**Byzantine Systems**

A *trustworthy system*

- does what you want
- nothing else!
- despite human and operator errors
- despite environmental disruptions
- despite attacks

**Trustworthy Systems**

- Basic PL research
- Program correctness
- Program verification
- User interfaces
- Fault tolerance
- Security

**The Odd Couple**

- Fault-tolerance
- Security
- Integrity
- Integrity
- Availability
- Availability
- Confidentiality

**A working hypothesis**

- Model compromised processes as Byzantine
  - Faulty processes can deviate arbitrarily (maliciously) from spec
  - Faulty processes can collude

- Build replicated services that can tolerate (a threshold of) Byzantine failures
Outline

The Rise and Fall of State Machine Replication
- State Machine Replication
- Paxos
- Byzantine agreement
- Byzantine fault-tolerance can be fast!
  - PBFT
- The Emperor is naked...

The Problem

Clients

Server

Solution: replicate server!

The Solution

1. Make server deterministic (state machine)
The Solution

1. Make server **deterministic** (state machine)
2. Replicate server
3. Ensure correct replicas step through the same sequence of state transitions
4. Vote on replica outputs for fault-tolerance

Clients

State machine

Voter

State machine
A conundrum

A: voter and client share fate!

Replica Coordination

All non-faulty state machines receive all requests in the same order

AGREEMENT: Every non-faulty state machine receives every request

ORDER: Every non-faulty state machine processes the requests it receives in the same relative order

The Part-Time Parliament

Parliament determines laws by passing sequence of numbered decrees
Legislators can leave and enter the chamber at arbitrary times
No centralized record of approved decrees—instead, each legislator carries a ledger

Government 101

If a majority of legislators were in the Chamber and no one entered or left the Chamber for a sufficiently long time, then
any decree proposed by a legislator would eventually be passed
any passed decree would appear on the ledger of every legislator
Supplies

Each legislator receives
- ledger
- scratch paper
- pen with indelible ink
- hourglass
- lots of messengers

Back to the future

- A set of processes that can propose values
- Processes can crash and recover
- Processes have access to stable storage
- Asynchronous communication via messages
- Messages can be lost and duplicated, but not corrupted

The Game: Consensus

SAFETY
- Only a value that has been proposed can be chosen
- Only a single value is chosen
- A process never learns that a value has been chosen unless it has been

LIVENESS
- Some proposed value is eventually chosen
- If a value is chosen, a process eventually learns it

The Players

- Proposers
- Acceptors
- Listeners
Choose a value...

1. A single acceptor

Choose a value...

1. A single acceptor
   2. A majority of acceptors (forces a single value)

Choose a value...

1. A single acceptor
   2. A majority of acceptors (forces a single value)

When should an acceptor accept?

1. Acceptors must accept first received proposal
2. Acceptors must accept multiple proposals
Choose a value…

1. A single acceptor
2. A majority of acceptors (forces a single value)

When should an acceptor accept?

① Acceptors must accept first received proposal
② Acceptors must accept multiple proposals

(pid, value)

…a unique value…

② If a proposal with value v is chosen, then every higher-numbered proposal that is chosen has value v

② If a proposal with value v is chosen, then every higher-numbered proposal accepted by any acceptor has value v

① + ② = trouble
...a unique value...

1. If a proposal with value $v$ is chosen, then every higher-numbered proposal that is chosen has value $v$
2. If a proposal with value $v$ is chosen, then every higher-numbered proposal accepted by any acceptor has value $v$
3. If a proposal with value $v$ is chosen, then every higher-numbered proposal issued by any proposer has value $v$

...and only a unique value...

2. If a proposal with value $v$ is chosen, then every higher-numbered proposal issued by any proposer has value $v$
3. For any $v$ and $n$, if a proposal with value $v$ and pid $n$ is issued, then there is a majority-set $S$ of acceptors such that one of the following holds:
   a. no acceptor in $S$ has accepted any proposal numbered less than $n$
   b. $v$ is the value of the highest-numbered proposal among all proposals numbered less than $n$ accepted by acceptors in $S$

Say I do:
The proposer’s protocol

1. A proposer chooses a new $n$ and sends $\langle \text{prepare},n \rangle$ to each member of some set of acceptors, asking to respond with:
   a. A promise never again to accept a pid less than $n$, and
   b. The accepted proposal with highest pid less than $n$ if any.
2. If proposer receives a response from a majority of acceptors, then it can issue $\langle \text{accept}(n,v) \rangle$ where $v$ is the value of the highest pid among the responses, or is any value selected by the proposer if responders returned no proposals

Say I do:
The acceptor’s protocol

1. Always respond to $\text{prepare}$ messages
2. Respond to $\langle \text{accept}(n,v) \rangle$ iff it has not responded to $\langle \text{prepare},n' \rangle$ with $n' > n$
3. Write intended response to stable storage before sending it

Note that (2) $\Rightarrow$ (1)
The Learning Channel

i. Each acceptor informs each learner
ii. Acceptors contact a distinguished learner, which informs other learners
iii. Acceptors contact a set of learners...

Don’t stop me now

Liveness (surprise!) is not guaranteed:

\[ n_1 < n_2 < n_3 < n_4 < \ldots \]

\[ \text{P_1} \quad \text{P_2} \]

\[ \langle \text{propose,} n_1 \rangle \quad \langle \text{propose,} n_2 \rangle \]
\[ \langle \text{accept}(n_1, v_1) \rangle \quad \langle \text{accept}(n_2, v_2) \rangle \]
\[ \langle \text{propose,} n_3 \rangle \quad \langle \text{propose,} n_4 \rangle \]

Time

All proposers are equal, but some more so than others

- Elect a distinguished proposer
- Can’t be done reliably in asynchronous systems, so...
  - real time
  - randomization

Agreement and Byzantine Generals

- One General G, a set of Lieutenants L_i
- General can order Attack (A) or Retreat (R)
- General may be a traitor; so may be some of the Lieutenants
  - * * *

I. If G is trustworthy, every trustworthy L_i must follow G’s orders
II. Every trustworthy L_i must follow same battleplan
The plot thickens...
One traitor

A lower bound (LSP82)

There is no algorithm that solves Byzantine agreement when $n \leq 3f$

A Byzantine Renaissance
- Practical Byzantine Fault-Tolerance (CL99, CL00)
  - first to be safe in asynchronous systems
  - fast! PBFT NSF only 3% slower than standard NFS on Andrew benchmark
  - uses proactive recovery to tolerate more failures over system lifetime
- BASE (RCL 01)
  - uses abstraction to reduce correlated faults

Major issue: Assumptions
- Replication algorithms make assumptions
  - behavior of faulty process
  - synchrony
  - bound of number of faults
- Service fails if assumptions are not valid
  - attacker can make service fail by making assumptions invalid
- Most earlier algorithms assume too much, and are thus vulnerable
Second issue: Performance
- Replication has performance overhead
  - Extra communication and computation
- Practical algorithms require low overhead
- Till now: replication algorithms that do not assume too much perform poorly!

Contributions of PBFT
- Practical replication algorithm
  - Weak assumptions
  - Good performance
- Implementation
  - Replicated library service
  - Byzantine tolerant NFS implementation

Bad assumption: benign faults
- Most previous replication techniques assume:
  - Replicas fail by omitting/ stopping
  - Invalid with malicious attacks
  - Compromised replicas may behave arbitrarily
  - Single such fault can compromise service
  - Lesser resiliency to malicious attacks!

Bad assumption: synchrony
- Synchrony: assuming known bounds on
  - Delay between steps
  - Message delays
- Assumption invalid with denial-of-service attacks
  - Bad replies due to increased delays
  - System fails
- Synchrony is assumed by most Byzantine fault tolerant schemes...
Issues with asynchrony

- No delay bounds
- Problem is: FLP!
- Solution in BFT:
  1. Provide safety without using synchrony
     □ guarantees no bad replies
  2. Assume eventual time bounds for liveness
     □ System may not reply with active denial-of-service attack
     □ But will reply when the attack ends

Bad assumption: Bound on number of faults

- Given enough time, more than $f$ replicas are likely to malfunction
- Detection of faults is hard and slow

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Unavoidable

Bad assumption: Bound on number of faults

- Given enough time, more than $f$ replicas are likely to malfunction
- Detection of faults is hard and slow
- Unavoidable

Solution in BFT:

1. Proactive recovery - periodic recovery tasks scheduled even when no faults are suspected
2. Frequent recoveries
   High availability if at most $f$ failures in a “window”
To summarize: THEM bad...

- Strong assumptions
- Safety relies on synchrony - easy to break in
- Unbounded storage - impractical
- Absolute bound on number of faults
- Too slow to be used in practice
- Extensive use of public key cryptography
- High communication overhead

...BFT goooood!

- Supports complex operation requests from clients
- Safety
  - System behaves like a correct centralized service
- Liveness
  - Clients eventually receive replies to requests

BFT assumptions

- $3f+1$ replicas to tolerate $f$ Byzantine faults
- Strong cryptography
- Eventual time bounds - only for liveness

Ordering Requests

- Idea: Use quorums (remember Paxos?)
  - But now need to tolerate Byzantine faults...
- Primary-Backup
Ordering Requests

- Idea: Use quorums (remember Paxos?)
- But now need to tolerate Byzantine faults...

Primary-Backup
- Protocol proceeds in Views
- Current view designates the Primary
- Primary orders the requests by assigning sequence numbers
- Backups ensure correct behavior of Primary:
  - Certify correct ordering by Primary
  - Trigger view change to replace faulty primary

Client-Service interactions

<REQUEST,o,t,c>\sigma_c

Client-Service interactions

<REQUEST,o,t,c>\sigma_c

Client-Service interactions

<REQUEST,o,t,c>\sigma_c

Client-Service interactions

<REQUEST,o,t,c>\sigma_c

Client-Service interactions

<REQUEST,o,t,c>\sigma_c
Client-Service interactions

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

client id

signature

Client-Service interactions

\[ \langle \text{REPLY}, v, t, c, i, r \rangle_{\sigma_i} \]
**Client-Service interactions**

Before accepting $r$, $c$ waits for $f+1$ replies with same $t$ and $r$ from different replicas.

**Troubleshooting**

- If $c$ times out waiting for reply, it broadcasts its request to all replicas.
- If replica has already computed response, it just returns it.
- Otherwise, replica forward request to primary.
- If primary does not multicast, it is eventually suspected.

**Quorums and Certificates**

- Quorums contain at least $2f+1$ replicas.
- Any two quorums intersect in at least one correct replica.
- Always one quorum available with non-faulty replicas.
- Certificate: set of messages from a quorum which guarantees or certifies a certain property.
- Algorithm steps are justified by certificates.

**Algorithm Components**

- Normal case operation
- Garbage collection
- View changes
- Recovery
Normal case operation

3 phase algorithm:
  i. Pre-prepare phase picks order of requests
  ii. Prepare phase ensure ordering of requests within views
  iii. Commit phase ensures order across views

Replicas remember messages on stable log
Messages are authenticated

Pre-prepare

Primary multicasts <<PRE-PREPARE,v,n,d>!p,m>

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Pre-prepare

Primary multicasts <<PRE-PREPARE,v,n,d>!p,m>
Pre-prepare

Primary multicasts $<$PRE-PREPARE, v,n,d, i$_{P}$, m$>$

- PRE-PREPARE is well formed
- i is in view v
- i has not accepted another PRE-PREPARE for v,n with a different d
- n is between two water-marks

Backup i accepts PRE-PREPARE if:

Prepare

Backup i multicasts $<$PREPARE, v,n,d,i$_{P}$, m$>$

Prepare Certificate

- $P$-certificates ensure total order within views
- Replica produces $P$-certificate(m,v,n) iff its log holds:
  - The request m
  - A pre-prepare for m in view v with sequence number n
  - 2f prepares from different backups that match the pre-prepare
**Prepare Certificate**

- **P-certificate** ensure total order within views
- Replica produces P-certificate(m, v, n) iff its log holds:
  - The request m
  - A pre-prepare for m in view v with sequence number n
  - 2f prepares from different backups that match the pre-prepare
- A P-certificate(m, v, n) means that a quorum agrees with assigning sequence number n to m in view v
- NO two non-faulty replicas with P-certificate(m₁, v, n) and P-certificate(m₂, v, n)

**Commit Certificate**

- A replica has a C-certificate(m, v, n) if:
  - It had a P-certificate(m, v, n)
  - Log contains 2f+1 matching commits from different replicas
- Replica executes a request after it gets C-certificate for it, and has cleared all previous requests

**Commit**

After receiving a P-certificate, replica i multicasts <COMMIT_v,d,i>!i

**A useful invariant**

Some replica has C-certificate(m, v, n) \( \equiv f+1 \) correct replicas have a P-certificate

It ensures the following properties:

i. Non-faulty replicas agree on sequence number of requests that commit locally even across view changes

ii. If non-faulty replica builds C-certificate, eventually \( f+1 \) non-faulty replicas do so
Reply

After executing request, replica replies

Primary
Backup 1
Backup 2
Backup 3
Pre-prepare phase  Prepare phase  Commit phase  Reply phase

Garbage Collection

- Truncate Log with Certificate
  - Each replica periodically checkpoints state and builds certificate to prove state is correct
  - Multicasts \(<CHECKPOINT,n,d,i>_{\sigma_1}\)
Garbage Collection

- Truncate Log with Certificate
  - Each replica periodically checkpoints state and builds certificate to prove state is correct
  - Multicasts <CHECKPOINT,n,d,i>_{qi}

- CK-Certificate \(= 2f+1 \) checkpoint messages for same n,d from different i's
- CK-certificate used in view changes
- CK-certificate advances low, high watermarks

View changes

- If primary in view v times out, replica i:
  - stops accepting messages (except CHEKPOINT, VIEW-CHANGE, NEW-VIEW)
  - multicasts <VIEW-CHANGE,v+1,n,CK-cert,P,i>_{qi}

last provedckpt

{P-certificates held by i
for requests with sn > n}
If primary in view v times out, replica i:
- stops accepting messages (except CHEKPOINT, VIEW-CHANGE, NEW-VIEW)
- multicasts <VIEW-CHANGE, v+1, n, CK-cert, P_i>_{σ_j}

When primary j for v+1 receives 2f VIEW-CHANGE:
- multicasts <NEW-VIEW, v+1, V, O>_{σ_j}

If primary in view v times out, replica i:
- stops accepting messages (except CHEKPOINT, VIEW-CHANGE, NEW-VIEW)
- multicasts <VIEW-CHANGE, v+1, n, CK-cert, P_i>_{σ_j}

When primary j for v+1 receives 2f VIEW-CHANGE:
- multicasts <NEW-VIEW, v+1, V, O>_{σ_j}
  {2f+1 VIEW-CHANGE messages}
O’s

A set of $<\text{PRE-PREPARE}, v+1, n, d>_{\sigma_j}$
for all $n$: $\min-s < n \leq \max-s$, where
- $\min-s = \text{sn of latest proved checkpoint in } V$
- $\max-s = \text{sn of latest P-certificate in } V$

$d = \begin{cases} 
\text{digest of } m \text{ with } \text{P-certificate}<m, v, n> \text{ (if any)} \\
\sigma_{null}
\end{cases}$

Safety

Within a view, replicas agree on sn of requests for
which a C-certificate can be built

Across views?
**Safety**

- Within a view, replicas agree on sn of requests for which a C-certificate can be built
- Across views?
  - $\text{C-certificate}(m,v,n) \Rightarrow 2f+1 \text{ P-certificate}(m,v,n)$
  - $<\text{NEW-VIEW},v+1,V,O>_j$ accepted $\Rightarrow 2f+1 \text{ VIEW-CHANGE}$
- At least 1 correct replica in v+1 has P-certificate(m,v,n)!

**Communication Optimizations**

i. One replica sends response, other send digests
ii. Replicas mayoptimistically execute requests for which hold a P-certificate
   - return tentative response
   - client needs 2f+1 tentative responses to accept
iii. Read Only requests
   - replicas execute in current state
   - client accepts if it receives 2f+1 responses
   - otherwise, send regular R/W request

**Liveness**

Install new views conservatively:

Try maximizing period T where 2f+1 correct replicas are in the same view

Increase T exponentially until some request executes

**Fast Authentication**

- Use MACs instead of digital signatures
- MAC is 1000x faster than PK signatures
- Public key cryptography used to setup MAC keys, VIEW-CHANGE and NEW-VIEW messages
- Non-trivial
  - MAC less powerful than signatures
  - Receiver cannot prove authenticity to others...
Back to the Dark Ages

- Too many replicas
  - Who cares? Machines are cheap...
- But achieving independent failures is expensive
  - Independently failing hardware
  - Independently failing software!

Back to the Dark Ages

- No confidentiality

Rethinking State Machine Replication

Not Agreement + Order
but rather Agreement on Order + Execution
Rethinking State Machine Replication

Not Agreement + Order

but rather Agreement on Order + Execution

Benefits

- $2f+1$ state machine replicas
- $3f+1$ state machine replicas

Replication helps confidentiality

Separation reduces replication costs

Not all nodes are created equal!

- Nodes in E: expensive
  - (different across applications and within same application)
- Nodes in A: cheap
  - (simple and reusable across applications)

The implementation...

1. A assigns unique sequence number to request
2. $\langle \text{request, } rsn \rangle_A$: request is certified unique
3. E executes in $rsn$ order
4. $\langle \text{reply, } rsn \rangle_E$: reply is certified unique
...is simple

Separating agreement and execution is easy

- No need to change agreement protocol
- Just forward request instead of executing
- Just a couple of subtle points

To handle message loss, implement retransmission in E
Retransmission occurs only if a message is really lost

Separation enables confidentiality

Agreement nodes can filter incorrect replies

The Privacy Firewall

Three design principles:

1. Use redundant filters for fault tolerance
2. Restrict communication
3. Eliminate nondeterminism
Inside the PF

- $(h+1)^2$-filter grid tolerates $h$ Byzantine failures
- A filter only communicates with filters immediately above or below
- Each filter checks both reply and request certificates
- Safe
  - $h+1$ rows $\to$ one is correct
- Live
  - $h+1$ columns $\to$ one is correct
- restricts nondeterminism
  - threshold cryptography for replies
  - cluster $A$ locks $rsn$
  - controlled message retransmission
Inside the PF

- $(h+1)^2$-filter grid tolerates $h$ Byzantine failures
- A filter only communicates with filters immediately above or below
- Each filter checks both reply and request certificates
- Safe
  - $h+1$ rows → one is correct
- Live
  - $h+1$ columns → one is correct
- **Restricts nondeterminism**
  - threshold cryptography for replies
  - cluster A locks rsn
  - controlled message retransmission

Privacy Firewall guarantees

Output-set confidentiality
Output sequence through of correct cut is a legal sequence of outputs produced by a correct node accessed through an asynchronous, unreliable link

Timing Attacks

- Faulty node in E can influence response latency

<table>
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<th>fast node</th>
<th>slow node</th>
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Timing Attacks

- Faulty node in E can influence response latency
- Information theoretic confidentiality appears impossible without synchrony

Prototype

- Built on top of BASE (RCL '01)
- Implements BFT-confidential NFS
- 10 machines: 1 client, 4 in A and PF, 2 in A, 3 in E
- 128 MB RAM, 100 Mbps switch
- Tolerates one fault in each of E, A, and PF

Limitations

- No uninterruptible power supply
- The nodes in E are identical
- Communication not physically restricted

Micro-Benchmark

(req/resp: 40B/4KB)

- No optimizations

Modified Andrew Benchmark (MAB 500)

Confidentiality adds an extra 16%
Conclusions

Trustworthy distributed systems through BFT

- A new architecture for state machine replication
- separates agreement from execution
- reduces the number of expensive replicas
- improves confidentiality
- may lead to more efficient algorithms

Chino: Quorum Systems
- single replica may not know entire state...
- but a quorum of replicas will
- very active research area

Are these the Emperor’s new clothes?