Distributed Algorithms
Practical Byzantine Fault Tolerance – Part 2

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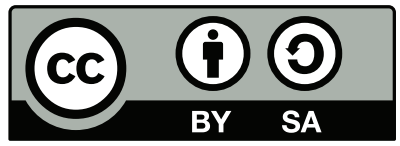
Acknowledgments: Lorenzo Alvisi



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Overview

After PBFT, several others papers started to appear:

- **HQ**: J. Cowling, D. Myers, B. Liskov, R. Rodrigues, and L. Shrira.

  HQ replication: A hybrid quorum protocol for Byzantine fault tolerance.
  In *Proc. of the Symposium on Operating systems design and implementation*, OSDI'06, Oct. 2005

- **Q/U**: M. Abd-El-Malek, G. Ganger, G. Goodson, M. Retier, and

  J. Wylie. Fault-scalable Byzantine fault-tolerant services.
  In *Proc. of the ACM Symposium on Operating Systems Principles*, SOSP'05, Oct. 2005

The end results has been to complicate the adoption of Byzantine solutions.

Overview

- "In the regions we studied (up to $f = 5$), if contention is low and low latency is the main issue, then if it is acceptable to use $5f + 1$ replicas, Q/U is the best choice, else HQ is the best since it outperforms PBFT with a batch size of 1."
- "Otherwise, PBFT is the best choice in this region: It can handle high contention workloads, and it can beat the throughput of both HQ and Q/U through its use of batching."
- "Outside of this region, we expect HQ will scale best: HQ's throughput decreases more slowly than Q/U's (because of the latter's larger message and processing costs) and PBFT's (where eventually batching cannot compen- sate for the quadratic number of messages)."

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Zyzzyva[1]

OSDI'06

R. Kotla, A. Clement, E. Wong, L. Alvisi, and M. Dahlin. Zyzzyva: Speculative byzantine fault tolerance.
In *Proc. of the ACM Symposium on Operating Systems Principles*, (SOSP'07), Stevenson, WA, Oct. 2007. ACM.

http://www.disi.unitn.it/~montreso/ds/papers/Zyzzyva.pdf

- One protocol to rule them all!
- Zyzzyva is the last word on BFT!
- (Is it?)

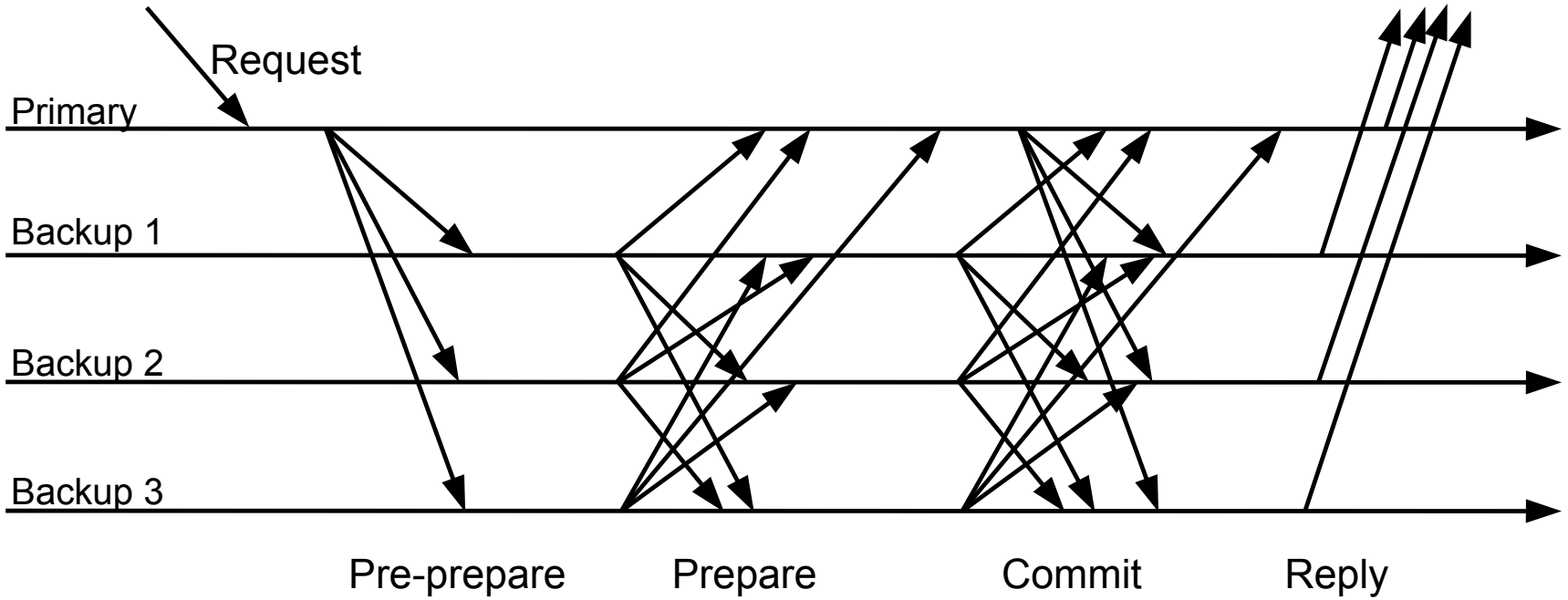
http://www.flickr.com/photos/matthewfch/2478230533/

[1] Zyzzyva is the last word of the English dictionary – Apart from Zyzzyzus

Replica coordination

- All correct replicas execute the same sequence of commands
- For each received command c, correct replicas:
  - Agree on c's position in the sequence
  - Execute c in the agreed upon order
  - Reply to the client

How it is done now



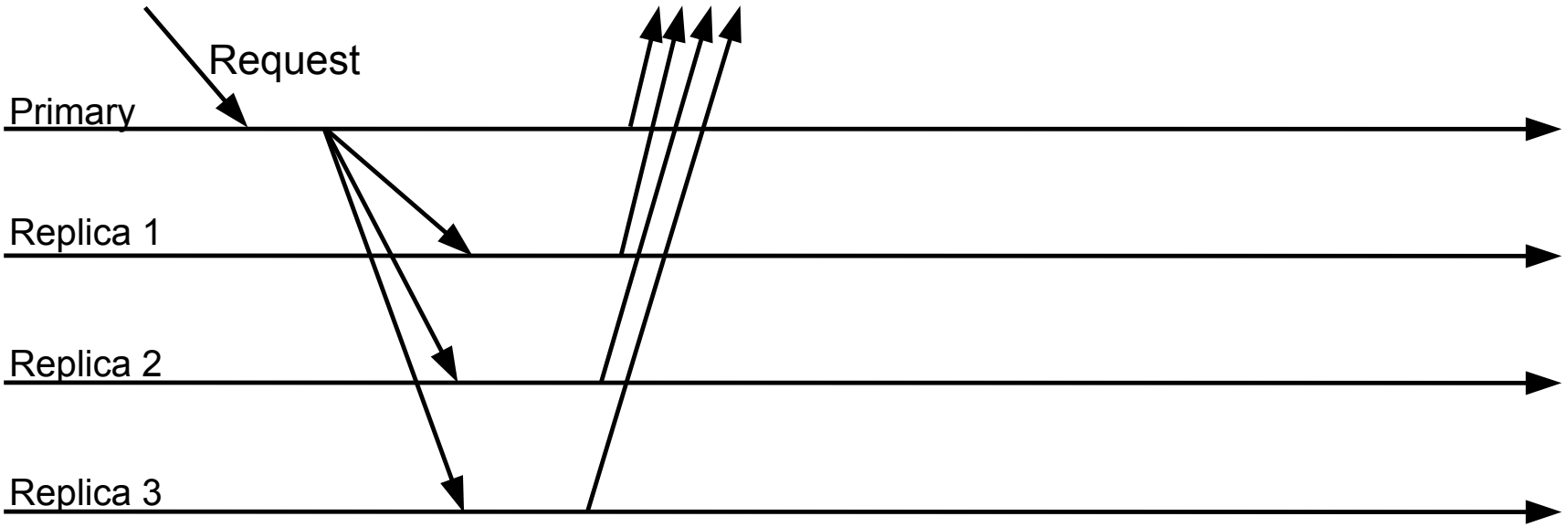
The engineer's Rule of thumb

Citation

> *Handle normal and worst case separately as a rule, because the requirements for the two are quite different: the normal case must be fast; the worst case must make some progress*

Butler Lampson, "Hints for Computer System Design"

How Zyzzyva does it



Specification for State Machine Replication (SMR)

Stability

A command is stable at a replica once its position in the sequence cannot change

Safety

Correct clients only process replies to stable commands

Liveness

All commands issued by correct clients eventually become stable and elicit a reply

Enforncing safety

- Safety requires:
  - Correct clients only process replies to stable commands
- ...but SMR implementations enforce instead:
  - Correct replicas only execute and reply to commands that are stable
- Service performs an output commit with each reply

Speculative BFT (Trust, but verify)

- Replicas execute and reply to a command without knowing whether it is stable
  - trust order provided by primary
  - no explicit replica agreement!
- Correct client, before processing reply, verifies that it corresponds to stable command
  - if not, client takes action to ensure liveness

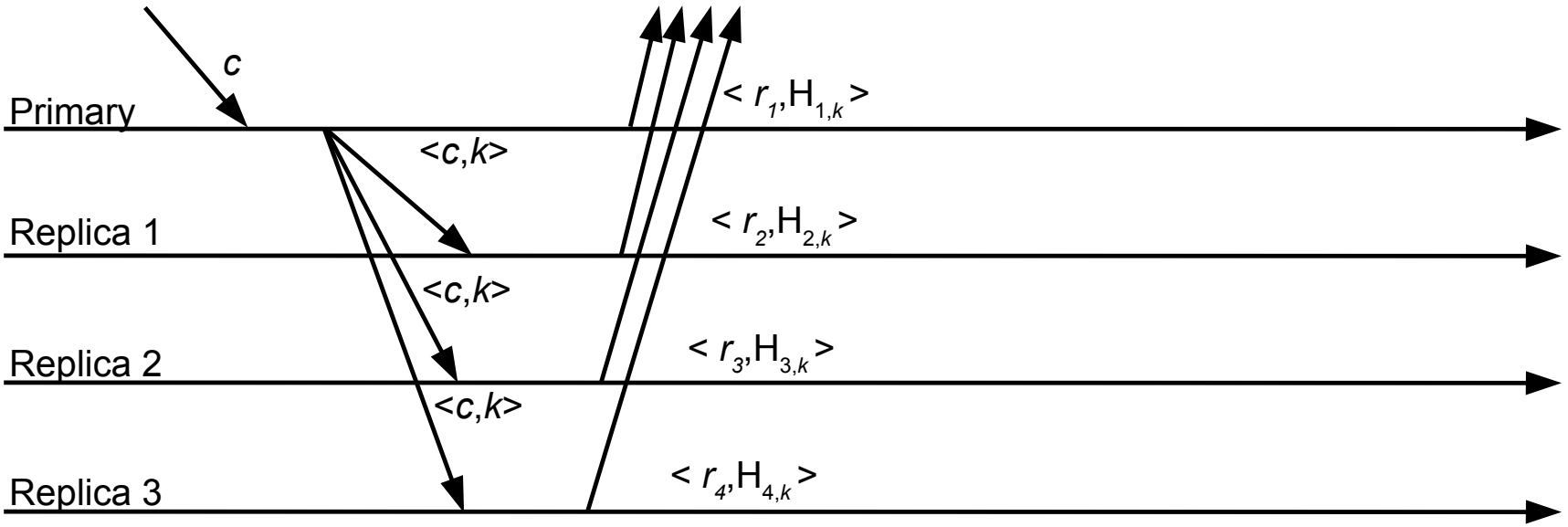
Verifying stability

- Necessary condition for stability in Zyzzyva:
  - A command c can become stable only if a majority of correct replicas agree on its position in the sequence
- Client can process a response for c iff:
  - a majority of correct replicas agrees on c's position
  - the set of replies is incompatible, for all possible future executions, with a majority of correct replicas agreeing on a different command holding c's current position

History

- History $H_{i,k}$ is the sequence of the first k commands executed by replica i
- On receipt of a command c from the primary, replica appends c to its command history
- Replica reply for c includes:
  - the application-level response
  - the corresponding command history
- Additional details:
  - Can be hashed through incremental hashing

Case 1: Unanimity



- Client processes response if all replies match:

$$r_1 = \ldots = r_4 \wedge H_{1,k} = \ldots = H_{4,k}$$

Case 1: Unanimity

Some comments:

- Note that although a client has a proof that the request position in the command history is irremediately set, no server has such a proof
- Comparison of histories may be based on incremental hash
- Three message hops to complete the request in the good case

Is it safe to accept the reply in this case?

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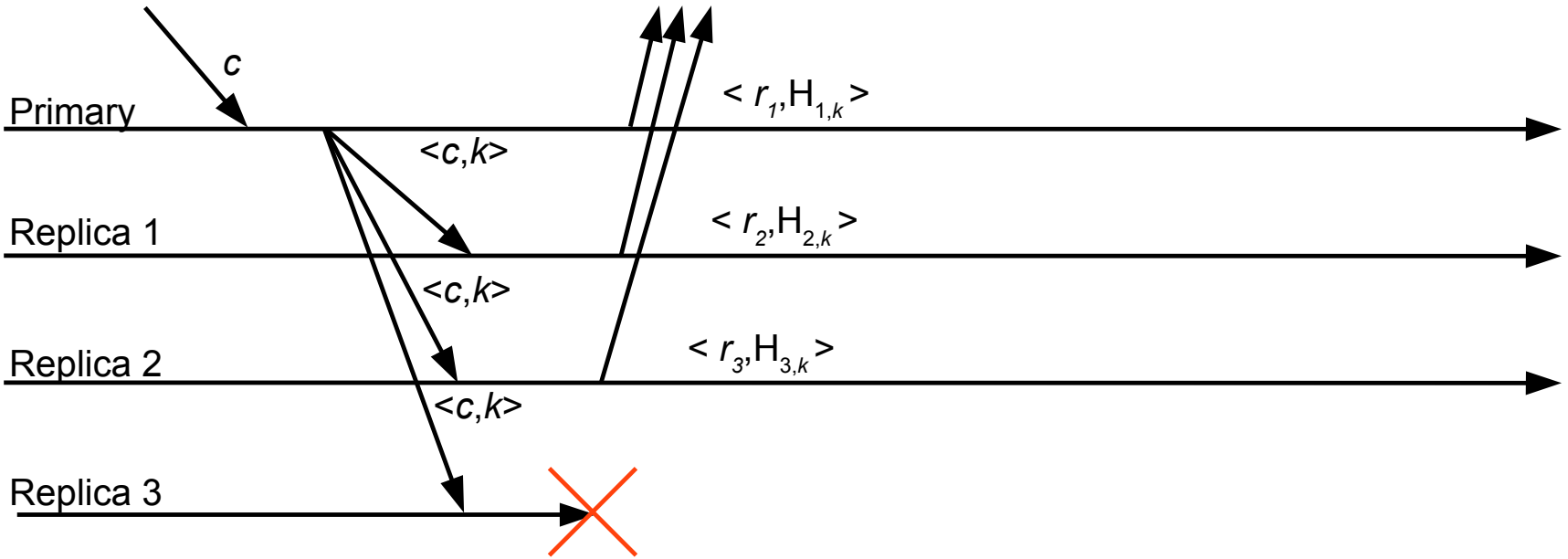
Is it safe to accept the reply in this case?

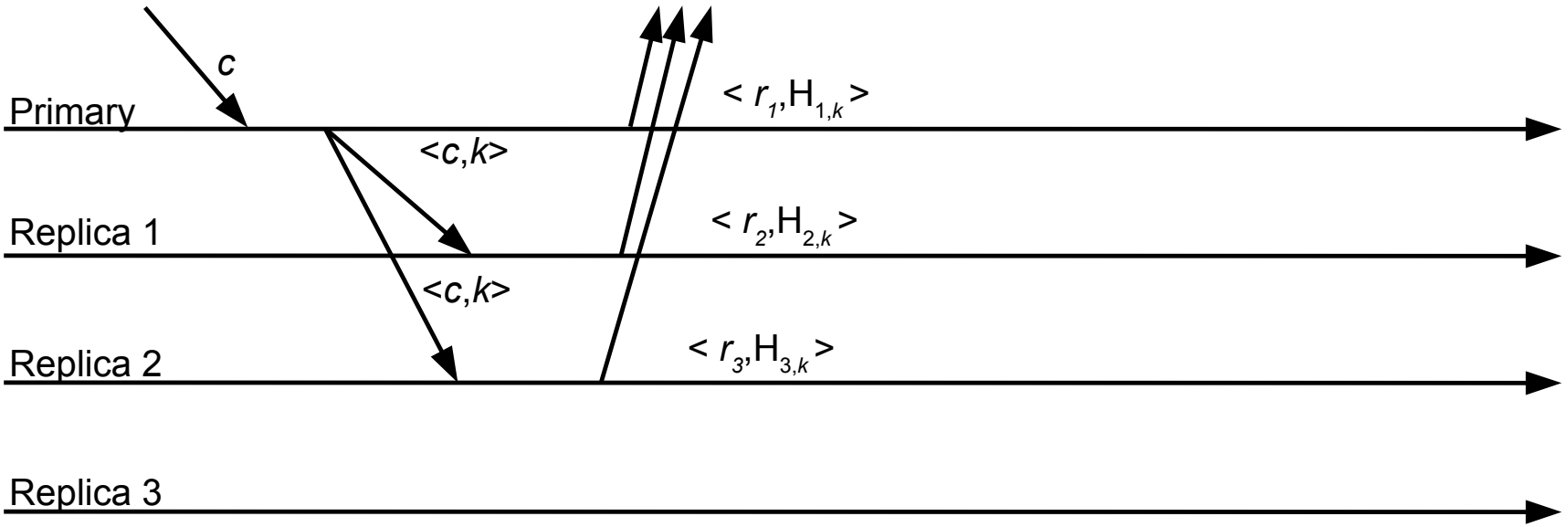
- All processes have agreed on ordering
- Correct processes cannot change their mind later
- New primary can ask $n - f$ replicas for their histories

Case 2: A majority of correct replicas agree



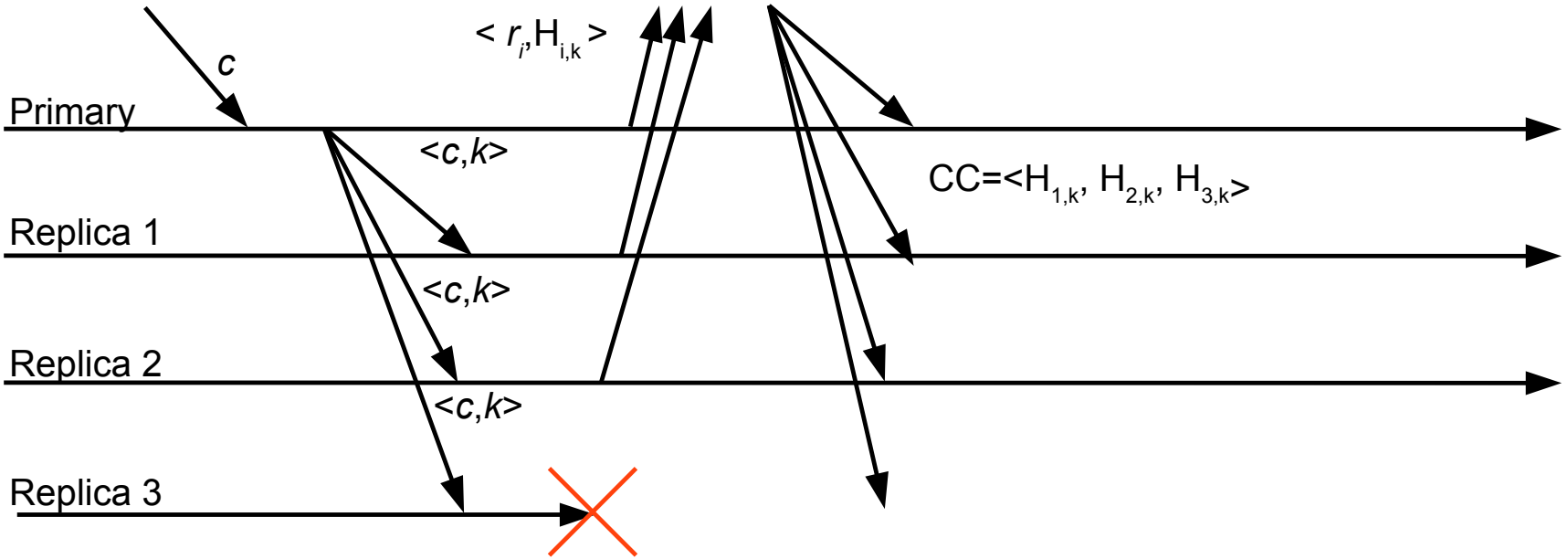
Is it safe to accept such a message?

Case 2: A majority of correct replicas agree



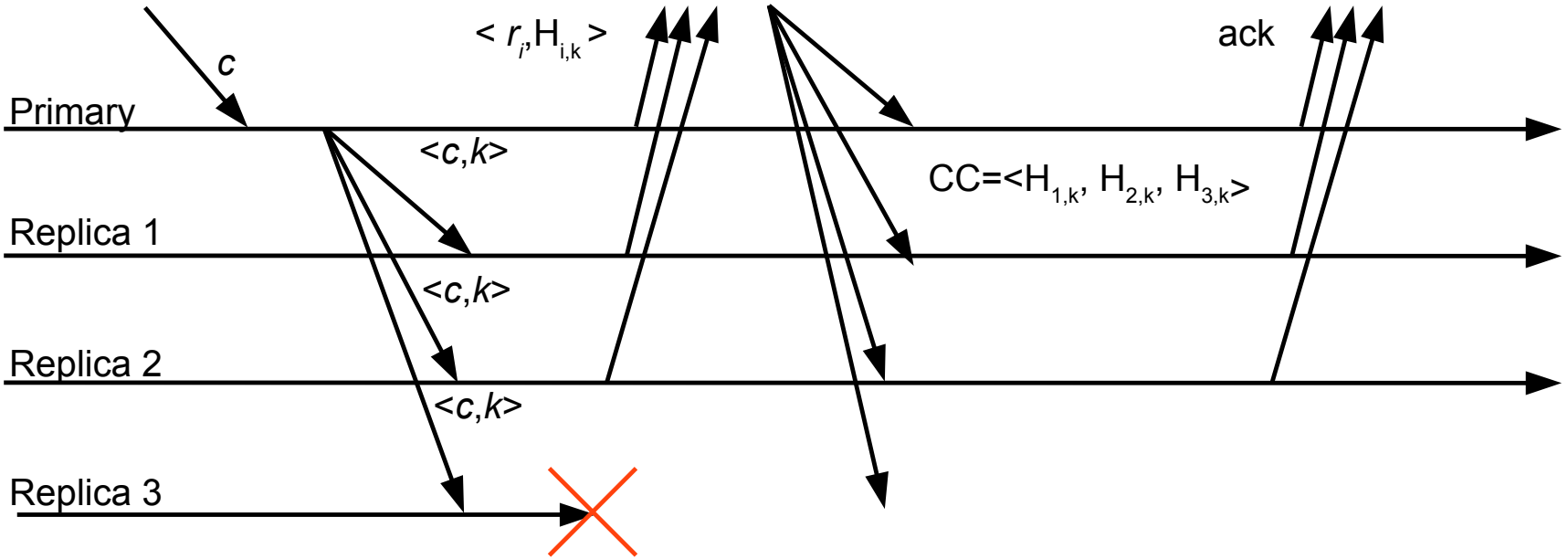
Consider this case...

Case 2: A majority of correct replicas agree



Client sends to all a commit certificate containing $2f + 1$ matching histories

Case 2: A majority of correct replicas agree



Client processes response if it receives at least $2f + 1$ acks

Case 2: A majority of correct replicas agree

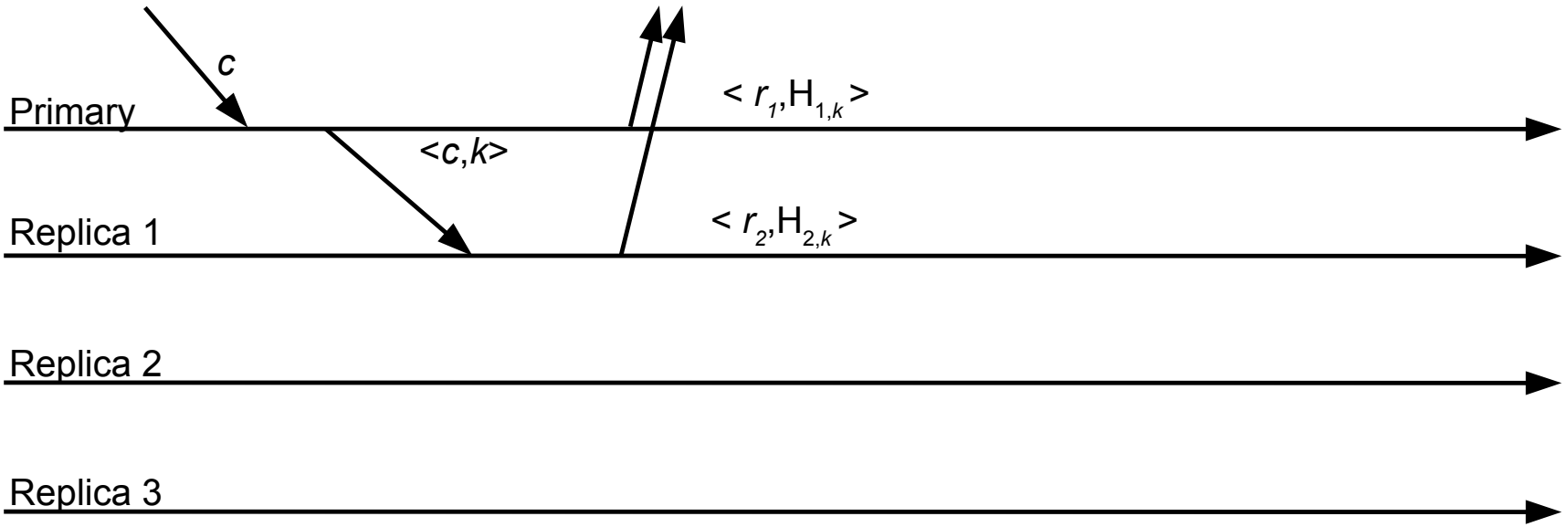
Safe?

- Certificate proves that a majority of correct processes agree on its position in the sequence
- Incompatible with a majority backing a different command for that position

Stability

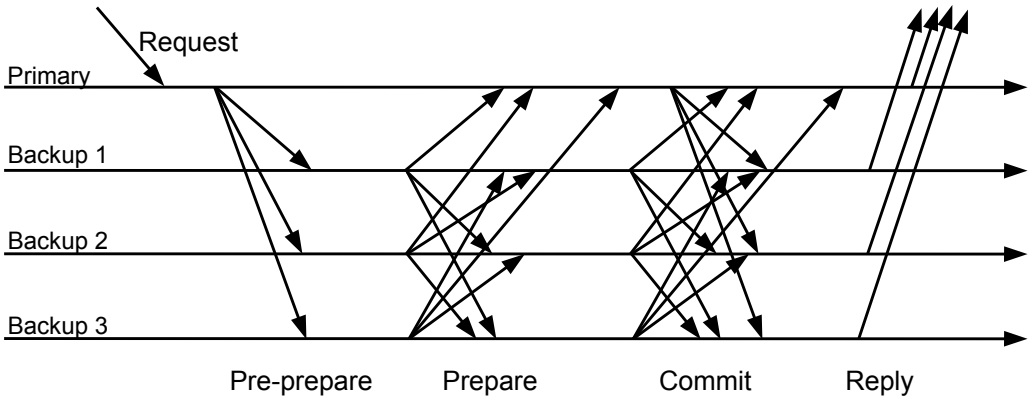
- Stability depends on matching command histories
- Stability is prefix-closed:
  - If a command with sequence number k is stable, then so is every command with sequence number $k' < k$

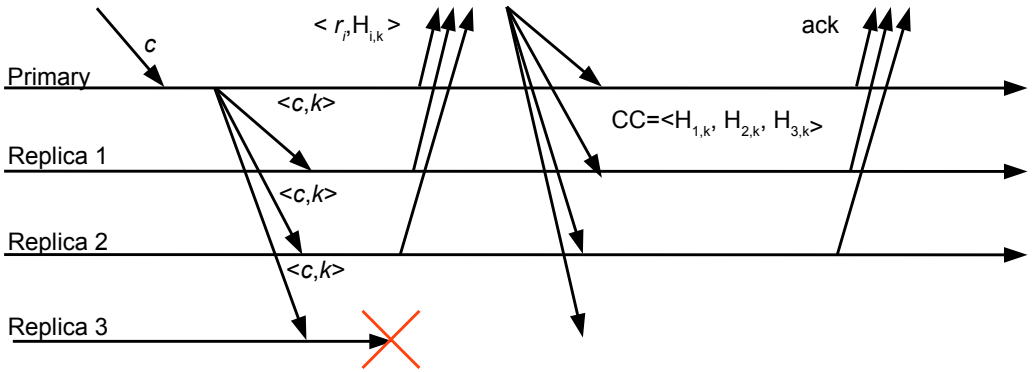
Case 3: None of the above



- Fewer than $2f + 1$ replies match
- Clients retransmits c to all replicas – hinting primary may be faulty

The case of the missing phase





- Where did the third phase go?
- Why was it there to begin with?

The missing phase – COMMIT

Consider this scenario:

- f malicious replicas, including the primary
- The primary stops communicating with f correct replicas
- They go on strike – they stop accepting messages in this view, ask a view change
- $f + f$ replicas stops accepting messages, $f + 1$ replicas keep working
- The remaining $f + 1$ replicas are not enough to conclude the PRE-PREPARE and PREPARE phases
- The f correct processes that are asking a view change are not enough to conclude one, so there is no opportunity to regain liveness by electing a new primary

The missing phase – COMMIT

The third phase of PBFT breaks this stalemate:

- The remaining $f + 1$ replicas
  - either gather the evidence necessary to complete the request,
  - or determine that a view change is necessary
- Commit phase needed for liveness

Where the third phase go?

In PBFT

What compromises liveness in the previous scenario is that the PBFT view change protocol lets correct replicas commit to a view change and become silent in a view without any guarantee that their action will lead to the view change

In Zyzzyva

A correct replica does not abandon view v unless it is guaranteed that every other correct replica will do the same, forcing a new view and a new primary

View change

- Two phases:
  - Processes unsatisfied with the current primary sent a message $\langle$I-HATE-THE-PRIMARY, $v\rangle$ to all
  - If a process collect $f + 1$ I-HATE-THE-PRIMARY messages, sends a message to all containing such messages and starts a new view change (similar to the traditional one)
- Extra phase of agreement protocol is moved to the view change protocol

Optimizations

- Checkpoint protocol to garbage collect histories
- Replacing digital signatures with MAC
- Replicating application state at only $2f + 1$ replicas
- Batching

Performance

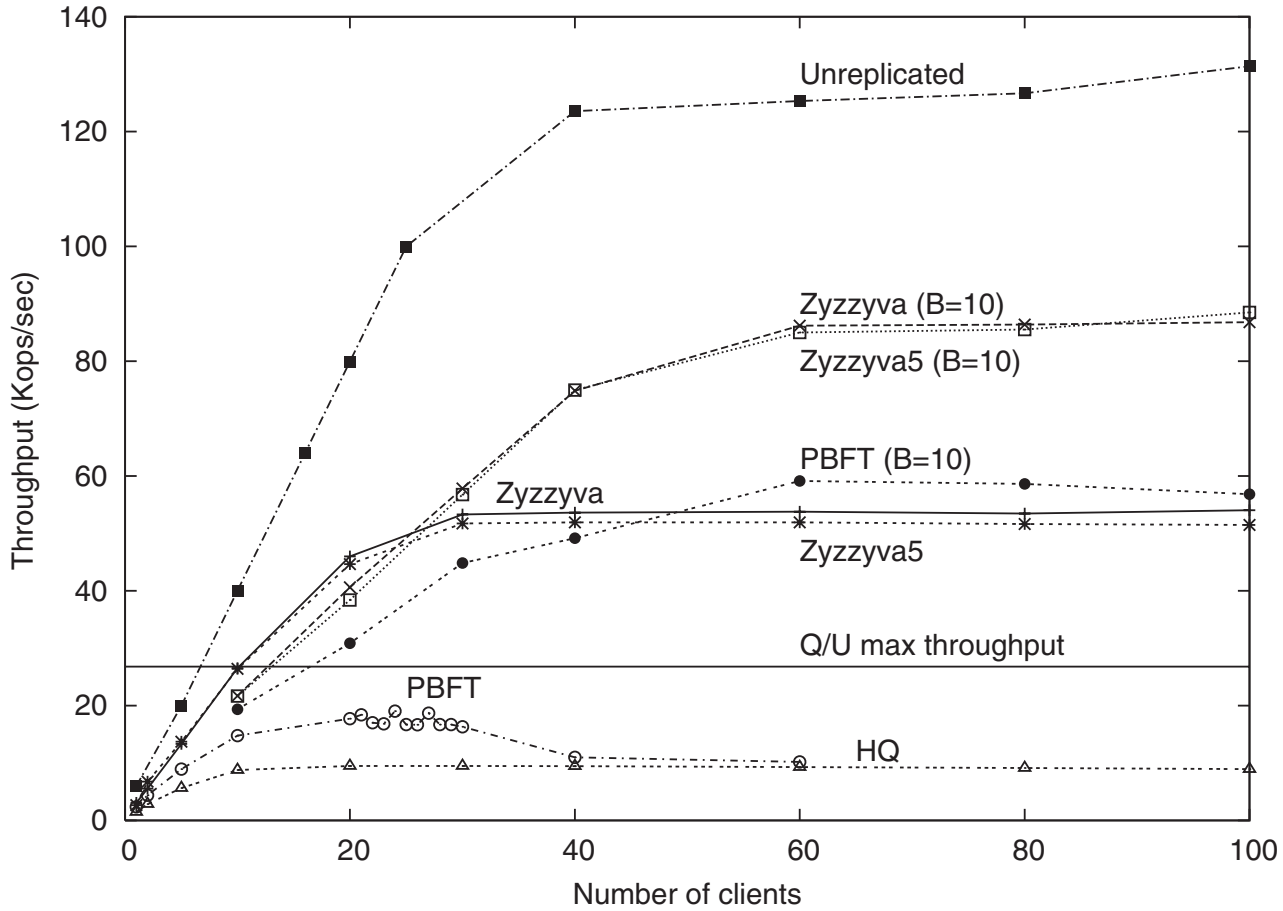


Fig. 4. Realized throughput for the 0/0 benchmark as the number of client varies for systems configured to tolerate $f = 1$ faults.

Discussion

- What have you learned?
- Do you agree on the principles?

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Aardvark[2]

NSDI'09

A. Clement, E. Wong, L. Alvisi, M. Dahlin, and M. Marchetti. Making Byzantine fault tolerant systems tolerate Byzantine faults.
In *Proc. of the 6th USENIX symposium on Networked systems design and implementation*, NSDI'09, pages 153–168. USENIX Association, 2009.
http://www.disi.unitn.it/~montreso/ds/papers/Aardvark.pdf

- A new beginning!
- `http://en.wikipedia.org/wiki/File:Porc_formiguer.JPG`

[2] Aardvark is the first word of the English dictionary – Oritteropo in Italian

From the article

Surviving vs tolerating

Although current BFT systems can survive Byzantine faults without compromising safety, we contend that a system that can be made completely unavailable by a simple Byzantine failure can hardly be said to tolerate Byzantine faults.

Conventional wisdom

- Handle normal and worst case separately
  - remain safe in worst case
  - make progress in normal case
- Maximize performance when
  - the network is synchronous
  - all clients and servers behave correctly

Conventional wisdom

- Misguided
  - encourages systems that fail to deliver BFT
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Conventional wisdom

- Misguided
  - encourages systems that fail to deliver BFT
- Dangerous
  - it encourages fragile optimizations
- Futile
  - it yields diminishing return on common case

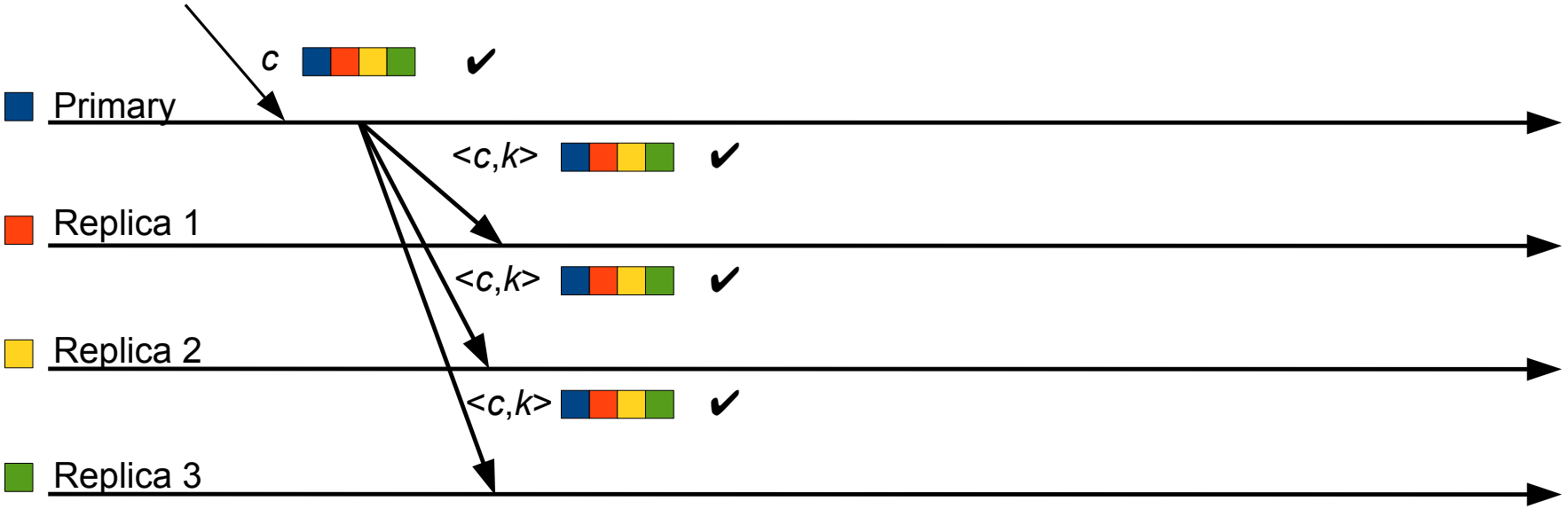
Blueprint

- Build the system around execution path that:
  - provides acceptable performance across the broadest set of executions
  - it is easy to implement
  - it is robust against Byzantine attempts to push the system away from it

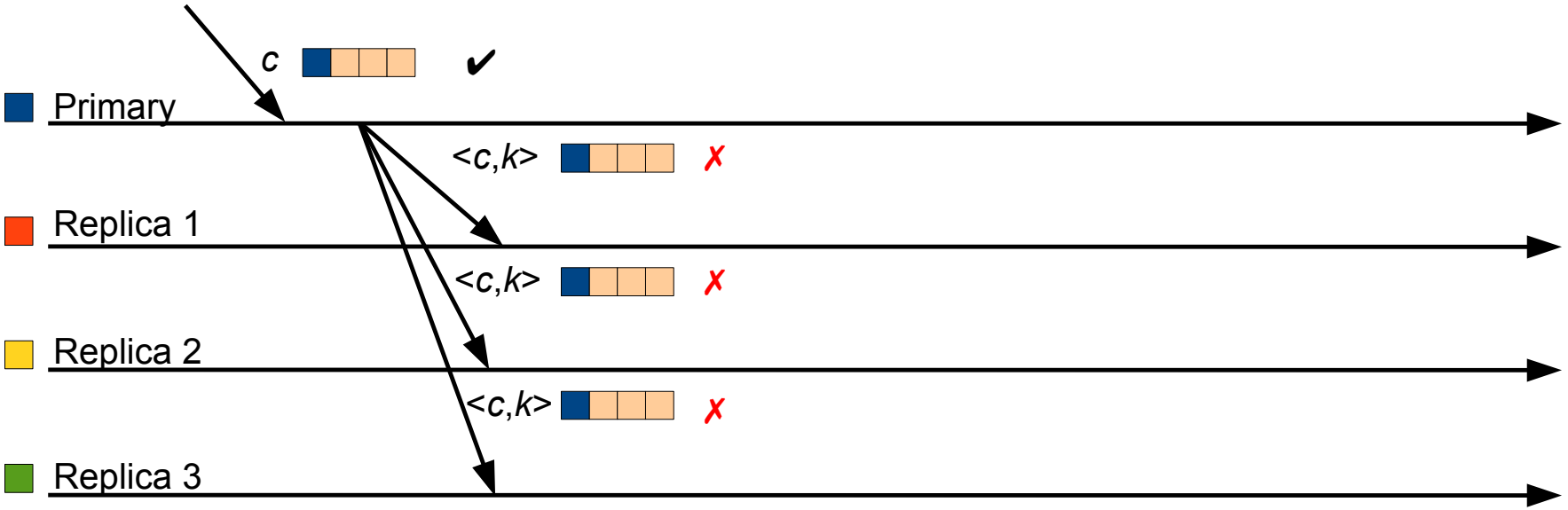
Revisiting conventional wisdom

- Signatures are expensive – use MACs
  - Faulty clients can use MACs to generate ambiguity
    (One node validating a MAC authenticator does not guarantee that any other nodes will validate that same authenticator)
  - Aardvark requires clients to sign requests
- View changes are to be avoided
  - Aardvark uses regular view changes to maintain high throughput despite faulty primaries
- Hardware multicast is a boon
  - Aardvark uses separate work queues for clients and individual replicas
  - Aardvark uses fully connected topology among replicas (separate NICs)

MAC Attack



MAC Attack



Throughput

	Best case	Faulty client	Client flood	Faulty primary	Faulty replica
PBFT	62K	0	crash	1k	250
QU	24K	0	crash	NA	19k
HQ	15K	NA	4.5K	NA	crash
Zyzzyva	80K	0	crash	crash	0
Aardvark	39K	39K	7.8K	37K	11K

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UpRight

Bibliography

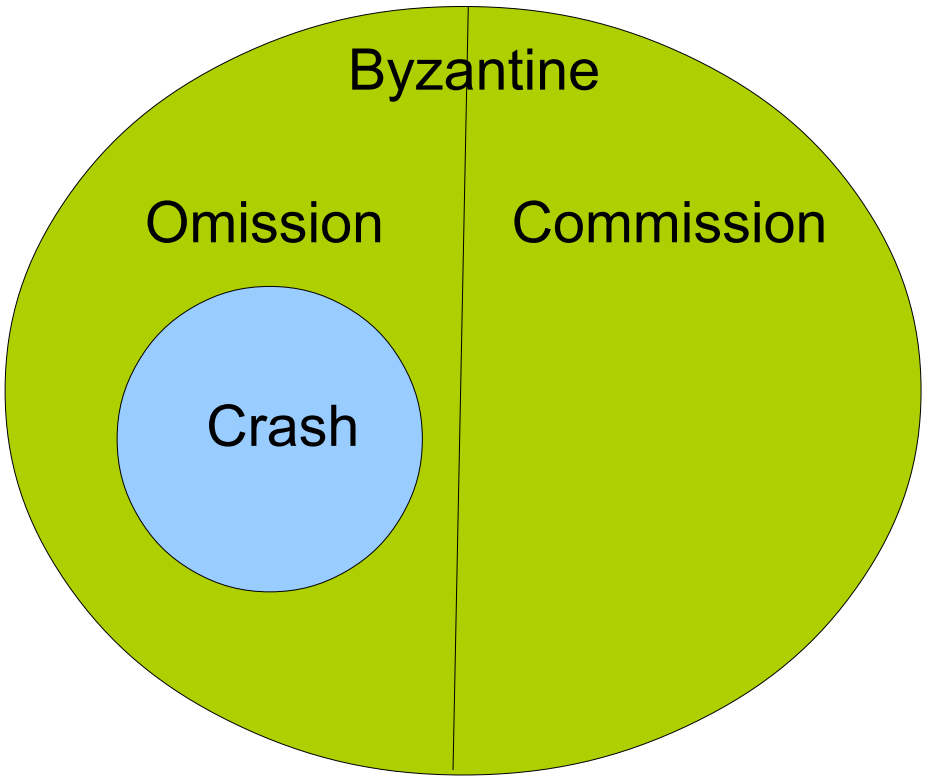
A. Clement, M. Kapritsos, S. Lee, Y. Wang, L. Alvisi, M. Dahlin, and T. Riche.

UpRight cluster services.
In *Proc. of the ACM Symposium on Operating Systems Principles*, SOSP'09, Oct. 2009.
http://www.disi.unitn.it/~montreso/ds/papers/UpRight.pdf

- A new (B)FT replication library
- Minimal intrusiveness for existing apps
- Adequate performance
- Goal:
  - ease BFT deployment
  - make explicit incremental cost of BFT
  - switching to BFT: simple change in a config file

UpRight

- u= max number of failures to ensure liveness
- r = max number of commission failures to preserve safety



- $r = u = f$: BFT
- $r = 0$: CFT

UpRight

- Exposes incremental cost of BFT
  - Byzantine agreement
  - if $r << u$, BFT $\approx$ CFT in replication cost
- Allows richer design options
  - Byzantine faults are rare: $u > r$
  - Safety more critical than liveness: $r > u$

Reality Check

- Bft-SMaRt[3](Java; still maintained)
- Used in Hyperledger Fabric (Blockchain)

[3] `http://bft-smart.github.io/library/`

For (far in the) future lectures

- S. Gaertner, M. Bourennane, C. Kurtsiefer, A. Cabello, and H. Weinfurter. Experimental demonstration of a quantum protocol for byzantine agreement and liar detection.
  Physical Review Letters, 100(7), Feb. 2008

Reading material

- M. Castro and B. Liskov. Practical Byzantine fault tolerance.
  In *Proc. of the 3rd Symposium on Operating systems design and implementation*, OSDI'99, pages 173–186, New Orleans, Louisiana, USA, 1999. USENIX Association.
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- R. Kotla, A. Clement, E. Wong, L. Alvisi, and M. Dahlin. Zyzzyva: Speculative byzantine fault tolerance.
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- A. Clement, E. Wong, L. Alvisi, M. Dahlin, and M. Marchetti. Making Byzantine fault tolerant systems tolerate Byzantine faults.
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