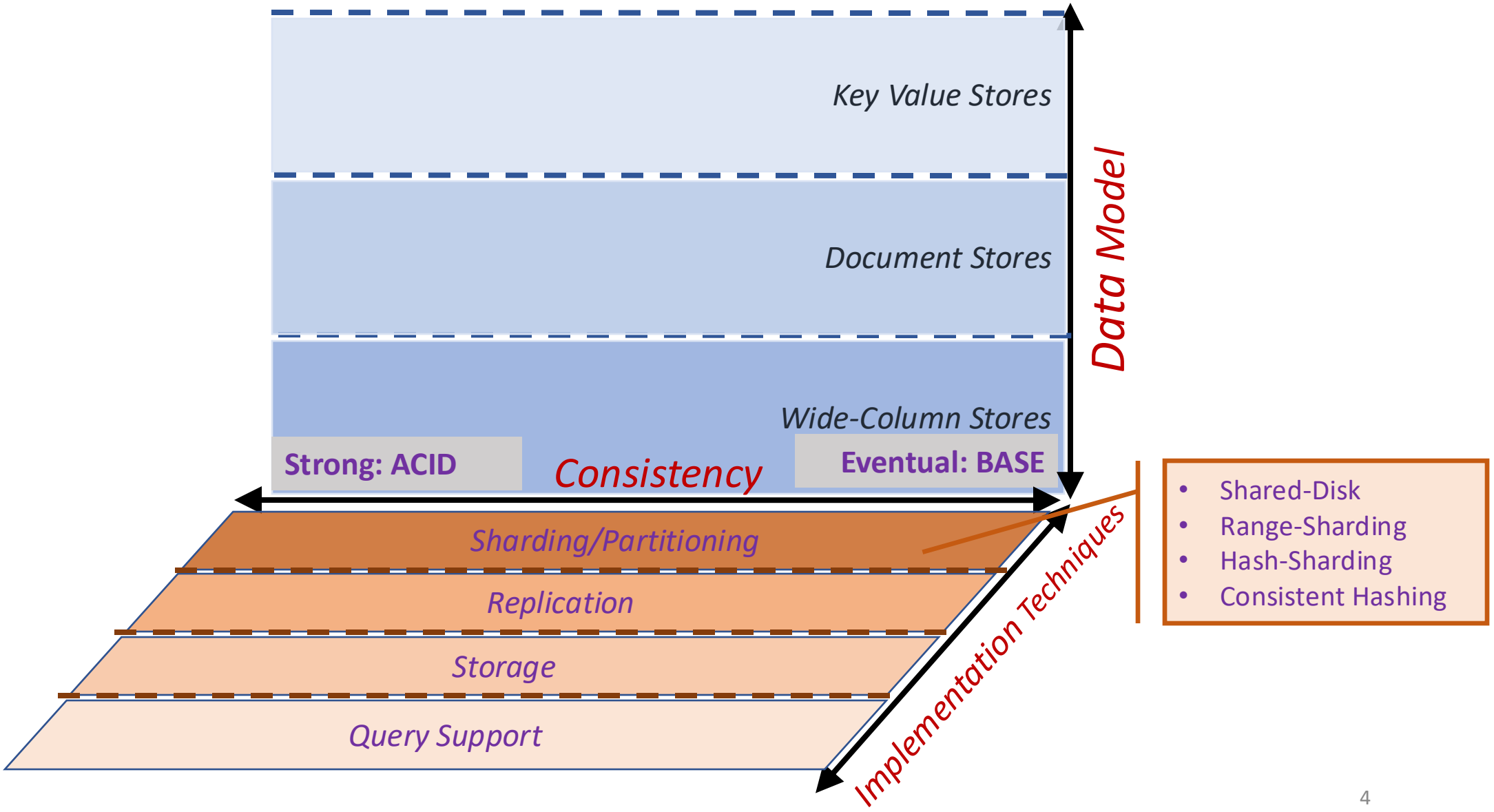

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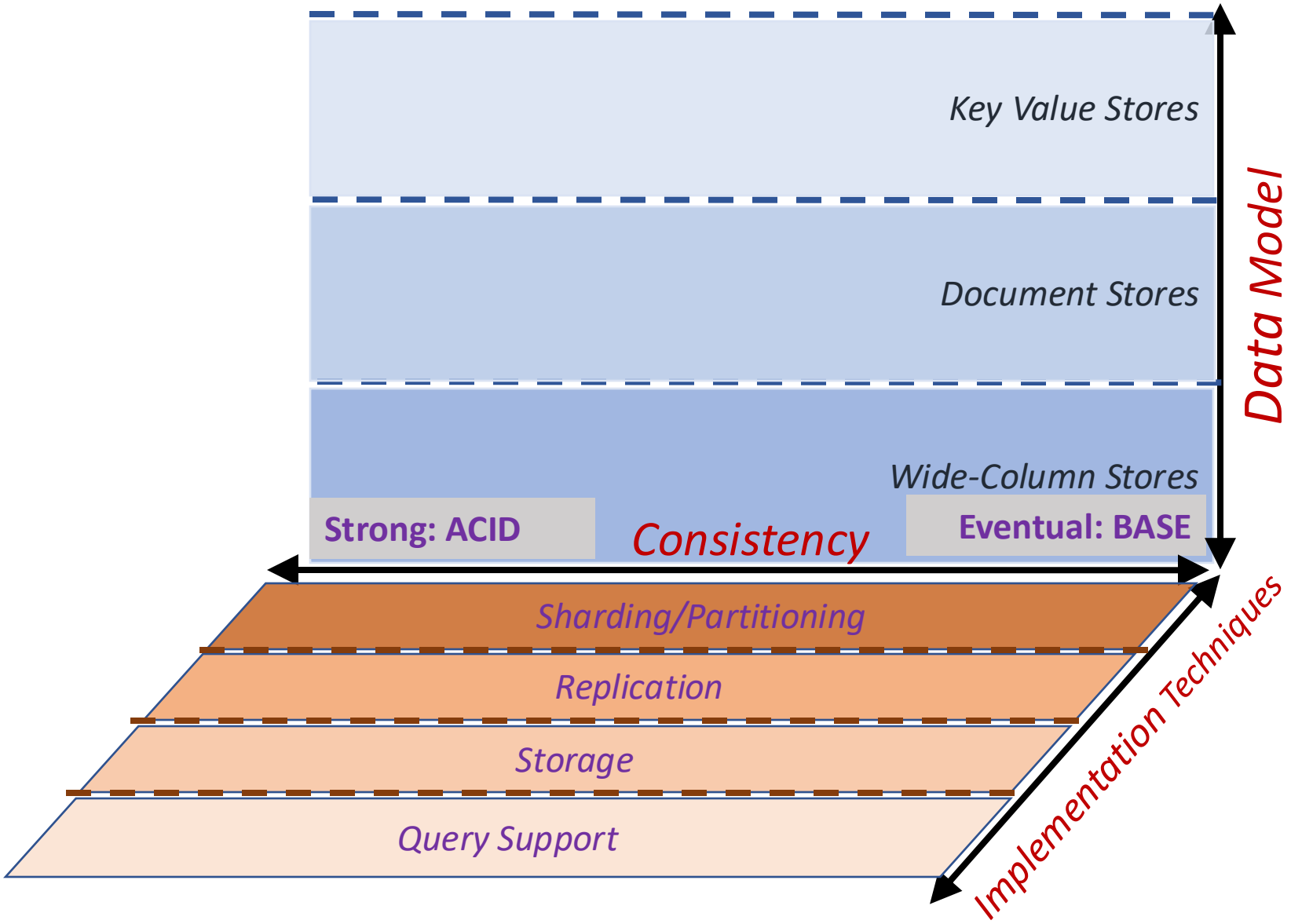

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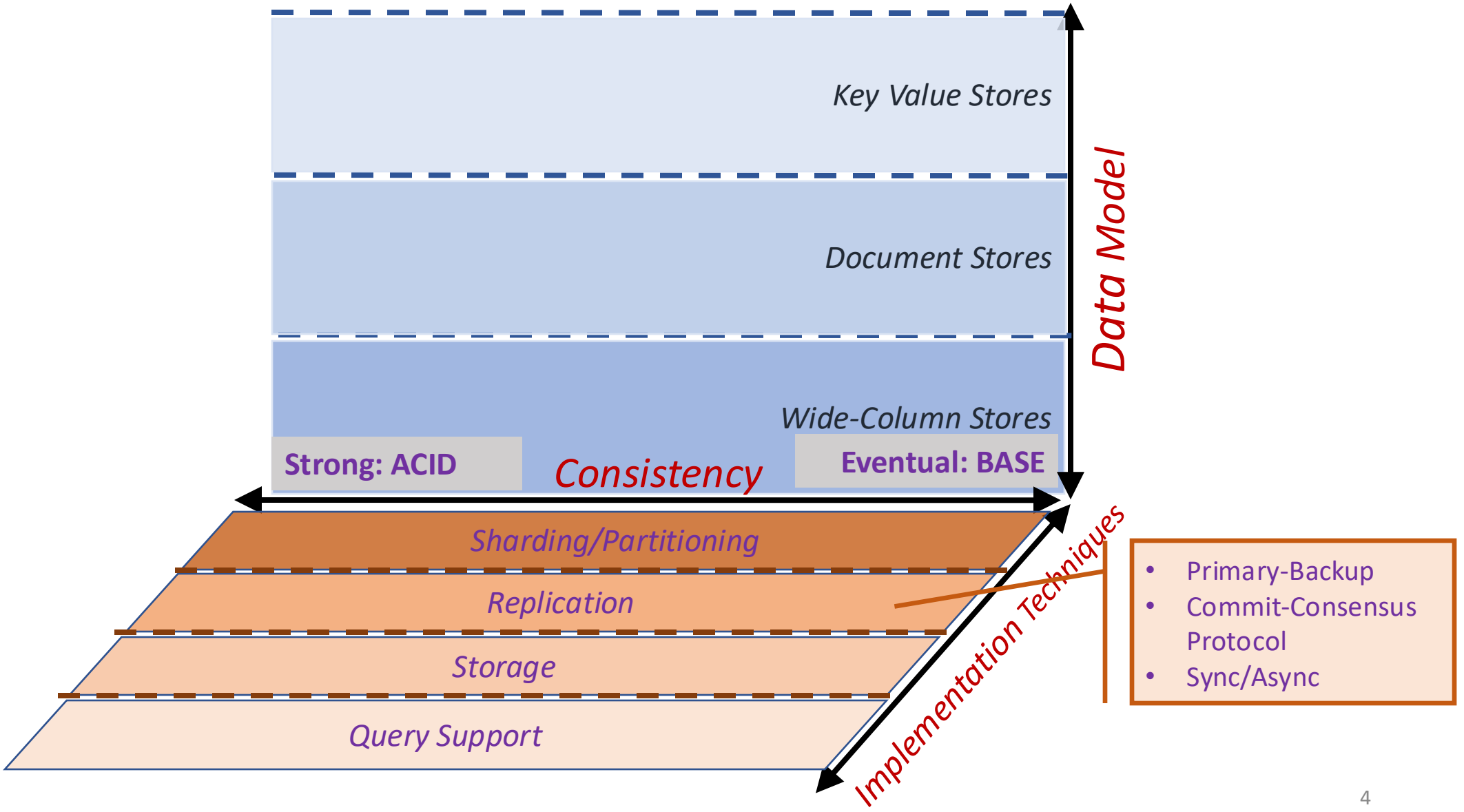

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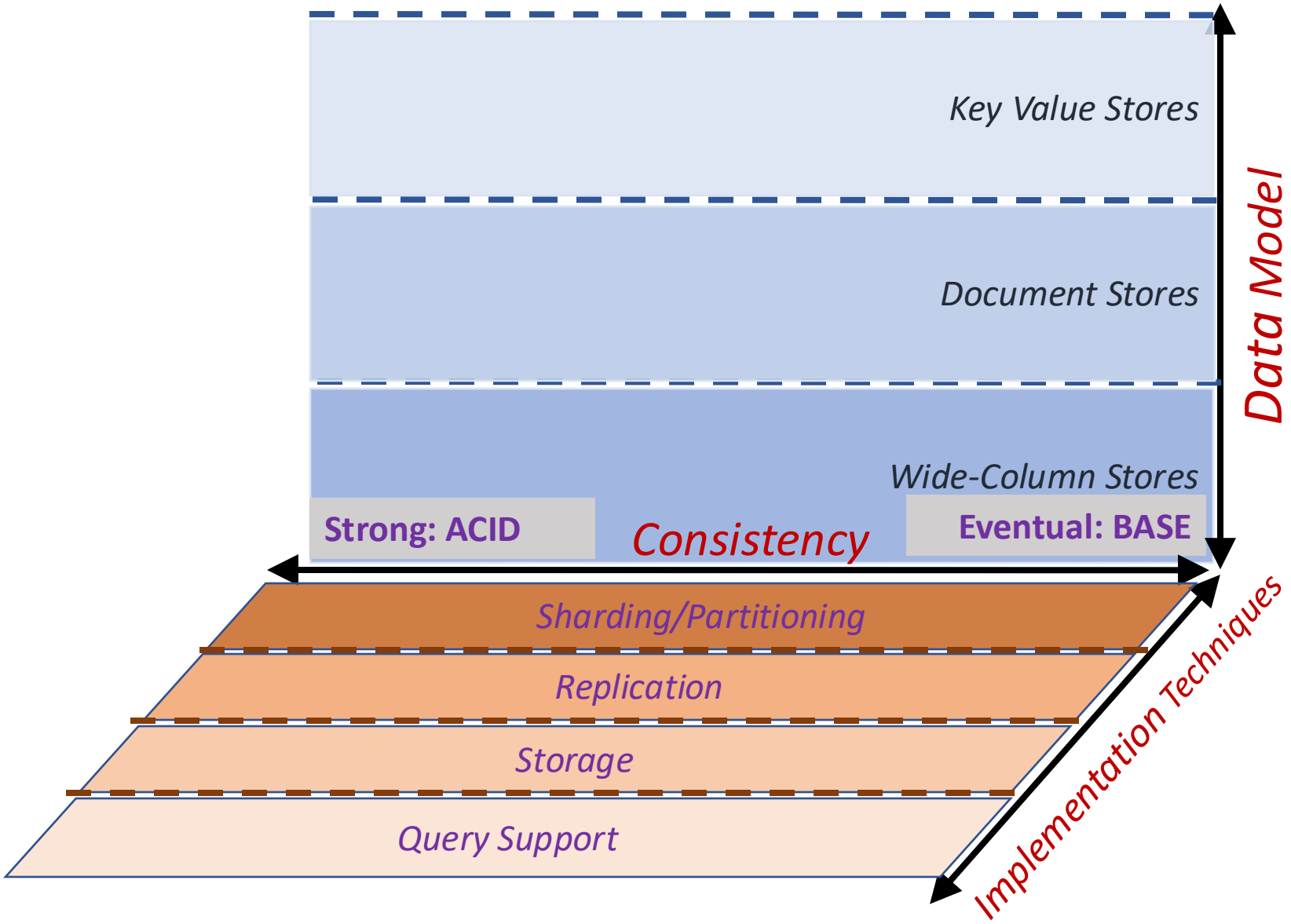

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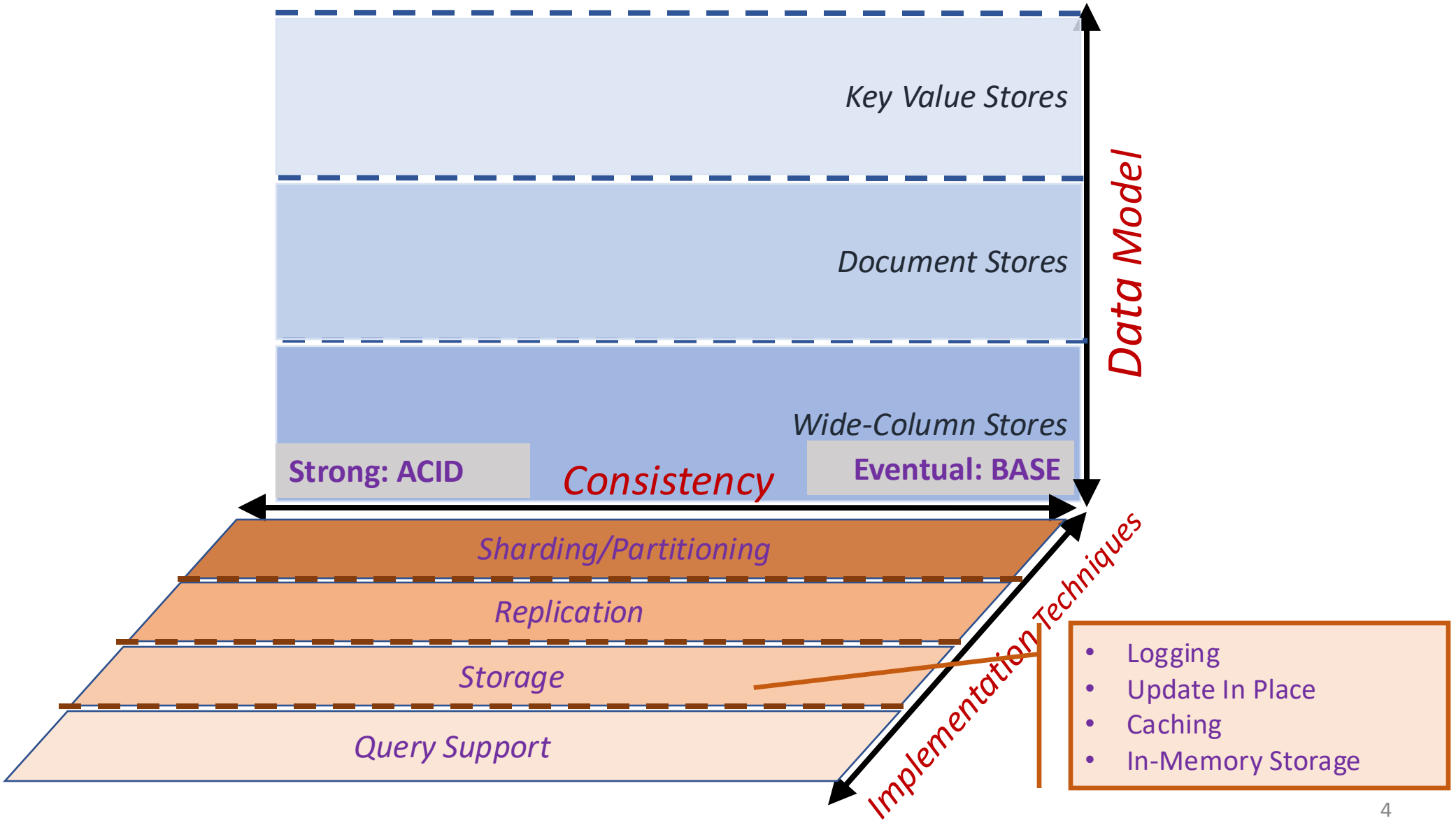

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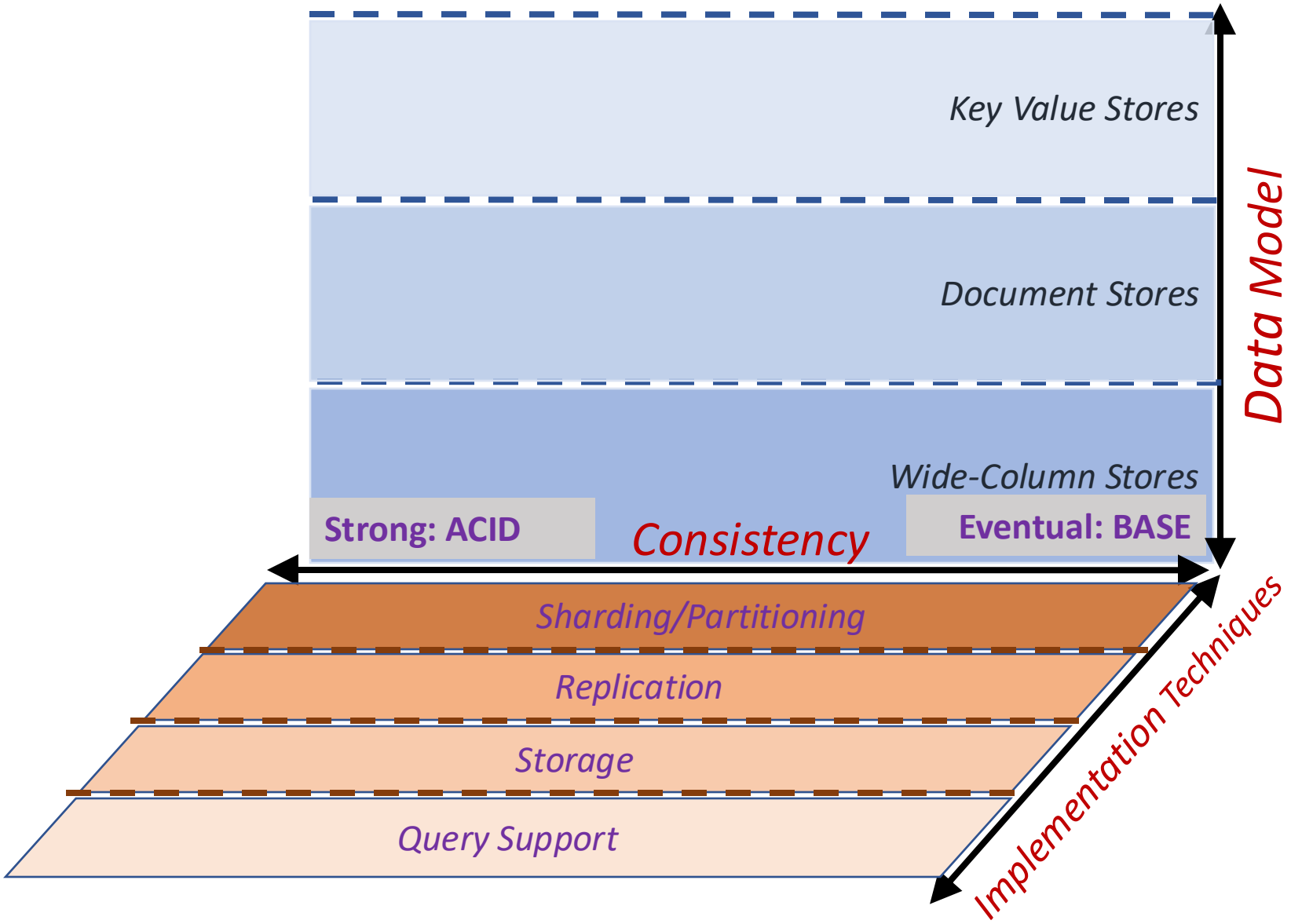

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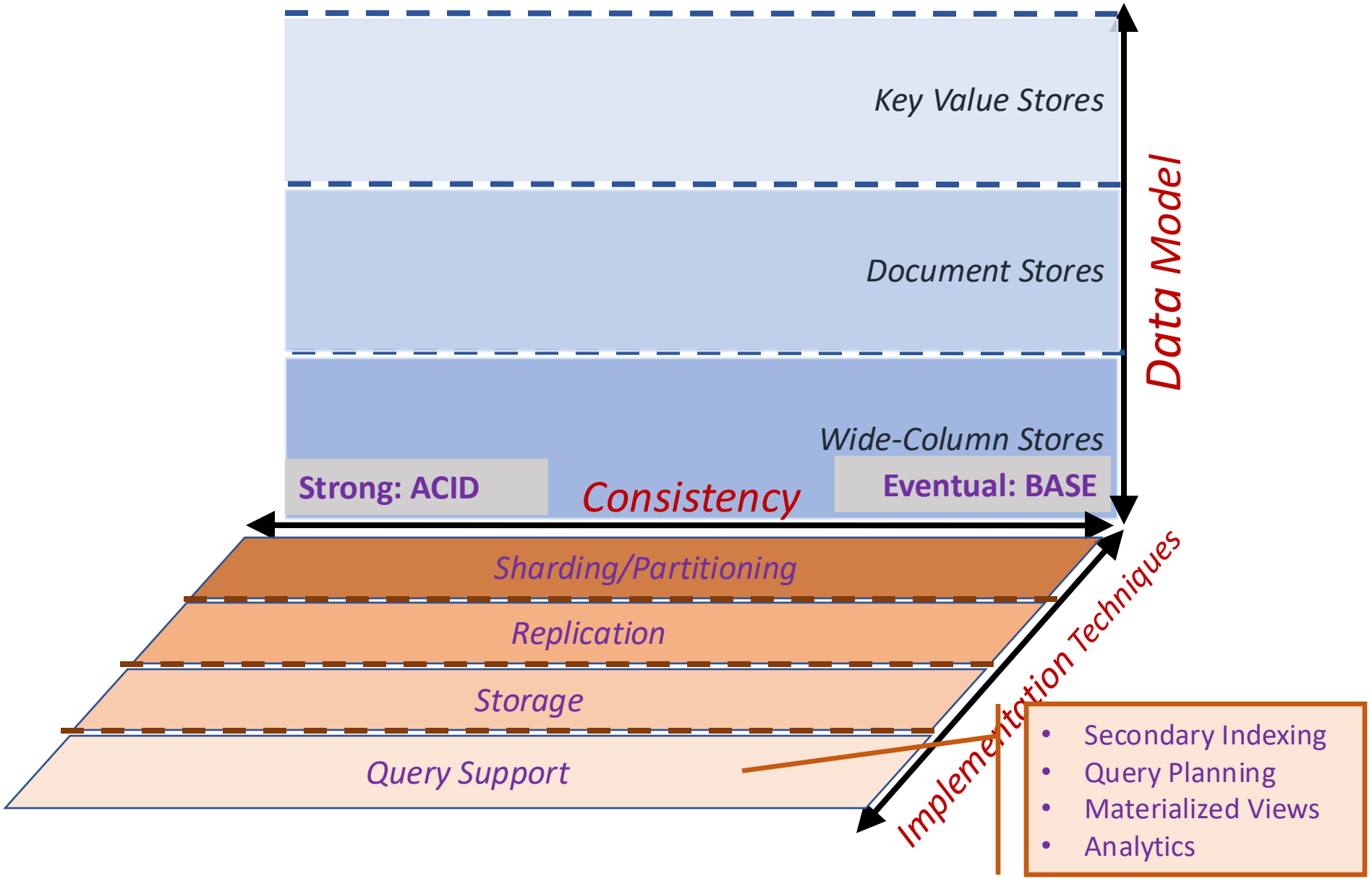

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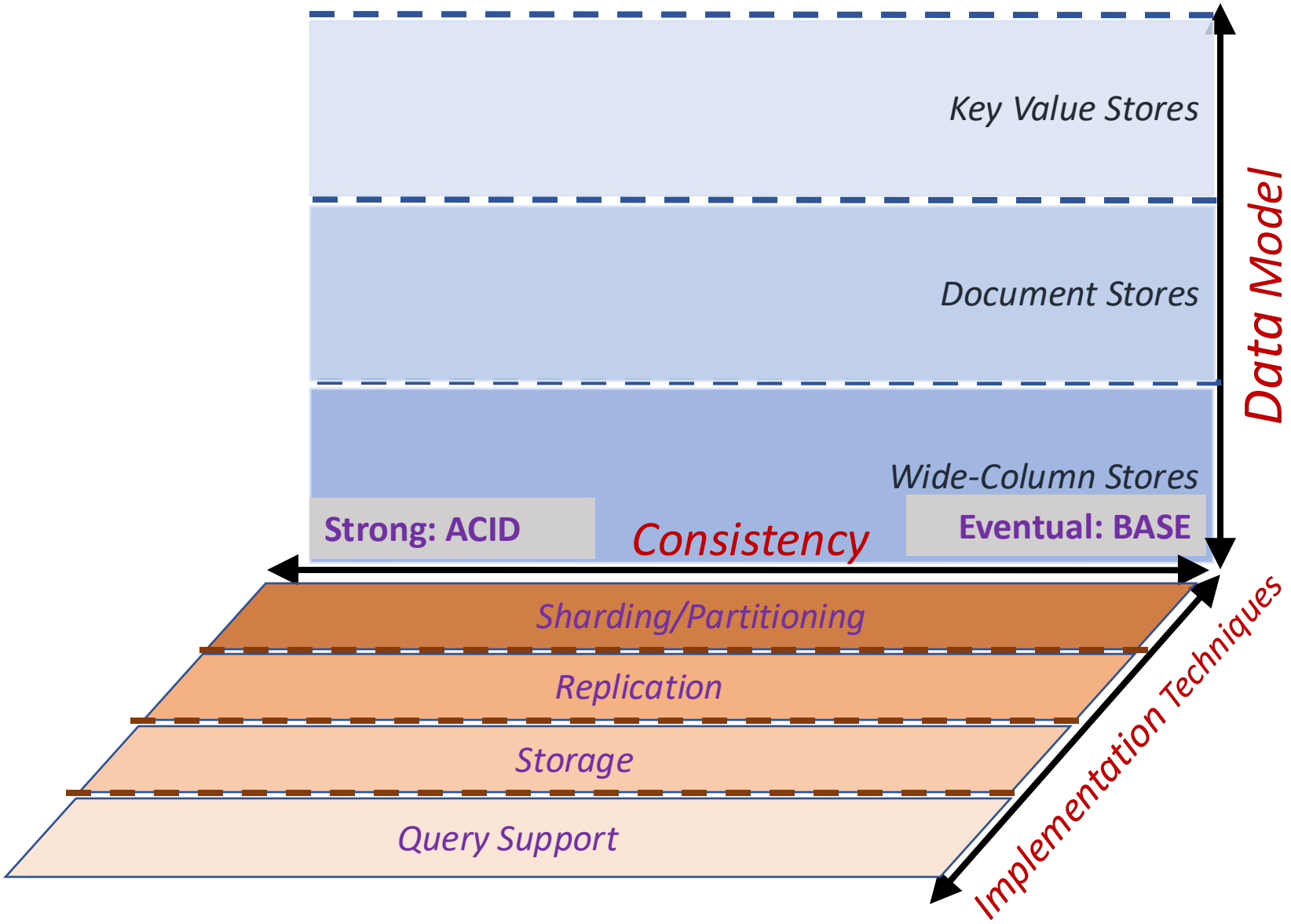


(Yet) Another Framework

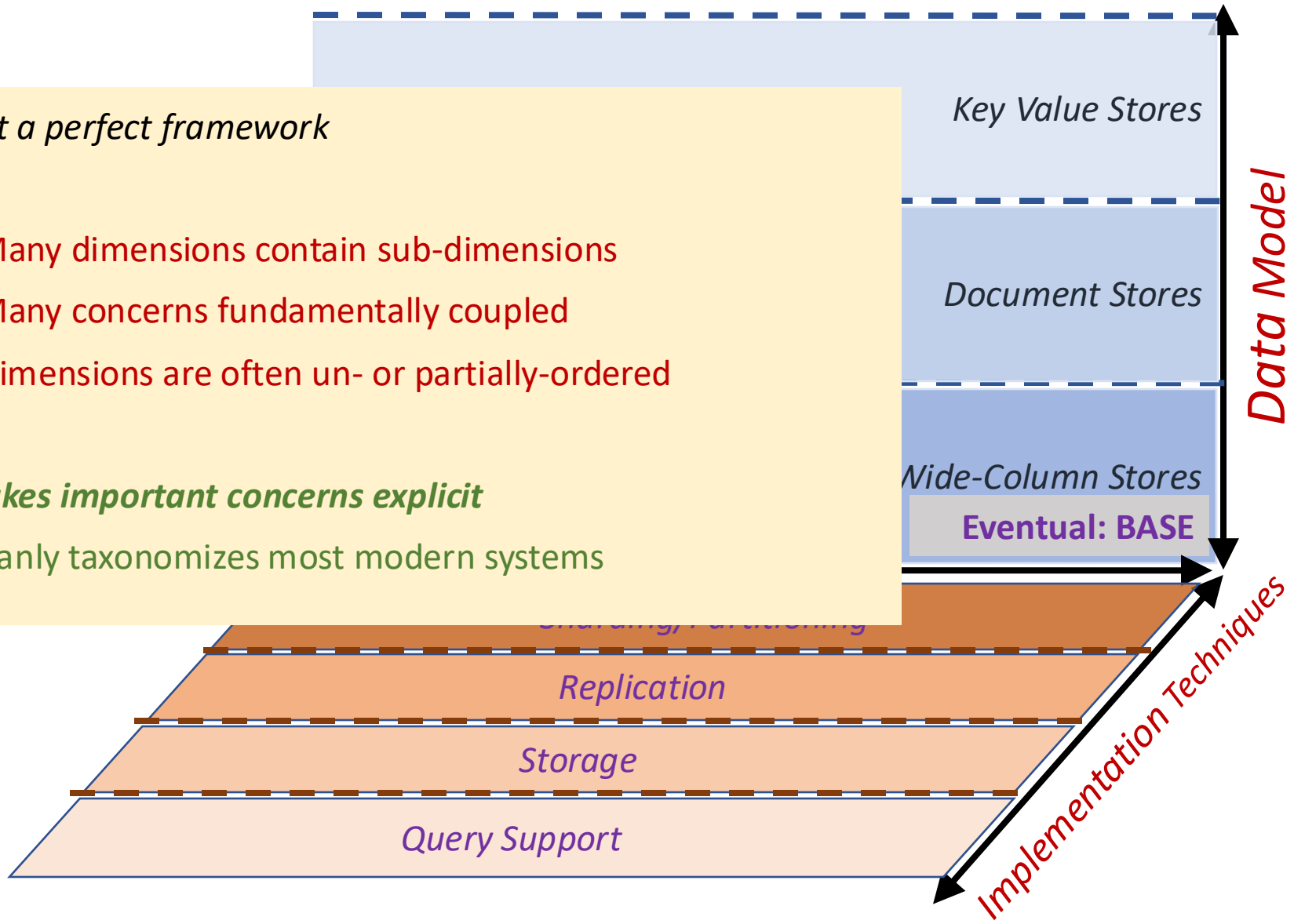
Still not a perfect framework

Cons:

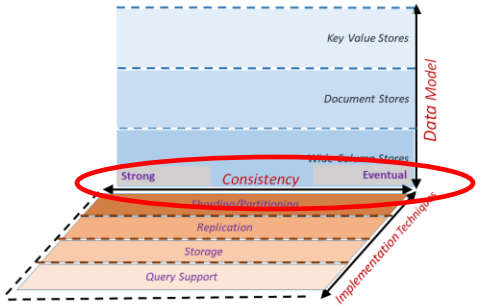
- Many dimensions contain sub-dimensions
- Many concerns fundamentally coupled
- Dimensions are often un- or partially-ordered

Pros:

- ***Makes important concerns explicit***
- Cleanly taxonomizes most modern systems

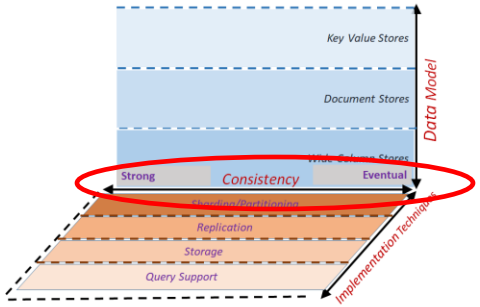


Consistency



col	col	col_2	. . .	col_c
0	1			

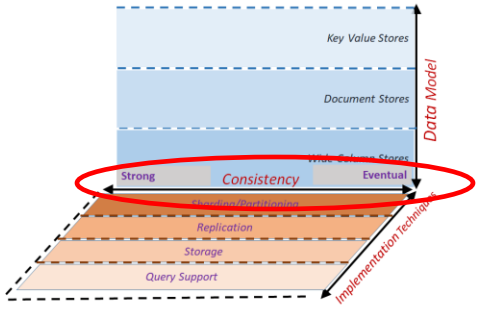
Consistency

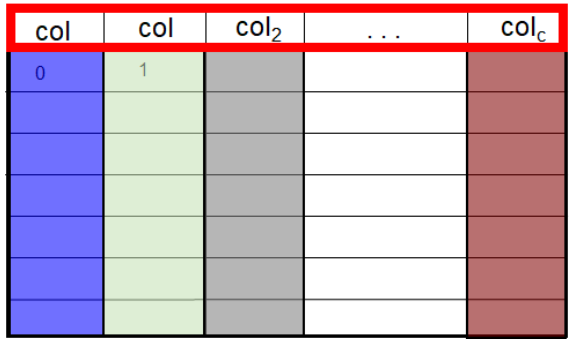


col	col	col_2	. . .	col_c
0	1			

How to keep data in sync?

Consistency

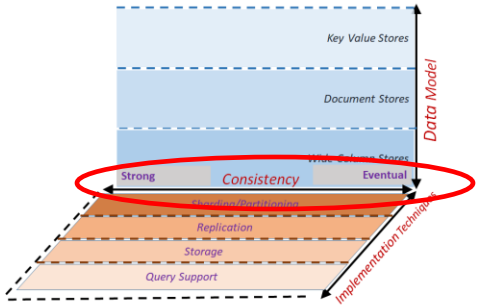


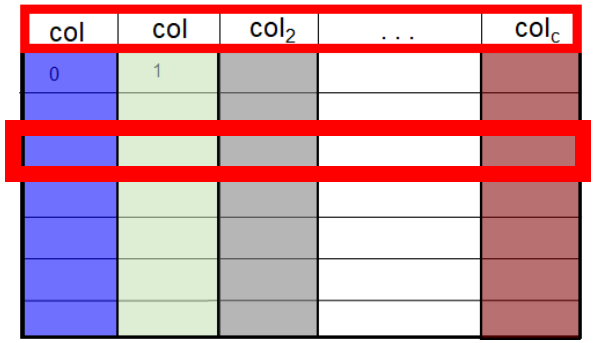


How to keep data in sync?

- Partitioning → single row spread over multiple machines

Consistency





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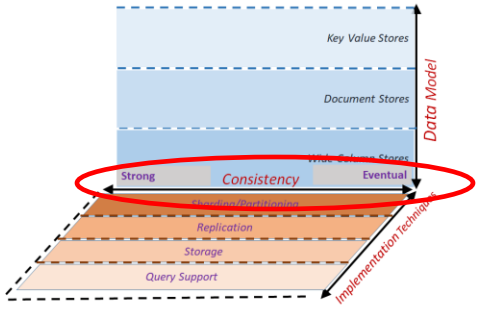

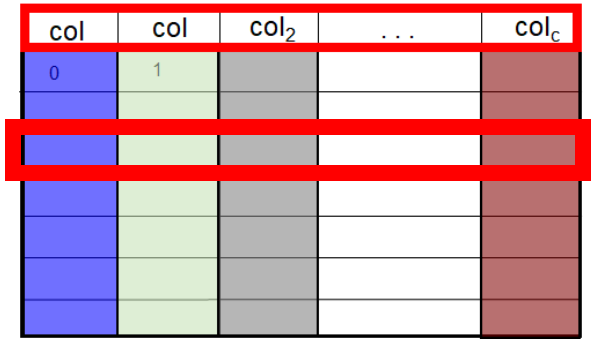

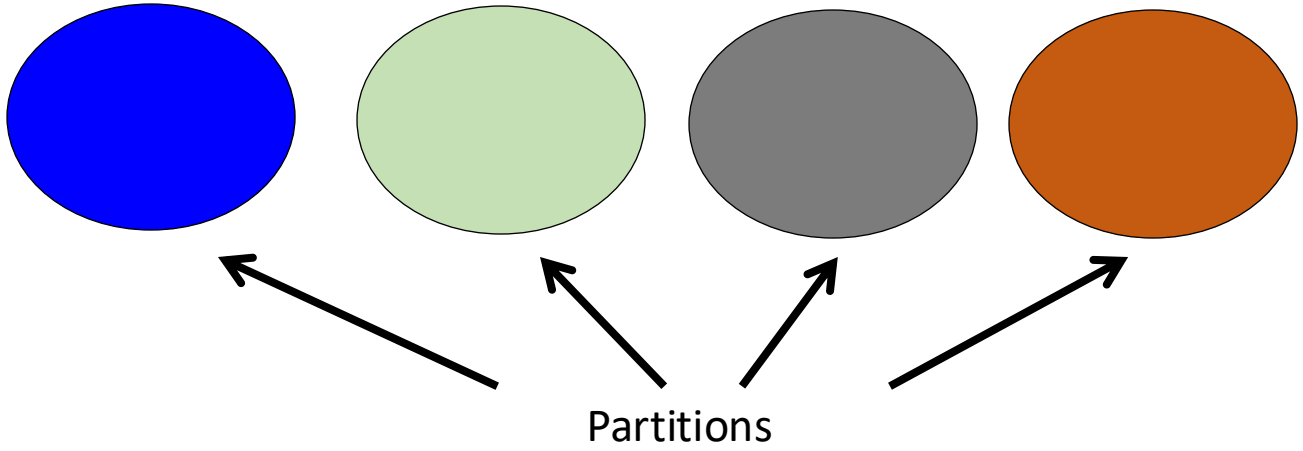

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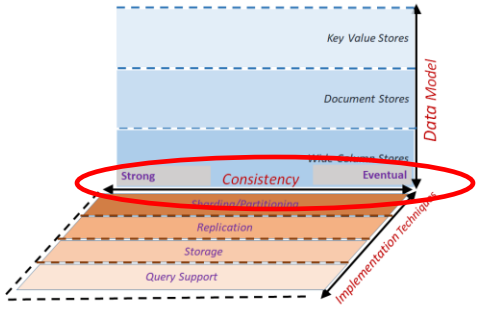

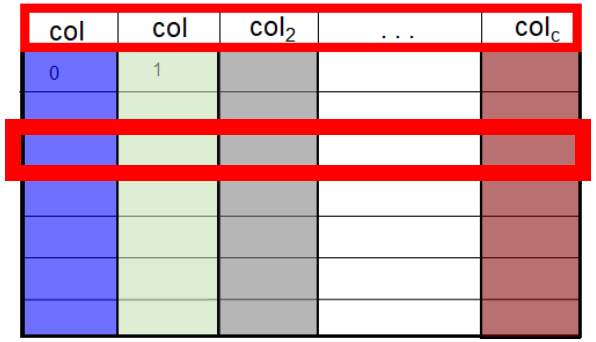

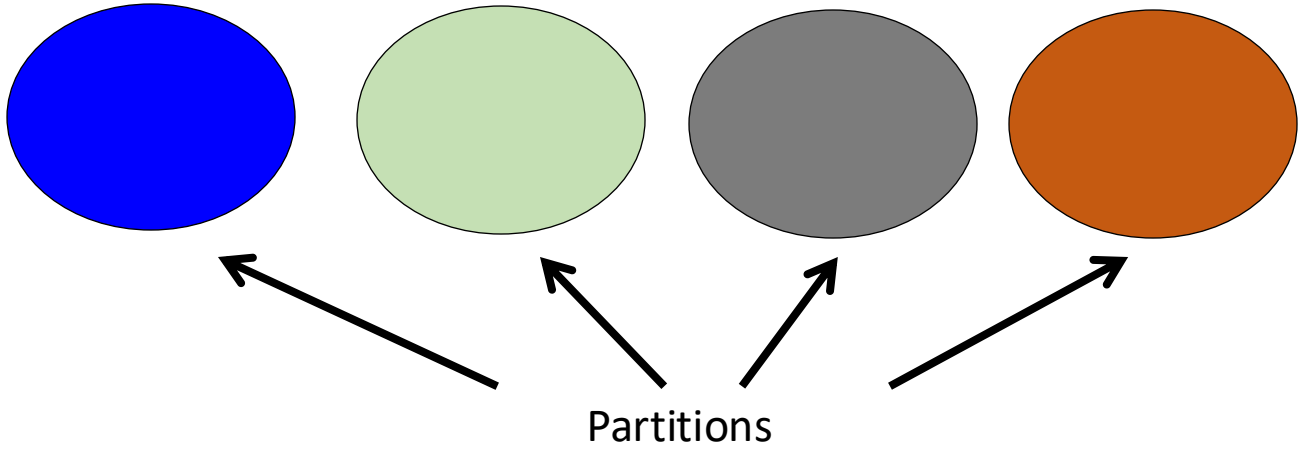

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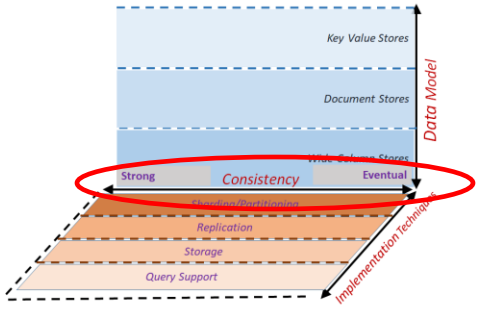
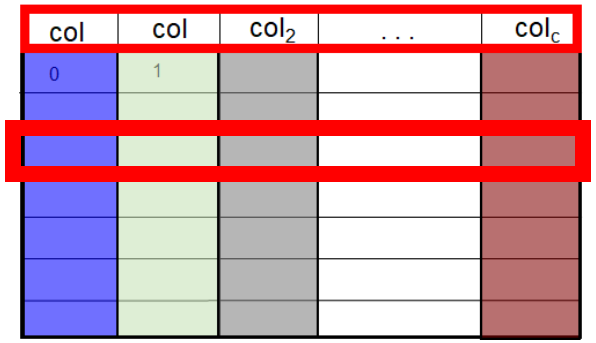
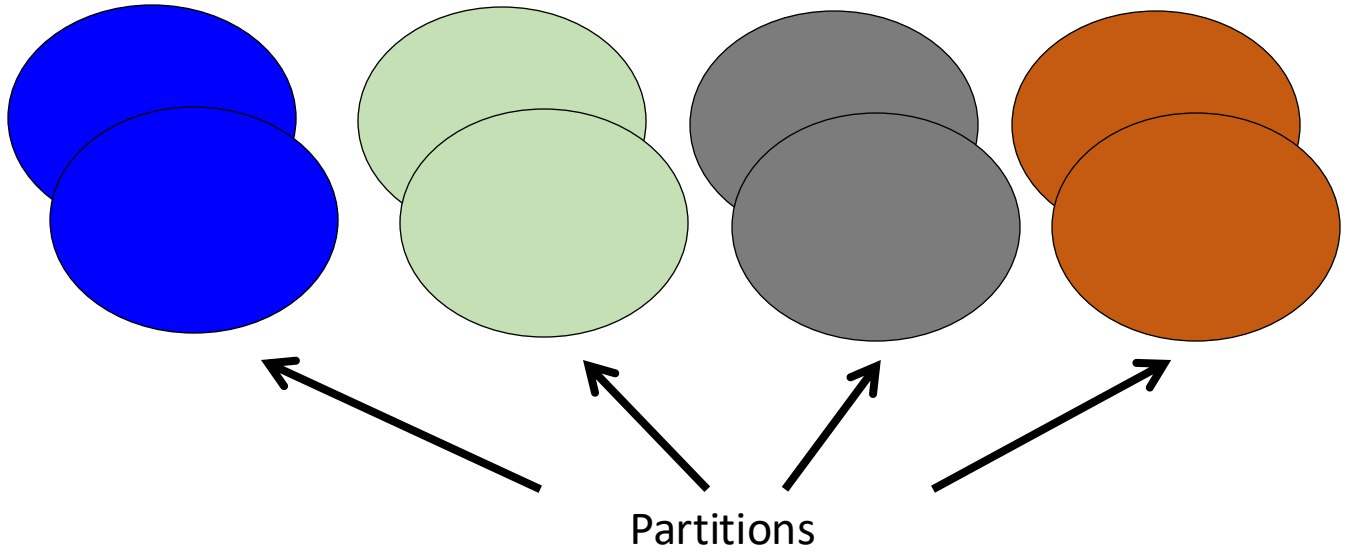
- Redundancy → single datum spread over multiple machines

Consistency







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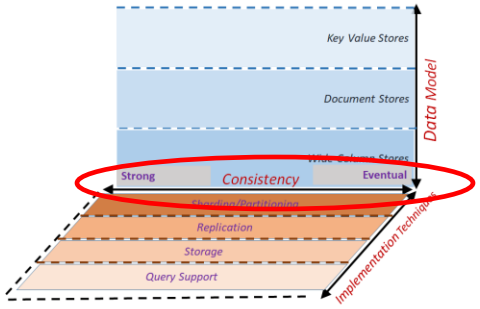

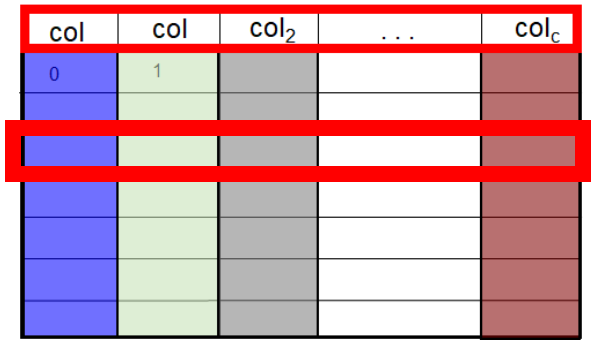

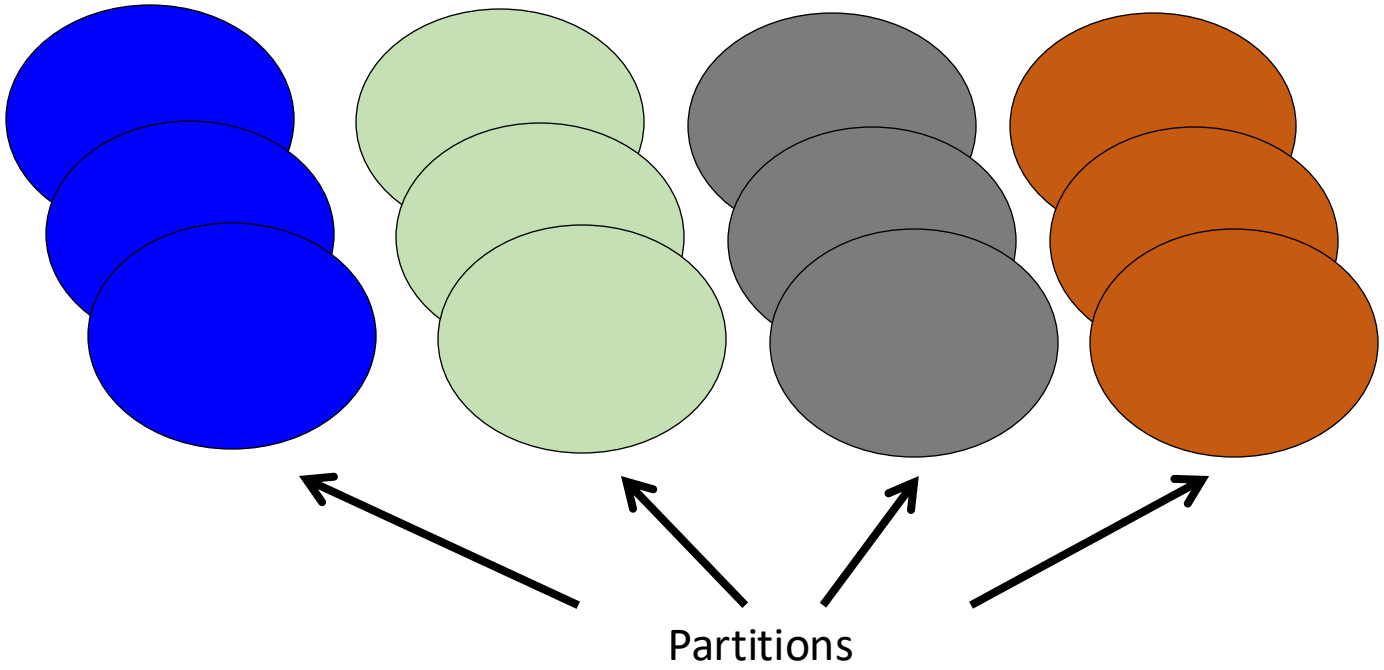

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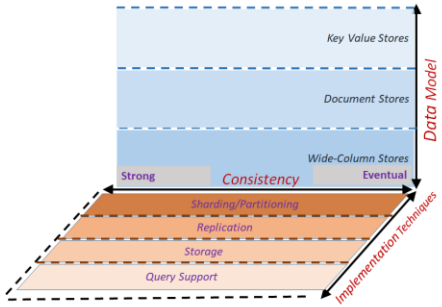
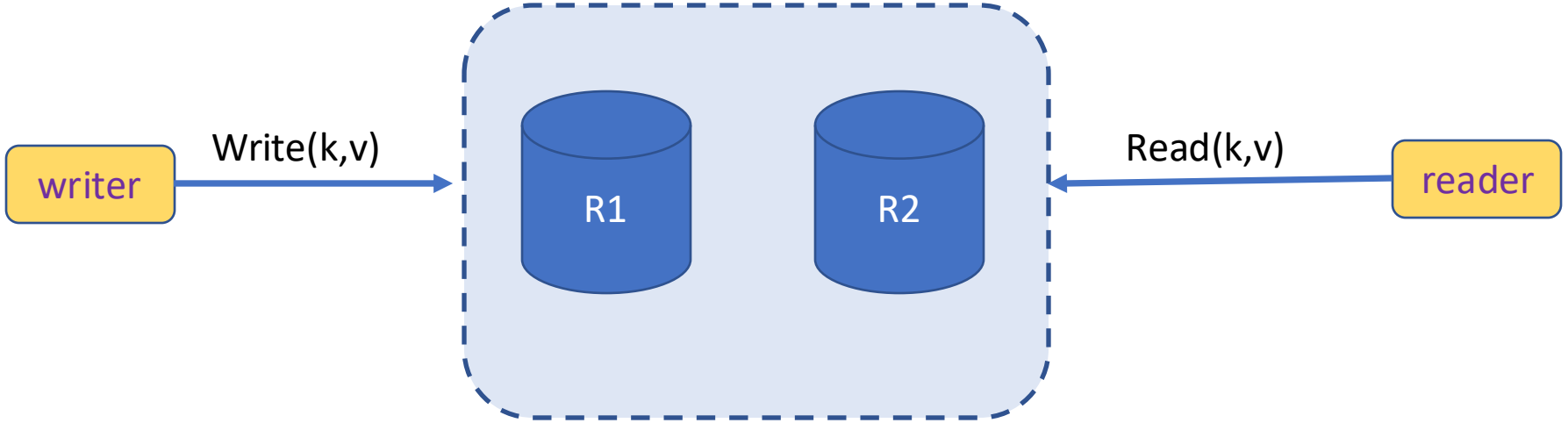
- Redundancy → single datum spread over multiple machines

Consistency: the core problem





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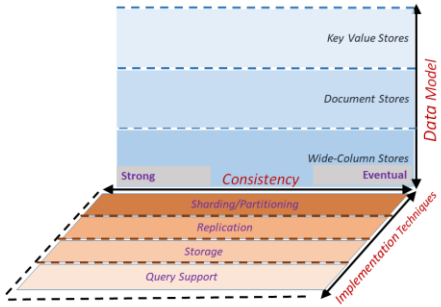

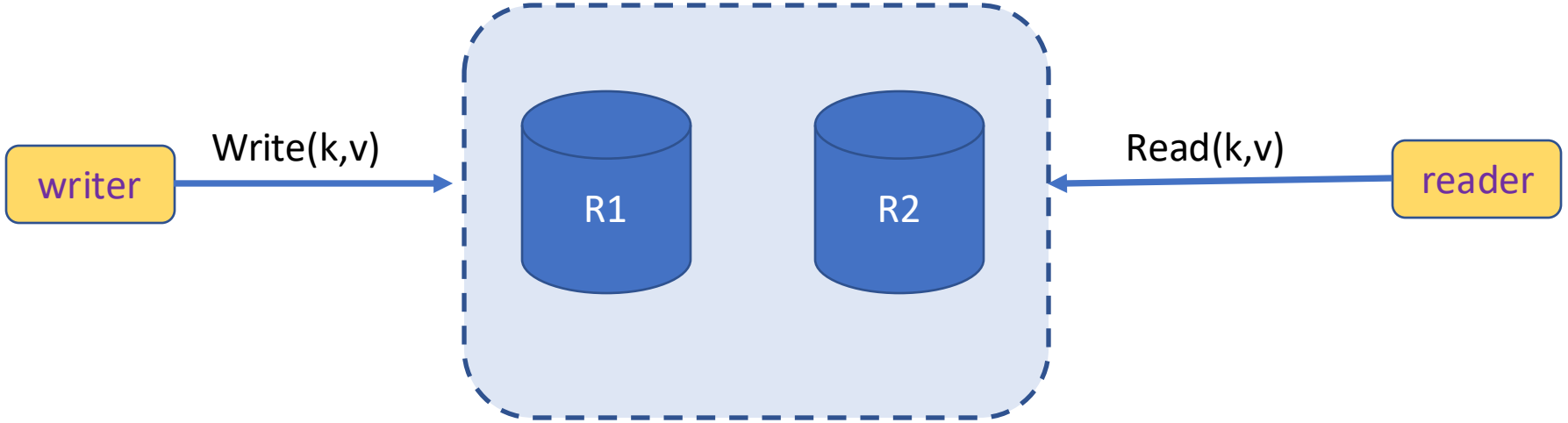

- Clients perform reads and writes

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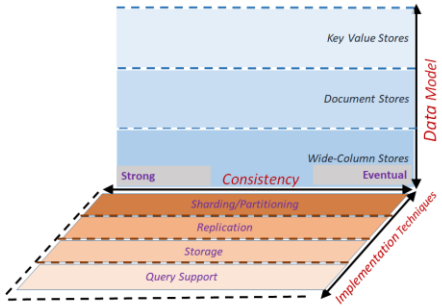
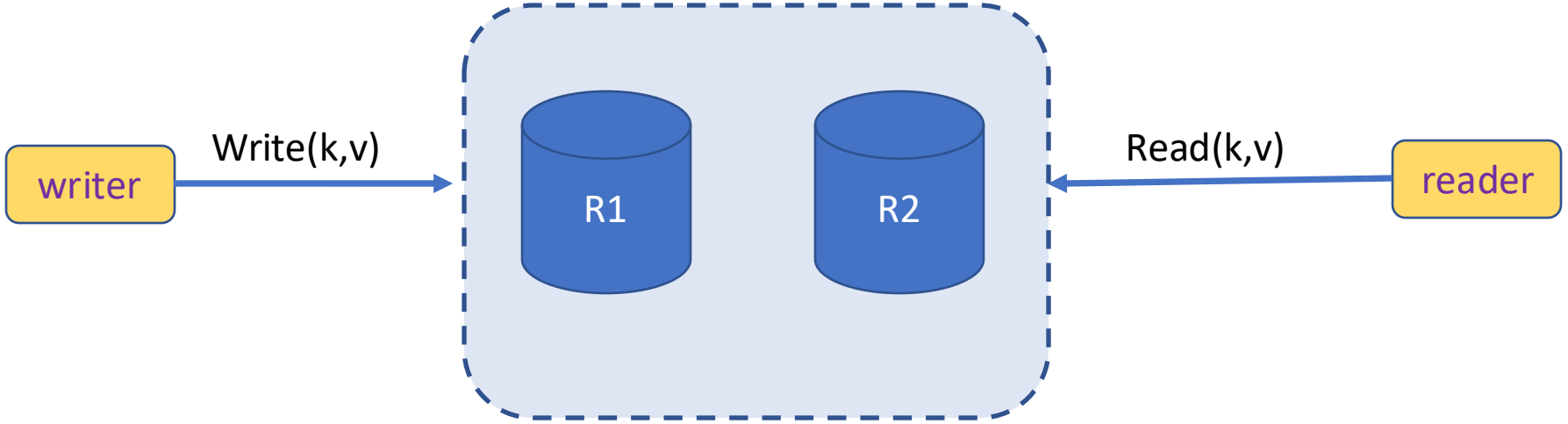
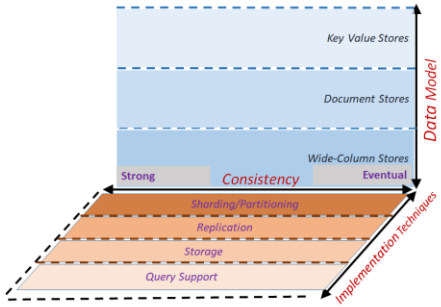
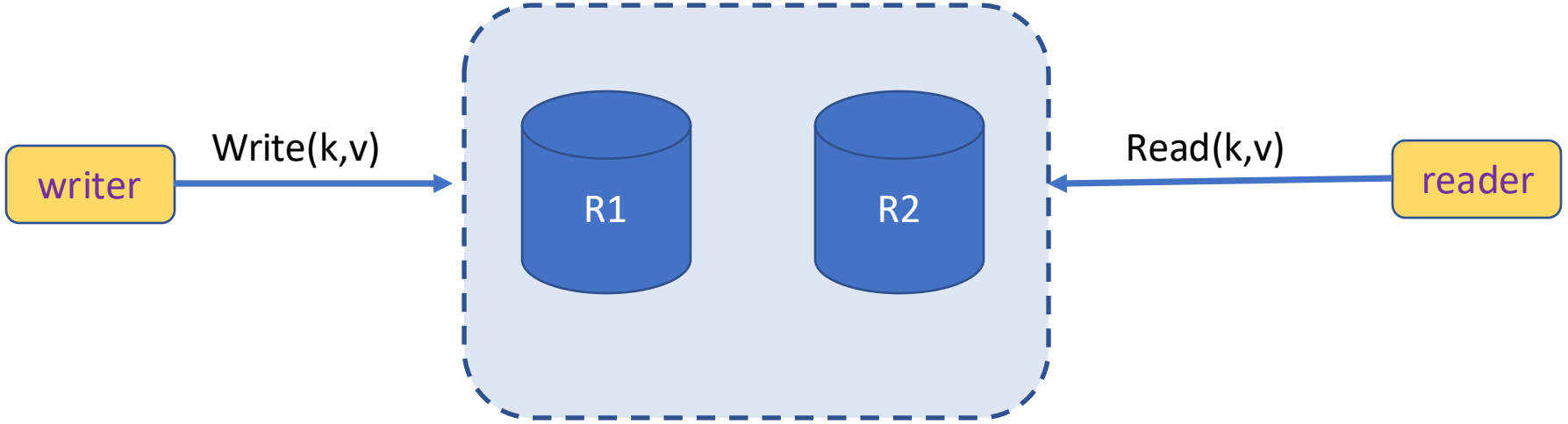




- Clients perform reads and writes
- Data is replicated among a set of servers

Consistency: the core problem





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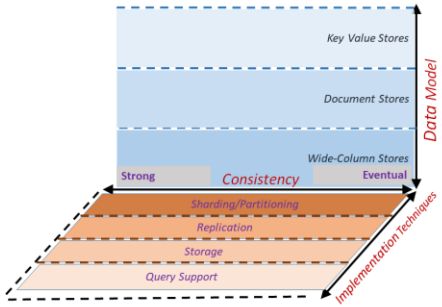

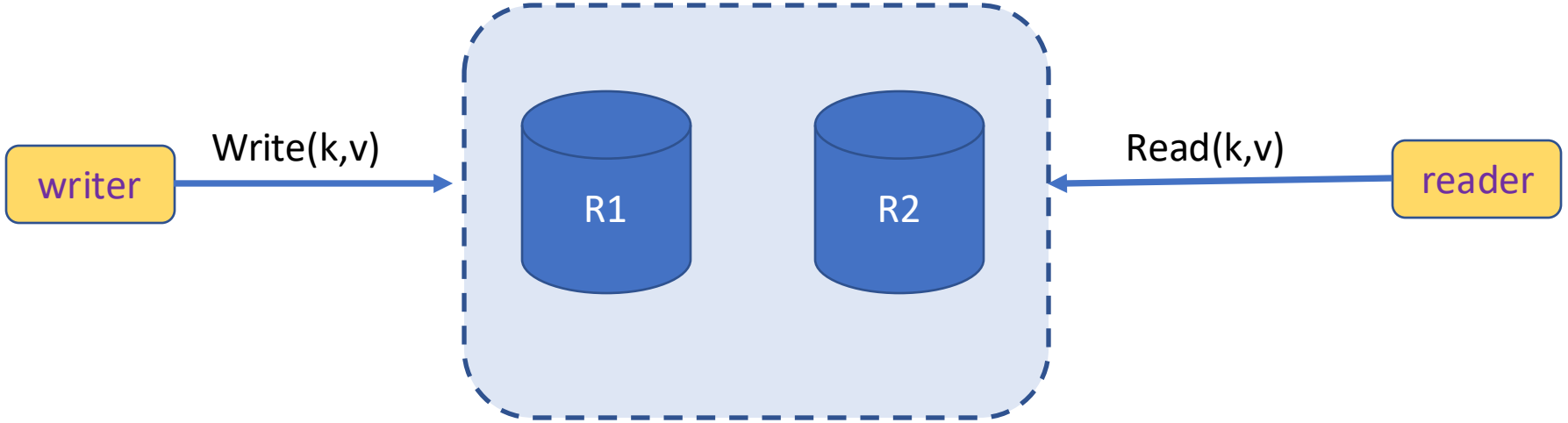

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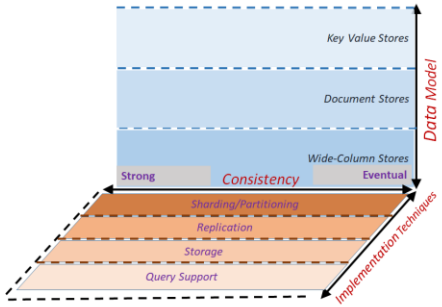

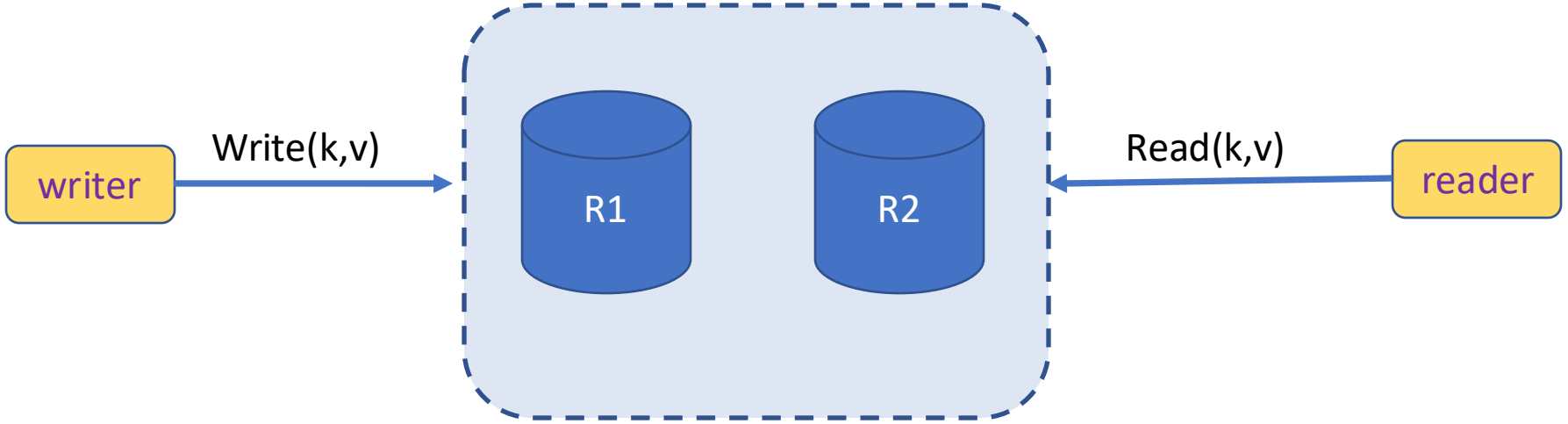

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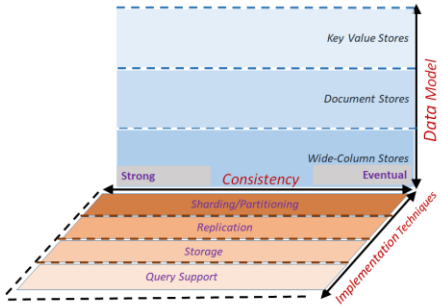

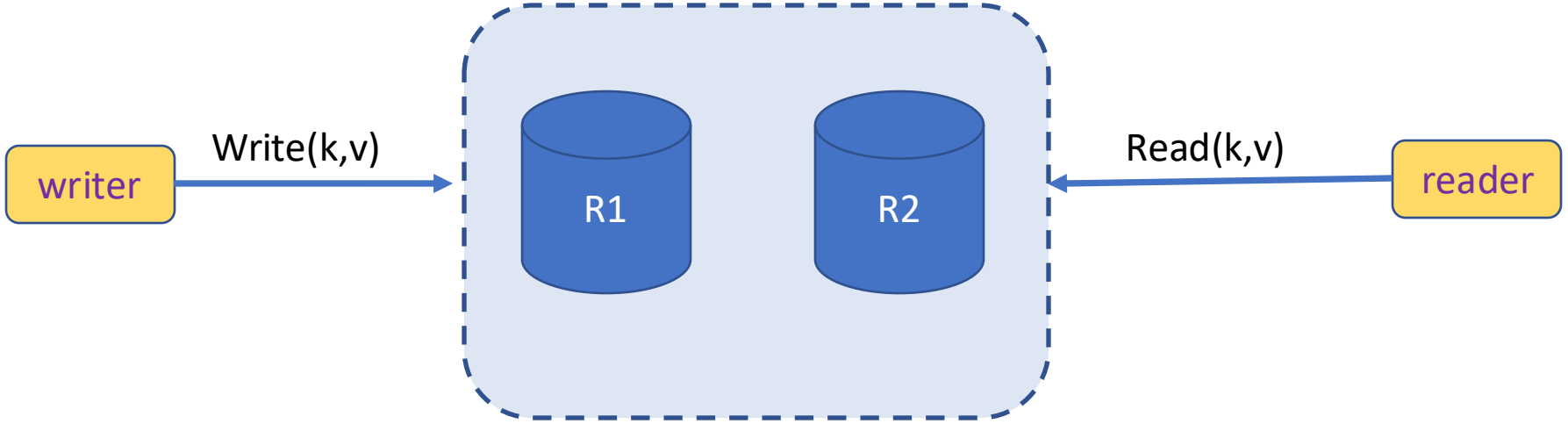

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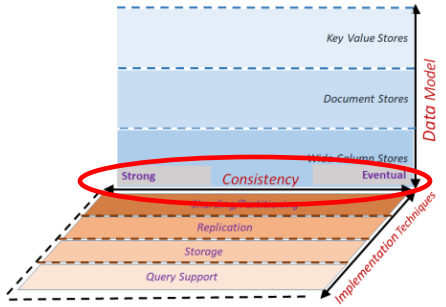
- How should we *implement* write?
- How to *implement* read?

Consistency: CAP Theorem



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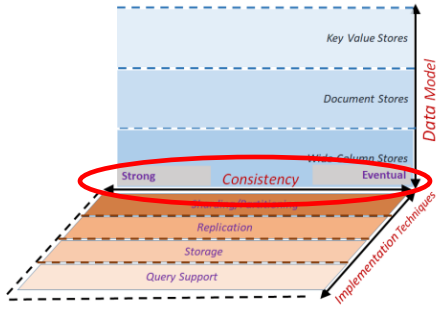

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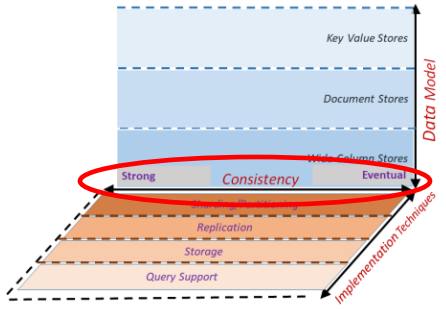
Consistency: CAP Theorem



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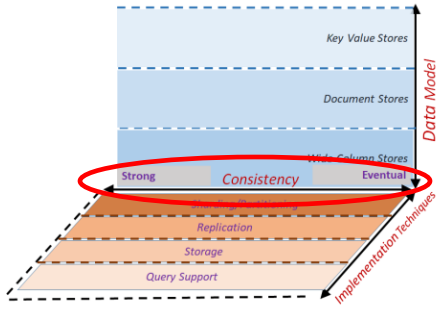

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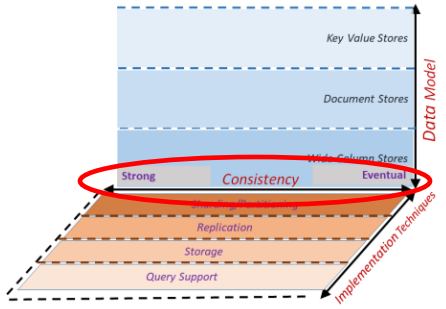

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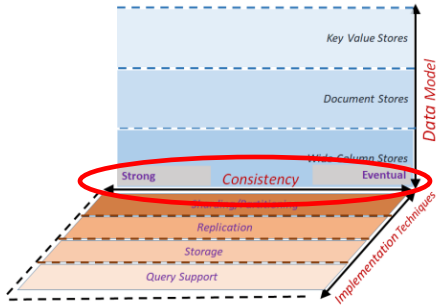

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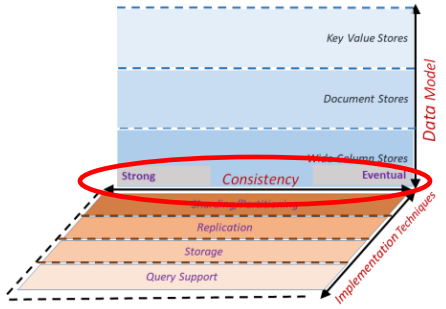

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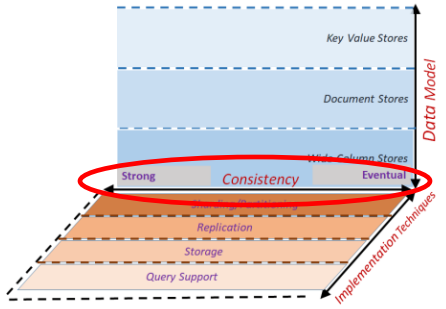

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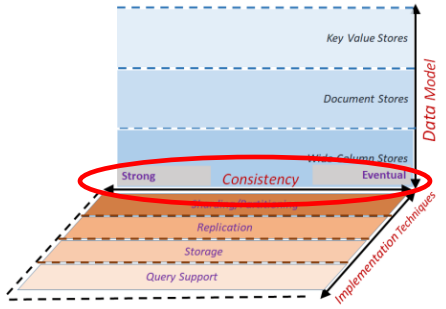
Consistency: CAP Theorem



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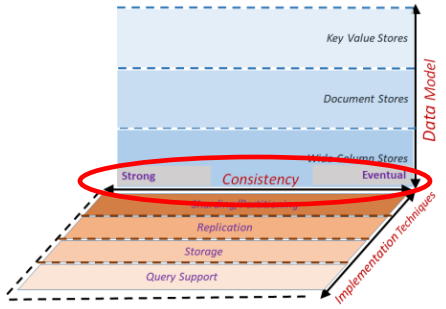

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Why care about CAP Properties?

Availability

- Reads/writes complete reliably and quickly.
- E.g. Amazon, each ms latency → $6M yearly loss.

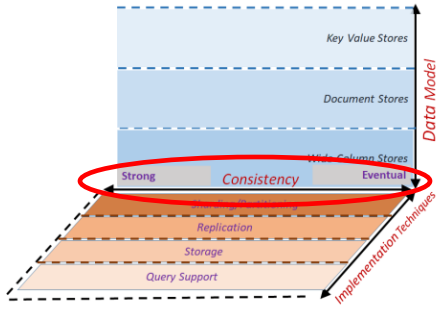
Partitions

- Internet router outages
- Under-sea cables cut
- rack switch outage
- *system should continue functioning normally!*

Consistency

- all nodes see same data at any time, or reads return latest written value by any client.
- ***This basically means correctness!***

Consistency: CAP Theorem



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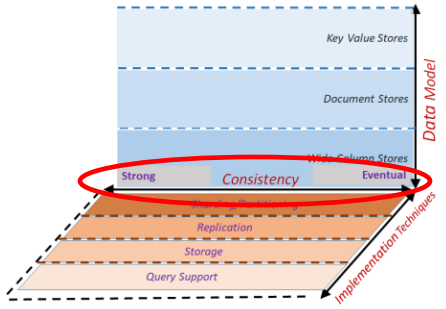

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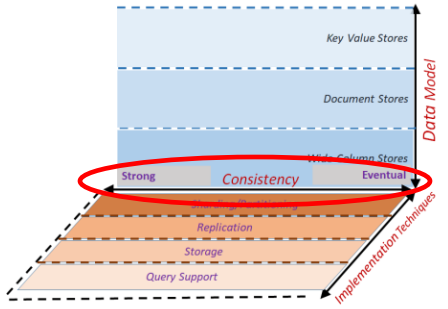
Consistency: CAP Theorem



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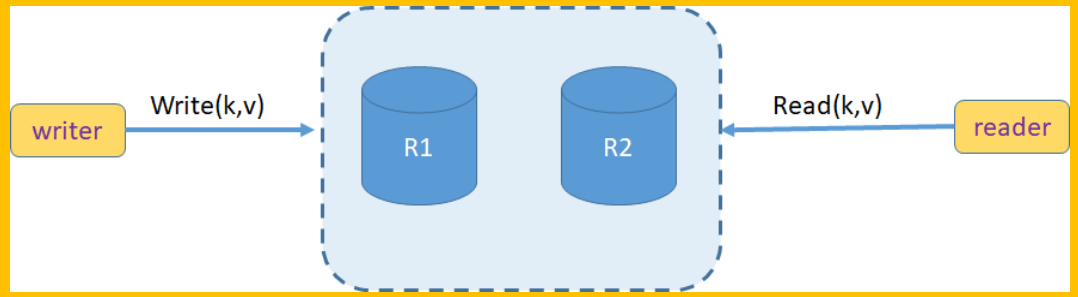

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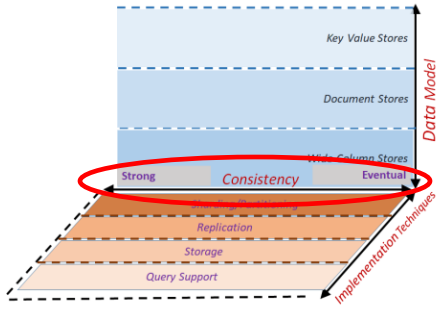

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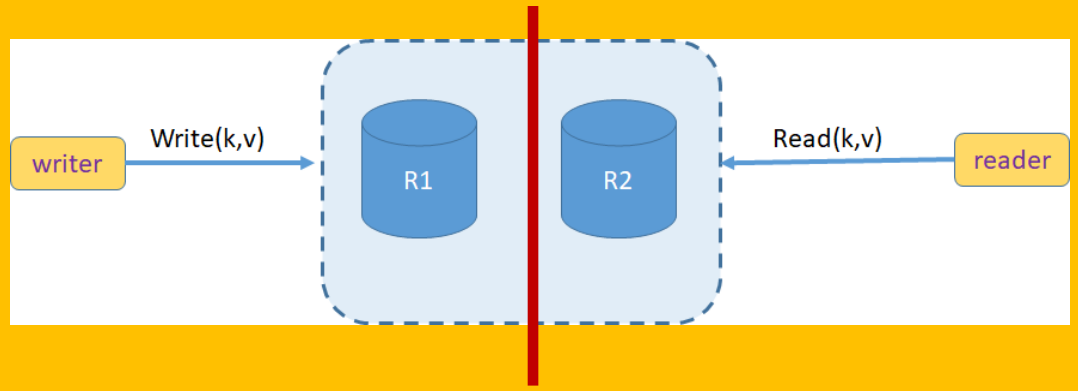

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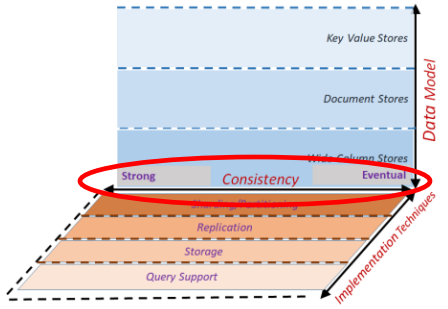

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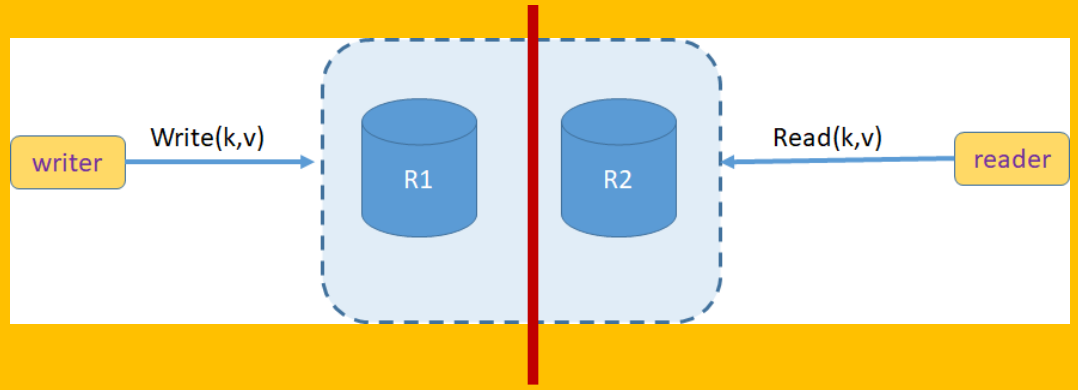
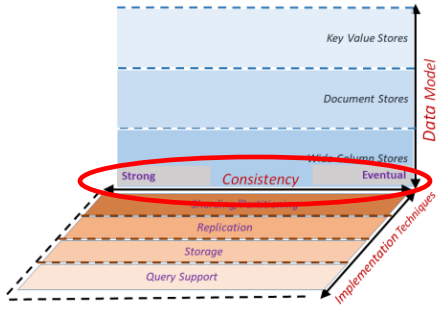


if(partition) { keep going } → !consistent && available

Consistency: CAP Theorem



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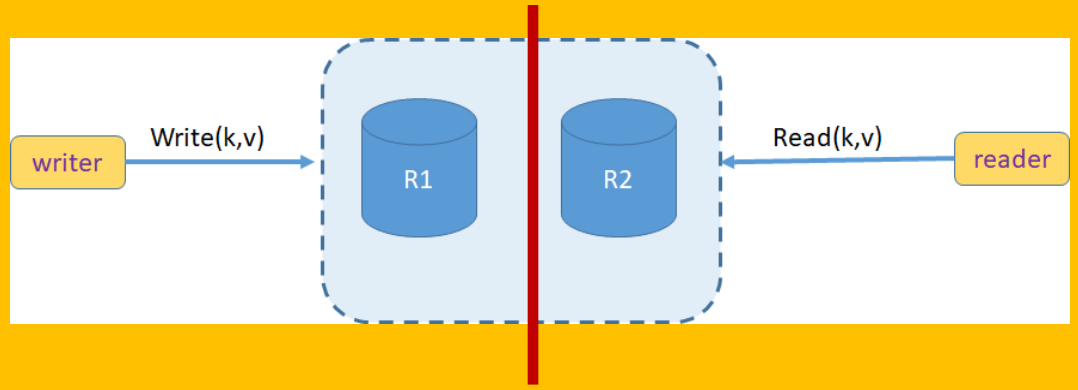
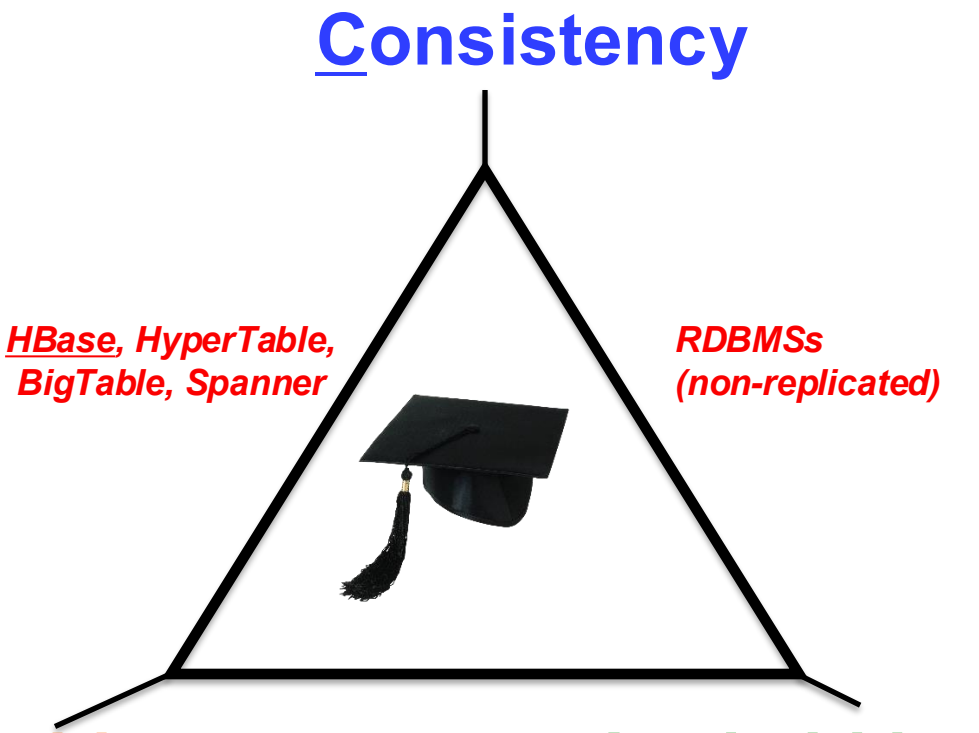


if(partition) { keep going } → !consistent && available

if(partition) { stop } → consistent && !available

CAP Implications

- A distributed storage system can achieve at most two of C, A, and P.
- When partition-tolerance is important, you have to choose between consistency and availability



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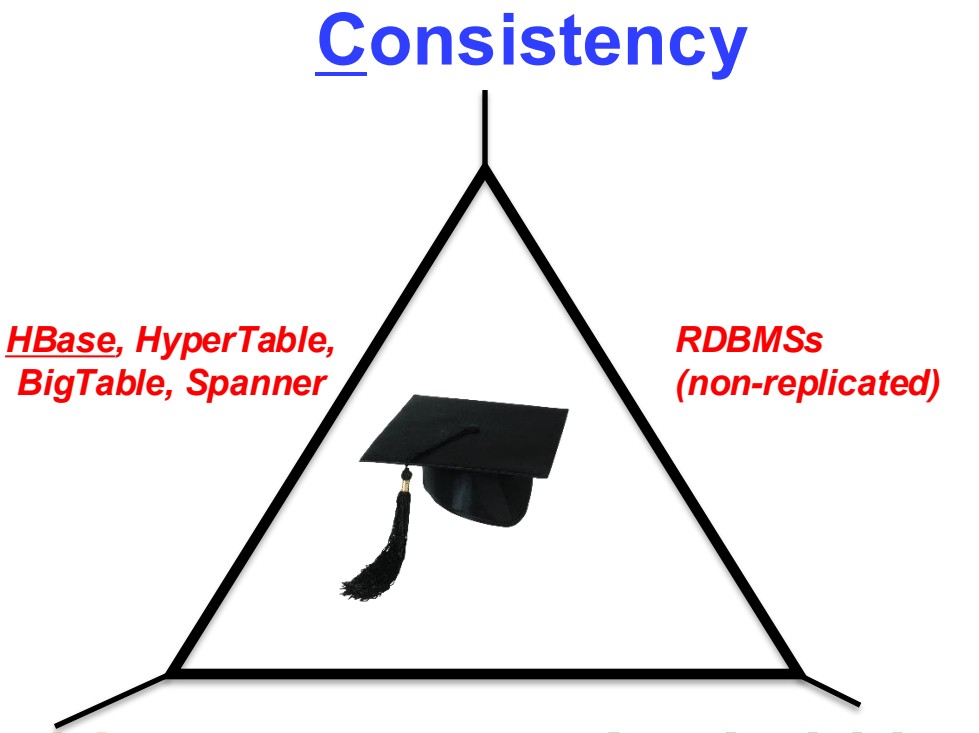

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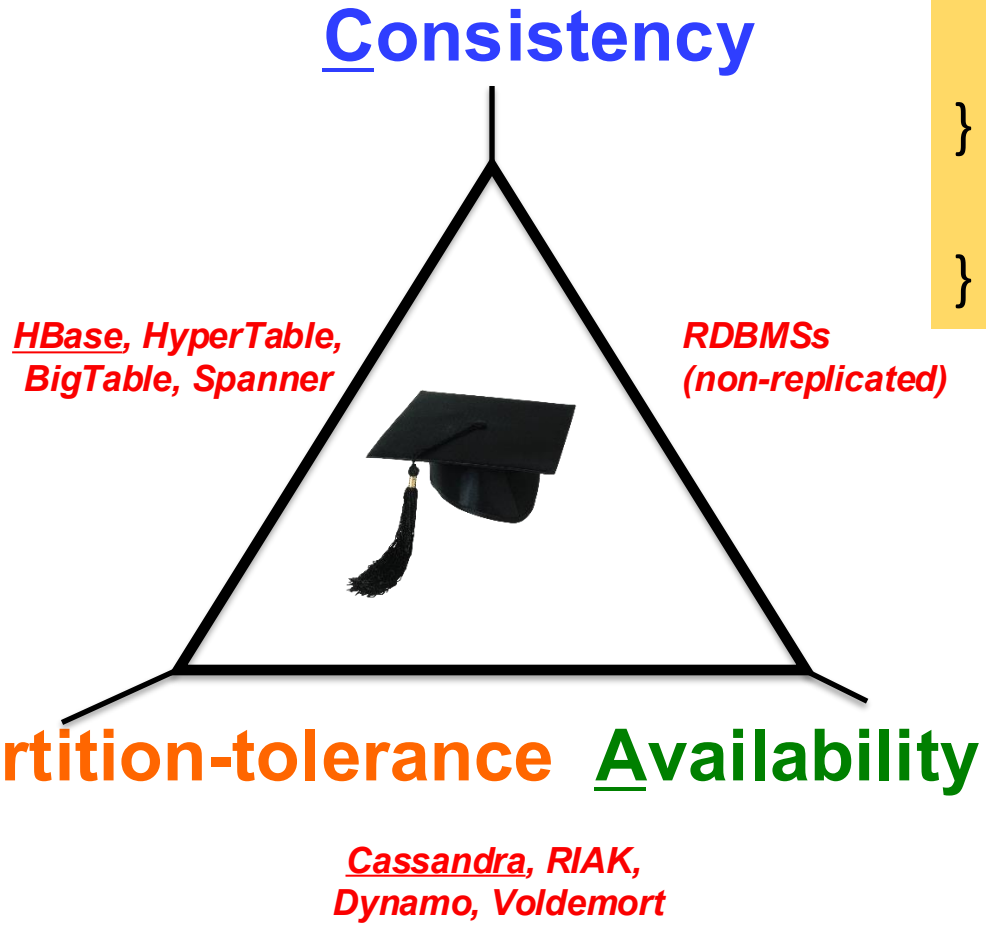
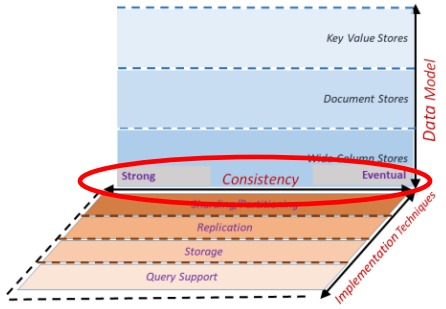
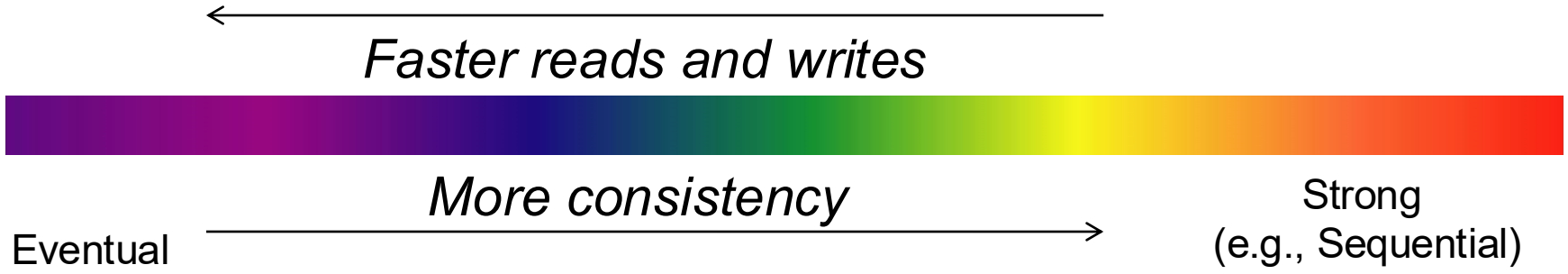


PACELC:

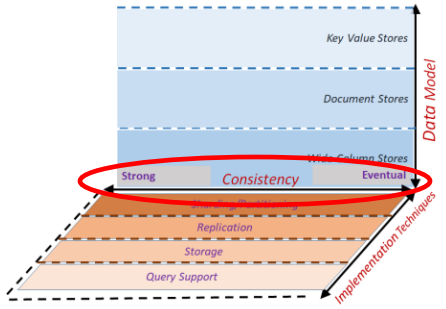
```
if(partition) {
   choose A or C
} else {
   choose latency or consistency
}
```

Consistency Spectrum

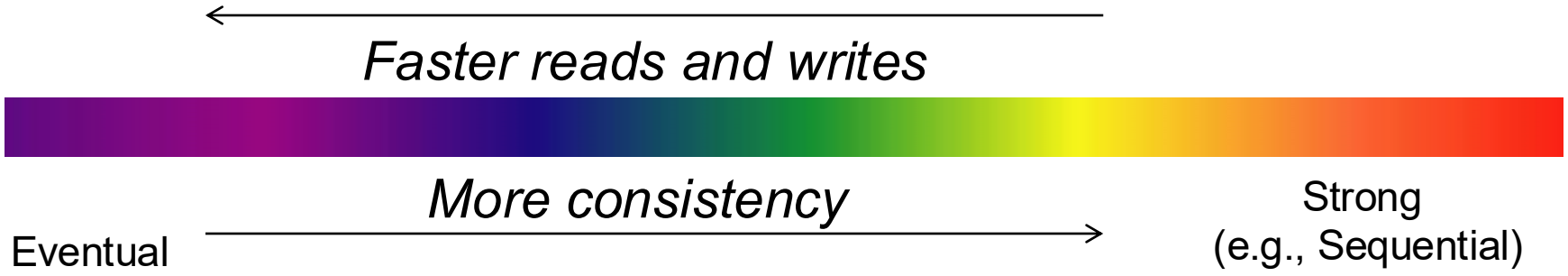




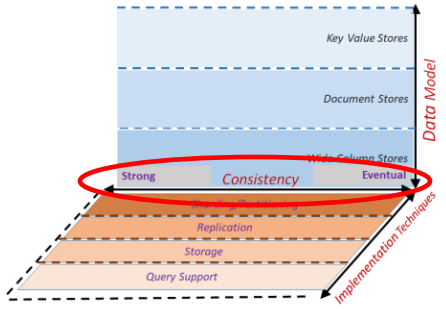
Spectrum Ends: Eventual Consistency



- Eventual Consistency
  - If writes to a key stop, all replicas of key will converge
  - Originally from Amazon's Dynamo and LinkedIn's Voldemort systems

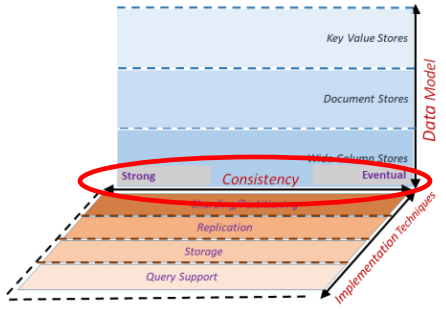


Spectrum Ends: Strong Consistency



- **Strict/Strong:**
  - Absolute time ordering of all shared accesses, reads always return last write
- **Linearizability**:
  - Each operation is visible (or available) to all other clients in real-time order
- **Sequential Consistency** [Lamport]:
  - *"... the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program.*
  - After the fact, find a "reasonable" ordering of the operations (can re-order operations) that obeys sanity (consistency) at all clients, and across clients.
- **ACID** properties

Many *Many* Consistency Models



Red-Blue

Causal

Probabilistic

Eventual

Per-key sequential

CRDTs

Strong
(e.g., Sequential, Strict)

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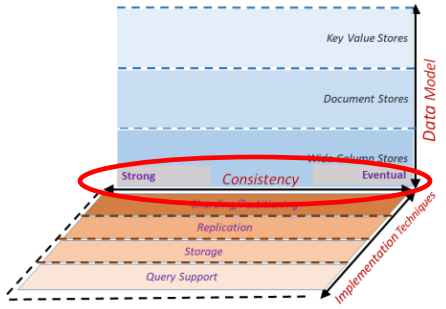

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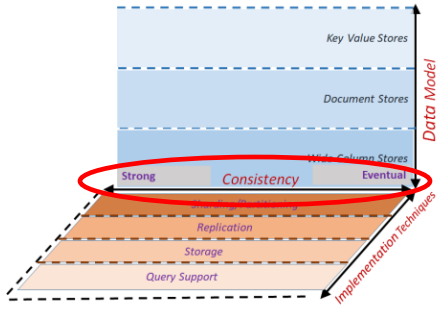
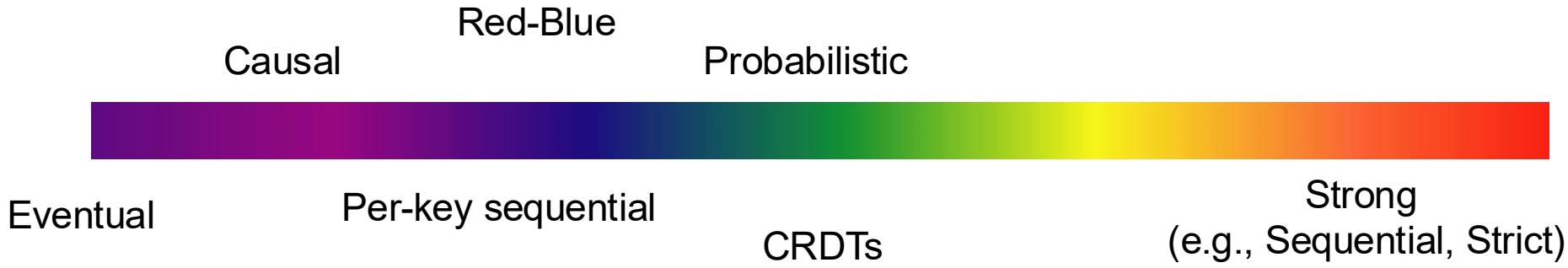
Strong
(e.g., Sequential, Strict)

- Amazon S3 – **eventual** consistency
- Amazon Simple DB – **eventual** or strong
- Google App Engine – **strong** or eventual
- Yahoo! PNUTS – **eventual** or strong
- Windows Azure Storage – **strong** (or eventual)
- Cassandra – **eventual** or strong (if R+W > N)
- …

Many *Many* Consistency Models





- Amazon S3 – **eventual** consistency
- Amazon Simple DB – **eventual** or strong
- Google App Engine – **strong** or eventual
- Yahoo! PNUTS – **eventual** or strong
- Windows Azure Storage – **strong** (or eventual)
- Cassandra – **eventual** or strong (if R+W > N)
- …

Question: How to choose what to use or support?

Review: Some Consistency Guarantees

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
Consistent Prefix	See initial sequence of writes.
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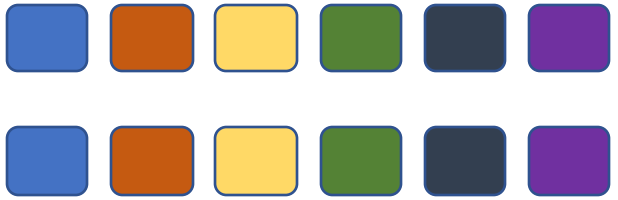

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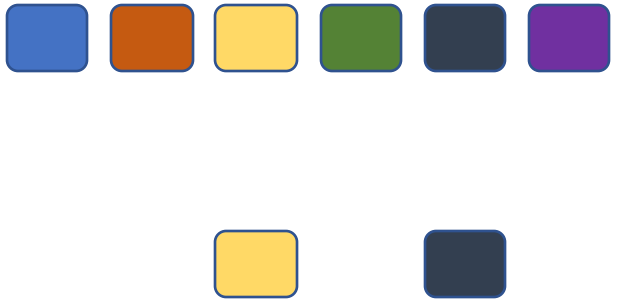

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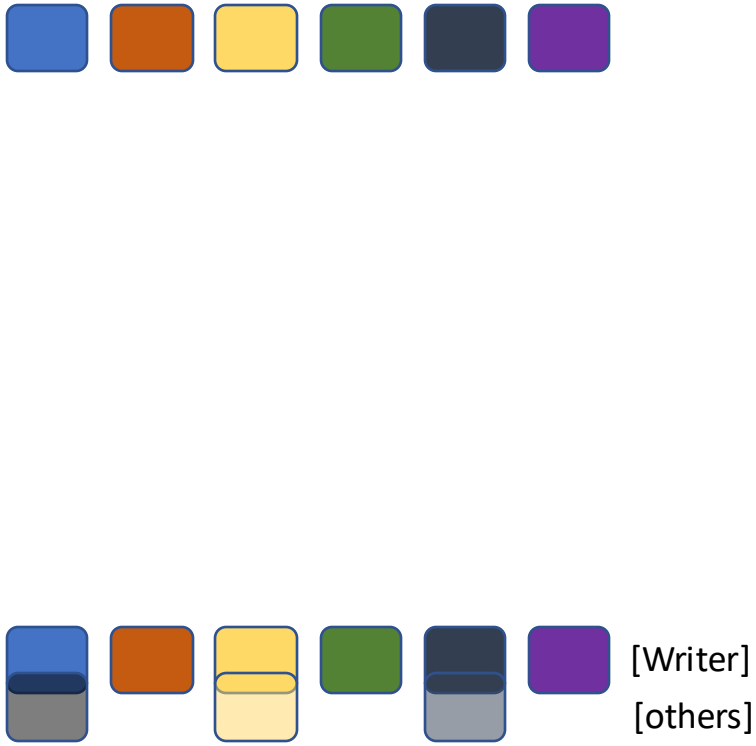

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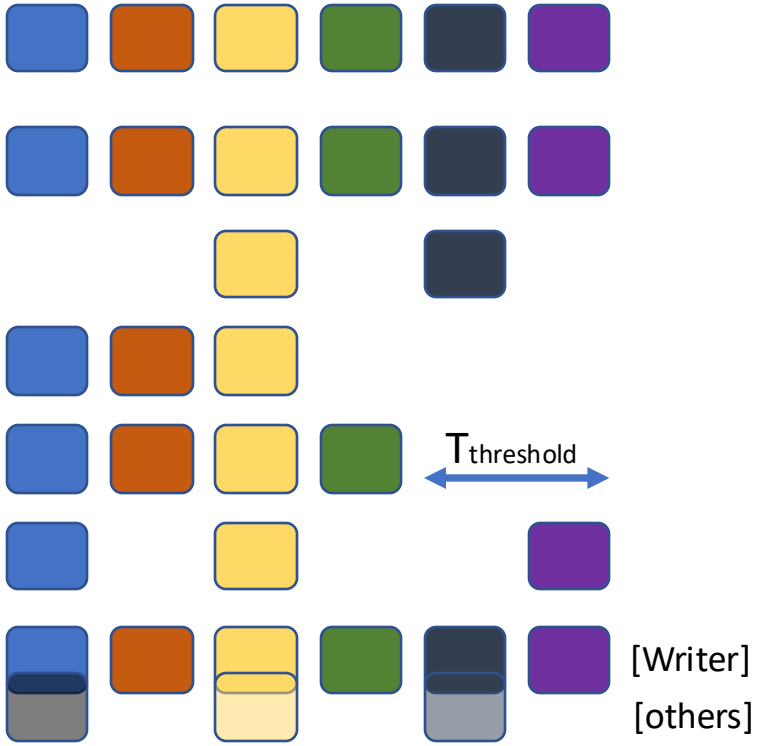
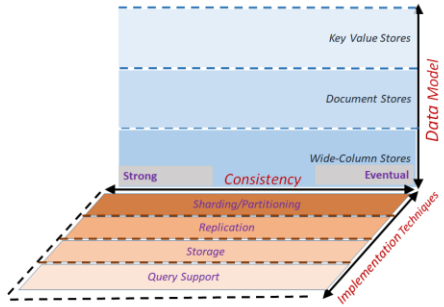
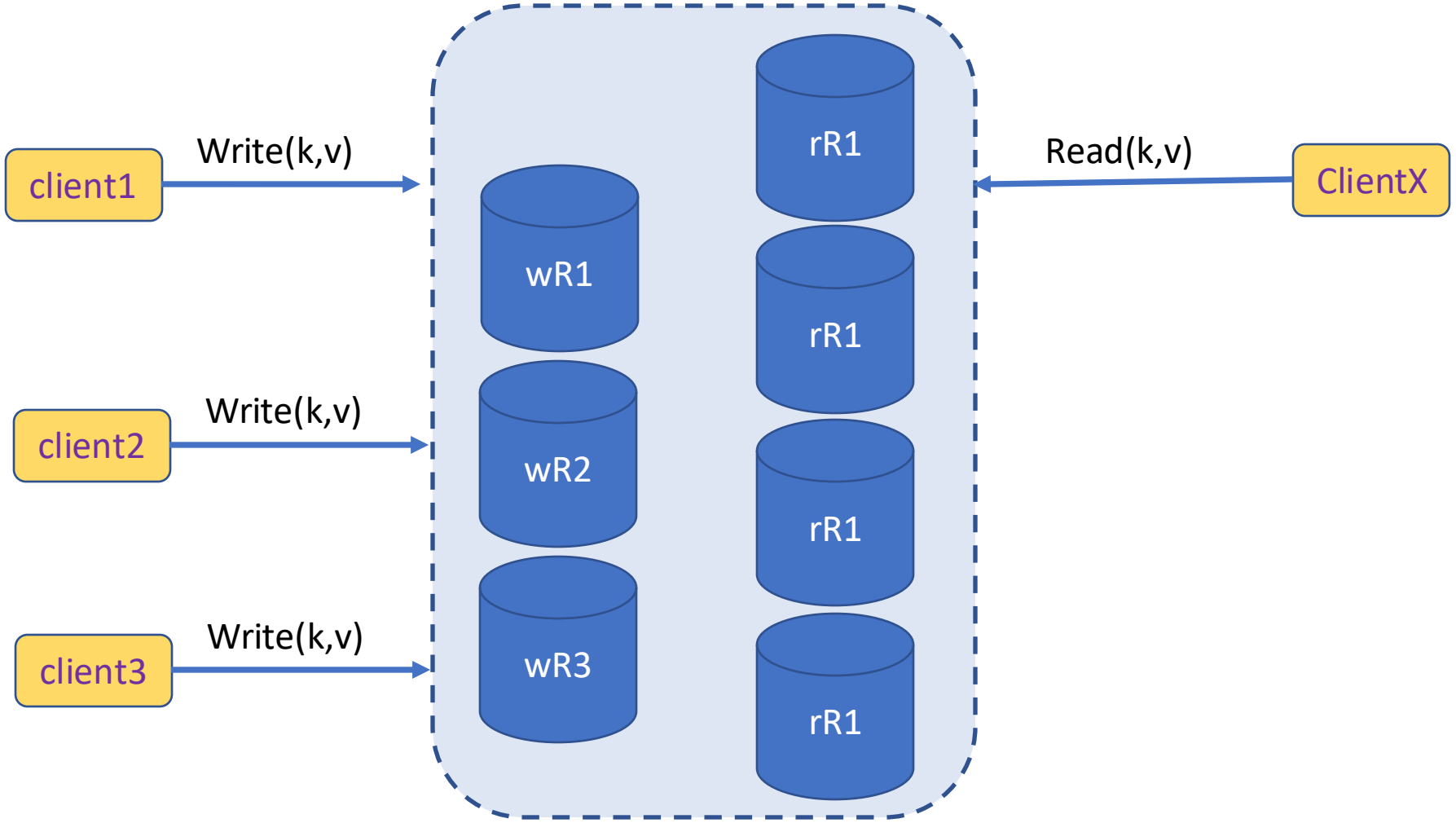


Hold the phone!

How can all these different guarantees come up?





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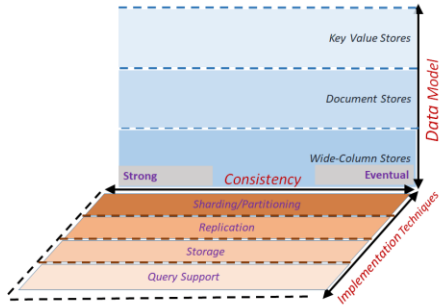

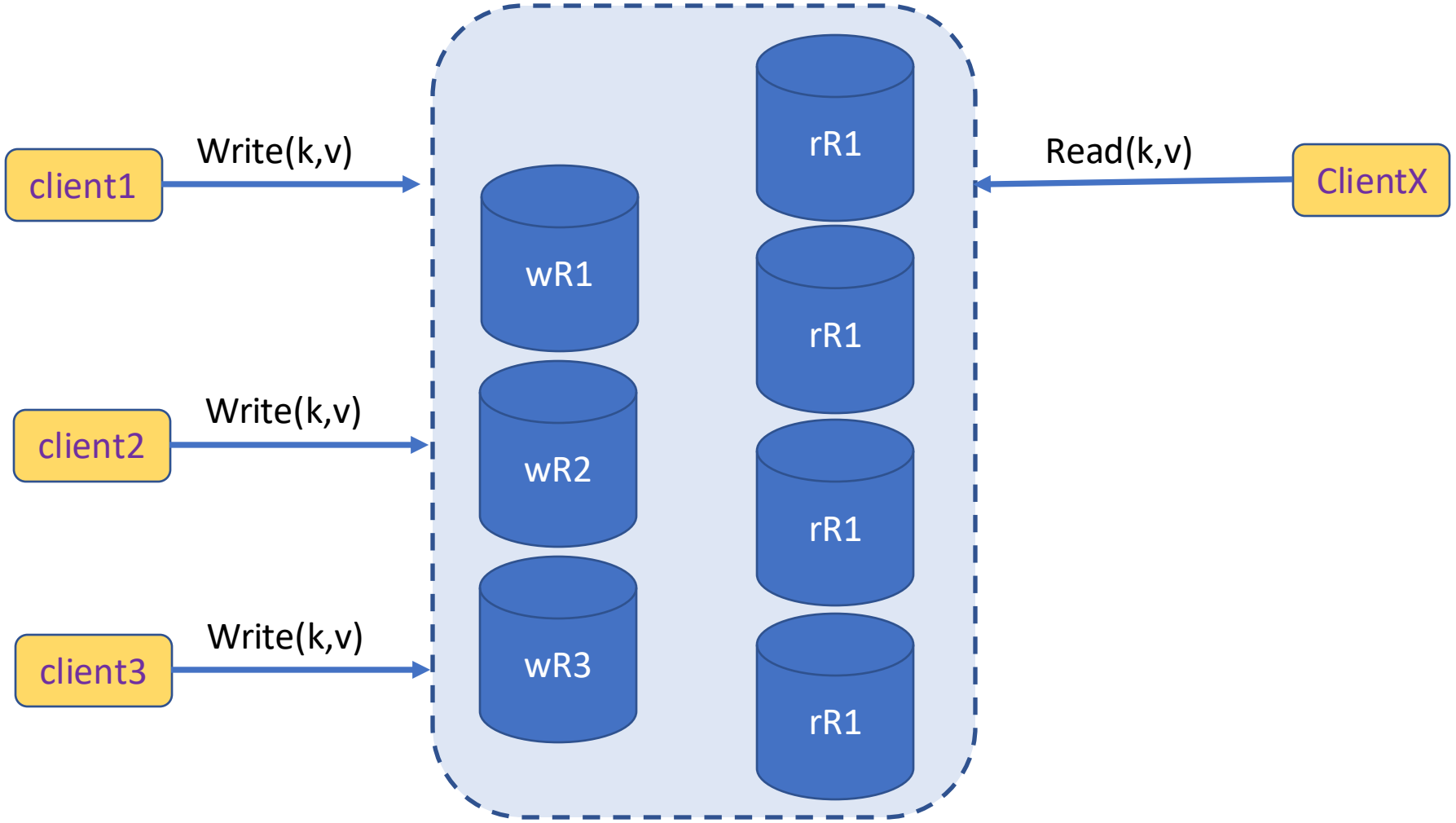

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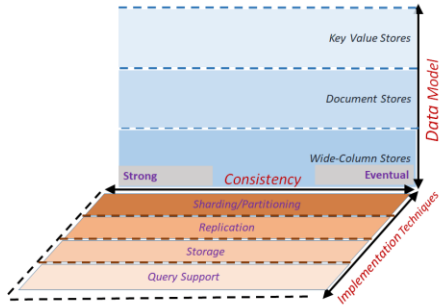

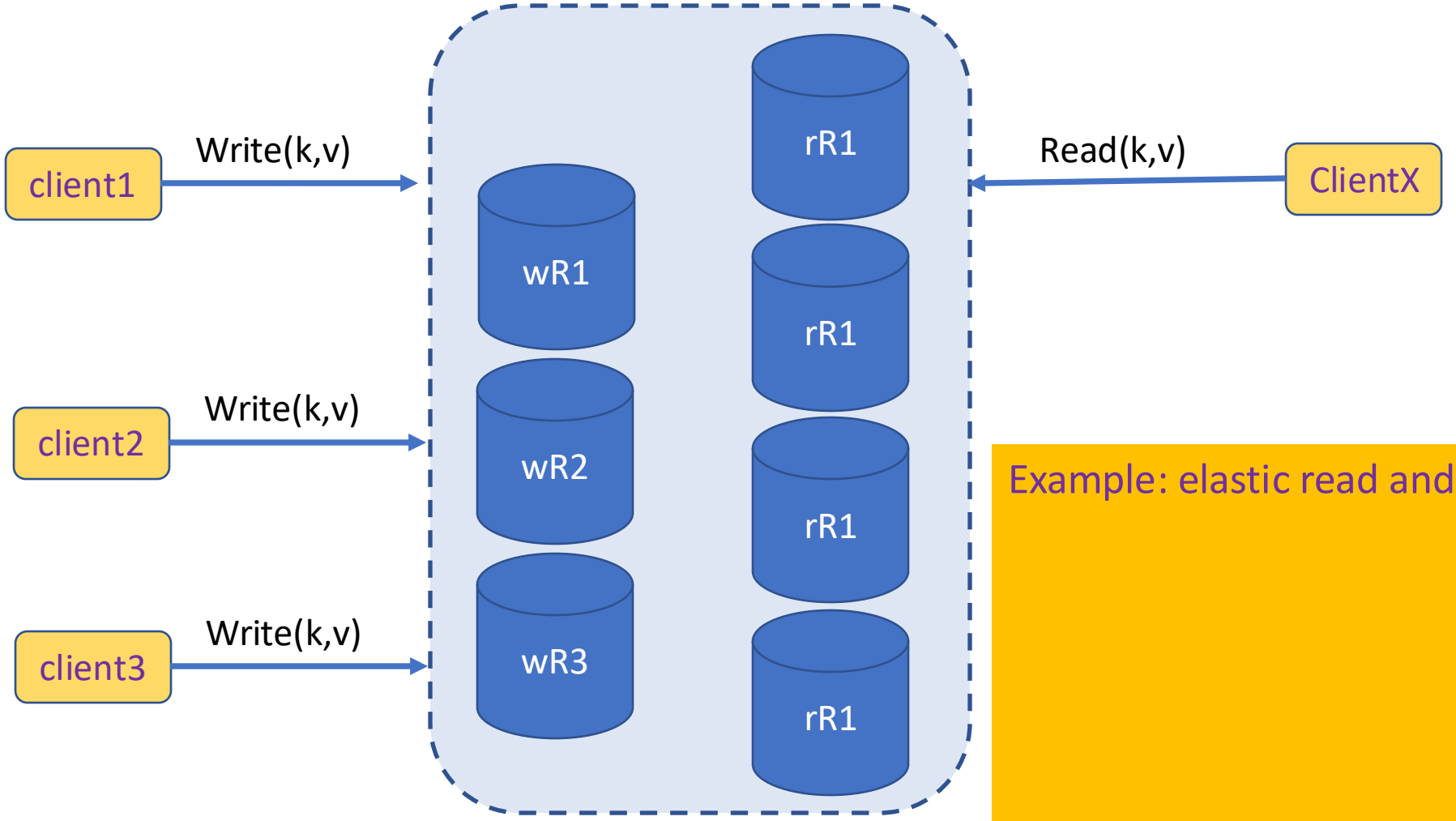

Example: elastic read and writes

Hold the phone!

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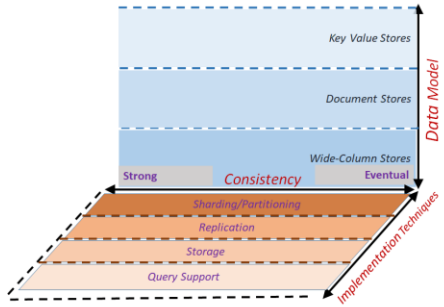

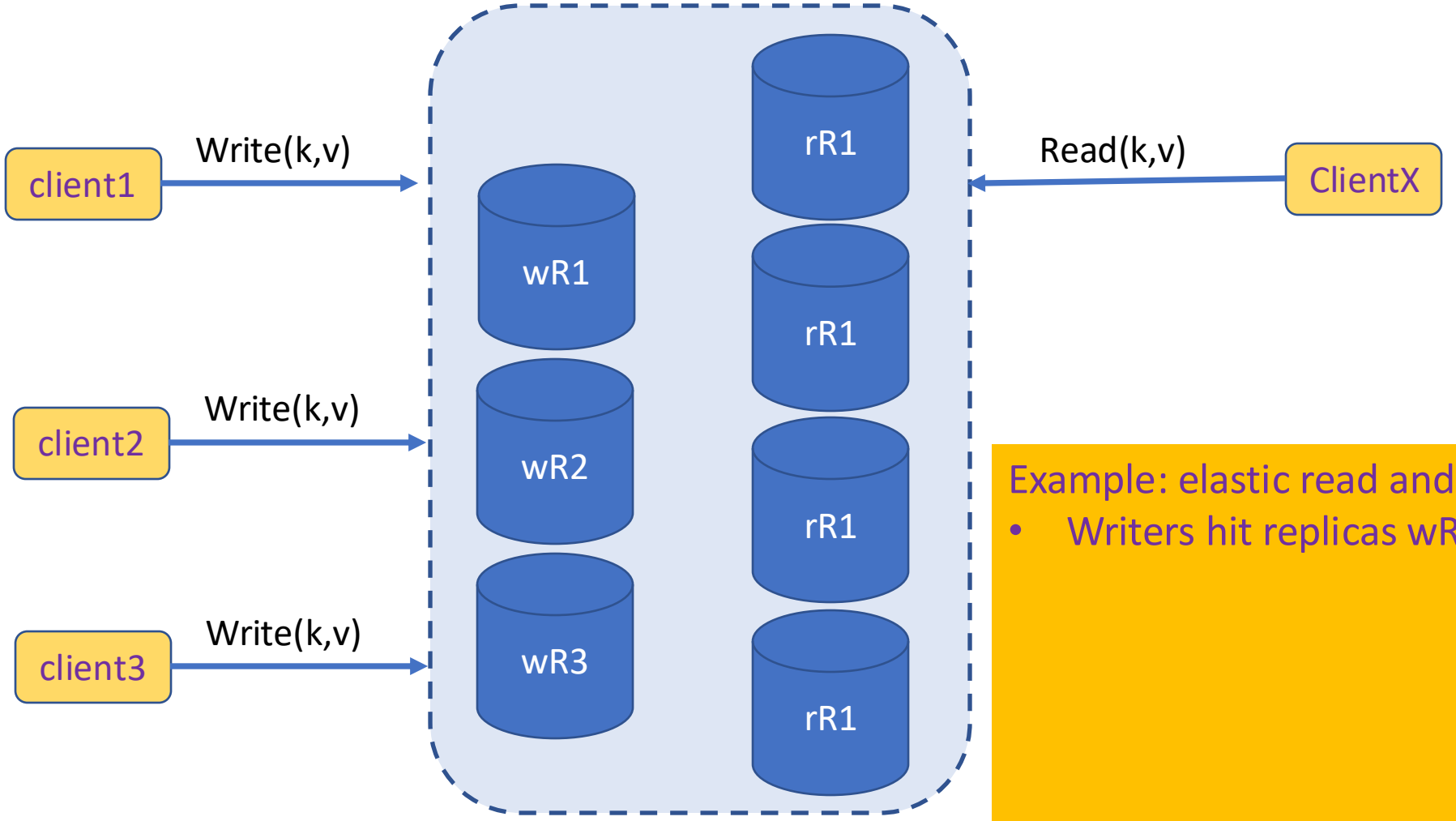

Example: elastic read and writes

- Writers hit replicas wR1..wR3

Hold the phone!

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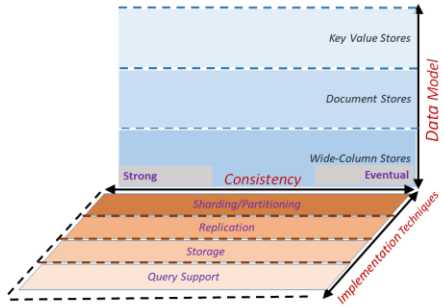

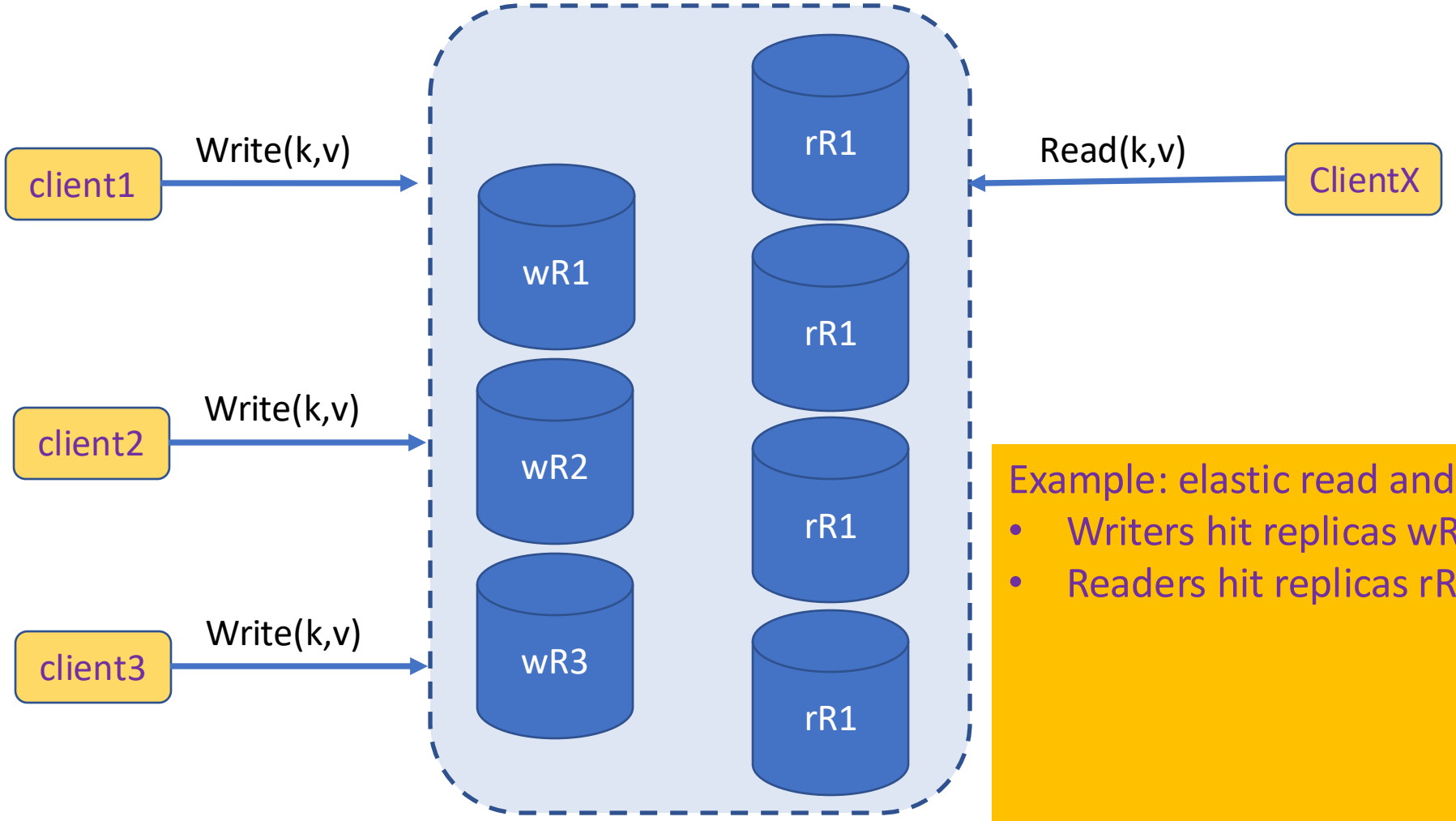

Example: elastic read and writes

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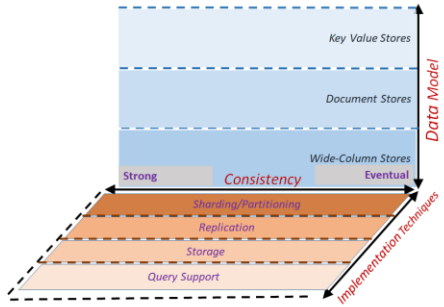

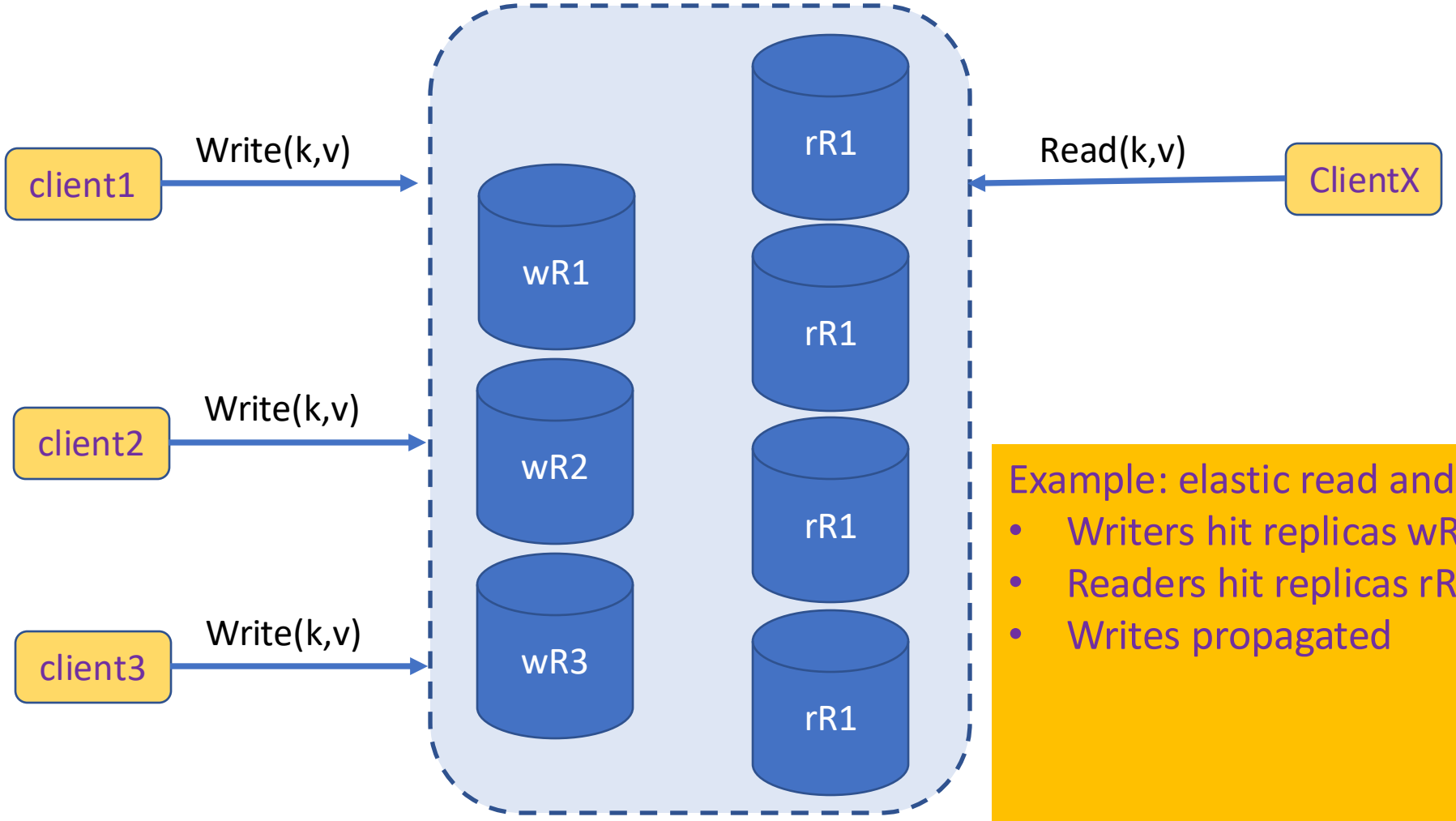

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- Writers hit replicas wR1..wR3
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Hold the phone!

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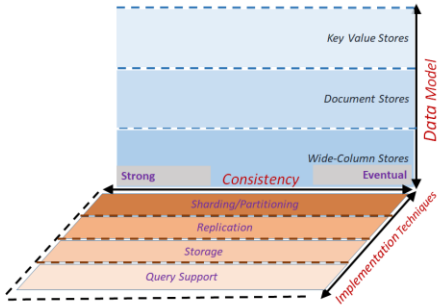

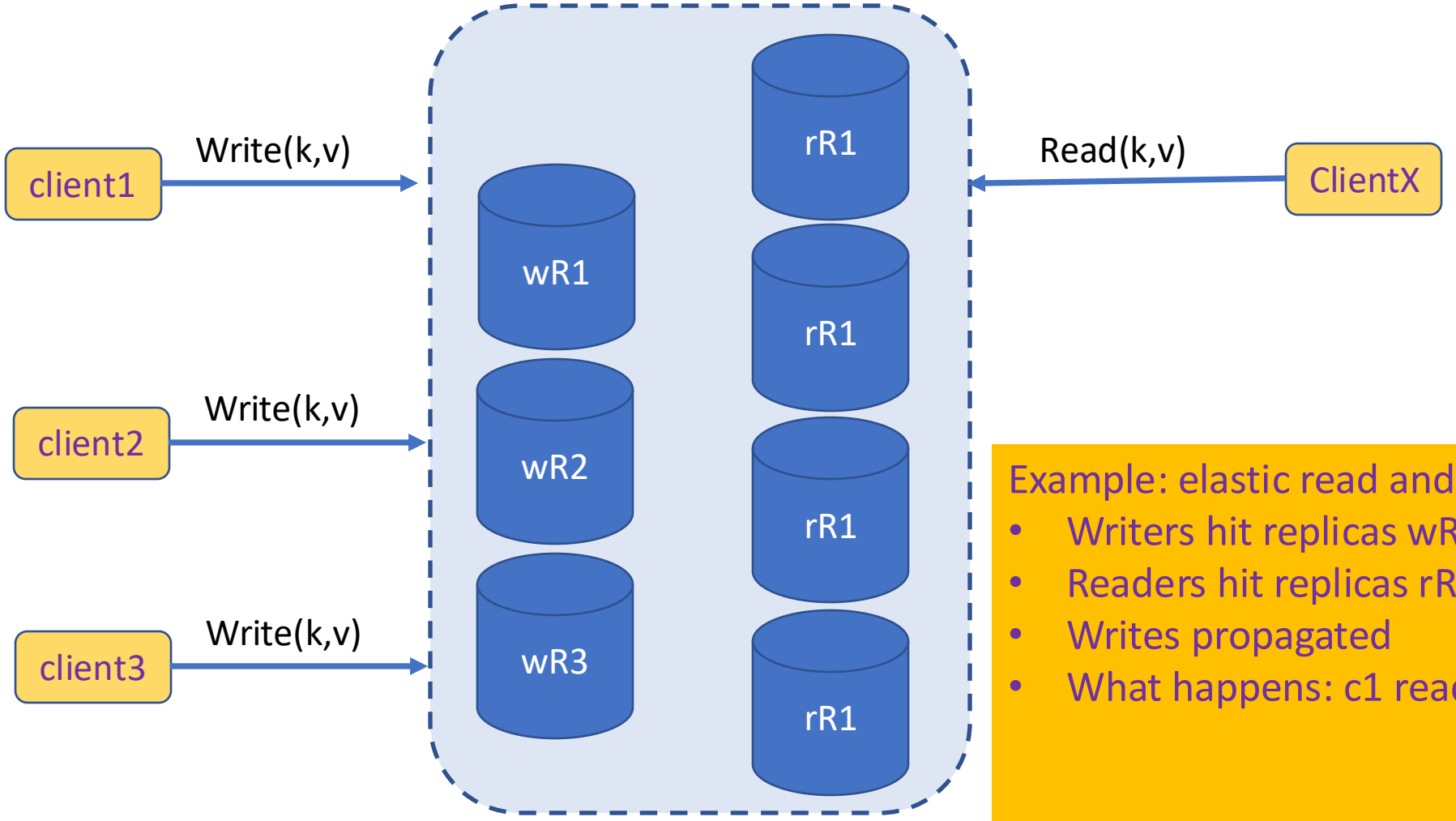

Example: elastic read and writes

- Writers hit replicas wR1..wR3
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- What happens: c1 reads own writes?

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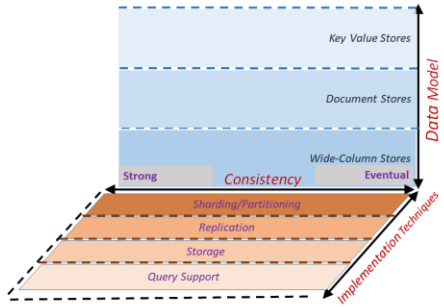

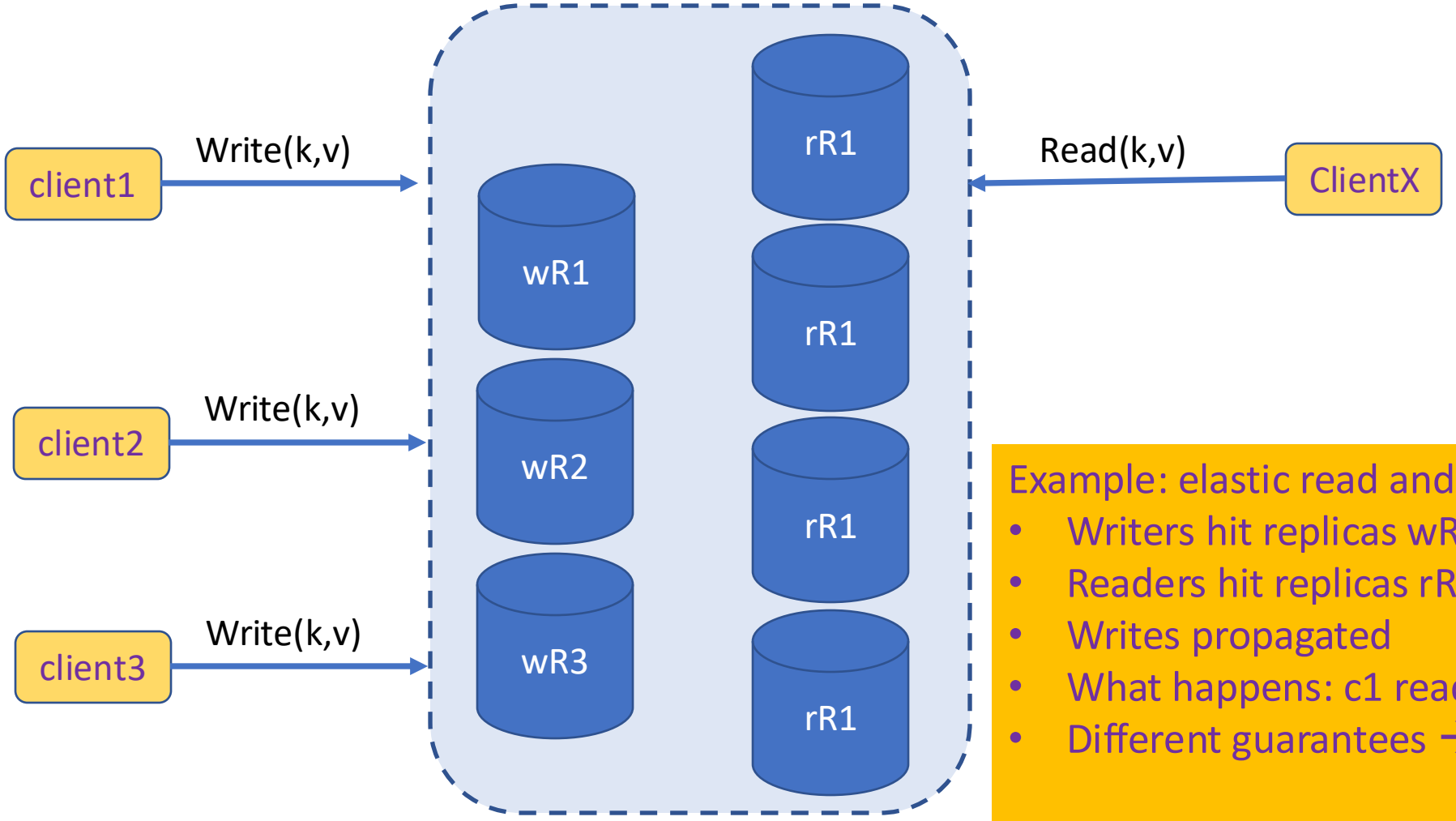

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- What happens: c1 reads own writes?
- Different guarantees →

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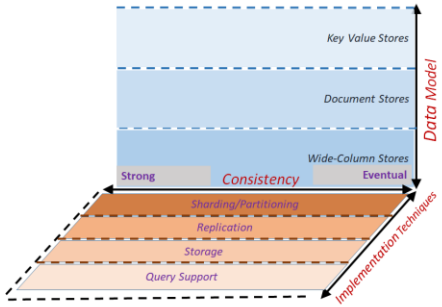
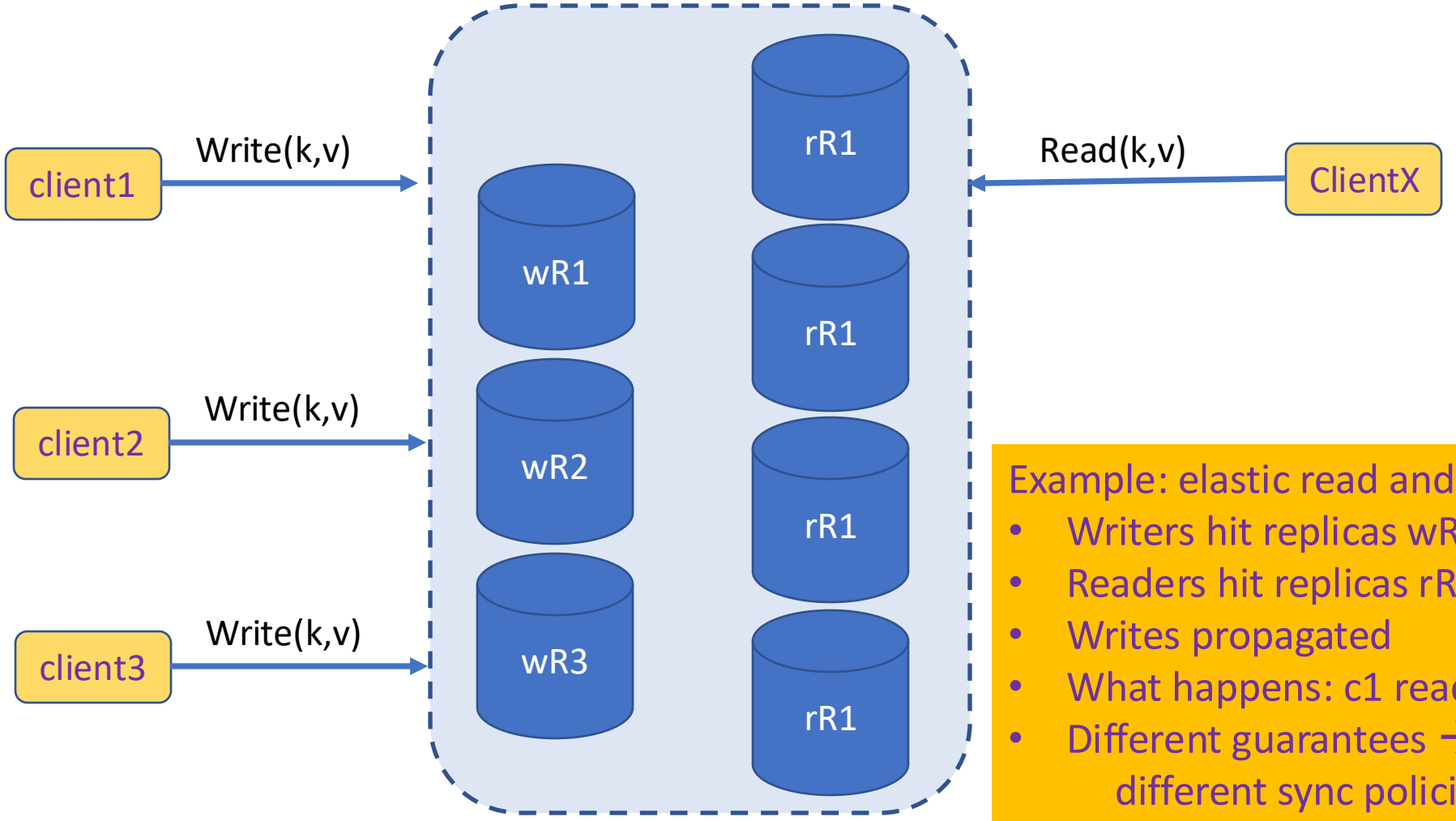


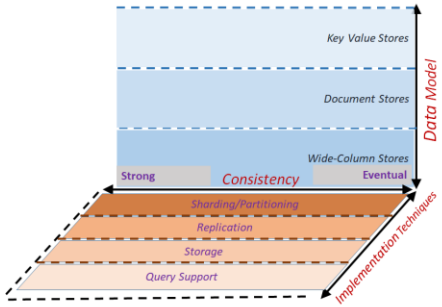


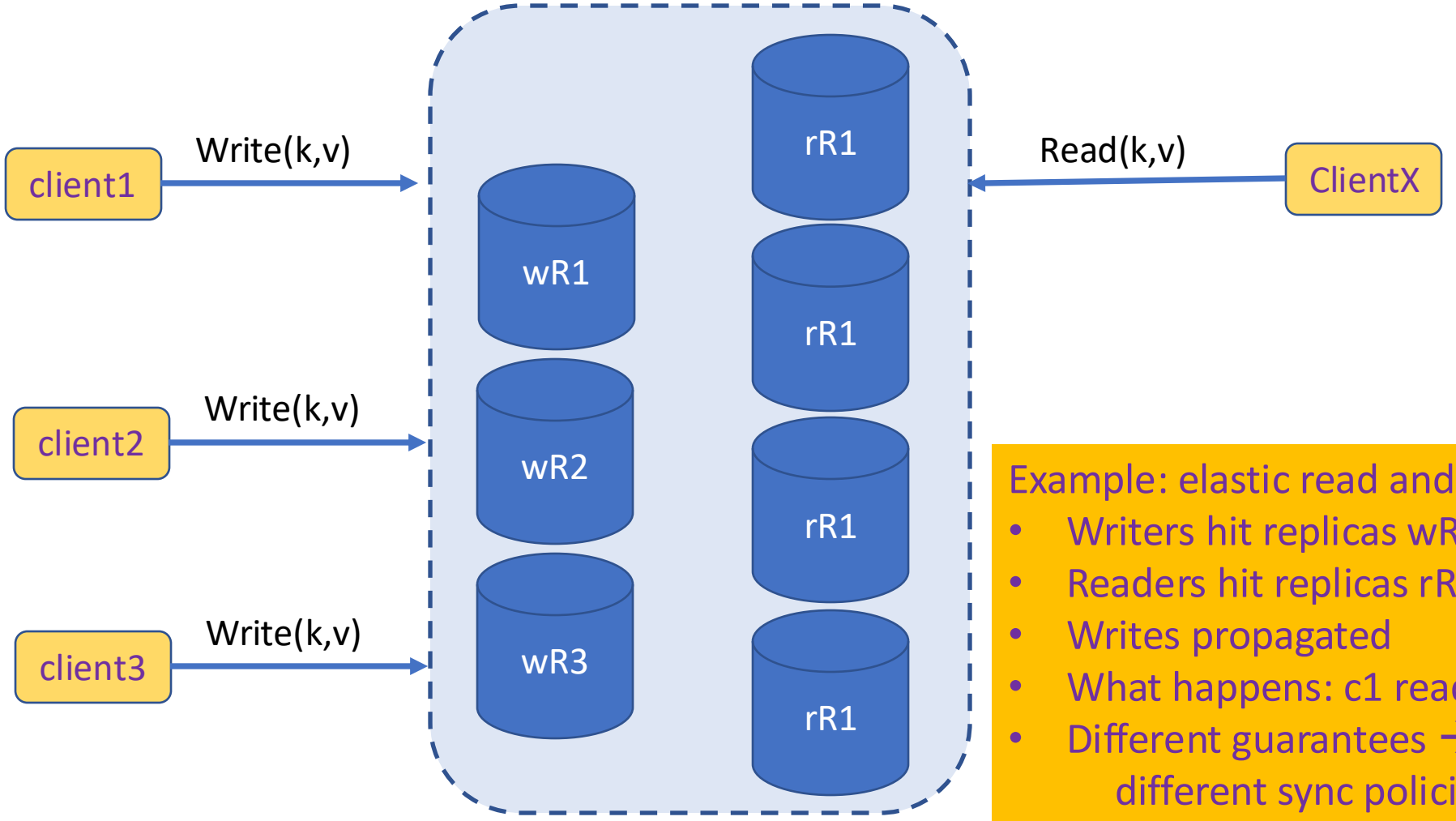
Example: elastic read and writes

- Writers hit replicas wR1..wR3
- Readers hit replicas rR1..rR4
- Writes propagated
- What happens: c1 reads own writes?
- Different guarantees → different sync policies

Hold the phone!

How can all these different guarantees come up?





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- Writes propagated
- What happens: c1 reads own writes?
- Different guarantees →
  - different sync policies
  - different w/r routing policies

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		consistency	*performance*	*availability*
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Eventual Consistency	See subset of previous writes.	D	A	A
Consistent Prefix	See initial sequence of writes.	C	B	A
Bounded Staleness	See all “old” writes.	B	C	D
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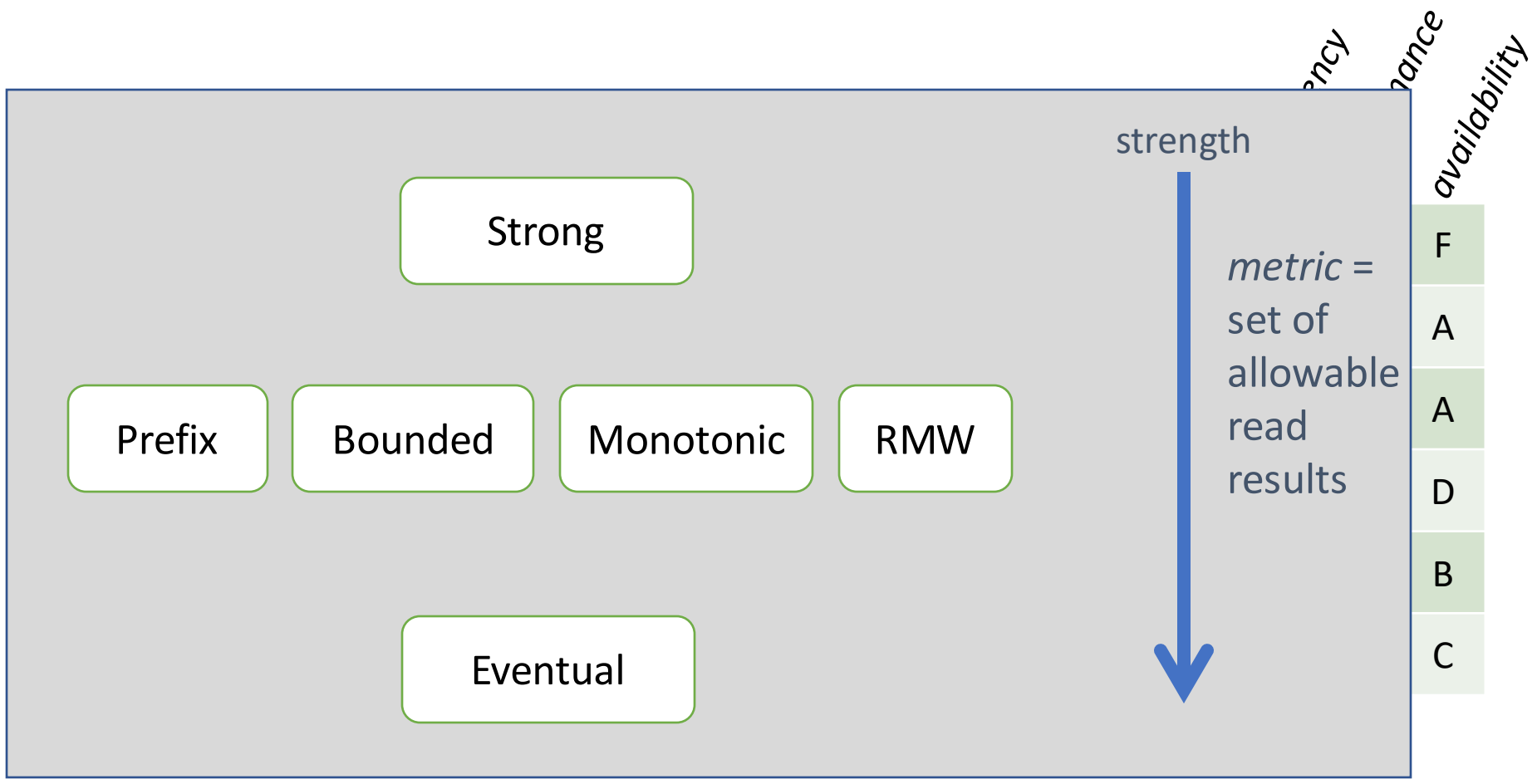
Some Consistency Guarantees



The Game of Soccer

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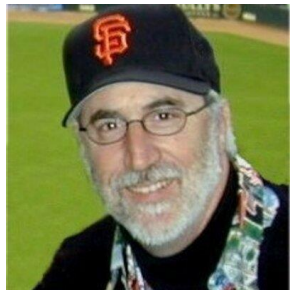

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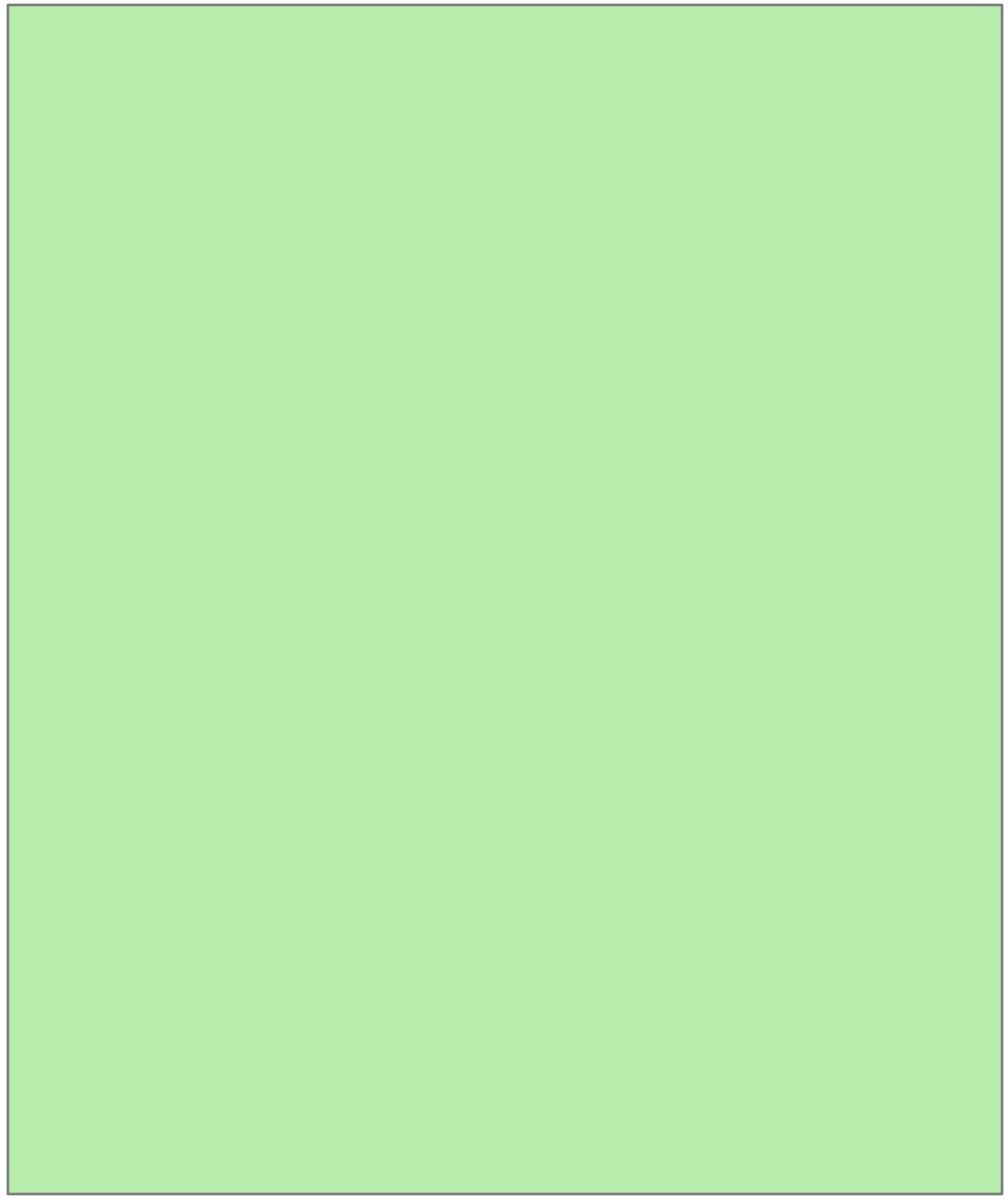

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for half = 1 .. 2  {
```

The Game of Soccer

```
for half = 1 .. 2  {
   while half not over {
```

The Game of Soccer

```
for half = 1 .. 2  {
   while half not over {
        kick-the-ball-at-the-goal
```

The Game of Soccer

```
for half = 1 .. 2  {
   while half not over {
        kick-the-ball-at-the-goal
        for each goal {
```

The Game of Soccer

```
for half = 1 .. 2  {
   while half not over {
        kick-the-ball-at-the-goal
        for each goal {
          if visiting-team-scored {
```

The Game of Soccer

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for half = 1 .. 2  {
   while half not over {
        kick-the-ball-at-the-goal
        for each goal {
          if visiting-team-scored {
             score = Read ("visitors");
```

The Game of Soccer

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for half = 1 .. 2  {
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        for each goal {
          if visiting-team-scored {
            score = Read (“visitors”);
            Write (“visitors”, score + 1);
```

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        for each goal {
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hScore = Read("home");
```

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vScore = Read("visit");
```

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          } } }
hScore = Read("home");
vScore = Read("visit");
if (hScore == vScore)
```

The Game of Soccer

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          if visiting-team-scored {
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vScore = Read("visit");
if (hScore == vScore)
    play-overtime
```

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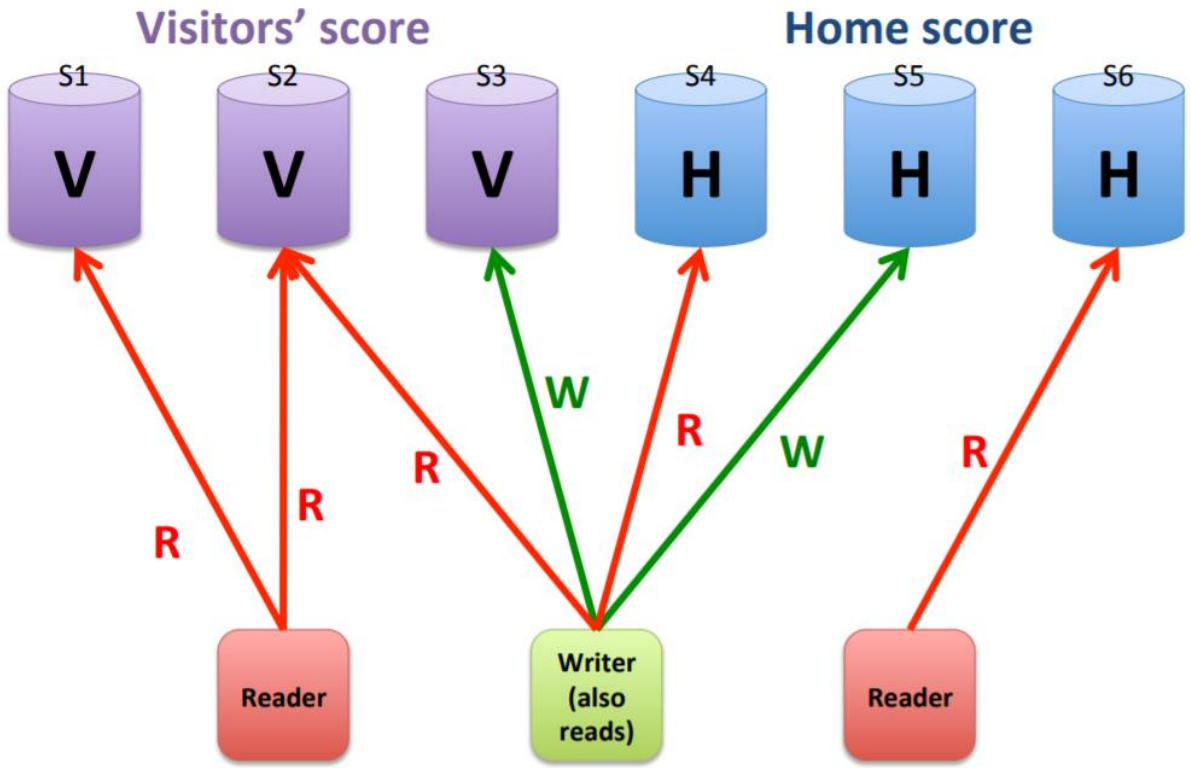
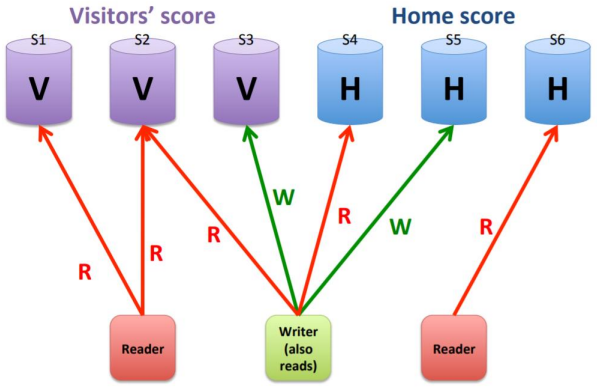


Official Scorekeeper



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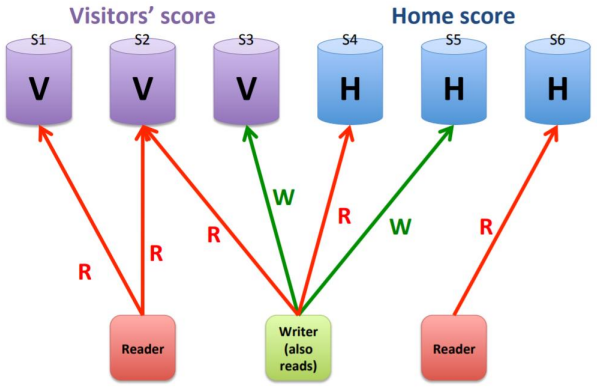

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Desired consistency?

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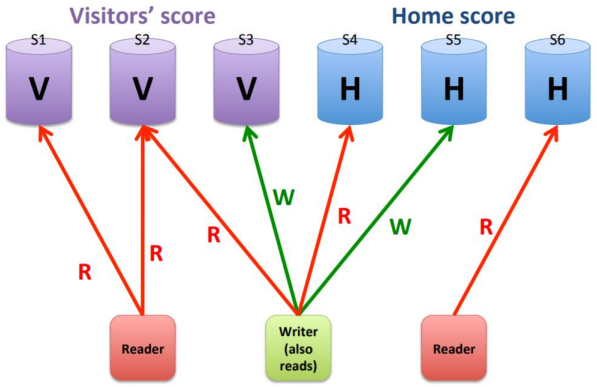
Official Scorekeeper



score = **Read** ("visitors");
Write ("visitors", score + 1);

Desired consistency?

Strong

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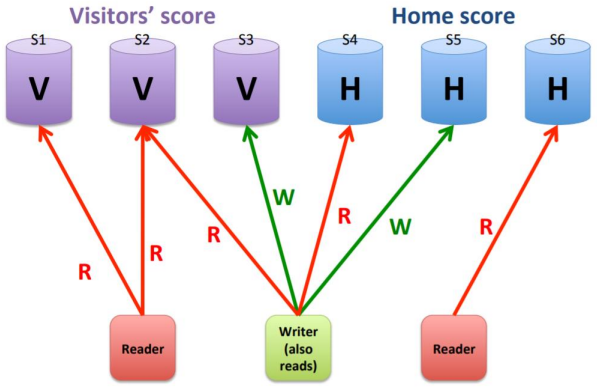

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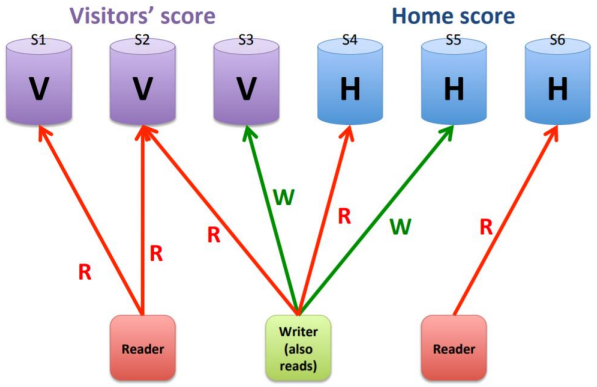

score = **Read** ("visitors");
Write ("visitors", score + 1);

```
Write ("home", 1);
Write ("visitors", 1);
Write ("home", 2);
Write ("home", 3);
Write ("visitors", 2);
Write ("home", 4);
Write ("home", 5);
```

```
Visitors = 2
Home = 5
```

Desired consistency?

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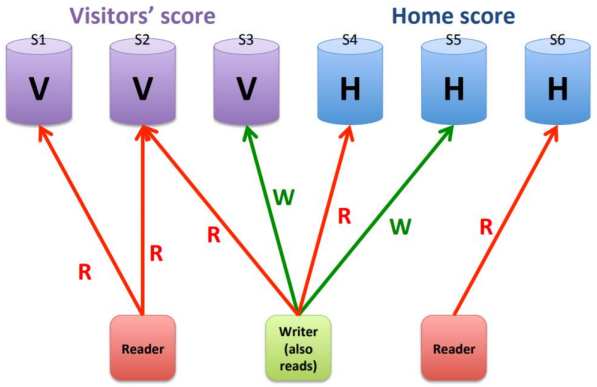


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vScore = Read ("visitors");
hScore = Read ("home");
if vScore == hScore
      play-overtime
```

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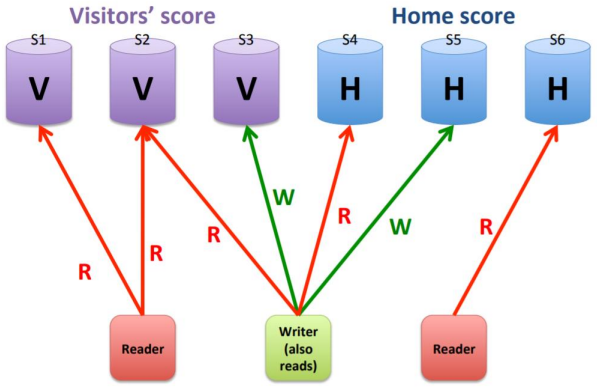


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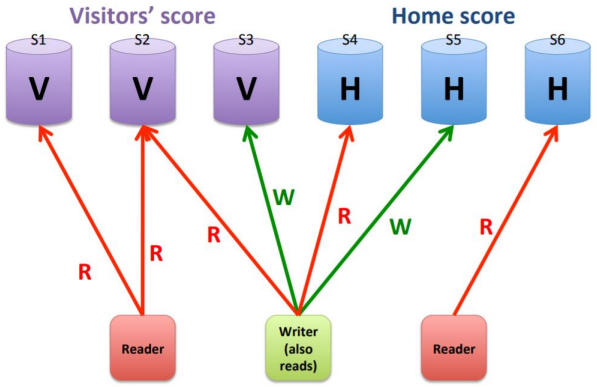


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Radio Reporter

```
do {
    BeginTx();
        vScore = Read ("visitors");
        hScore = Read ("home");
    EndTx();
    report vScore and hScore;
    sleep (30 minutes);
}
```

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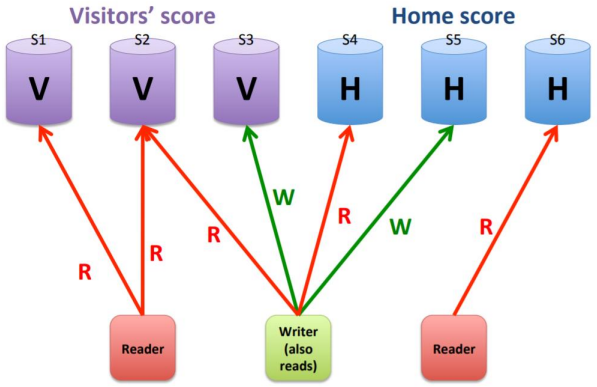


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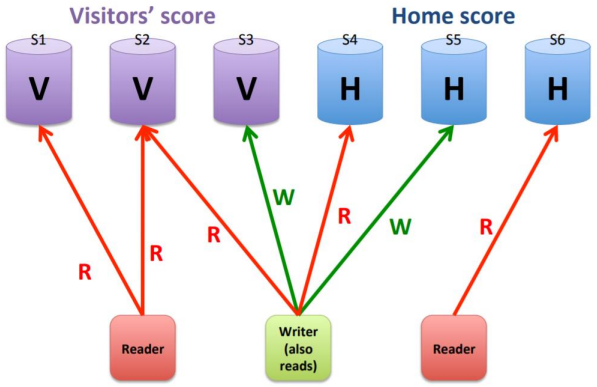


```
While not end of game {
    drink beer;
    smoke cigar;
}
go out to dinner;
vScore = Read ("visitors");
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write article;
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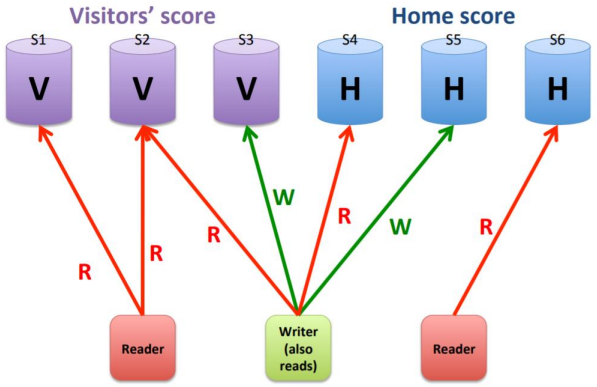


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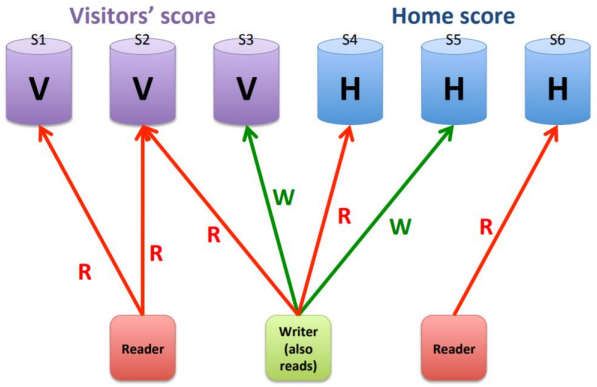


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Desired consistency?

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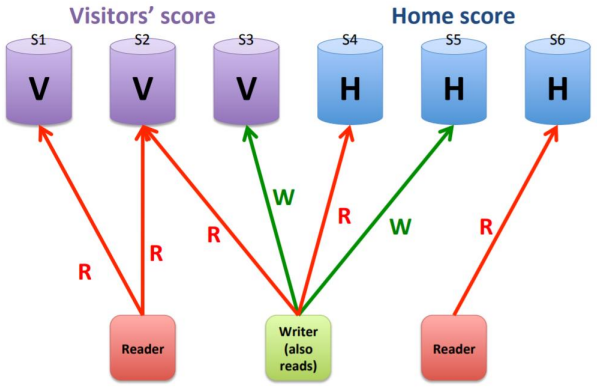


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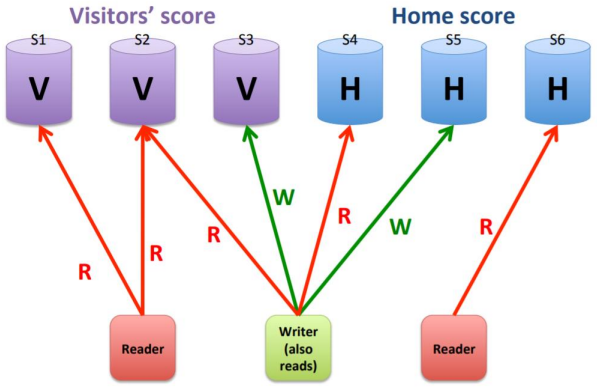

Wait for end of game;

score = **Read** ("home");

stat = **Read** ("season-goals");

Write ("season-goals", stat + score);

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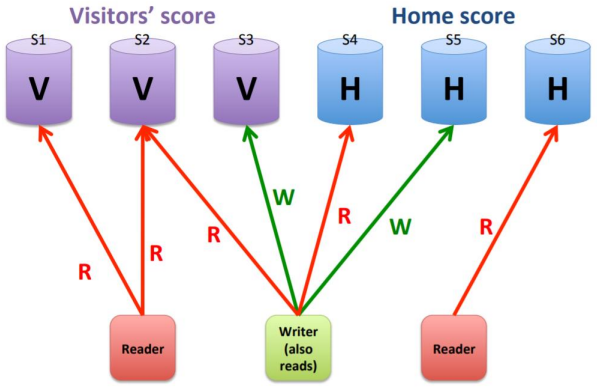

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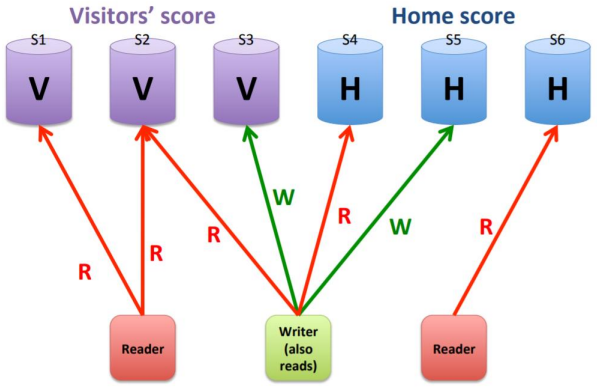

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Desired consistency?

Strong Consistency (1st read)

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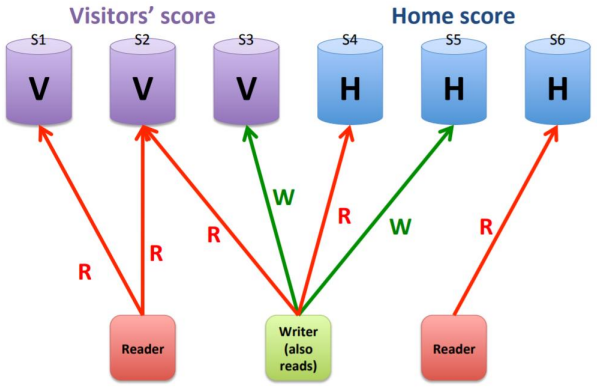

Wait for end of game;

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Write ("season-goals", stat + score);

Desired consistency?

Strong Consistency (1st read)

Read My Writes (2nd read)

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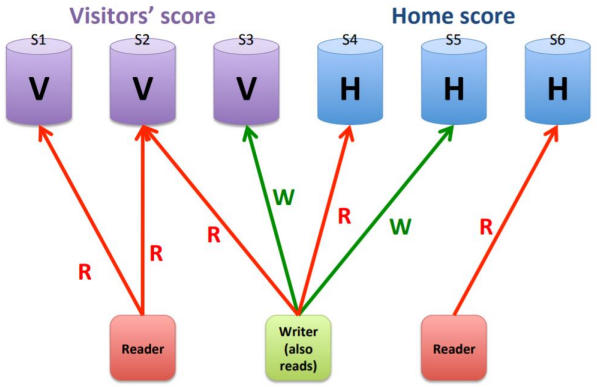
Stat Watcher




```
do {
    stat = Read ("season-goals");
    discuss stats with friends;
    sleep (1 day);
}
```

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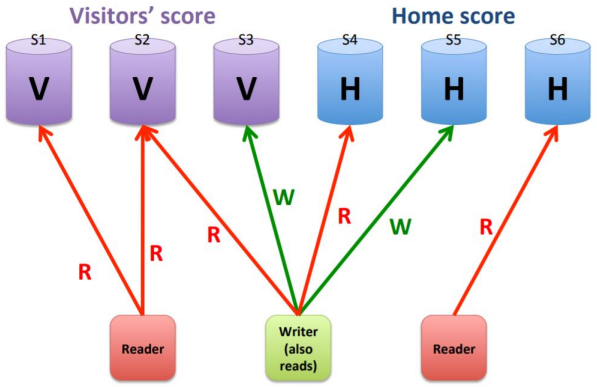


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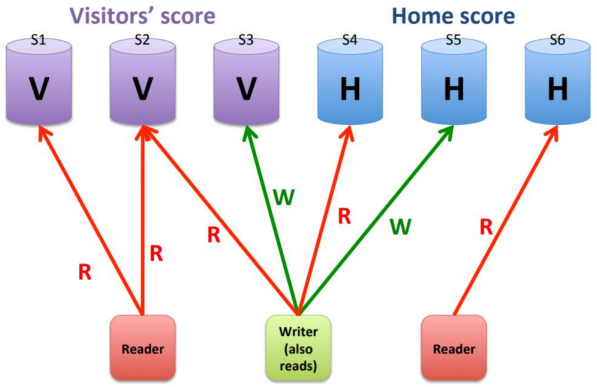


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Stat watcher:
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Sequential Consistency

- weaker than strict/strong consistency
  - All operations are executed in *some* sequential order
  - each process issues operations in program order
    - Any valid interleaving is allowed
    - All agree on the same interleaving
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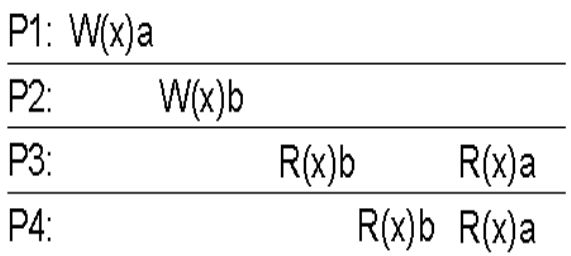
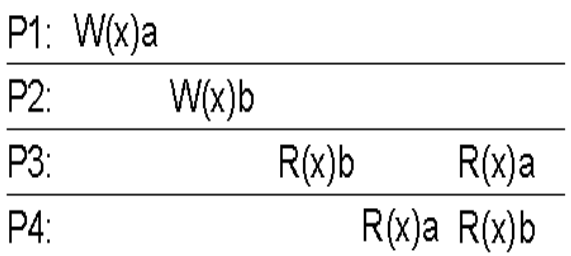


(a)



(b)

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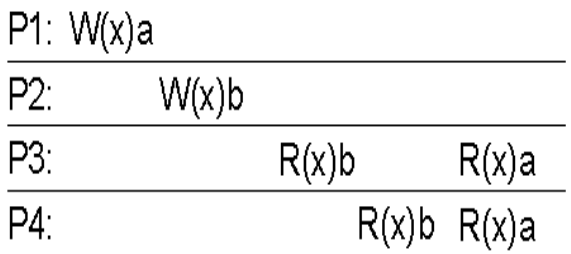

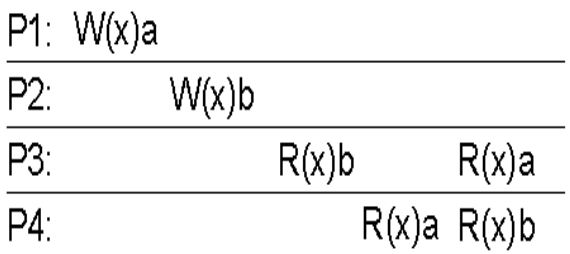

(b)

- ***Why is this weaker than strict/strong?***

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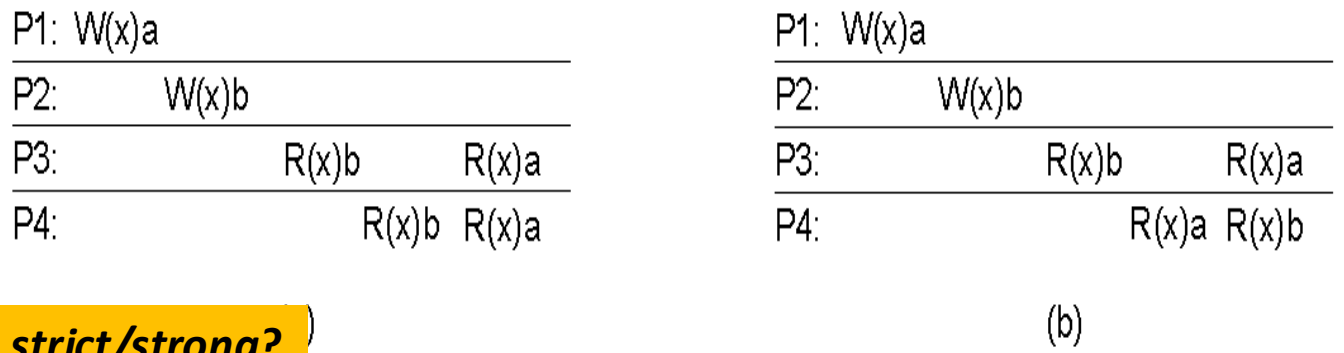

- ***Why is this weaker than strict/strong?***
- ***Nothing is said about "most recent write"***

Linearizability

Linearizability

- Assumes sequential consistency *and*
  - If TS(x) < TS(y) then OP(x) should precede OP(y) in the sequence
  - Stronger than sequential consistency
  - Difference between linearizability and serializability?
    - Granularity: reads/writes versus transactions

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  - Difference between linearizability and serializability?
    - Granularity: reads/writes versus transactions
- Example:
  - Stay tuned…relevant for lock free data structures
  - Importantly: *a property of concurrent objects*

Causal consistency

Causal consistency

- Causally related writes seen by all processes in same order.

Causal consistency

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  - *Causally?*

Causal consistency

- Causally related writes seen
  - *Causally?*

Causal:
If a write produces a value that
causes another write, they are causally related

```
X = 1
if(X > 0) {
   Y = 1
}
```

Causal consistency → all see X=1, Y=1 in same order

Causal consistency

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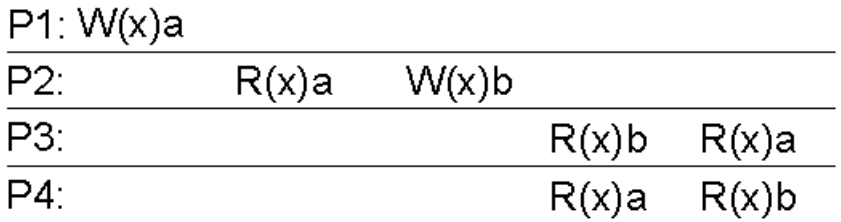

(a)

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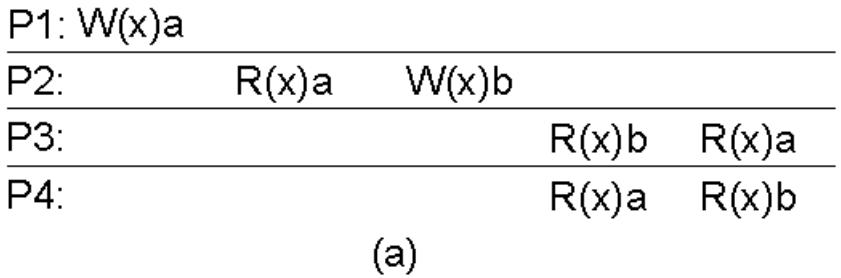

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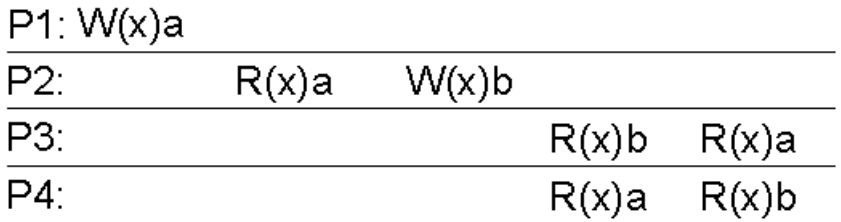

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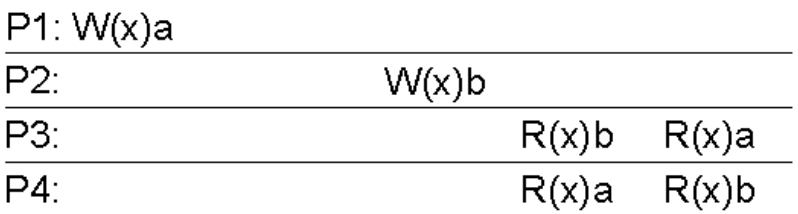

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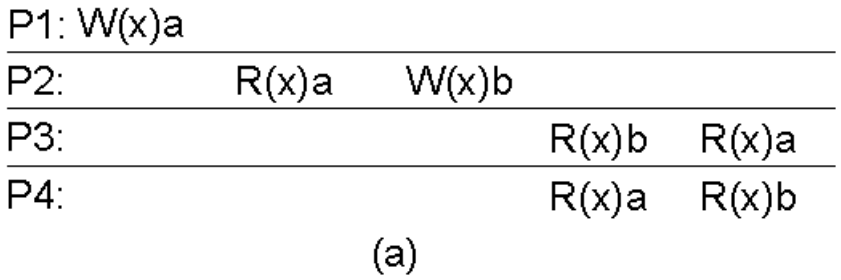
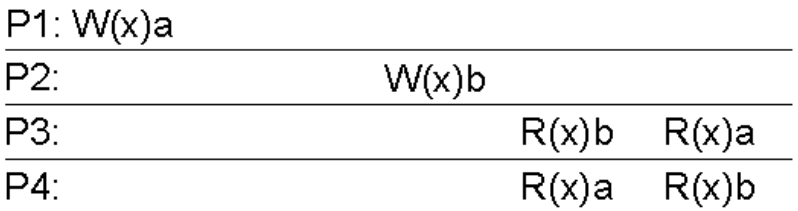
  - *Causally?*
  - *Concurrent* writes may be seen in different orders on different machines



(a)

Not permitted



(b)

Permitted

Consistency models summary

Consistency models summary

Consistency	Description
Strict	Absolute time ordering of all shared accesses matters.
Linearizability	All processes must see all shared accesses in the same order. Accesses are furthermore ordered according to a (nonunique) global timestamp
Sequential	All processes see all shared accesses in the same order. Accesses are not ordered in time
Causal	All processes see causally-related shared accesses in the same order.
FIFO	All processes see writes from each other in the order they were used. Writes from different processes may not always be seen in that order

(a)

Consistency	Description
Weak	Shared data can be counted on to be consistent only after a synchronization is done
Release	Shared data are made consistent when a critical region is exited
Entry	Shared data pertaining to a critical region are made consistent when a critical region is entered.

(b)