[544] Cassandra Partitioning+Replication

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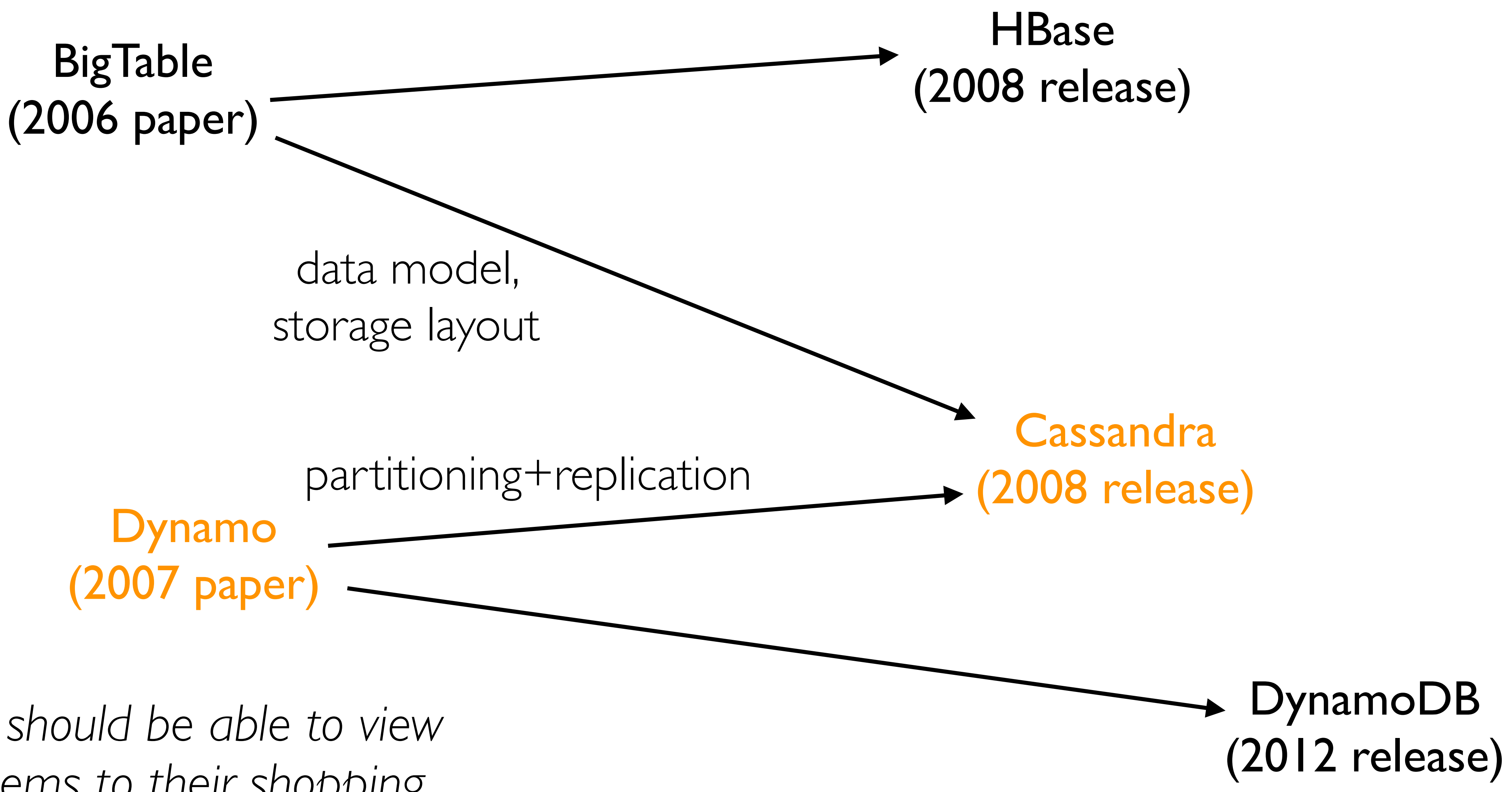
Cassandra Influences



BigTable
(2006 paper)

HBase
(2008 release)

data model,
storage layout

Cassandra
(2008 release)

partitioning+replication

Dynamo
(2007 paper)

DynamoDB
(2012 release)

"*customers should be able to view and add items to their shopping cart even if disks are failing, network routes are flapping, or data centers are being destroyed by tornados*"
~ authors of first Dynamo paper

goal: highly available when things are failing

Outline: Cassandra Partitioning+Replication

Partitioning

Replication

Quorum Reads/Writes

Conflict Resolution

Cassandra Demos

Partitioning Approaches

Given many machines and a partition of data, *how do we decide where it should live?*

Mapping Data Structure

- locations = {"fileA-block0": [datanode1, ...], ...}
- HDFS NameNode uses this

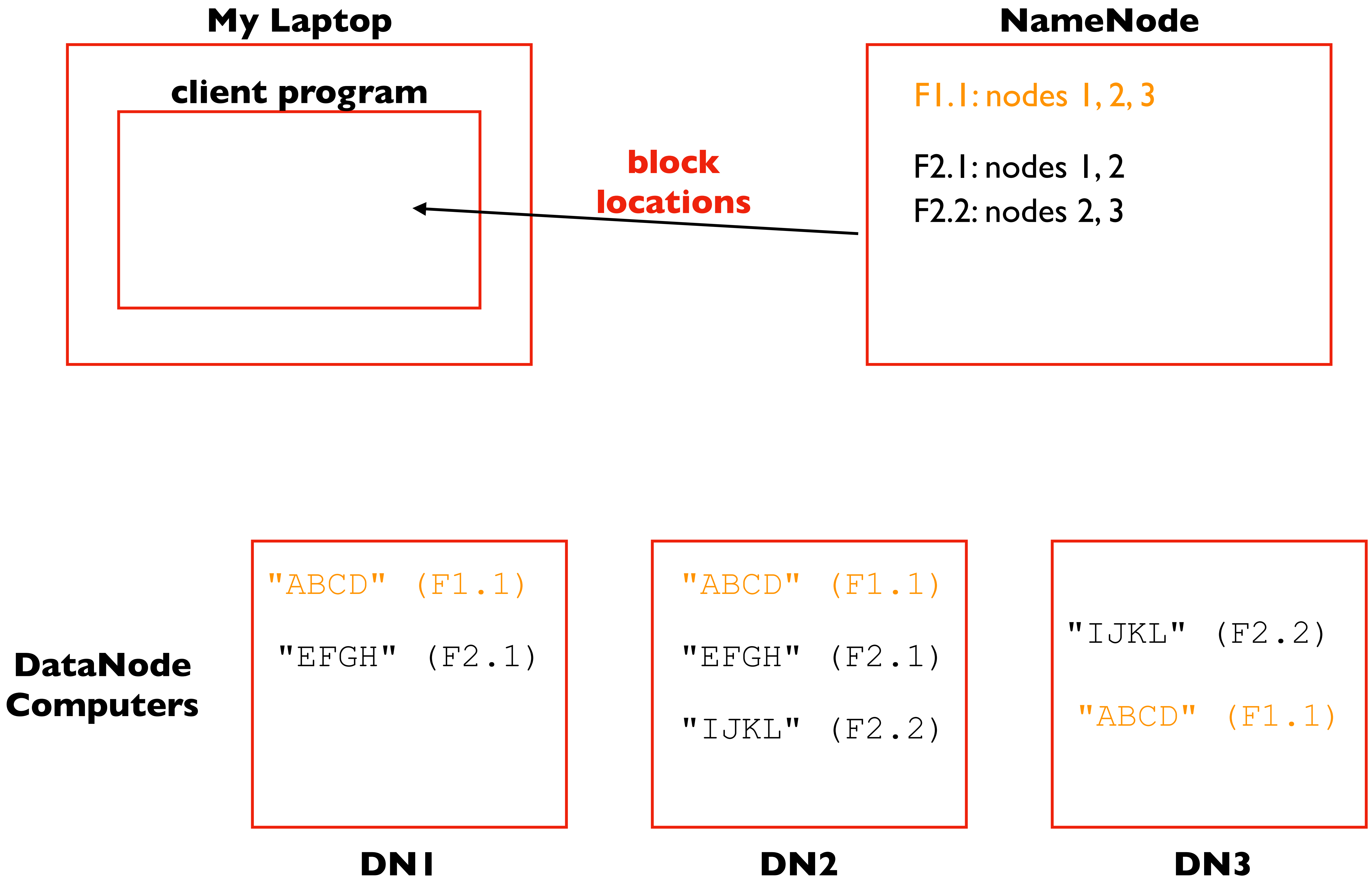
Hash Partitioning

- partition = hash(key) % partition_count
- Spark shuffle uses this (for grouping, joining, etc); data structures associate partitions with worker machines

Consistent Hashing

- Dynamo and Cassandra use this

Review: HDFS Partitioning



My Laptop

client program

block locations

NameNode

F1.1: nodes 1, 2, 3

F2.1: nodes 1, 2

F2.2: nodes 2, 3

DataNode Computers

`"ABCD" (F1.1)`

`"EFGH" (F2.1)`

DN1

`"ABCD" (F1.1)`

`"EFGH" (F2.1)`

`"IJKL" (F2.2)`

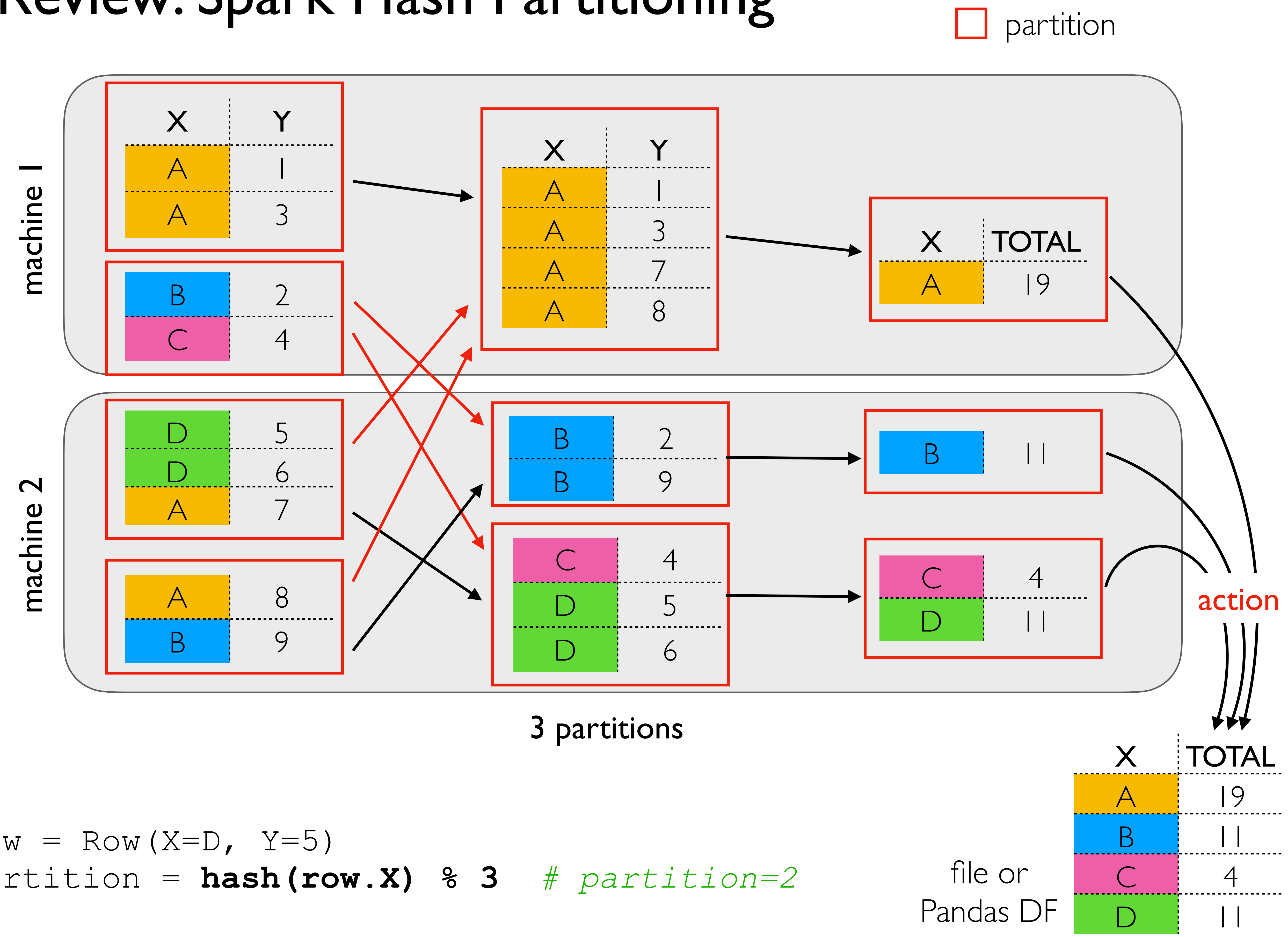
DN2

`"IJKL" (F2.2)`

`"ABCD" (F1.1)`

DN3

Review: Spark Hash Partitioning



X	Y
A	1
A	3

B	2
C	4

D	5
D	6
A	7

A	8
B	9

X	Y
A	1
A	3
A	7
A	8

B	2
B	9

C	4
D	5
D	6

X	TOTAL
A	19

B	11

C	4
D	11

X	TOTAL
A	19
B	11
C	4
D	11

```
row = Row(X=D, Y=5)
partition = hash(row.X) % 3   # partition=2
```

Discuss Scalability: HDFS and Spark

Scalability: we can make efficient use of many machines for big data

Two ways we can have big data:

- very many file blocks or rows
- files or tables containing many bytes of data

Will HDFS struggle with either kind of big data? Spark?

Elasticity: Easily Growing/Shrinking Clusters

Incremental Scalability: can we efficiently add more machines to an already large cluster?

What happens when we add a new DataNode to an HDFS cluster?

What would need to happen if we able to add an RDD partition in the middle of a Spark hash-partitioned shuffle?

Elasticity: Easily Growing/Shrinking Clusters

Incremental Scalability: can we efficiently add more machines to an already large cluster?

What happens when we add a new DataNode to an HDFS cluster?

What would need to happen if we able to add an RDD partition in the middle of a Spark hash-partitioned shuffle?

Demo: hash partition 26 letters over 4 "machines".
Add a 5th machine. How many letters must move?

Partitioning Approaches

Given many machines and a partition of data, *how do we decide where it should live?*

Mapping Data Structure

- locations = {"fileA-block0": [datanode1, ...], ...}
- HDFS NameNode uses this

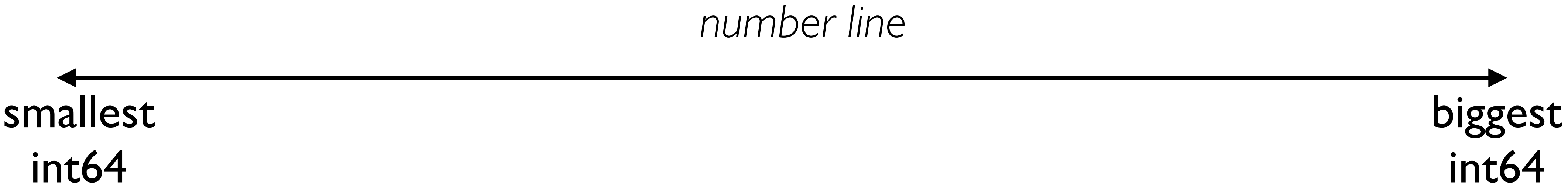
Hash Partitioning

- partition = hash(key) % partition_count
- Spark shuffle uses this (for grouping, joining, etc); data structures associate partitions with worker machines

Consistent Hashing

- Dynamo and Cassandra uses this
- token = hash(key) *# every token is in a range, indicating the worker*
- locations = {range(0,10): "worker1", range(10,20): "worker2", ...}

Consistent Hashing



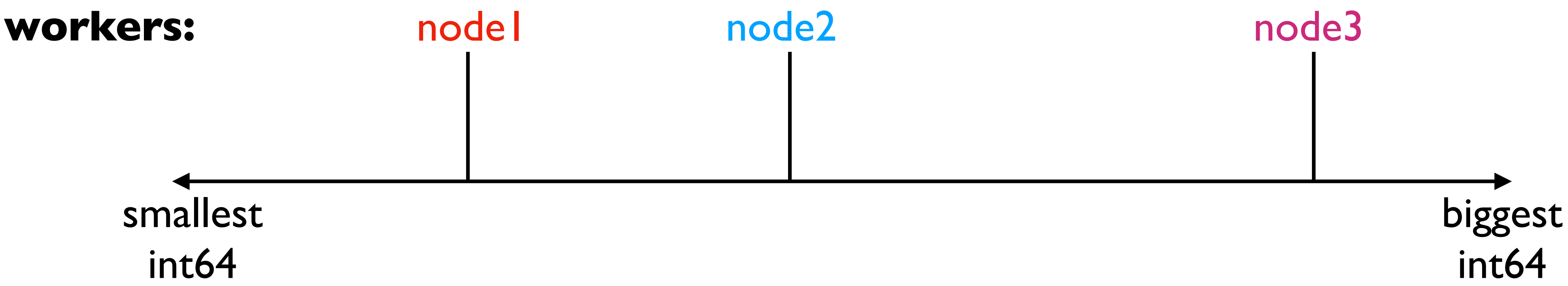
number line

smallest
int64

biggest
int64

Consistent Hashing

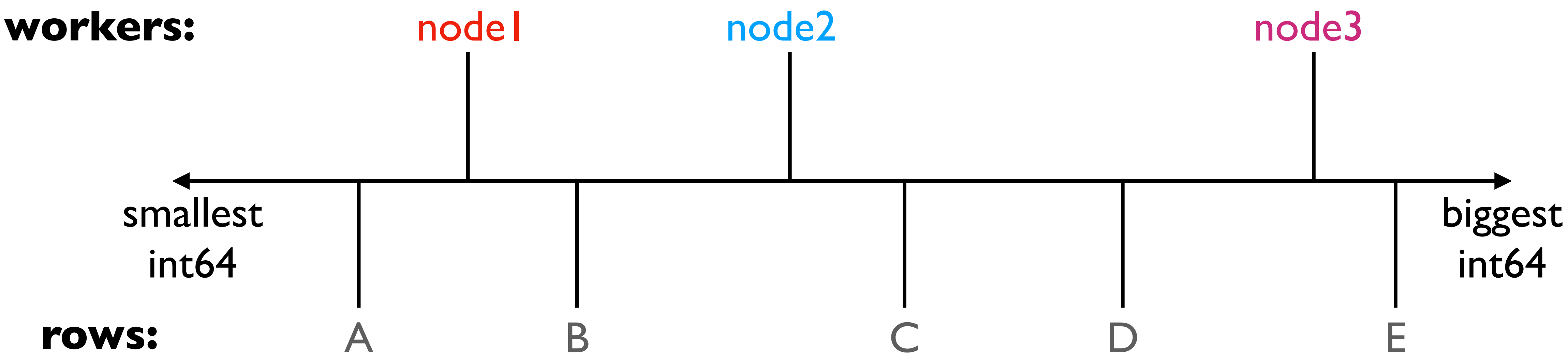
Token Map:
token(node1) = pick something
token(node2) = pick something
token(node3) = pick something



assign every **worker** a point on the number line.
Could be random (though newer approaches are more clever).
No hashing needed, *yet*!

Consistent Hashing

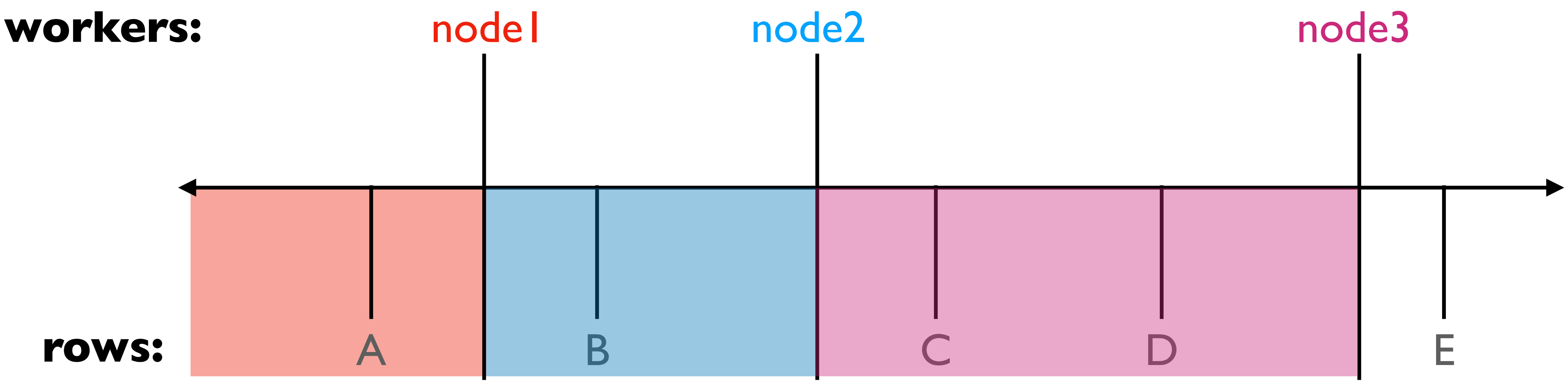
Token Map:
token(node1) = pick something
token(node2) = pick something
token(node3) = pick something



assign every **row** a point on the number line.
token(row) = hash(row's **partition** key)

Consistent Hashing

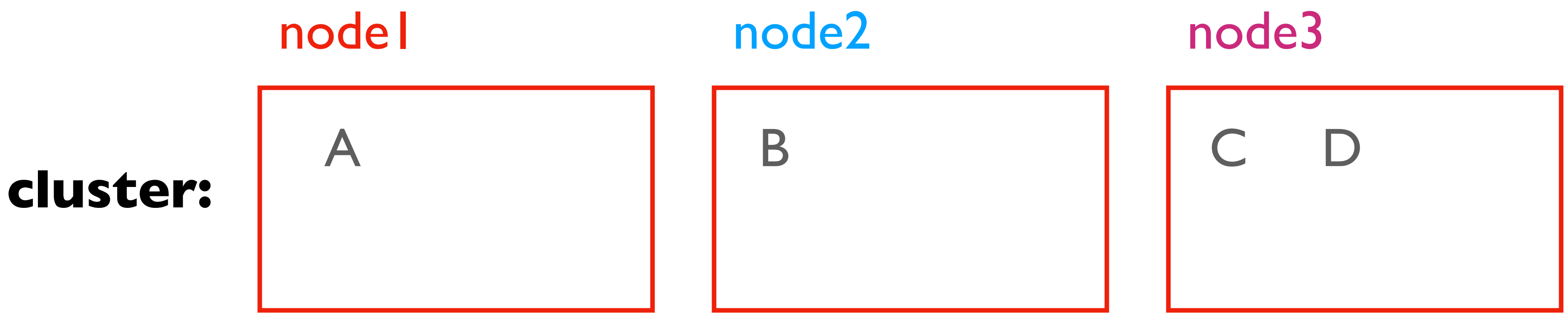
Token Map:
token(node1) = pick something
token(node2) = pick something
token(node3) = pick something



workers:
node1
node2
node3

rows:
A
B
C
D
E

each node's token is the **inclusive end** of a range.
A row is mapped to a node based on the range it is in.

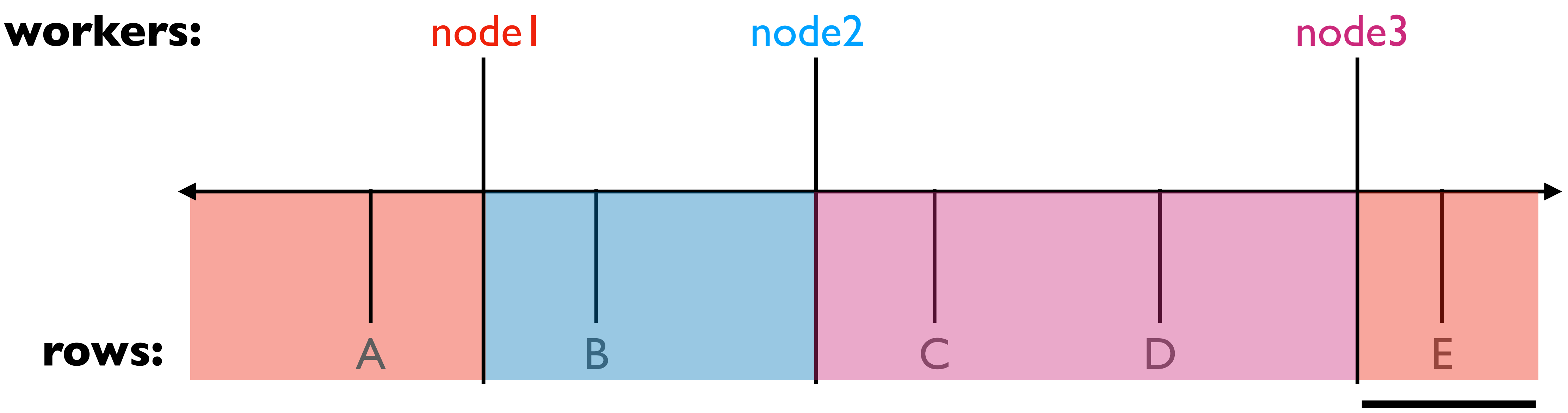


node1
node2
node3

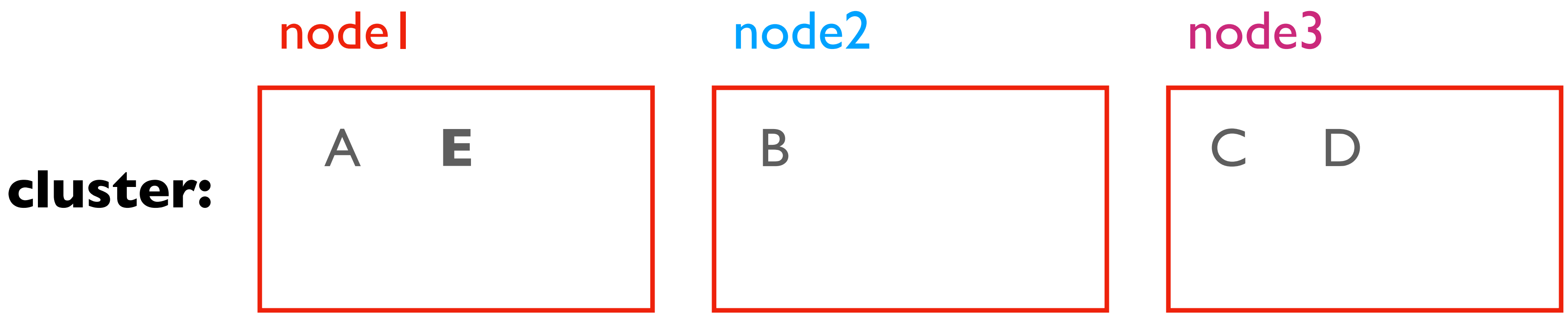
cluster:
A
B
C D

Consistent Hashing

Token Map:
token(node1) = pick something
token(node2) = pick something
token(node3) = pick something



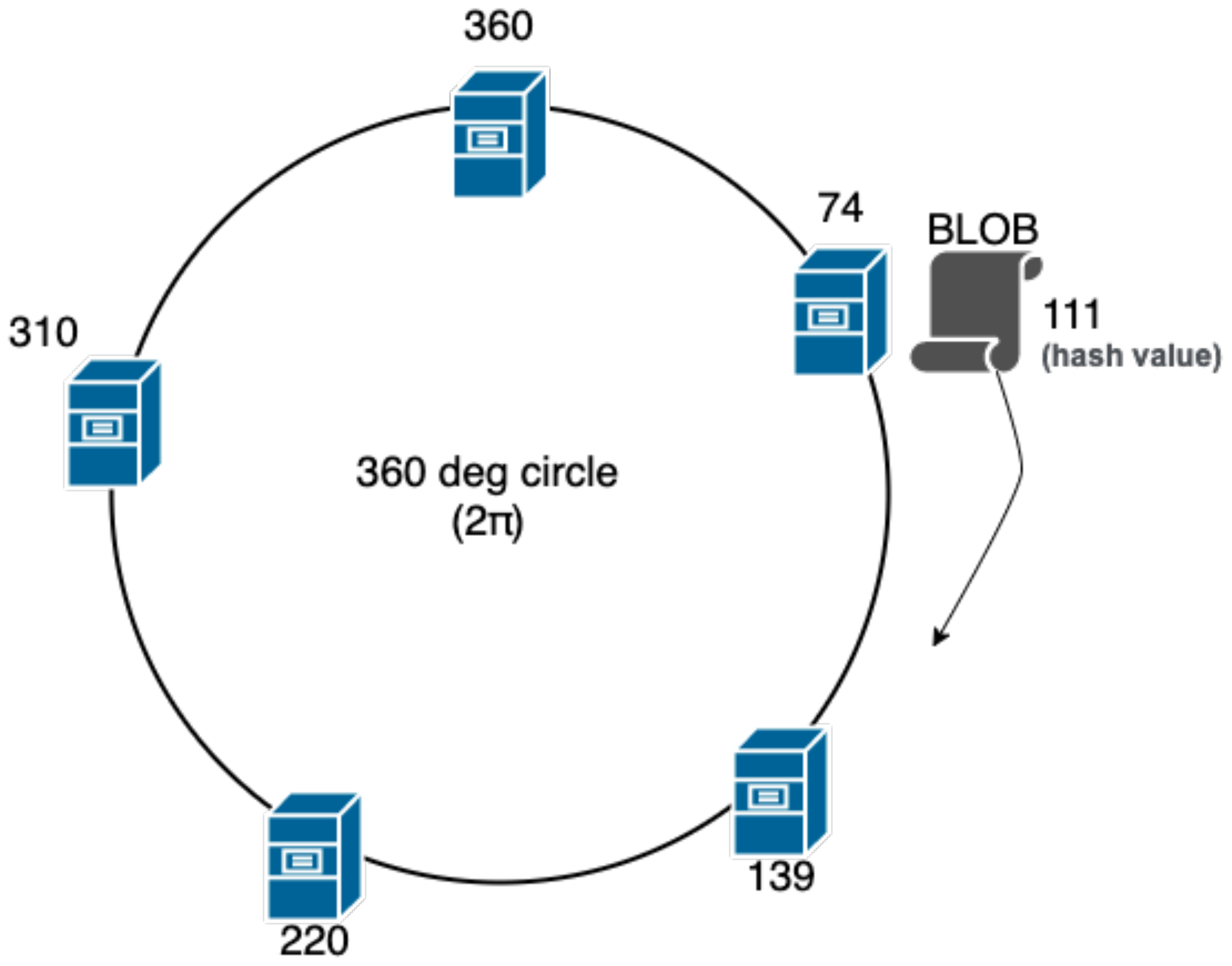
tokens > biggest node token are in the *wrapping range*. Rows in this region go to the node with the smallest token.



Alternate Visualization

Given the wrapping, clusters using consistent hashing are called "token rings"

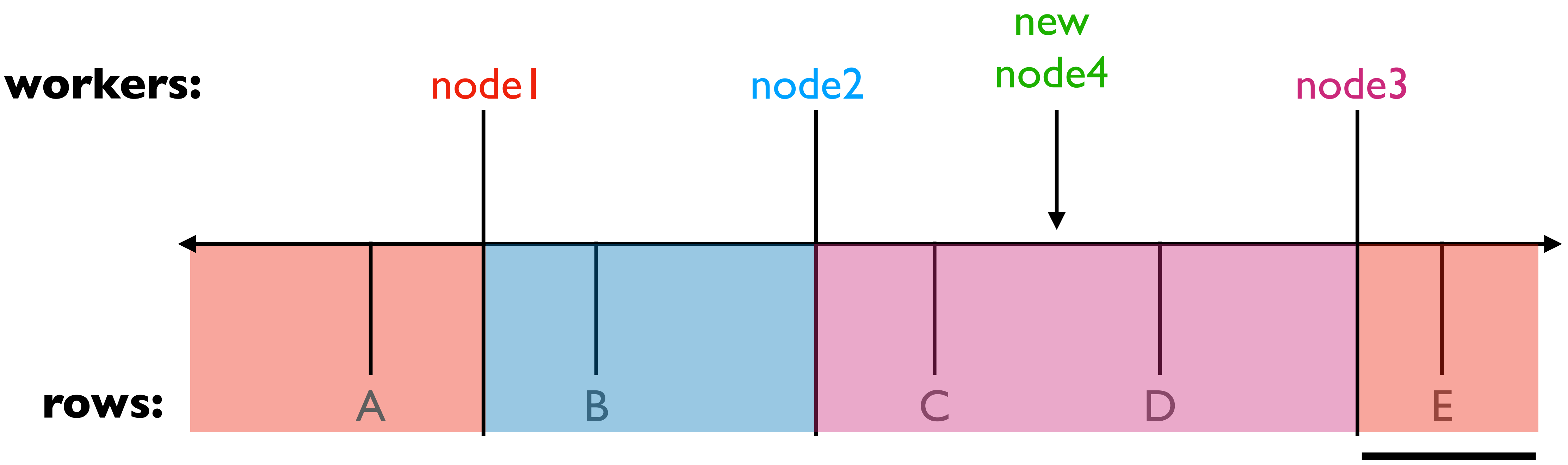
Common visuazilation (e.g., from Wikipedia)



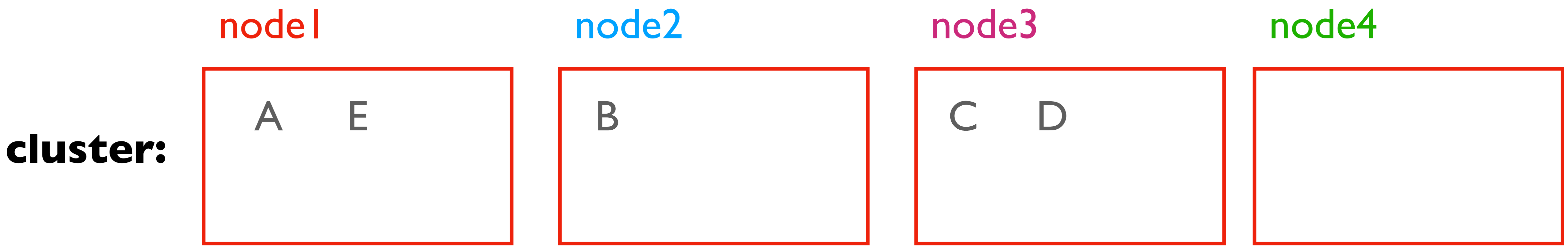
https://en.wikipedia.org/wiki/Consistent_hashing#/media/File:Consistent_Hashing_Sample_Illustration.png

Adding a Node

Token Map:
token(node1) = pick something
token(node2) = pick something
token(node3) = pick something
token(node4) = pick something



which rows will have to move?
which nodes will be involved?



Adding a Node

Token Map:
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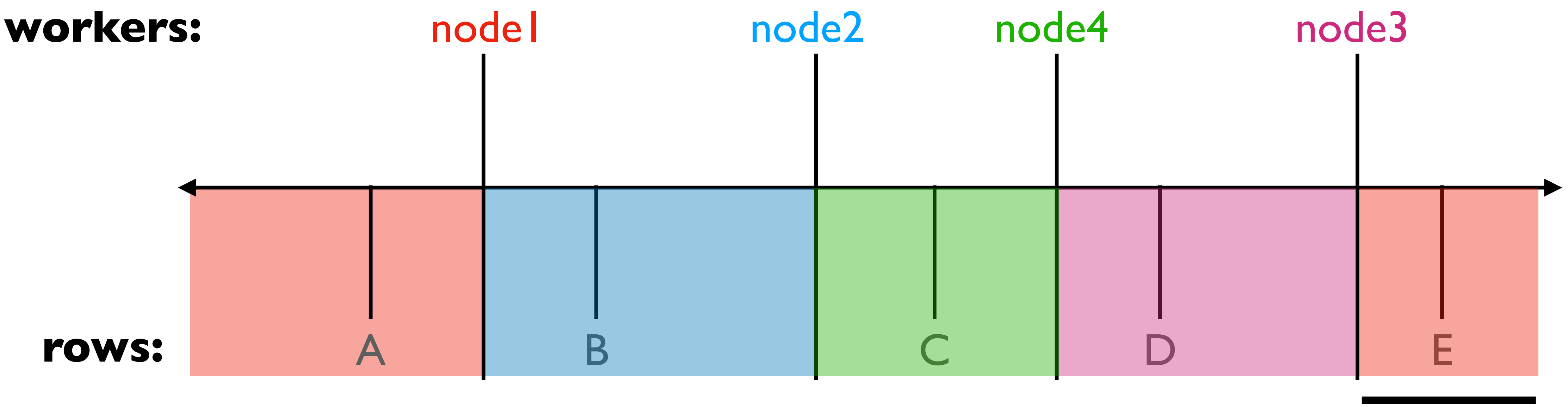
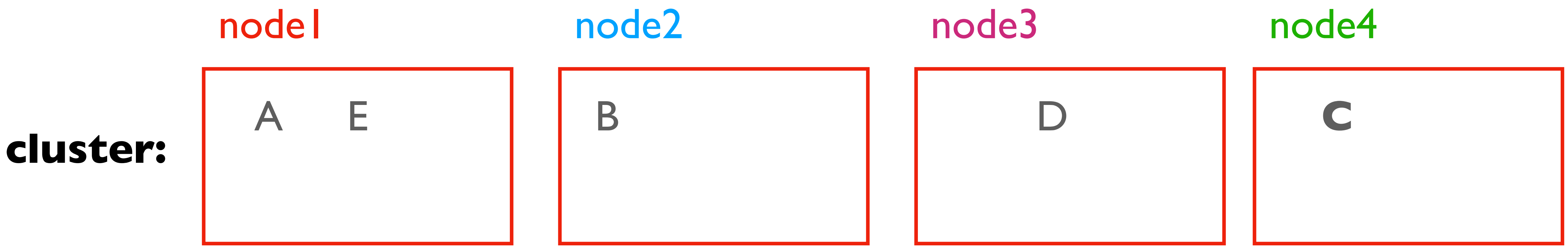


which rows will have to move? Only C
which nodes will be involved? Only node3 and node4



Adding a Node

Token Map:
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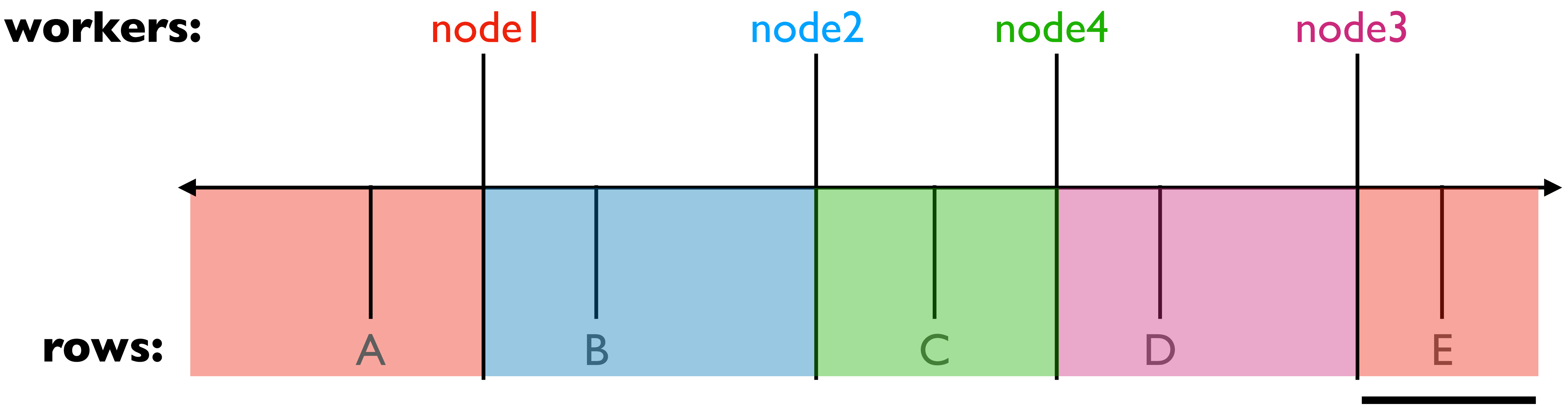
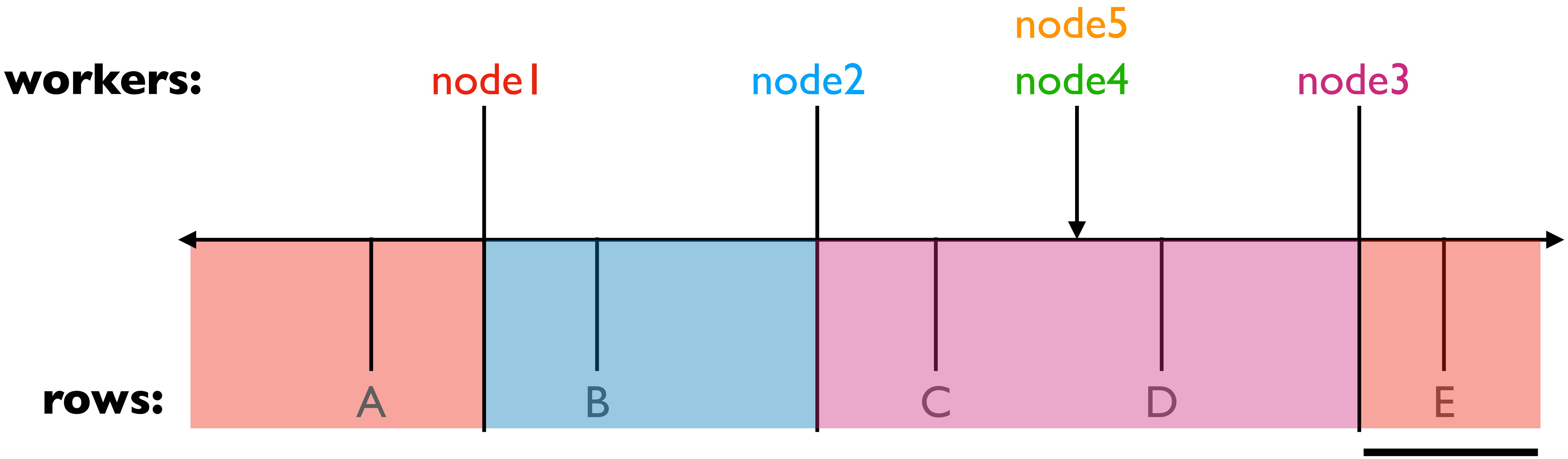


Typically, what fraction of the data must move when we scale from N-1 to N?
Hash partinioning: about (N-1)/N of the data
Consistent hashing: about (size of new range)/(size of combined range) of the data must move.

Collisions

Token Map:
token(node1) = pick something
token(node2) = pick something
token(node3) = pick something
token(node4) = pick something

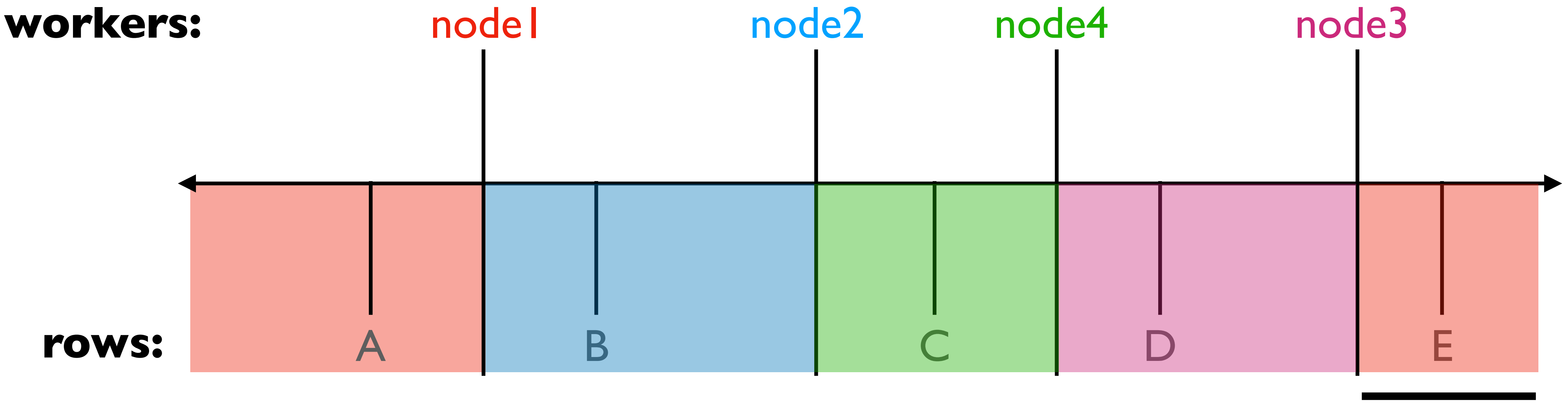


Problem: latest Cassandra versions by default try to choose new node tokens to split big ranges for better balance (instead of randomly picking). Adding multiple nodes simultaneously can lead to collisions, preventing nodes from joining.

Solution: add one at a time (after initial "seed" nodes)

Sharing the Work

Token Map:
token(node1) = pick something
token(node2) = pick something
token(node3) = pick something
token(node4) = pick something



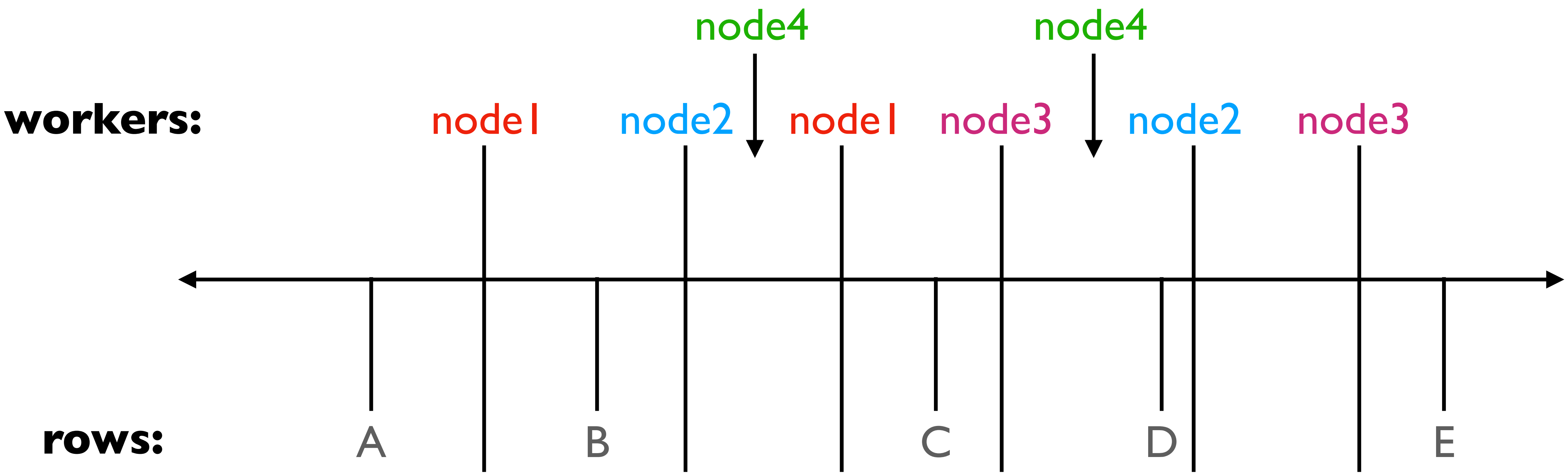
Other problems with adding node 4

- long term: only load of node 3 is alleviated
- short term: node 3 bears all the burden of transferring data to node 4

Solution: "vnodes"

Virtual Nodes (vnodes)

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}
token(node4) = {t7, t8}


node4 node4
workers: node1 node2 node1 node3 node2 node3
rows: A B C D E

Each node is resonsible for multiple ranges

- how many is configurable
- node 4 will take some load off nodes 1 and 2 (those to the right of its vnodes)

Token Map Storage

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}

where should this live?

we don't want a single point of failure
(like an HDFS NameNode)

Token Map Storage

node1

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}

node2

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}

node3

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}

every node has a copy of the token map

they should all get updated when new nodes join

Adding Nodes: Bad Approach

uh oh, node 3 won't know about node 4 when it comes back

node1

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}
token(node4) = {t7, t8}

node2

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}
token(node4) = {t7, t8}

node3

table rows
...lots of data...

rebooting...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}

node4

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}
token(node4) = {t7, t8}

Better Approach: Gossip

just inform one or a few nodes
about the new one

node1

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}

node2

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
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node3

table rows
...lots of data...

rebooting...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}

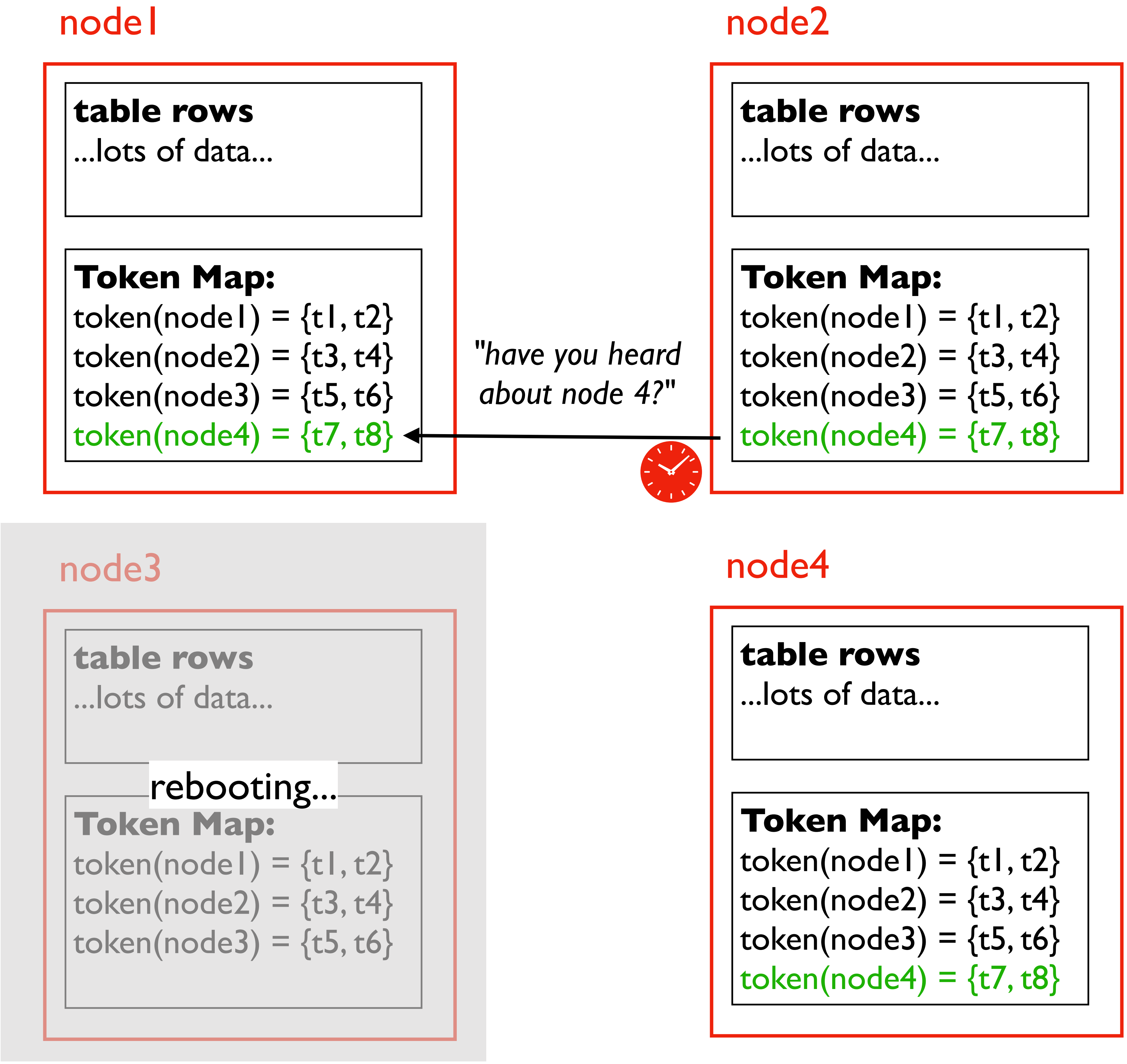
node4

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}
token(node4) = {t7, t8}

Better Approach: Gossip

once per second:
choose a random friend
gossip about new nodes



node1

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}
token(node4) = {t7, t8}

"have you heard about node 4?"

node2

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}
token(node4) = {t7, t8}

node3

table rows
...lots of data...

rebooting...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}

node4

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
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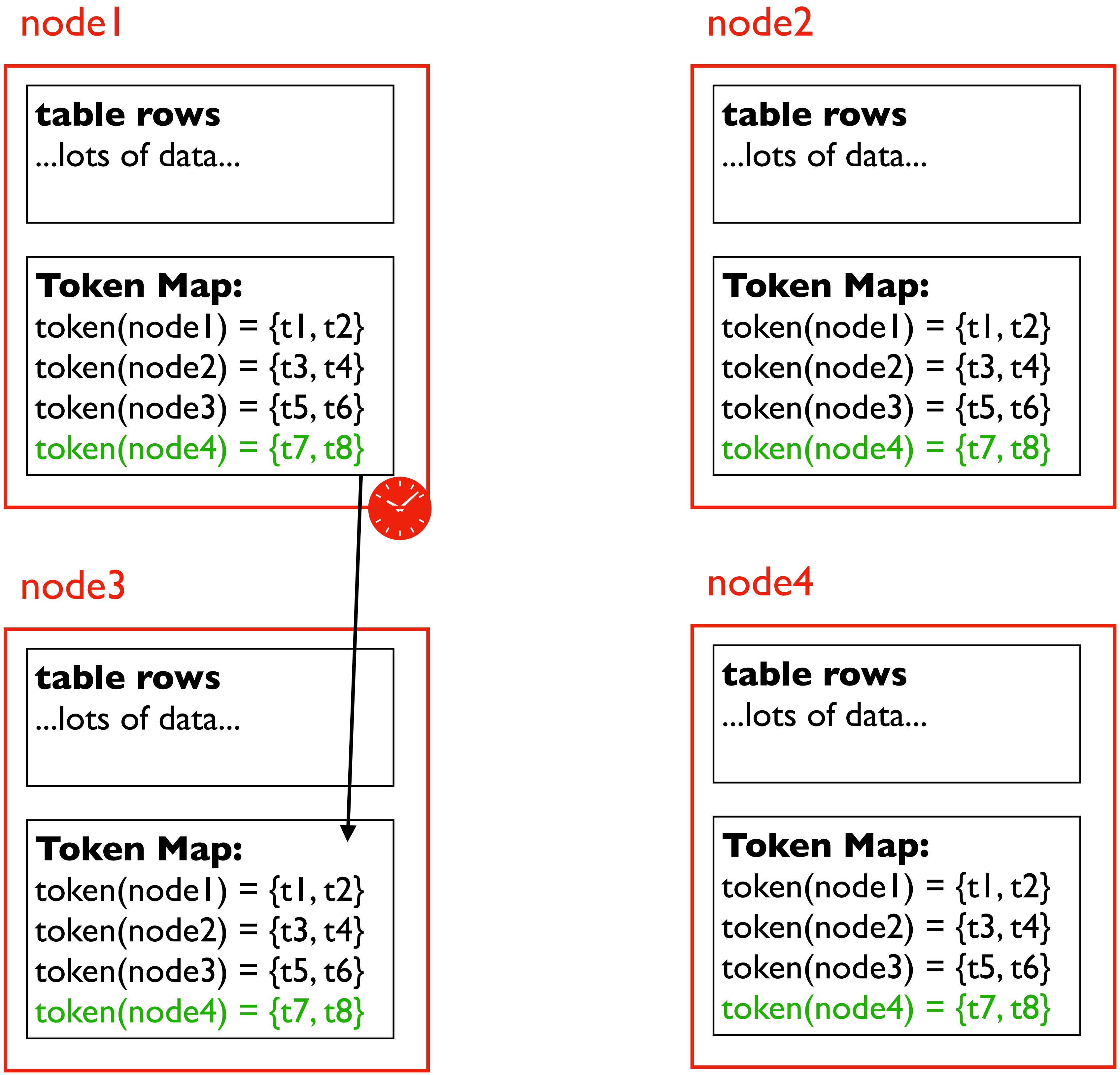
Better Approach: Gossip

eventually, every node should find out



node1

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
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node2

table rows
...lots of data...

Token Map:
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token(node2) = {t3, t4}
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node3

table rows
...lots of data...

Token Map:
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node4

table rows
...lots of data...

Token Map:
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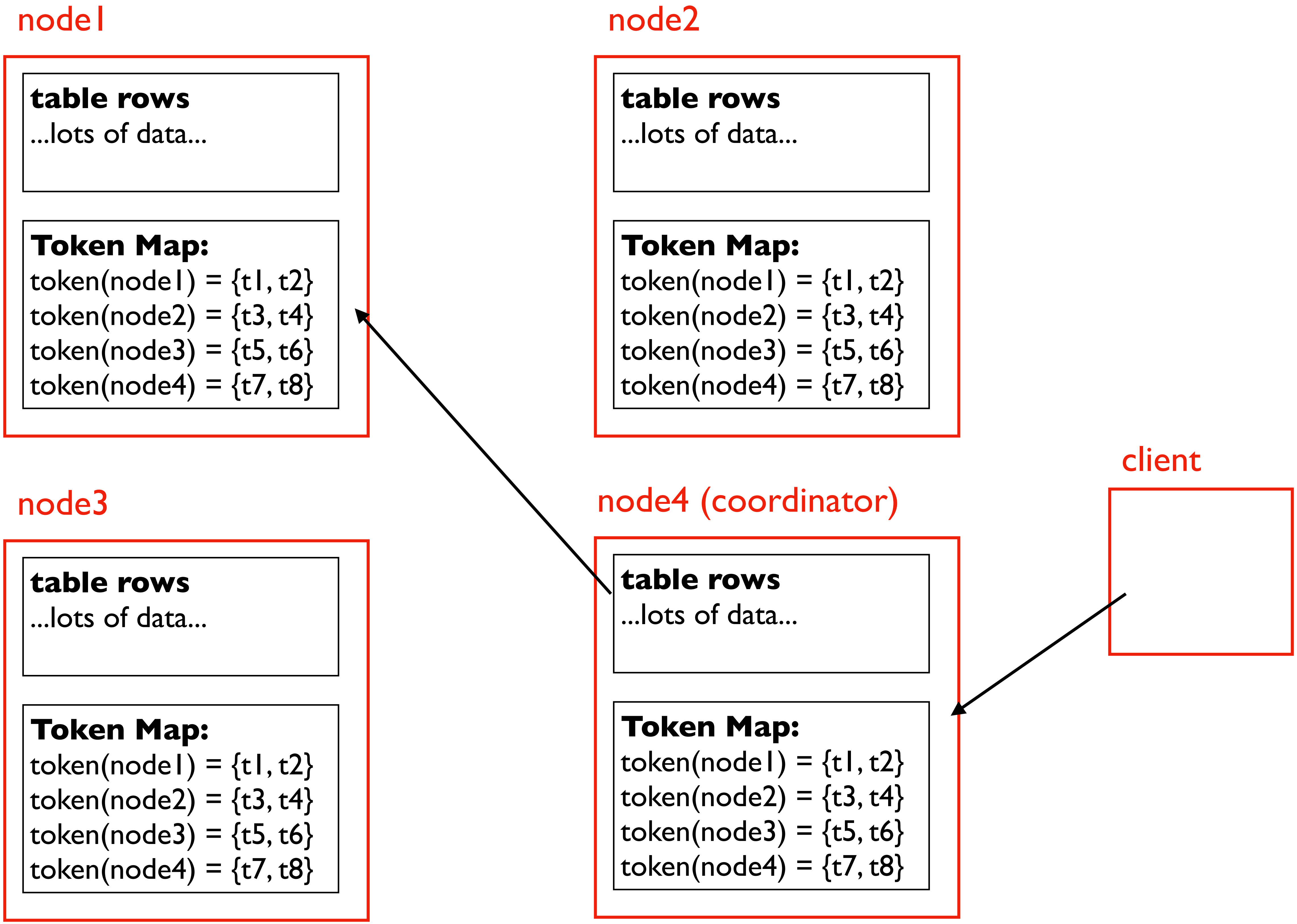
Better Approach: Gossip

when a client wants to write a row, they can contact any node -- it should know where the data should live and coordinate the operation



node1

table rows
...lots of data...

Token Map:
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node2

table rows
...lots of data...

Token Map:
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node3

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
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node4 (coordinator)

table rows
...lots of data...

Token Map:
token(node1) = {t1, t2}
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token(node3) = {t5, t6}
token(node4) = {t7, t8}

client

TopHat, Worksheet

Outline: Cassandra Partitioning+Replication

Partitioning

Replication

Quorum Reads/Writes

Conflict Resolution

Cassandra Demos

Replication

We *replicate* (create multiple copies on different nodes) to improve *durability* -- meaning we don't want data to be lost when nodes die.

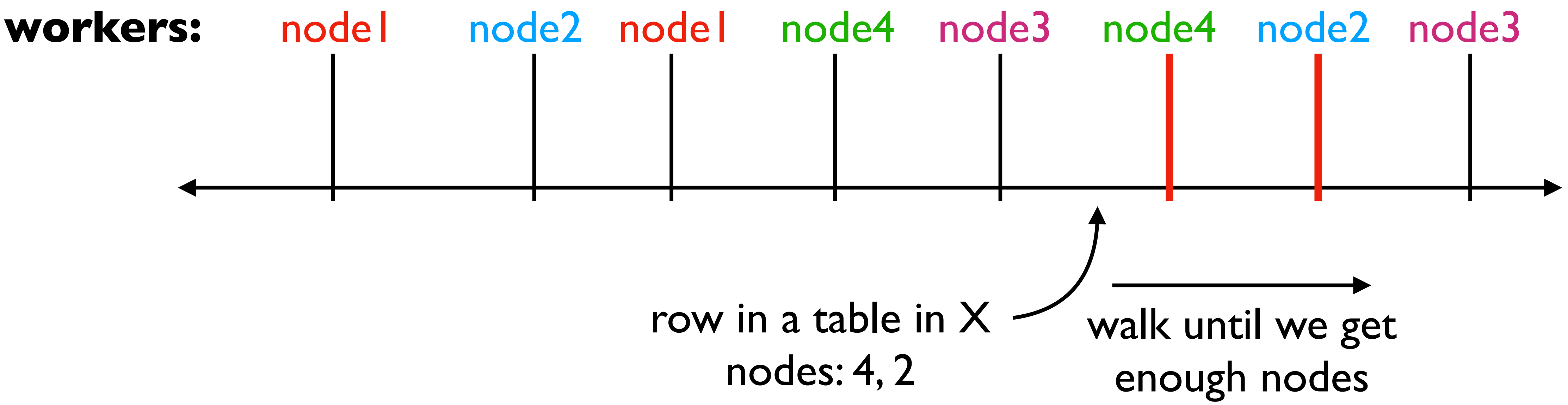
Cassandra lets us choose a different RF (replication factor) for each keyspace:

```
create keyspace X
with replication={'class': 'SimpleStrategy',
                  'replication_factor': 2};

create keyspace Y
with replication={'class': 'SimpleStrategy',
                  'replication_factor': 3};
```

Replication

Token Map:
token(node1) = {t1, t2}
token(node2) = {t3, t4}
token(node3) = {t5, t6}
token(node4) = {t7, t8}



workers: node1 node2 node1 node4 node3 node4 node2 node3

row in a table in X
nodes: 4, 2

walk until we get
enough nodes

```
create keyspace X
with replication={'class': 'SimpleStrategy',
                  'replication_factor': 2};
```

```
create keyspace Y
with replication={'class': 'SimpleStrategy',
                  'replication_factor': 3};
```

Replication

Token Map:
token(node1) = {t1, t2}
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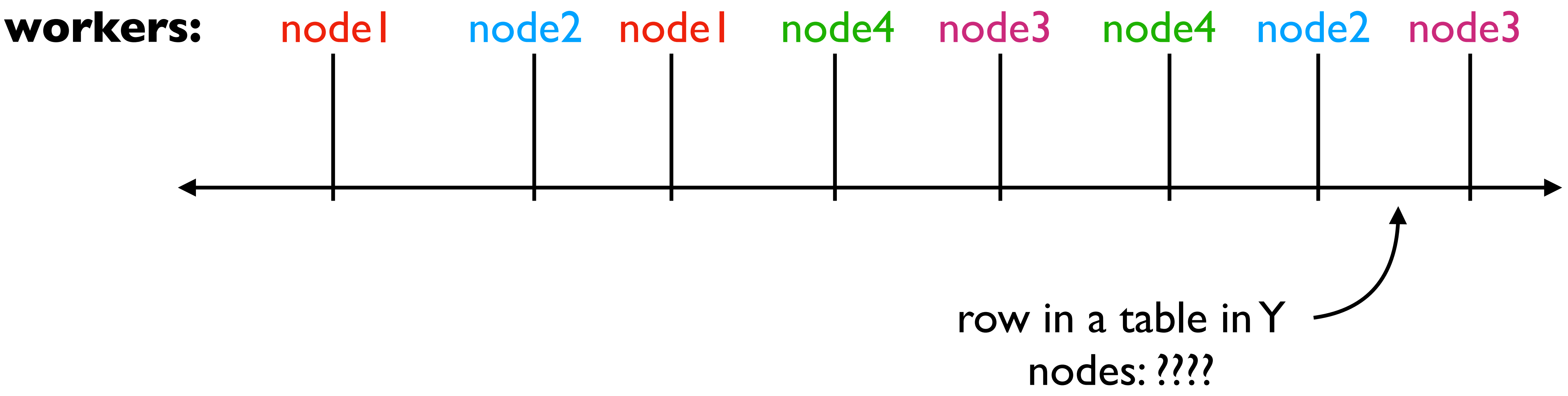

workers: node1 node2 node1 node4 node3 node4 node2 node3

row in a table in Y
nodes: ????

```
create keyspace X
with replication={'class': 'SimpleStrategy',
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```

```
create keyspace Y
with replication={'class': 'SimpleStrategy',
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```

Replication

Token Map:
token(node1) = {t1, t2}
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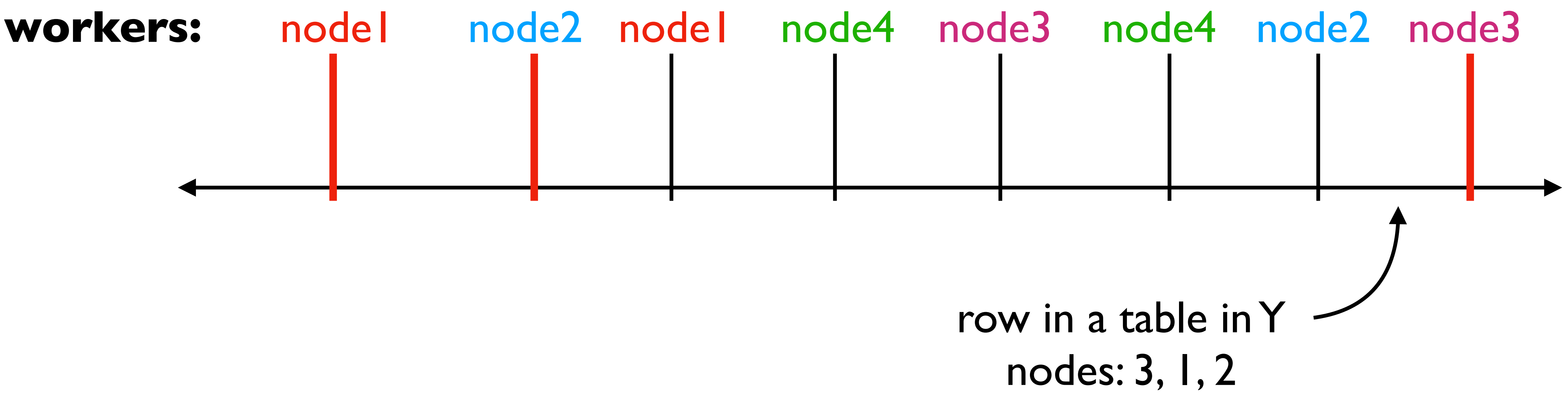

row in a table in Y
nodes: 3, 1, 2

```
create keyspace X
with replication={'class': 'SimpleStrategy',
                  'replication_factor': 2};


create keyspace Y
with replication={'class': 'SimpleStrategy',
                  'replication_factor': 3};
```

Replication

Token Map:

token(node1) = {t1, t2}
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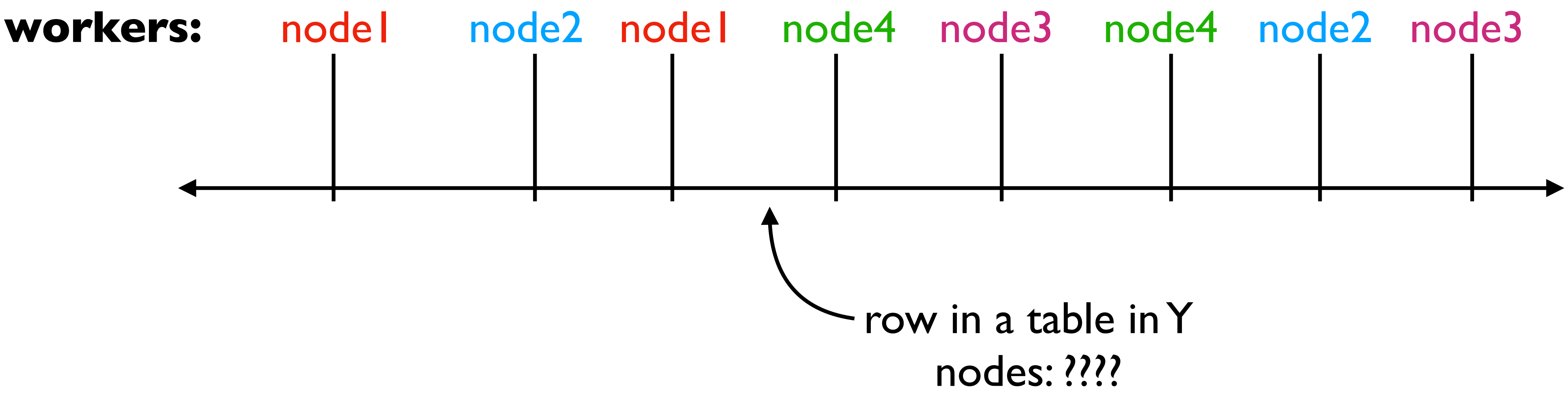

workers: node1 node2 node1 node4 node3 node4 node2 node3

row in a table in Y
nodes: ????

```
create keyspace X
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```
create keyspace Y
with replication={'class': 'SimpleStrategy',
                  'replication_factor': 3};
```

Replication

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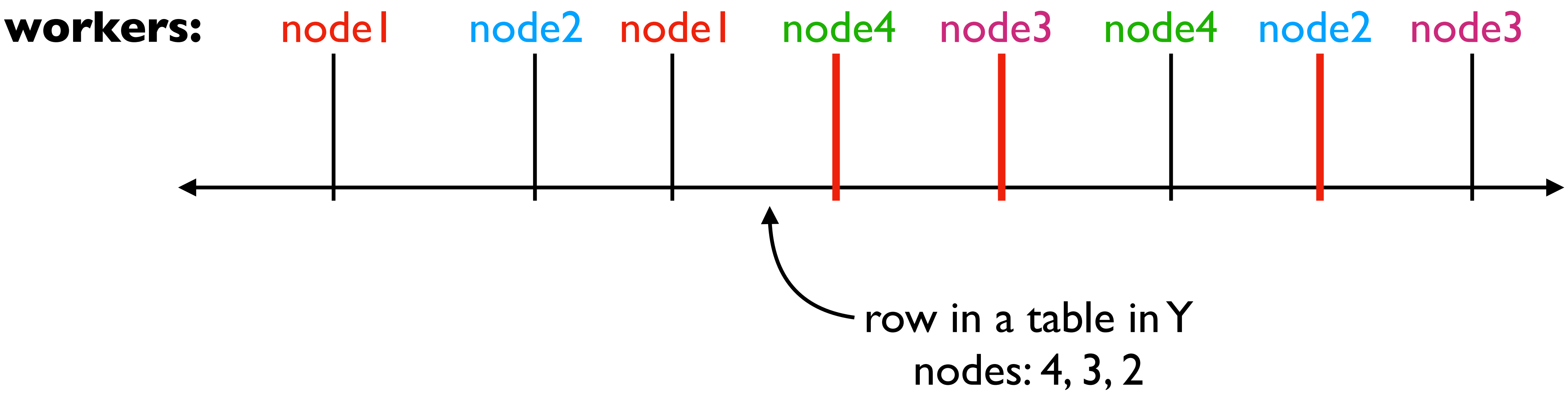


workers: node1 node2 node1 node4 node3 node4 node2 node3

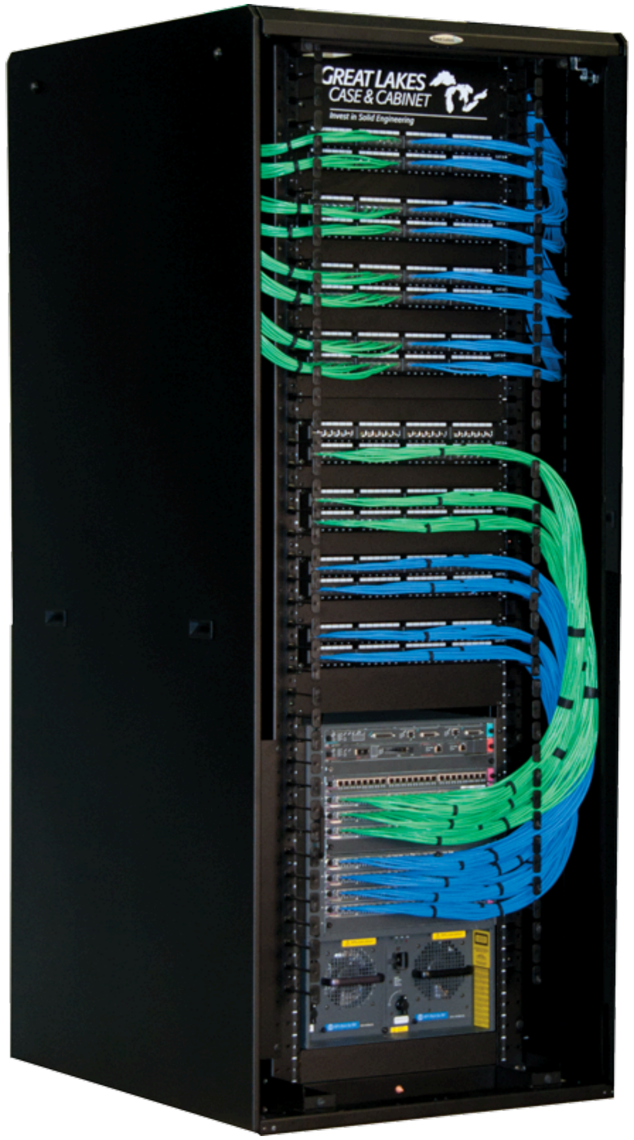
row in a table in Y
nodes: 4, 3, 2

Important! Keeping multiple copies on vnodes on the same node provides little safety (when a node dies, all its vnodes die). Same "failure domain".

Cassandra can skip nodes as it "walks the ring".

Network Infrastructure

Server



Rack

Data Center

https://www.dotmagazine.online/issues/digital-infrastructure-and-transforming-markets/data-center-models

https://buy.hpe.com/us/en/servers/proliant-dl-servers/proliant-dl10-servers/proliant-dl20-server/hpe-proliant-dl20-gen10-plus-e-2336-2-9ghz-6-core-1p-16gb-u-4sff-500w-rps-server/p/p44115-b21?ef_id=Cj0KCQiAt66eBhCnARIsAKf3ZNFJsg49UV6Zm33R7lkRqi-XOd_JECmdyqNMAm2CKLSm_F-z6JTYDTQaAgMTEALw_wcB:G:s&s_kwcid=AL!13472!3!331628972784!!!g!318267171339!!1707918369!67076417419&gclsrc=aw.ds&gclid=Cj0KCQiAt66eBhCnARIsAKf3ZNFJsg49UV6Zm33R7lkRqi-XOd_JECmdyqNMAm2CKLSm_F-z6JTYDTQaAgMTEALw_wcB

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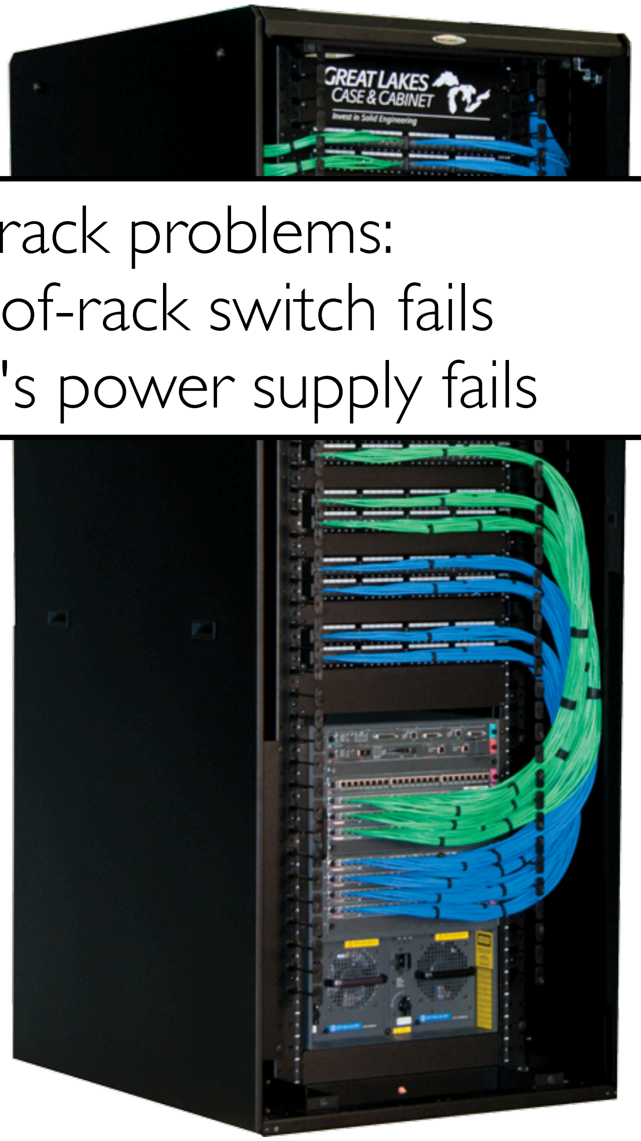
Correlated Failures

One server goes down, all of its vnodes are gone.

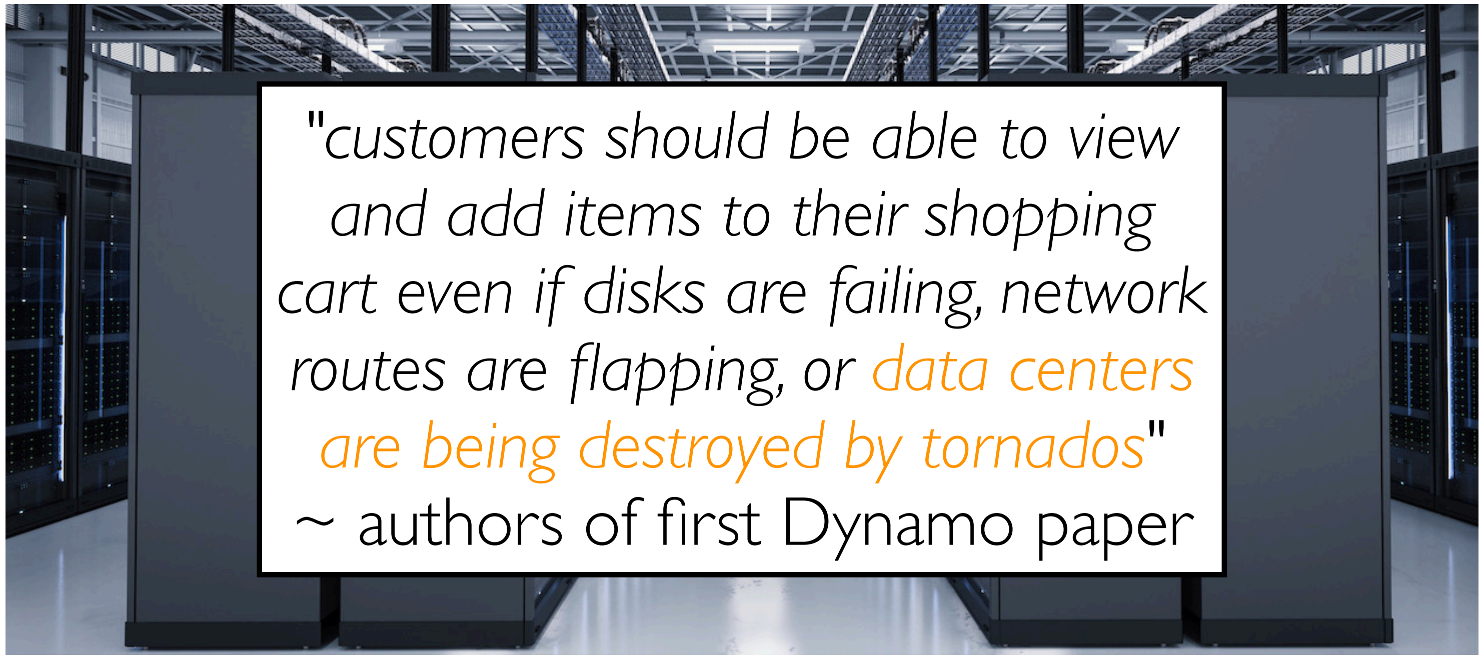
Server

Whole-rack problems:

- top-of-rack switch fails
- rack's power supply fails



Rack



"customers should be able to view and add items to their shopping cart even if disks are failing, network routes are flapping, or data centers are being destroyed by tornados"

~ authors of first Dynamo paper

Data Center

https://www.dotmagazine.online/issues/digital-infrastructure-and-transforming-markets/data-center-models

https://buy.hpe.com/us/en/servers/proliant-dl-servers/proliant-dl10-servers/proliant-dl20-server/hpe-proliant-dl20-gen10-plus-e-2336-2-9ghz-6-core-1p-16gb-u-4sff-500w-rps-server/p/p44115-b21?ef_id=Cj0KCQiAt66eBhCnARIsAKf3ZNFJsg49UV6Zm33R7lkRqi-XOd_JECmdyqNMAm2CKLSm_F-z6JTYDTQaAgMTEALw_wcB:G:s&s_kwcid=AL!13472!3!331628972784!!!g!318267171339!!17079183691!67076417419&gclsrc=aw.ds&gclid=Cj0KCQiAt66eBhCnARIsAKf3ZNFJsg49UV6Zm33R7lkRqi-XOd_JECmdyqNMAm2CKLSm_F-z6JTYDTQaAgMTEALw_wcB

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Replication Policy

Cassandra replication strategies are "pluggable", with a couple built-in options.

SimpleStrategy
- all nodes are considered equal
- skips vnodes on same machine
- ignores rack and data center placement
- used in CS 544

NetworkTopologyStrategy
- considers data centers and racks
- when walking the ring, some vnodes may be skipped to protect against multiple kinds of correlated failure

Worksheet

Outline: Cassandra Partitioning+Replication

Partitioning

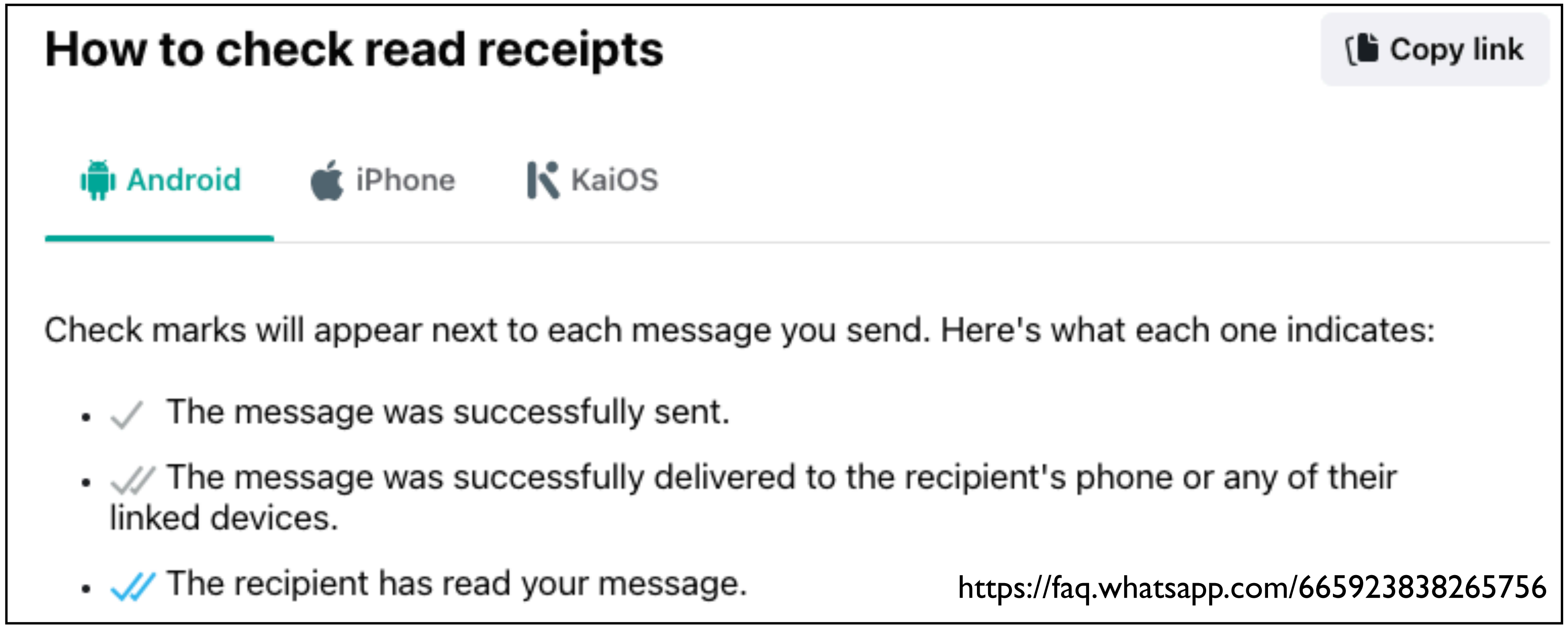
Replication

Quorum Reads/Writes

Conflict Resolution

Cassandra Demos

Write Acks: WhatsApp Example



How to check read receipts

Check marks will appear next to each message you send. Here's what each one indicates:

- ✓ The message was successfully sent.
- ✓✓ The message was successfully delivered to the recipient's phone or any of their linked devices.
- ✓✓ The recipient has read your message.

https://faq.whatsapp.com/665923838265756

these are examples of "acks" (acknowledgements)

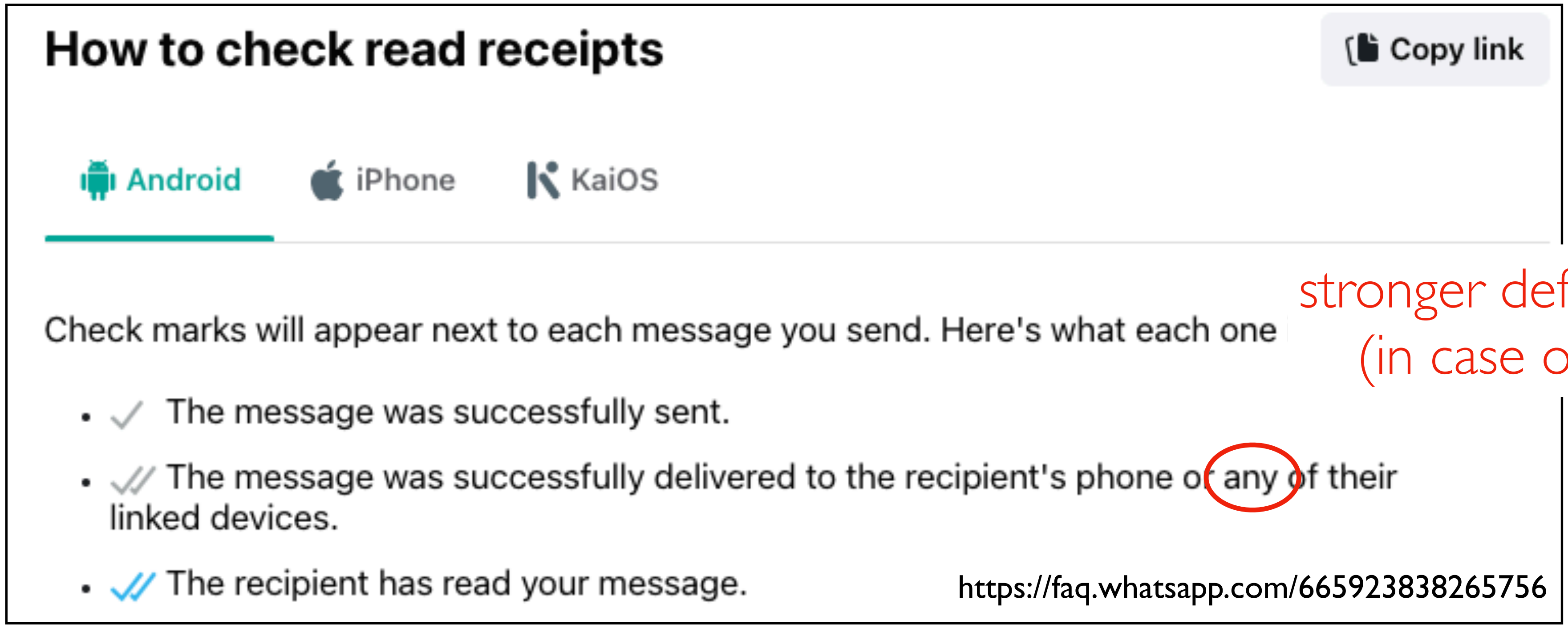
In distributed storage systems/databases, an *ack* means our data is *committed*.

"Committed" means our data is "safe", even if bad things happen. The definition varies system to system, based on what bad things are considered. For example:

- a node could hang until rebooted; a node's disk could permanently fail
- a rack could lose power; a data center could be destroyed

Obviously, no data is ever completely safe against any circumstance (e.g., comet strikes earth, leading to destruction of humankind and all our data centers).

Write Acks: WhatsApp Example



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stronger definition: **all** devices
(in case one device fails)

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In distributed storage systems/databases, an ack means our data is committed.

"Committed" means our data is "safe", even if bad things happen. The definition varies system to system, based on what bad things are considered. For example:

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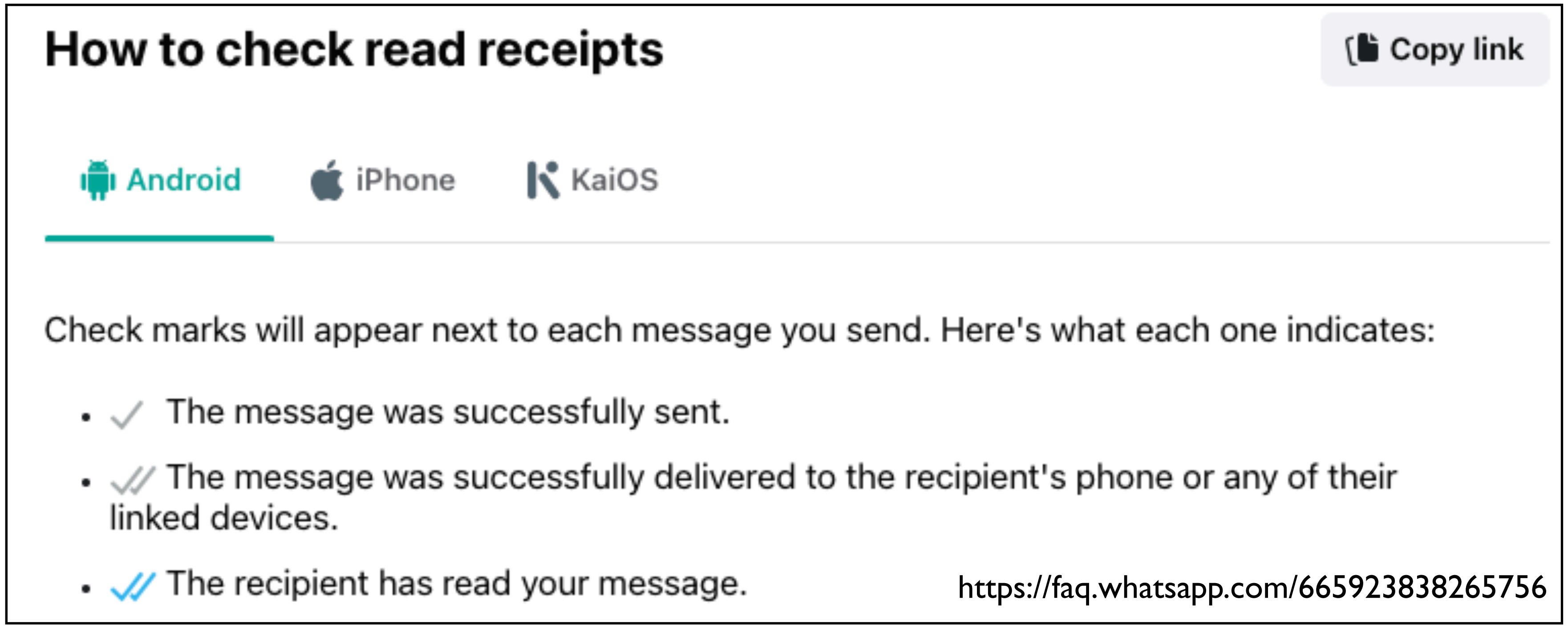

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two checks (in WhatsApp) mean the message reached the destination.

Does only one check mean the message has NOT reached the destination?

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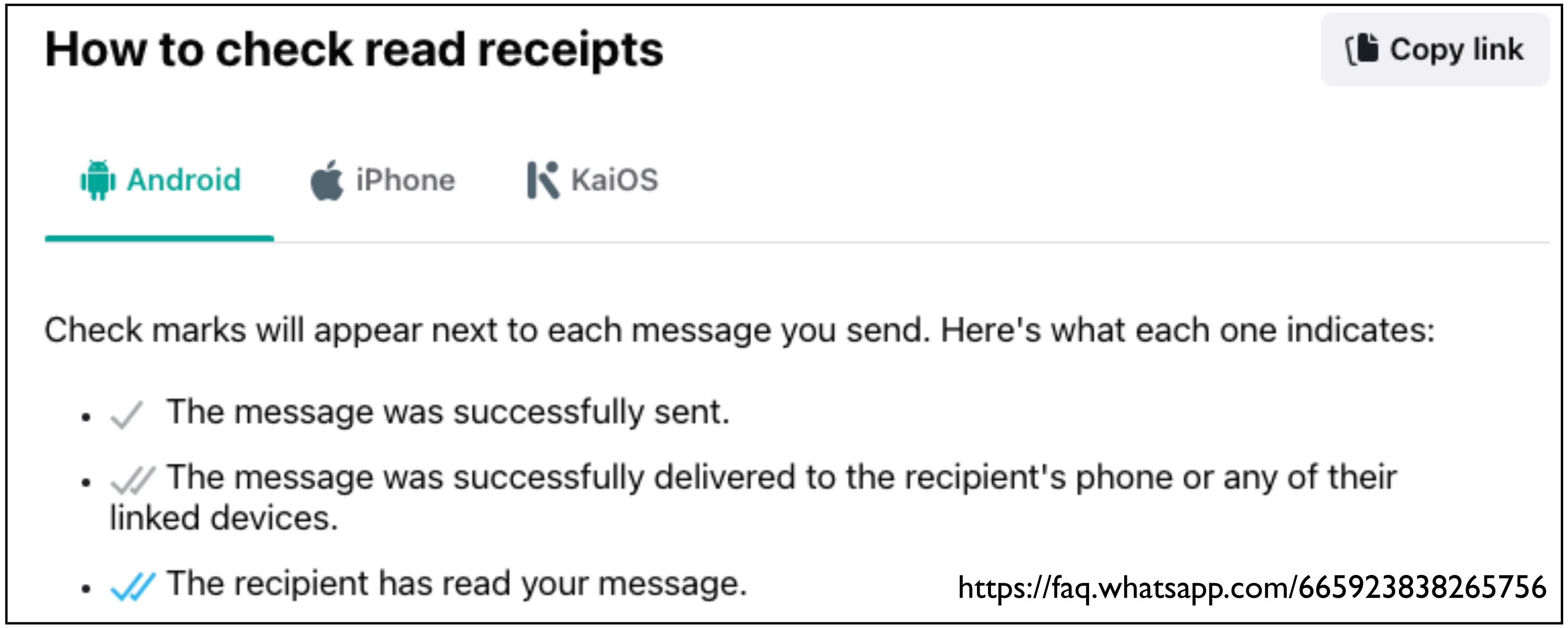

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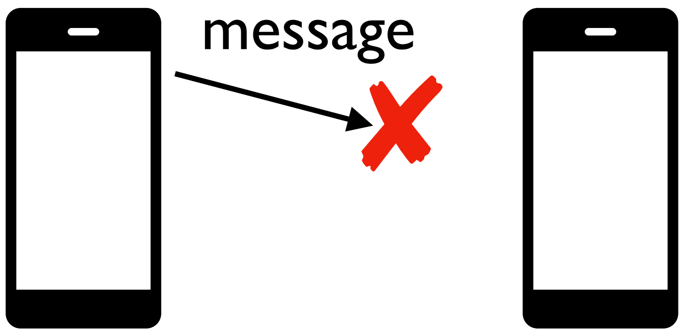
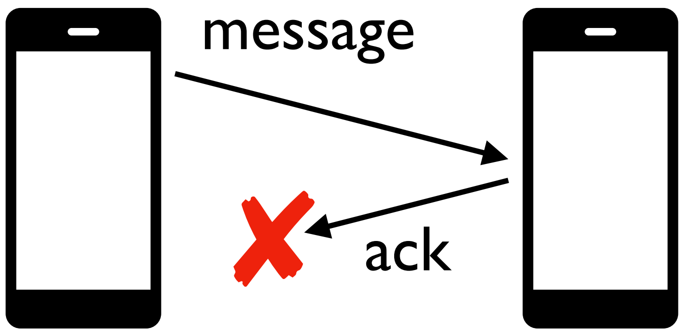
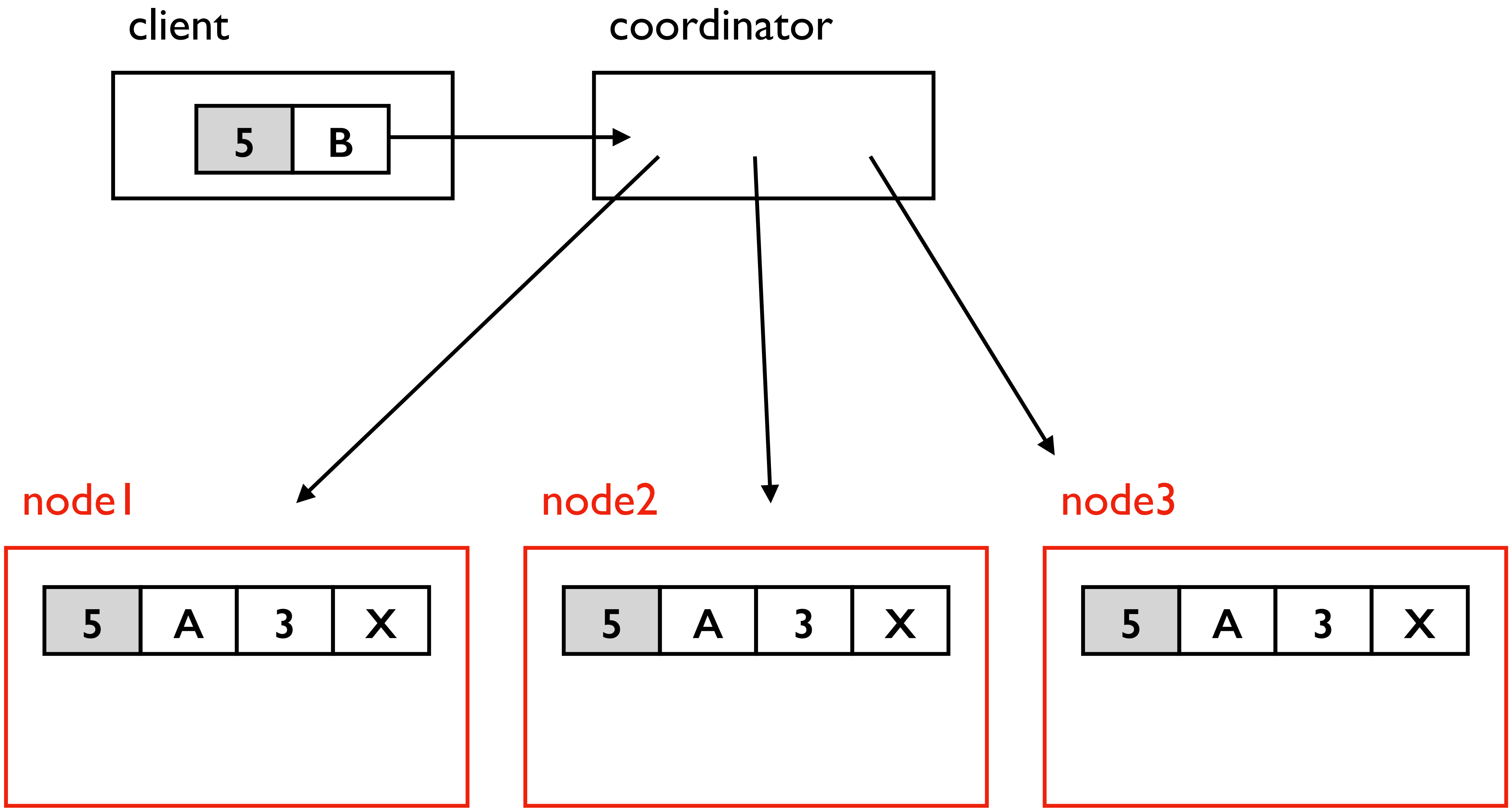


scenario 1



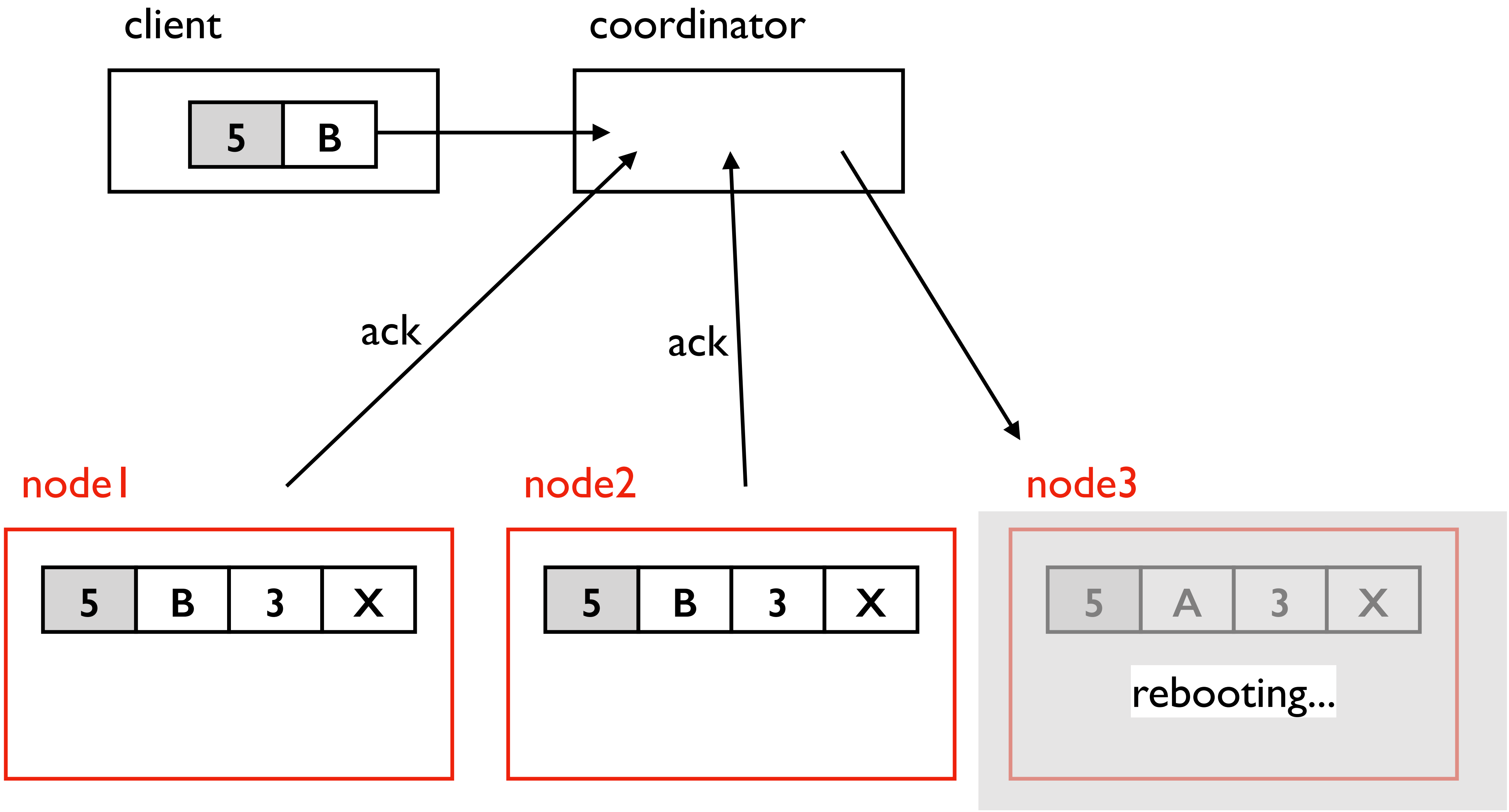
scenario 2

Cassandra Writes



Say RF=3. Coordinator will attempt to write data to all 3 replicas.

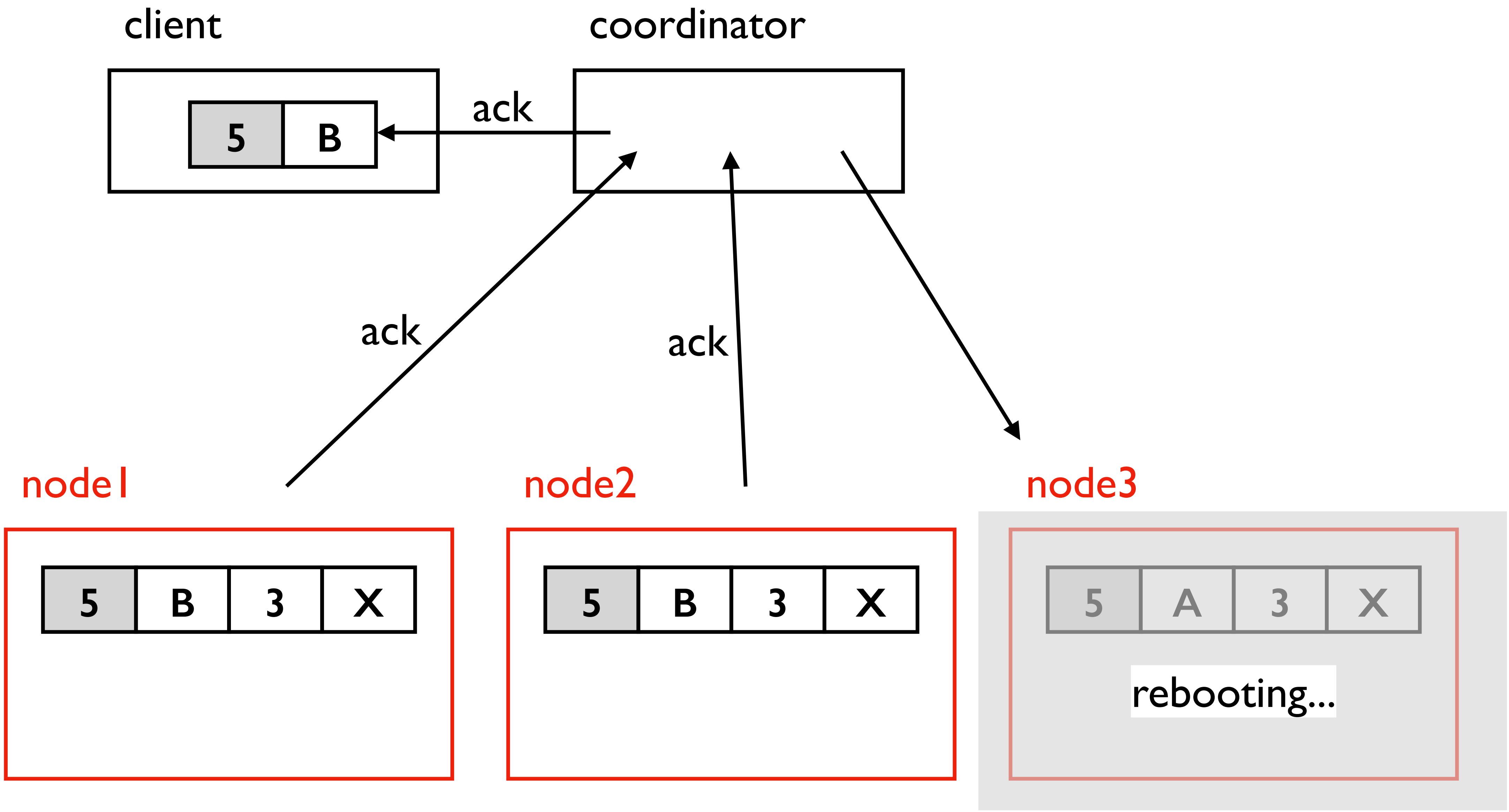
Cassandra Writes



Say RF=3. Coordinator will attempt to write data to all 3 replicas.

At what point should we send an ack to the client?

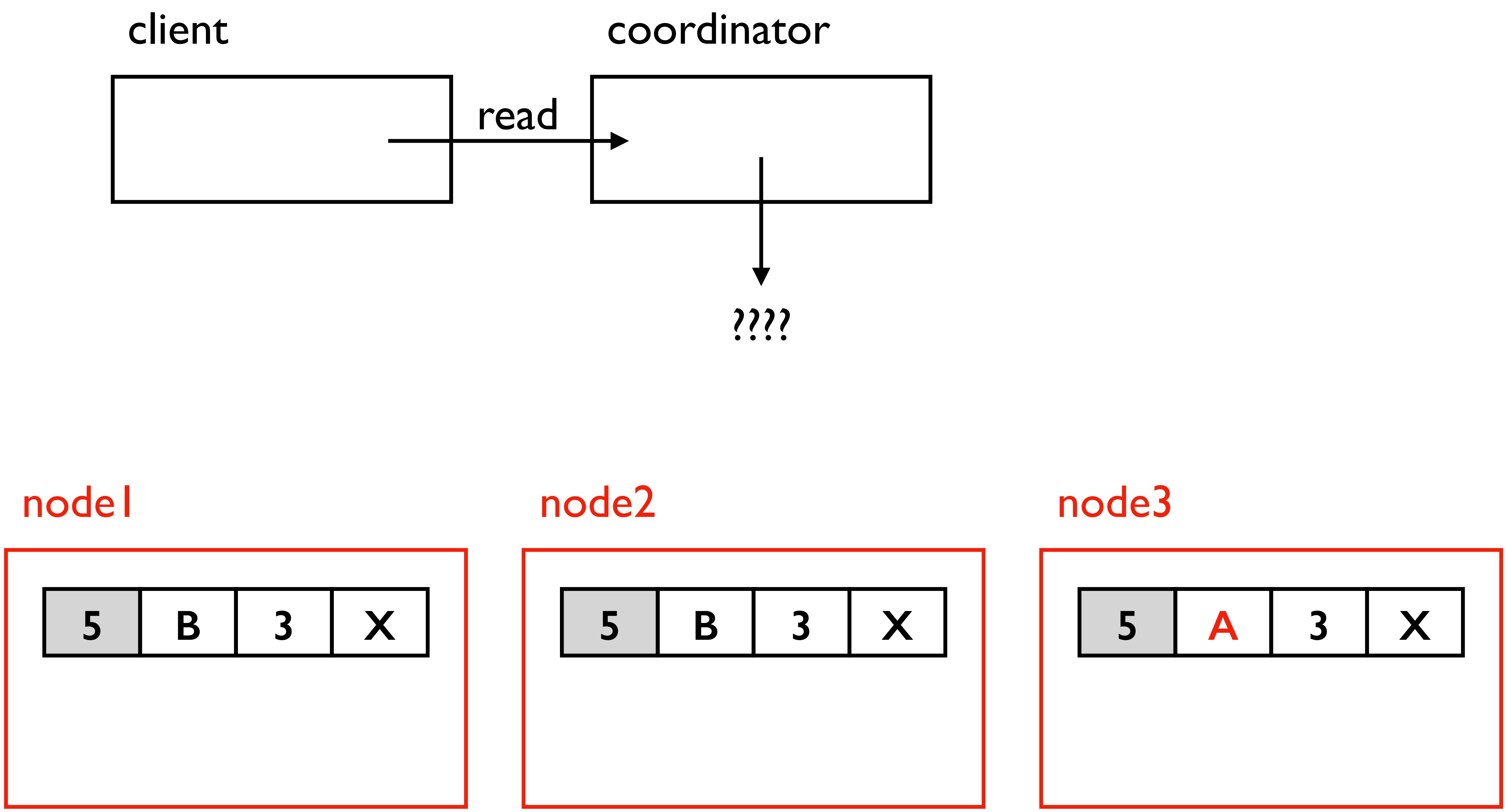
Cassandra Writes



Say RF=3. Coordinator will attempt to write data to all 3 replicas.

At what point should we send an ack to the client?
Configurable. W=2 lets coordinator ack now, and data is fairly safe.

Cassandra Reads



client

read

coordinator

????

node1

5 B 3 X

node2

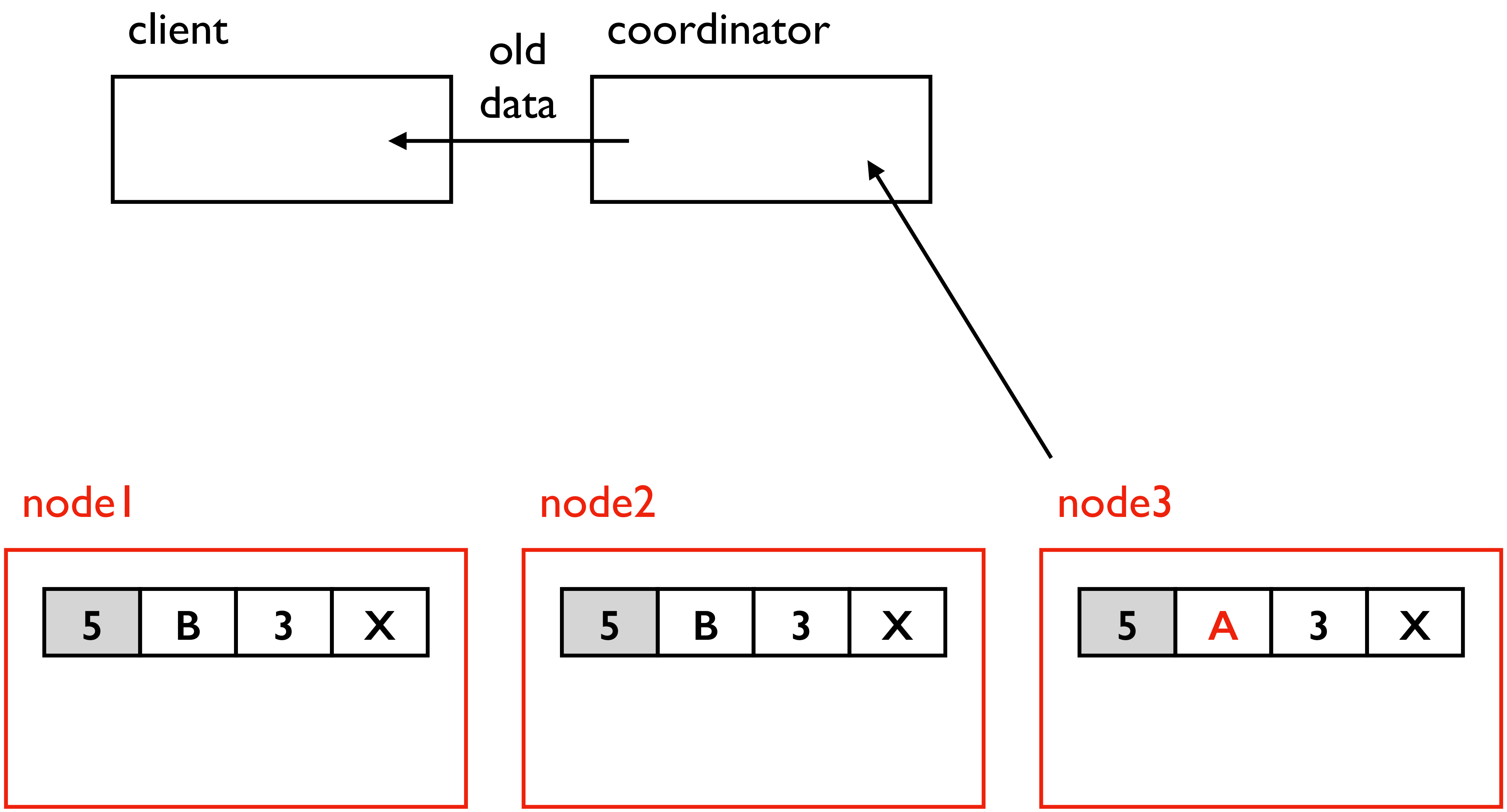
5 B 3 X

node3

5 A 3 X

HDFS reads go to one replica. What if Cassandra tries that?

Cassandra Reads



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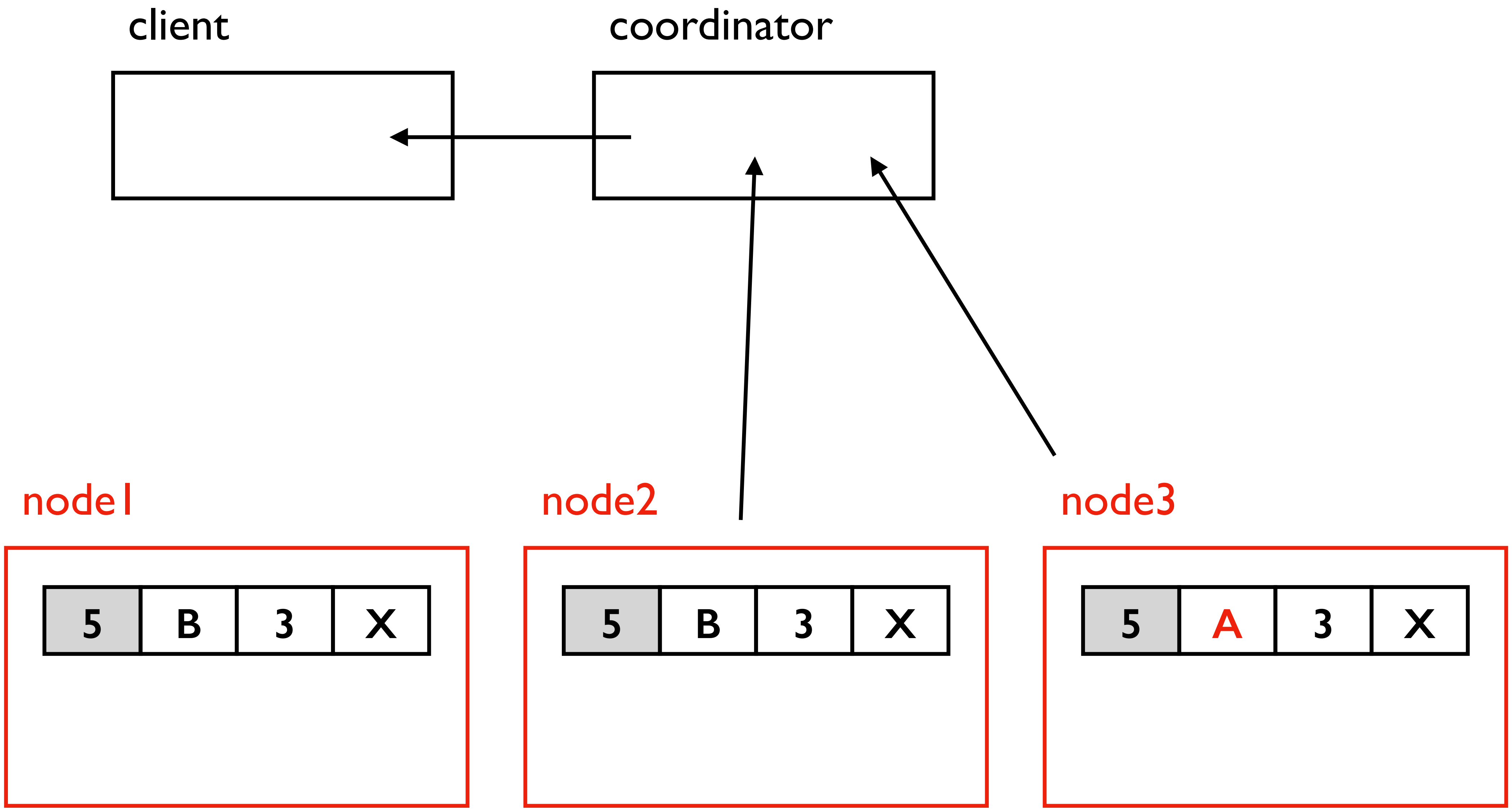


client

coordinator

node1

5	B	3	X

node2

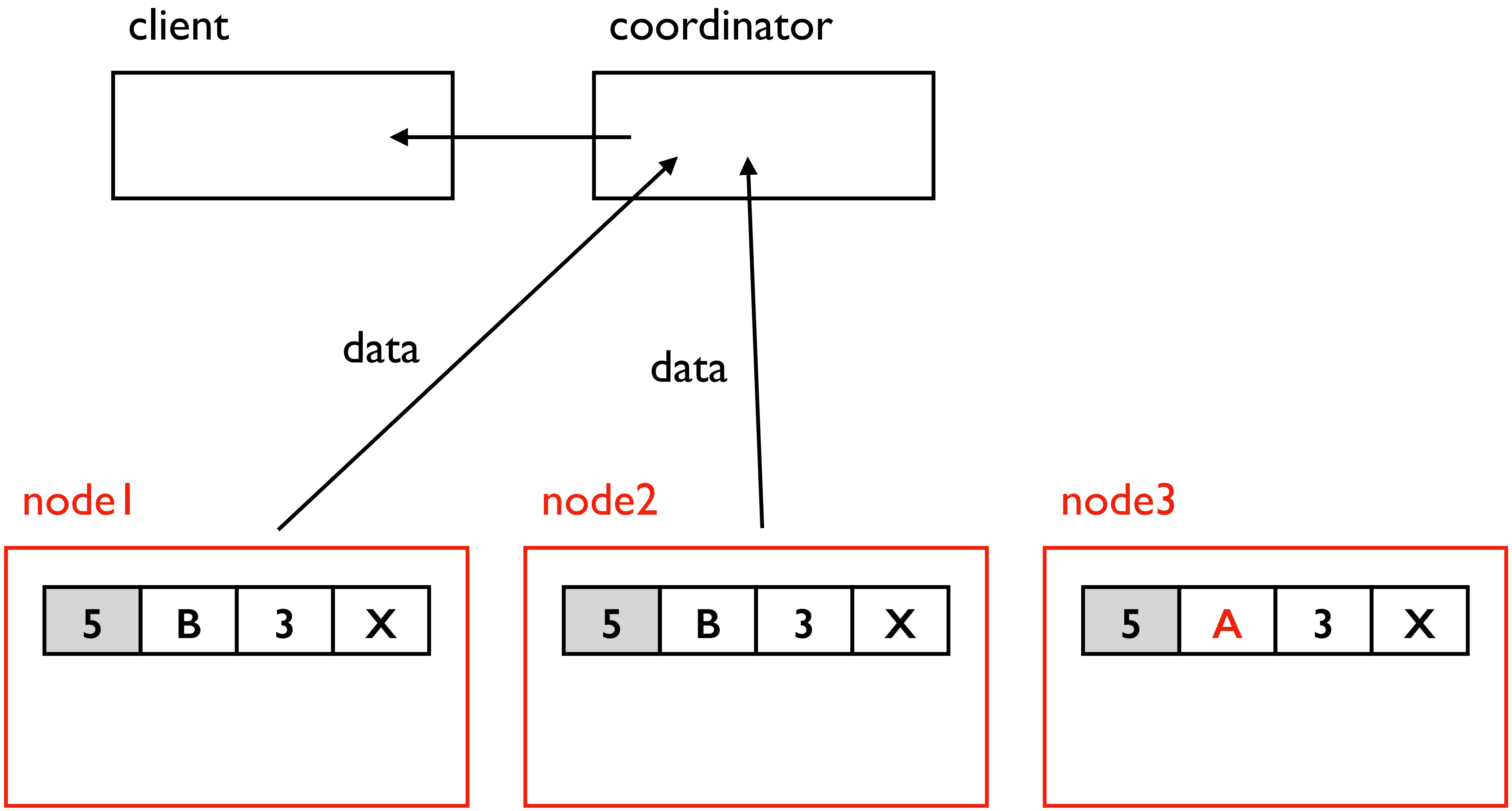
5	B	3	X

node3

5	A	3	X

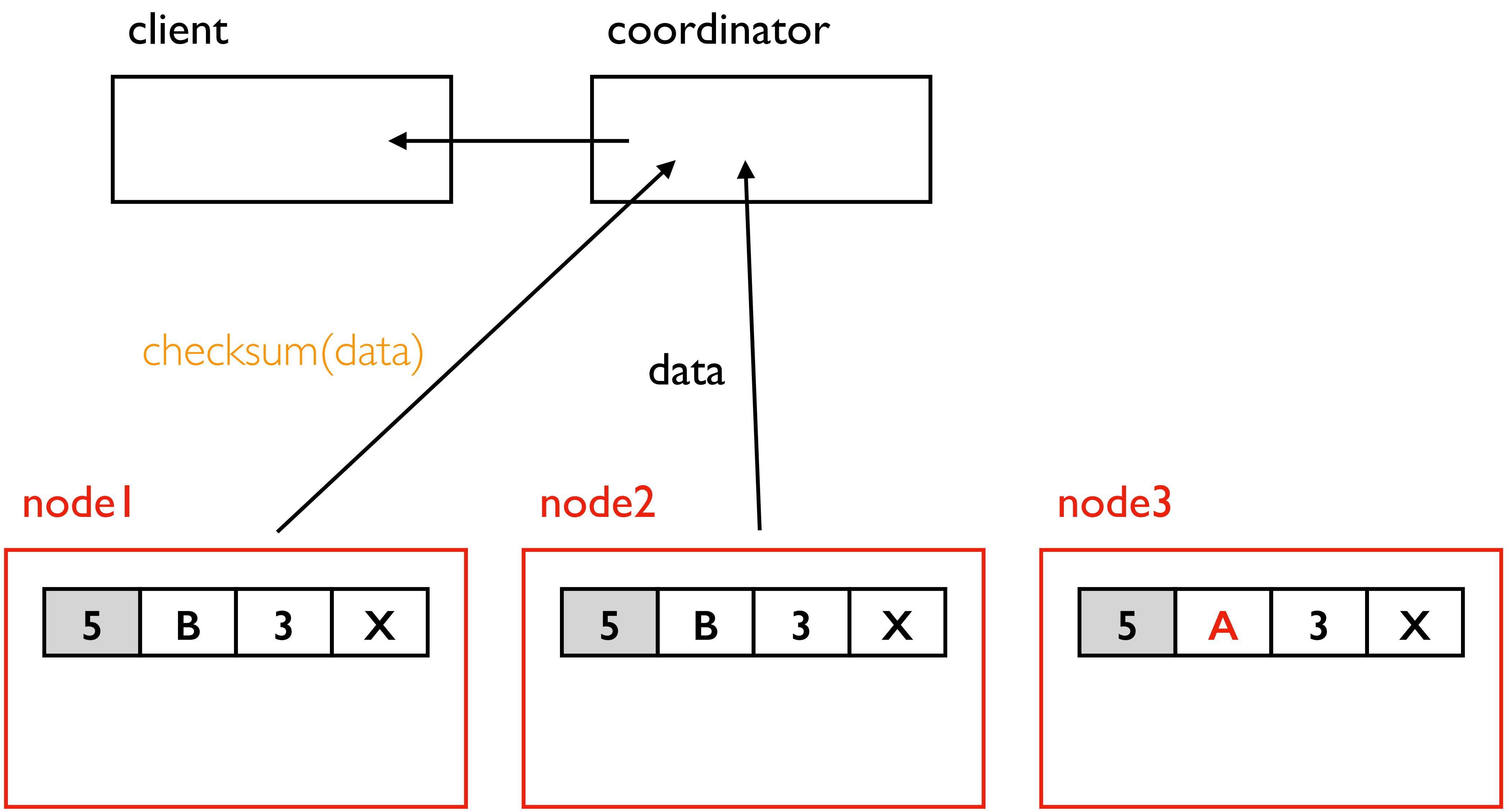
Read from R replicas (configurable). Here R=2.
Hopefully at least one of the replicas has new data.

Cassandra Reads



R=2 means we'll often read identical data from two replicas (wasteful!)

Cassandra Reads

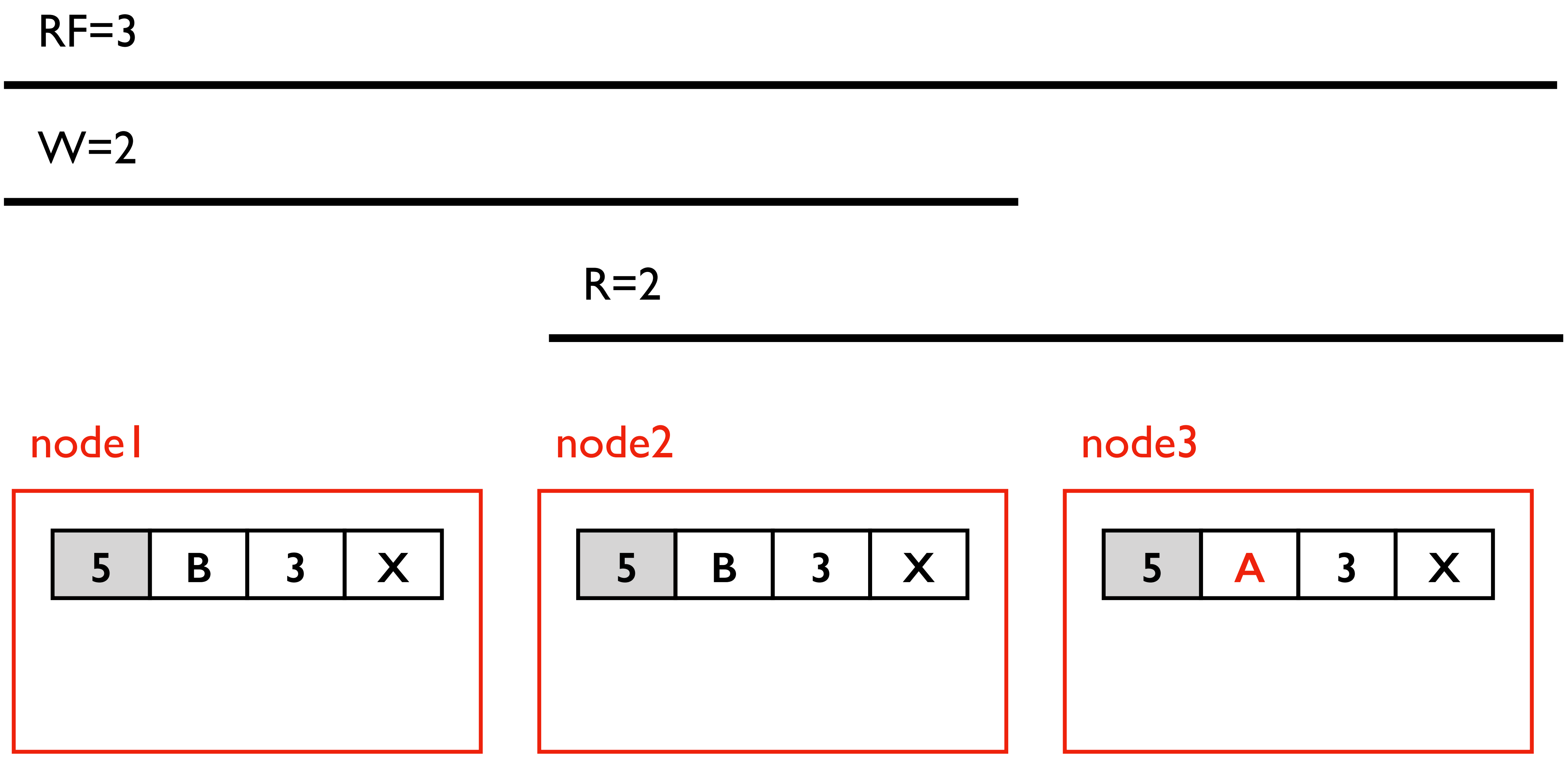


R=2 means we'll often read identical data from two replicas (wasteful!)

Improvement: read one copy, and only request checksum from others.

A *checksum* (like md5) is a hash function where collisions are extremely rare and hard to find.

When R+W > RF



RF=3

W=2

R=2

node1

5 B 3 X

node2

5 B 3 X

node3

5 A 3 X

When R+W > RF, the replicas read+written will overlap.

There are some caveats (related to ring membership and something called "hinted handoff") not covered in 544.

Tuning R and W

Say RF=3

W=3, R=1

- reads are highly available and fast -- only need one replica to respond before we can get back to the client!
- writes will not succeed (from the clients perspective) if even one node is down. But the data may still get recorded on some nodes.

W=1, R=3

- writes are highly available and fast -- only need one replica to respond before we can get back to the client!
- reads will not return data when even one node is down.
- risky: if the one node that took the write fails permanently, we'll lose committed data

W=2, R=2

- relatively balanced approach

W=1, R=1

- speed+availability more important that correct data

Worksheet

Outline: Cassandra Partitioning+Replication

Partitioning

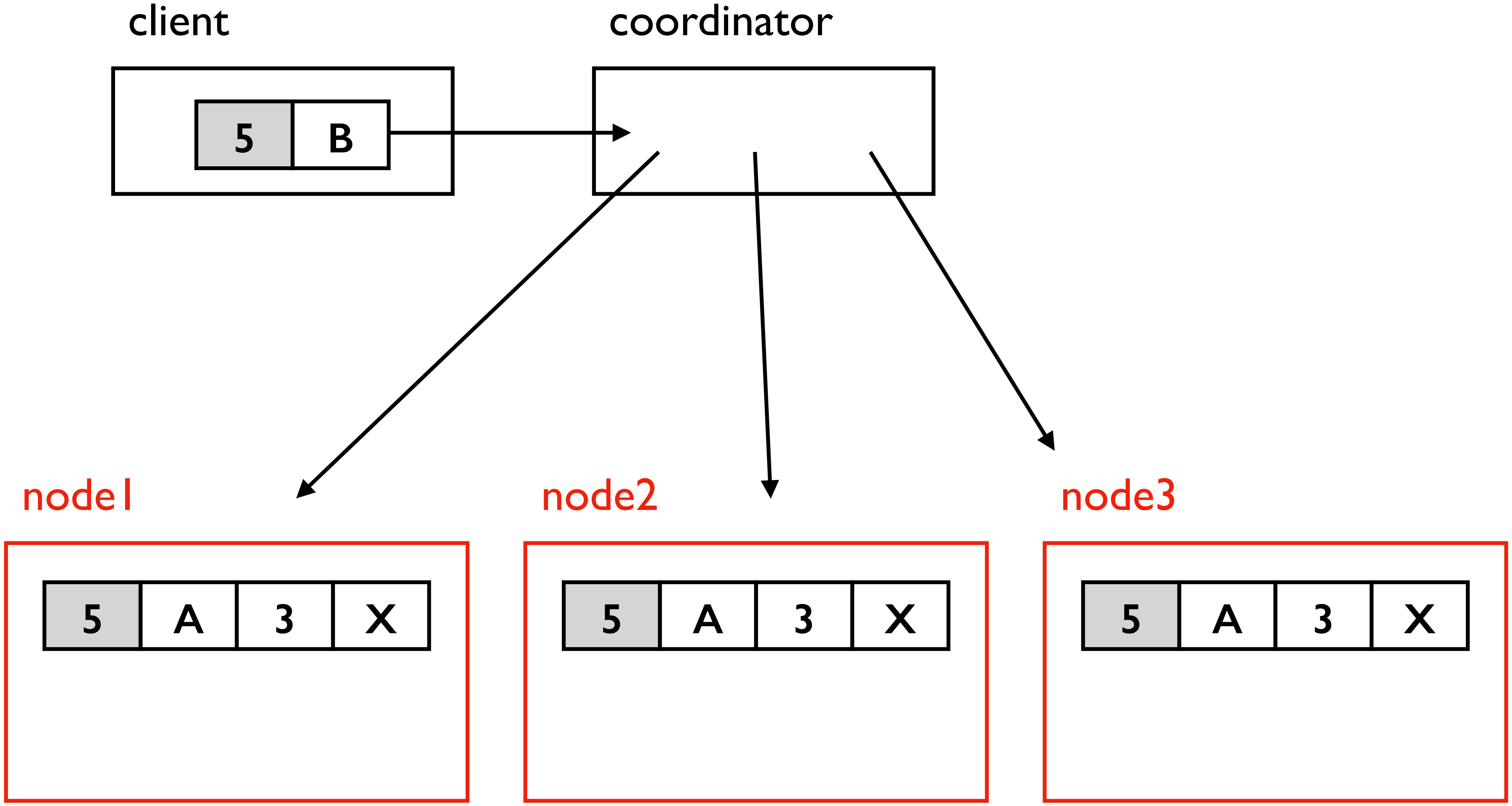
Replication

Quorum Reads/Writes

Conflict Resolution

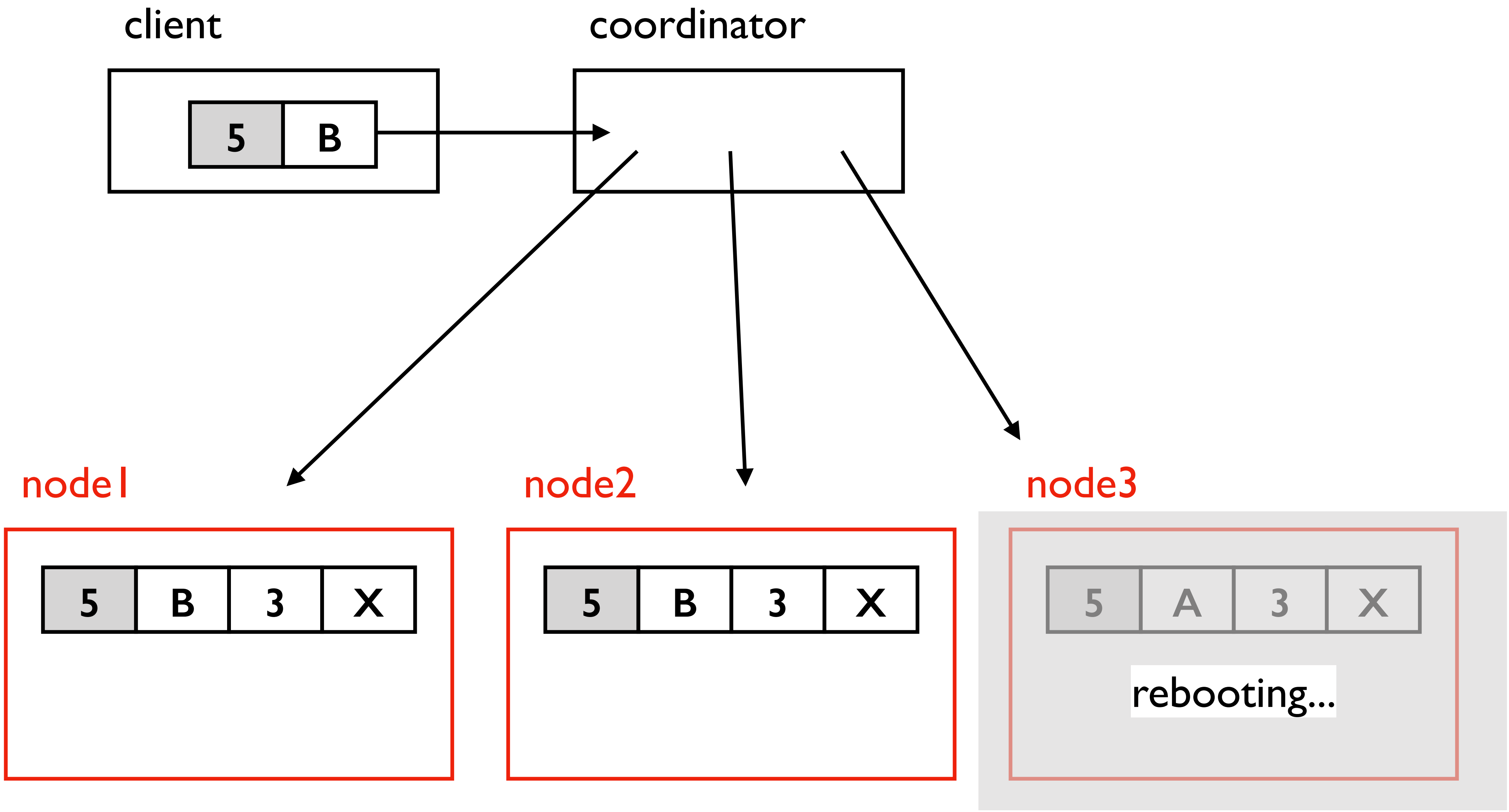
Cassandra Demos

Getting Conflicting Versions



Let RF=3, R=2, W=2

Getting Conflicting Versions



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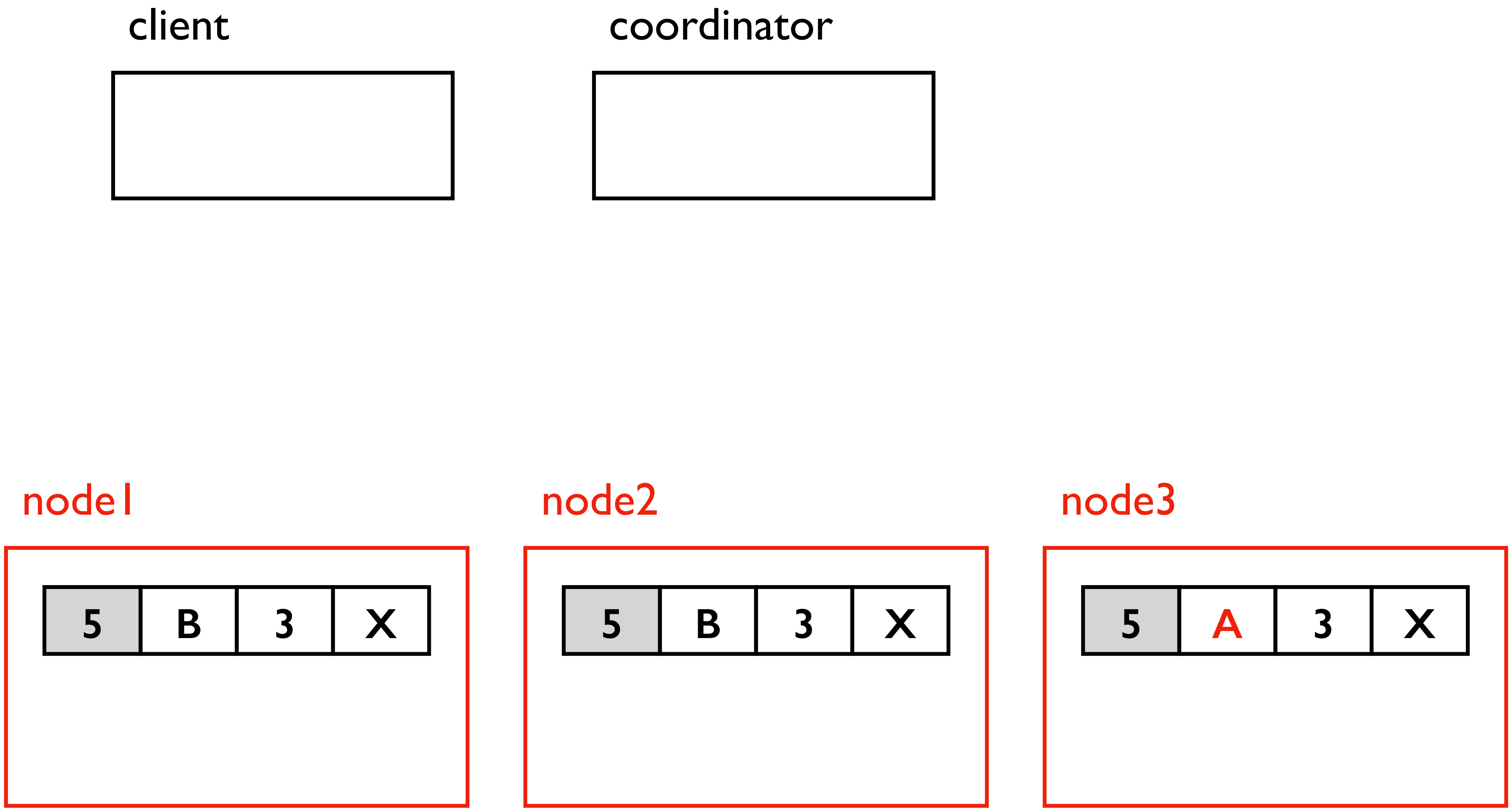
Getting Conflicting Versions



client

coordinator

node1

5	B	3	X

node2

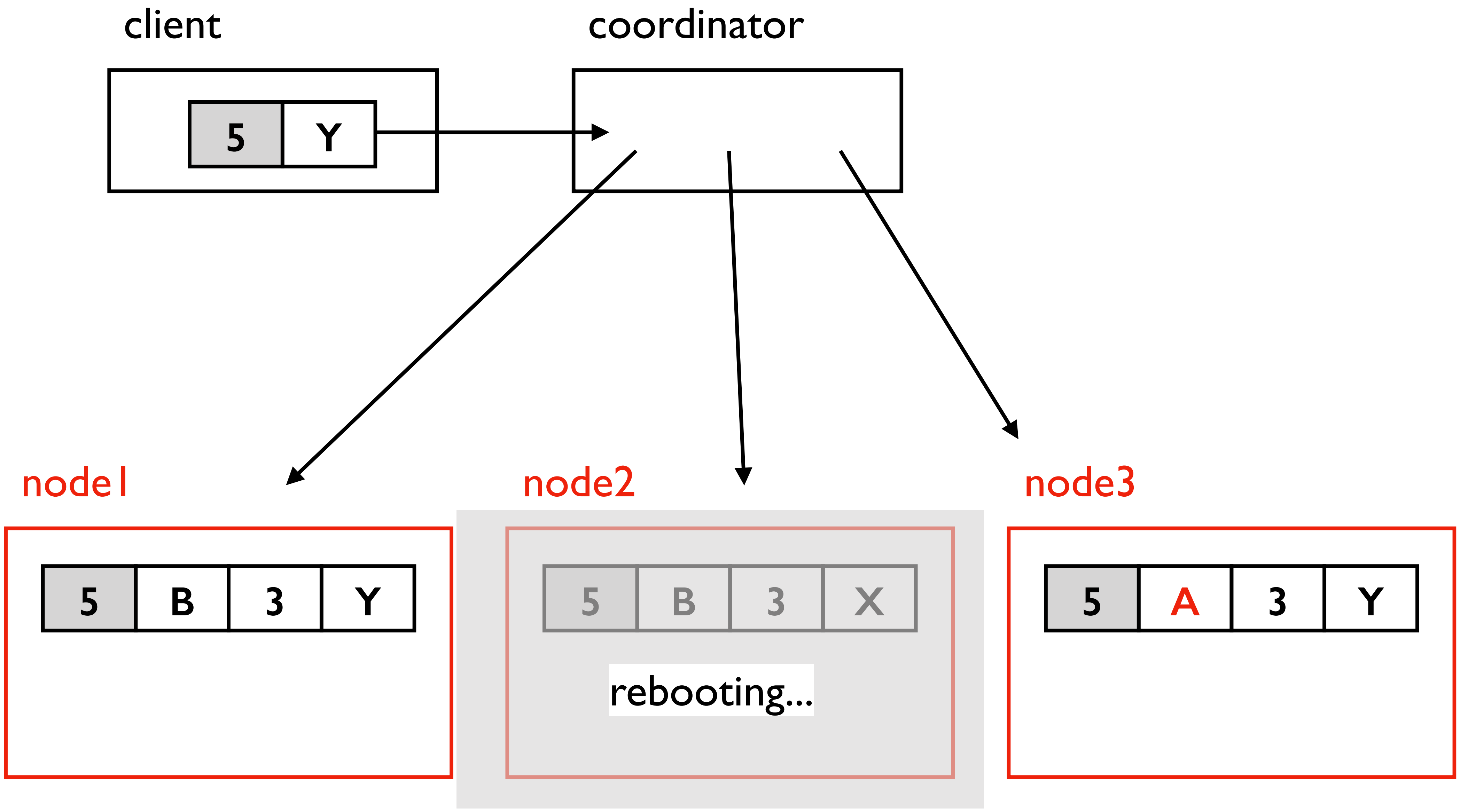
5	B	3	X

node3

5	A	3	X

Let RF=3, R=2, W=2

Getting Conflicting Versions



Let RF=3, R=2, W=2

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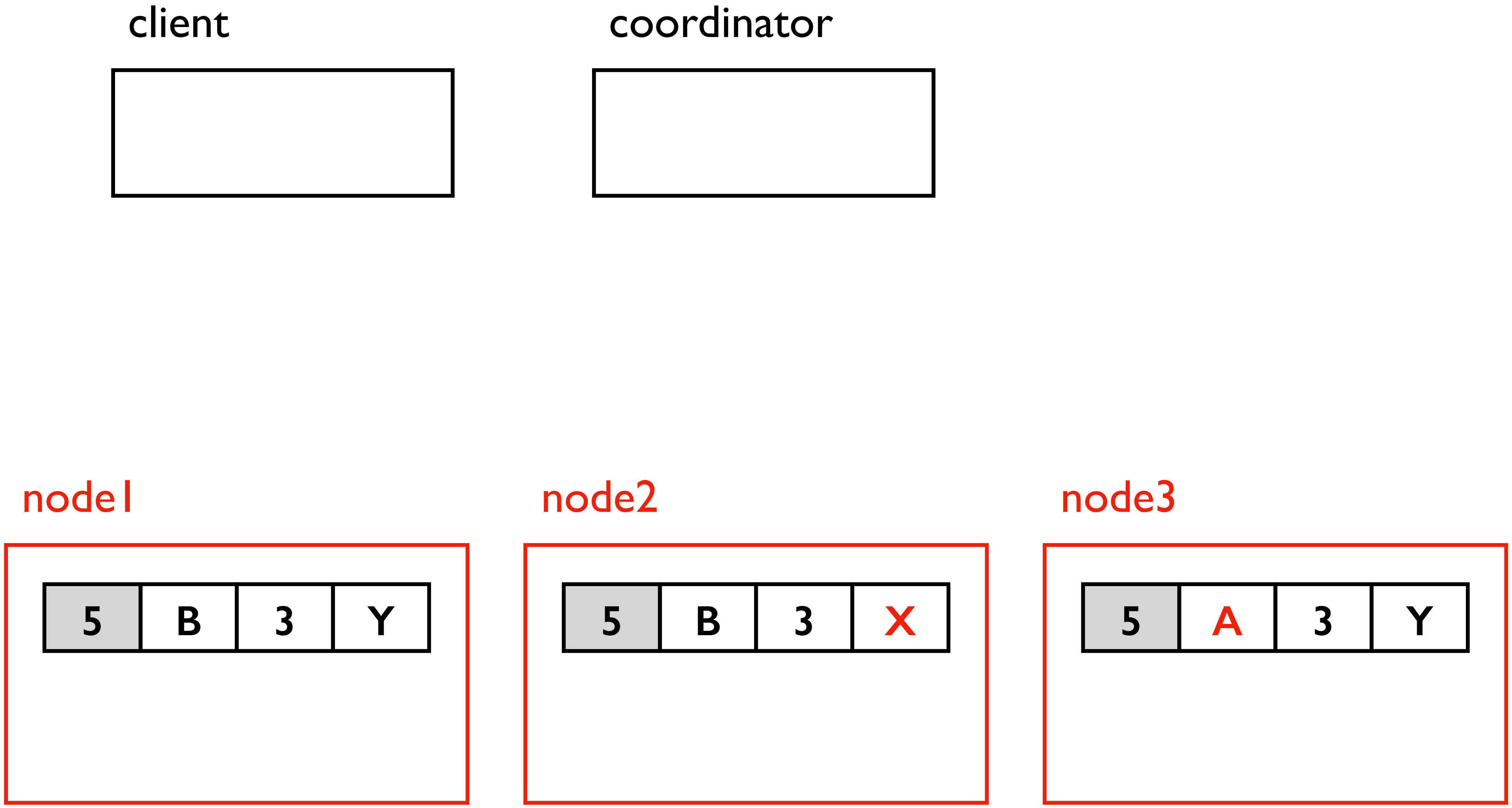


client

coordinator

node1

5	B	3	Y

node2

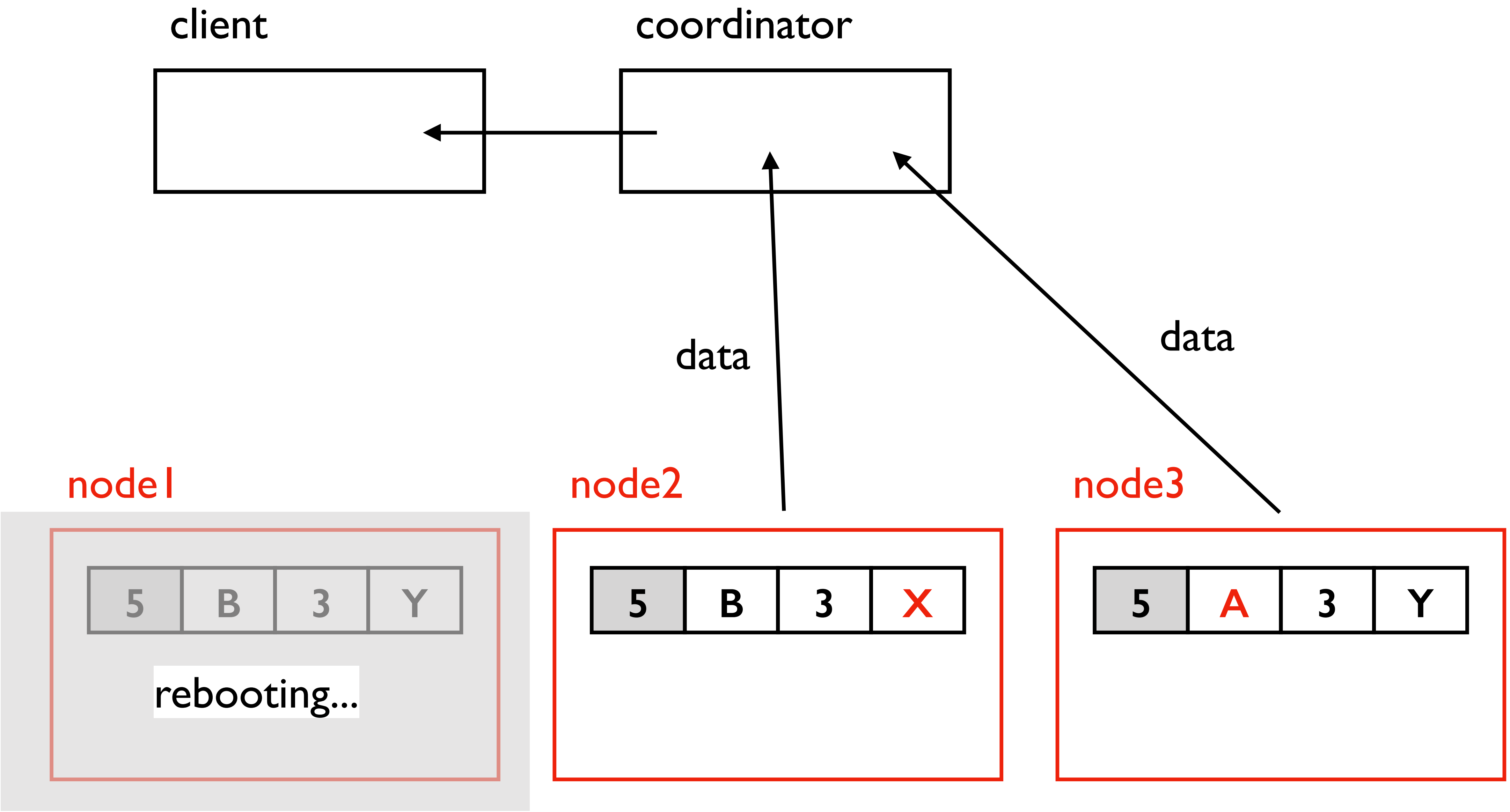
5	B	3	X

node3

5	A	3	Y

Let RF=3, R=2, W=2

Getting Conflicting Versions



client

coordinator

data

data

node1

5	B	3	Y

rebooting...

node2

5	B	3	X

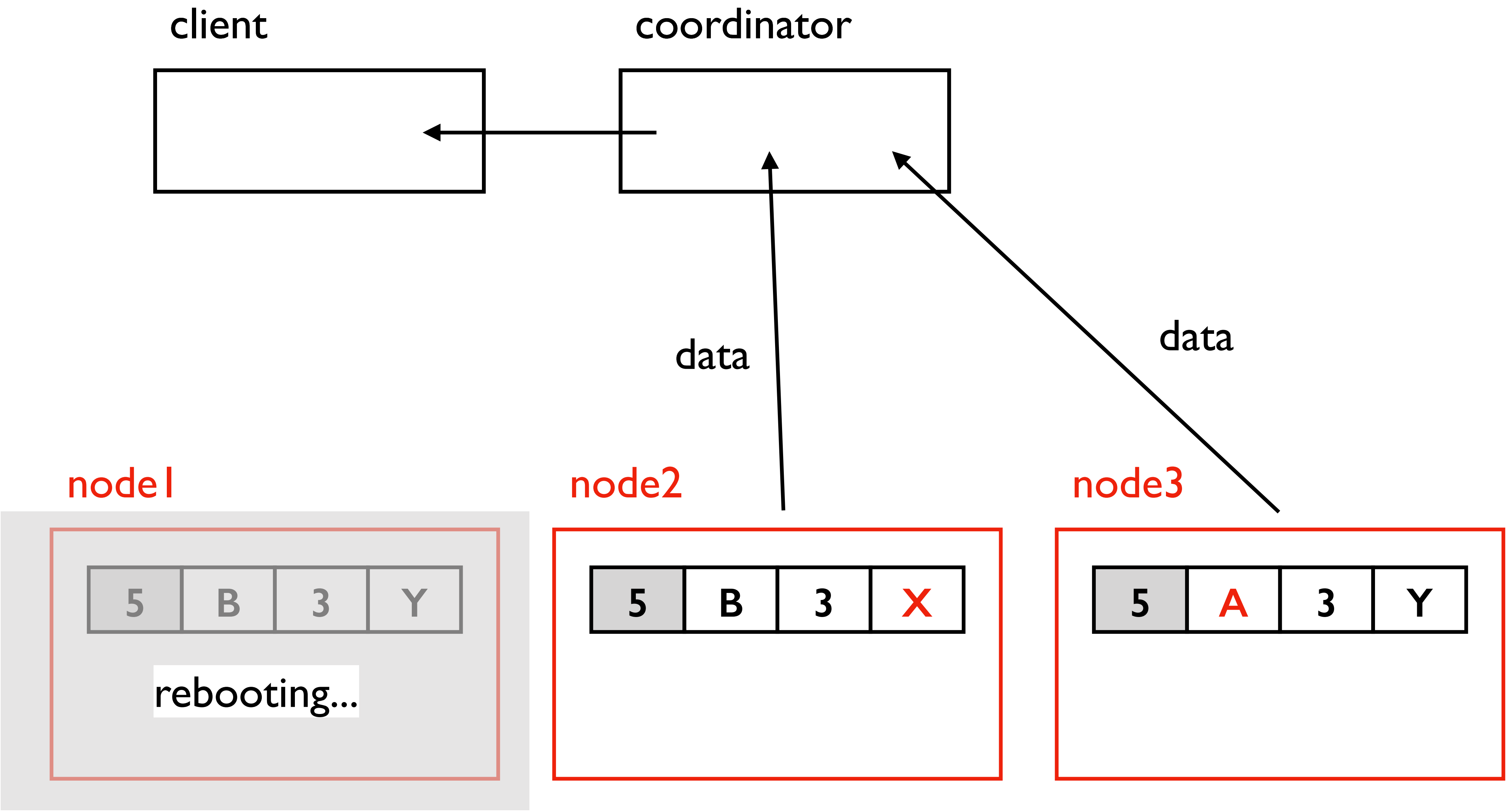
node3

5	A	3	Y

Which version of row 5 should be sent back?
Both contain some new data not contained by other.

Systems that allow conflicting versions to co-exist,
fixing it up later are "*eventually consistent*"

Getting Conflicting Versions

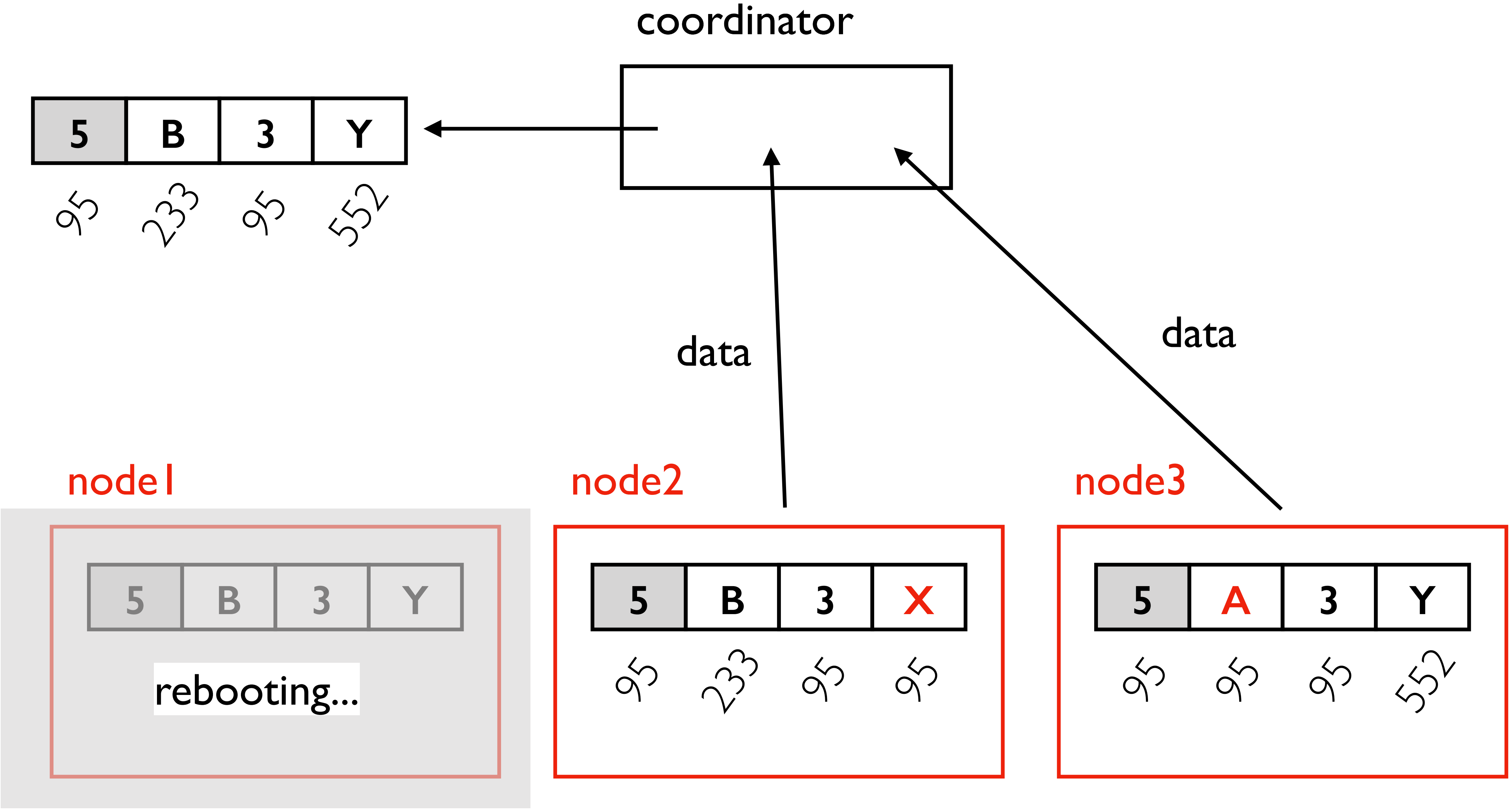


Approaches:

- send all version back to the client, which will need specialized conflict resolution code
- automatically combine them into a new row, and write that (if possible to all replicas)

Dynamo supports both. Cassandra uses second approach.

Timestamps



Every cell of every table has a timestamp:

- approximate (since clocks of nodes in a cluster are never perfectly in sync)
- policy is LWW (last writer wins), meaning prefer newer data
- Cassandra lets you query the timestamp of each cell

Outline: Cassandra Partitioning+Replication

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