

Paxos: Agreement for Replicated State Machines

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Review: Types of Distributedness

- NFS: distributed to share data across clients through filesystem interface
- Ivy: distributed to provide illusion of seamless shared memory across clients
- 2PC: distributed because different nodes have different functions (e.g., Bank A, Bank B)
- What about distributedness to make system more **available?**

Centralization: Single Points of Failure

- Consider what happens when nodes fail:
 - NFS server?
 - Bank A?
 - CPU that owns a page in Ivy?
- In all these systems, there is single node with “authoritative” copy of some data
- Single point of failure: kill one node, clients may grind to halt
- How can we do better?

Replication

- **Replicate** data on several servers
- If server(s) fail, hopefully others still running; data still available, **clients can still make progress**
- **Consistency?**
 - Informally speaking, all replicas should hold identical copies of data
 - So as users' requests modify data, must somehow *keep* all data identical on all replicas

2PC vs. Replication

- 2PC works well if different nodes play different roles (e.g., Bank A, Bank B)
- 2PC isn't perfect
 - Must wait for all sites and TC to be up
 - Must know if each site voted yes or no
 - TC must be up to decide
 - Doesn't tolerate faults well; must wait for repair
- Can clients make progress when some nodes unreachable?
 - Yes! When data replicated.

State Machine Replication

- Any server essentially a **state machine**
 - Disk, RAM, CPU registers are state
 - Instructions transition among states
 - User requests cause instructions to be executed, so cause transitions among states
- Replicate state machine on multiple hosts
 - Every replica must see same operations in same order
 - If deterministic, replicas end in same state

Ensuring All Replicas See Operations in Same Order

- Nominate one “special” server: **primary**
- Call all other servers **backups**
- Clients send all operations to **current primary**
- Primary's role:
 - Chooses order for clients' operations
 - Sends clients' operations to backups
 - Replies to clients

Ensuring All Replicas See Operations in Same Order

Didn't we say the whole point was availability, and fault-tolerance?

What if primary fails?

primary

- Primary's role:
 - Chooses order for clients' operations
 - Sends clients' operations to backups
 - Replies to clients

Primary Failure

- Last operation received by primary may not be complete
- Need to pick new primary
- Can't allow two simultaneous primaries! (Why?)
- Define: lowest-numbered live server is primary
 - After failure, everyone pings everyone
 - Does everyone now know who new primary is?
- Maybe not:
 - Pings may be lost: two primaries
 - Pings may be delayed: two primaries
 - Network partition: two primaries

Idea: Majority Consensus

- Require a majority of nodes to agree on primary
- At most one network partition can contain majority
- If pings lost, and thus two potential primaries, **majorities must overlap**
 - Node(s) in overlap can see both potential primaries, raise alarm about non-agreement!

Technique: View Change Algorithm

- Entire system goes through sequence of views
- View: {view #, set of participant nodes}
- View change algorithm must ensure agreement on unique successor for each view
- Participant set within view allows all nodes to agree on primary
 - Same rule: lowest-numbered ID in set is primary

Technique: View Change Algorithm

If two nodes agree on view, they will agree on primary

- View: {view #, set of participant nodes}
- View change algorithm must ensure agreement on **unique successor for each view**
- Participant set within view allows all nodes to agree on primary
 - Same rule: lowest-numbered ID in set is primary

View Change Requires Fault-Tolerant Agreement

- Envision view as **opaque value**
- Want all nodes to agree on same value (i.e., same view)
- At most one value may be chosen
- Want to agree **despite lost messages and crashed nodes**
- **Can't guarantee to agree!**
 - Can guarantee **not to agree** on different values!
 - i.e., guarantee **safety**, but not liveness

Paxos:

Fault-Tolerant Agreement Protocol

- Protocol eventually succeeds provided
 - Majority of participants reachable
 - Participants know how to generate value to agree on
 - i.e., Paxos doesn't determine the value nodes try to agree on—value is an **opaque input** to Paxos
- Only widely used algorithm for fault-tolerant agreement in state machine replication

Review: State Machine Replication, Primary-Backup, Paxos

- **How did we get here?**
- Want to replicate a system for availability
- View system as state machine; replicate the state machine
- Ensure all replicas see same ops in same order
- Primary orders requests, forwards to replicas
- All nodes must agree on primary
- All nodes must agree on view
 - Participant with lowest address in view is primary
- **Paxos** guaranteed to complete only when all nodes agree on input (in this case, input is view)

Overview of Paxos

- One (or more) nodes decide to be **leader**
- Leader chooses **proposed value** to agree on
 - (In our case, value is view: {view #, participant set})
- Leader contacts Paxos participants, tries to assemble majority
 - Participants can be fixed set of nodes (configured)
 - Or can be all nodes in old view (including unreachable nodes)
- If a majority respond, **successful agreement**

Agreement is Hard!

- What if two nodes decide to be leader?
- What if network partition leads to two leaders?
- What if leader crashes after persuading only some nodes?
- What if leader got majority, then failed, without announcing result?
 - Or announced result to only a few nodes?
 - **New leader might choose different value, despite previous agreement**

Paxos: Structure

- Three phases in algorithm
- May need to restart if nodes fail or timeouts waiting for replies
- State in each node running Paxos, per-value (view):
 - n_a : greatest n accepted by node (init: -1)
 - v_a : value received together with n_a (init: nil)
 - n_h : greatest n seen in Q1 message (init: -1)
 - done: leader says agreement reached; can use new value (i.e., start new view) (init: 0)

Paxos: Phase 1

A node (maybe more than one) decides to be leader, then it

picks proposal number, n

must be unique, good if higher than any known proposal number

use last known proposal number + 1,
append node's own ID

sends $Q1(n)$ message to all nodes (including self)

if node receives $Q1(n)$ and $n > n_h$

$n_h = n$

send reply $R1(n_a, v_a)$ message

Paxos: Phase 2

if leader receives R1 messages from majority of nodes (including self)

if any $R1(n, v)$ contained a value (v)

v = value sent with highest n

else leader gets to choose a value (v)

$v = \{\text{old view\#} + 1, \text{set of pingable nodes}\}$

send $Q2(n, v)$ message to all responders

if node receives $Q2(n, v)$ and $n \geq n_h$

$n_h = n_a = n$

$v_a = v$

send reply $R2()$ message

Paxos: Phase 3

if leader receives R2() messages from
majority of protocol participants

send Q3() message to all participants

if node receives Q3()

done = true

agreement reached; agreed-on value is v_a

(primary is lowest-numbered node in
participant list within v_a)

Paxos: Timeouts

- All nodes wait a maximum period (timeout) for messages they expect
- Upon timeout, a node declares itself a leader and initiates a new Phase 1 of algorithm

Paxos with One Leader, No Failures: Phase 1

	0	1	2	3	4
n_a	-1	-1	-1	-1	-1
v_a	nil	nil	nil	nil	nil
n_h	-1	-1	-1	-1	-1
done	F	F	F	F	F

Paxos with One Leader, No Failures: Phase 1

n = 11

	0	1	2	3	4
n_a	-1	-1	-1	-1	-1
v_a	nil	nil	nil	nil	nil
n_h	-1	-1	-1	-1	-1
done	F	F	F	F	F

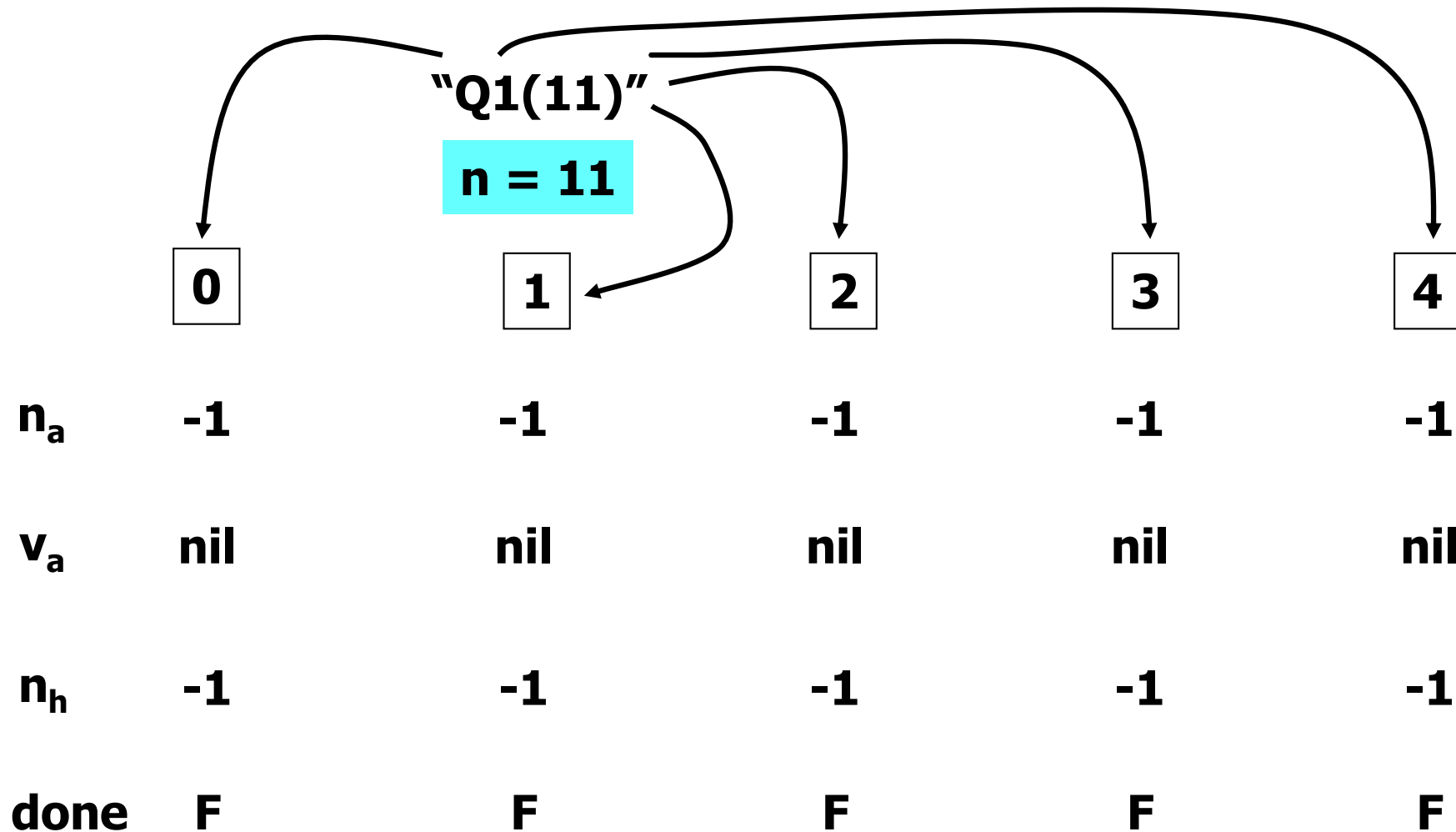
Paxos with One Leader, No Failures: Phase 1

"Q1(11)"

n = 11

	0	1	2	3	4
n_a	-1	-1	-1	-1	-1
v_a	nil	nil	nil	nil	nil
n_h	-1	-1	-1	-1	-1
done	F	F	F	F	F

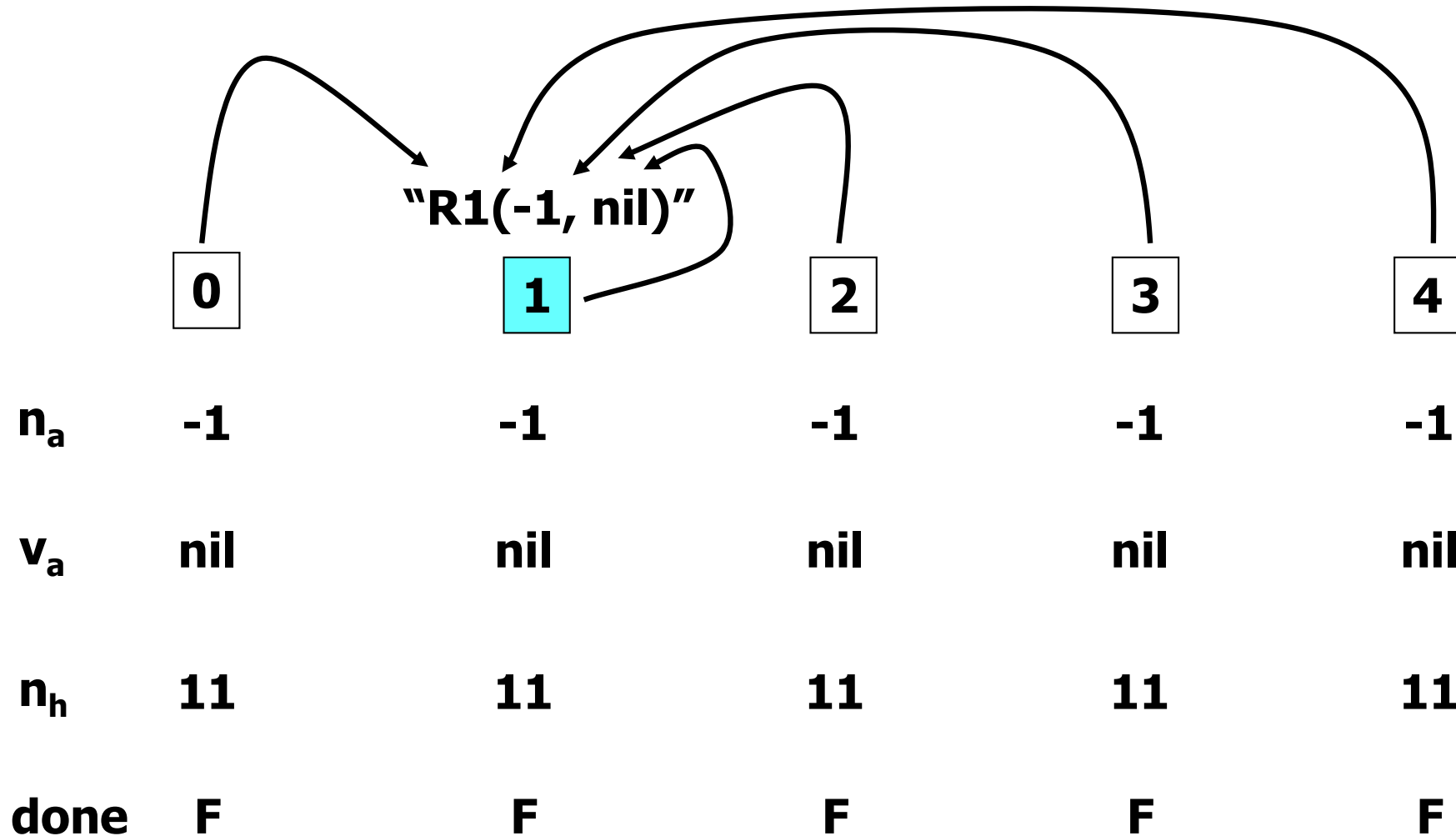
Paxos with One Leader, No Failures: Phase 1



Paxos with One Leader, No Failures: Phase 1

	0	1	2	3	4
n_a	-1	-1	-1	-1	-1
v_a	nil	nil	nil	nil	nil
n_h	11	11	11	11	11
done	F	F	F	F	F

Paxos with One Leader, No Failures: Phase 1



Paxos with One Leader, No Failures: Phase 2

R1 from
majority!
all v's nil

	0	1	2	3	4
n_a	-1	-1	-1	-1	-1
v_a	nil	nil	nil	nil	nil
n_h	11	11	11	11	11
done	F	F	F	F	F

Paxos with One Leader, No Failures: Phase 2

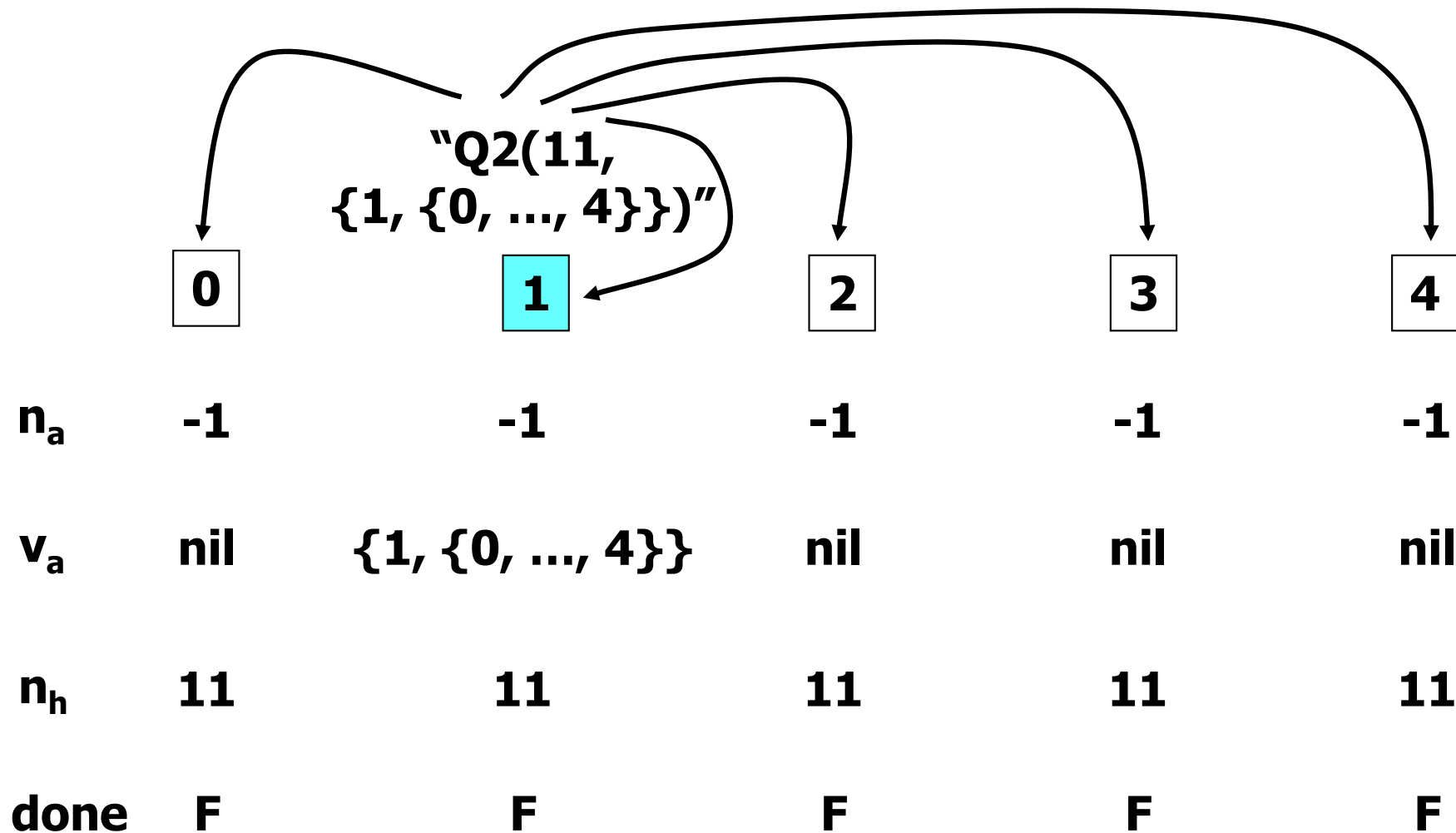
	0	1	2	3	4
n_a	-1	-1	-1	-1	-1
v_a	nil	$\{1, \{0, \dots, 4\}\}$	nil	nil	nil
n_h	11	11	11	11	11
done	F	F	F	F	F

Paxos with One Leader, No Failures: Phase 2

"Q2(11,
{1, {0, ..., 4}})"

	0	1	2	3	4
n_a	-1	-1	-1	-1	-1
v_a	nil	{1, {0, ..., 4}}	nil	nil	nil
n_h	11	11	11	11	11
done	F	F	F	F	F

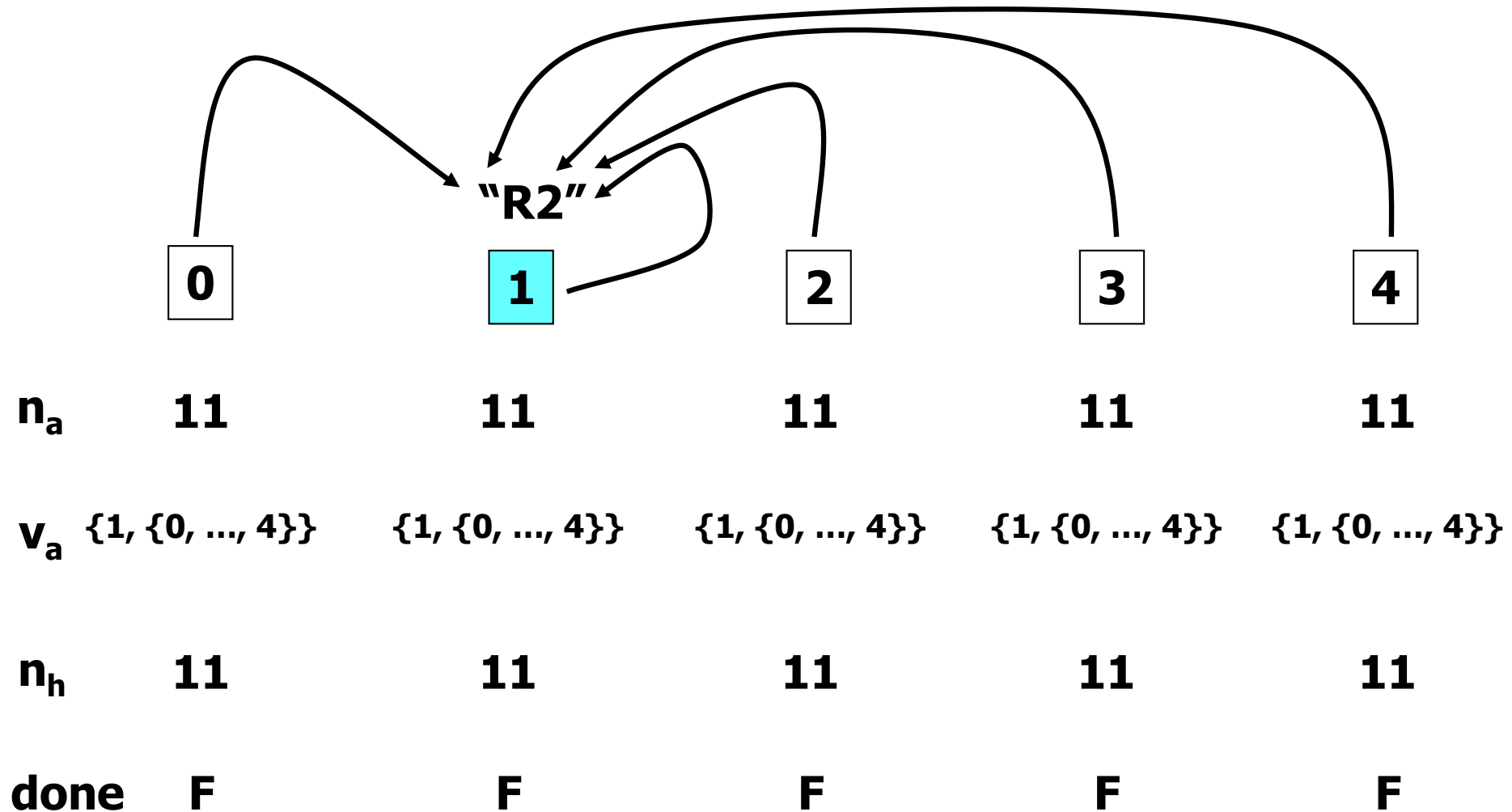
Paxos with One Leader, No Failures: Phase 2



Paxos with One Leader, No Failures: Phase 2

	0	1	2	3	4
n_a	11	11	11	11	11
v_a	{1, {0, ..., 4}}	{1, {0, ..., 4}}	{1, {0, ..., 4}}	{1, {0, ..., 4}}	{1, {0, ..., 4}}
n_h	11	11	11	11	11
done	F	F	F	F	F

Paxos with One Leader, No Failures: Phase 2

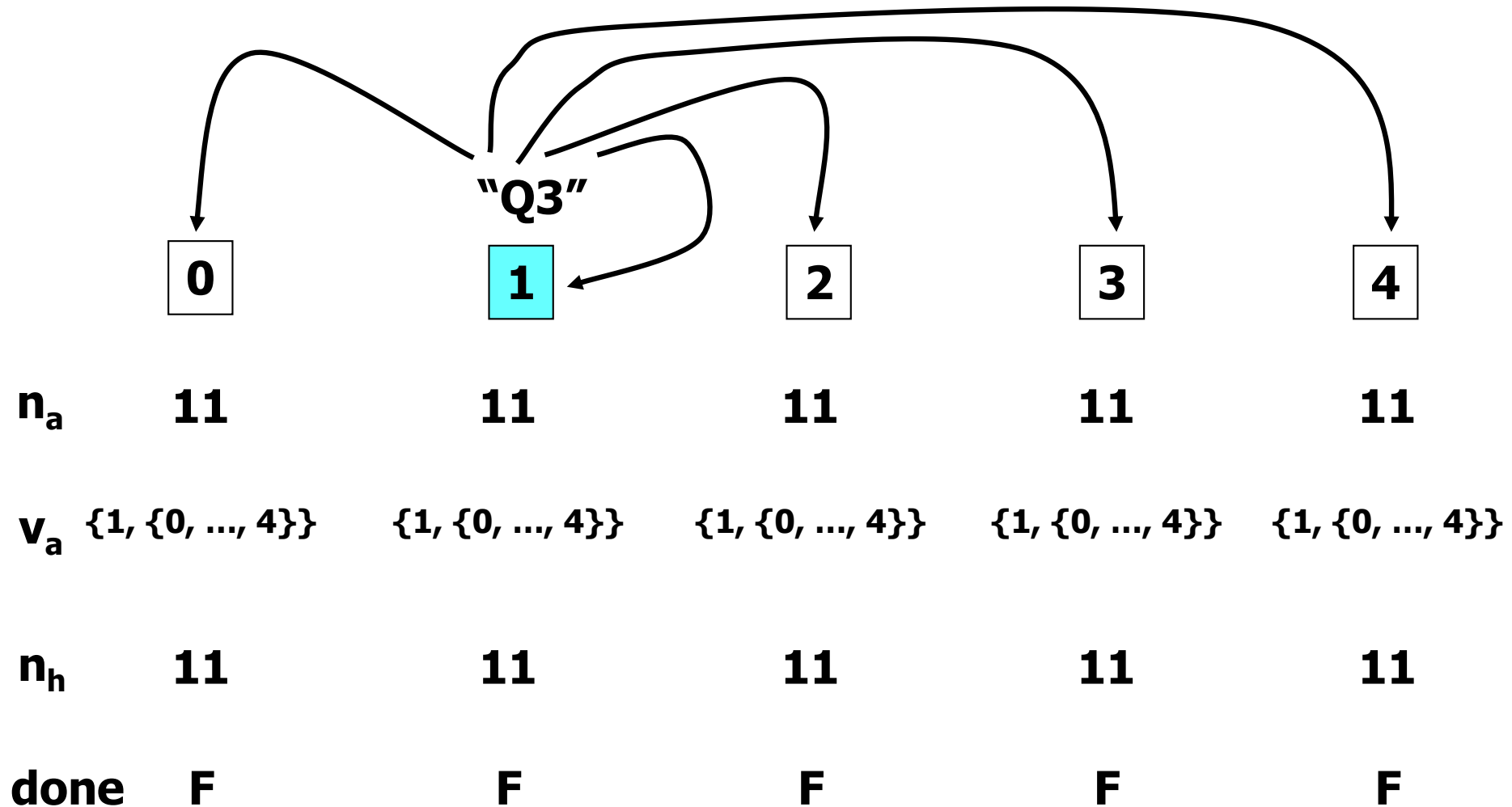


Paxos with One Leader, No Failures: Phase 3

R2 from
majority!

	<div>0</div>	<div>1</div>	<div>2</div>	<div>3</div>	<div>4</div>
n_a	11	11	11	11	11
v_a	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$
n_h	11	11	11	11	11
done	F	F	F	F	F

Paxos with One Leader, No Failures: Phase 3



Paxos with One Leader, No Failures: Phase 3

	0	1	2	3	4
n_a	11	11	11	11	11
v_a	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$
n_h	11	11	11	11	11
done	T	T	T	T	T

Paxos with One Leader, No Failures: Phase 3

**All nodes agree on view $\{1, \{0, \dots, 4\}\}$
New primary: lowest ID, so node 0**

	0	1	2	3	4
n_a	11	11	11	11	11
v_a	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$	$\{1, \{0, \dots, 4\}\}$
n_h	11	11	11	11	11
done	T	T	T	T	T

Paxos: Number of Leaders

- Clearly, when no failures, no message losses, and one leader, **Paxos reaches agreement**
- How can one ensure that with high probability, only one leader?
 - Every node must be willing to become leader in case of failures
 - Every node should delay random period after realizing pingable nodes have changed, or delay own ID x some constant

Paxos: Ensuring Agreement

- When would non-agreement occur?
 - When nodes with different v_a receive Q3
- Safety goal:
 - If Q3 could have been sent, future Q3s guaranteed to reach nodes with same v_a

Risk: More Than One Leader

- Can occur after timeout during Paxos algorithm, partition, lost packets
- Two leaders must use different n in their $Q1()$ s, by construction of n
- Suppose two leaders proposed $n = 10$ and $n = 11$

More Than One Leader (2)

- Case 1: proposer of 10 **didn't receive R2()s from majority of participants**
 - Proposer never will receive R2()s from majority, as no node will send R2() in reply to Q2(10,...) after seeing Q1(11)
 - Or proposer of 10 may be in network partition with minority of nodes

More than One Leader (3)

- Case 2: proposer of 10 (10) **did receive R2()s from majority of participants**
 - Thus, 10's originator may have sent Q3()!
 - But 10's majority must have seen 10's Q2() before 11's Q1()
 - Otherwise, would have ignored 10's Q2, and no majority could have resulted
 - Thus, 11 must receive R1 from at least one node that saw 10's Q2
 - Thus, 11 must be aware of 10's value
 - Thus, 11 would have used 10's value, rather than creating one!

More than One Leader (3)

Result: agreement on 10's proposed value!

from majority of participants

- Thus, 10's originator may have sent Q3()!
- But 10's majority must have seen 10's Q2() before 11's Q1()
 - Otherwise, would have ignored 10's Q2, and no majority could have resulted
- Thus, 11 must receive R1 from at least one node that saw 10's Q2
- Thus, 11 must be aware of 10's value
- Thus, 11 would have used 10's value, rather than creating one!

Risk: Leader Fails Before Sending Q2()s

- Some node will time out and become a leader
- Old leader didn't send any Q3()s, so no risk of non-agreement caused by old leader
- Good, but not required, that new leader chooses higher n for proposal
 - Otherwise, timeout, some other leader will try
 - Eventually, will find leader who knew old n and will use higher n

Risks: Leader Failures

- Suppose leader fails after sending minority of Q2()s
 - Same as two leaders!
- Suppose leader fails after sending majority of Q2()s
 - i.e., potentially after reaching agreement!
 - Also same as two leaders!

Risk: Node Fails After Receiving Q2(), and After Sending R2()

- If node doesn't restart, possible timeout in Phase 3, new leader
- If node does restart, it must remember v_a and n_a on disk!
 - Leader might have failed after sending a few Q3()s
 - New leader must choose same value
 - This failed node may be only node in intersection of two majorities!

Paxos: Summary

- Original goal: replicated state machines!
 - Want to continue, even if some nodes not reachable
- After each failure, perform **view change** using **Paxos agreement**
- i.e., agree on exactly which nodes in new view
- Thus, everyone can agree on new primary
- No discussion here of how to render **data** consistent across replicas!