Reducing the Costs of Large-Scale BFT Replication

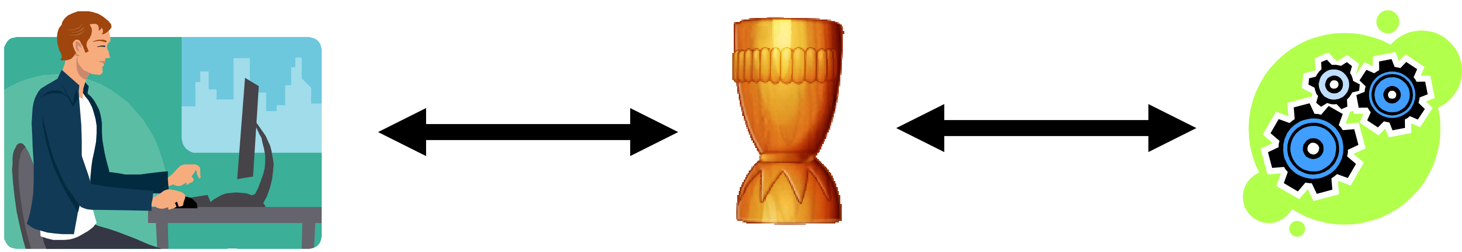
Marco Serafini & Neeraj Suri

TU Darmstadt, Germany

BFT Replication

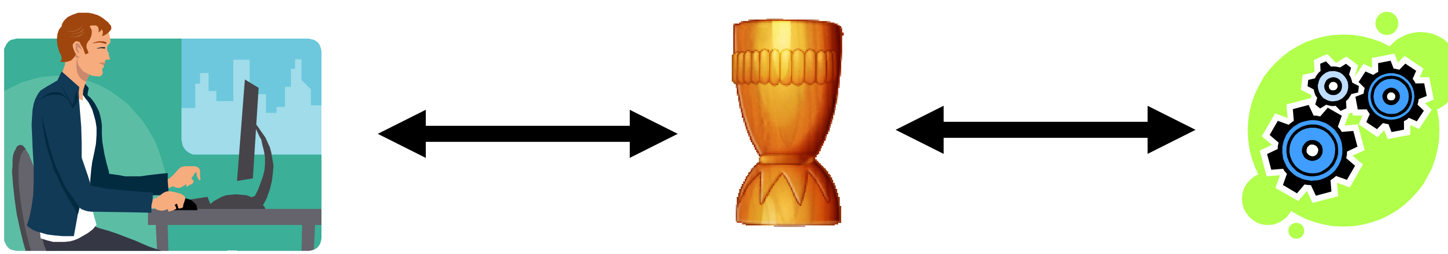
❑ BFT state machine replication

- Potential holy grail of reliable distributed computing
- Can be used to make any deterministic application tolerant to worst case failures
- Replication is transparent to clients and applications



Generality = Optimality

- **Generality of BFT requires:**
  - **Minimizing** performance overhead and replication costs…
  - … for the **widest** range of scenarios / workloads
- **Goal: Identify a general (= optimal) solution for a general problem**



Generic client
Sees a single reliable server

BFT replication library

Generic application
Single-server implementation

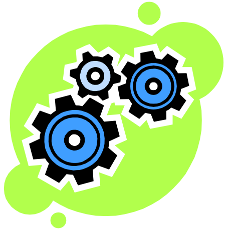
Toward optimal BFT Replication

❑ Much work on the topic

- PBFT [OSDI’99] – Use MACs instead of signatures
- Q/U [SOSP’05] – Reduce latency using quorum systems
- FaB [TDSC’06] – Fast agreement
- Zyzzyva [SOSP’07] – Speculation

Generic client
Sees a single reliable server

BFT replication library



Generic application
Single-server implementation

State of the Art

- The search for the holy grail has done a long way
- Still, it is not yet over

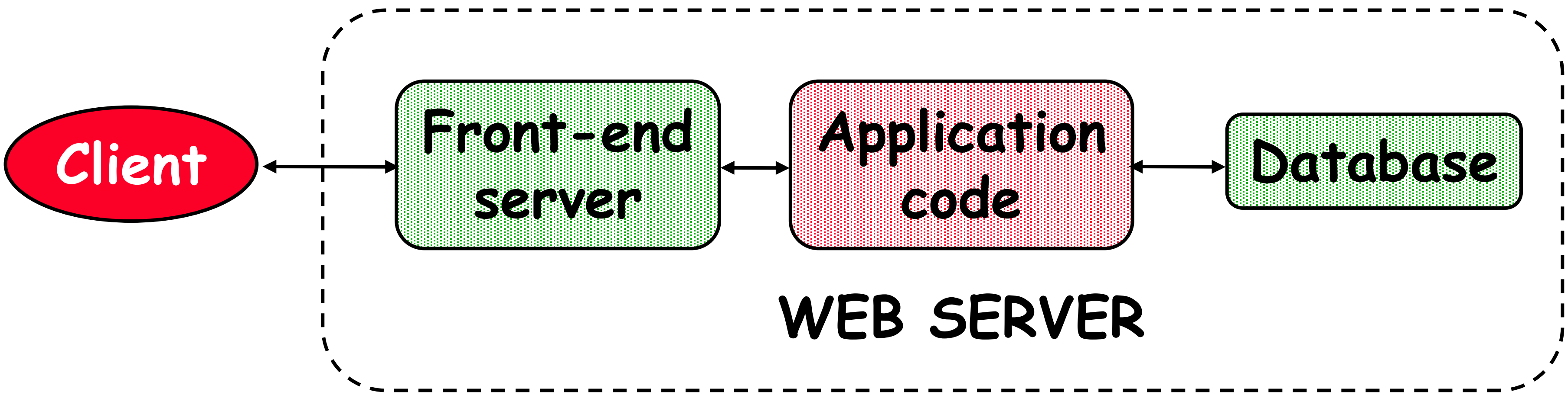
	Replication costs	Optimal Fault-free	Optimal w. faults	Strengthen for attacks
PBFT	*3f* + *1*	NO	NO	YES*
Zyzzyva	*3f* + *1*	YES	NO	NO
Zyzzyva5	*5f* + *1*	YES	YES	NO

* *A. Clement et al.,* "Making Byzantine Fault Tolerant Systems Tolerate Byzantine Faults." *Univ. Texas Tech. Rep., 2008*

Example: Web Applications

❑ Ideal setting for applying BFT

- Exposed to the Internet, strong reliability requirements



Web Applications’ Requirements

- **Large scale: Benign faults are the common case**

- **High performance for ALL requests**
  - Example: Dynamo’s SLA specifies worst-case latency for 99,9% of the requests under high load [SOSP’07]
  - ALL = in presence of (benign) failures

- **Low replication costs**
  - 100s to 1,000s of replicated services
  - Additional replication costs must be multiplied over the number of services

Web Applications and BFT Facts

- **Existing approaches are not optimal**
  - **PBFT: Poor throughput with web application workload**
    - BFS has 45% throughput reduction for replicated vs. non-replicated BFS using a the Postmark benchmark [TOCS'02]

Web Applications and BFT Facts

- **Existing approaches are not optimal**
  - **PBFT: Poor throughput with web application workload**
    - BFS has 45% throughput reduction for replicated vs. non-replicated BFS using a the Postmark benchmark [TOCS'02]
  - **Zyzzyva: Improves on PBFT in fault-free runs but has performance degradation in faulty runs**
    - Up to 2x higher throughput than PBFT in fault-free runs [SOSP07]
    - Up to 35% throughput reduction with benign failures [SOSP'07]

Web Applications and BFT Facts

- **Existing approaches are not optimal**
  - **PBFT: Poor throughput with web application workload**
    - BFS has 45% throughput reduction for replicated vs. non-replicated BFS using a the Postmark benchmark [TOCS'02]
  - **Zyzzyva: Improves on PBFT in fault-free runs but has performance degradation in faulty runs**
    - Up to 2x higher throughput than PBFT in fault-free runs [SOSP07]
    - Up to 35% throughput reduction with benign failures [SOSP'07]
  - **Zyzzyva5: Improves on PBFT also in faulty runs but has 50% higher replication costs** [SOSP'07]

Web Applications and BFT Facts

- **Existing approaches are not optimal**
  - **PBFT: Poor throughput with web application workload**
    - BFS has 45% throughput reduction for replicated vs. non-replicated BFS using a the Postmark benchmark [TOCS'02]
  - **Zyzzyva: Improves on PBFT in fault-free runs but has performance degradation in faulty runs**
    - Up to 2x higher throughput than PBFT in fault-free runs [SOSP07]
    - Up to 35% throughput reduction with benign failures [SOSP'07]
  - **Zyzzyva5: Improves on PBFT also in faulty runs but has 50% higher replication costs** [SOSP'07]

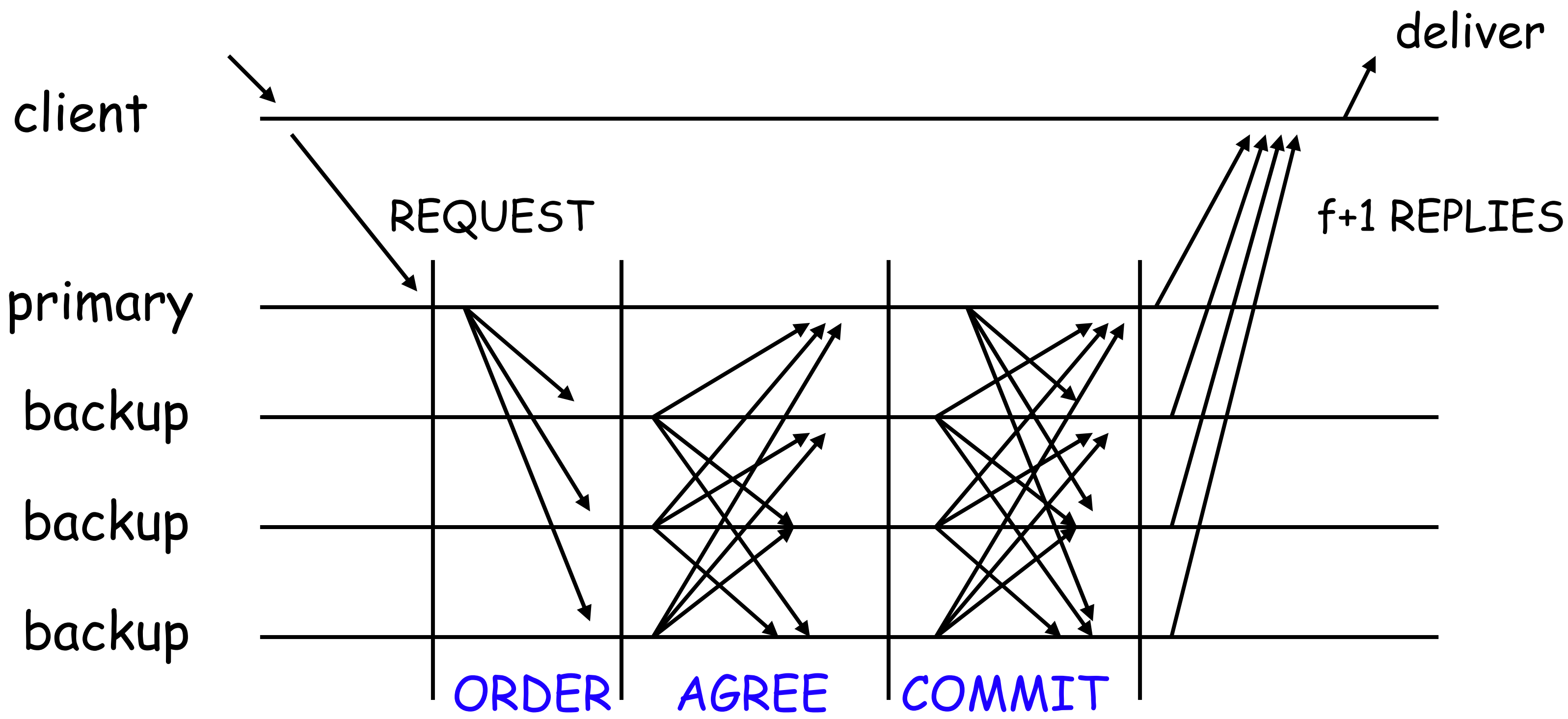
- **Can we improve on this?**

Contribution: The Scrooge Protocol

- **Optimal solution for common applications**
  - Tolerate 1 Byzantine fault (+ crashes)

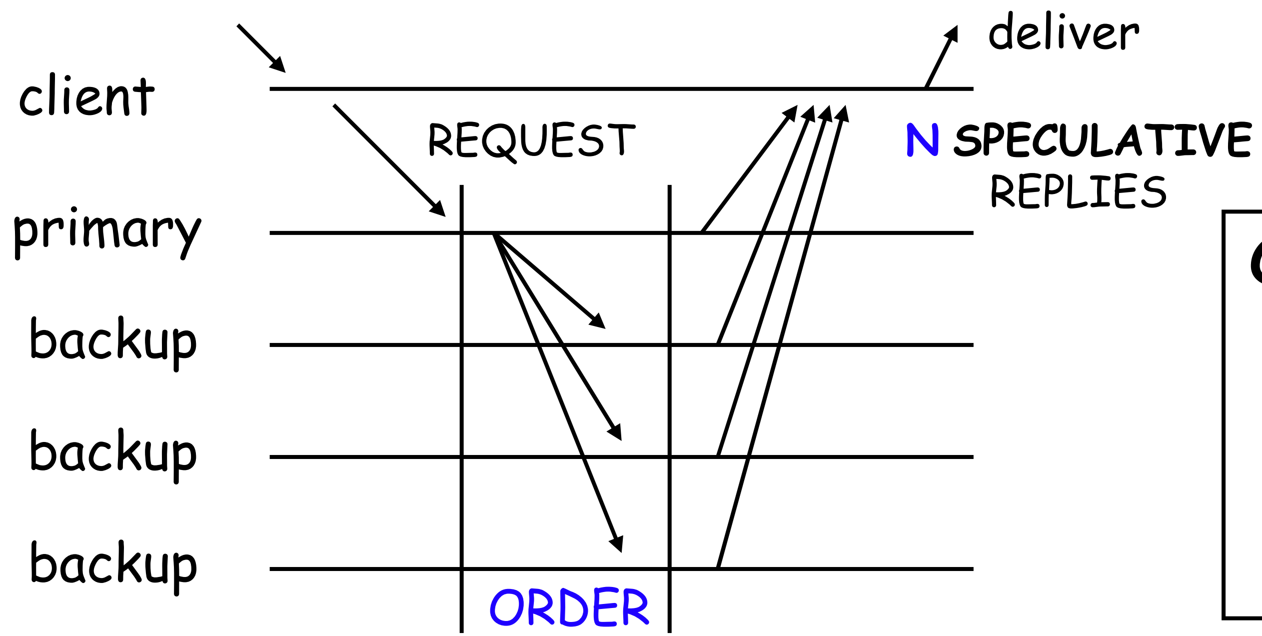
	Replication costs	Optimal fault-free	Optimal benign faults	Strengthen for attacks
PBFT	*3f + 1*	NO	NO	YES
Zyzzyva	*3f + 1*	YES	NO	NO
Zyzzyva5	*5f + 1*	YES	YES	NO
Scrooge	*4f*	YES	YES	YES

Practical BFT [OSDI'99]



- **Seminal work on reducing the costs of BFT**
  - **Optimal** resilience
  - **Three** phases: **Non-optimal**
  - **O(n^2)** message complexity: **Non-optimal**

Zyzzyva - Speculative BFT [SOSP'07]

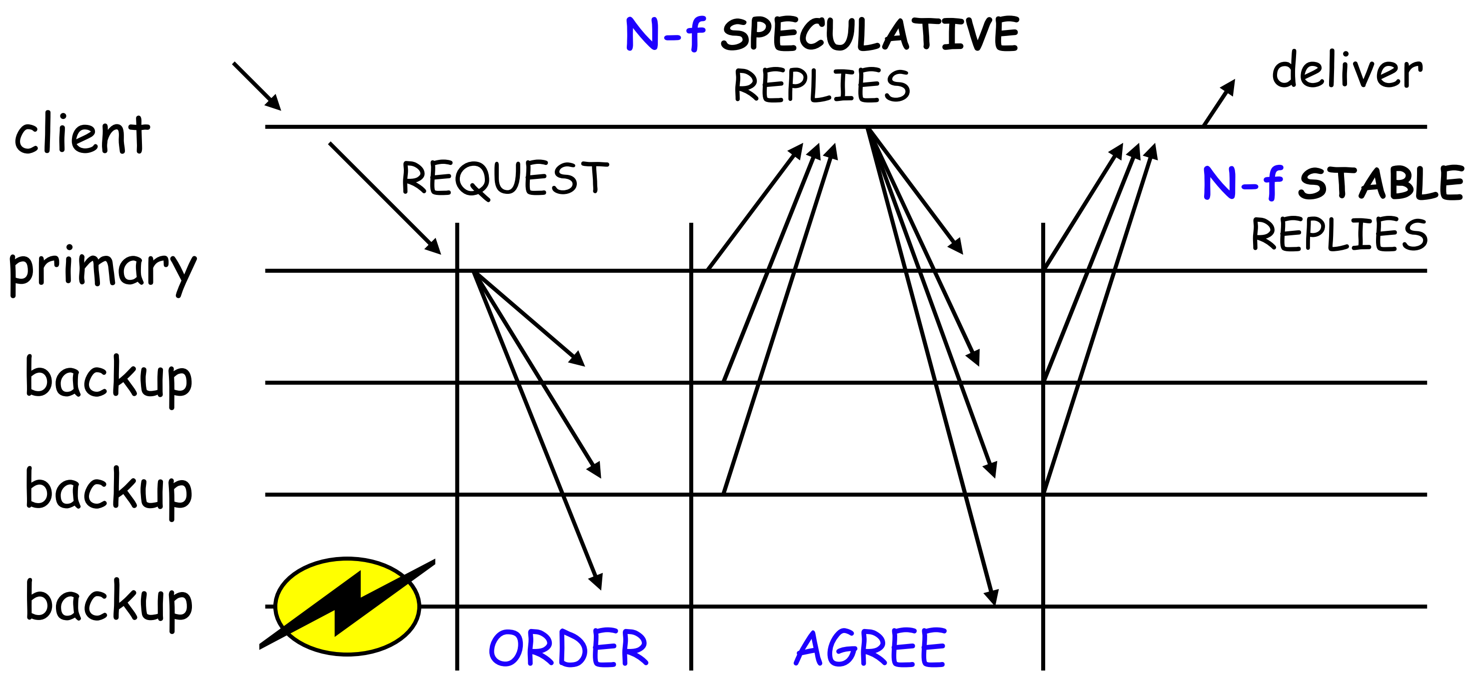


Optimal latency for consensus

O(n) message complexity

- **Optimized for common, *speculative* runs**
- **Speculative replies contain *history digests***
  - Clients can check that all correct replicas are consistent before delivery → no explicit agreement is required

Zyzzyva - Speculative BFT [SOSP'07]



- **In *non-speculative* runs**
  - Execute second phase for all subsequent requests
  - Client acts as a relay to complete it
  - Remove the third phase

What is a Speculative Run?

- Definition depends on the redundancy used

What is a Speculative Run?

- **Definition depends on the redundancy used**

- **With *3f+1* replicas: *Fault-free* runs**
  - Benign clients
  - **Fault-free** replicas

What is a Speculative Run?

- **Definition depends on the redundancy used**

- **With *3f+1* replicas: *Fault-free* runs**
  - Benign clients
  - **Fault-free** replicas

- **With *5f+1* replicas: *Faulty* runs**
  - Benign clients
  - Correct primary and **faulty** backups

Scrooge Contribution

- **Speculation in *faulty* runs with *4f* replicas**
  - Optimal resilience for common applications

Scrooge Contribution

- **Speculation in *faulty* runs with *4f* replicas**
  - Optimal resilience for common applications

- **Two novel ideas**

Scrooge Contribution

- **Speculation in *faulty* runs with *4f* replicas**
  - Optimal resilience for common applications

- **Two novel ideas**

1. **Explicitly identify a *Repliers Quorum***

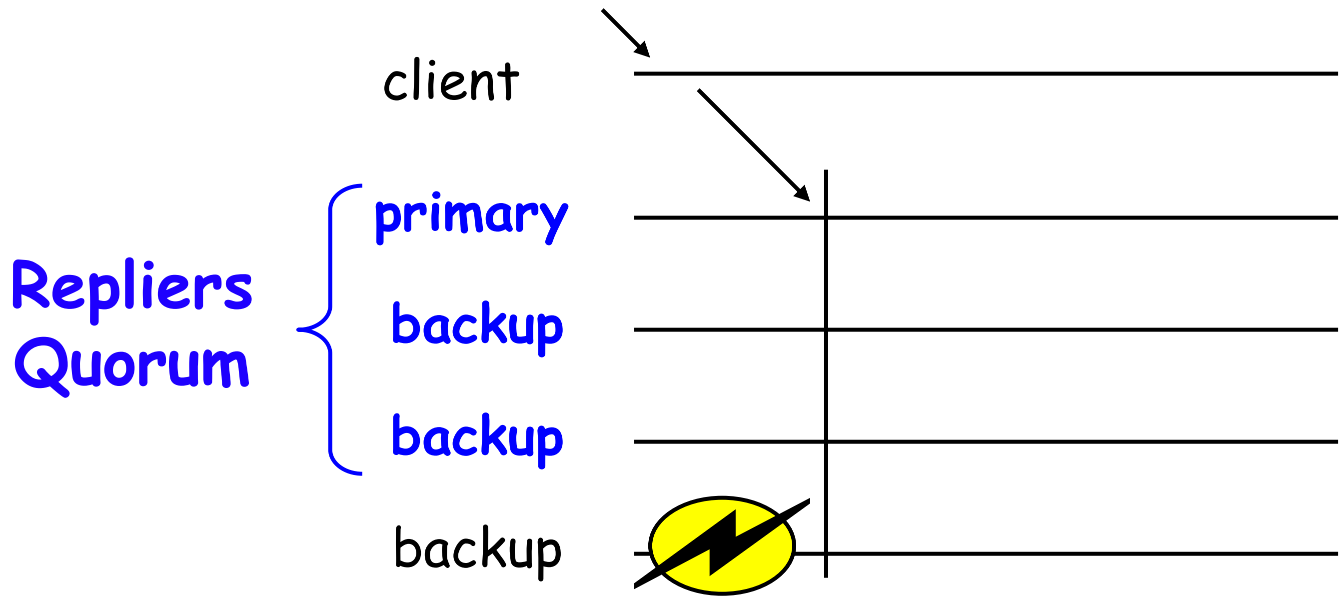
Scrooge Contribution

- **Speculation in *faulty* runs with *4f* replicas**
  - Optimal resilience for common applications

- **Two novel ideas**

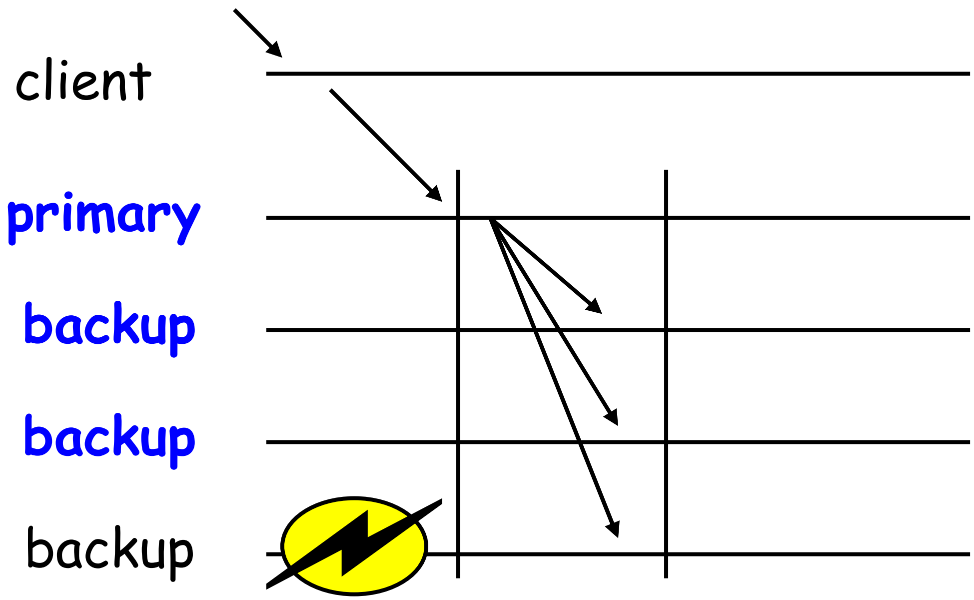
1. **Explicitly identify a *Repliers Quorum***
2. **Backups store *whole order request messages* from the *primary* in their *history***

Scrooge operations



Initially identify a Repliers Quorum of *N-f* replicas

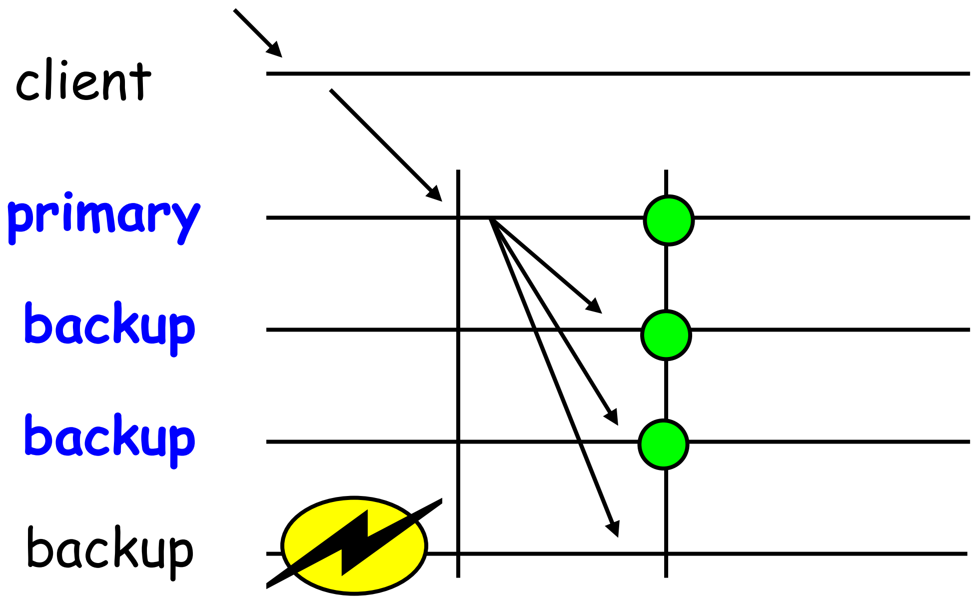
Scrooge operations



Initially identify a Repliers Quorum of *N-f* replicas

1. **Primary orders the requests**

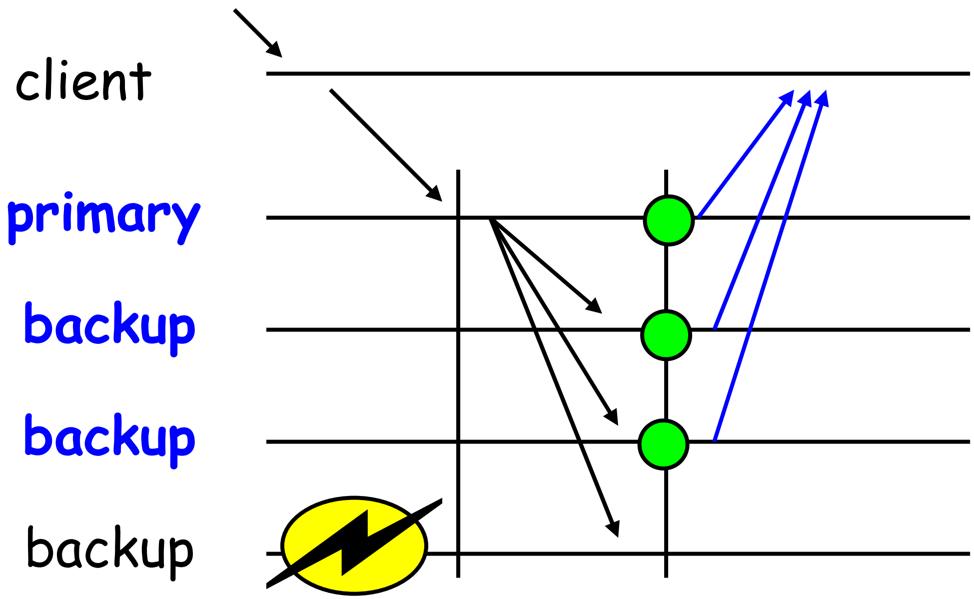
Scrooge



Initially identify a Repliers Quorum of *N-f* replicas

1. Primary orders the request
2. **Backups store the whole message in the history**

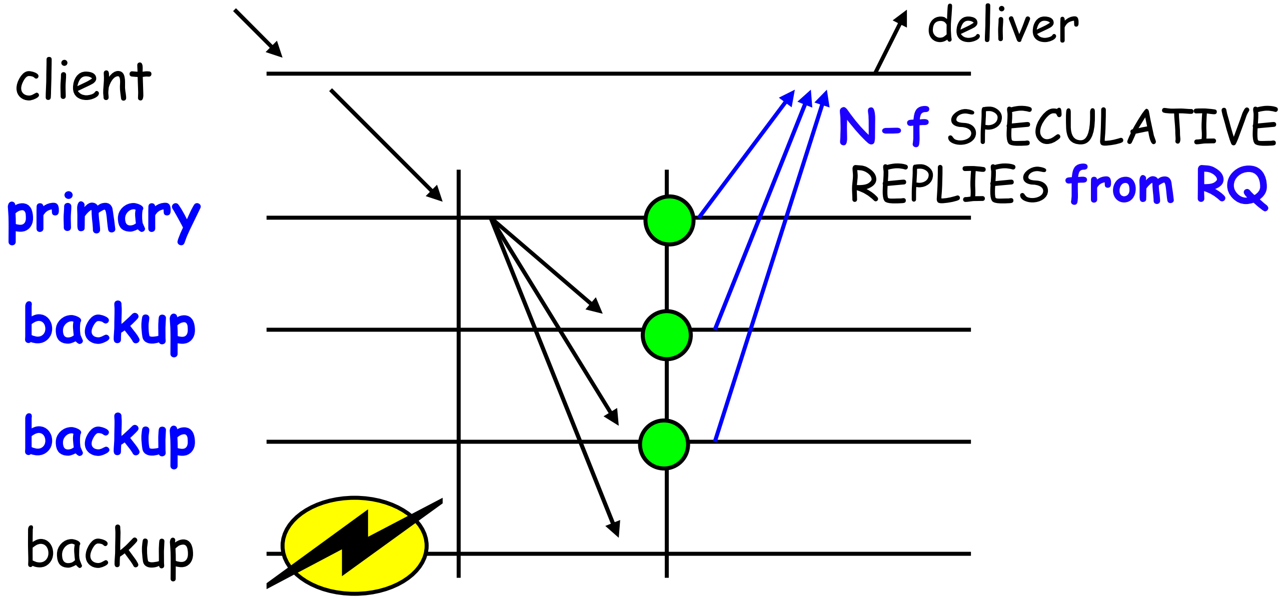
Scrooge



Initially identify a Repliers Quorum of *N-f* replicas

1. Primary orders the request
2. Backups store the whole message in the history
3. **Only replicas in the Repliers Quorum reply**

Scrooge



Initially identify a Repliers Quorum of *N-f* replicas

1. Primary orders the request
2. Backups store the whole message in the history
3. Only replicas in the Repliers Quorum reply
4. **Clients deliver after receiving *N-f* replies from *RQ***

Existing Lower Bounds

- **Additional replicas are necessary for *fast agreement* in *all faulty* runs**

Existing Lower Bounds

- **Additional replicas are necessary for *fast agreement* in *all faulty* runs**

- **Scrooge: No additional replicas in common applications & fast agreement in faulty runs**

Existing Lower Bounds

- **Additional replicas are necessary for *fast agreement* in *all faulty* runs**

- **Scrooge: No additional replicas in common applications & fast agreement in faulty runs**

- **Why is Scrooge consistent with the lower bounds?**
  - **Eventually** re-establish speculation upon failure events
  - **Detect and isolate** faults, no speculation in the meanwhile - for a **bounded** time
  - System model: All BFT protocols use **MACs** – leverage this

Strengthening BFT

- **Aardvark*: PBFT live under attacks**
  - Periodically change primary and estimate throughput
  - Use few alternative communication patterns

- **Why Zyzzyva is not suitable**
  - No third phase, replicas cannot observe progress
  - Multiple alternative patterns if clients are faulty

- **Scrooge does not have these limitations**
  - Can be strengthened similar to PBFT

* *A. Clement et al.*, "Making Byzantine Fault Tolerant Systems Tolerate Byzantine Faults." *Univ. Texas Tech. Rep., 2008*

Conclusions

- **BFT protocols must be optimal to represent a truly generic technique for dependability**
- **Scrooge reaches optimality for common applications where *f = 1***

	Replication costs	Optimal fault-free	Optimal w. faults	Strengthen for attacks
Scrooge	*4f*	YES	YES	YES

- **Scrooge opens up new issues**
  - Scrooge is an upper bound. Does it represent a **lower bound** too?
  - Can we have a more sophisticated failure detection?

Thank you for your attention