

# Large-Scale Byzantine Fault Tolerance: Safe but Not Always Live

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## Big picture

Choosing an adequate model to implement a system is crucial

- ***Optimistic***: the system is very efficient but likely to fail
- ***Conservative***: the system is very robust but inefficient (or impossible to implement)

How to find a good balance?

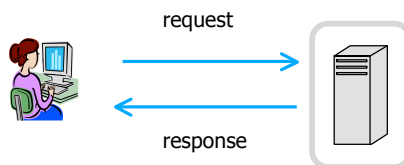
## Prepare for the worst and hope for the best

- How good is the best and how bad is the worst?
  - ✓ Best case – failures are few
  - ✓ Worst case – almost everything can be faulty
- What do we mean by “prepare” and “hope”?
  - ✓ The system is very efficient in the best case
  - ✓ The system never produces inconsistent output (even in the worst case), but ...
- ✓ May become unavailable in the (rare) “intermediate” case

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## The context: clients and services

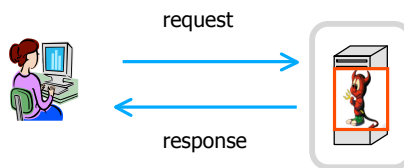
- A client issues a request to a service
- The service executes the request and returns a response to the client



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## The *fault-tolerant* computing challenge

- Even if some system components (clients or service units) fail, the correct clients still get something useful from the service
- Failures can be Byzantine: a component can arbitrarily deviate from its expected behavior

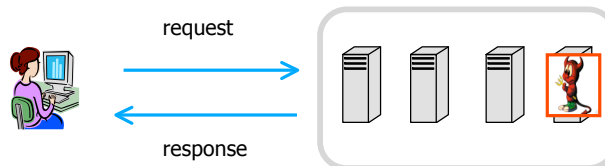


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## The replication approach

[Lamport, 1990; Schneider, 1990]

- Replicate the service
- Correct clients treat the distributed service as one correct server:
  - ✓ Requests are totally ordered, respecting the precedence relation (safety)
  - ✓ Every request issued by a correct client is served (liveness)
- Byzantine fault-tolerance (BFT) [Castro and Liskov, 1999]



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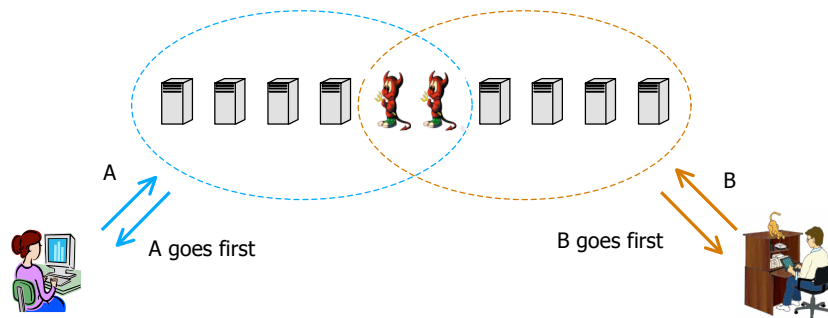
## BFT: costs and optimistic assumptions

- A request (a batch of requests) involves a three-phase agreement protocol to be executed
- A large fraction (more than  $2/3$ ) of the service replicas (servers) must be correct
  - ✓ Ok if faults are independent (hardware failures)
  - ✓ Questionable for software bugs or security attacks
  - ✓ An obstacle for scalability (unlikely to hold for large number of *replica groups*)

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## Why $2/3$ ?

- Safety: every two requests should involve at least one common correct server



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## Why 2/3?

$n$  – number of servers

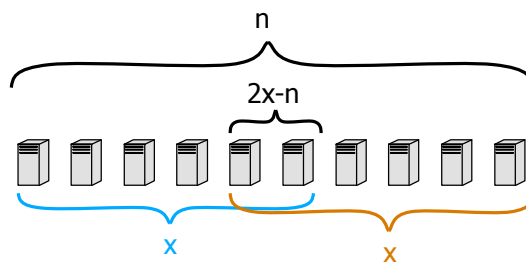
$x$  – quorum size (number of servers involved in processing a request)

$f$  – upper bound on the number of faulty servers

$2x - n \geq f + 1$  or  $x \geq (n + f + 1) / 2$  (**safety**)

$\Rightarrow n \geq 3f + 1$

$n - f \geq x$  (**liveness**)



## Trading off liveness for safety

- Every request involves at least  $(n + f + 1) / 2$  servers  
 $\Rightarrow$  safety is ensured as long as  $f$  or less servers fail
- Liveness will be provided if not more than  $n - (n + f + 1) / 2 = (n - f - 1) / 2$  servers fail
- $n = 10, f = 7$ : liveness tolerates at most one failure

## Trading off liveness for safety

- $f < n/3$ 
  - ✓ Both safety and liveness are ensured with quorums of size  $2/3n+1$
- $f = n-1$ 
  - ✓ Safety:  $n-1$  or less faulty servers
  - ✓ Liveness: no fault-tolerance at all

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## Unexpected benefits!

- Large quorums may make things faster!
- Very fast in the good case
- Very slow (unavailable) in the (rare) intermediate case
- But always correct
  
- Holds only for the special case  $f = n-1$ ?

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## Using the trade-off

- A “bimodal” failure model?
  - ✓ Few failures is the common case
  - ✓ Many failures is a possible (but rare) case ( $f \gg n/3$ )
    - Software bugs and security attacks?
- Modified BFT looks like a perfect fit!

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## Challenge: scalable BFT

- Farsite, Rosebud, OceanStore, ...
  - ✓ All of them use multiple *BFT groups*
  - ✓ A group is responsible for a part of the system state (an object)
  - ✓ Each group is supposed to be safe and live (the 2/3 assumption is not violated)
- The more groups we have - the more likely one of them fails: the system safety is in danger
- Going beyond 2/3 per group?

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## Using the trade-off: scalable BFT

- The (large) bound on the number of faulty servers *per group* is never exceeded
- Each group runs the modified BFT: can be seen as a *crash-fault* processor

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## Addressing liveness

- Primary-backup: from  $p$  to  $p^2$ 
  - ✓ Every object is associated with a pair of groups
- Speculative executions [Nightingale et al.,2005]
  - ✓ Primary group produces tentative results
  - ✓ Backup group assist in committing them

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## Normal case

### Client

- Run operations on the primary group tentatively
- Check whether the tentative results turned into definitive (the state was successfully transferred to the backup group)

### Backup-primary

- Periodically transfer the system state from primary to backup

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## Liveness checks and recovery

Takeover protocol: when the primary fails the backup takes over the speculative execution

- Primary fails: backup takes over in speculative executions
- Backup fails: select a new backup
- Configuration changes: elect new primary and backup (at least one of the old ones must remain live until the state is transferred)

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## Properties

- Safety: always
- Liveness: as long as at least one group is available

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## Related work

- BFT, Castro and Liskov, 1999
- “Scalable” BFT: OceanStore, 2000; Farsite, 2002; Rosebud, 2003,...
- Safety-liveness trade-offs, Lamport, 2003
- Fork consistency, Li and Mazieres, 2007
- Singh et al., 2007
- Speculative executions, Nightingale et al., 2005
- Fault isolation, Douceur et al., 2007

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## Conclusions and Future

- Safety at the expense of liveness [HotDep07]
  - ✓ Security and tolerance to software errors
  - ✓ Scalability
- Safety + conditional liveness
  - ✓ Crash fault computing: safe algorithms + failure detectors
  - ✓ Software transactional memory: optimistic STMs + contention managers
- Does this stuff work?
  - ✓ Fault model analysis
  - ✓ Multiple backups: from  $p^2$  to  $p^k$
  - ✓ Paxos?
  - ✓ Implementation

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