TDDD25
Distributed Systems

Replication

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Agenda

REPLICATION

1. Motivation and Requirements
2. Architectural Model
3. Request Ordering
4. Implementing Total and Causal Ordering
5. Update Protocols

Motivation

Replication is the maintenance of on-line copies of data (files).

- Each copy is located on a separate **replica manager** (server).
- Each copy is called a **replica**.

Benefits of replication:

- Increased **availability** and **fault tolerance**:
  - The system remains operational and available to the users despite failures.
  - Alternate copies of a replicated data can be used when a primary copy is unavailable.
- **Performance** enhancement:
  - Data shared between a large number of clients should not be held at a single server; such a single server becomes a bottleneck.
  - Data should be replicated on several servers, each one providing service to a group of users close to the server.
  - Thus, network traffic is also reduced.

Main Requirements with Replication

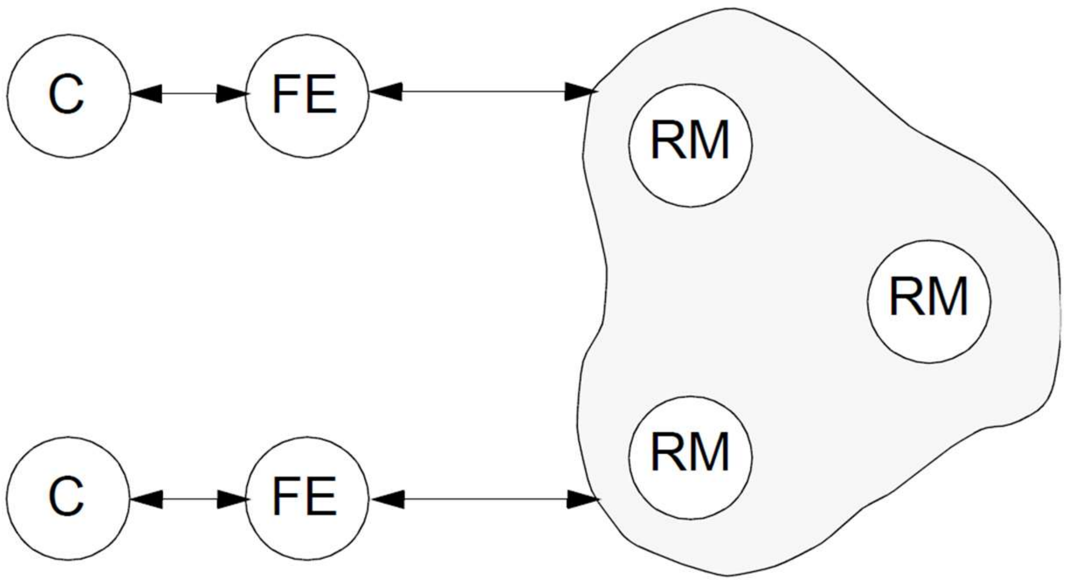
- **Replication transparency:**
  - The clients should not be aware that multiple physical copies of data exist.
- **Consistency:**
  - Consistency implies that any access from a client should be served with correct data (regardless of the replica manager it directly has access to)
  - What *correct* means, depends on the particular application:
    - In some situations, it is enough that all operations are *eventually* performed on all copies; it is acceptable that, at certain moments, different clients read *different* versions of the replicated data.
      - Question: *how* different?
    - Often, client access has to provide the **most recent** version of the data.

Problems:

1. The **order** in which operations are performed on the different replicas.
2. Do we always need to **update** all replicas?
   If not, how can we guarantee that an access is always served with the latest version?
3. The effect of replication on **performance**:
   strong requirements on consistency can lead to significant overheads.

Architectural Model

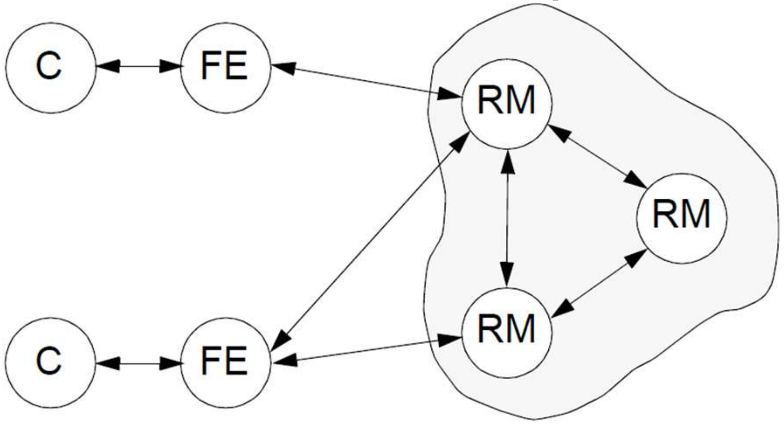
- **Client** (C): makes a request (read or update)
- **Front-end** (FE): proxy server, communicates with one or more replica managers (provides replication transparency)
- **Replica managers** (RM): contain the replicas and perform operations on them



Different alternative models are possible, depending on the particular communication pattern between FEs and RMs, and between the different RMs.

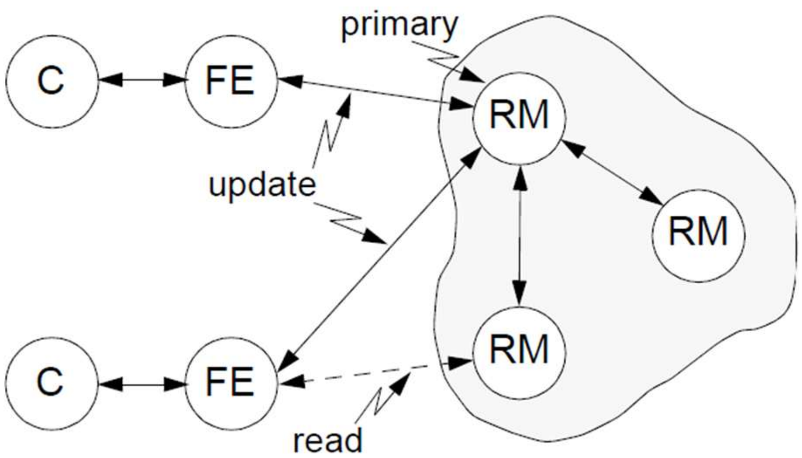
Architectural Model

All RMs communicate with each other in order to agree on operations so that **coherence** is preserved between copies.



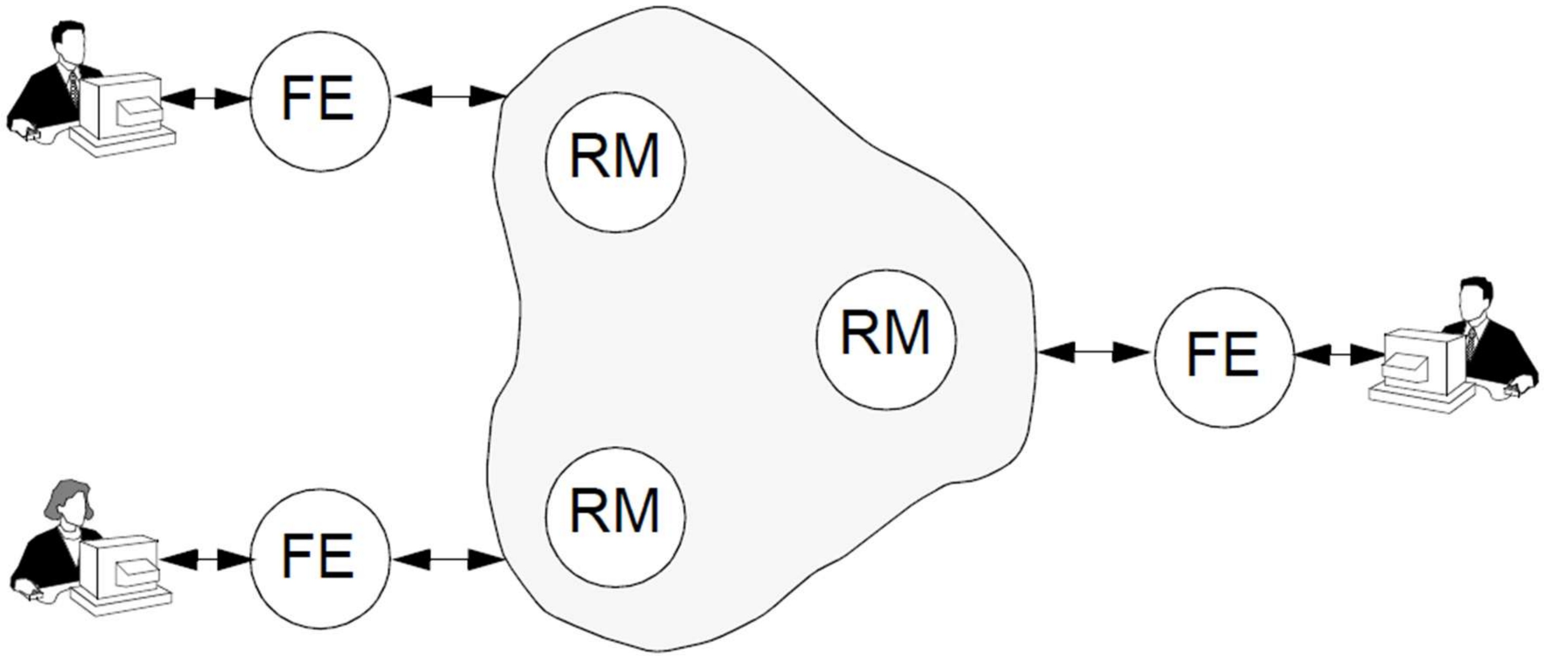
A **"primary" RM** coordinates the other RMs managing copies of the same data

- **Update requests** are directed from FEs to that primary RM, which propagates them to the other RMs.
- **Read requests** can be directed to any RM.



Example: Bulletin Board System

- **Users** at different sites share a **bulletin board**.
- A **server** at each site hosts a **replica** of the board content.
- Each user can
  - **post** new items,
  - **select** a certain item to visualise, and
  - **respond** to a given message.



Example: Bulletin Board System

- Items are displayed as available at a certain server, *in the order in which they have been received*.

Erik's view

Item	From	Subject
14	Johansson	weather
15	Ericsson	Java
16	Perkins	clocks
17	Johansson	Re:Java
18	Schmidt	Re: weather

Diana's view

Item	From	Subject
17	Perkins	clocks
18	Johansson	Re:Java
19	Pop	lab
20	Ericsson	Java
21	Schmidt	Re: weather
22	Larsson	bandy

Request Ordering

Ordering of requests at the replica manager is sometimes essential in order to preserve consistency as required by the specific application.

- **Total ordering**
  - If r_1 and r_2 are requests, then either r_1 is processed before r_2 at all replica managers or r_2 is processed before r_1 at all replica managers.

Erik's view

Item	From	Subject
17	Perkins	clocks
18	Ericsson	Java
19	Johansson	weather
20	Johansson	Re:Java
21	Schmidt	Re: weather
22	Larsson	bandy

Diana's view

Item	From	Subject
17	Perkins	clocks
18	Ericsson	Java
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20	Johansson	Re:Java
21	Schmidt	Re: weather
22	Larsson	bandy

- In this case, users at different sites will see the items in identical order and can refer to them by their **number**.

Request Ordering

Causal ordering

- If two requests r_1 and r_2 are in a happened-before relation $r_1 \rightarrow r_2$, then r_1 is processed before r_2 at <u>all</u> replica managers.

Erik's view

Item	From	Subject
14	Johansson	weather
15	Ericsson	Java
16	Perkins	clocks
17	Johansson	Re:Java
18	Schmidt	Re: weather

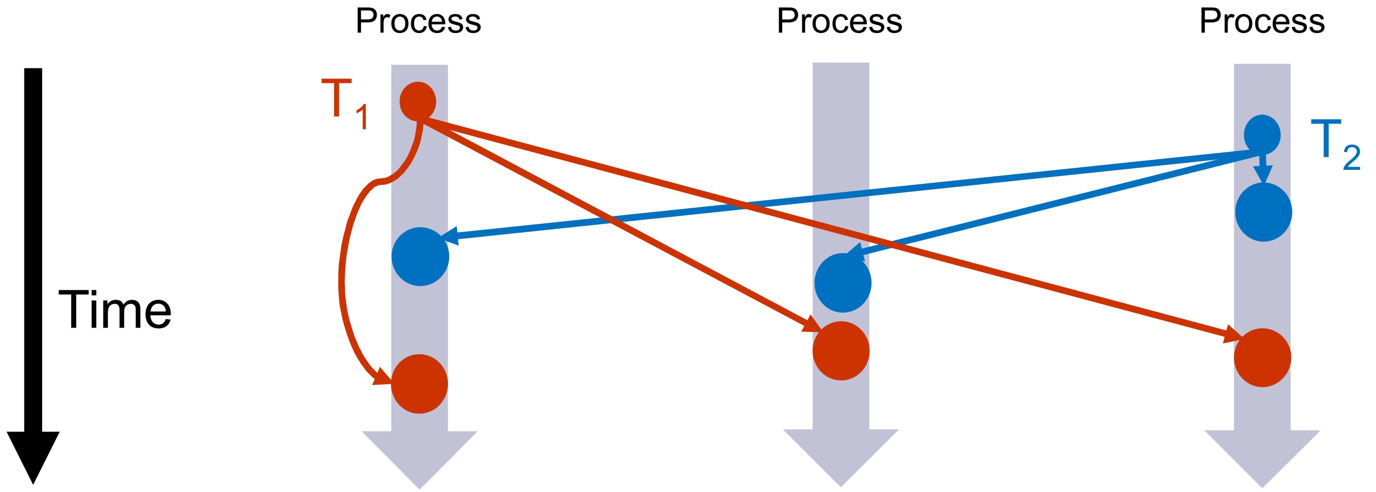
Diana's view

Item	From	Subject
17	Perkins	clocks
18	Larsson	bandy
19	Pop	lab
20	Ericsson	Java
21	Johansson	Re:Java

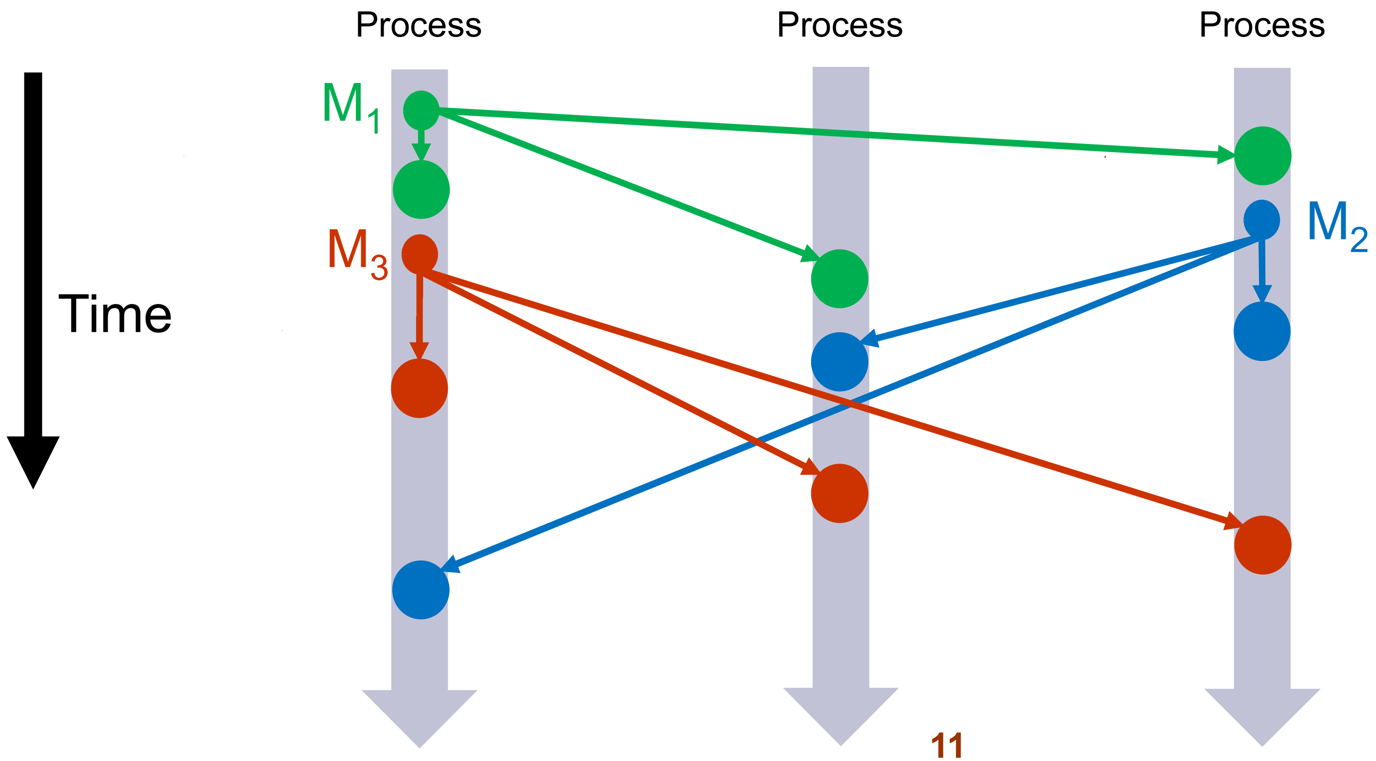
In this case, a user will never see an answer message before she has seen the initial message.

In general, total ordering does *not* necessarily imply causal ordering; it only means that all replica managers handle requests in the *same* (possibly, non-causal) order.

Total vs. Causal Ordering of Multicast Messages / Requests



Totally ordered



Causally ordered for causally related messages M1→M2, M1→M3, but not totally ordered (M2 || M3)

Implementing Total Ordering

The basic idea:

- Assign **totally ordered identifiers** *uid*(*r*) to requests;
- Each replica manager makes the same ordering decision based on these identifiers.

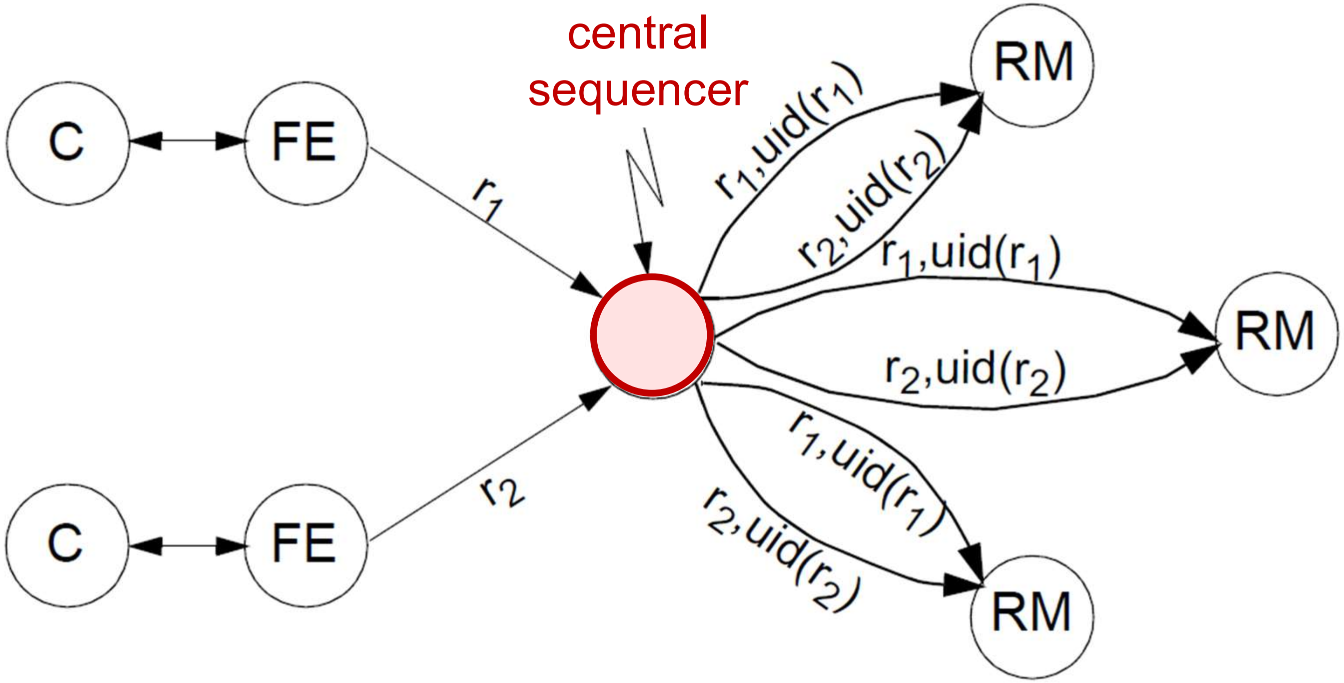
- Notice: it is not sufficient the identifiers to be unique:
  - For a total ordering algorithm, it is needed that a site knows *when* to process a request r_1 with unique identifier $uid(r_1)$, so that no other request r_2 can arrive later so that $uid(r_2) < uid(r_1)$.

Implementing Total Ordering

- Total ordering with **central sequencer**

- Total ordering based on **distributed agreement**

Total Ordering with Central Sequencer



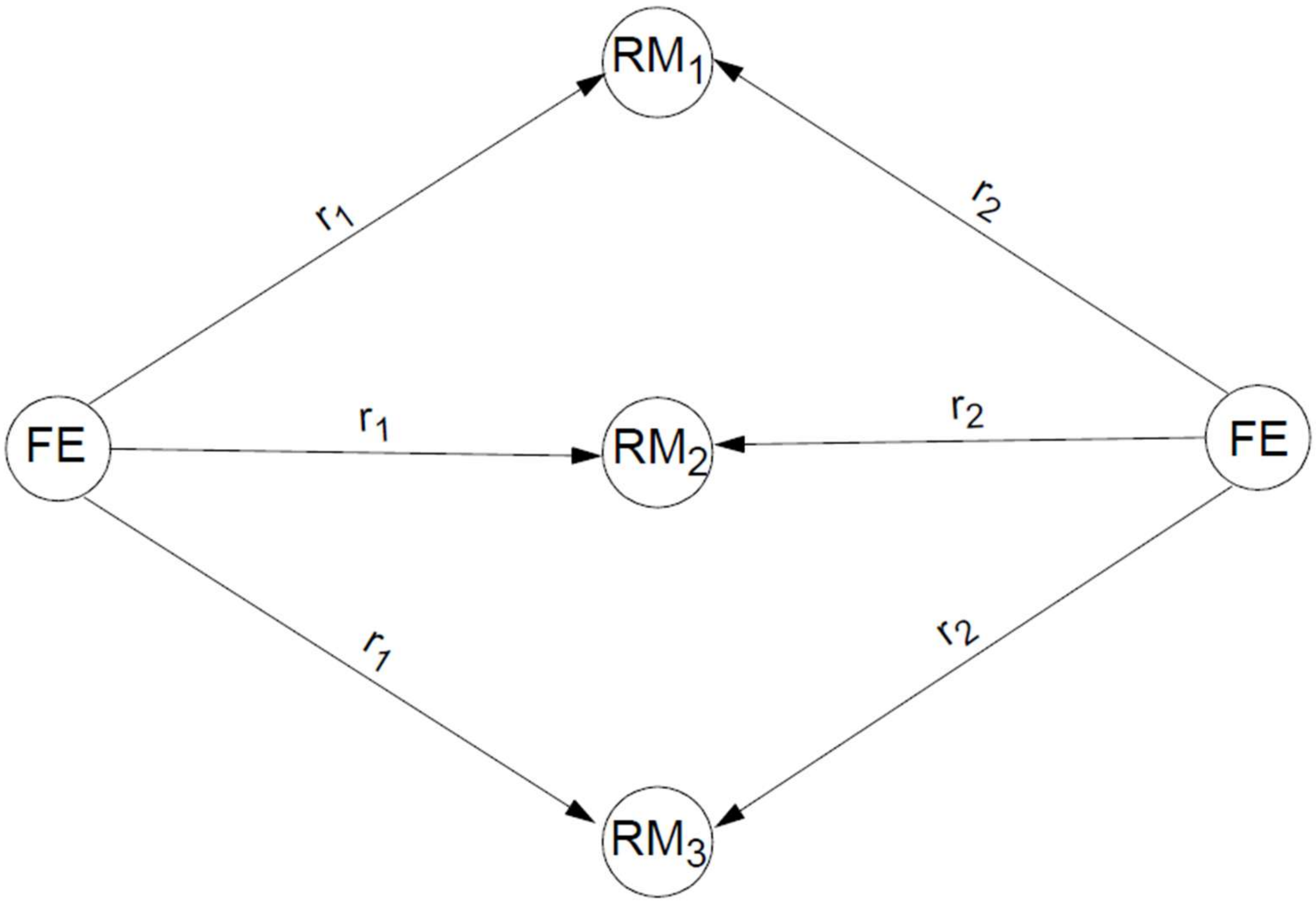
All requests are sent to the **sequencer**.

The sequencer assigns consecutive increasing identifiers to requests as it receives them, and forwards the requests with the corresponding identifier to the RMs.

- One of the RMs, appointed after election, can act as central sequencer.
- The sequencer becomes a performance bottleneck and a critical point of failure.

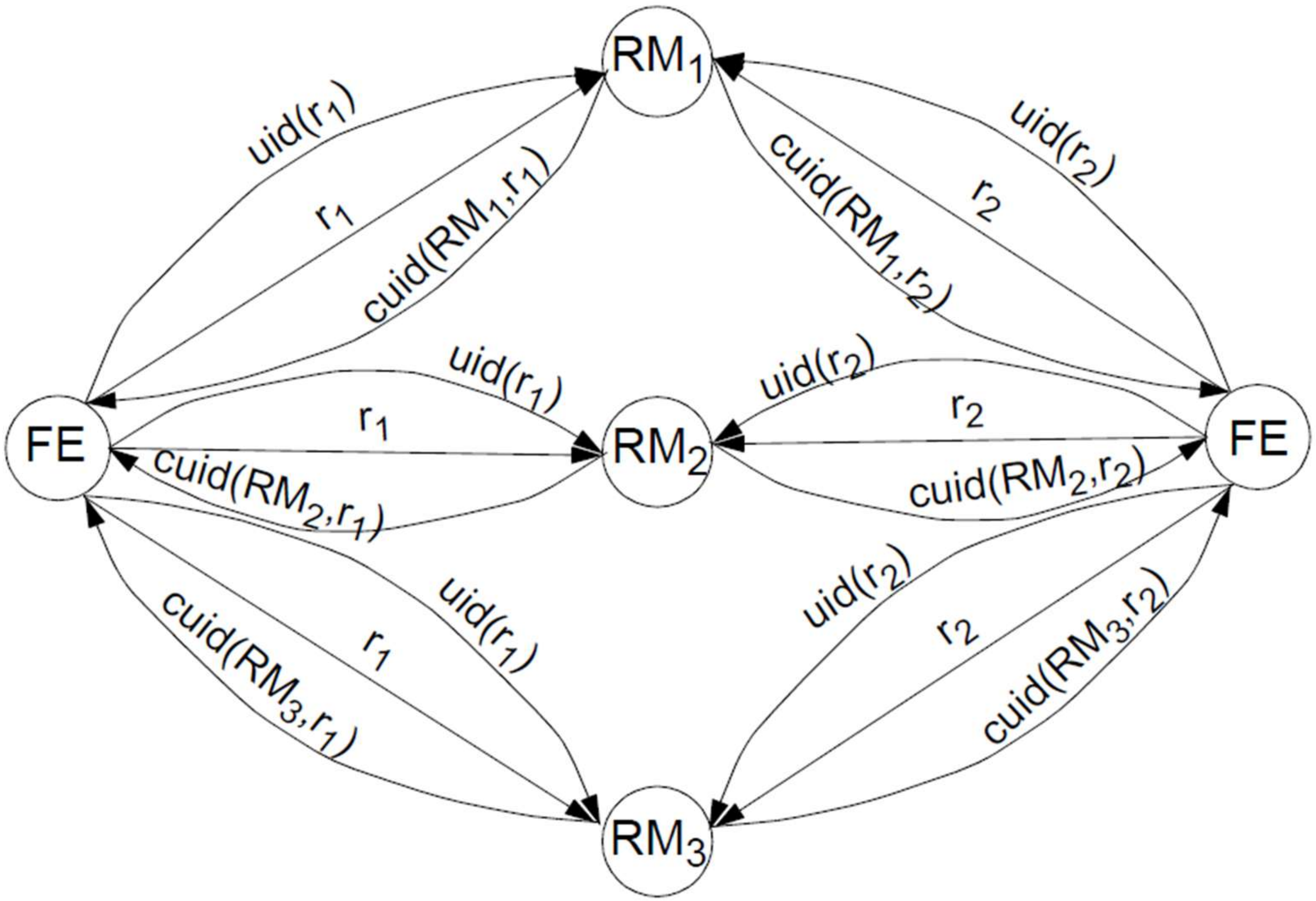
Total Ordering Based on Distributed Agreement

- This method avoids the need for a centralized sequencer.



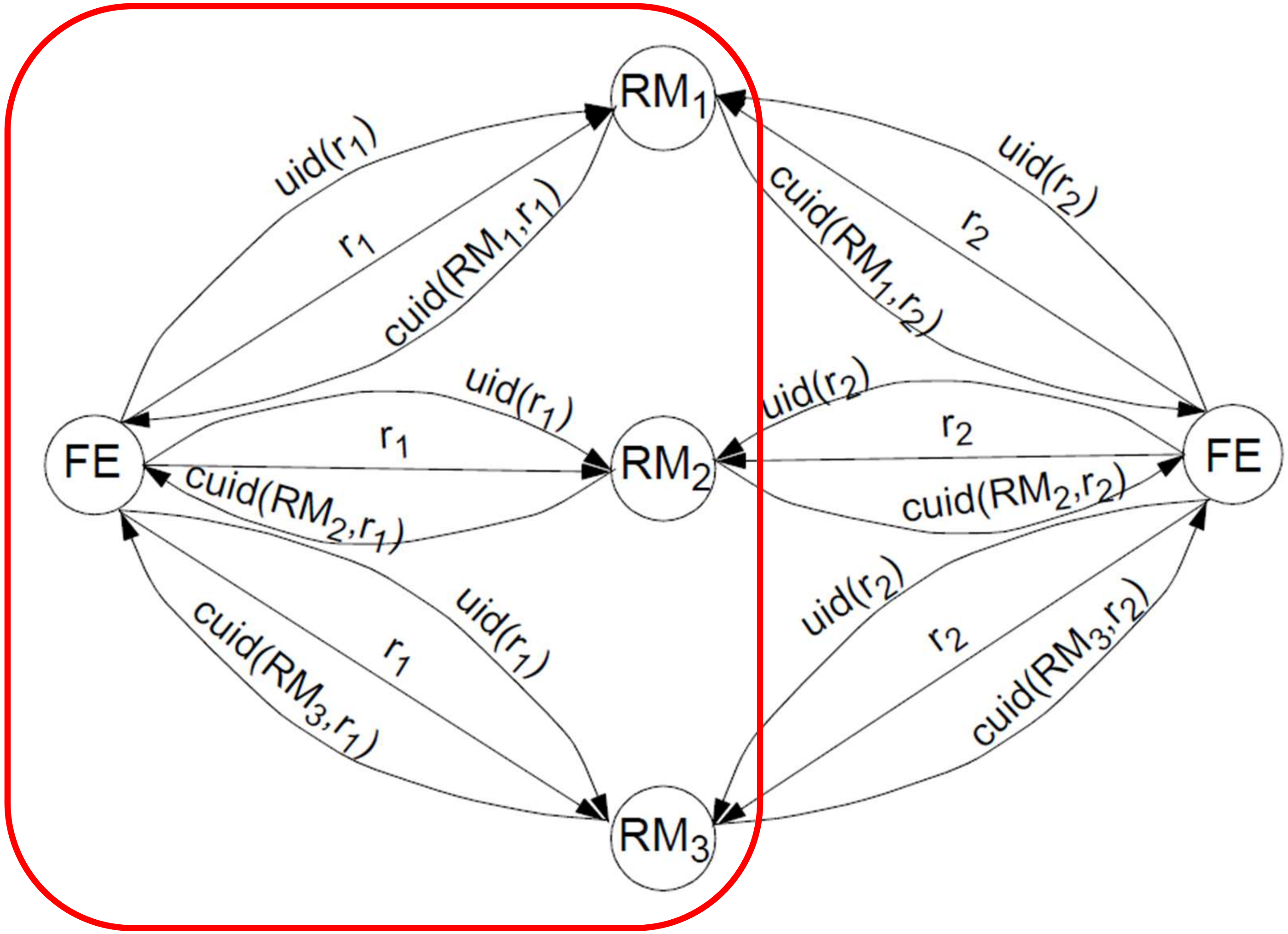
Total Ordering
Based on Distributed Agreement

- This method avoids the need for a centralized sequencer.
- Identifiers are assigned to requests as result of distributed agreement

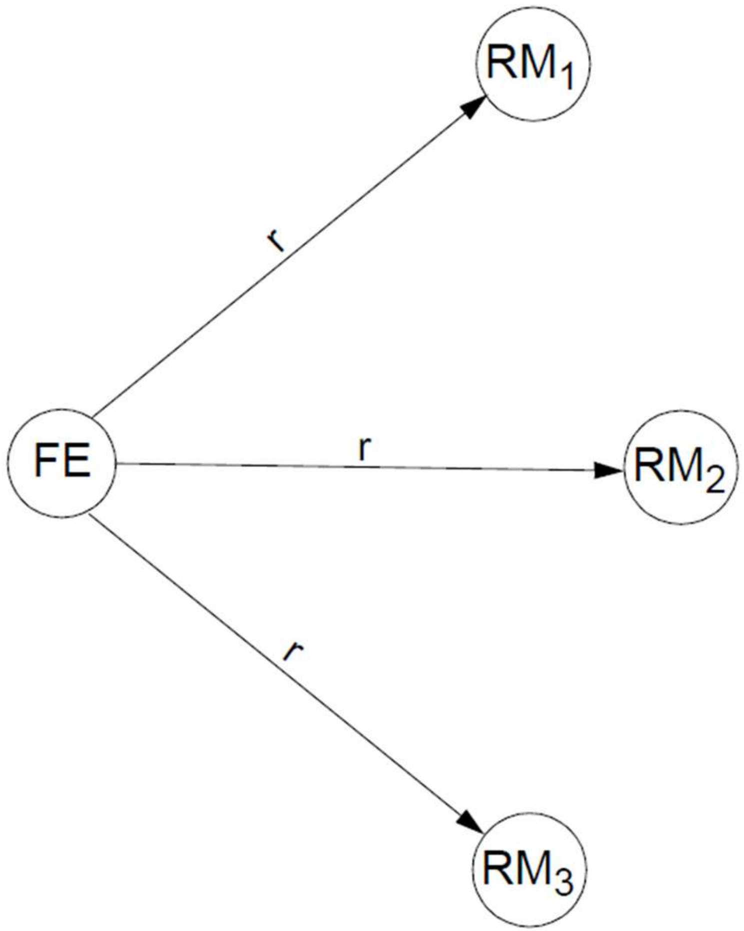


Total Ordering
Based on Distributed Agreement

- This method avoids the need for a centralized sequencer.
- Identifiers are assigned to requests as result of distributed agreement



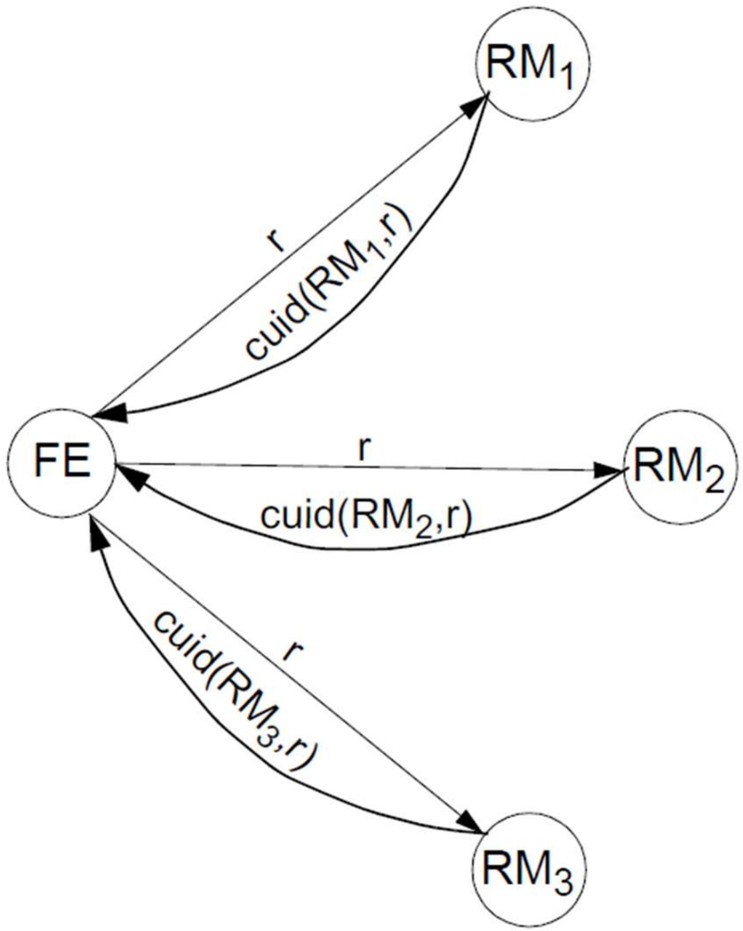
Total Ordering Based on Distributed Agreement



Total Ordering
Based on Distributed Agreement

Unique identifiers are computed in two phases:

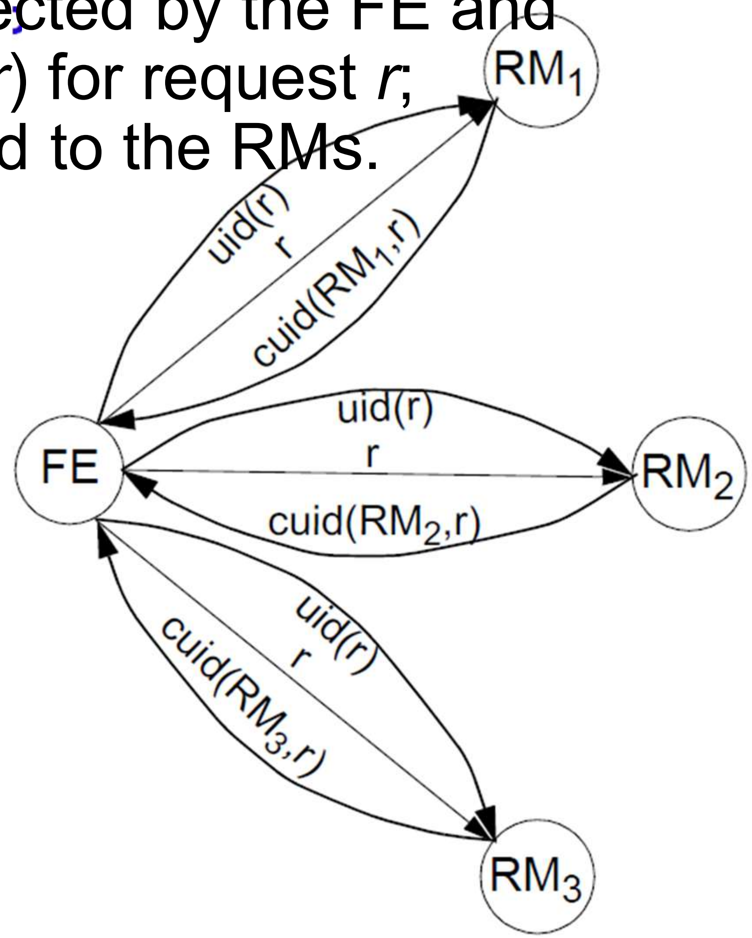
1. Each RM proposes a **candidate unique identifier** *cuid*(RM,*r*) for a request *r*; the *cuid* is forwarded to the FE that issued the request.



Total Ordering
Based on Distributed Agreement

Unique identifiers are computed in two phases:

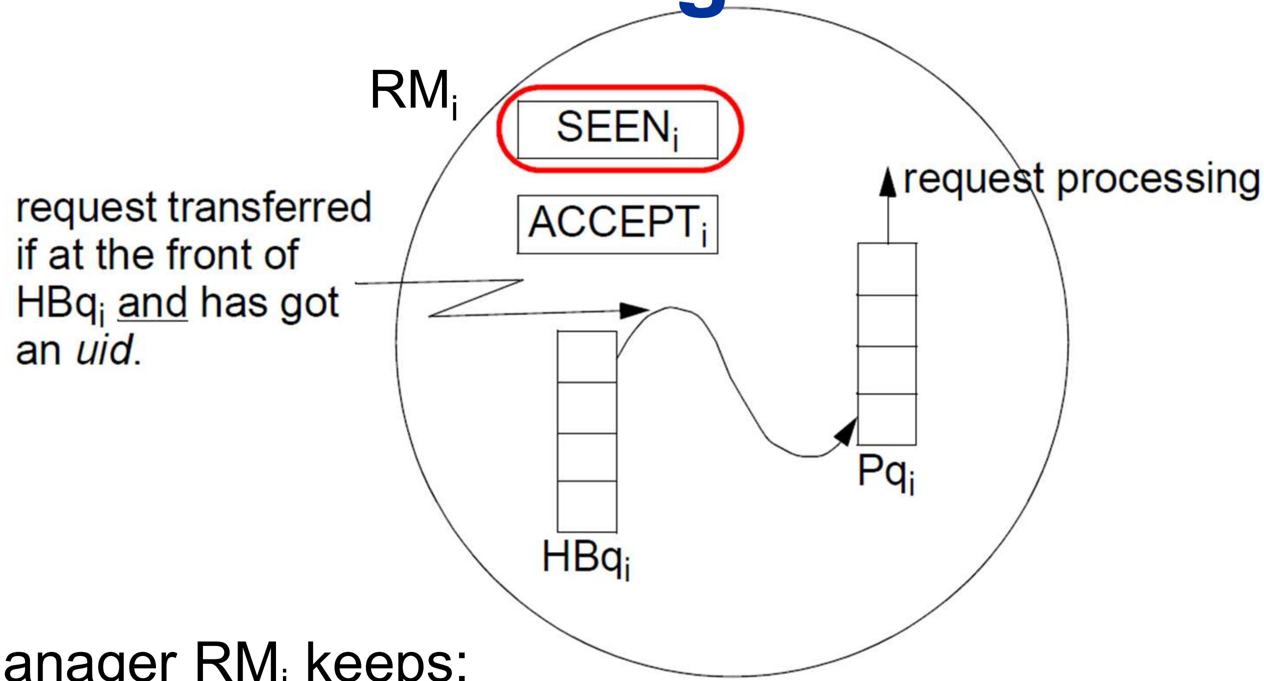
1. Each RM proposes a **candidate unique identifier** *cuid*(RM,*r*) for a request *r*; the *cuid* is forwarded to the FE that issued the request.
2. One of the candidate identifiers is selected by the FE and it becomes the **unique identifier** *uid*(*r*) for request *r*; the selected identifier is communicated to the RMs.



Total Ordering
Based on Distributed Agreement

- A replica manager RM_i has **seen** a request *r* once RM_i has received *r* and has proposed a *cuid*(RM_i,*r*) to be forwarded to the respective FE.
- A replica manager RM_i has **accepted** a request *r*, once RM_i knows the ultimate choice of *uid*(*r*) made for *r* by the respective FE.

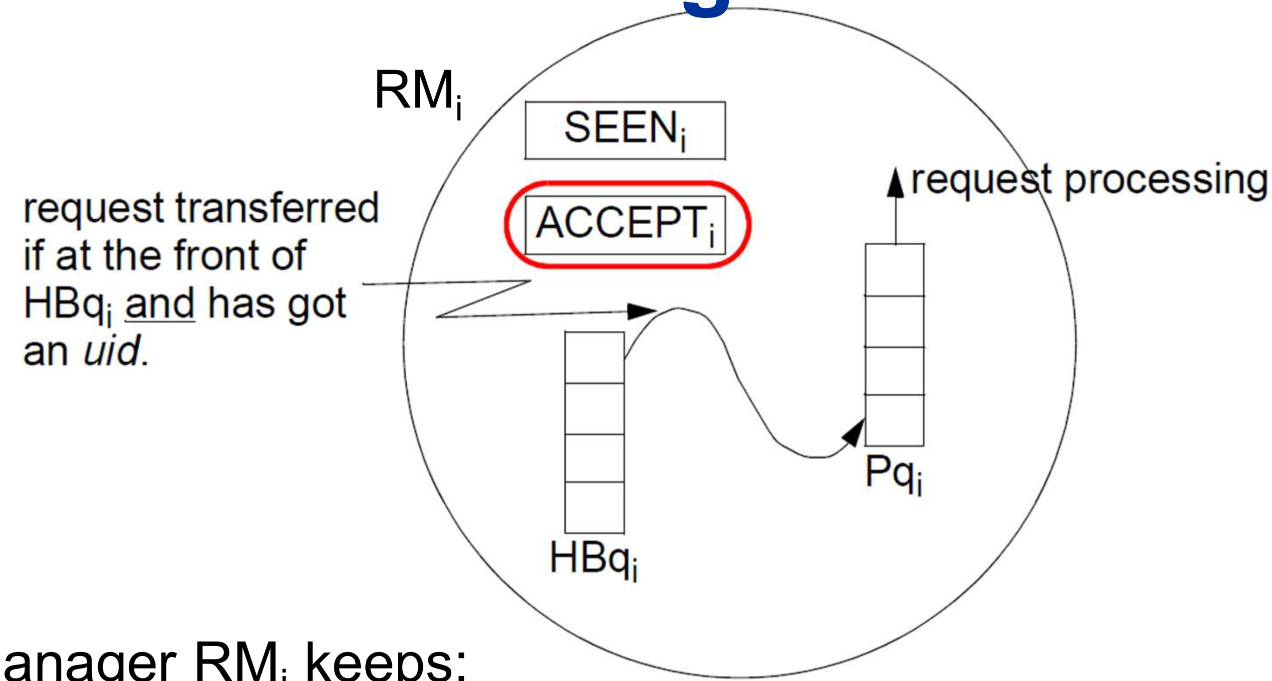
Total Ordering
Based on Distributed Agreement



Each replica manager RM$_i$ keeps:

- SEEN$_i$: the largest *cuid*(RM$_i$,*r*) assigned to any request *r* so far seen by RM$_i$

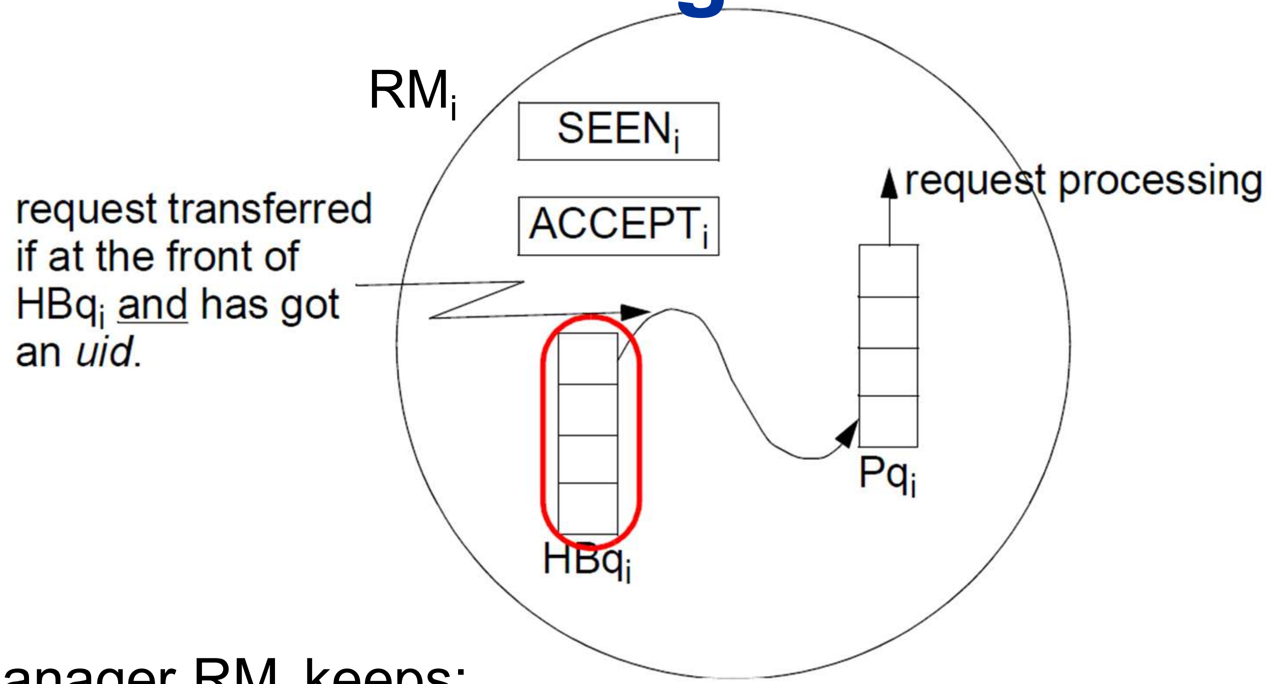
Total Ordering Based on Distributed Agreement



Each replica manager RM_i keeps:

- $SEEN_i$: the largest *cuid*(RM_i,*r*) assigned to any request *r* so far seen by RM_i
- $ACCEPT_i$: the largest *uid*(*r*) assigned to any request *r* so far accepted by RM_i

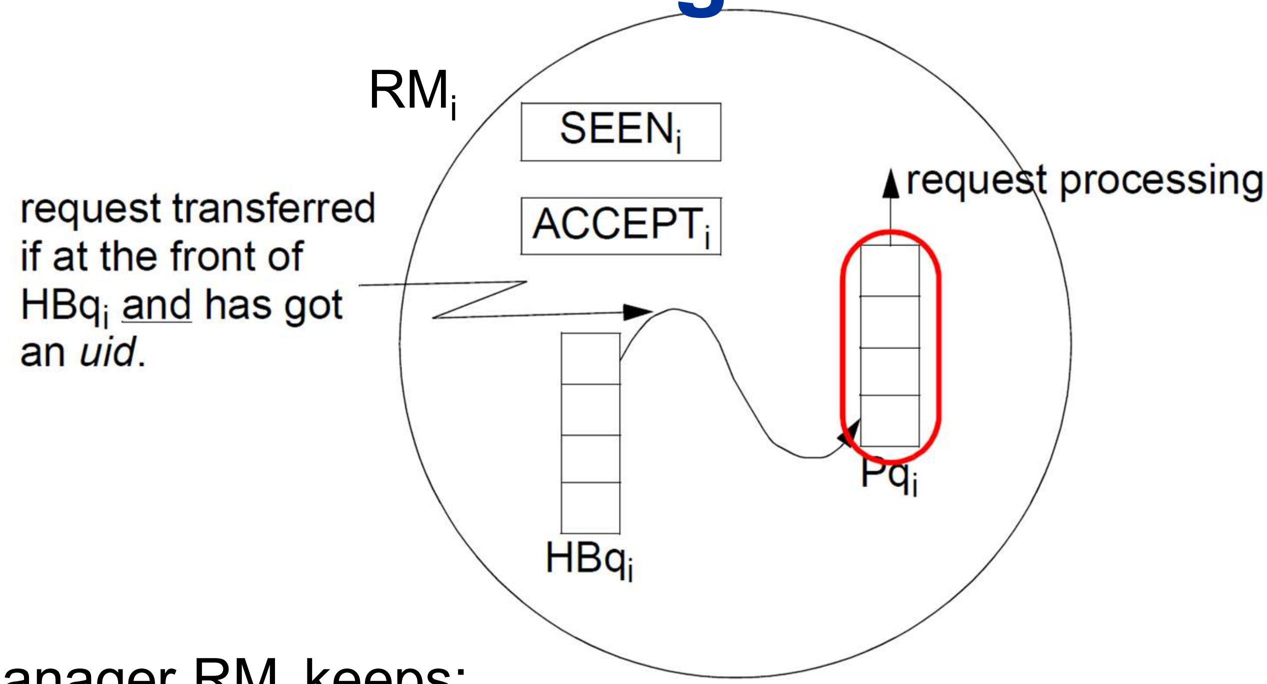
Total Ordering Based on Distributed Agreement



Each replica manager RM$_i$ keeps:

- SEEN$_i$: the largest *cuid*(RM$_i$,*r*) assigned to any request *r* so far seen by RM$_i$
- ACCEPT$_i$: the largest *uid*(*r*) assigned to any request *r* so far accepted by RM$_i$
- **Hold-back queue** (HBq$_i$): When arrived at RM$_i$, a request *r* is kept on the HBq$_i$, ordered according to its *cuid*(RM$_i$,*r*).
  - When the final *uid*(*r*) is received, HBq$_i$ is **reordered** so that *r* is placed according to its *uid*.
  - When a request is at the front of HBq$_i$ and got an *uid*, it is **moved** to Pq$_i$.

Total Ordering
Based on Distributed Agreement



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- SEEN$_i$: the largest *cuid*(RM$_i$,*r*) assigned to any request *r* so far seen by RM$_i$
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- **Hold-back queue** (HBq$_i$): When arrived at RM$_i$, a request *r* is kept on the HBq$_i$, ordered according to its *cuid*(RM$_i$,*r*).
  - When the final *uid*(*r*) is received, *HBq*$_i$ is **reordered** so that *r* is placed according to its *uid*.
  - When a request is at the front of *HBq*$_i$ and got an *uid*, it is **moved** to *Pq*$_i$.
- **Processing queue** (*Pq*$_i$): *Pq*$_i$ holds accepted requests which before had been placed at the front of *HBq*$_i$; these requests are processed in order of their *uid*.

Total Ordering
Based on Distributed Agreement

- The *cuid* proposed by RM_i for a certain request *r* is:
  (*N* is the number of RMs)

  $$cuid(RM_i, r) = \mathbf{max}(\, SEEN_i\, , ACCEPT_i\,) + 1 + i / N$$

  the identifier is unique per RM_i (covers $\mathbf{max}(SEEN_i, ACCEPT_i) + 1$)

  the identifier is unique in the system (covers $\mathbf{max}(SEEN_i, ACCEPT_i) + 1 + i / N$)

- Once a FE has received, for a certain request *r*, the *cuid*(RM_i,*r*) from all RM_i, it decides on the *uid* for *r*:

  $$uid(r) = \mathbf{max}_{i=1\,..\,N}\,(\, cuid(RM_i, r))$$

Question: Once a request r_1 with *uid*(r_1) has been moved to *Pq*, is it possible that another request r_2 will be moved later and *uid*(r_2) < *uid*(r_1)?

Total Ordering
Based on Distributed Agreement

In order to be moved to *Pq*, the request has

- to be at the front of *HBq*, and
- to have got an *uid*.

Possible alternatives:

- r_2 has already got an *uid* when r_1 is moved
  → $uid(r_2) > uid(r_1)$ (r_1 is in front of *HBq*)
- r_2 has no *uid* yet, but has already got a *cuid* when r_1 is moved (r_2 has been seen, but not accepted)
  → $uid(r_2) \geq cuid(\mathrm{RM}, r_2)$
  $cuid(\mathrm{RM}, r_2) > uid(r_1)$ (r_1 is in front of *HBq*)
  → $uid(r_2) > uid(r_1)$
- r_2 has no *cuid* yet when r_1 is moved (r_2 has not been seen yet) .
  $\mathrm{ACCEPT} \geq uid(r_1)$
  $cuid(\mathrm{RM}, r_2) > \mathrm{ACCEPT}$
  $uid(r_2) \geq cuid(\mathrm{RM}, r_2)$
  → $uid(r_2) > uid(r_1)$

Total Ordering Based on Distributed Agreement

Rule for initialization:

/* performed by each RM_i at initialization */

[RI1]: $SEEN_i := 0$
$ACCEPT_i := 0$
$HBq_i := \varnothing$
$Pq_i := \varnothing$

Rule for handling incoming requests at an RM:

/* performed whenever a request *r* is **received** by a replica manager RM_i */

[RC1]: $cuid(RM_i, r) = \mathbf{max}(SEEN_i, ACCEPT_i) + 1 + i / N$

[RC2]: $SEEN_i := cuid(RM_i, r)$

[RC3]: Introduce *r* in HBq_i, ordered according to its *cuid*

[RC4]: RM_i **sends** $cuid(RM_i, r)$ to the FE which issued *r*.

Total Ordering
Based on Distributed Agreement

Rule for handling incoming *uid*'s at an RM:

/* performed whenever a decision concerning the *uid* of a request *r* is **received** by a replica manager RM_i */

[RU1]: $ACCEPT_i$:= **max** ($ACCEPT_i$, *uid*(*r*))

[RU2]: **if** *uid*(*r*) ≠ *cuid*(RM_i,*r*) then

HBq_i is **reordered** so that *r* is placed according to its *uid*

end if

[RU3]: If the request at the front of HBq_i has an *uid*, it is moved to Pq_i in order to be processed.

Rule for issuing requests at an FE:

/* performed by FE when it issues request *r* and assigns the corresponding *uid* */

[RF1]: FE sends request *r* to all RM_i, $i \in \{1,...,N\}$

[RF2]: After *cuid*(RM_i,*r*) has been received from all RM_i,

$uid(r) := \max_{i \in \{1,...,N\}} cuid(RM_i, r)$

[RF3]: FE **sends** the final *uid* for *r* to all RM_i

Total Ordering
Based on Distributed Agreement

- Compared to the central sequencer approach,
there is no performance bottleneck and unique point of failure.

- If the FE fails before sending out the final *uid*,
an RM can take over after an election process.

- If an RM fails before sending its *cuid*,
the FE can detect this after a time-out, and ignore the RM.

Implementing Causal Ordering

- The *total ordering* implemented by the previous algorithm is not necessarily causal:

  if we have two requests $r_1 \rightarrow r_2$, it is possible that they will be processed on *all* RMs in the order r_2, r_1. →

- For *causal ordering*, if two requests r_1 and r_2 are in a happened-before relation $r_1 \rightarrow r_2$, then r_1 should be processed before r_2 at all replica managers.

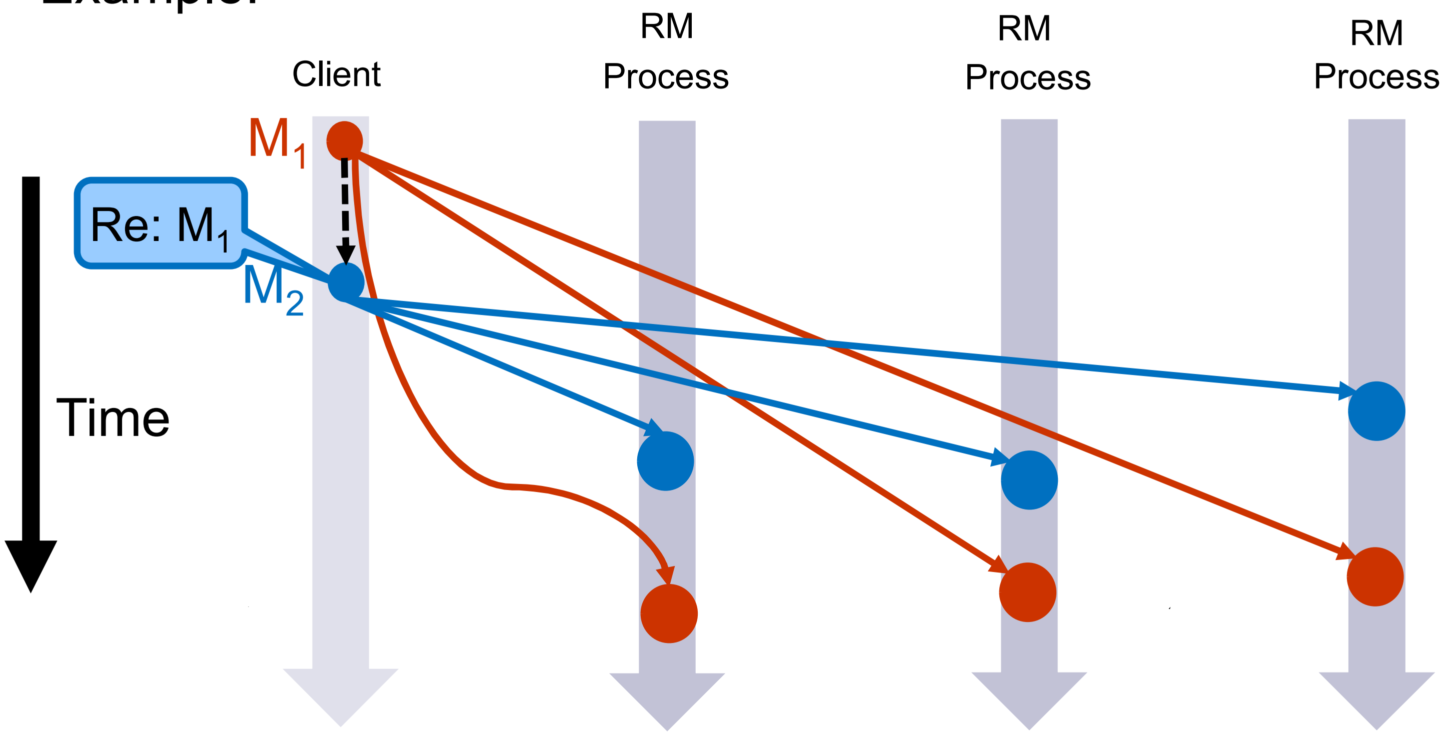
- Causal ordering of requests can be implemented using vector clocks.

  (See also Lecture 6, slides on causality with vector clocks)

  Details and pseudocode in the book, page 673.

Total vs. Causal Ordering of Multicast Messages / Requests

Example:



Totally ordered, but not causally ordered

Update Protocols

Update Protocols

Problem:

- We have a **replicated file**;
  how do we solve that a user request is always provided with the **most recent version** of the file?

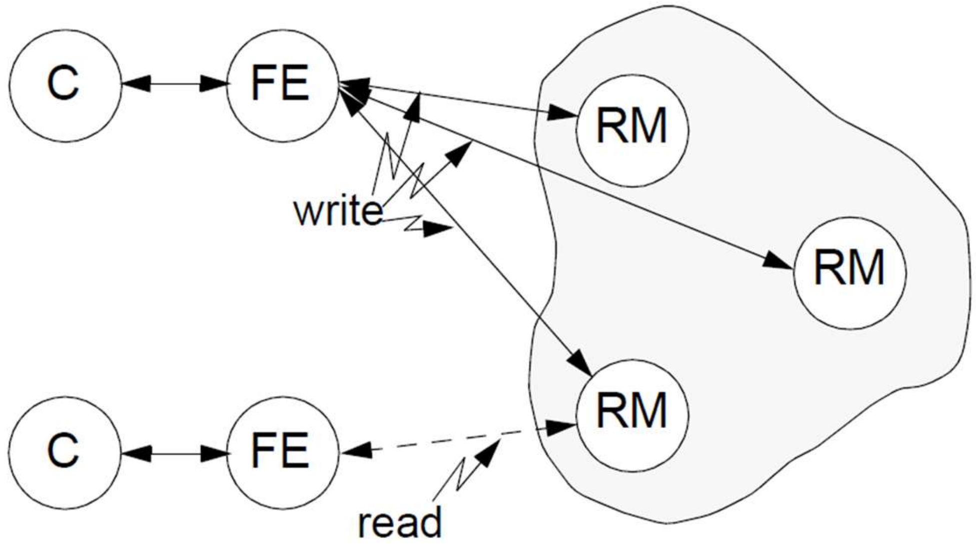
Some approaches:

- Read-any - Write-all protocol
- Available-copies protocol
- Primary-copy protocol
- Voting protocols

Read-any - Write-all Protocol

A **read** operation is performed by reading ***any*** available copy of the file.

A **write** operation is performed by writing to ***all*** copies of the file.



- Some simple kind of **locking** is required: before updating, all copies are locked, and after all have been updated, the lock is released.
- For write operations to succeed, **all** RMs must be **available**; for read operations, only one RM must be available.
- If write operations are frequent compared to reads, this protocol performs poorly.

Available-Copies Protocol

- This protocol is just a practical variant of read-any – write-all:

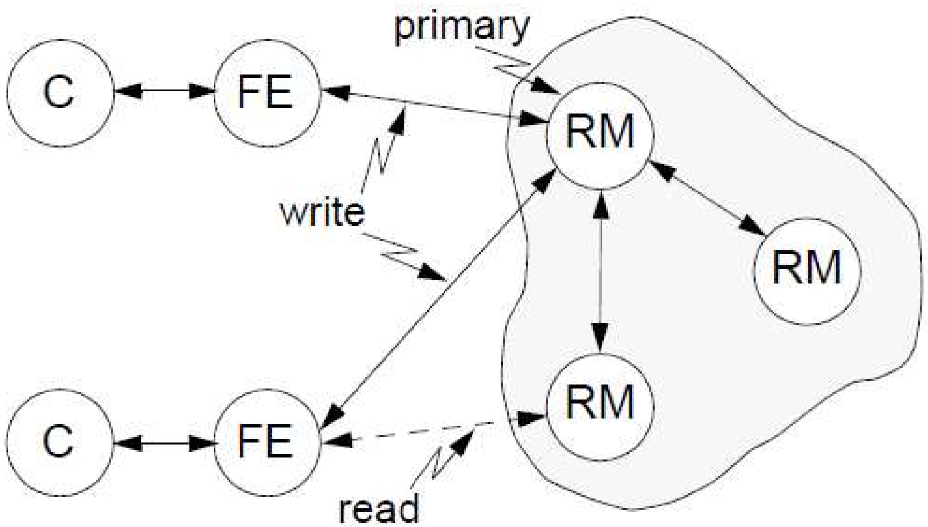
  → not *all* RMs, but only those which are *not down*, must be available to perform a write.

  - A **read** operation is performed by **reading any** available copy of the file.
  - A **write** operation is performed by **writing** to **all available** copies.
  - When a RM **recovers** after a failure, it brings itself up to date by copying from another server, **before** accepting any user request.

- Failed RMs have to be detected and configured out of the system; recovered RMs have to be configured back.

Primary-Copy Protocol

- A **read** operation is performed by **reading any** available copy of the file.
- A **write** operation is performed by **writing** to the **primary copy**.



- If **consistency** requirements are **strong** (any read should get the most recent version):
  - When the primary copy gets an update,
    it immediately locks the secondary copies and updates them.
- If **consistency** requirements are **looser**:
  updating secondary copies can be performed in the background

→ all the secondary copies will ultimately get updated.

Voting Protocols

- With voting protocols, the requirement of writing to *all* copies can be softened, without giving up strong consistency.

The price?

- One has to read *several* copies, not only one,
in order to be sure to get the most recent version.

The benefit?

- Write-performance can be improved:
updating becomes more efficient.
- Availability can be improved:
RMs can fail and updating/reading can still go on
(as long as quorums can be obtained).

Voting Protocols

Suppose there are *n* copies of the file (*n* RMs):

- To read the file, a minimum of *r* copies have to be consulted
  - *r* is the **read quorum**.
- To perform a write operation, a minimum of *w* copies have to be "acquired" and written
  - *w* is the **write quorum**.

The rules for *r* and *w*:

- In order to avoid two writes updating the same data at the same time:

$$w > n / 2$$

→ We are also sure that each write quorum includes at least one copy that is up-to-date and has the largest version number.

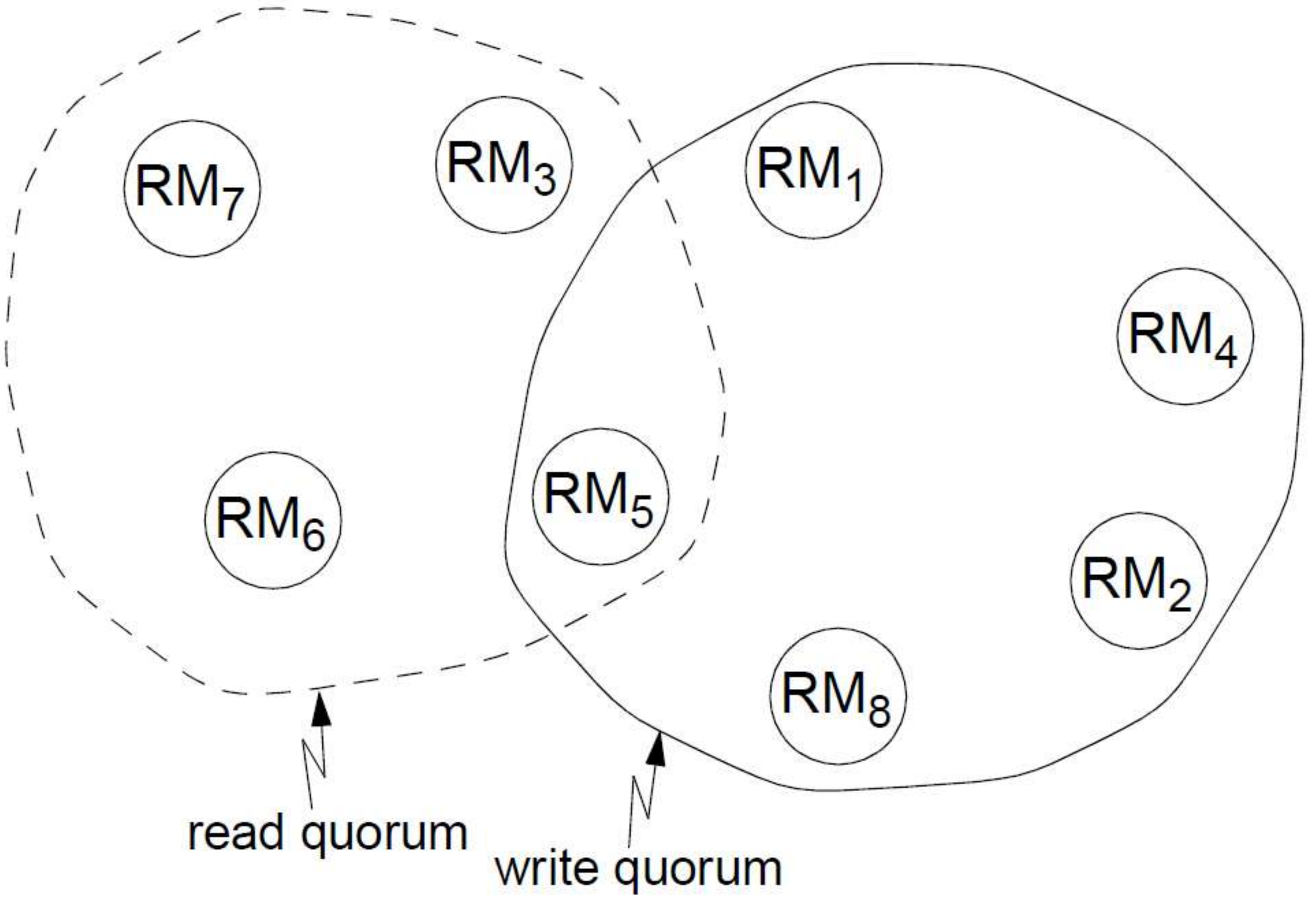
- In order to ensure that each read gets the latest copy:

$$r + w > n$$

→ It is guaranteed that there is a non-null intersection between every read quorum and every write quorum.

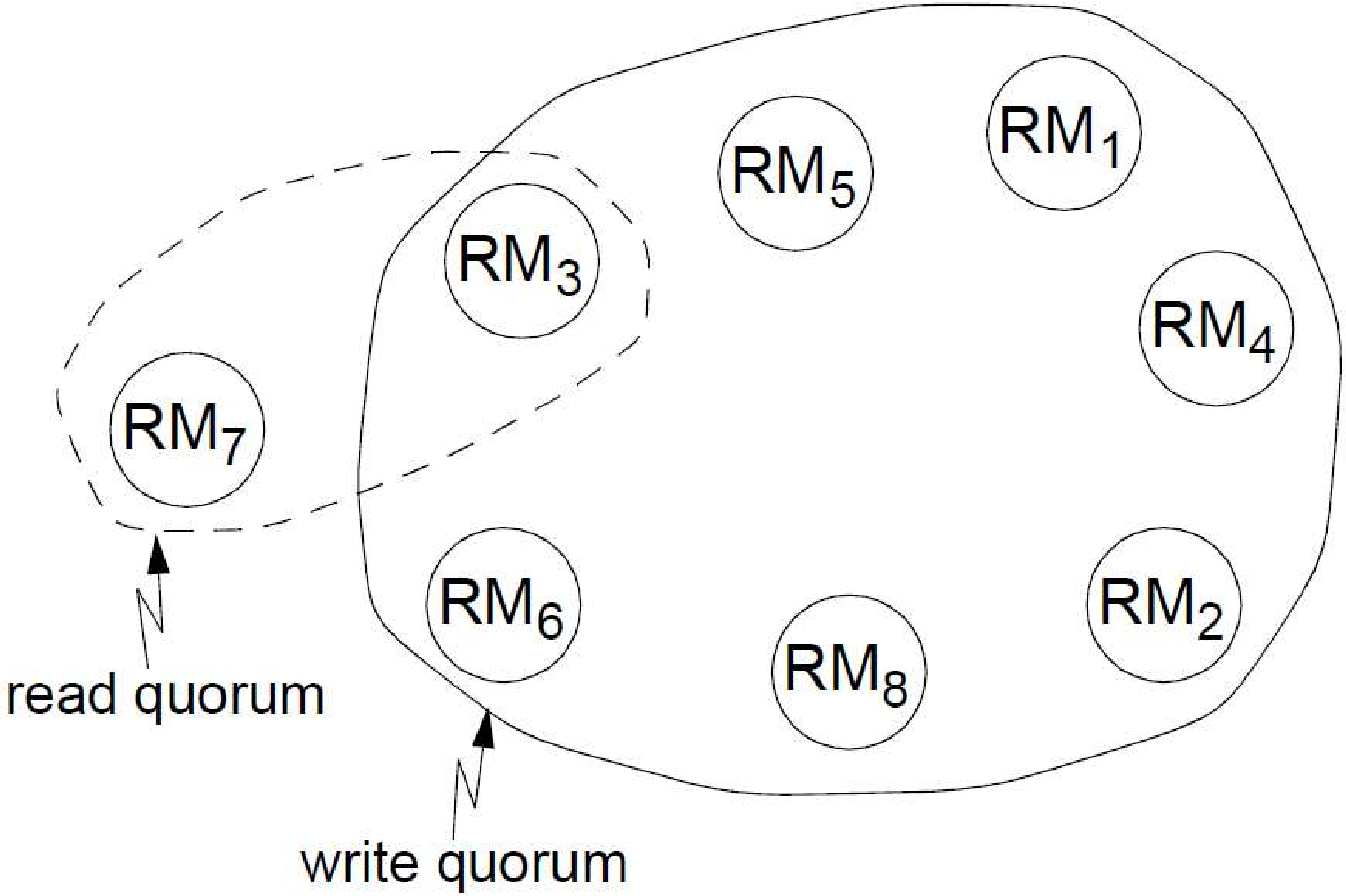
Voting Protocols

- Example 1: $n = 8, \quad w = 5, \quad r = 4$



Voting Protocols

- Example 2: $n = 8$, $w = 7$, $r = 2$



Voting Protocols

Rule for executing a read:

- Retrieve a read quorum (any *r* copies).
- Of the *r* copies retrieved,
  select the one with the largest version number.
- Perform the read operation on the selected copy.

Rule for executing a write:

- Retrieve a write quorum (any *w* copies).
- Of the *w* copies retrieved,
  select the one with the largest version number.
- Increment the version number.
- Perform the update and write the new version with the new version number into all the *w* copies of the write quorum.

Voting Protocols

- The constraints given above allow several possible selections of *r* and *w*.

  This depends on required performance and reliability characteristics.

  - A large *w* with small *r* is suitable for systems with a large ratio of read operations relative to the writes.
  - A small *w* with large *r* performs well if the ratio of writes is large relative to the reads.

- The *Read-any - Write-all* protocol is a particular case of a voting protocol, with $r = 1$ and $w = n$.

Acknowledgments

- Most of the slide contents is based on a previous version by Petru Eles, IDA, Linköping University.