Programming at Fast Scale: Consistency + Lock Freedom

cs378h

Today

Questions?

Administrivia

- Project Proposal Due Today!

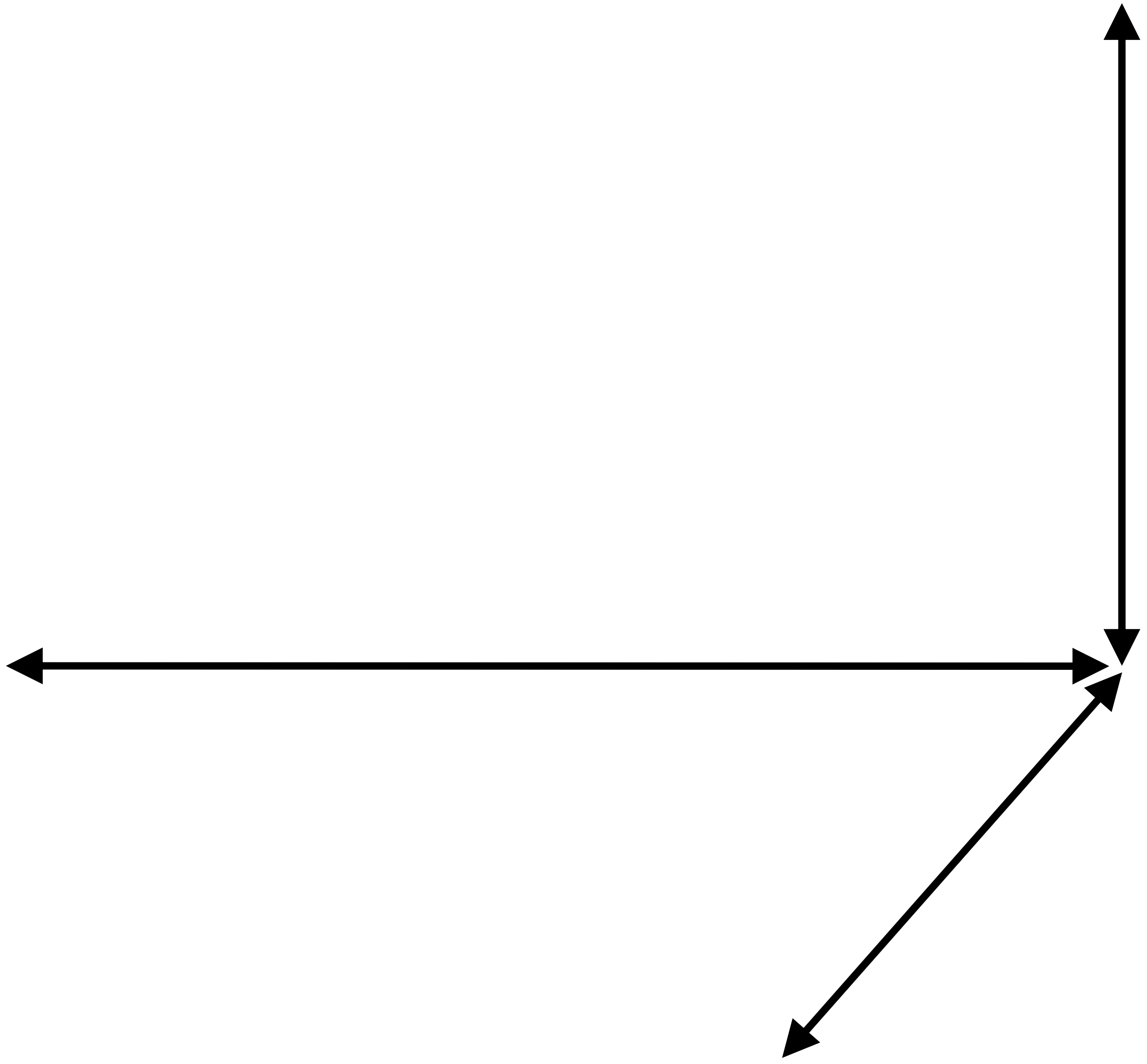
Agenda:

- Consistency
- Lock Freedom

Faux Quiz Questions

- What is the CAP theorem? What does "PACELP" stand for and how does it relate to CAP?
- What is the difference between ACID and BASE?
- Why do NoSQL systems claim to be more horizontally scalable than RDMBSes? List some features NoSQL systems give up toward this goal?
- What is eventual consistency? Give a concrete example of how of why it causes a complex programming model (relative to a strongly consistent model).
- Compare and contrast Key-Value, Document, and Wide-column Stores
- Define and contrast the following consistency properties:
  - strong consistency, eventual consistency, consistent prefix, monotonic reads, read-my-writes, bounded staleness
- What is causal consistency?
- What is chain replication?
- What is obstruction freedom, wait freedom, lock freedom?
- How can one compose lock free data structures?
- Why should I want a lock free hash table instead of a fine-grain lock-based one?
- What is the difference between linearizability and strong consistency? Between linearizability and serializability?
- What is the ABA problem? Give an example.
- How do lock-free data structures deal with the "inconsistent view" problem?

Another Framework



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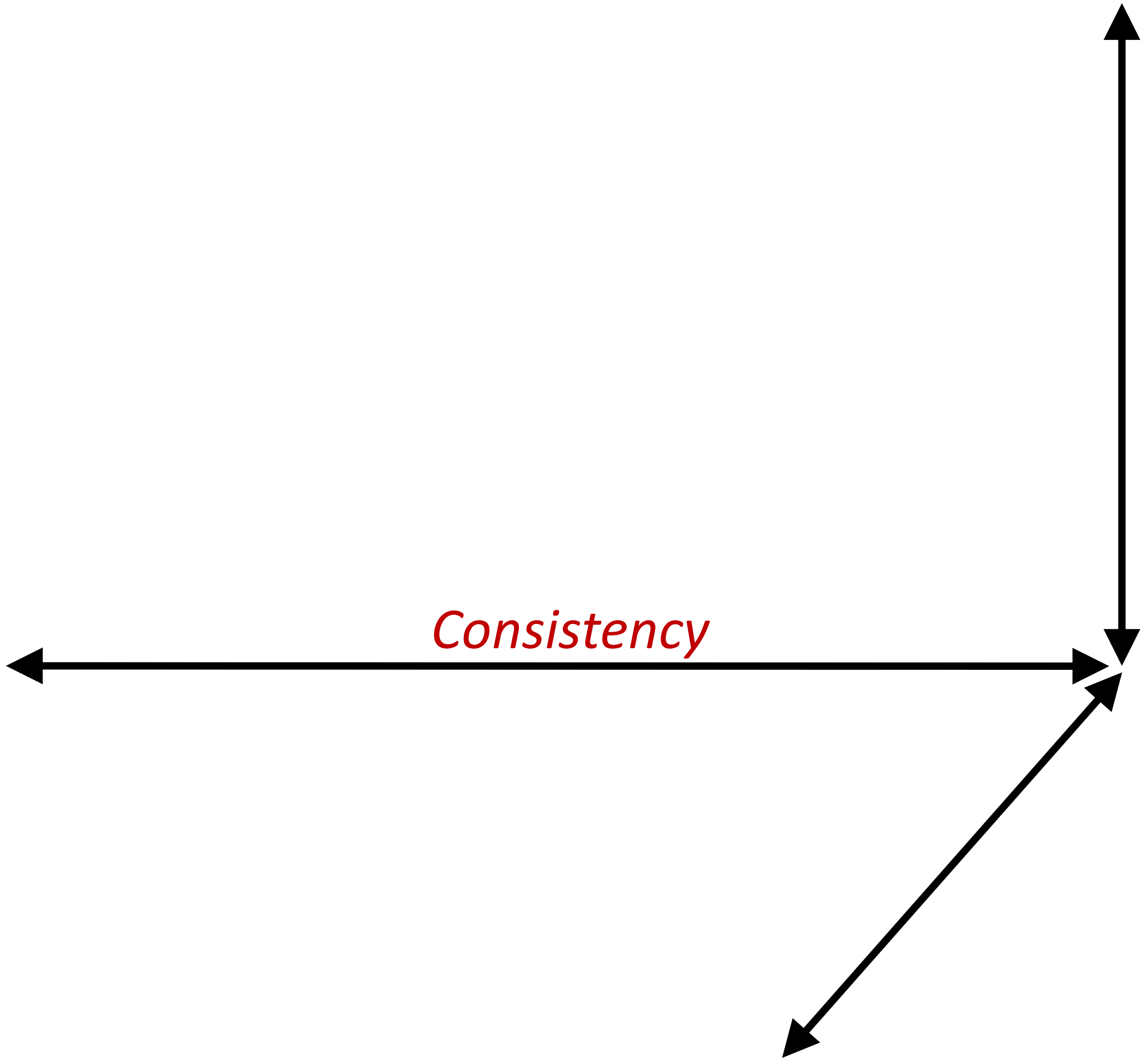

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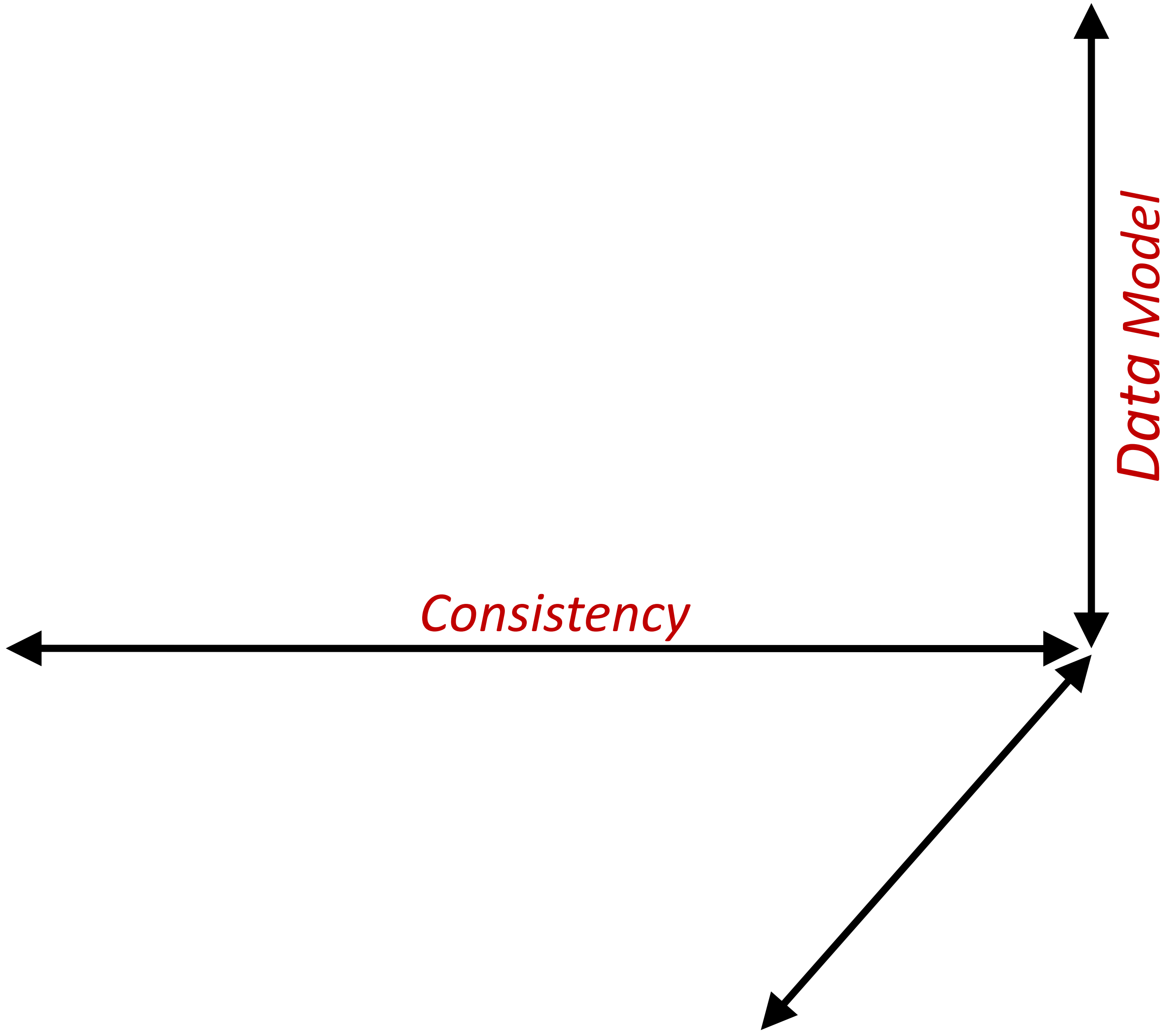

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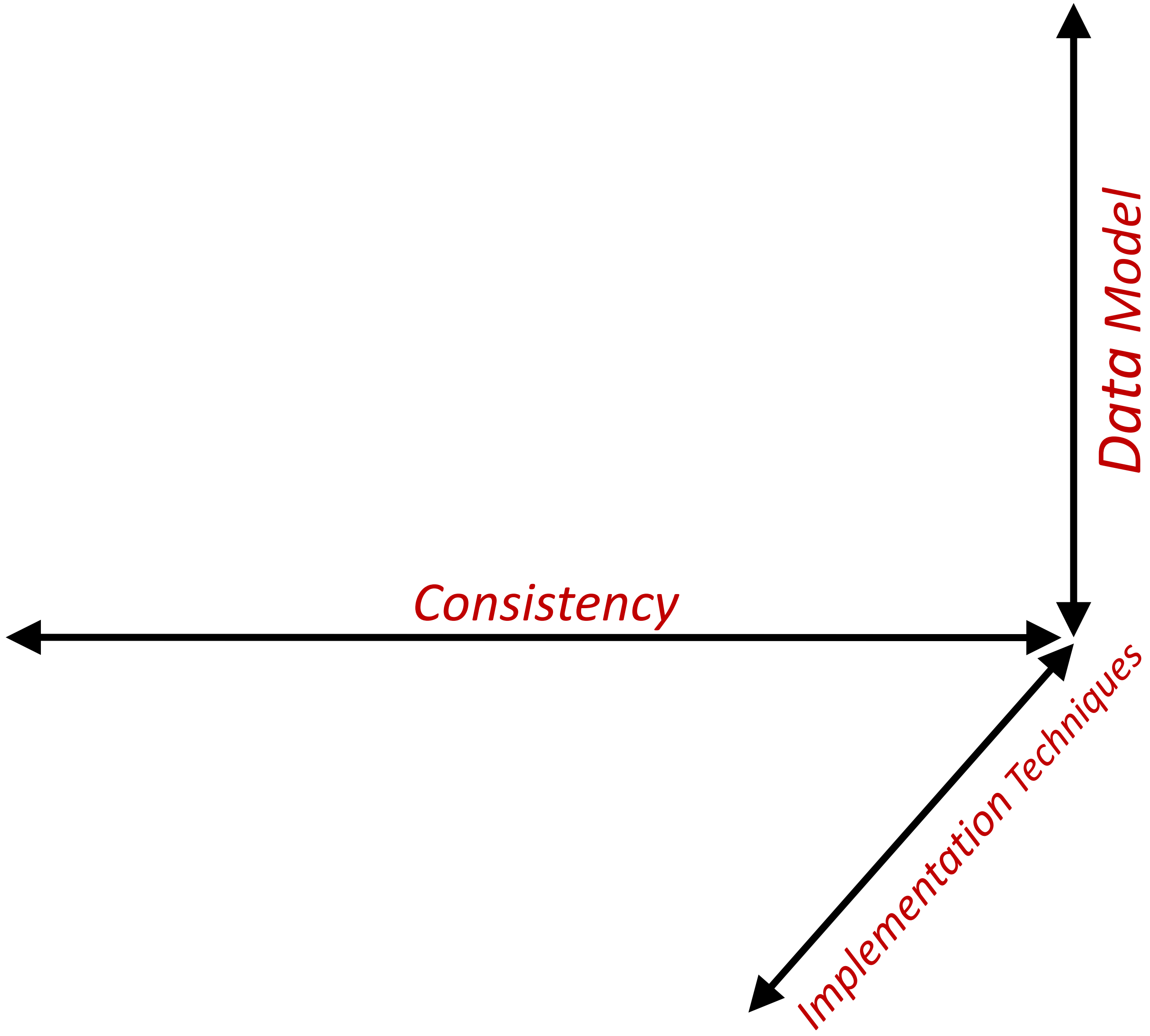

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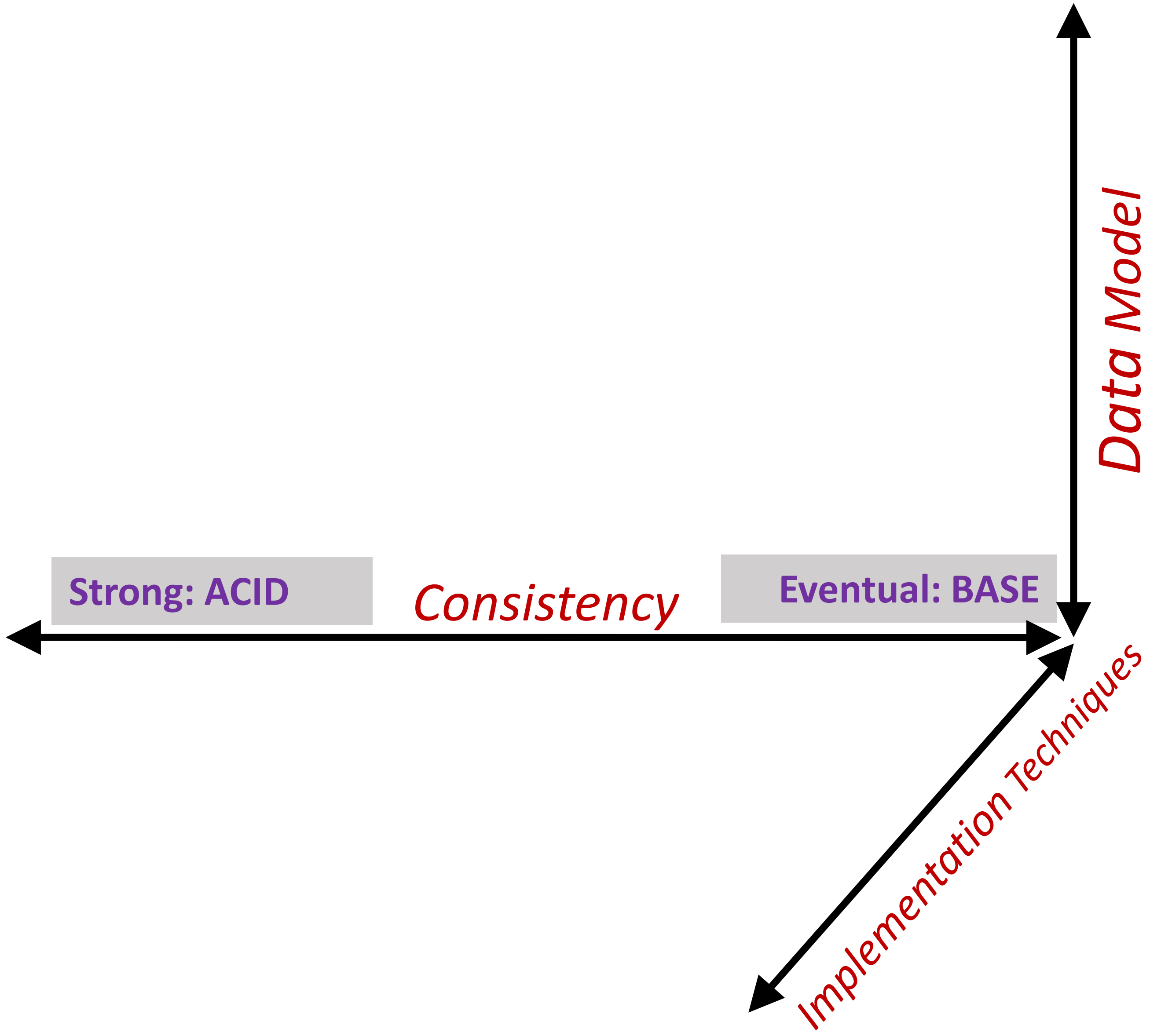

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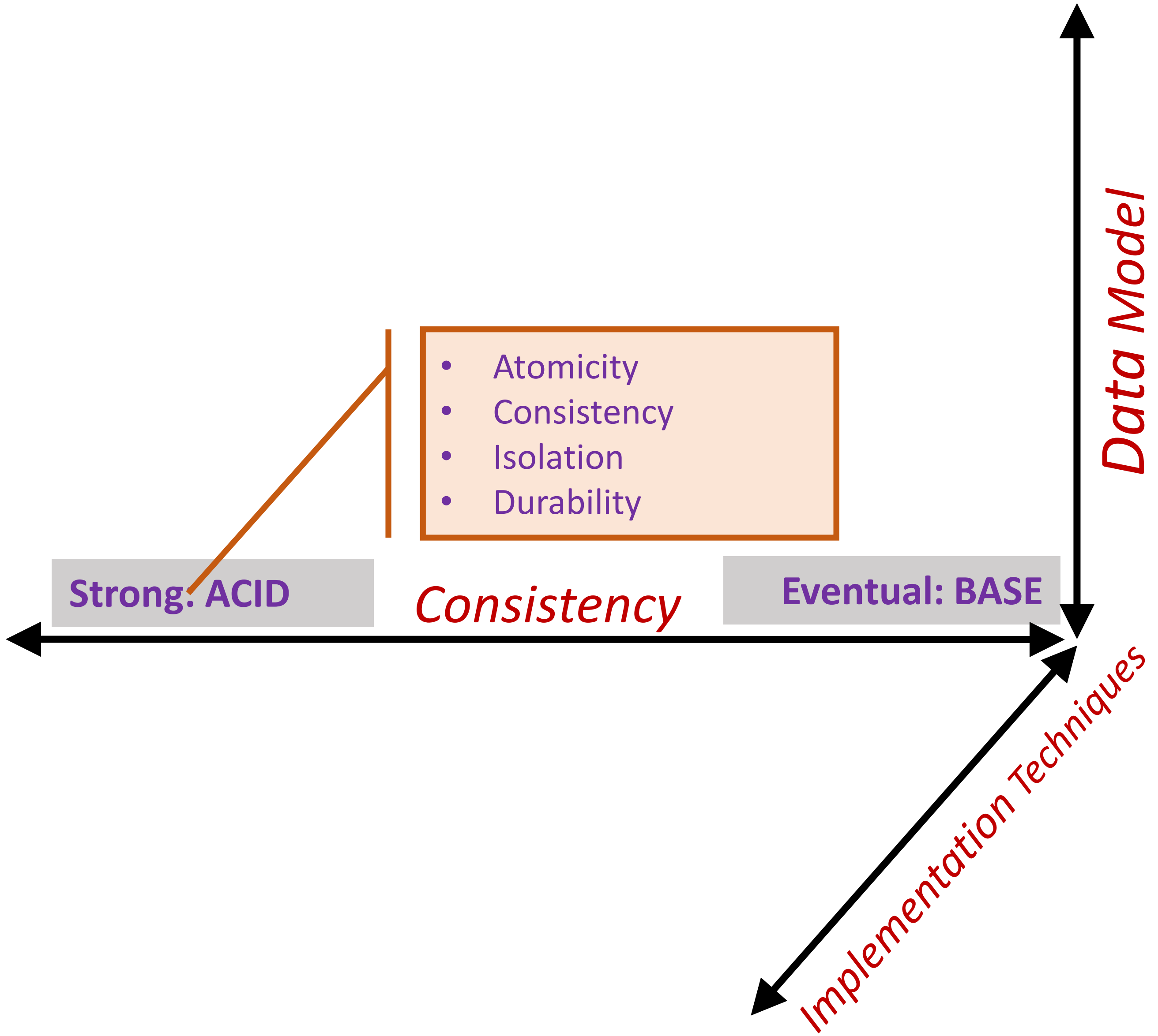

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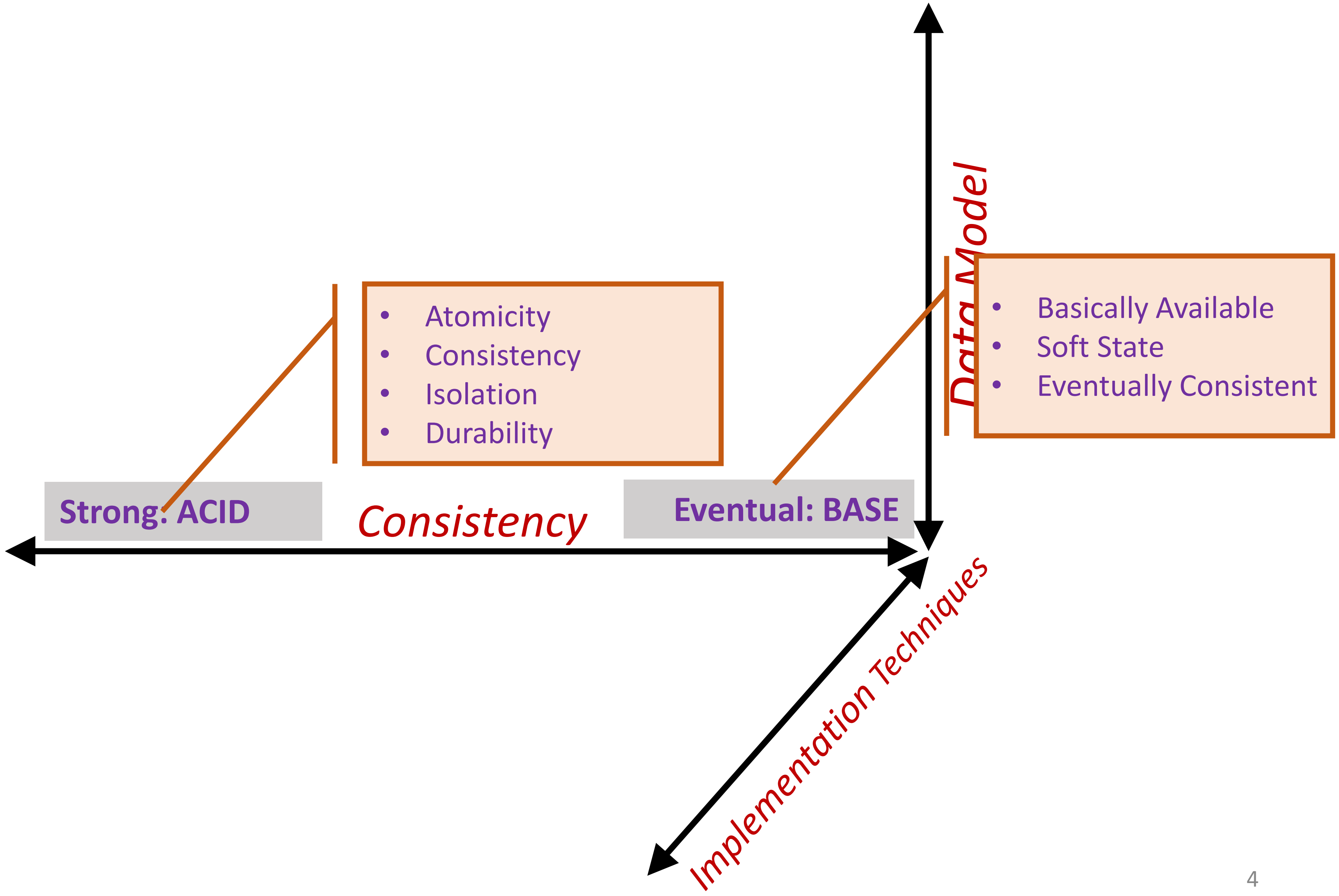

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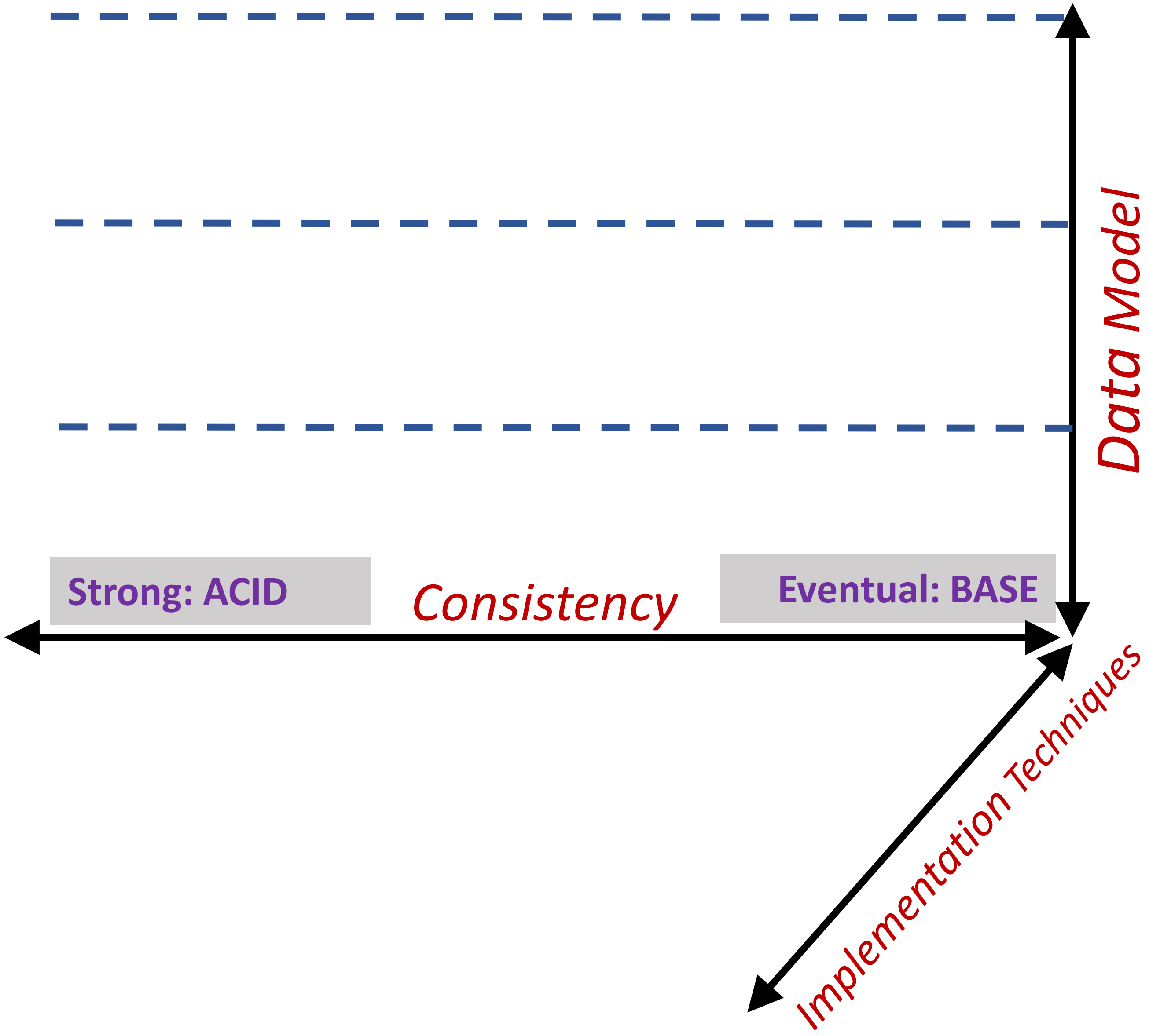

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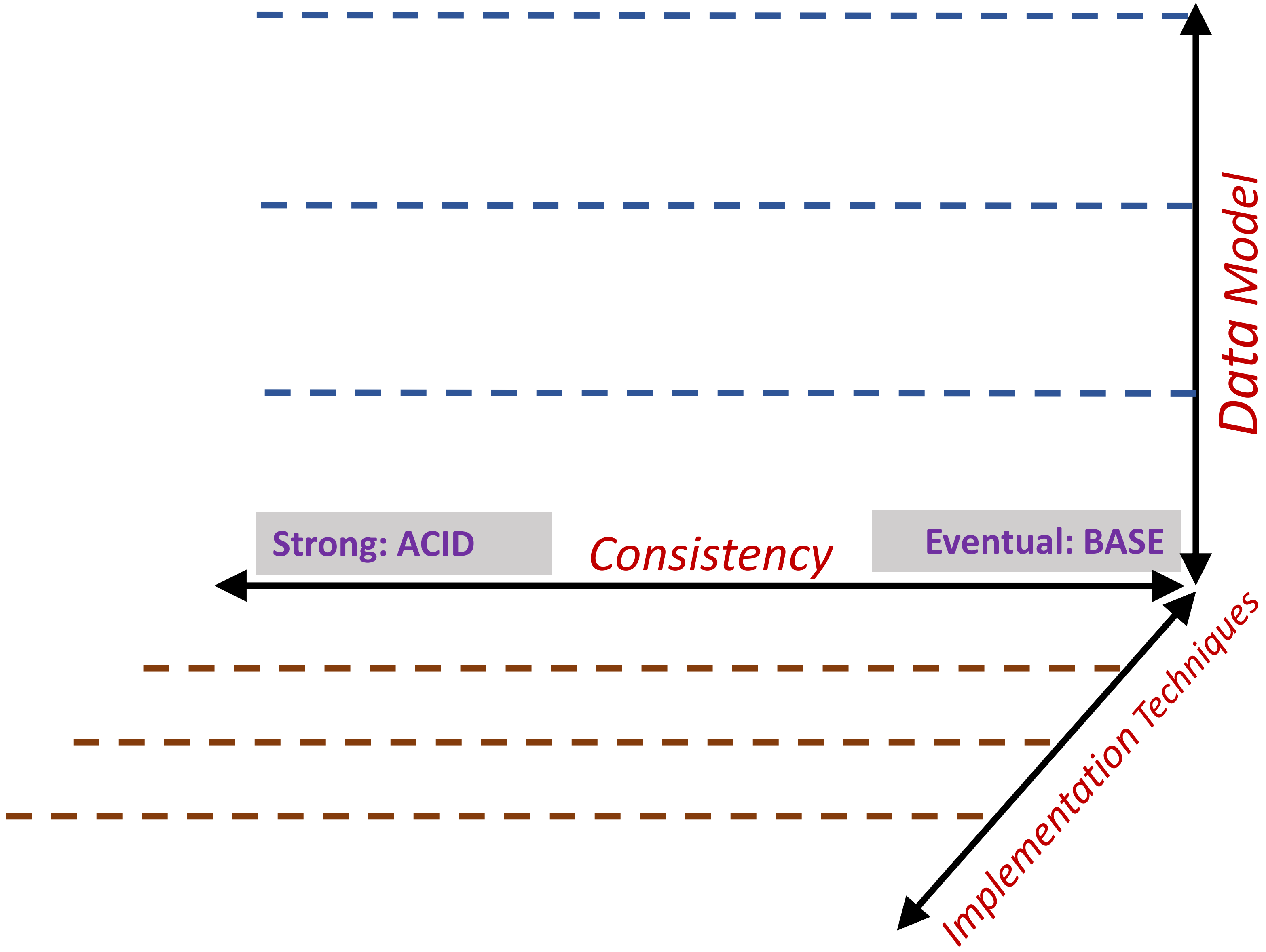

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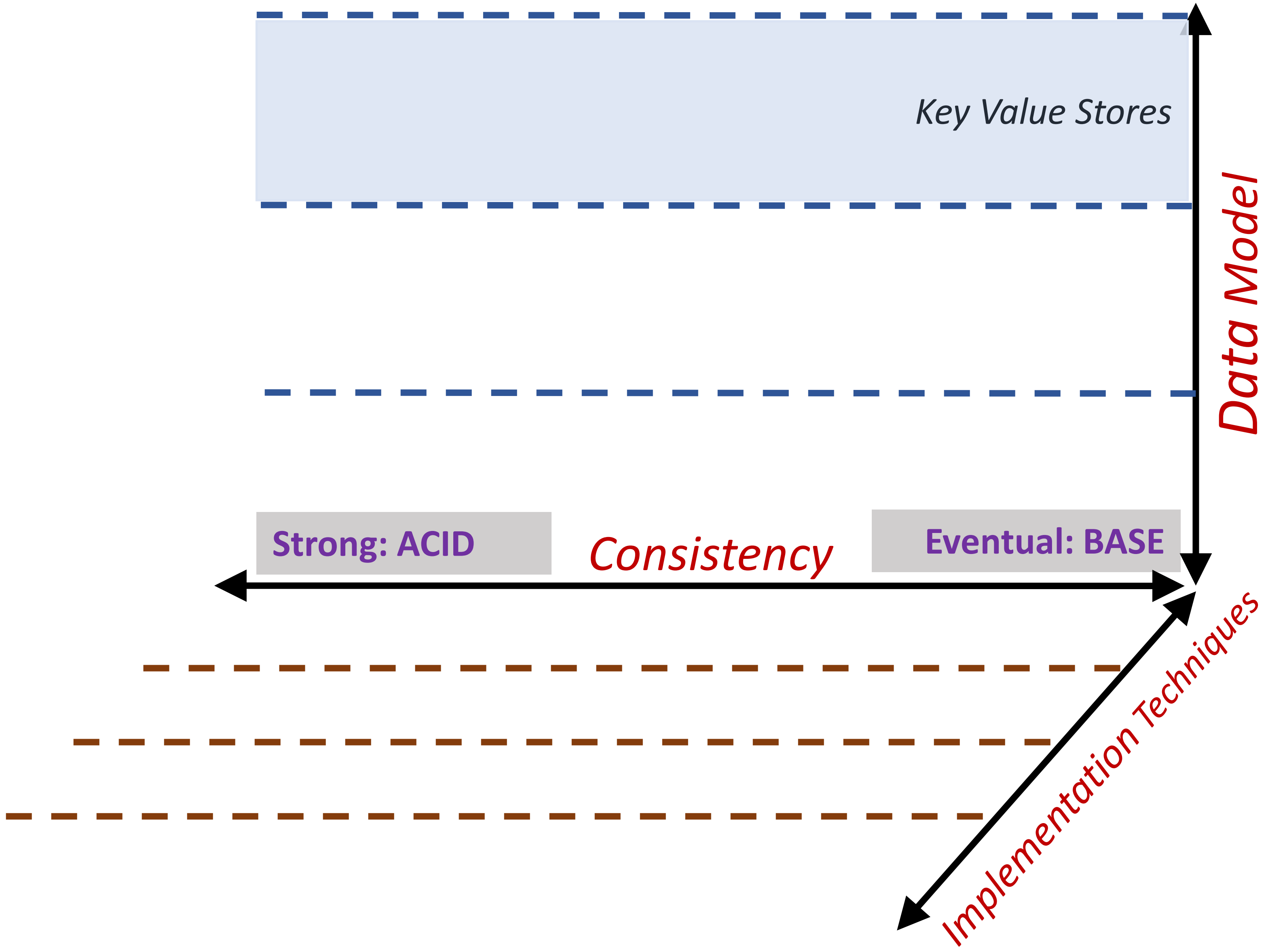

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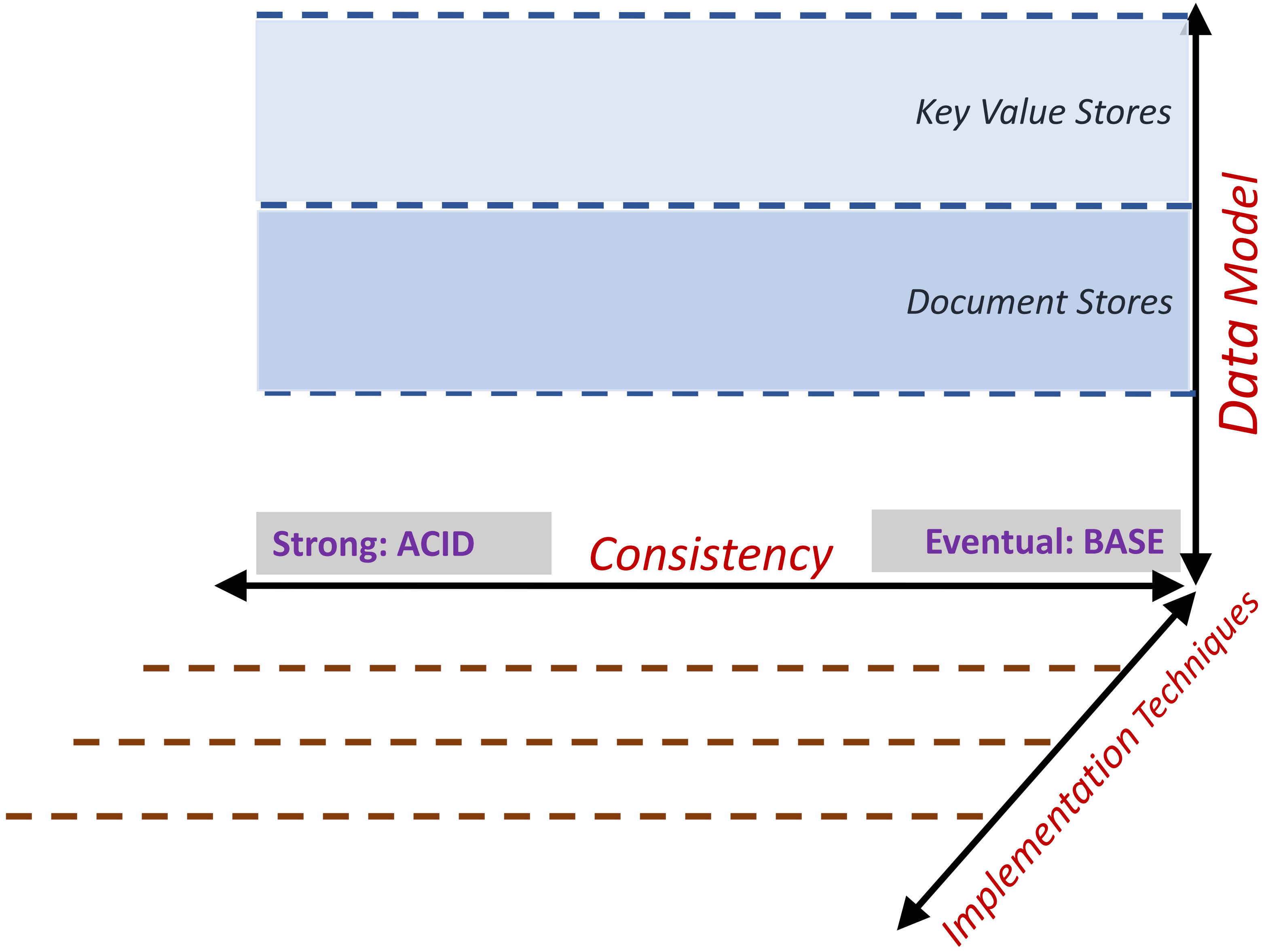

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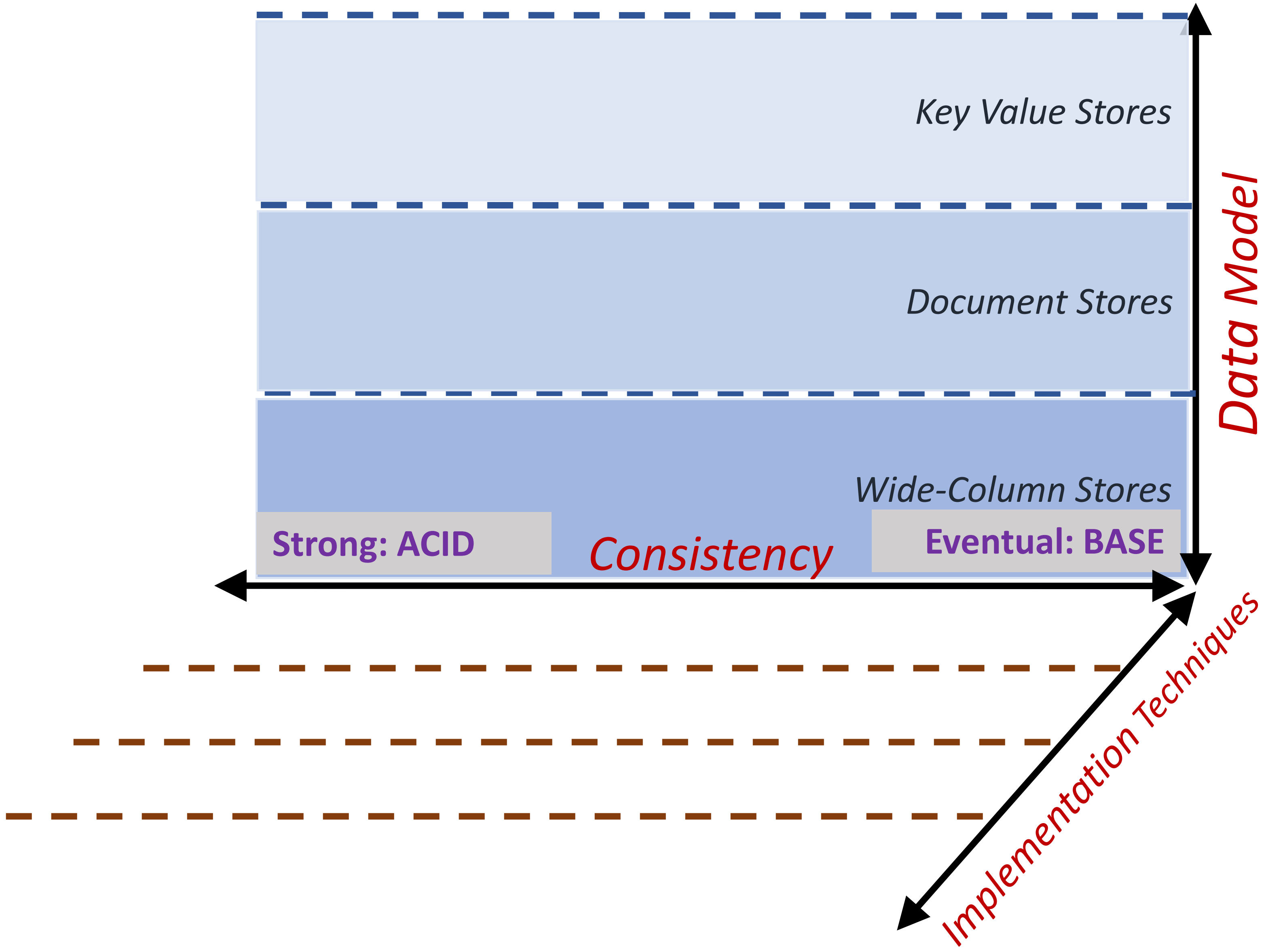

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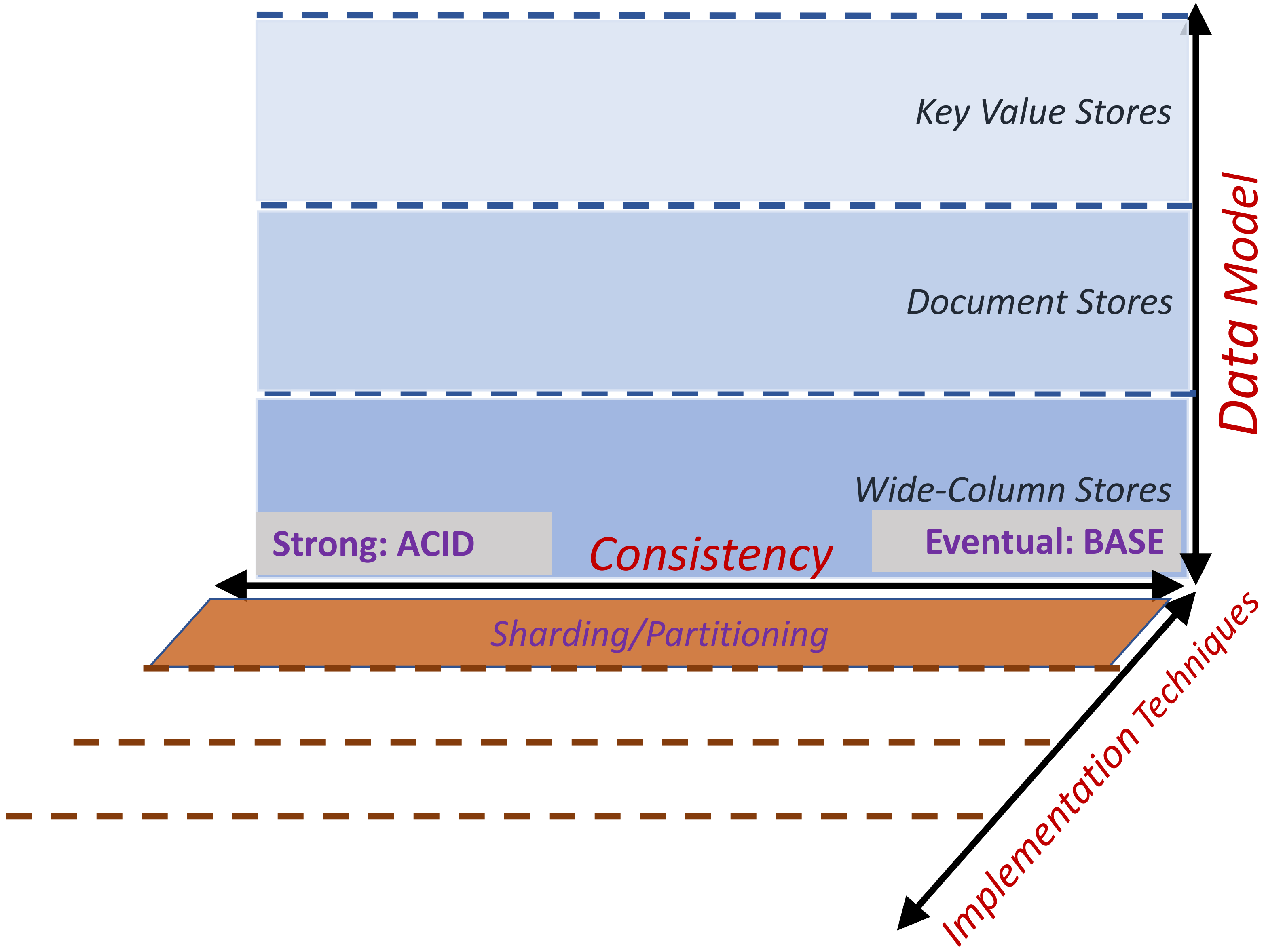

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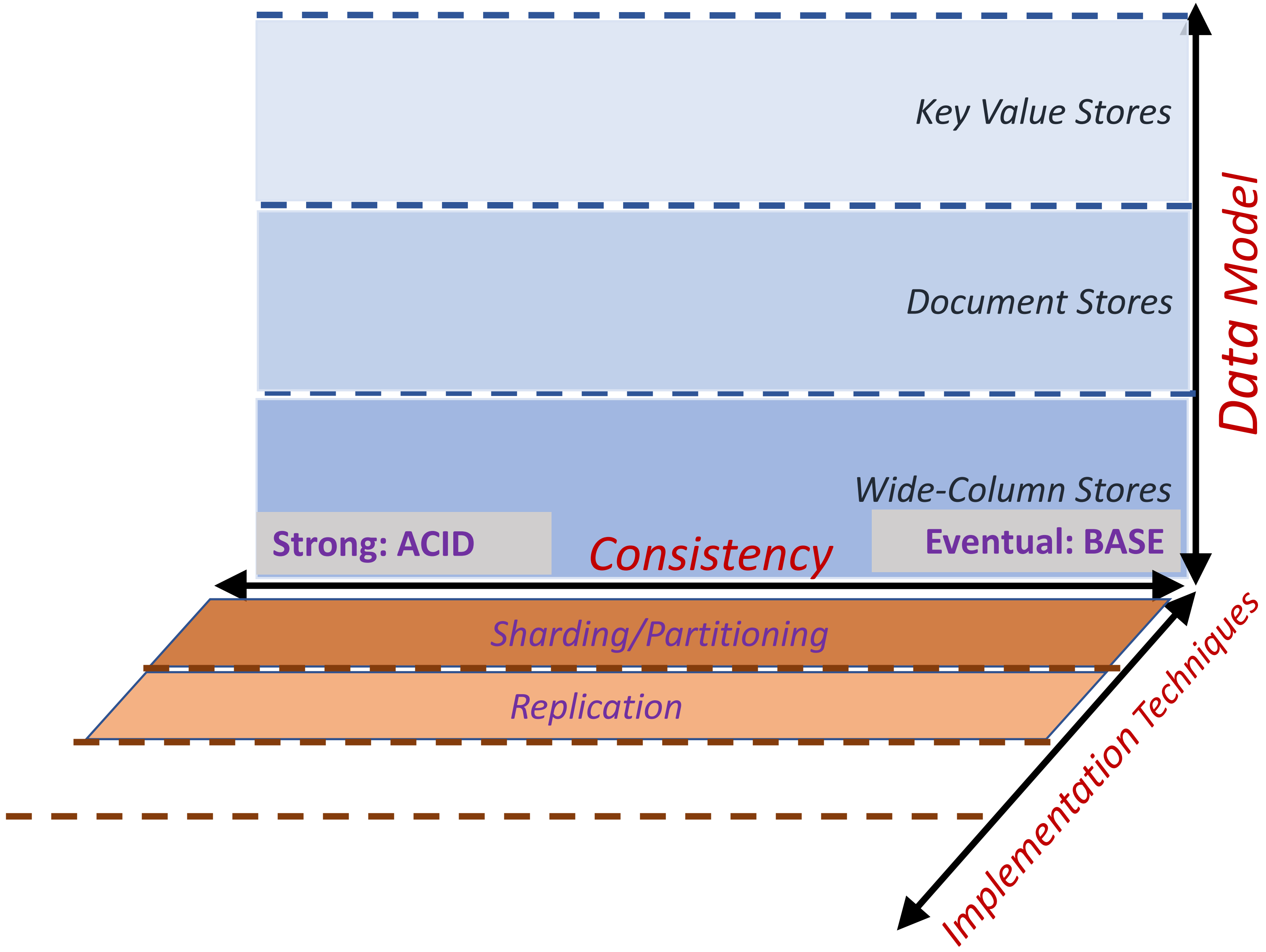

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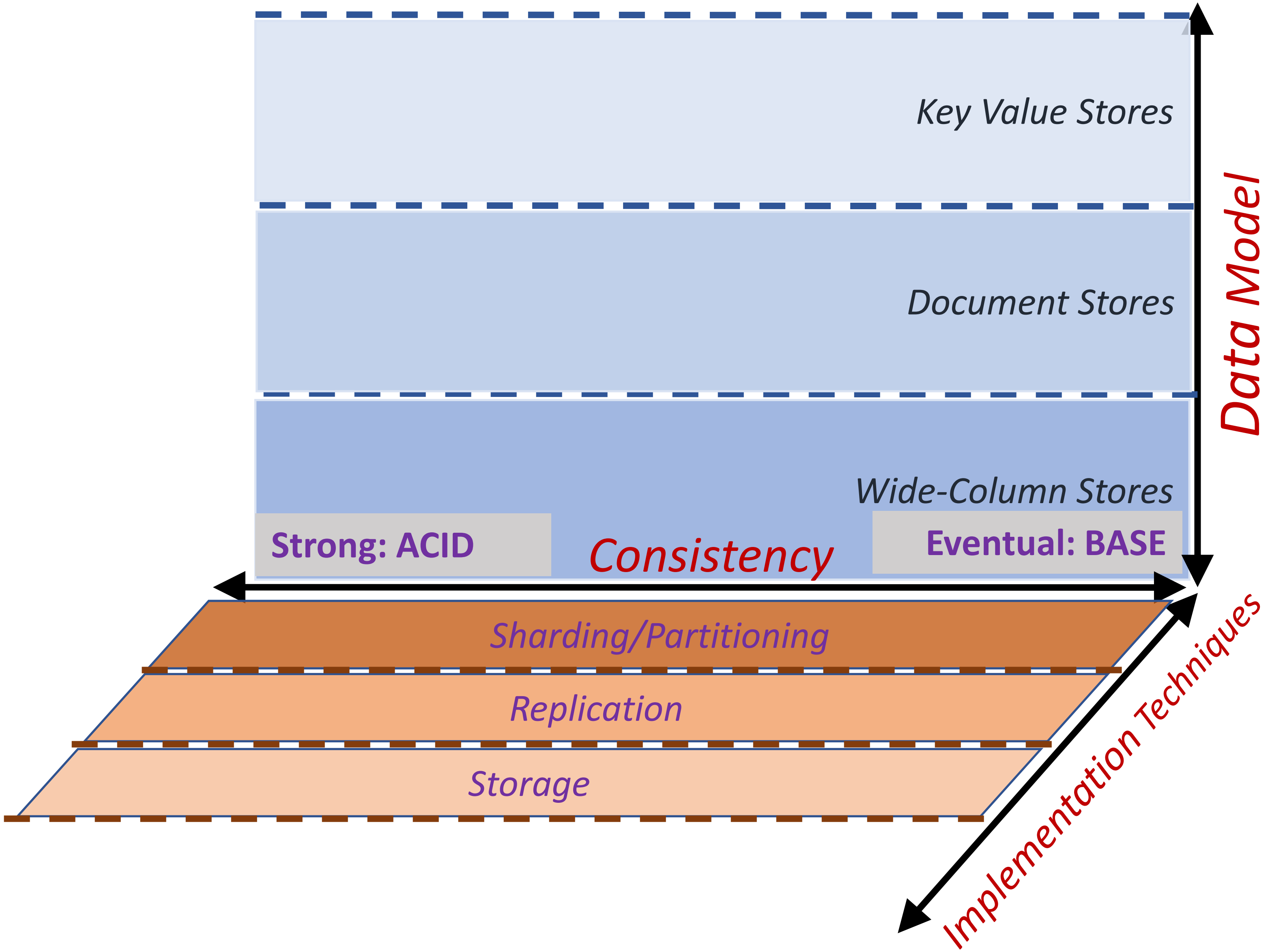

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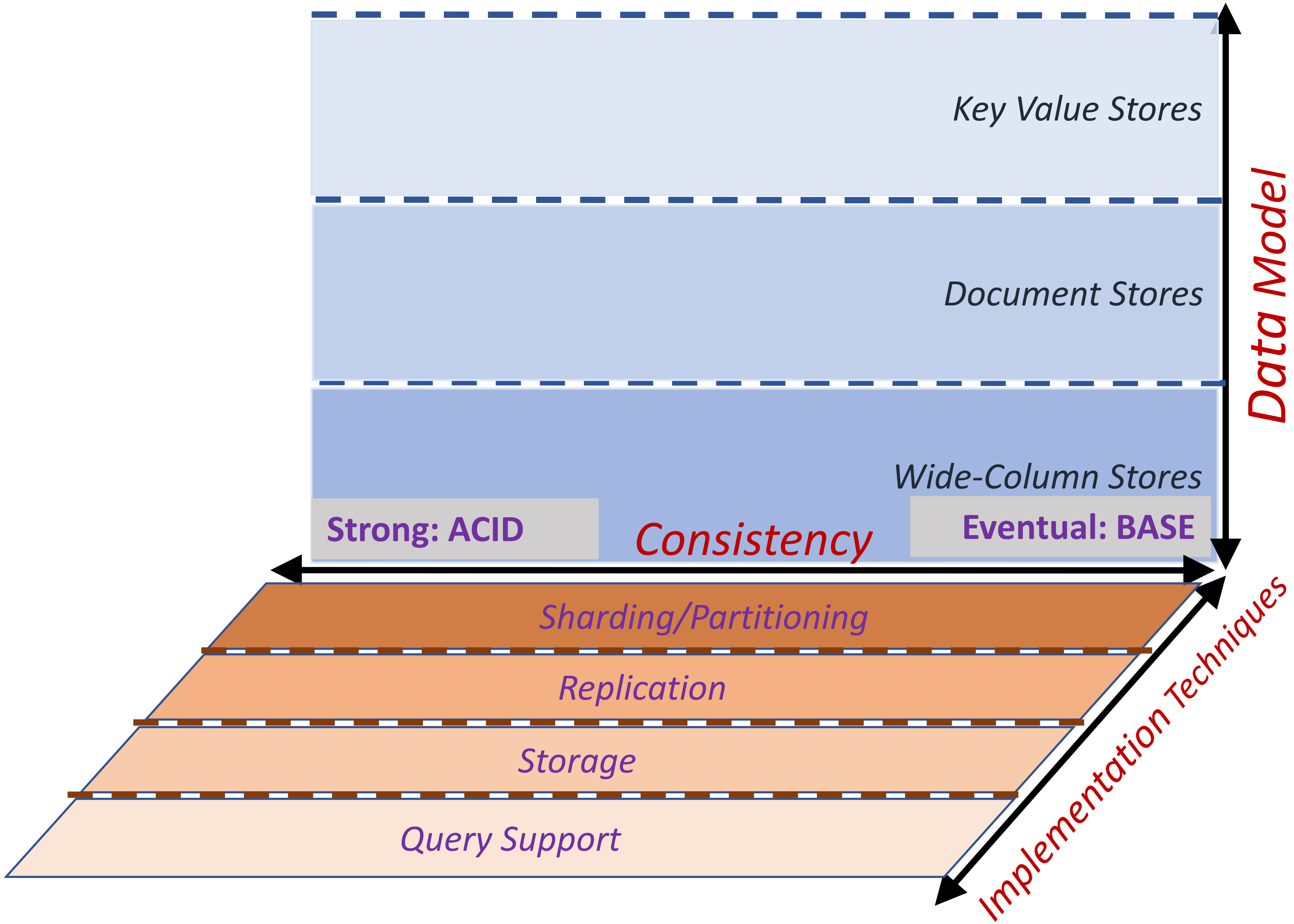

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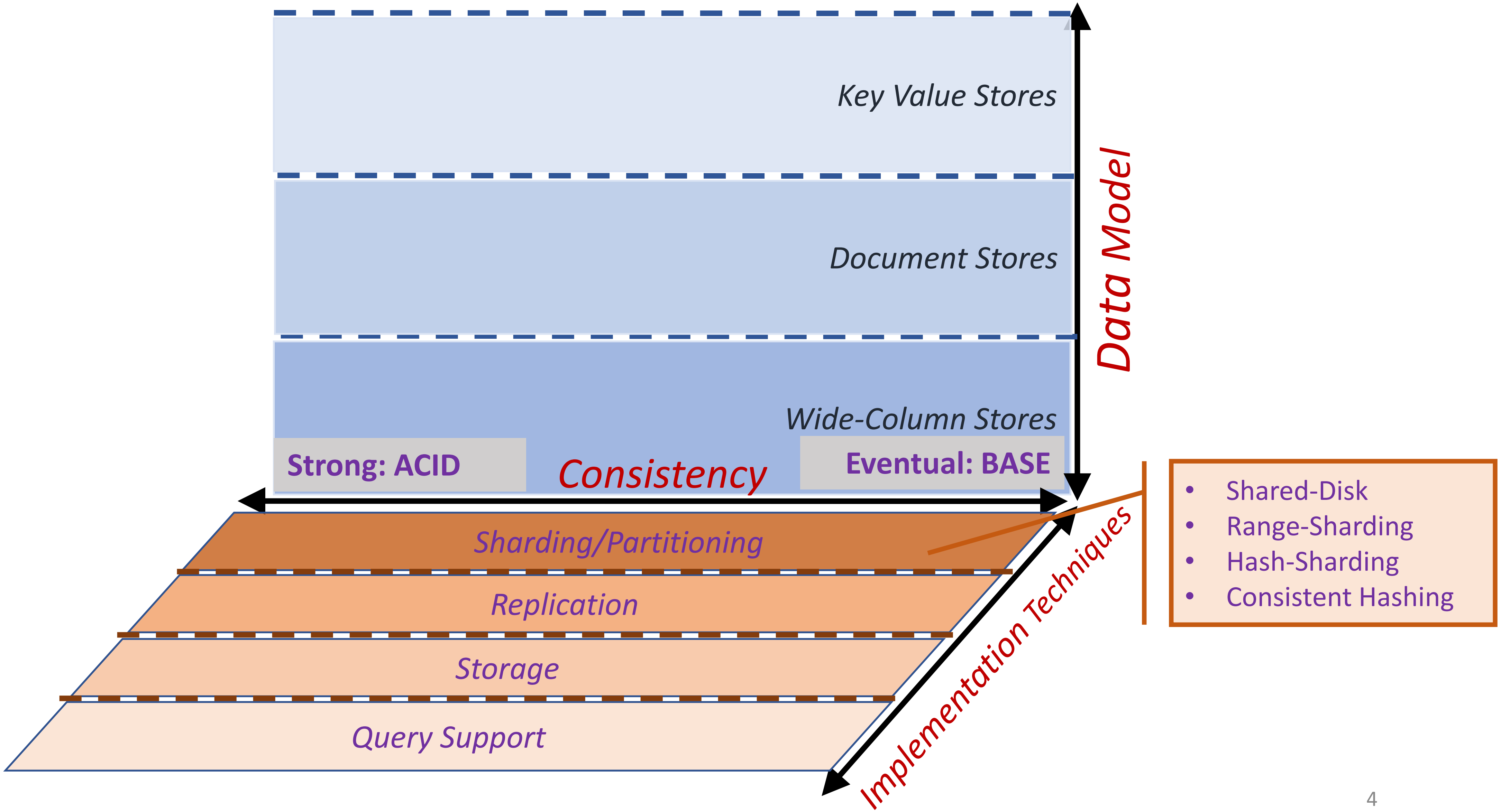

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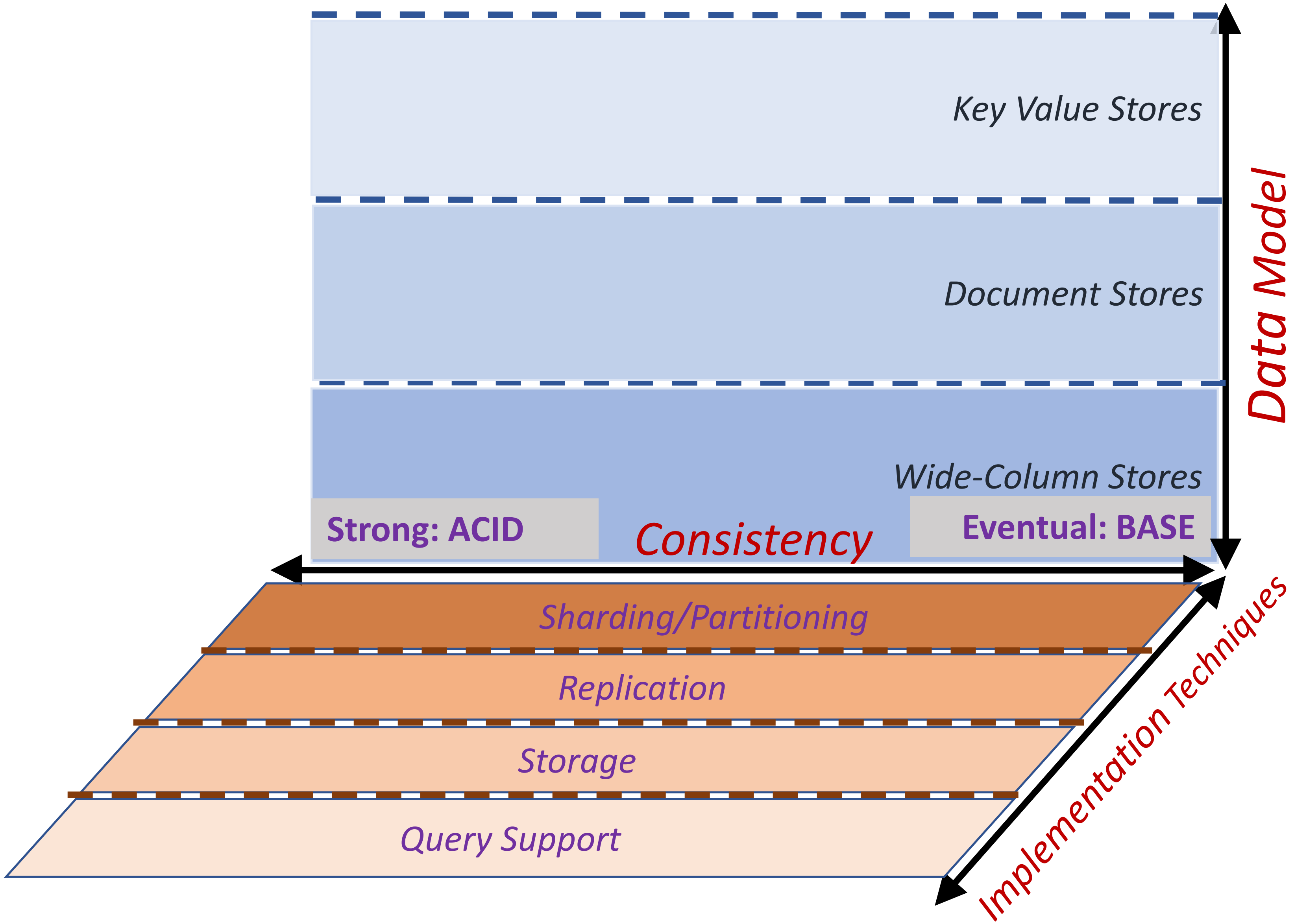

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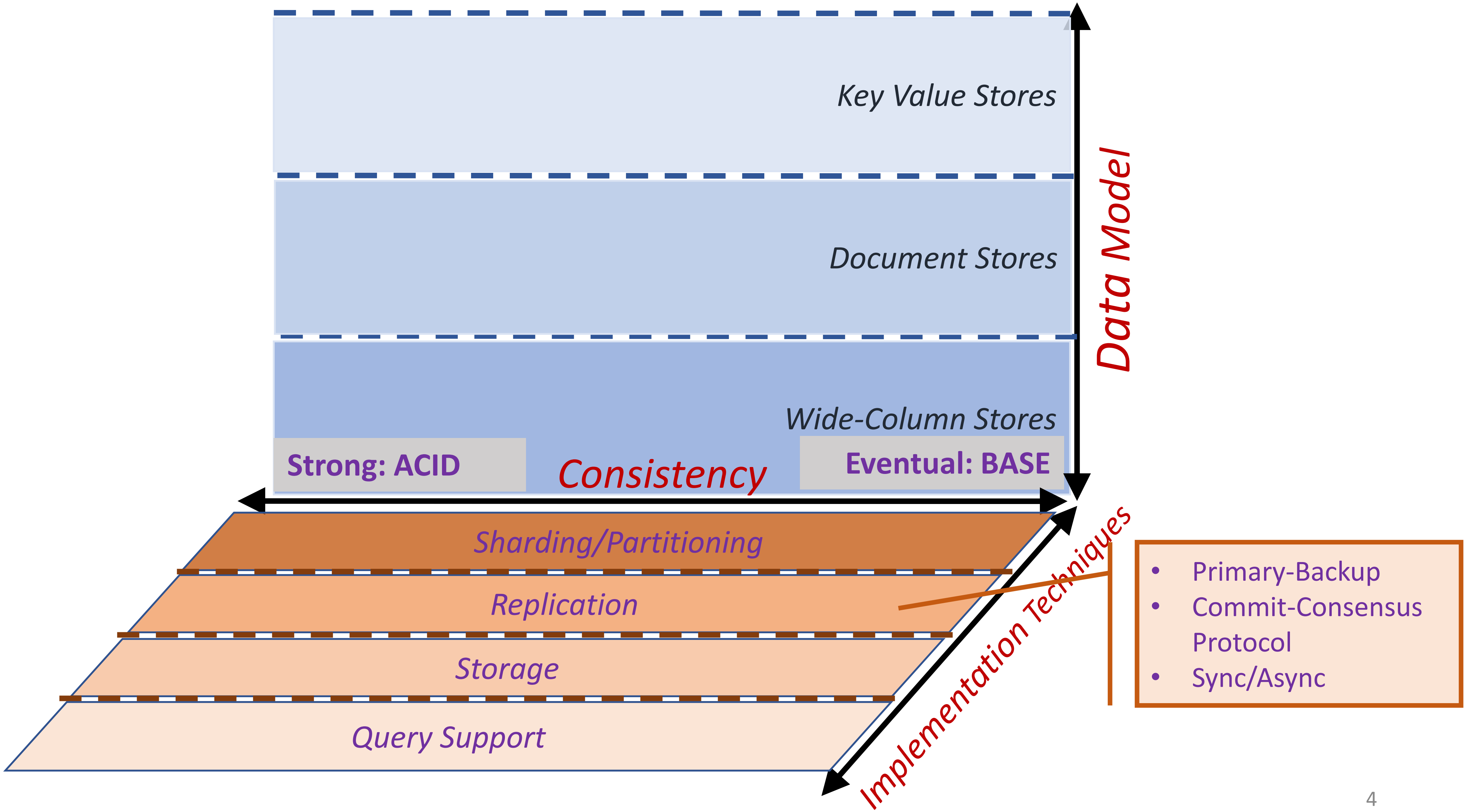

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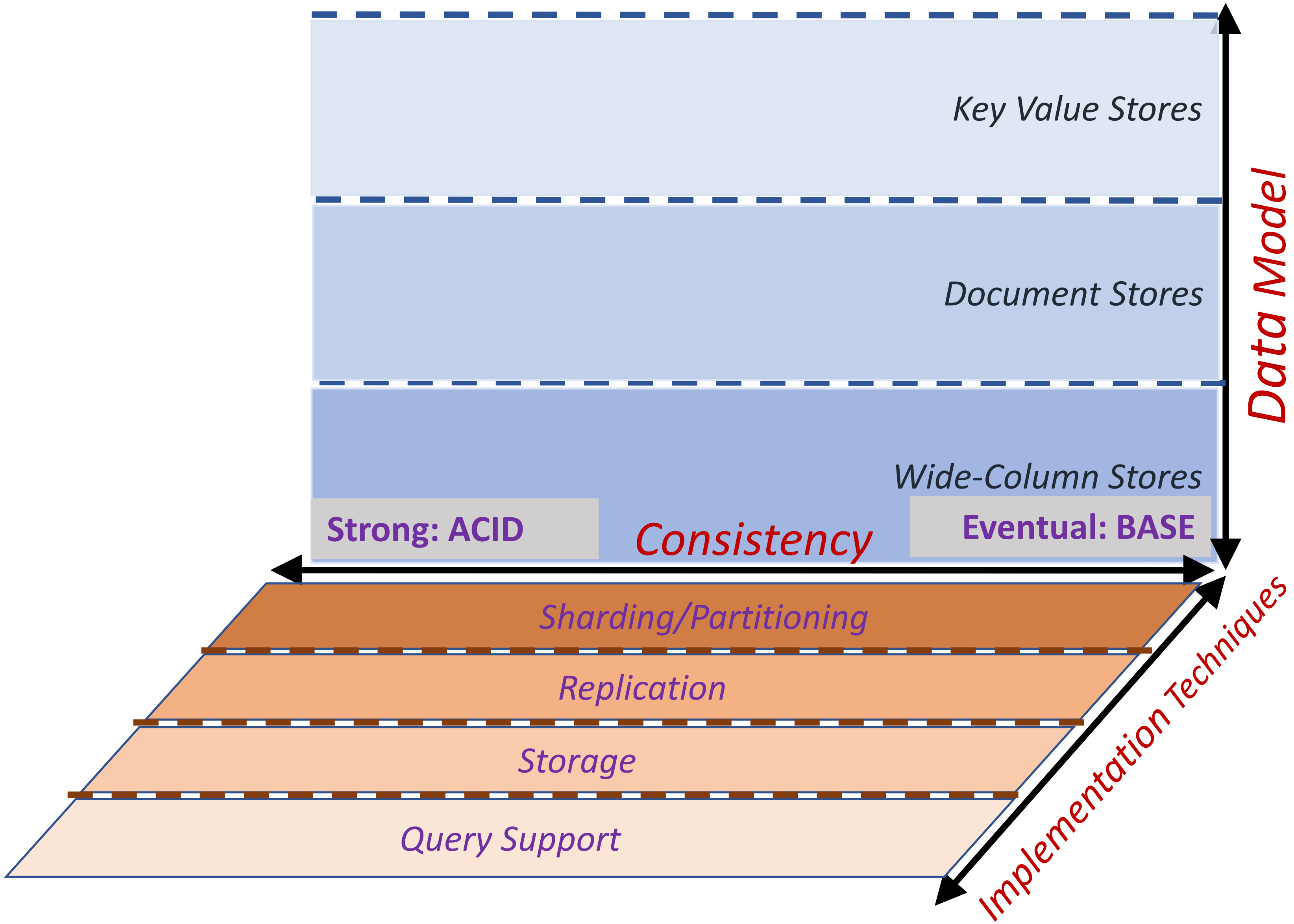

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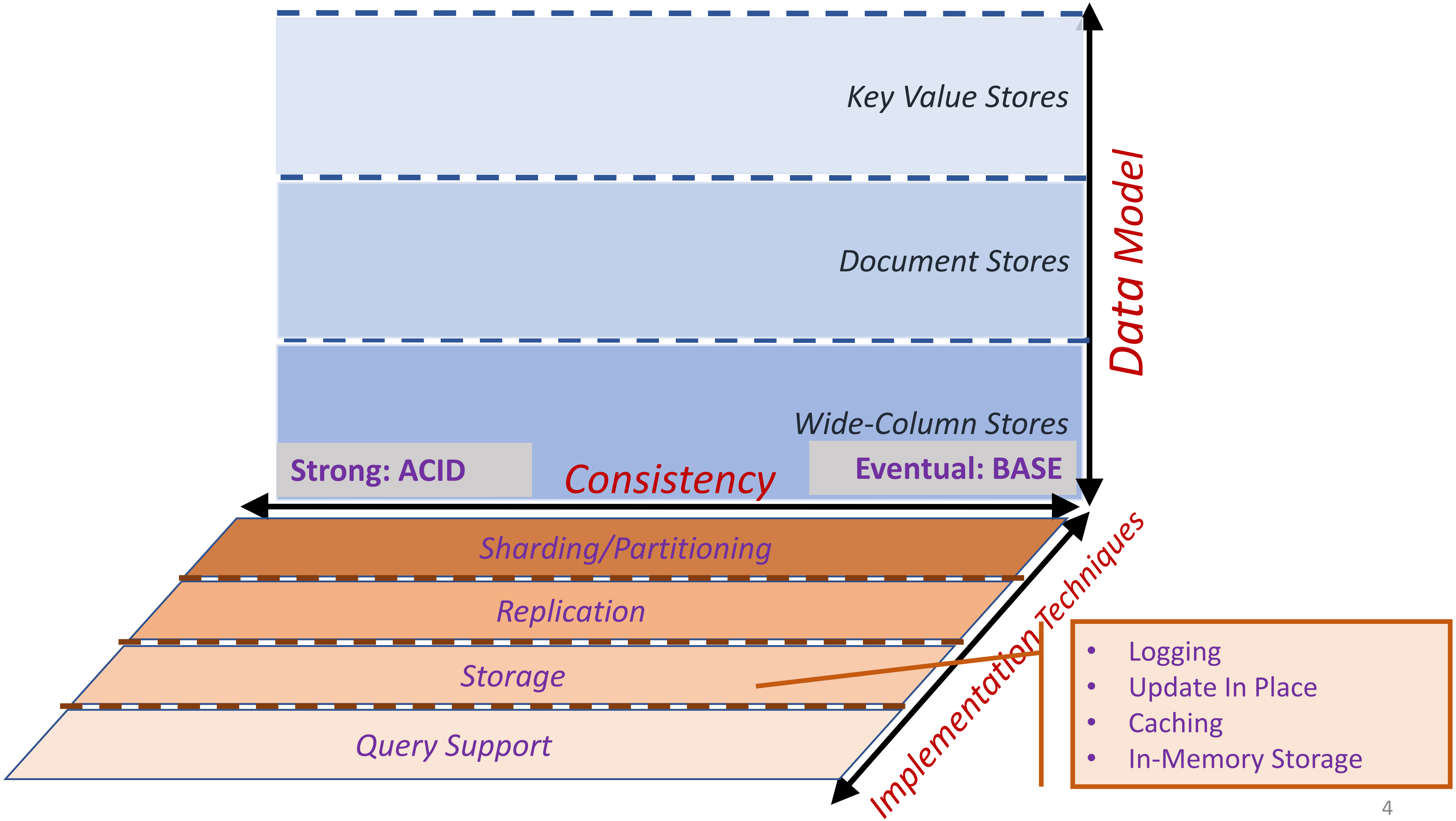

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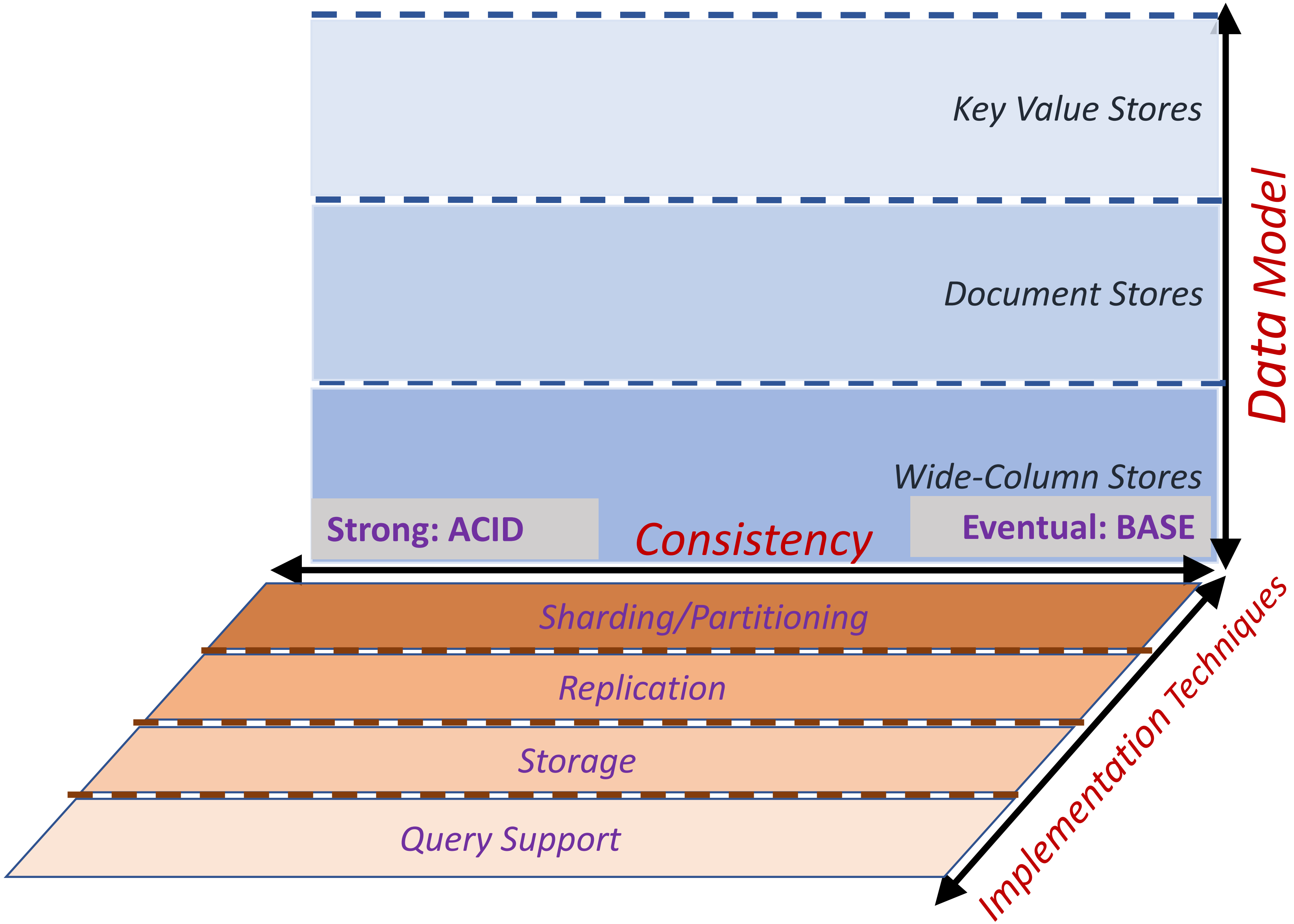

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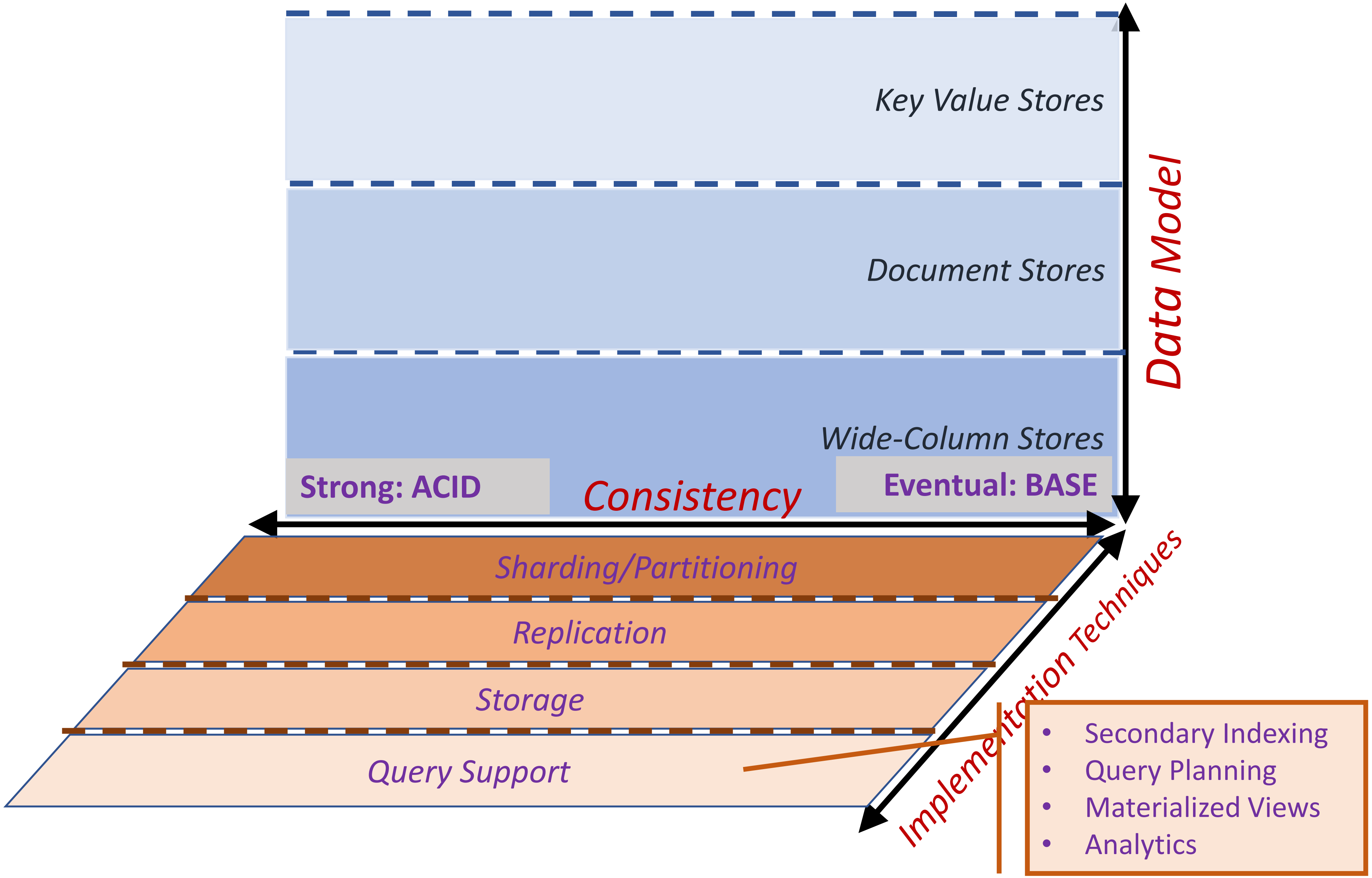

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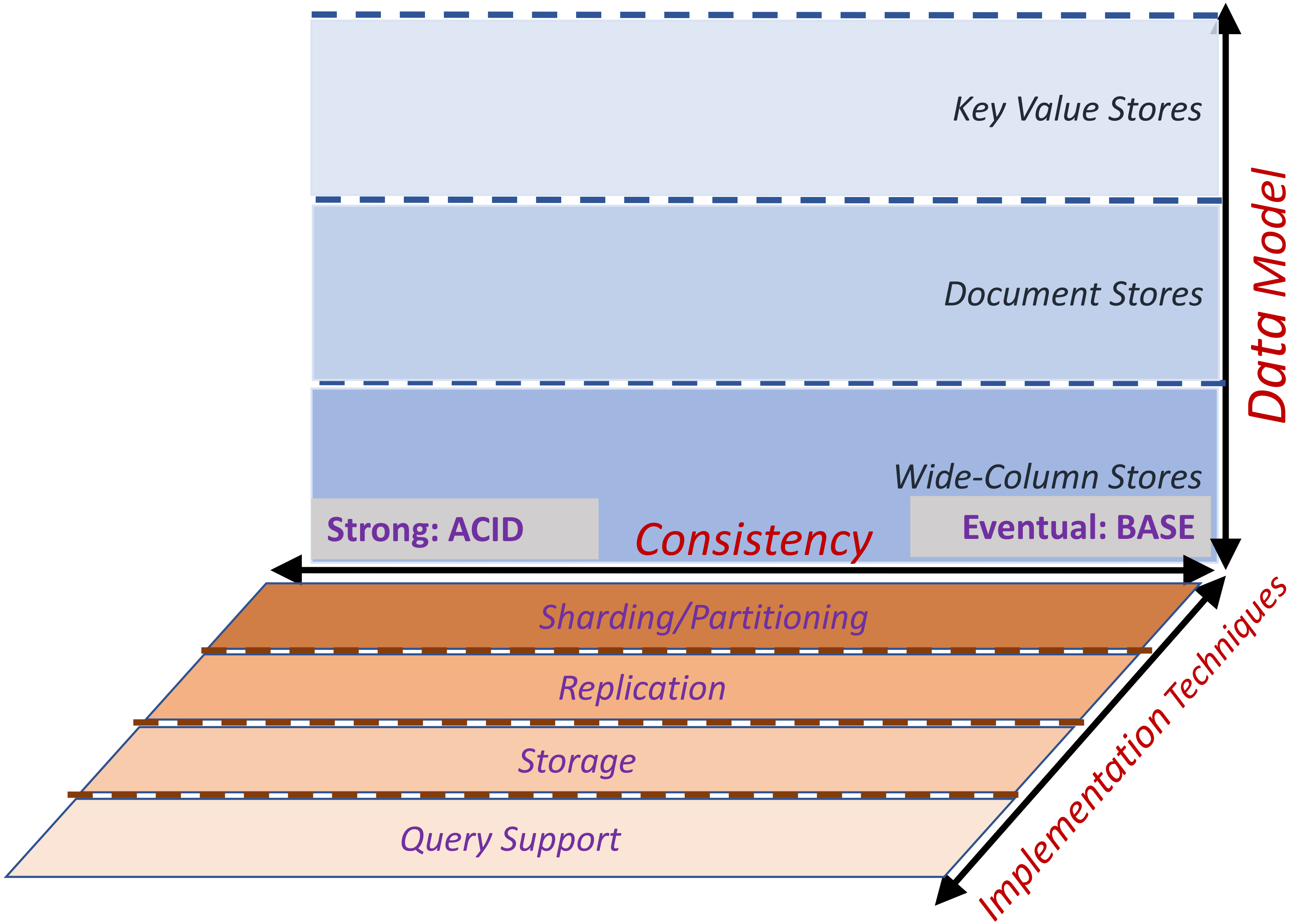


Another Framework

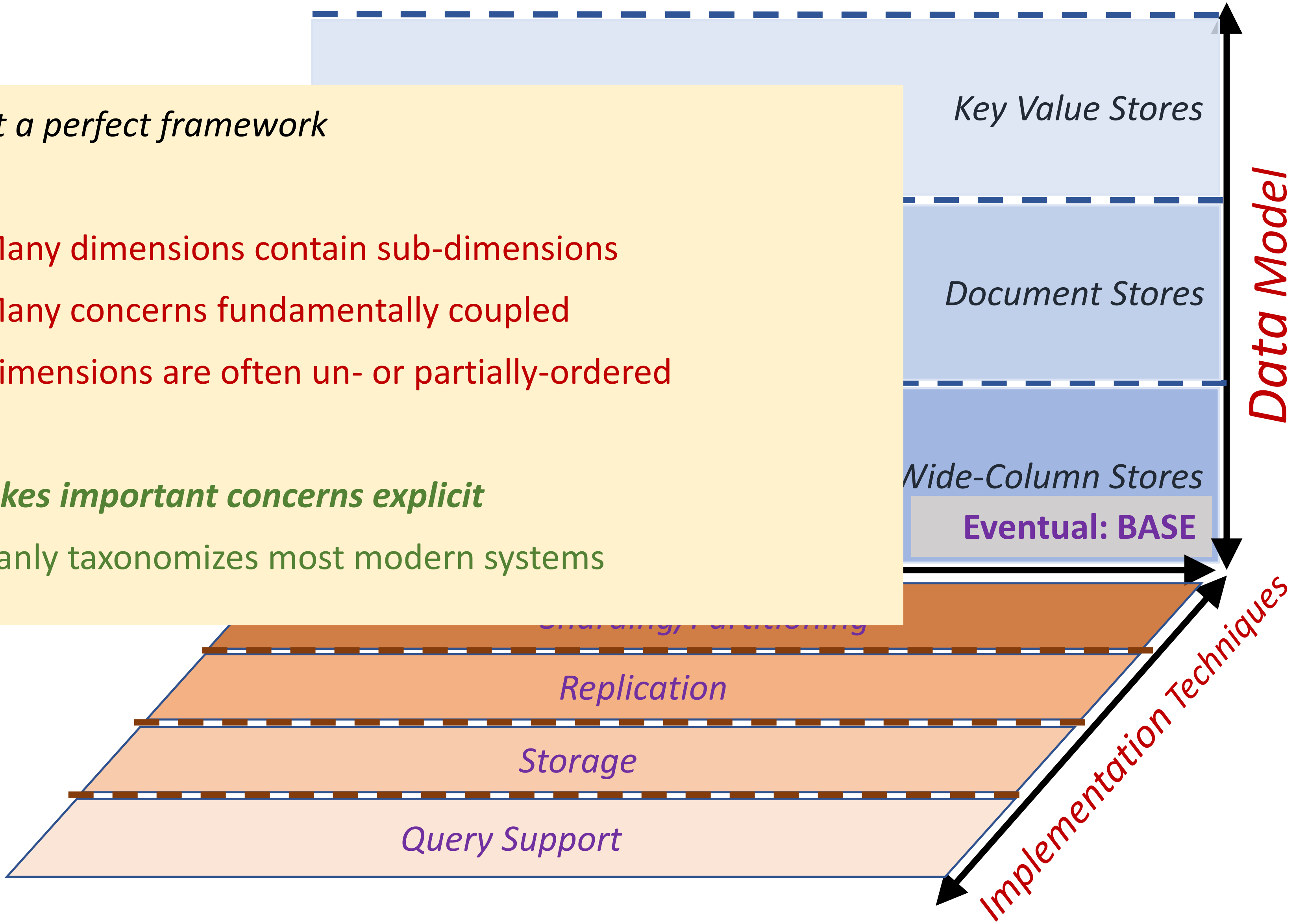
Still not a perfect framework

Cons:

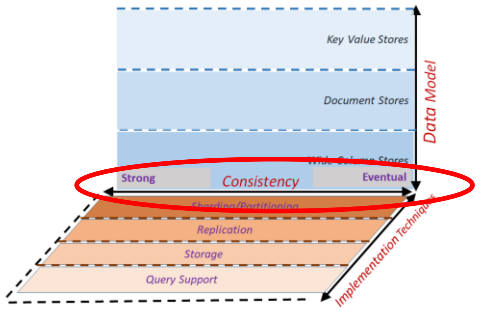
- Many dimensions contain sub-dimensions
- Many concerns fundamentally coupled
- Dimensions are often un- or partially-ordered

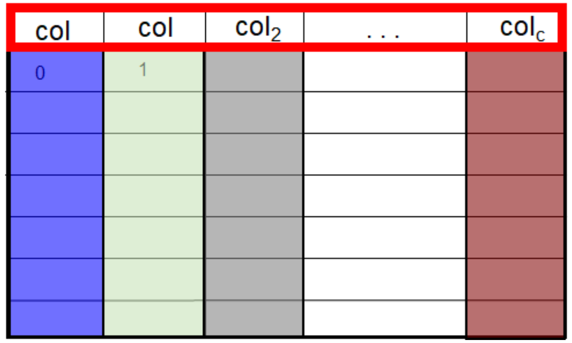
Pros:

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



Consistency





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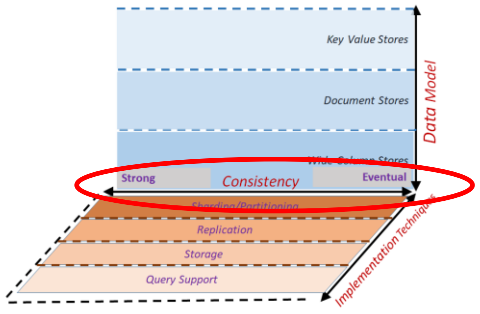
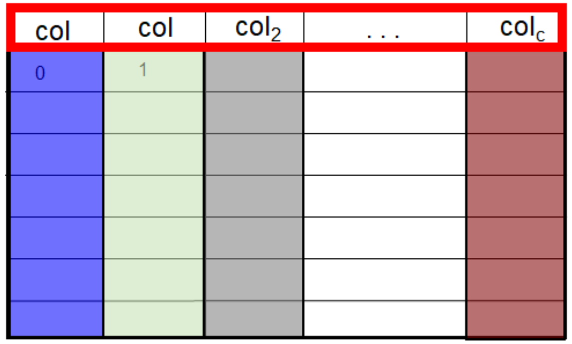
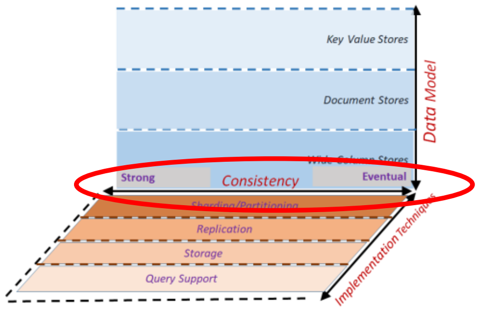




How to keep data in sync?



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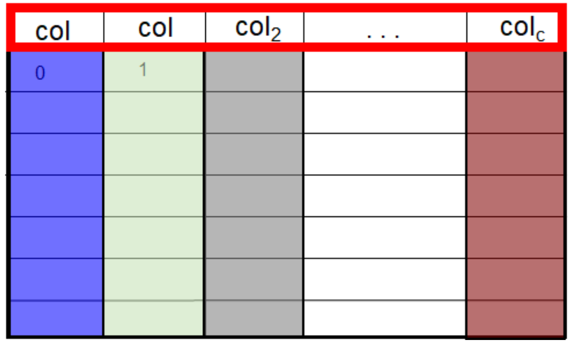

How to keep data in sync?

- Partitioning → single row spread over multiple machines

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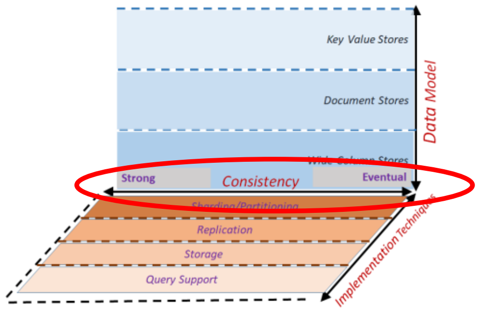

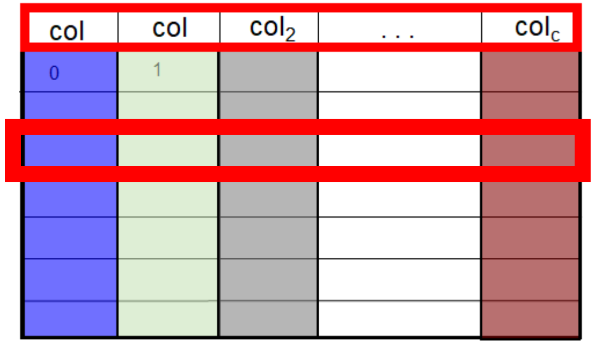

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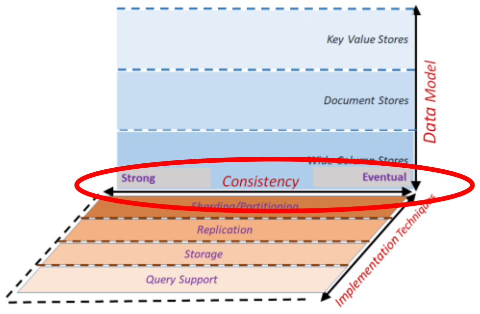

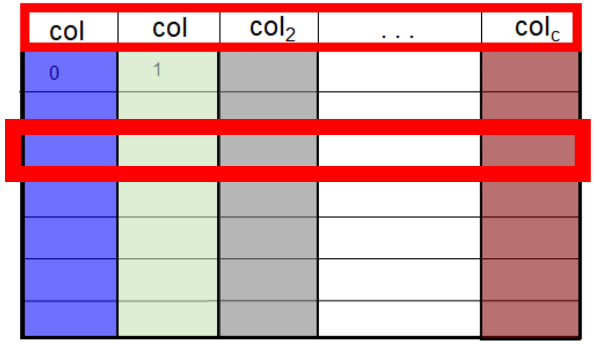

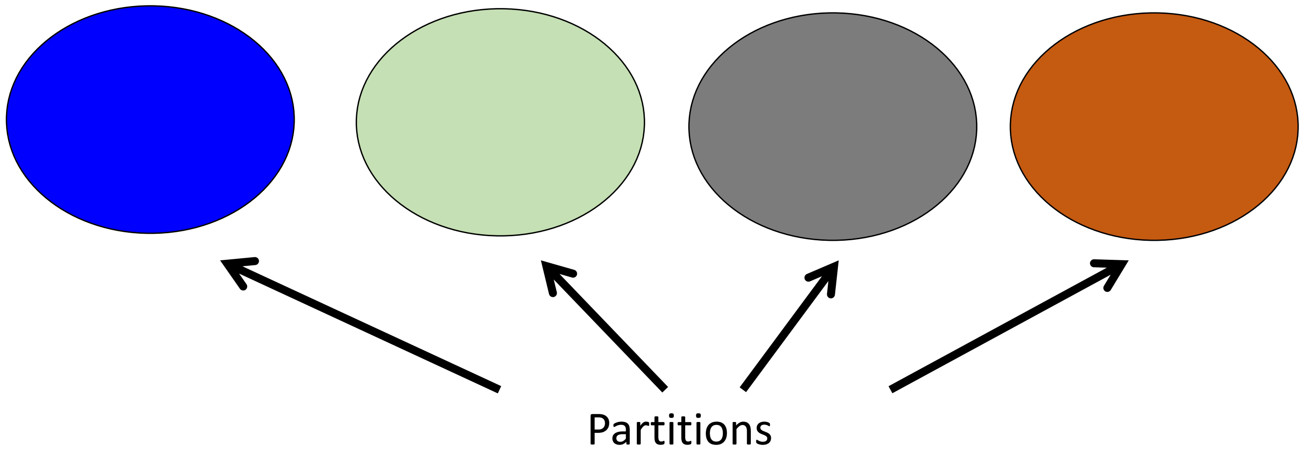

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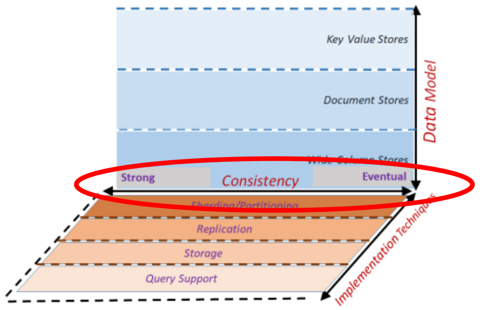

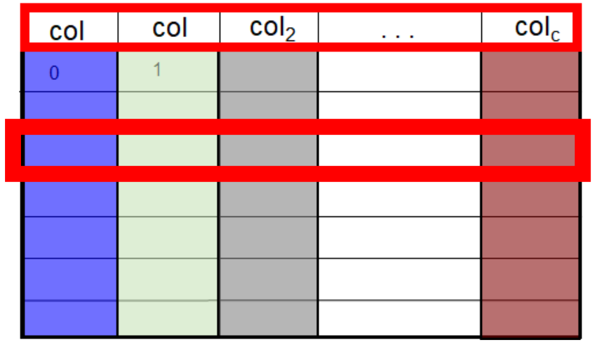

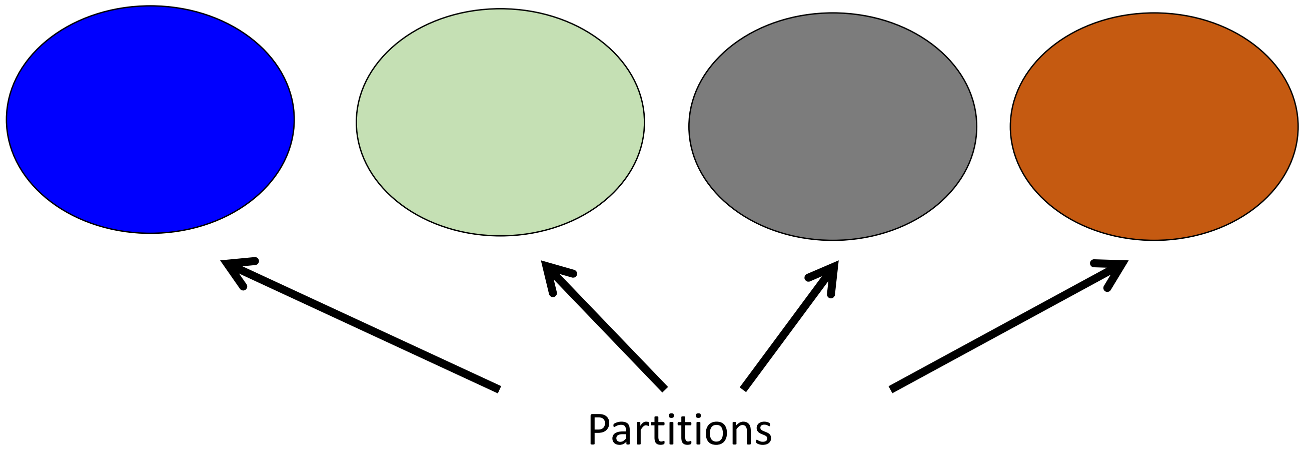

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- Redundancy → single datum spread over multiple machines

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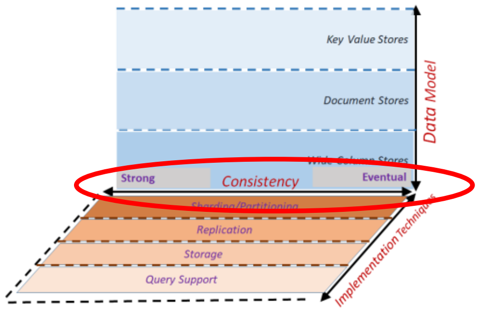

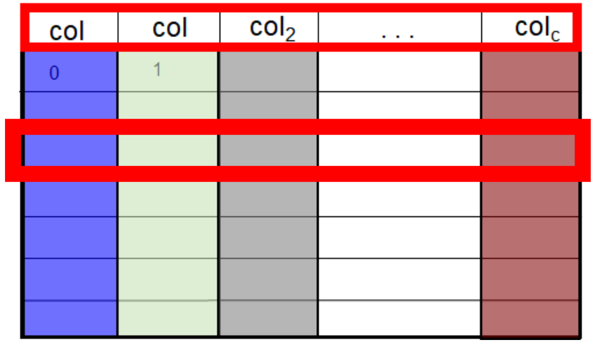

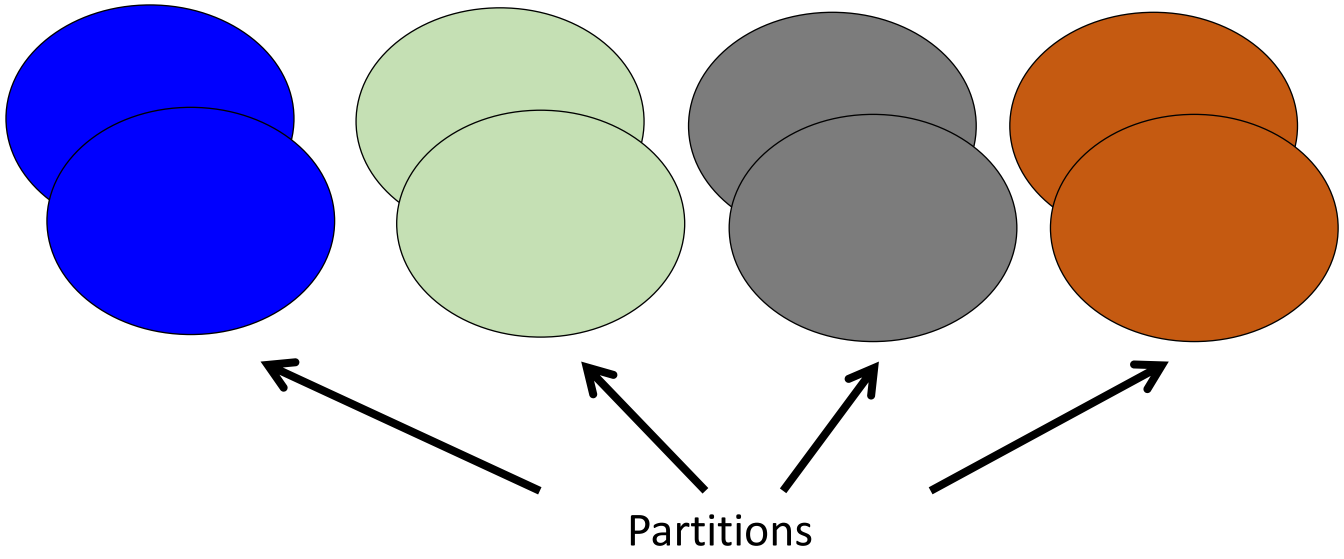

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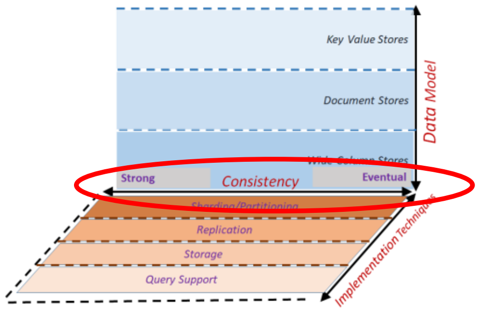

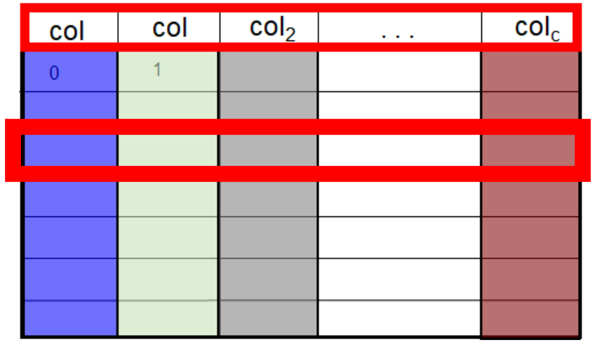

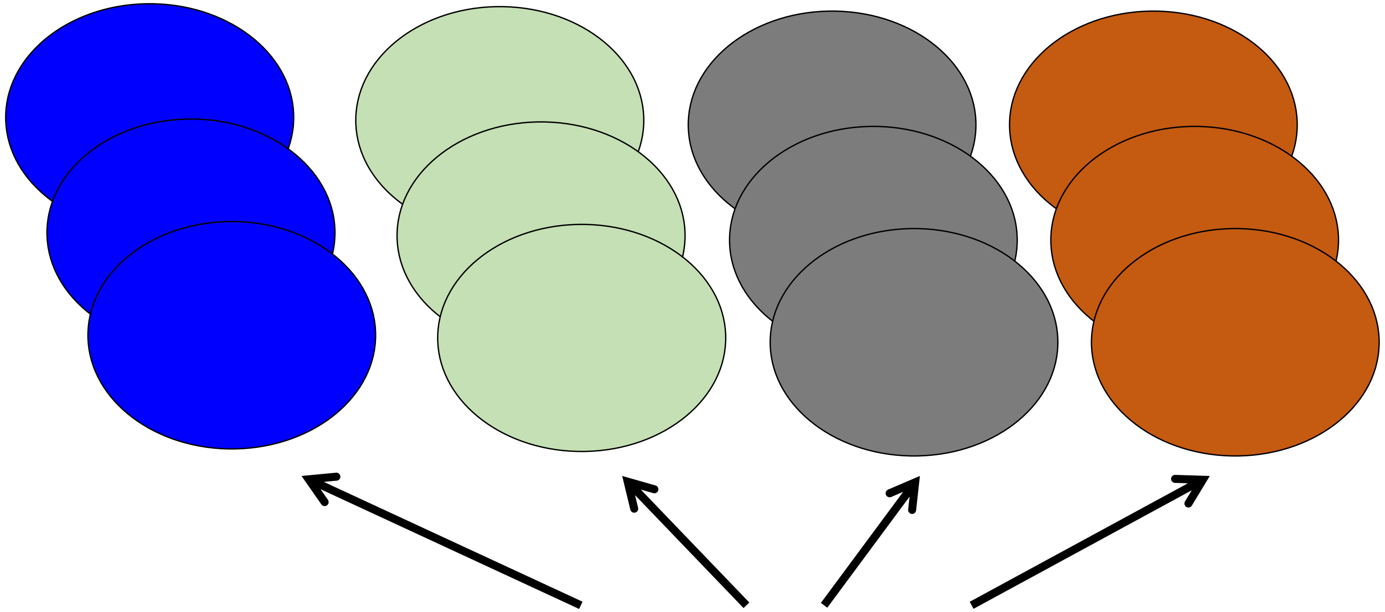

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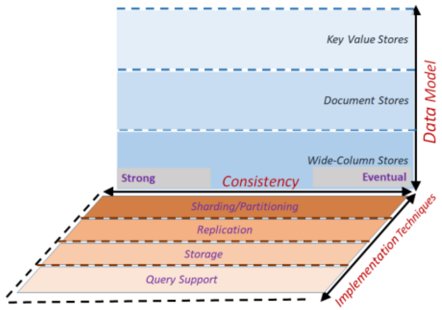
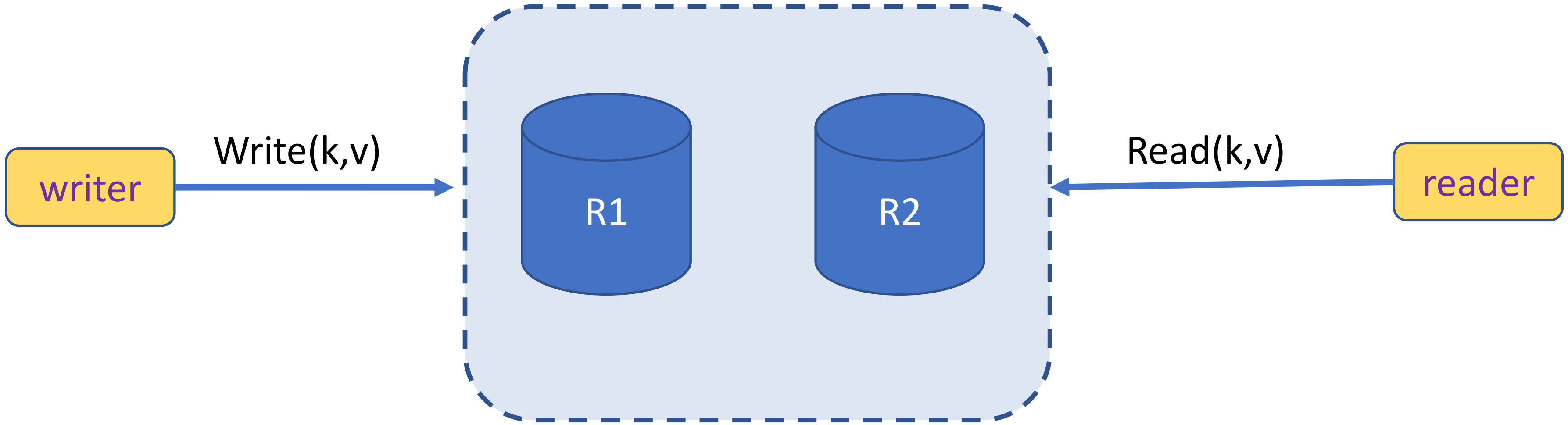
Consistency: the core problem





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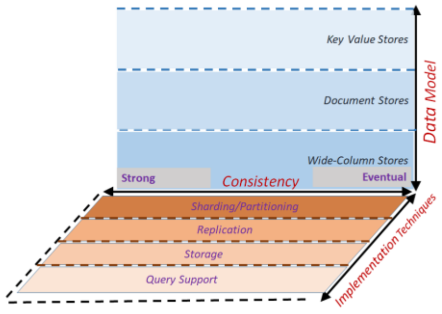
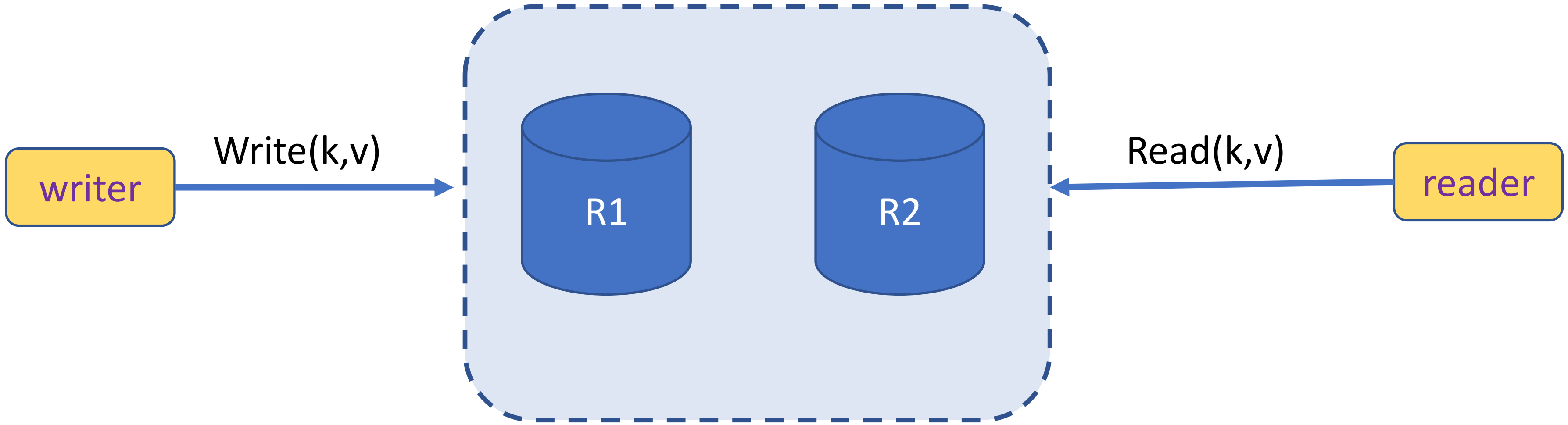
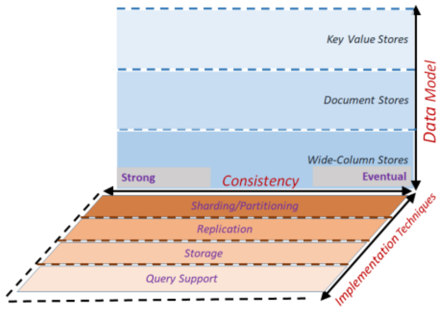
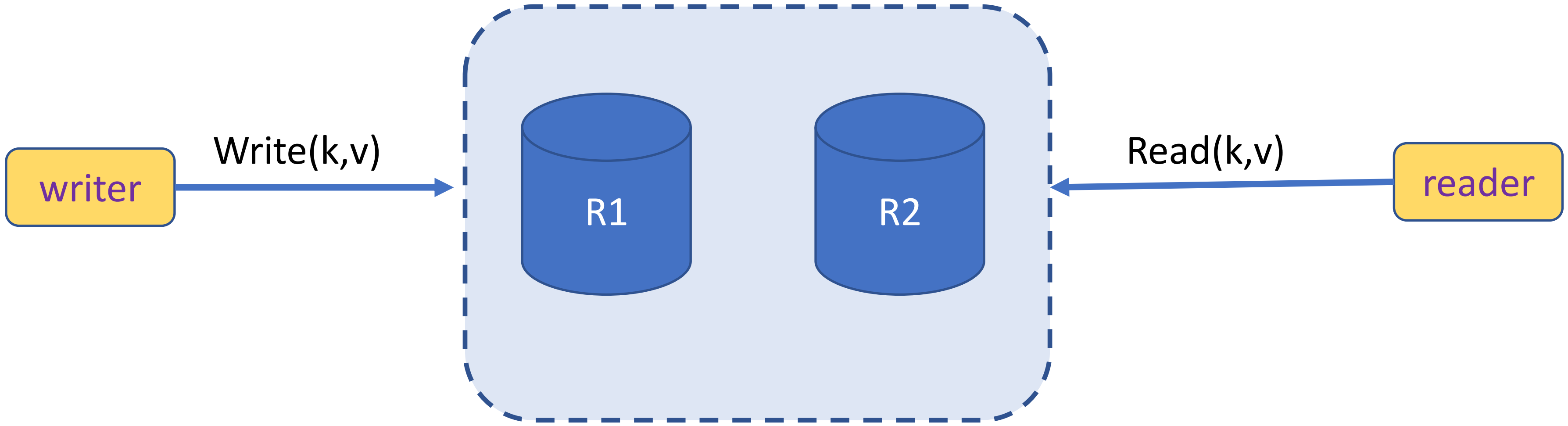




- Clients perform reads and writes

Consistency: the core problem





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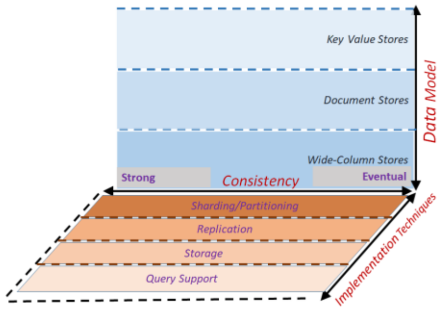

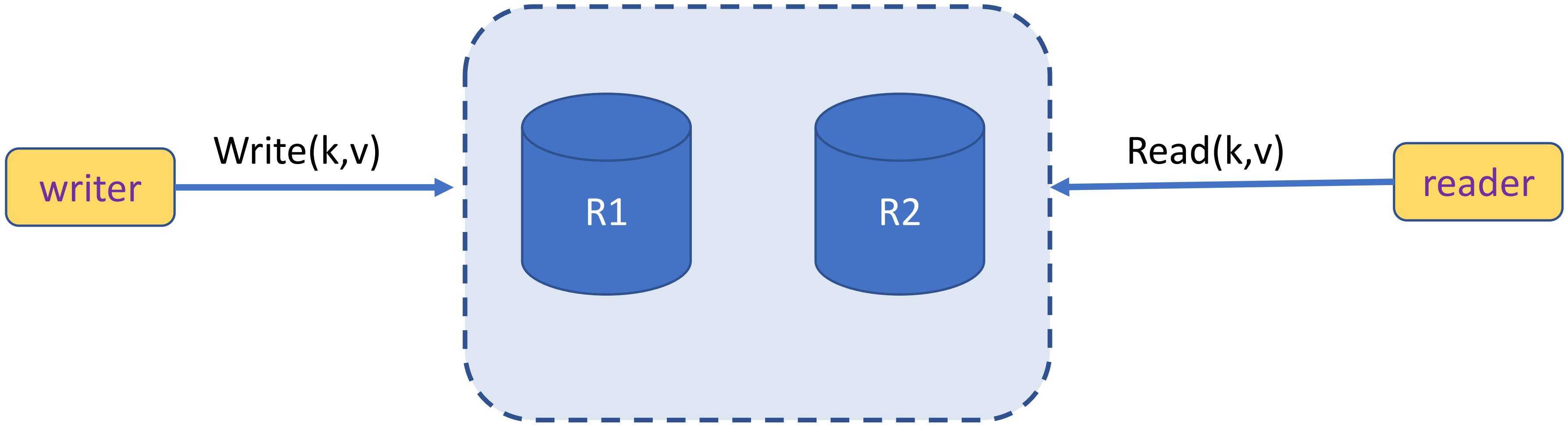

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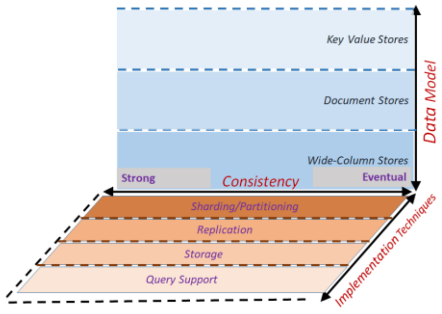

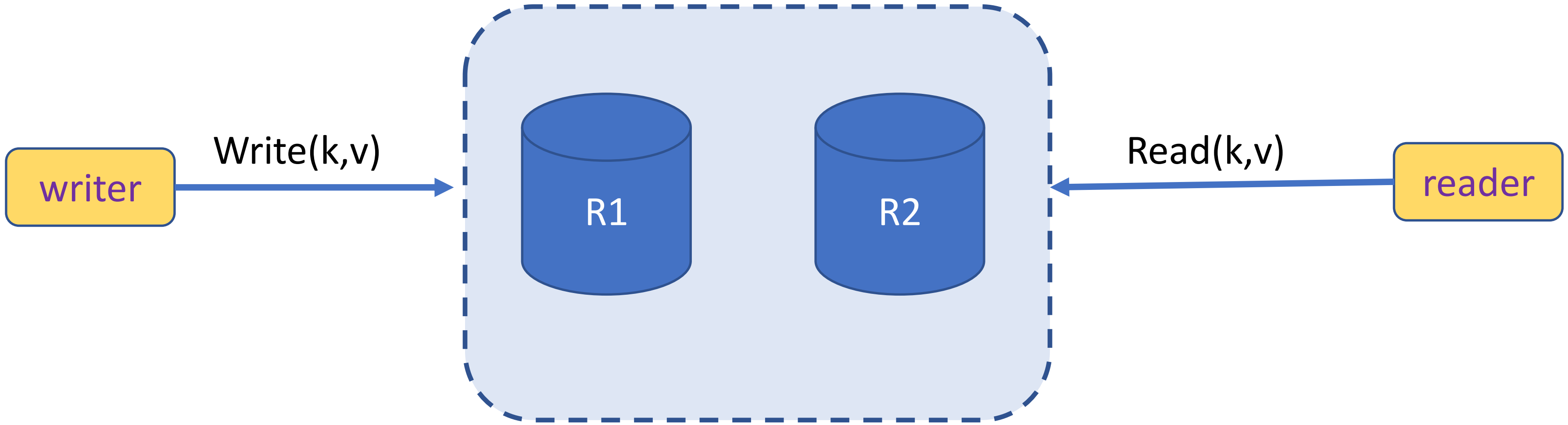

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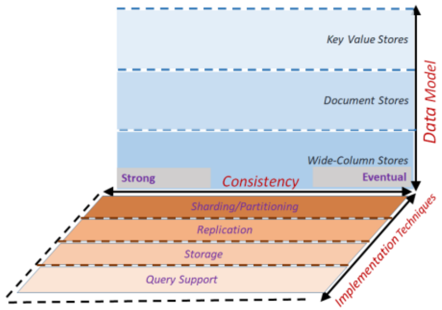
- Reads return the result of one or more past writes



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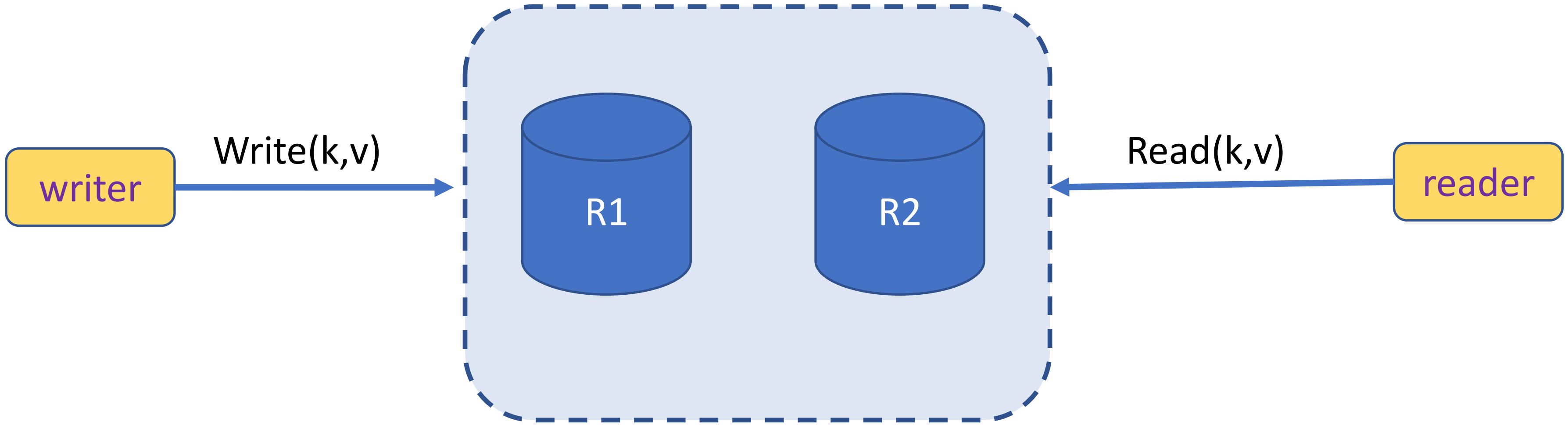

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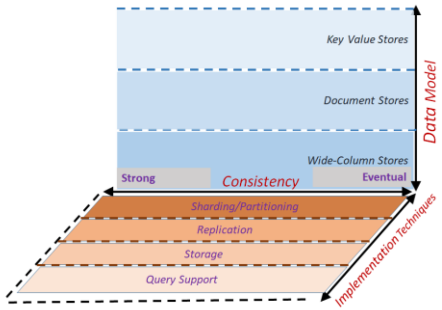
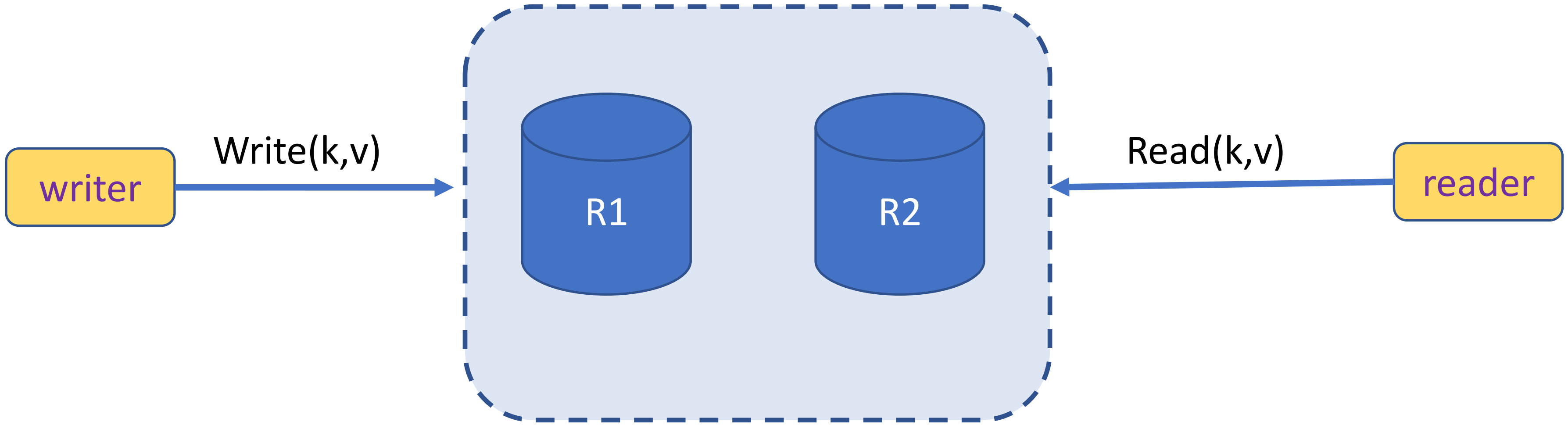
- How should we *implement* write?

Consistency: the core problem





- Clients perform reads and writes
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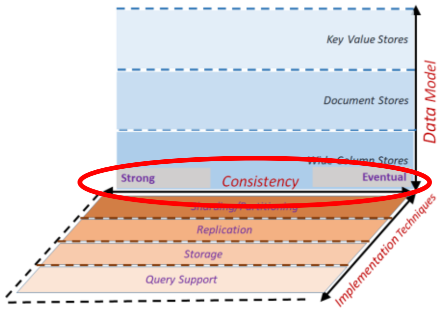
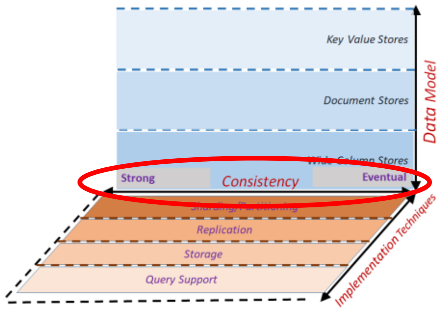
- How should we *implement* write?
- How to *implement* read?

Consistency: CAP Theorem

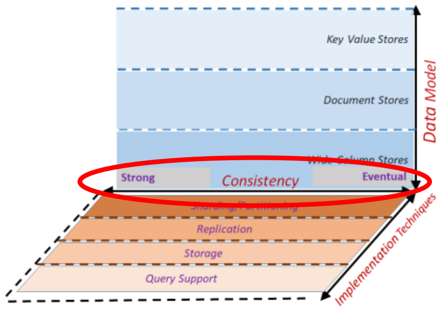


Consistency: CAP Theorem



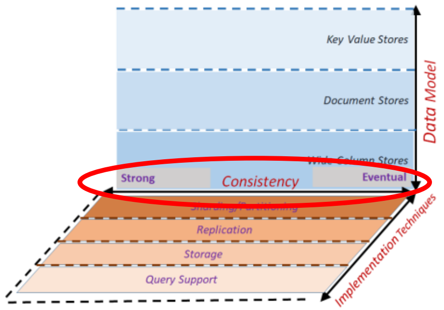
- A distributed system can satisfy at most 2/3 guarantees of:

Consistency: CAP Theorem



- A distributed system can satisfy at most 2/3 guarantees of:
    1. **Consistency**:

Consistency: CAP Theorem



- A distributed system can satisfy at most 2/3 guarantees of:
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     - all nodes see same data at any time
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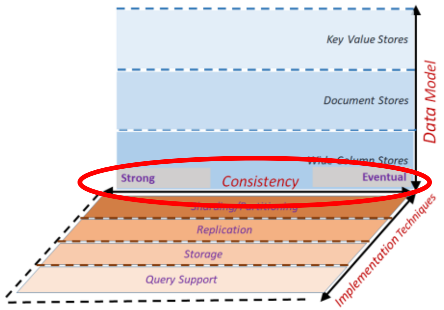
Consistency: CAP Theorem



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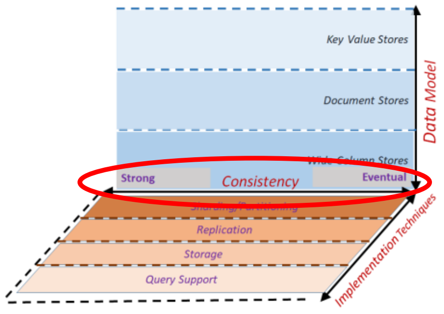
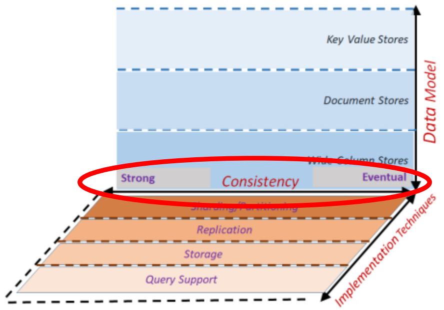
  2. **Availability**:

Consistency: CAP Theorem



- A distributed system can satisfy at most 2/3 guarantees of:
  1. **Consistency**:
     - all nodes see same data at any time
     - or reads return latest written value by any client
  2. **Availability**:
     - system allows operations all the time,
     - and operations return quickly

Consistency: CAP Theorem



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  3. **Partition-tolerance**:

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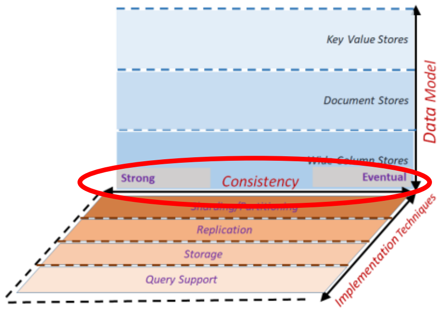

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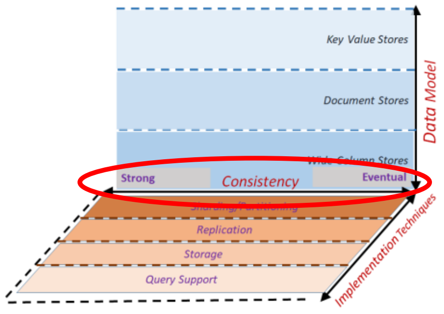

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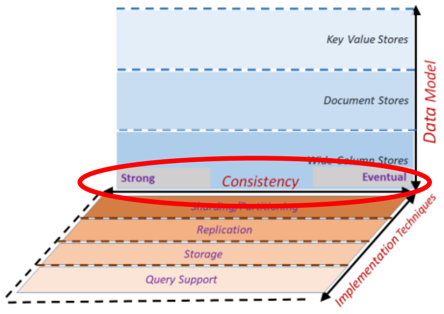

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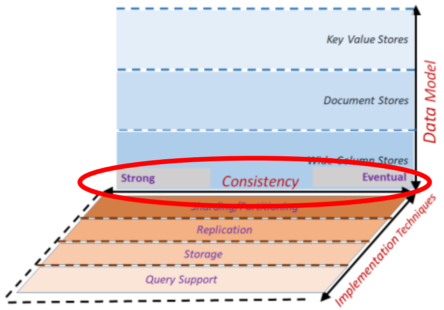
Why care about CAP Properties?
Availability
- Reads/writes complete reliably and quickly.
- E.g. Amazon, each ms latency → $6M yearly loss.

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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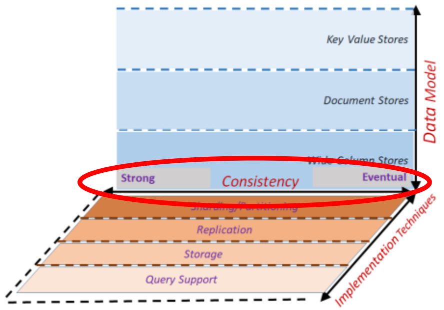

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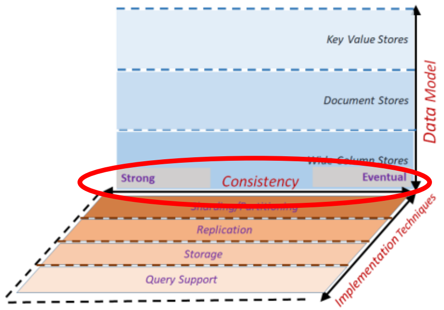
Consistency: CAP Theorem



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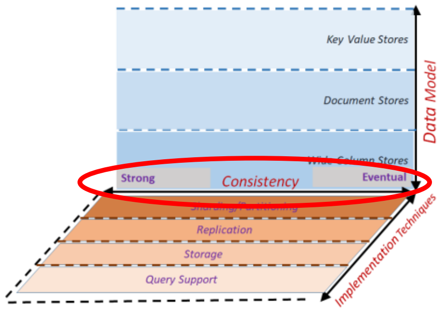

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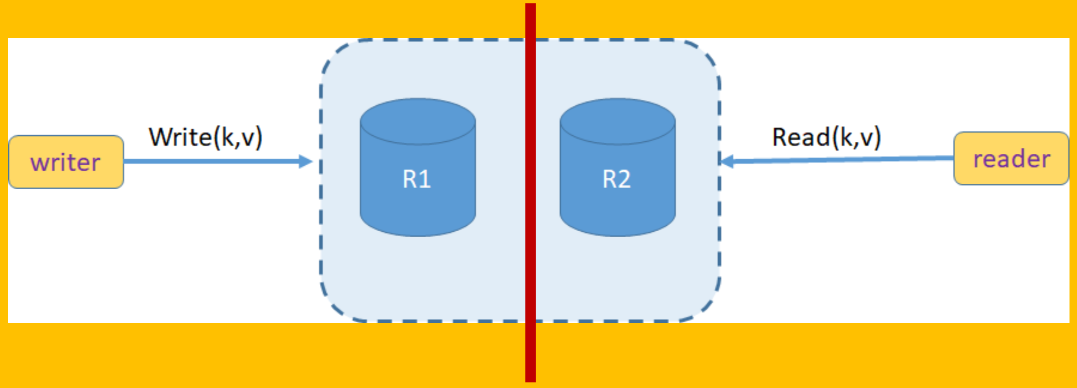

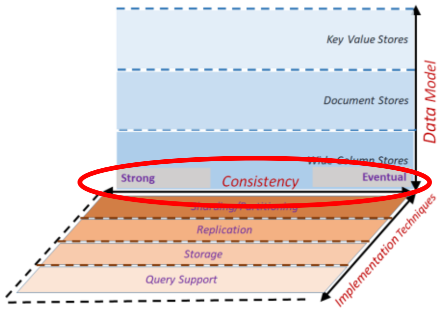

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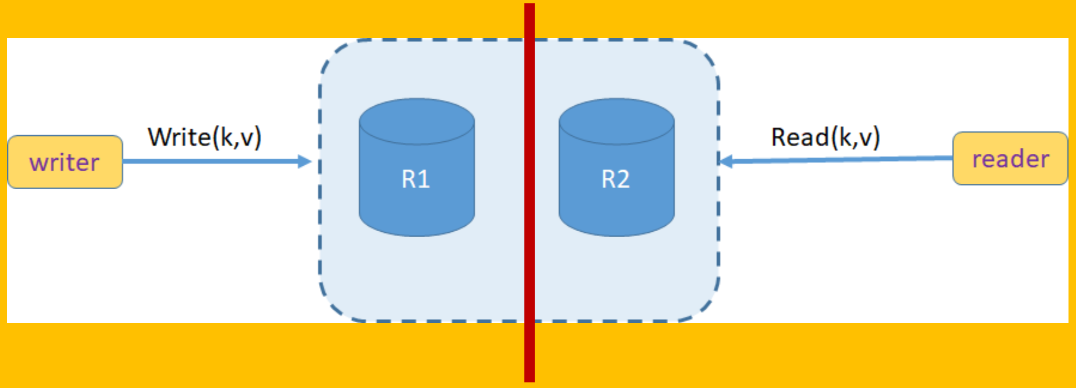
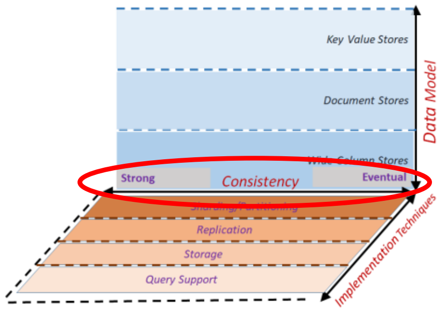


if(partition) { keep going } → !consistent && available

Consistency: CAP Theorem



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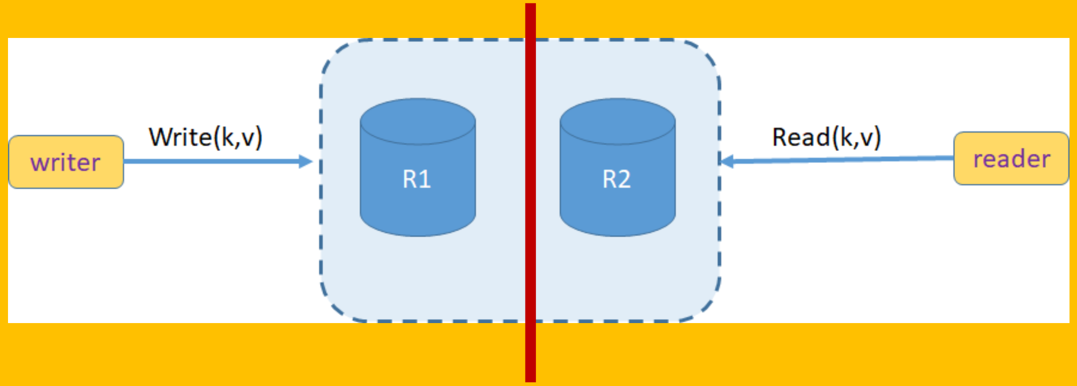
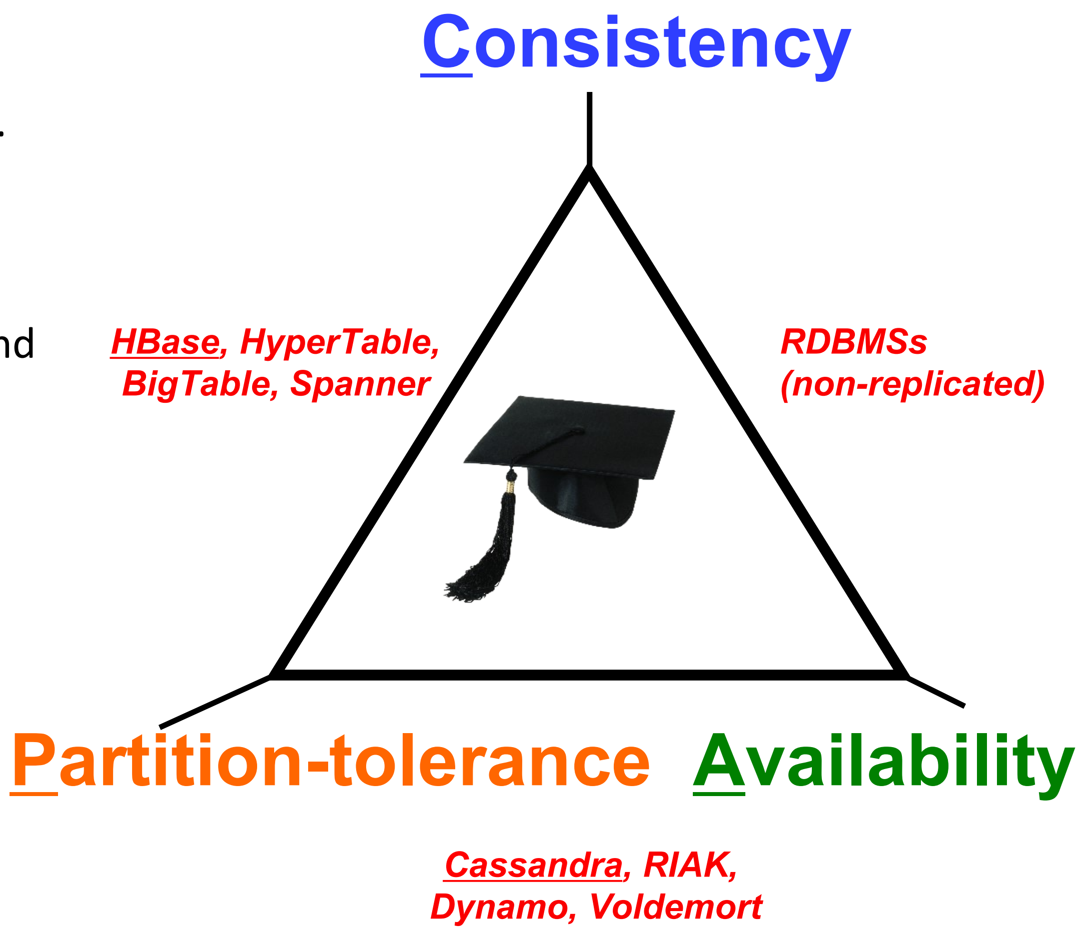


if(partition) { keep going } → !consistent && available
if(partition) { stop } → consistent && !available

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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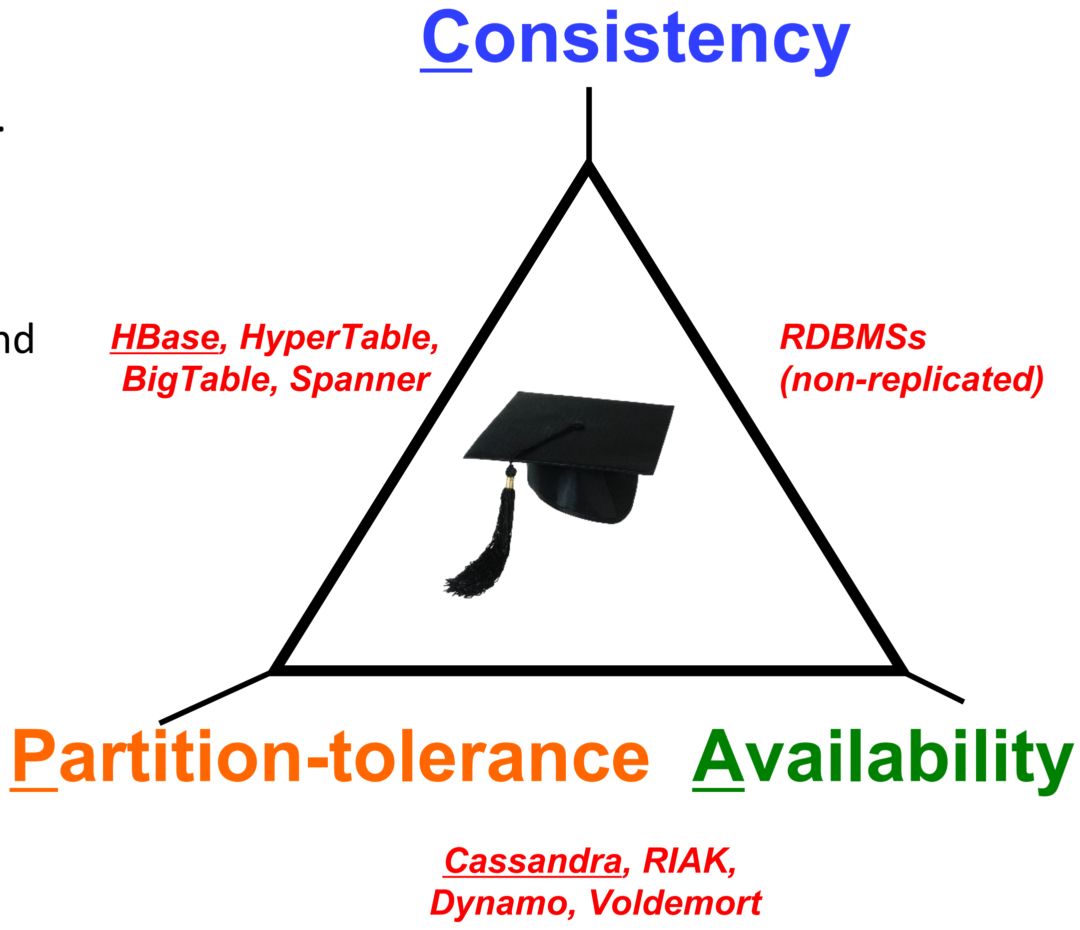

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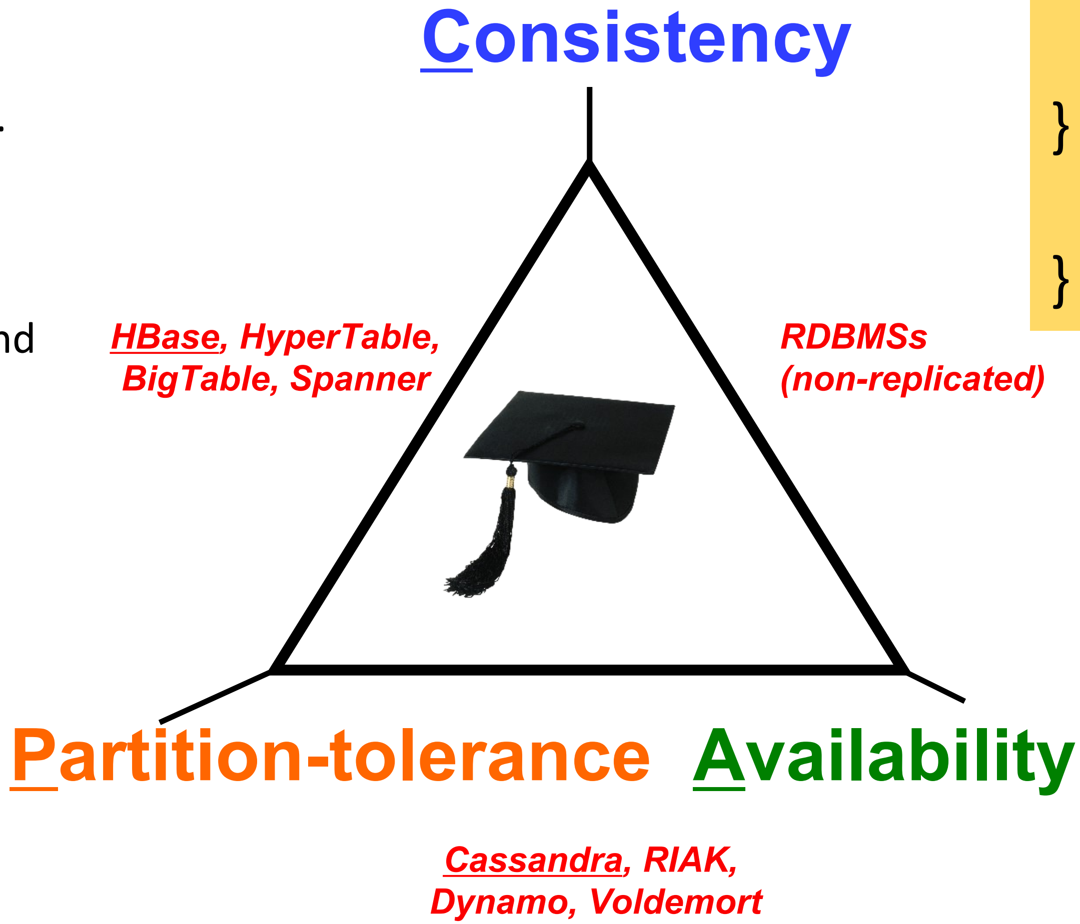
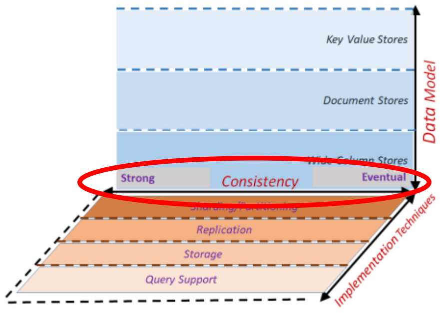
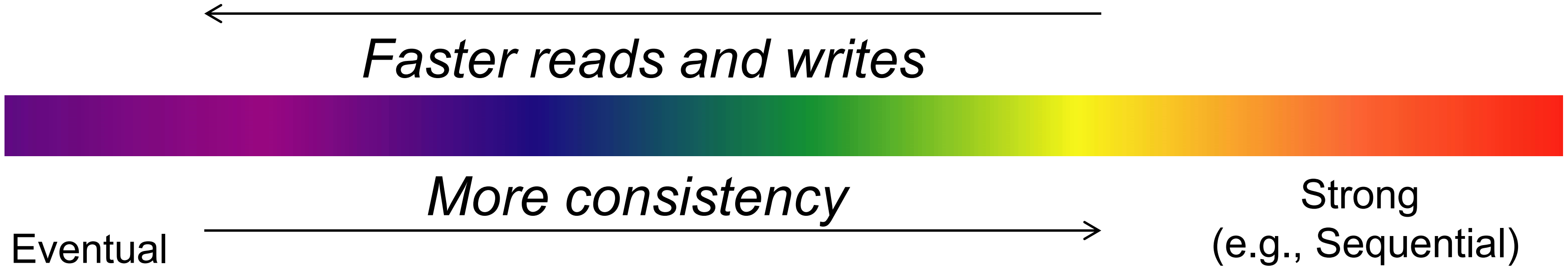


PACELC:

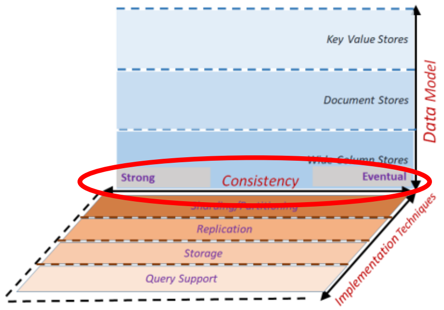
```
if(partition) {
   choose A or C
} else {
   choose latency or consistency
}
```

Consistency Spectrum

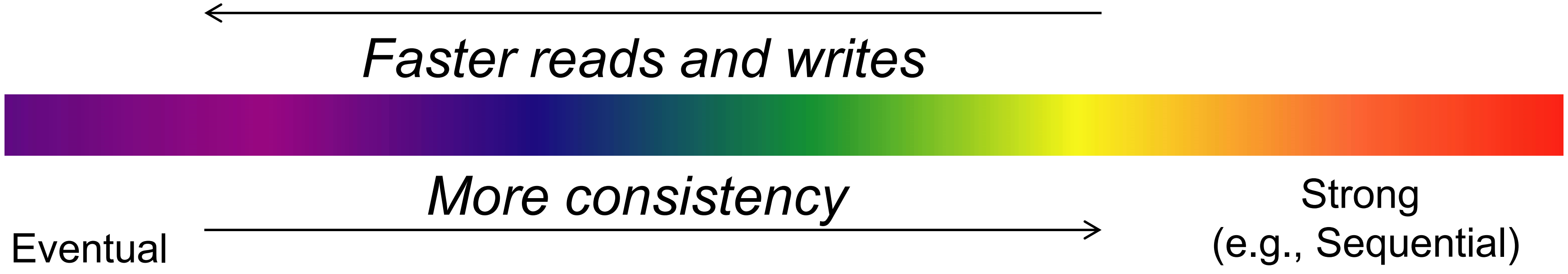




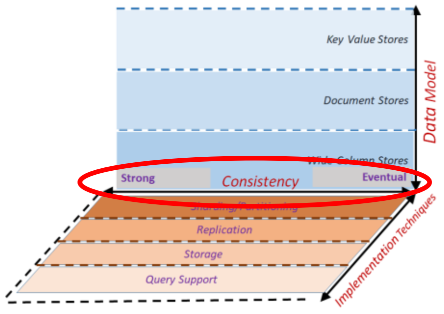
Spectrum Ends: Eventual Consistency



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

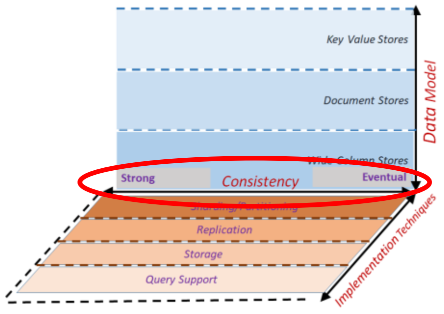


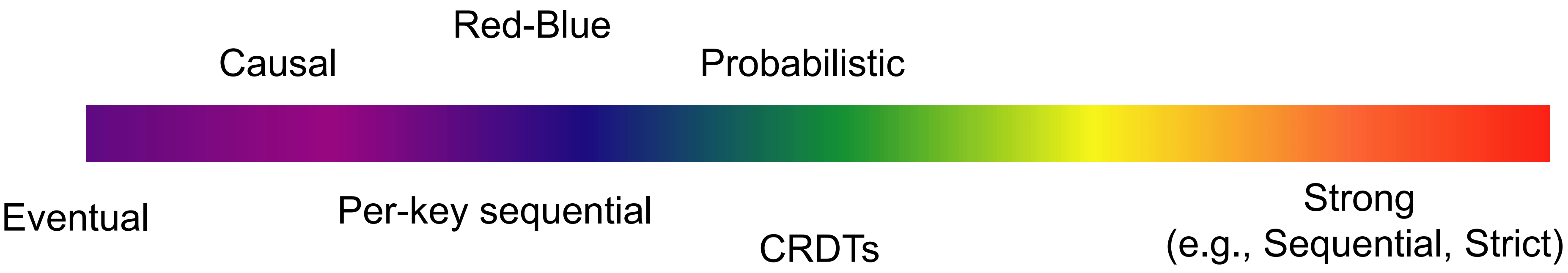
Spectrum Ends: Strong Consistency

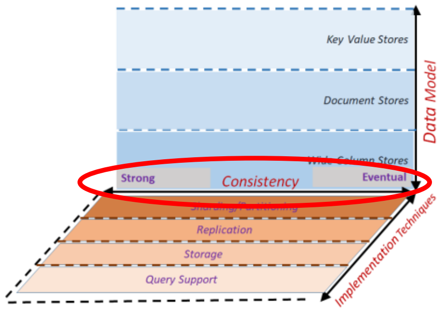


- **Strict:**
  - Absolute time ordering of all shared accesses, reads always return last write
- **Linearizability**:
  - Each operation is visible (or available) to all other clients in real-time order
- **Sequential Consistency** [Lamport]:
  - *"... the result of any execution is the same as if the 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







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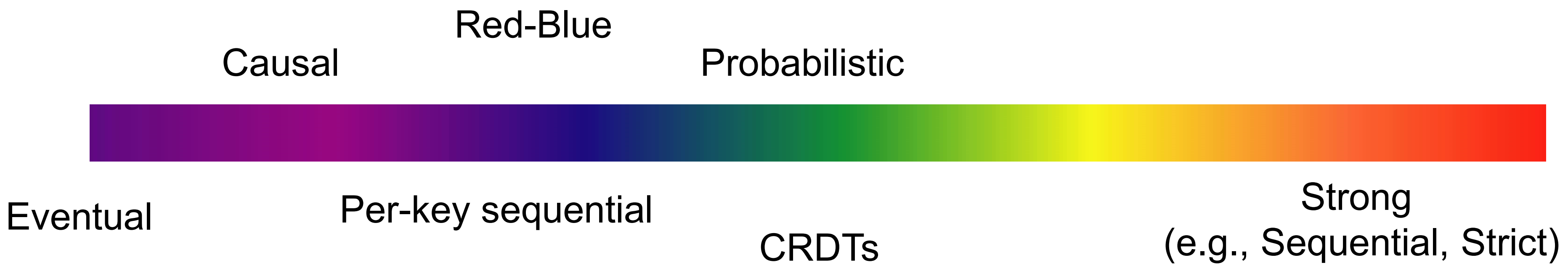

- Amazon S3 – **eventual** consistency
- Amazon Simple DB – **eventual** or strong
- Google App Engine – **strong** or eventual
- Yahoo! PNUTS – **eventual** or strong
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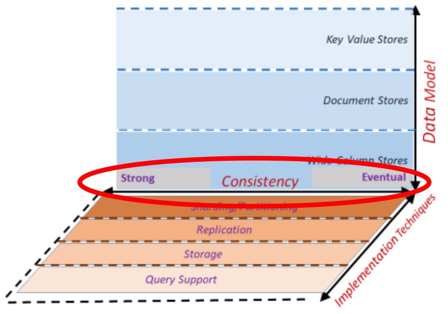

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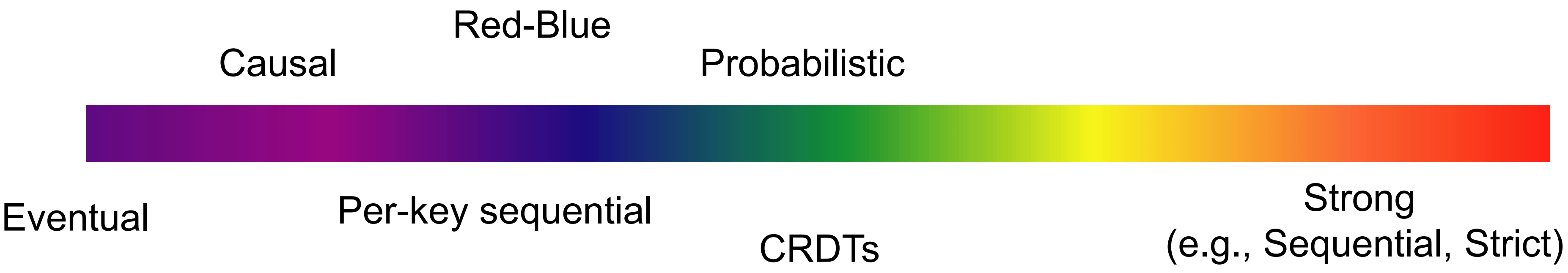

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<u>Question</u>: How to choose what to use or support?

Some Consistency Guarantees

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
Consistent Prefix	See initial sequence of writes.
Bounded Staleness	See all “old” writes.
Monotonic Reads	See increasing subset of writes.
Read My Writes	See all writes performed by reader.

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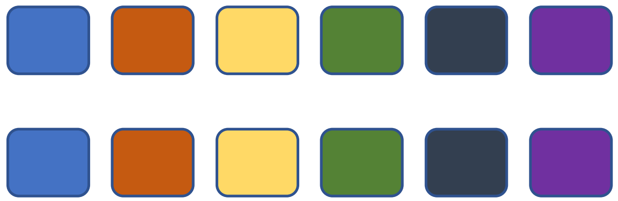

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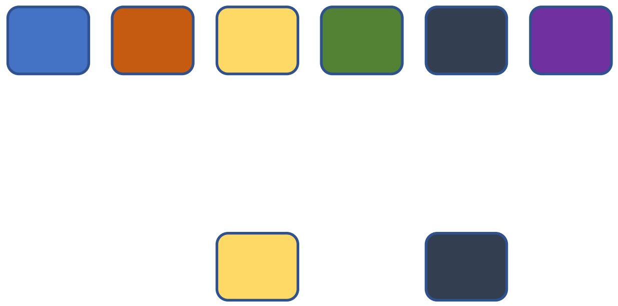

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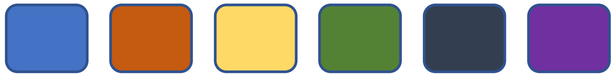

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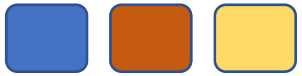

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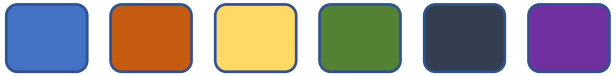

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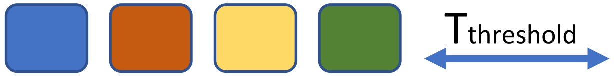

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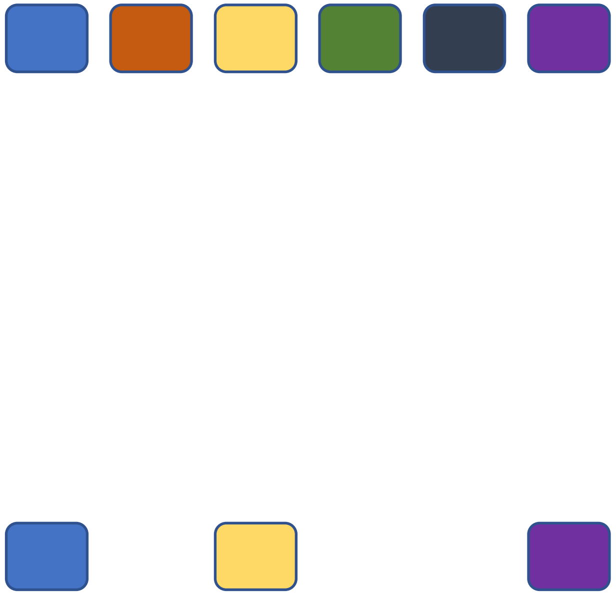

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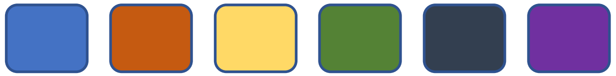

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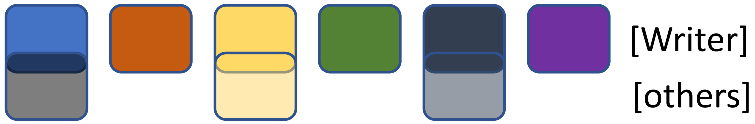

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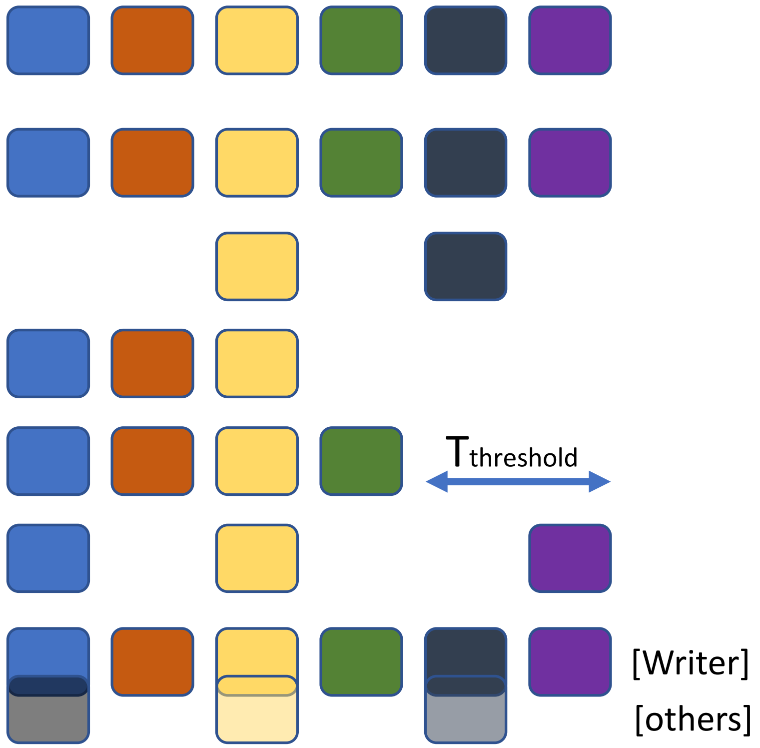

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Some Consistency Guarantees

		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
Monotonic Reads	See increasing subset of writes.	C	B	B
Read My Writes	See all writes performed by reader.	C	C	C

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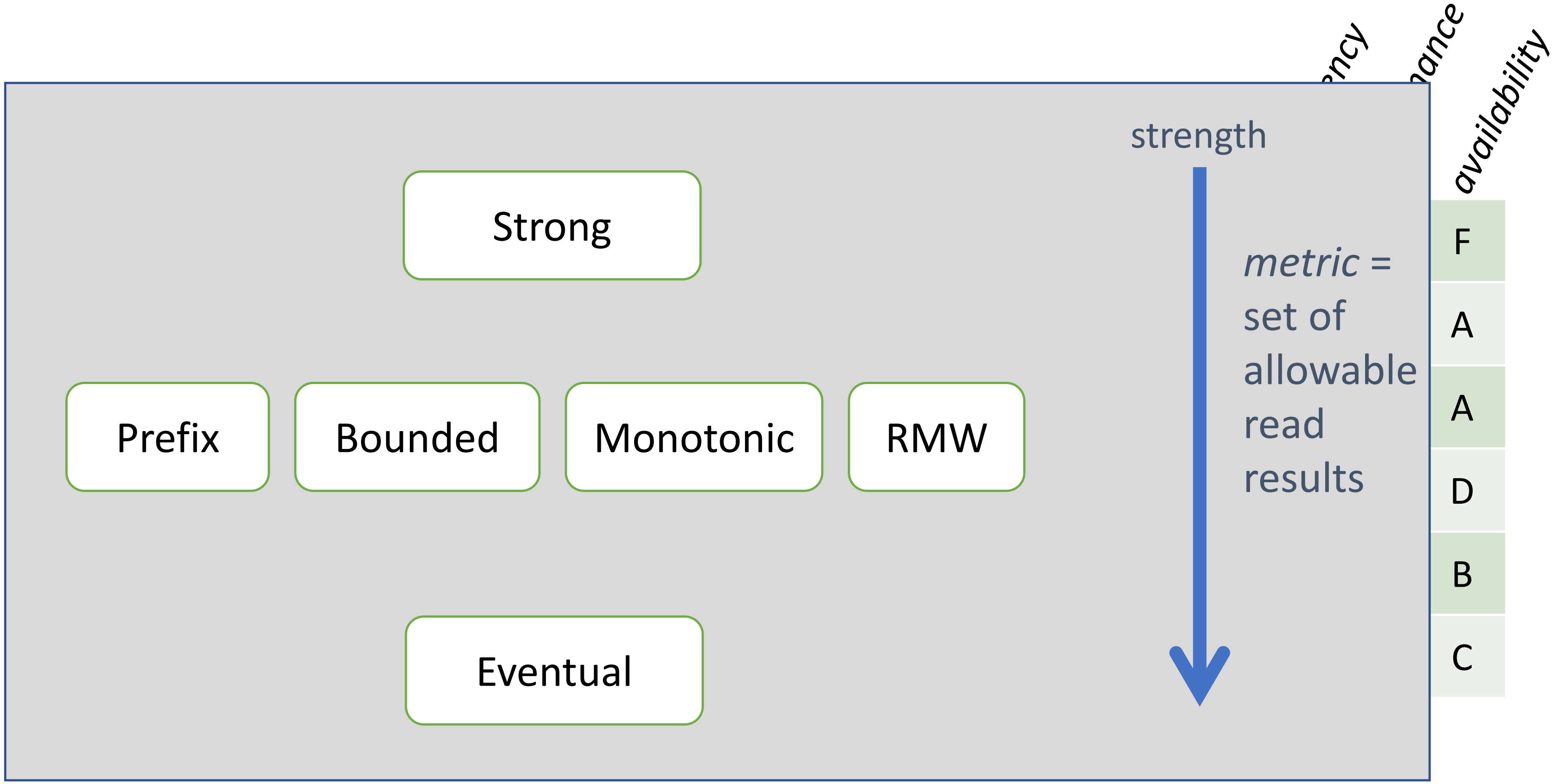
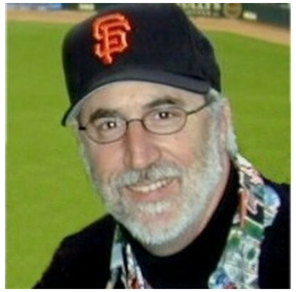


The Game of Soccer

The Game of Soccer



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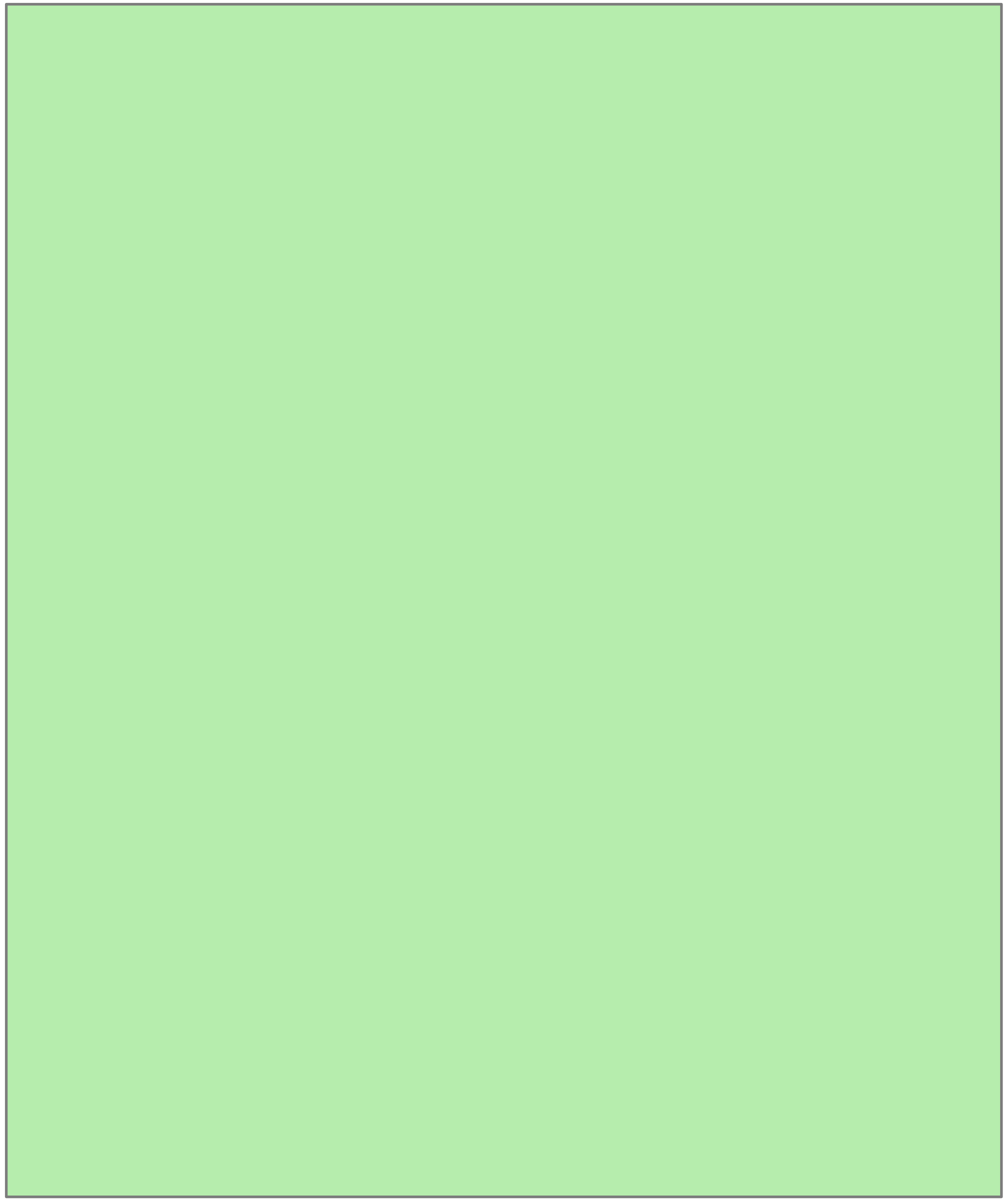

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```
for half = 1 .. 2  {
```

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

```
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  {
  while half not over {
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      for each goal {
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        } else {
```

The Game of Soccer

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      for each goal {
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           score = Read ("home");
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The Game of Soccer

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  while half not over {
      kick-the-ball-at-the-goal
      for each goal {
        if visiting-team-scored {
          score = Read ("visitors");
          Write ("visitors", score + 1);
        } else {
          score = Read ("home");
          Write ("home", score + 1);
```

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 {
          score = Read ("visitors");
          Write ("visitors", score + 1);
        } else {
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          Write ("home", score + 1);
        } } }
```

The Game of Soccer

```
for half = 1 .. 2  {
   while half not over {
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              score = Read ("visitors");
              Write ("visitors", score + 1);
           } else {
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              Write ("home", score + 1);
           } } }
hScore = Read("home");
```

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 {
           score = Read ("visitors");
           Write ("visitors", score + 1);
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           Write ("home", score + 1);
        } } }
hScore = Read("home");
vScore = Read("visit");
```

The Game of Soccer

```
for half = 1 .. 2  {
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      kick-the-ball-at-the-goal
      for each goal {
        if visiting-team-scored {
          score = Read ("visitors");
          Write ("visitors", score + 1);
        } else {
          score = Read ("home");
          Write ("home", score + 1);
        } } }
hScore = Read("home");
vScore = Read("visit");
if (hScore == vScore)
```

The Game of Soccer

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

The Game of Soccer

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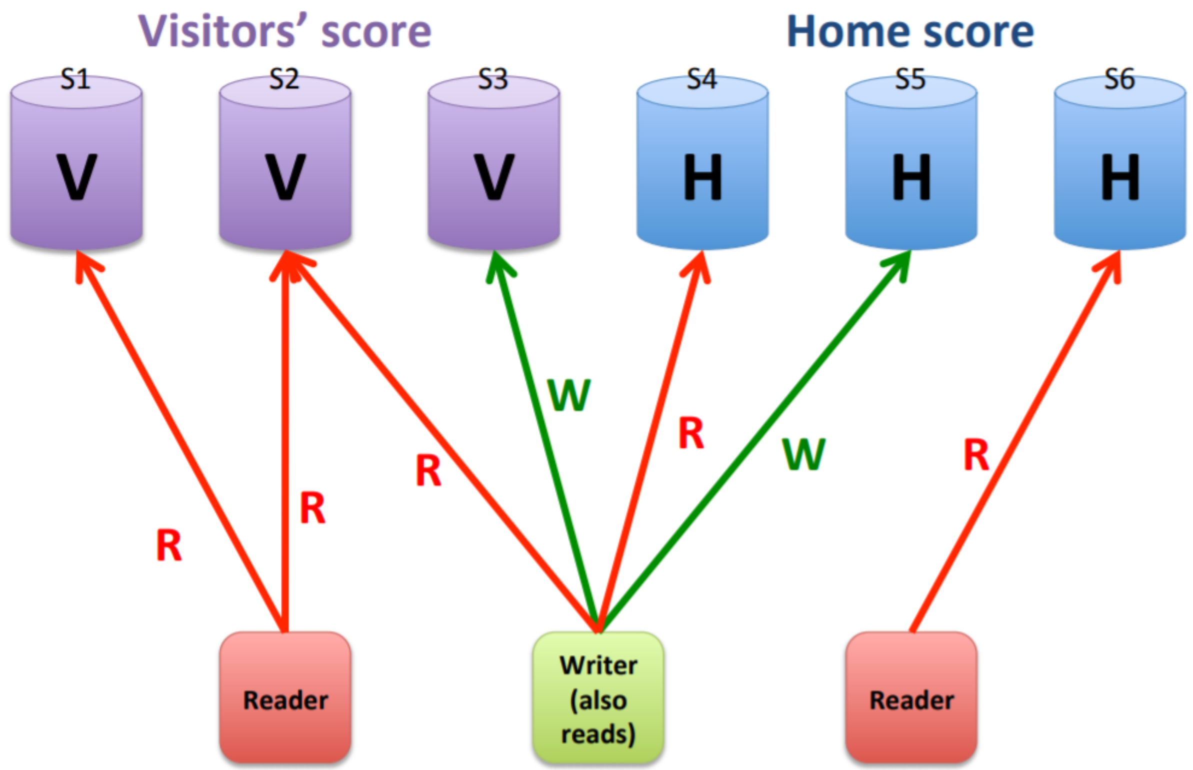
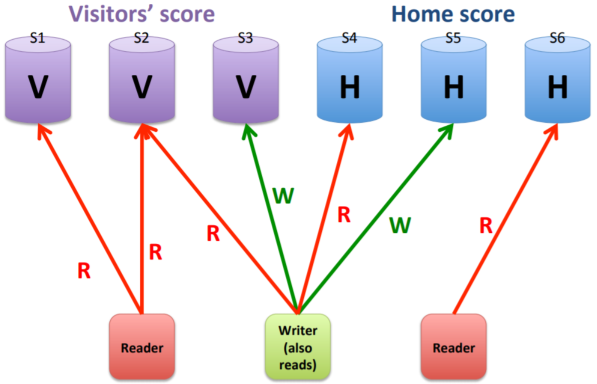


Official Scorekeeper

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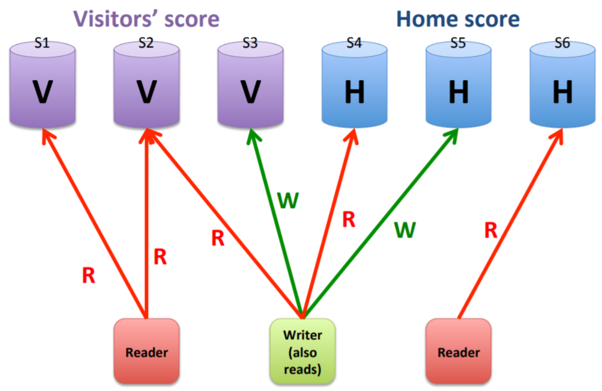


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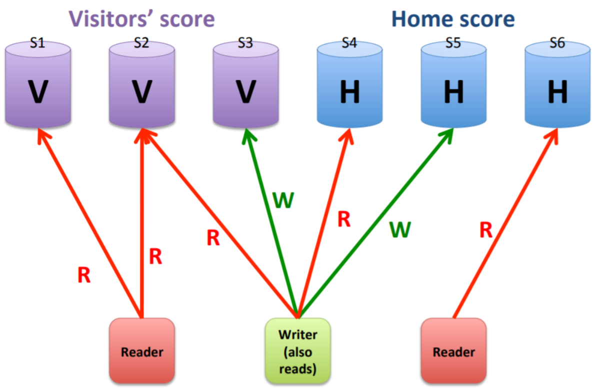


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```

Desired consistency?

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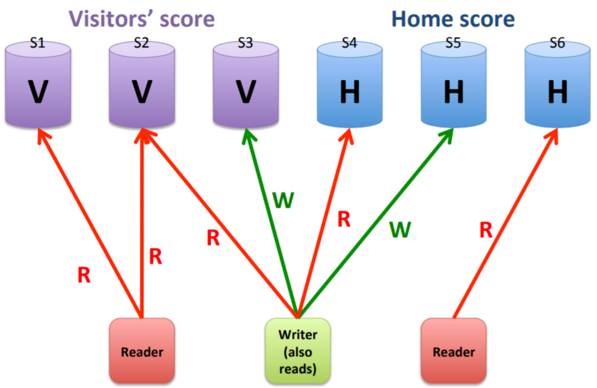


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= Read My Writes!

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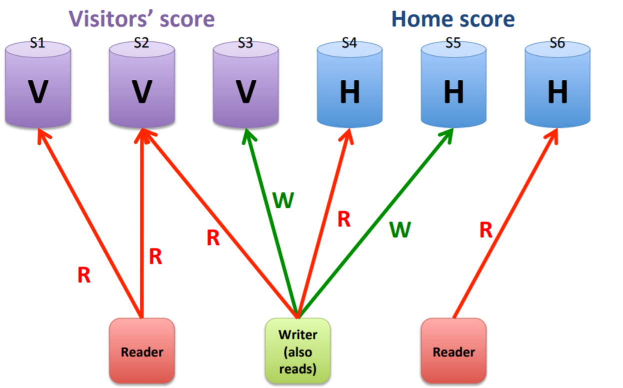

Official Scorekeeper

```
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?

Strong

= Read My Writes!

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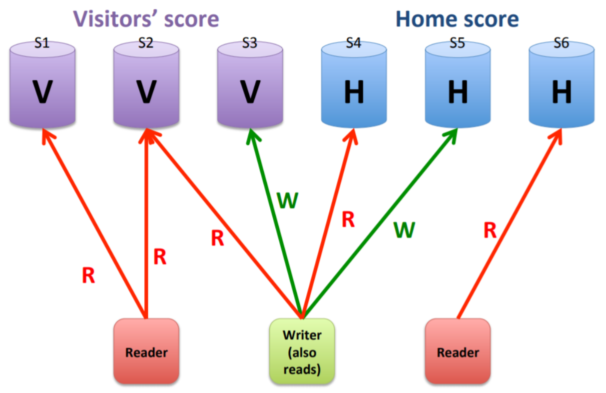


```
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hScore = Read ("home");
if vScore == hScore
    play-overtime
```

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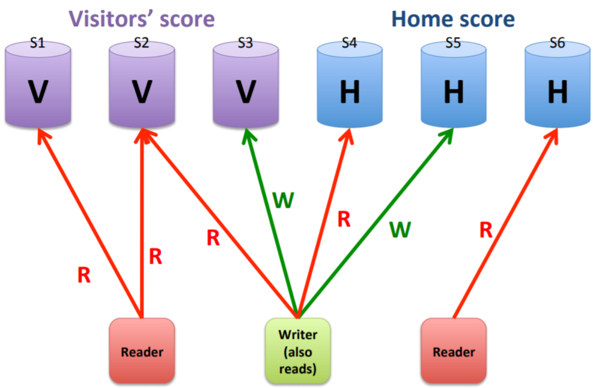


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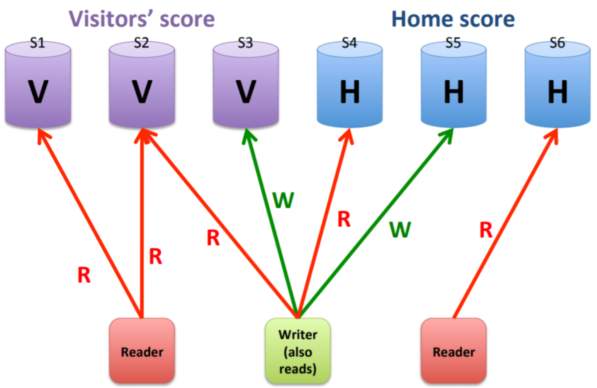


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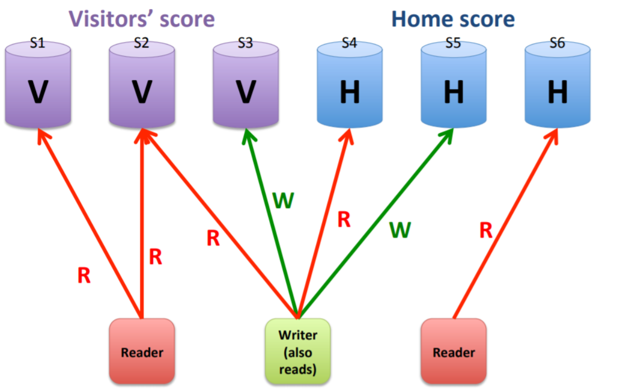

Radio Reporter

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

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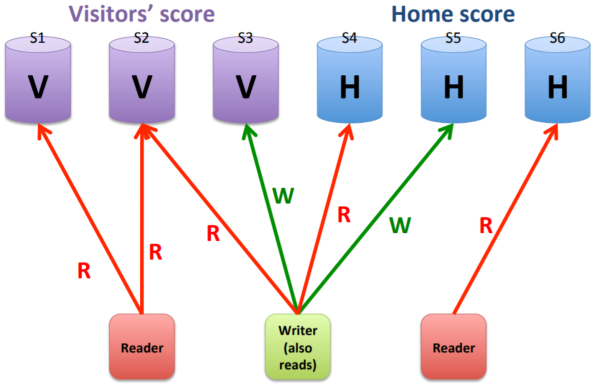


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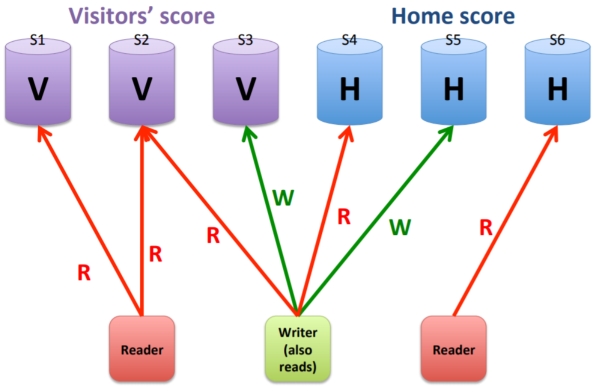


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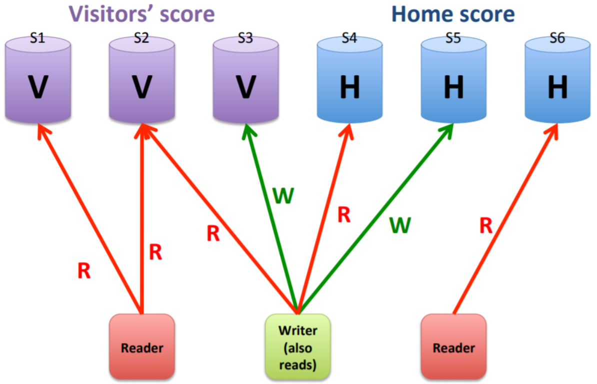


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Desired consistency?

Consistent Prefix

or Bounded Staleness

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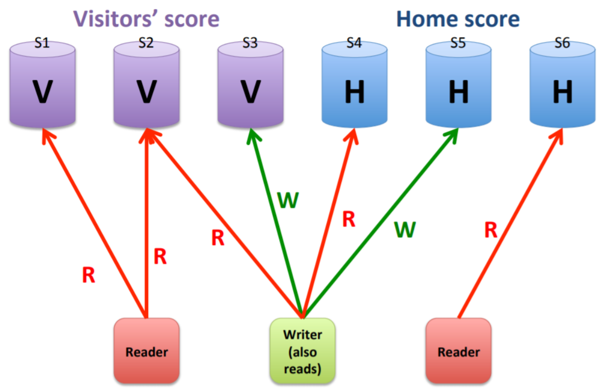
Sportswriter




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

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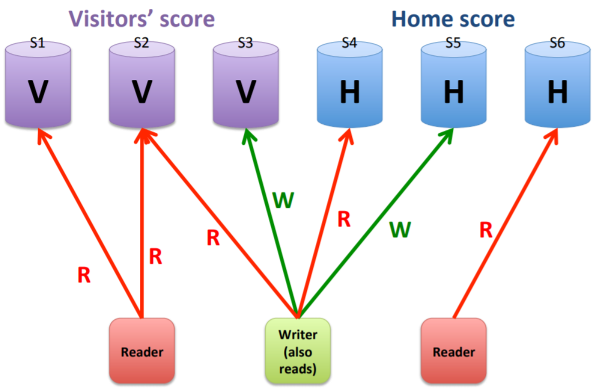


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write article;
```

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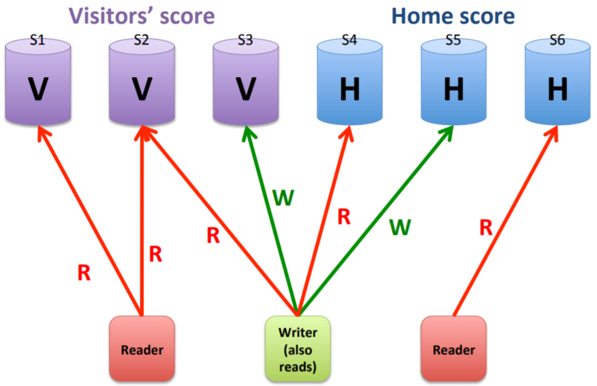


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Desired consistency?

Eventual

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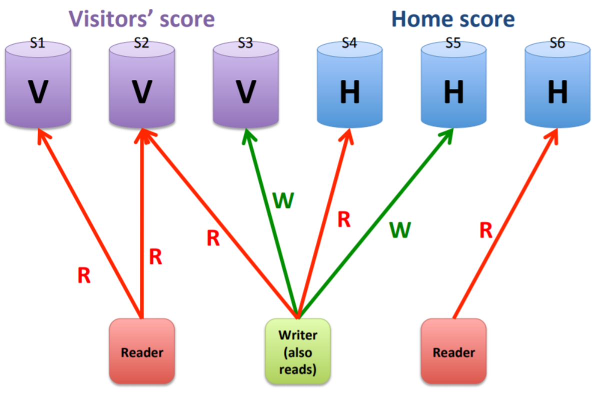


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    smoke cigar;
}
go out to dinner;
vScore = Read ("visitors");
hScore = Read ("home");
write article;
```

Desired consistency?

Eventual

Bounded Staleness

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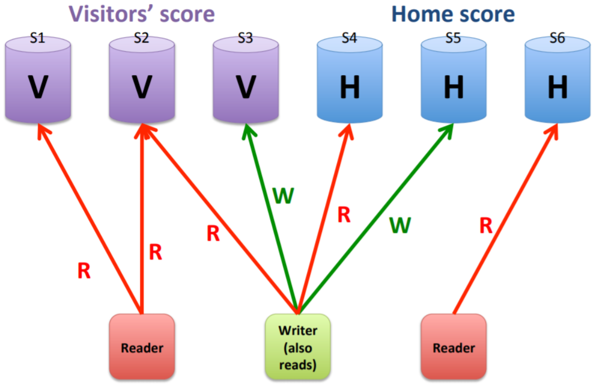
Statistician



Wait for end of game;
score = **Read** ("home");
stat = **Read** ("season-goals");
Write ("season-goals", stat + score);

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
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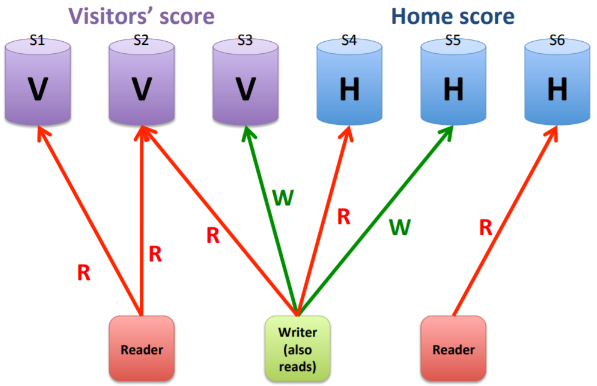


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```

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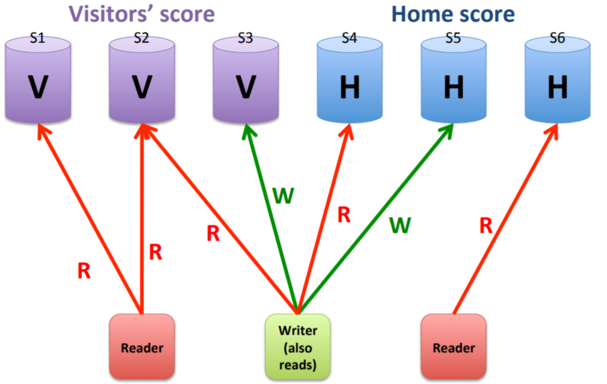


```
Wait for end of game;
score = Read ("home");
stat = Read ("season-goals");
Write ("season-goals", stat + score);
```

Desired consistency?

Strong Consistency (1st read)

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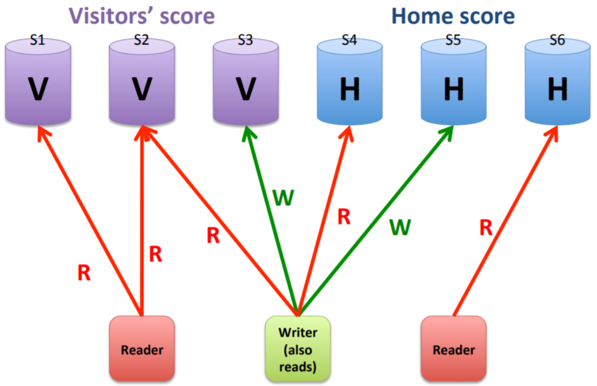


```
Wait for end of game;
score = Read ("home");
stat = Read ("season-goals");
Write ("season-goals", stat + score);
```

Desired consistency?

Strong Consistency (1st read)

Read My Writes (2nd read)

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Eventual Consistency	See subset of previous writes.
Consistent Prefix	See initial sequence of writes.
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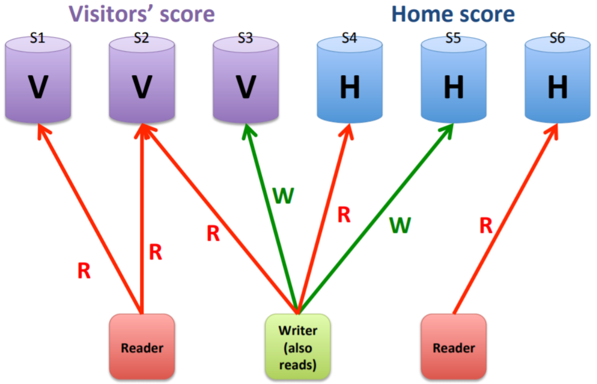
Stat Watcher




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

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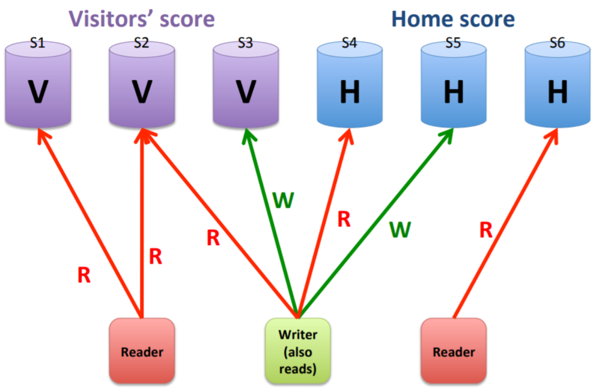


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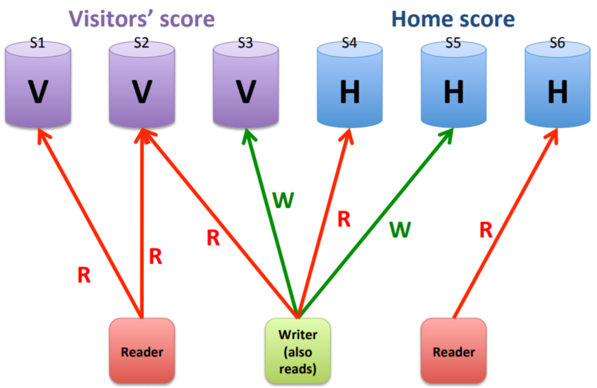


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Official scorekeeper:

score = **Read** (“visitors”);

Write (“visitors”

Read My Writes

Referee:

Strong Consistency

Radio reporter:

```
do {
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    report vScore and hSc
    sleep (30 minutes)
}
```

Consistent Prefix

Monotonic Reads

Sportswriter:

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Bounded Staleness

Statistician:

```
Wait for end of game;
score = Read ("home");
stat = Read ("season-goals");
Write ("season-goals", stat +
```

Strong Consistency

Read My Writes

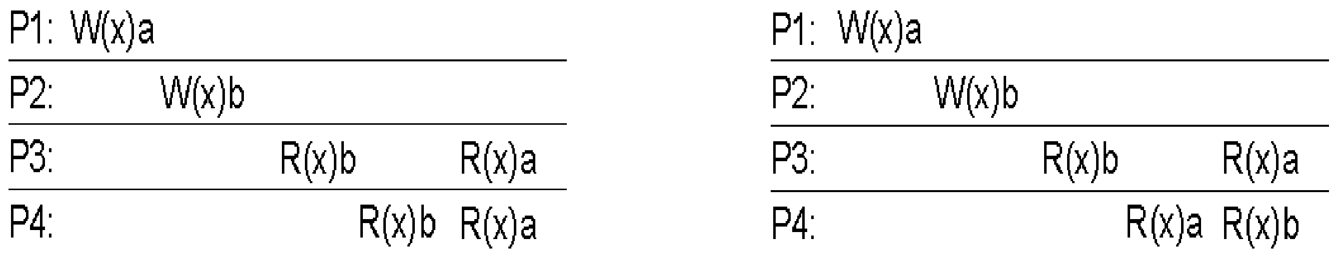
Stat watcher:

```
stat = Read ("season-runs")
discuss sta
```

Eventual Consistency

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
    - Each process preserves its program order



(a) (b)

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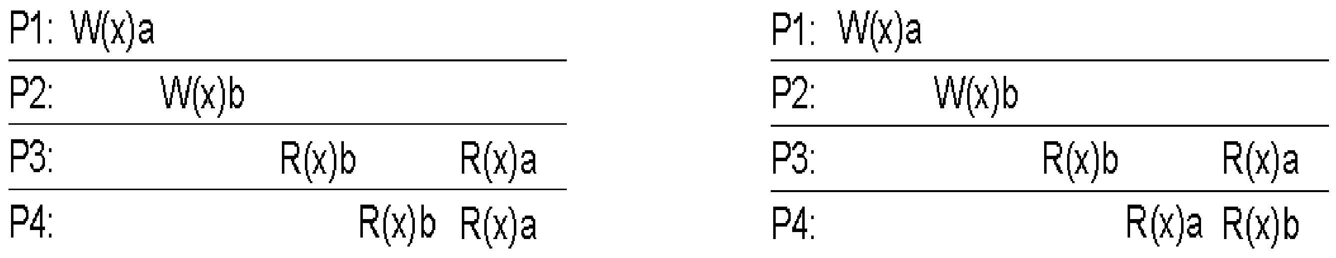

)

(b)

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

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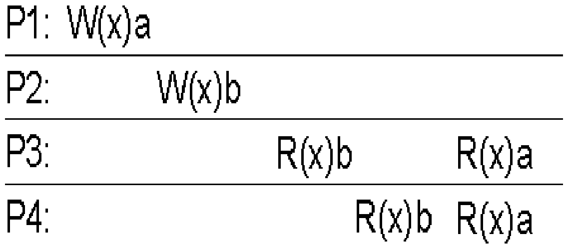

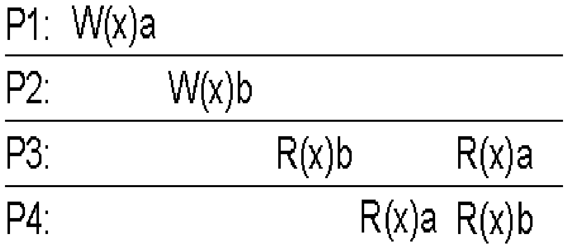

(b)

- ***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

Linearizability

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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

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

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

Causal consistency

- Causally related writes seen by all processes in same order.
  - *Causally?*
  - *Concurrent* writes may be seen in different orders on different machines

Causal consistency

- Causally related writes seen by all processes in same order.
  - *Causally?*
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P2:		R(x)a	W(x)b		
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(a)

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(a)

P1:	W(x)a			
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(b)

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(a)

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P1:	W(x)a			
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P4:			R(x)a	R(x)b

(b)

Permitted

Consistency models summary

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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

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.

Non-Blocking Synchronization

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Locks: a litany of problems

Non-Blocking Synchronization

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- Deadlock

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Solution: don’t use locks

Non-Blocking Synchronization

Locks: a litany of problems

- Deadlock
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Lock-free programming

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- Subset of a broader class: ***Non-blocking Synchronization***

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- Built on atomic instructions like CAS + clever algorithmic tricks
- Lock-free *algorithms* are hard, so
- General approach: encapsulate lock-free algorithms in data structures
  - Queue, list, hash-table, skip list, etc.
  - New LF data structure → research result

Basic List Append

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```
struct Node
{
  int data;
  struct Node *next;
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void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data, head_ref);
    if (*head_ref == NULL) {
       *head_ref = new_node;
       return;
    }
    while (last->next != NULL)
        last = last->next;
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}
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```

- Is this thread safe?
- What can go wrong?

Example: List Append

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struct Node
{
  int data;
  struct Node *next;
};
```

```
void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data, head_ref);
    lock();
    if (*head_ref == NULL) {
        *head_ref = new_node;
    } else {
        while (last->next != NULL)
            last = last->next;
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    }
    unlock();
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```

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- What property do the locks enforce?

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- What property do the locks enforce?
- What does the mutual exclusion ensure?
- Can we ensure consistent view (invariants hold) sans mutual exclusion?

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- What property do the locks enforce?
- What does the mutual exclusion ensure?
- Can we ensure consistent view (invariants hold) sans mutual exclusion?
- Key insight: allow inconsistent view and fix it up algorithmically

Example: List Append

struct Node

: data;
:uct Node *next;

```
void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data);
    new_node->next = NULL;
    while(TRUE) {
        Node * last = *head_ref;
        if(last == NULL) {
            if(cas(head_ref, new_node, NULL))
                break;
        }
        while(last->next != NULL)
            last = last->next;
        if(cas(&last->next, new_node, NULL))
            break;
    }
}
```

e?

nsure?

- Can we ensure consistent view (invariants hold) sans mutual exclusion?
- Key insight: allow inconsistent view and fix it up algorithmically

Example: SP-SC Queue

```
next(x):
    if(x == Q_size-1) return 0;
    else return x+1;

Q_get(data):
    t = Q_tail;
    while(t == Q_head)
      ;
    data = Q_buf[t];
    Q_tail = next(t);
```

```
Q_put(data):
    h = Q_head;
    while(next(h) == Q_tail)
      ;
    Q_buf[h] = data;
    Q_head = next(h);
```

- Single-producer single-consumer
- Why/when does this work?

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next(x):
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    h = Q_head;
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    Q_buf[h] = data;
    Q_head = next(h);
```

- Single-producer single-consumer
- Why/when does this work?

1. Q_head is last write in Q_put, so Q_get never gets “ahead”.
2. *single* p,c only (as advertised)
3. Requires fence before setting Q head
4. Devil in the details of “wait”
5. No lock → “optimistic”

Lock-Free Stack

```
struct Node
{
  int data;
  struct Node *next;
};
```

```
void push(int t) {
    Node* node = new Node(t);
    do {
        node->next = head;
    } while (!cas(&head, node, node->next));
}
```

```
bool pop(int& t) {
    Node* current = head;
    while(current) {
        if(cas(&head, current->next, current)) {
            t = current->data;
            return true;
        }
        current = head;
    }
    return false;
}
```

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- Why does is it work?

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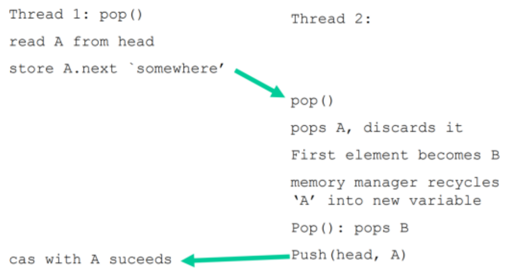
```

- Why does is it work?
- Does it enforce all invariants?

Lock-Free Stack: ABA Problem



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Node* pop() {
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}
```

Thread 1: pop()	Thread 2:
read A from head	
store A.next `somewhere’	
	pop()
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	First element becomes B
	memory manager recycles ‘A’ into new variable
	Pop(): pops B
cas with A suceeds	Push(head, A)

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Node* pop() {
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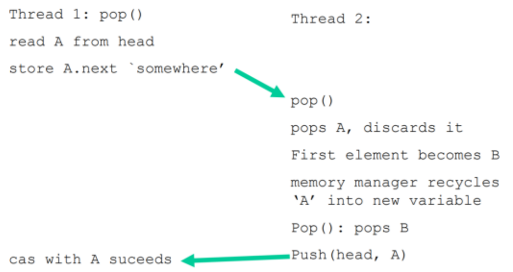
```
Node * node = pop();
delete node;
node = new Node(blah_blah);
push(node);
```



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cas with A suceeds

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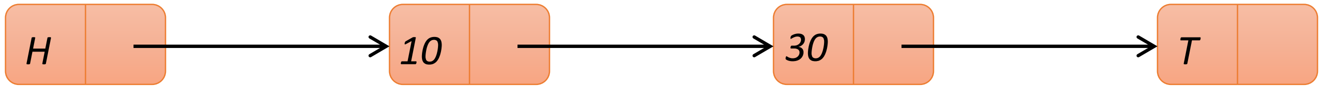
ABA Problem

- Thread 1 observes shared variable → 'A'
- Thread 1 calculates using that value
- Thread 2 changes variable to B
  - if Thread 1 wakes up now and tries to CAS, CAS fails and Thread 1 retries
- Instead, Thread 2 changes variable back to A!
  - CAS succeeds despite mutated state
  - Very bad if the variables are pointers

- Keep update count → DCAS
- Avoid re-using memory
- Multi-CAS support → HTM

Correctness: Searching a sorted list

- find(20):



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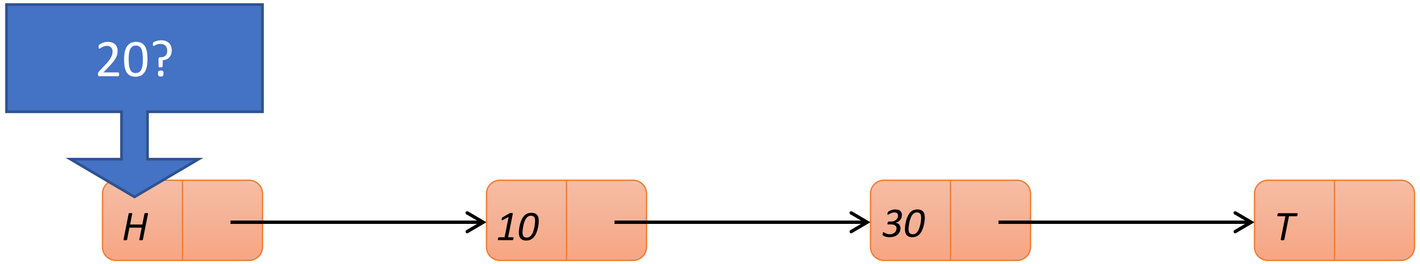

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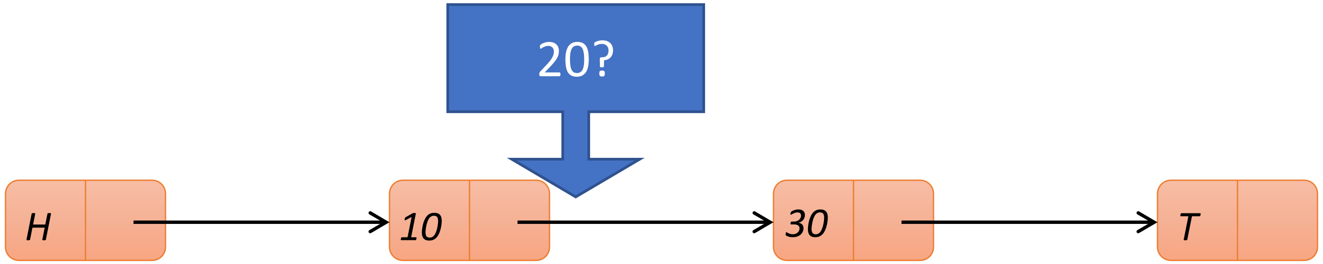

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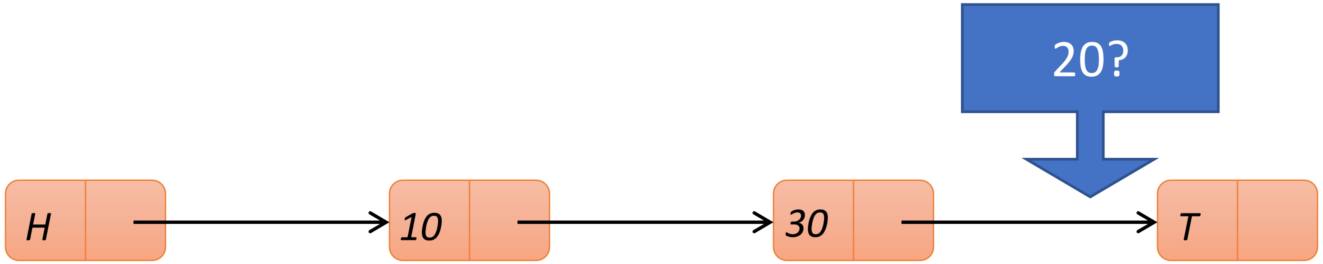
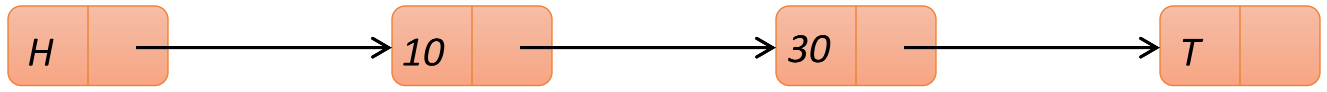


find(20) -> false

Inserting an item with CAS

- insert(20):



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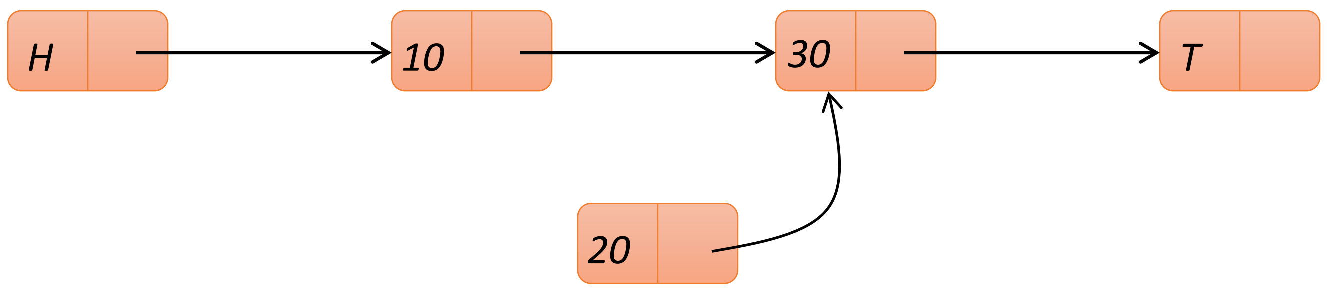

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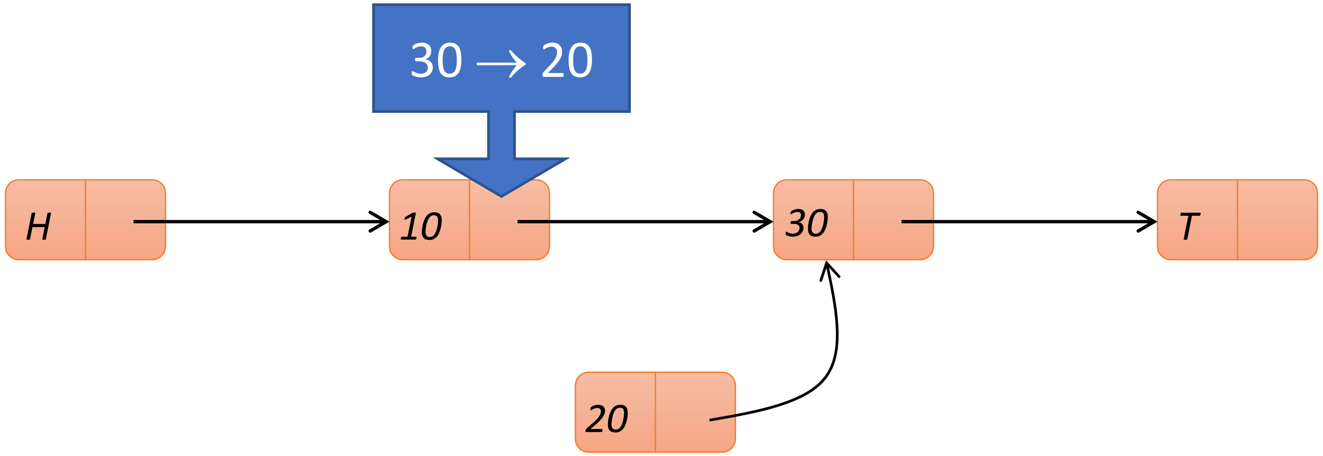

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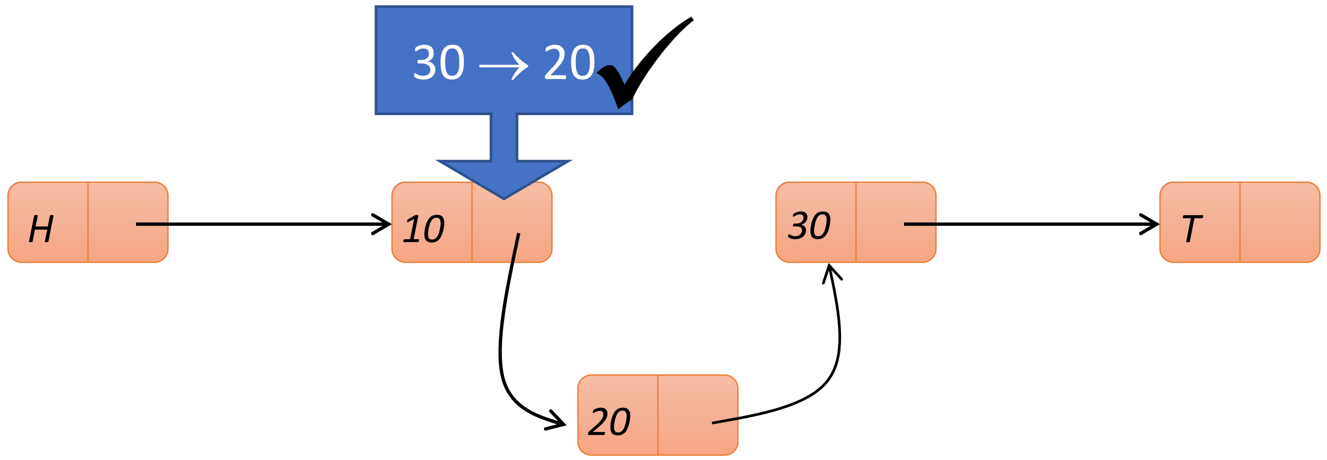
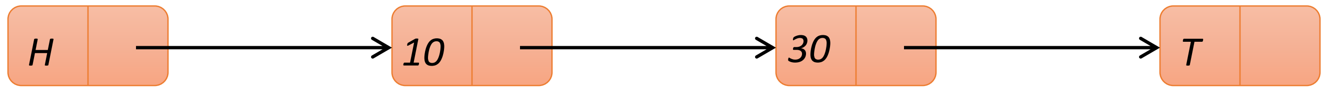


insert(20) -> true

Inserting an item with CAS



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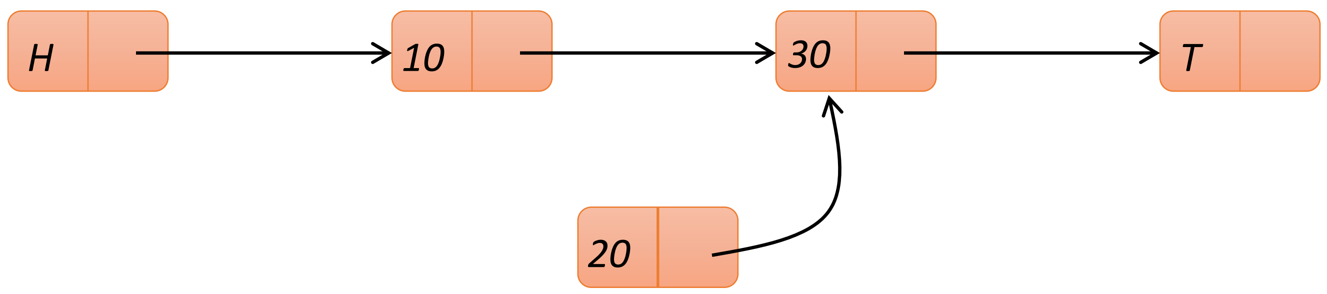

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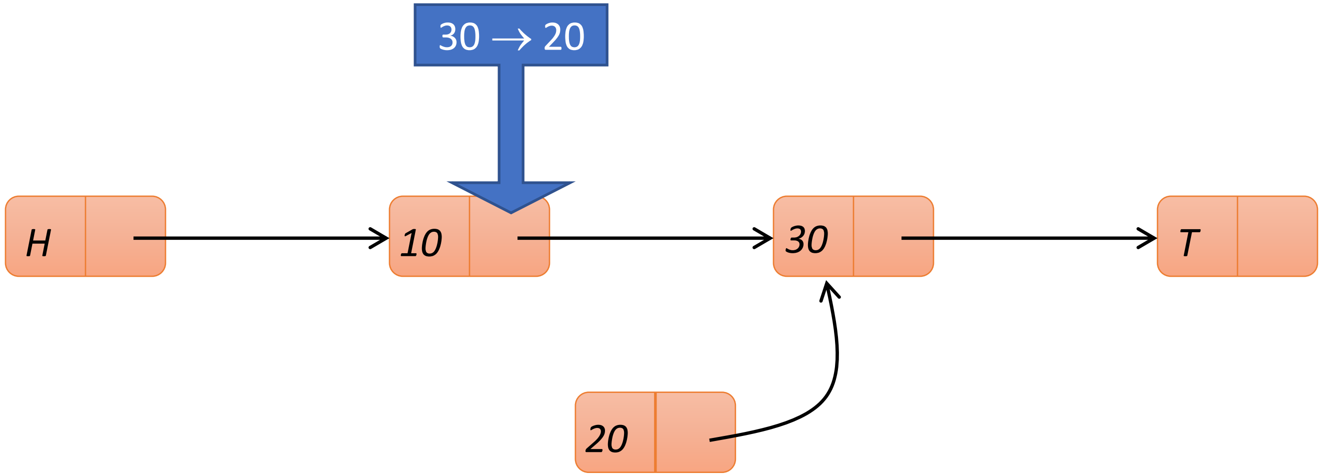
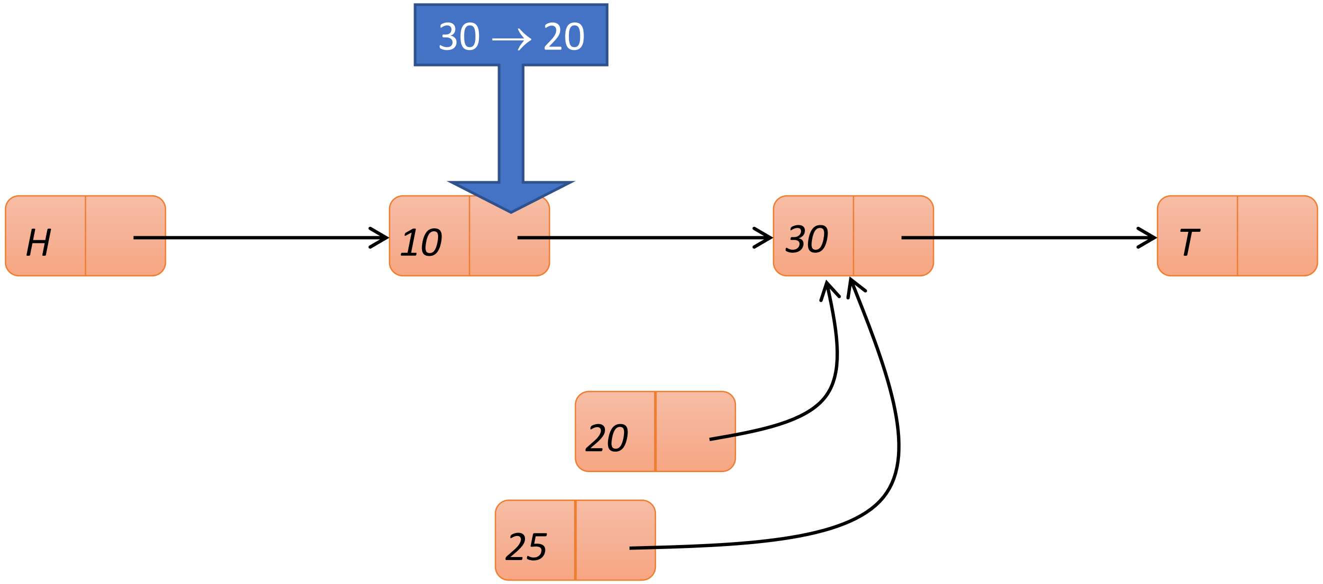


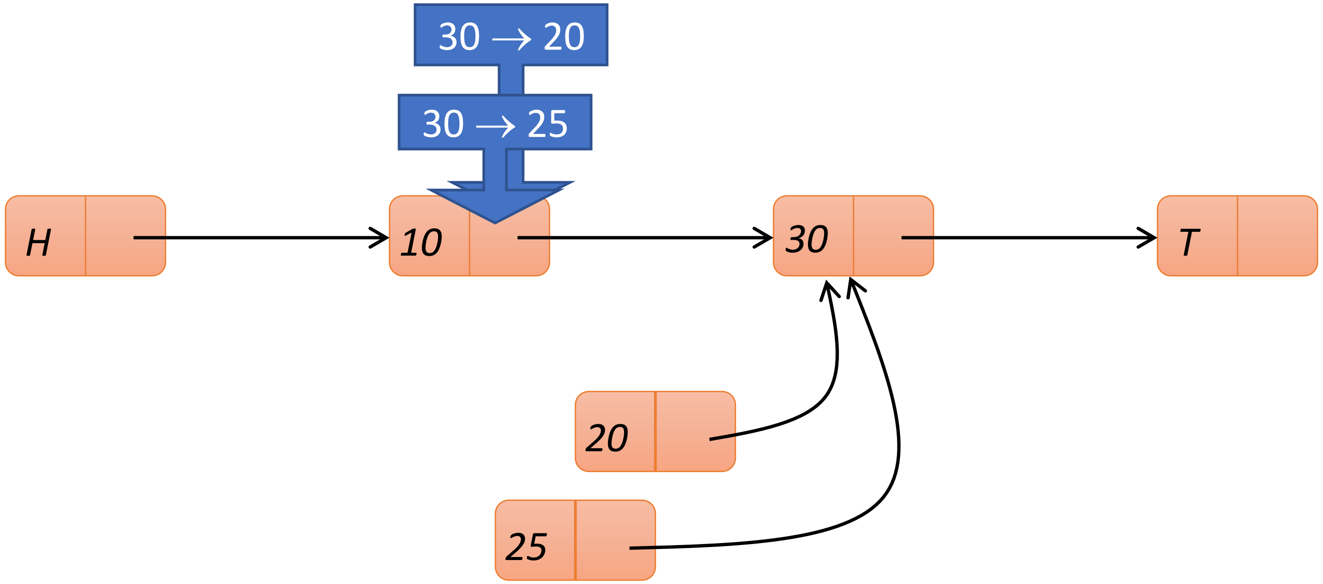
Inserting an item with CAS

- insert(20):
- insert(25):



Inserting an item with CAS

- insert(20):
- insert(25):



Inserting an item with CAS

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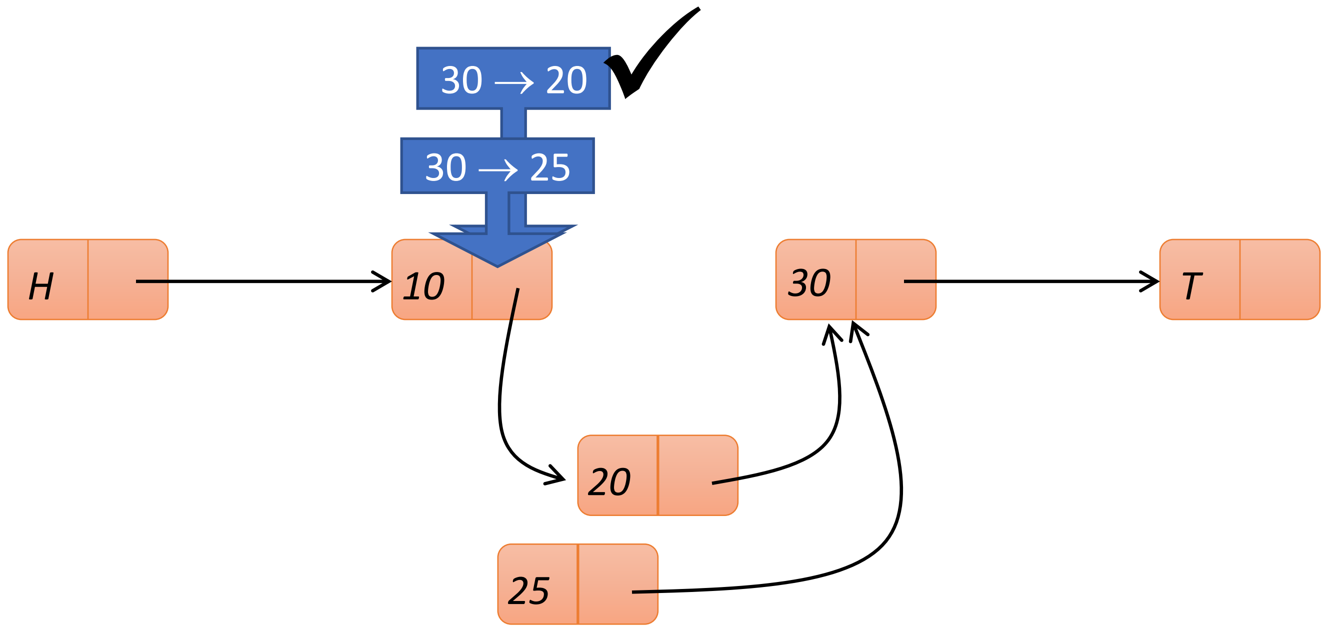

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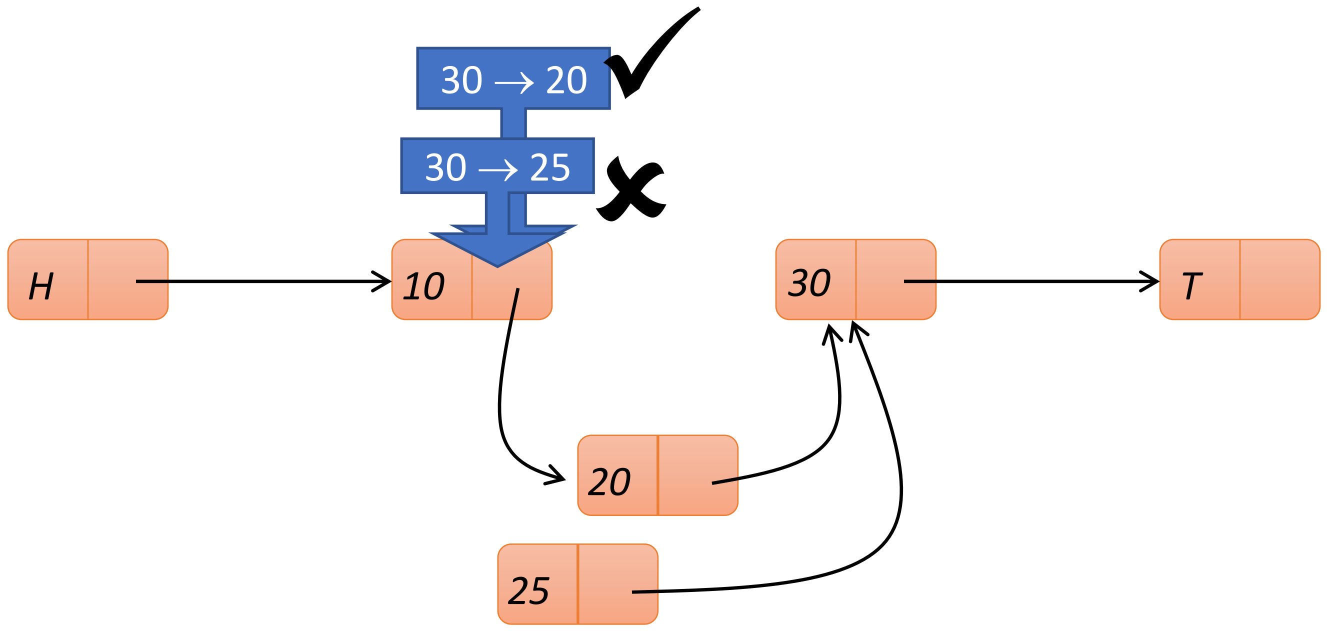
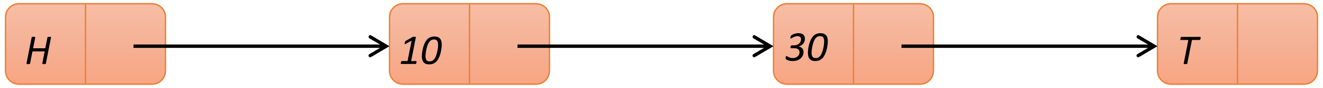


Searching and finding together

- find(20)



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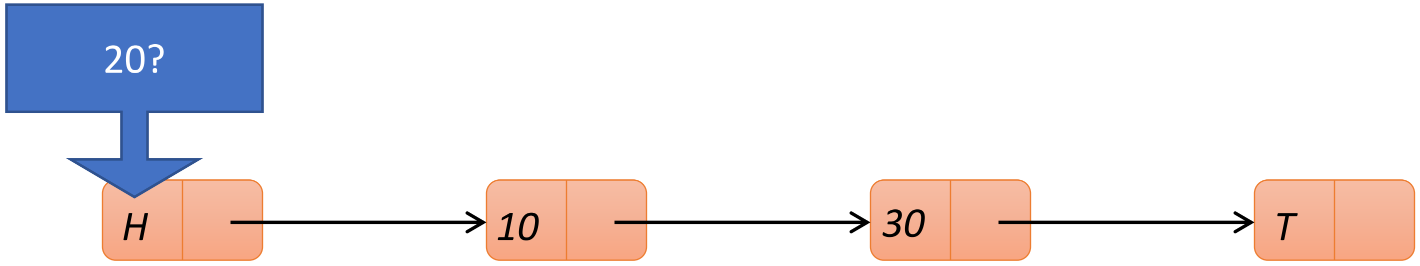

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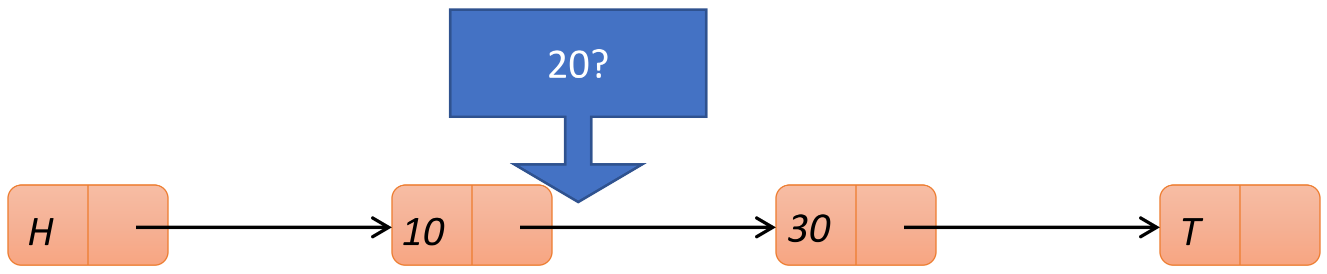

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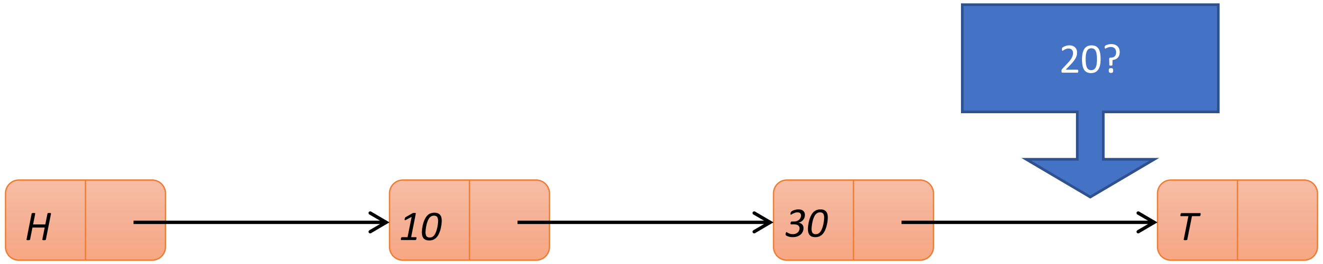

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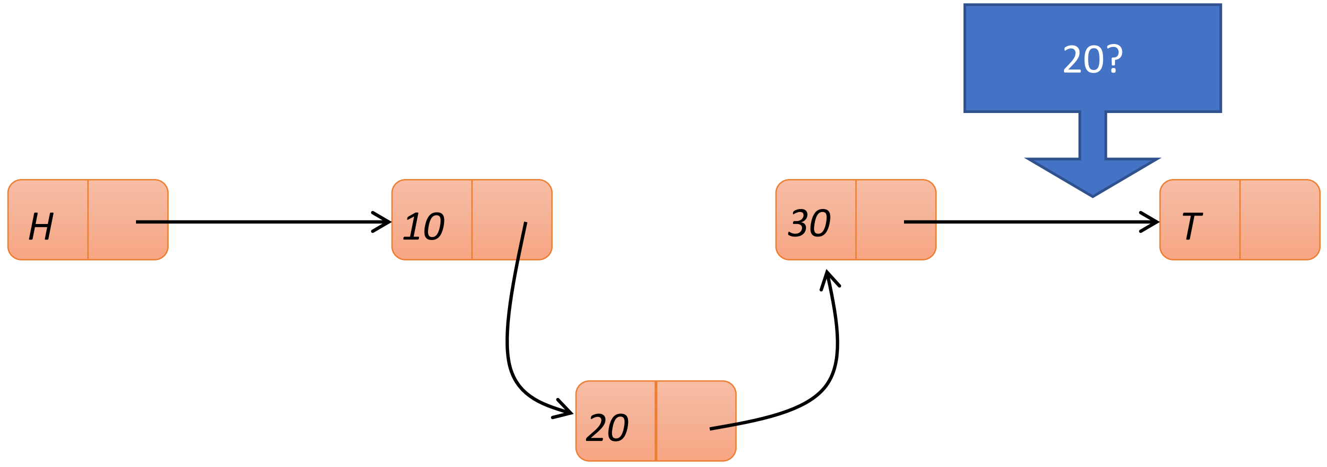

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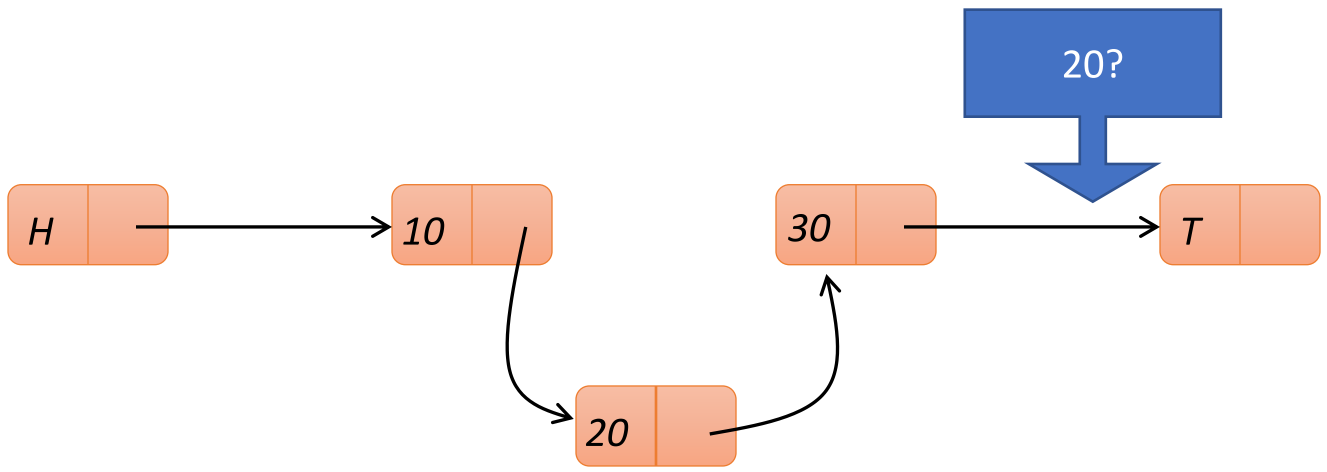


Searching and finding together

- find(20) -> false
- insert(20) -> true

This thread saw 20 was not in the set...

...but this thread succeeded in putting it in!

- Is this a correct implementation?
- Should the programmer be surprised if this happens?
- What about more complicated mixes of operations?

Correctness criteria

Informally:

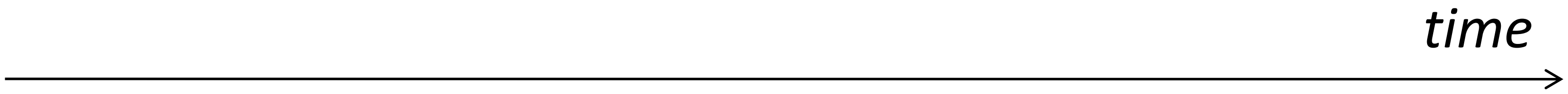
Look at the behavior of the data structure

- what operations are called on it
- what their results are

If behavior is indistinguishable from atomic calls to a sequential implementation then the concurrent implementation is correct.

Sequential history

- No overlapping invocations



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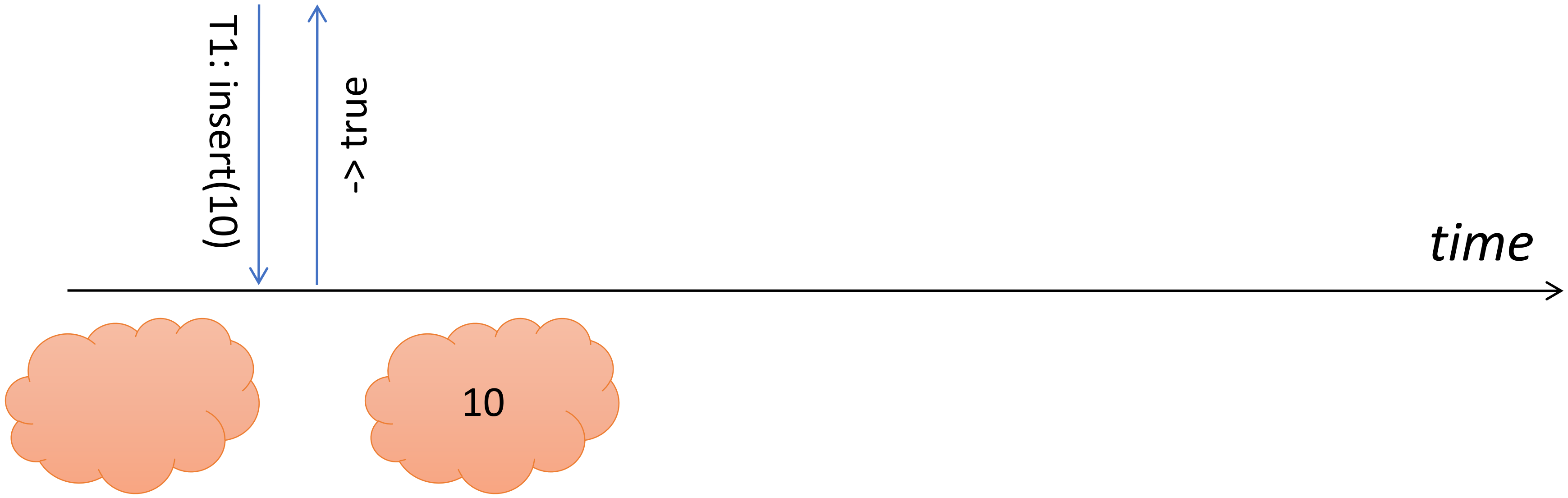

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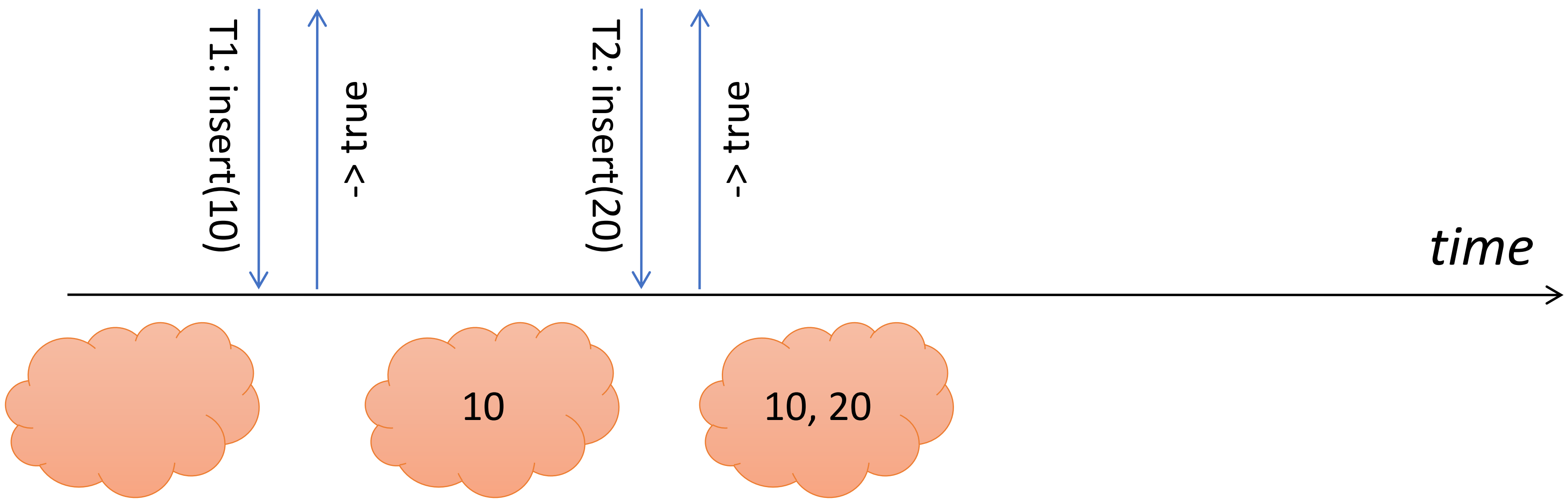

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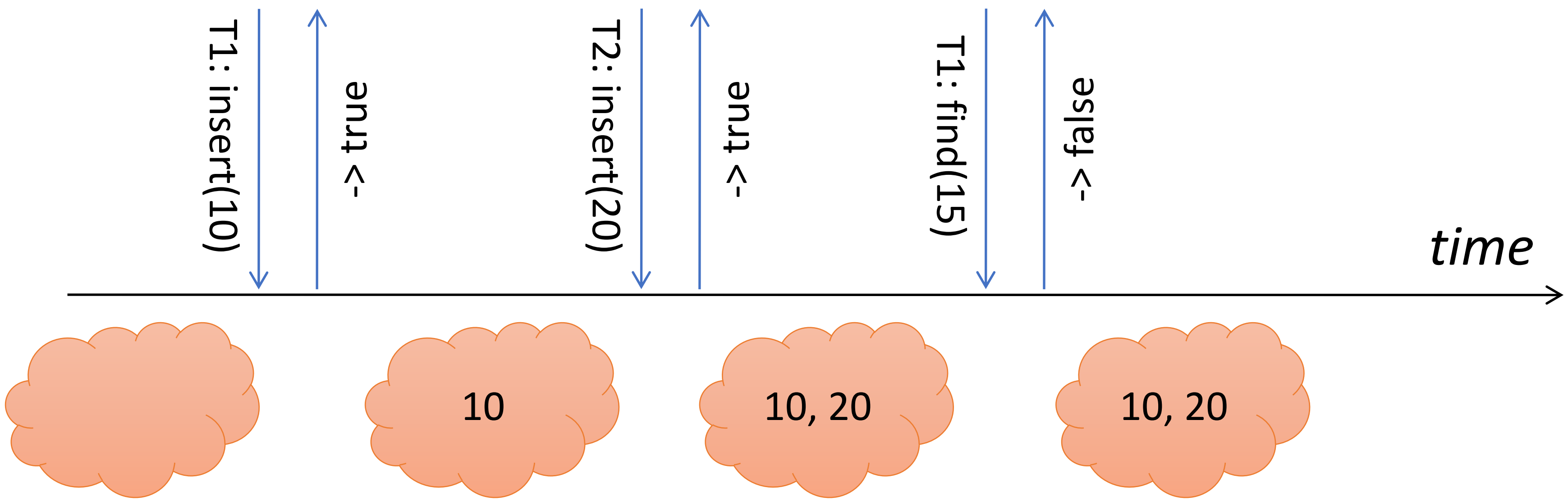

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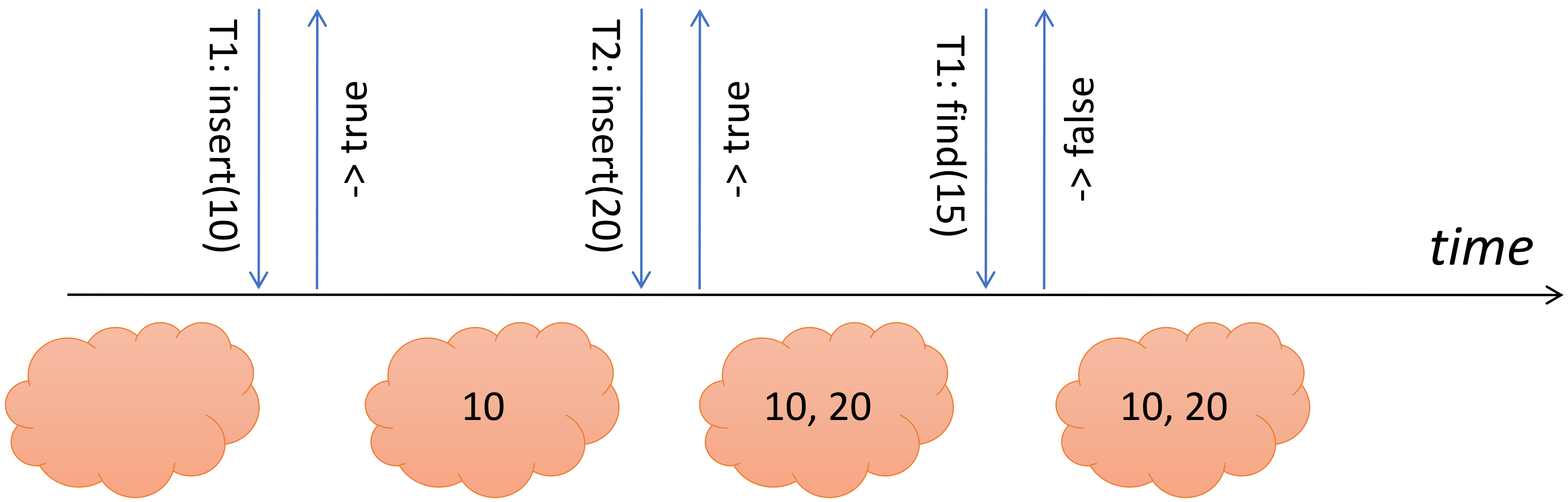
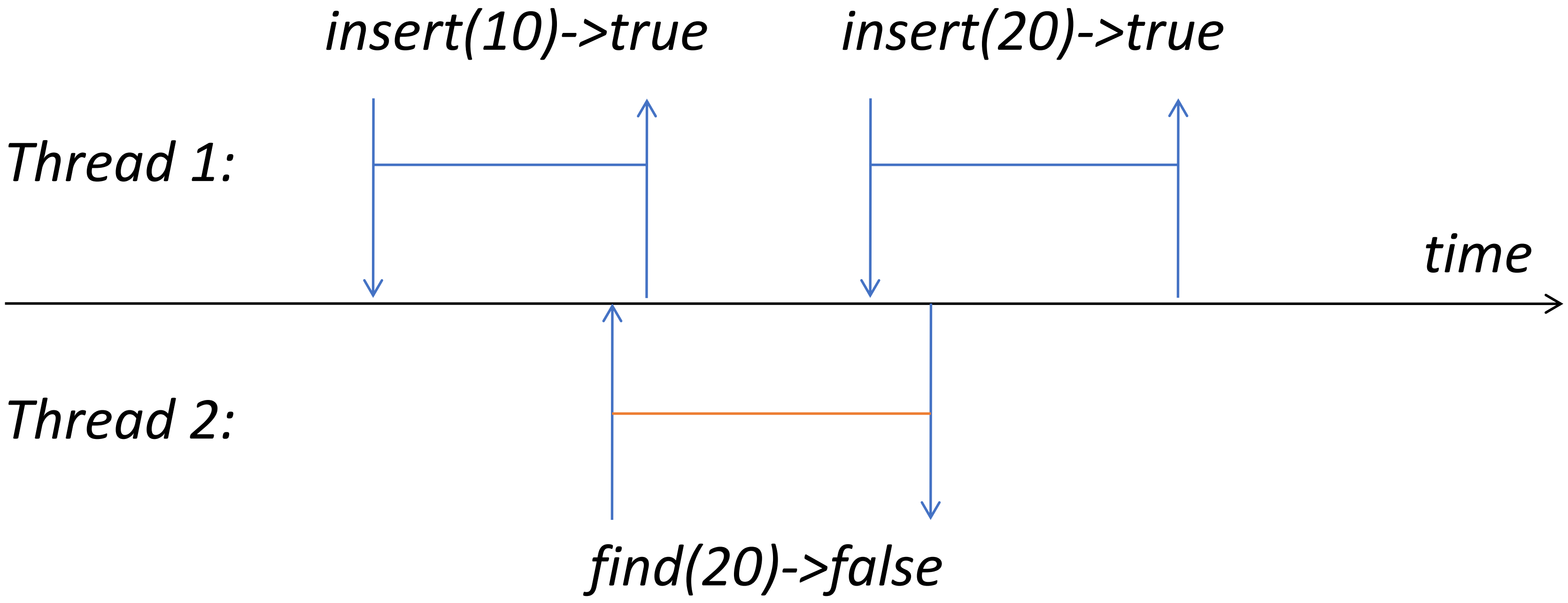


Linearizability: concurrent behaviour should be similar

- even when threads can see intermediate state
- Recall: mutual exclusion precludes overlap

Concurrent history

Allow *overlapping* invocations



Concurrent history

Linearizability:

- Is there a correct sequential history:
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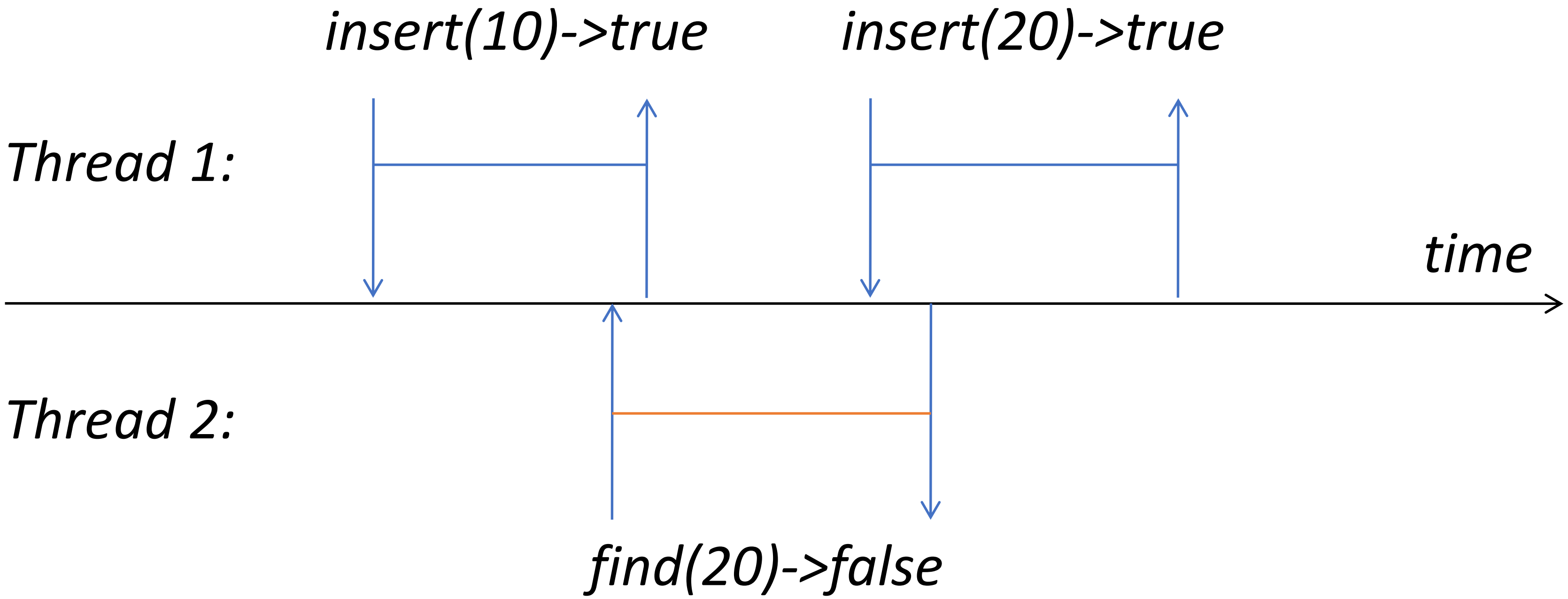

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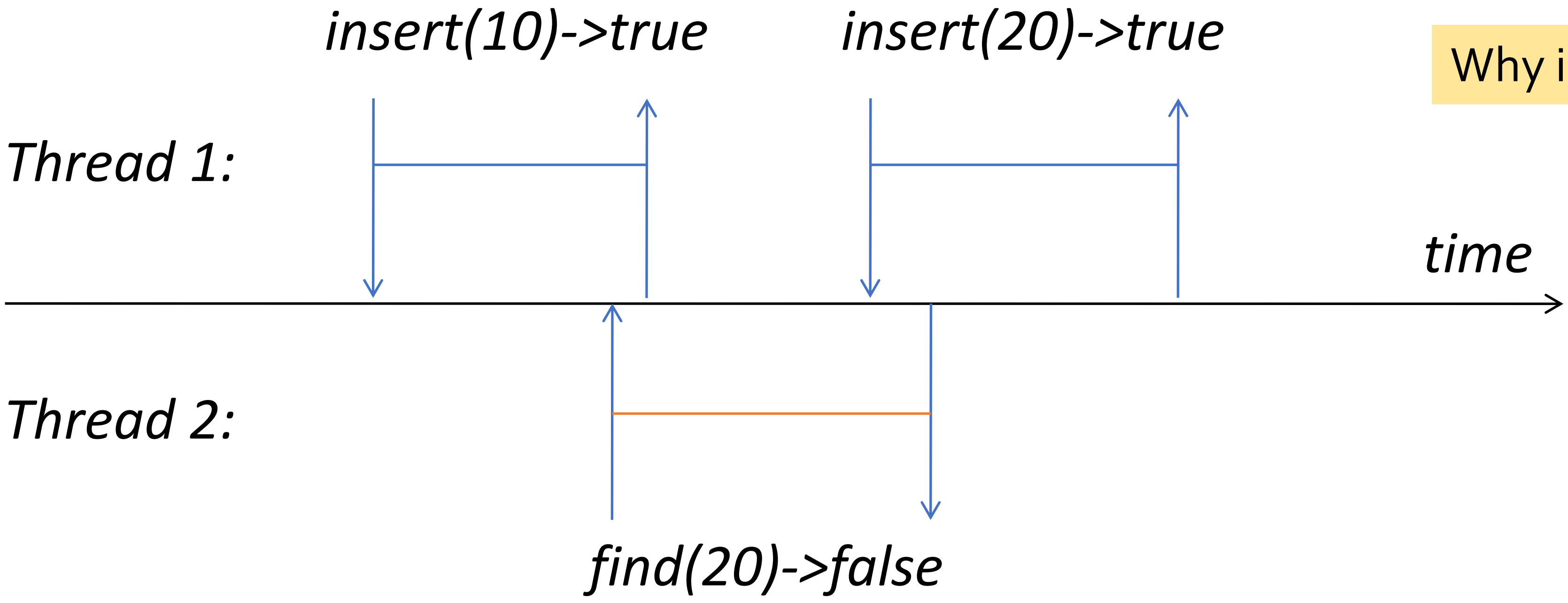

Why is this one OK?

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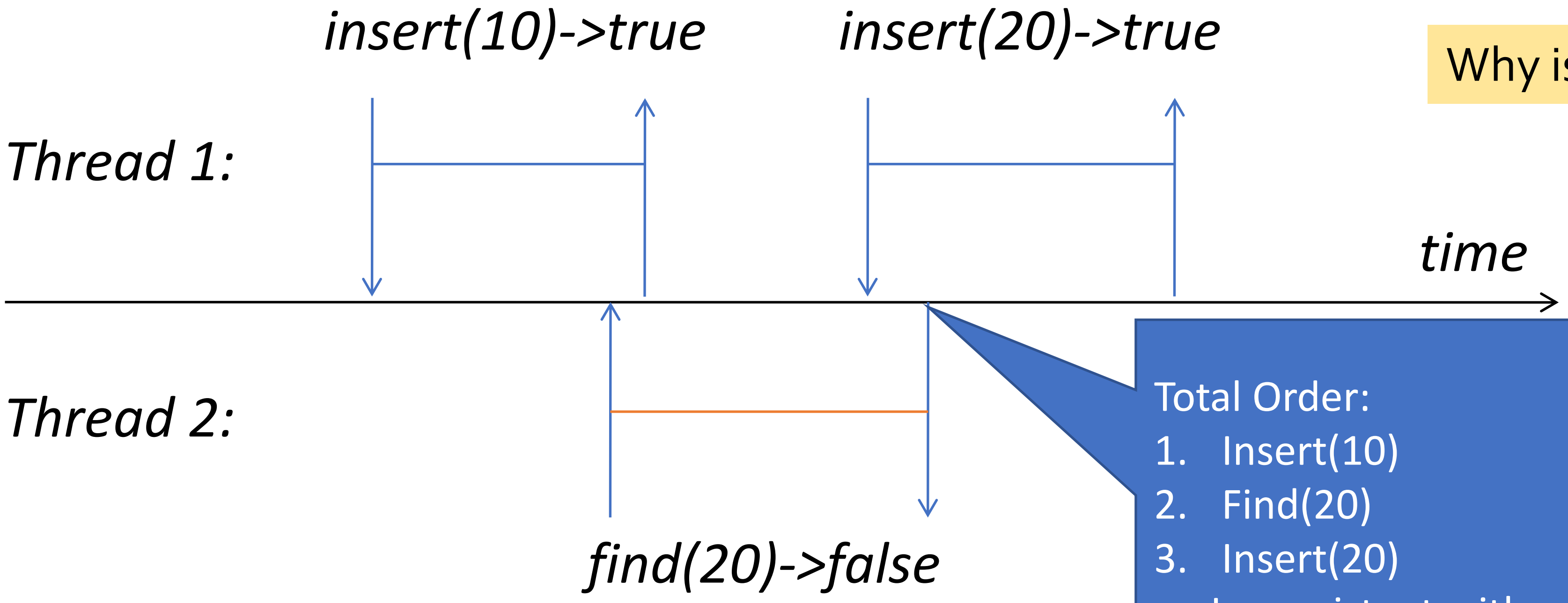
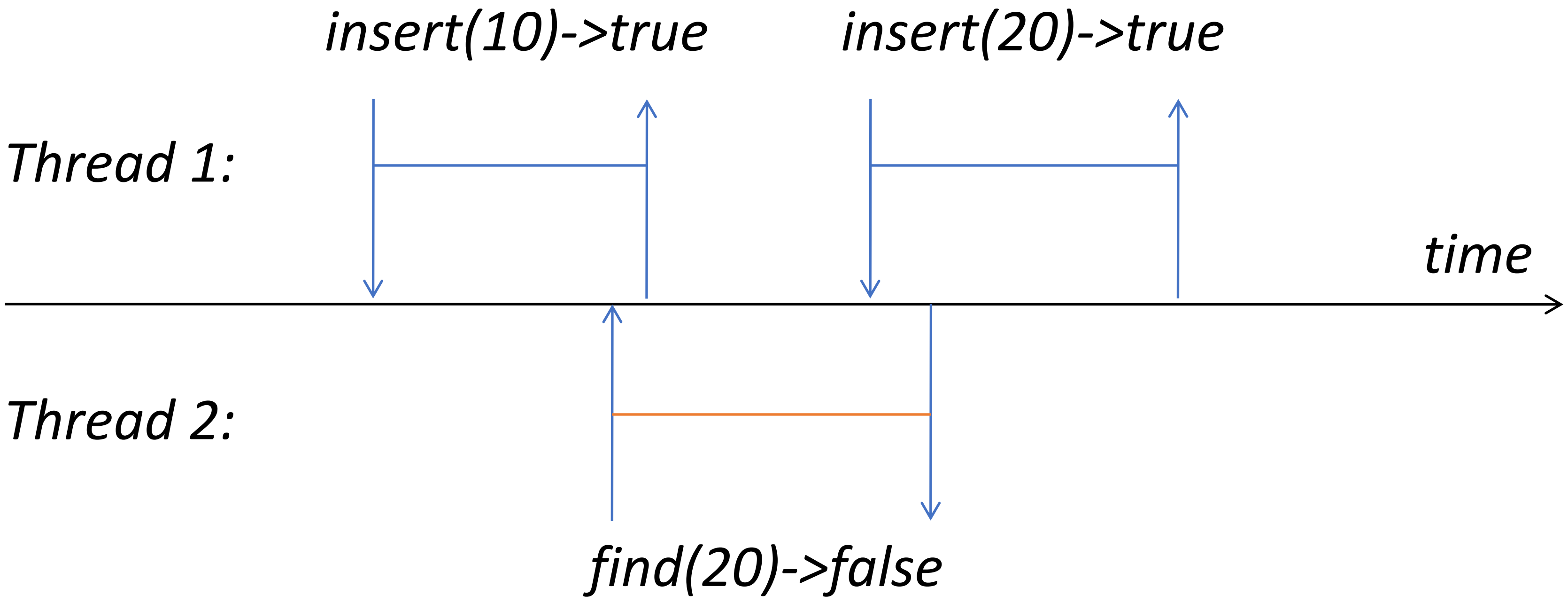


Total Order:

1. Insert(10)
2. Find(20)
3. Insert(20)

- Is consistent with real-time order
- 2, 3 overlap, but return order OK

Example: linearizable



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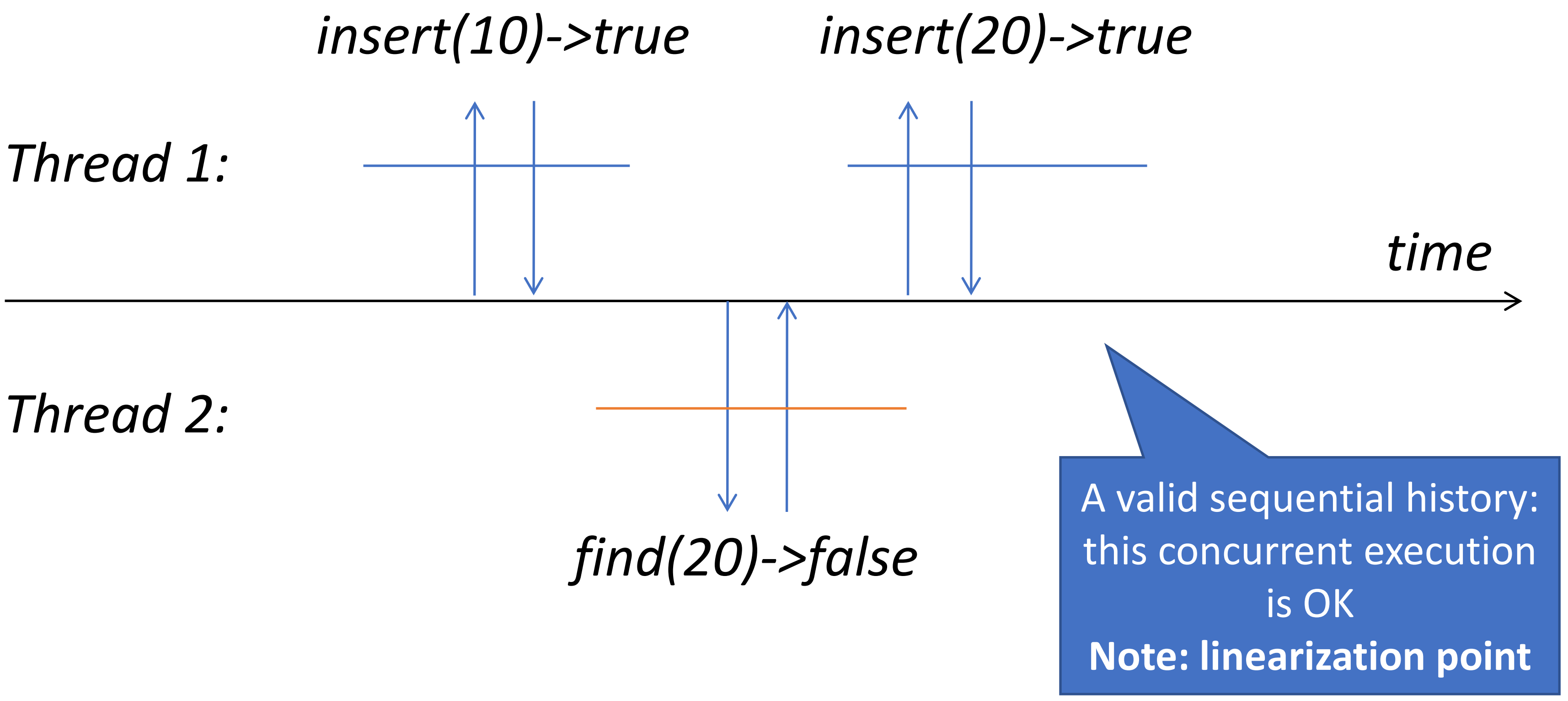

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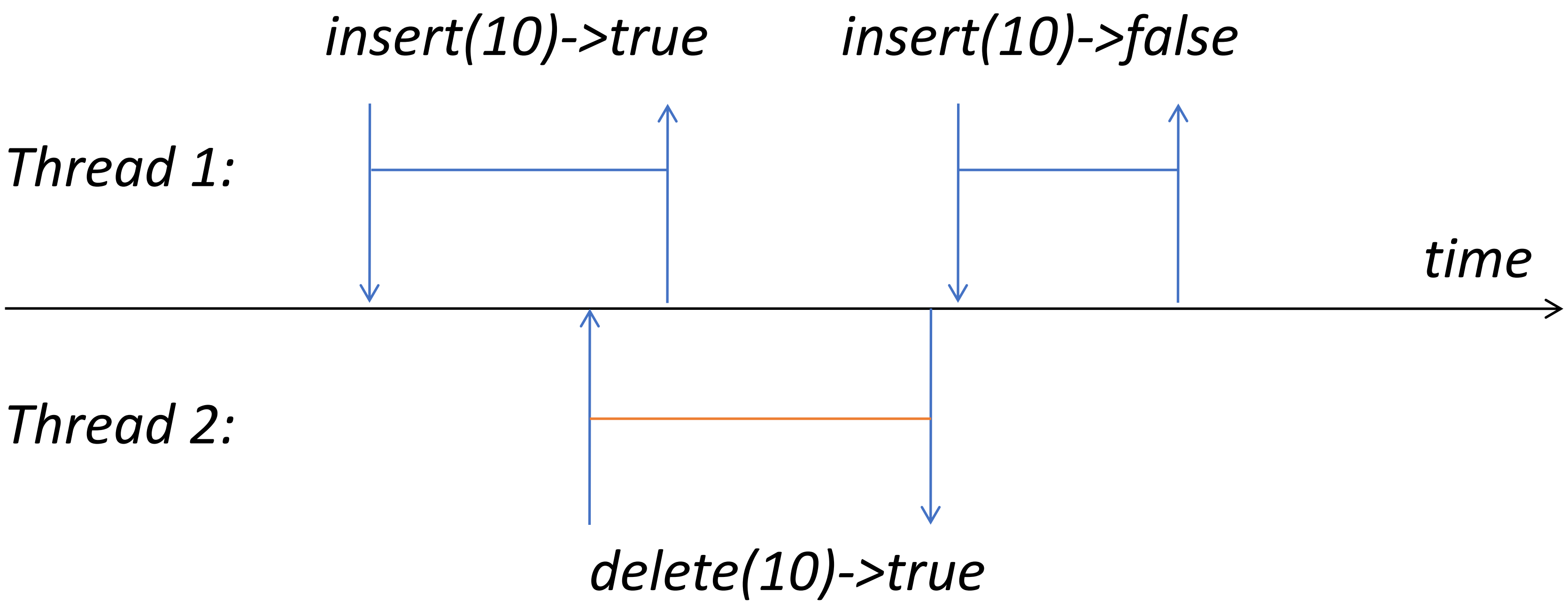

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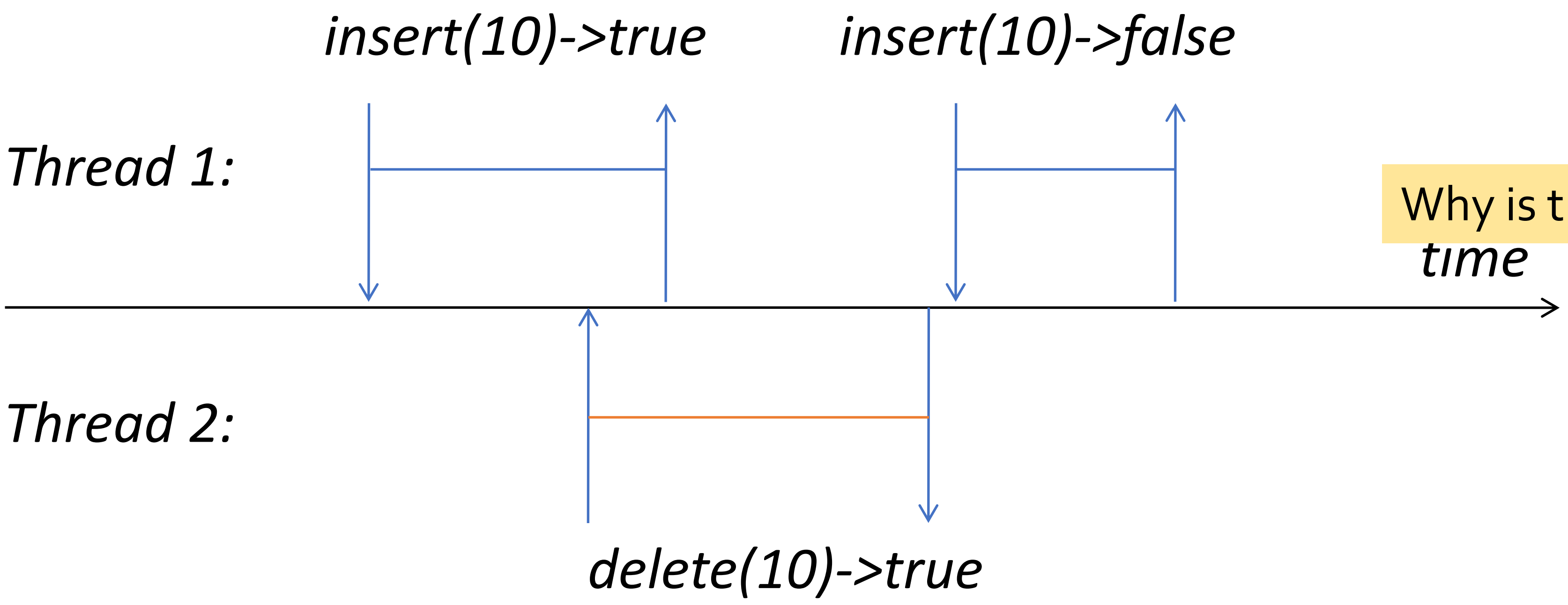

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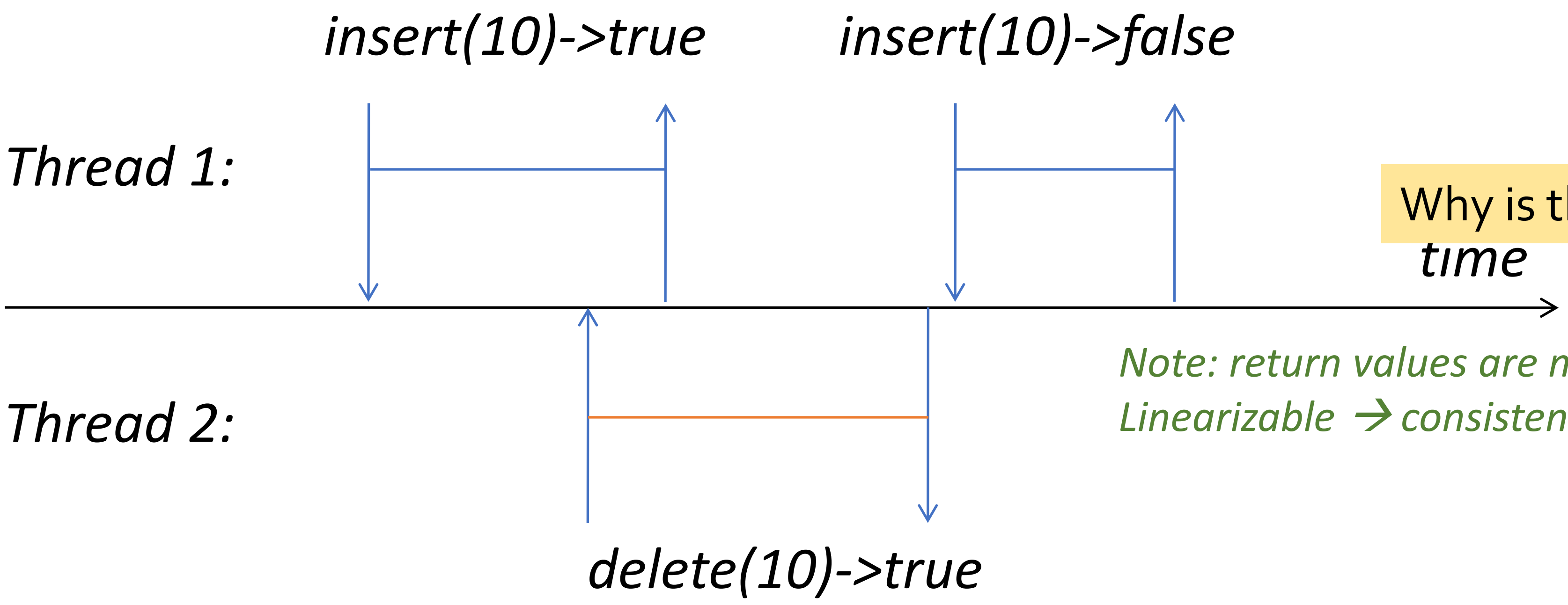

Why is this one NOT OK?

Note: return values are meaningful!
Linearizable → consistent with return values

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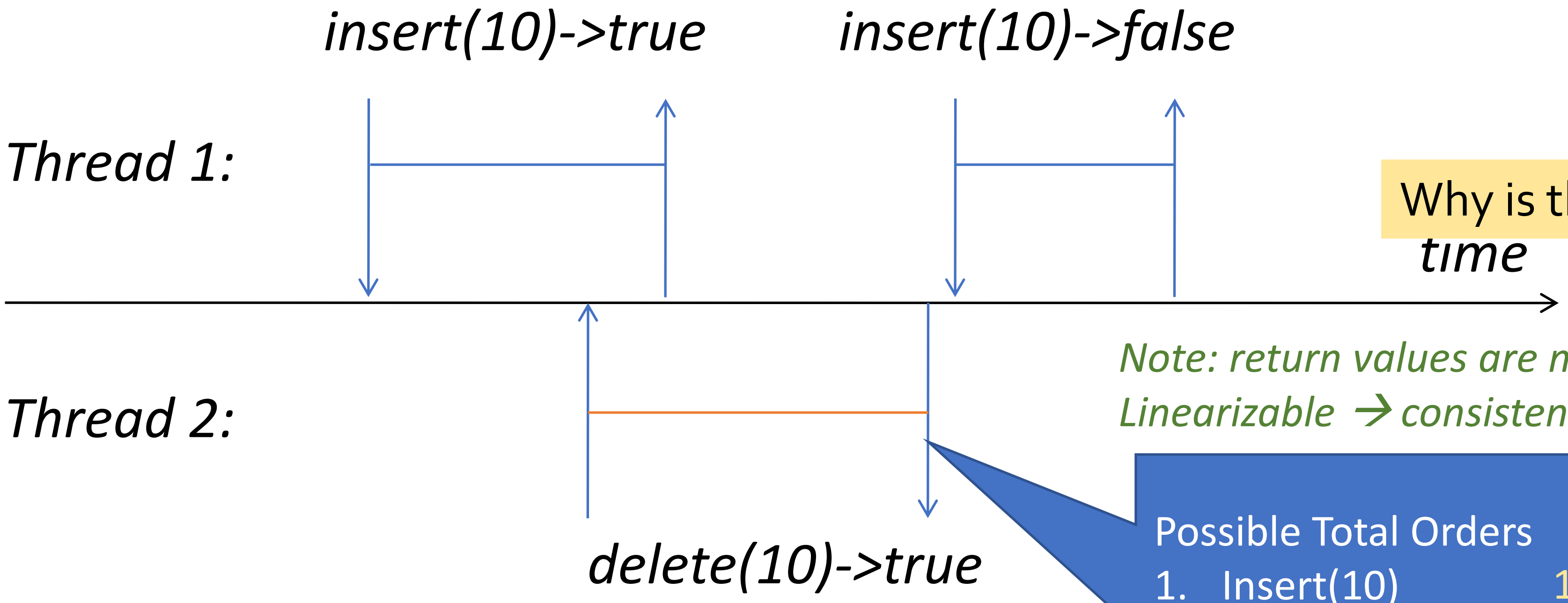

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1. Insert(10)
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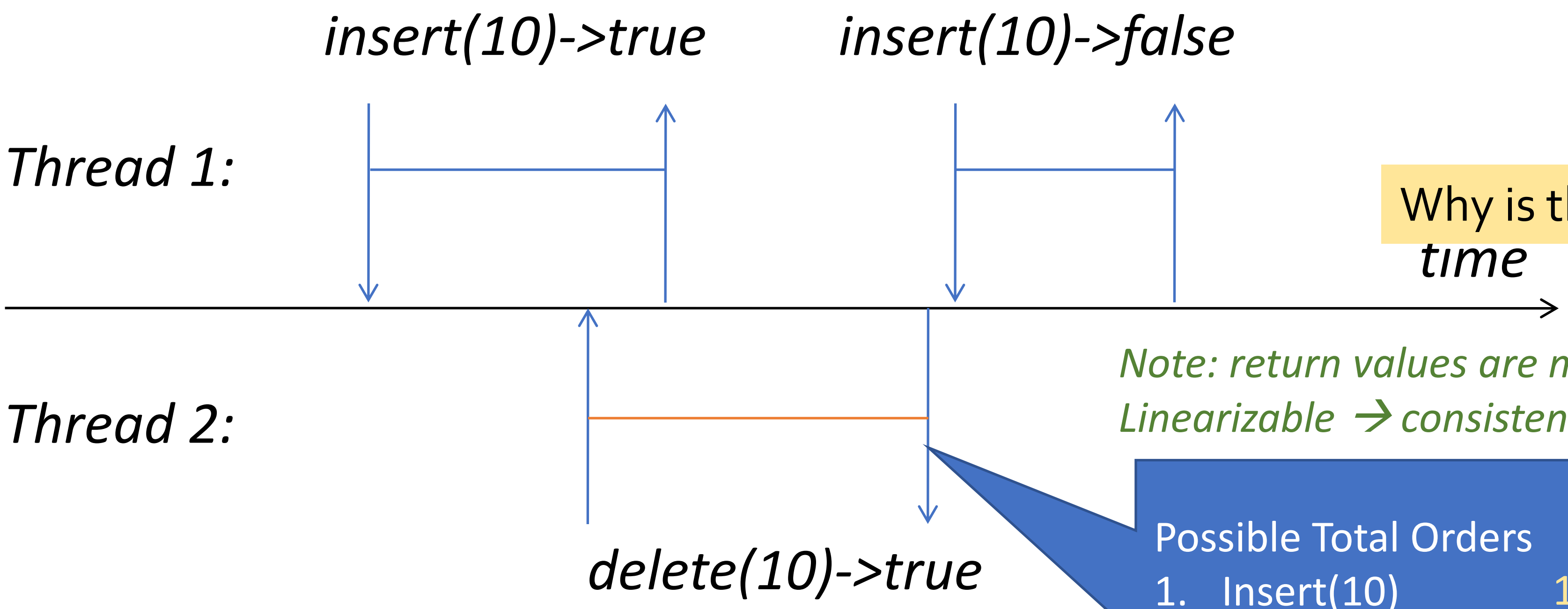

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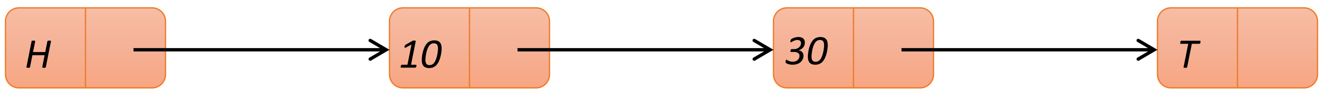
How can things like this happen?

Example Revisited

- find(20)



Thread 1:

Thread 2:

Example Revisited

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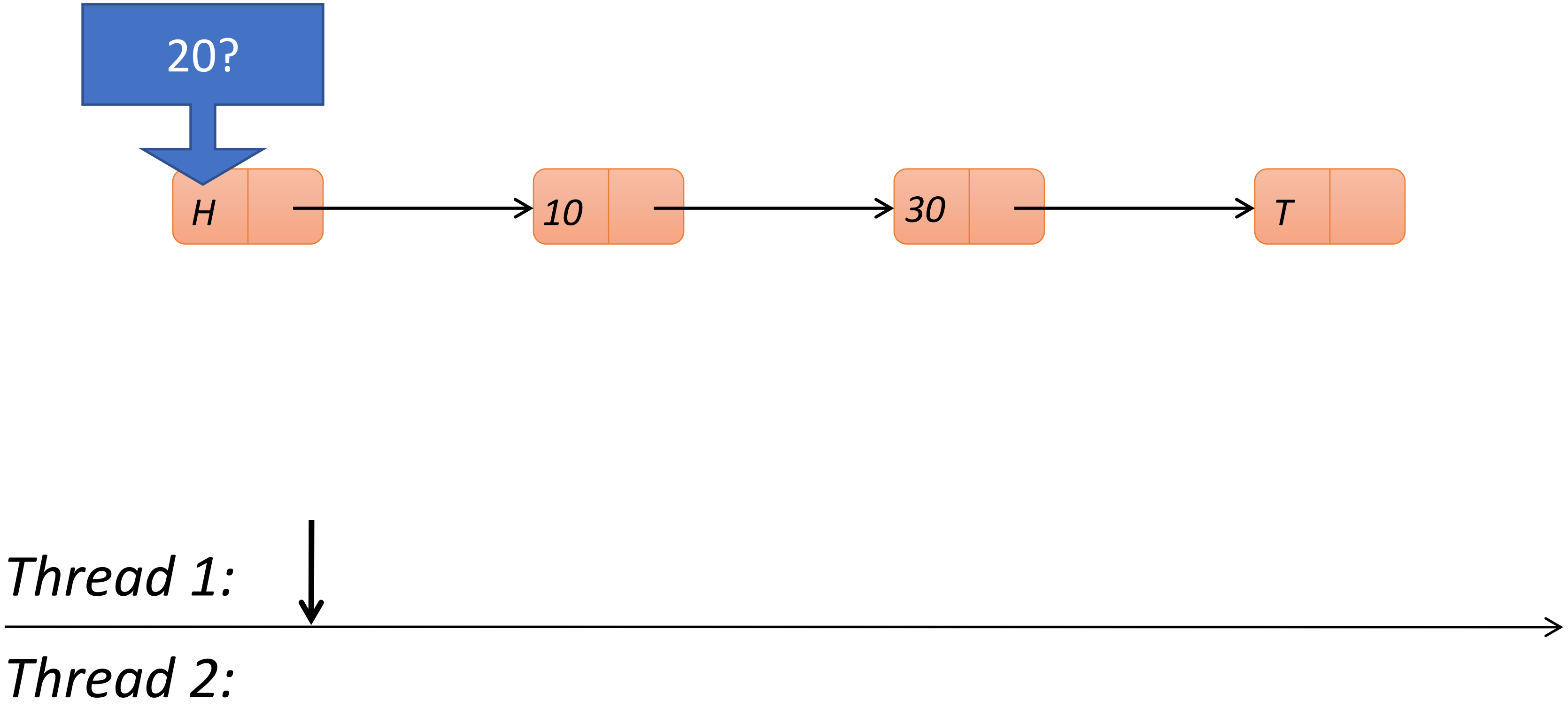

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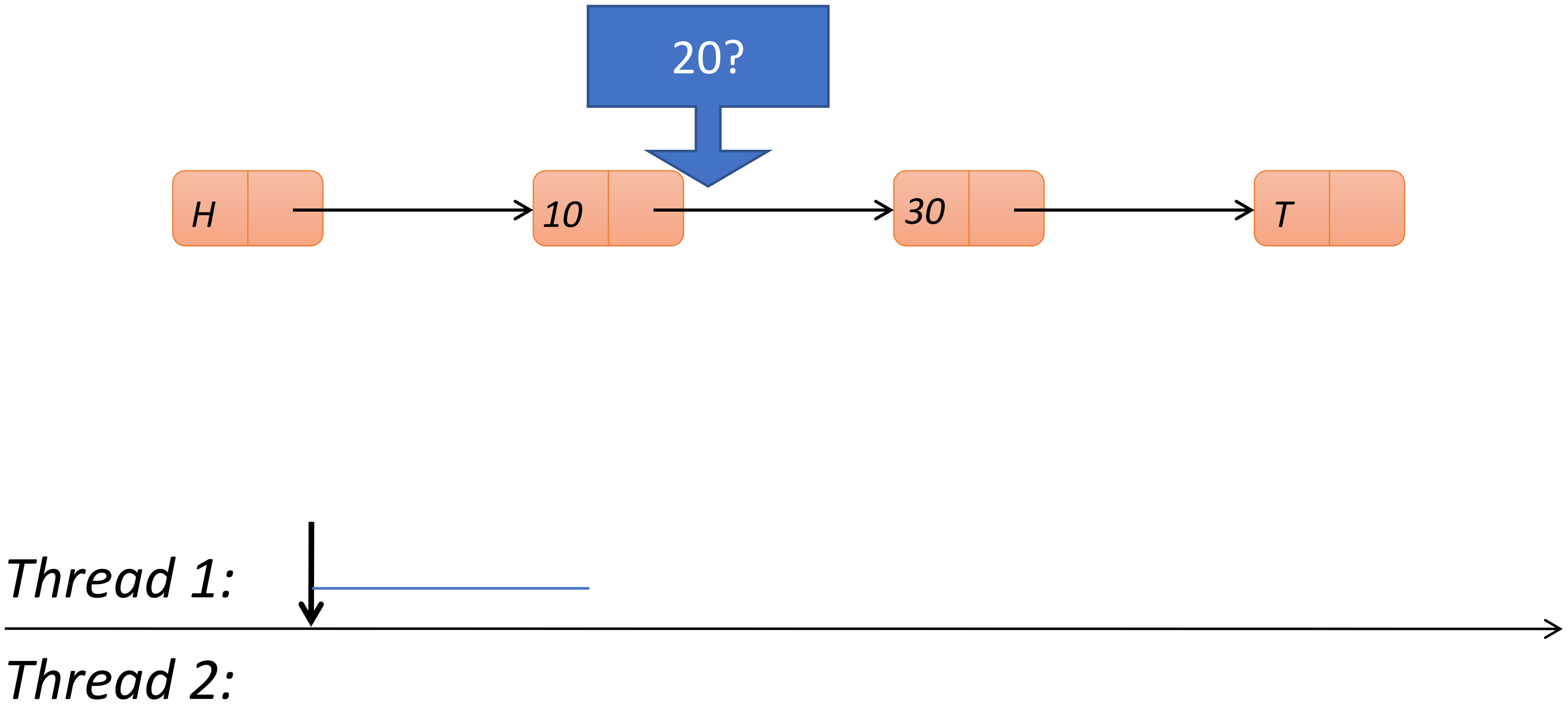

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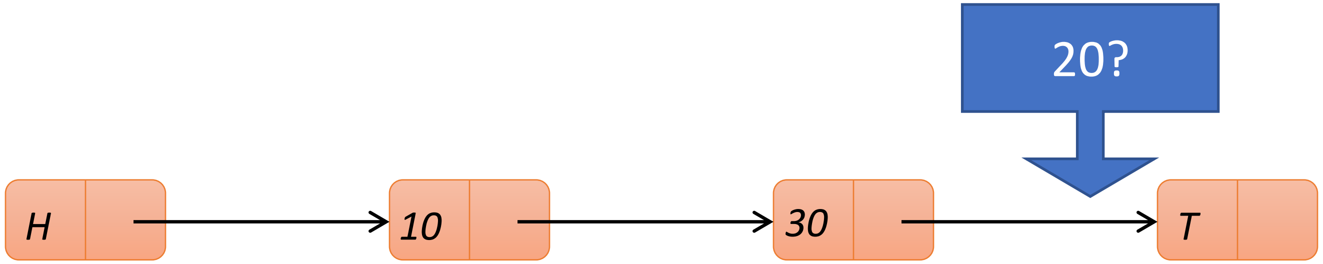

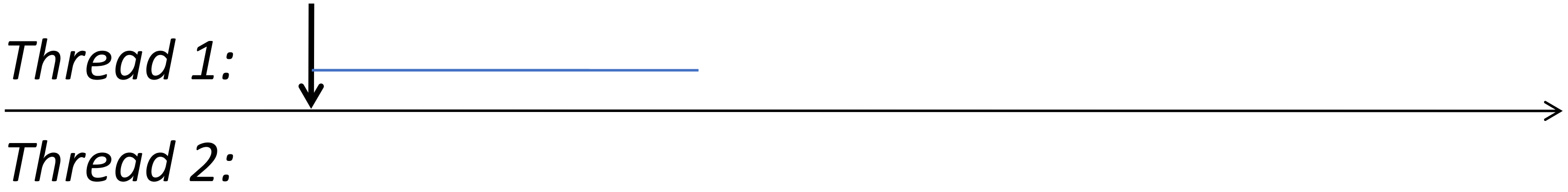

Example Revisited

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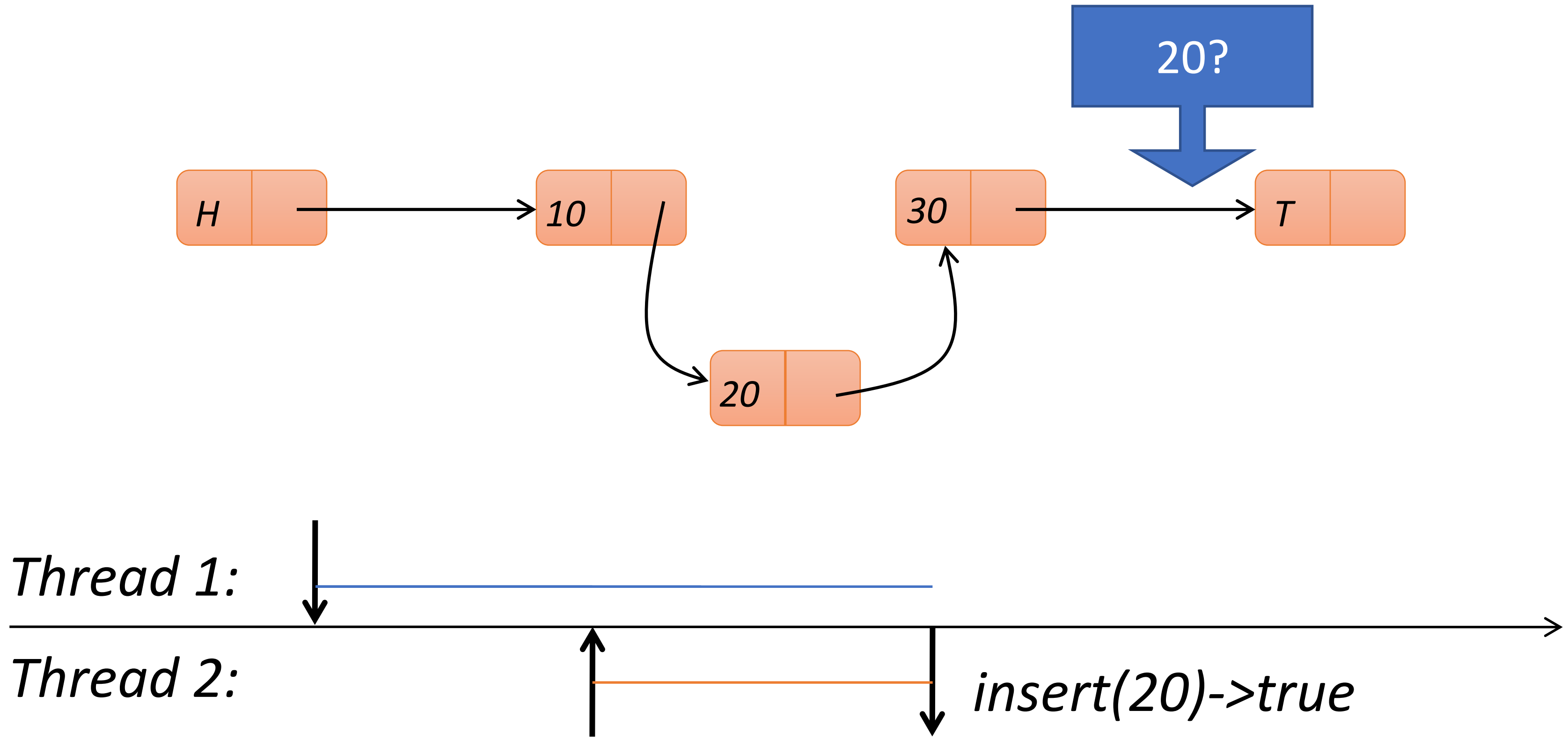

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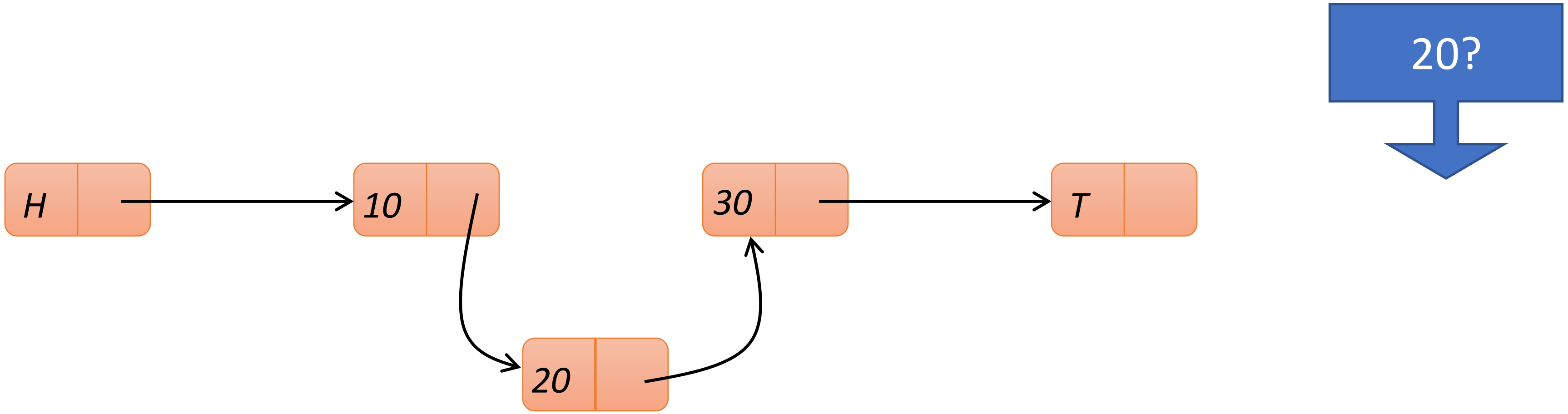

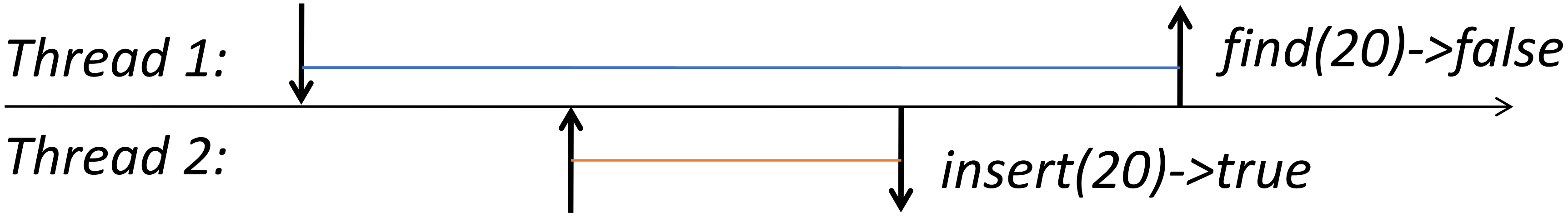

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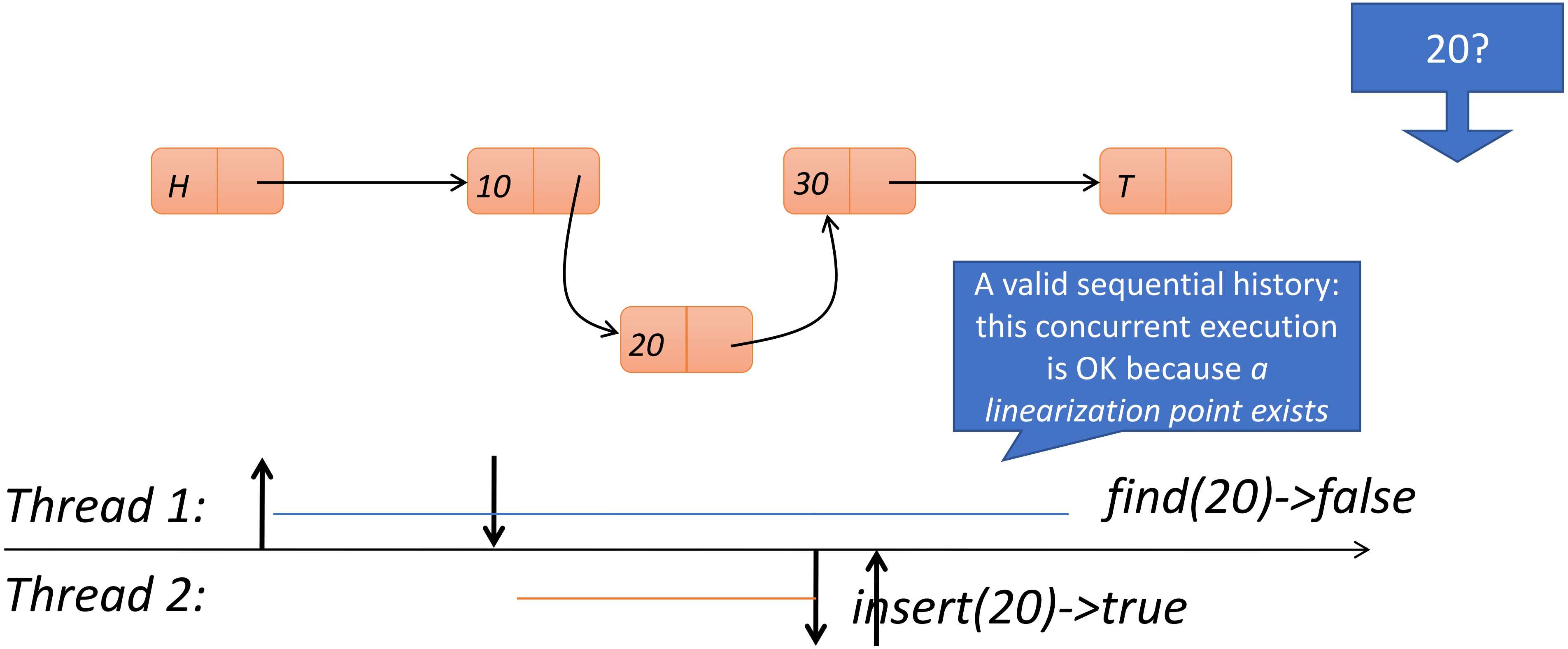

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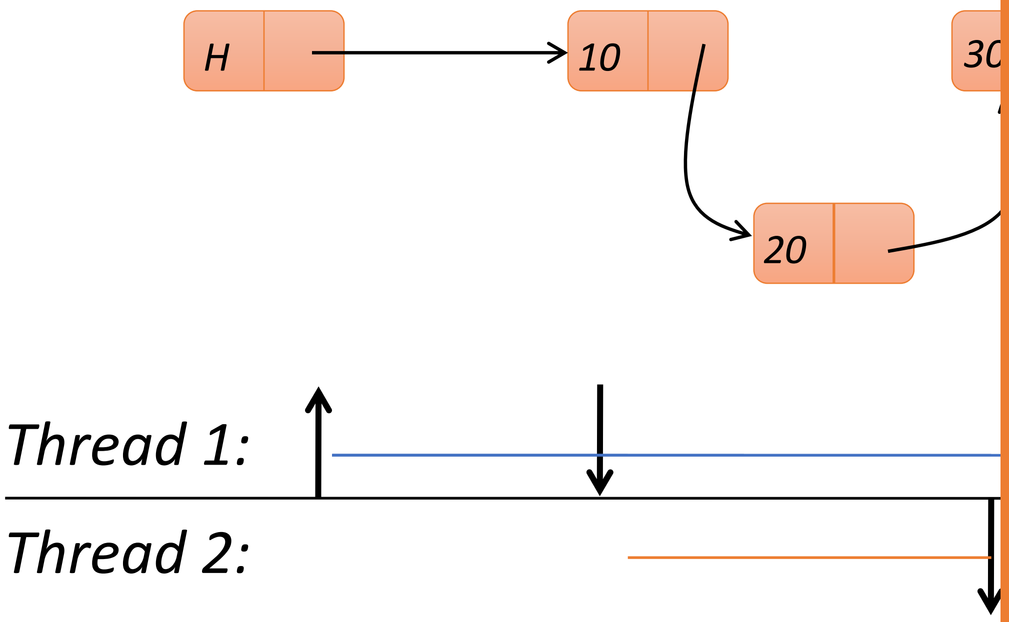

Recurring Techniques:

- For updates
  - Perform an essential step of an operation by a single atomic instruction
  - E.g. CAS to insert an item into a list
  - This forms a "linearization point"
- For reads
  - Identify a point during the operation's execution when the result is valid
  - Not always a specific instruction

Formal Properties

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  - Very weak. Means if you remove contention, someone finishes

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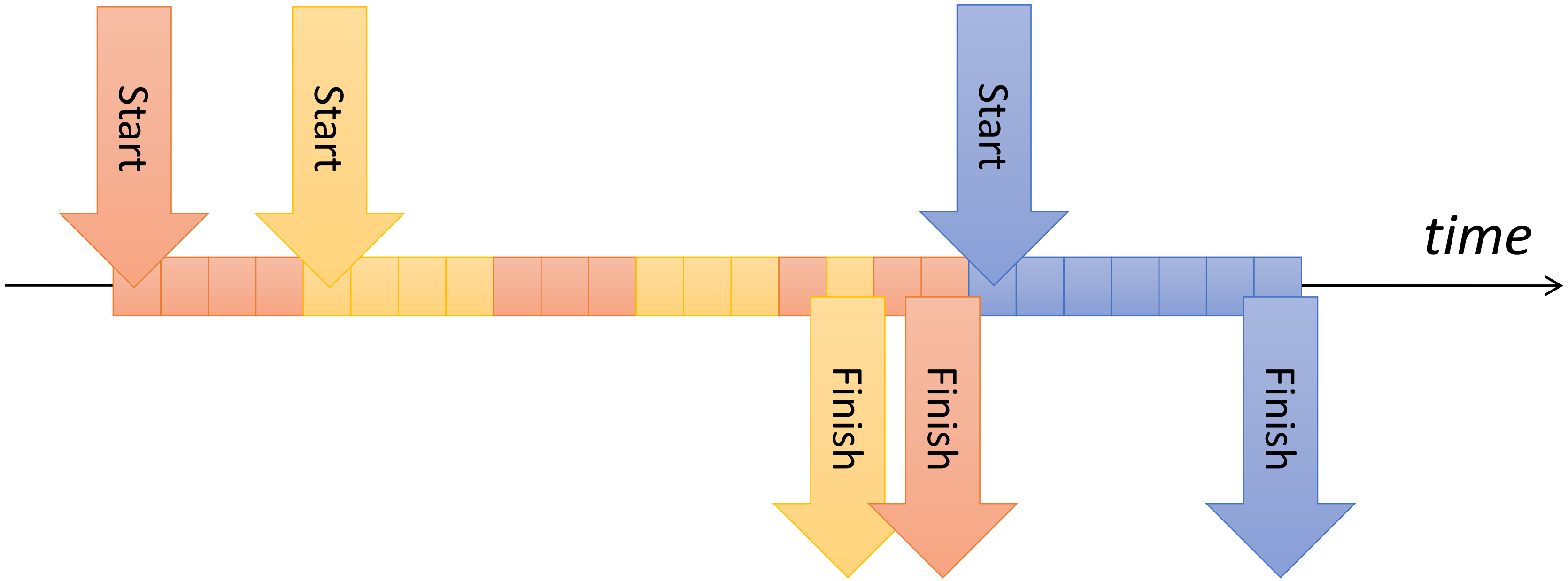

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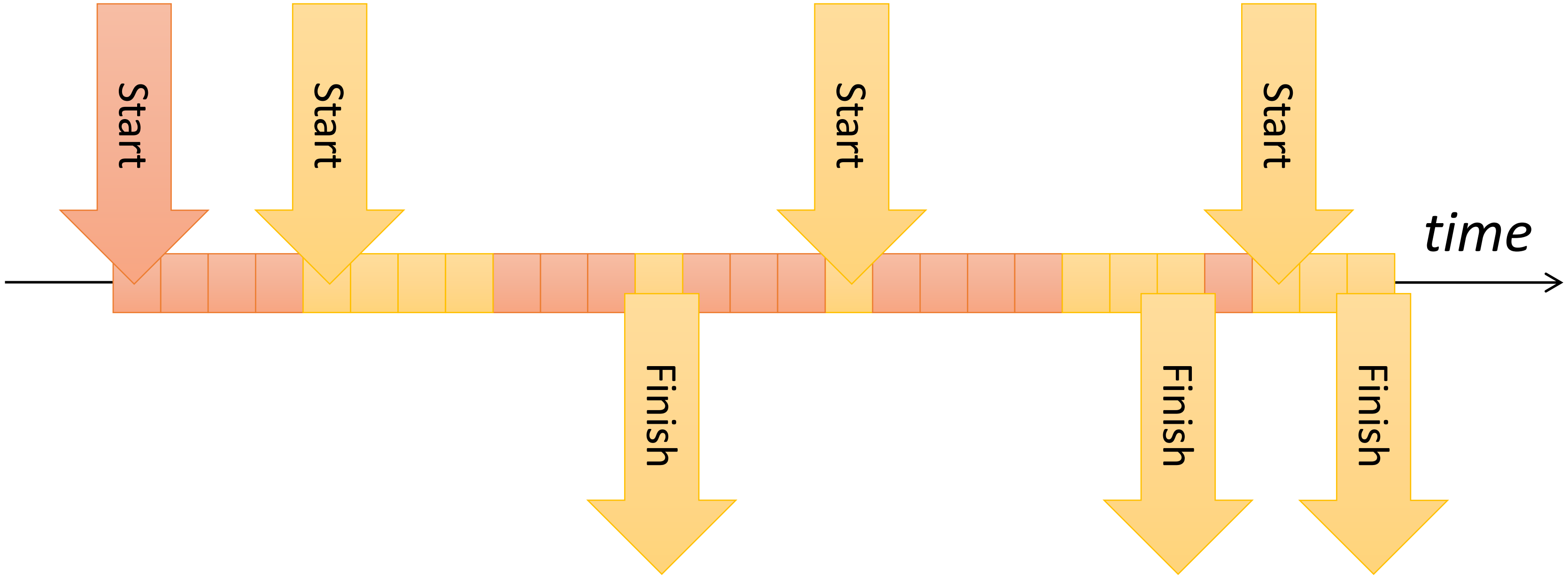

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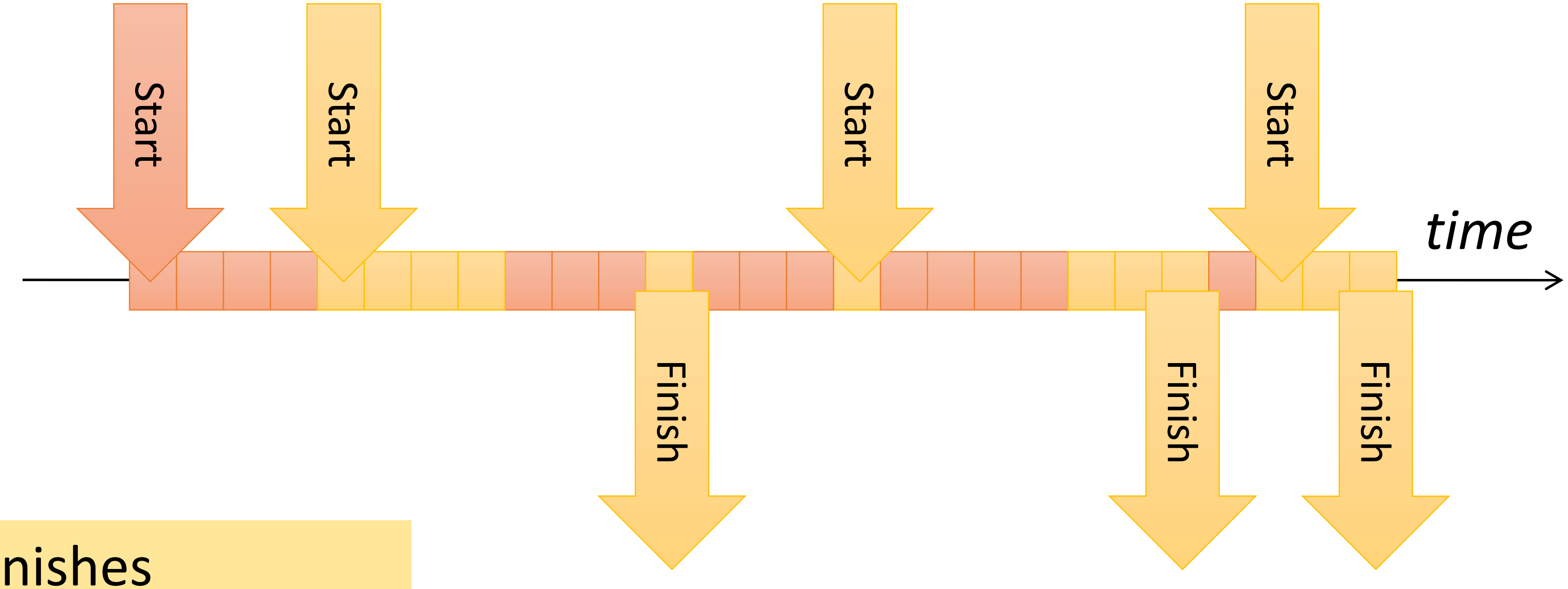

- Red never finishes
- Orange does
- Still lock-free

Obstruction-free

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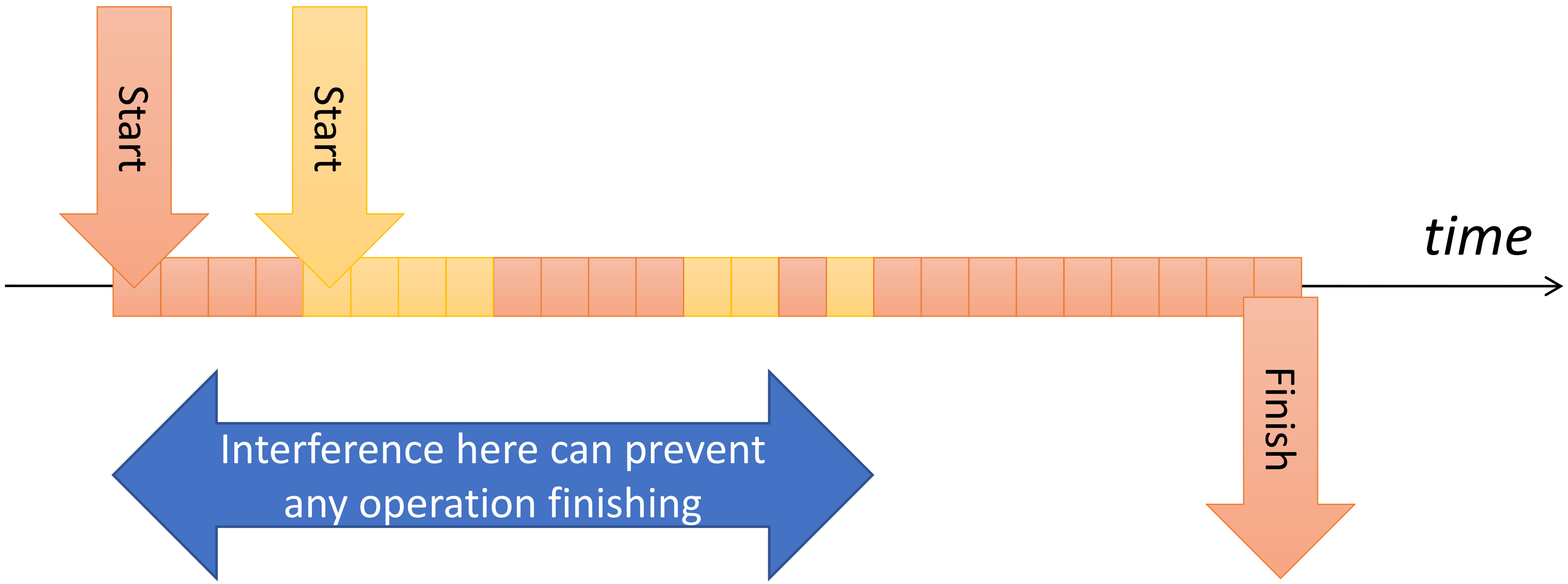

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Formal Properties

Blocking
1. Blocking
2. Starvation-Free

Obstruction-Free
3. Obstruction-Free

Lock-Free
4. Lock-Free (LF)

Wait-Free
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6. Wait-Free Bounded (WFB)
7. Wait-Free Population Oblivious (WFPO)

stronger

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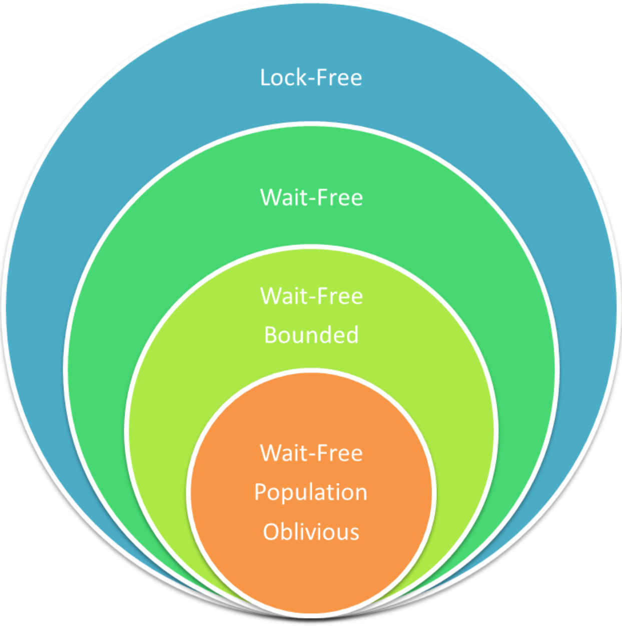

Linearizability Properties

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Huh? Composable?

Composability

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T * list::remove(Obj key){
  LOCK(this);
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Composability

Thread-safe?

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- Lock-based code doesn't compose

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- Lock-based code doesn't compose
- If list were a linearizable concurrent data structure, composition OK

Linearizability Properties

- non-blocking
  - one method is never forced to wait to sync with another.
- local property:
  - a system is linearizable iff each individual object is linearizable.
  - gives us **composability**.
- Why is it important?
  - Serializability is not composable.
  - Core hypotheses:
    - structuring all as concurrent objects buys composability
    - structuring all as concurrent objects is tractable/possible

Practical difficulties:

- Key-value mapping
- Population count
- Iteration
- Resizing the bucket array

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Options to consider when implementing a “difficult” operation:

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Design a clever implementation
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Use a different data structure
(e.g., skip lists)