Replicated Data Consistency Explained Through Baseball

slides by
Landon Cox
with some others from elsewhere
prepended and appended
(cultural history lesson)

Preview/overview

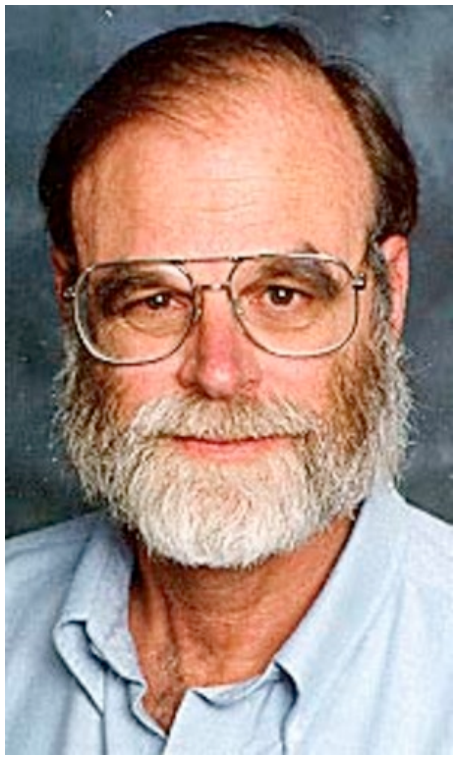
- K-V stores are a common data tier for mega-services.
- They evolved during the Web era, starting with DDS.
- Today they often feature **geographic replication**.
  - Multiple replicas in different data centers.
  - Geo-replication offers better scale and reliability/availability.
- But updates are slower to propagate, and network partitions may interfere.
  - A read might not see the “latest” write.
- So we have to think carefully about what consistency properties we need: “BASE” might be “good enough”.
  - FLP and CAP tell us that there are fundamental limits on what we can guarantee….but many recent innovations in this space.

Key-value stores

- Many mega-services are built on **key-value stores**.
  - Store variable-length content objects: think “tiny files” (**value**)
  - Each object is named by a “**key**”, usually fixed-size.
  - Key is also called a **token**: not to be confused with a crypto key! Although it may be a content hash (SHAx or MD5).
  - Simple **put/get** interface with no offsets or transactions (yet).
  - Goes back to literature on Distributed Data Structures [Gribble 2000] and **Distributed Hash Tables (DHTs)**.

[image from Sean Rhea, opendht.org, 2004]

ACID vs. BASE



Jim Gray
ACM Turing Award 1998

Eric Brewer
ACM SIGOPS
Mark Weiser Award
2009

ACID vs. BASE

Inktomi

ACID

- Strong consistency
- Isolation
- Focus on "commit"
- Nested transactions
- Availability?
- Conservative (pessimistic)
- Difficult evolution (e.g. schema)
- "small" Invariant Boundary
- The "inside"

BASE

- Weak consistency
  - stale data OK
- Availability first
- Best effort
- Approximate answers OK
- Aggressive (optimistic)
- "Simpler" and faster
- Easier evolution (XML)
- "wide" Invariant Boundary
- Outside consistency boundary

but it's a *spectrum*

All Things Distributed

Werner Vogels' weblog on building scalable and robust distributed systems.

Dr. Werner Vogels is Vice President & Chief Technology Officer at Amazon.com.

Prior to joining Amazon, he worked as a researcher at Cornell University.

Building reliable distributed systems at a worldwide scale demands trade-offs between consistency and availability.

BY WERNER VOGELS

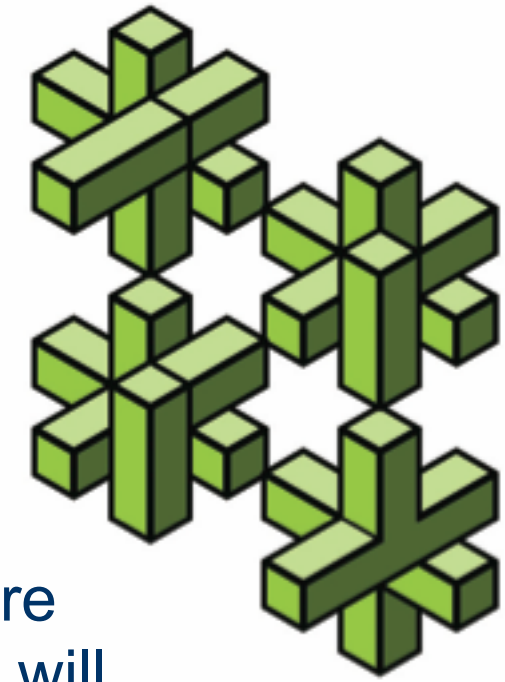
Vogels on consistency

The scenario

A updates a “data object” in a “storage system”.

Consistency “has to do with how observers see these updates”.

Strong consistency: “After the update completes, any subsequent access will return the updated value.”



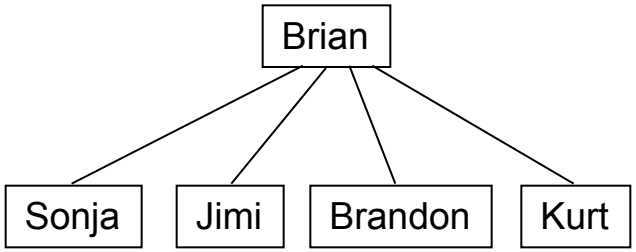
Eventual consistency: “If no new updates are made to the object, eventually all accesses will return the last updated value.”

PNUTS: Yahoo!'s Hosted Data Serving Platform

Brian F. Cooper, Raghu Ramakrishnan, Utkarsh Srivastava, Adam Silberstein, Philip Bohannon, Hans-Arno Jacobsen, Nick Puz, Daniel Weaver and Ramana Yerneni

Yahoo! Research

Example: social network updates



flickr LOVES YOU

★★☆☆☆
by mjbee42 04/27/2007
Wouldn't come back: The food wasn't that great and the restaurant interior was not well lit. I know this place is popular but I'm not sure why.

YAHOO! LOCAL Yellow Pages

YAHOO! MESSENGER

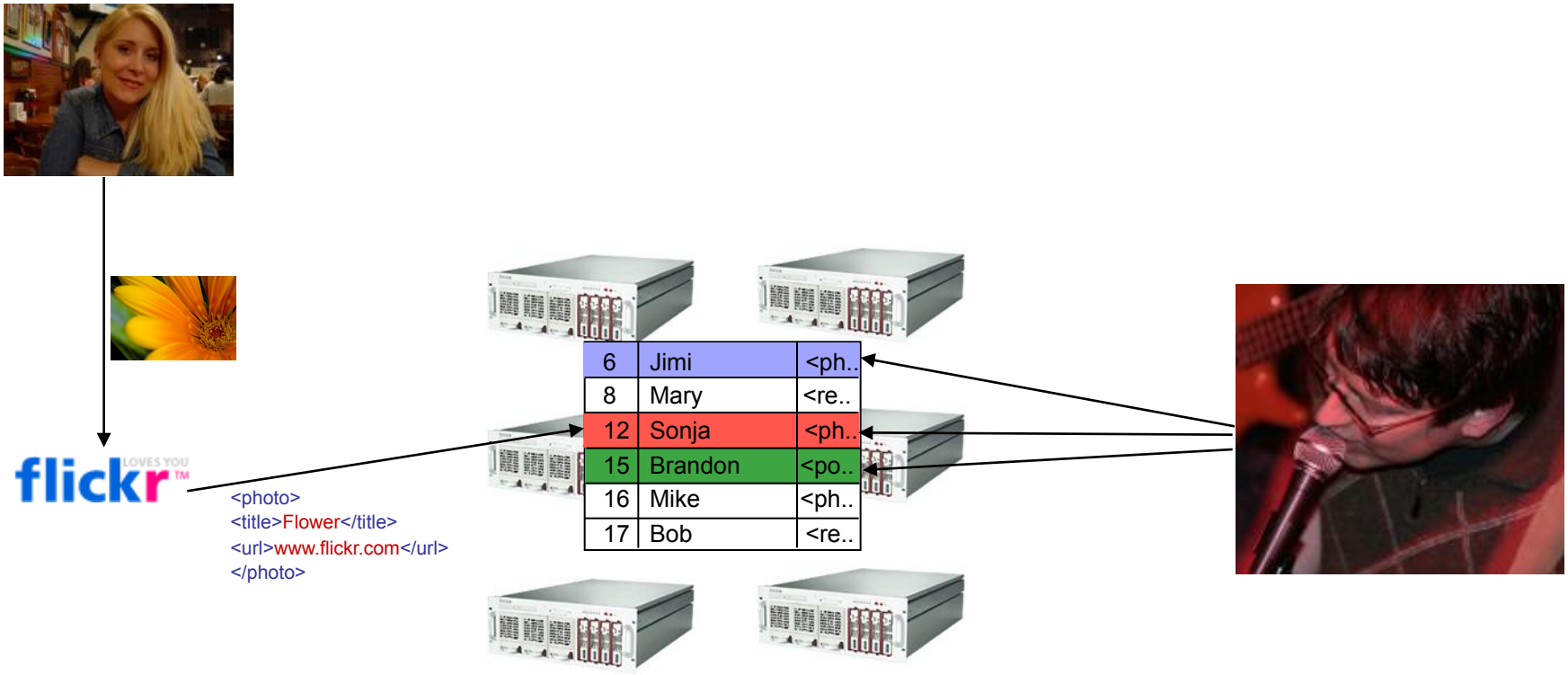
What are my friends up to?

Sonja:

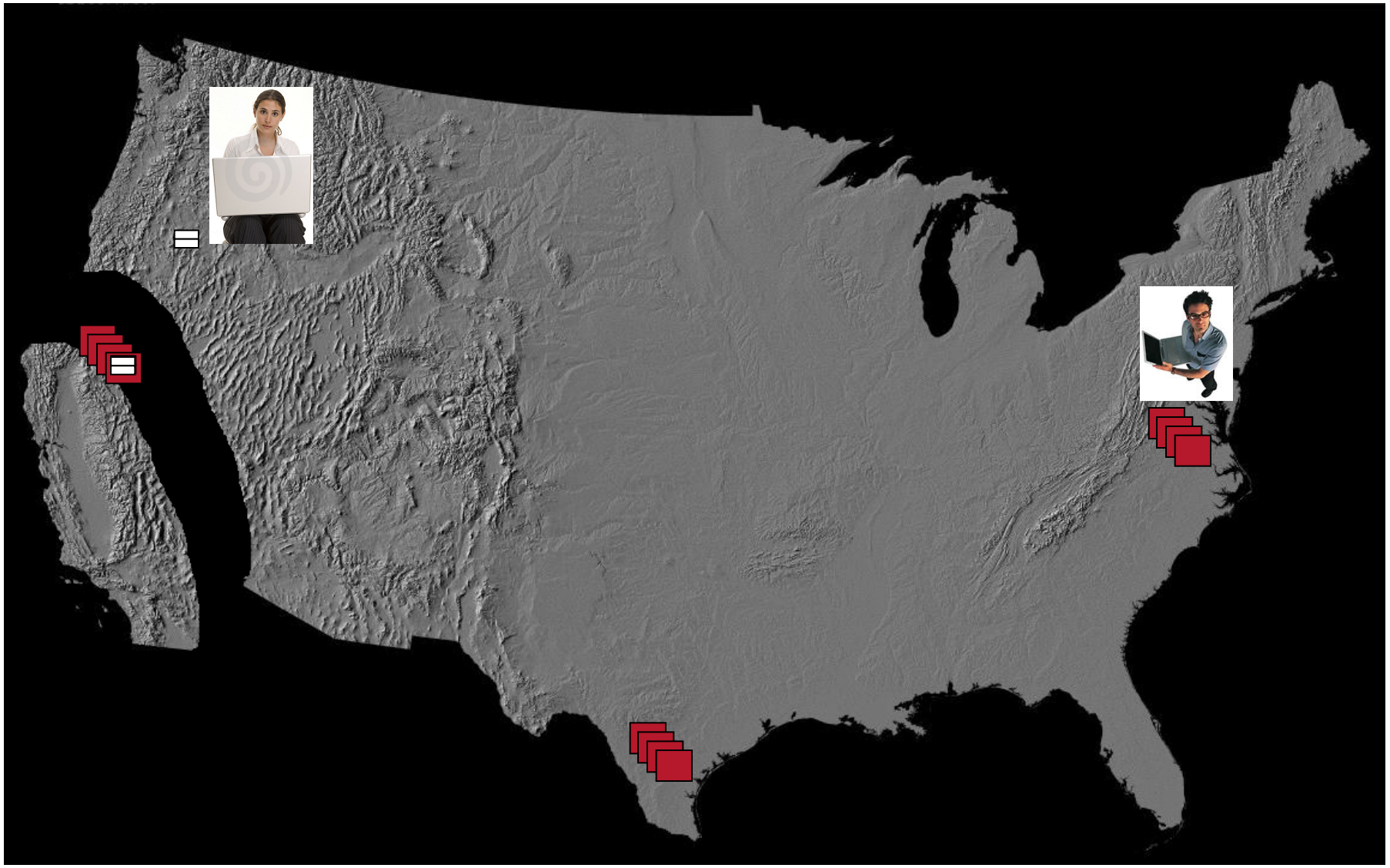
Brandon:

★★☆☆☆
by mjbee42 04/27/2007
Wouldn't come back: The food wasn't that great and the restaurant interior was not well lit. I know this place is popular but I'm not sure why.

Example: social network updates

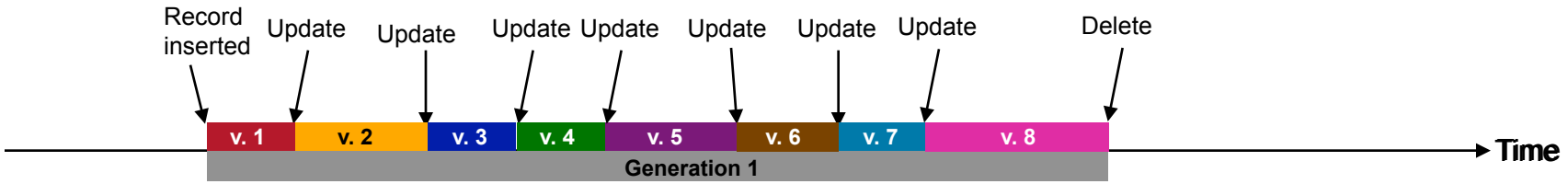


Asynchronous replication

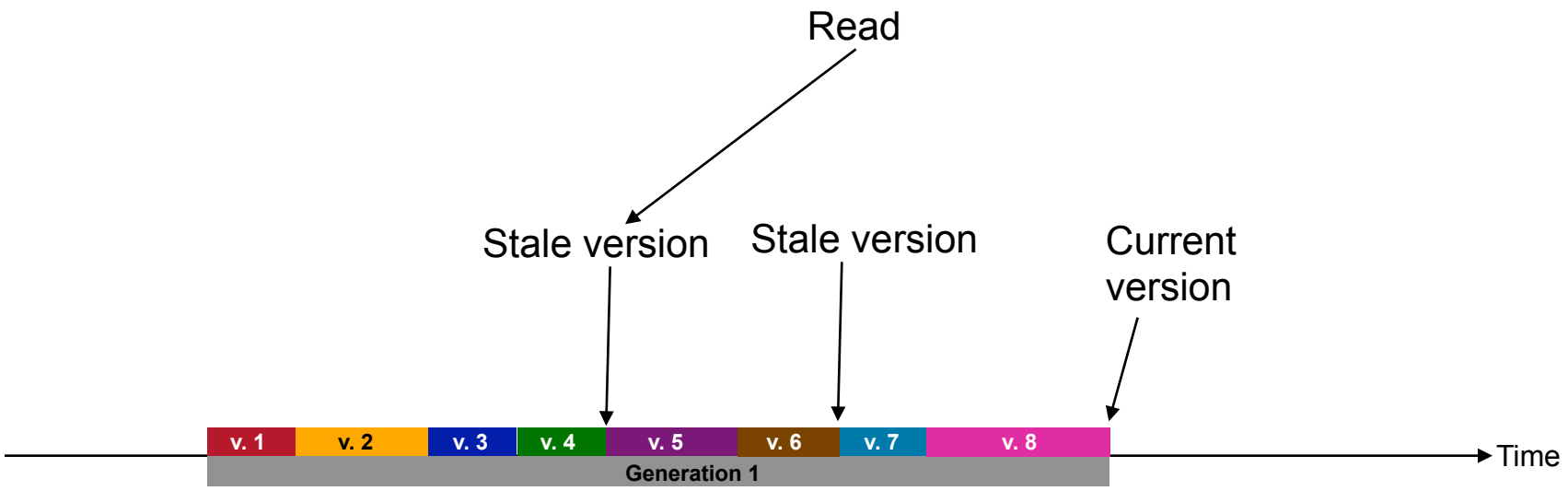


Consistency model

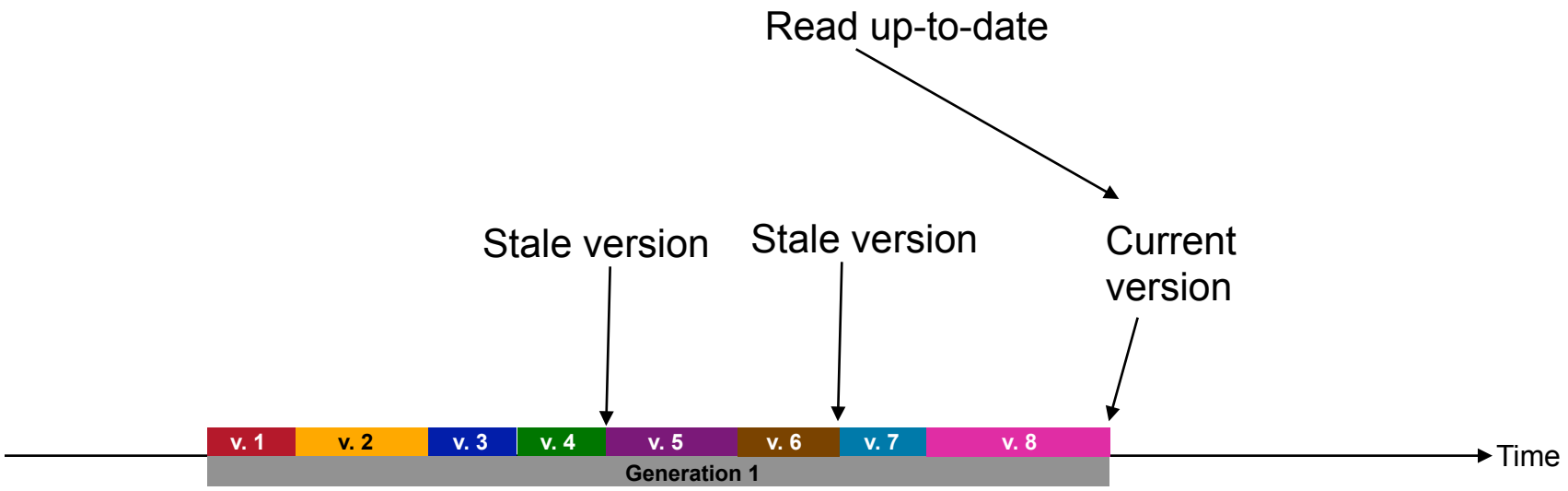
- Goal: make it easier for applications to reason about updates and cope with asynchrony
- What happens to a record with primary key "Brian"?



Consistency model

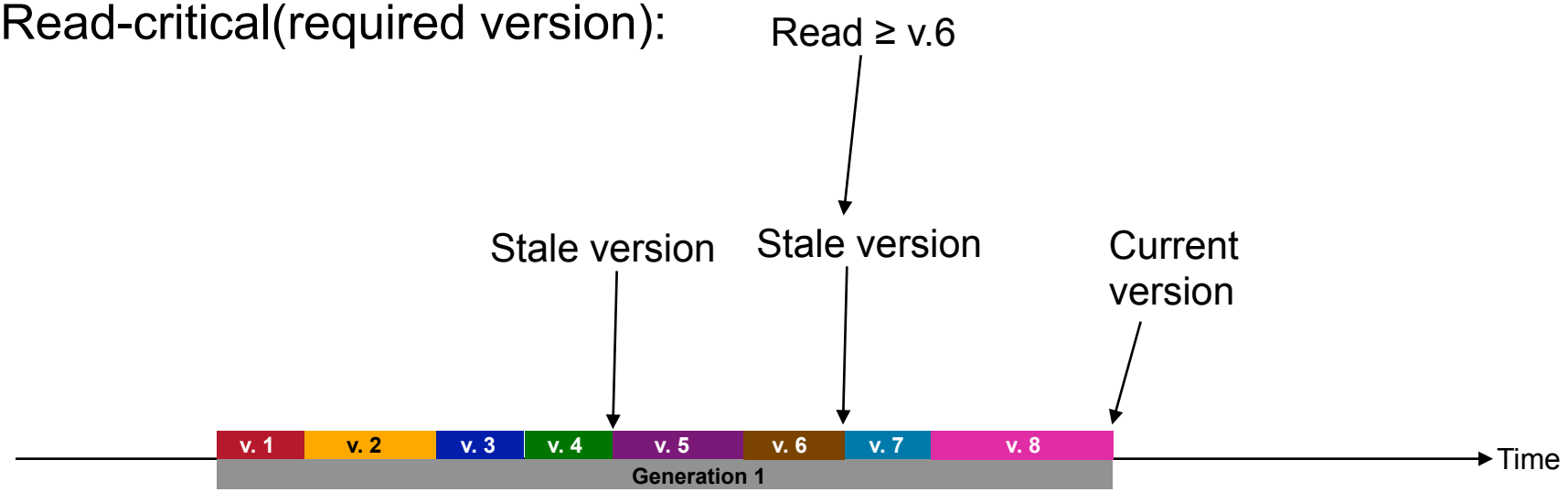


Consistency model



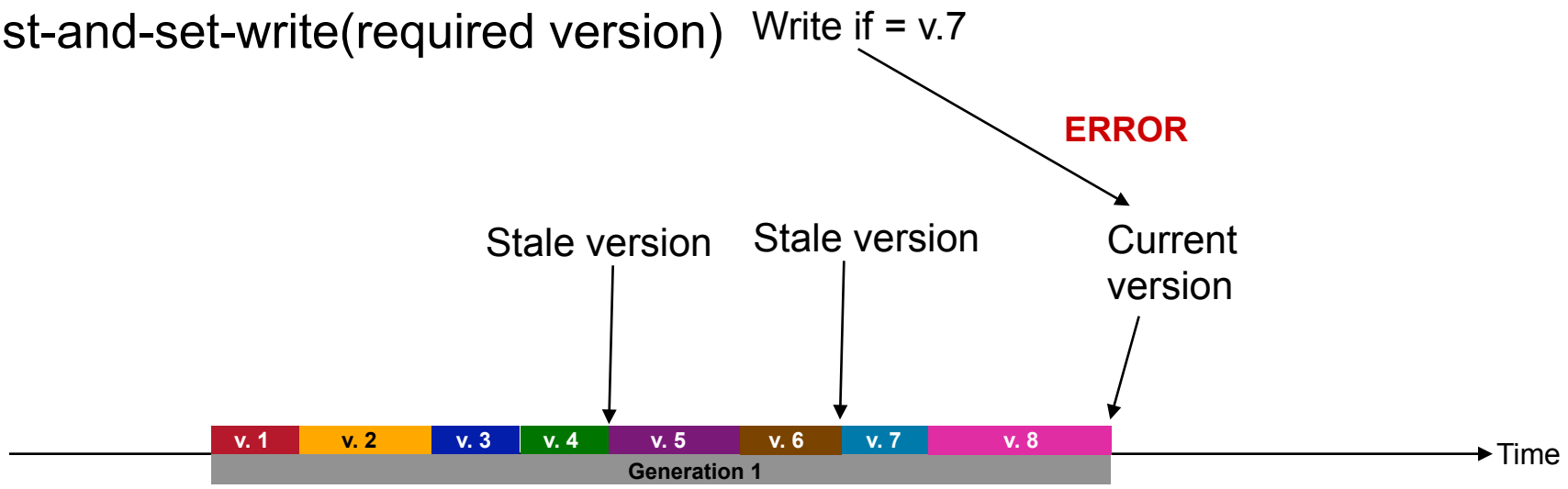
Consistency model

Read-critical(required version):



Consistency model

Test-and-set-write(required version)



Don't Settle for Eventual:

Scalable Causal Consistency for Wide-Area Storage with COPS

Wyatt Lloyd*
Michael J. Freedman*
Michael Kaminsky†
David G. Andersen‡
*Princeton, †Intel Labs, ‡CMU

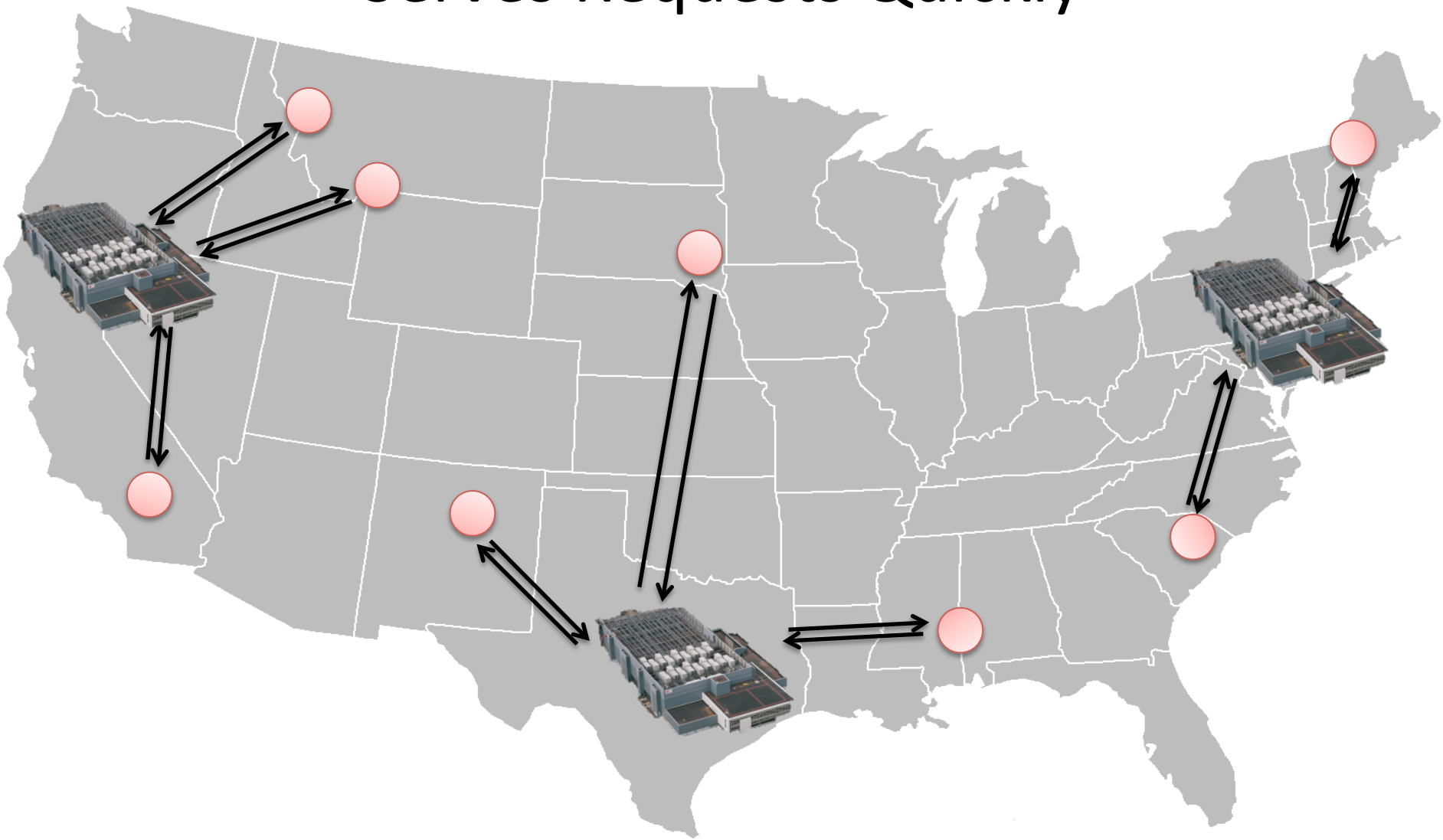
Wide-Area Storage

Stores:
Status Updates
Likes
Comments
Photos
Friends List

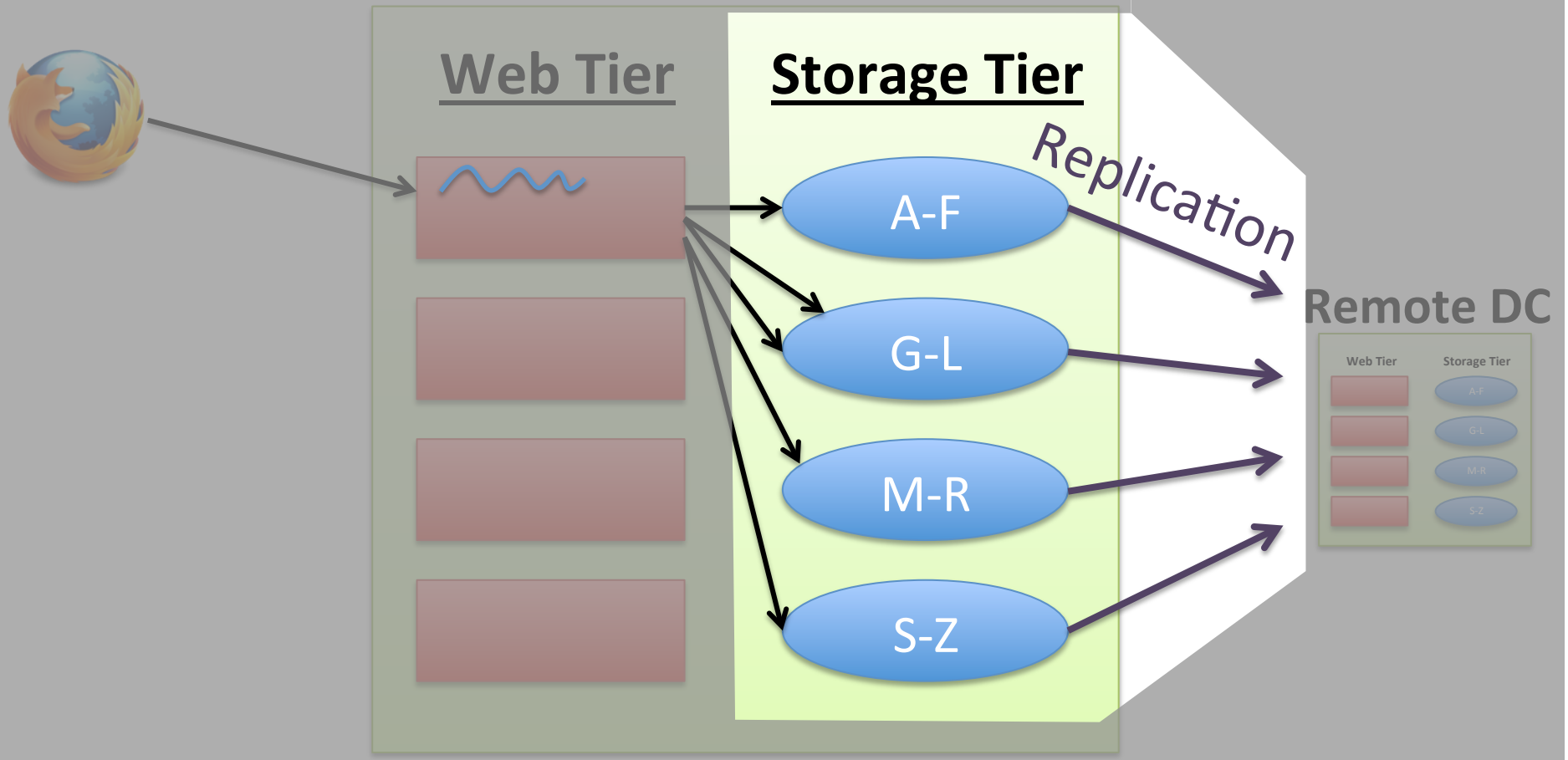
Stores:
Tweets
Favorites
Following List

Stores:
Posts
+1s
Comments
Photos
Circles

Wide-Area Storage
Serves Requests Quickly

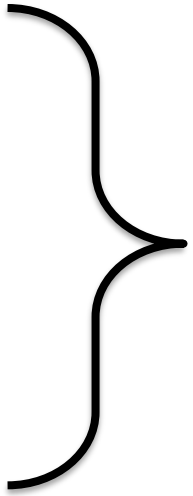


Inside the Datacenter



Desired Properties: ALPS

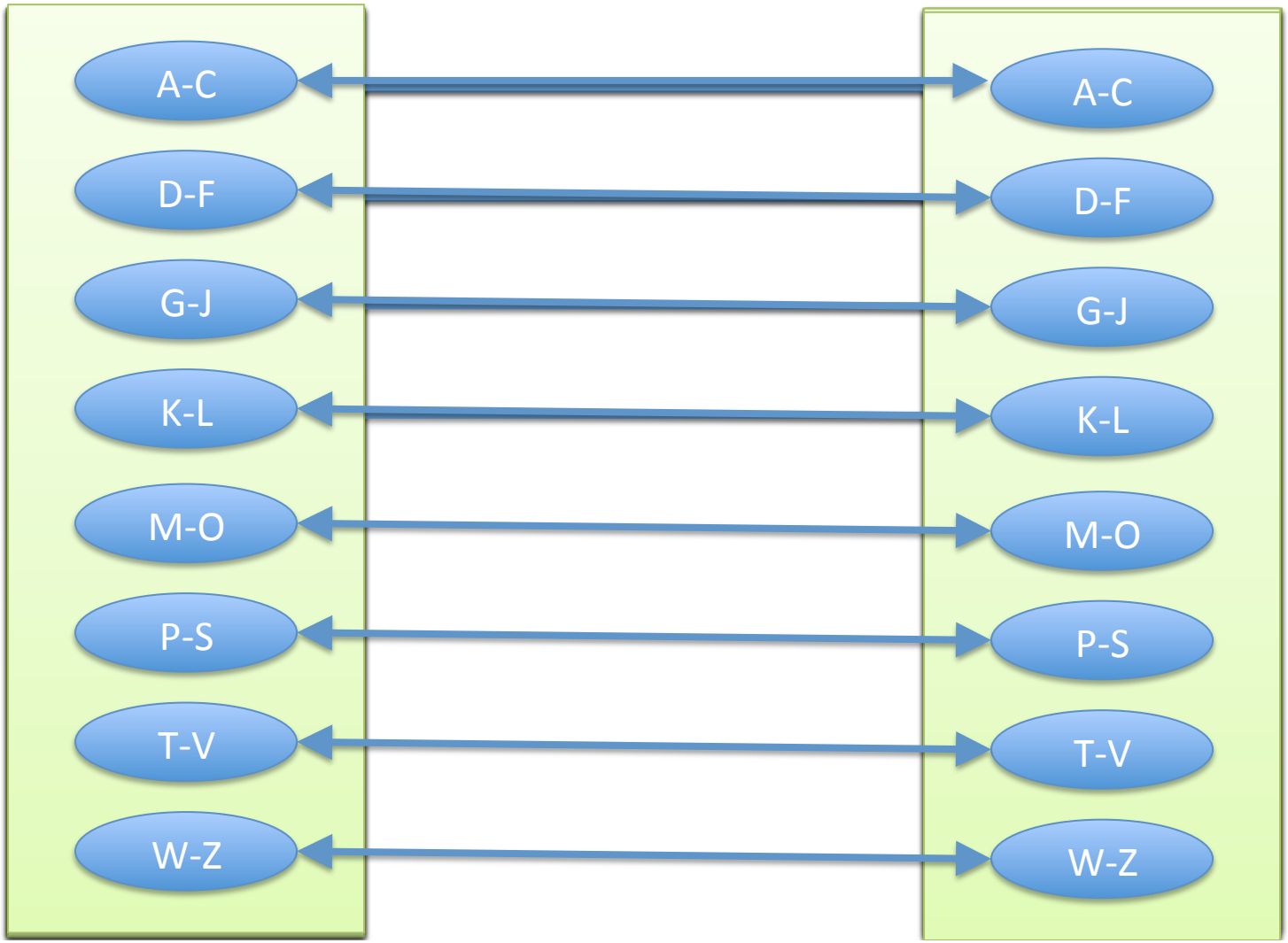
- **A**vailability
- **L**ow Latency
- **P**artition Tolerance
- **S**calability



"Always On"

Scalability

Increase capacity and throughput in each datacenter



Desired Property: Consistency

- Restricts order/timing of operations

- Stronger consistency:
  - Makes programming easier
  - Makes user experience better

Consistency with ALPS

Strong — Impossible [Brewer00, GilbertLynch02]

Sequential — Impossible [LiptonSandberg88, AttiyaWelch94]

Causal —  COPS

Eventual — Amazon Dynamo; LinkedIn Voldemort; Facebook/Apache Cassandra

System	A	L	P	S	Consistency
Scatter	✗	✗	✗	✓	✓ Strong
Walter	✗	✗	✗	?	PSI + Txn
COPS	✓	✓	✓	✓	Causal+
Bayou	✓	✓	✓	✗	Causal+
PNUTS	✓	✓	?	✓	Per-Key Seq.
Dynamo	✓	✓	✓	✓	✗ Eventual

Replicated-data consistency

- **A set of invariants on each read operation**
  - Which **writes** are guaranteed to be reflected?
  - What **write orders** are guaranteed?
- **Consistency is an application-level concern**
  - When consistency is too weak, applications break
  - Example: auction site must not tell two people they won
- **What are consequences of too-strong consistency?**
  - Worse performance (for reads and writes)
  - Worse availability (for reads and writes)

- **The following are slides on the Doug Terry paper by Landon Cox.**
- **We went through these pretty fast in class, but you should understand these models and why we might use them.**

Assumptions for our discussion

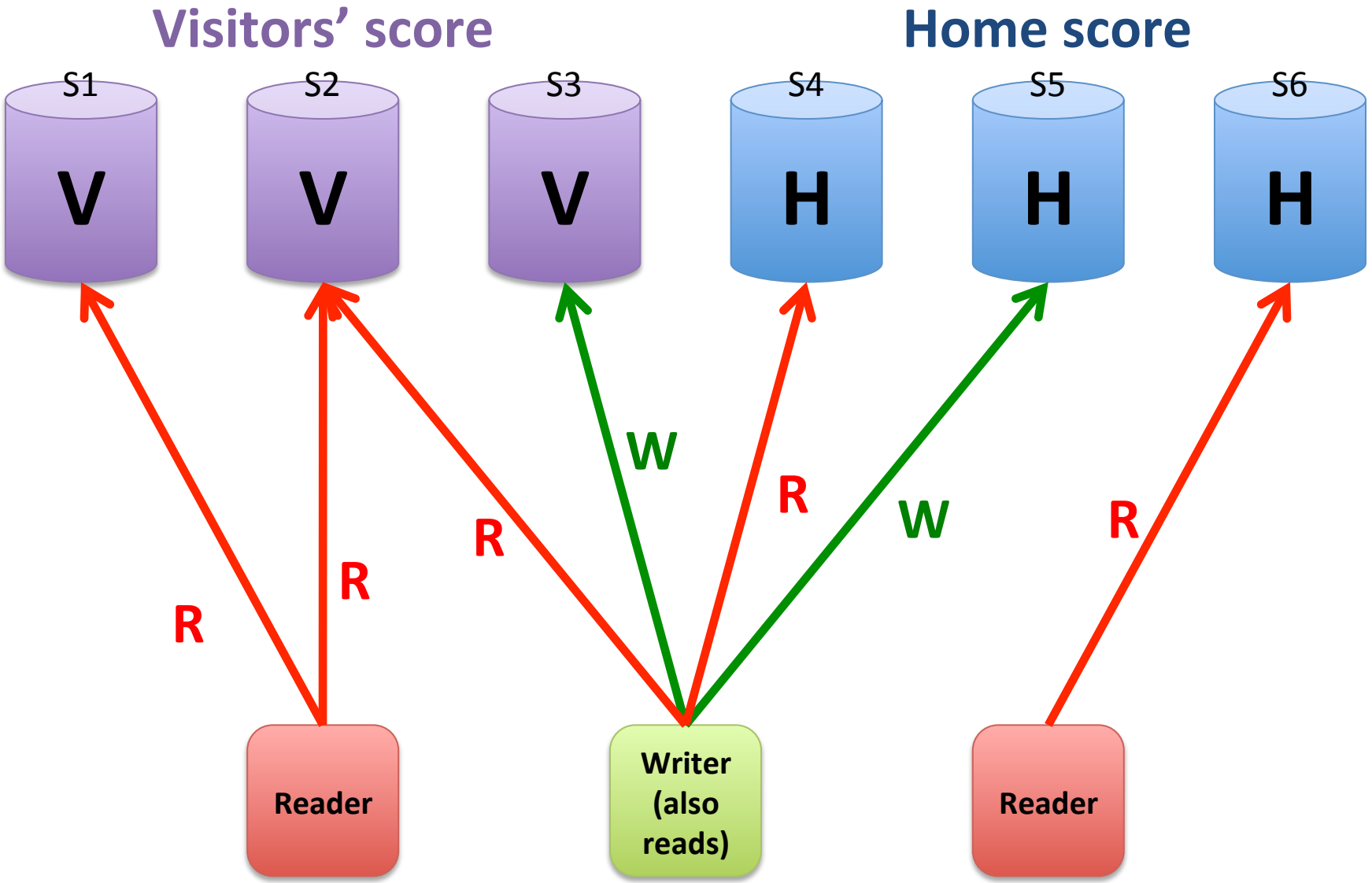
1. **Clients perform reads and writes**
2. **Data is replicated among a set of servers**
3. **Writes are serialized (logically, one writer)**
    1. Performed in the same order at all servers
    2. Write order consistent with write-request order
4. **Reads result of one or more past writes**

Consistency models

1. **Strong consistency**
   - Reader sees effect of all prior writes
2. **Eventual consistency**
   - Reader sees effect of subset of prior writes
3. **Consistent prefix**
   - Reader sees effect of initial sequence of writes
4. **Bounded staleness**
   - Reader sees effect of all “old” writes
5. **Monotonic reads**
   - Reader sees effect of increasing subset of writes
6. **Read my writes**
   - Reader sees effect of all writes performed by reader

Setting: baseball game

```
Write ("visitors", 0);
Write ("home", 0);
for inning = 1..9
  outs = 0;
  while outs < 3
    visiting player bats;
    for each run scored
      score = Read ("visitors");
      Write ("visitors", score + 1);
  outs = 0;
  while outs < 3
    home player bats;
    for each run scored
      score = Read ("home");
      Write ("home", score + 1);
end game;
```


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V
V
V
H
H
H
R
R
R
W
R
W
R
Reader
Writer (also reads)
Reader

Example 1: score keeper

```
score = Read ("visitors");
Write ("visitors", score + 1);
…
score = Read ("home");
Write ("home", score + 1);
```

Example 1: score keeper

```
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
```

What invariant is the score keeper maintaining on the game's score?

Both values increase monotonically

Example 1: score keeper

```
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
```

What invariant must the store provide so the score keeper can ensure monotonically increasing scores?

Reads must show effect of all prior writes (strong consistency)

Example 1: score keeper

```
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
```

Under strong consistency, what possible scores can the score keeper read after this write completes?

2-5

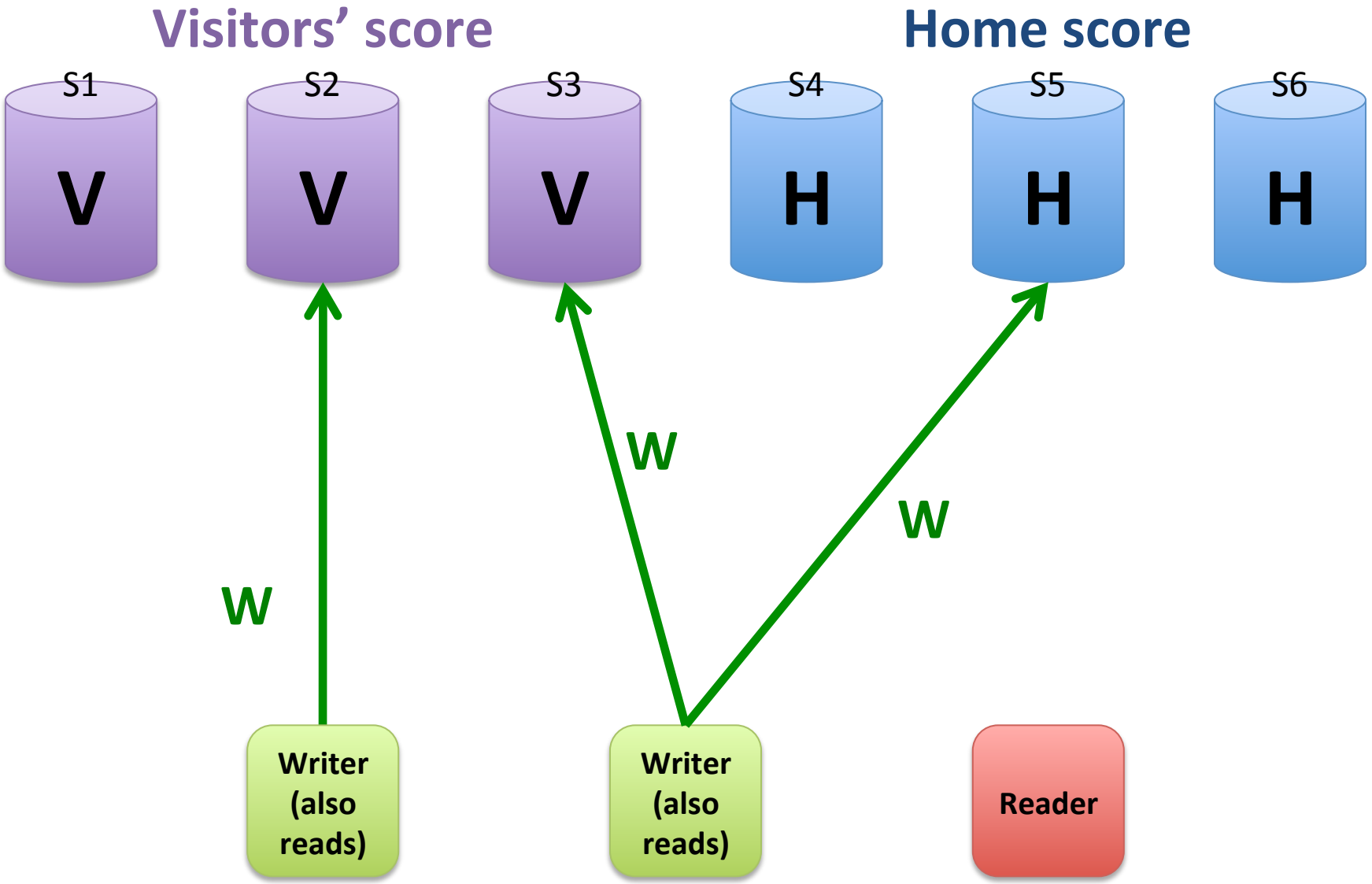
Example 1: score keeper

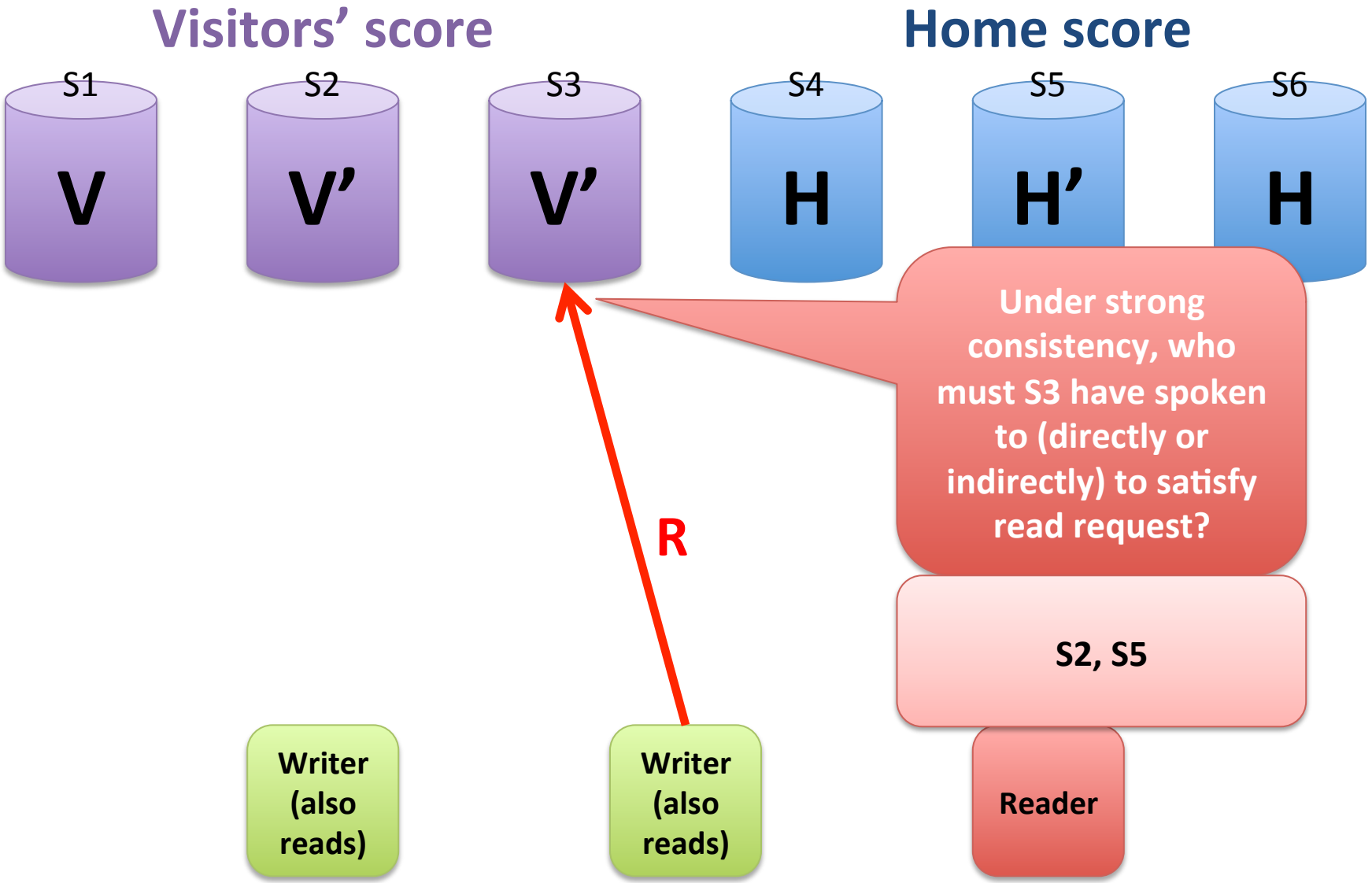
```
Write ("home", 1);
Write ("visitors", 1);
Write ("home", 2);
Write ("home", 3);
Write ("visitors", 2);
Write ("home", 4);
Write ("home", 5);
```

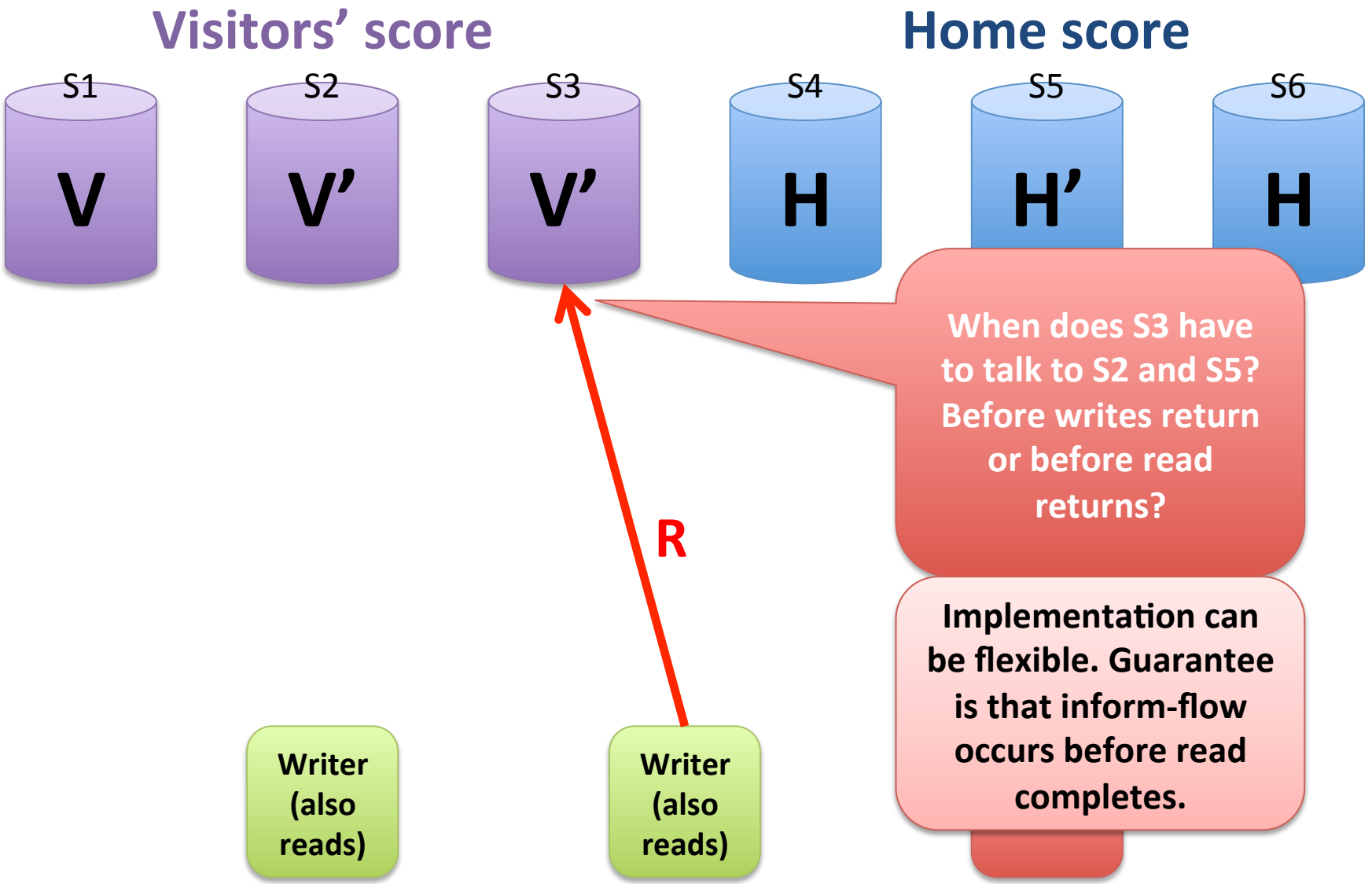
```
Visitors = 2
Home = 5
```

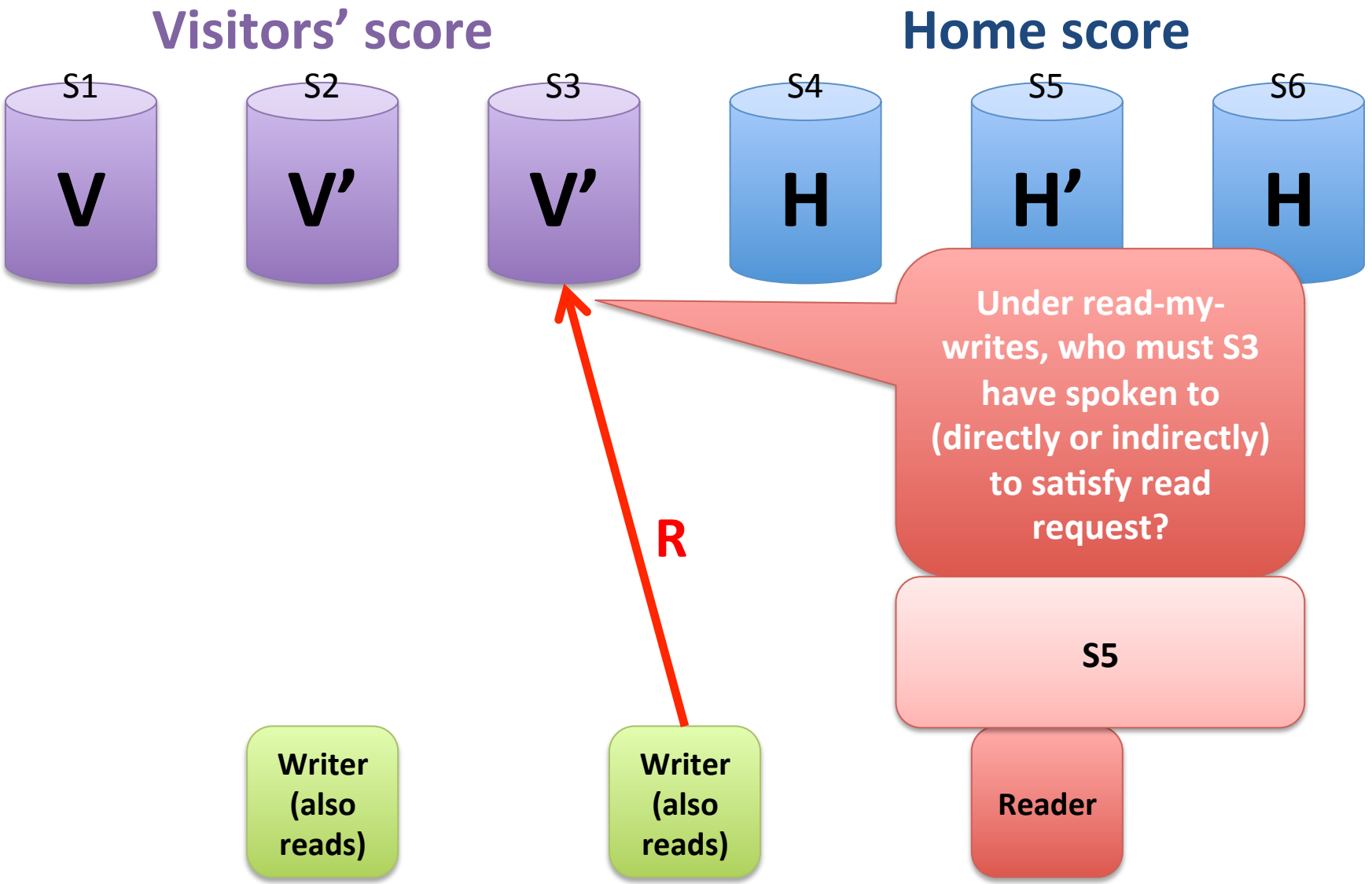
Under read-my-writes, what possible scores can the score keeper read after this write completes?

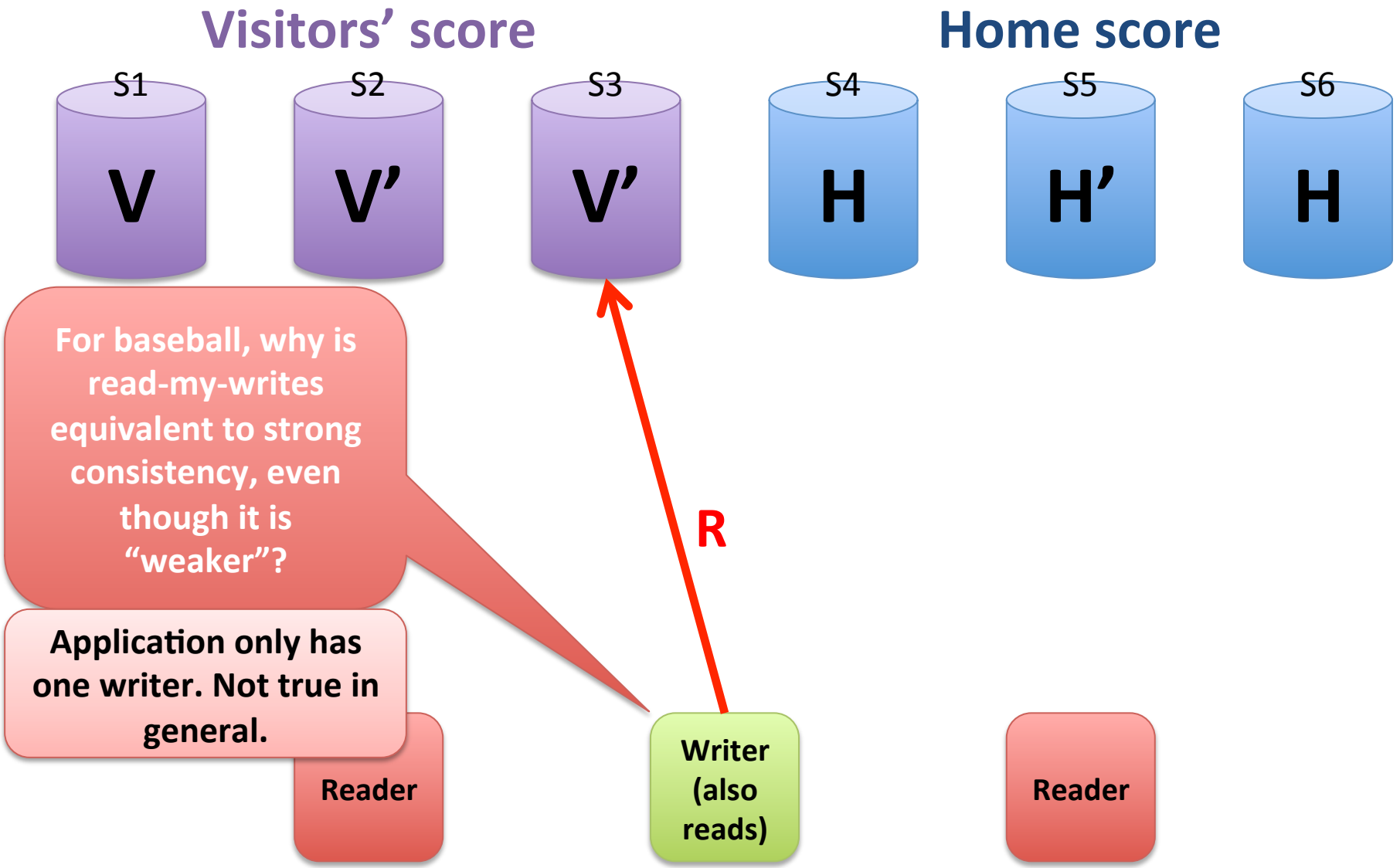
2-5


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V
V
V
H
H
H
W
W
W
Writer (also reads)
Writer (also reads)
Reader


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V
V'
V'
H
H'
H
Under strong consistency, who must S3 have spoken to (directly or indirectly) to satisfy read request?
R
S2, S5
Writer (also reads)
Writer (also reads)
Reader


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V
V'
V'
H
H'
H
When does S3 have to talk to S2 and S5? Before writes return or before read returns?
R
Implementation can be flexible. Guarantee is that inform-flow occurs before read completes.
Writer (also reads)
Writer (also reads)


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V
V'
V'
H
H'
H
Under read-my-writes, who must S3 have spoken to (directly or indirectly) to satisfy read request?
R
S5
Writer (also reads)
Writer (also reads)
Reader


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V
V'
V'
H
H'
H
For baseball, why is read-my-writes equivalent to strong consistency, even though it is "weaker"?
Application only has one writer. Not true in general.
R
Reader
Writer (also reads)
Reader

Example 1: score keeper

```
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
```

Common theme:

(1) Consider application invariants

(2) Reason about what store must ensure to support application invariants

Example 2: umpire

```
if first half of 9th inning complete then
  vScore = Read ("visitors");
  hScore = Read ("home");
  if vScore < hScore
    end game;
```

Idea: home team doesn't need another chance to bat if they are already ahead going into final half inning

Example 2: umpire

```
if first half of 9th inning complete then
  vScore = Read ("visitors");
  hScore = Read ("home");
  if vScore < hScore
    end game;
```

What invariant must the umpire uphold?

Game should end if home team leads going into final half inning.

Example 2: umpire

```
if first half of 9th inning complete then
  vScore = Read ("visitors");
  hScore = Read ("home");
  if vScore < hScore
    end game;
```

What subset of writes must be visible to the umpire to ensure game ends appropriately?

Reads must show effect of all prior writes (strong consistency)

Example 2: umpire

```
if first half of 9th inning complete then
  vScore = Read ("visitors");
  hScore = Read ("home");
  if vScore < hScore
    end game;
```

Would read-my-writes work as it did for the score keeper?

No, since the umpire doesn't issue any writes

Example 3: radio reporter

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

Idea: periodically read score and broadcast it to listeners

Example 3: radio reporter

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

What invariants must the radio reporter uphold?

Should only report scores that actually occurred, and score should monotonically increase

Example 3: radio reporter

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

Do we need strong consistency?

No, since listeners can accept slightly old scores.

Example 3: radio reporter

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

Can we get away with eventual consistency (some subset of writes is visible)?

No, eventual consistency can return scores that never occurred.

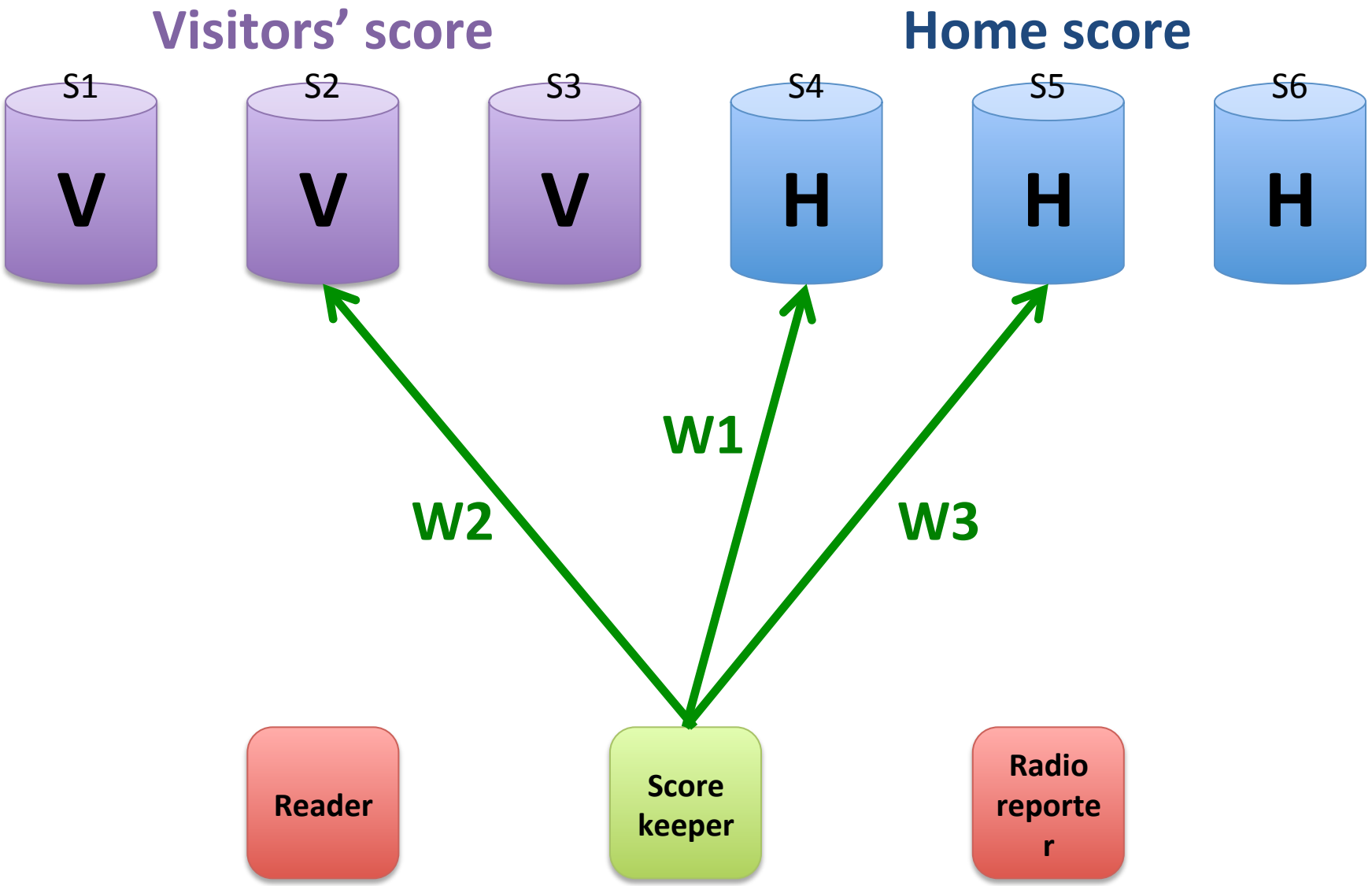
Example 3: radio reporter

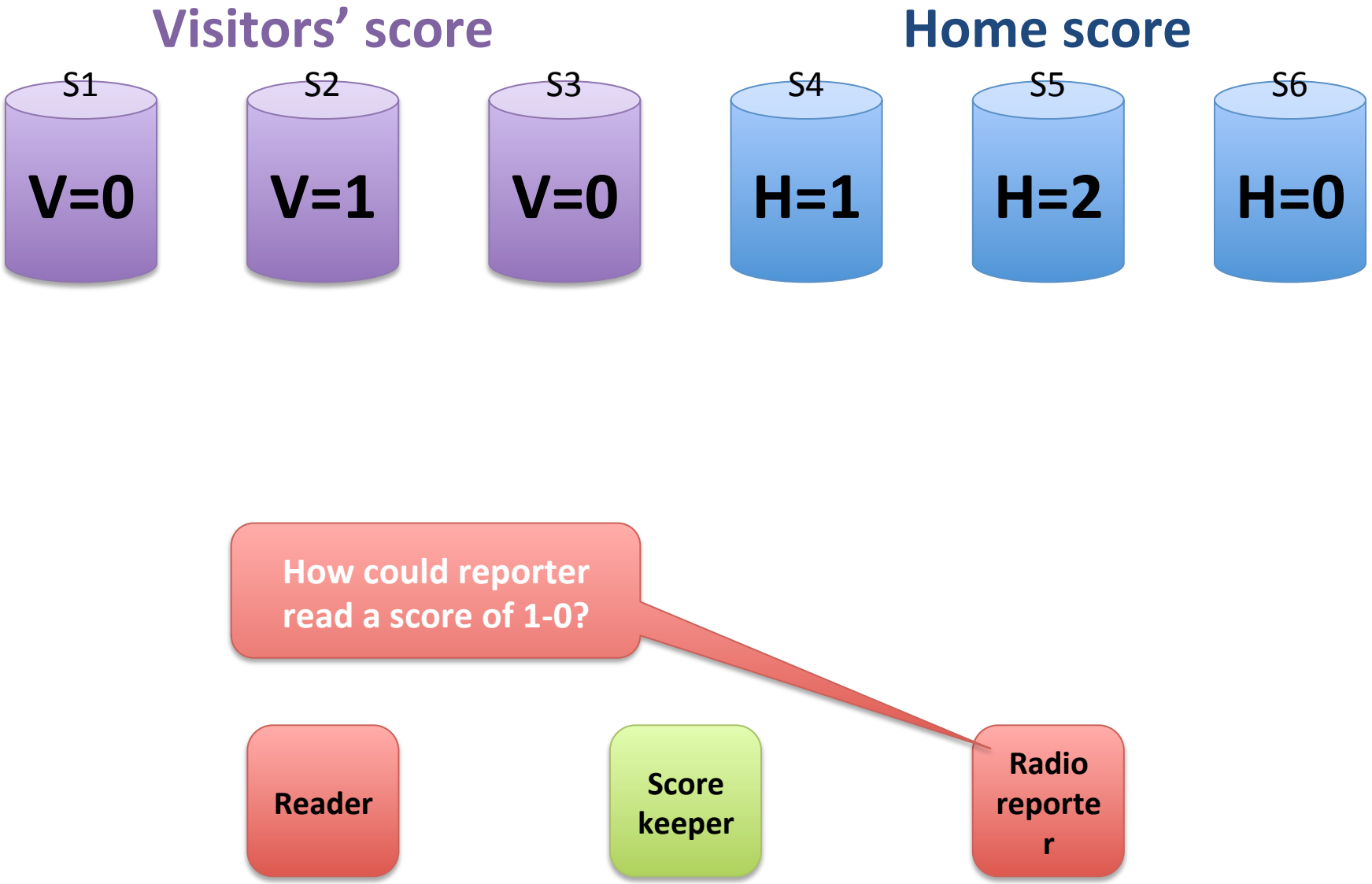
```
Write ("home", 1);
Write ("visitors", 1);
Write ("home", 2);
Write ("home", 3);
Write ("visitors", 2);
Write ("home", 4);
Write ("home", 5);
```

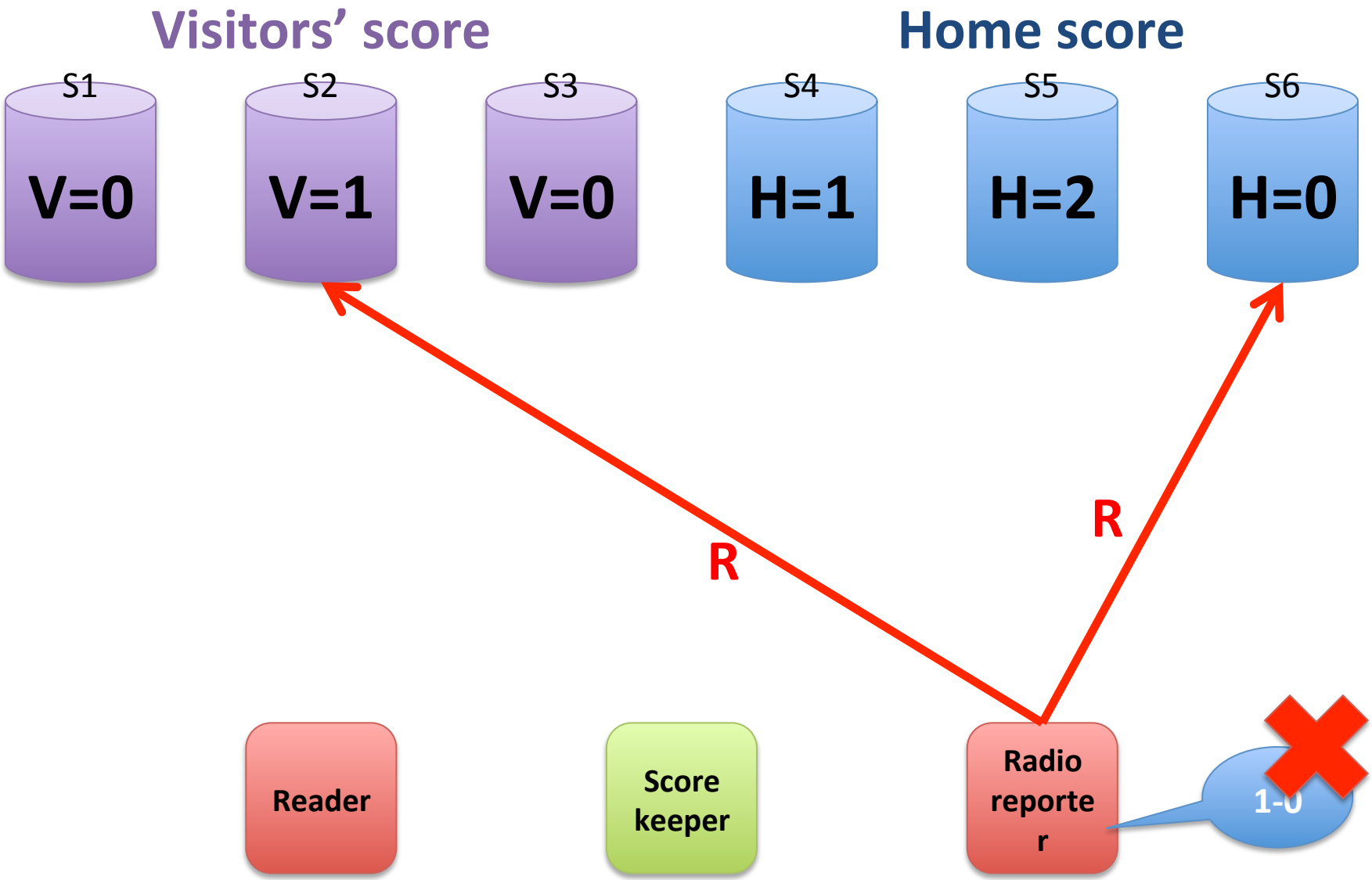
```
Visitors = 2
Home = 5
```

Under eventual consistency, what possible scores could the radio reporter read after this write completes?

0-0, 0-1, 0-2, 0-4, 0-5, 1-0, … 2-4, 2-5


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V
V
V
H
H
H
W1
W2
W3
Reader
Score keeper
Radio reporte r


Visitors' score
Home score
S1
V=0
S2
V=1
S3
V=0
S4
H=1
S5
H=2
S6
H=0
How could reporter read a score of 1-0?
Reader
Score keeper
Radio reporte r

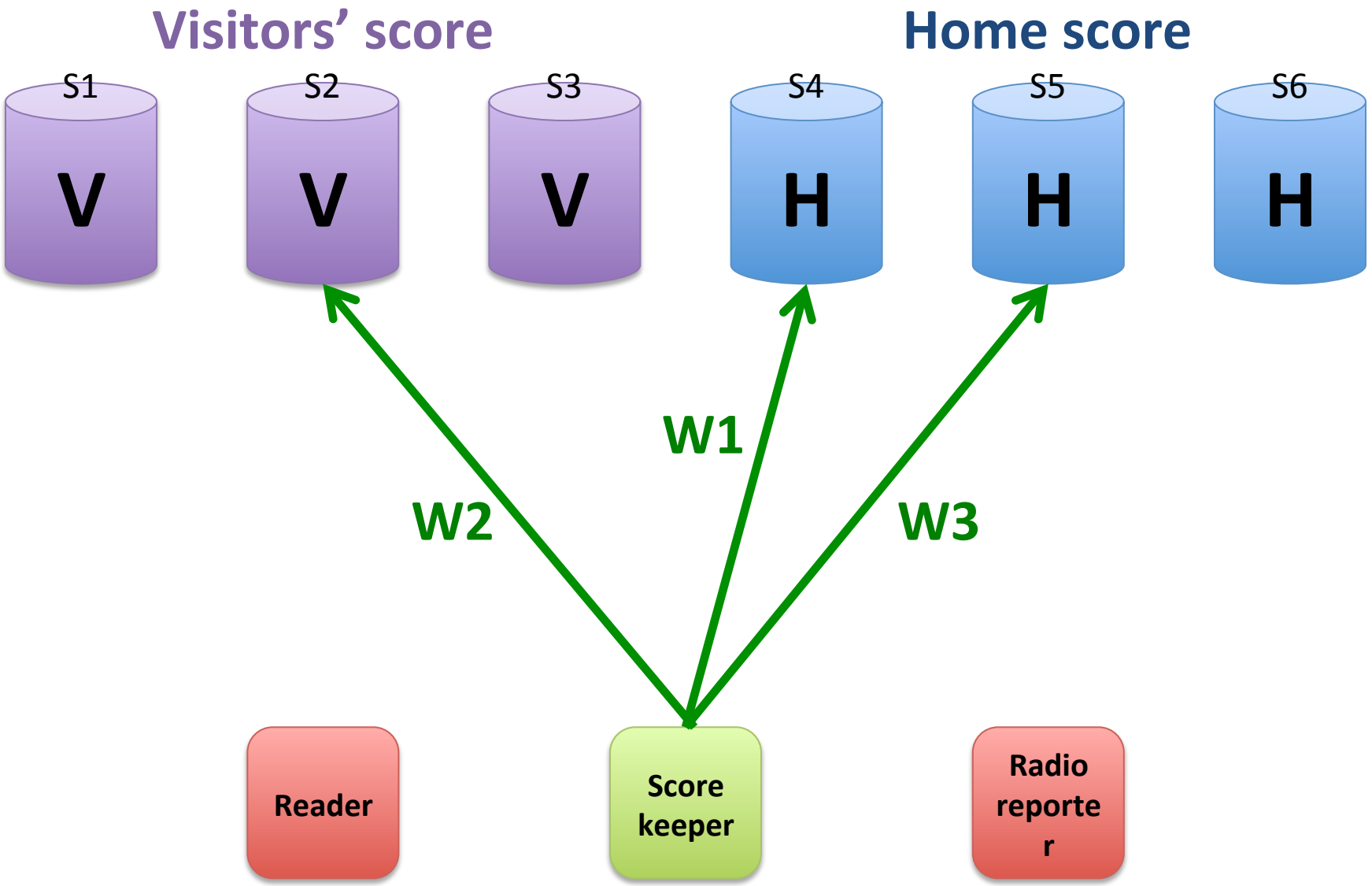

Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V=0
V=1
V=0
H=1
H=2
H=0
R
R
Reader
Score keeper
Radio reporte r
1-0

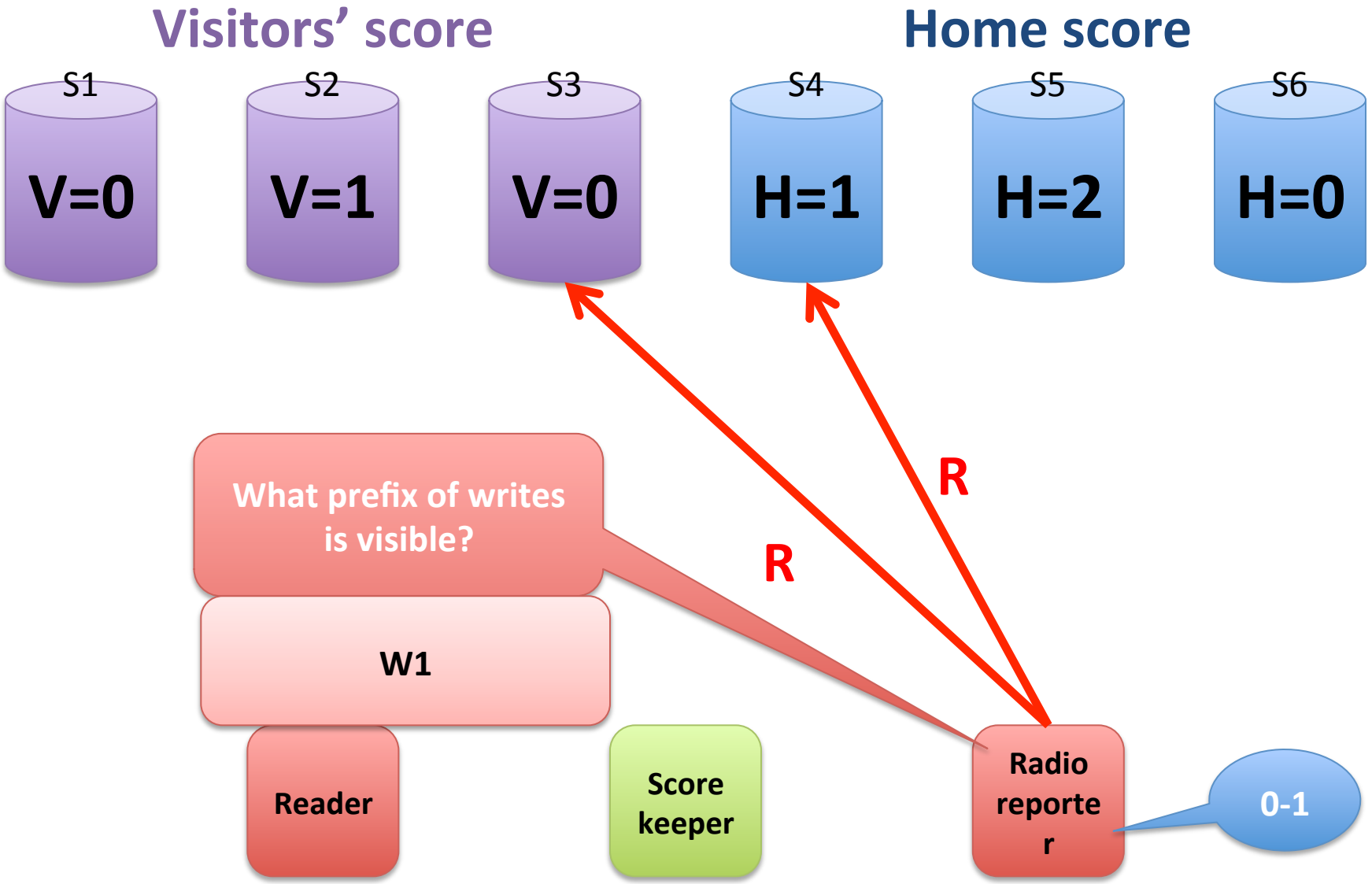
Example 3: radio reporter

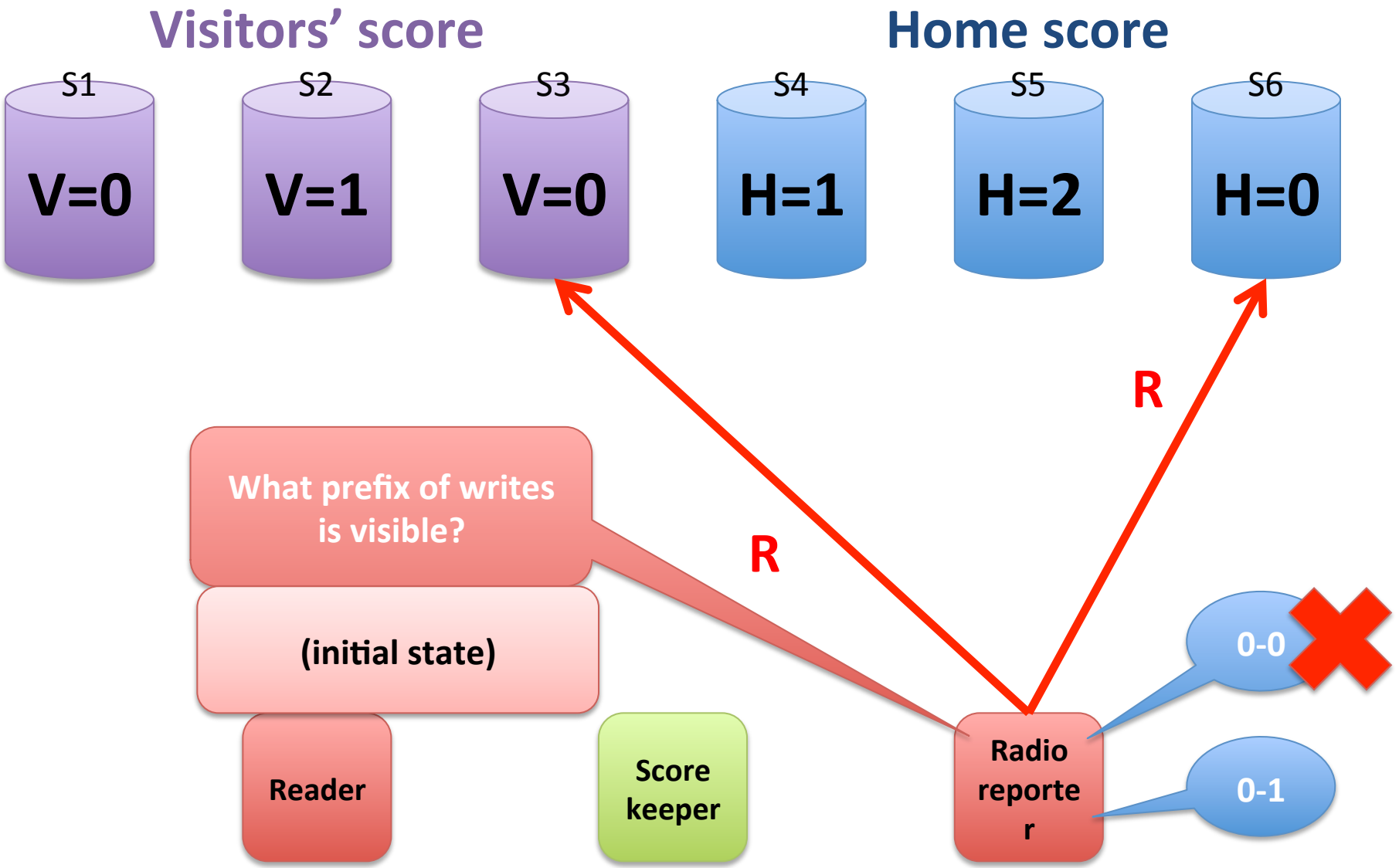
```
do {
  vScore = Read ("visitors");
  hScore = Read ("home");
  report vScore, hScore;
  sleep (30 minutes);
}
```

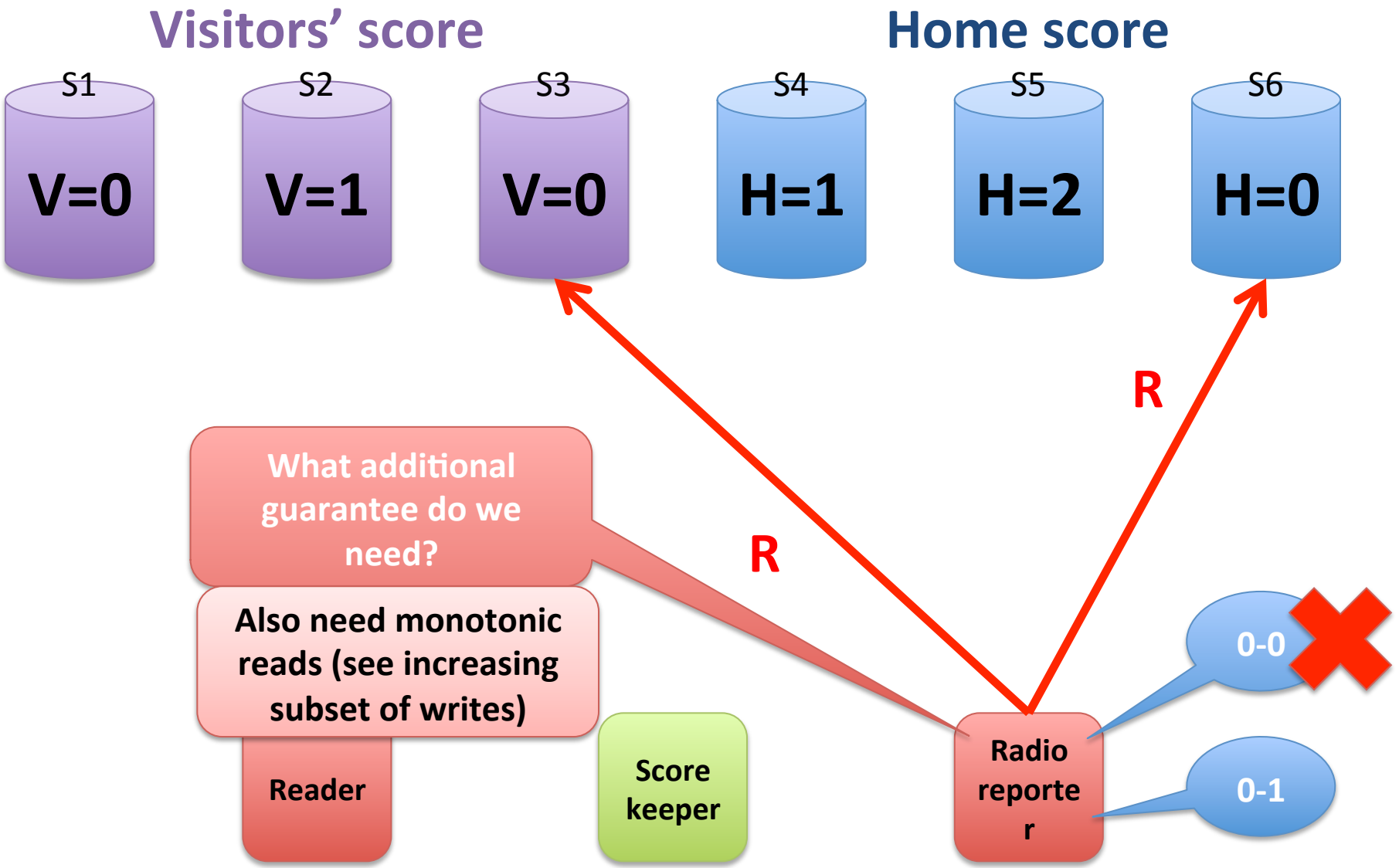
How about only consistent prefix (some sequence of writes is visible)?

No. Would give us scores that occurred, but not monotonically increasing.


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V
V
V
H
H
H
W1
W2
W3
Reader
Score keeper
Radio reporte r


Visitors' score
Home score
S1
V=0
S2
V=1
S3
V=0
S4
H=1
S5
H=2
S6
H=0
R
R
What prefix of writes is visible?
W1
Reader
Score keeper
Radio reporte r
0-1


Visitors' score
Home score
S1
V=0
S2
V=1
S3
V=0
S4
H=1
S5
H=2
S6
H=0
R
R
What prefix of writes is visible?
(initial state)
Reader
Score keeper
Radio reporte r
0-0
0-1


Visitors' score
Home score
S1
V=0
S2
V=1
S3
V=0
S4
H=1
S5
H=2
S6
H=0
R
R
What additional guarantee do we need?
Also need monotonic reads (see increasing subset of writes)
Reader
Score keeper
Radio reporte r
0-0
0-1

Monotonic reads

- **Also called "session consistency"**
  - Reads are grouped under a "session"
- **What extra state/logic is needed for monotonic reads?**
  - System has to know which reads are related
  - Related reads have to be assigned a sequence (i.e., a total order)
- **What extra state/logic is needed for read-my-writes?**
  - System has to know which reads/writes are related
  - Related reads/writes have to be assigned a total order
- **Does read-my-writes guarantee monotonic reads?**
  - (get into groups for five minutes to discuss)

Example 3: radio reporter

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

Can we get away with bounded staleness (see all "old" writes)?

If we also have consistent prefix, and as long as bound is < 30 minutes.

Example 3: radio reporter

```
T0 Read ("home");
T1 Read ("visitors");
T2 sleep (30 minutes);
T3 Read ("home");
T4 Read ("visitors");
T5 sleep (30 minutes);
T6 Read ("visitors");
T7 Read ("home");
T8 sleep (30 minutes);
…
```

Under bounded staleness (bound = 15 minutes, no consistent prefix), what writes must these reads reflect?

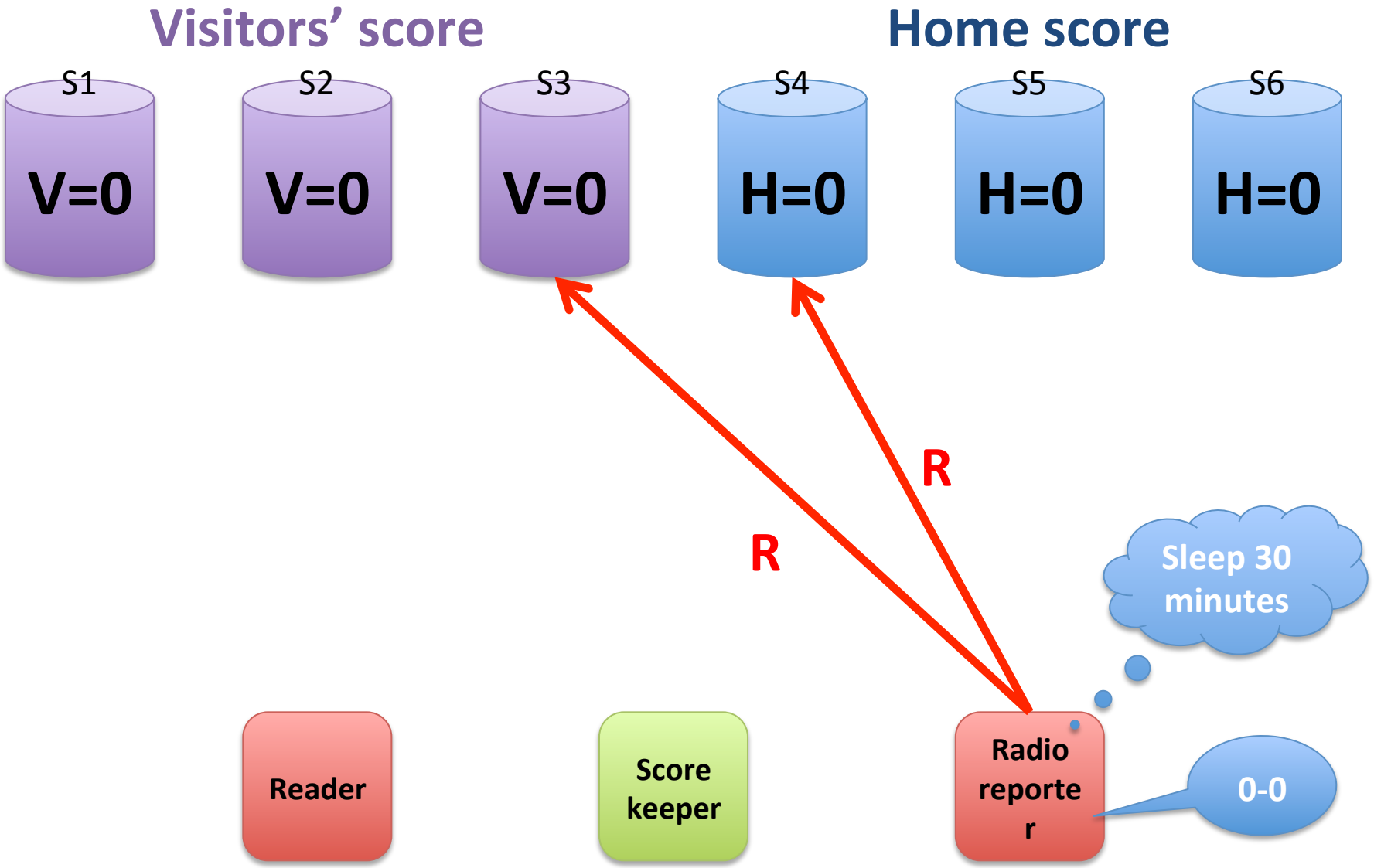
Any write that occurred before T3 – 15 minutes

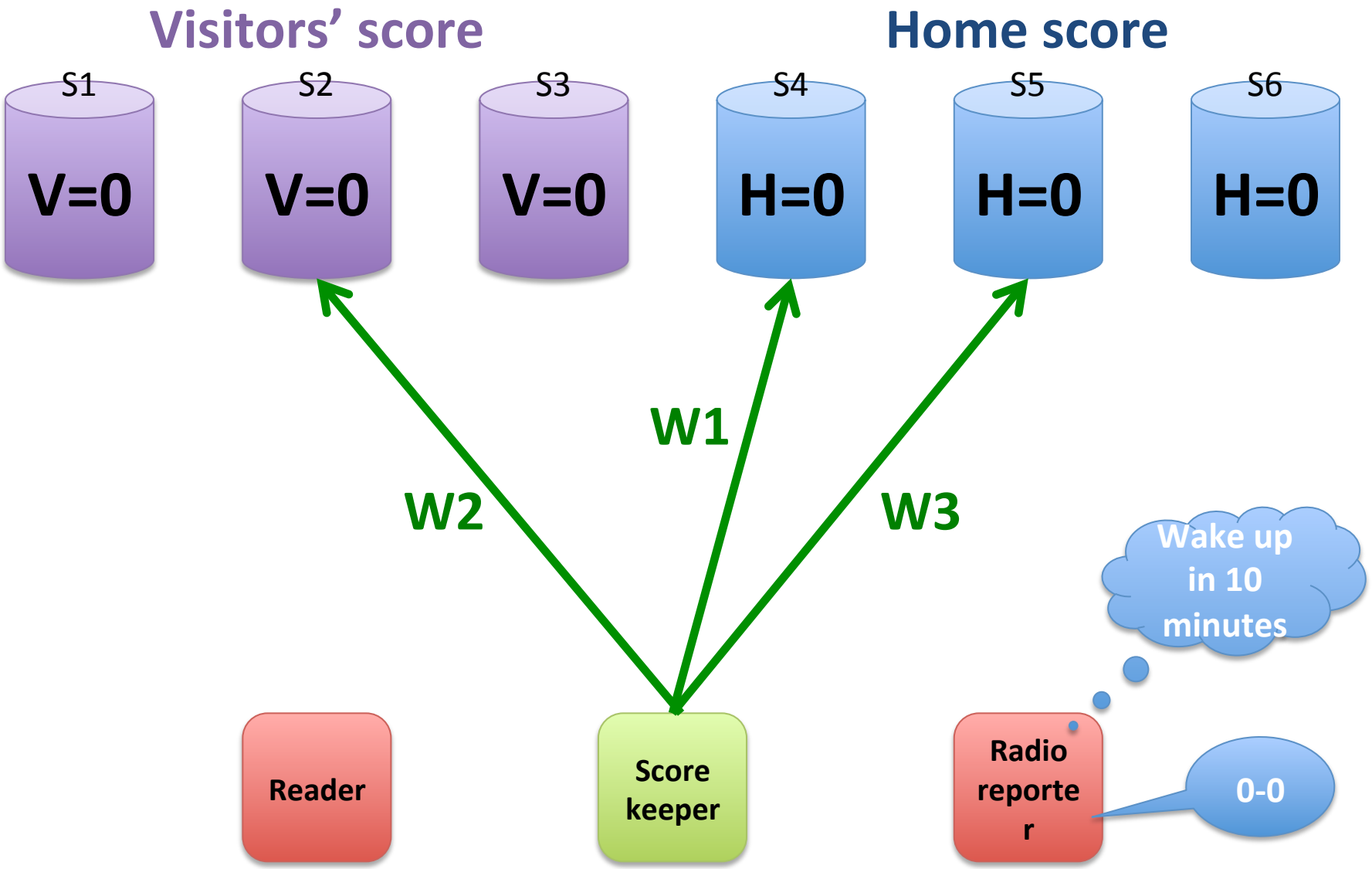
Example 3: radio reporter

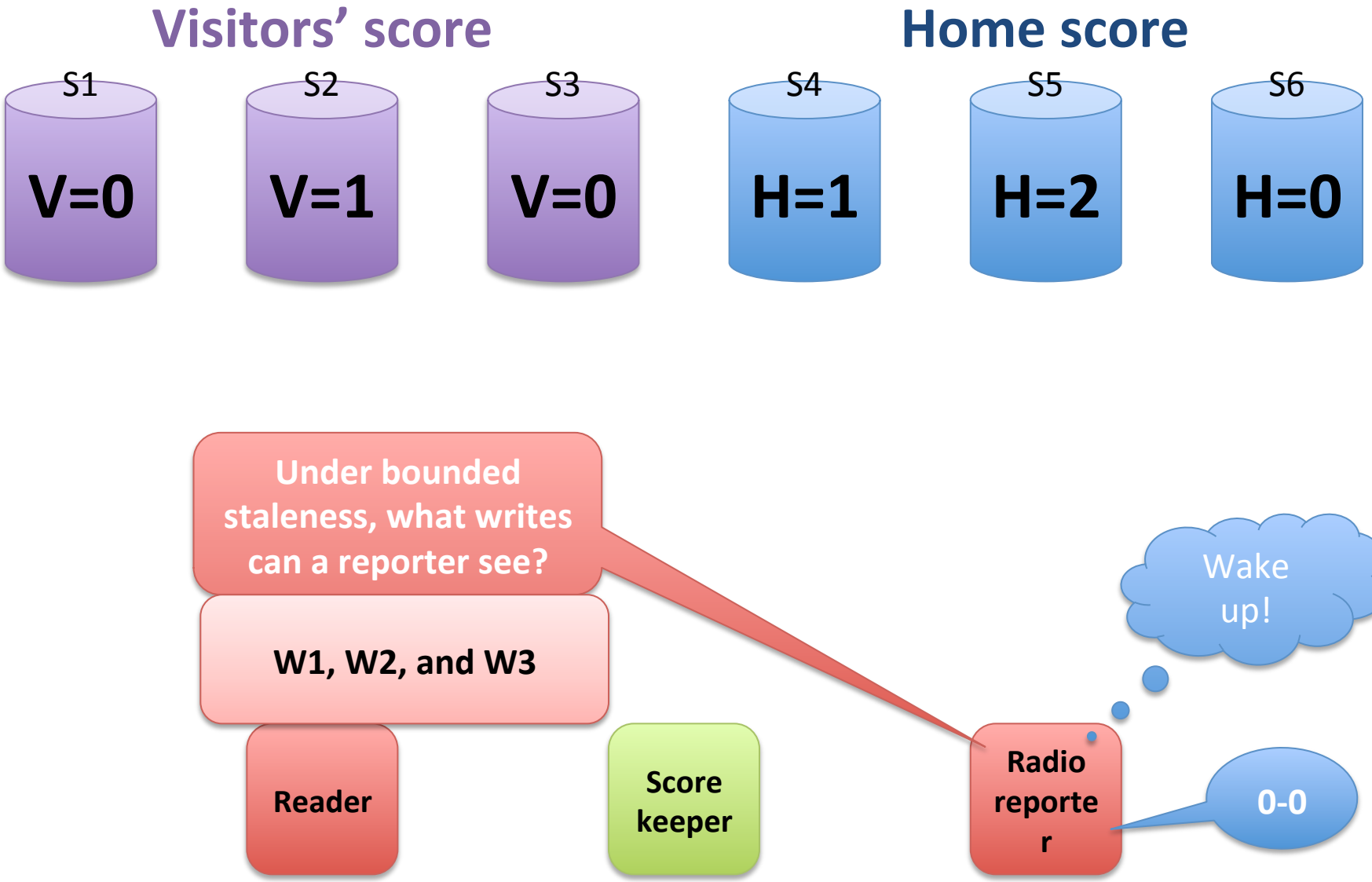
```
T0 Read ("home");
T1 Read ("visitors");
T2 sleep (30 minutes);
T3 Read ("home");
T4 Read ("visitors");
T5 sleep (30 minutes);
T6 Read ("visitors");
T7 Read ("home");
T8 sleep (30 minutes);
…
```

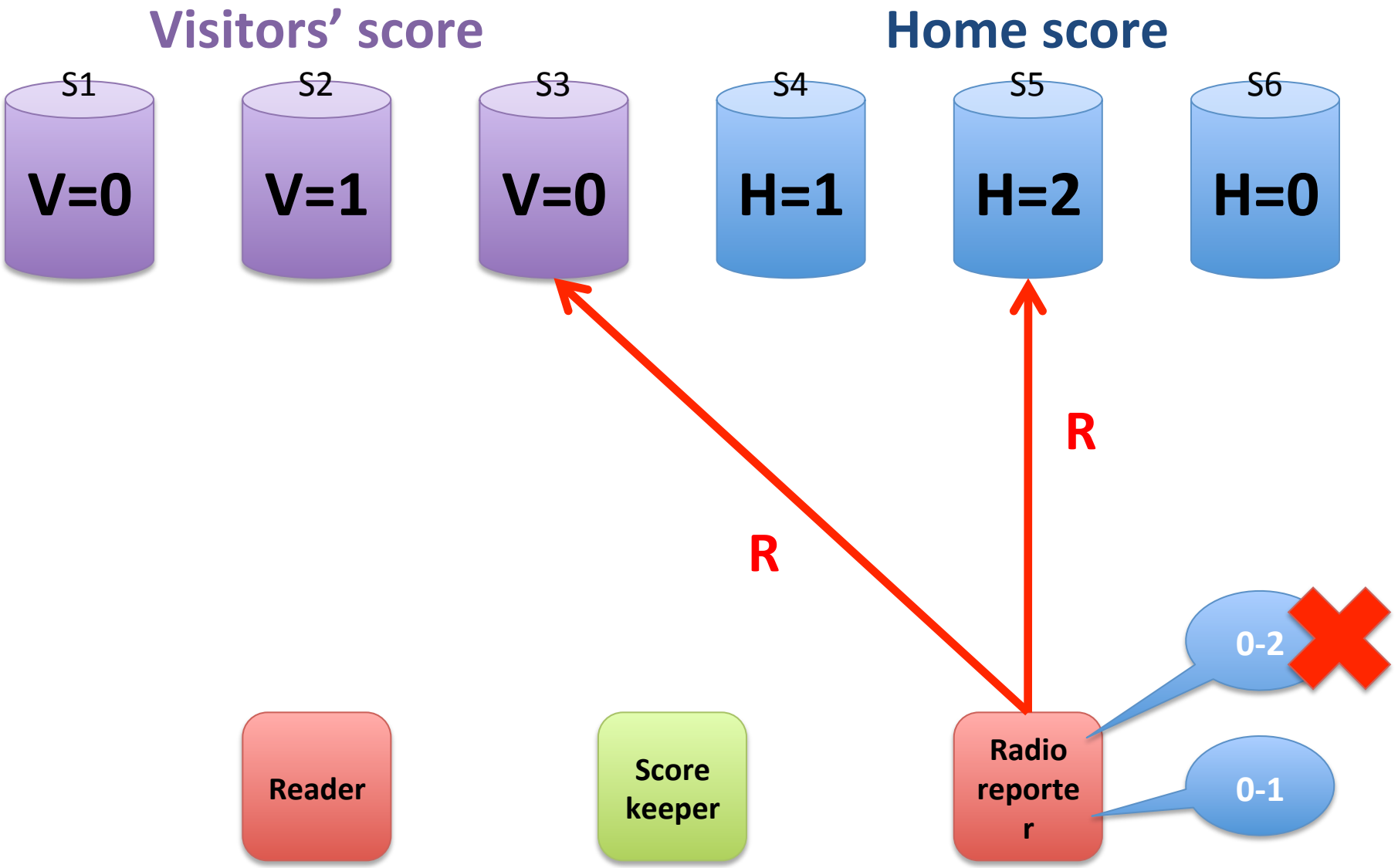
Why isn't unbounded staleness by itself sufficient?

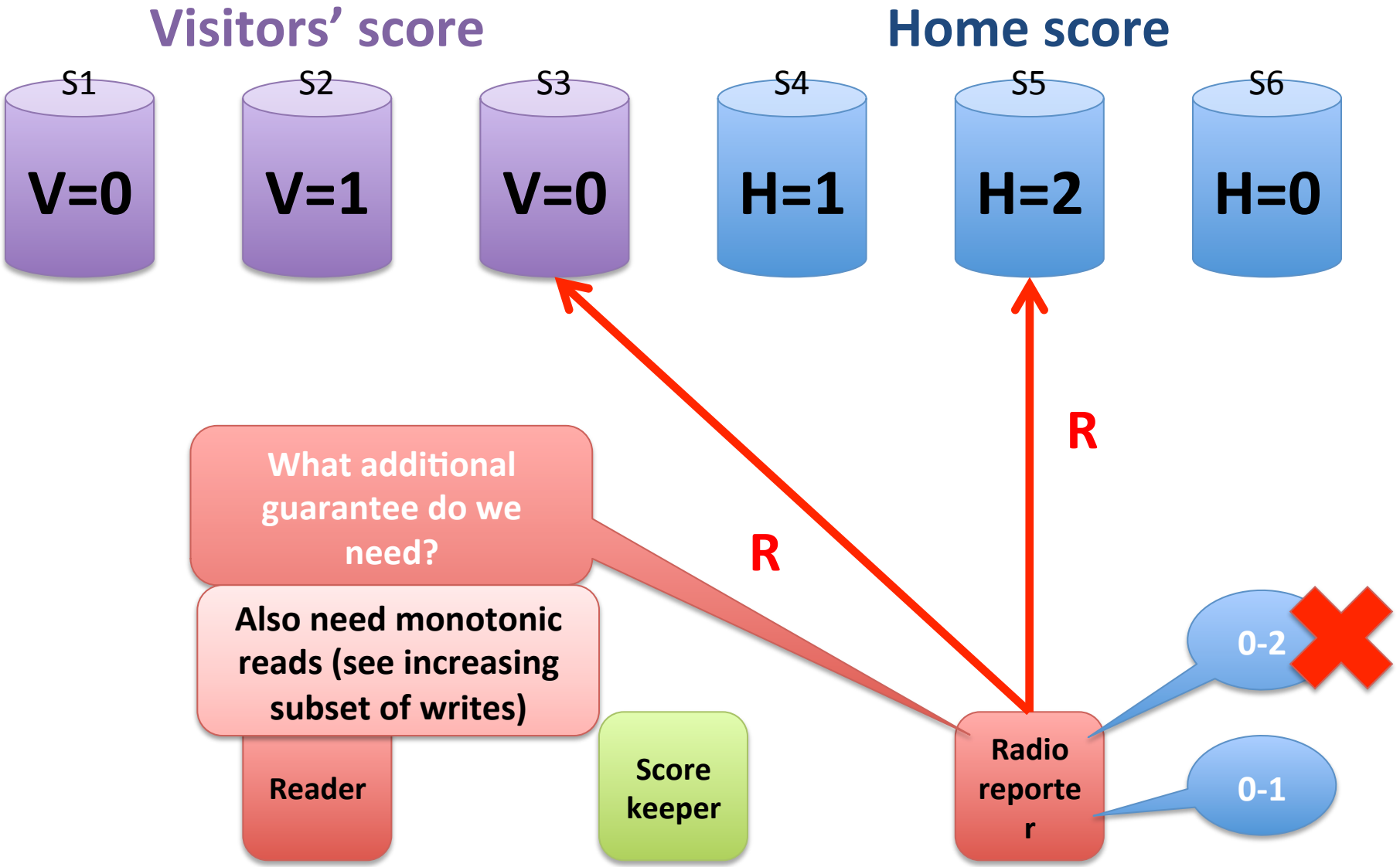
Score must reflect writes that occurred before T3 – (15 minutes), could also reflect more recent writes


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V=0
V=0
V=0
H=0
H=0
H=0
R
R
Sleep 30 minutes
Reader
Score keeper
Radio reporte r
0-0


Visitors' score
Home score
S1
S2
S3
S4
S5
S6
V=0
V=0
V=0
H=0
H=0
H=0
W1
W2
W3
Wake up in 10 minutes
Reader
Score keeper
Radio reporte r
0-0


Visitors' score
Home score
S1
V=0
S2
V=1
S3
V=0
S4
H=1
S5
H=2
S6
H=0
Under bounded staleness, what writes can a reporter see?
W1, W2, and W3
Reader
Score keeper
Radio reporte r
Wake up!
0-0


Visitors' score
Home score
S1
V=0
S2
V=1
S3
V=0
S4
H=1
S5
H=2
S6
H=0
R
R
0-2
0-1
Reader
Score keeper
Radio reporte r


Visitors' score
Home score
S1
V=0
S2
V=1
S3
V=0
S4
H=1
S5
H=2
S6
H=0
R
R
What additional guarantee do we need?
Also need monotonic reads (see increasing subset of writes)
Reader
Score keeper
Radio reporte r
0-2
0-1

Example 4: game-recap writer

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

Idea: write about game several hours after it has ended

Example 4: game-recap writer

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

What invariant must the recapper uphold?

Reads must reflect all writes.

Example 4: game-recap writer

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

What consistency guarantees could she use?

Strong consistency or bounded staleness w/ bound < time to eat dinner

Example 4: game-recap writer

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

What about eventual consistency?

Probably OK most of the time. Bounded to ensure you always get right output.

Example 5: team statistician

```
wait for end of game;
hScore = Read ("home");
stat = Read ("season-runs");
Write ("season-runs", stat + hScore);
```

What invariants must statistician uphold?

Season-runs increases monotonically by amount home team scored at the end of the game

Example 5: team statistician

```
wait for end of game;
hScore = Read ("home");
stat = Read ("season-runs");
Write ("season-runs", stat + hScore);
```

What consistency is appropriate for this read?

Could use strong consistency, bounded staleness (with appropriate bound), maybe eventual consistency

Example 5: team statistician

```
wait for end of game;
hScore = Read ("home");
stat = Read ("season-runs");
Write ("season-runs", stat + hScore);
```

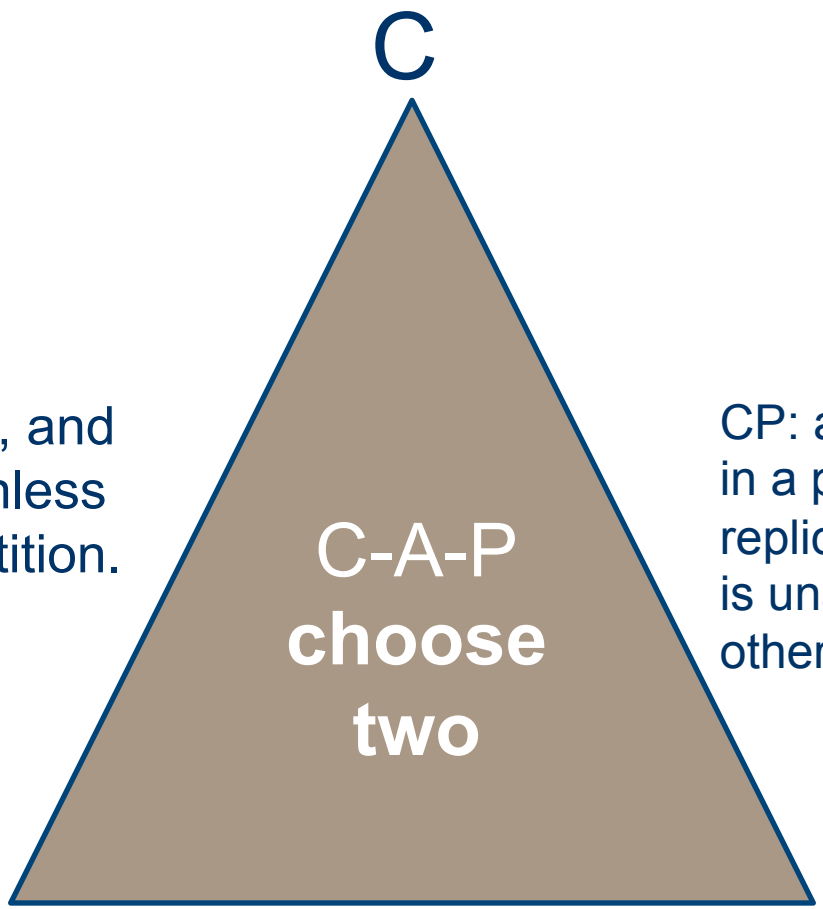
What consistency is appropriate for this read?

Could use strong consistency, bounded staleness, or read-my-writes if statistician is only writer

- **Geo-replicated stores face fundamental limits common to all distributed systems.**
- **FLP result: consensus is impossible in asynchronous distributed systems.**
  - Distributed systems may "partly fail", and the network may block or delay network traffic arbitrarily.
  - In particular, a network partition may cause a "split brain" in which parts of the system function without an ability to contact other parts of the system (see material on leases).
  - Example of consensus: what was the last value written for X?
- **Popular form of FLP: "Brewer's conjecture" also known as "CAP theorem".**
  - We can build systems that are CA, CP, or AP, but we cannot have all three properties at once, ever.
- **To a large extent these limits drive the consistency models.**
- (Following slides by Chase)

“CAP theorem”

Dr. Eric Brewer



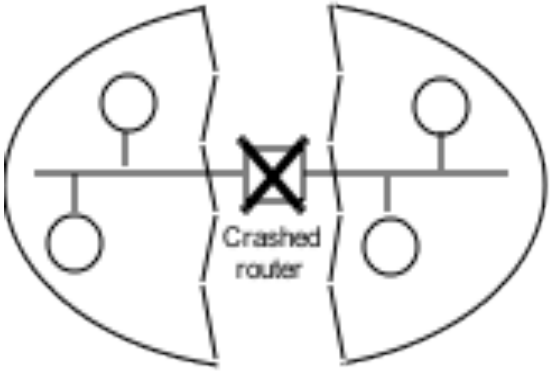
CA: available, and consistent, unless there is a partition.

CP: always consistent, even in a partition, but a reachable replica may deny service if it is unable to agree with the others (e.g., quorum).

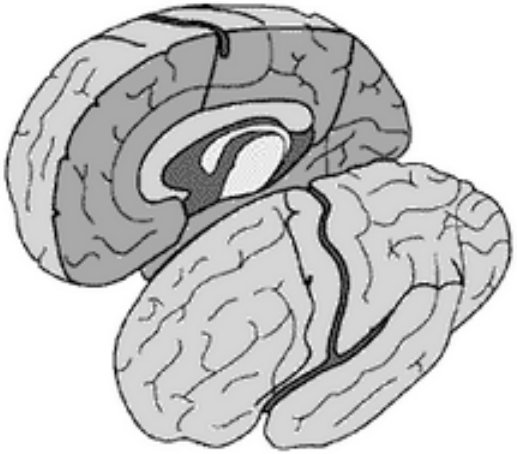
AP: a reachable replica provides service even in a partition, but may be inconsistent.

Fischer-Lynch-Patterson (1985)

- **No consensus can be guaranteed in an asynchronous system in the presence of failures.**
- **Intuition: a "failed" process may just be slow, and can rise from the dead at exactly the wrong time.**
- **Consensus may occur recognizably, rarely or often.**



Network partition



Split brain

Getting precise about CAP #1

- What does consistency mean?
- Consistency → Ability to implement an atomic data object served by multiple nodes.
- Requires linearizability of ops on the object.
  - Total order for all operations, consistent with causal order, observed by all nodes
  - Also called one-copy serializability (1SR): object behaves as if there is only one copy, with operations executing in sequence.
  - Also called atomic consistency ("atomic")

Brewer's Conjecture and the Feasibility of Consistent, Available, Partition-Tolerant Web Services. Seth Gilbert, Nancy Lynch. *MIT manuscript*.

Getting precise about CAP #2

- **Availability** → Every request received by a node must result in a response.
  - Every algorithm used by the service must terminate.
- **Network partition** → Network loses or delays arbitrary runs of messages between arbitrary pairs of nodes.
  - Asynchronous network model assumed
  - Service consists of at least two nodes

Brewer's Conjecture and the Feasibility of Consistent, Available, Partition-Tolerant Web Services. Seth Gilbert, Nancy Lynch. *MIT manuscript*.

Getting precise about CAP #3

- **Theorem. It is impossible to implement an atomic data object that is available in all executions.**
  - **Proof. Partition the network. A write on one side is not seen by a read on the other side, but the read must return a response.**
- **Corollary. Applies even if messages are delayed arbitrarily, but no message is lost.**
  - **Proof. The service cannot tell the difference.**

***Brewer's Conjecture and the Feasibility of Consistent, Available, Partition-Tolerant Web Services*. Seth Gilbert, Nancy Lynch. *MIT manuscript*.**

Getting precise about CAP #4

- **Atomic and partition-tolerant**
  - **Trivial: ignore all requests.**
  - **Or: pick a primary to execute all requests**
- **Atomic and available.**
  - **Multi-node case not discussed.**
  - **But use the primary approach.**
  - **Need a terminating algorithm to select the primary. Does not require a quorum if no partition can occur. Left as an exercise.**

***Brewer's Conjecture and the Feasibility of Consistent, Available, Partition-Tolerant Web Services*. Seth Gilbert, Nancy Lynch. *MIT manuscript*.**

Getting precise about CAP #5

- **Available and partition-tolerant**
  - **Trivial: ignore writes; return initial value for reads.**
  - **Or: make a best effort to propagate writes among the replicas; reads return any value at hand.**

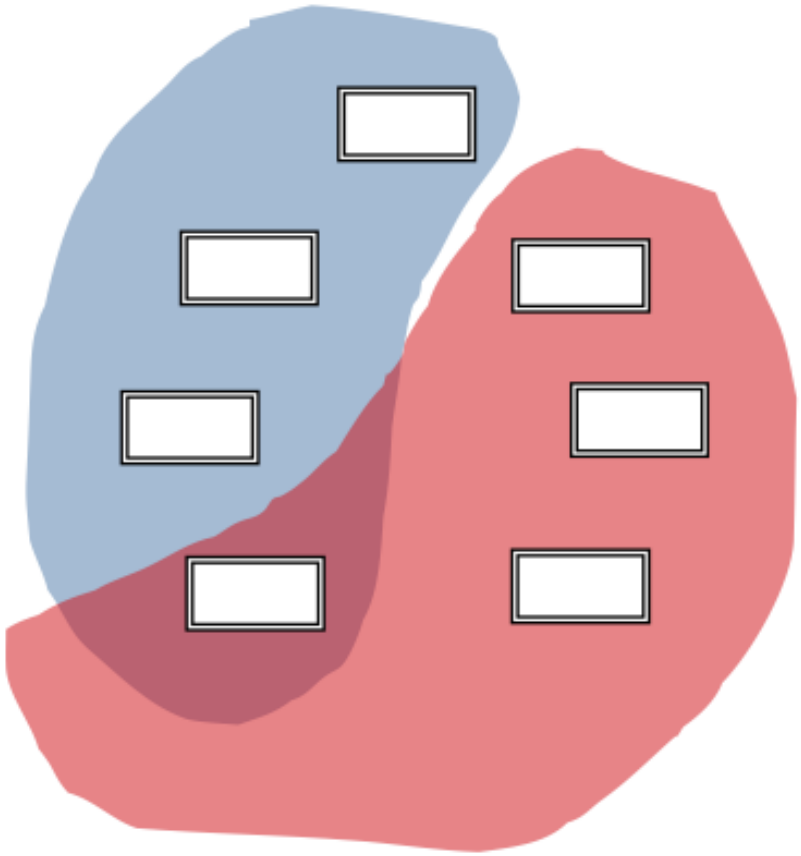
***Brewer's Conjecture and the Feasibility of Consistent, Available, Partition-Tolerant Web Services*. Seth Gilbert, Nancy Lynch. *MIT manuscript*.**

Quorum

- How to build a replicated store that is atomic (consistent) always, and available unless there is a partition?
  - Read and write operations complete only if they are acknowledged by some minimum number (a **quorum**) of replicas.
  - Set the quorum size so that any **read set** is guaranteed to overlap with any **write set**.
  - This property is sufficient to ensure that any read "sees" the value of the "latest" write.
  - So it ensures consistency, but it must deny service if "too many" replicas fail or become unreachable.

Quorum consistency

$n = 7$
$rv = 4$
$wv = 4$

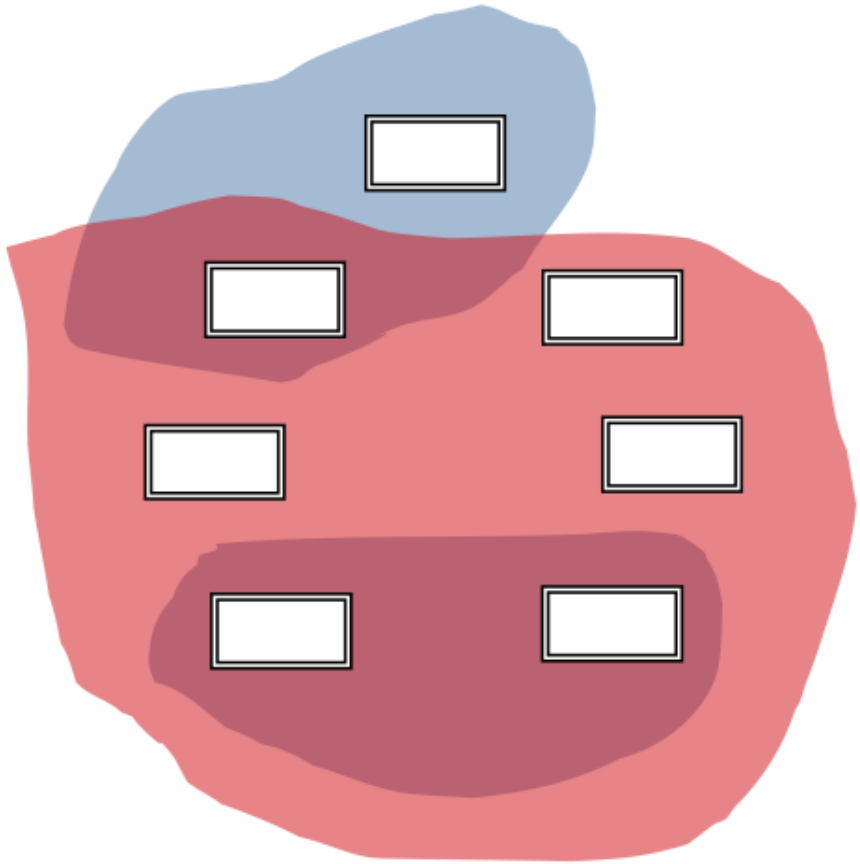


rv=wv=f
n=2f+1

[Keith Marzullo]

Weighted quorum voting

$n = 7$
$rv = 2$
$wv = 6$



rv+wv=n+1

Any write quorum must intersect every other quorum.

[Keith Marzullo]