State-Machine Reconfiguration: Past, Present, and the Cloudy Future

Leslie Lamport
Microsoft Research

The Forecast: Clouds

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I'll discuss state-machine reconfiguration, and make my own forecast.

Part I: (More or Less Ancient) History

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Those who cannot remember the past are young enough to enjoy rediscovering it.

In the Beginning

The Maintenance of Duplicate Databases
by Paul Johnson and Bob Thomas. (1976?)

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How to keep consistent copies of a database in a network.

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- Commands not executed in causal order.

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How to keep consistent copies of a database in a network.

They missed two things:

relativistic

- Commands not executed in causal order.
- It could be used to implement any system.

Time, Clocks and the Ordering of Events in a Distributed System (1978)

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State machine implicit in the software structure:
tasks executed iteratively.

Synchronous implementation.

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*Assumes known bound on communcication delay.

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Reconfiguration an important part of the system.

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High reliability (mean time to failure of 1M years) depended on software rapidly identifying faulty processors and removing them from the system.

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High reliability (mean time to failure of 1M years) depended on software rapidly identifying faulty processors and removing them from the system.

One iterative task decided what processors should execute the next iteration of each task.

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The Asynchronous Case

Synchronous systems designed for process control.

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Showed asynchronous consensus impossible

For asynchronous systems:

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The Part-Time Parliament (1989)

Making Paxos tolerate Byzantine faults:

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Practical Byzantine Fault Tolerance
by Miguel Castro and Barbara Liskov (1999)

State Machines

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almost

An example: A Toy Banking System

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$State$: The balance of each depositor's account

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$Command$: Deposit \$20 to Alice's account.

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$Response$: "OK"

An example: A Toy Banking System

$State$: The balance of each depositor's account

$Command$: Deposit $20 to Alice's account.

$Response$: "OK"

$NewState$ = $Oldstate$ with $20 added to Alice's account

$State$: The balance of each depositor's account

$Command$: Withdraw \$100 from Bob's account.

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$Response$: "Insufficient Funds"

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$Response$: To Alice: "Done"
To Bob: "$100 received from Alice"

$State$: The balance of each depositor's account

$Command$: Transfer \$100 from Alice's account to Bob's account.

$Response$: To Alice: "Done"
To Bob: "\$100 received from Alice"

$NewState$ = $Oldstate$ with \$100 removed from Alice's account and added to Bob's

A Possible State-Machine Command

```
if (k <= 3) {
   int start = GF_256_ANTILOG (0);
   int factor = GF_256_ANTILOG (1);
   for (i = 0; i != k; i++) {
      int j;
      int colentry = GF_256_ANTILOG (0);
      int colfactor = start;
      for (j = 0; j != m; j++) {
         rs->matrix[i*m + j] = GF_256_LOG (colentry);
         colentry = GF_256_MUL (colentry, colfactor); }
   start = GF_256_MUL (start, factor);  }
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```

It just has to be deterministic.

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No concurrency/distribution.

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    Just implement once.

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    Just implement once. (Middleware)

A Typical Non-Byzantine State-Machine Implementation

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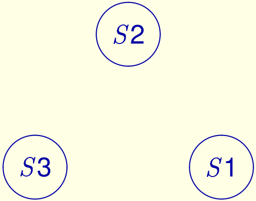
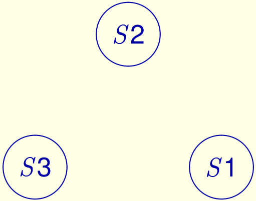


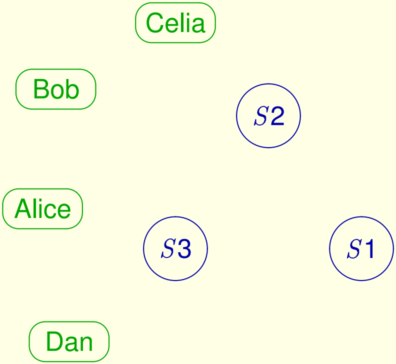
The servers.

A Typical Non-Byzantine State-Machine Implementation



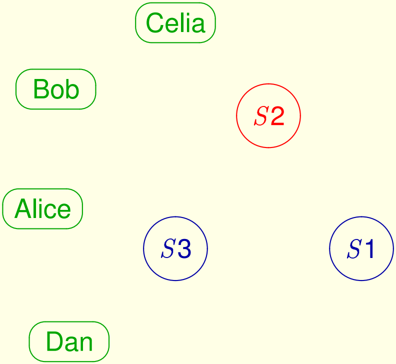
The servers. To tolerate 1 failure, need 3 servers.

A Typical Non-Byzantine State-Machine Implementation

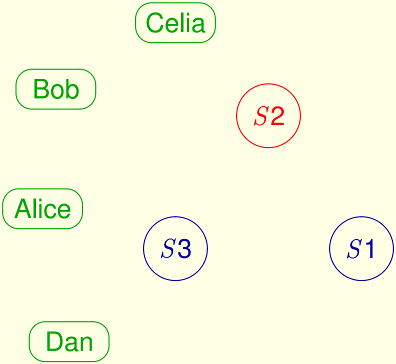


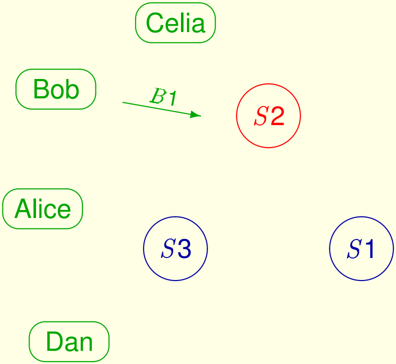
The clients.

A Typical Non-Byzantine State-Machine Implementation

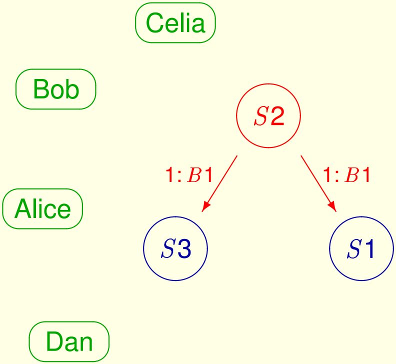


One server chosen to be leader.

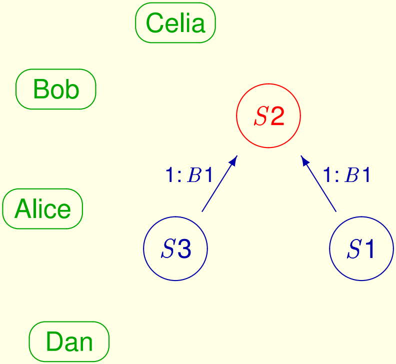

Celia
Bob
S2
Alice
S3
S1
Dan



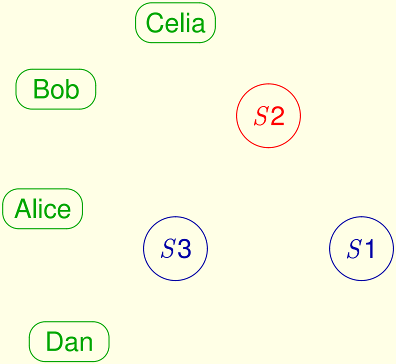
Bob sends command $B1$ to leader.



Leader assigns number 1 to command and sends to servers.



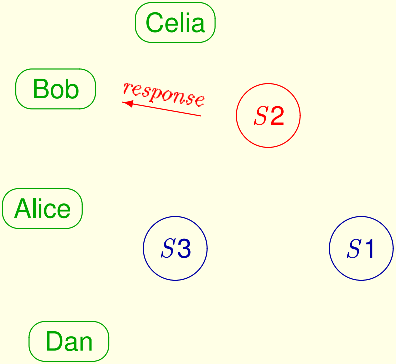
Servers remember $1\colon B1$ and ack.



Chosen Commands

1: $B1$

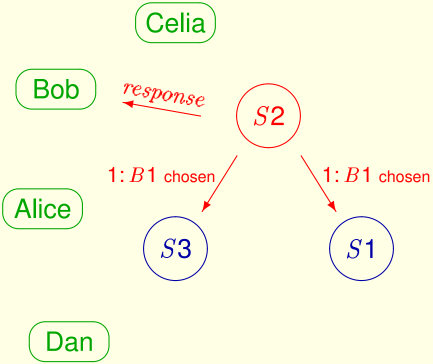
Server knows $B1$ chosen as command 1.



Chosen Commands

1: $B1$

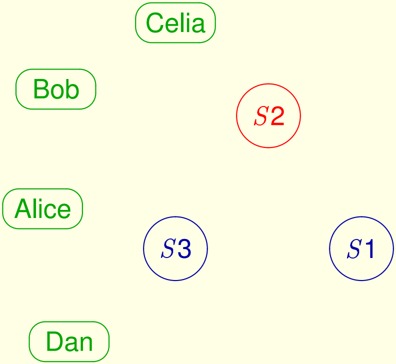
Sends response obtained by executing $B1$



Chosen Commands

1: $B1$

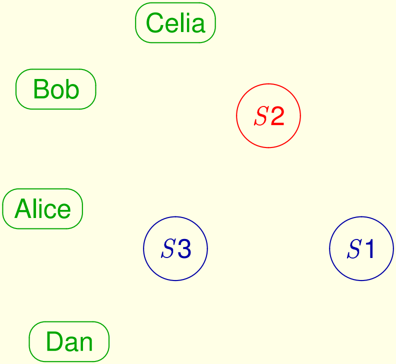
Sends response obtained by executing $B1$ and notifies servers that 1: $B1$ chosen.



Chosen Commands

1: $B1$

From now on, I will ignore responses to clients
and notification of servers



Chosen Commands

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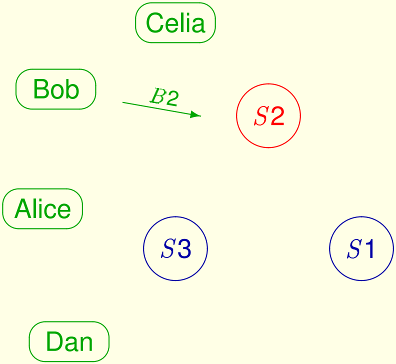
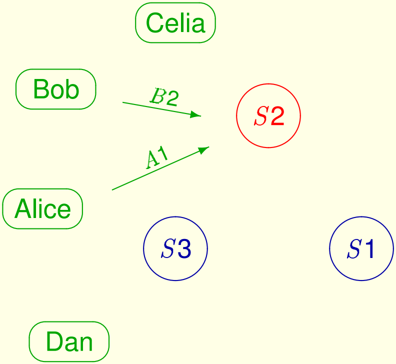


Chosen Commands

1: $B1$

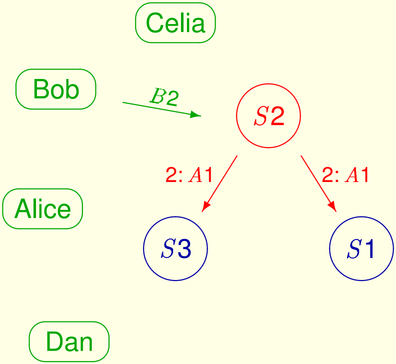
Bob issues command $B2$.



Chosen Commands

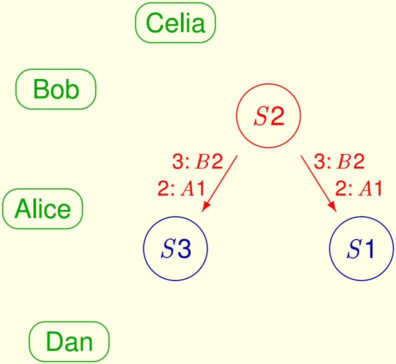
1: $B1$

Alice issues command $A1$.



Chosen Commands
1: $B1$

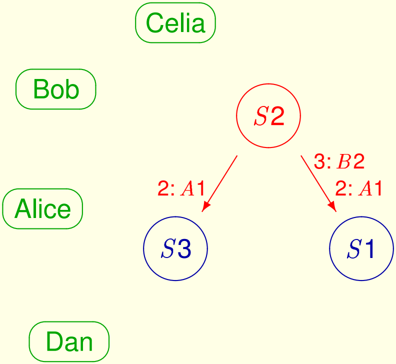
Leader assigns command number 2 to $A1$ and sends to servers.



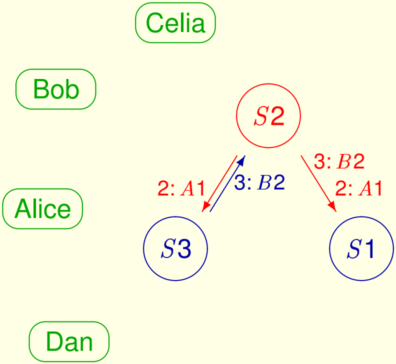
Chosen Commands

1: $B1$

Leader assigns command number 3 to $B2$ and sends to servers.



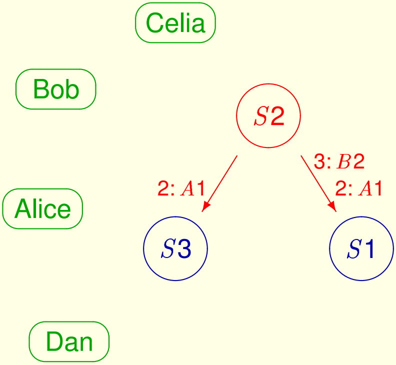
$S3$ receives 3: $B2$.



<u>Chosen Commands</u>

1: $B1$

$S3$ acks 3: $B2$.

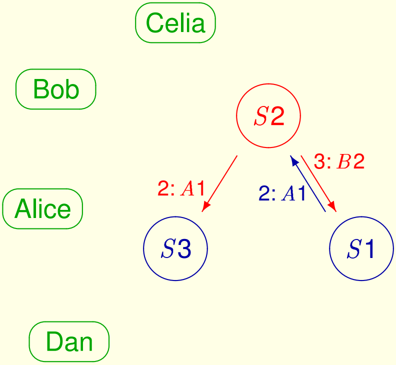


Chosen Commands

1: $B1$

3: $B2$

Leader receives 3: $B2$ and knows it is chosen.

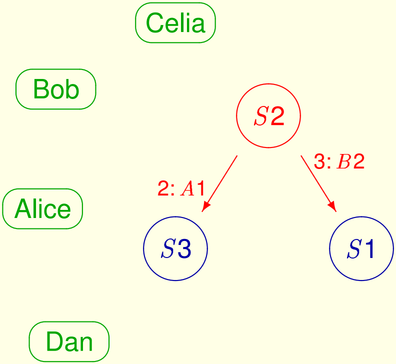


Chosen Commands

1: $B1$

3: $B2$

$S1$ receives 2: $A1$ and acks it.

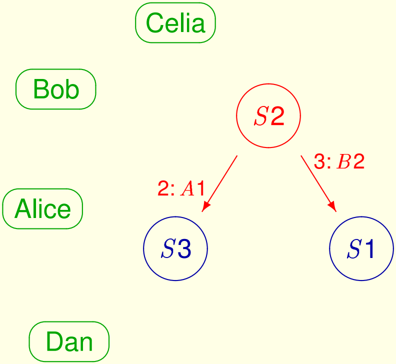


Chosen Commands

1: $B1$

3: $B2$

Leader receives ack and knows $A1$ chosen as command 2.



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1: $B1$

2: $A1$

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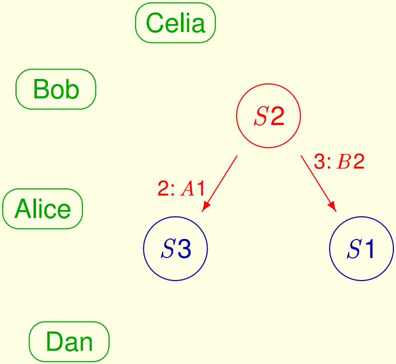

Chosen Commands

1: $B1$
2: $A1$
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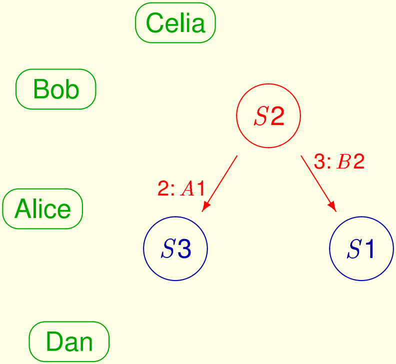
The remaining messages are redundant.



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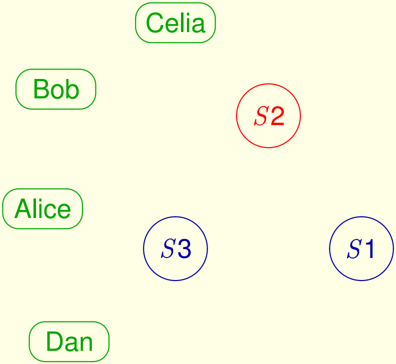

<u>Chosen Commands</u>

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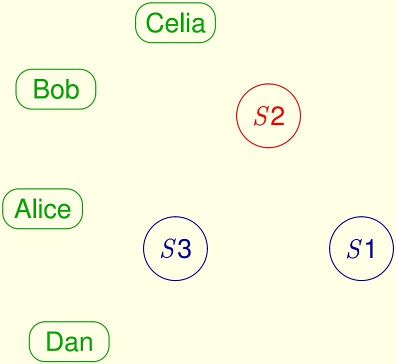
1-fault tolerance means leader needs only 1 ack.



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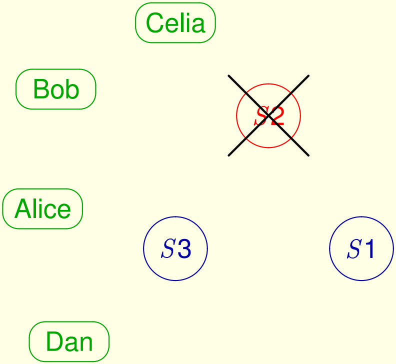

Chosen Commands

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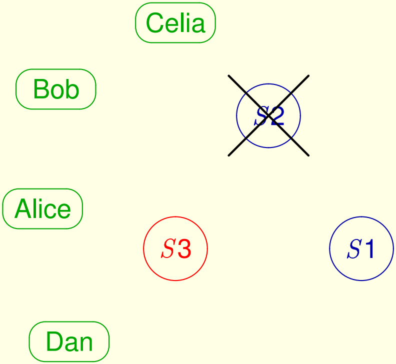
Suppose $S2$ fails.



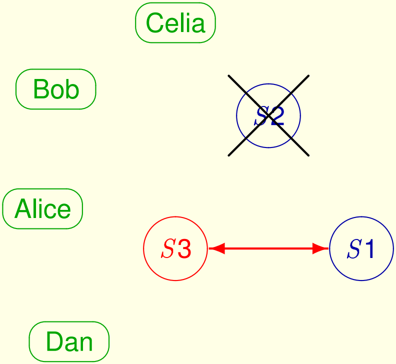
Chosen Commands

1: $B1$

2: $A1$

3: $B2$

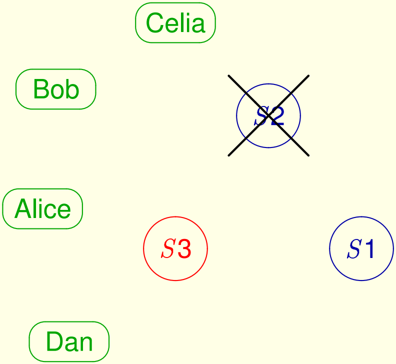
A new leader is chosen.



Chosen Commands

1: $B1$
2: $A1$
3: $B2$

New leader learns what other servers have done.



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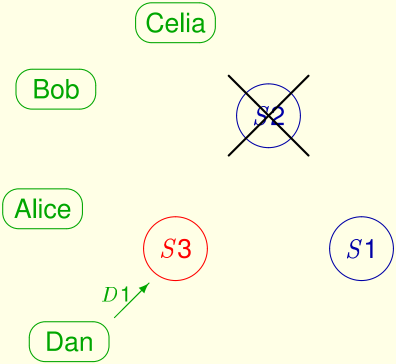
System can new resume normal operation.



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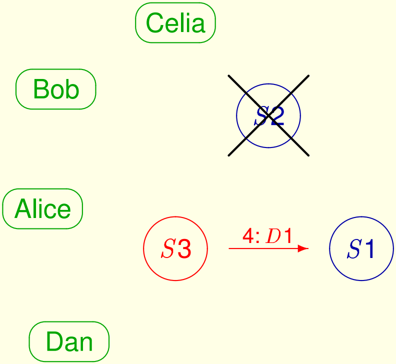

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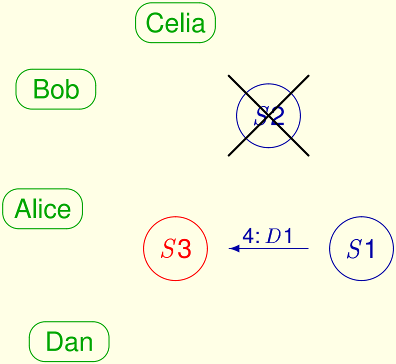

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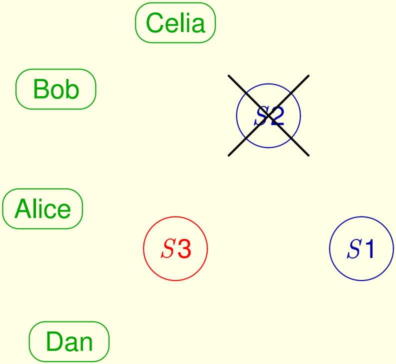

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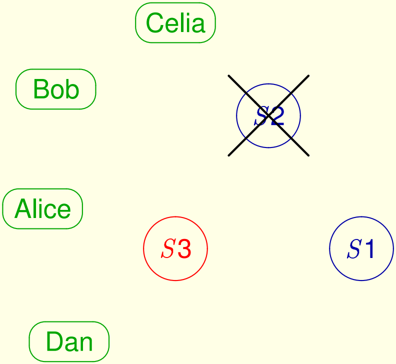
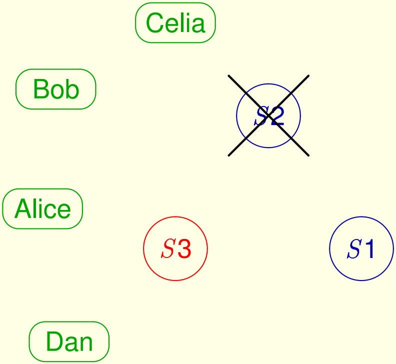
2: $A1$
3: $B2$



Chosen Commands

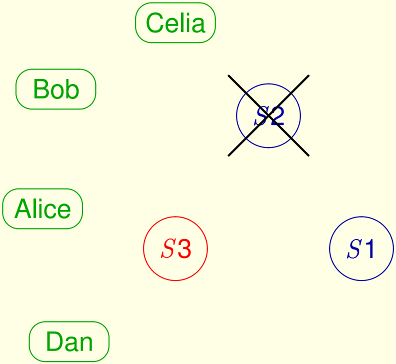
1: $B1$
2: $A1$
3: $B2$
4: $D1$



<u>Chosen Commands</u>

1: $B1$
2: $A1$
3: $B2$
4: $D1$

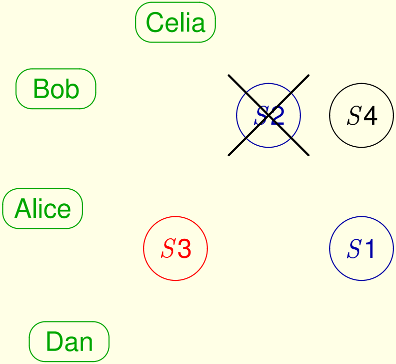
The system can no longer tolerate the failure of a server.



Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$

To restore 1-fault tolerance, must reconfigure — to replace $S2$ with a new server.



<u>Chosen Commands</u>

1: $B1$
2: $A1$
3: $B2$
4: $D1$

To restore 1-fault tolerance, must reconfigure —
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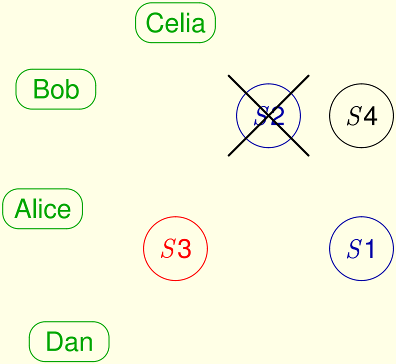
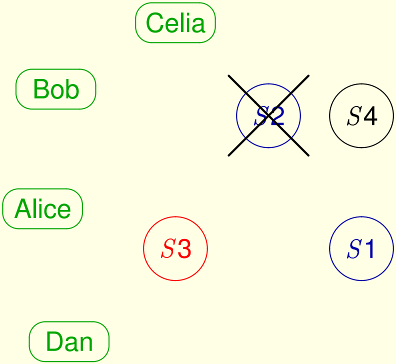


Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$

Make the configuration part of the state.

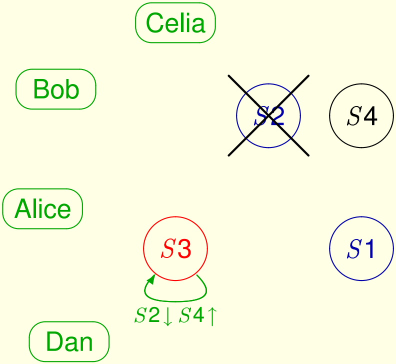


Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$

Make the configuration part of the state.

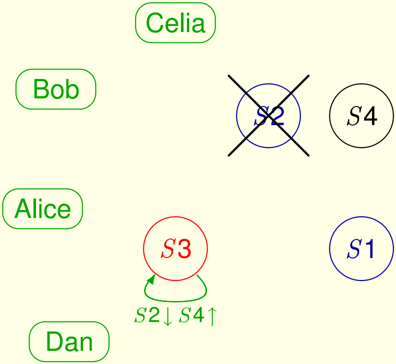
Command n chosen by configuration after command $n-1$.



Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$

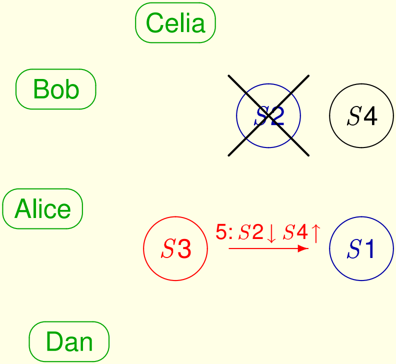
$S3$, acting as a client, issues a reconfiguration command to change the configuration by removing $S2$ and adding $S4$.



Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$

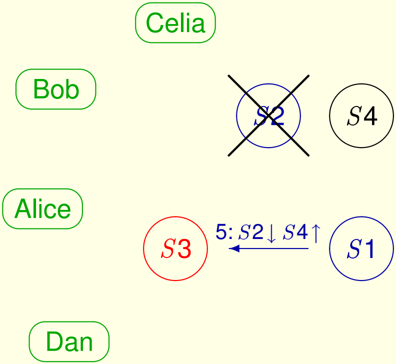
This is treated like an ordinary command.



Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$

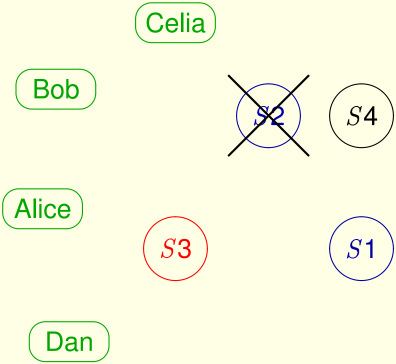
This is treated like an ordinary command.



Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$

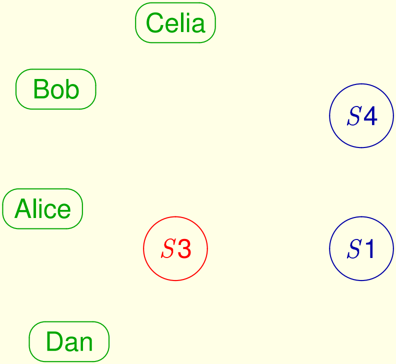
This is treated like an ordinary command.



Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2\downarrow S4\uparrow$

This is treated like an ordinary command.



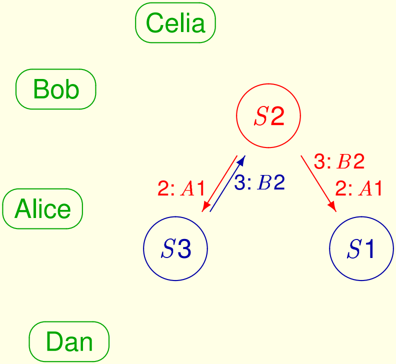
Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2\downarrow S4\uparrow$

Commands starting from number 6 chosen by $S1$, $S3$, and $S4$.

A Problem

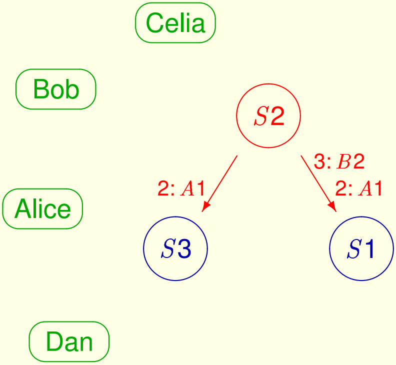
A Problem



Chosen Commands

1: $B1$

A Problem



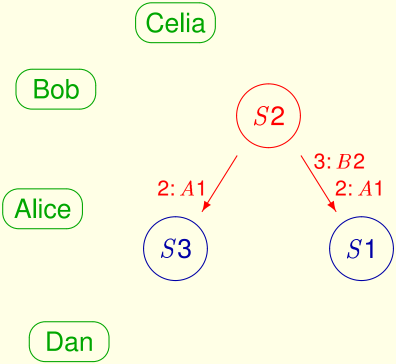
Chosen Commands

1: $B1$

3: $B2$

Leader receives 3: $B2$ from $S3$ and knows it is chosen.

A Problem



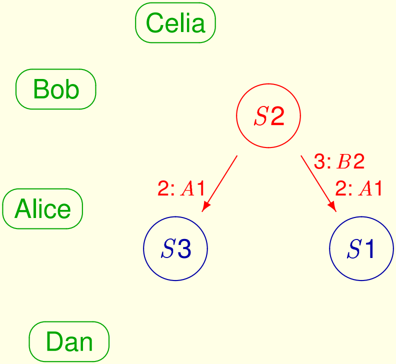
Chosen Commands

1: $B1$

3: $B2$

What if command 2 were a reconfiguration command that removed $S3$?

A Problem



Chosen Commands

1: $B1$

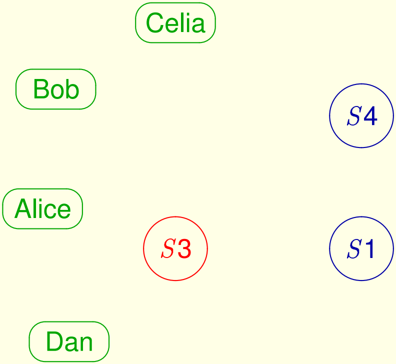
3: $B2$

What if command 2 were a reconfiguration command that removed $S3$?

We have to wait until command 2 is chosen before we can start choosing command 3.

A Solution

A Solution

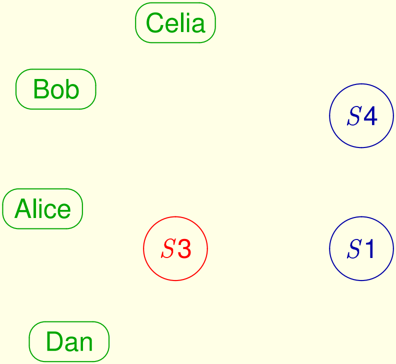


<u>Chosen Commands</u>

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2{\downarrow}\, S4{\uparrow}$

Commands starting from number 6 chosen by $S1$, $S3$, and $S4$.

A Solution

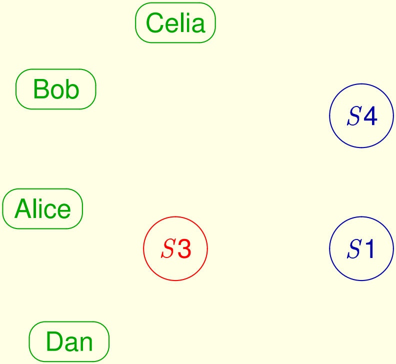


<u>Chosen Commands</u>

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2\downarrow S4\uparrow$

Commands starting from number ~~6~~ $5+\alpha$ chosen by $S1$, $S3$, and $S4$.

A Solution



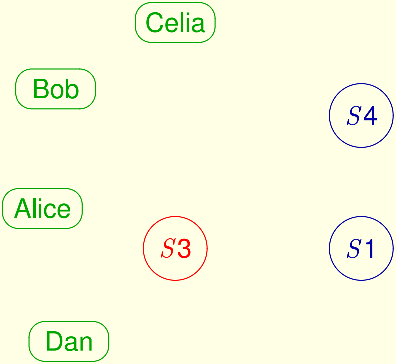
Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2\!\downarrow S4\!\uparrow$

Make the configuration part of the state.

Command n chosen by configuration after command $n-1$.

A Solution



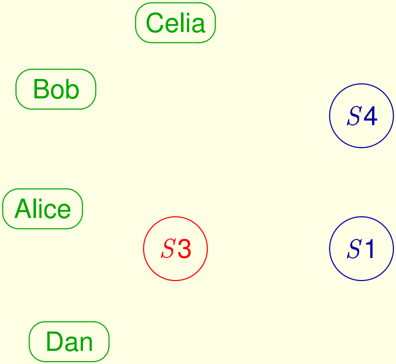
<u>Chosen Commands</u>

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2\downarrow S4\uparrow$

Make the configuration part of the state.

Command n chosen by configuration after command $n - \alpha$.

Problem

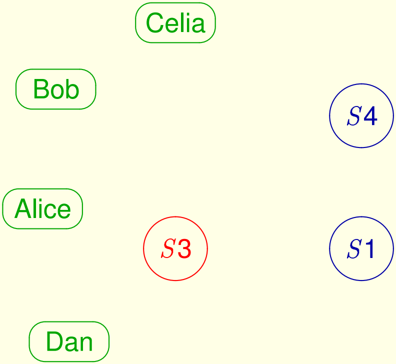


Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2\downarrow S4\uparrow$

Commands starting from number $5+\alpha$ chosen by $S1$, $S3$, and $S4$.

Problem



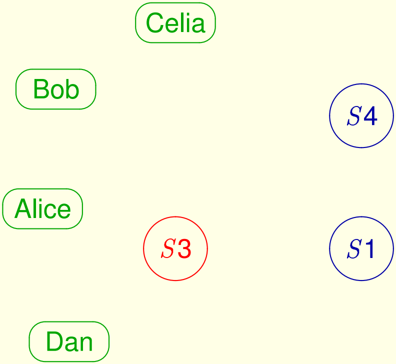
Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2\downarrow S4\uparrow$

Commands starting from number $5+\alpha$ chosen by $S1$, $S3$, and $S4$.

Must choose next $\alpha-1$ commands before reconfiguration takes effect.

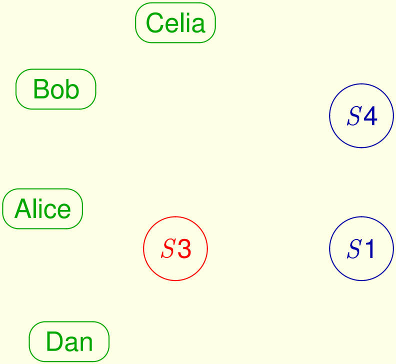
Solution



Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2\downarrow S4\uparrow$

Solution

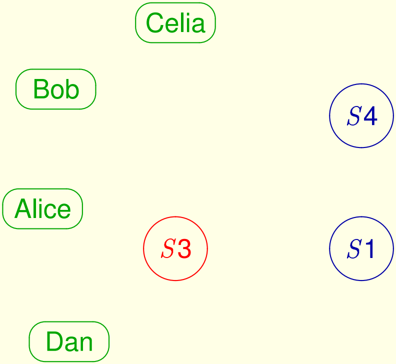


Chosen Commands

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2{\downarrow}\, S4{\uparrow}$

Immediately choose $\alpha - 1$ *no-op* commands

Solution



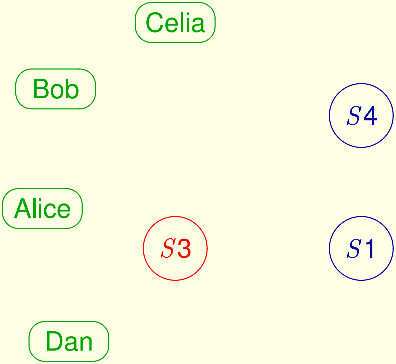
<u>Chosen Commands</u>

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2{\downarrow}\, S4{\uparrow}$

Immediately choose $\alpha - 1$ *no-op* commands

No problem letting $\alpha = 2^{32}$.

Solution



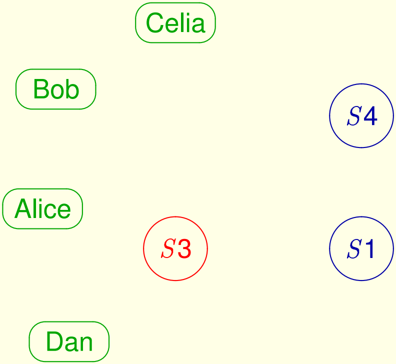
<u>Chosen Commands</u>

1: $B1$
2: $A1$
3: $B2$
4: $D1$
5: $S2{\downarrow}\, S4{\uparrow}$

Immediately choose $\alpha - 1$ *no-op* commands

No problem letting $\alpha = 2^{32}$.
All chosen with same messages as reconfiguration command.

Solution



<u>Chosen Commands</u>

1: B1
2: A1
3: B2
4: D1
5: S2$\downarrow$ S4$\uparrow$

Immediately choose $\alpha - 1$ *no-op* commands

No problem letting $\alpha = \infty$

$$command\ number = \langle epoch\ number, number \rangle$$

What About Byzantine Failures?

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The only problem: a malicious node could propose a bad reconfiguration.

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The only problem: a malicious node could propose a bad reconfiguration.

The solution: define the state machine so enough nodes must agree to a reconfiguration for it to take effect.

Part IIa: The Present: Vertical Paxos

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Joint work with Dahlia Malkhi and Lidong Zhou.

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Joint work with Dahlia Malkhi and Lidong Zhou.

For non-Byzantine Failures.

A Closer Look at Paxos

1 2 3 4 5 6 7 8 $\ldots$

command number

ballot number

⋮

6

5

4

3

2

1

1	2	3	4	5	6	7	8	...

command number

Each ballot number used by at most one leader.

ballot number									
⋮									
6									
5									
4									
3									
2	B1								
1									
	1	2	3	4	5	6	7	8	...

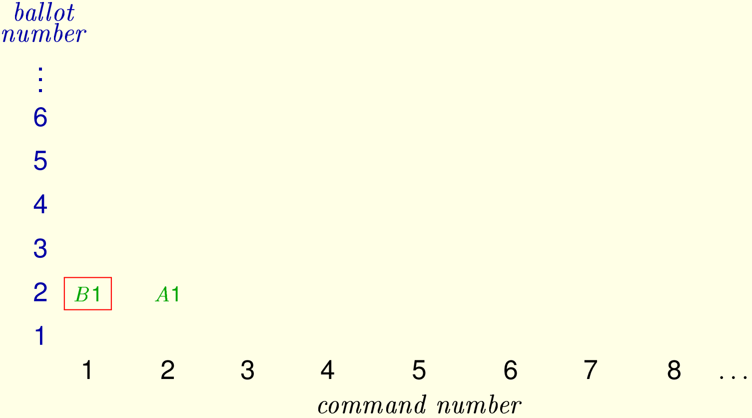
command number

S2 proposes B1 in ballot 2 of command 1.

ballot number									
⋮									
6									
5									
4									
3									
2	$\boxed{B1}$								
1									
	1	2	3	4	5	6	7	8	...

command number

$B1$ chosen in ballot 2 of command 1.

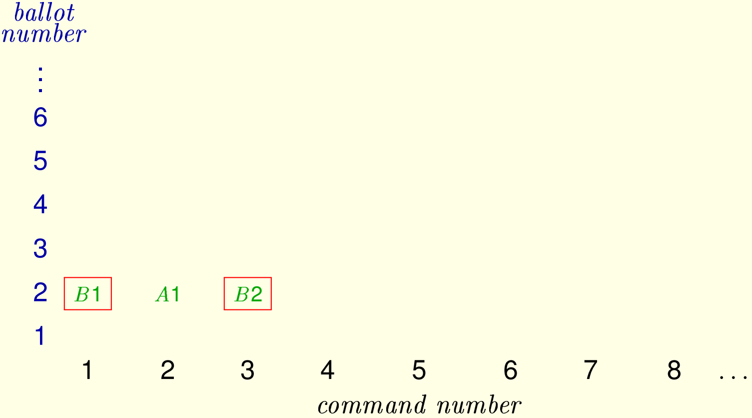


$S2$ proposes $A1$ in ballot 2 of command 2.

ballot number									
⋮									
6									
5									
4									
3									
2	$\boxed{B1}$	$A1$	$B2$						
1									
	1	2	3	4	5	6	7	8	. . .

command number

$S2$ proposes $B2$ in ballot 2 of command 3.



B2 chosen in ballot 2 of command 3.

ballot number									
⋮									
6									
5									
4									
3									
2	$\boxed{B1}$	$\boxed{A1}$	$\boxed{B2}$						
1									
	1	2	3	4	5	6	7	8	...

command number

$A1$ chosen in ballot 2 of command 2.

ballot number									
⋮									
6									
5									
4									
3									
2	$\boxed{B1}$	$\boxed{A1}$	$\boxed{B2}$	$C1$					
1									
	1	2	3	4	5	6	7	8	...

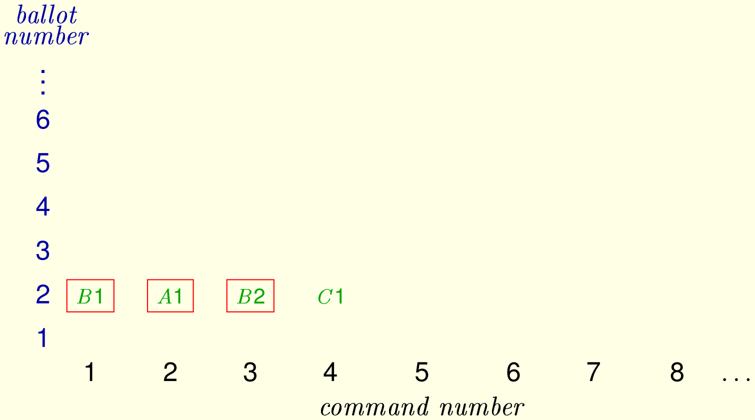
command number

$S2$ proposes $C1$ in ballot 2 of command 4.

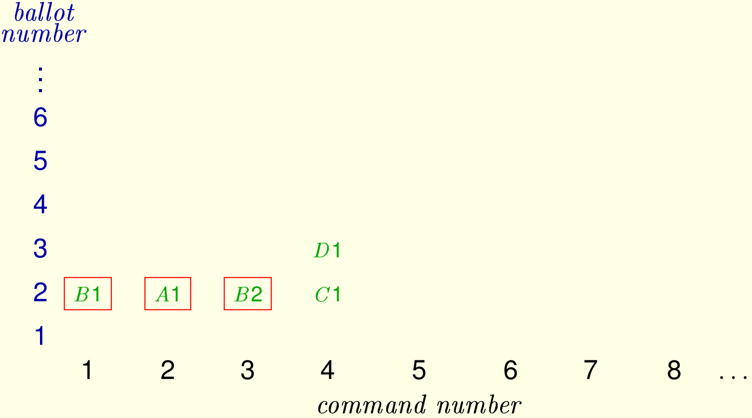
ballot number									
⋮									
6									
5									
4									
3									
2	$\boxed{B1}$	$\boxed{A1}$	$\boxed{B2}$	$C1$					
1									
	1	2	3	4	5	6	7	8	. . .

command number

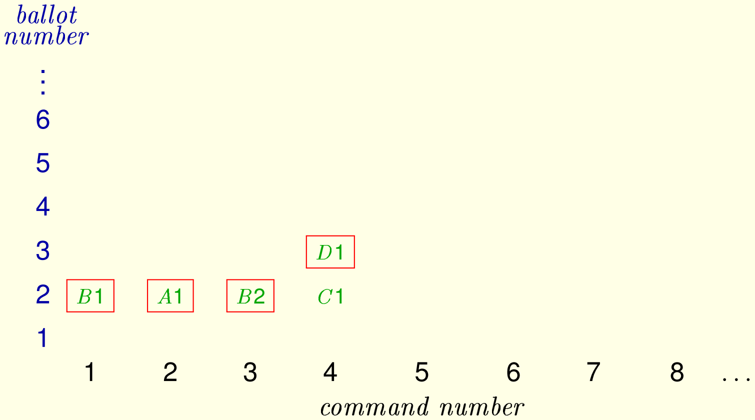
$S2$ fails.



$S3$ elected leader and chooses ballot 3.



$S3$ proposes $D1$ in ballot 3 of command 4.



$D1$ chosen in ballot 3 of command 4.

ballot number									
⋮									
6									
5									
4									
3				$\boxed{D1}$	$S2{\downarrow}\,S4{\uparrow}$				
2	$\boxed{B1}$	$\boxed{A1}$	$\boxed{B2}$	$C1$					
1									
	1	2	3	4	5	6	7	8	...

command number

$S3$ proposes $S2{\downarrow}\,S4{\uparrow}$ in ballot 3 of command 5

ballot number									
⋮									
6									
5									
4									
3				$\boxed{D1}$	$S2{\downarrow}\,S4{\uparrow}$	*no-op*	*no-op*		
2	$\boxed{B1}$	$\boxed{A1}$	$\boxed{B2}$	$C1$					
1									
	1	2	3	4	5	6	7	8	. . .

command number

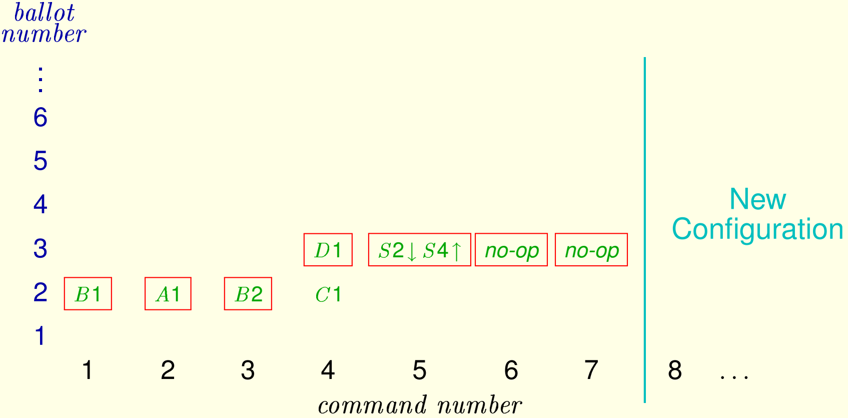
$S3$ proposes $S2{\downarrow}\,S4{\uparrow}$ in ballot 3 of command 5

and *no-op* in ballot 3 of commands 6 and 7 ($\alpha = 3$)

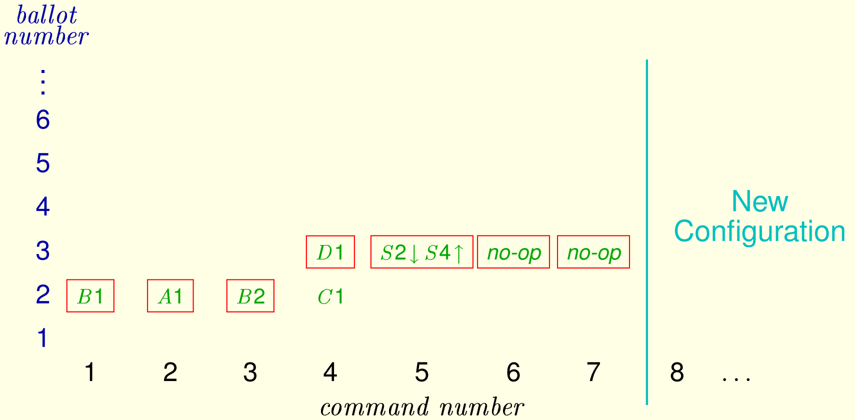
ballot number									
⋮									
6									
5									
4									
3				$\boxed{D1}$	$\boxed{S2{\downarrow}\ S4{\uparrow}}$	$\boxed{\textit{no-op}}$	$\boxed{\textit{no-op}}$		
2	$\boxed{B1}$	$\boxed{A1}$	$\boxed{B2}$	$C1$					
1									
	1	2	3	4	5	6	7	8	. . .

command number

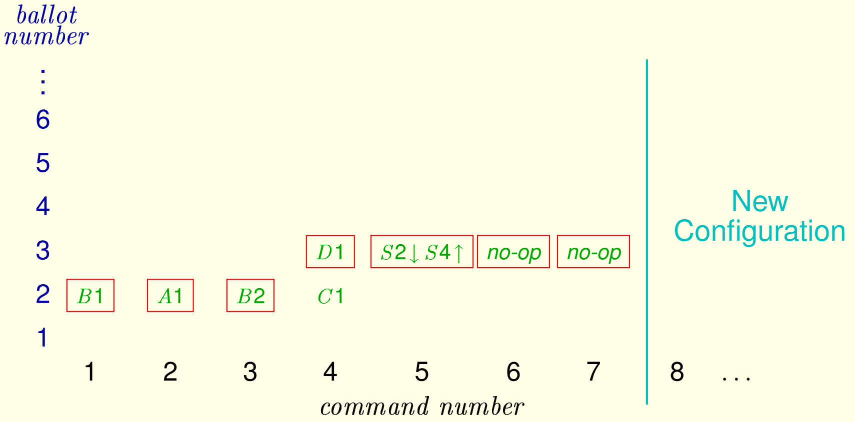
Commands number 5–7 chosen.



New configuration takes effect with command number 8.

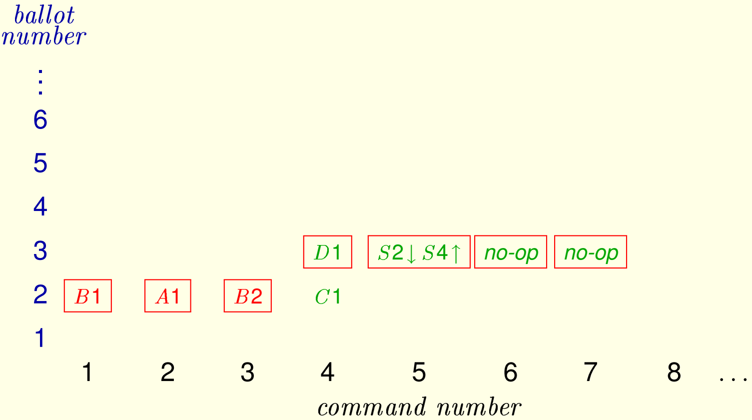


New configuration takes effect with command number 8. $(\alpha = 3)$



New configuration takes effect with command number 8. ($\alpha = 3$)

Horizontal Reconfiguration.



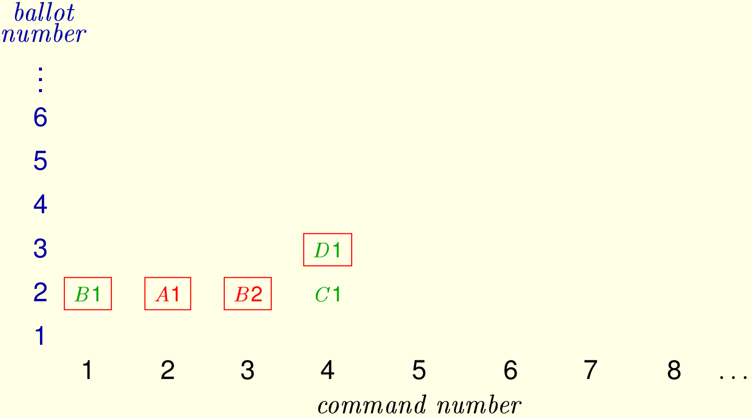
Vertical Reconfiguration

ballot number									
⋮									
6									
5									
4									
3				$\boxed{D1}$	$\boxed{S2\downarrow S4\uparrow}$	$\boxed{\textit{no-op}}$	$\boxed{\textit{no-op}}$		
2	$\boxed{B1}$	$\boxed{A1}$	$\boxed{B2}$	$C1$					
1									
	1	2	3	4	5	6	7	8	. . .

command number

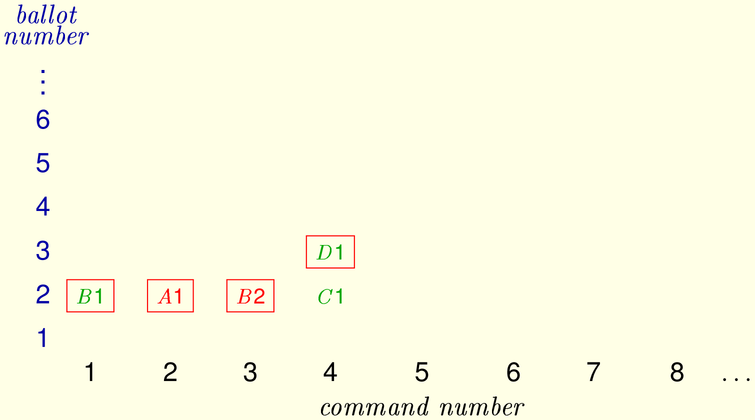
Vertical Reconfiguration

– No state-machine reconfiguration commands.



Vertical Reconfiguration

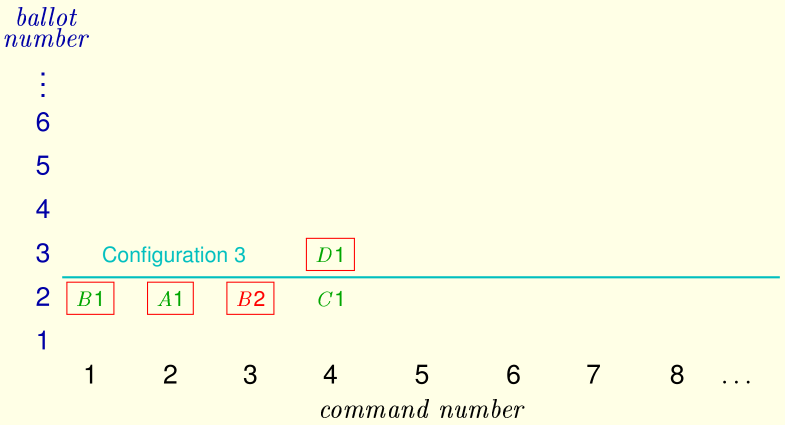
– No state-machine reconfiguration commands.



Vertical Reconfiguration

– No state-machine reconfiguration commands.

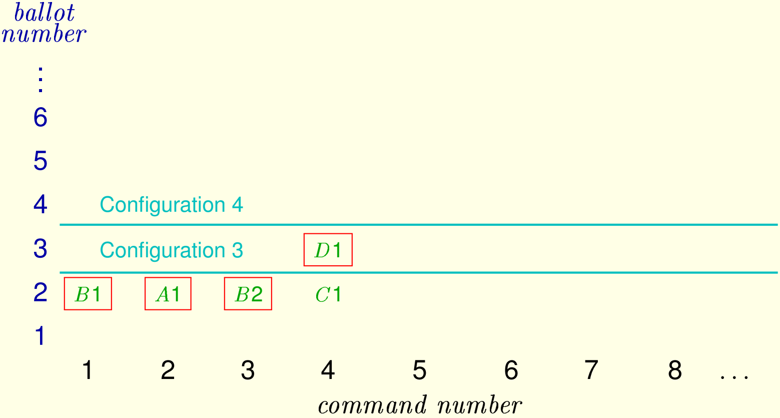
– Each ballot number uses its own configuration.



Vertical Reconfiguration

– No state-machine reconfiguration commands.

– Each ballot number uses its own configuration.

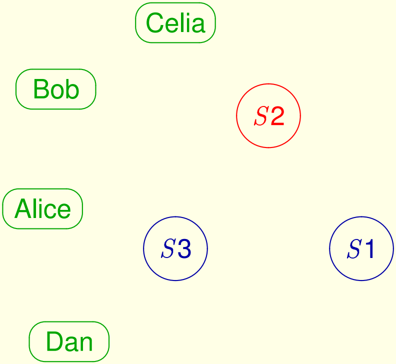


Vertical Reconfiguration

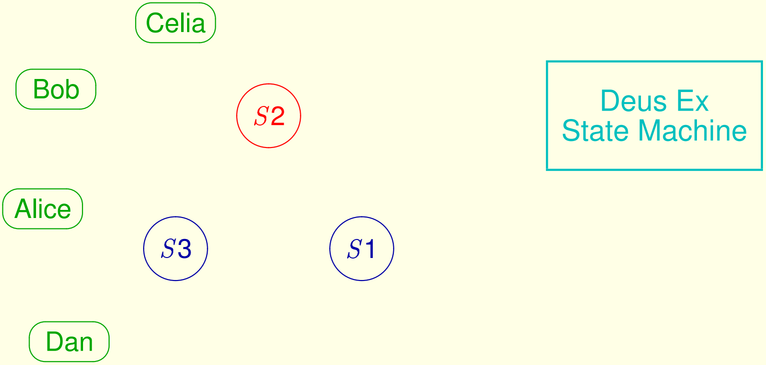
– No state-machine reconfiguration commands.

– Each ballot number uses its own configuration.

How It's Done

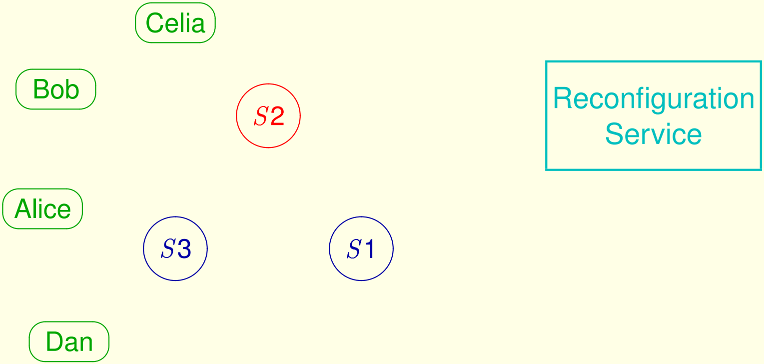


How It's Done



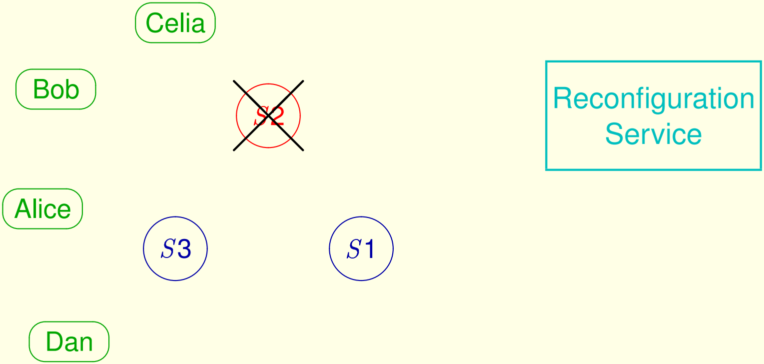
Get external help.

How It's Done



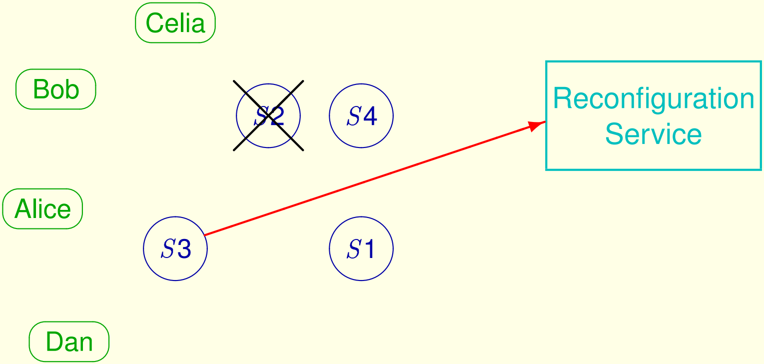
Assume a reliable reconfiguration service.

How It's Done



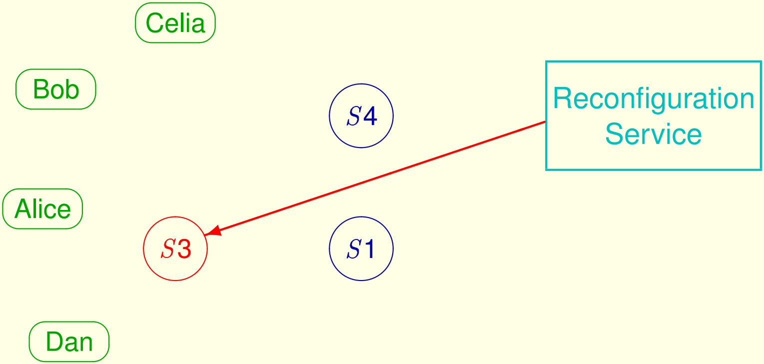
Suppose $S2$ fails.

How It's Done



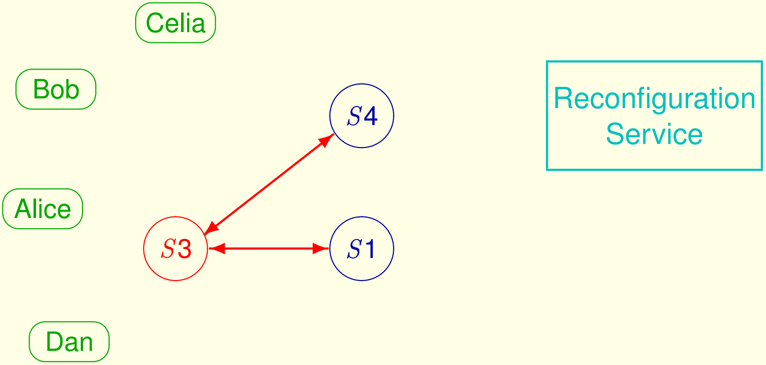
$S3$ asks to be new leader of configuration $S3$, $S1$, $S4$.

How It's Done



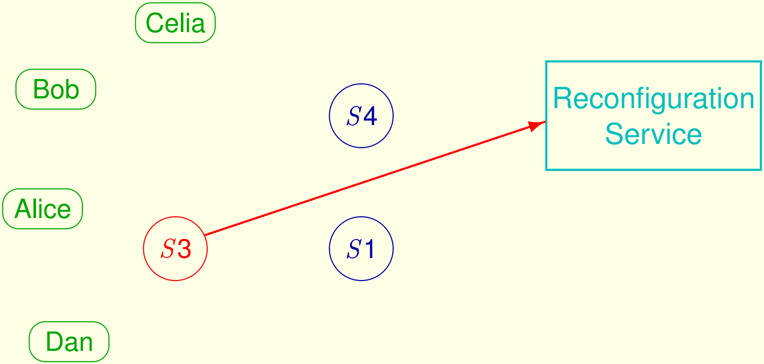
Told to try with ballot number 3.

How It's Done



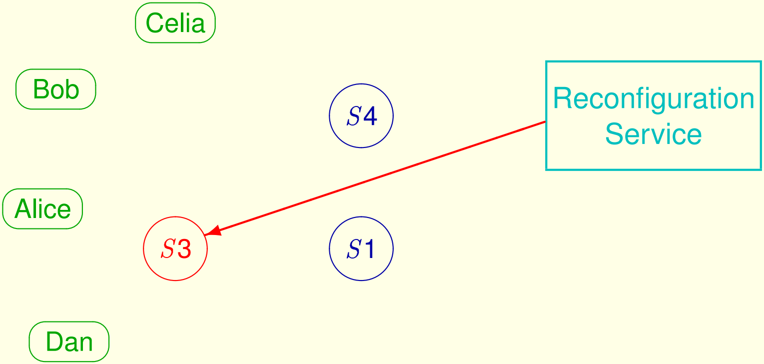
$S3$ ends ballot 2 and starts ballot 3.

How It's Done



$S3$ reports that it has successfully started ballot 3.

How It's Done



Told to resume normal operation of ballot 3.

Where Do We Get a Reconfiguration Service?

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Many different state machines being run by many different computers.

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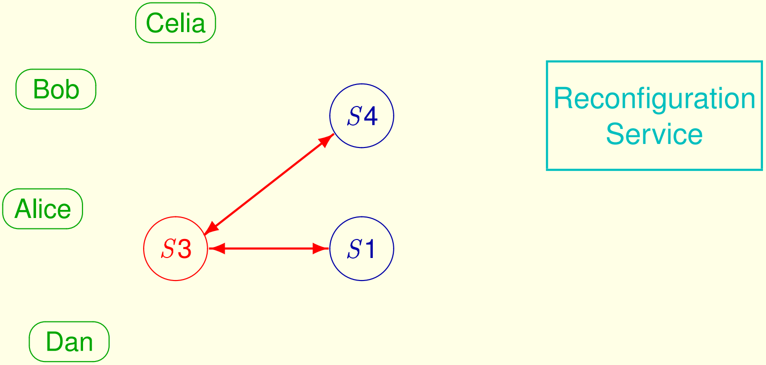
Run the Reconfiguration Service as a reliable state machine (with horizontal reconfiguration).

It can handle lots of different state machines and provide other services as well.



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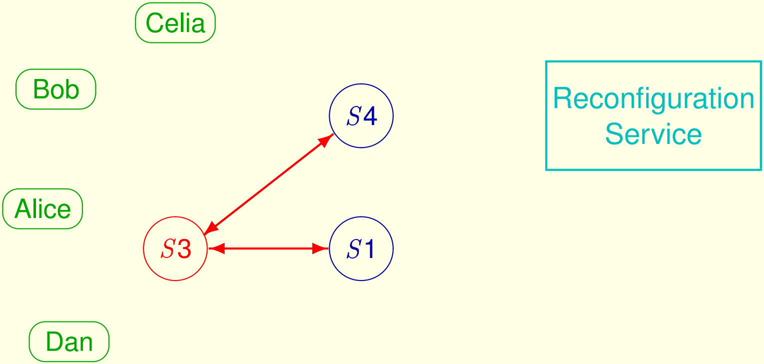
What's Going On Here?



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In case (ii), it proposes in ballot b the next command it receives from a client.

Done simultaneously for all command numbers.

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Observation: Can use different servers in different ballots.

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Hence, can reconfigure when starting a new ballot.

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Problem: removing reliance on ancient configurations.

A new leader starts ballot b by contacting a majority of servers *in all previous ballots* and learning either

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(ii) all commands are safe at b.

In case (i), it proposes (tells servers to vote for) C in ballot b.

In case (ii), it proposes in ballot b the next command it receives from a client.

The Solution

A new leader starts ballot b by contacting a majority of servers and learning either

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In case (i), it proposes (tells servers to vote for) C in ballot b.

tells ballot-b servers that all values are safe; later it

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ballot $b-1$

A new leader starts ballot b by contacting a majority of servers and learning either

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This is what a new leader does—simultaneously for all command numbers.

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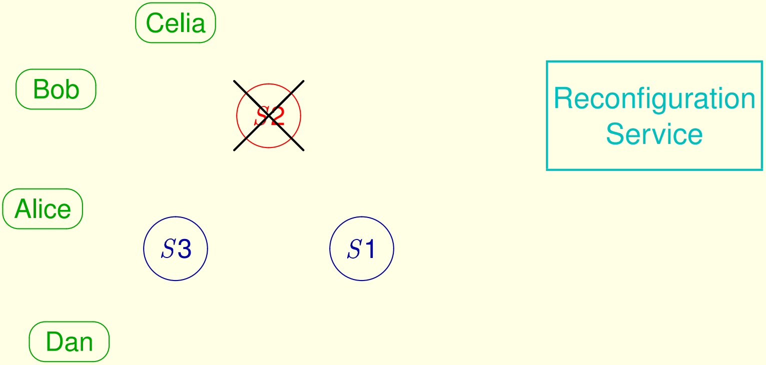
This is what a new leader does—simultaneously for all command numbers.

It then tells the reconfiguration service that it has successfully started ballot b.

Remember How It's Done



Suppose $S2$ fails.

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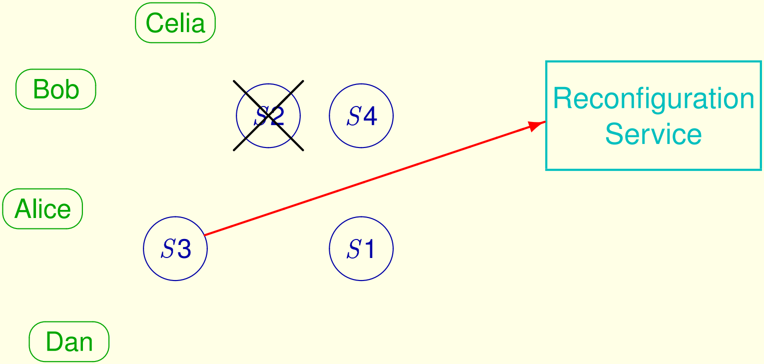

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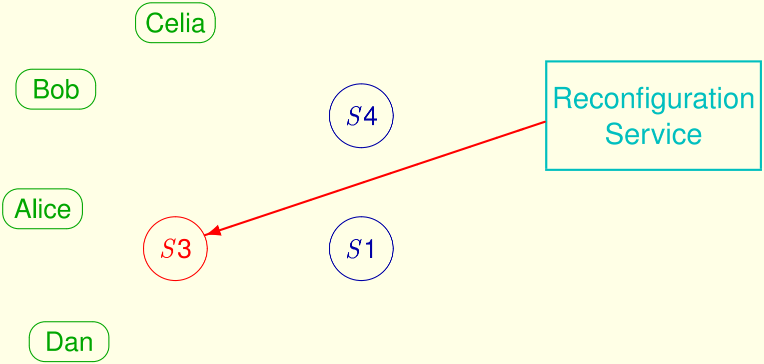

Told to try with ballot number 3.

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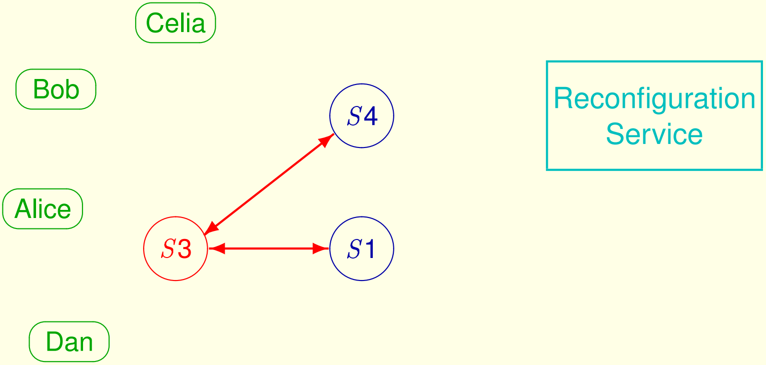

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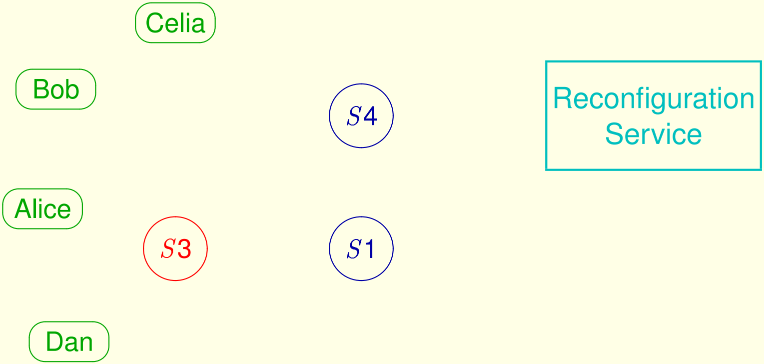

$S3$ ends ballot 2 and starts ballot 3.

This is the processing at the beginning of ballot 3.

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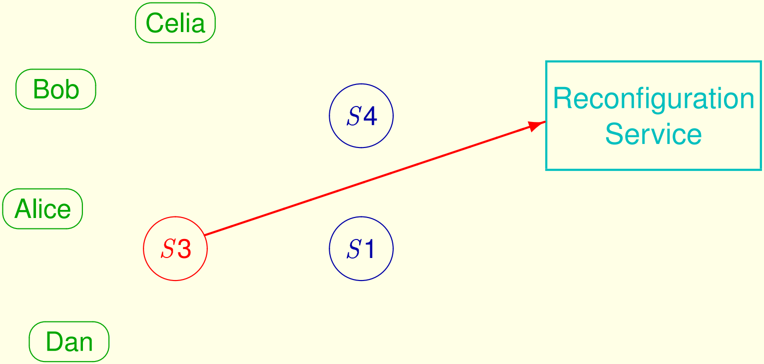

$S3$ reports that it has successfully started ballot 3.

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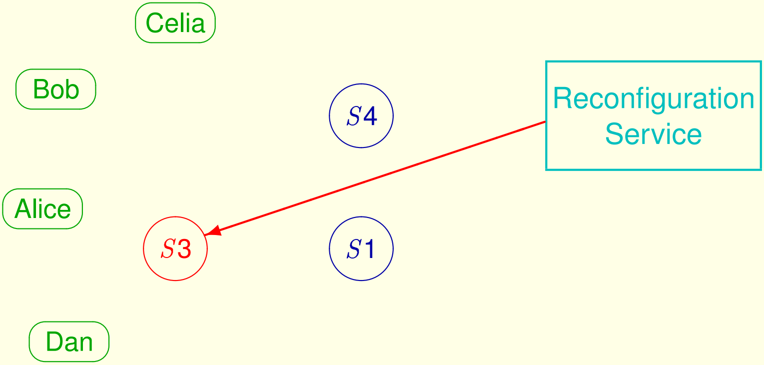
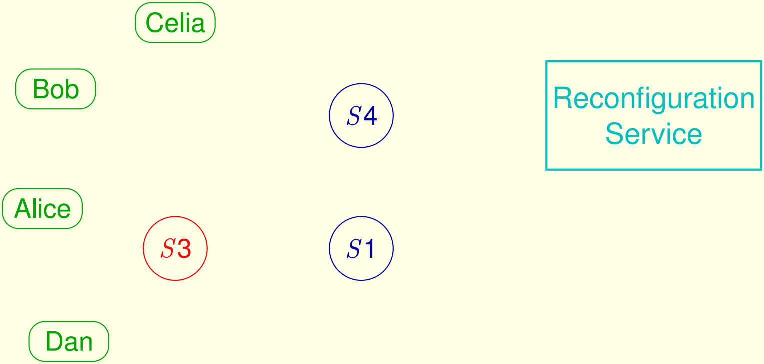


Told to resume normal operation of ballot 3.

Remember How It's Done



Told to resume normal operation of ballot 3.

$S3$ now proposes new client commands.

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Requirement: write quorum $\cap \left\{\begin{array}{c}\text{read}\\ \text{write}\end{array}\right\}$ quorum $\neq \phi$

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Useful with vertical reconfiguration.

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Not a problem with vertical reconfiguration.

The Solution

ballot $b-1$

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The Solution

A new leader starts ballot b by contacting a ~~majority~~ read quorum of ballot $b-1$ servers
and learning either

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In most cases, the new leader will be a ballot $b-1$ server,
so it need contact only itself.

Part IIb: The Present: Primary-Backup

Tolerating f Failures

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Primary-backup approach:

- Use a primary and f backups.
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A popular approach (e.g., Tandem).

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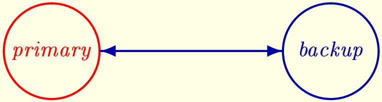
With a primary backup system



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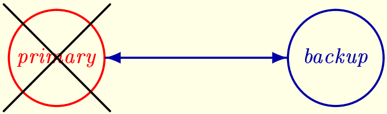

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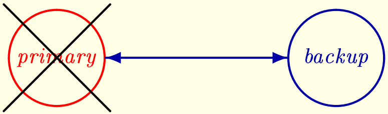
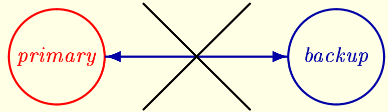
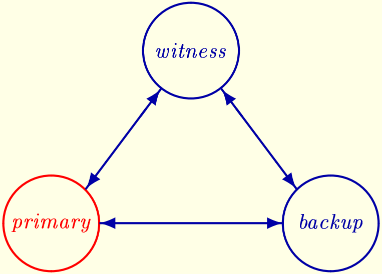


and



Requires an extra “witness” process.



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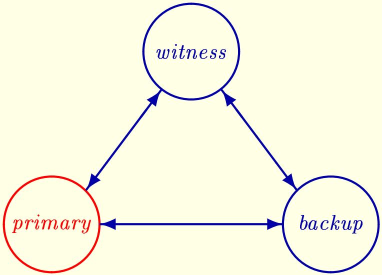

The “witness” need not maintain the system state.

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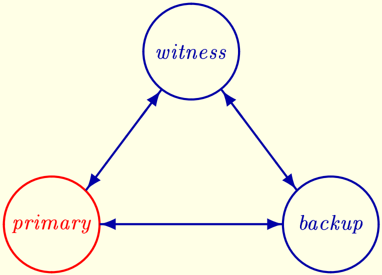

The “witness” need not maintain the system state.

It just votes, not even caring what commands are chosen.

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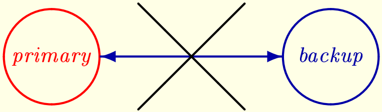

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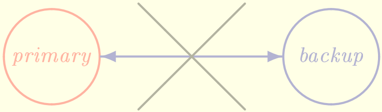

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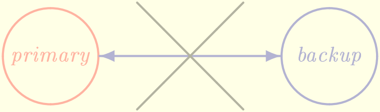

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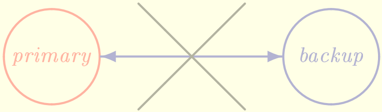

- Rely on an external service (possibly human), using an *ad hoc* algorithm (also known as code).

  Just like the reconfiguration service of Vertical Paxos.

Vertical Paxos provides a rigorous primary-backup algorithm.

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With proof.

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Vertical Paxos and Primary-Backup Replication
by Leslie Lamport, Dahlia Malkhi, and Lidong Zhou

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With proof.

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Available on my publications page, accessible from
`http://lamport.org`

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A PhD thesis topic?

Part III: The Cloudy Future

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- 1000s of machines, not just 10s.
- Have to find the state machine.
- Initial configuration, not just reconfiguration.

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Use 10s of them to execute the state machine.

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Will this really work with malicious nodes?

We won't know until someone builds it and finds out what the engineering problems are.

The problem of a malicious leader

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The weak point of Byzantine Paxos

The problem of a malicious leader

The weak point of Byzantine Paxos

Will it really work?

Eliminating the Leader

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Fatemeh Borran and André Schiper *DISC 2009*

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– Implement a virtual leader as a state machine, using synchronous Byzantine agreement.

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– But agreement failure just leads to malicious a leader, which affects only progress in Byzantine Paxos.

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We have lots of ideas about how to build those trusted services.

THANK YOU