Trustworthy Systems

A trustworthy system

- does what you want
- nothing else!

} Basic PL research, Program correctness, Program verification

- despite human and operator errors } User interfaces
- despite environmental disruptions } Fault tolerance
- despite attacks } 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...

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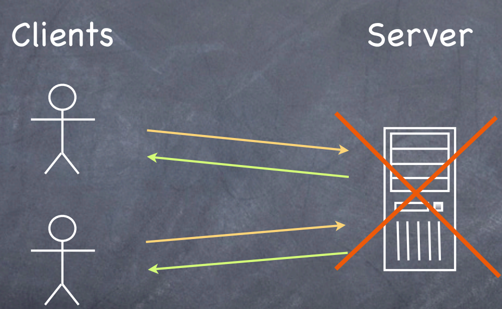
Rethinking State Machine Replication

- The principle: <u>separate agreement from execution</u>
- The payoffs:
  - lower replication costs/stronger confidentiality

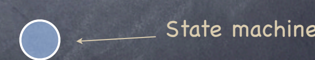
The Problem



Solution: replicate server!

The Solution

1. Make server deterministic (state machine)



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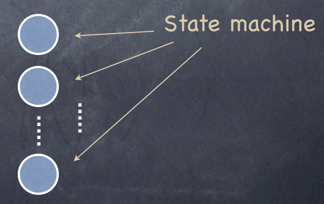
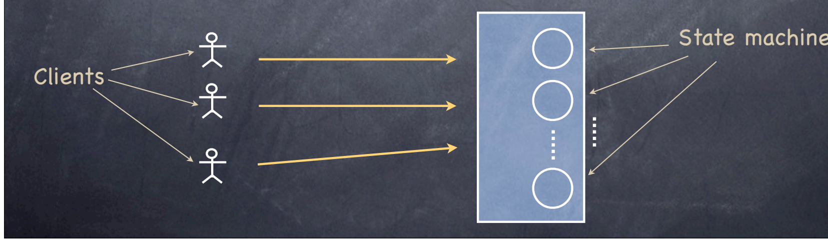


The Solution

1. Make server deterministic (state machine)
2. Replicate server
3. Ensure correct replicas step through the same sequence of state transitions



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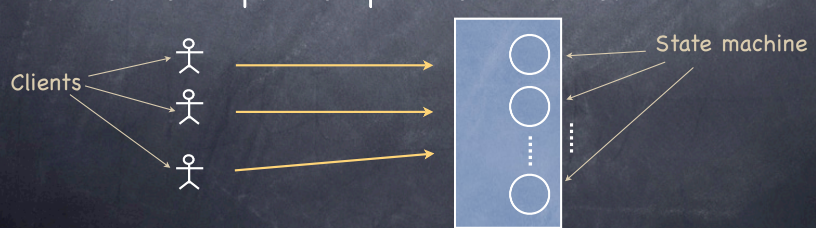

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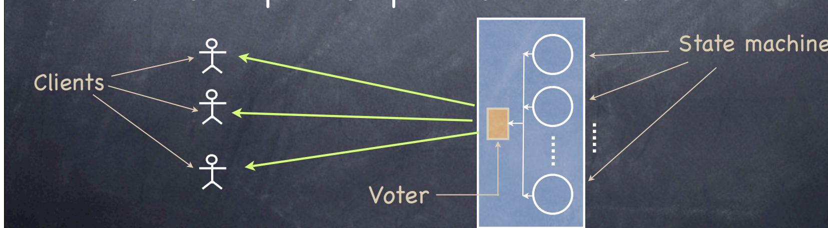
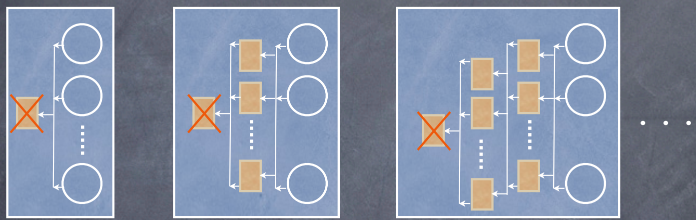
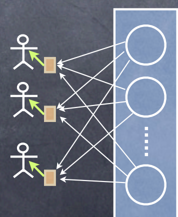


A conundrum



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

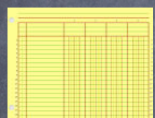
Government 101

If a majority of legislators were in the Chamber and no one entered or left the Chamber for a sufficiently long time, then

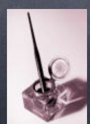
- any decree proposed by a legislator would eventually be passed
- any passed decree would appear on the ledger of every legislator

Supplies

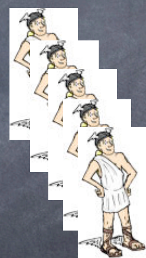
Each legislator receives



ledger



pen with indelible ink



lots of messengers

scratch paper

hourglass

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)

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

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When should an acceptor accept?

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- 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

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①+②=trouble

…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*
- ② 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*
- ② 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 <*prepare,n*> 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 <*accept*(*n*,*v*)> 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 *prepare* messages
2. Respond to <*accept*(*n*,*v*)> iff it has not responded to <*prepare,n'*> with *n'* > *n* ①
3. Write intended response to stable storage before sending it

Note that ① ⇒ ①

The Learning Channel

i. Each acceptor informs each learner

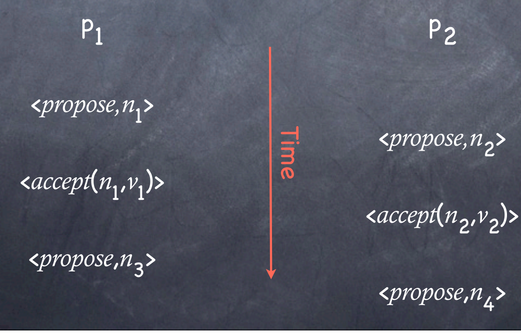
ii. Acceptors contact a distinguished learner, which informs other learners

iii. Acceptors contact a set of learners...

Don't stop me now

Liveness (surprise!) is not guaranteed:

$n_1 < n_2 < n_3 < n_4 < \ldots$



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

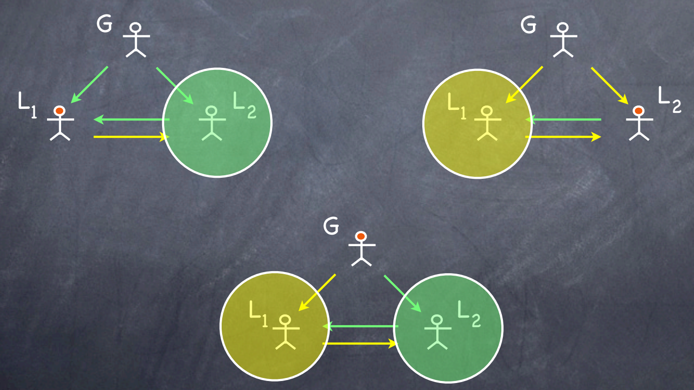
* * *

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:
  i. Provide safety without using synchrony
     - guarantees no bad replies
  ii. 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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- Detection of faults is hard and slow
- Unavoidable
- Solution in BFT :
  i. Proactive recovery – periodic recovery tasks scheduled even when no faults are suspected
  ii. 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 gooood!

- 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

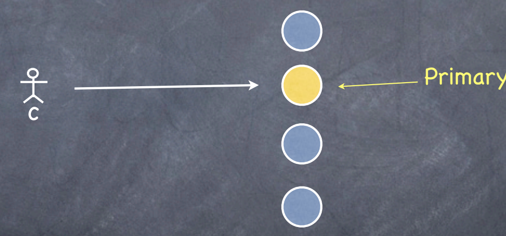
Ordering Requests

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

Ordering Requests

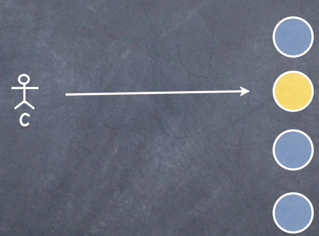
- Idea : Use quorums (remember Paxos?)
  - But now need to tolerate Byzantine faults...
- Primary-Backup
  - Protocol proceeds in Views
  - Current view designates the Primary
  - Primary orders the requests by assigning sequence numbers
  - Backups ensure correct behavior of Primary
    - Certify correct ordering by Primary
    - Trigger view change to replace faulty primary

Client-Service interactions



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

Client-Service interactions



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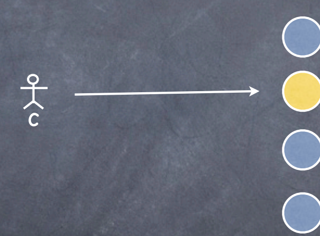
state machine operation

Client-Service interactions



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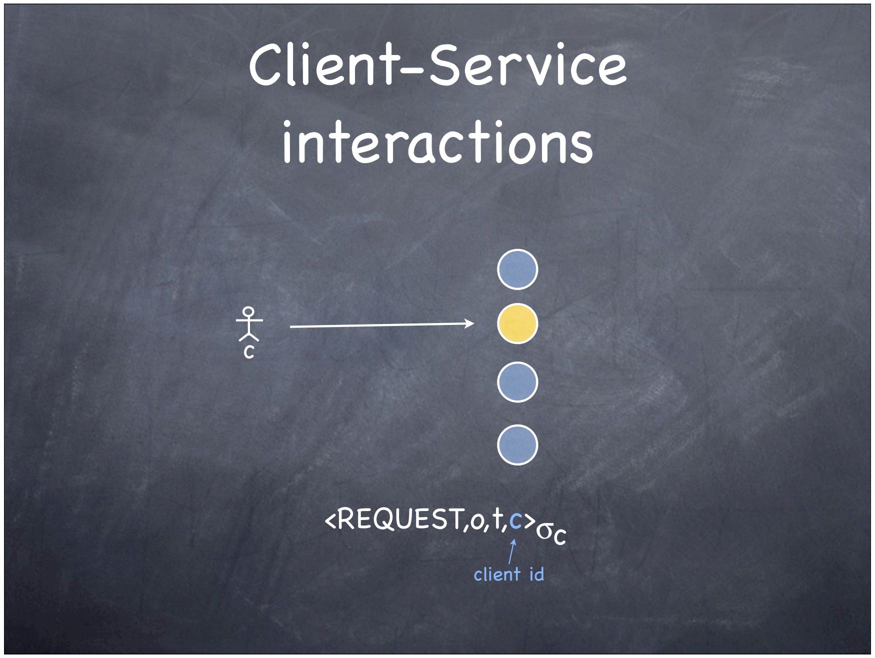
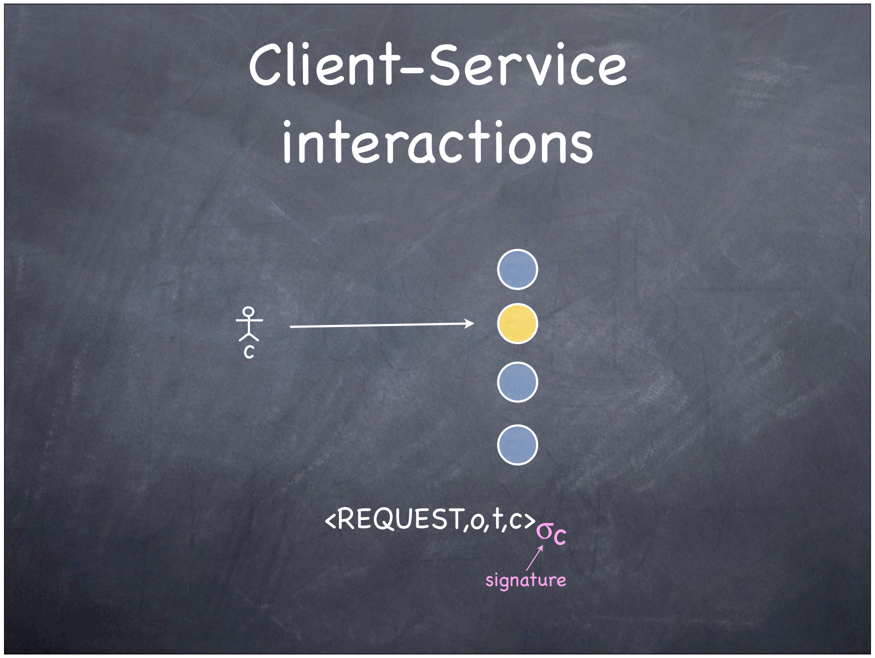
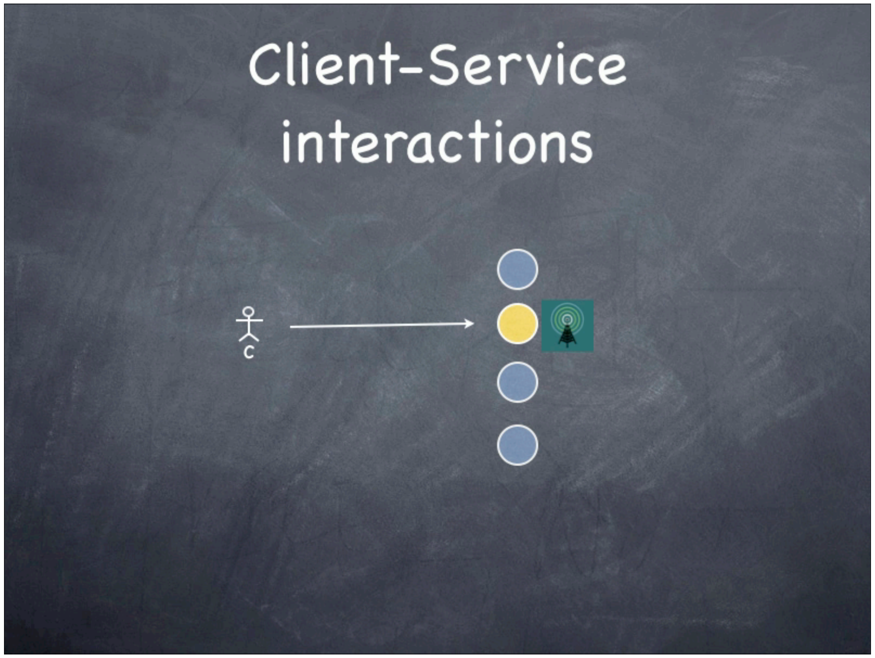
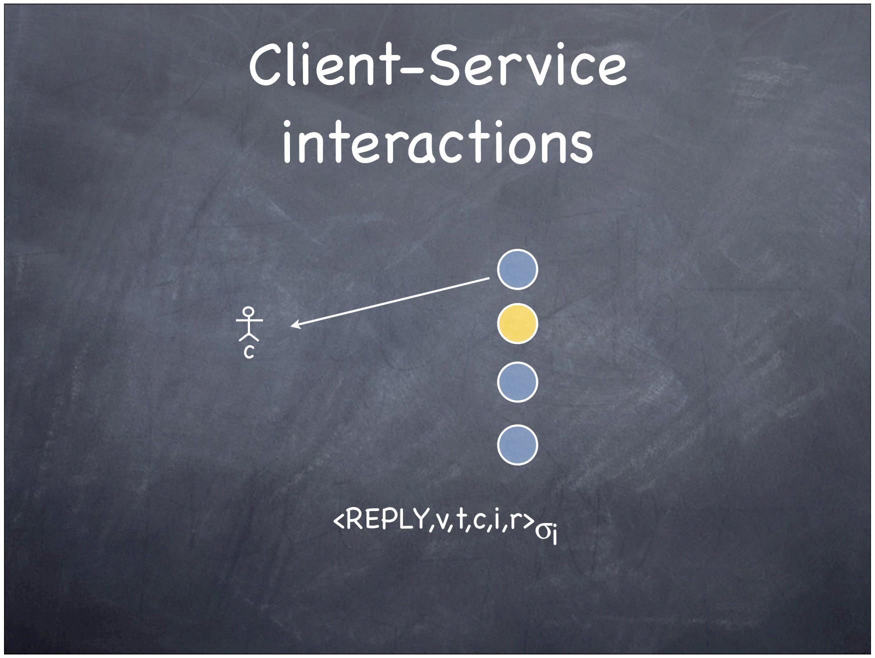
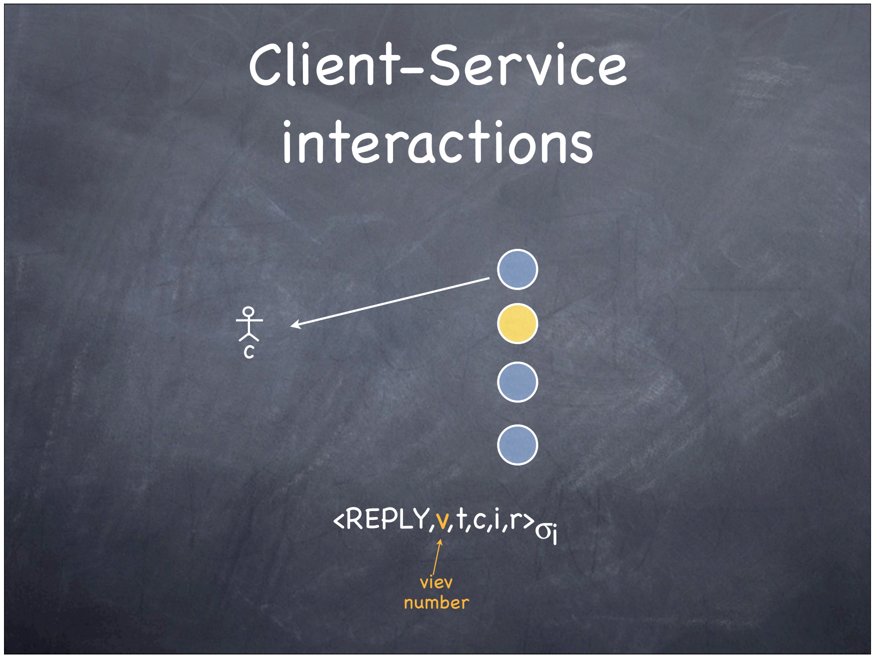
timestamp


Client-Service interactions
c
<REQUEST,o,t,c>σc
client id


Client-Service interactions
c
<REQUEST,o,t,c>σc
signature


Client-Service interactions
c


Client-Service interactions
c
<REPLY,v,t,c,i,r>σi


Client-Service interactions
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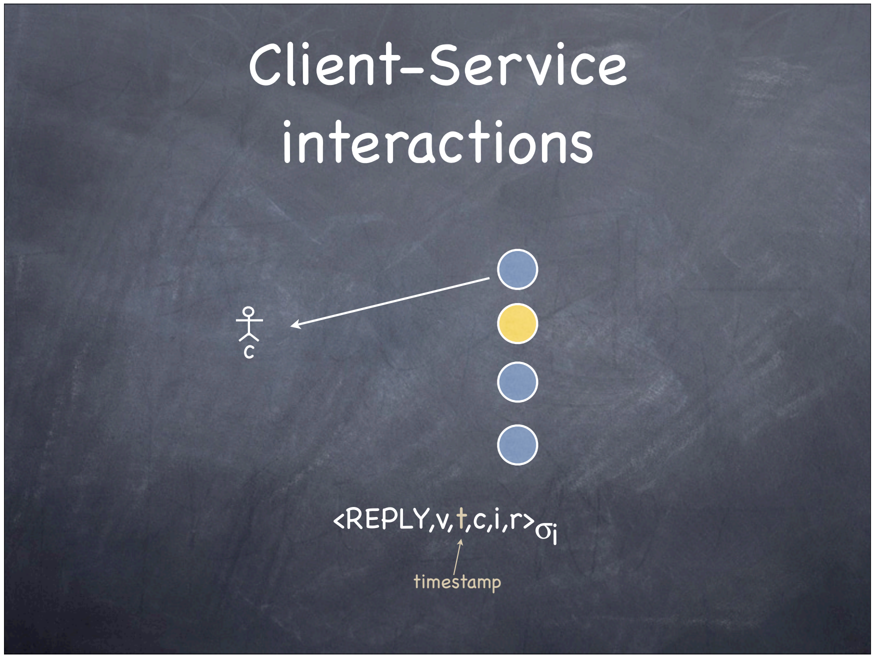
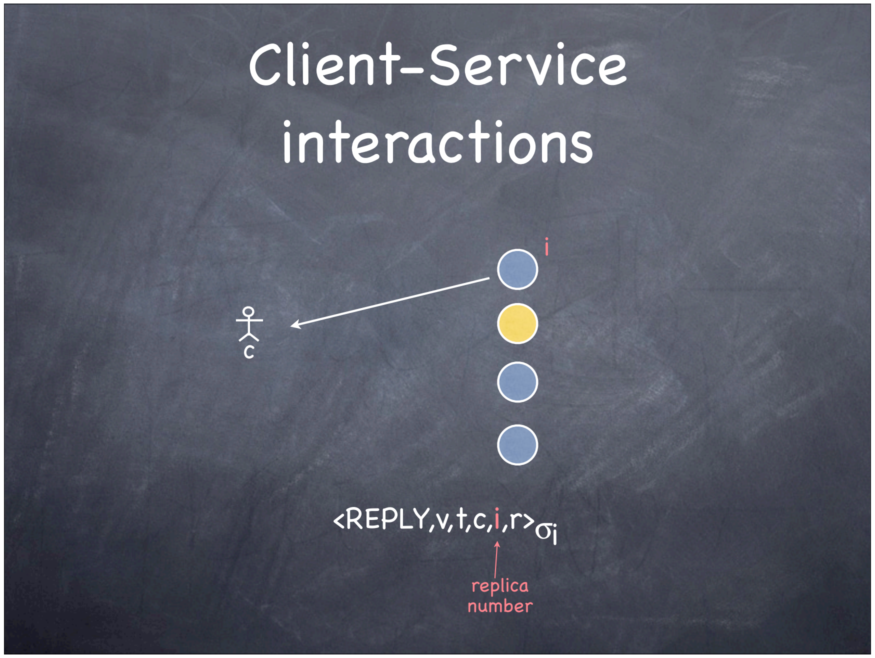
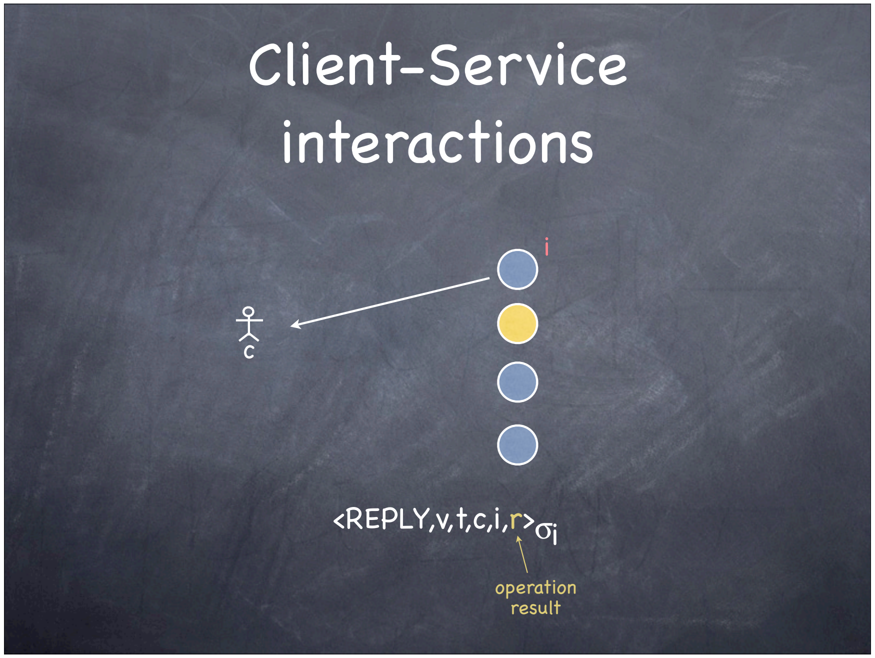
<REPLY,v,t,c,i,r>$_{\sigma_i}$
viev number


Client-Service interactions
c
<REPLY,v,t,c,i,r>$_{\sigma_i}$
timestamp


Client-Service interactions
i
c
<REPLY,v,t,c,i,r>$_{\sigma_i}$
replica number


Client-Service interactions
i
c
<REPLY,v,t,c,i,r>$_{\sigma_i}$
operation result

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

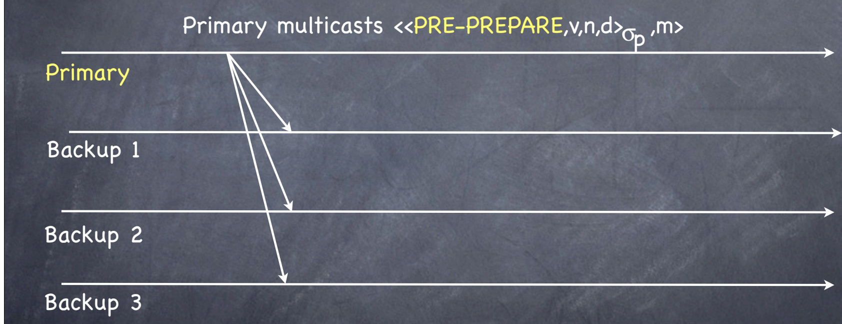
Algorithm Components

- 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



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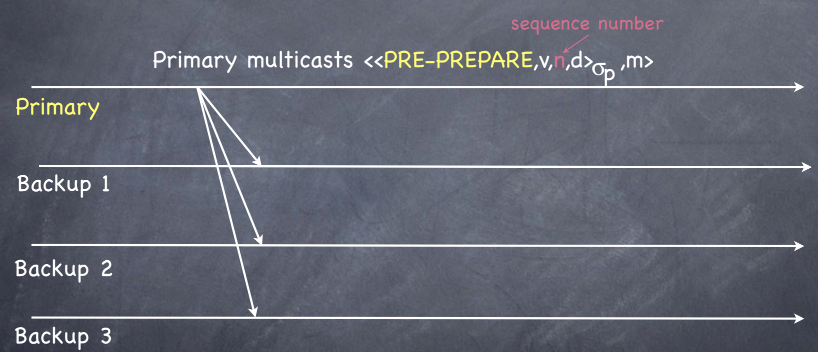

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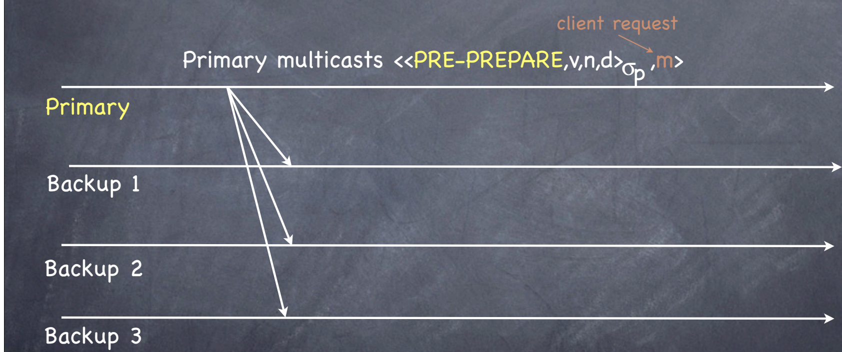

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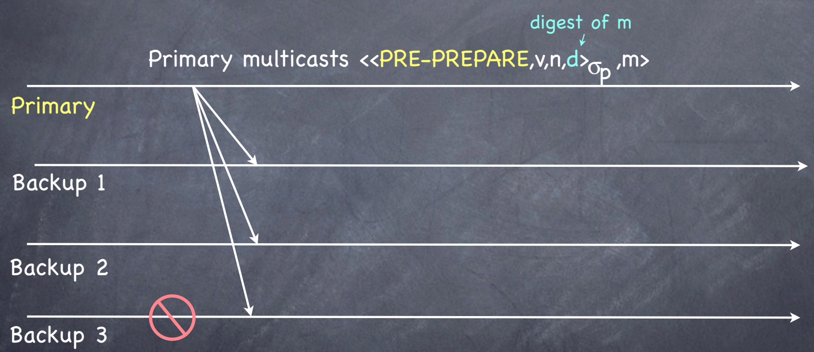
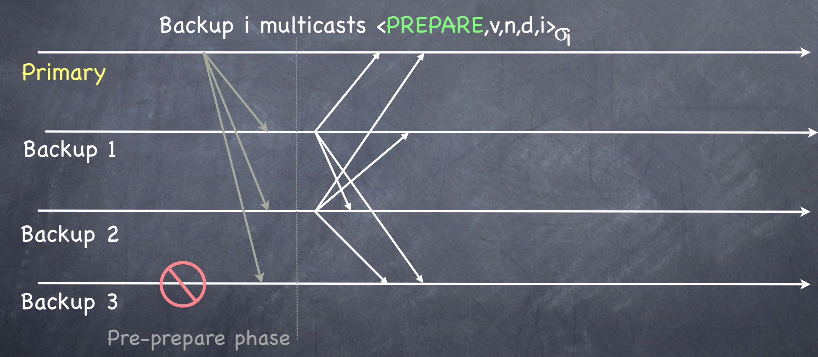


Backup i accepts PRE-PREPARE if:

- 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

Prepare



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  - 2f prepares from different backups that match the pre-prepare

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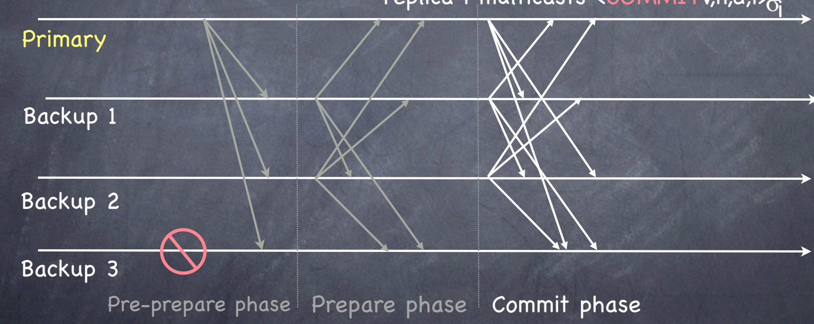
- Replica produces P-certificate(m,v,n) iff its log holds:
  - The request m
  - A pre-prepare for m in view v with sequence number n
  - 2f prepares from different backups that match the pre-prepare
- A P-certificate(m,v,n) means that a quorum agrees with assigning sequence number n to m in view v
  - NO two non-faulty replicas with P-certificate(m_1,v,n) and P-certificate(m_2,v,n)

Commit

After receiving a P-certificate, replica i multicasts <COMMIT v,n,d,i>$_{\sigma_i}$



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

A useful invariant

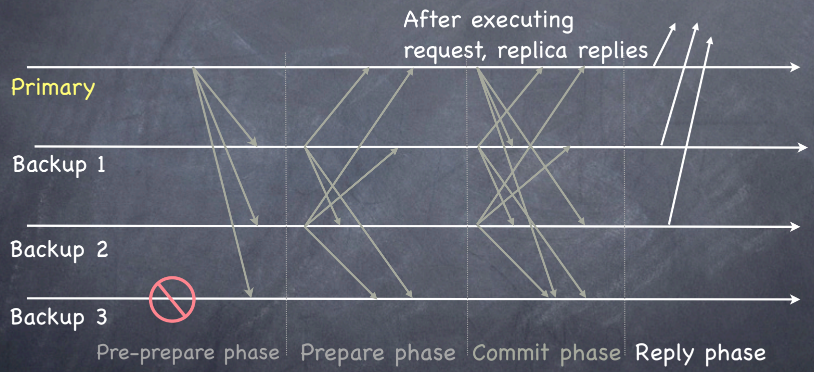
Some replica has C-certificate(m,v,n) ≡
f+1 correct replicas have a P-certificate

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



Garbage Collection

- Truncate Log with Certificate
  - Each replica periodically checkpoints state and builds certificate to prove state is correct
  - Multicasts $\langle CHECKPOINT, n, d, i \rangle_{\sigma_i}$

Garbage Collection

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    last request

Garbage Collection

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    state digest

Garbage Collection

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

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    - n: last proved ckpt

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    - P: {P-certificates held by i for requests with sn > n}

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

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    {2f+1 VIEW-CHANGE messages}

View changes

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  - multicasts <VIEW-CHANGE,v+1,n,CK-cert,P,i>$_{\sigma_i}$
- When primary j for v+1 receives 2f VIEW-CHANGE:
  - multicasts <NEW-VIEW,v+1,V,O>$_{\sigma_j}$

    set of PRE-PREPARE messages

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>$_{\sigma_i}$
- When primary j for v+1 receives 2f VIEW-CHANGE:
  - multicasts <NEW-VIEW,v+1,V,O>$_{\sigma_j}$
  - appends messages in O to its log
  - enters view v+1

O's

A set of <PRE-PREPARE,v+1,n,d>$_{\sigma_j}$,
for all n: min-s < n ≤ max-s, where

- min-s = sn of latest proved checkpoint in V
- max-s = sn of latest P-certificate in V
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-

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

Safety

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

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- Across views?
  - C-certificate(m,v,n) ⇒ 2f+1 P-certificate(m,v,n)
  - $\langle \text{NEW-VIEW}, v+1, V, O \rangle_{\sigma_j}$ accepted ⇒ 2f+1 VIEW-CHANGE
  - At least 1 correct replica in v+1 has P-certificate(m,v,n) !

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

Communication Optimizations

i. One replica sends response, other send digests

ii. Replicas may optimistically 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

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...

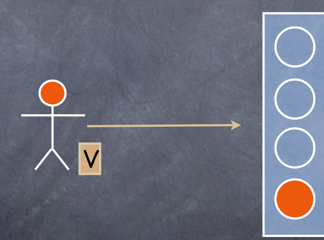
  But achieving independent failures is expensive

  – Independently failing hardware

  – Independently failing software!

Back to the Dark Ages

- No confidentiality



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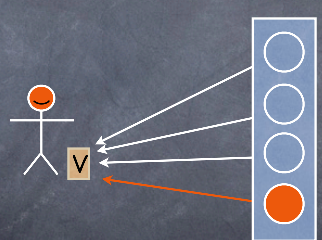

Rethinking State Machine Replication

Not Agreement + Order

but rather Agreement on Order + Execution

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Benefits

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

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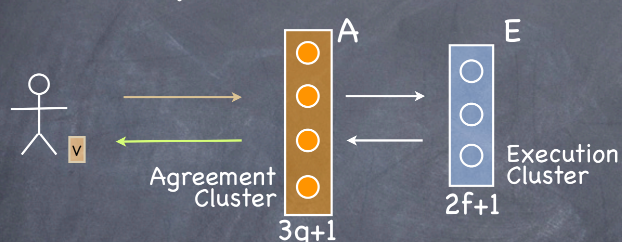
Benefits

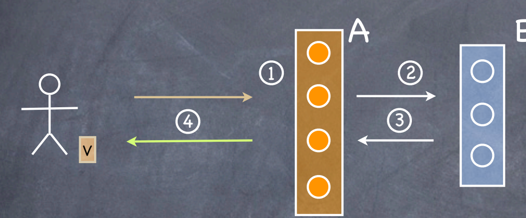
- ~~3f+1~~ 2f+1 state machine replicas
- Replication ~~hurts~~ helps confidentiality

Separation reduces replication costs



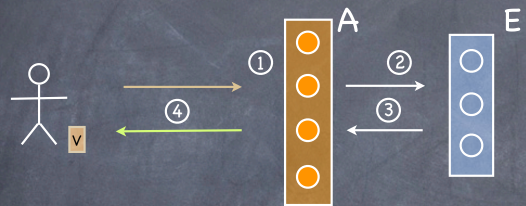
- Not all nodes are created equal!
  - Nodes in E: expensive
    - (different across applications and within same application)
  - Nodes in A: cheap
    - (simple and reusable across applications)

The implementation...



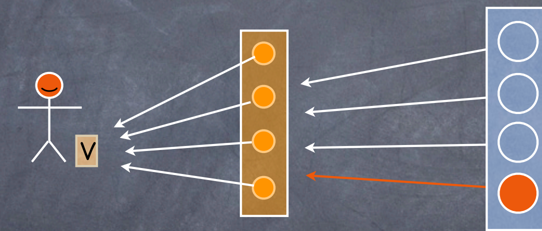
1. A assigns unique sequence number to request
2. <request, rsn>$_A$: request is certified unique
3. E executes in rsn order
4. <reply, rsn>$_E$: reply is certified unique

...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



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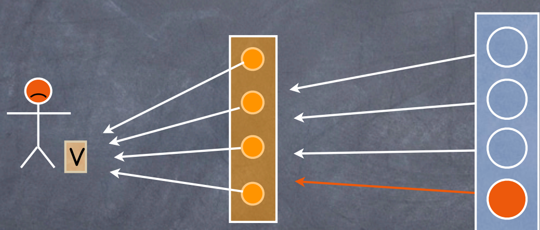
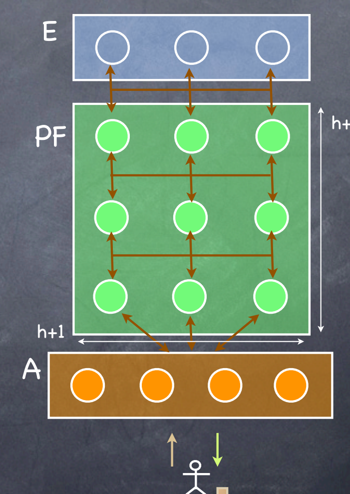


Agreement nodes can filter incorrect replies

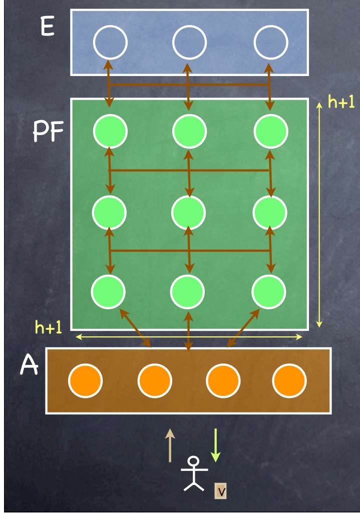
The Privacy Firewall

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 → one is correct
- Live
  - h+1 columns → one is correct
- Restricts nondeterminism
  - threshold cryptography for replies
  - cluster A locks rsn
  - controlled message retransmission

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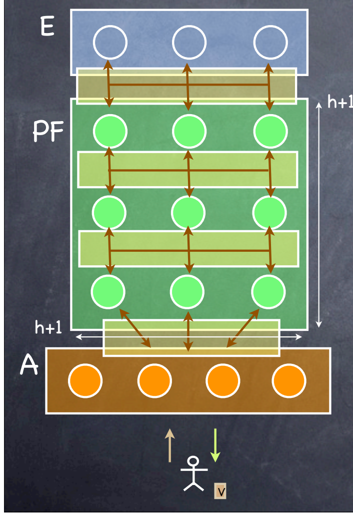

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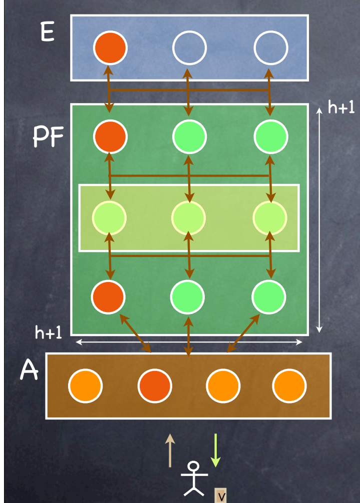

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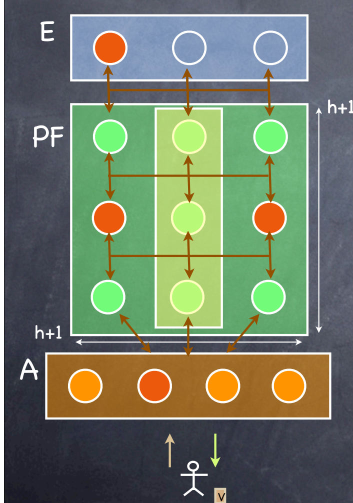

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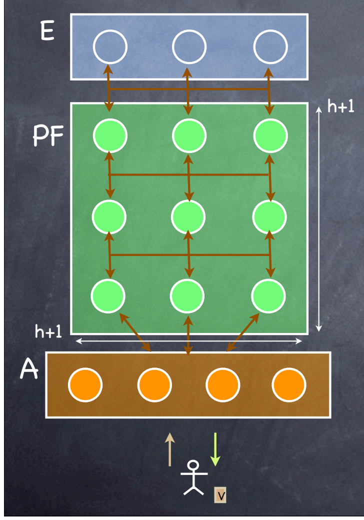

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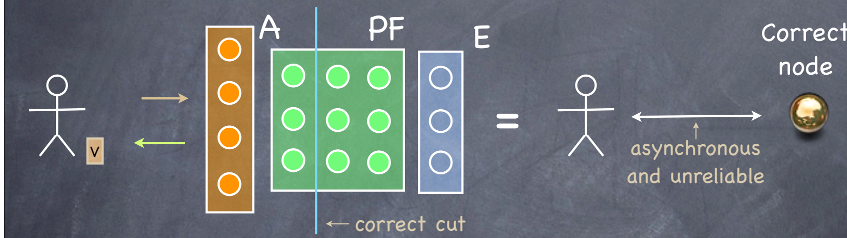
Privacy Firewall guarantees



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

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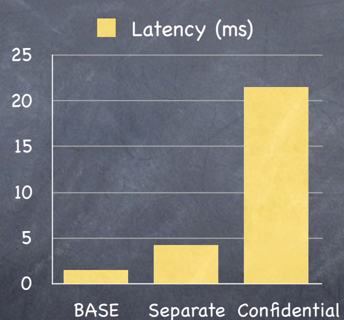
- Information theoretic confidentiality appears impossible without synchrony

Prototype

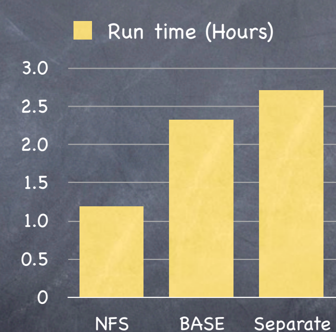
- Built on top of BASE (RCL '01)
- Implements BFT-confidential NFS
- 10 machines: 1 client, 4 in A and PF, 2 in A, 3 in E
  - 128 MB RAM, 100 Mbps switch
- Tolerates one fault in each of E, A, and PF
- Limitations
  - No uninterruptible power supply
  - The nodes in E are identical
  - Communication 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
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- Are these the Emperor's new clothes?