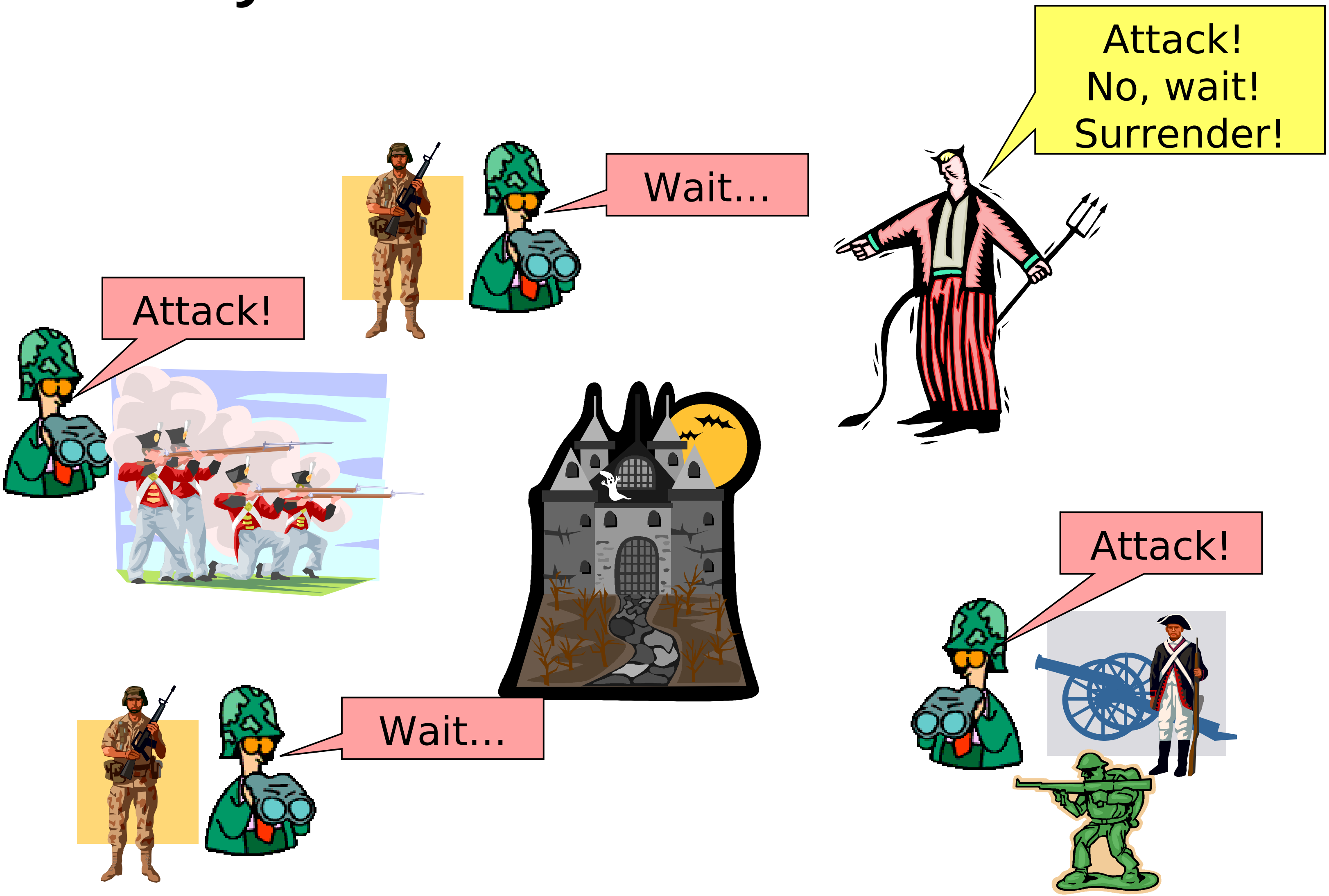
Practical Byzantine Fault Tolerance

(The Byzantine Generals Problem)

Introduction

- Malicious attacks and software errors that can cause arbitrary behaviors of faulty nodes are increasingly common
- Previous solutions assumed synchronous system and/or were too slow to be practical
  - e.g. Rampart, OM, SM
- This paper describes a new replication algorithm that tolerates Byzantine faults and practical (asynchronous environment, better performance)
- Why PBFT is practical (compared to the solutions from the Byzantine Generals Problem)

The Byzantine Generals Problem



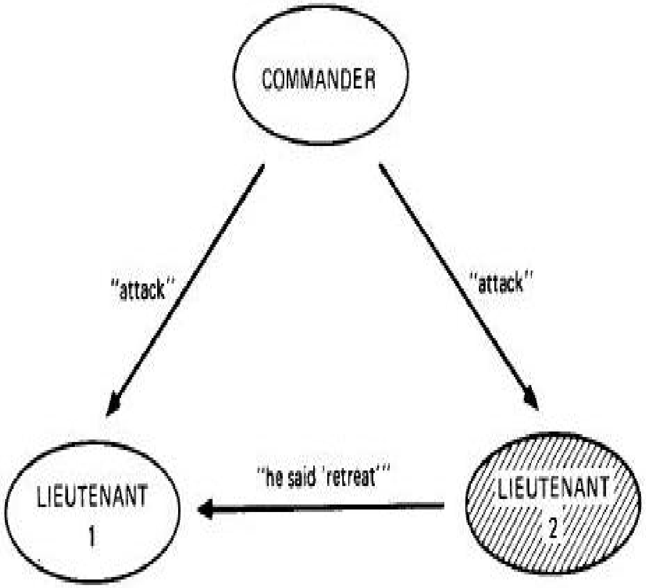
From cs4410 fall 08 lecture

The Byzantine Generals Problem

- A commanding general must send an order to his n-1 lieutenant generals such that
  -IC1. All loyal lieutenants obey the same order.
  -IC2. If the commanding general is loyal, then every loyal lieutenant obeys the order he sends.

Byzantine Generals Problem

Attack!



Attack?
Retreat?

Fig. 1. Lieutenant 2 a traitor.

Algorithm OM(0).

(1) The commander sends his value to every lieutenant.
(2) Each lieutenant uses the value he receives from the commander, or uses the value RETREAT if he receives no value.

Algorithm OM(m), $m > 0$.

(1) The commander sends his value to every lieutenant.
(2) For each i, let v_i be the value Lieutenant i receives from the commander, or else be RETREAT if he receives no value. Lieutenant i acts as the commander in Algorithm OM($m - 1$) to send the value v_i to each of the $n - 2$ other lieutenants.
(3) For each i, and each $j \neq i$, let v_j be the value Lieutenant i received from Lieutenant j in step (2) (using Algorithm OM($m - 1$)), or else RETREAT if he received no such value. Lieutenant i uses the value *majority*($v_1, \ldots, v_{n-1}$).

Byzantine Generals Problem

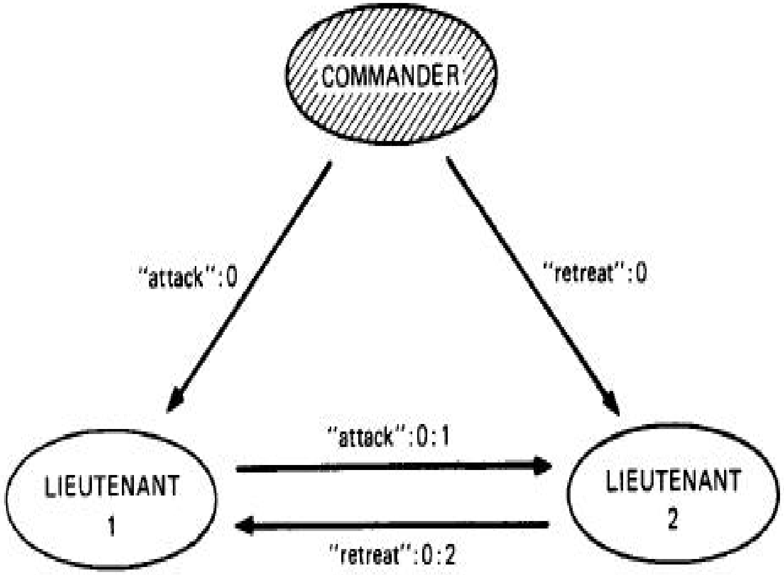


Fig. 5. Algorithm SM(1); the commander a traitor.

Algorithm SM(m).

Initially $V_i = \emptyset$.

(1) The commander signs and sends his value to every lieutenant.

(2) For each i:

(A) If Lieutenant i receives a message of the form $v:0$ from the commander and he has not yet received any order, then

(i) he lets V_i equal $\{v\}$;

(ii) he sends the message $v:0:i$ to every other lieutenant.

(B) If Lieutenant i receives a message of the form $v:0:j_1:\cdots:j_k$ and v is not in the set V_i, then

(i) he adds v to V_i;

(ii) if $k < m$, then he sends the message $v:0:j_1:\cdots:j_k:i$ to every lieutenant other than $j_1, \ldots, j_k$.

(3) For each i: When Lieutenant i will receive no more messages, he obeys the order $choice(V_i)$.

Byzantine Generals Problem

- *Theorem 1. For any m, Algorithm OM(m) satisfies conditions IC1 and IC2 if there are more than 3m generals and at most m traitors*
- Theorem 2. For any m, Algorithm SM(m) solves the Byzantine Generals Problem if there are at most m traitors
- Both require message paths of length up to m+1 (very expensive)
- Both require that absence of messages must be detected (A3) via time-out (vulnerable to DoS)

System Model

- Asynchronous distributed system where nodes are connected by a network
- Byzantine failure model
  - faulty nodes behave arbitrarily
  - independent node failures
- Cryptographic techniques to prevent spoofing and replays and to detect corrupted messages
- Very strong adversary

Service Properties

- Any deterministic replicated service with a state and some operations
- Assuming less than one-third of replicas are faulty
  - safety (linearizability)
  - liveness (assuming delay(t) >> t)
- Access control to guard against faulty client
- The resiliency (3f+1) of this algorithm is proven to be optimal for an asynchronous system

The Algorithm

- Basic setup:

  \- $|\mathcal{R}| = 3f + 1$

  \- A view is a configuration of replicas (a primary and backups): $p = v \ mod \ |\mathcal{R}|$

  \- Each replica is deterministic and starts with the same initial state

  \- The state of each replica includes the state of the service, a message log of accepted messages, and a view number

The Algorithm

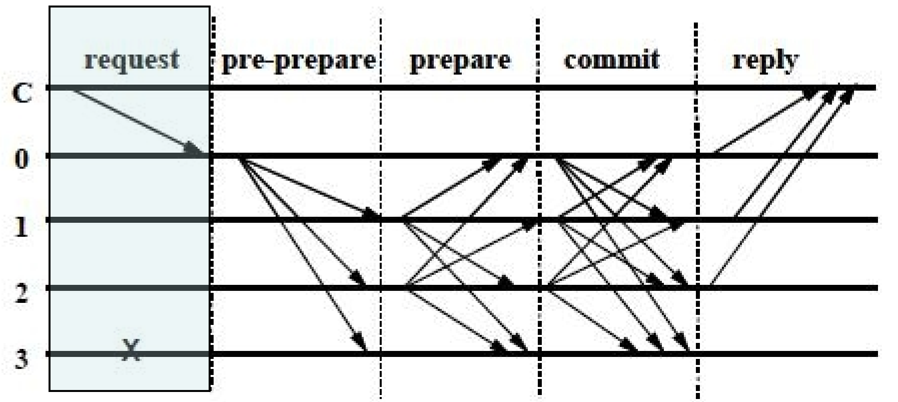


Figure 1: Normal Case Operation

- 1. A client sends a request to invoke a service operation to the primary

$$\langle \text{REQUEST}, o, t, c \rangle_{\sigma_c}$$

o= requested operation
t= timestamp
c= client
б= signature

The Algorithm

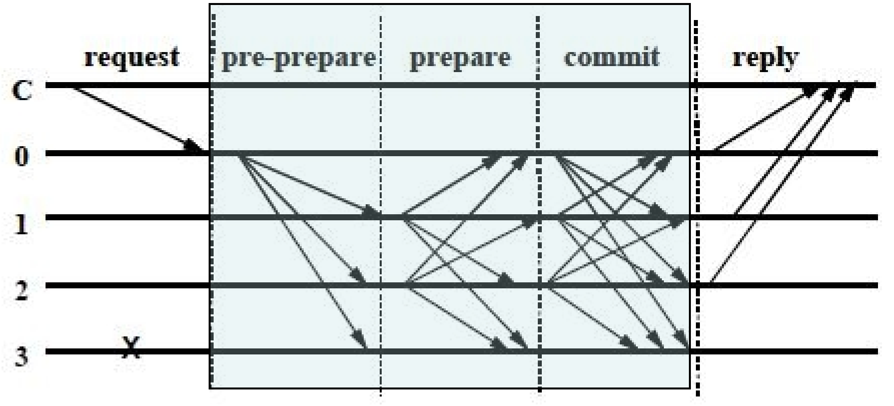


Figure 1: Normal Case Operation

- 2. The primary multicasts the request to the backups (three-phase protocol)

The Algorithm

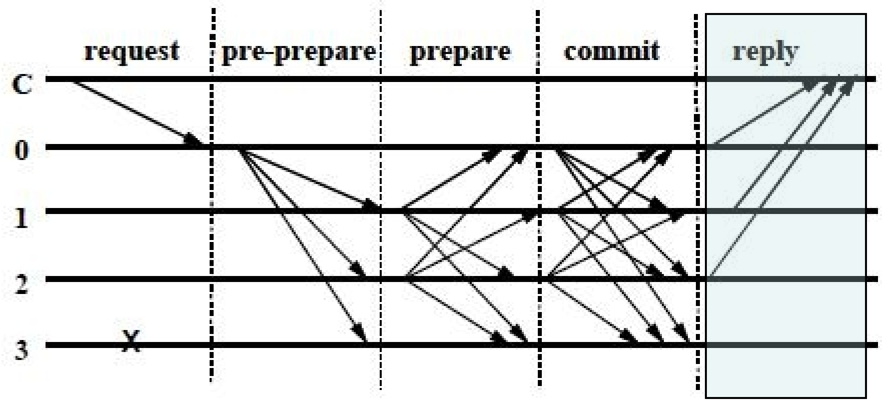


Figure 1: Normal Case Operation

- 3. Replicas execute the request and send a reply to the client

$$\langle \text{REPLY}, v, t, c, i, r \rangle_{\sigma_i}$$

o= requested operation
t= timestamp
c= client
б= signature

v= view
i= replica
r= result

The Algorithm

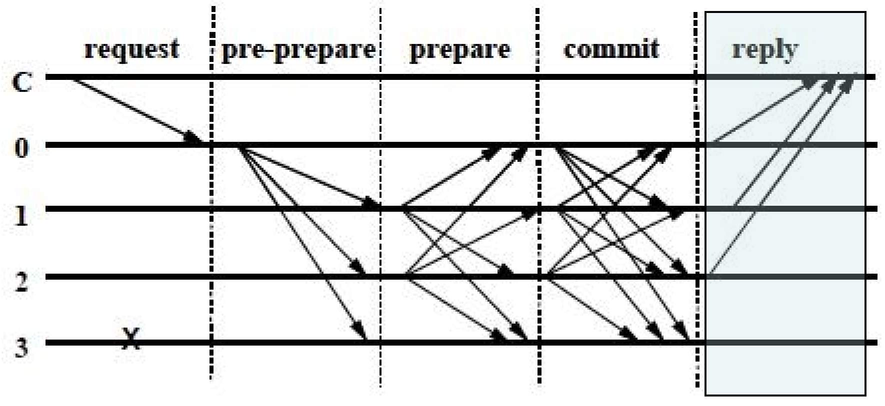


Figure 1: Normal Case Operation

- 4. The client waits for f+1 replies from different replicas with the same result; this is the result of the operation

Three-phase Protocol

- 1.pre-prepare
  - primary assigns n to the request; multicasts pp
  - request message m is piggy-backed (request itself is not included in pp)
  - accepted by backup if: $\langle\langle \text{PRE-PREPARE}, v, n, d\rangle_{\sigma_p}, m\rangle$
    - the messages are properly signed;
    - it is in the same view v;
    - the backup has not accepted a pp for the same v and n with different d
    - h <= n <= H
  - if accepted, then replica i enters prepare phase

Three-phase Protocol

- 2.prepare
  - if backup accepts pp, multicasts p
  - accepted by backup if: $\langle \text{PREPARE}, v, n, d, i \rangle_{\sigma_i}$
    - message signature is correct;
    - in the same view;
    - h<= n<= H
  - prepared(m,v,n,i) is true if i has logged:
    - request message m
    - pp for m in v
    - 2f matching prepares with the same (v,n,d)
  - if prepared becomes true, multicasts commit message and enters commit phase

Three-phase Protocol

- Pre-prepare – prepare phases ensure the following invariant:

  - *if prepared(m,v,n,i) is true then prepared(m',v,n,j) is false for any non-faulty replica j (inc. i=j) and any m' such that D(m') != D(m)*

- i.e. ensures requests in the same view are totally ordered (over all non-faulty replicas)

Three-phase Protocol

- 3.commit
  - accepted by backup if: $\langle \text{COMMIT}, v, n, D(m), i \rangle_{\sigma_i}$
    - message signature is correct;
    - in the same view;
    - h<= n<= H
  - committed(m,v,n) is true iff prepared(m,v,n,i) is true for all i in some set of f+1 non-faulty replicas
  - committed-local(m,v,n,i) is true iff prepared(m,v,n,i) is true and i has accepted 2f+1 matching commits
  - replica i executes the operation requested by m after committed-local(m,v,n,i) is true and i's state reflects the sequential execution of all requests with lower n

Three-phase Protocol

- Commit phase ensures the following invariant:
  - *if committed-local(m,v,n,i) is true for some non-faulty i then committed(m,v,n) is true*
- i.e. any locally committed request will eventually commit at f+1 or more non-faulty replicas
- The invariant and view change protocol ensure that non-faulty replicas agree on the sequence numbers of requests that commit locally even if they commit in different views at each replica
- Prepare – commit phases ensure requests that commit are totally ordered across views

The Algorithm

- Garbage Collection
  - must ensure the safety still holds after discarding messages from log
  - generates checkpoint (a snapshot of the state) every once in a while
  - when a replica generates a checkpoint, it multicasts checkpoint message with seq number and digest of state; if a replica receives 2f+1 matching checkpoint messages, the checkpoint becomes stable and any messages associated with seq numbers less than that of the checkpoint are discarded

- View Changes
  - provides liveness
  - triggered by timeout to prevent backups from waiting forever
  - timer starts when backup receives a valid request; it stops when the replica is no longer waiting to execute the request
  - with commit phase invariant, view change guarantees total ordering of requests across views (by exchanging checkpoint information across views)

The Algorithm

- The algorithm provides safety if all non-faulty replicas agree on the sequence numbers of requests that commit locally
- To provide liveness, replicas must change view if they are unable to execute a request
  - avoid view changes that is too soon or too late; the fact that faulty replicas can't force frequent view changes will guarantee liveness unless message delays grow faster than the timeout period indefinitely

Optimizations

- Reducing Communication
  - avoids sending most of large replies
    - only designated replica send the result
  - reduces the number of message delays for an operation invocation from 5 to 4
    - execute a request tentatively if prepared
    - client waits for matching 2f+1 tentative replies
  - improves the performance of read-only operations
    - client multicasts a read-only request to all
    - replicas execute it immediately in tentative state
    - send back replies after requests reflected in the tentative state commit
    - client waits for 2f+1 replies with the same result

Optimizations

- Cryptography
  - digital signatures used only for view-change and new-view messages (but view change is not implemented!)
  - authenticate all other messages using message authentication codes (MACs)

Implementation

- The Replication Library
  - basis for any replication service
  - client: invoke
  - server: execute, make_checkpoint, delete_checkpoint, get_digest, get_checkpoint, set_checkpoint
  - point-to-point communication using UDP
  - view change and retransmission can be used to recover from lost messages
  - It does not implement view-change or retransmission at present, but this does not compromise the accuracy of the results

Implementation

- A Byzantine-Fault-tolerant File System

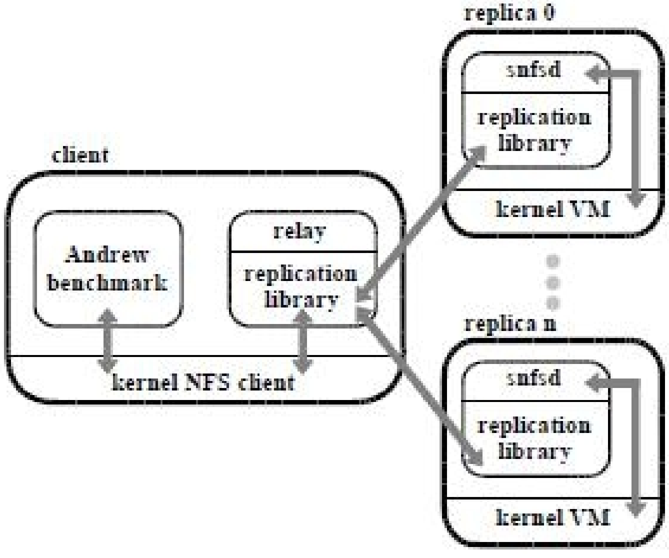


Figure 2: Replicated File System Architecture.

Implementation

- Maintaining Checkpoints
  - snfsd uses direct file system operations on memory mapped file system to preserve locality
  - checkpoint record (n, list of modified blocks, d) that keeps update information for the corresponding checkpoint

  - snfsd keeps a copy-on-write bit for every 512-byte block
  - copy-on-write technique to reduce space and time overhead in maintaining checkpoints

- Computing Checkpoint Digests
  - AdHash: sum of digest of each block (index+value)
  - efficient for a small number of modified blocks

Performance Evaluation

- Micro-benchmark: invoke null-op; provides service independent evaluation of the performance of the replication library
- Andrew-benchmark: emulates a software development workload; compares BFS with NFS V2 and BFS without replication
- Measured normal-case behaviors(i.e. no view changes) in an isolated network with 4 replicas
  - the first correct replicated service in asynchronous environment like internet?!
  - can tolerate Byzantine faults (liveness) with comparable normal-behavior performance?!

Performance Evaluation

arg./res. (KB)	replicated		without replication
	read-write	read-only	
0/0	3.35 (309%)	1.62 (98%)	0.82
4/0	14.19 (207%)	6.98 (51%)	4.62
0/4	8.01 (72%)	5.94 (27%)	4.66

Table 1: Micro-benchmark results (in milliseconds); the percentage overhead is relative to the unreplicated case.

phase	BFS		BFS-nr
	strict	r/o lookup	
1	0.55 (57%)	0.47 (34%)	0.35
2	9.24 (82%)	7.91 (56%)	5.08
3	7.24 (18%)	6.45 (6%)	6.11
4	8.77 (18%)	7.87 (6%)	7.41
5	38.68 (20%)	38.38 (19%)	32.12
total	64.48 (26%)	61.07 (20%)	51.07

Table 2: Andrew benchmark: BFS vs BFS-nr. The times are in seconds.

phase	BFS		NFS-std
	strict	r/o lookup	
1	0.55 (-69%)	0.47 (-73%)	1.75
2	9.24 (-2%)	7.91 (-16%)	9.46
3	7.24 (35%)	6.45 (20%)	5.36
4	8.77 (32%)	7.87 (19%)	6.60
5	38.68 (-2%)	38.38 (-2%)	39.35
total	64.48 (3%)	61.07 (-2%)	62.52

Table 3: Andrew benchmark: BFS vs NFS-std. The times are in seconds.

Conclusion

- PBFT is the first replicated system that works correctly in asynchronous system like internet and it improves performance of previous algorithms by more than an order of magnitude
- OM-SM algorithms are too slow to be used in practical (proportional to the number of faulty nodes vs. number of phases)