Declarative,
Secure,
Convergent
Edge Computation

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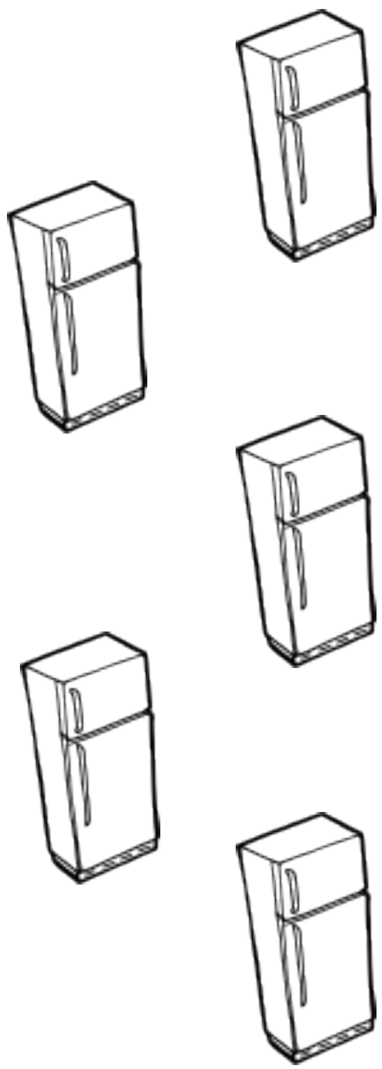
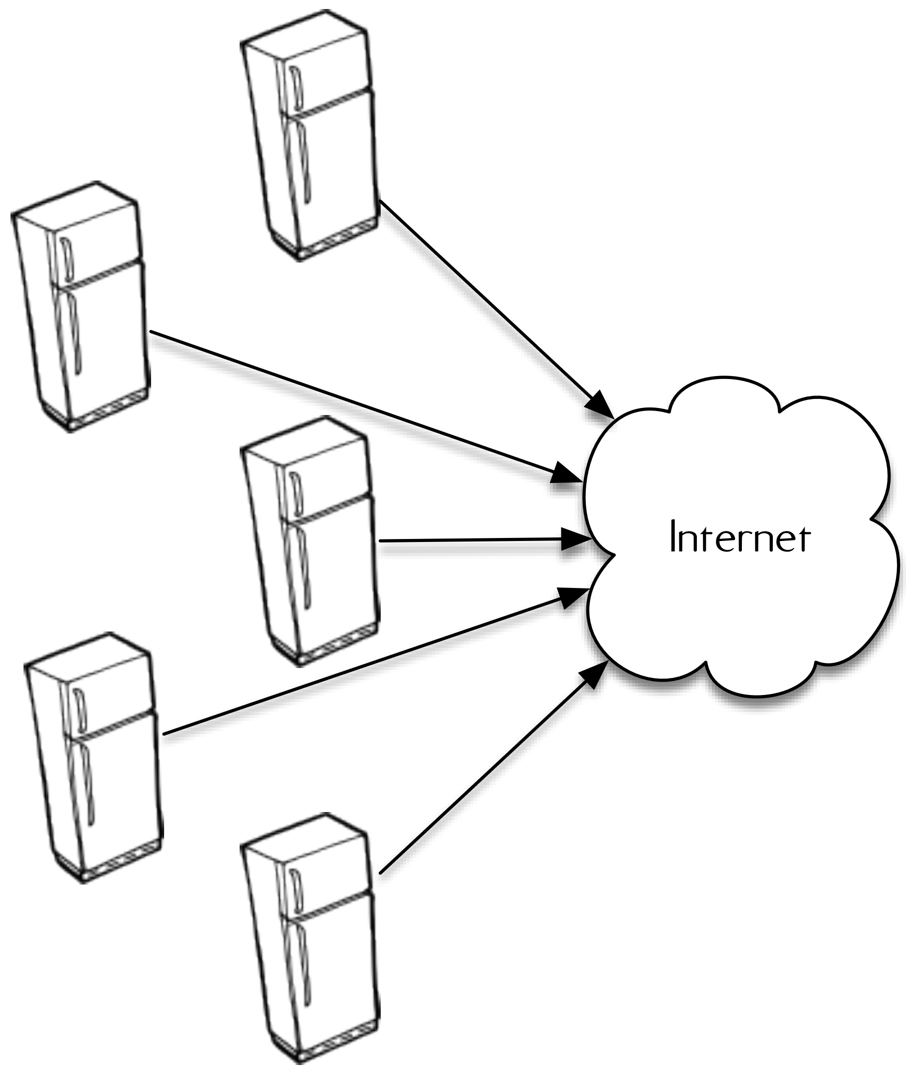
Example Application
Hospital Refrigerators

Hospital Refrigerators
Typical Topology

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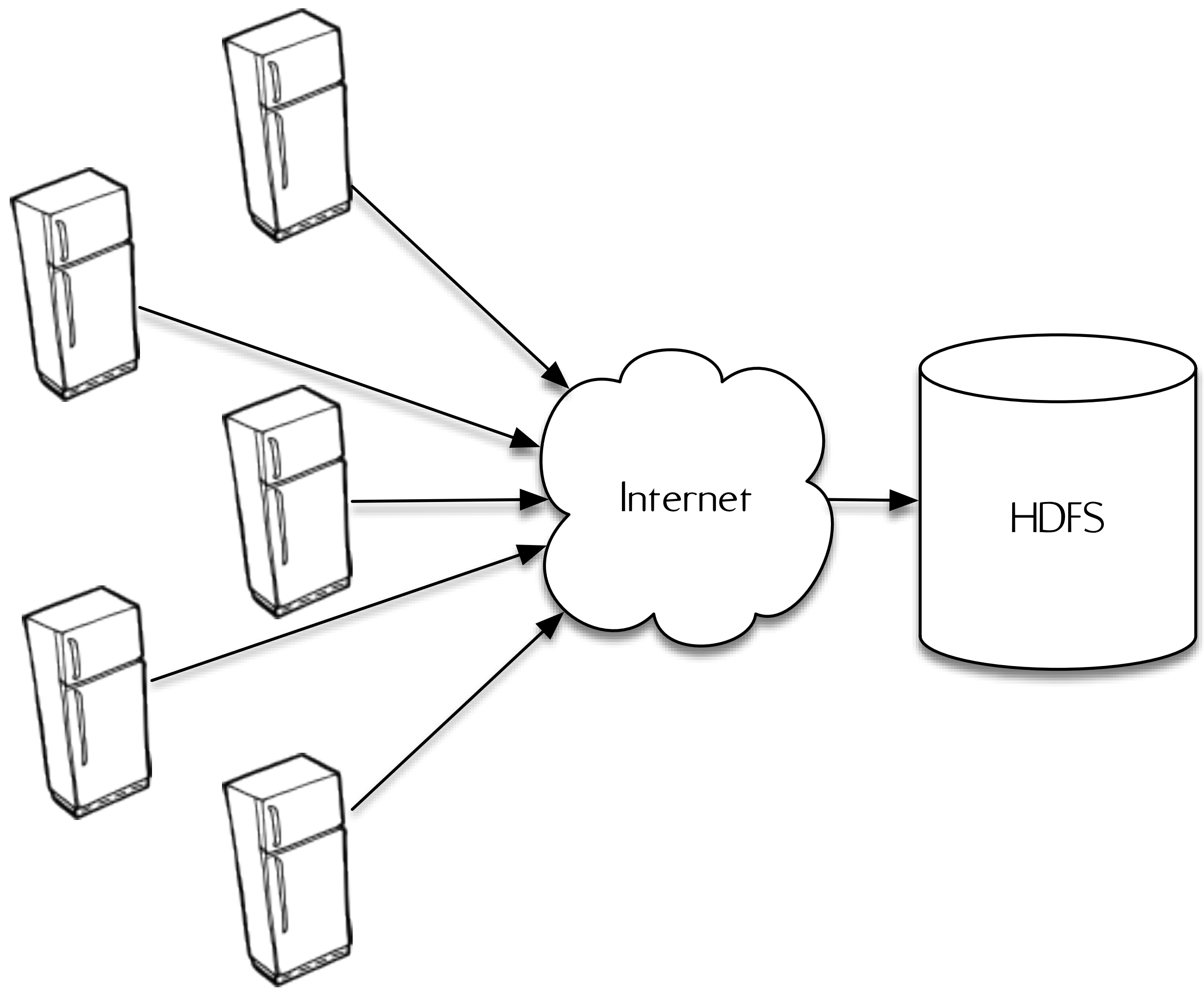
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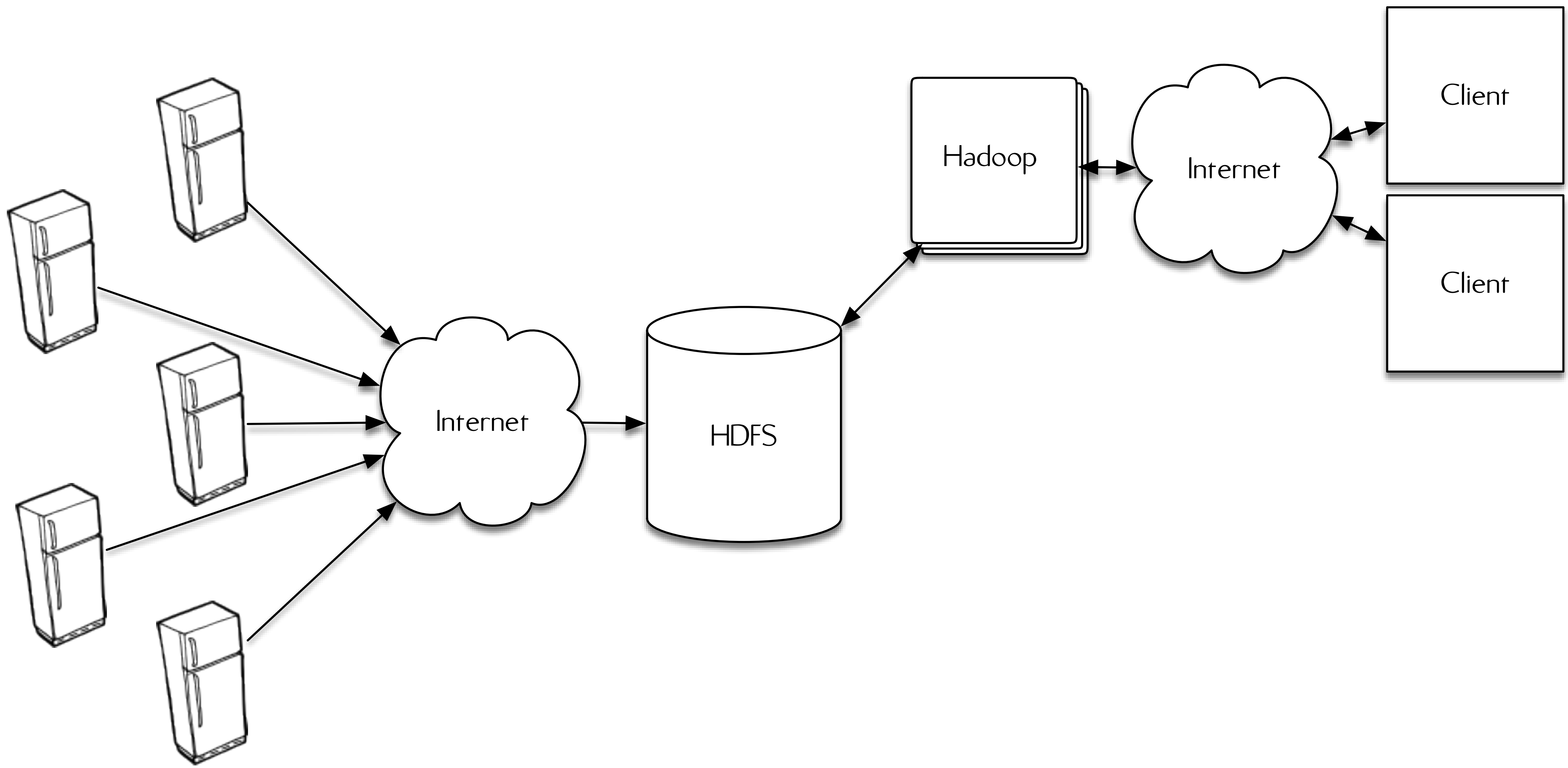
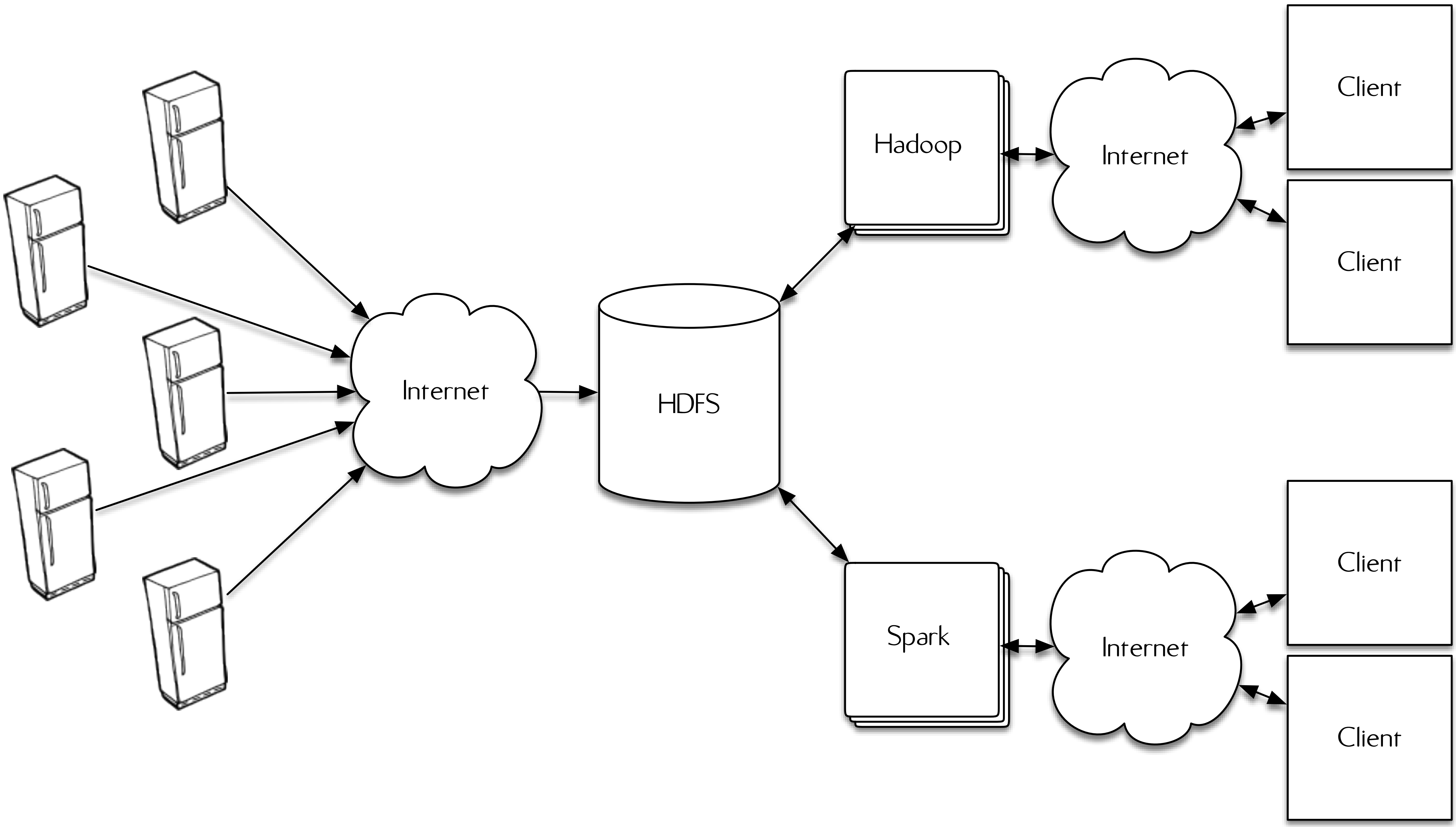
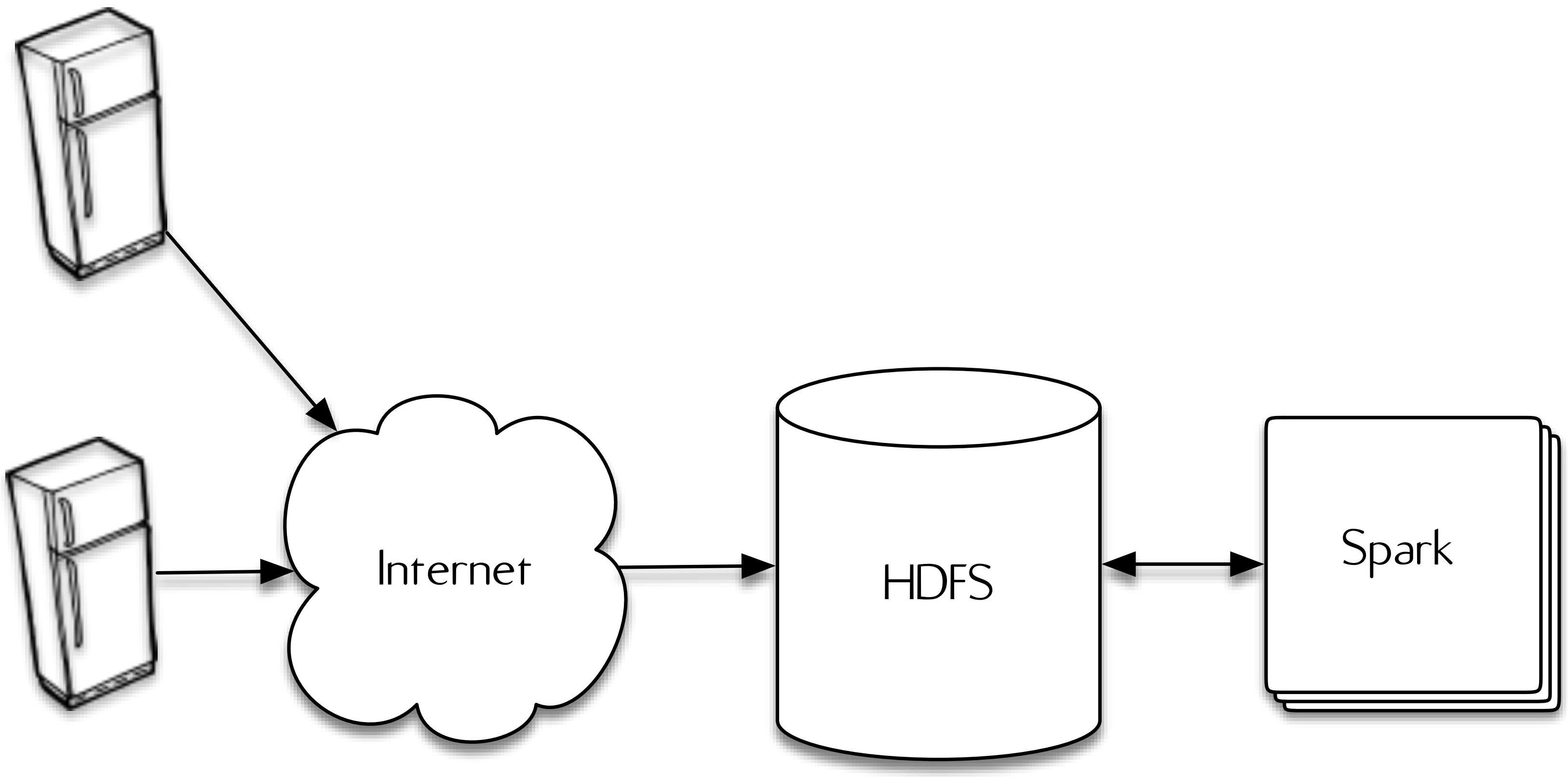
HDFS


Hadoop
Internet
Client
Client
Internet
HDFS


Internet
HDFS
Hadoop
Internet
Client
Client
Spark
Internet
Client
Client

Hospital Refrigerators
Ideal Execution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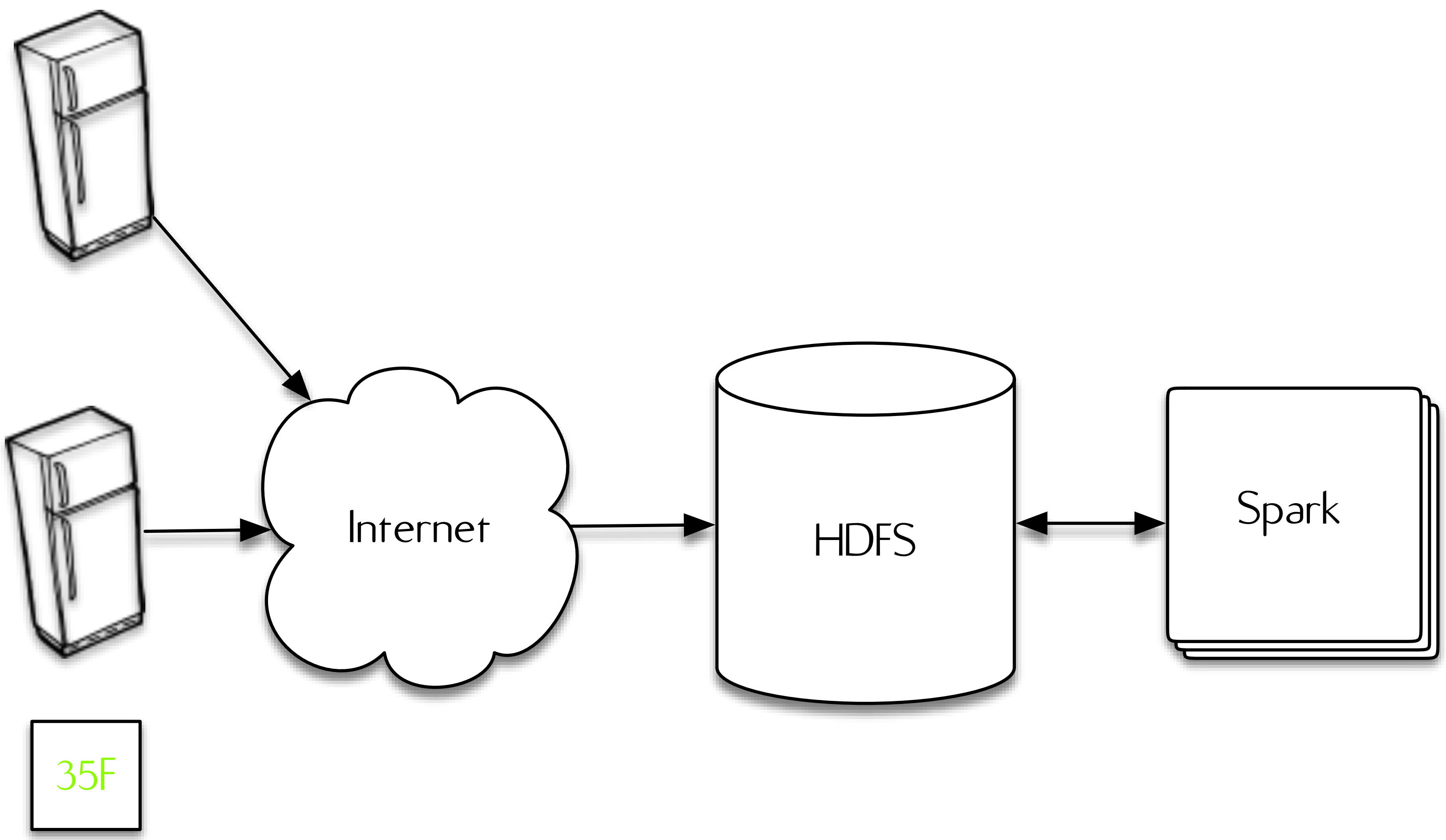
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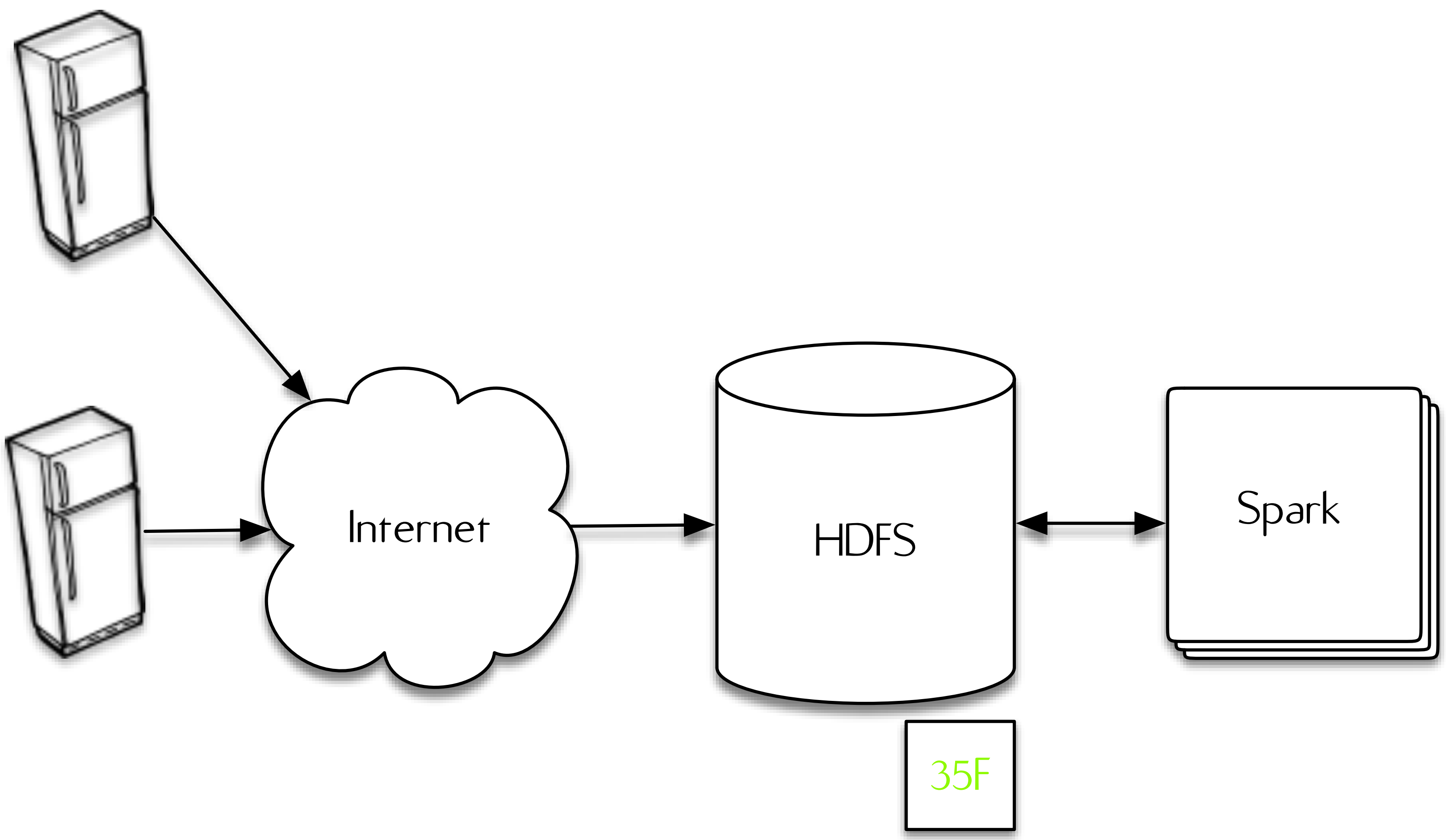
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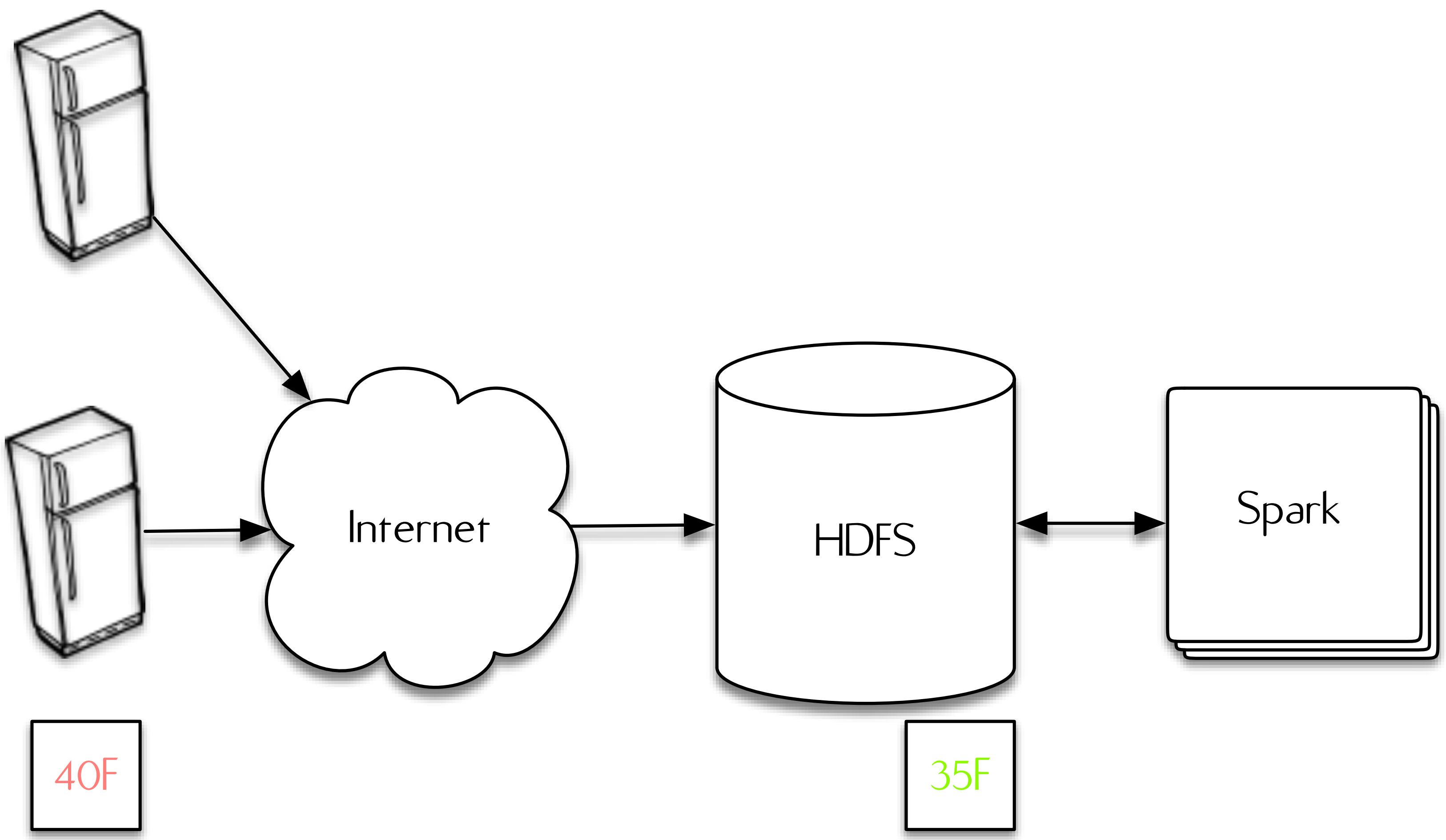
Internet
HDFS
Spark
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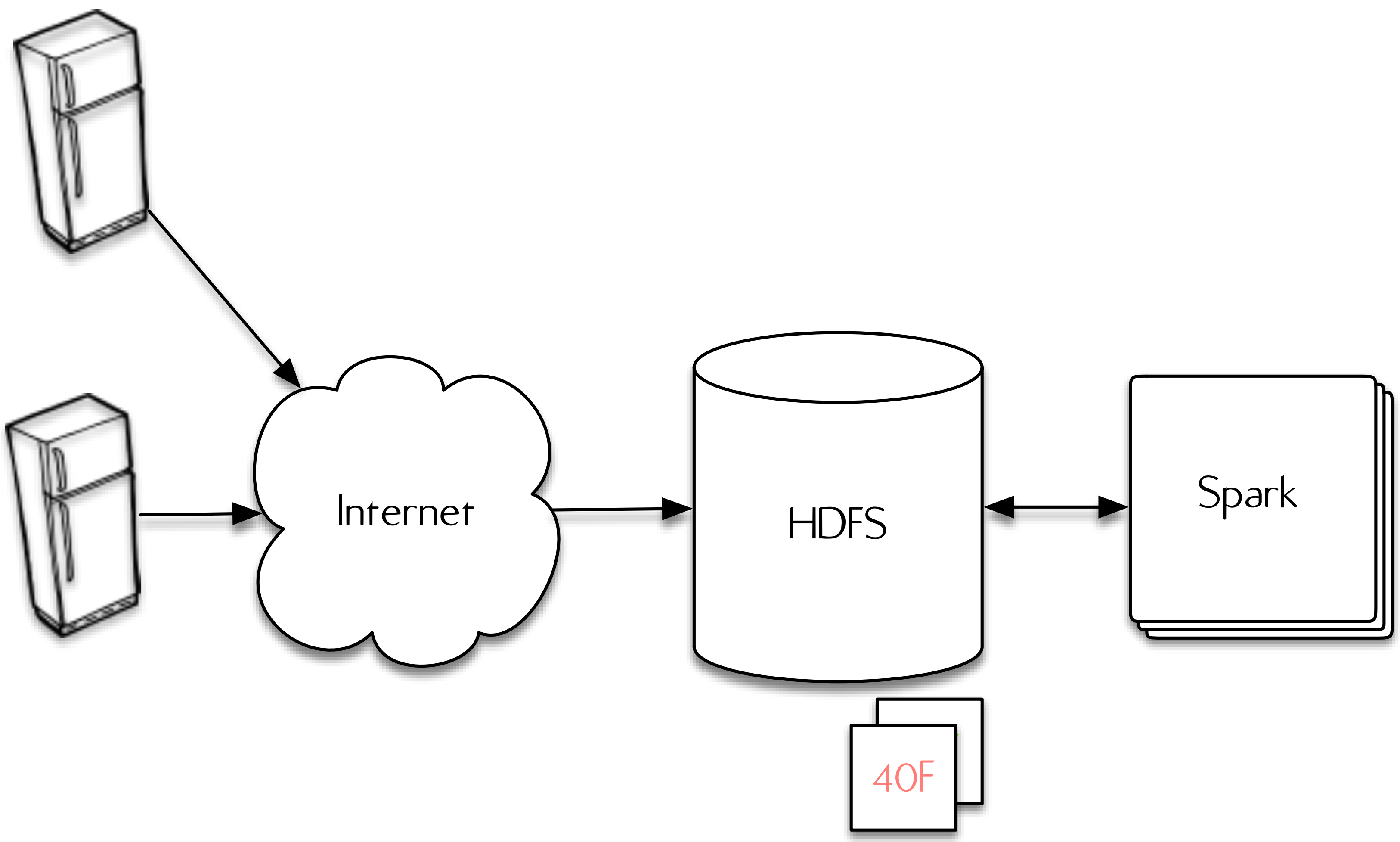
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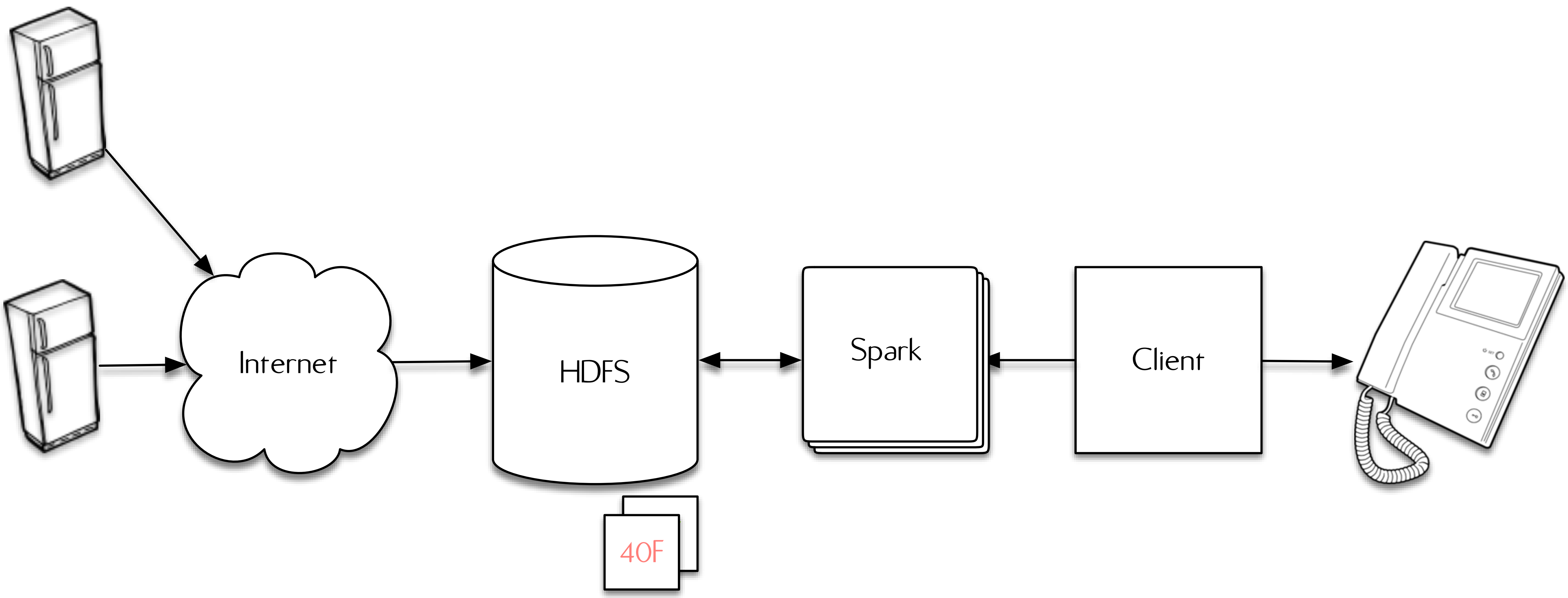
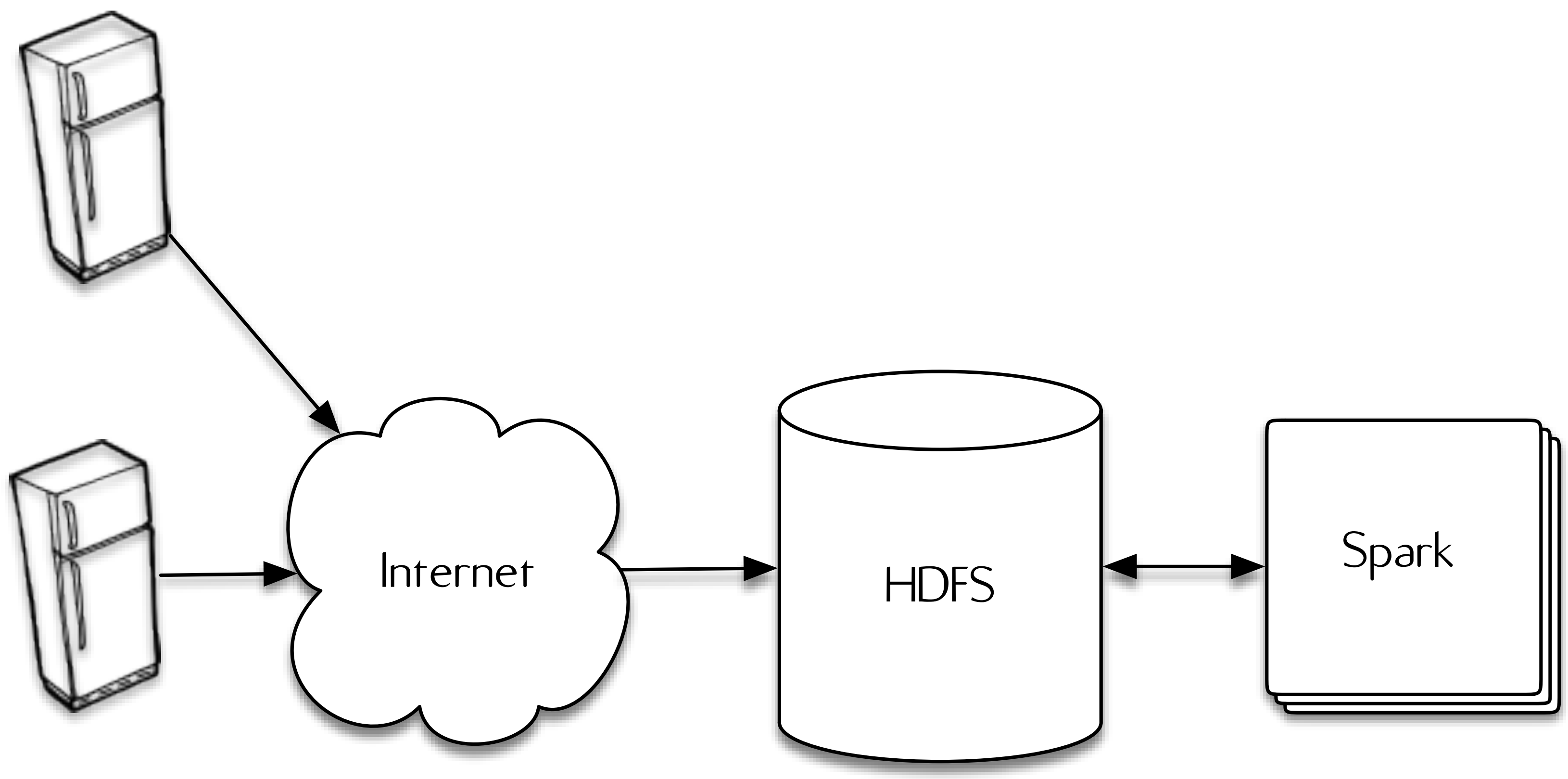

Internet
HDFS
40F
Spark
Client

Problem

Connectivity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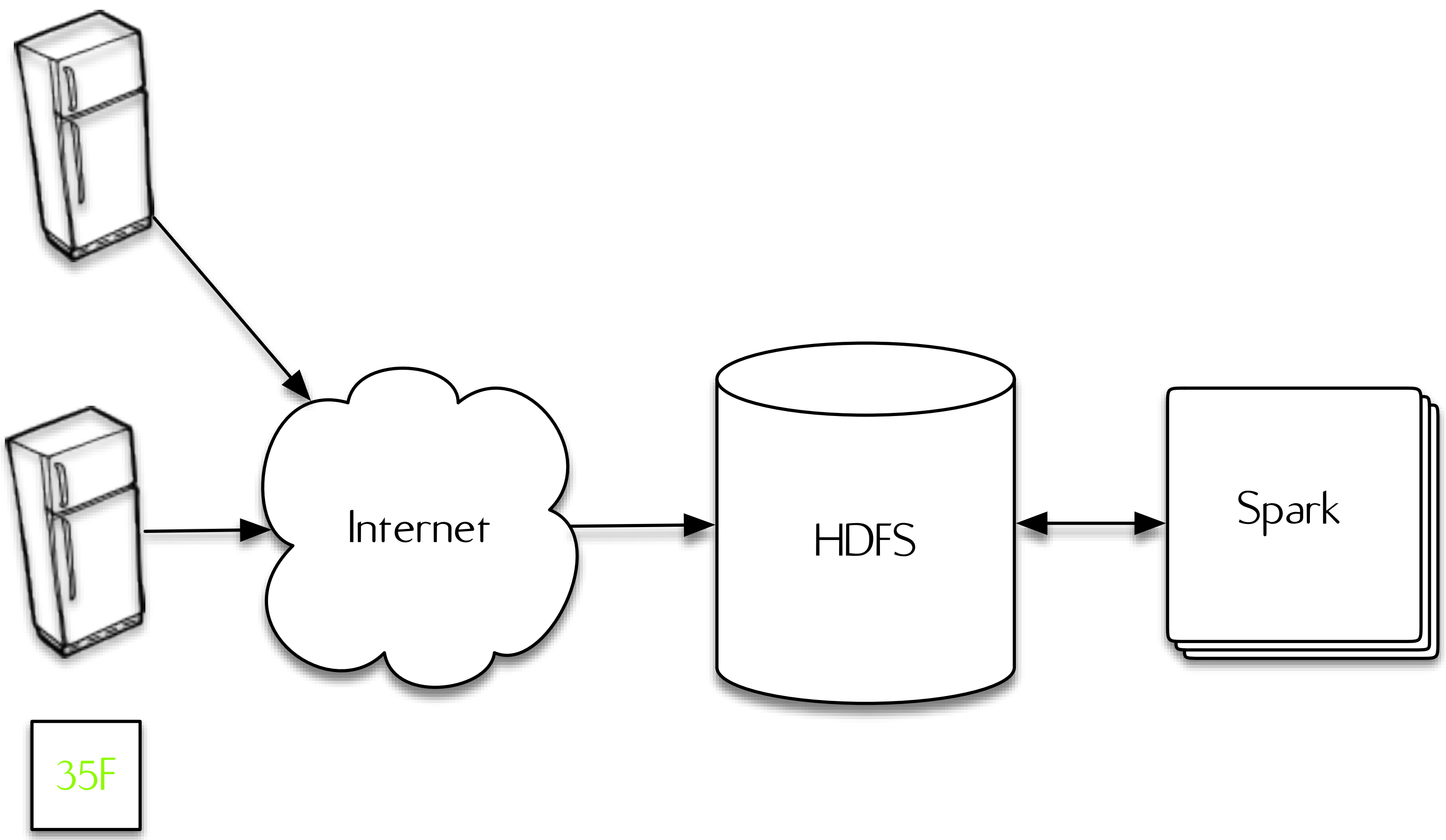
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HDFS
Spark
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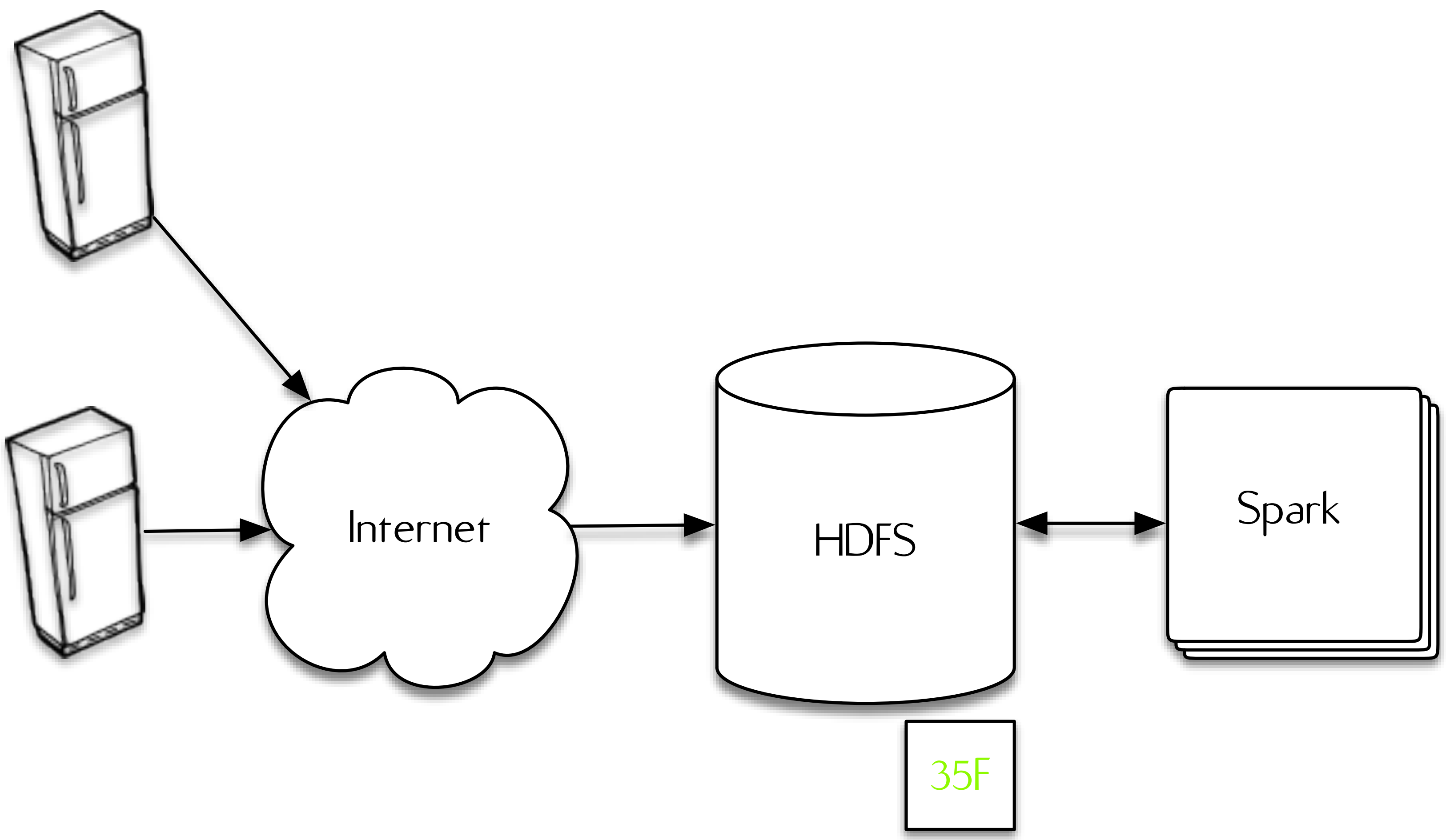
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HDFS
Spark
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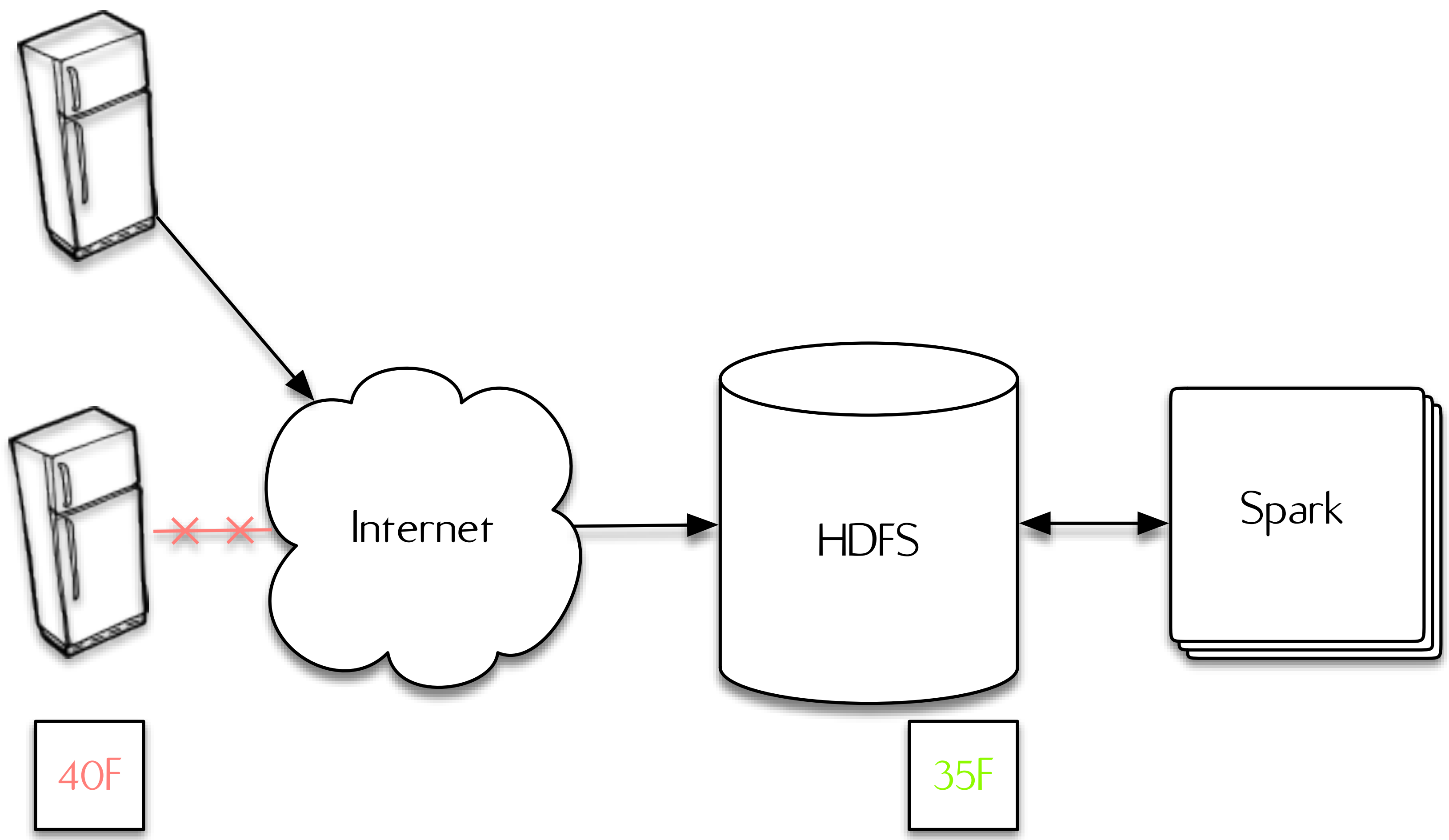
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HDFS
Spark
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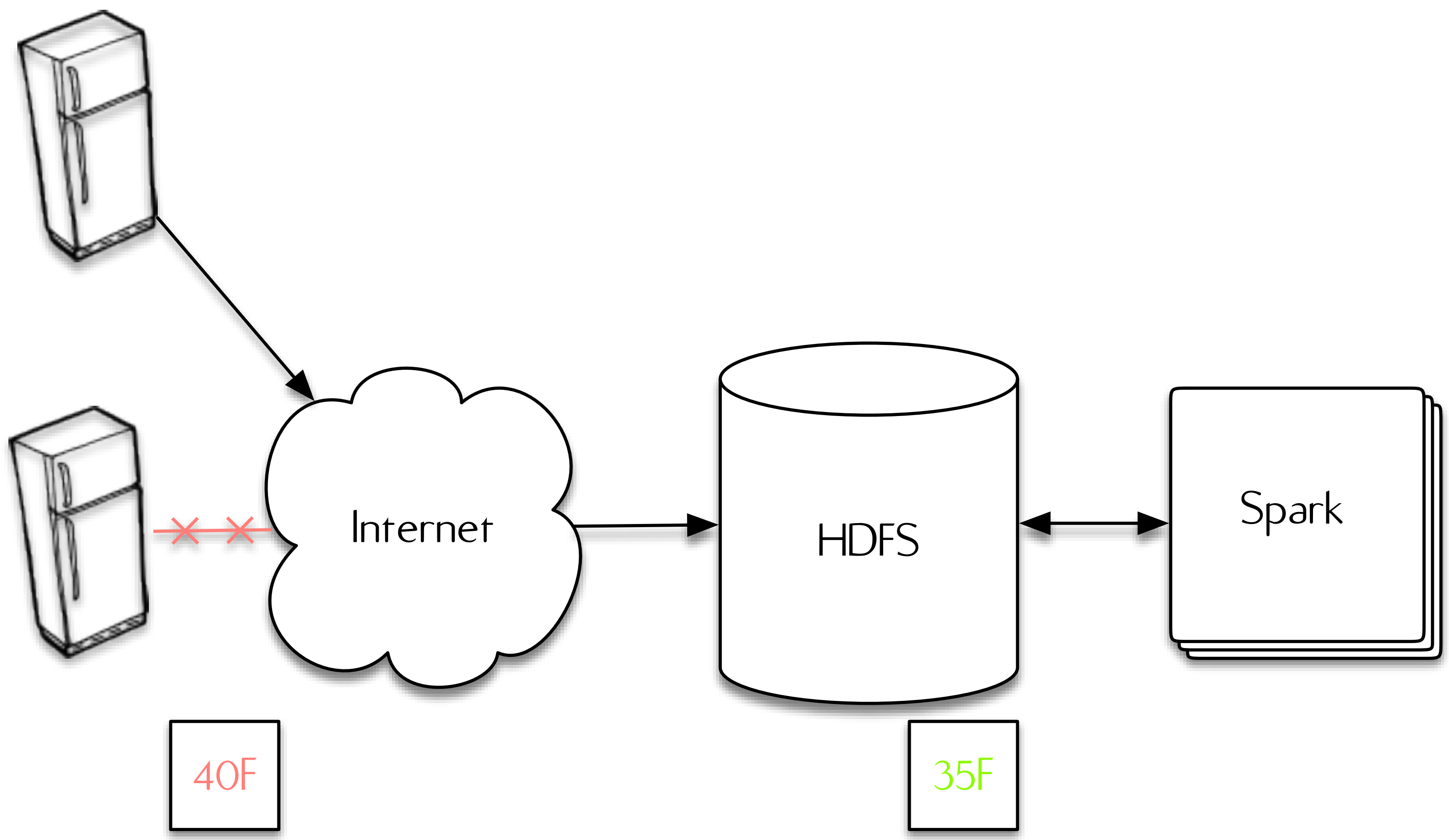
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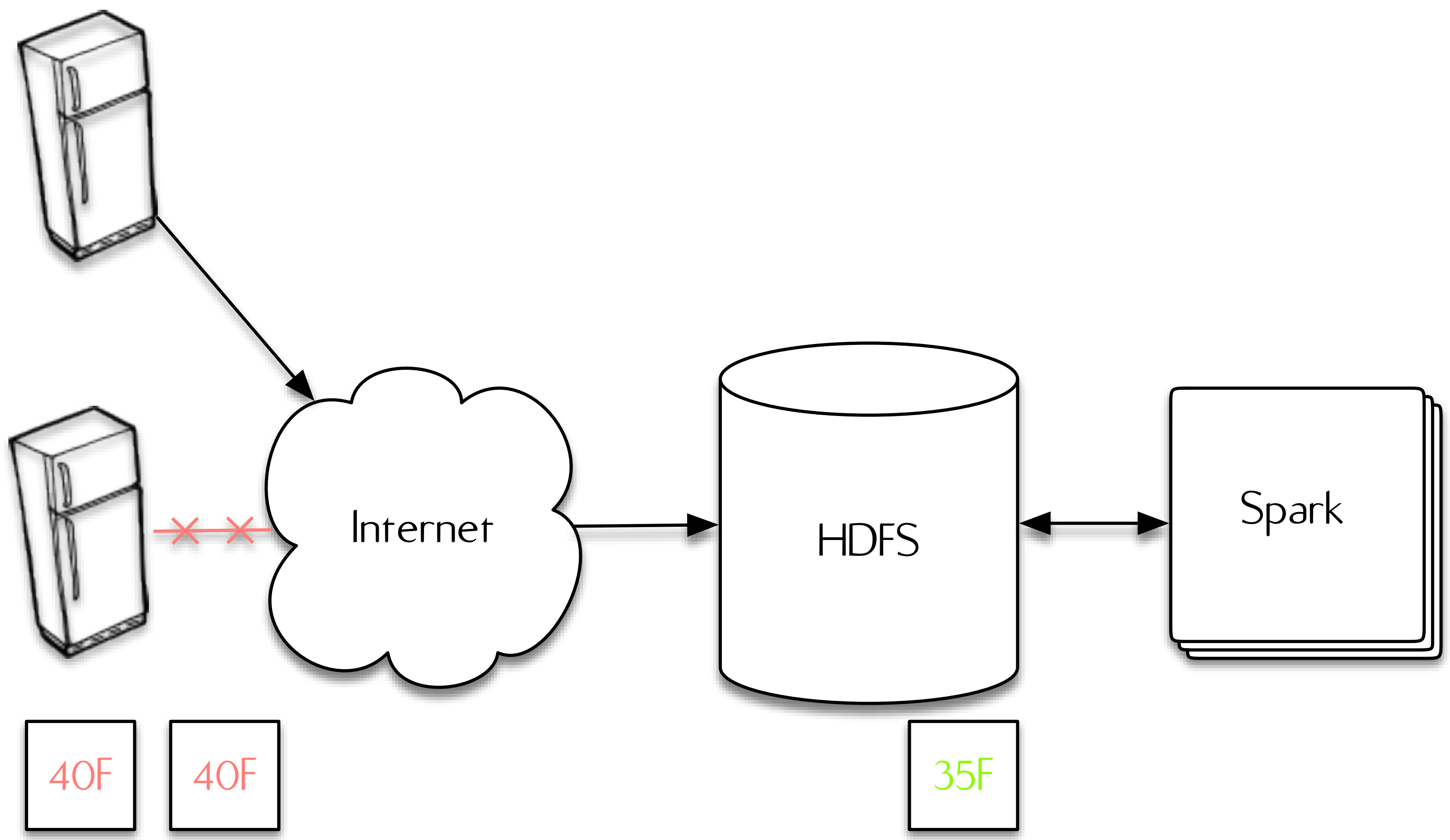

Internet
HDFS
Spark
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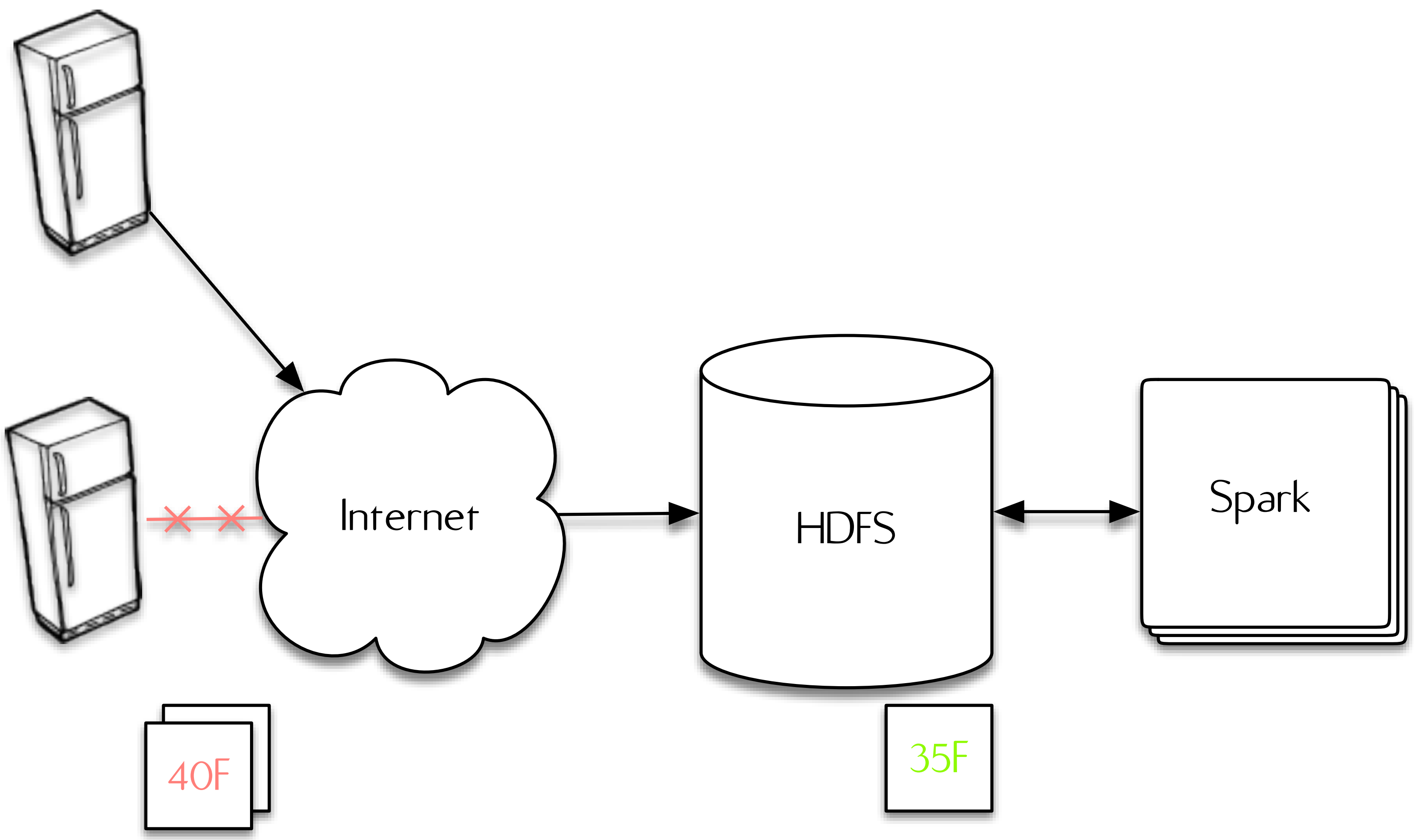
35F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HDFS
Spark
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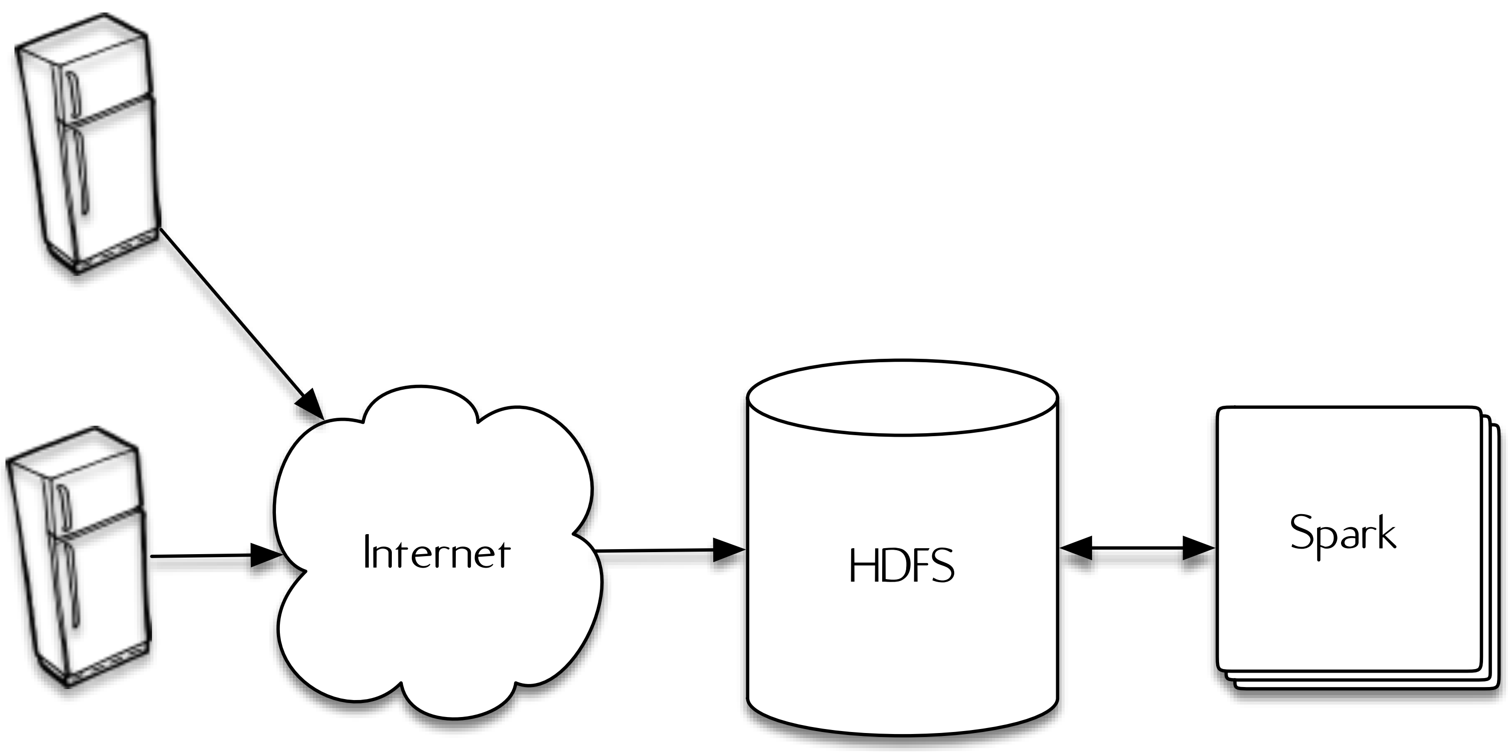
35F

Solution

Local Decisions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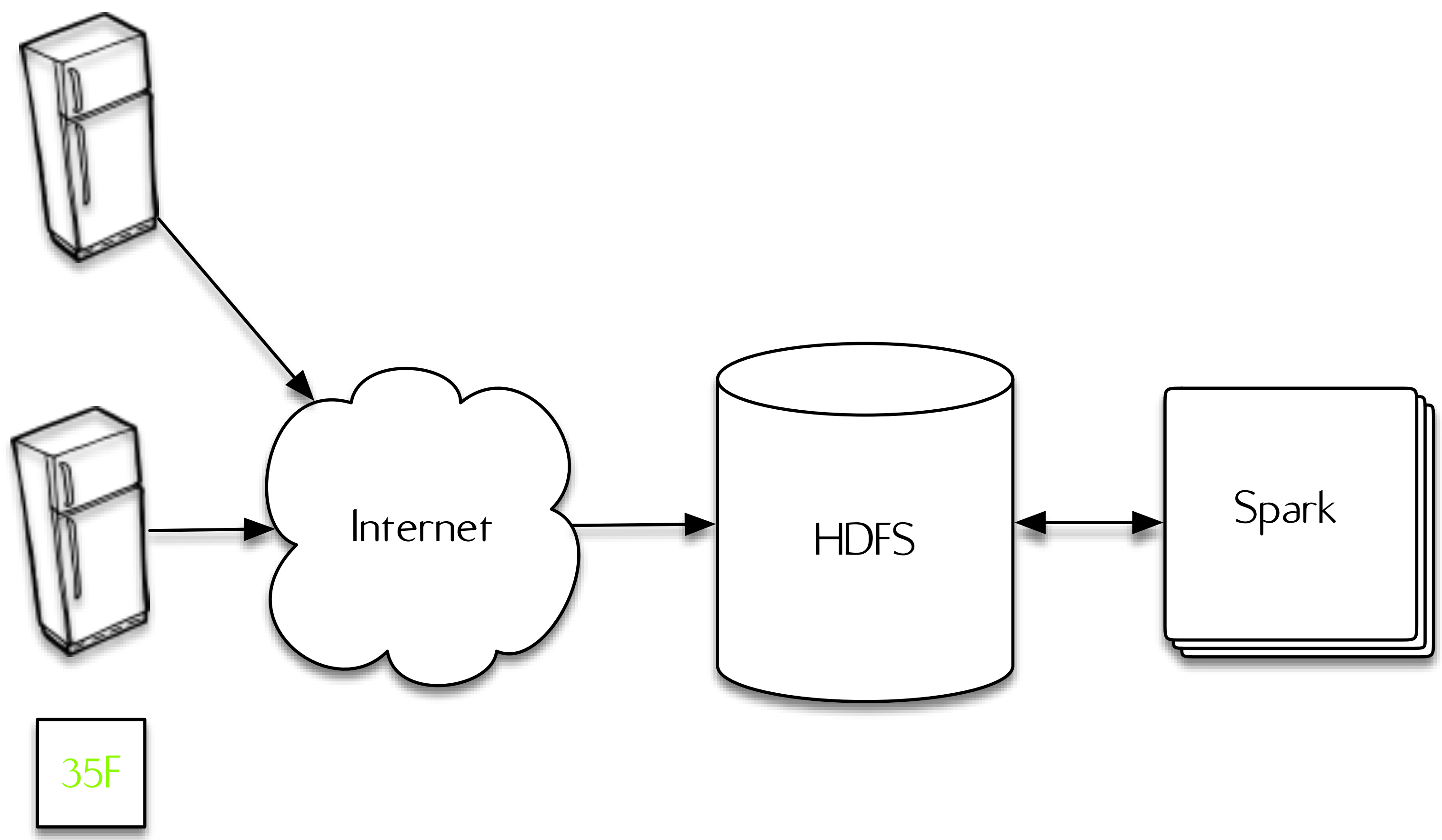
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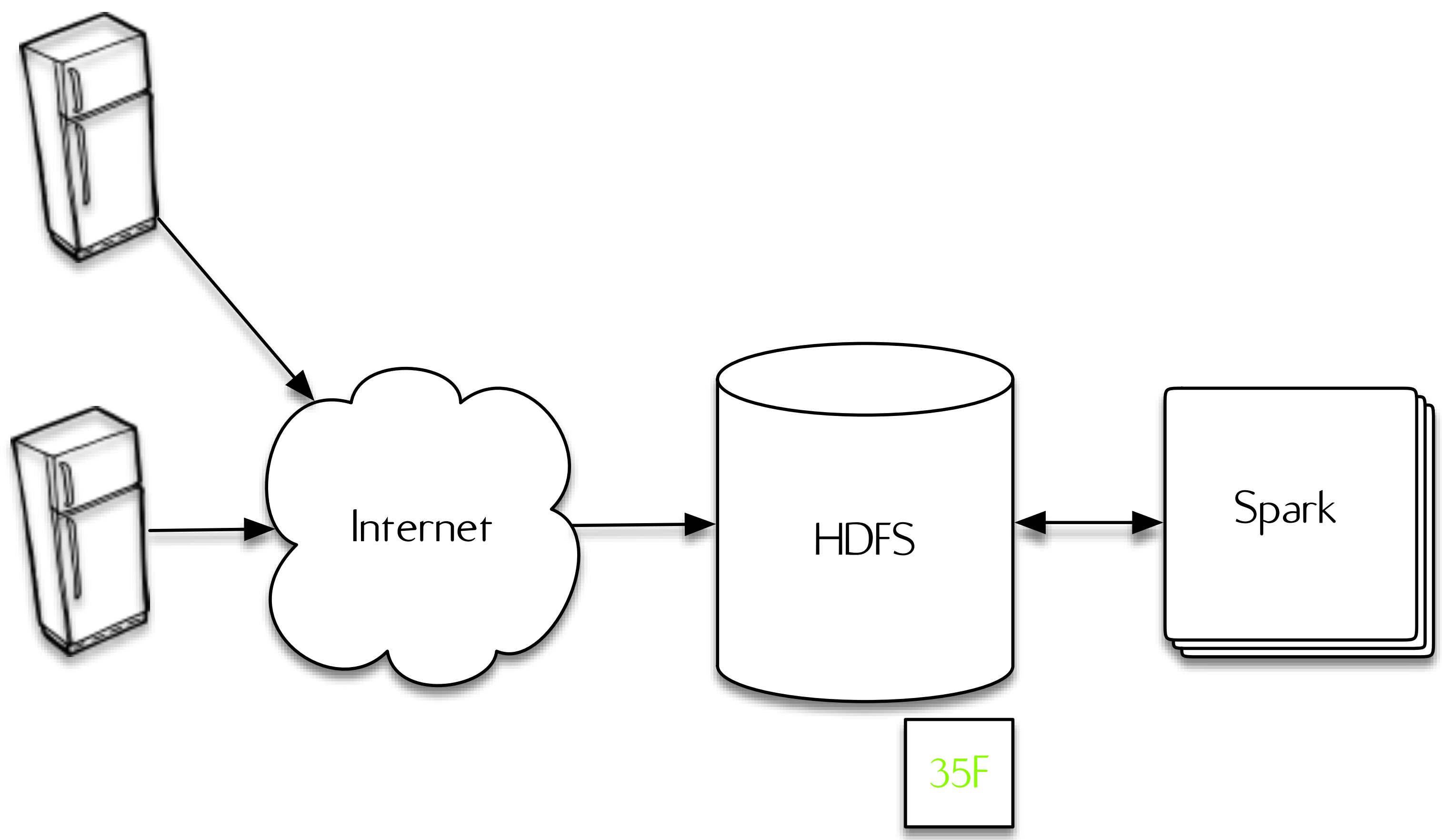
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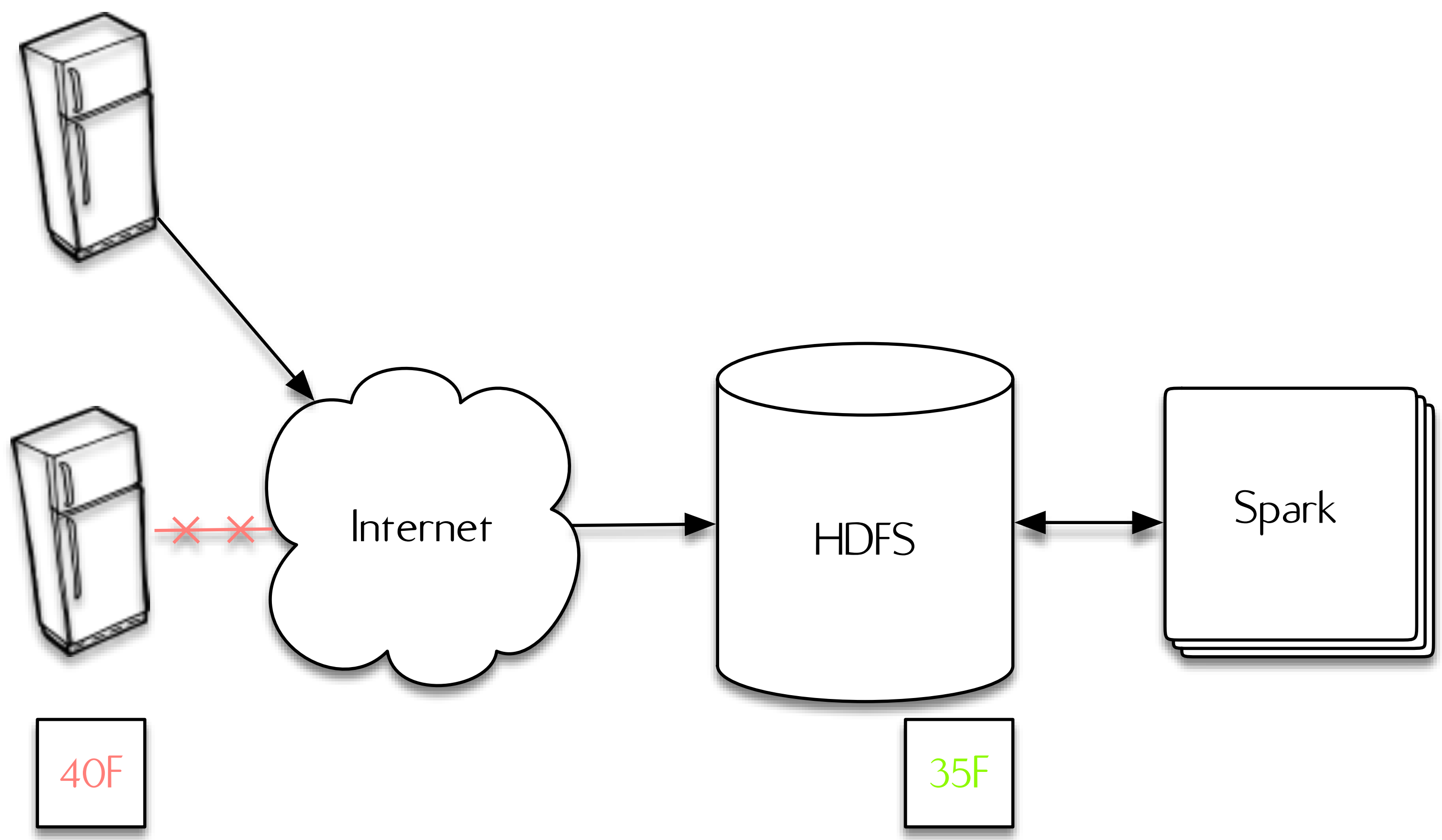
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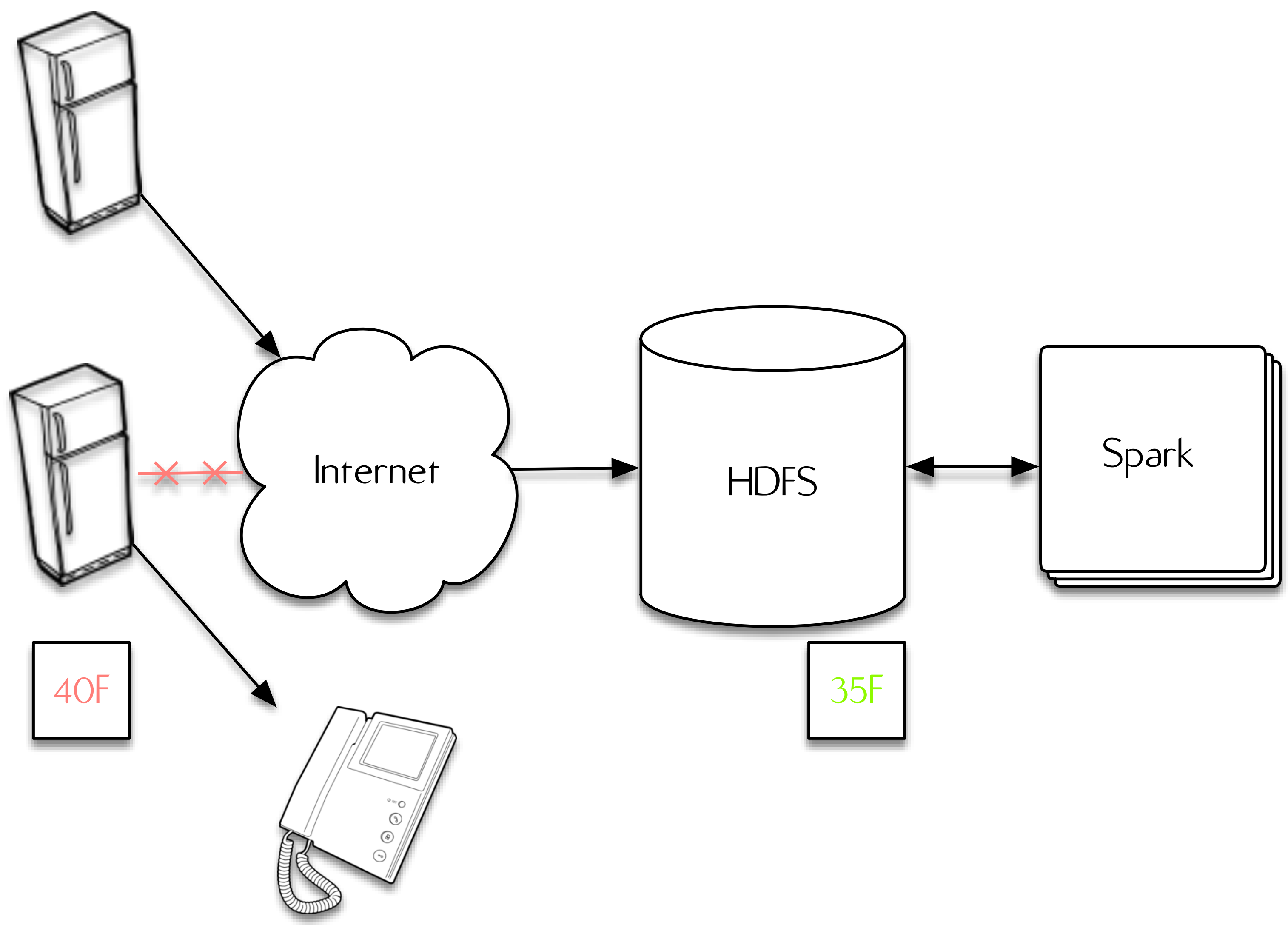
Internet
HDFS
Spark
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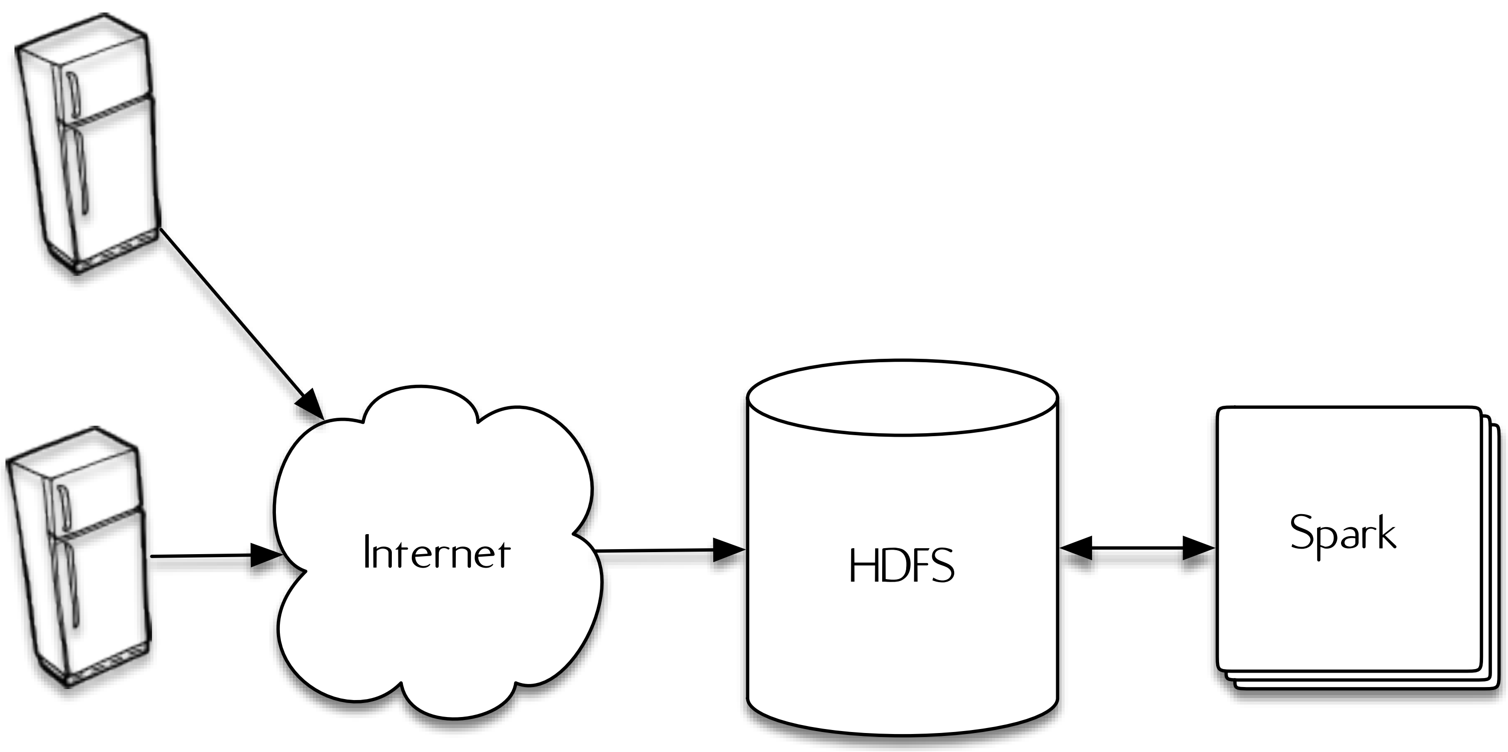
Solution

Transitive Dissemination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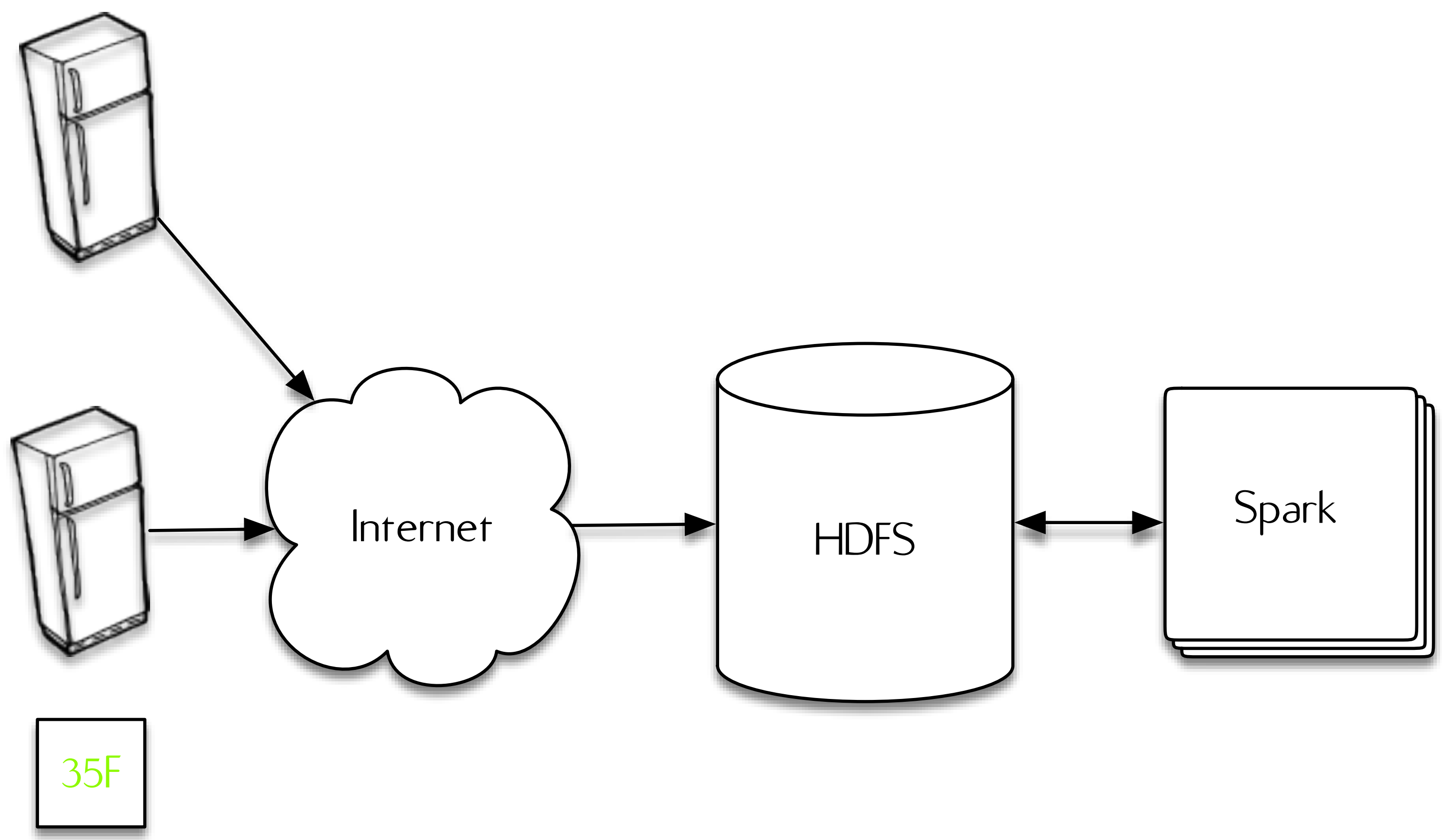
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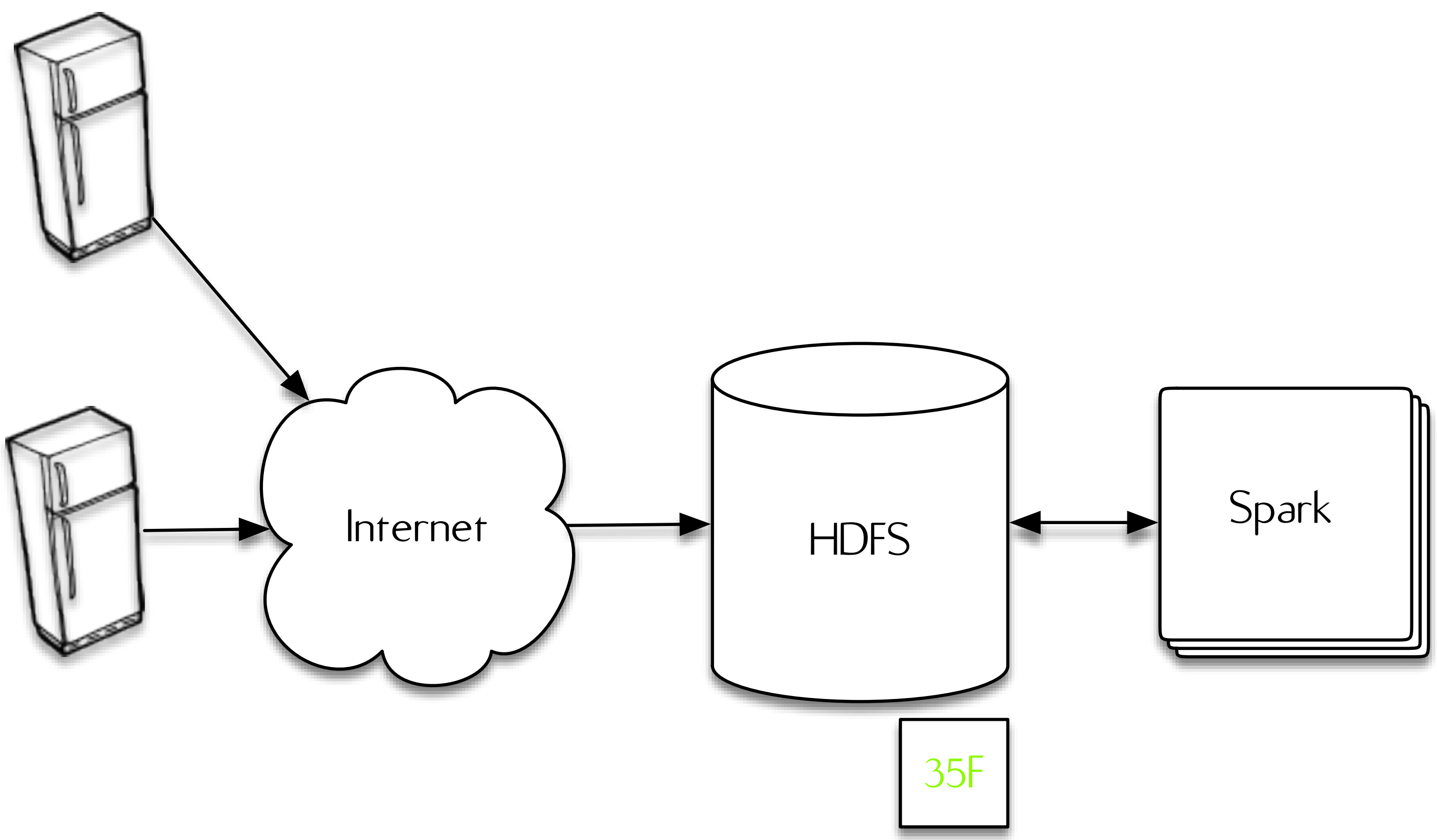
Internet
HDFS
Spark
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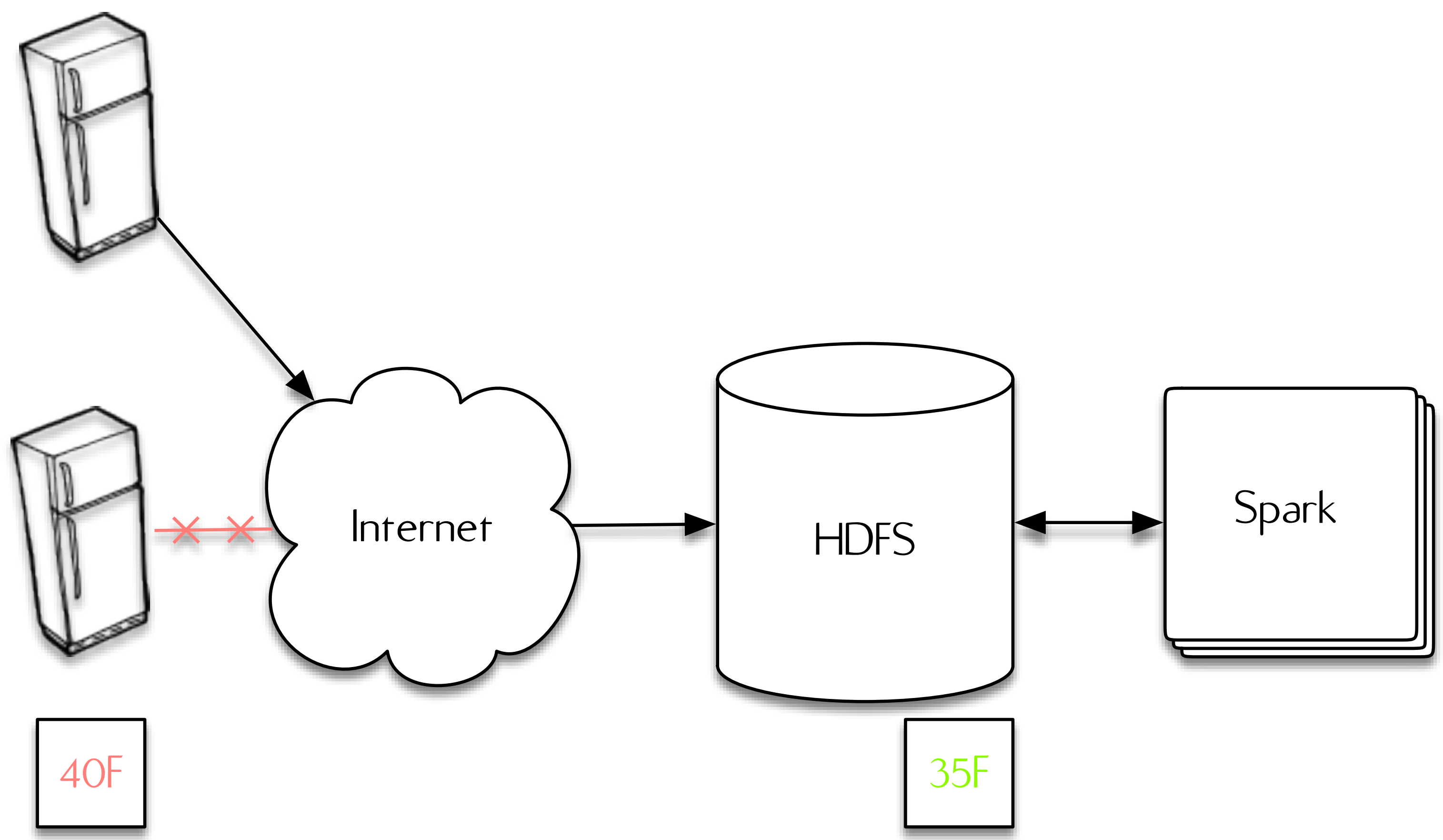
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HDFS
Spark
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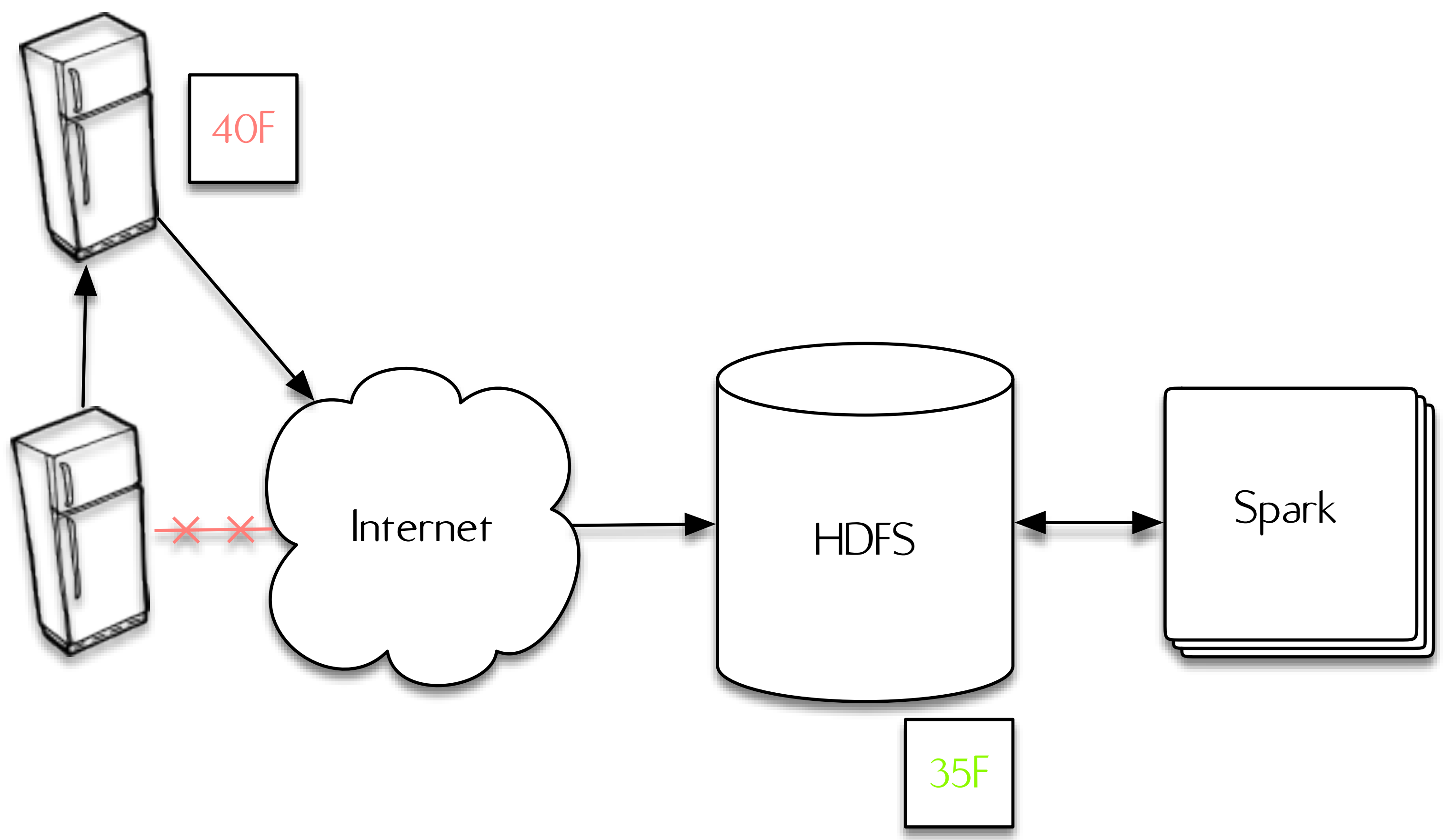
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Internet
HDFS
Spark
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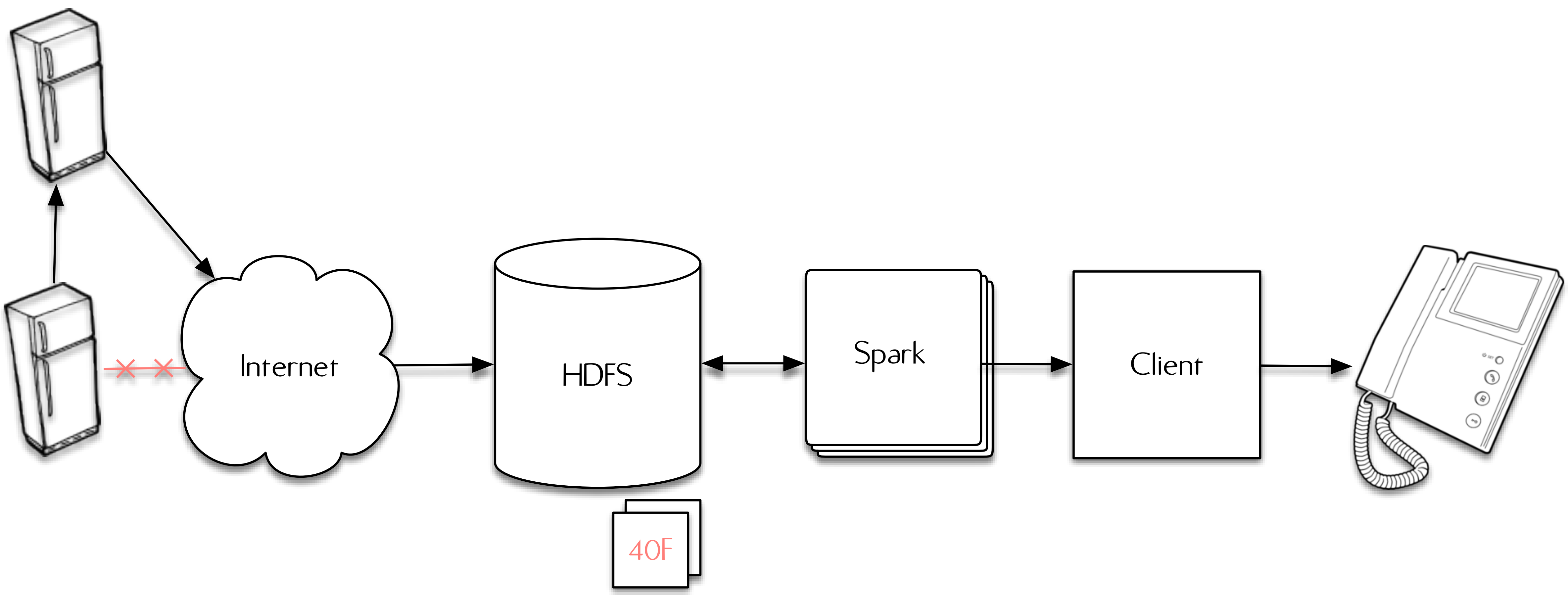
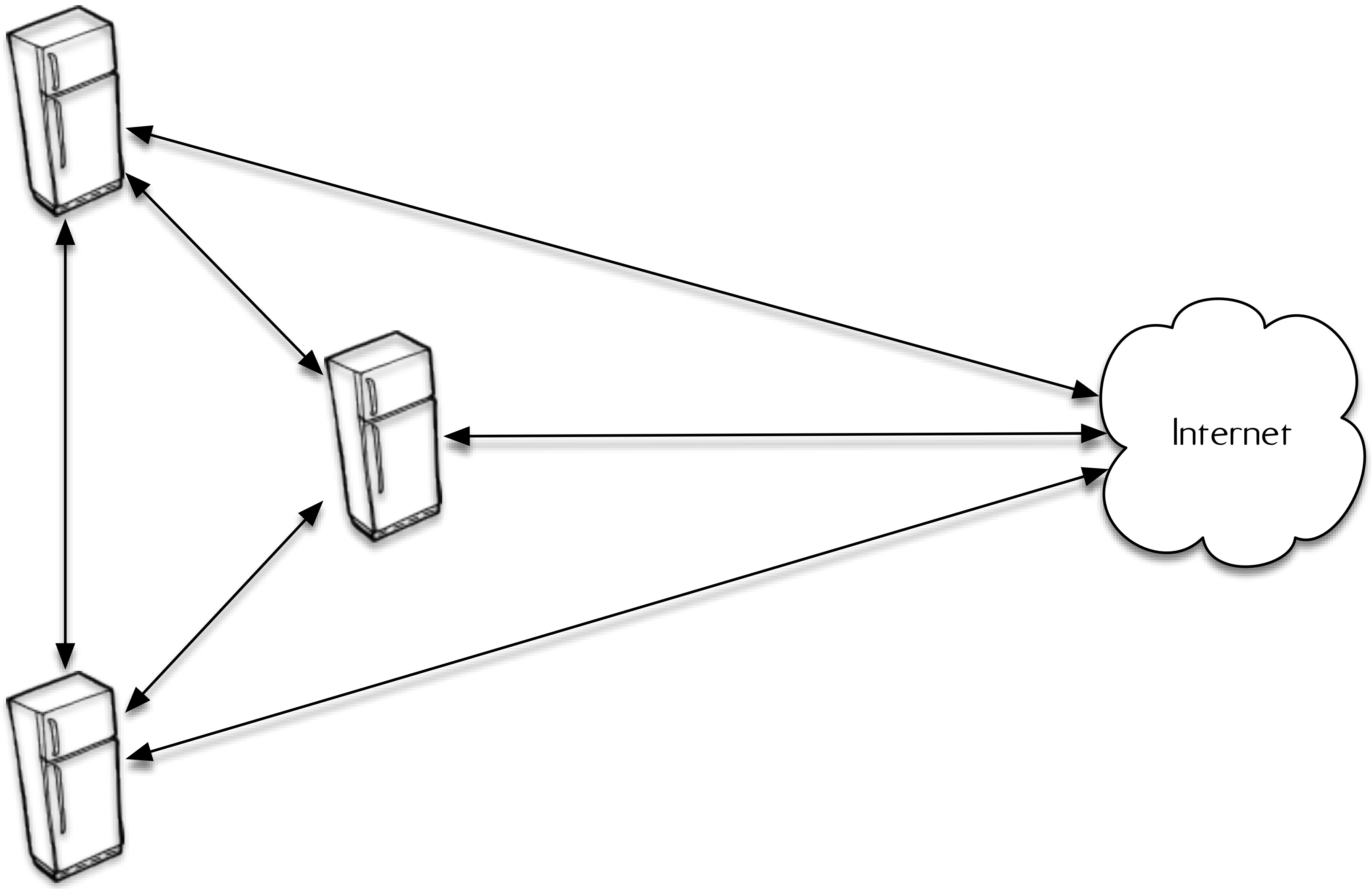


Internet
HDFS
40F
Spark
Client

Problem

State Transmission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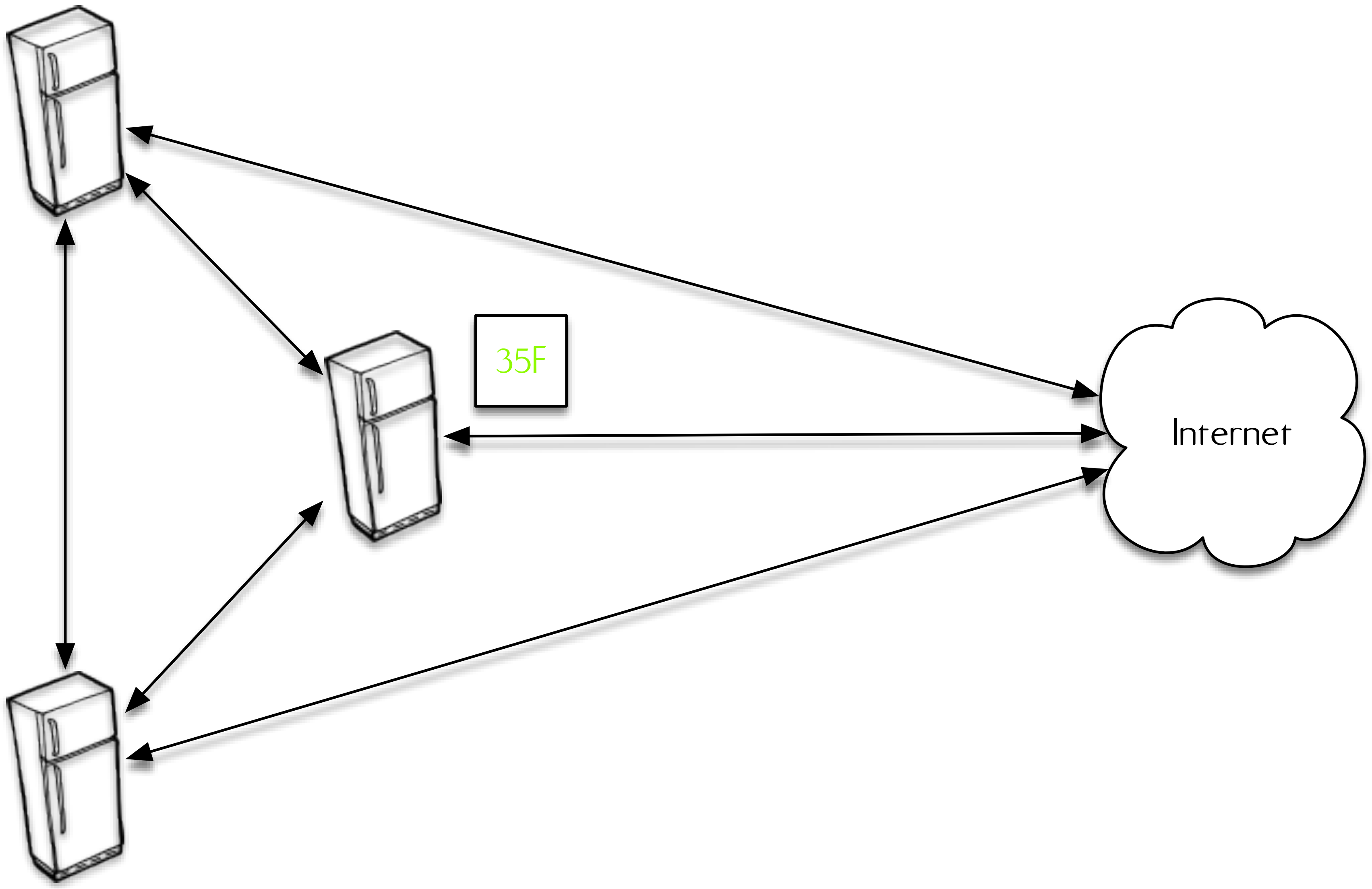
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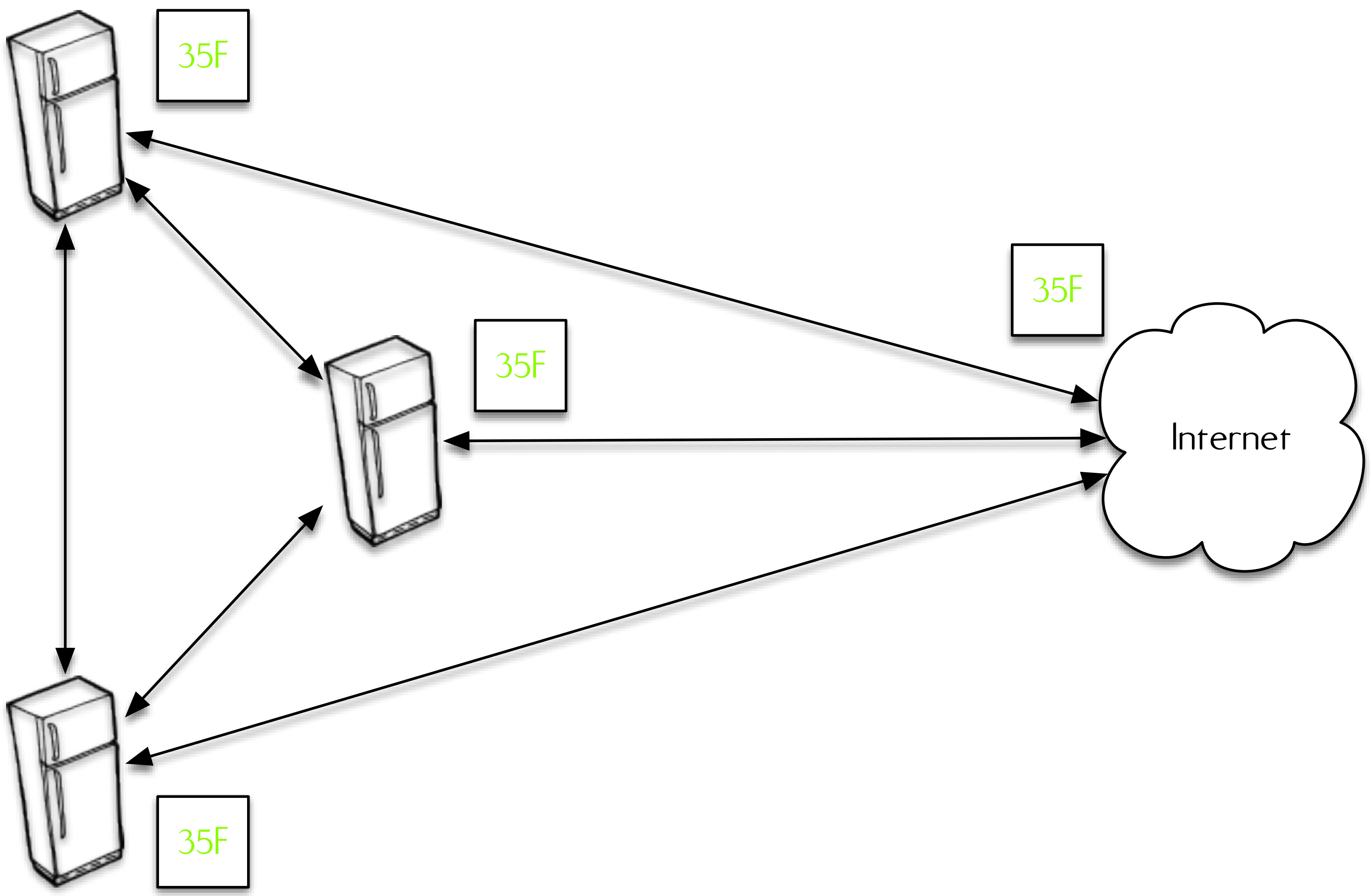
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35F
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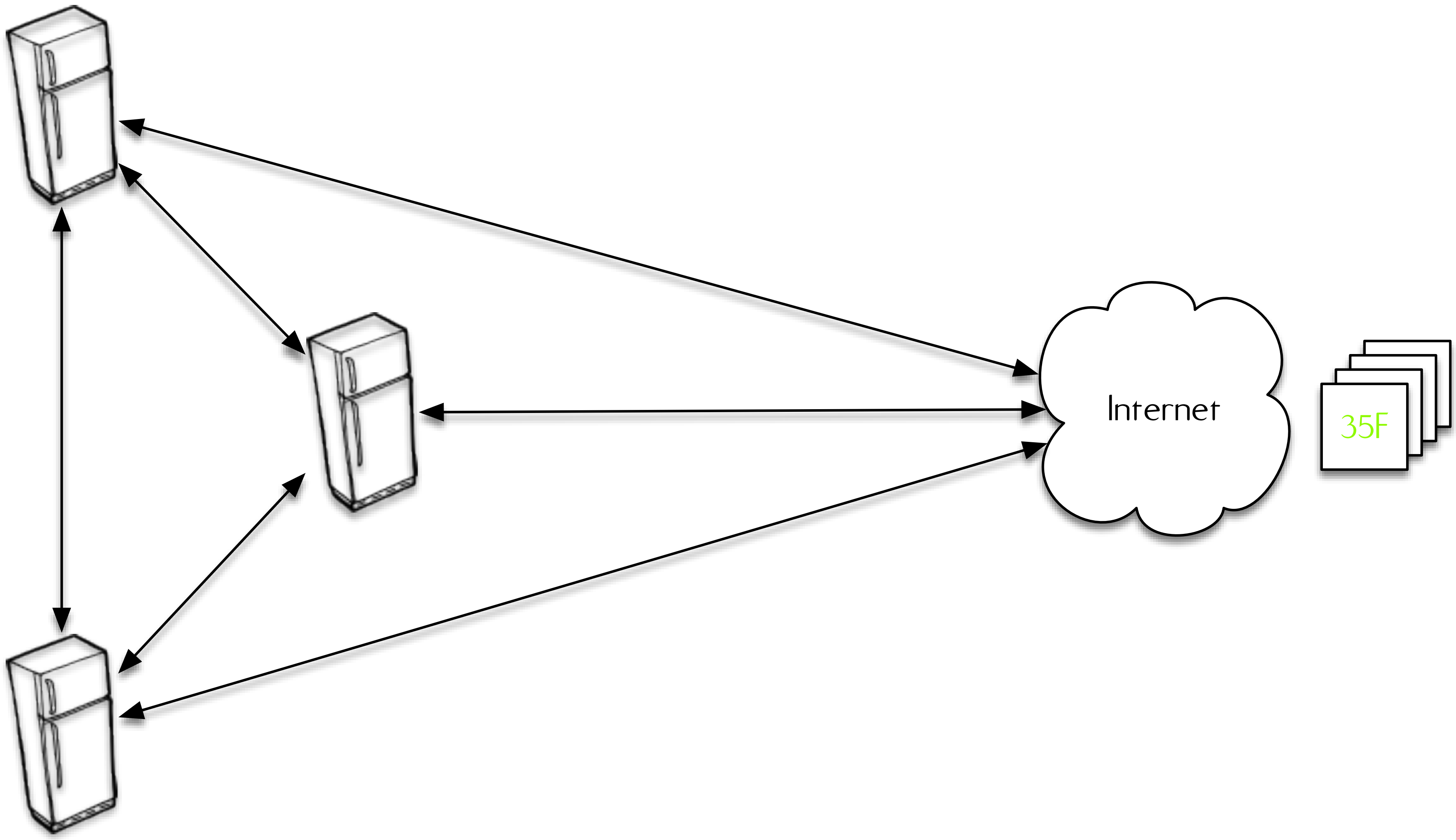
Internet
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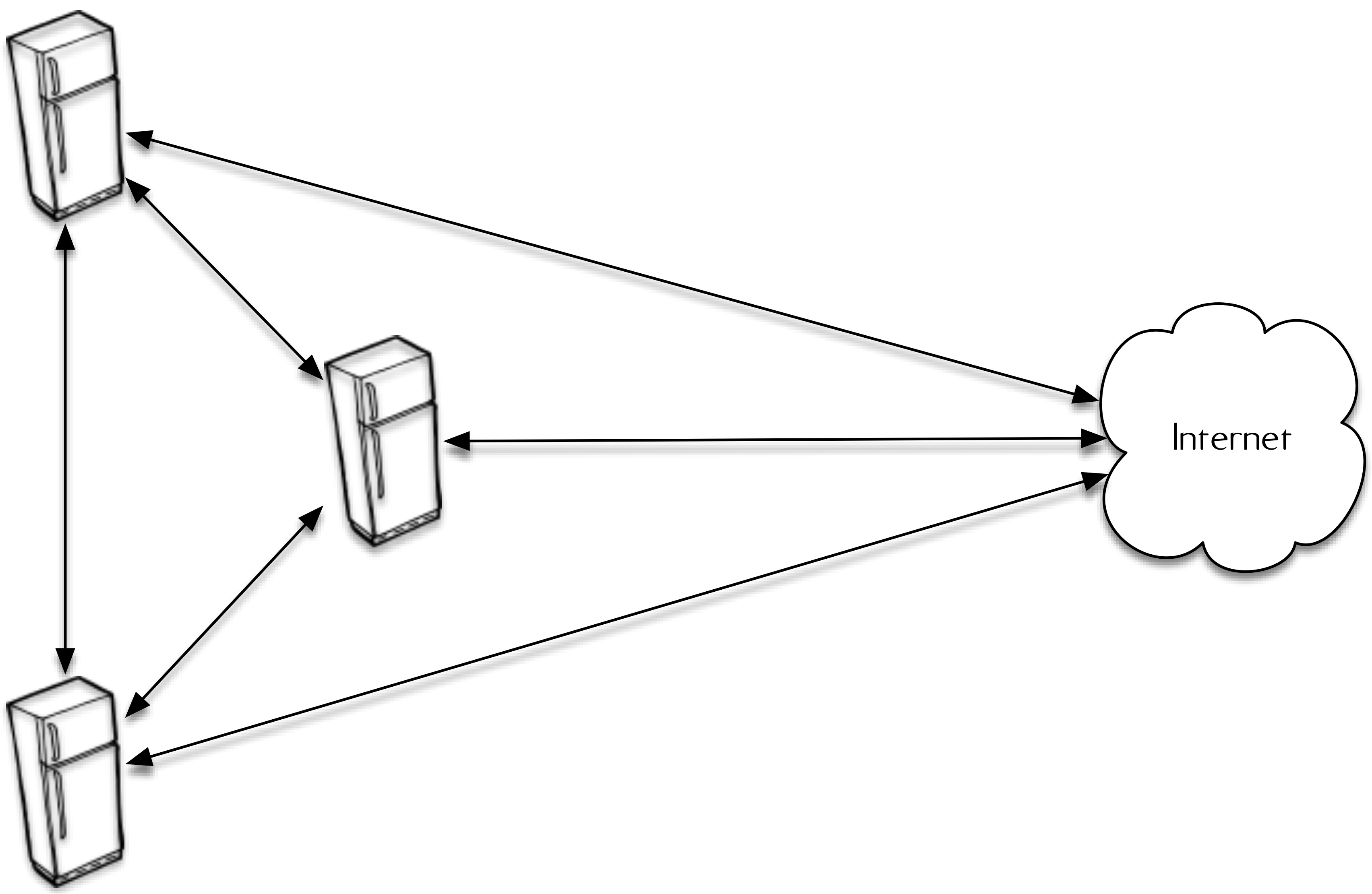
Solution

Aggregate Dissemination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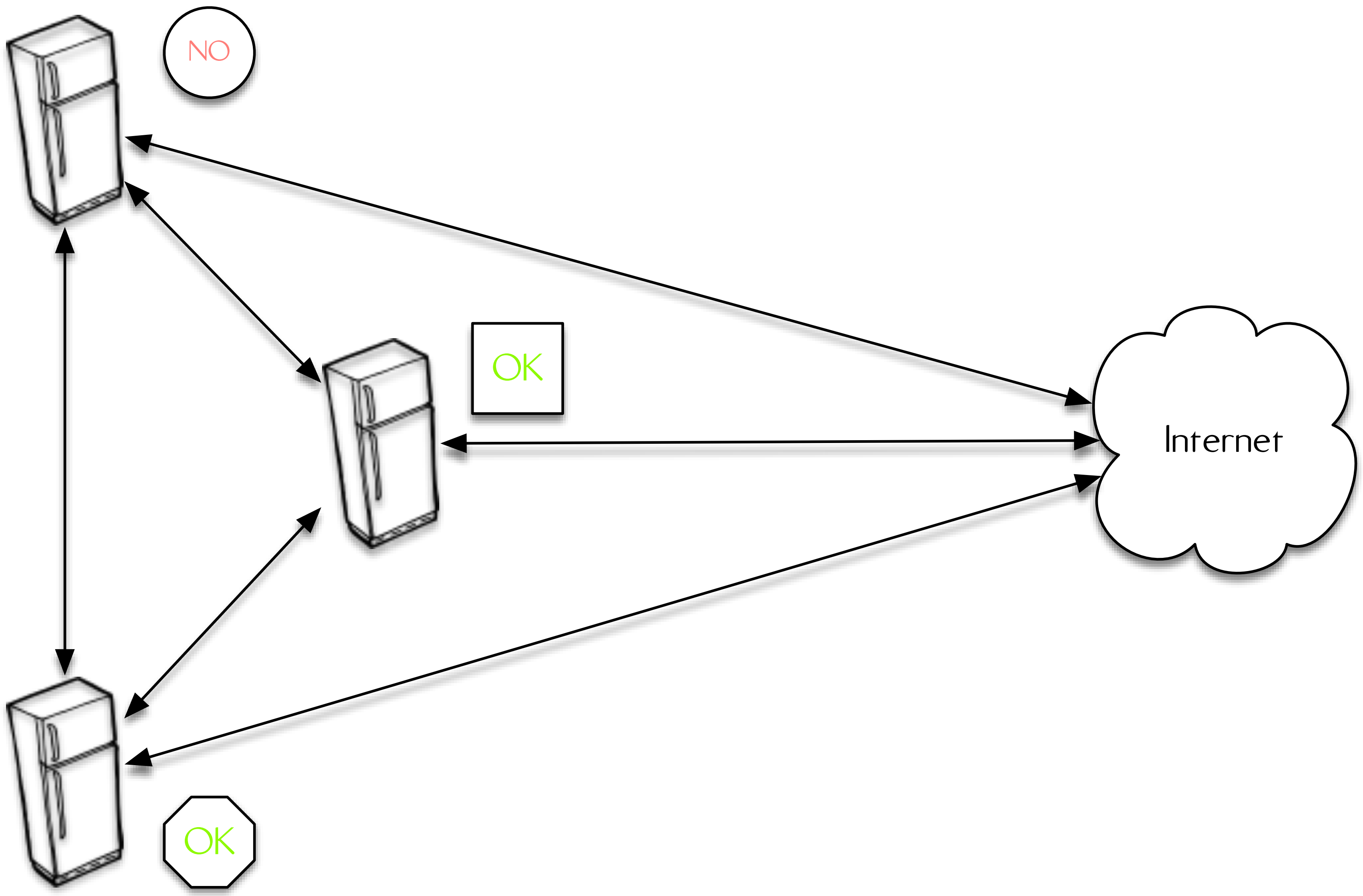
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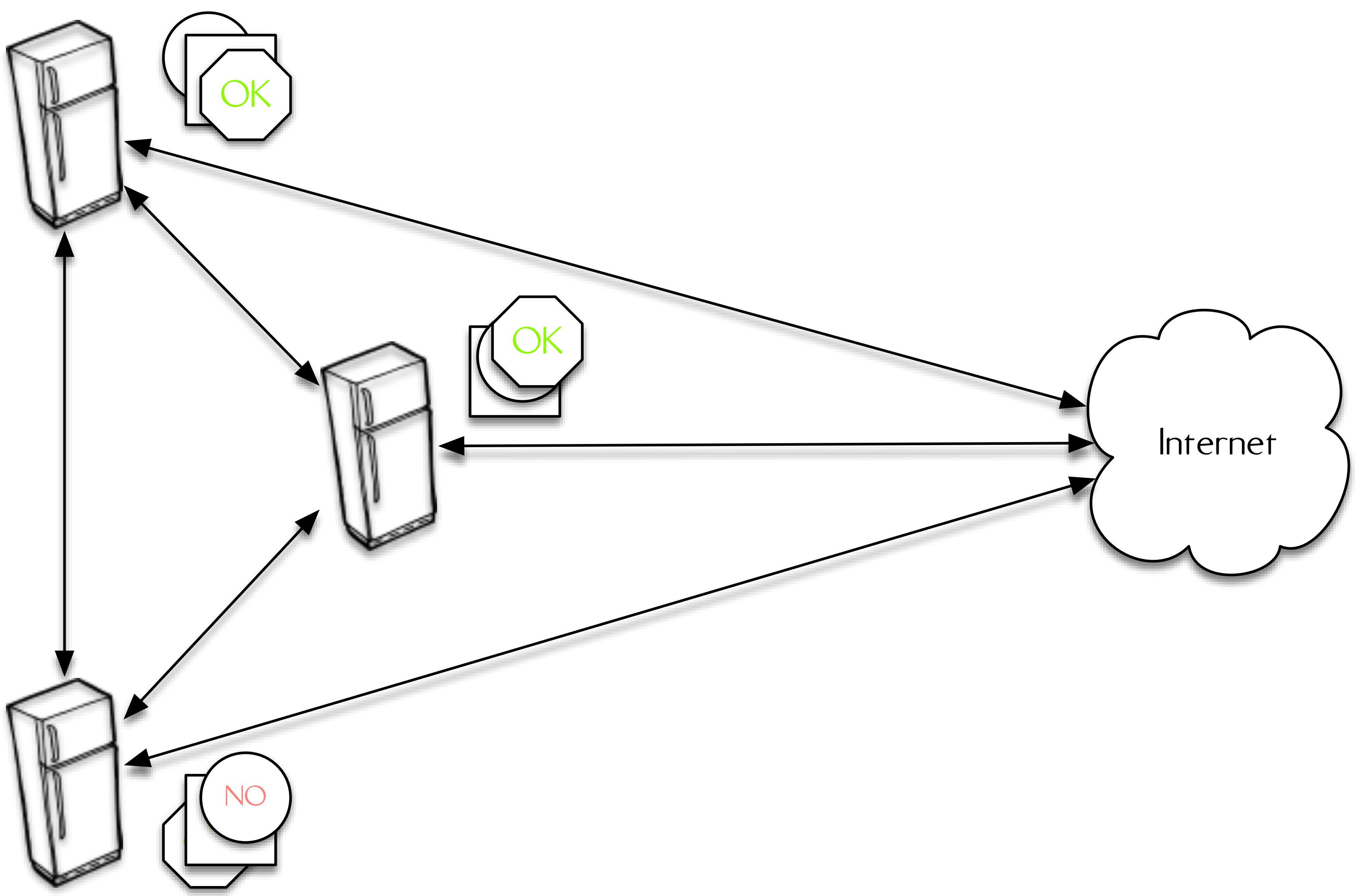

OK
OK
Internet
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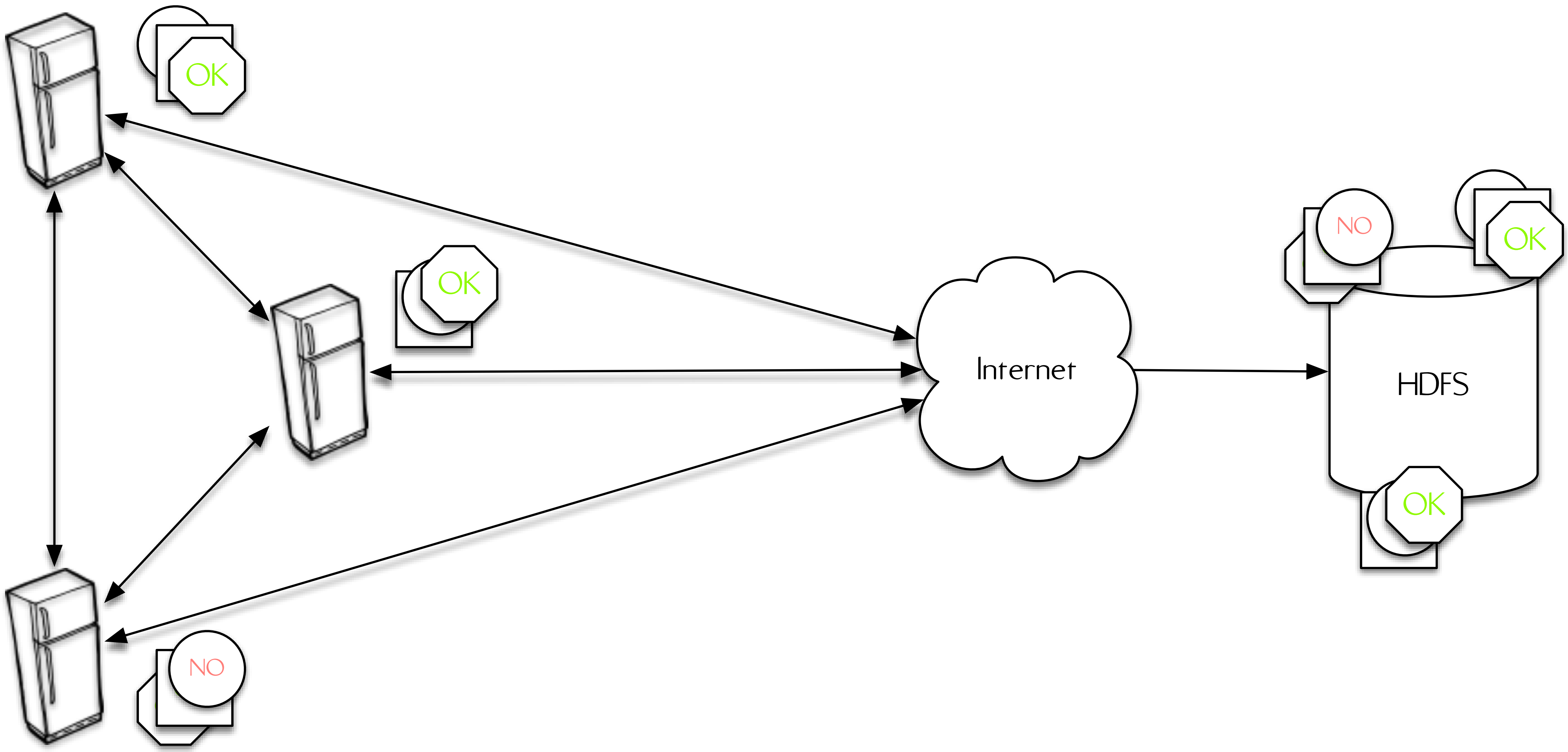
OK
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Internet
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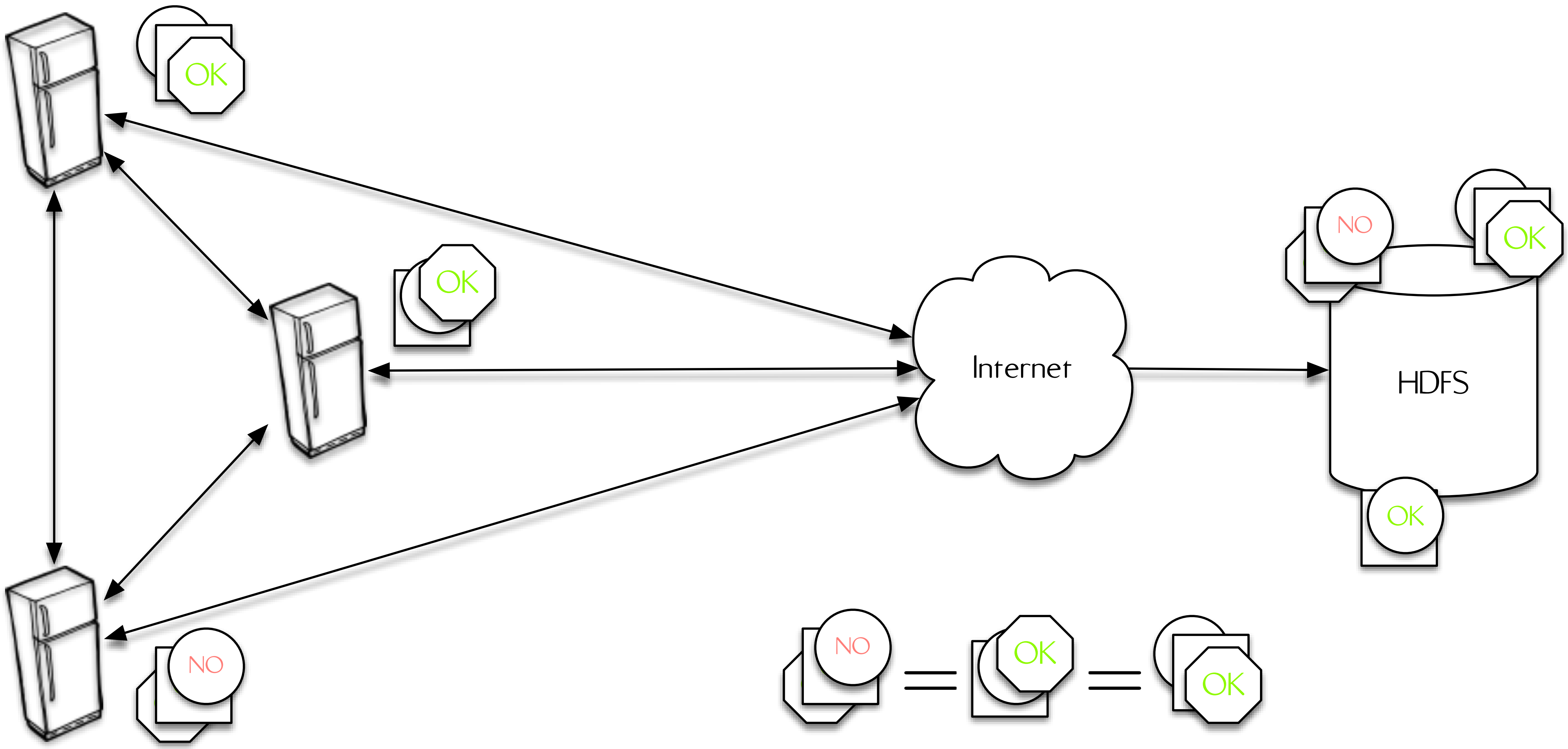
OK
HDFS
OK
NO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NO
Internet
HDFS
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OK
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OK
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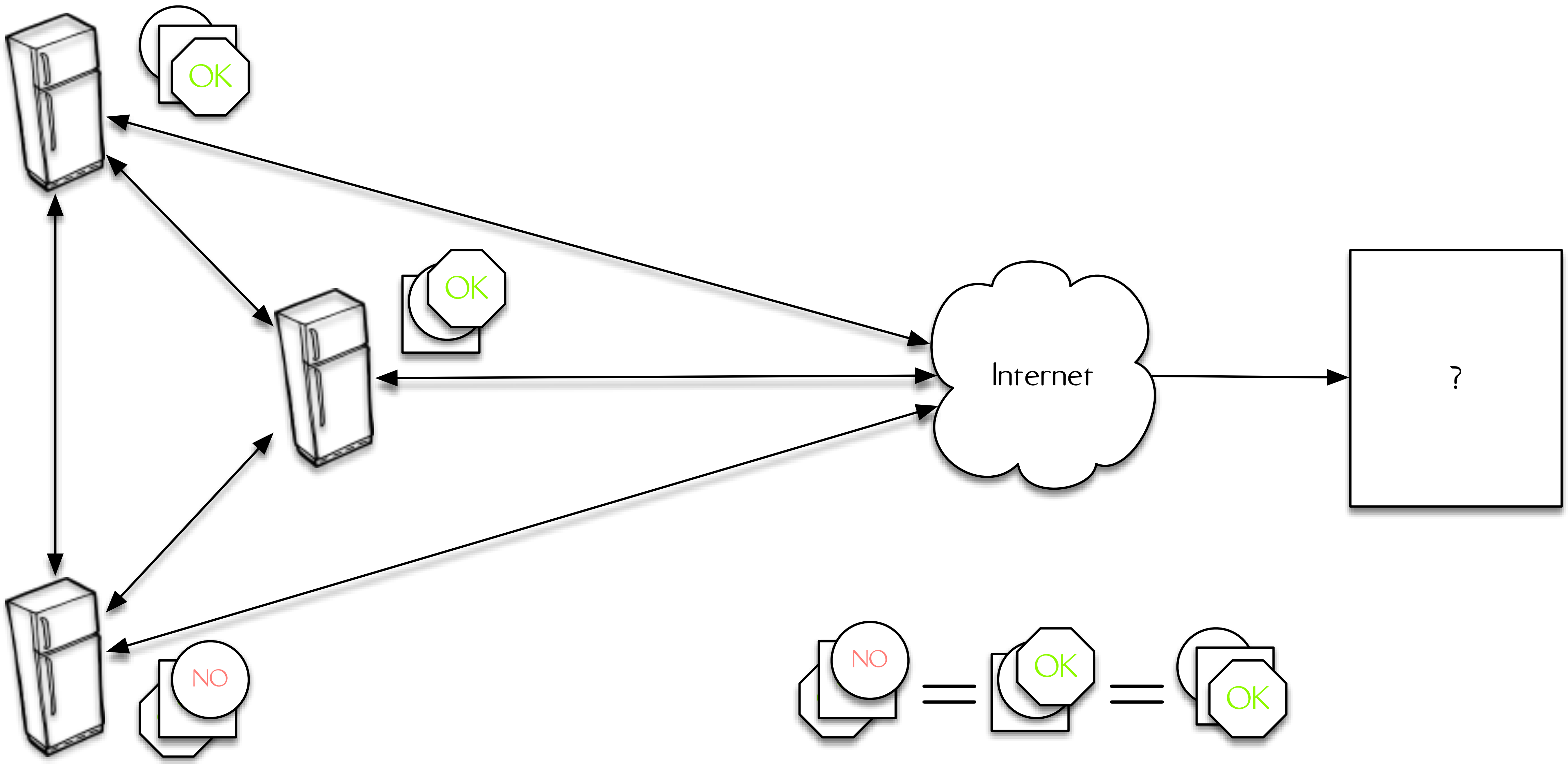
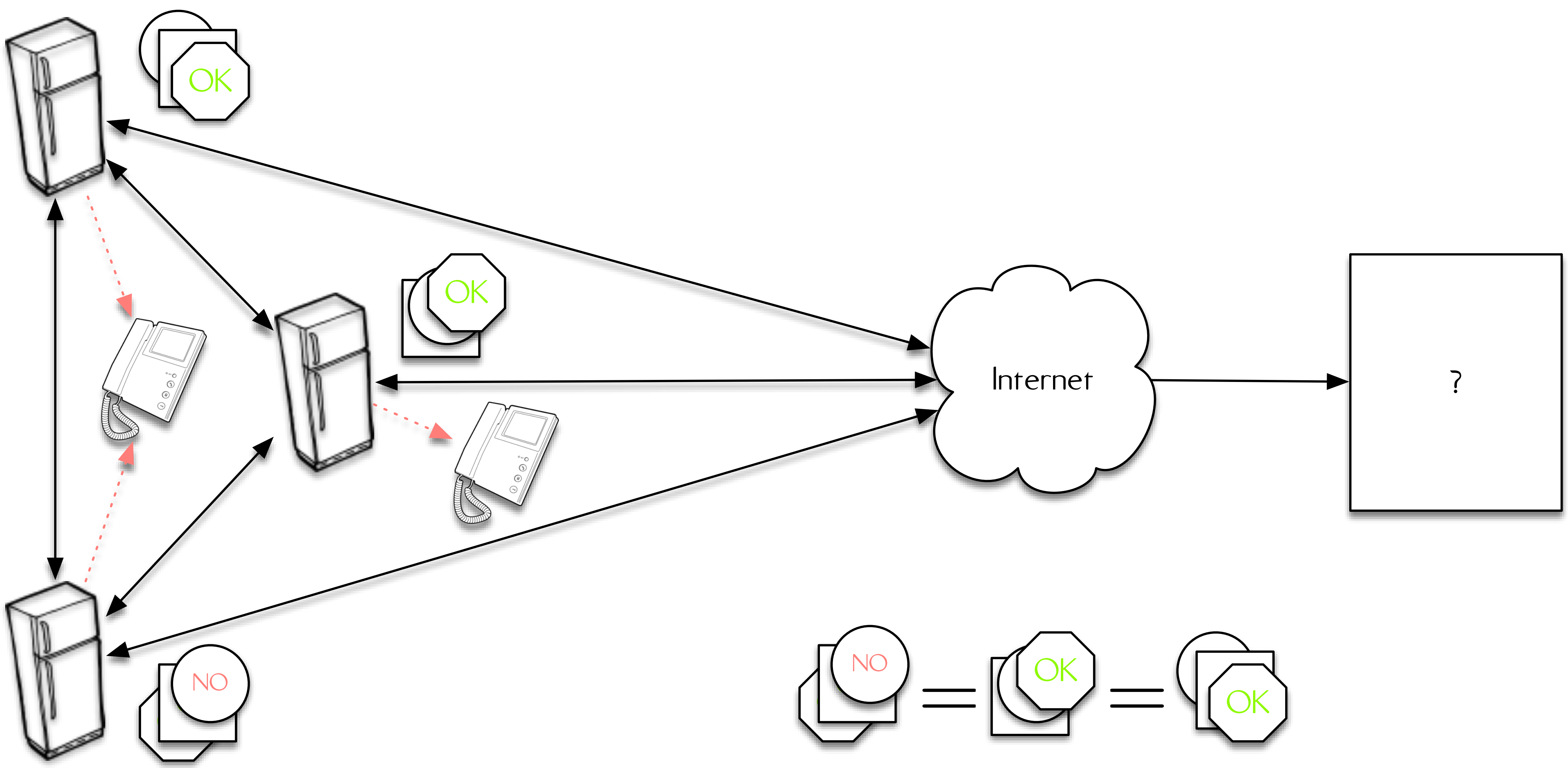

OK
OK
NO
Internet
?
NO
OK
OK


OK
OK
Internet
?
NO
NO
OK
OK

Local Computation

- **Reduce state transmission**
  Perform some local computation to reduce transmitted state on the wire

Local Computation

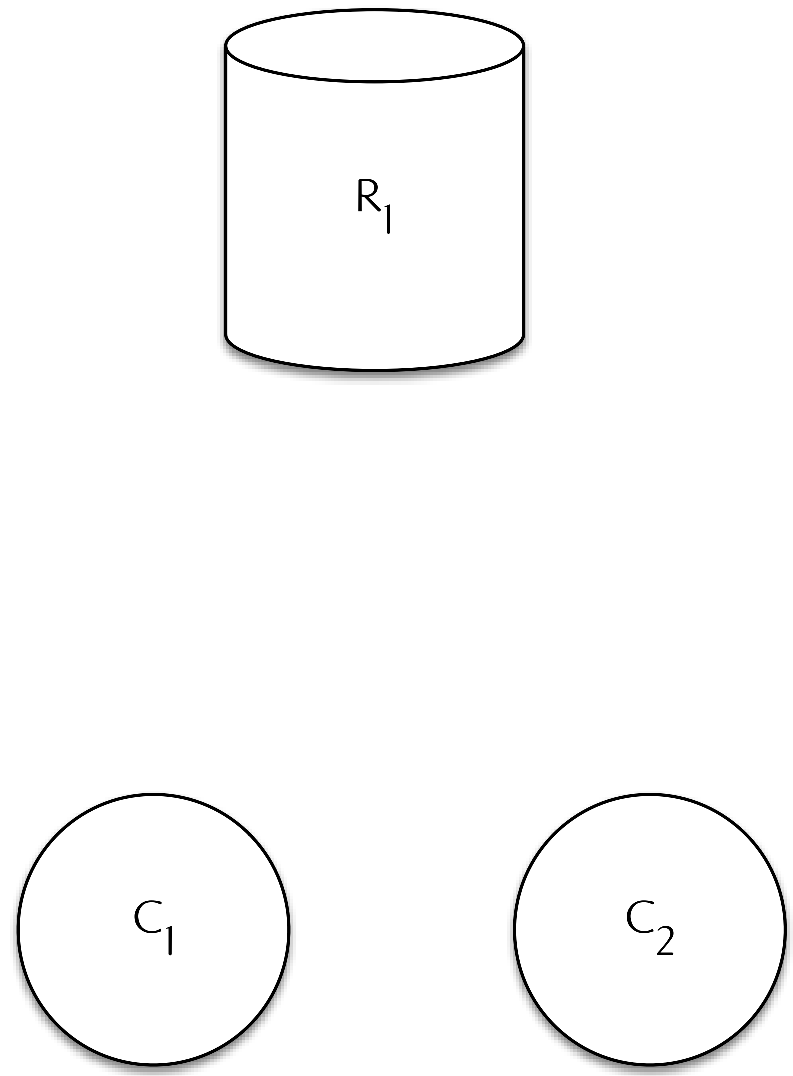
- **Reduce state transmission**
  Perform some local computation to reduce transmitted state on the wire

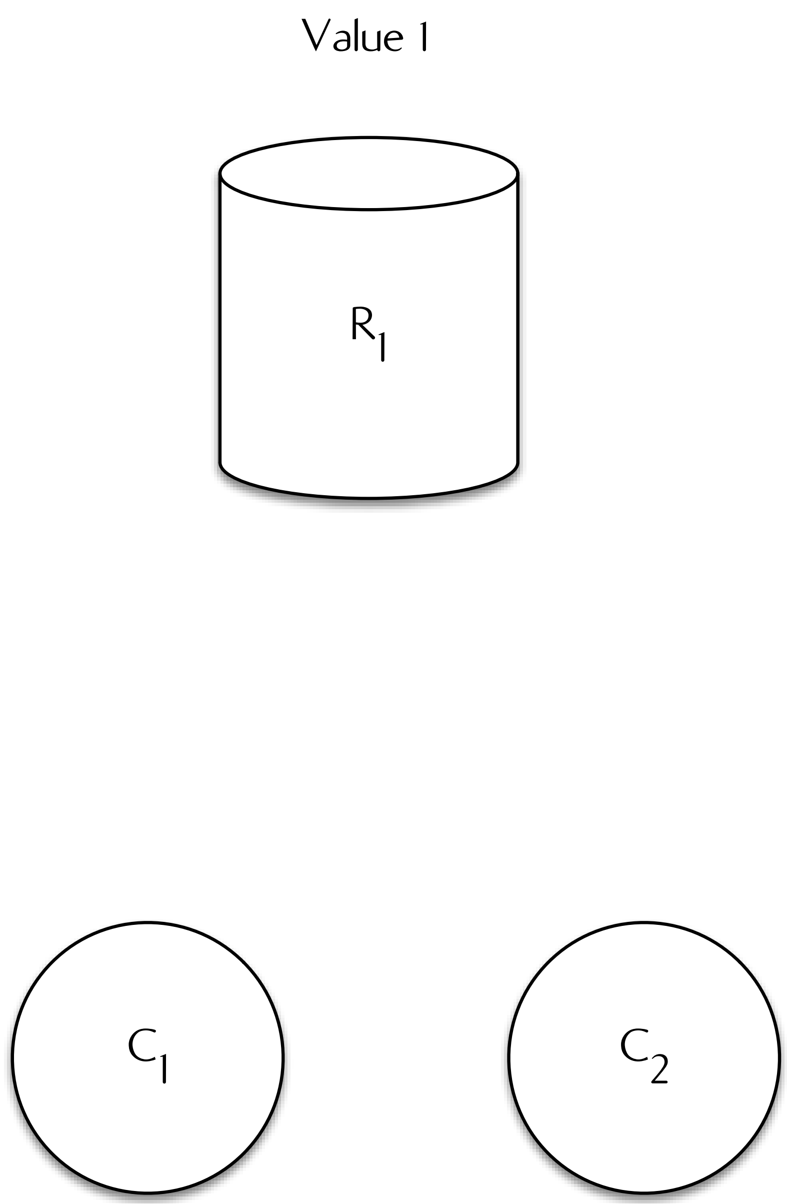
- **Make local decisions**
  Make decisions based on results of local computation

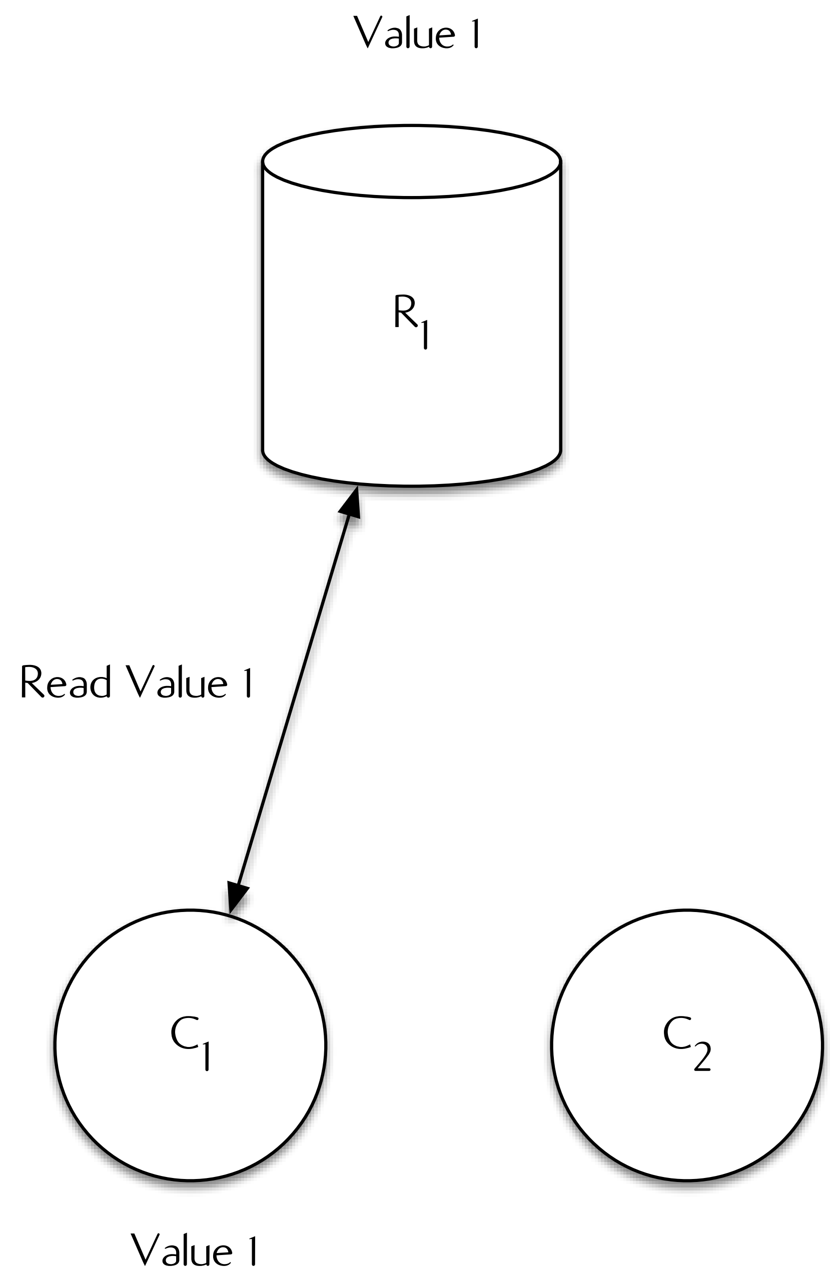
Databases

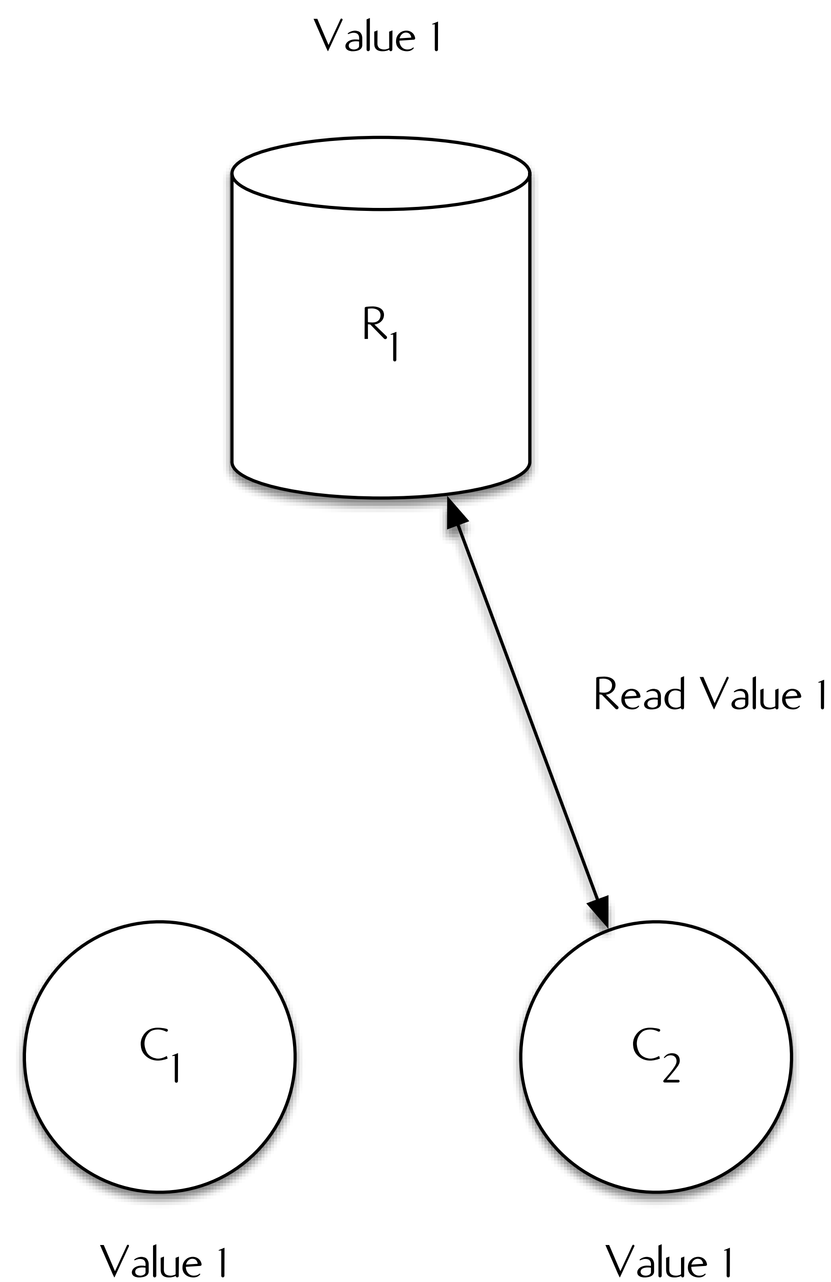
Consistency Models

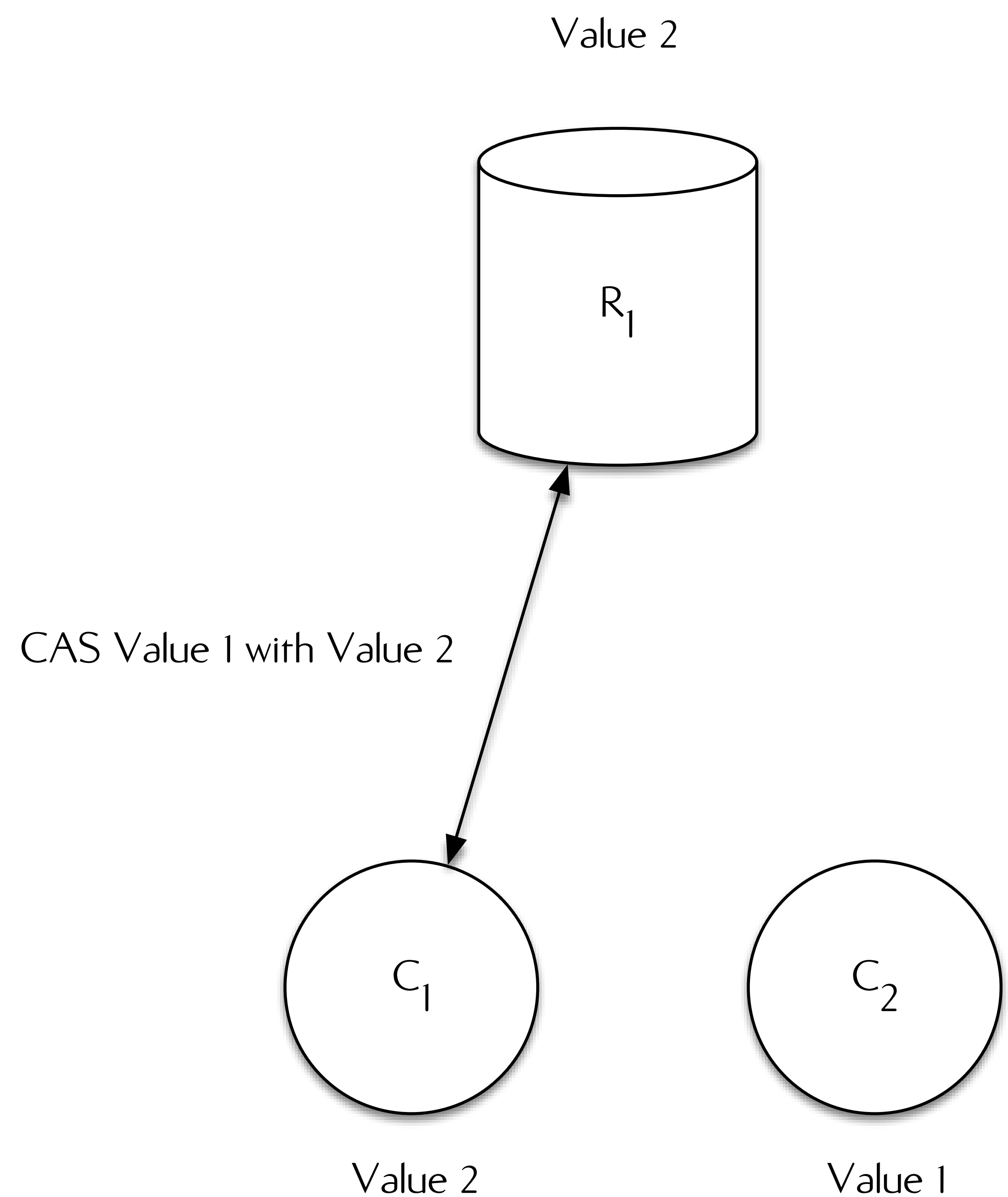
Databases
Strong Consistency

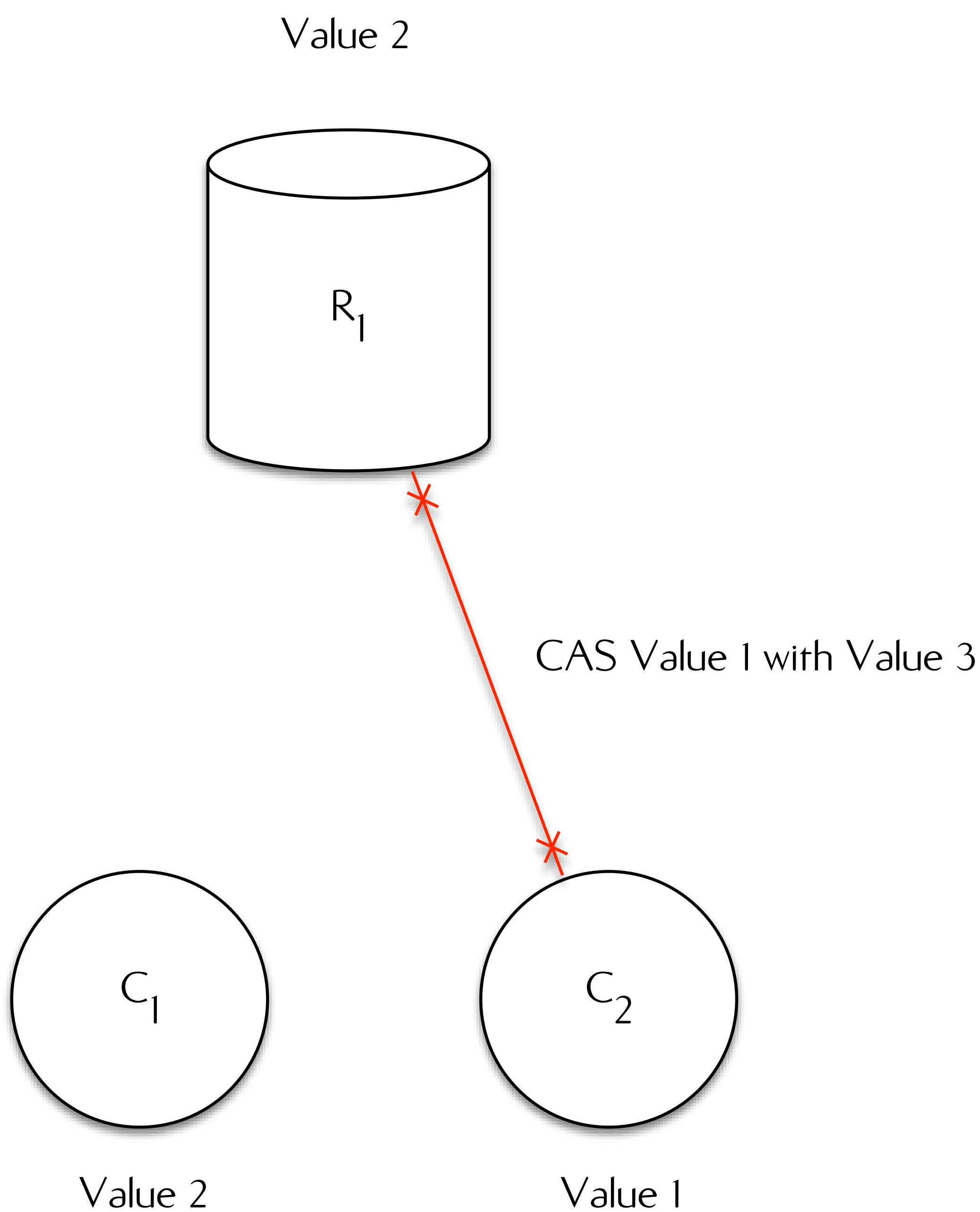

R_1
C_1
C_2


Value 1
R1
C1
C2

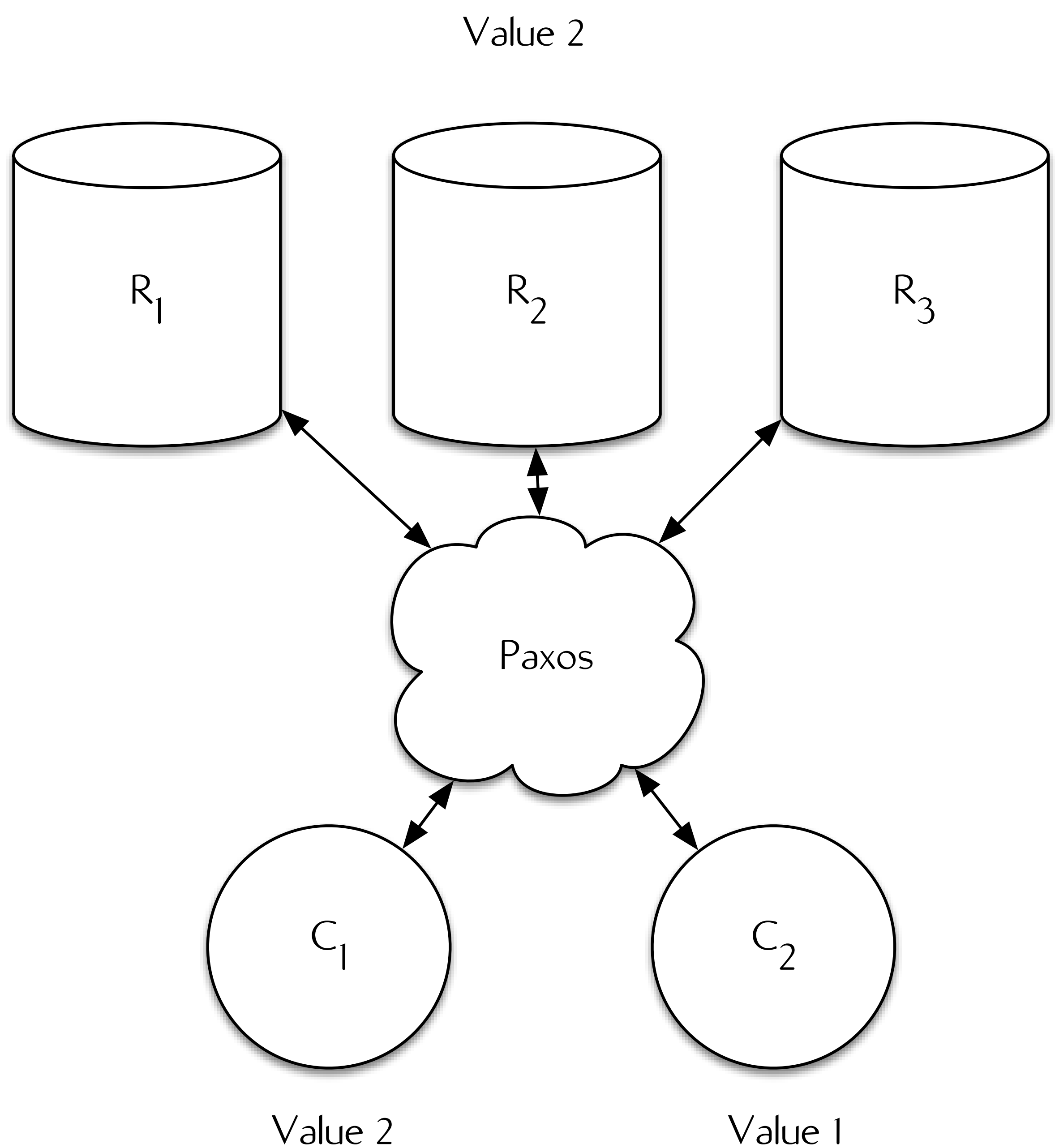

Value 1
R_1
Read Value 1
C_1
C_2
Value 1


Value 1
R1
Read Value 1
C1
C2
Value 1
Value 1

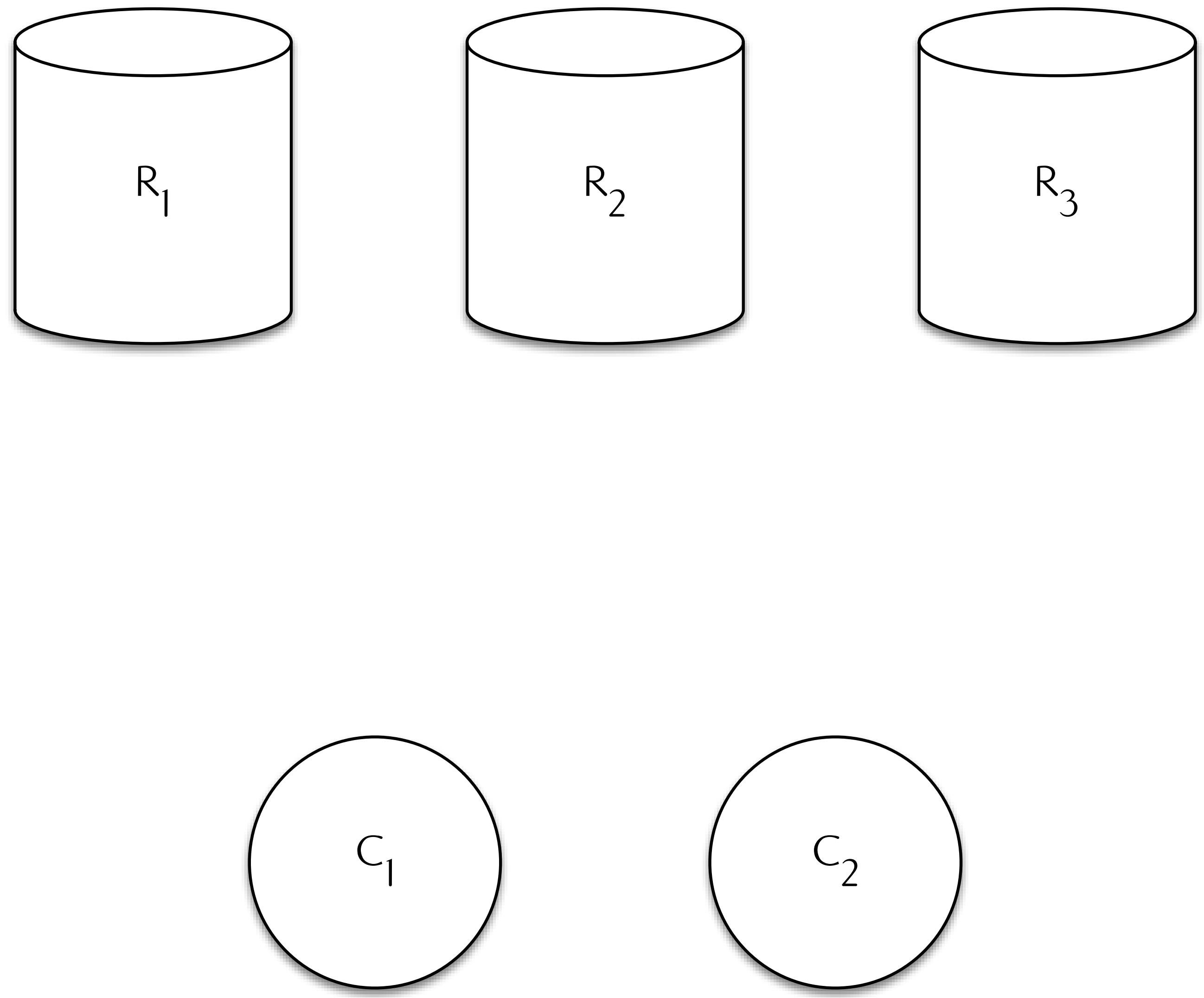

Value 2
R1
CAS Value 1 with Value 2
C1
C2
Value 2
Value 1

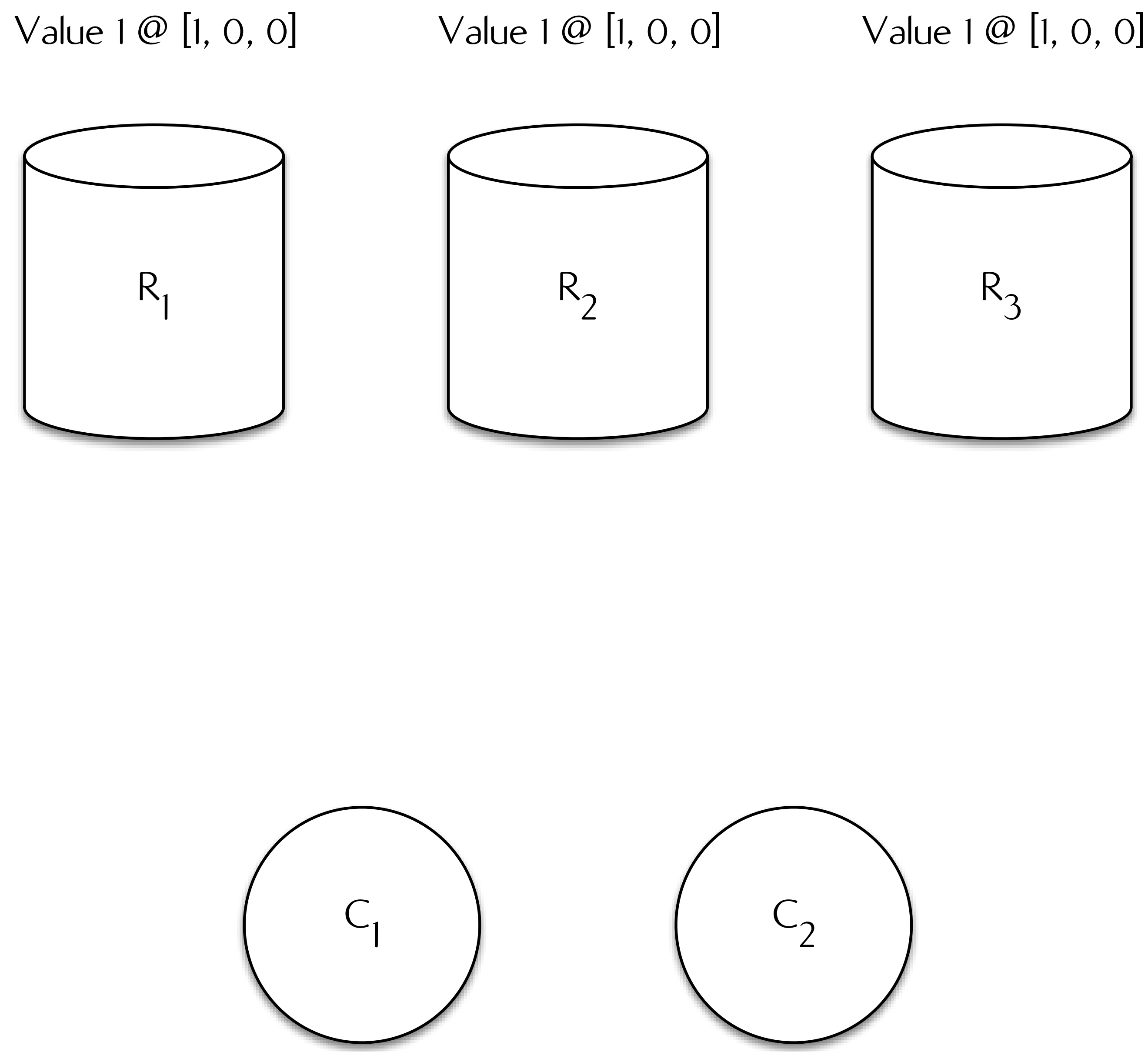

Value 2
R1
CAS Value 1 with Value 3
C1
C2
Value 2
Value 1

I won't diagram
the **Paxos** protocol


Value 2
R_1
R_2
R_3
Paxos
C_1
C_2
Value 2
Value 1

Databases
Eventual Consistency


R_1
R_2
R_3
C_1
C_2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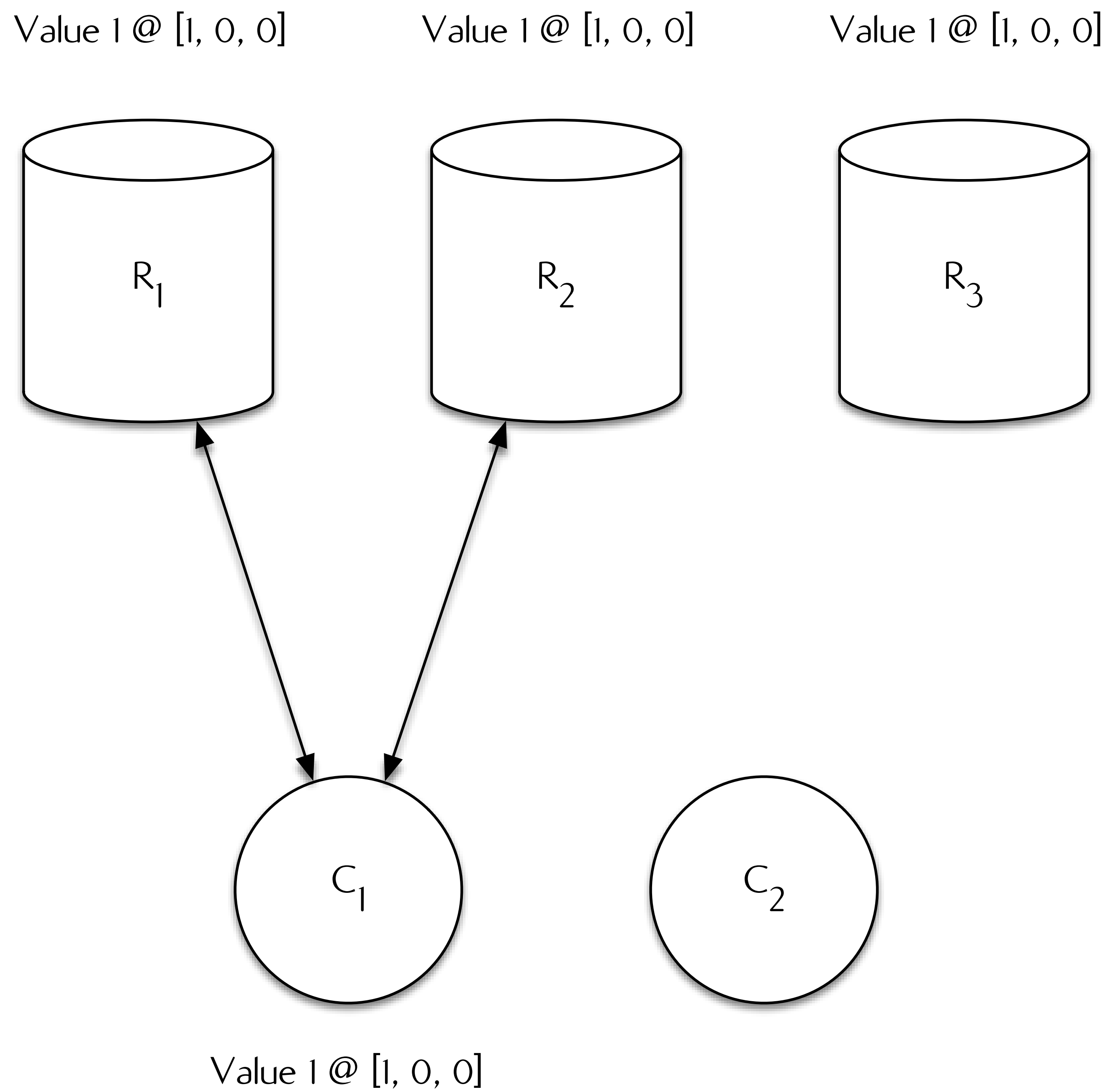
Value 1 @ [1, 0, 0]
Value 1 @ [1, 0, 0]
R1
R2
R3
C1
C2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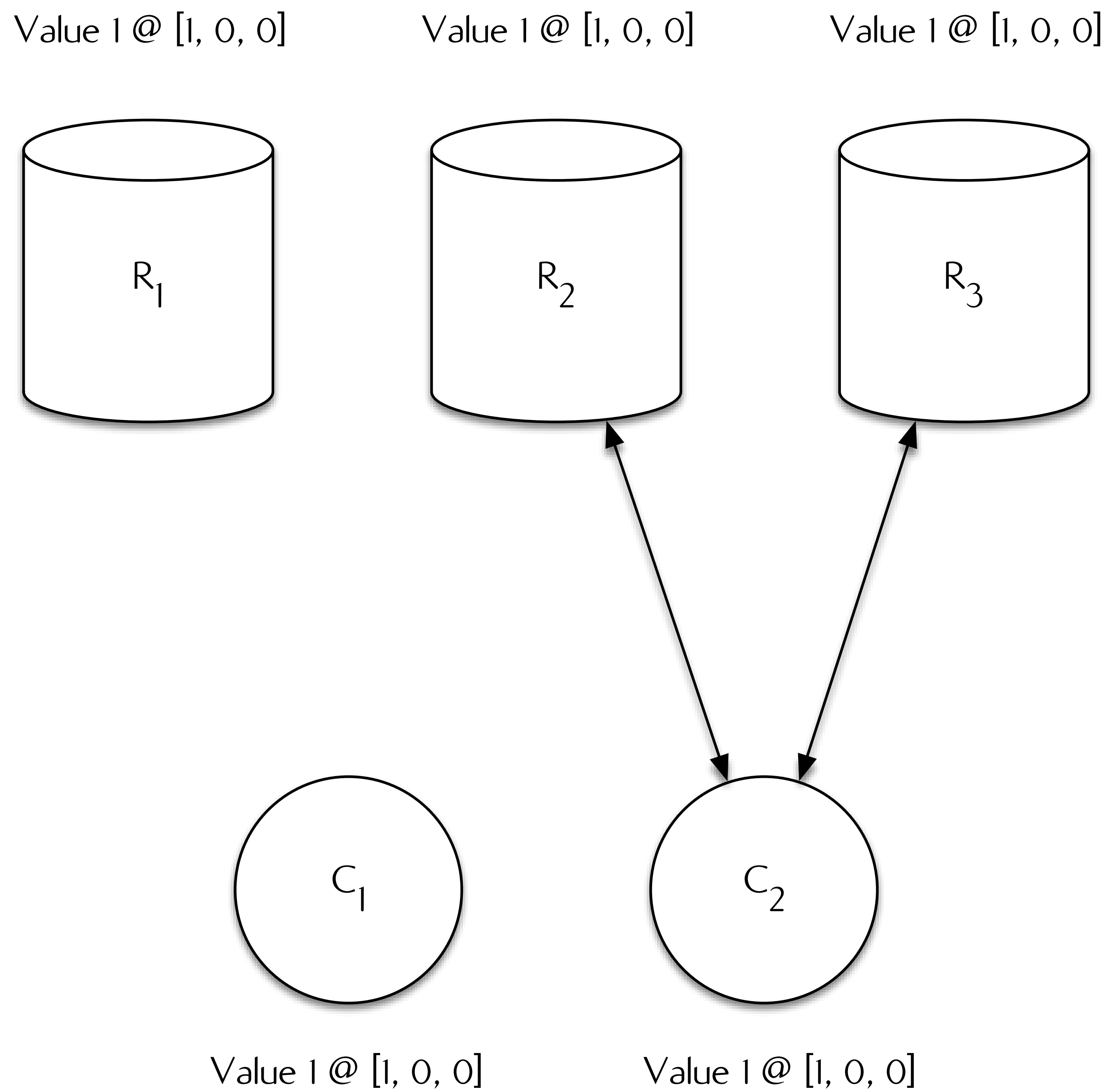
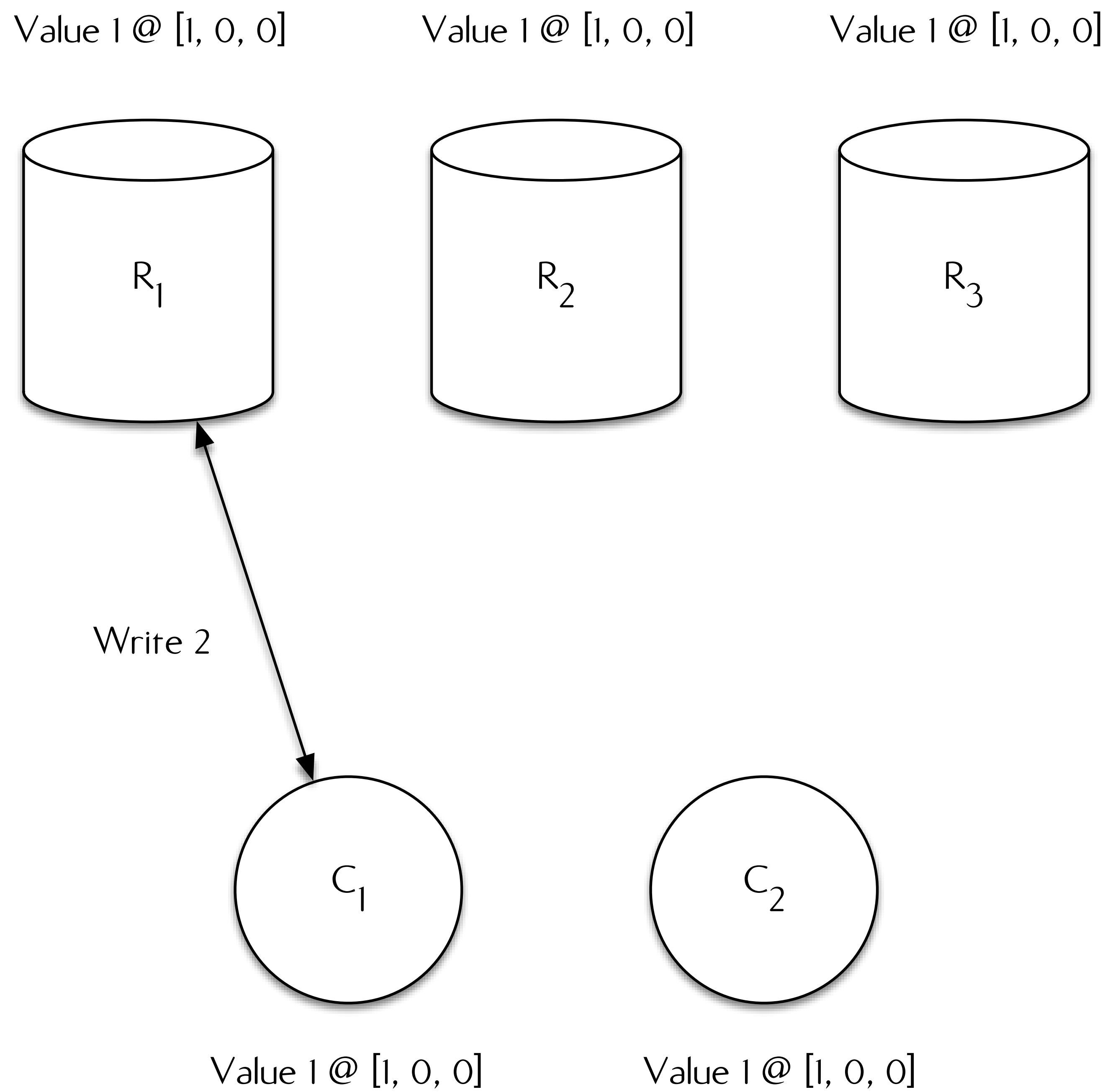
Value 1 @ [1, 0, 0]
Value 1 @ [1, 0, 0]
R1
R2
R3
C1
C2
Value 1 @ [1, 0, 0]


Value 1 @ [1, 0, 0]
Value 1 @ [1, 0, 0]
Value 1 @ [1, 0, 0]
R1
R2
R3
C1
C2
Value 1 @ [1, 0, 0]
Value 1 @ [1, 0, 0]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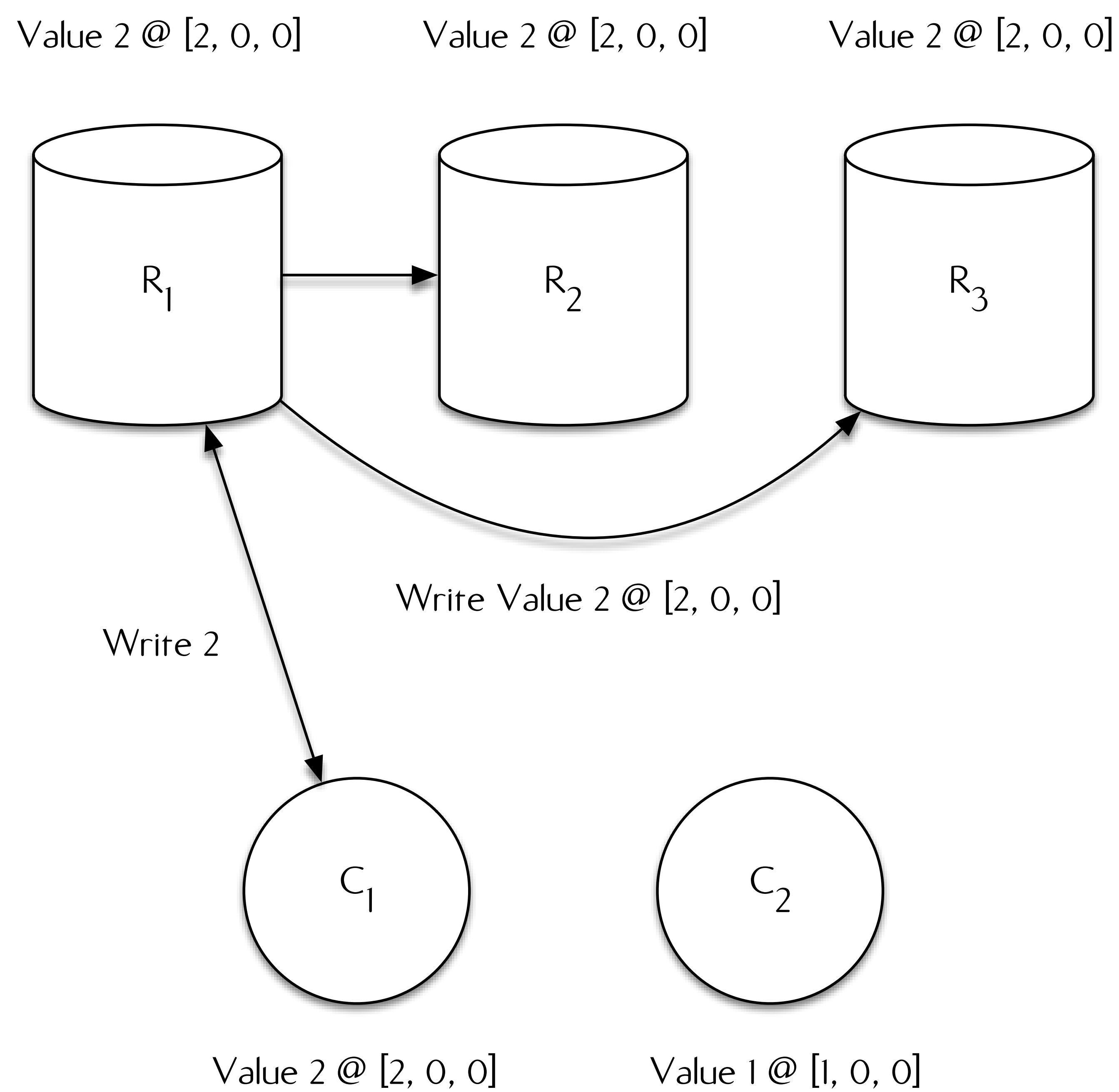
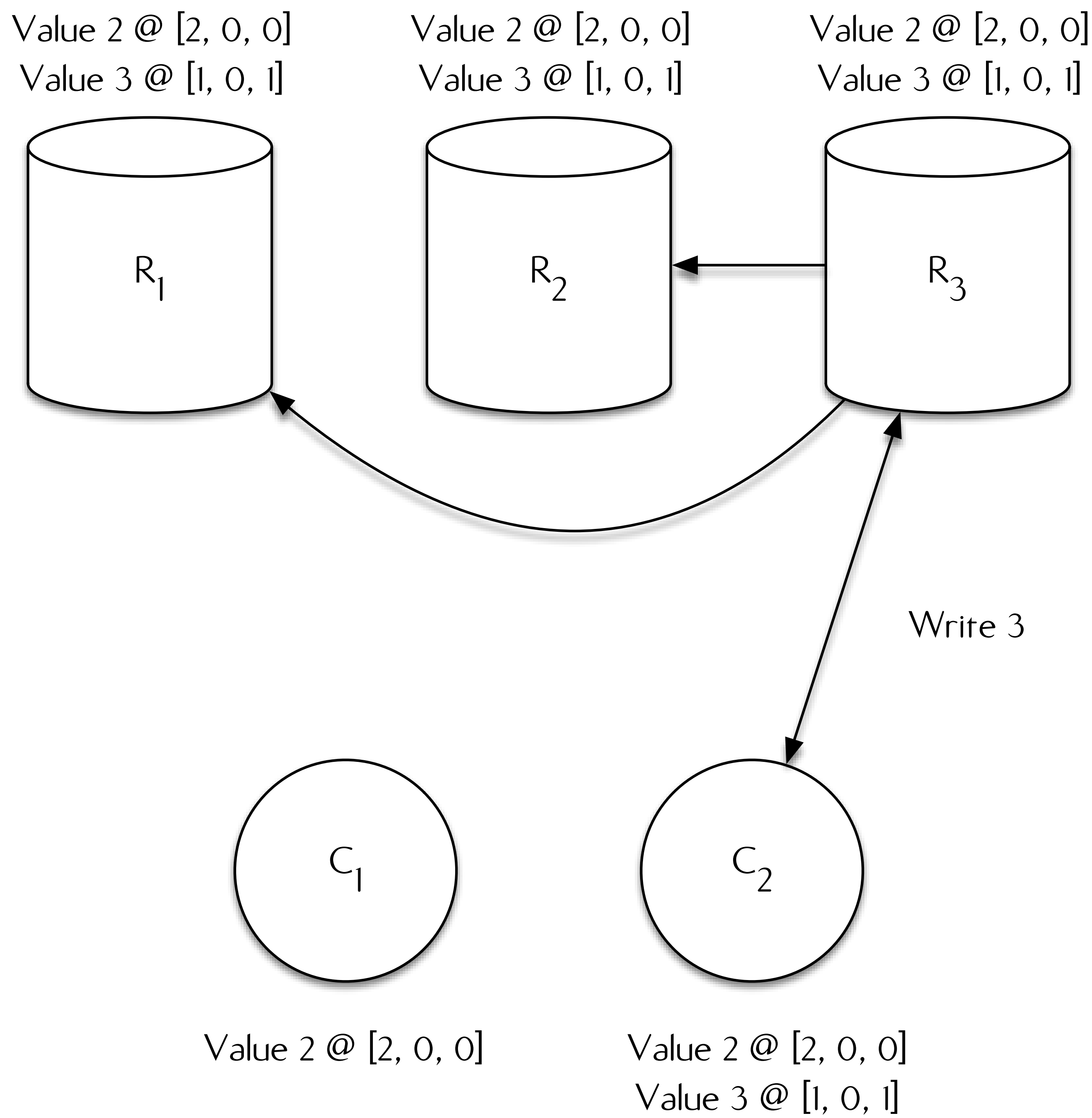
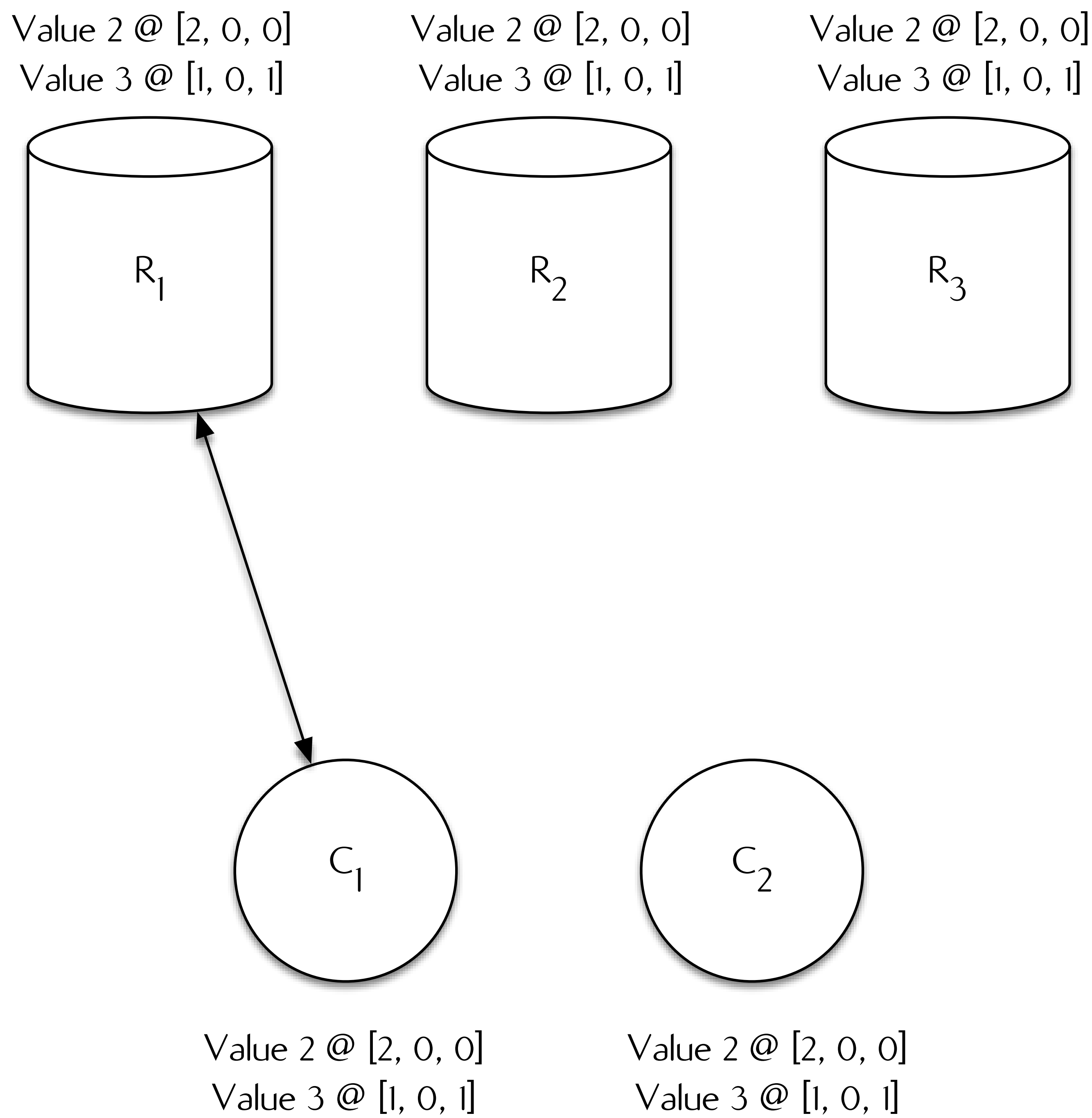
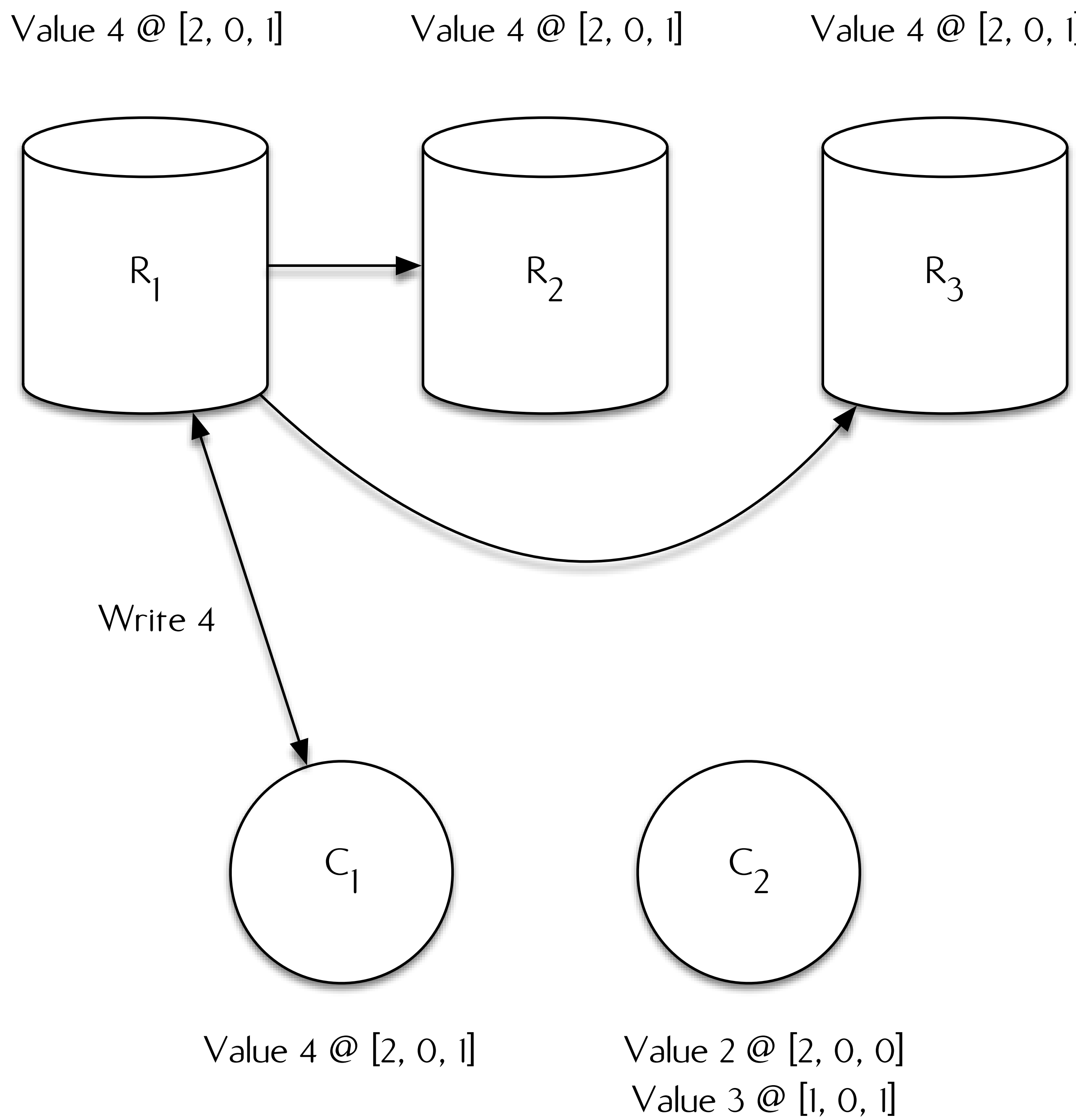
Value 1 @ [1, 0, 0]
Value 1 @ [1, 0, 0]
R1
R2
R3
Write 2
C1
C2
Value 1 @ [1, 0, 0]
Value 1 @ [1, 0, 0]


Value 2 @ [2, 0, 0]
Value 2 @ [2, 0, 0]
Value 2 @ [2, 0, 0]
R1
R2
R3
Write Value 2 @ [2, 0, 0]
Write 2
C1
C2
Value 2 @ [2, 0, 0]
Value 1 @ [1, 0, 0]



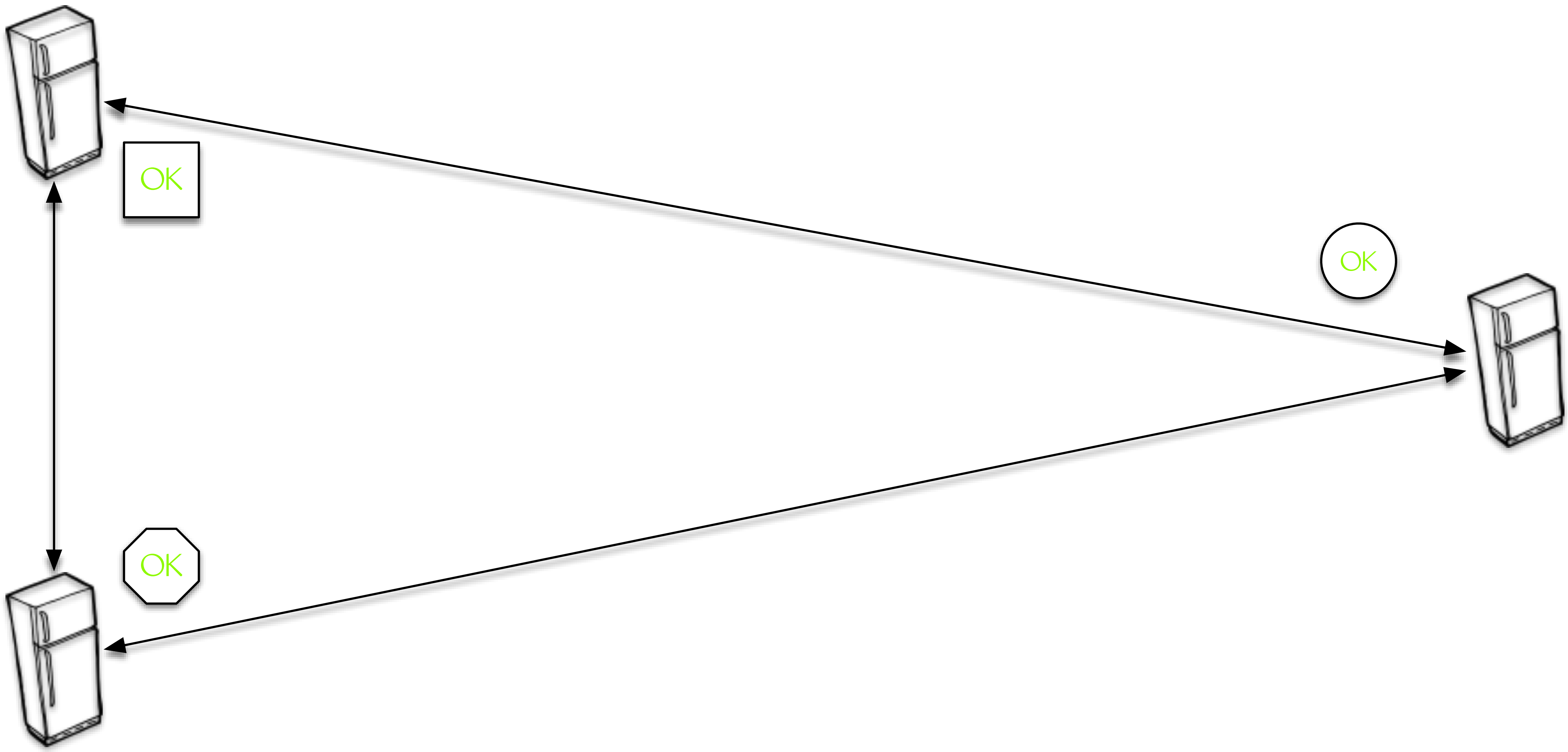
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]
R1
R2
R3
Write 3
C1
C2
Value 2 @ [2, 0, 0]
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]

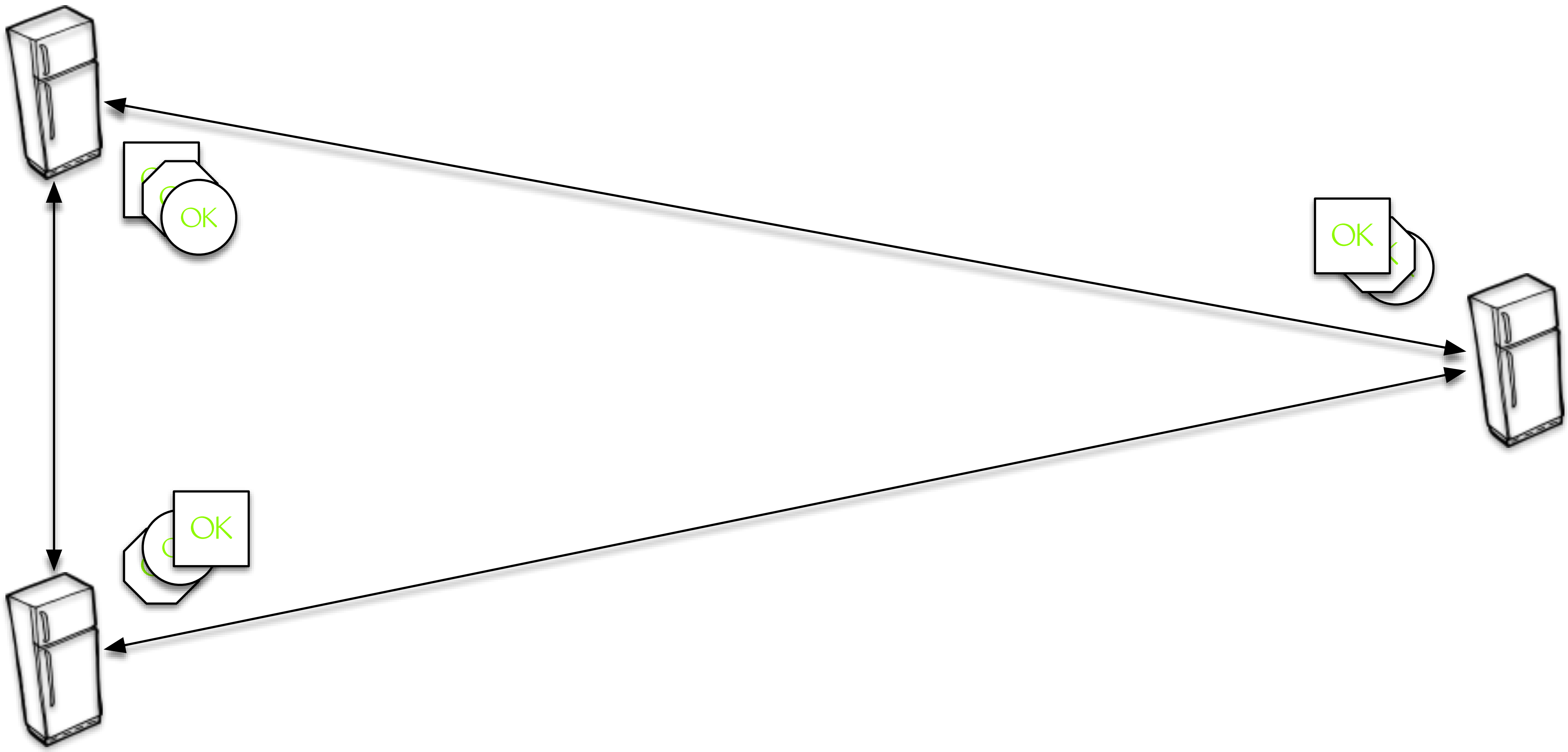

Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]
R1
R2
R3
C1
C2
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]

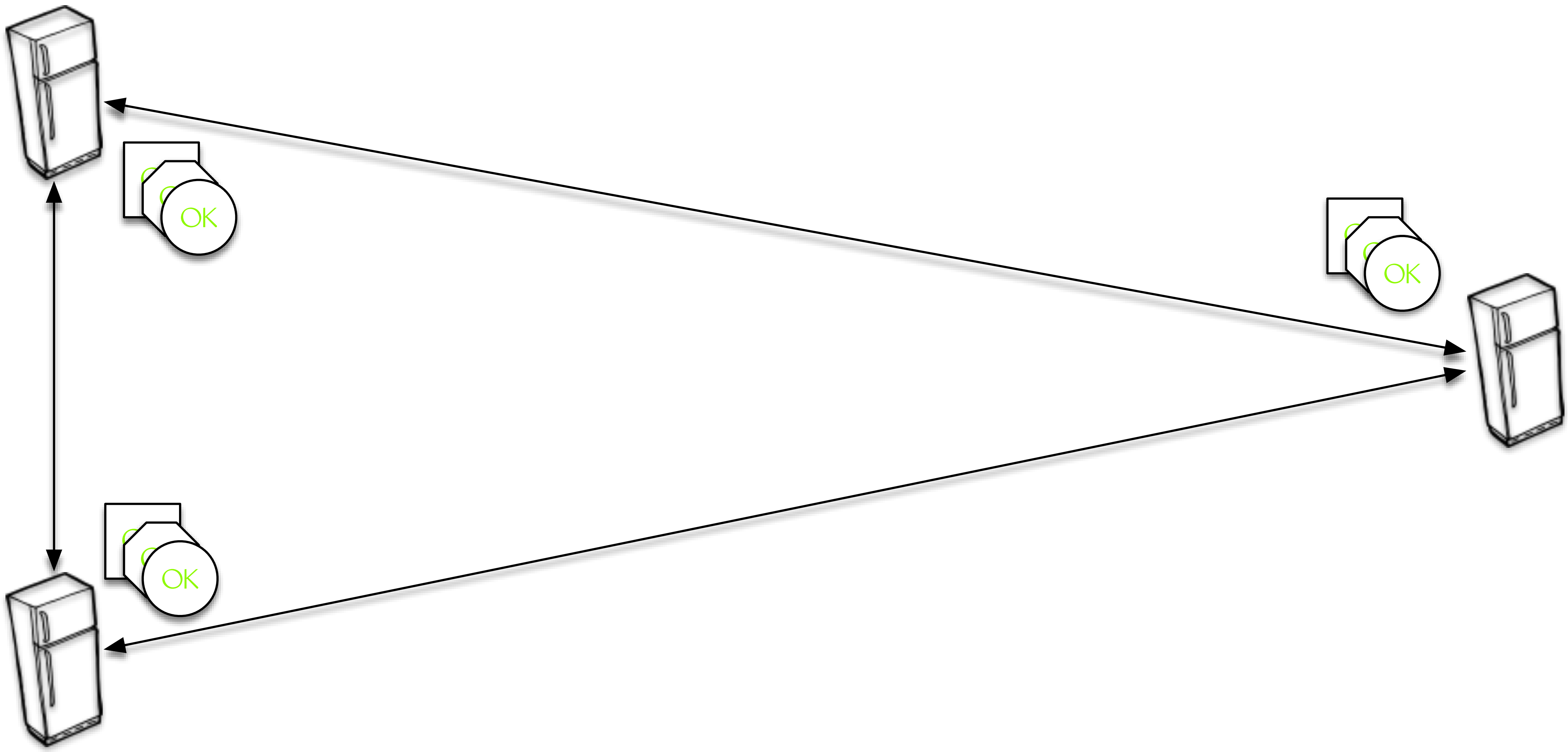

Value 4 @ [2, 0, 1]
Value 4 @ [2, 0, 1]
Value 4 @ [2, 0, 1]
R1
R2
R3
Write 4
C1
C2
Value 4 @ [2, 0, 1]
Value 2 @ [2, 0, 0]
Value 3 @ [1, 0, 1]

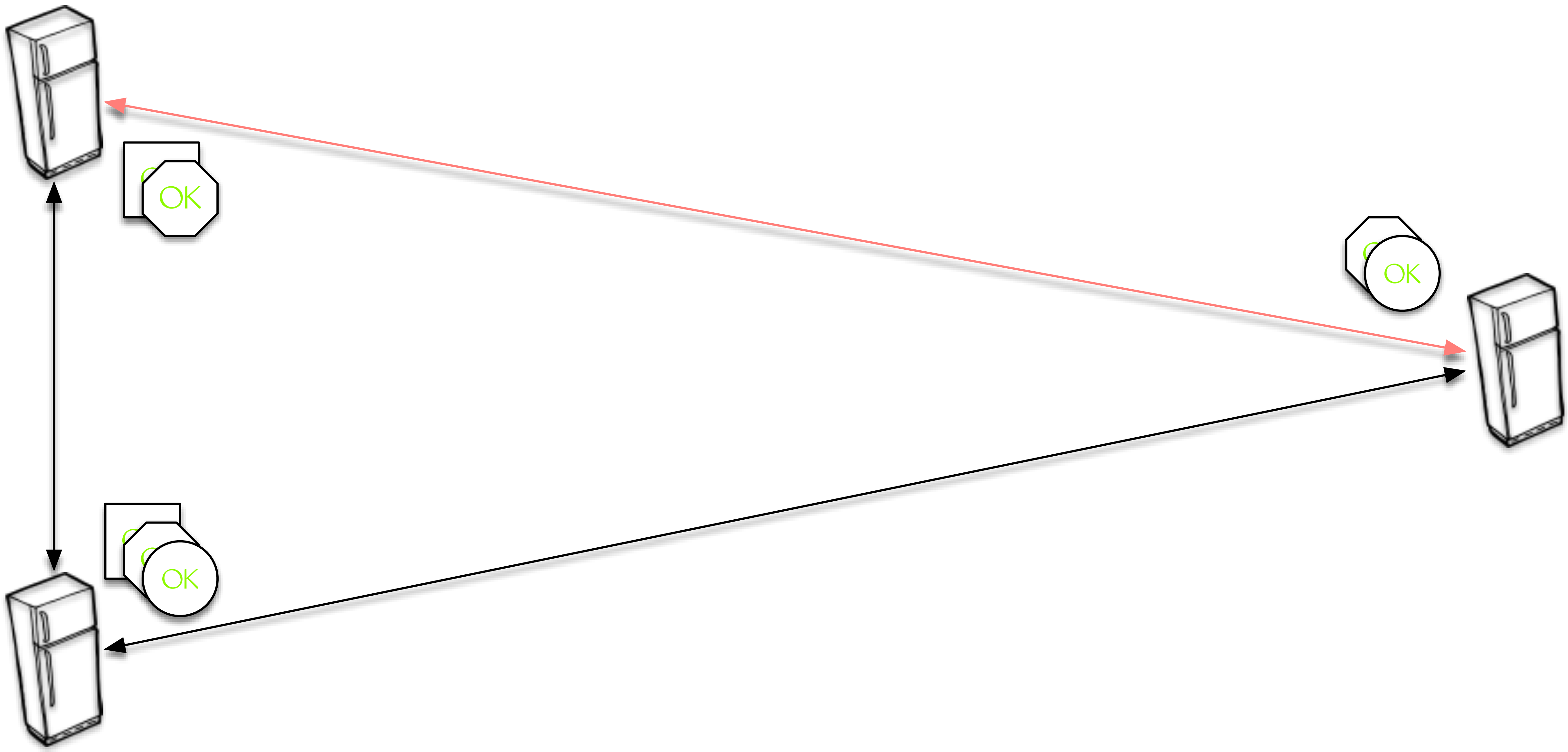
Eventual Consistency
As The Model

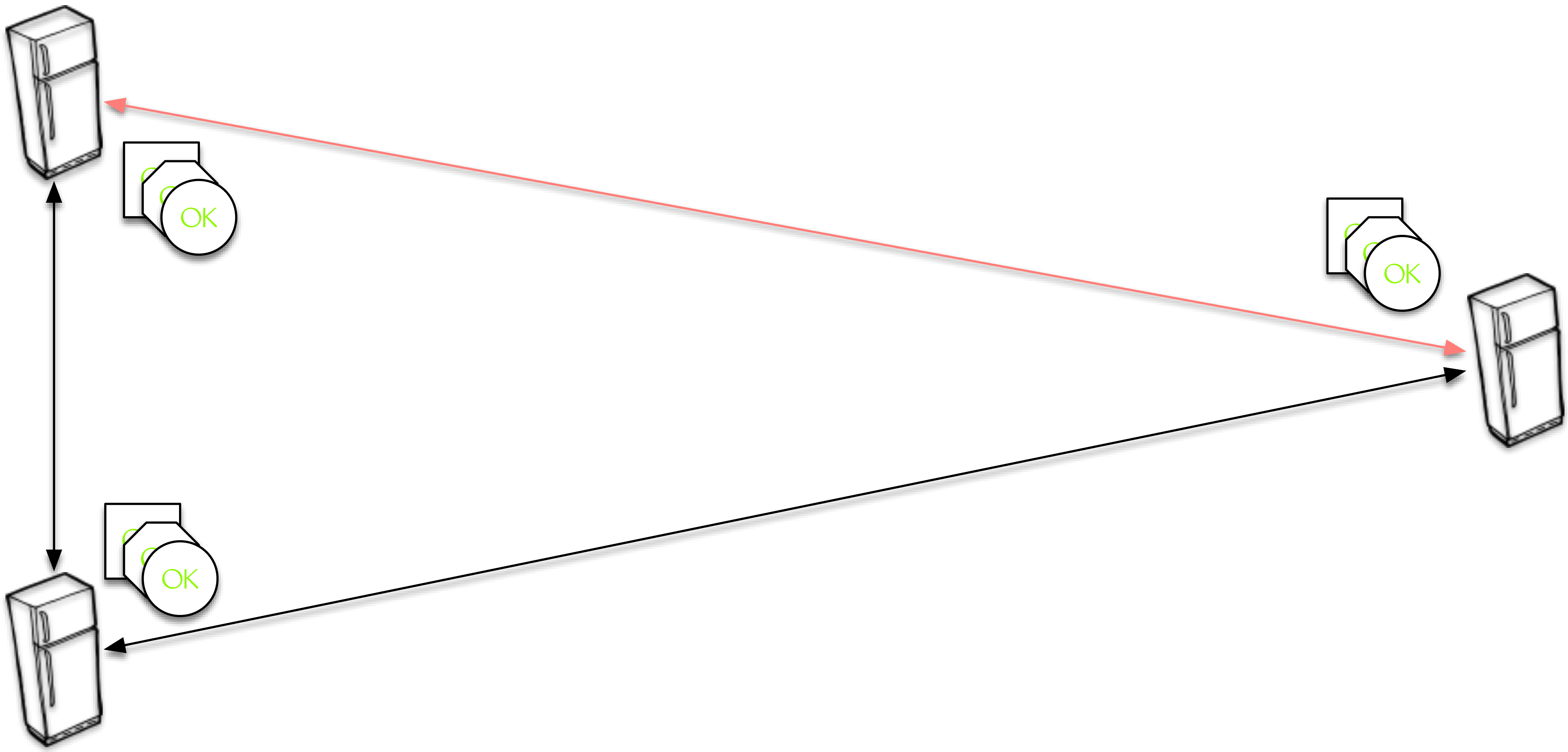
Clients
Own Their Data


OK
OK
OK

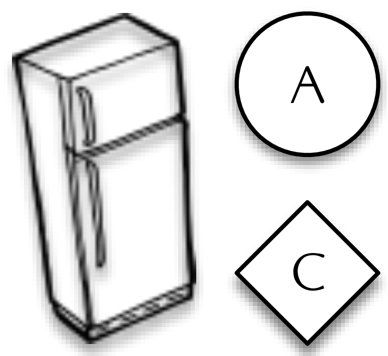

OK
OK
OK

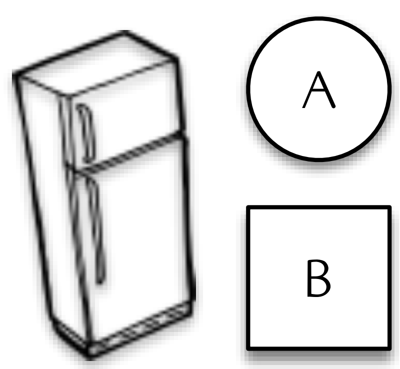

OK
OK
OK

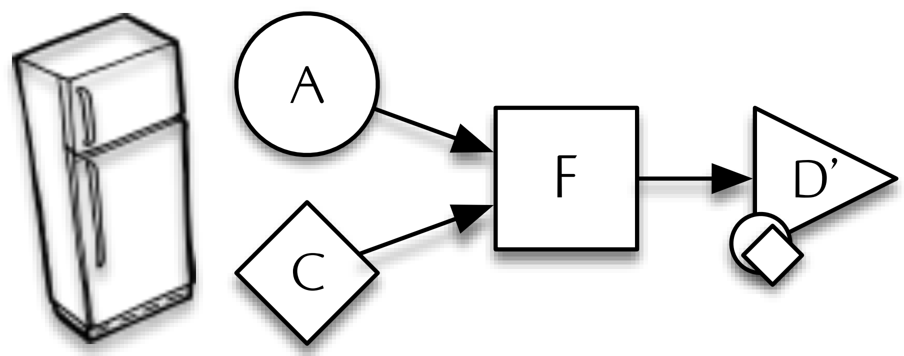

OK
OK
OK

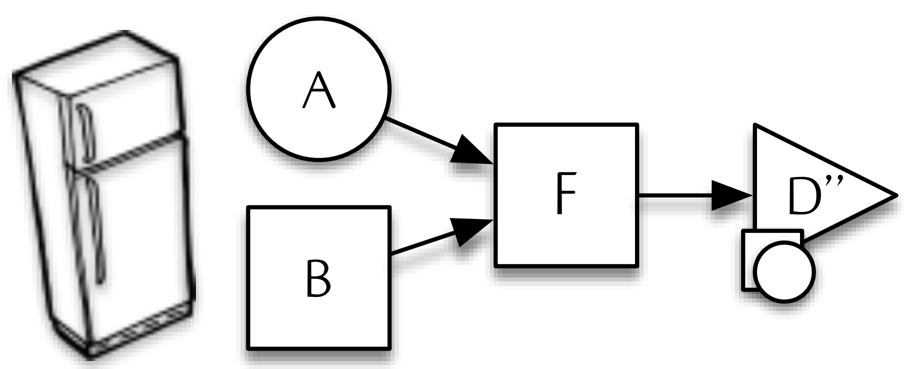

OK
OK
OK

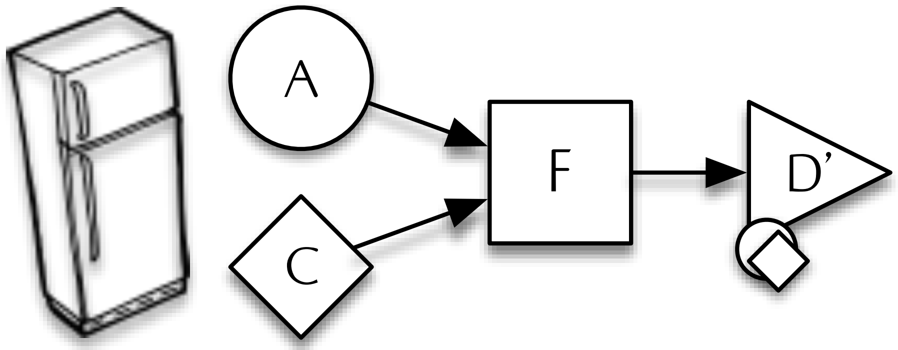
Computations
Mergability & Provenance

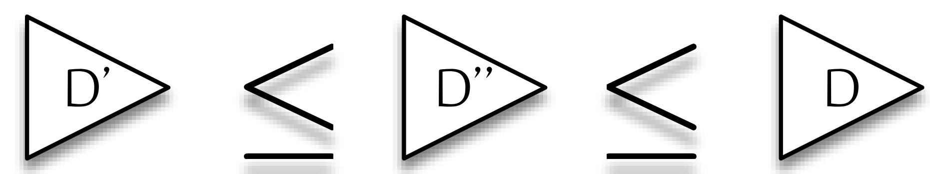

A
C

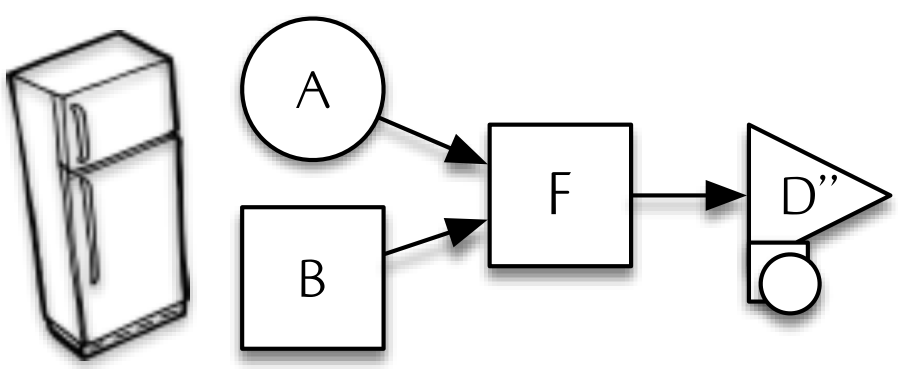

A
B

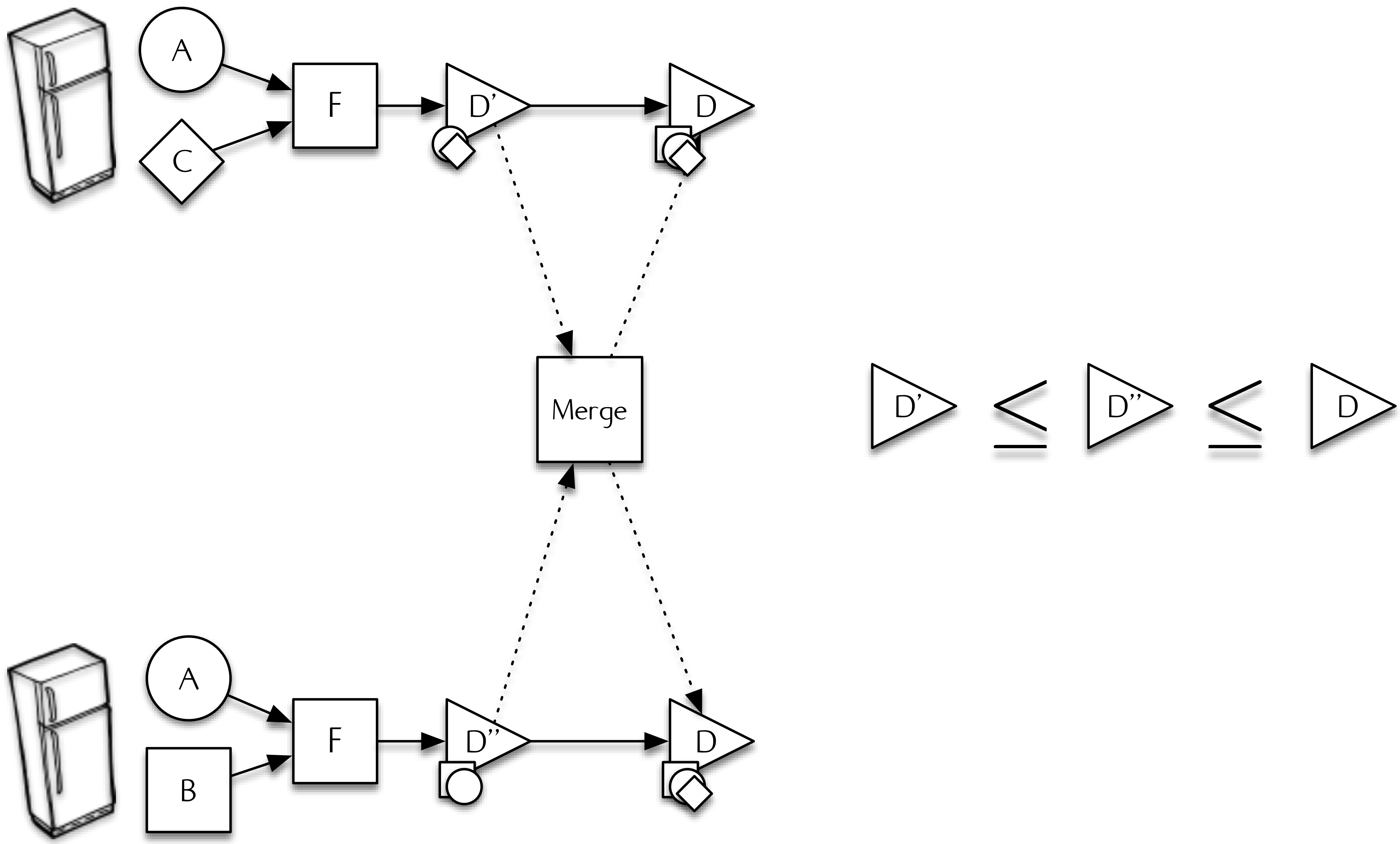

A
C
F
D’


A
B
F
D’’


A
C
F
D’


D’
≤
D’’
≤
D


A
B
F
D’’


A
C
F
D'
D
Merge
A
B
F
D''
D
D' ≤ D'' ≤ D

Example Application

Preliminary Results

Preliminary Results

- Conflict-Free Replicated Data Types
  Distributed data structures designed for convergence
  [Shapiro *et al.*, 2011]

Preliminary Results

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  Make decisions based on results of local computation
  [Meiklejohn & Van Roy, 2015]

Preliminary Results

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  Make decisions based on results of local computation
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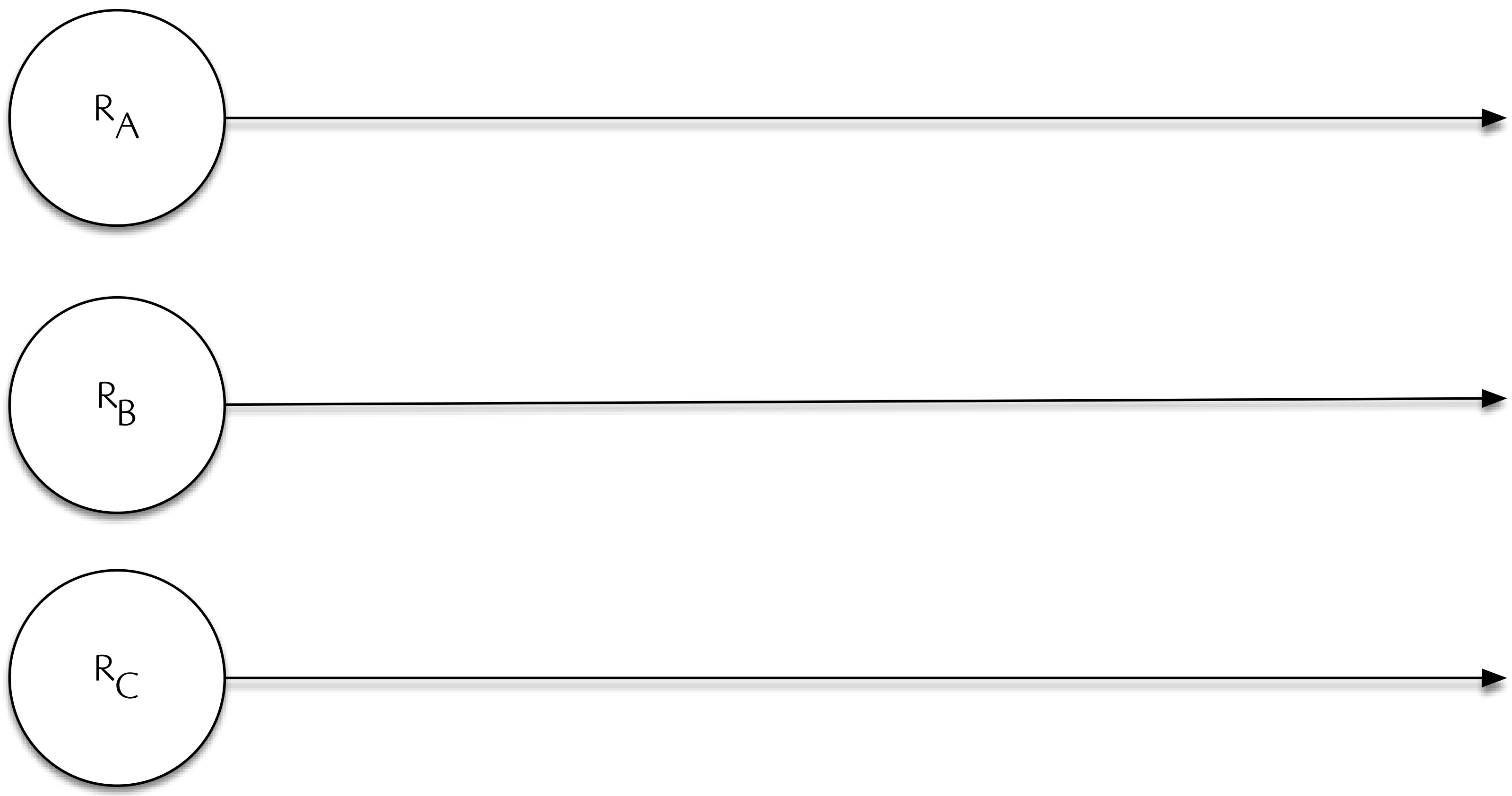
- Selective Hearing
  Epidemic broadcast based runtime system
  [Meiklejohn & Van Roy, 2015/2016]

Conflict-Free
Replicated Data Types

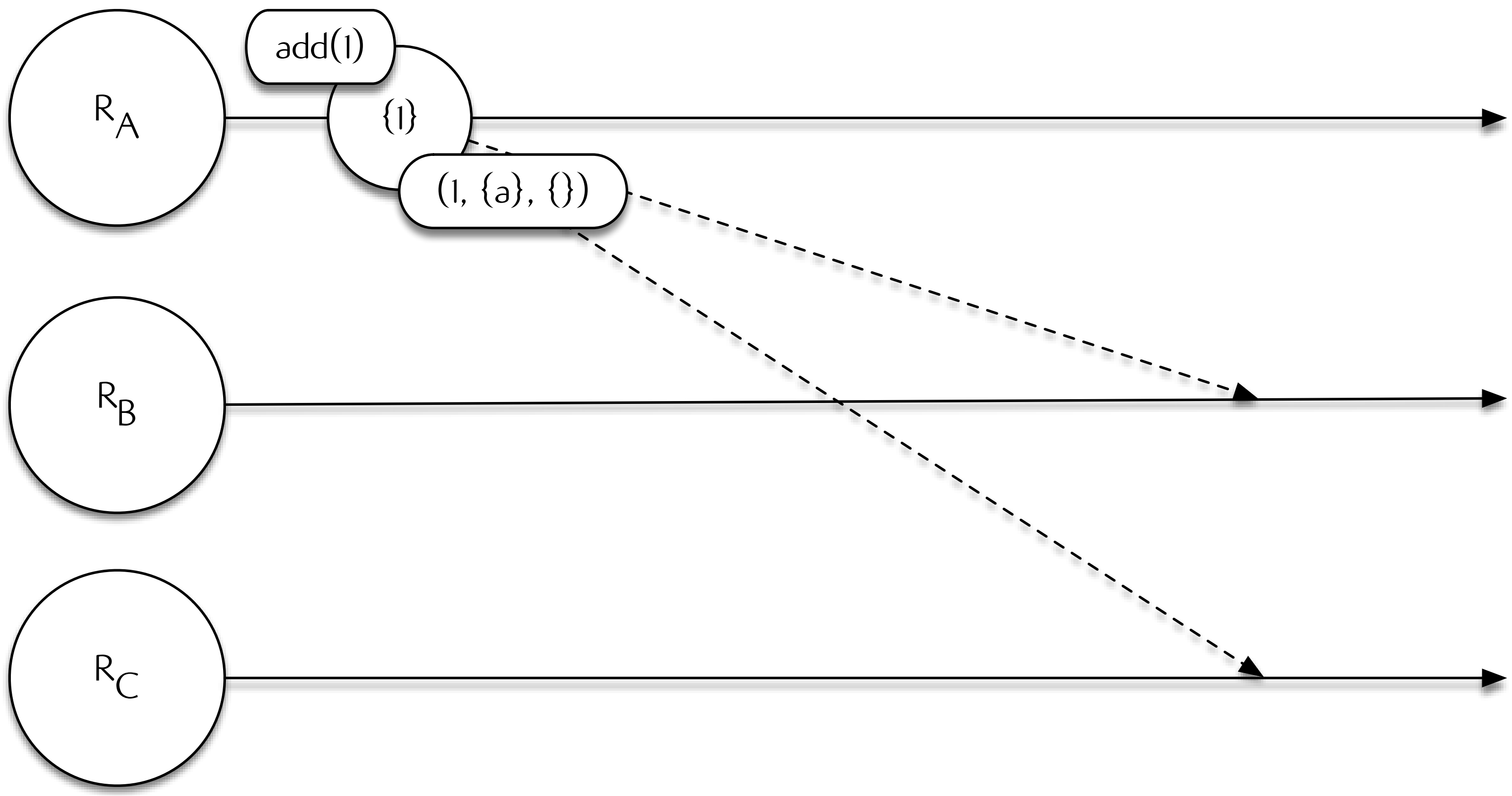
- Collection of types
  Sets, counters, registers, flags, maps

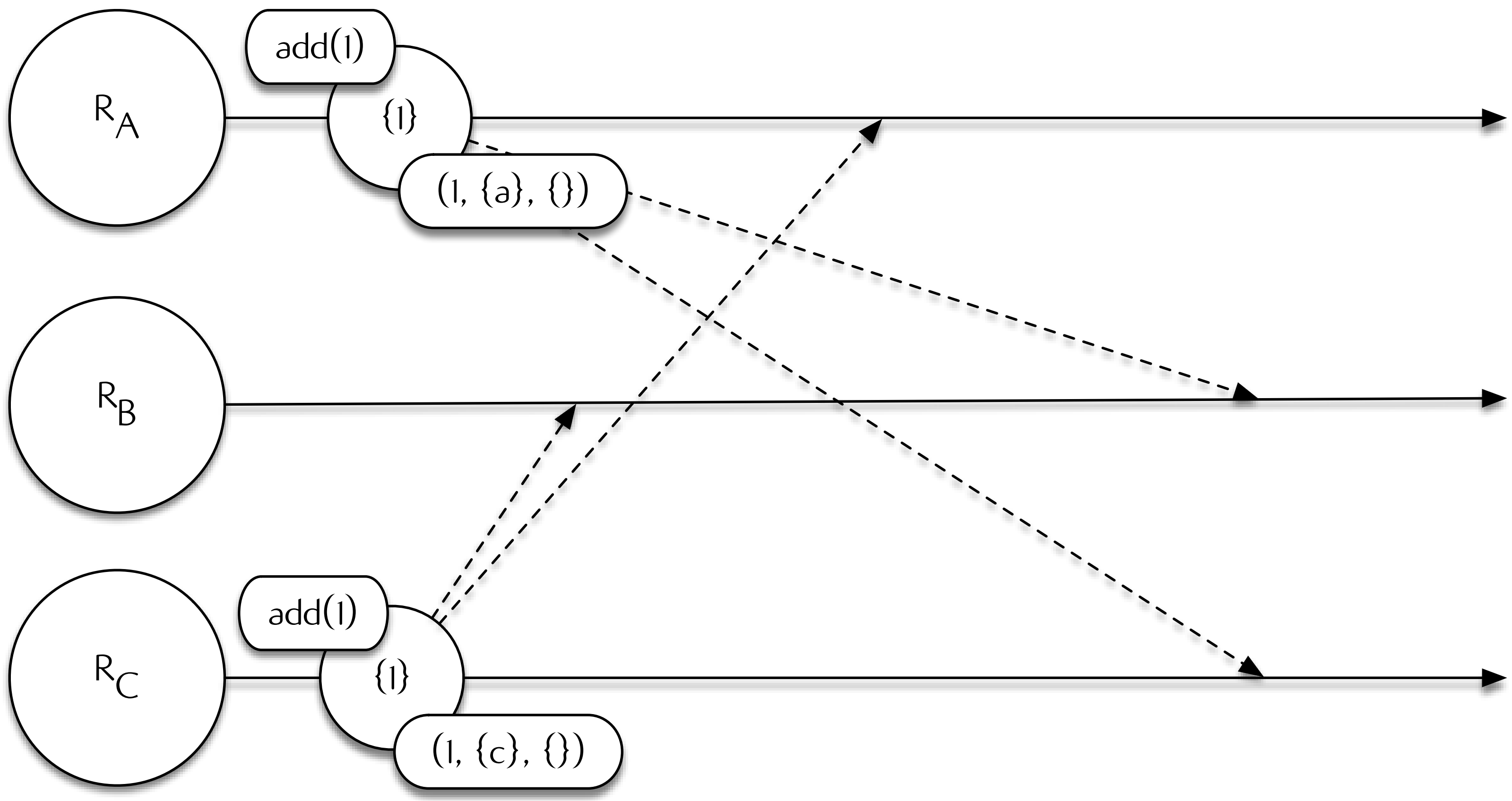
Conflict-Free
Replicated Data Types

- Collection of types
  Sets, counters, registers, flags, maps
- Strong Eventual Consistency
  Objects that receive the same updates, regardless of order, will reach equivalent state

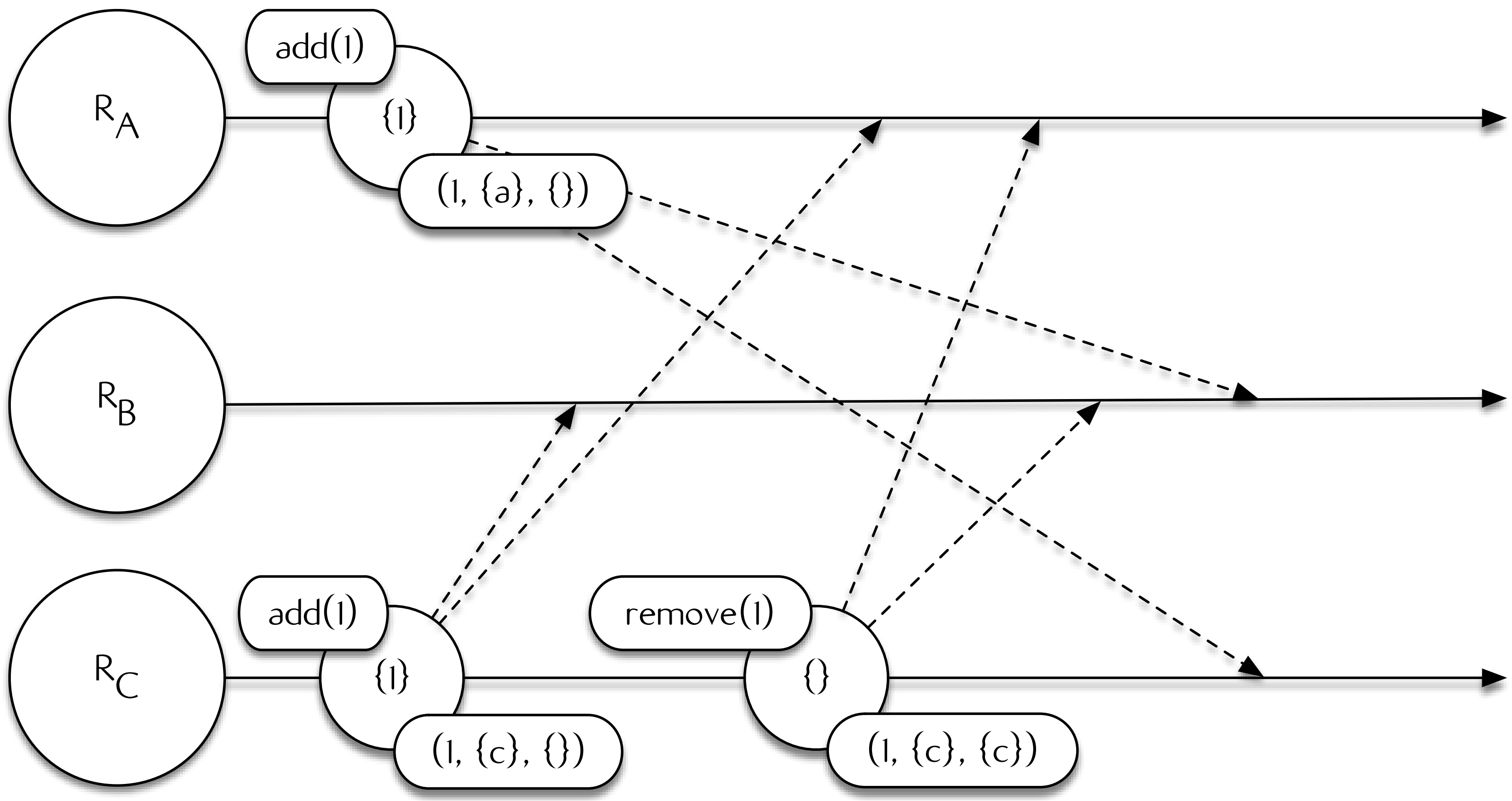


R_A
R_B
R_C

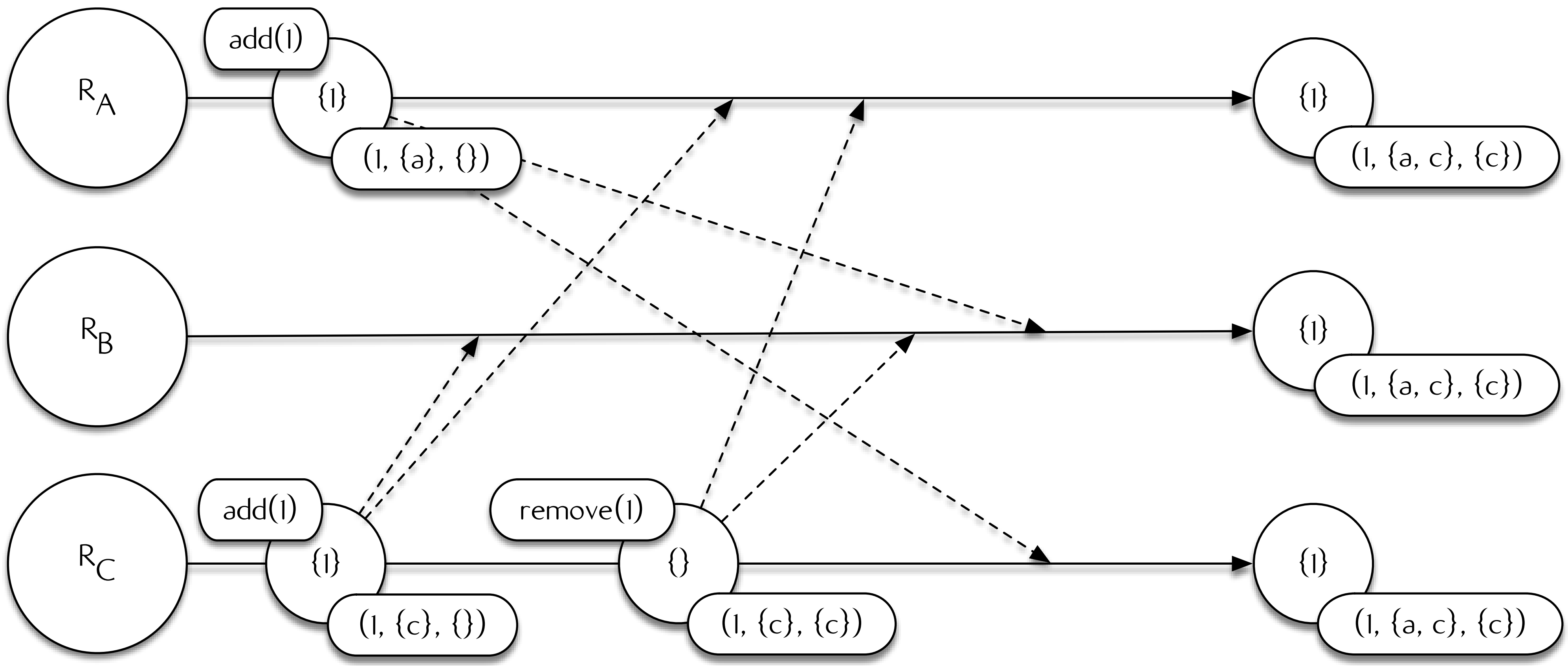

add(1)
R_A
{1}
(1, {a}, {})
R_B
R_C



R_A
add(1)
{1}
(1, {a}, {})
R_B
R_C
add(1)
{1}
(1, {c}, {})



add(1)
R_A
{1}
(1, {a}, {})
R_B
add(1)
R_C
{1}
(1, {c}, {})
remove(1)
{}
(1, {c}, {c})



R_A
add(1)
{1}
(1, {a}, {})
{1}
(1, {a, c}, {c})
R_B
{1}
(1, {a, c}, {c})
R_C
add(1)
{1}
(1, {c}, {})
remove(1)
{}
(1, {c}, {c})
{1}
(1, {a, c}, {c})

Lattice Processing

- **Distributed, deterministic dataflow**
  Distributed, dataflow programming model

Lattice Processing

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- **Convergent data structures**
  Data abstraction is the CRDT

Lattice Processing

- **Distributed, deterministic dataflow**
  Distributed, dataflow programming model

- **Convergent data structures**
  Data abstraction is the CRDT

- **Enables composition**
  Composition preserves SEC

```erlang
%% Create initial set.
S1 = declare(set),

%% Add elements to initial set and update.
update(S1, {add, [1,2,3]}),

%% Create second set.
S2 = declare(set),

%% Apply map operation between S1 and S2.
map(S1, fun(X) -> X * 2 end, S2).
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Selective Hearing

- Epidemic broadcast protocol
  Runtime system for application state & scope

Selective Hearing

- **Epidemic broadcast protocol**
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- **Peer-to-peer dissemination**
  Pairwise synchronization between peers
  without a central coordinator

Selective Hearing

- **Epidemic broadcast protocol**
  Runtime system for application state & scope

- **Peer-to-peer dissemination**
  Pairwise synchronization between peers without a central coordinator

- **No ordering guarantees on messages**
  Programming model can tolerate message reordering and duplication

What can we build?

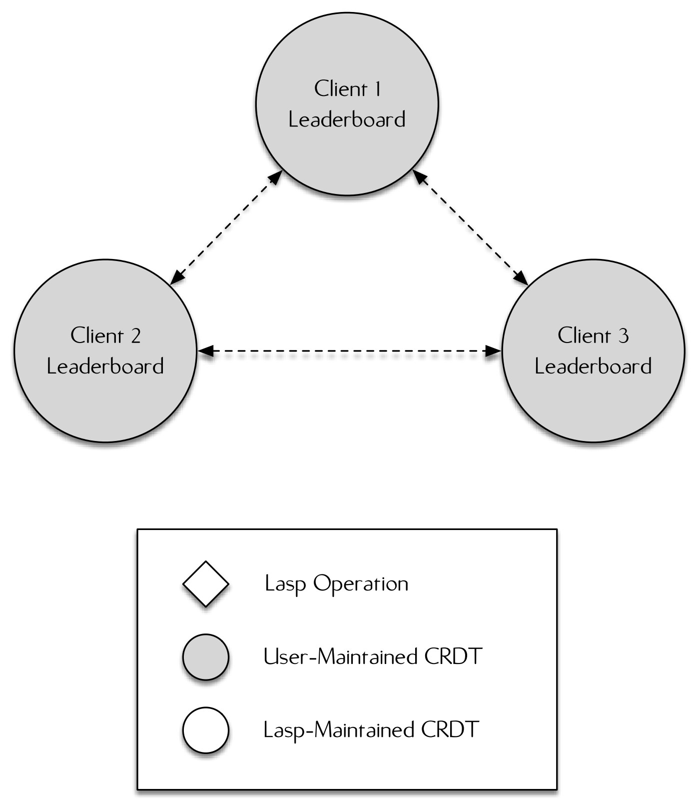
Leaderboard

Leaderboard

- Mobile game platform
  Local leaderboard tracking top-*k* highest scored games

Leaderboard

- **Mobile game platform**
  Local leaderboard tracking top-*k* highest scored games
- **Clients will go offline**
  Clients have limited connectivity and the system still needs to make progress while clients are offline


Client 1
Leaderboard
Client 2
Leaderboard
Client 3
Leaderboard
Lasp Operation
User-Maintained CRDT
Lasp-Maintained CRDT

Leaderboard

- Peer-to-peer dissemination
  Nodes periodically “merge” their state
  with a random peer

Leaderboard

- **Peer-to-peer dissemination**
  Nodes periodically “merge” their state with a random peer
- **Complexity in the data type**
  Each node tracks a top-*k* set of its own games in a bounded set

```erlang
%% Create a leaderboard datatype.
L = declare({top_k, [2]}).

%% Update leaderboard.
update({set, Name, Score}, L).
```

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What if we want to enhance the behavior?

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Without the creation of a new datatype

What can we build?

Per-User Leaderboard

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- Enhance existing design
  Only the top score for each user at each device

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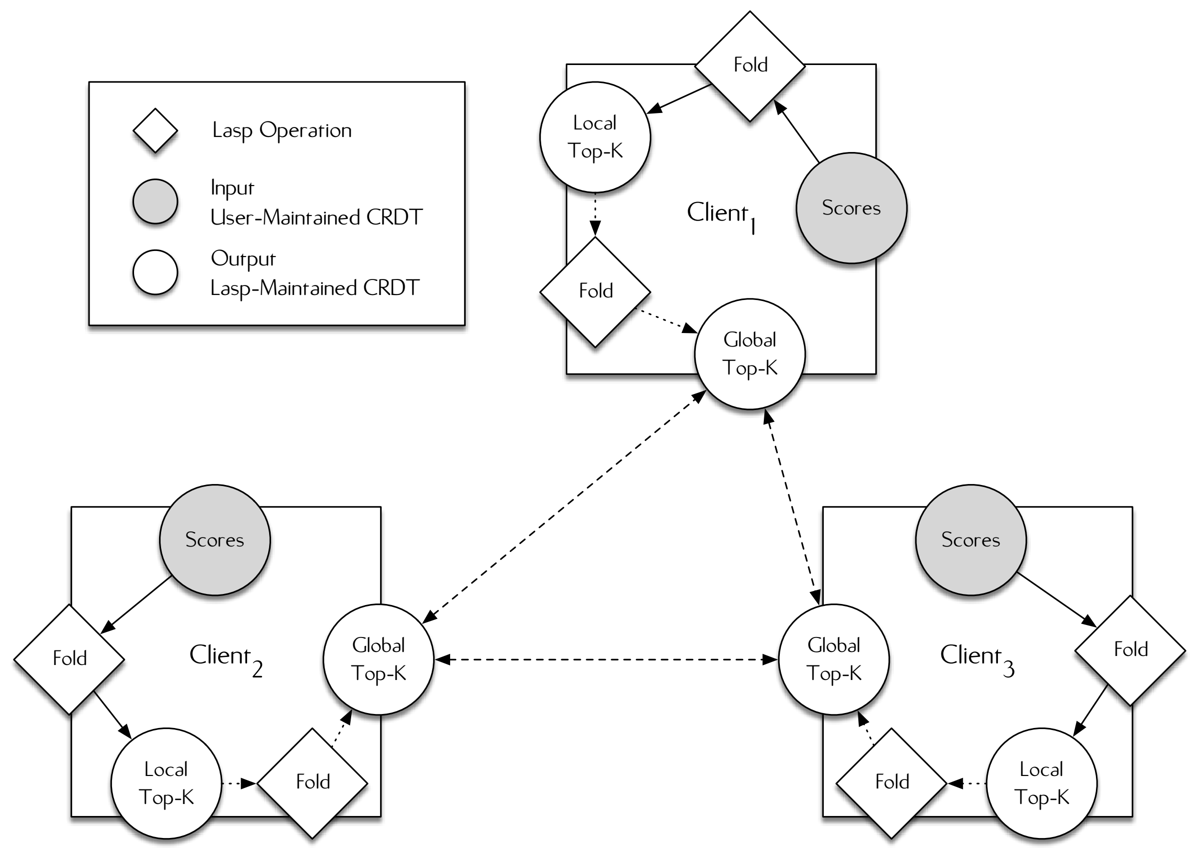
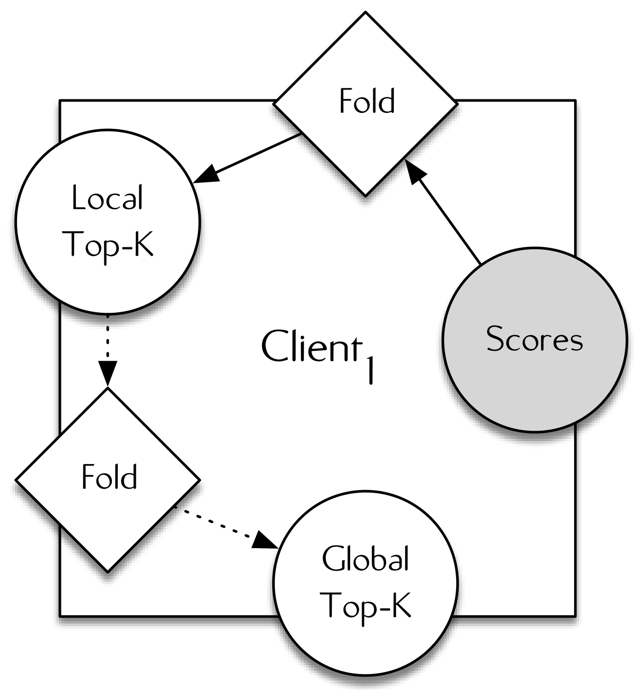
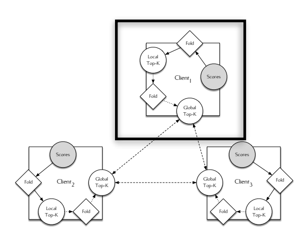
- Minimize transmitted state
  Prevent transmission of state that is not necessary to perform the computation

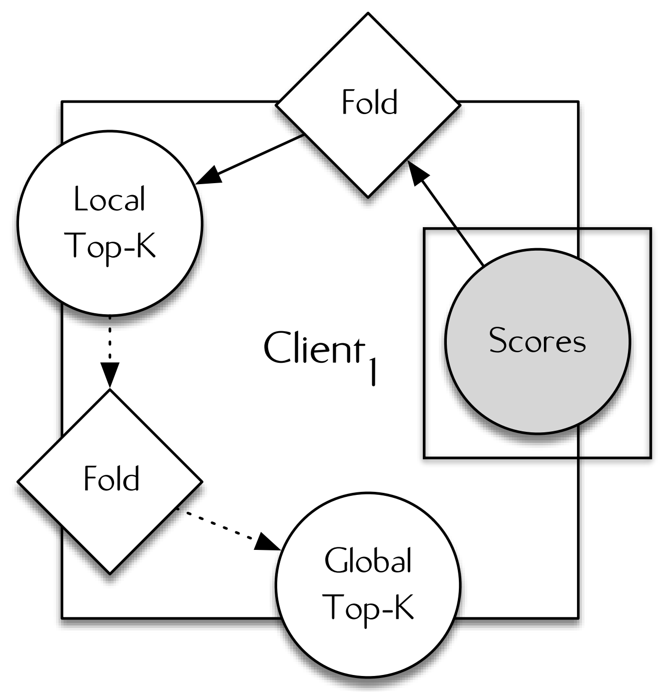
Per-User Leaderboard

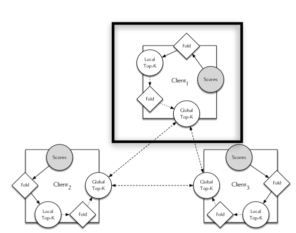
- **Enhance existing design**
  Only the top score for each user at each device
- **Minimize transmitted state**
  Prevent transmission of state that is not necessary to perform the computation
- **Compose data types**
  Build a per-user leaderboard through the composition of existing types

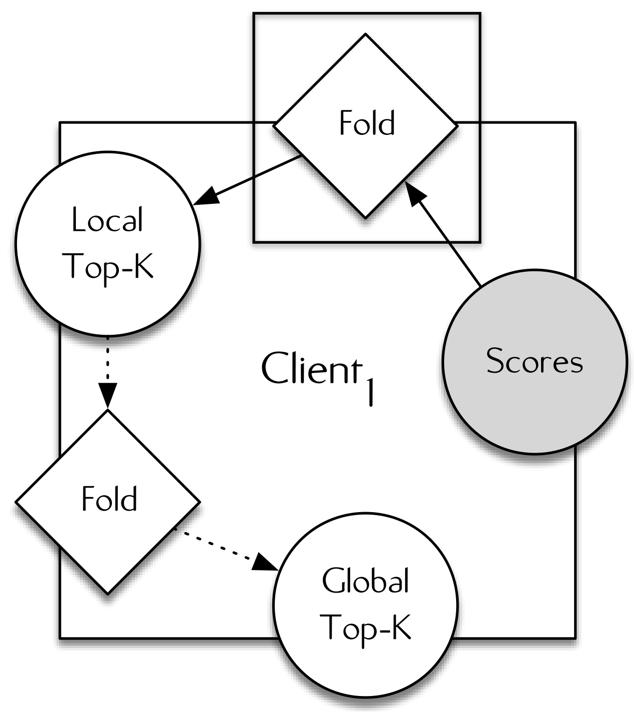

Lasp Operation
Input
User-Maintained CRDT
Output
Lasp-Maintained CRDT
Fold
Local
Top-K
Client1
Scores
Fold
Global
Top-K
Scores
Fold
Client2
Global
Top-K
Local
Top-K
Fold
Scores
Global
Top-K
Client3
Fold
Fold
Local
Top-K


Fold
Local Top-K
Client1
Scores
Fold
Global Top-K




Fold
Local
Top-K
Client$_1$
Scores
Fold
Global
Top-K




Fold
Local
Top-K
Client1
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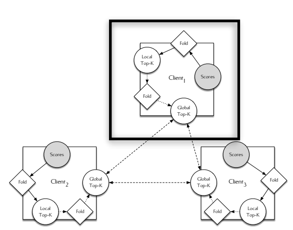
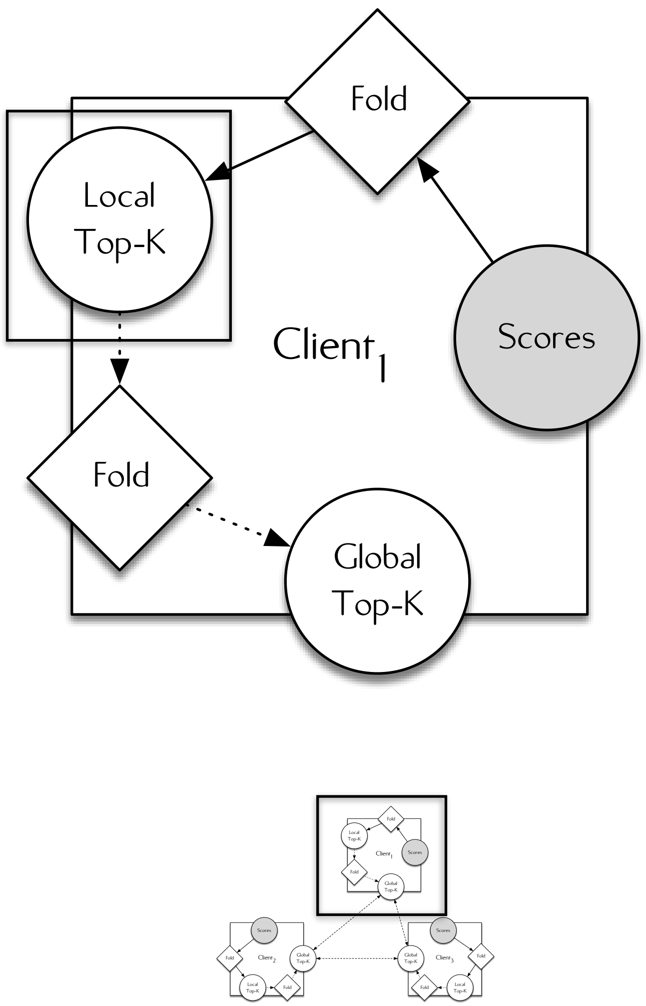
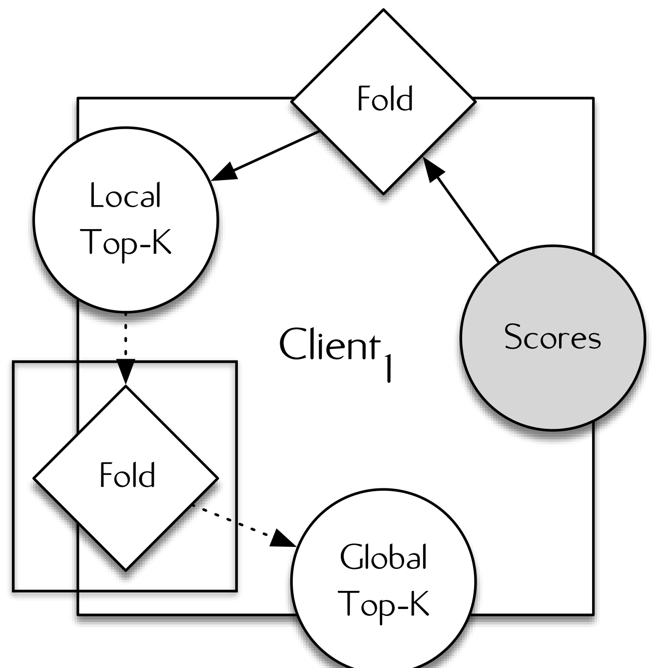
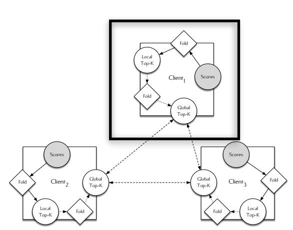
Fold
Global
Top-K

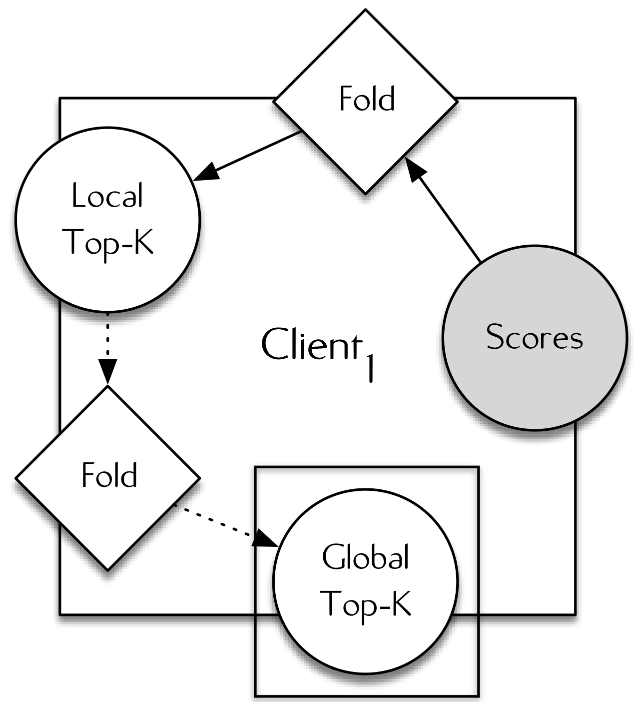



Fold
Local
Top-K
Client$_1$
Scores
Fold
Global
Top-K



Fold
Local
Top-K
Client1
Scores
Fold
Global
Top-K




Fold
Local
Top-K
Client1
Scores
Fold
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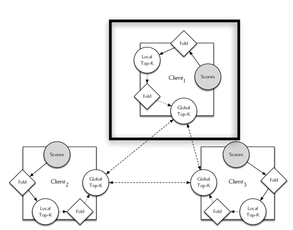
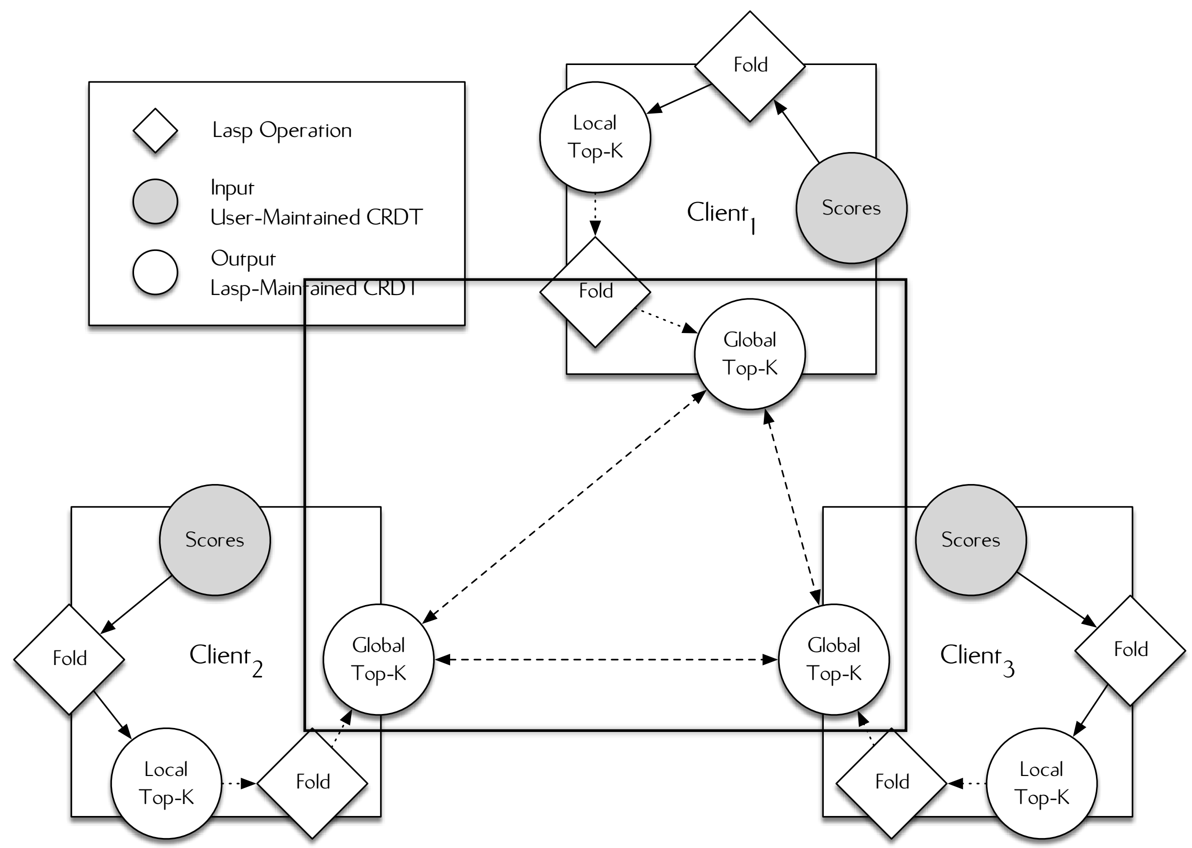
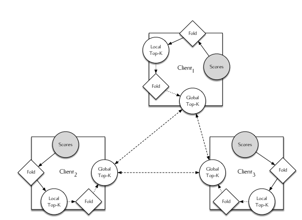
Top-K




Lasp Operation
Input
User-Maintained CRDT
Output
Lasp-Maintained CRDT
Fold
Local
Top-K
Client$_1$
Scores
Fold
Global
Top-K
Scores
Fold
Client$_2$
Global
Top-K
Local
Top-K
Fold
Global
Top-K
Client$_3$
Scores
Fold
Fold
Local
Top-K



Per-User Leaderboard

- Dynamically scoped variables
  Variable which take different values depending on where it is executing

Per-User Leaderboard

- Dynamically scoped variables
  Variable which take different values depending on where it is executing

- Dynamically scoped fold operation
  Perform a distributed “reduce” operation that combines the state of a dynamically scoped variables across

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%% Create a global leaderboard.
G = declare({top_k, [10]}).

%% Create a local leaderboard.
L = declare_dynamic({top_k, [10]}).

%% Create a set of scores.
S = declare_dynamic(set).

%% Compute local top-k list.
fold(S, fun max_by_name/2, L).

%% Compute global top-k list.
fold_dynamic(L, fun max_by_name/2, G).
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Let's look at a larger application

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With visible non-monotonicity

What can we build?

Advertisement Counter

Advertisement Counter

- Mobile game platform selling advertisement space
  Advertisements are paid according to a minimum number of impressions

Advertisement Counter

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  Advertisements are paid according to a minimum number of impressions

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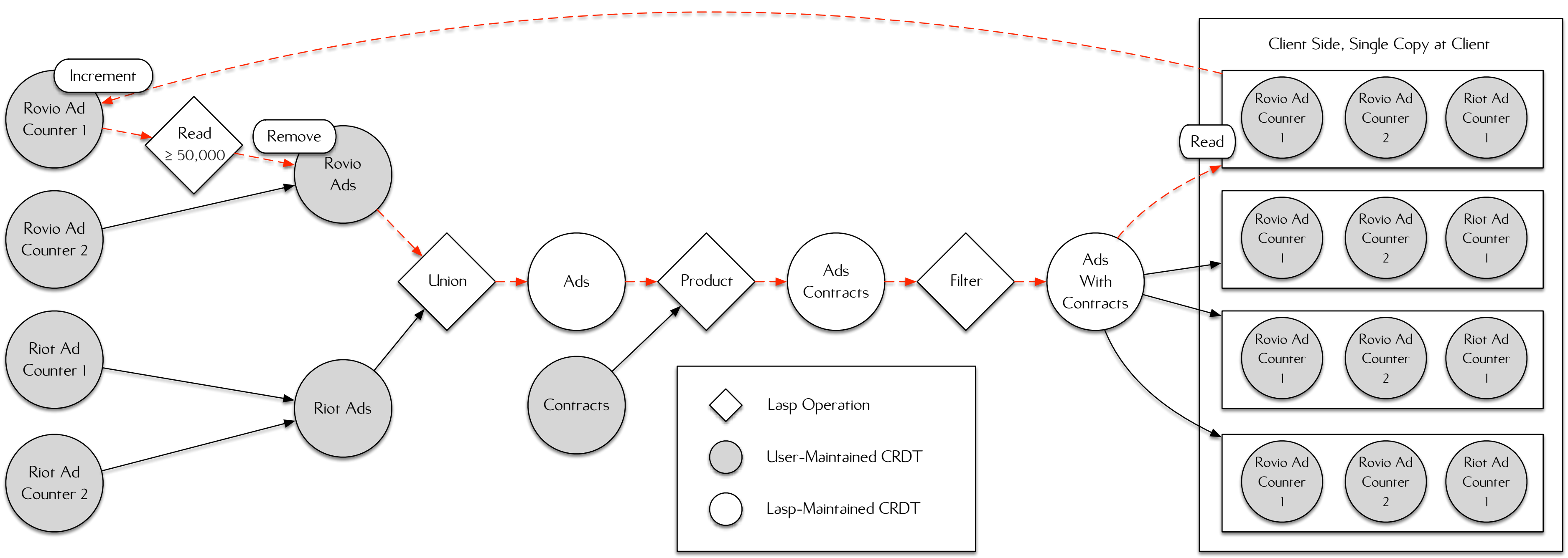
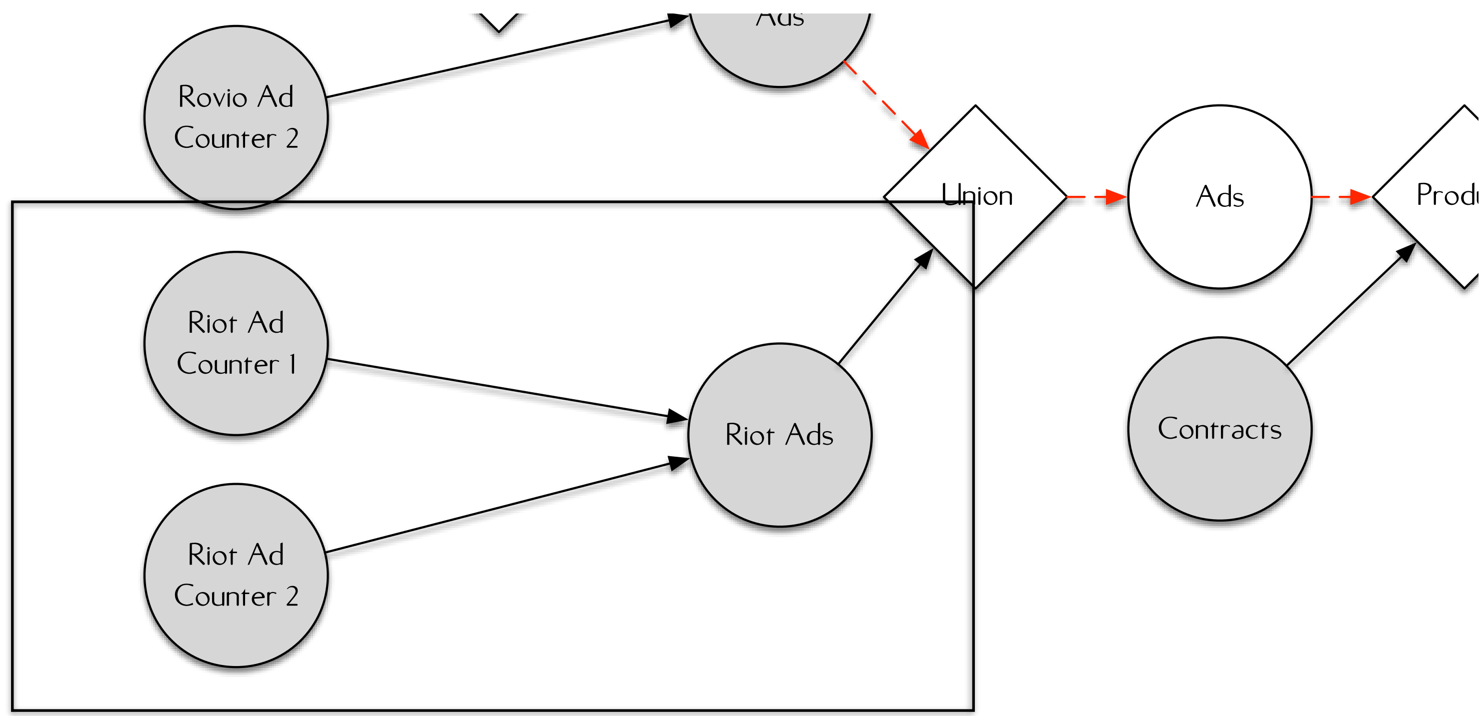
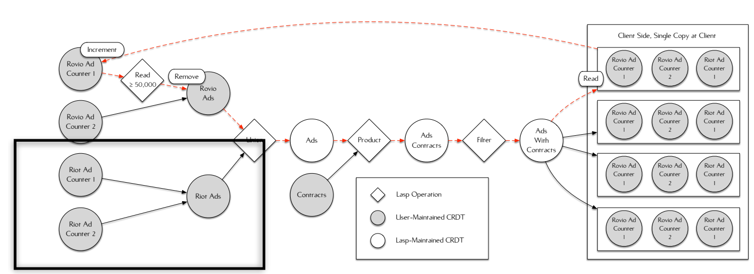
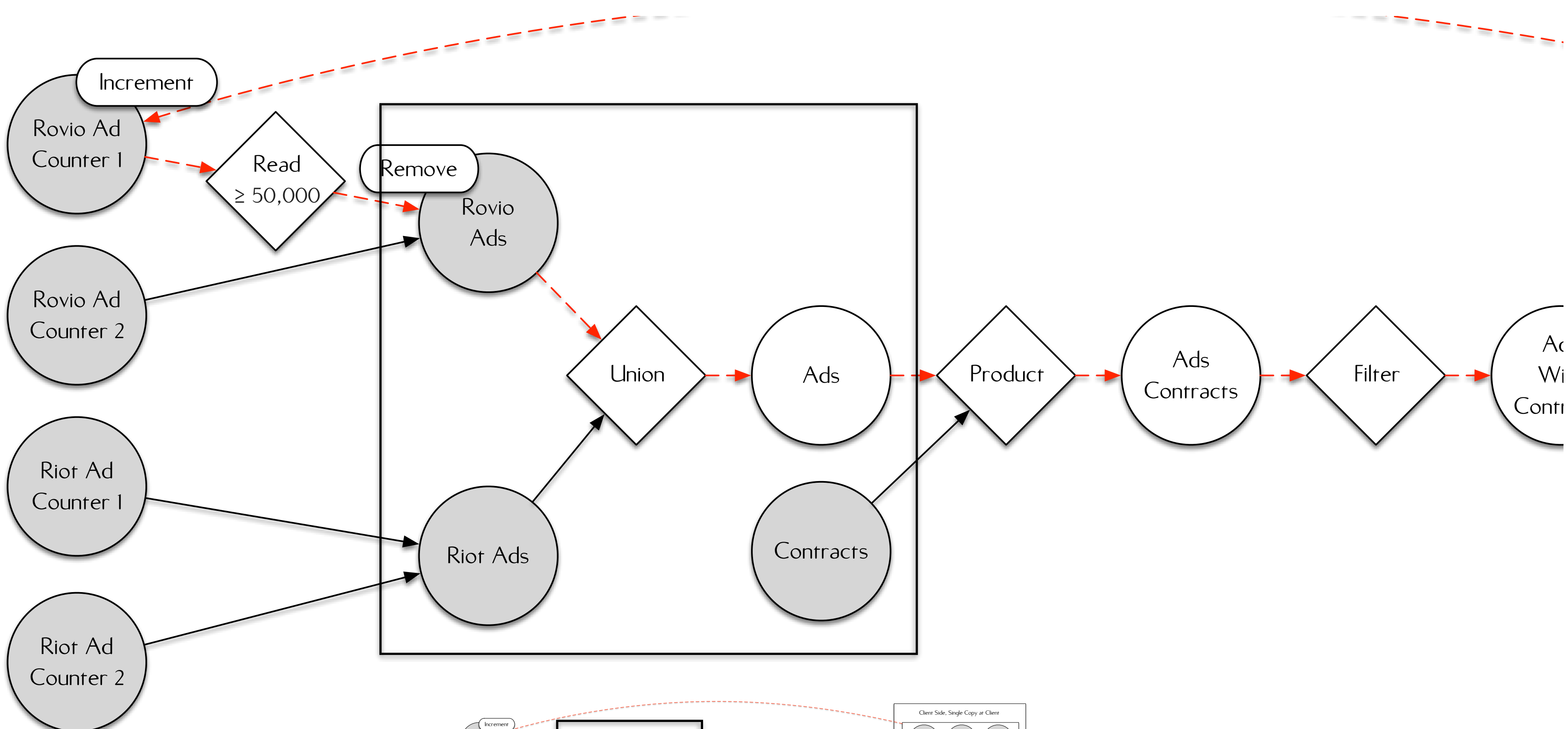
  Clients have limited connectivity and the system still needs to make progress while clients are offline


Client Side, Single Copy at Client
Increment
Rovio Ad Counter 1
Read ≥ 50,000
Remove
Rovio Ads
Rovio Ad Counter 2
Riot Ad Counter 1
Riot Ad Counter 2
Riot Ads
Union
Ads
Product
Contracts
Ads Contracts
Filter
Ads With Contracts
Read
Rovio Ad Counter 1
Rovio Ad Counter 2
Riot Ad Counter 1
Lasp Operation
User-Maintained CRDT
Lasp-Maintained CRDT


Ads
Rovio Ad Counter 2
Union
Ads
Riot Ad Counter 1
Riot Ad Counter 2
Riot Ads
Contracts





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Riot Ad Counter 1
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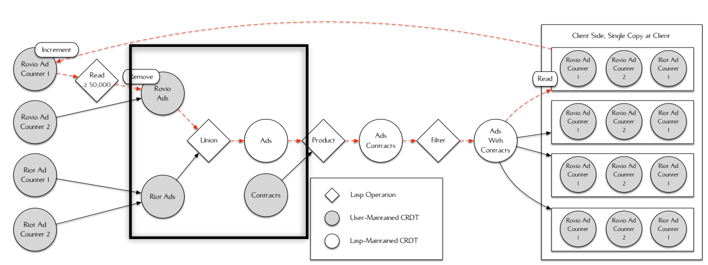
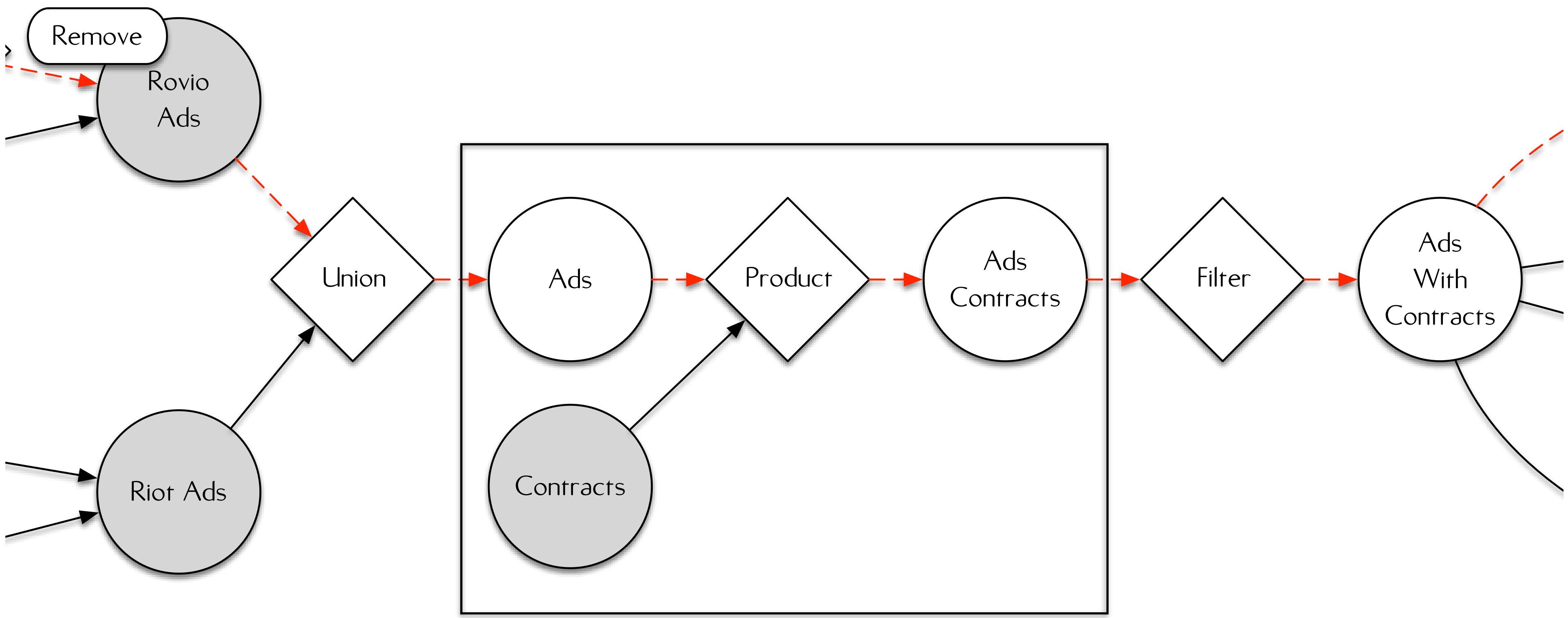
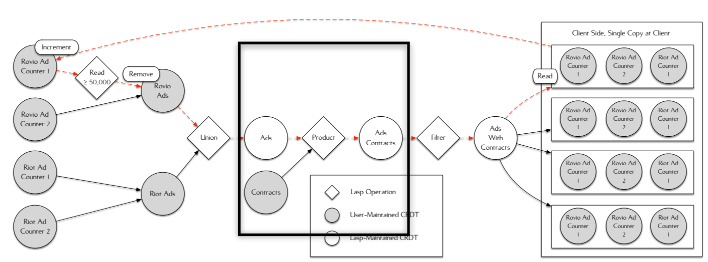
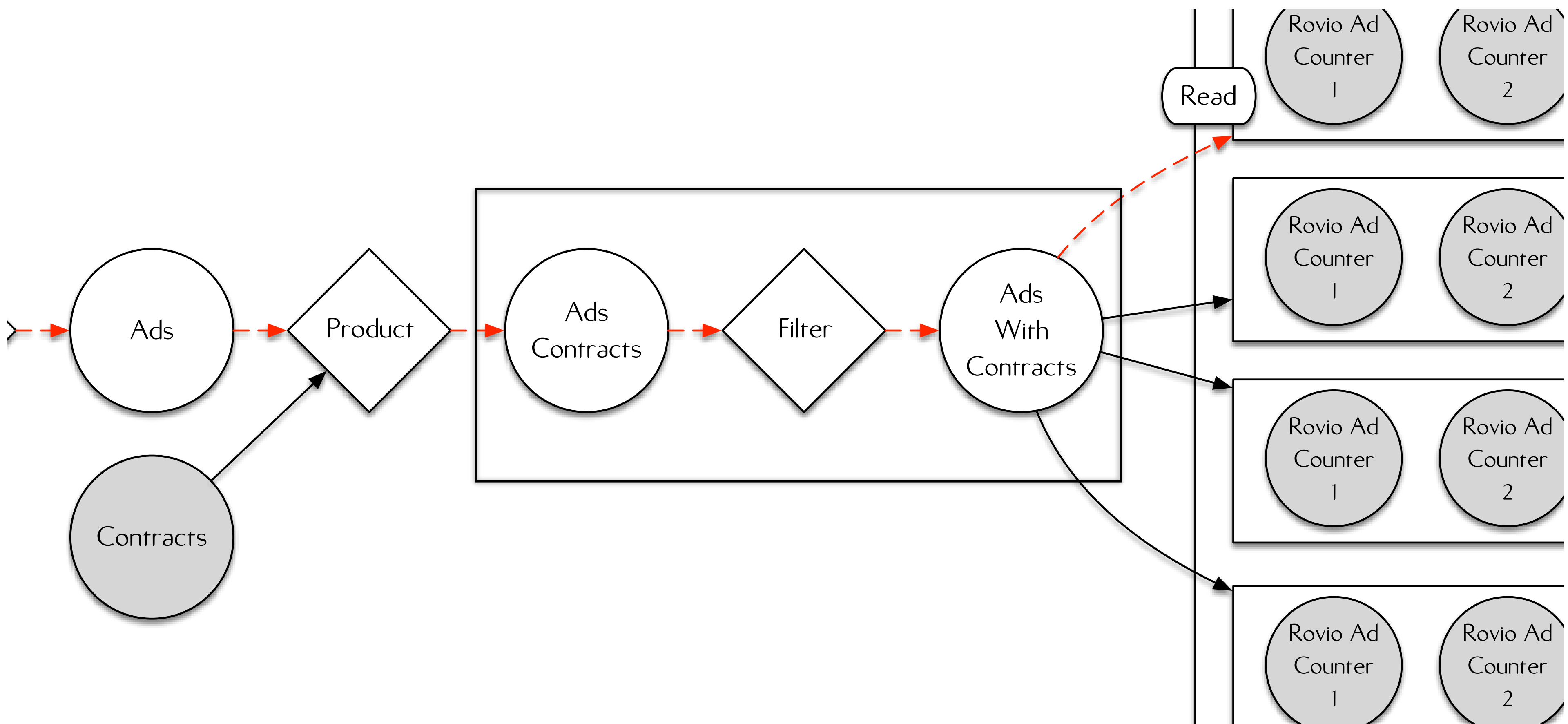
Contracts
Riot Ad Counter 2




Remove
Rovio Ads
Riot Ads
Union
Ads
Contracts
Product
Ads Contracts
Filter
Ads With Contracts




Ads
Product
Contracts
Ads Contracts
Filter
Ads With Contracts
Read
Rovio Ad Counter 1
Rovio Ad Counter 2
Rovio Ad Counter 1
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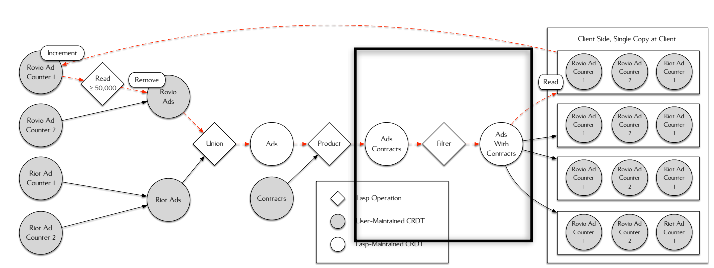
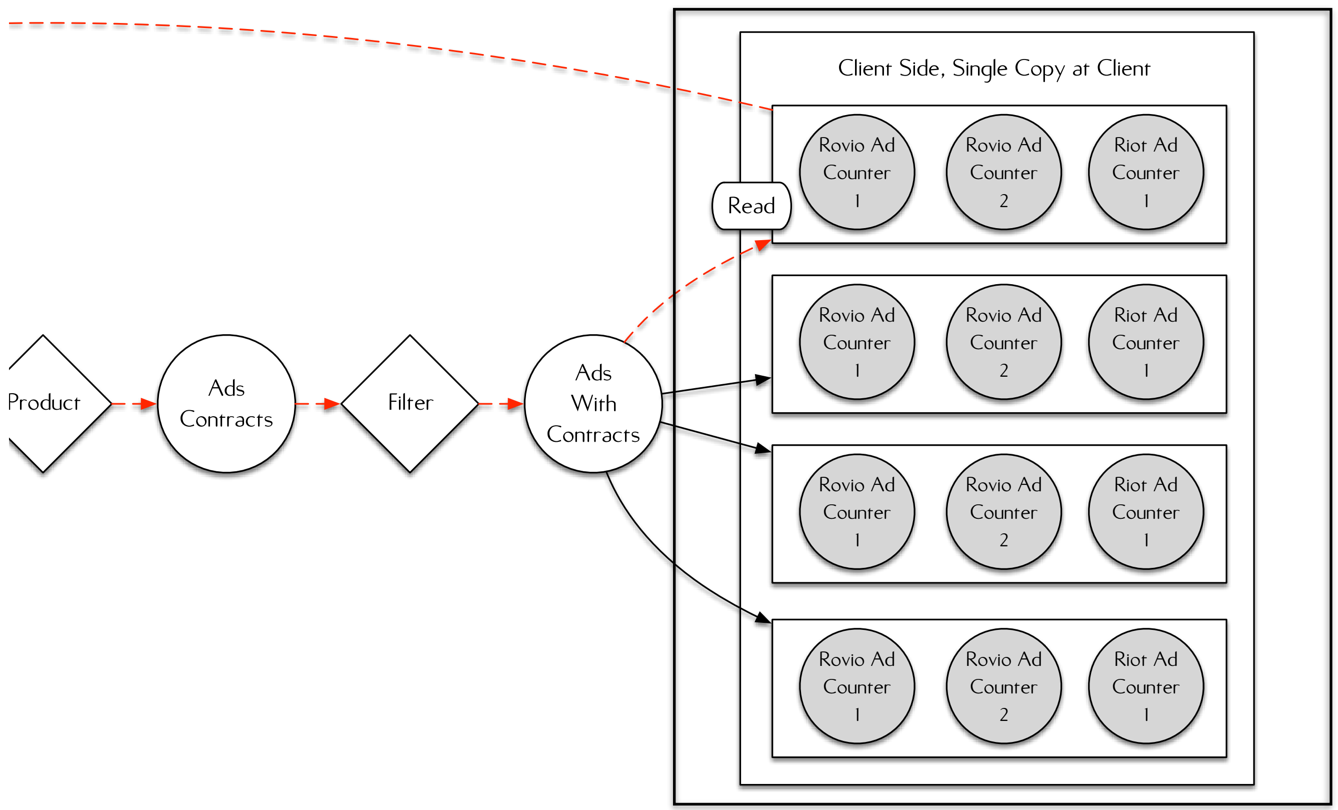
Rovio Ad Counter 1
Rovio Ad Counter 2
Rovio Ad Counter 1
Rovio Ad Counter 2

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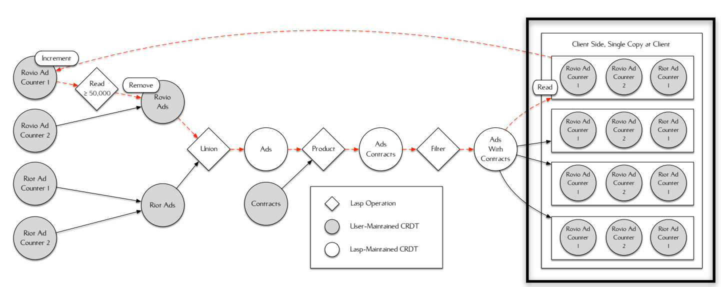
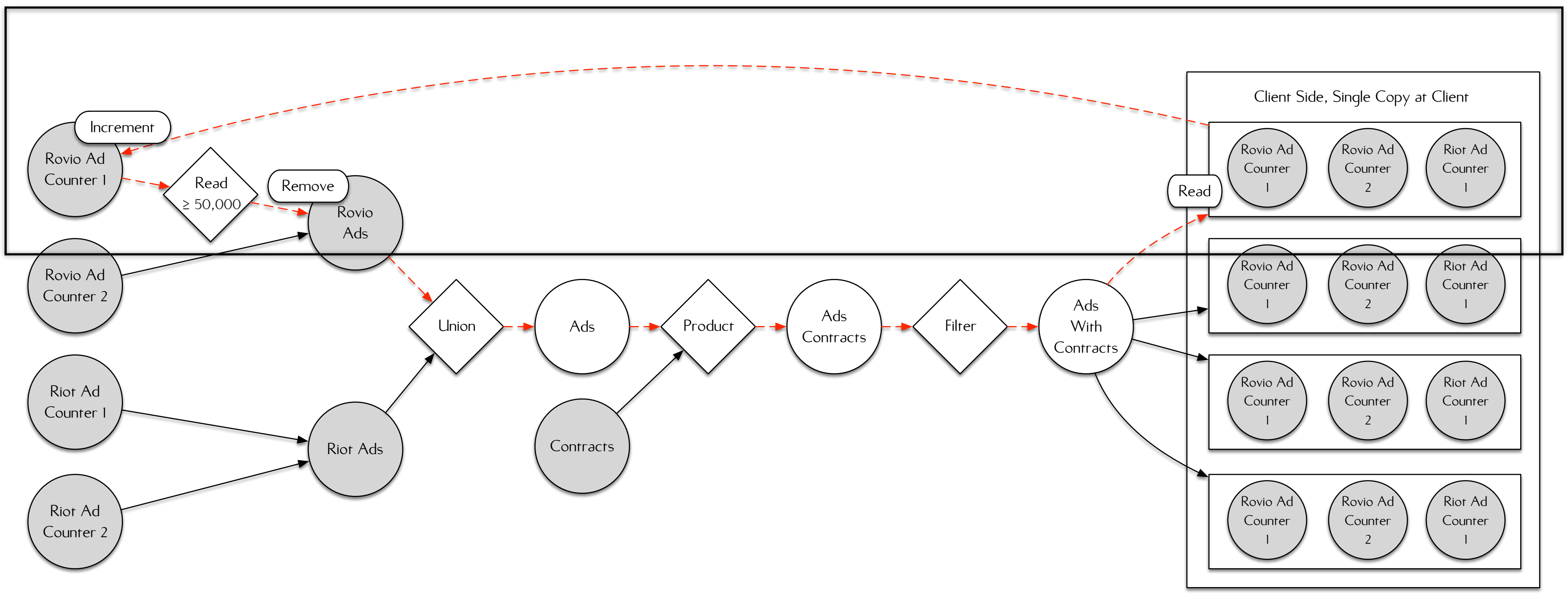
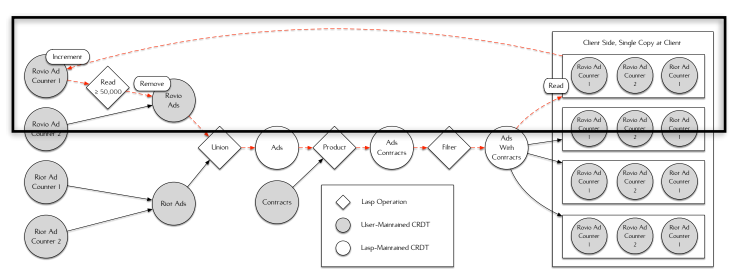
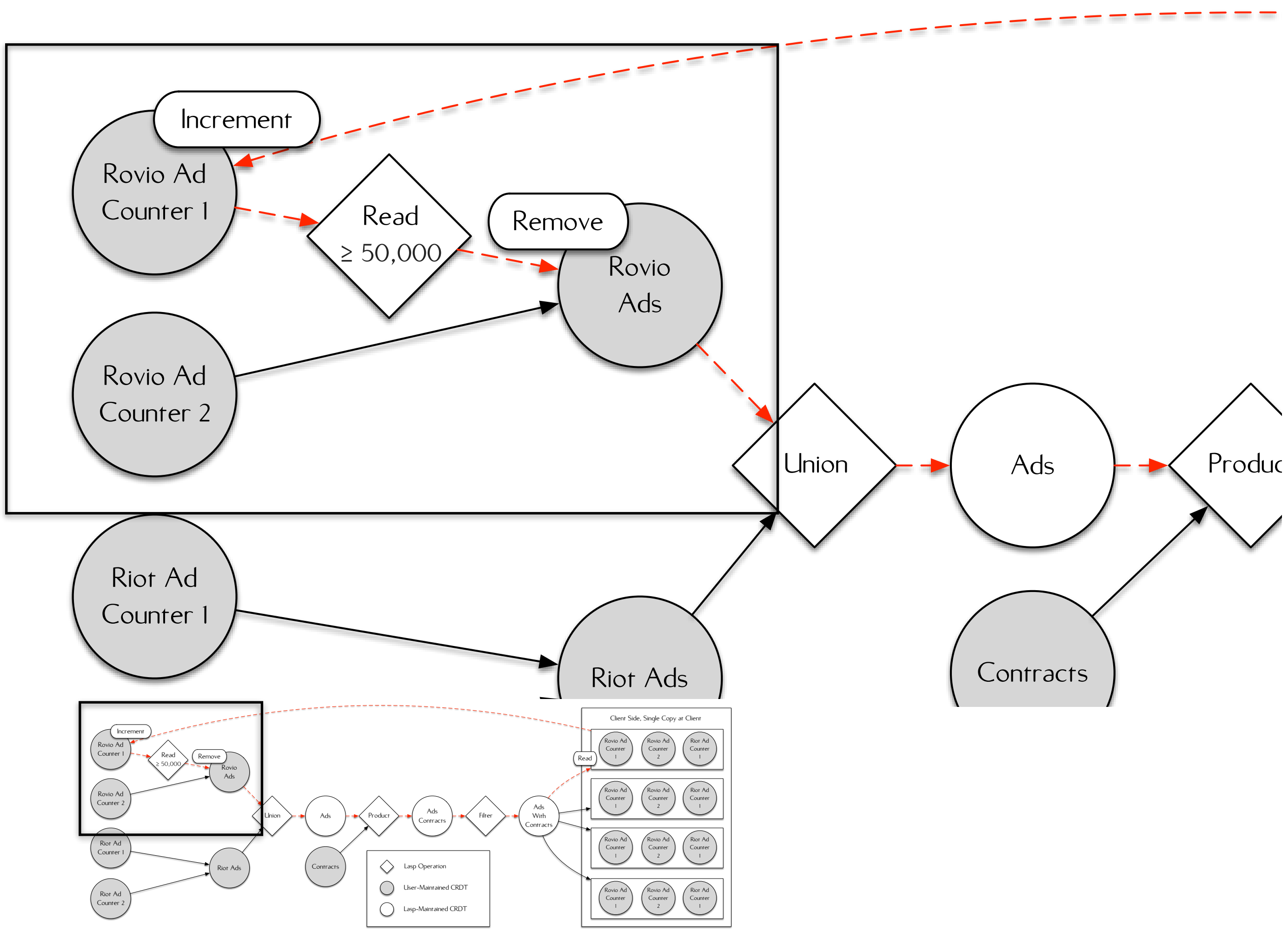
Riot Ad Counter 1
Rovio Ad Counter 1
Rovio Ad Counter 2
Riot Ad Counter 1
Rovio Ad Counter 1
Rovio Ad Counter 2
Riot Ad Counter 1




Client Side, Single Copy at Client
Increment
Rovio Ad Counter 1
Read ≥ 50,000
Remove
Rovio Ads
Rovio Ad Counter 2
Riot Ad Counter 1
Riot Ad Counter 2
Riot Ads
Union
Ads
Contracts
Product
Ads Contracts
Filter
Ads With Contracts
Read
Rovio Ad Counter 1
Rovio Ad Counter 2
Riot Ad Counter 1
Rovio Ad Counter 1
Rovio Ad Counter 2
Riot Ad Counter 1
Rovio Ad Counter 1
Rovio Ad Counter 2
Riot Ad Counter 1
Rovio Ad Counter 1
Rovio Ad Counter 2
Riot Ad Counter 1




Increment
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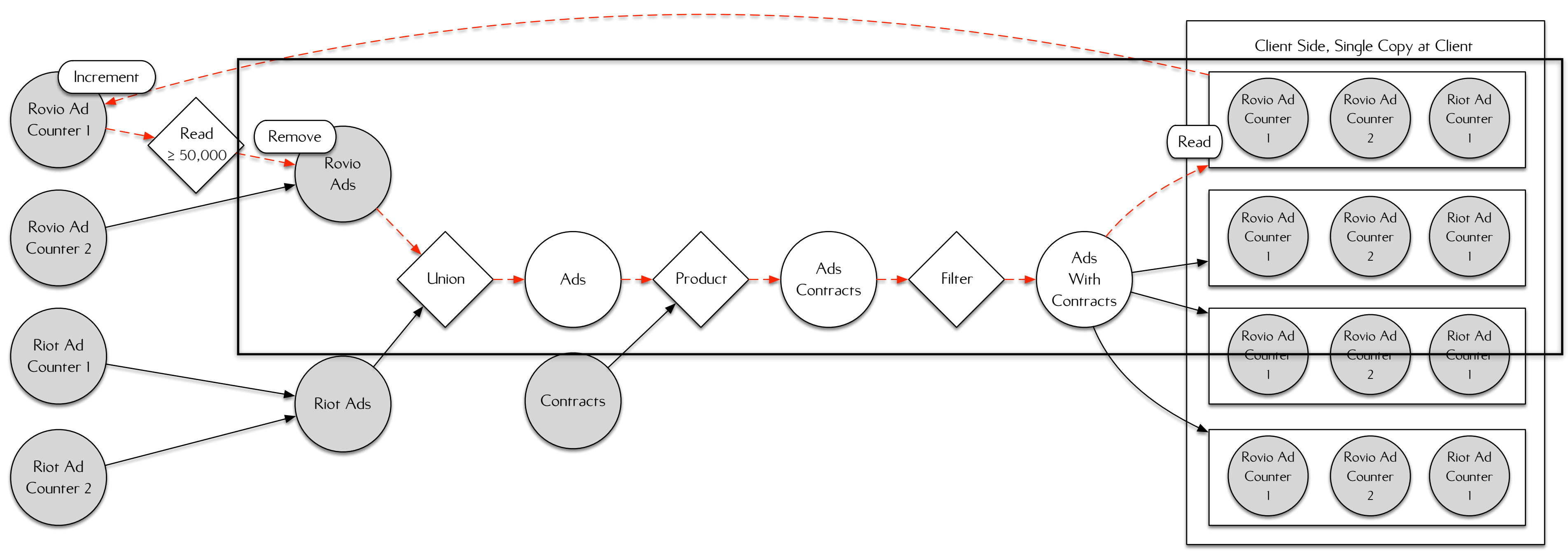
Ads
Produc
Riot Ad Counter 1
Riot Ads
Contracts



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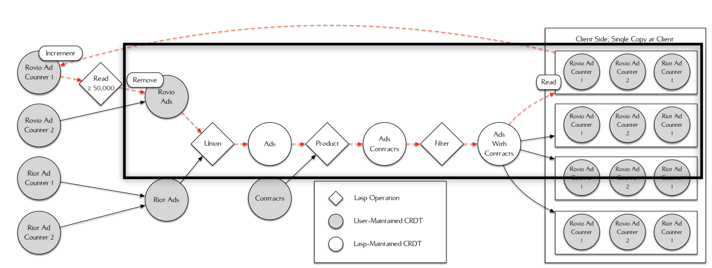

Lasp Operation
User-Maintained CRDT
Lasp-Maintained CRDT

Advertisement Counter

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  Disabling advertisements and contracts are all modeled through monotonic state growth

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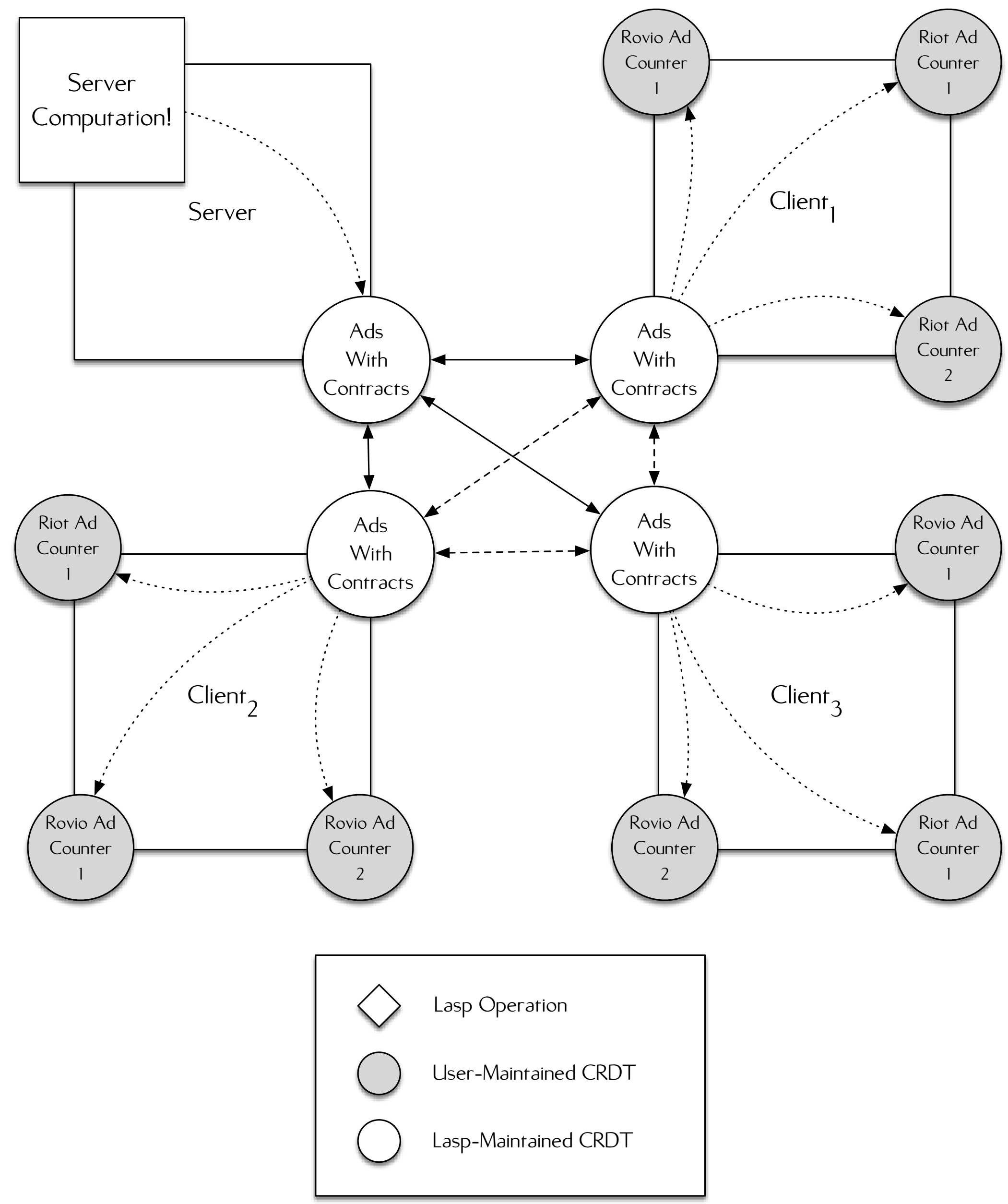
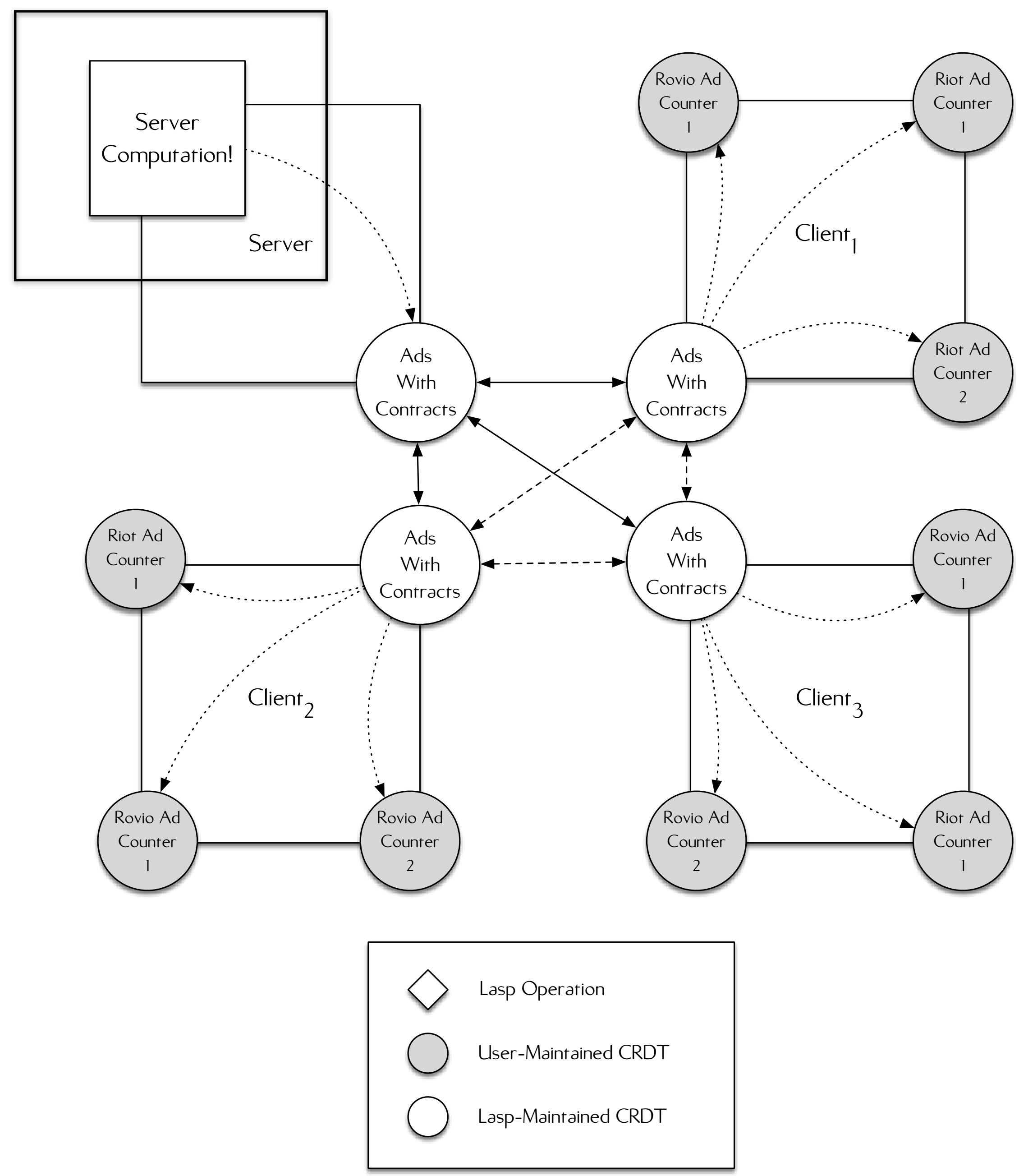
- Divergence
  Divergence is a factor of synchronization period


Server Computation!
Server
Ads With Contracts
Rovio Ad Counter 1
Riot Ad Counter 1
Client1
Riot Ad Counter 2
Ads With Contracts
Riot Ad Counter 1
Ads With Contracts
Ads With Contracts
Rovio Ad Counter 1
Client2
Client3
Rovio Ad Counter 1
Rovio Ad Counter 2
Rovio Ad Counter 2
Riot Ad Counter 1
Lasp Operation
User-Maintained CRDT
Lasp-Maintained CRDT


Server
Computation!
Server
Ads With Contracts
Ads With Contracts
Ads With Contracts
Ads With Contracts
Client$_1$
Client$_2$
Client$_3$
Rovio Ad Counter 1
Riot Ad Counter 1
Riot Ad Counter 2
Riot Ad Counter 1
Rovio Ad Counter 1
Rovio Ad Counter 2
Rovio Ad Counter 1
Rovio Ad Counter 2
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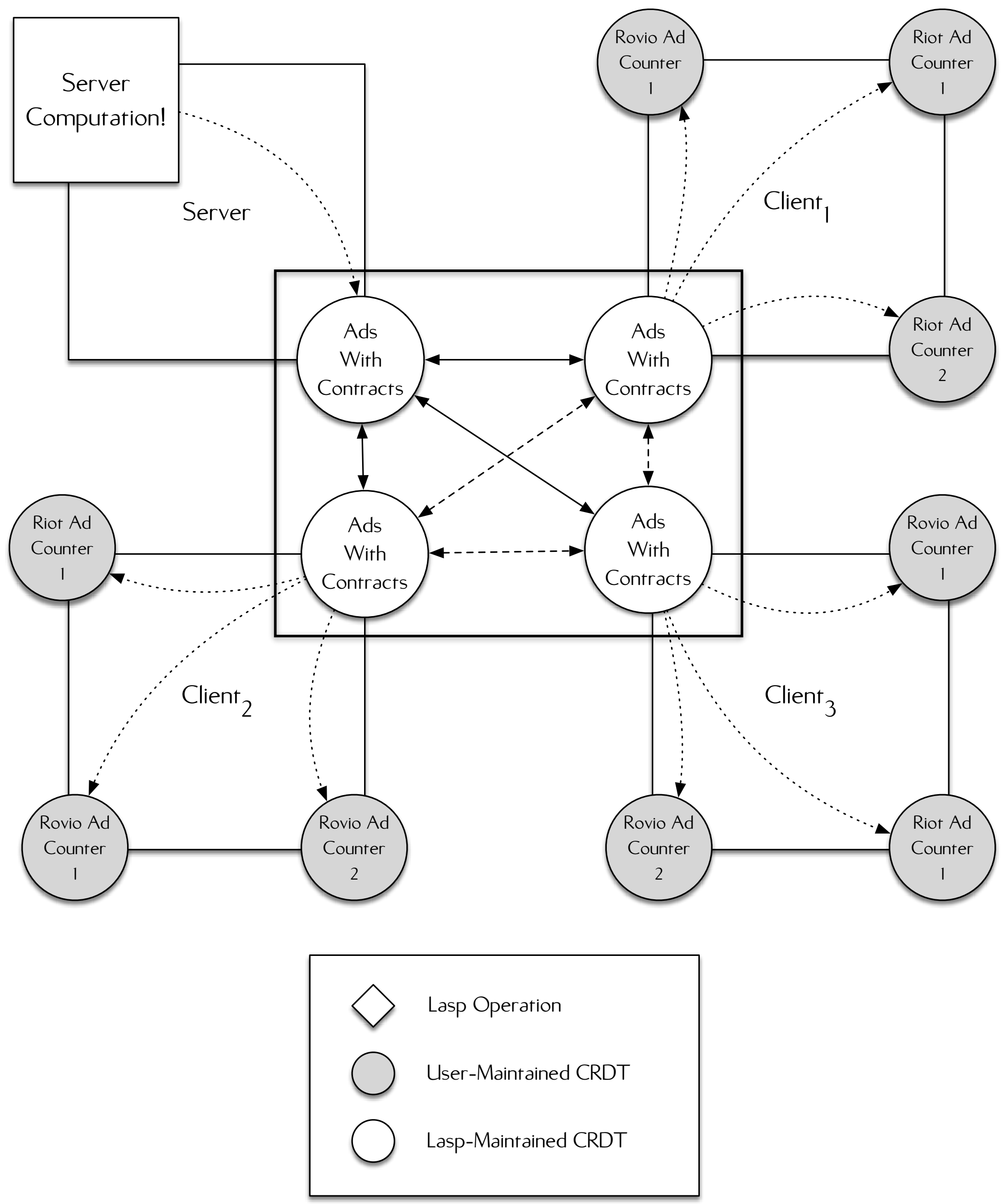
Server Computation!
Server
Client1
Client2
Client3
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Rovio Ad Counter 1
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Advertisement Counter

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  Servers are peers to clients that perform additional computation
  - Any node can disable an advertisement under this model given enough information
- **“Servers” as trusted nodes**
  Serve as a location for performing “exactly once” side-effects
  - Billing customers must be done at a central point by a trusted node in the system

We’ve build up from zero synchronization

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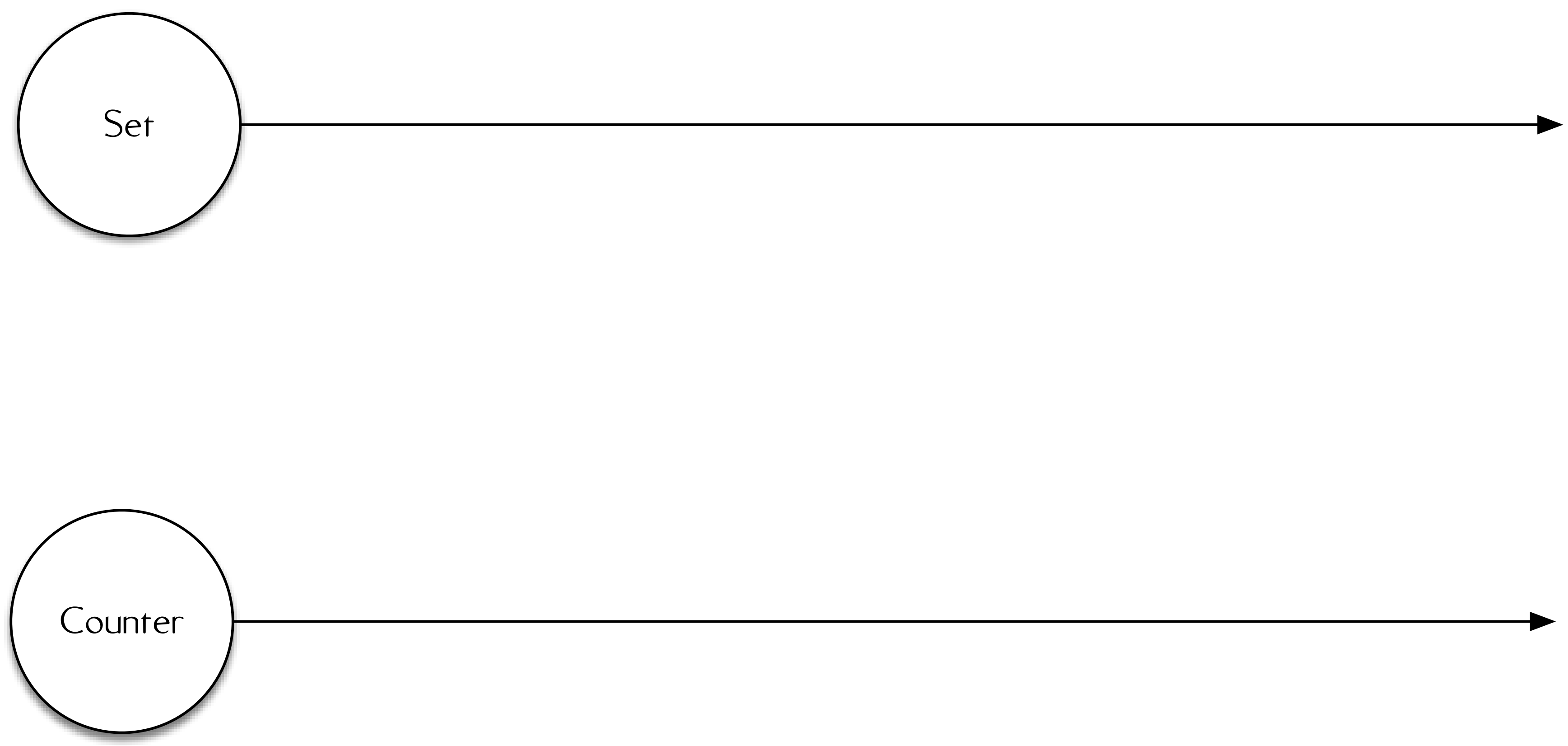
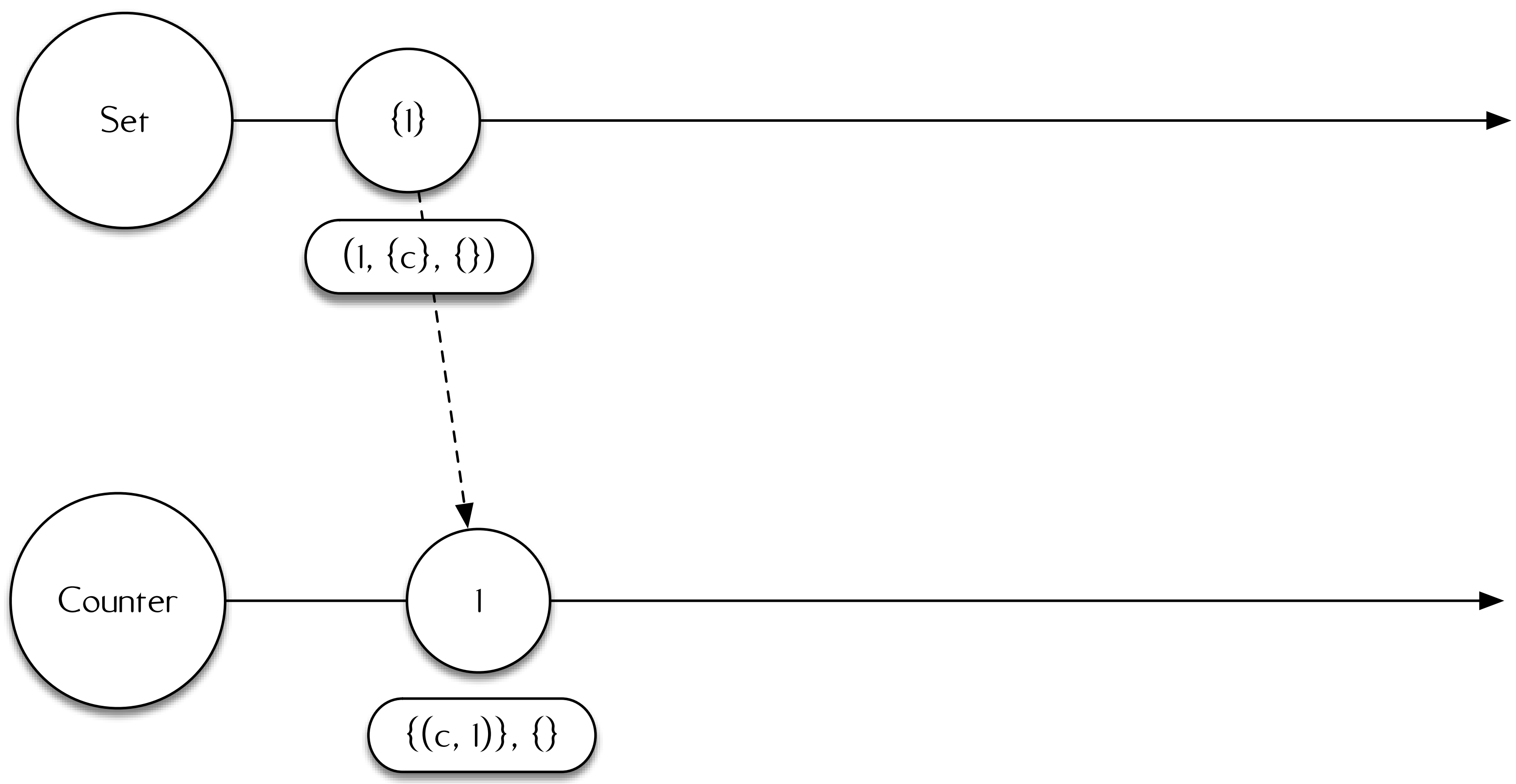
Instead of working to remove synchronization

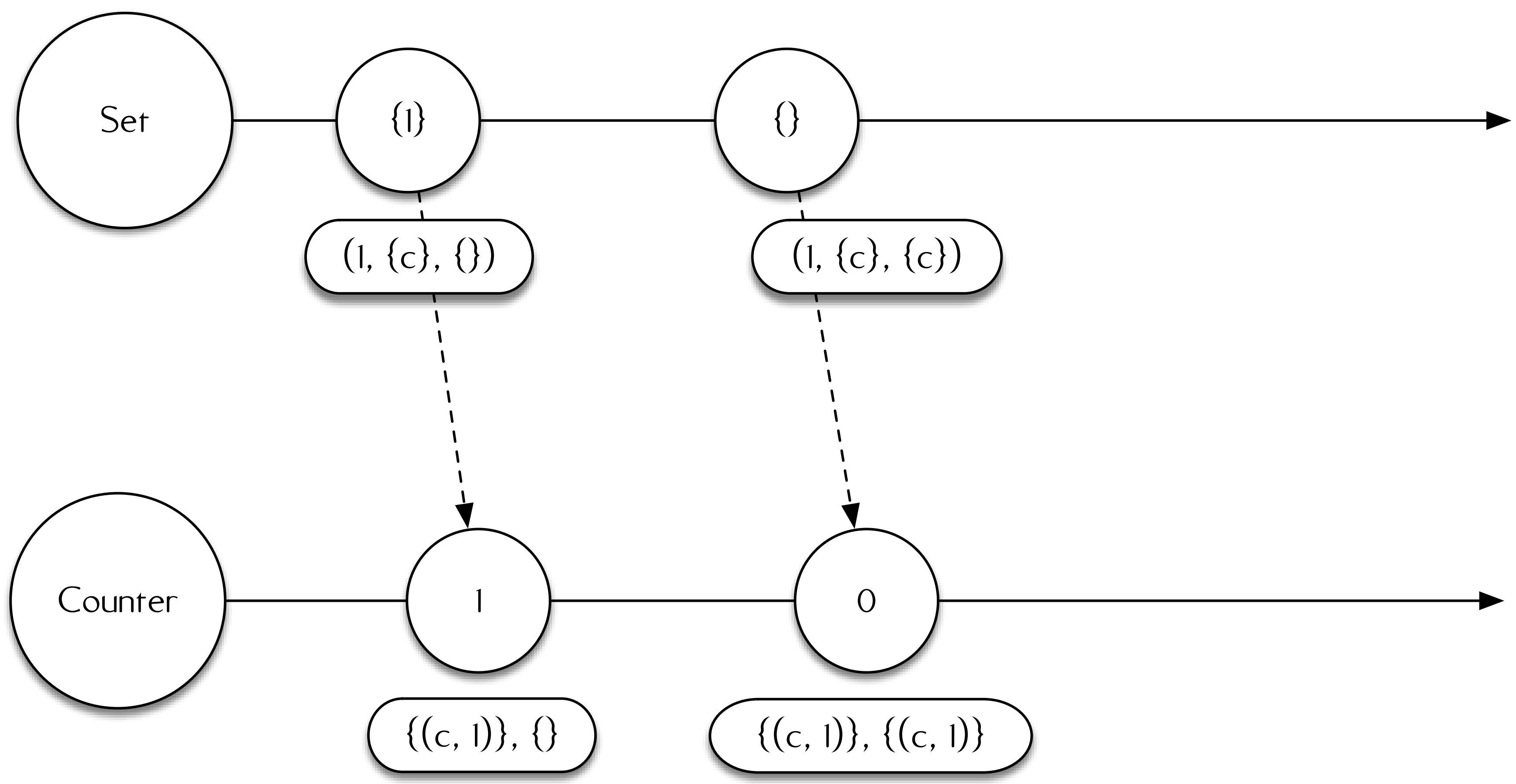
Challenges
Looking Ahead

Causality

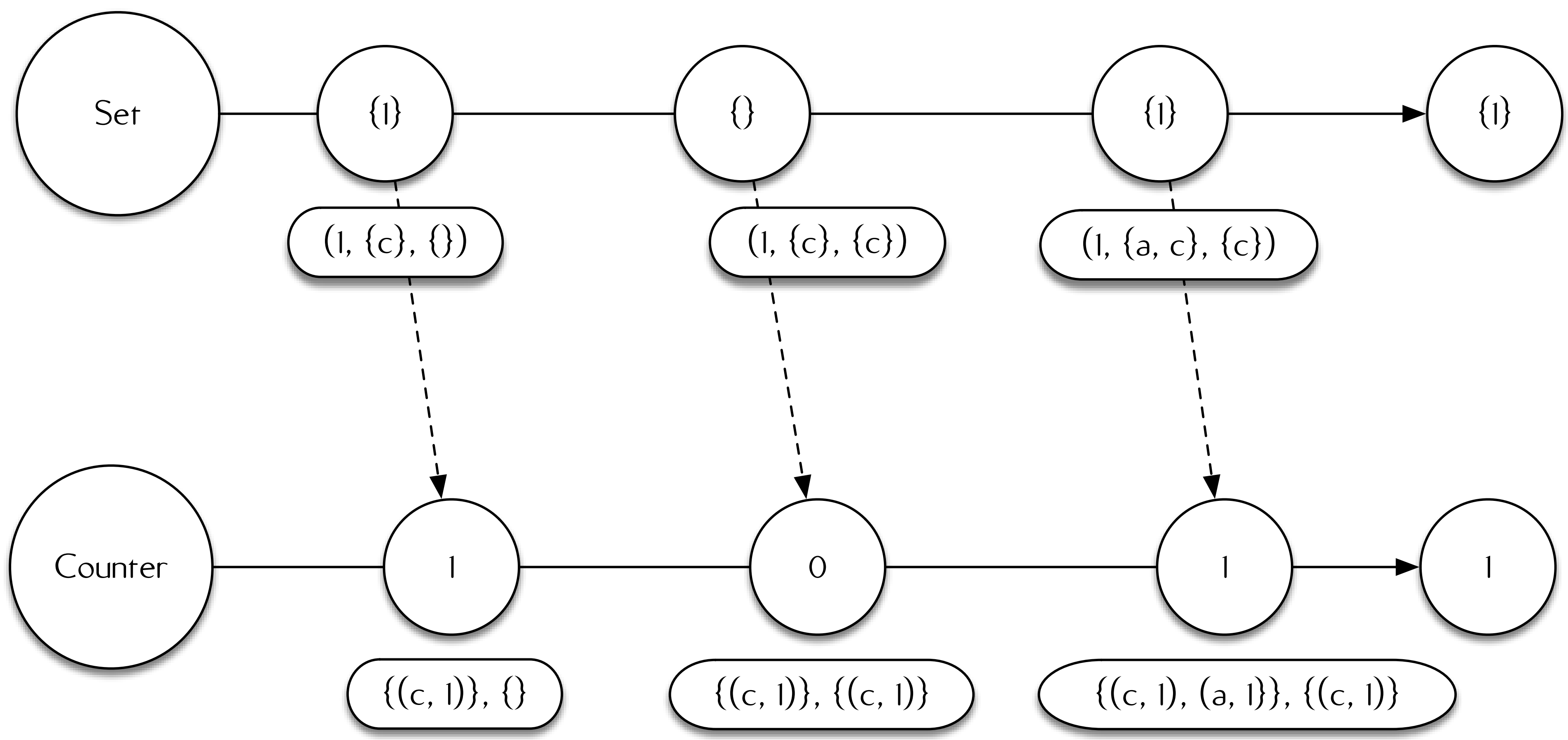
State Explosion


Set
Counter


Set
{1}
(1, {c}, {})
Counter
1
{(c, 1)}, {}



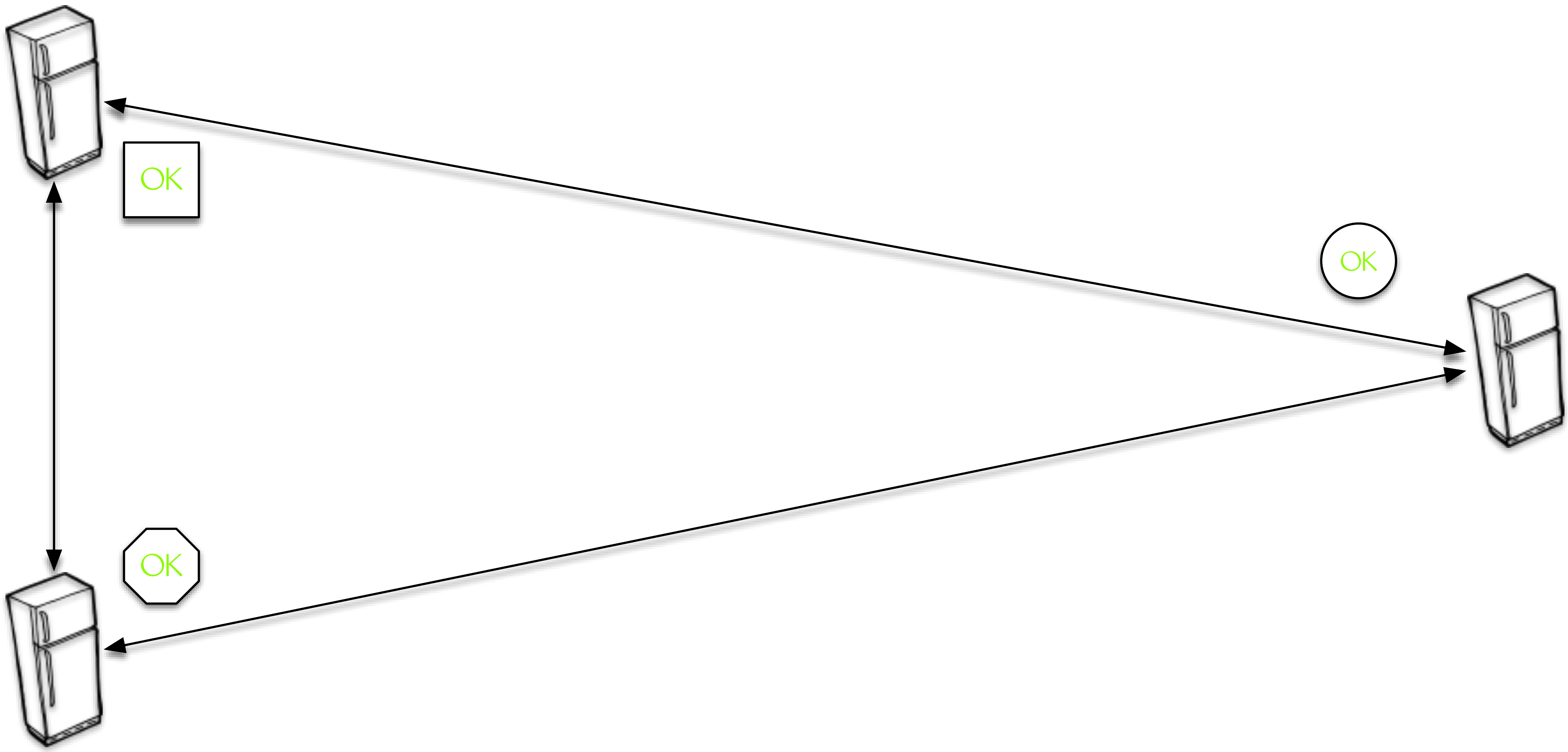
Set
{1}
{}
(1, {c}, {})
(1, {c}, {c})
Counter
1
0
{(c, 1)}, {}
{(c, 1)}, {(c, 1)}



Set
{1}
{}
{1}
{1}
(1, {c}, {})
(1, {c}, {c})
(1, {a, c}, {c})
Counter
1
0
1
1
{(c, 1)}, {}
{(c, 1)}, {(c, 1)}
{(c, 1), (a, 1)}, {(c, 1)}

Security

Computing at the Edge


OK
OK
OK

Computations

Expressiveness

How restrictive is a programming model where operations must be **associative**, **commutative**, and **idempotent**?

What's new?

Since Erlang Factory 2015

- Erlang 18, rebar3, Common Test
  Faster test suite, on Erlang 18 with rebar3

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- **Erlang 18, rebar3, Common Test**
  Faster test suite, on Erlang 18 with rebar3

- **No Riak Core**
  Plumtree distribution replaces the Riak Core distribution system

- **No NIFs**
  Allows us to cross-compile to other platforms and not worry about NIF scheduling

Semantics Improvements

- Delta-State Based Conflict-Free Replicated Data Types
  Optimized state dissemination by shipping deltas
  [Almeida *et al.*, 2016]

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- Fold
  New semantics for a more expressive fold operation for arbitrary computation over sets
  [Meiklejohn 2016, in review]

Runtime Improvements

- Delta-State Based Anti-Entropy
  Optimized AAE mechanism based on deltas
  [Almeida *et al.*, 2016]

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  [Meiklejohn and Yoo 2016, in review]

- Loquat
  Epidemic broadcast, partially replicated with
  Decentralized Information Flow Control
  [Meiklejohn 2016, in review]

Lasp Simulator

- Docker Containers
  Docker containers for EPMD and Lasp runtime system

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  Mechanisms for clustering Erlang nodes based on either Marathon application definitions of Mesos-DNS

- Instrumentation
  Transmission instrumentation and divergence measurement

Lasp Simulator

- Plumtree VM-to-VM
  VM-to-VM communication performed using the Plumtree epidemic broadcast protocol

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Lasp Simulator

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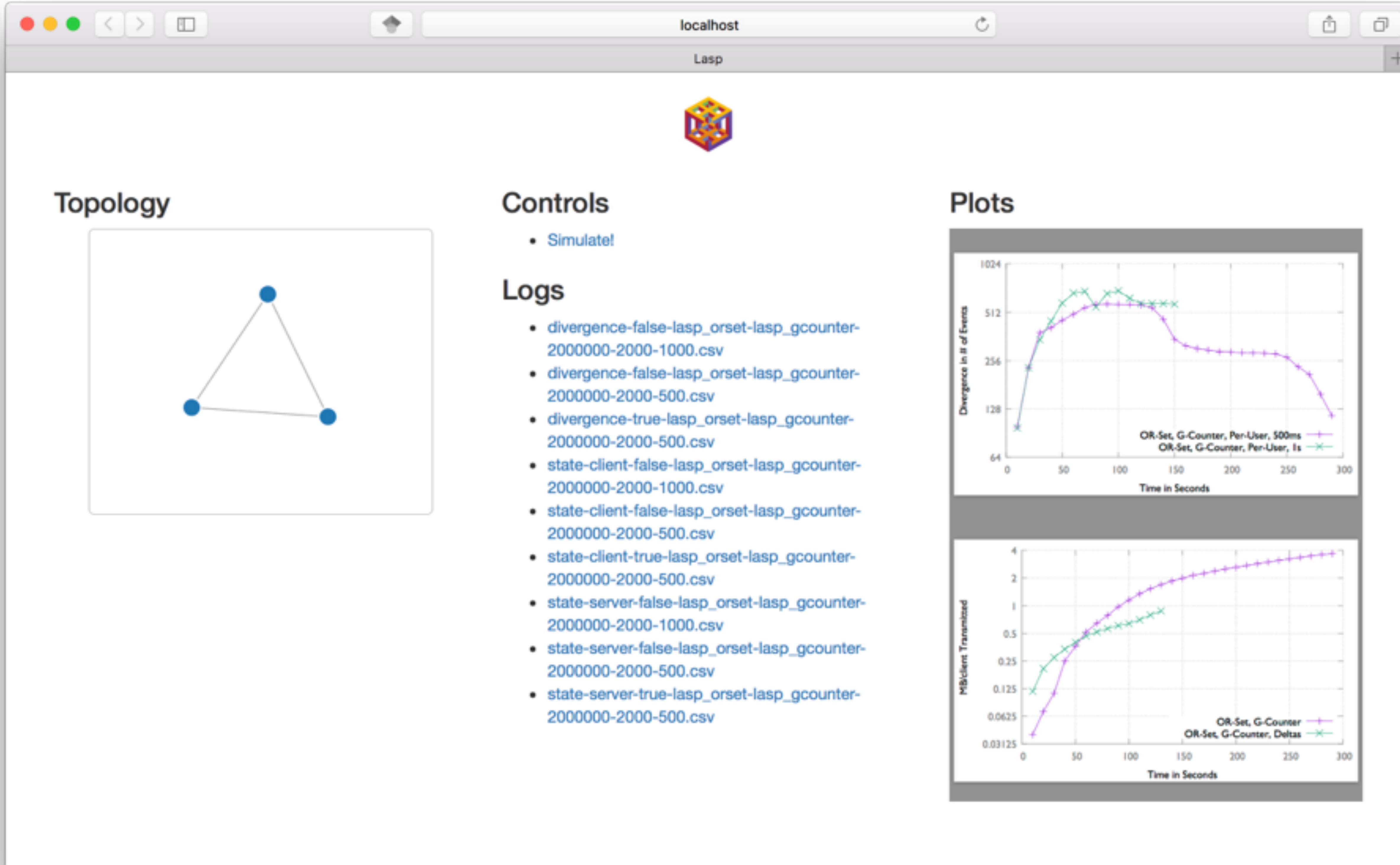
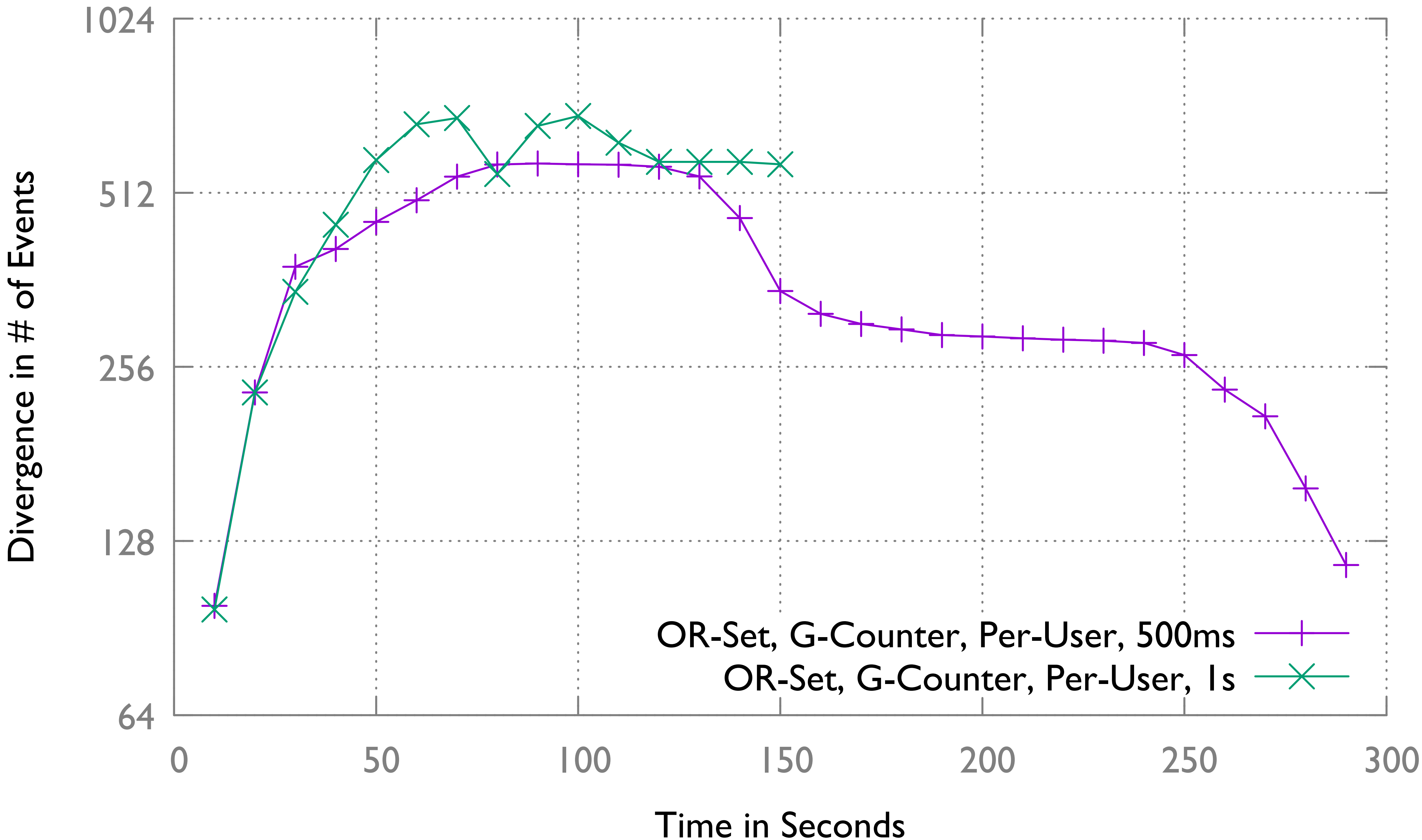
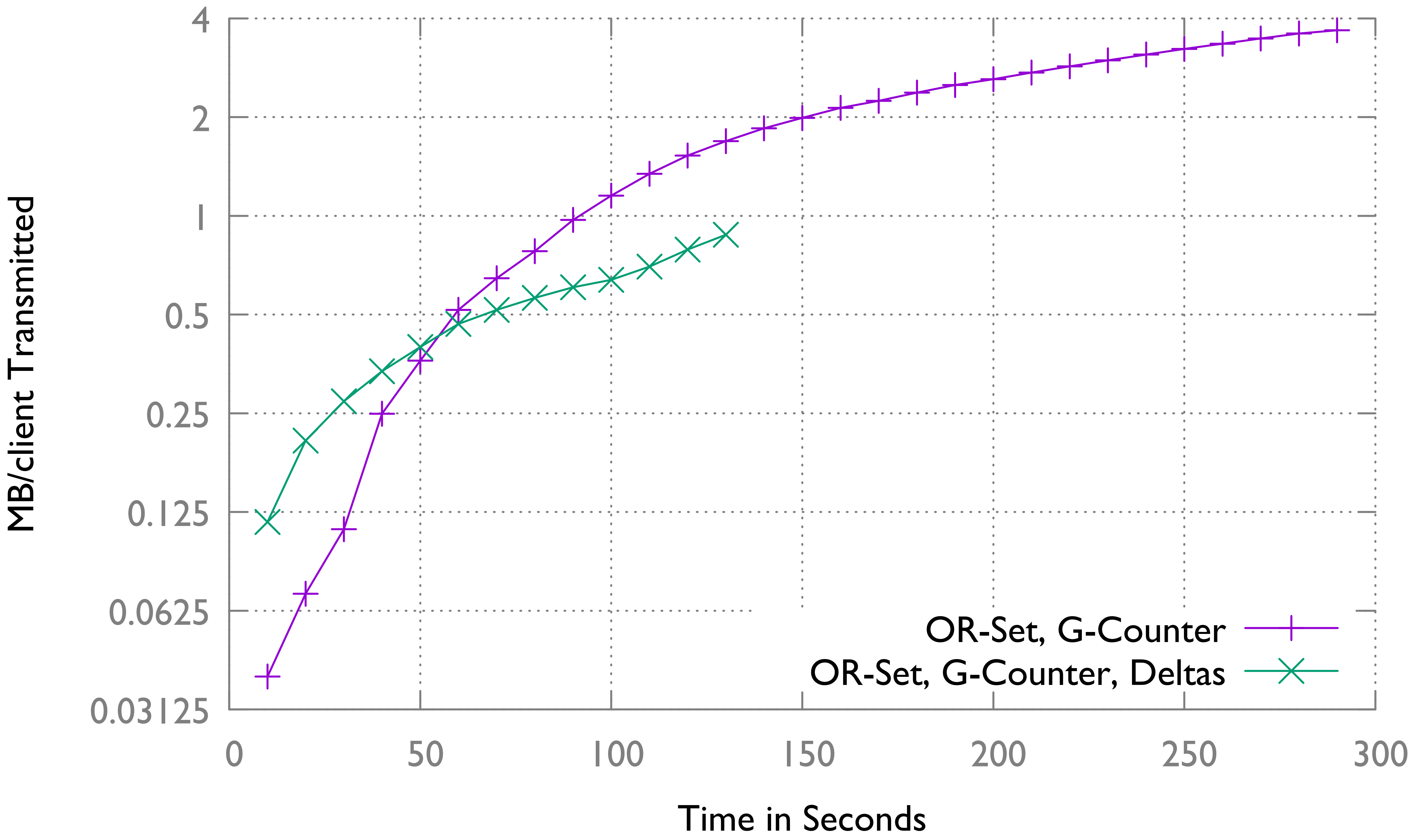
  VM-to-VM communication performed using the **Plumtree** epidemic broadcast protocol

- **Clients-as-processes**
  Multiple clients per virtual machine, acting as mobile/IoT devices that periodically simulate and can be partitioned

- **“Design in the small, run in the large”**
  Runtime configuration change for client-to-VM ratio, allows for **single laptop design of multi-machine evaluations** of the programming model


localhost
Lasp
Topology
Controls
Simulate!
Logs
divergence-false-lasp_orset-lasp_gcounter-2000000-2000-1000.csv
divergence-false-lasp_orset-lasp_gcounter-2000000-2000-500.csv
divergence-true-lasp_orset-lasp_gcounter-2000000-2000-500.csv
state-client-false-lasp_orset-lasp_gcounter-2000000-2000-1000.csv
state-client-false-lasp_orset-lasp_gcounter-2000000-2000-500.csv
state-client-true-lasp_orset-lasp_gcounter-2000000-2000-500.csv
state-server-false-lasp_orset-lasp_gcounter-2000000-2000-1000.csv
state-server-false-lasp_orset-lasp_gcounter-2000000-2000-500.csv
state-server-true-lasp_orset-lasp_gcounter-2000000-2000-500.csv
Plots
Divergence in # of Events
Time in Seconds
OR-Set, G-Counter, Per-User, 500ms
OR-Set, G-Counter, Per-User, 1s
MB/client Transmitted
Time in Seconds
OR-Set, G-Counter
OR-Set, G-Counter, Deltas


1024
512
256
128
64
0
50
100
150
200
250
300
Divergence in # of Events
Time in Seconds
OR-Set, G-Counter, Per-User, 500ms
OR-Set, G-Counter, Per-User, 1s



4
2
1
0.5
0.25
0.125
0.0625
0.03125
MB/client Transmitted
0
50
100
150
200
250
300
Time in Seconds
OR-Set, G-Counter
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What's next?

Google Summer of Code (and my Ph.D.!)

- Partial Evaluation
  Optimize execution based on analysis and annotations where we can determine local-vs-remote usage

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  General optimizations of the Erlang implementation of Lasp to improve performance of the runtime system

Google Summer of Code (and my Ph.D.!)

- Partial Evaluation
  Optimize execution based on analysis and annotations where we can determine local-vs-remote usage

- Optimizations
  General optimizations of the Erlang implementation of Lasp to improve performance of the runtime system

- Elixir / Macros
  Provide a nicer way for working with Lasp, outside of the current syntax.

How do I learn more?

Publications

- “Lasp: A Language for Distributed, Coordination-Free Programming”
  ACM SIGPLAN PPDP 2015
- “Selective Hearing: An Approach to Distributed, Eventually Consistent Edge Computation”
  IEEE W-PSDS 2015
- “The Implementation and Use of a Generic Dataflow Behaviour in Erlang”
  ACM SIGPLAN Erlang Workshop ’15
- “Lasp: A Language for Distributed, Eventually Consistent Computations with CRDTs"
  PaPoC 2015
- “Declarative, Sliding Window Aggregations for Computations at the Edge"
  IEEE EdgeCom 2016

Thanks!

Christopher Meiklejohn
@cmeik
http://www.lasp-lang.org