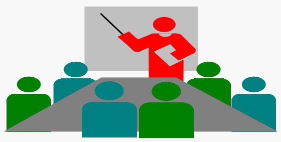
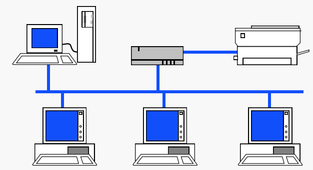




# Distributed Systems
# 601.417
## Intrusion-Tolerant Replication

Department of Computer Science
The Johns Hopkins University



# Intrusion Tolerant Replication

## Lecture 8

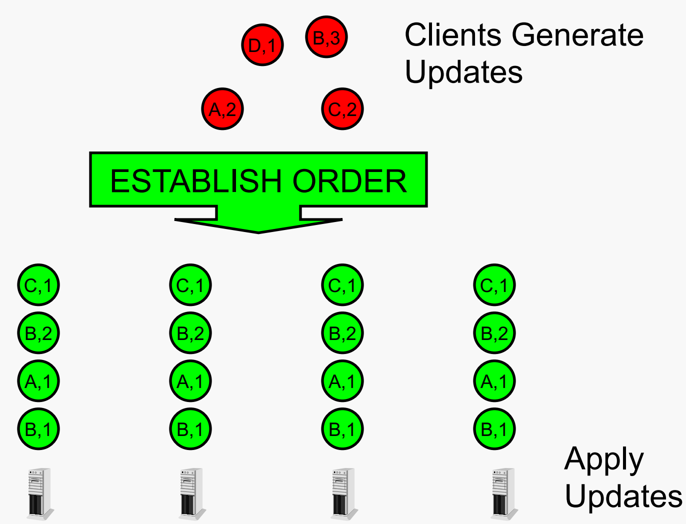
Further readings:
- *Practical Byzantine Fault Tolerance*, Miguel Castro and Barbara Liskov, OSDI 99.
- *Prime: Byzantine Replication Under Attack* IEEE TDSC 2011.
- *Towards a Practical Survivable Intrusion Tolerant Replication System* IEEE SRDS 2014.

# State Machine Replication

- Servers **start in the same state**.
- Servers change their state only when they execute an update.
- State changes are deterministic. **Two servers in the same state will move to identical states, if they execute the same update**.
- If servers **execute updates in the same order**, they will progress through exactly the same states. **State Machine Replication!**



# State Machine Replication



# Outline

- State Machine Replication
- Byzantine Fault Tolerant Replication (**BFT**)
  - Servers can lie
  - Safety and Liveness properties
  - Byzantine performance failure
- Performance Guarantees while Under Attack (**Prime**)
  - Bounded delay
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  - Suspect-Leader protocol
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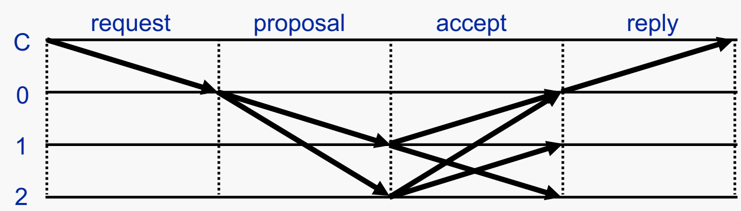
# System Model

- N servers
  - Uniquely identified in {1…N}
- Asynchronous communication
  - Message loss, duplication, and delay
  - Network partitions
  - No message corruption
- Benign faults
  - Crash/recovery with stable storage
- Byzantine faults
  - Byzantine behavior – up to *f* servers may lie
  - N >= 3f + 1

# Benign Faults: Paxos




- The Part-Time Parliament [Lamport, 98]
- A very resilient protocol. Only a majority of participants are required to make progress.
- Works well on unstable networks.
- Only handles benign failures (not Byzantine).



# What Happens If Servers Lie?

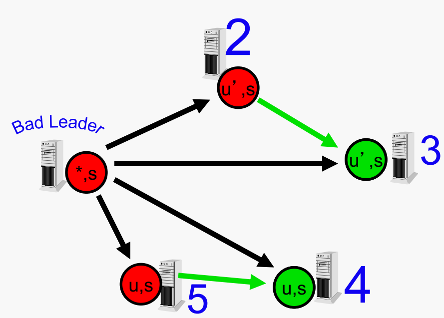
- Servers must be able to verify who sent each message.
  - **Crypto! Digital Signatures or HMACS**
- **The leader might be bad!**
- What might happen?

# What Happens If Servers Lie?

- Servers must be able to verify who sent each message.
  - **Crypto! Digital Signatures or HMACS**
- **The leader might be bad!**
- What might happen?
  - The leader can send Proposal(u,s) to 2 out of 5 servers and Proposal(u',s) to 2 out of 5 servers -- can we have a safety violation?
- **Correct servers must make sure the malicious servers do not cause safety errors.**
- The bad servers might send messages or they might not.



# Byzantine Leader Example




- Bad Leader Sends Proposal(u,s) to servers 4 and 5.
- Bad Leader Sends Proposal(u',s) to servers 2 and 3.
- Server 4 could **order** **(u,s)** and server 3 could **order** **(u',s).**

# How Do We Solve this Problem?

- Assume that there are at most **f malicious** servers, which can fail or become malicious. All of the other servers are correct.
- Let N denote the number of servers in our system.
- Any correct server can wait for at most N - f messages from servers, because f may fail or be malicious (and not send their messages).
- Can we add **more servers**?

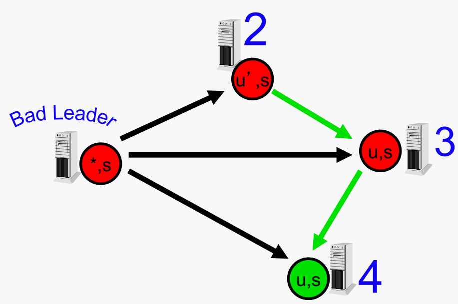


# How many servers do we need?

- **Malicious servers can lie.**
- **Good servers tell the truth.**
- We need to guarantee that a malicious server cannot generate two groups of Accept / Proposal messages that conflict. (i.e., (u,s) and (u',s)) within the same view.
- We need at least N=3f+1 servers to do this!!
- We wait for 2f+1 messages that say the same thing!
- **The f bad servers can say Accept(u,s) and Accept(u',s).**
- **The good servers say only one thing, but a bad leader can lie to them.**
- Let's try to generate the two sets of messages -- Can we do it?
- Liar tells f+1 of the good servers (u,s), and f of the good servers (u',s).

| (u,s)<br>f(bad) + f+1(good) | (u',s)<br>f(bad) + f(good) |
|---|---|
| total: 2f+1 | total: 2f |

# Let's use N=3f+1!

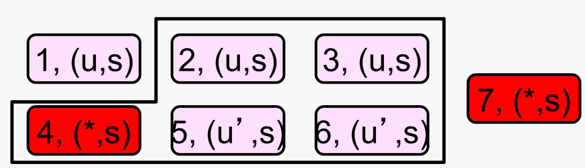



- **f = 1, N = 4**
- **Bad Leader** sends Proposal(u,s) to Server 3 and 4.
- **Bad Leader** sends Proposal(u',s) to Server 2.
- Can the **Bad Leader** violate safety?



# Is the Protocol Live?

- f = 2, N = 3*2+1 = 7
- Bad Leader is Server 7, and Server 4 is bad, too!
- Bad Leader sends Proposal(v,u,s) to Servers 1, 2, and 3
- Bad Leader sends Proposal(v,u',s) to Servers 4, 5, and 6
- There is a partition, Servers 2,3,4,5,6 are together.
- They can't determine which update server 1 ordered.



# How Can We Guarantee Liveness?

- **We can add another round to the fault tolerant protocol. The Normal Case Protocol becomes:**
  - The Leader broadcasts a Pre-Prepare(v,u,s)
  - If not Leader, Upon receiving a Pre-Prepare(v,u,s) that does not conflict with what I know about, broadcast a Prepare(v,u,s)
  - Upon receiving 2f Prepare(v,u,s) and 1 Pre-Prepare(v,u,s), broadcast Commit(v,u,s)
  - Upon receiving 2f+1 Commit Messages, Order the message
- Rounds 1 and 2 allow the correct servers to preserve safety within the same view.
- Round 3 preserves safety across view changes.

- Note that if N > 3f+1, then every process must receive at least n-f {Prepare and Pre-prepare messages} as well as n-f {Commit messages}.



# What About Changing Leaders?

- If any server orders (v,u,s), then 2f+1 servers must have collected a set of 2f Prepare(v,u,s) messages and 1 Pre-Prepare(v,u,s)
- We call such a set a **Prepare-Certificate(v,u,s)**.
- If **Prepare-Certificate(v,u,s)** exists, then **Prepare-Certificate(v,u',s)** cannot exist.
- How do we change Leaders (View Changes)?

# What About Changing Leaders?

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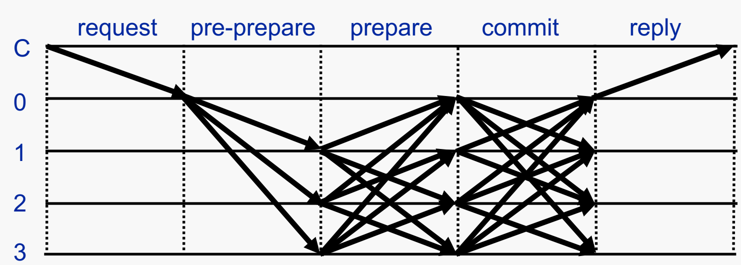
- We call such a set a **Prepare-Certificate(v,u,s)**.
- If **Prepare-Certificate(v,u,s)** exists, then **Prepare-Certificate(v,u',s)** cannot exist.
- How do we change Leaders (View Changes)?
  - The new leader collects information from 2f+1 servers. The servers supply Prepare-Certificates. If something was ordered, the new leader will find out.
  - The new leader needs to send this information to all of the correct servers, otherwise the correct servers will not participate in the protocol.
- A Prepare-Certificate can be viewed as a trusted message (agreed upon by all of the servers). We use it like we use a Proposal message in Paxos.



# We have: BFT




- Byzantine Fault Tolerance [*Castro and Liskov, 99*]
- Excellent LAN performance. Over 1000 updates/sec. (without stable storage costs)
- 2/3 total servers +1 are required to make progress
- Three rounds of message exchanges

# The Downside of Asynchrony

- Common correctness criteria: **safety** and **liveness**
  - Safety: servers remain consistent.
  - Liveness: each update is eventually executed.
- Protocols are designed to be safe in all executions**.**
  - Do not rely on synchrony for safety!
  - Guarantee liveness only when the network is **sufficiently stable.**
- Real systems are not completely asynchronous.
  - **Systems can satisfy much stronger performance guarantees than liveness during stable periods.**
- Consequence: Performance attacks!
  - **An attacker can exploit the gap between what is promised during stable periods (liveness) and what is possible.**



# Byzantine Performance Failures

Commonly Considered Byzantine Failures

| Failure Type | Failure Behavior | Mitigated by |
|---|---|---|
| Value Domain | Sending incorrect, conflicting, or invalid messages | Cryptography, agreement protocols |
| Time Domain | Messages arrive after timeouts or not at all | Timeouts, view change |

- If the adversary cannot violate safety and liveness, the next best thing is to slow down the system beyond usefulness.
- **Performance failures: send correct messages slowly but without triggering timeouts.**

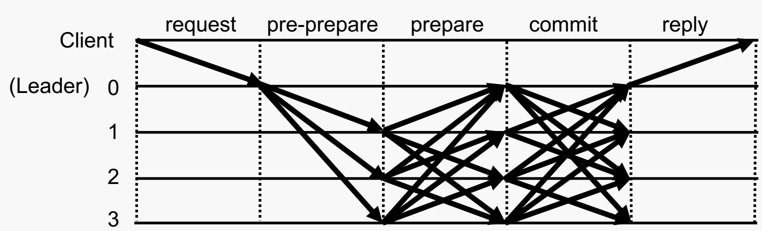
# A Problem: Performance Under Attack

- **BFT systems are vulnerable to performance attacks.**
  - A small number of faulty servers can cause the system to make progress at an extremely slow rate -- indefinitely!
- **Leader-based protocols** are vulnerable to performance attacks by a malicious leader
  - Problem is **magnified in wide-area networks**, where it is difficult to predict the performance that should be expected of the leader.
- **Main challenges:**
  - Developing **meaningful performance metrics** for evaluating Byzantine replication protocols
  - Designing protocols that **perform well according to these metrics**, even when the system is under attack



# Case Study: BFT Under Attack

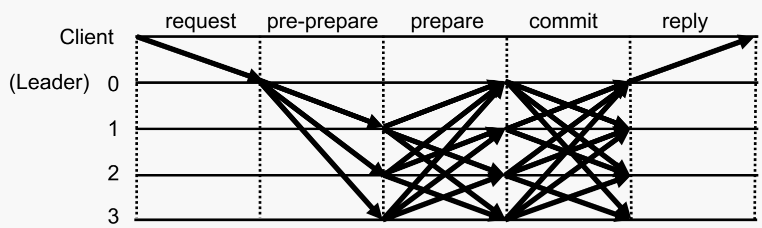
[Castro and Liskov 99]




- Attack 1: Pre-Prepare Delay
  - **Malicious leader can add delay into the ordering path by withholding its Pre-Prepare.**
  - Non-leaders maintain a FIFO queue of pending updates.
    - Use timeouts to monitor the leader.
    - Timeout placed on execution of first update in queue.
  - Malicious leader can stay in power by ordering one update per queue per timeout period!

# Case Study: BFT Under Attack

[Castro and Liskov 99]




- Attack 2: Timeout Manipulation
  - Timeout doubles every time the leader is replaced
  - **Use a denial of service attack to increase the timeout, then stop on a malicious leader**
- Each update is eventually executed, but performance is much worse than if there were only correct servers



# Outline

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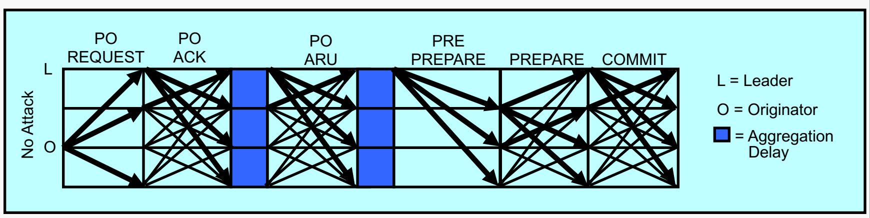
# The Prime Replication System

- **Performance-Oriented Replication in Malicious Environments**
  - Leader-based protocol providing **Bounded-Delay**, a stronger guarantee than liveness, when the network is stable
- **System components:**
  - **Prime Ordering Protocol** (Preordering phase, Global ordering phase)
  - **Suspect-Leader Protocol** for detecting malicious leaders
- **Main Ideas:**
  - Resources needed by the leader to do its job are bounded and independent of system throughput
    - **Leader has "no excuse" for not sending timely messages**
  - Non-leader servers compute a threshold level of acceptable performance that the leader should meet
    - **Upper-bounded by a function of the latency between correct servers after the network stabilizes**

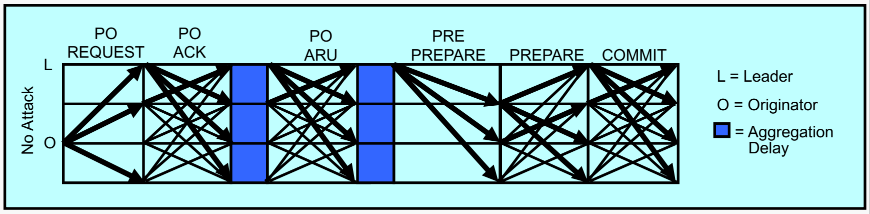


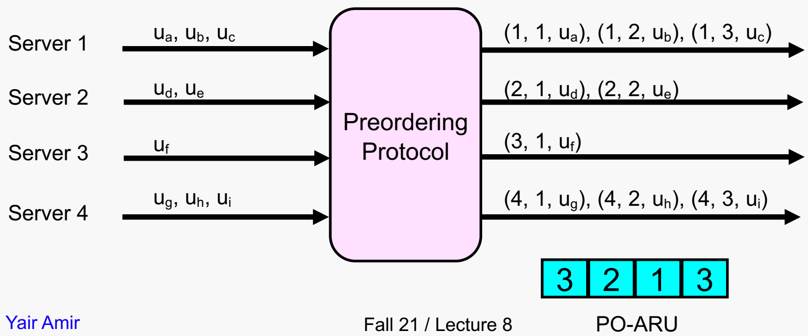
# Prime: Ordering Protocol




- **Preordering (PO) Phase:**
  - Each originating server *o*, disseminates its updates to the other servers (PO-Request).
  - Agreement protocol binds update *u* to **preorder identifier** (*o*, *i*), where *u* is the $i^{th}$ update originated by server *o* (PO-ACK).
  - Each server cumulatively acknowledges the updates it preorders (PO-ARU).

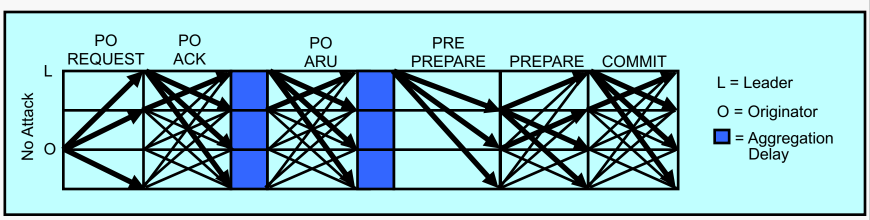
# Prime: Ordering Protocol



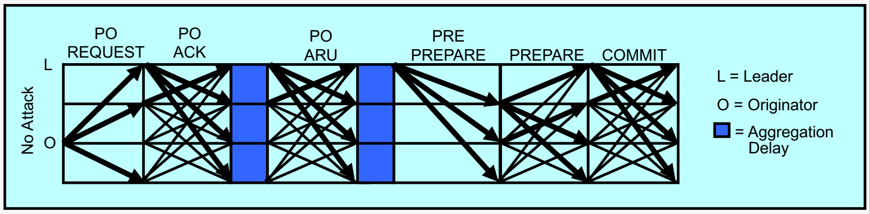


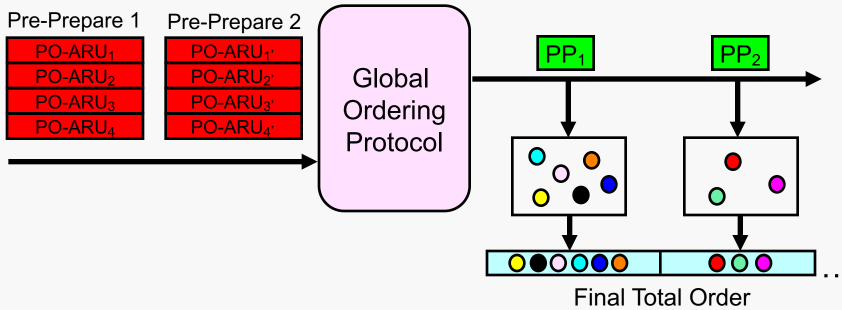

# Prime: Ordering Protocol




- **Global Ordering Phase:**
  - Similar to BFT (Pre-Prepare, Prepare, Commit)
  - Leader periodically sends a Pre-Prepare containing a proof matrix (vector of PO-ARU messages).
  - Each globally ordered Pre-Prepare maps to a batch of preordered updates based on contents of proof matrix.
  - Final total order is obtained by deterministically ordering the updates in each batch based on preorder identifier.

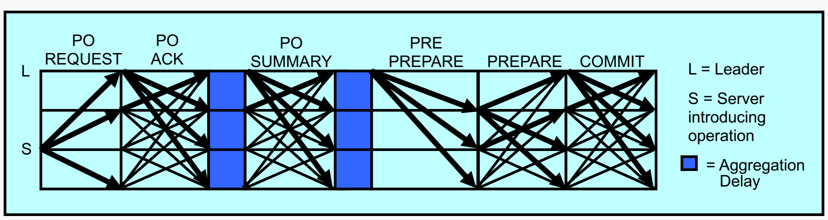
# Prime: Ordering Protocol



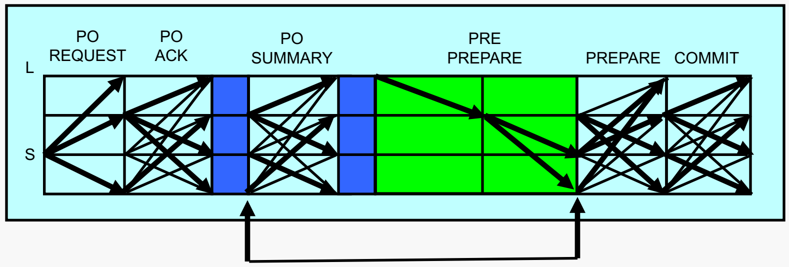



# Attack Analysis




- **Two key observations:**
  - Preordering of operations introduced by correct servers cannot be slowed down by faulty servers (including faulty leader)
  - Once all correct servers receive a Pre-Prepare, global ordering cannot be slowed down by faulty servers (including faulty leader)
- **Possible Attacks:**
  - 1. Leader sends its Pre-Prepare to only some correct servers
  - 2. Leader sends a Pre-Prepare with out-of-date PO-Summaries
  - 3. Leader delays its Pre-Prepare

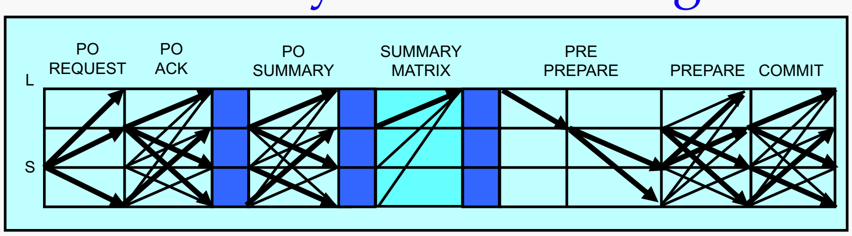
# Addition 1: Pre-Prepare Flooding




- **Intuition:**
  1. The leader must withhold the Pre-Prepare from **all** correct servers to significantly impact latency
  2. **If we can force the leader to send timely, up-to-date Pre-Prepares to at least one correct server, we can ensure timely ordering!**

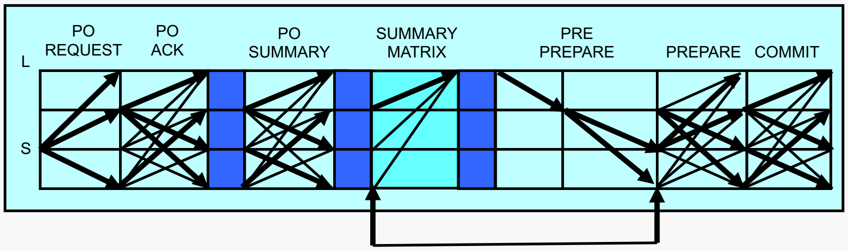


# Addition 2: Summary Matrix Messages




- Each server periodically sends a **Summary-Matrix** message, containing the latest PO-Summary messages it has received, to the leader
  - **A correct server expects a leader to include, in its next Pre-Prepare, PO-Summary messages that are at least as up-to-date as those in the Summary-Matrix message**
- **Why is this expectation justified?**
  - A correct leader can simply adopt any PO-Summary messages that are more up to date than what it currently has

# Key Idea: Turn-Around Time




- **Turn-around time**
  - Time between sending a Summary-Matrix message, SM, and receiving a Pre-Prepare "covering" all of the PO-Summary messages in SM
- **Key Observation:**
  - The resources required by the leader to send a Pre-Prepare (bandwidth, CPU) are bounded and independent of the offered load.
  - **We can use turn-around time as a measure by which to judge the leader!**
- **Intuition: Force the leader to be timely by ensuring that it provides a fast enough turn-around time to at least one correct server**

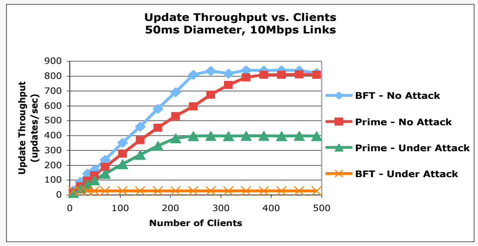


# Suspect-Leader Protocol

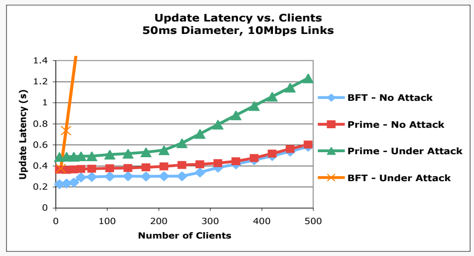
- **Protocol Strategy:**
  - Dynamically determine an acceptable turn-around time (**TAT**) based on roundtrip measurements **(TAT_acceptable)**
  - Use turn-around times measured in the current view to compute a measure of the current leader's performance **(TAT_leader)**
  - Suspect the leader if **TAT_leader** > **TAT_acceptable**

# Experimental Results

- 7 servers (f = 2)
- Symmetric network
  - 50ms diameter, 10 Mbps links
- Leader performs just well enough to stay in power.
- BFT: aggressive timeout (300ms)




- BFT: Pre-Prepare delay
- Prime:
  - Leader adds as much delay as possible.
  - Non-leader servers force as much reconciliation as possible.






# Prime - Recap

- BFT replication protocols are vulnerable to performance attacks
  - Liveness is not a meaningful performance metric for evaluating Byzantine replication protocols
- **Bounded-Delay**: a new performance metric.
  - Can we provide stronger guarantees?
  - Can we guarantee a minimum throughput?
- **Prime**: a Byzantine replication protocol with performance guarantees while under attack
  - Achieves Bounded-Delay when the network is sufficiently stable

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# Survivable Intrusion-Tolerant Replication Defense across Space and Time

- BFT with performance guarantees while under attack is a short-term solution
  - The adversary can exploit a single vulnerability to compromise all replicas
- We need to diversify the execution environment
  - Static diversity [Rodrigues2001, Castro2002, Sousa2008-2010, Roeder2010, ...]
  - Complexity for the adversary: from O(1) to O(n)
  - Not survivable over long system lifetime
- Proactive recovery to clean the system from potential intrusions
- Survivability requires defense across space and time: dynamic diversity + proactive recovery
  - A rejuvenated replica is different from all previous replica instances
  - Complexity for the adversary: from O(n) over the system lifetime to O(n) within a bounded time (i.e. rejuvenation cycle)

## Dynamic Diversity

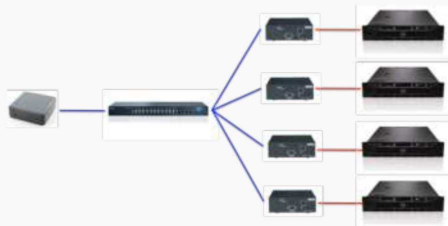
- MultiCompiler from UC Irvine (https://github.com/securesystemslab)
  - NOP insertion
  - stack padding
  - shuffling the stack frames
  - substituting instructions for equivalent instructions
  - randomizing the register allocation
  - randomizing instruction scheduling
- Generate different versions of the program starting from its bitcode (no source code required)



## Proactive Recovery

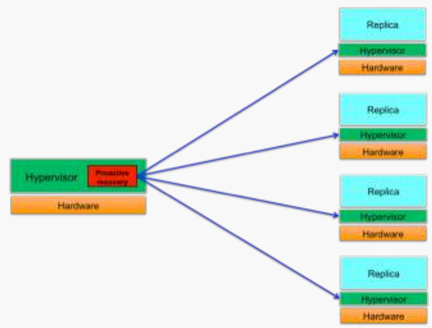
- A component trusted to periodically initiate proactive recovery in a round robin manner by rejuvenating a replica from a clean state
- Each correct replica completes recovery before the beginning of the rejuvenation of the next replica
- The system may not be available if the f replicas fail and a correct replica is rejuvenating.
- We solve this problem by adding more replicas in the system
  - 3f+2k+1 replicas as in [Sousa2010], with k replicas that rejuvenate at the same time

# Physical and Virtualized Approaches



Proactive recovery logic runs in an isolated Next Unit of Computing (NUC). Periodically, the NUC activates a remote power switch, which cycles the power to restart the server that hosts a Prime replica, rebooting a fresh copy from a read-only device

Proactive recovery runs in a hypervisor installed in an isolated server. Periodically a replica is refreshed by instantiating a new virtual machine.






# Proactive Recovery Operation Sequence

- Replica rejuvenation
  - The replica is restarted periodically from a fresh copy of OS and application code from read-only memory
  - Getting a random number from the Trusted Platform Module (TPM) and use of fine-grained diversity
- Session key replacement
  - If the replica was malicious, its private key can be used to forge messages
  - Session key is based on the TPM
- State validation
- State transfer if needed
- Client updates transfer

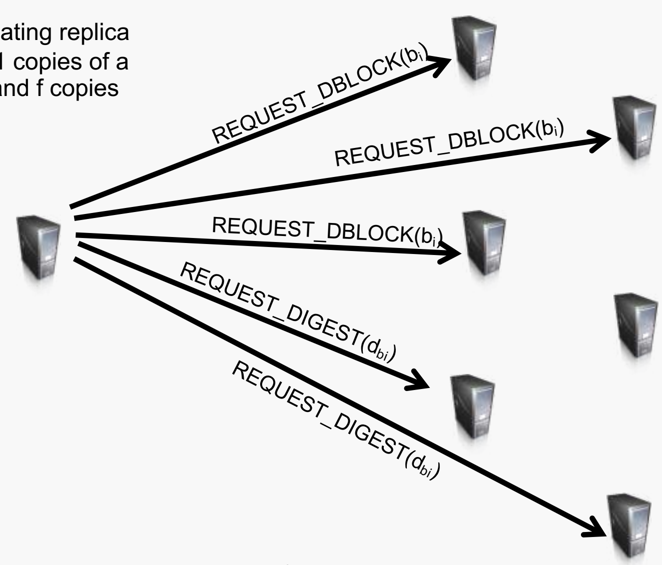
# State transfer

- The state transfer protocol has to be efficient
  - A compromised replica completes recovery quickly
  - Replicas can be rejuvenated more often
  - The adversary does not have enough time to compromise more than f replicas
- Two strategies
  - Reducing latency
  - Reducing bandwidth usage in the best case
- The state is logically partitioned into data blocks of fixed size
- Assumption: the adversary totally compromises the state (i.e. all data blocks)



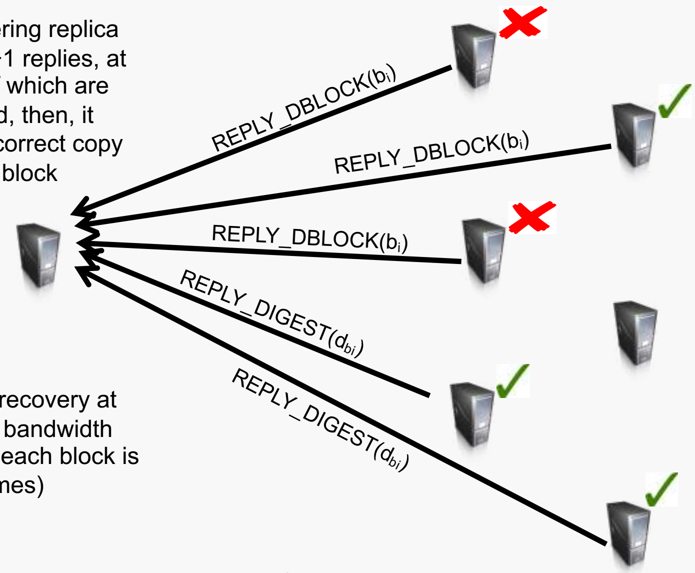
# State transfer – Reducing latency

The rejuvenating replica requests f+1 copies of a data block and f copies of its digest



# State transfer – Reducing latency

The recovering replica collects 2f+1 replies, at least f+1 of which are correct, and, then, it can find a correct copy of the data block

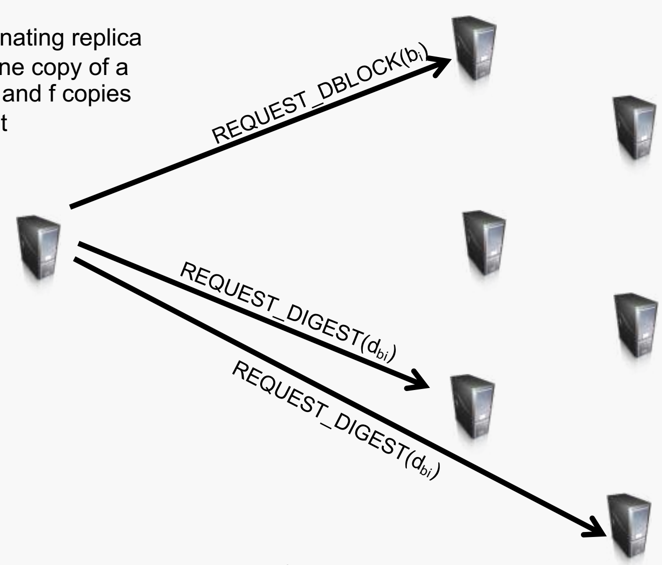



Fast state recovery at the cost of bandwidth overhead (each block is sent f+1 times)



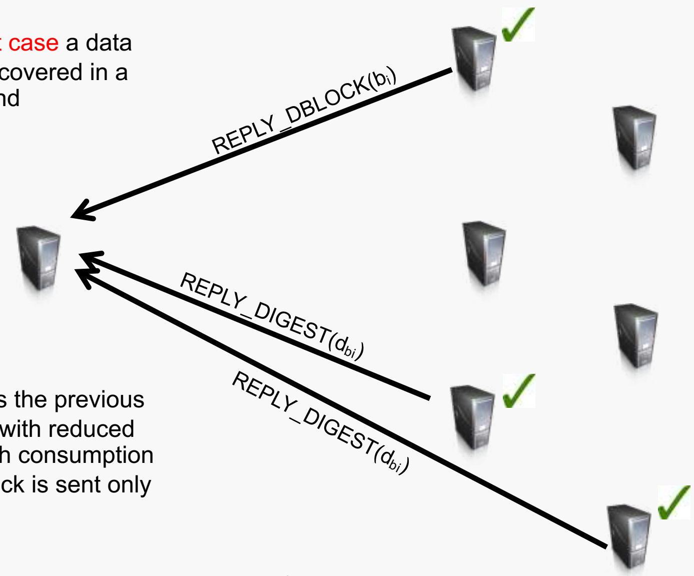
# State transfer – Reducing bandwidth usage

The rejuvenating replica requests one copy of a data block and f copies of its digest



# State transfer – Reducing bandwidth usage

In the best case a data block is recovered in a single round

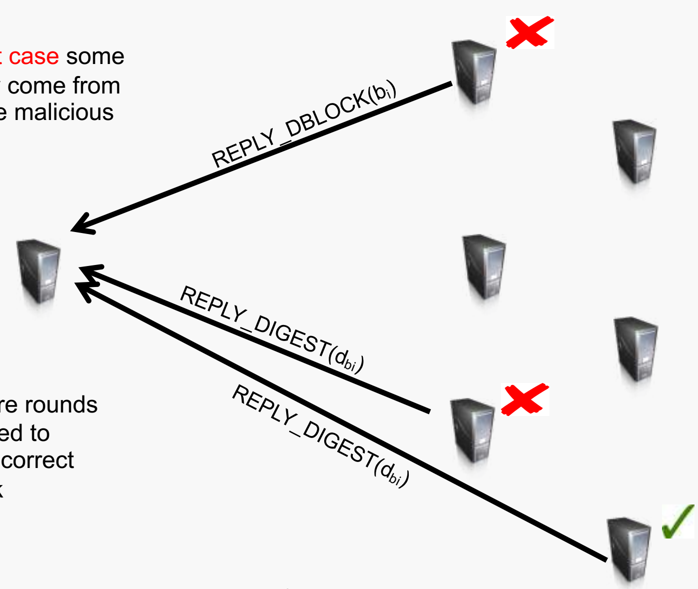



As fast as the previous strategy, with reduced bandwidth consumption (each block is sent only once)



# State transfer – Reducing bandwidth usage

In the worst case some replies may come from one or more malicious replicas




Some more rounds are required to retrieve a correct data block

# State transfer – Reducing bandwidth usage

- We define two variants to retrieve a correct data block in the presence of incorrect replies
- Variant 1
  - The recovering replica keeps requesting a copy of the data block at a time until a correct copy is found (at most f-1 additional requests)
- Variant 2
  - The recovering replica requests f additional copies of the data block in a single round
  - The recovering replica can find a correct copy among 2f+1 replies (f+1 copies of the same block and f digests)
- We blacklist the senders of invalid replies
  - The impact of malicious replicas is negligible



# State transfer - Experimental results

- Time taken to validate and transfer the state (if compromised) after rejuvenation
- The state is fragmented in blocks of fixed size (1 Mbyte)
- Data blocks are transferred in parallel (5 at a time)

| state size | state reading | state transfer | | |
|---|---|---|---|---|
| | | 4 replicas | 7 replicas | 10 replicas |
| 1 Gb | 9 sec | 36 sec | 25 sec | 23 sec |
| 10 Gb | 1 m, 27 sec | 6 m | 4 m | 4 m |
| 40 Gb | 5 m, 47 sec | 24 m | 15 m | 15 m |
| 80 Gb | 11 m, 30 sec | 48 m | 31 m | 31 m |
| 120 Gb | 17 m, 15 sec | 1 h, 12 m | 48 m | 48 m |
| 240 Gb | 34 m, 30 sec | 2 h, 24 m | 1 h, 38 m | 1h, 36 m |
| 520 Gb | 1 h, 14 m | 5 h, 9 m | 3 h, 28 m | 3 h, 24 m |
| 1 Tb | 2 h, 24 m | 9 h, 50 m | 6 h, 17 m | 6 h, 17 m |

# Outline

- State Machine Replication
- Byzantine Fault Tolerant Replication (**BFT**)
  - Servers can lie
  - Safety and Liveness properties
  - Byzantine performance failure
- Performance Guarantees while Under Attack (**Prime**)
  - Bounded delay
  - Pre-Ordering and Ordering protocols
  - Suspect-Leader protocol
- Survivable Intrusion Tolerant Replication
  - BFT with performance guarantees under attack
  - Defense across Space and Time
    - Dynamic diversity
    - Proactive recovery
  - Support to large-state application
    - State transfer (if needed when rebuilding a compromised node)
    - Optimizing either latency or bandwidth consumption