Byzantine Fault Tolerance

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CS 240: Computing Systems and Concurrency
Lecture 15

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So far: Fail-stop failures

- Traditional state machine replication tolerates **fail-stop failures:**
  - Node crashes
  - Network breaks or partitions

- State machine replication with $N = 2f+1$ replicas can tolerate f **simultaneous fail-stop failures**
  - **Two algorithms:** Paxos, RAFT

Byzantine faults

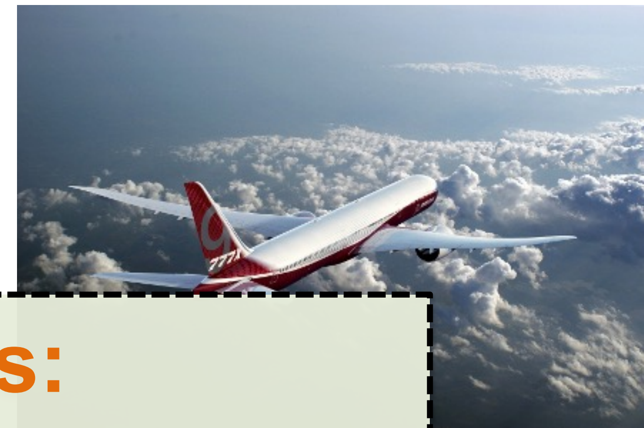
- ***Byzantine fault:*** Node/component **fails arbitrarily**
  - Might perform **incorrect computation**
  - Might give **conflicting information** to different parts of the system
  - Might **collude** with other failed nodes
- Why might nodes or components fail arbitrarily?
  - **Software bug** present in code
  - **Hardware failure** occurs
  - **Hack** attack on system

Today: Byzantine fault tolerance

- Can we provide state machine replication for a service **in the presence of Byzantine faults?**
- Such a service is called a **Byzantine Fault Tolerant** (**BFT**) service
- *Why might we care about this level of reliability?*

Mini-case-study: Boeing 777 fly-by-wire primary flight control system

- **Triple-redundant, dissimilar** processor hardware:
  1. Intel 80486
  2. Motorola
  3. AMD
- Each processor runs code from a different compiler



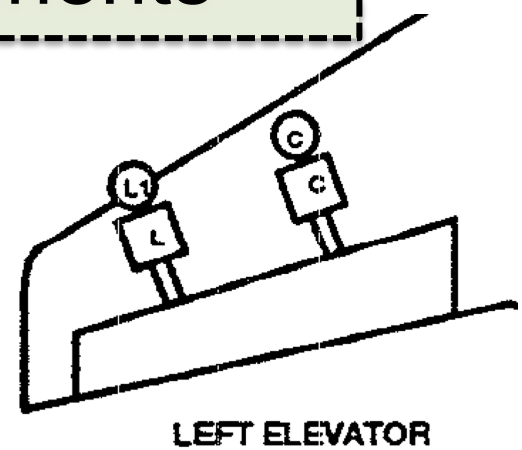
Key techniques:

Hardware and software **diversity**

Voting between components

Simplified design:

- Pilot inputs → three processors
- Processors vote → **control surface**



Today

1. **Traditional state-machine replication for BFT?**

2. Practical BFT replication algorithm

3. Performance and Discussion

Review: Tolerating one fail-stop failure

- **Traditional state machine replication (Paxos)** requires, *e.g.*, $2f + 1$ = **three** replicas, if $f = 1$

- Operations are totally ordered → correctness
  - A two-phase protocol

- Each operation uses $\geq f + 1 = 2$ of them
  - **Overlapping** quorums
    - So at **least one replica** "remembers"

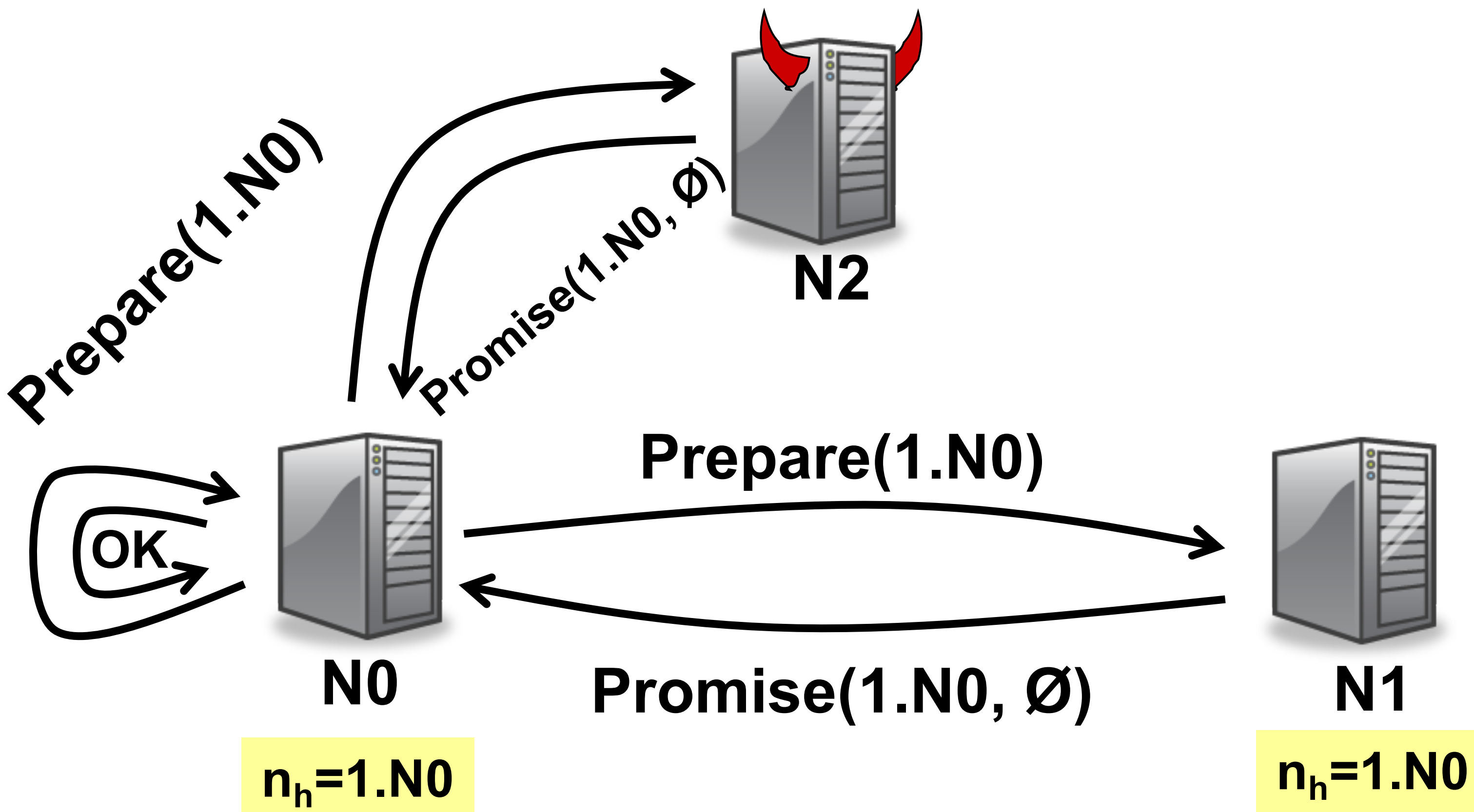
Use Paxos for BFT?

1. **Can't rely on the primary** to assign proposal #
   – Could assign same proposal # to different requests

2. **Can't use Paxos** for view change
   – Under Byzantine faults, the intersection of two majority (*f* + 1 node) quorums **may be bad node**

   – Bad node tells **different** quorums **different things!**
   - *e.g.* tells N0 accept **val1,** but N1 accept **val2**

Paxos under Byzantine faults (*f* = 1)



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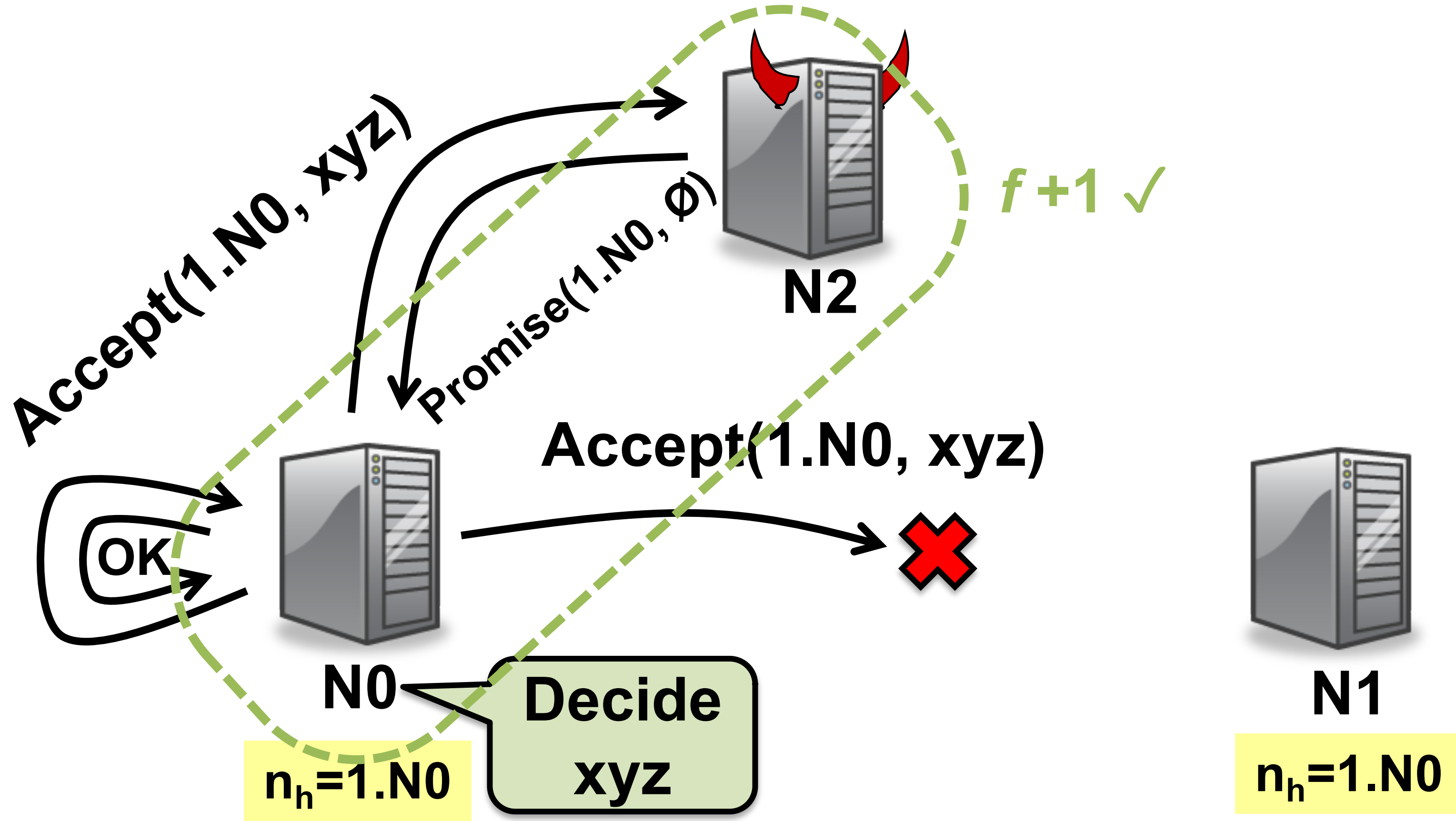

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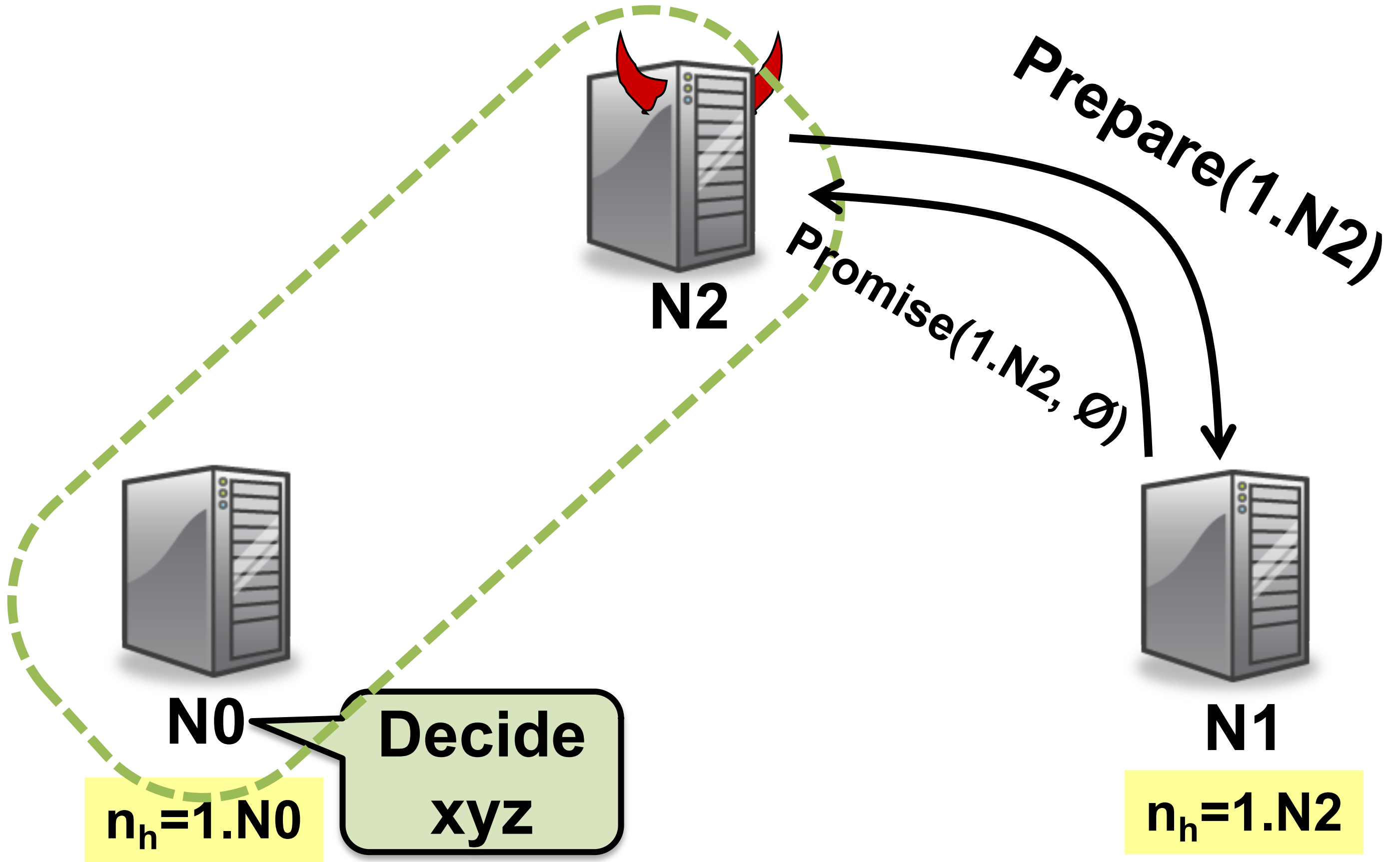
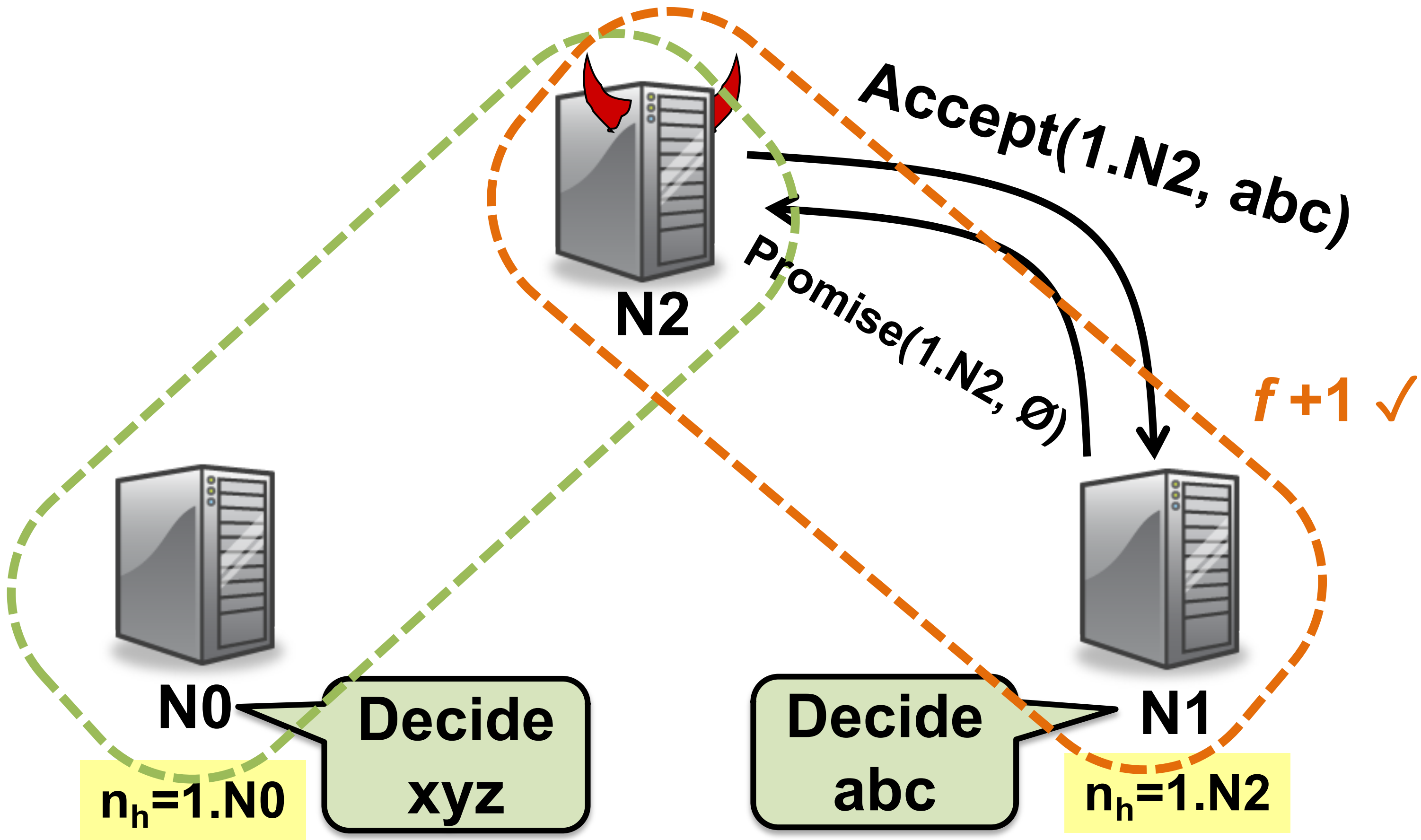


Paxos under Byzantine faults (*f* = 1)



Conflicting decisions!

Theoretical fundamentals: Byzantine Generals

Result: Using messengers, problem **solvable iff > ⅔** of the generals are loyal

Put burden on client instead?

- Clients **sign** input data before storing it, then **verify** signatures on data retrieved from service

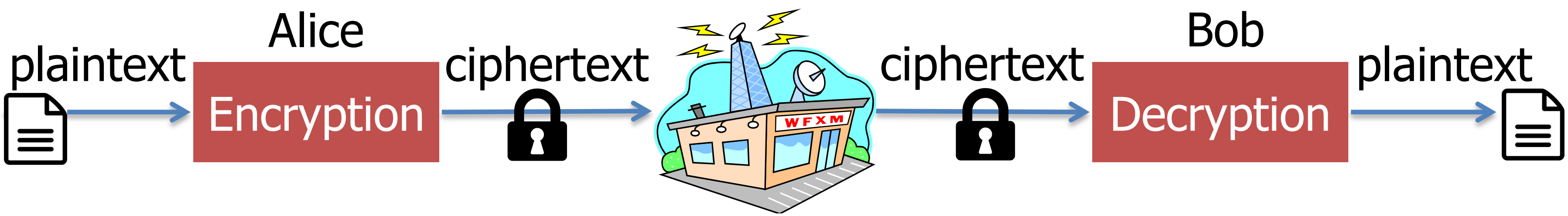
- **Example:** Store signed file f1="aaa" with server
  - Verify that returned f1 is correctly signed

<cryptography in 6 slides>

κρυπτό + γραφή (Cryptography)

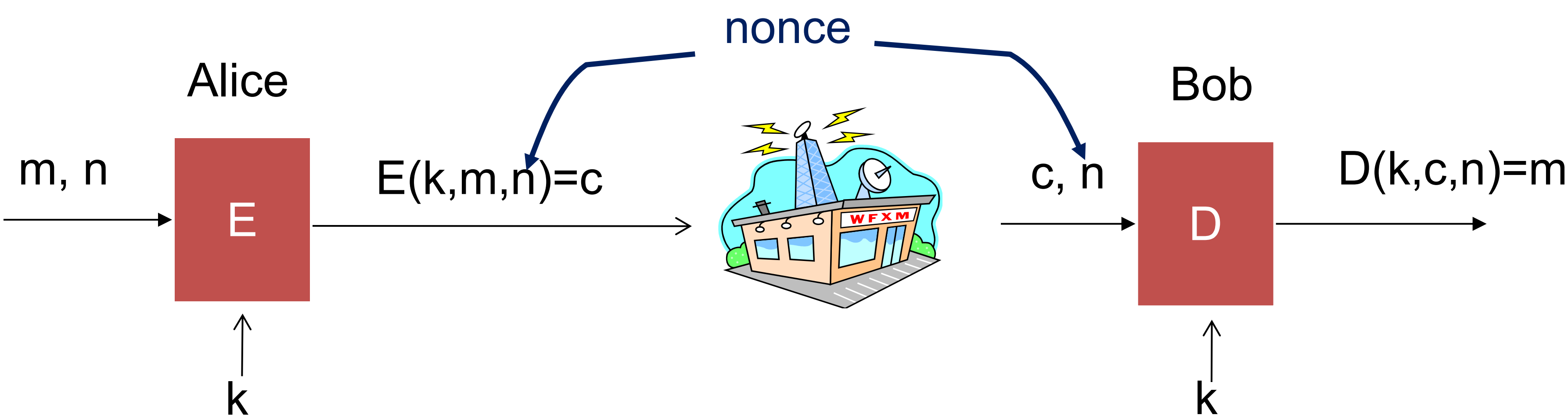
- Greek for "secret writing"
- **Confidentiality**
  - Obscure a message from eavesdroppers
- **Integrity**
  - Assure recipient that the message was not altered
- **Authentication**
  - Verify the identity of the source of a message
- **Non-repudiation**
  - Convince a 3rd party that what was said is accurate

Terminology



- Encryption algorithm
  - Transforms a **plaintext** into a **ciphertext** that is **unintelligible for non-authorized parties**
  - Usually parametrized with a cryptographic key
- **Asymmetric (Public) key cryptography**
  - Crypto system: encryption + decryption algorithms + key generation
- **Symmetric (Shared) key cryptography**
  - Cipher/decipher: symmetric-key encryption/decryption algorithms

Symmetric key encryption



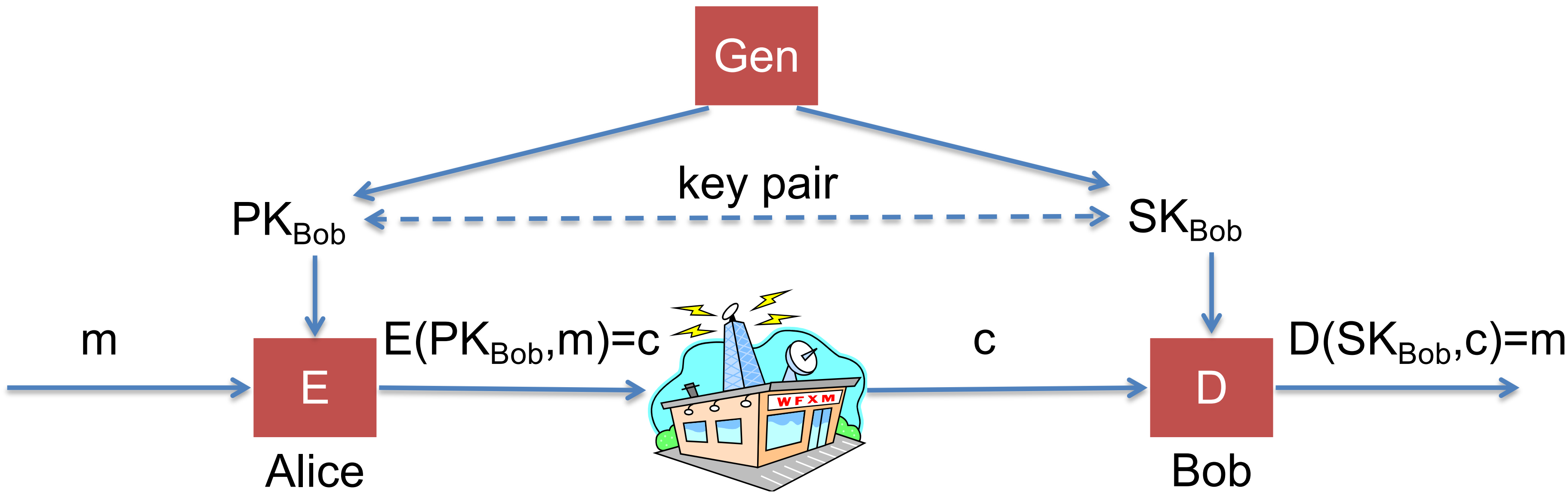
E, D: cipher   k: secret key (e.g. 128 bits)

m, c: plaintext, ciphertext   n: nonce (aka IV)

Encryption algorithm is **publicly known**

- Never use a proprietary cipher

Public key encryption



PK: public key , SK: secret key (e.g., 1024 bits)

Example: Bob generates (PK_{Bob}, SK_{Bob}) and gives PK_{Bob} to Alice

Applications

- Public-key encryption
  - Alice public key for encryption
  - Anyone can send encrypted message
  - Only Alice can decrypt messages (with secret key)

- Digital signature scheme
  - Alice public key for verifying signatures
  - Anyone can check a message signed by Alice
  - Only Alice can sign messages (with secret key)

Establishing a shared secret

Alice

Bob

(pk, sk) ⟵ G()

“Alice”, pk

choose random x

“Bob”, c⟵E(pk,x)

D(sk,c) ⟶ x

x shared secret

</cryptography in 6 slides>

Put burden on client instead?

- Clients **sign** input data before storing it, then **verify** signatures on data retrieved from service

- **Example:** Store signed file f1="aaa" with server
  - Verify that returned f1 is correctly signed

But a Byzantine node can **replay stale,** signed **data** in its response

Inefficient: Clients have to perform computations and sign data

Today

1. Traditional state-machine replication for BFT?

2. **Practical BFT replication algorithm**
   [Liskov & Castro, 2001]

3. Performance and Discussion

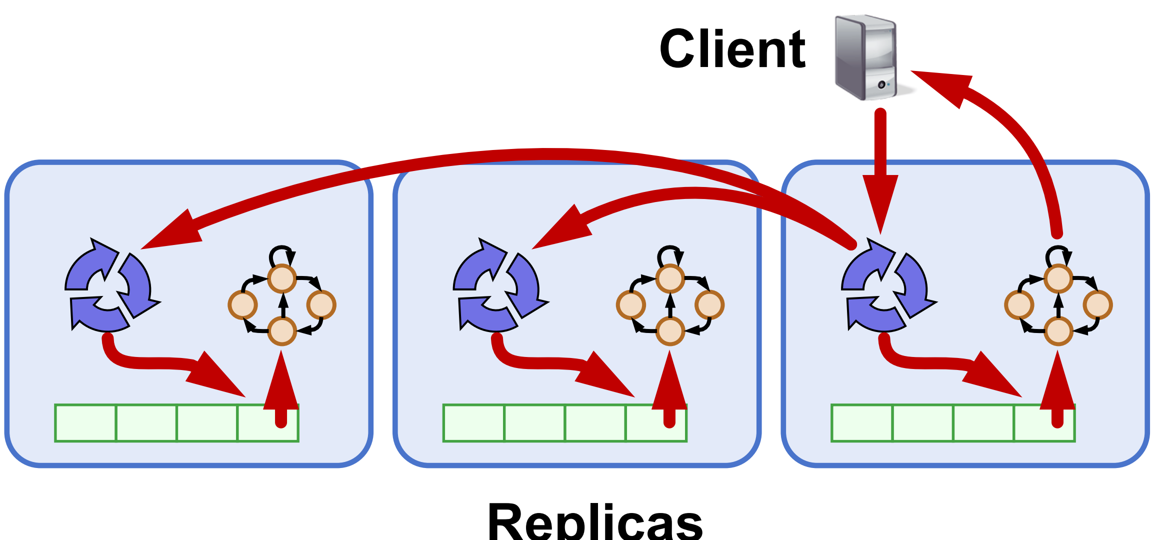
Practical BFT: Overview

- Uses 3*f*+1 **replicas** to survive *f* **failures**
  - Shown to be **minimal** **(Lamport)**
- Requires **three phases (not two)**
- Provides **state machine replication**
  - Arbitrary service accessed by operations
    - E.g., file system ops read and write files and directories
  - **Tolerates** Byzantine-faulty clients

Correctness argument

- Assume operations are **deterministic**
- Assume replicas **start in same state**

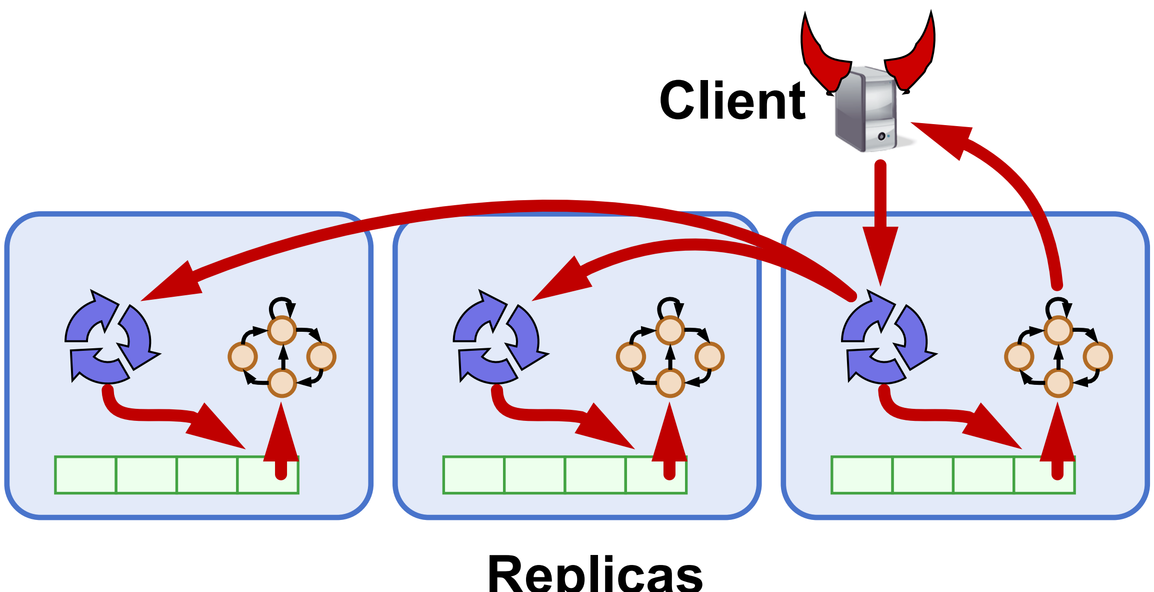
- If replicas execute **same requests** in **same order:**
  - Correct replicas will produce **identical results**



Non-problem: Client failures

- Clients **can't** cause replica inconsistencies

- Clients **can** write bogus data to the system
  - **Sol'n:** Authenticate clients and separate their data
    - This is a **separate problem**

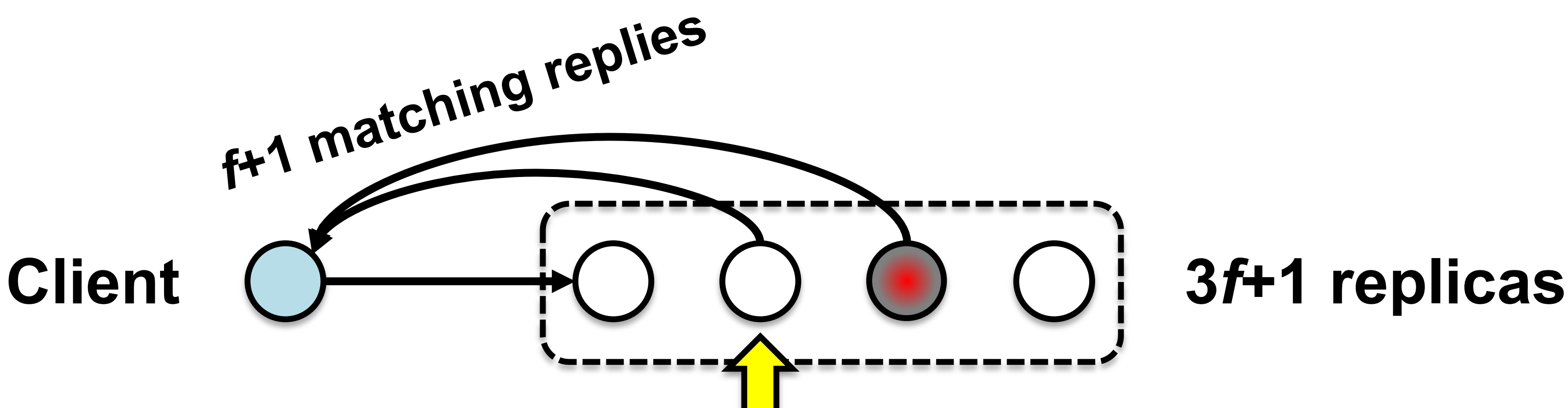


What clients do

1. Send requests to the primary replica

2. Wait for *f*+1 **identical** replies
   - **Note:** The replies may be deceptive
     - *i.e.* replica returns "correct" answer, but locally does otherwise!

- But **≥ one** reply is **actually** from a **non-faulty replica**

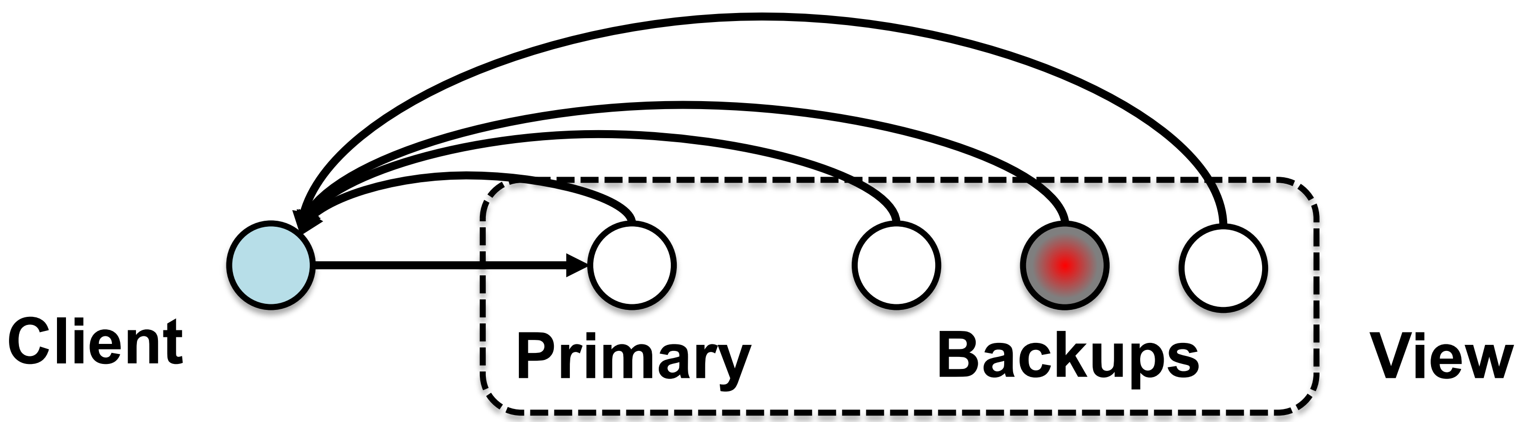


What replicas do

- Carry out a protocol that ensures that
  - Replies from honest replicas are correct
  - Enough replicas process each request to ensure that
    - The **non-faulty** replicas process the **same requests**
    - In the **same order**
- Non-faulty replicas obey the protocol

Primary-Backup protocol

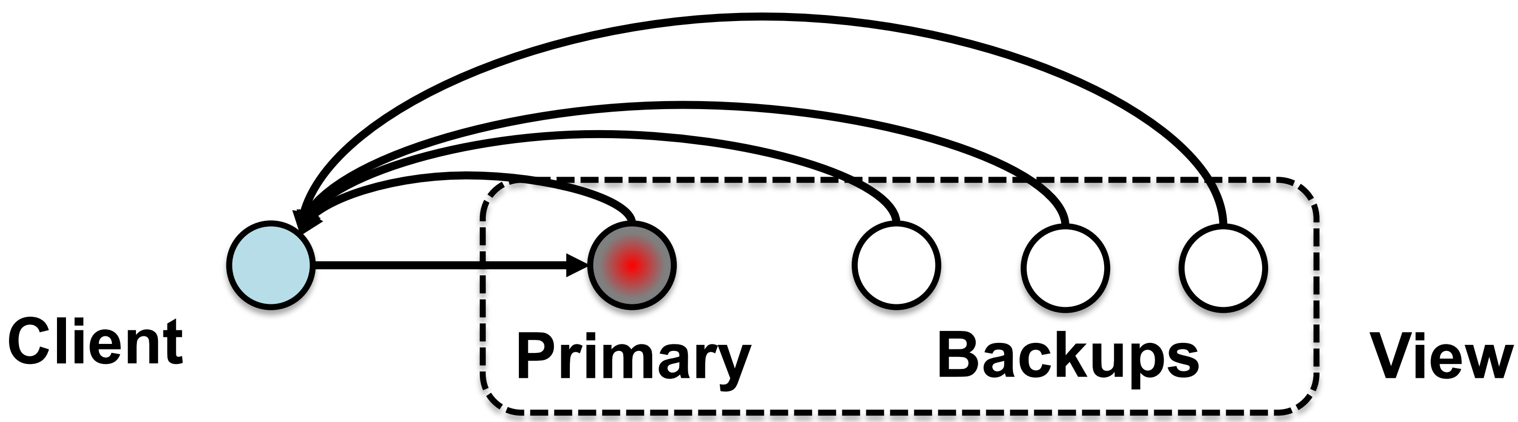
- Primary-Backup protocol: Group runs in a **view**
  - – View **number** designates the **primary** replica



- Primary is the node whose **id (modulo view #) = 1**

Ordering requests

- Primary picks the ordering of requests
  - But the **primary** **might be a liar!**

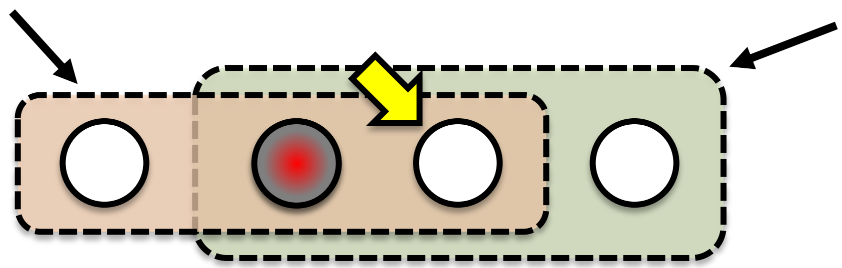


- Backups ensure primary behaves correctly
  - Check and certify correct ordering
  - Trigger **view changes** to replace faulty primary

Byzantine quorums

($f = 1$)

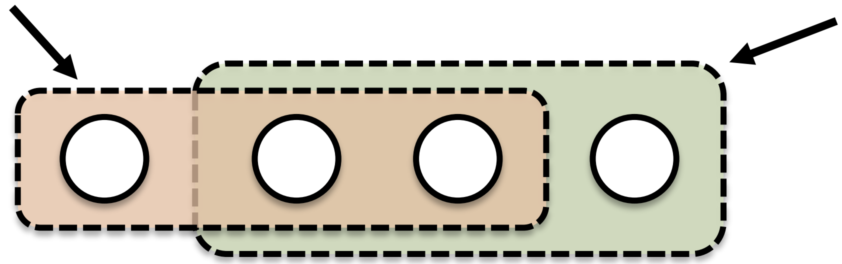
A ***Byzantine quorum*** **contains ≥ 2*f*+1 replicas**



- One op's quorum **overlaps** with next op's quorum
  - There are **3*f*+1 replicas, in total**
    - **So overlap is ≥ *f*+1 replicas**
- *f*+1 replicas must contain ≥ **1 non-faulty replica**

Quorum certificates

A *Byzantine quorum* contains ≥ $2f$+1 replicas



- ***Quorum certificate:*** a collection of $2f + 1$ signed, **identical** messages from a Byzantine quorum
  - All messages agree on the **same statement**

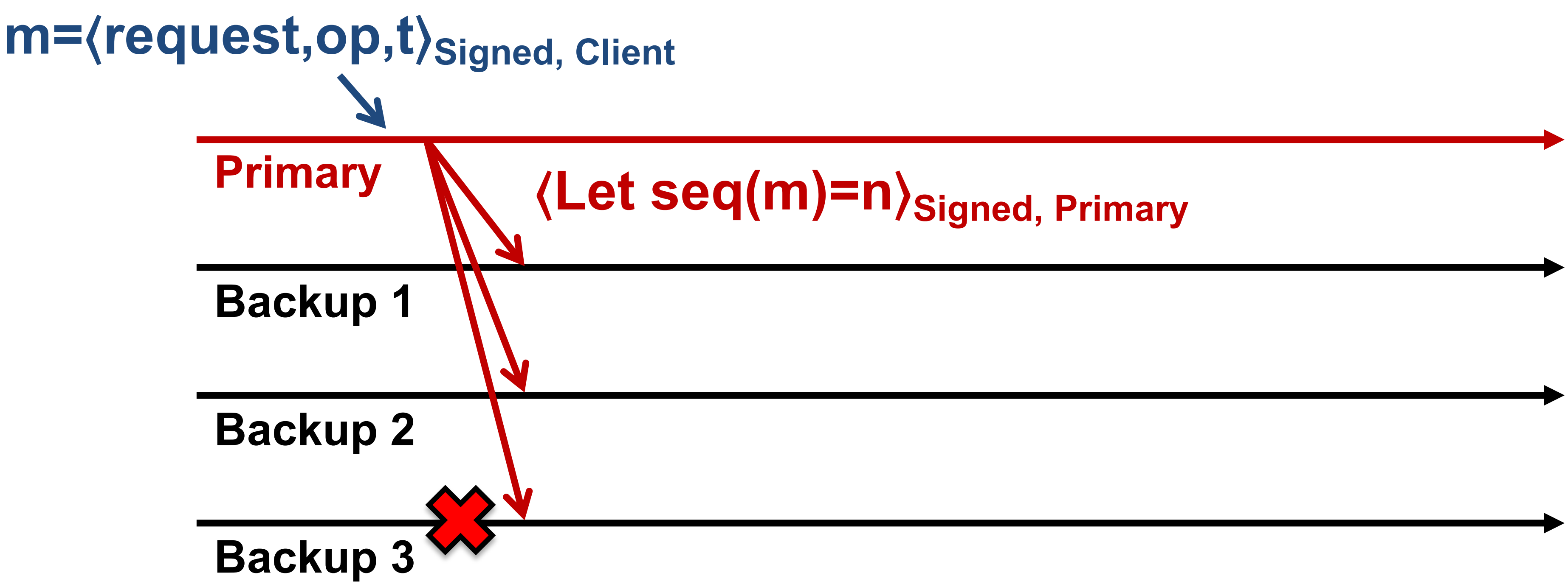
Keys

- Each client and replica has a **private-public keypair**

- **Secret keys:** symmetric cryptography
  - Key is known only to the two communicating parties
  - Bootstrapped using the public keys

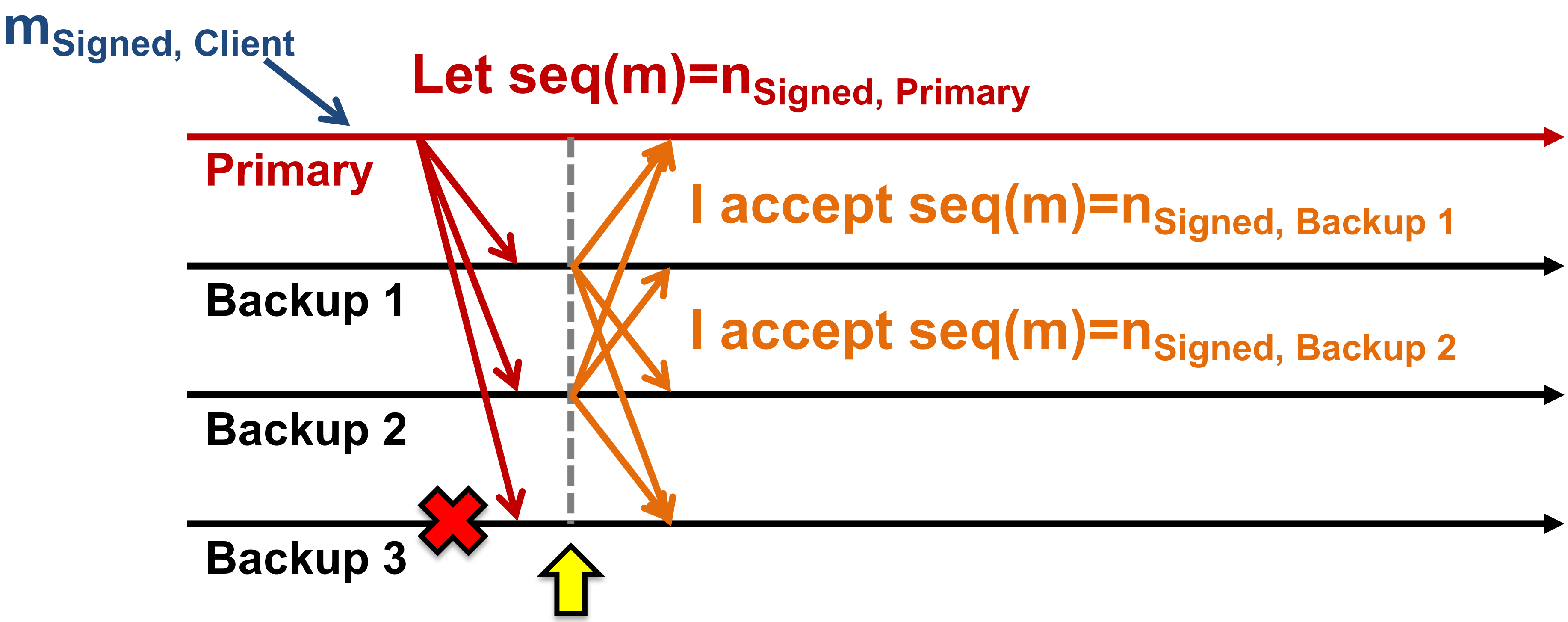
- **Each client, replica** has the following secret keys:
  - One key per node for sending messages
  - One key per node for receiving messages

Ordering requests



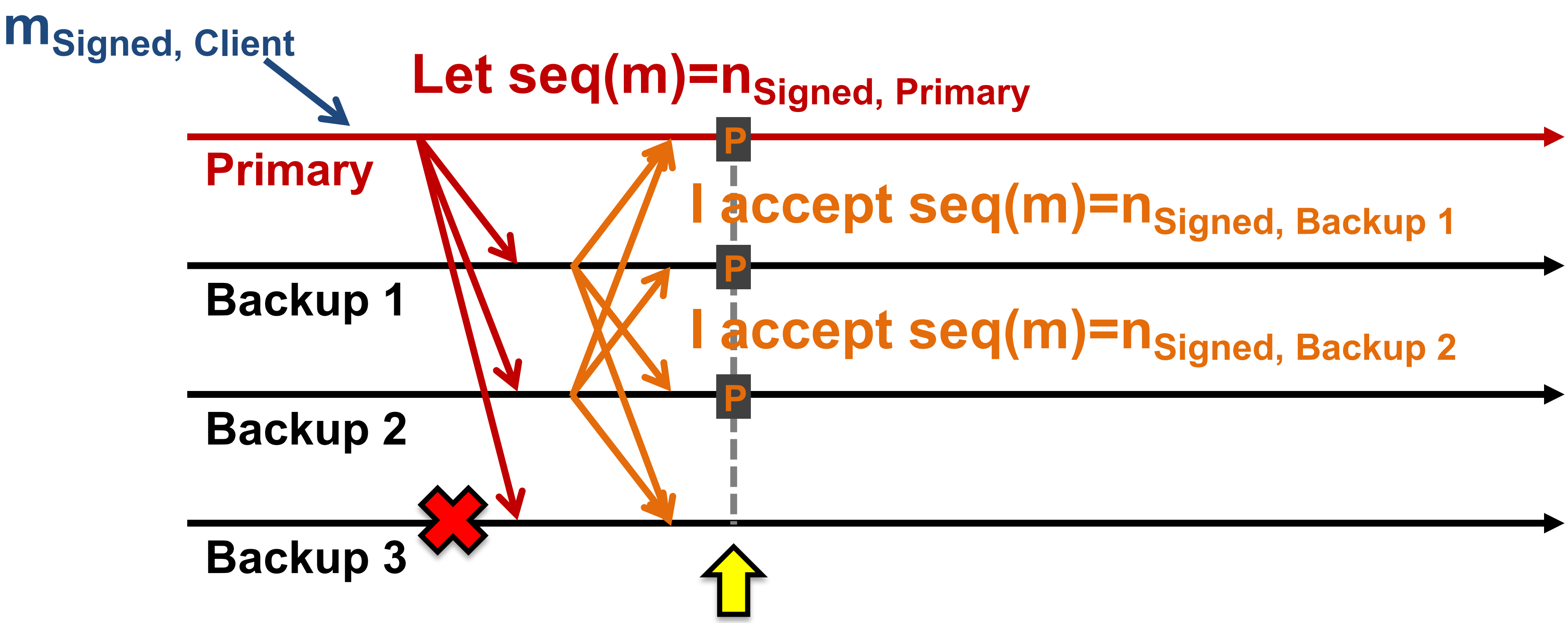
- Client requests operation **op** with ***timestamp*** *t*
- Primary chooses the request's ***sequence number*** (*n*)
  – Sequence number determines order of execution

Checking the primary's message



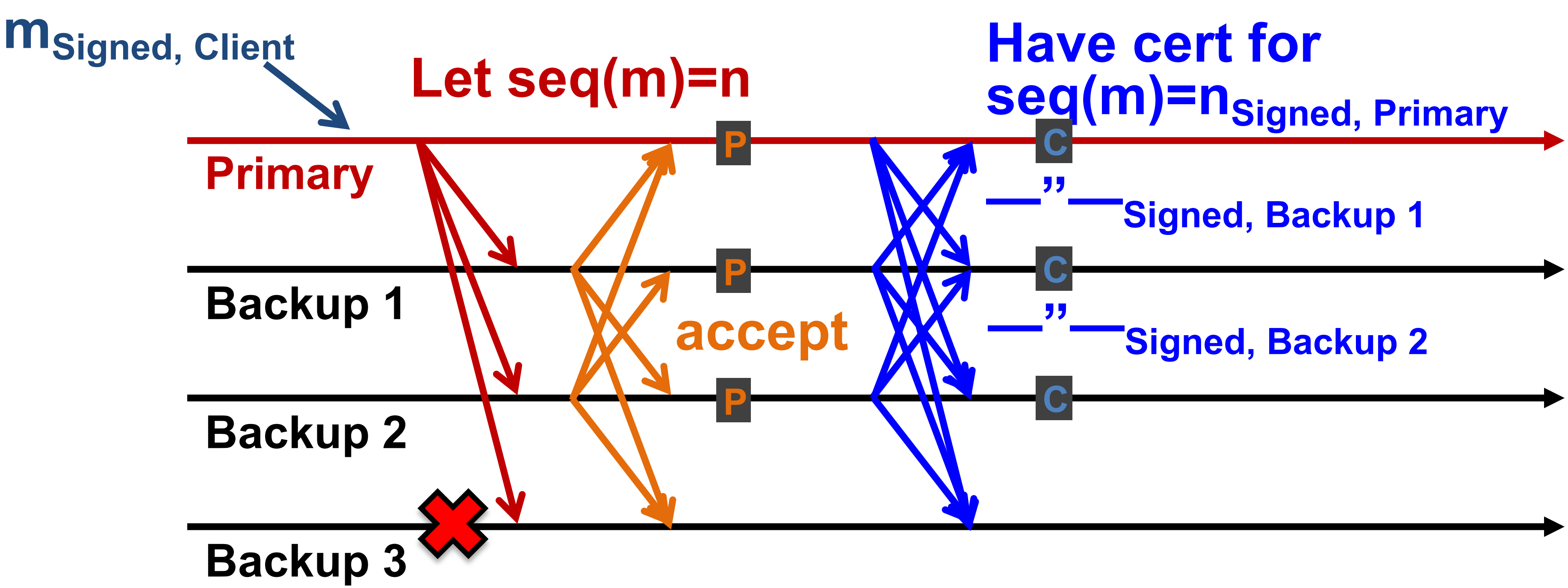
- Backups **locally** verify they've seen **≤ one** client request for sequence number *n*
  - If local check passes, replica broadcasts ***accept*** message
    - Each replica makes this decision **independently**

Collecting a *prepared certificate* (*f* = 1)



Each **correct** node has a prepared certificate **locally**, but does not **know** whether the **other correct nodes** do too! So, we **can't commit** yet!

Collecting a *committed* certificate ($f = 1$)



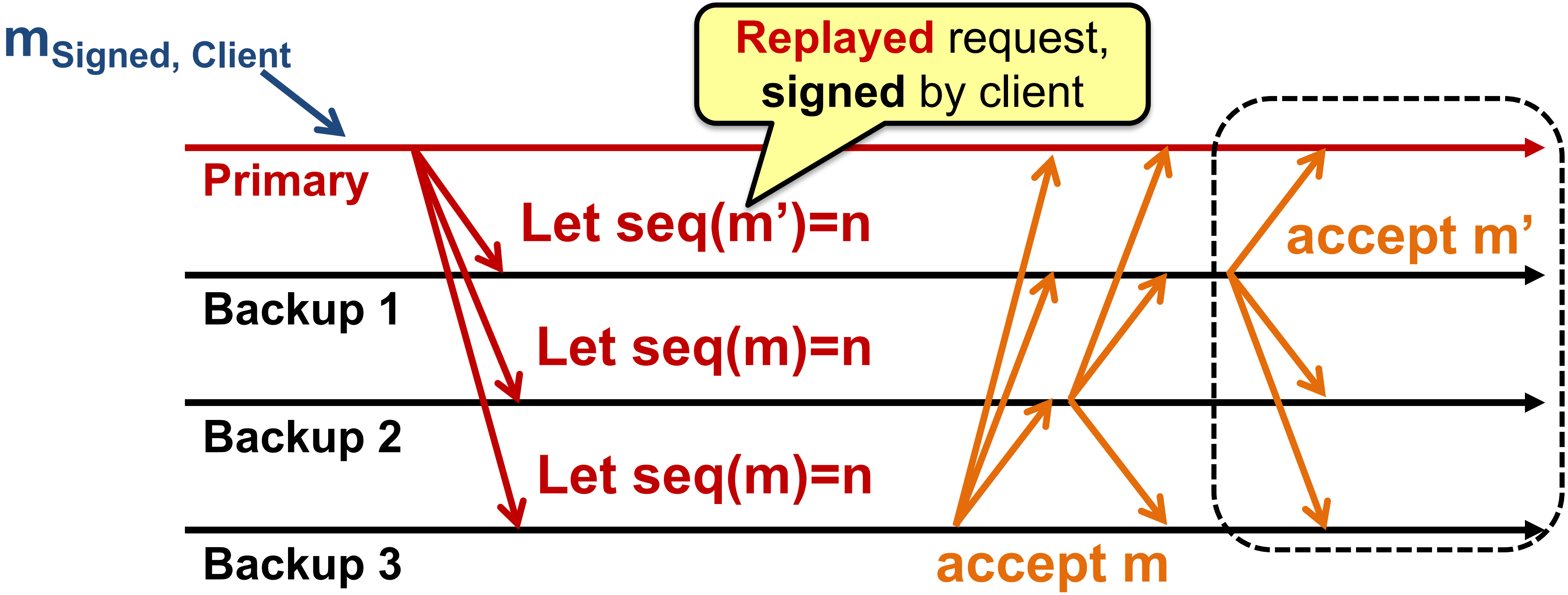
Once the request is **committed**, replicas **execute** the operation and send a reply directly back to the client.

Byzantine primary: replaying old requests

- The client assigns each request a unique, monotonically increasing ***timestamp*** *t*
- Servers track greatest *t* executed for each client *c*, **T(c),** and their corresponding reply
  - On receiving request to execute with timestamp *t*:
    - If $t < T(c)$, skip the request execution
    - If $t = T(c)$, resend the reply but skip execution
    - If $t > T(c)$, execute request, set $T(c) \leftarrow t$, remember reply

Malicious primary can invoke $t = T(c)$ case but **cannot compromise safety**

Byzantine primary: Splitting replicas (*f* = 1)



- **Recall:** To **prepare**, need primary message and 2*f* accepts
  - Backup 1: **Won't prepare m'**
  - Backups 2, 3: Will prepare m

Splitting replicas

- In general, backups **won't prepare two different requests with the same seqno** if primary lies

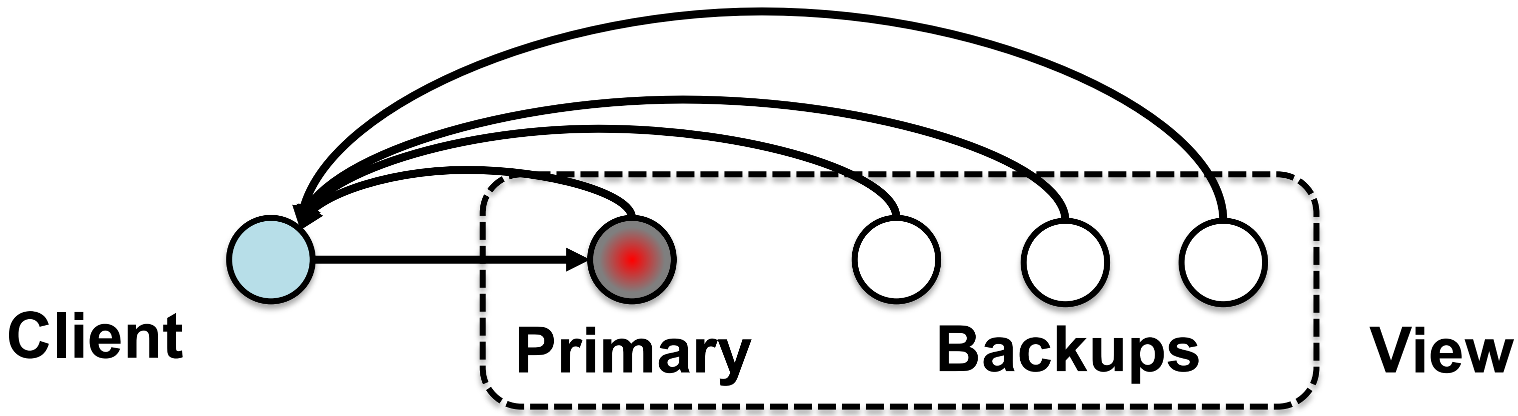
- **Suppose they did:** two distinct requests **m** and **m'** for the same sequence number n

  – Then prepared quorum certificates (each of size $2f+1$) would **intersect** at an **honest** replica

  – So that honest replica would have sent an accept message for both m and m′ which **can't happen**

    - **So m = m'**

View change



- If a replica suspects the primary is faulty, it requests a ***view change***
  – Sends a ***view change*** request to all replicas
    - Everyone acks the view change request

- New primary collects a quorum (2*f*+1) of responses
  – Sends a ***new-view*** message with this certificate

Considerations for view change

- Need committed operations to **survive** into next view
  - Client may have gotten answer
- Need to **preserve liveness**
  - If replicas are too fast to do view change, but really primary is okay – then performance problem
  - Or malicious replica tries to subvert the system by proposing a **bogus view change**

Garbage collection

- Storing all messages and certificates into a **log**
  - Can't let log **grow without bound**

- Protocol to **shrink the log** when it gets too big
  - Discard messages, certificates on commit?
    - No! Need them for view change
  - Replicas have to agree to shrink the log

Proactive recovery

- What we've done so far: good service provided there are no more than *f* failures **over system lifetime**
  - But cannot **recognize** faulty replicas!

- Therefore **proactive recovery:**
  - ***Recover*** the replica to a **known good state** whether faulty or not

- Correct service provided no more than *f* failures in a small time window – *e.g.,* 10 minutes

Recovery protocol sketch

- Watchdog timer
- Secure co-processor
  – Stores node's **private** key (of private-public keypair)
- Read-only memory

- Restart node periodically:
  – Saves its state (timed operation)
  – Reboot, reload code from read-only memory
  – Discard all secret keys (prevent impersonation)
  – Establishes new secret keys and state

Today

1. Traditional state-machine replication for BFT?

2. Practical BFT replication algorithm
   [Liskov & Castro, 2001]

3. **Performance and Discussion**

File system benchmarks

- ***BFS*** filesystem runs atop BFT
  - Four replicas tolerating one Byzantine failure
  - Modified Andrew filesystem benchmark

- What's performance relative to NFS?
  - Compare BFS versus Linux NFSv2 (unsafe!)
    - BFS **15% slower:** claim **can be used in practice**

Practical limitations of BFT

- Protection is achieved only when at most *f* nodes fail
  - Is one node more or less secure than four?
    - Need **independent implementations** of the service
- Needs **more messages, rounds** than conventional state machine replication
- **Does not prevent** many classes of attacks:
  - Turn a machine into a botnet node
  - Steal data from servers

Large impact

- Inspired **much follow-on work** to address its limitations
- The **ideas surrounding Byzantine fault tolerance** have found numerous applications:
  - Boeing 777 and 787 flight control computer systems
  - Digital currency systems
- Being picked up again in developments of **permissioned blockchain systems**