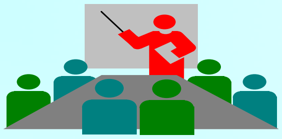
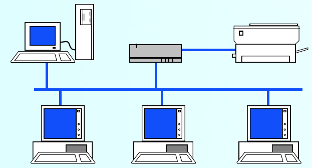




Distributed Systems
600.437
Replication

Department of Computer Science
The Johns Hopkins University

Replication

Lecture 7

Further readings:
- *Distributed Systems (second edition) Sape Mullender, chapters 7,8 (Addison-Wesley) 1994.*
- *Concurrency Control and Recovery in Distributed Database Systems Bernstein, Hadzilacos and Goodman (Addison Wesley) 1987.*
- *From Total Order to Database Replication ICDCS 2002*
- *Paxos Made Simple*, Leslie Lamport ACM Sigact News 2001
- *Paxos for System Builders: An Overview* LADIS 2008

www.dsn.jhu.edu/publications web page.

Replication

- Benefits of replication:
  - **High Availability.**
  - **High Performance.**
- Costs of replication:
  - **Synchronization.**
- Requirements from a generic solution:
  - Strict consistency – one copy serializability.
  - Sometimes too expensive so requirements are tailored to applications.

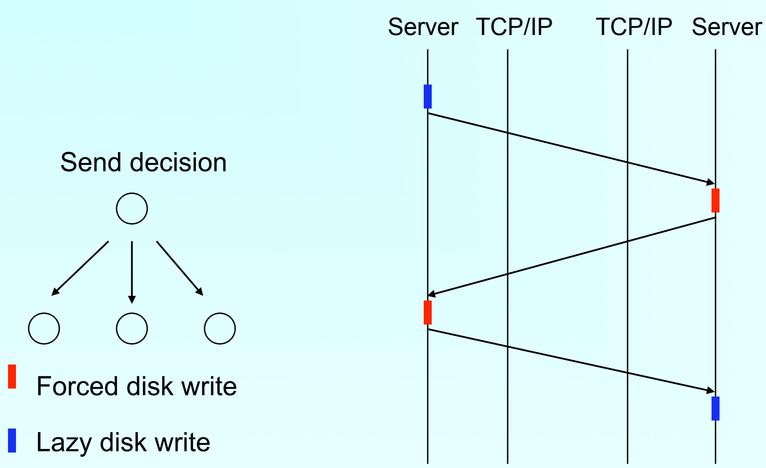
Replication Methods

- Two phase commit, three phase commit
- Primary and backups
- Weak consistency (weaker update semantics)
- Primary component.
  - What happens when there is no primary component?
- Congruity: Virtual Synchrony based replication.
- Paxos

Two Phase Commit

- Built for updating distributed databases.
- Can be used for the special case of replication.
- Consistent with a generic update model.
- Relatively expensive.

Two Phase Commit

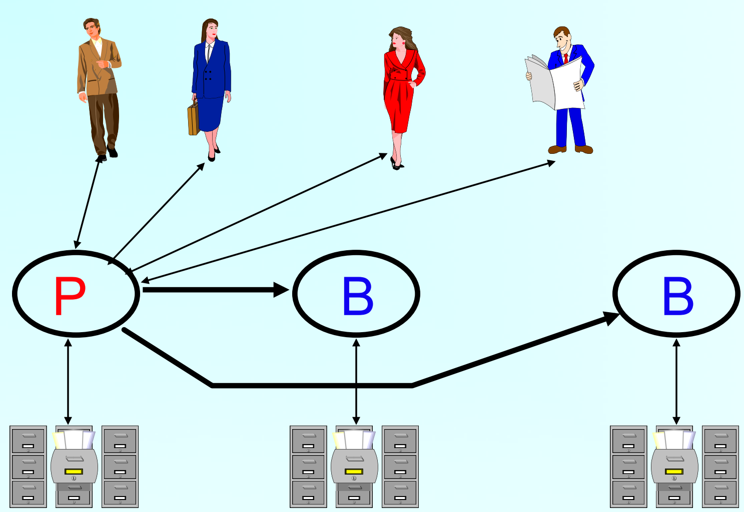


Primary and Backups

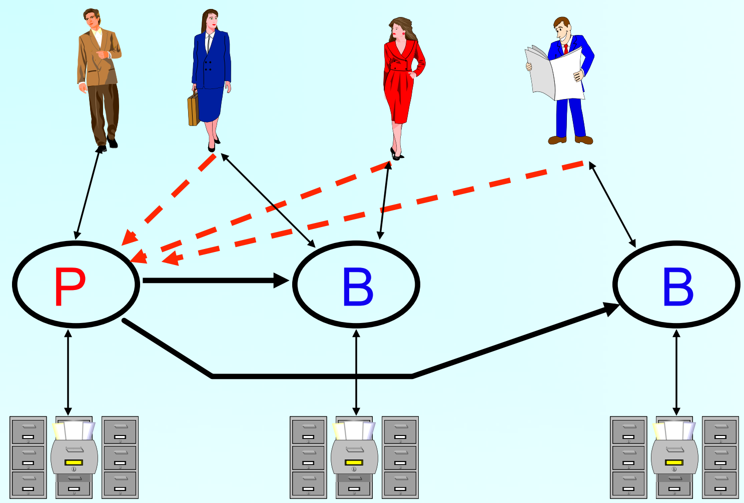
Possible options:

- Backups are maintained for availability only.
- Backups can improve performance for reads, updates are sent to the primary by the user.
  - **What is the query semantics? How can one copy serializability be achieved?**
- The user interacts with one copy, and if it is a backup, the updates are sent to the primary
  - **What is the query semantics with regards to our own updates?**

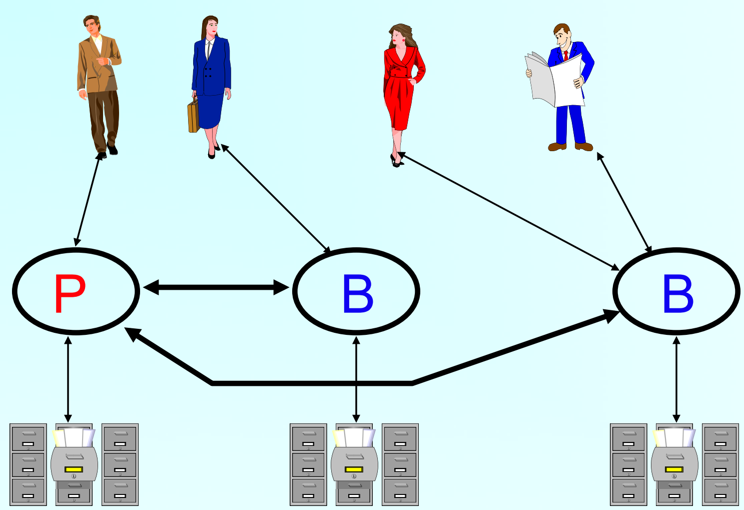
Primary and Backups (1)



Primary and Backups (2)



Primary and Backups (3)



Weak Consistency (weaker update semantics)

The Anti-Entropy method: Golding 92

- State kept by the replication servers can be weakly consistent. i.e. copies are allowed to diverge temporarily. They will eventually come to agreement.
- From time to time, a server picks another server and these two servers exchange updates and converge to the same state.
- Total ordering is obtained after getting one message from every server.
- Lamport time stamps are used to order messages.

The Anti-Entropy method

Knowledge at Server A

A	1	3	5	12
B	2			
C	2	3	4	

Knowledge at Server B

A	1	3			
B	2	5	6	9	11
C	2				

Summary A

12
2
4

Summary B

3
11
2

Numbers refer to Lamport time stamps.

The Anti-Entropy Method (cont.)

Knowledge at Server A

A	1	3	5	12	
B	2				
C	2	3	4		

Knowledge at Server B

A	1	3			
B	2	5	6	9	11
C	2				

Summary A

12
2
4

Summary B

3
11
2

Summary After merge

12
11
4

The Anti-Entropy Method (cont.)

Knowledge at Server A

A	1	3	5	12	
B	2	5	6	9	11
C	2	3	4		

Knowledge at Server B

A	1	3	5	12	
B	2	5	6	9	11
C	2	3	4		

Summary A

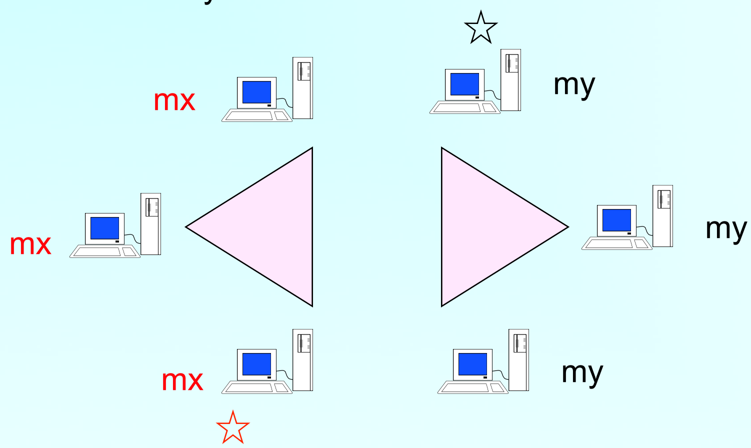
12
11
4

Summary B

12
11
4

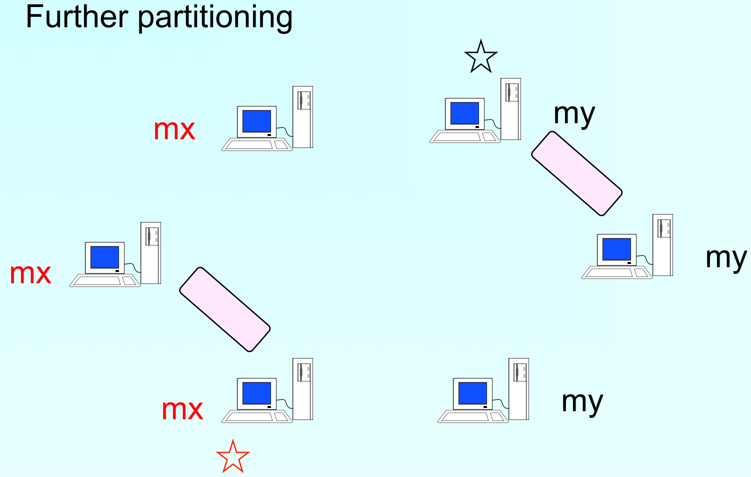
Eventual Path Propagation

Partitioned system



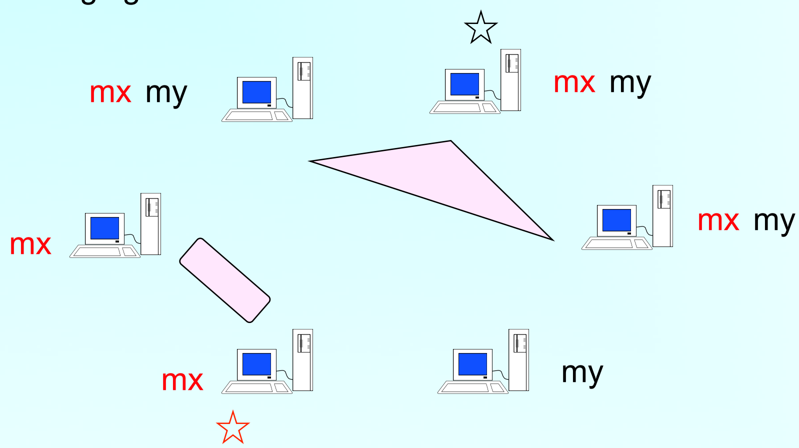
Eventual Path Propagation (cont.)

Further partitioning



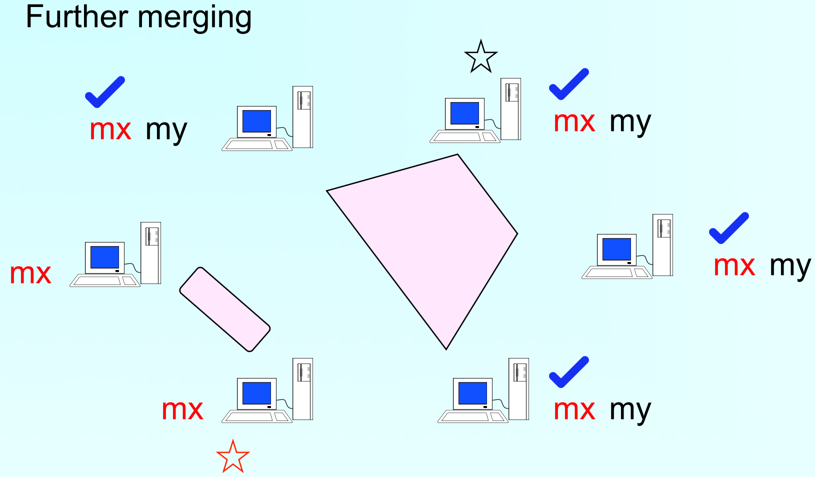
Eventual Path Propagation (cont.)

Merging



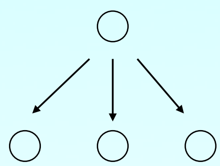
Eventual Path Propagation (cont.)

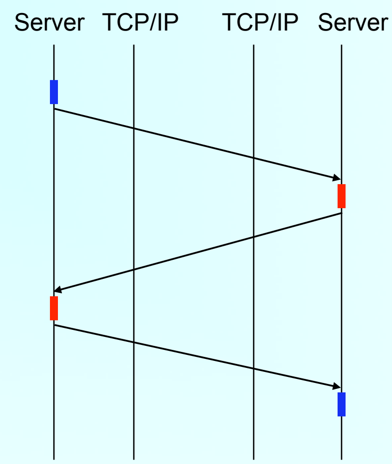
Further merging



Going back to 2 Phase Commit

Send decision





Forced disk write

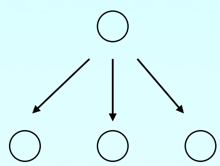
Lazy disk write

Primary Component

- A quorum can proceed with updates.
  - **Remember that for distributed transactions, every DM had to agree**
  - **But in the more specific problem of replication, a quorum can continue (not all DM have to agree)**
- When the network connectivity changes, if there is a quorum, the members can continue with updates
- Dynamic methods will allow the next quorum to be formed based on the current quorum
  - **Dynamic Linear Voting: the next quorum is a majority of the current quorum**
  - **Useful to put a minimum cap on the size of a viable quorum to avoid relying on too few specific remaining replicas, which can lead to potential vulnerability**

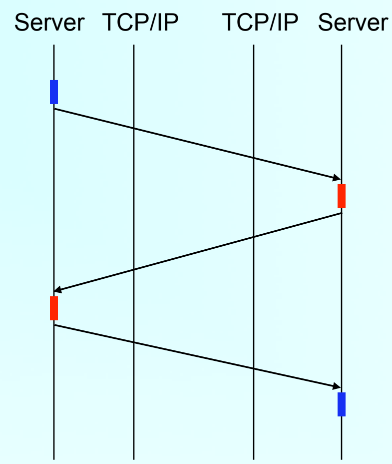
Going back to 2 Phase Commit

Send decision



Forced disk write

Lazy disk write



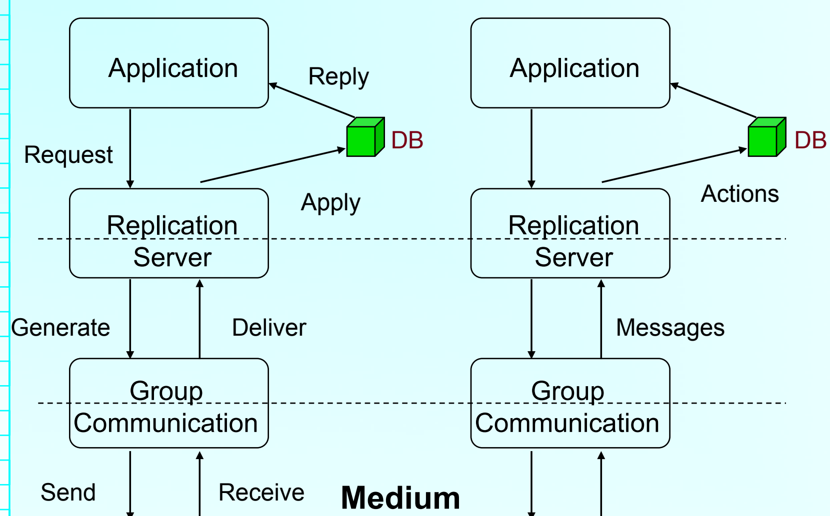
What can be improved?

- Reduce number of forced writes to disk
- Reduce number of messages
  - **Aggregate acknowledgements**
- Avoid end-to-end (application to application) acknowledgements
- Robustness

Group Communication "Tools"

- Efficient message delivery
  - Group multicast
- Message delivery/ordering guarantees
  - Reliable
  - FIFO/Causal
  - Total Order
- Partitionable Group Membership
- Strong semantics (what is actually needed?)

Congruity: Virtual-Synchrony based replication

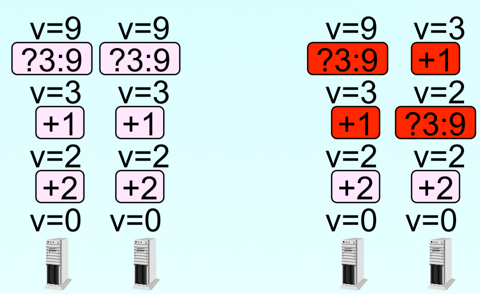


State Machine Replication

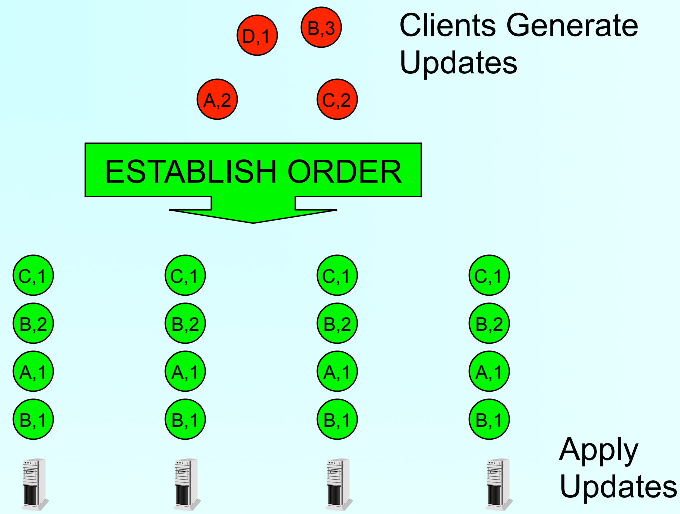
- Servers **start in the same state**.
- Servers change their state only when they execute an update.
- State changes are deterministic. **Two servers in the same state will move to identical states, if they execute the same update**.
- If servers **execute updates in the same order**, they will progress through exactly the same states. **State Machine Replication!**

State Machine Replication Example

- Our State: one variable
- Operations (cause state changes)
  - Op 1) + n : Add n to our variable
  - Op 2) ?v:n : If variable = v, then set it to n
- Start: All servers have variable = 0
- If we apply the above operations in the same order, then the servers will remain consistent



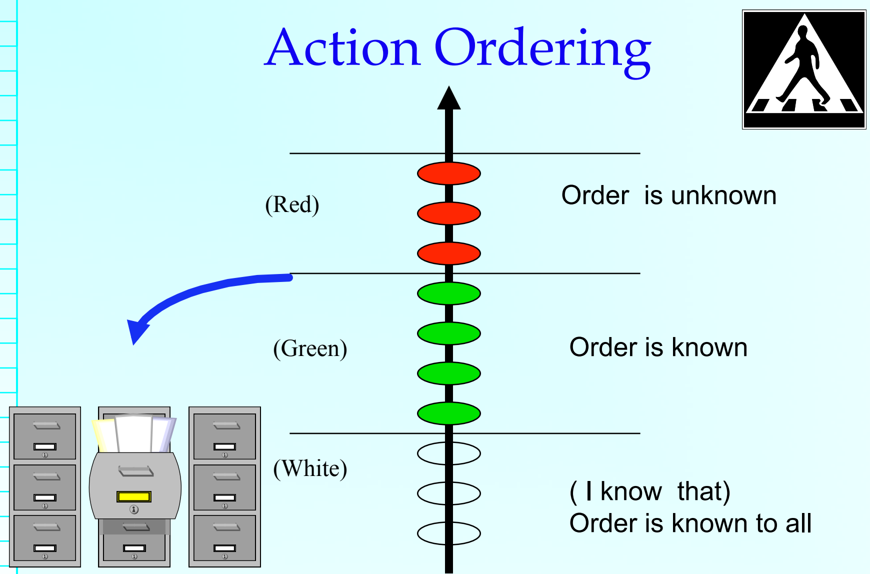
State Machine Replication



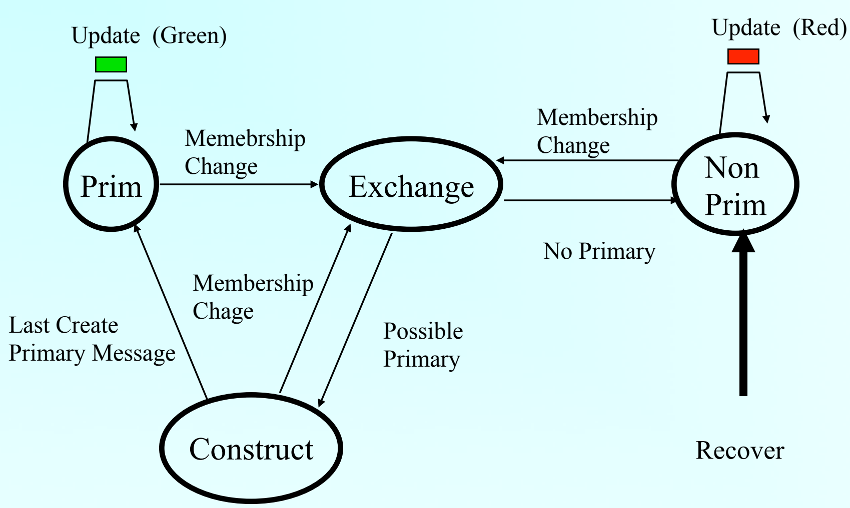
Congruity: The Basic Idea

- Reduce database replication to **G**lobal **C**onsistent **P**ersistent **O**rder
  – Use group communication ordering to establish the Global Consistent Persistent Order on the updates.
  – deterministic + serialized = consistent
- Group Communication membership + quorum = **primary** partition.
  – Only replicas in the **primary** component can commit updates.
  – Updates ordered in a primary component are marked **green** and applied. Updates ordered in a non-primary component are marked red and will be delayed.

Action Ordering

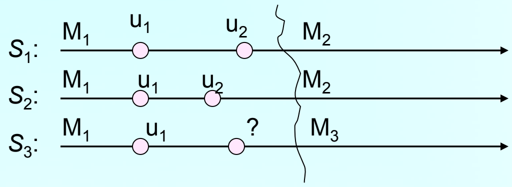


Congruity: Conceptual State Machine



Not so simple…

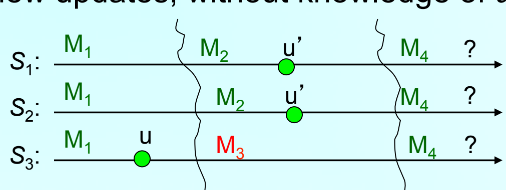
- **Virtual Synchrony**: If s_1 and s_2 move directly from membership M_1 to M_2, then they deliver the same ordered set of messages in M_1.
  - What about s_3 that was part of M_1but is not part of M_2?



- Total (Agreed) Order **with no holes** is not guaranteed across partitions or server crashes/ recoveries!

Delicate Points

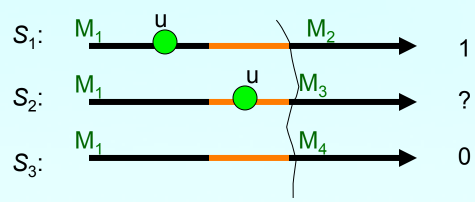
- s_3 receives update *u* in Prim and commits it right before a partition occurs, but s_1 and s_2 do not receive *u*. If s_1 and s_2 will form the next primary component, they will commit new updates, without knowledge of *u*!!



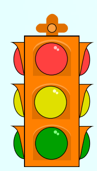
- s_1 receives all CPC messages in Construct, and moves to Prim, but one of the servers that were with s_1 in Construct does not receive the last CPC message. A new primary is created possibly without having the desired majority!!

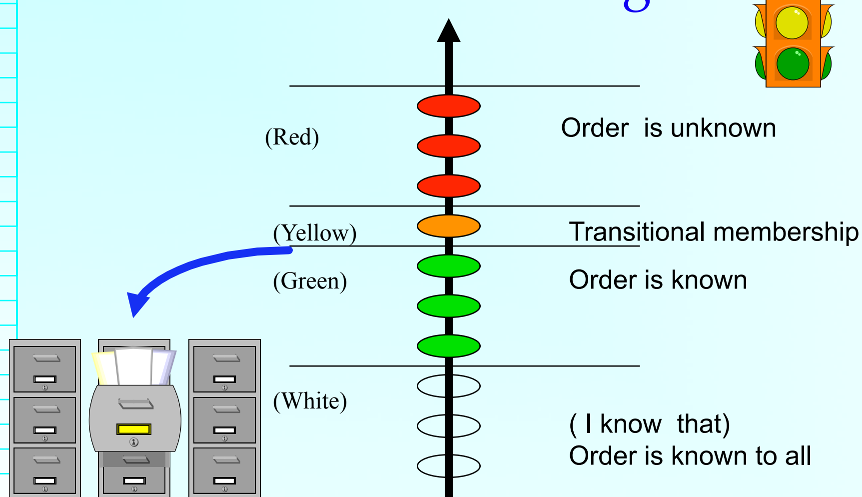
Extended Virtual Synchrony

- Transitional/Regular membership notification
- Safe message = Agreed plus every server in the current membership will deliver the message unless it crashes.
- Safe delivery breaks the two-way uncertainty into 3 possible scenarios, the extremes being mutually exclusive!



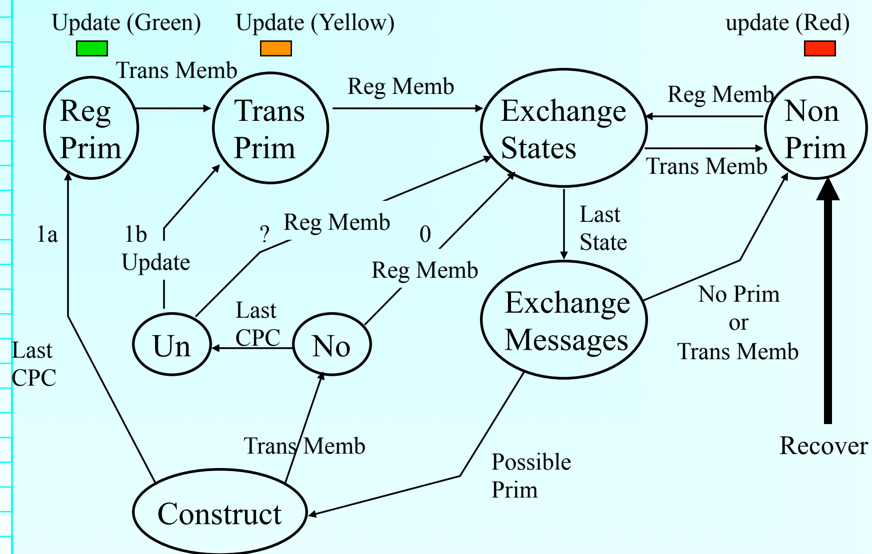
Action Ordering





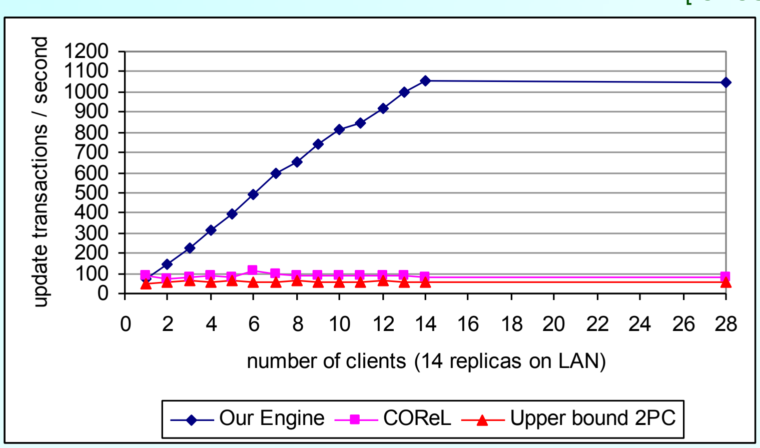
Congruity State Diagram

[ICDCS02]



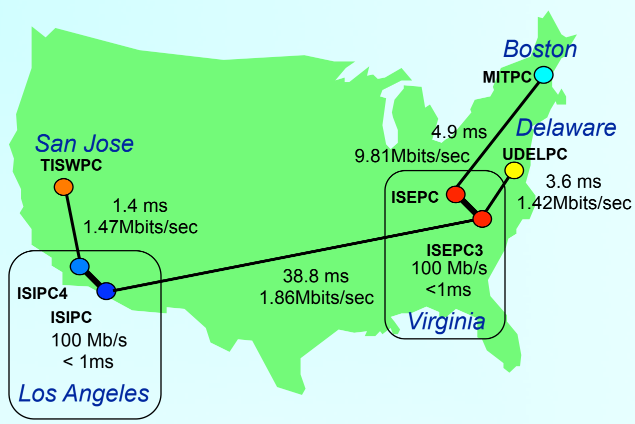
Throughput Comparison (LAN)

[ICDCS02]



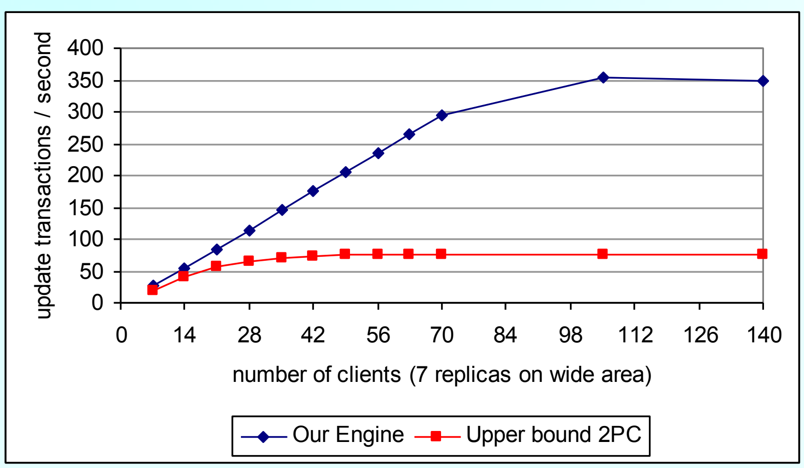
COReL – by Dolev and Keidar, using Agreed order + additional round.

The CAIRN Wide-Area Network



- A real experimental network (CAIRN).
- Was also modeled in the Emulab facility.

Throughput Comparison (WAN)



Congruity Recap

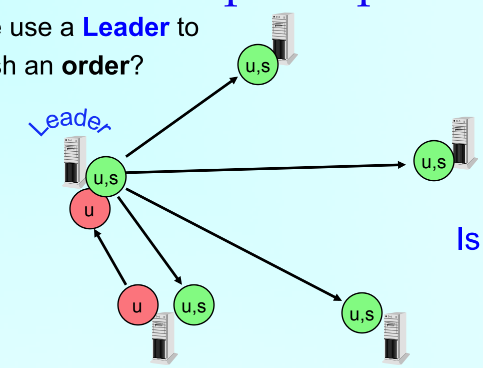
- Knowledge propagation
  - Eventual Path Propagation
- Amortizing end-to-end acknowledgments
  - Low level Ack derived from Safe Delivery of group communication
  - End-to-end Ack upon membership changes
- Primary component selection
  - Dynamic Linear Voting

What about Dynamic Networks?

- Group communication requires stable membership to work well
  - If membership is not stable, group communication based scheme will spend a lot of time synchronizing
- A more robust replication algorithm is needed for such environments – **Paxos**
  - Requires a stable-enough network to elect a leader that will stay stable for a while
  - Requires a (potentially changing) majority of members to support the leader (in order to make progress)

Simple Replication

Can we use a **Leader** to establish an **order**?



Is this resilient?

If leader fails, then the system is not live!

- **Server sends update, u, to Leader**
- **Leader assigns a sequence number, s, to u, and sends the update to the non-leader servers.**
- **Servers order update u with sequence number s.**

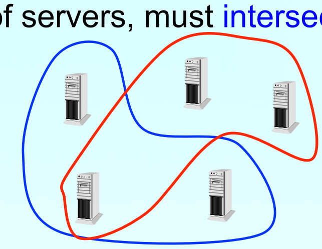
How can we improve resiliency?

Elect another leader.

Use more messages.

Assign a sequence number to each leader. (Views)

Use the fact that two sets, each having at least a majority of servers, must intersect!



First… We need to describe our system model and service properties.

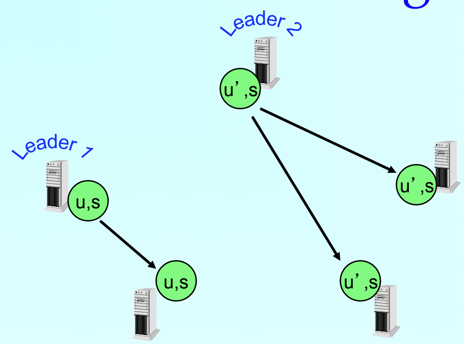
Paxos System Model

- N servers
  - Uniquely identified in {1…N}
- Asynchronous communication
  - Message loss, duplication, and delay
  - Network partitions
  - No message corruption
- Benign faults
  - Crash/recovery with stable storage
  - No Byzantine behavior - Not yet anyway :)

What is Safety?

- Safety: **If two servers execute the ith update, then these updates are the same.**
- Another way to look at safety:
  - If there exists an ordered update (u,s) at some server, then there cannot exist an ordered update (u',s) at any other server, where u' not = u.
- We will now focus on achieving safety -- making sure that we don't execute updates in different orders on different servers.

Achieving Safety



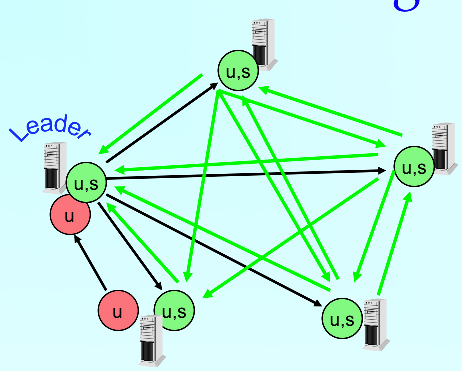
Is this safe?

A new leader can violate safety!

Can we fix this?

- A new leader must not violate previously established ordering!
- The new leader must know about all updates that may have been ordered.

Achieving Safety



What does this give us?

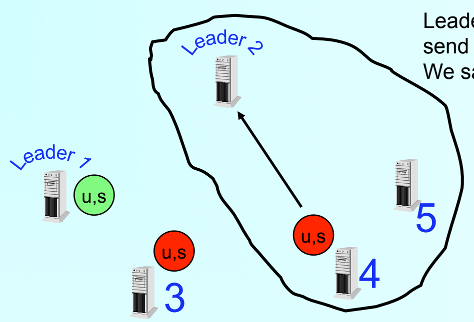
If a new leader gets information from **any** majority of servers, it can determine what **may** have been ordered!

- Leader sends Proposal(u,s) to all servers
- All servers send Accept(u,s) to all servers.
- Servers order (u,s) when they receive a majority of Proposal/ Accept(u,s) messages

Changing Leaders

- Changing Leaders is commonly called a **View Change.**
- Servers use timeouts to detect failures.
- If the current leader fails, the servers **elect** a new leader.
- The new leader cannot propose updates until it collects information from a majority of servers!
  - Each server reports any Proposals that it knows about.
  - If any server ordered a Proposal(u,s), then at least one server in any majority will report a Proposal for that sequence number!
  - The new server will never violate prior ordering!!
  - **Now we have a safe protocol!!**

Changing Leaders Example



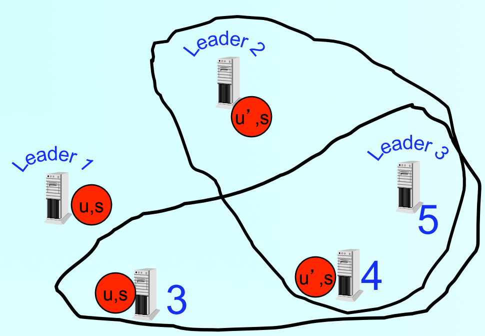
Leader 2 can send a Proposal(u,s). We say it **replays** (u,s)

- If any server orders (u,s), then at least majority of servers must have received Proposal(u,s).
- If a new server is elected leader, it will gather Proposals from a majority of servers.
- **The new leader will learn about the ordered update!!**

Is Our Protocol Live?

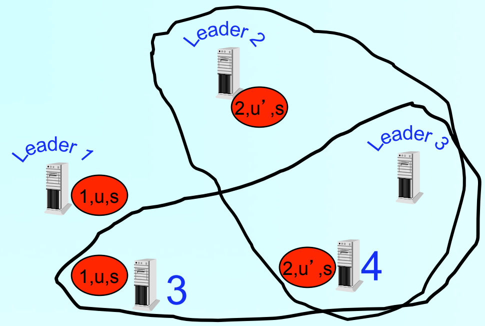
- Liveness: If there is a set, C, consisting of majority of connected servers, then if any server in set C has a new update, then this update will eventually be executed.
- Is there a problem with our protocol? It is safe, but is it live?

Liveness Example



- Leader 3 gets conflicting Proposal messages!
- **Which one should it choose?**
- **What should we add??**

Adding View Numbers



- We add view numbers to the Proposal(v,u,s)!
- Leader 3 gets conflicting Proposal messages!
- Which one should it choose?
- It chooses the one with the greatest view number!!

Normal Case

Assign-Sequence()

A1. u := NextUpdate()

A2. next_seq++

A3. SEND: Proposal(view, u,next_seq)

Upon receiving Proposal(v, u,s):

B1. if not leader and v == my_view

B2. SEND: Accept(v,u,s)

Upon receiving Proposal(v,u,s) and majority - 1 Accept(v,u,s):

C1. ORDER (u,s)

We use **view numbers** to determine which Proposal may have been ordered previously.

A server sends an Accept(v,u,s) message only for a view that it is currently in, and never for a lower view!

Leader Election

Elect Leader()

Upon Timer T Expire:
A1. my_view++
A2. SEND: New-Leader(my_view)

Upon receiving New-Leader(v):
B1. if Timer T expired
B2. if v > my_view, then my_view = v
B3. SEND: New-Leader(my_view)

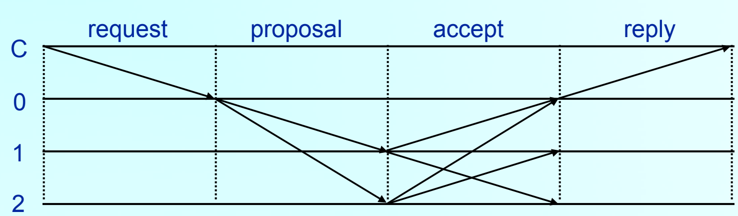
Upon receiving majority New-Leader(v)
where v == my_view:
C1. timeout *= 2; Timer T = timeout
C2. Start Timer T

Let V_max be the highest view that any server has. Then, at least a majority of servers are in view V_max or V_max - 1.

Servers will stay in the maximum view for at least one full timeout period.

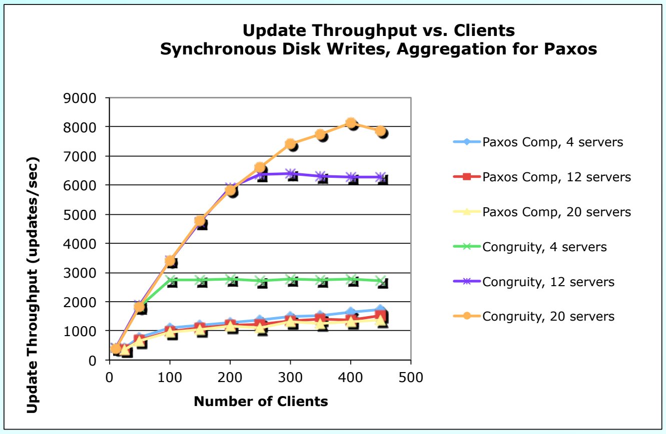
A server that becomes disconnected/connected repeatedly cannot disrupt the other servers.

We Have: Paxos



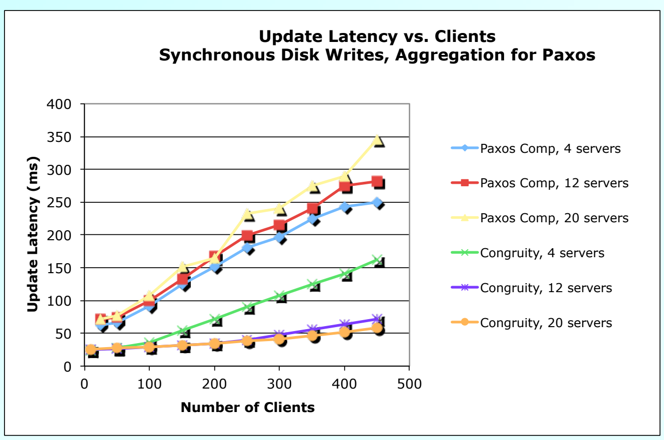
- The Part-Time Parliament [Lamport, 98]
- A very resilient protocol. Only a majority of participants are required to make progress.
- Works well on unstable networks.
- Only handles benign failures (not Byzantine).

Performance Results (Paxos-SB)

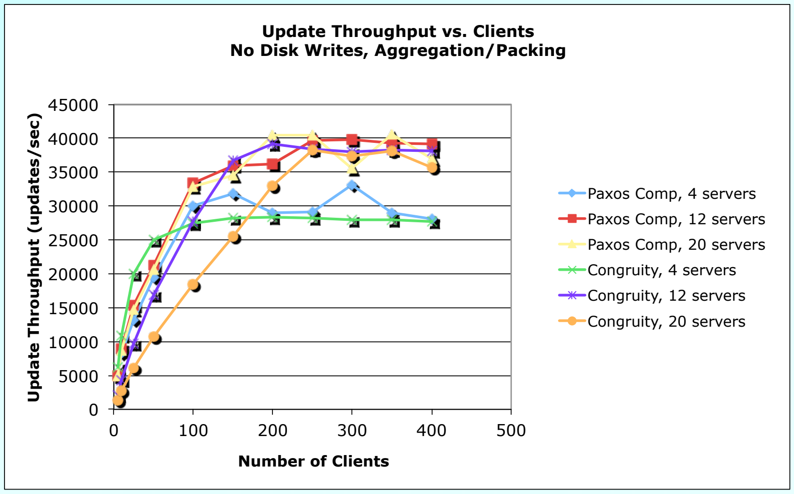


Local area network cluster.
Congruity: group communication-based replication.

Performance Results (Paxos-SB)



Performance Results (Paxos-SB)



Performance Results (Paxos-SB)