Decentralizing Authorities into Scalable Strongest-Link Cothorities

Ewa Syta, Iulia Tamas, Dylan Visher, David Wolinsky, **Bryan Ford**

Yale University
Computer Science Department

National Institute of Standards and Technology – June 10, 2015

"Authorities" are Everywhere

Conceptually simple but **security-critical** services

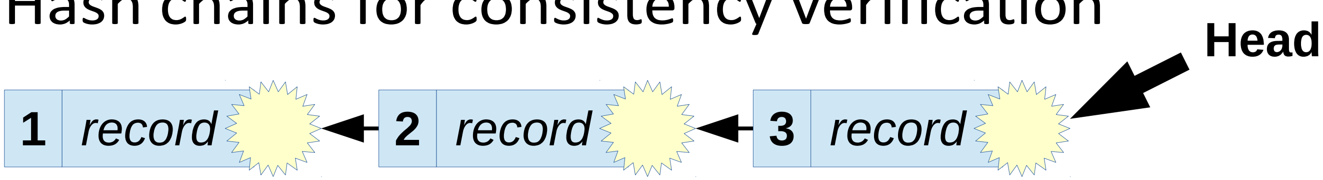
- Logging, Time-stamping Authorities
- Naming Authorites
- Certificate Authorities
- Randomness Authorities (e.g., Lotteries)
- Digital Notaries

Talk Outline

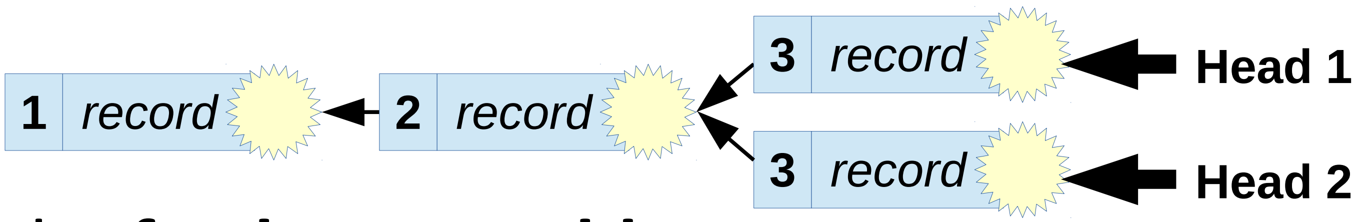
- Troubles with Authorities
- Cothorities: Large-scale Collective Authorities
- A Basic Tool: Scalable Collective ElGamal Log-Signing
- The Availability Problem, and Two Solutions
- Prototype and Preliminary Results
- Future Work: Potential Applications

Authorities Make Statements

- Often recorded in **tamper-evident public logs**
  - Each log entry signed by the authority
  - Hash chains for consistency verification



- But hashes don't solve the **forking problem…**



- Or the **freshness problem…**

When authorities go bad...

Compromised authority services can:

- Tamper with history: e.g., forge log entries
- Pre-date or post-date a timestamp
- Equivocate: customize history for each user
- Impersonate names and MITM attack
- Look into the future: e.g., win the lottery

And usually you're trusting one entity to be good

Example: Bad Randomness

CYBER CRIME SCAMS AND FRAUD

This Dude Hacked Lottery Computers To Win $14.3M Jackpot In U.S.

By *Waqas* on April 14, 2015 Email @hackread

If we trust **many** authorities…

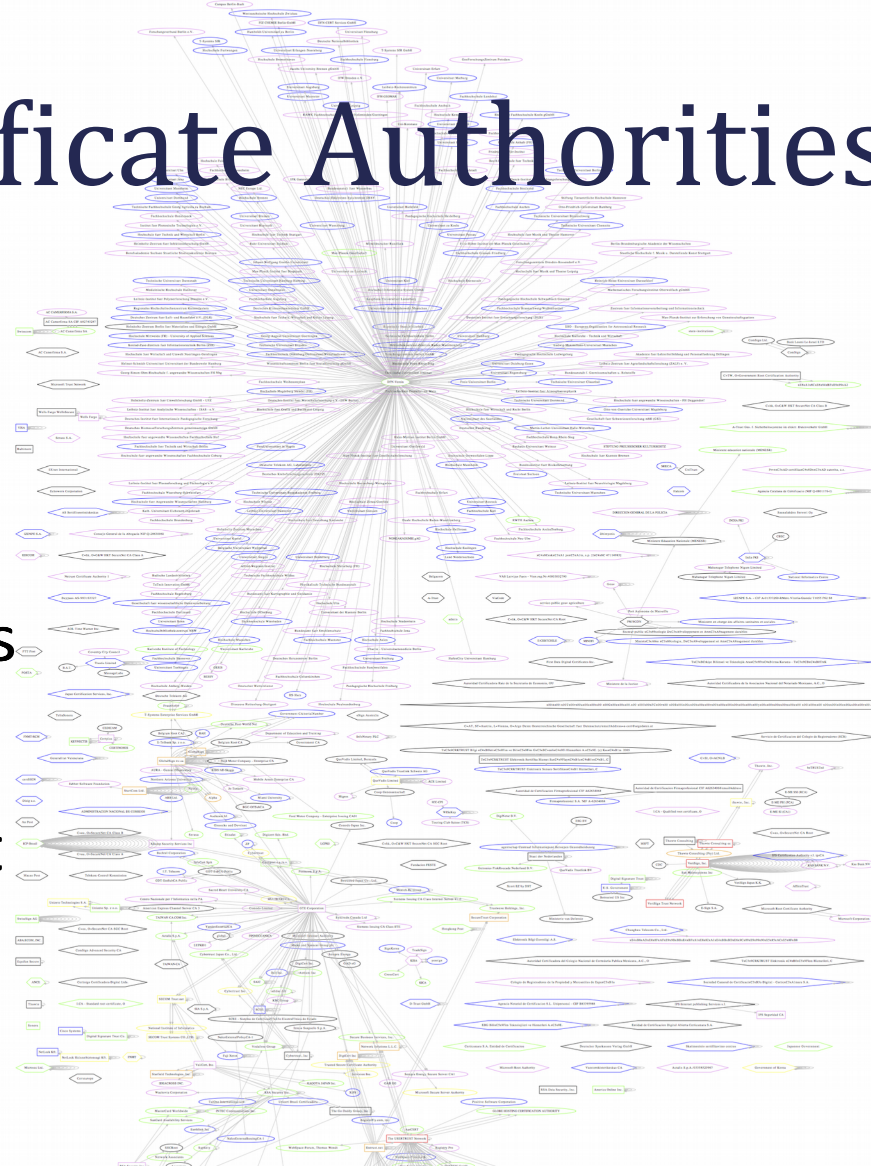
Attacker gets to choose which authority to attack

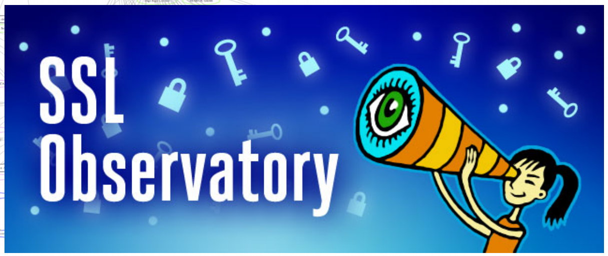
→ Weakest-link security overall

Example: Certificate Authorities

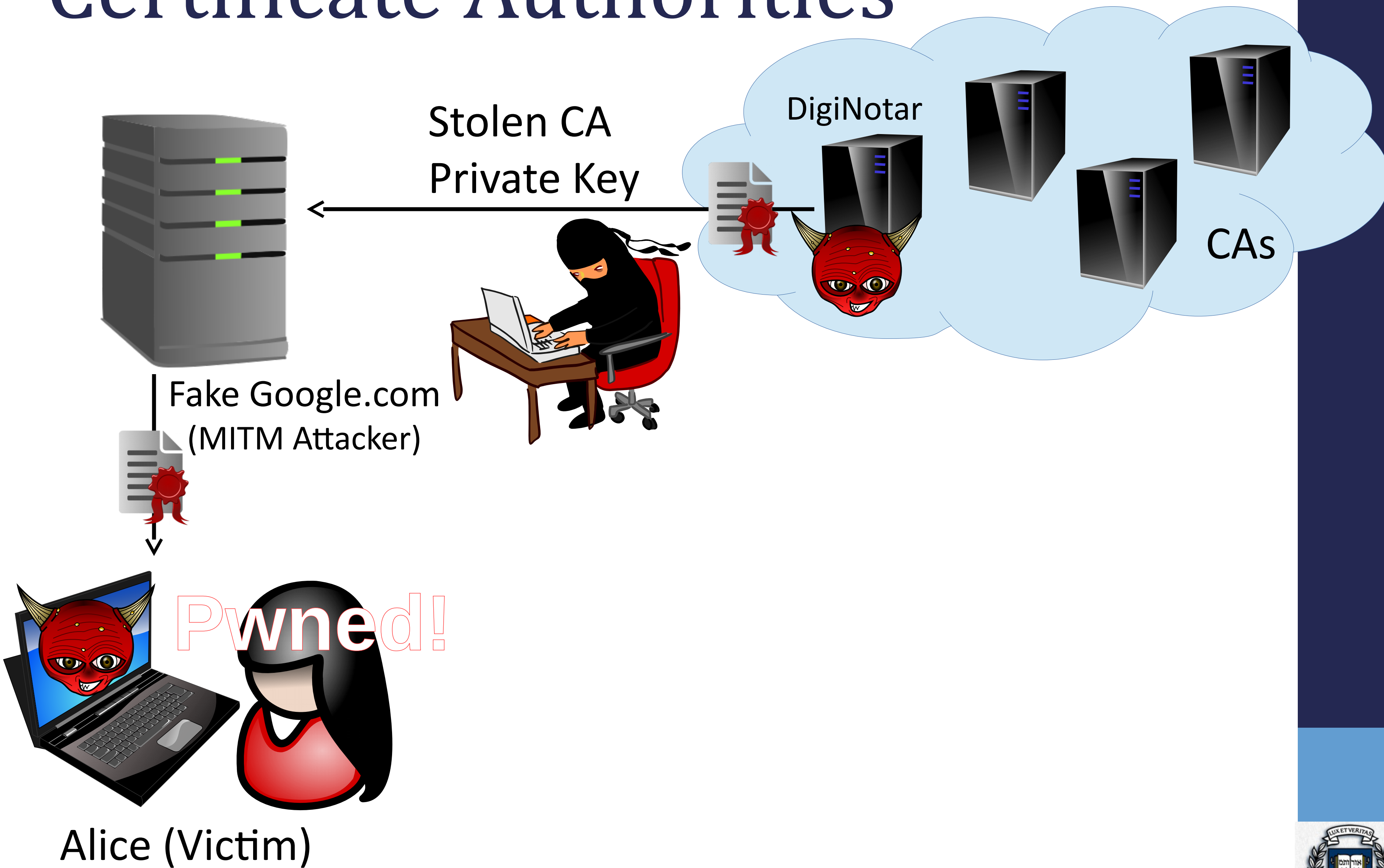
EFF SSL Observatory:

- ~650 CAs trusted by Mozilla or Microsoft
- Any CA can issue certs for any domain name
- Prime key theft target
  - MITM attack power
- Breaches do happen
  - DigiNotar, Comodo, CNNIC/MCS

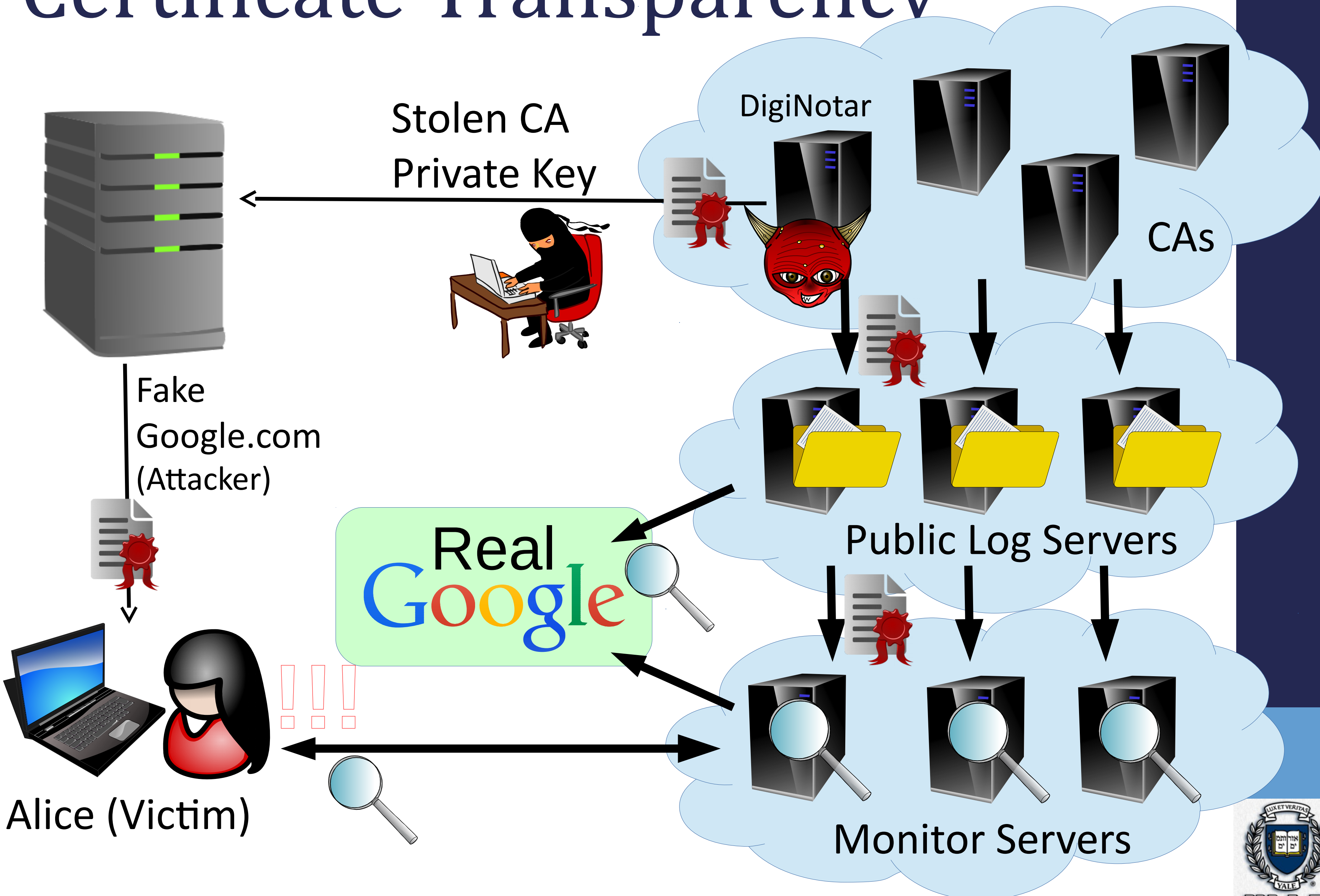




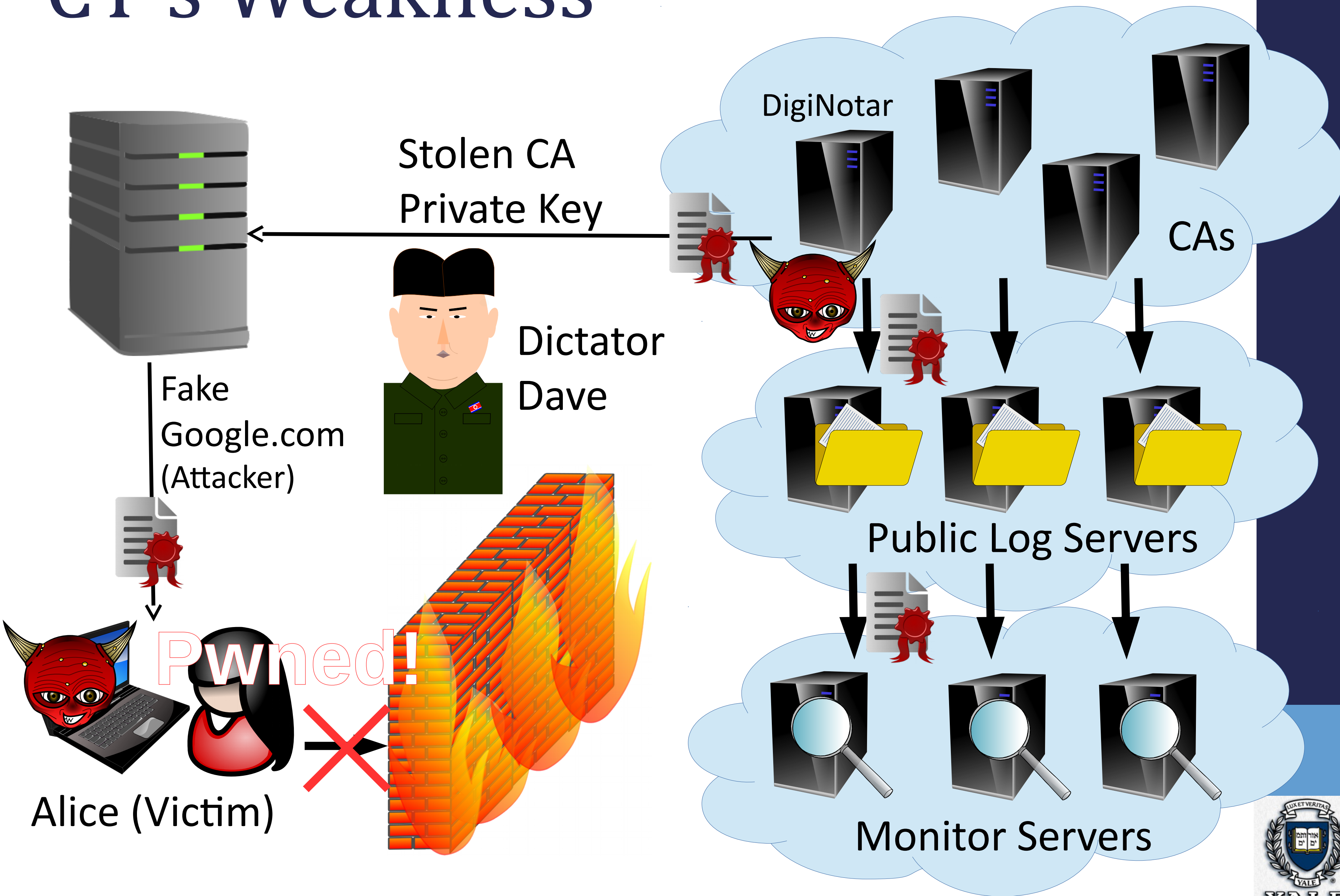
Certificate Authorities



Certificate Transparency



CT's Weakness



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Splitting Trust in Authorities

We know how to:

- Split trust across a few servers, typically <10
  - "Anytrust": only 1-of-k servers need be honest, but all k servers need to remain live
  - Byzantine Fault Tolerance (BFT): 2/3 of k servers need to be honest, 2/3 need to be live
- Split cryptographic keys, operations
  - Threshold cryptography, multisignatures

Example: **Tor** directory authority (8 servers)

Small-Scale Trust-Splitting

Is splitting trust across 5-10 replicas “enough”?

- Who owns/controls these replicas?
  - Truly independent operators (decentralized), or within one organization (merely distributed)?
  - All in same country? All in “five-eyes” territory?
- What is the real cost of targeted attacks?
  - 5 Tor directory server private keys might be well worth the cost of a 0-day exploit or two
- Who chooses the 5-10 replicas?
  - Why should “everyone” trust them?

Large-Scale Trust Splitting

Main proposition:

We *can* and *should* build authority services to split trust across *large-scale collectives*

- e.g., thousands of replicas/monitors or more

Result:

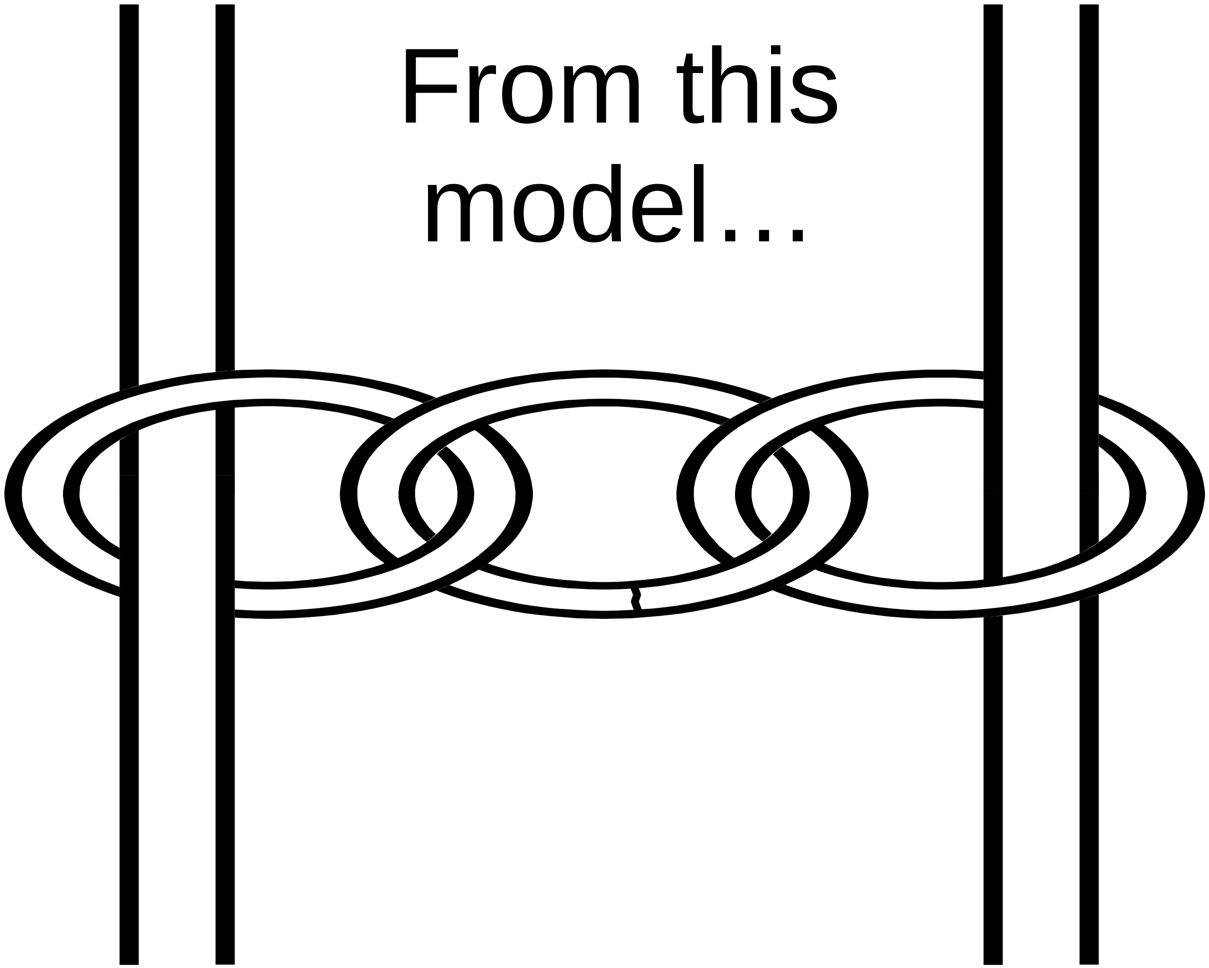
Collective Authorities or **Cothorities**

Why Large-Scale Trust Splitting

Basic goals:

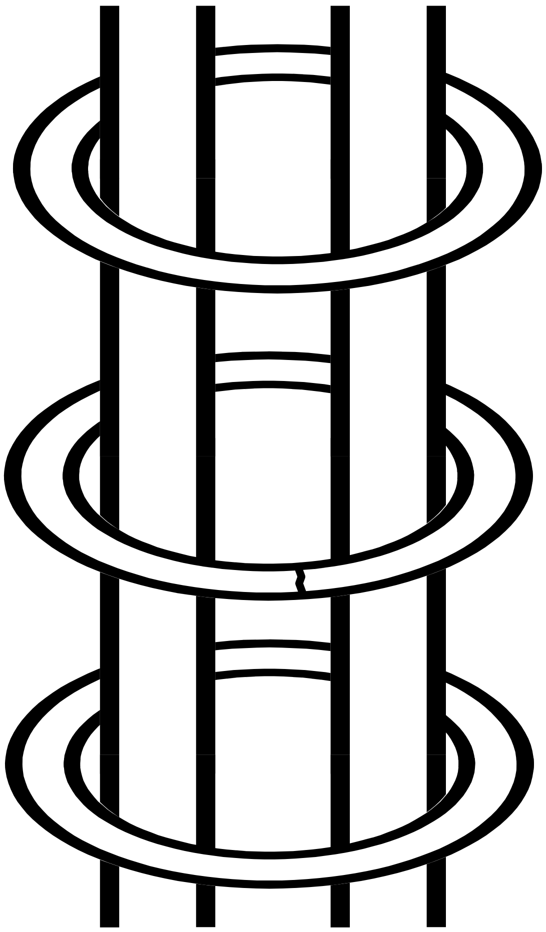
- Transform authorities from "weakest-link" to "strongest-link" security model
  - Remain secure unless **many nodes** compromised
- Split trust across *broad diversity* of servers, operators, organizations, countries, interests, alternative software implementations, …
  - Every user can find someone they **really do trust**
- Make adding participants cheap and always beneficial → *can only increase security*

Why Large-Scale Trust Splitting



Why Large-Scale Trust Splitting

To this model



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CoSi: Collective Signing

Basic primitive: a **tamper-evident logging cothority**

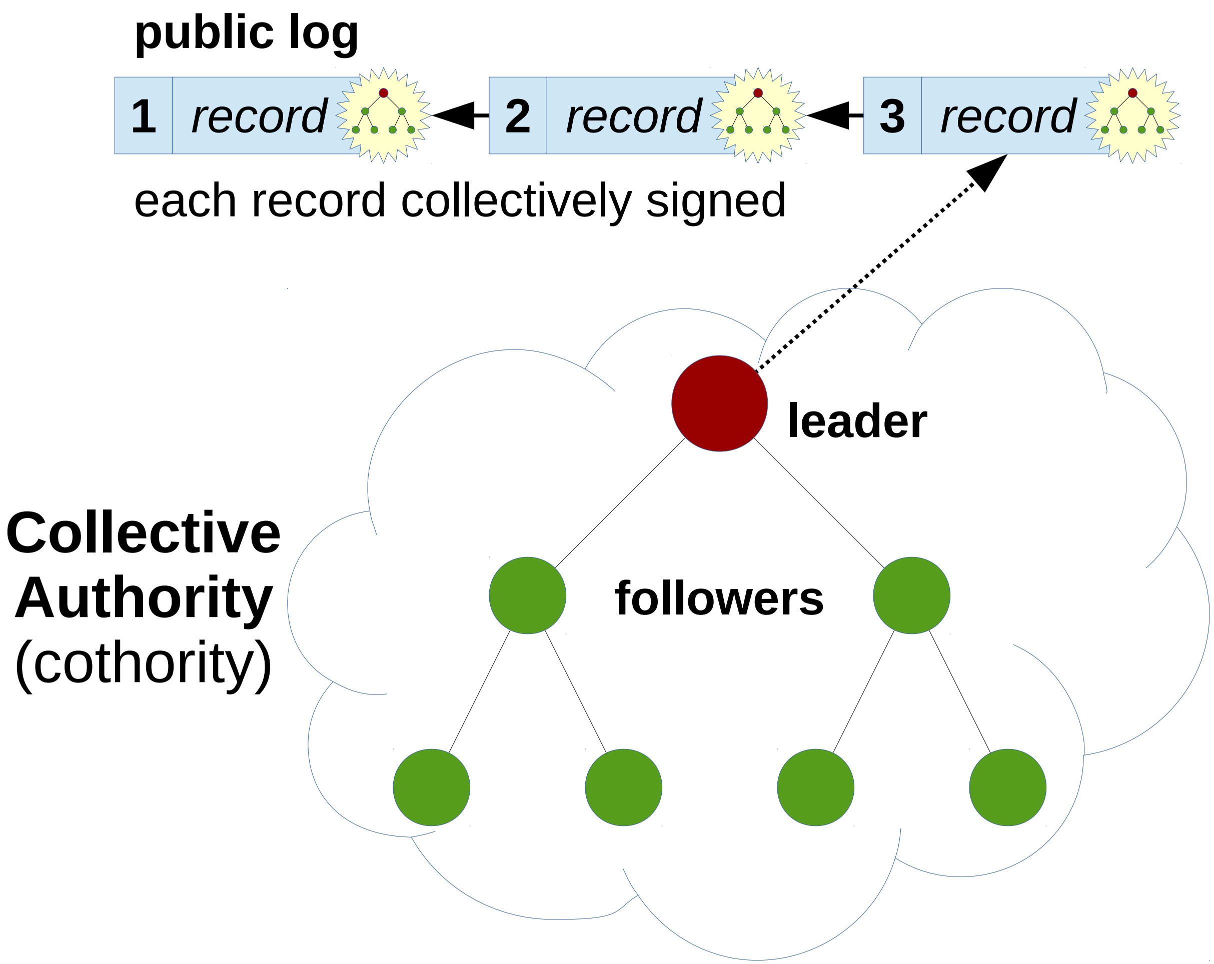
Simple operation model (for now):

- **Leader** server generates log entries, timeline
- **Follower** servers (e.g., thousands) collectively witness and "sign off" on log entries
- Each log entry gets **single collective signature**: small, quick and easy for anyone to verify

→ Leader cannot roll back or rewrite history, or equivocate, without *many* colluding followers

  – Can't sign valid log entries without followers!

CoSi: Collective Signing



CoSi Crypto Primitives

Builds on well-known primitives:

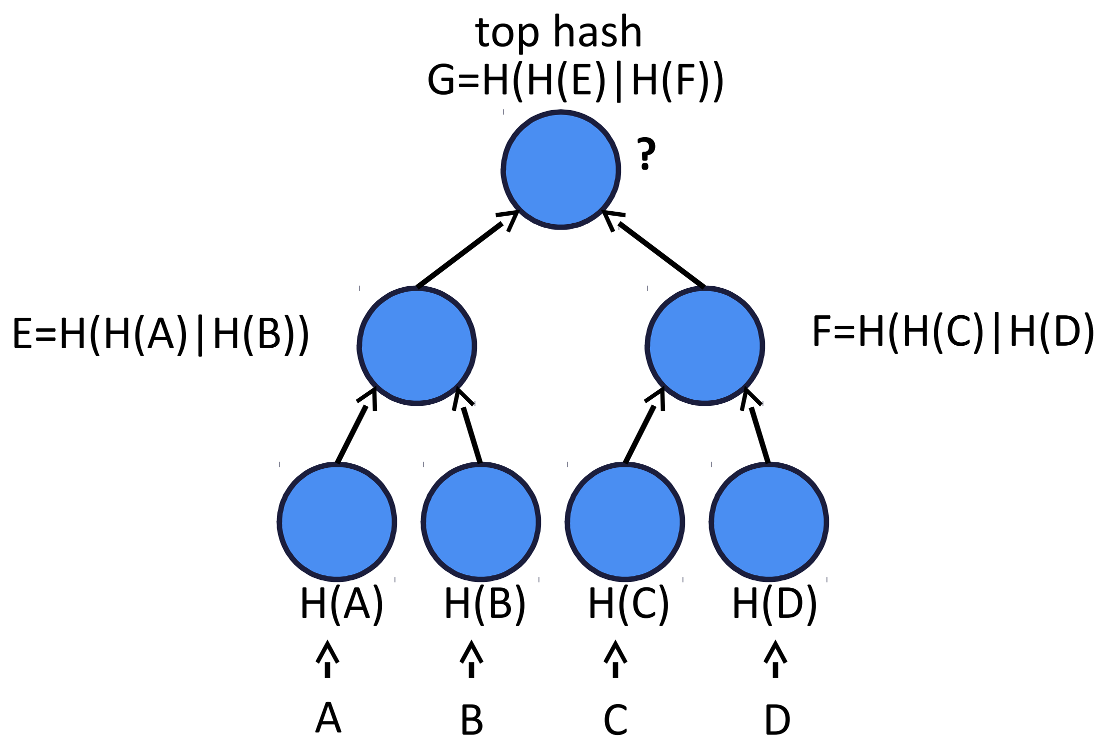
- Merkle Trees
- Schnorr Signature and Multisignatures

CoSi builds upon existing primitives but makes it possible to scale to thousands of nodes

- Using communication trees and aggregation, as in scalable multicast protocols

Merkle Trees

- Every non-leaf node labeled with the hash of the labels of its children.
- Efficient verification of items added into the tree
- Authentication path - top hash and siblings hashes



Schnorr Signature

- Generator *g* of prime order *q* group
- Public/private key pair: $(K=g^k, k)$

	Signer		Verifier
Commitment	$V=g^v$	⟶	V
Challenge	c	⟵	$c = H(M\|V)$
Response	$r = (v - kc)$	⟶	r

Signature on M: (c, r)

Commitment recovery	$V' = g^r K^c \quad = g^{v-kc} g^{kc} \; = g^v = V$
Challenge recovery	$c' = H(M\|V')$
Decision	$c' = c$? ✓

Collective Signing

- Our goal is collective signing with N signers
  - Everyone produces a signature
  - N signers-> N signatures -> N verifications!
  - Bad for thousands of signers!

- Better choice – a multisignature

Schnorr Multisignature

- Key pairs: $(K_1=g^{k_1}, k_1)$ and $(K_2=g^{k_2}, k_2)$

	Signer 1		Signer 2	Verifier		
Commitment	$V_1=g^{v_1}$		$V_2=g^{v_2}$ →	V_1	V_2	$V=V_1*V_2$
Challenge	c	c	←	$c = H(M\|V_1)$		$c = H(M\|V)$
Response	$r_1 = (v_1 - k_1c)$		$r_2 = (v_2 - k_2c)$ →	r_1	r_2	$r=r_1+r_2$

Signature on M: (c, r) (c, r_1) Same signature!

Commitment recovery	Same verification!	$V' = g^rK^c$	$K=K_1*K_2$
Challenge recovery	Done once!	$c' = H(M\|V')$	
Decision		$c' = c$?	

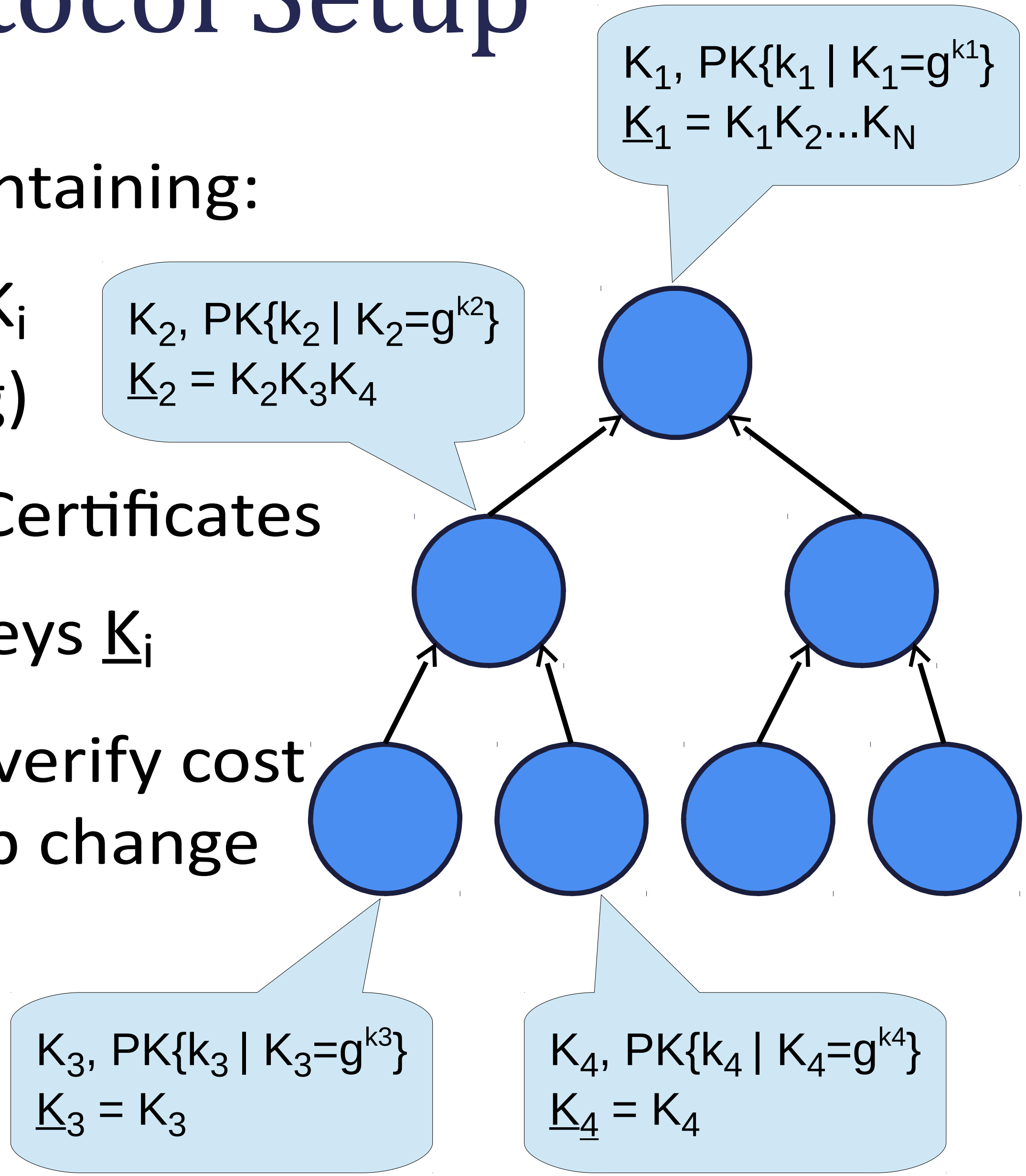
CoSi Protocol Setup

Merkle tree containing:

- Public keys K_i (discrete-log)
- Self-signed Certificates
- Aggregate keys $\underline{K}_i$

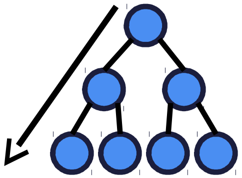
O(n) one-time verify cost

O(|n'-n|) group change

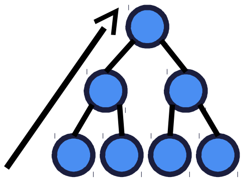


CoSi Protocol Rounds

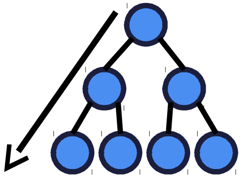
1. Announcement Phase



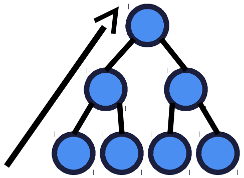
2. Commitment Phase



3. Challenge Phase



4. Response Phase

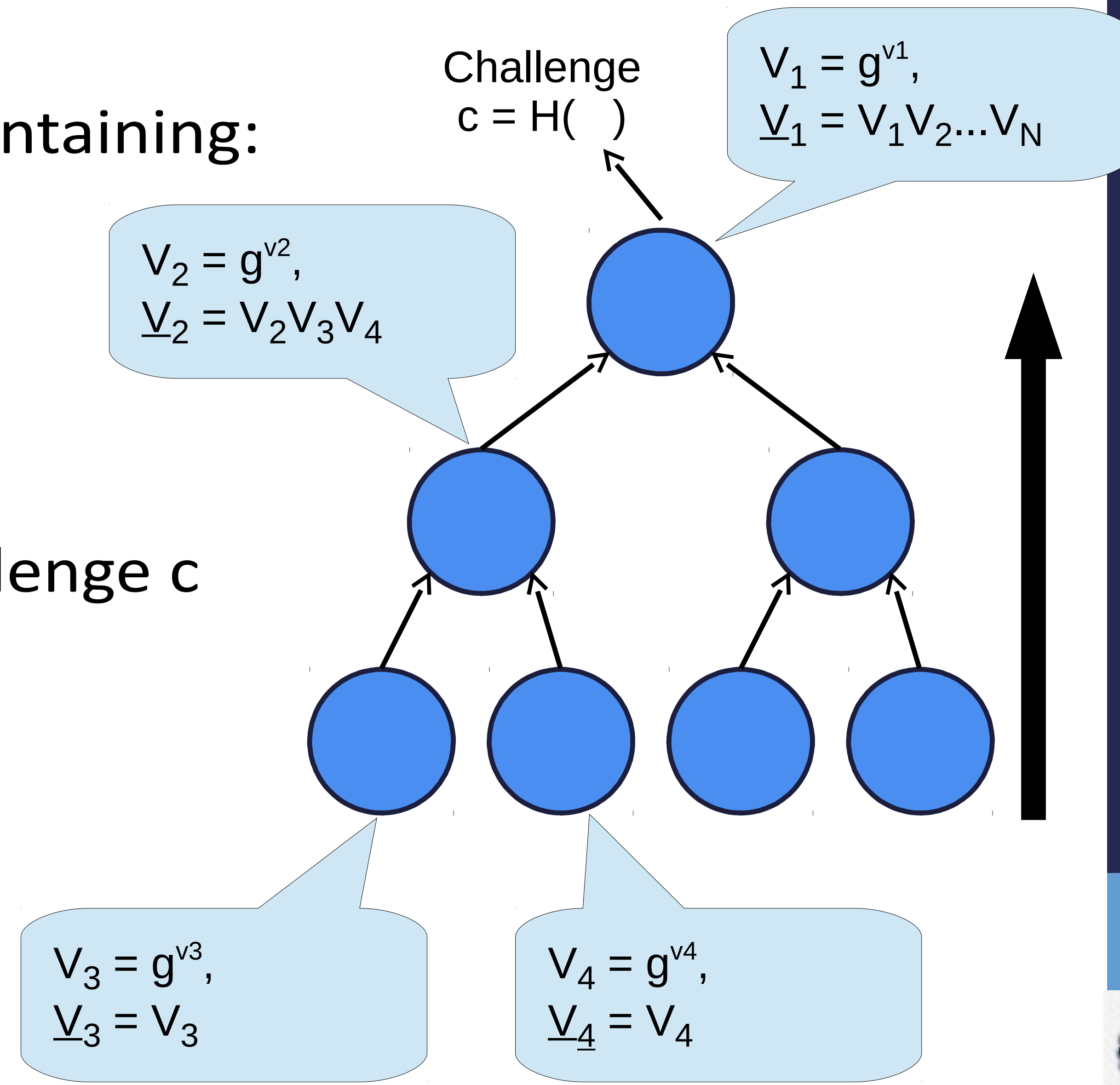


CoSi Commit Phase

Merkle tree containing:

- Commits V_i
- Aggregate commits $\underline{V}_i$

Collective challenge c is **root hash** of per-round Merkle tree



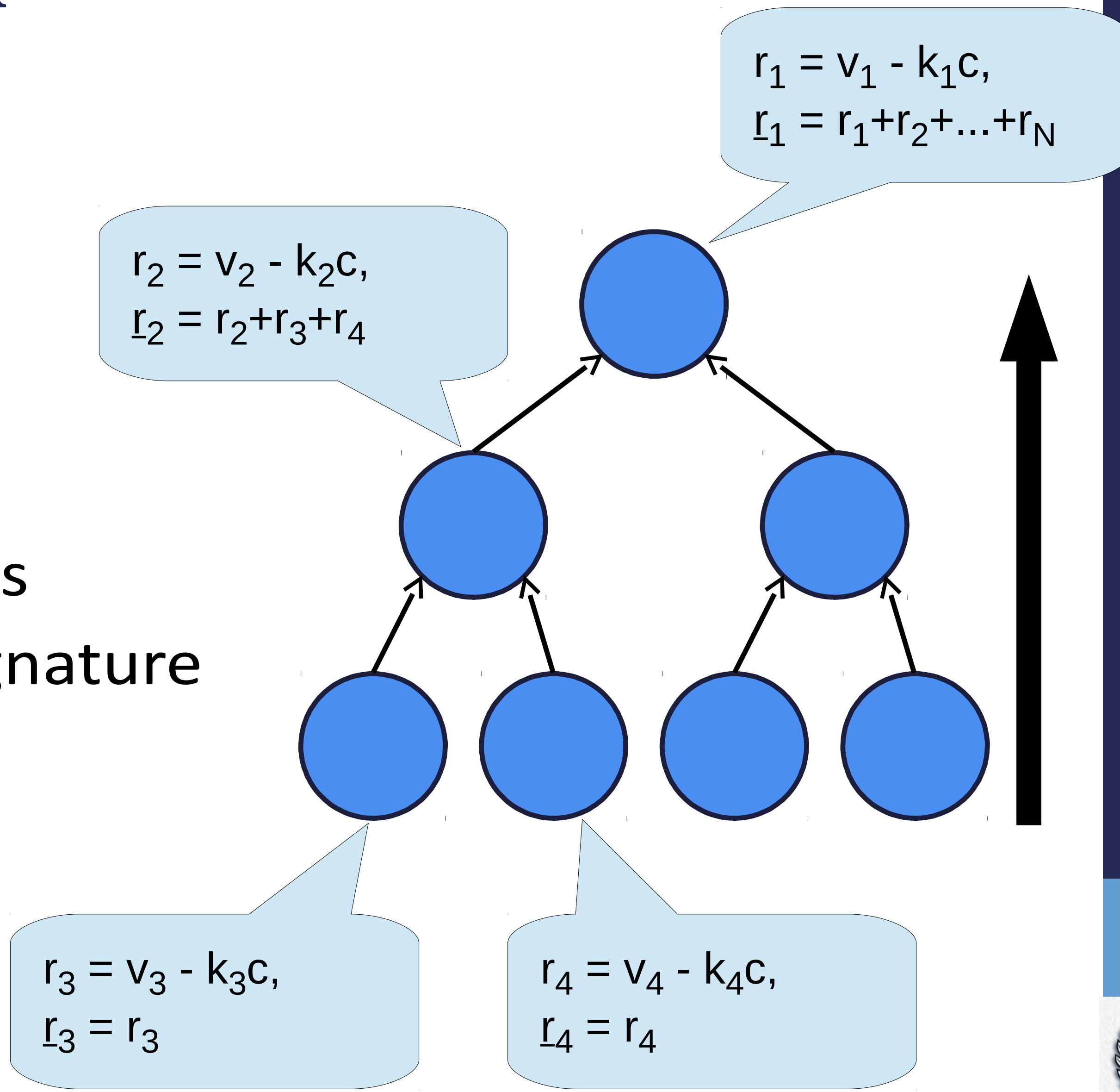
CoSi Response Phase

Compute

- Responses r_i
- Aggregate responses $\underline{r}_i$

Each $(c,\underline{r}_i)$ forms valid **partial** signature

$(c,\underline{r}_1)$ forms **complete** signature

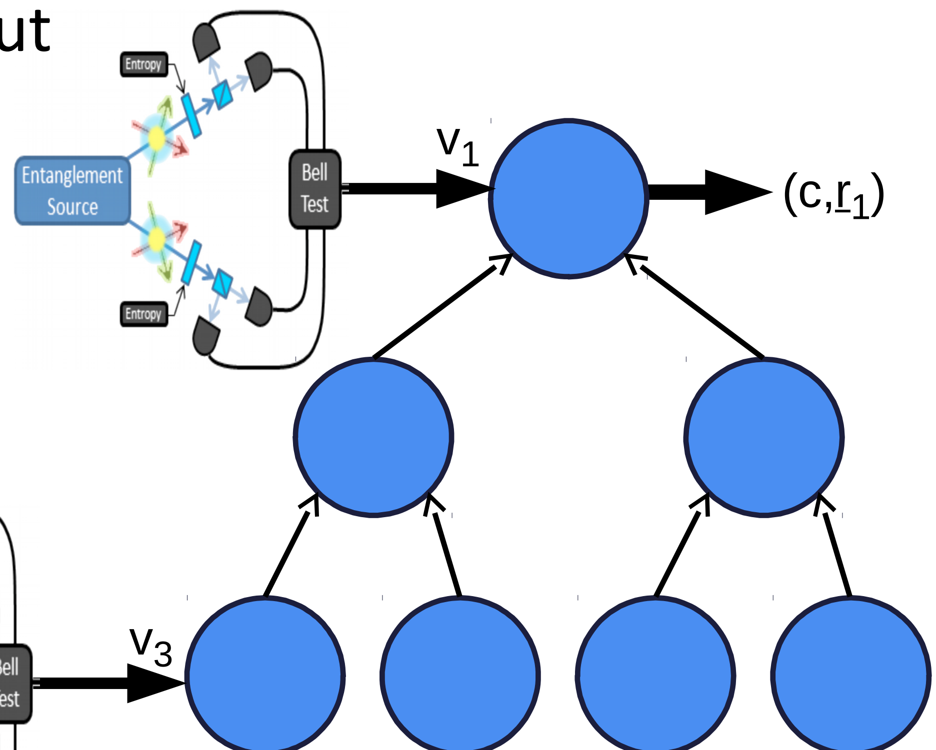


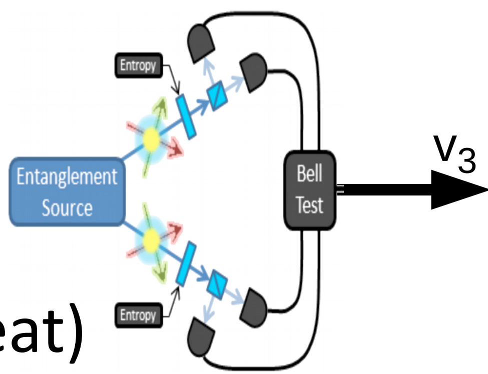
Collective Public Randomness

Any/all servers in tree contribute (ideally true) randomness via secrets v_i and commitments V_i

Collective random output is final response $\underline{r}_1$

- **Unpredictable** to *all* participants
- **Tamper-resistant**
- **Bias-resistant** (with caveat)





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The Availability Problem

Assume server failures are **rare** but **non-negligible**

- Availability loss, DoS vulnerability if not addressed
- But *persistently bad* servers administratively booted

Two approaches:

- Exceptions – currently implemented, working
- Life Insurance – partially implemented, in-progress

Approach 1: Exceptions

- If node A fails, the remaining nodes can provide a valid signature but
  - For a modified collective key: $K' = K * K^{-1}_A$
  - Using a modified commitment: $V' = V * V^{-1}_A$
  - And response: $r' = r - r_A$
- Client gets a signature under K' along with an exception e_A
  - e_A also lists conditions under which it was issued
- Client accepts **only** if a quorum of nodes maintained

Public Randomness: The Caveat

Current version with exceptions for availability:

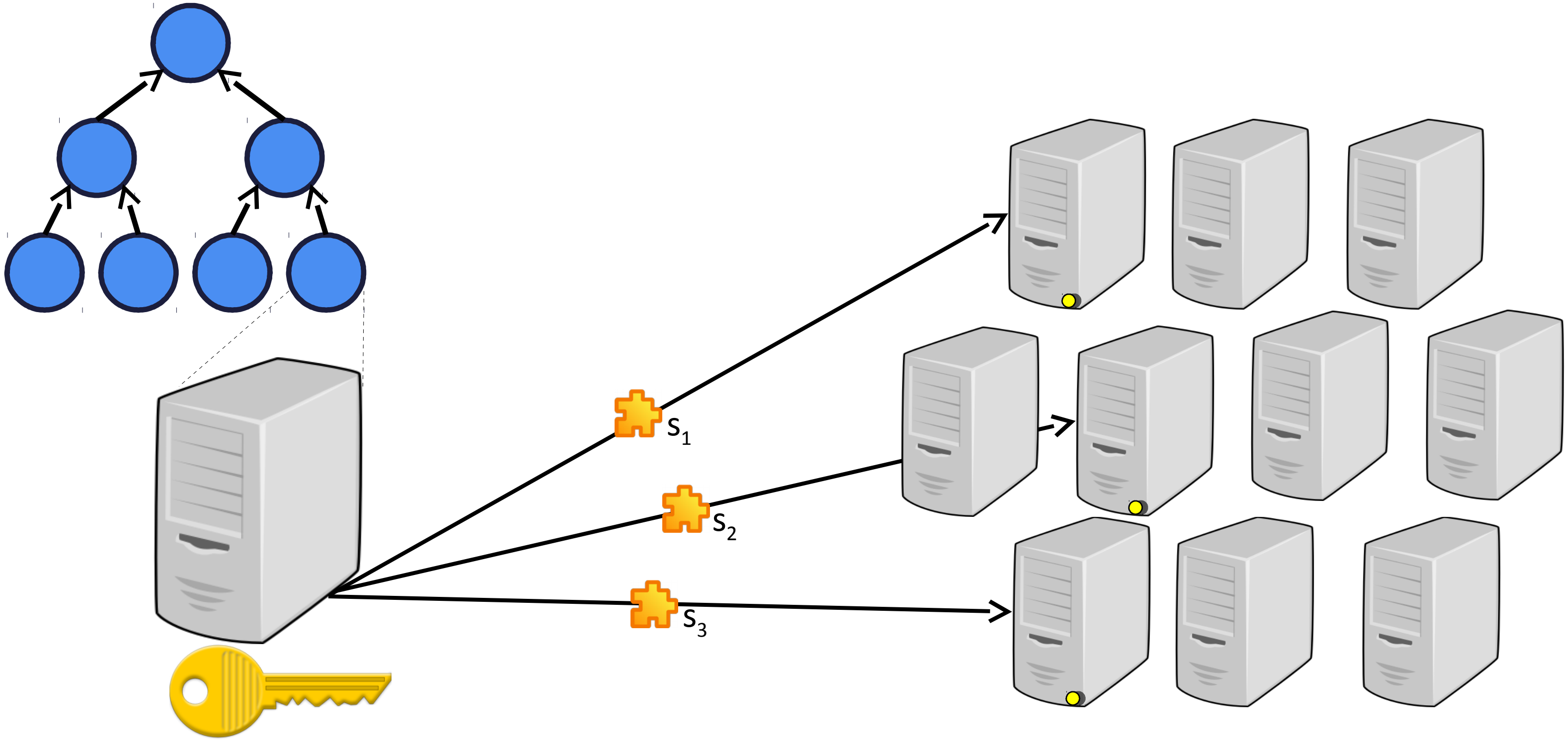
- Protects from anyone **predicting the future**
- Protects from anyone **rigging the outcome**
- ***Not*** fully **bias-protected** if leader is malicious

Attack: assume leader colludes with k followers

- Followers pretend to be offline in 2^k configs
- Leader picks "best" of 2^k possible outcomes

Approach 2: Life insurance

- Node "insures" its private key by depositing the key shares with other servers (insurers)
- If node fails, others recover the key and continue
- Use Shamir verifiable secret sharing (VSS)



Unbiasable Public Randomness

Life insurance approach can fix bias vulnerability

- Collective commits to *single unknown value*
  - Aggregate secret $\underline{v}_1$ combines *every* secret v_i
  - Fully unpredictable if *any* server is honest
- Collective response can be *only one value*
  - Response $\underline{r}_1$ depends only on $\underline{k}_1$, $\underline{v}_1$, c
  - Fully unbiasable if protocol completes at all

Leader could still "self-DoS-attack"…
but such failures are rather noticeable

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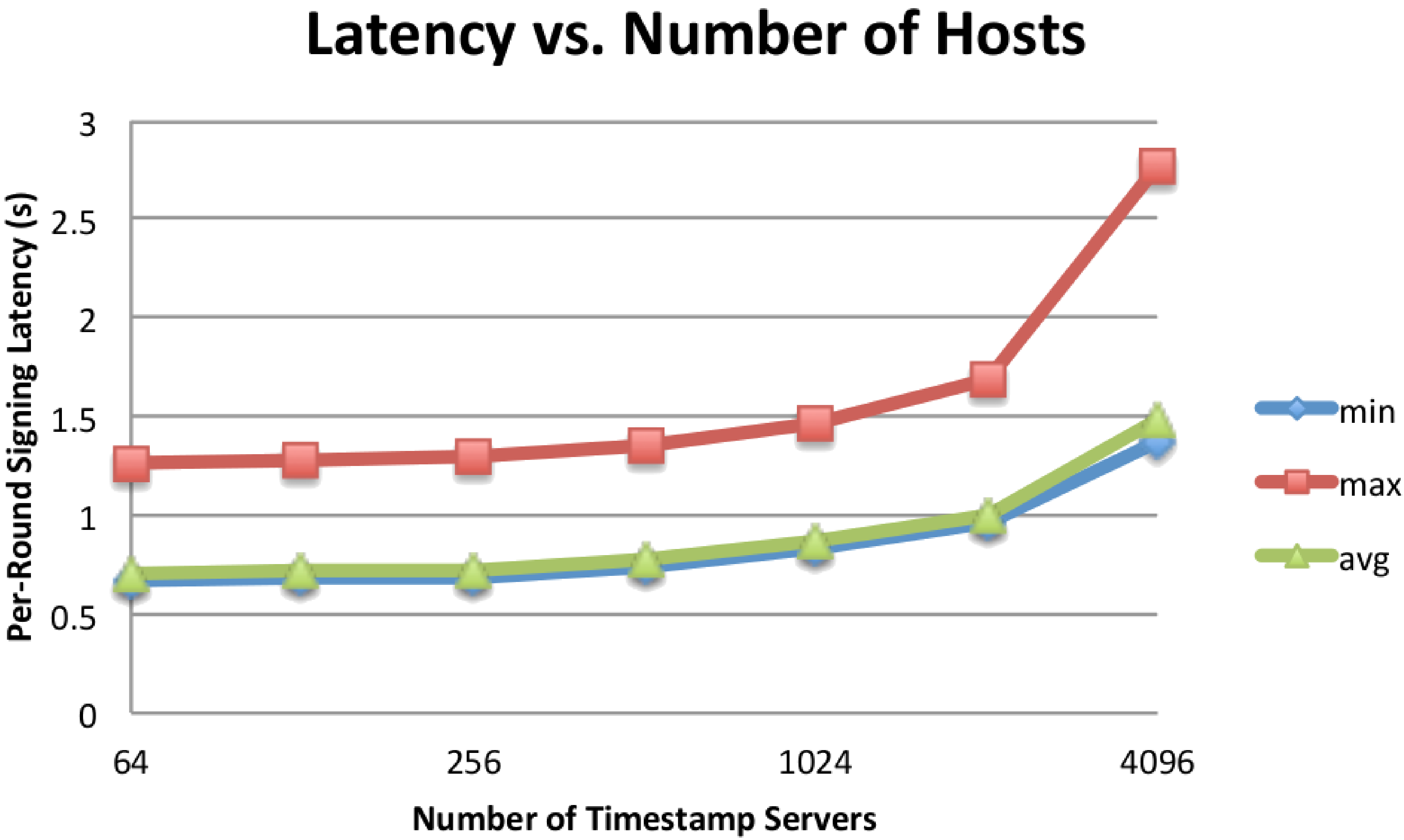
Implementation

- Implemented in Go with dedis crypto library
  - https://github.com/DeDiS/crypto
- Schnorr multisignatures on Ed25519 curve
  - AGL's Go port of DJB's optimized code
- Run experiments on DeterLab
  - Up to 4096 virtual CoSi nodes
  - Multiplexed atop up 32 physical machines
  - Latency: 100ms roundtrip between two servers

Preliminary Results



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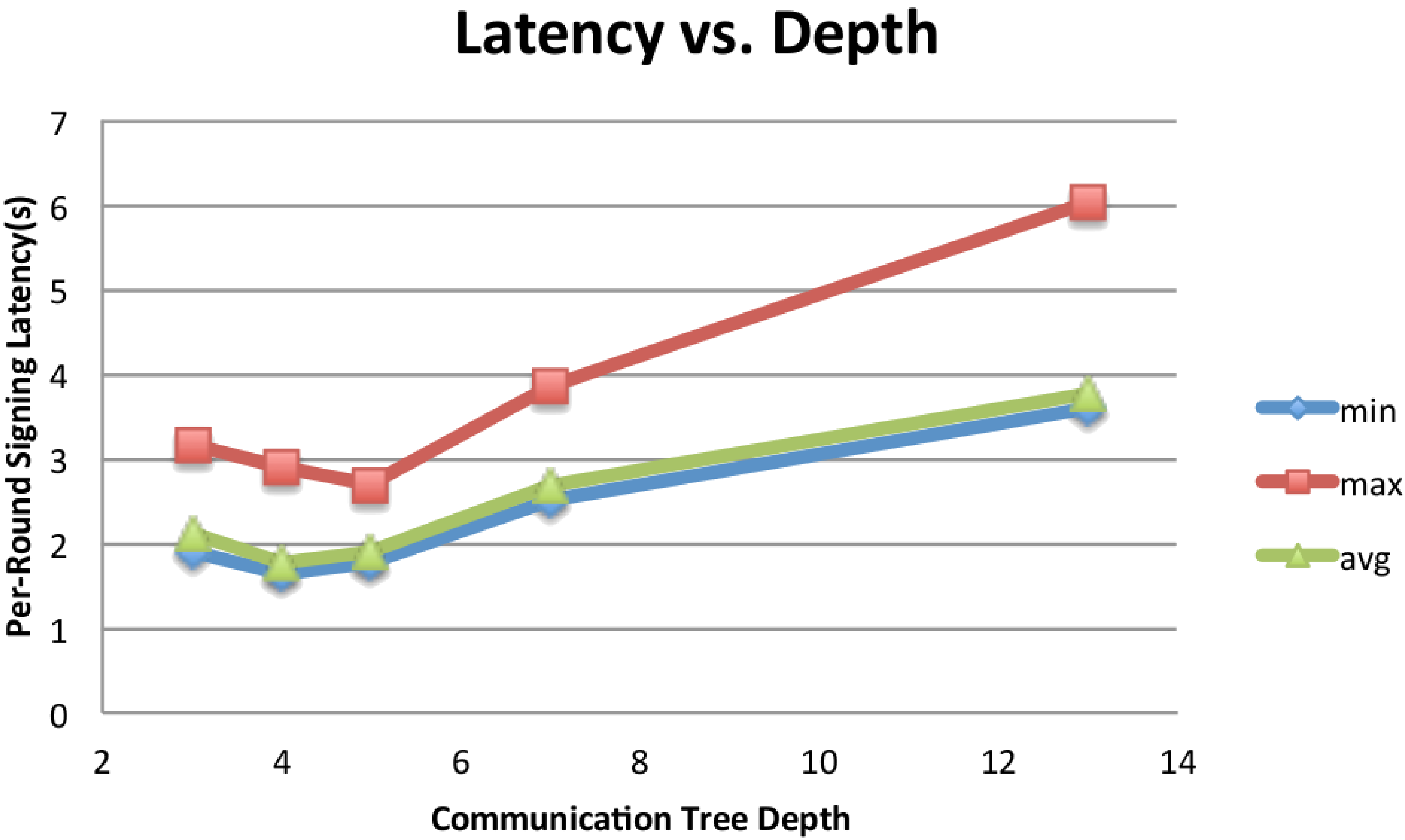

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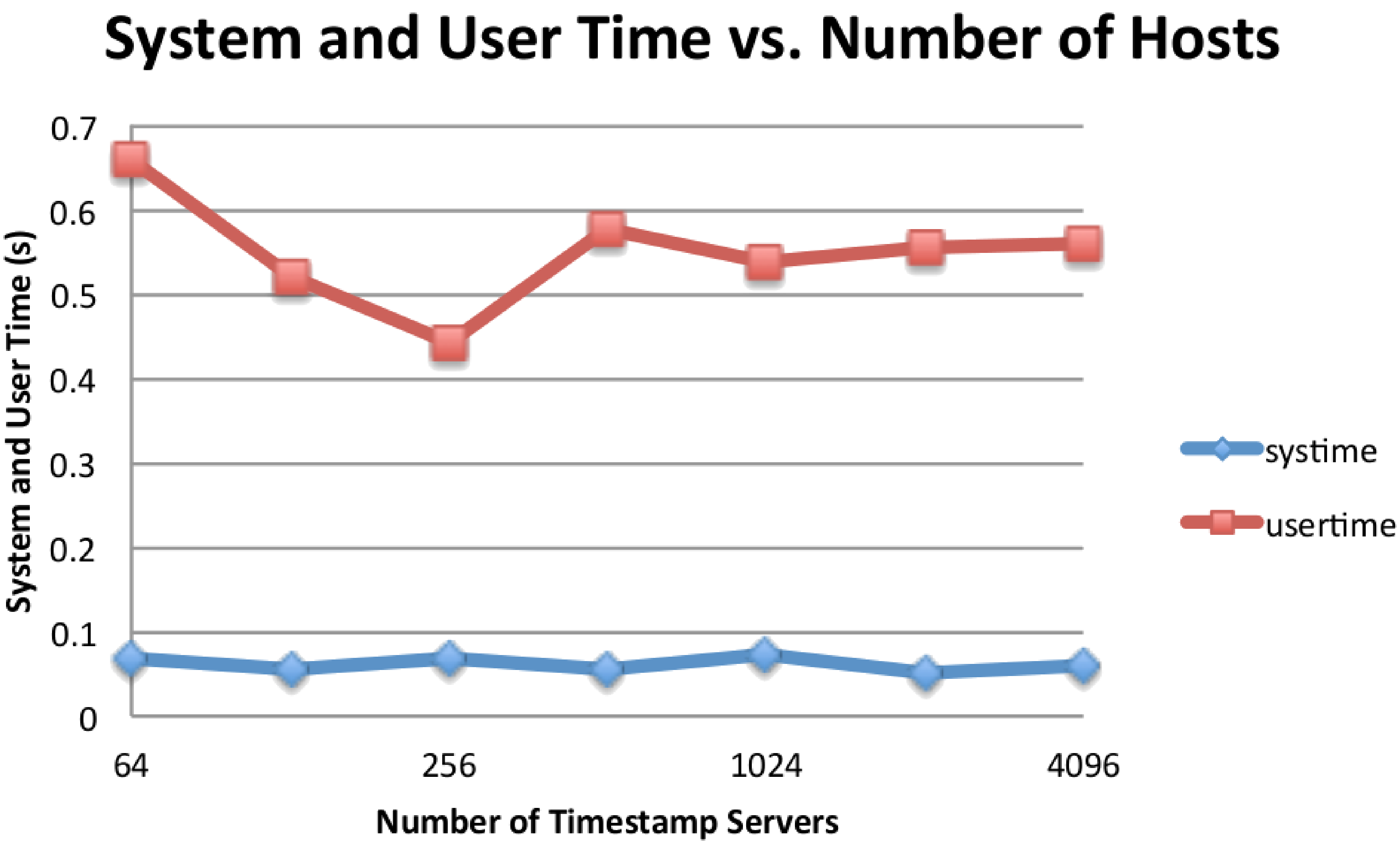

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Logging and Timestamping

Already (or close to) usable for:

- Tamper-evident logging
  - History rewriting protection
  - Equivocation protection
- Secure timestamping
  - Pre/post-dating protection
- Large-scale Byzantine Consensus
  - Propose/commit, view changes implemented
  - Still need validation, evaluation, optimization

Secure Randomness/Lotteries

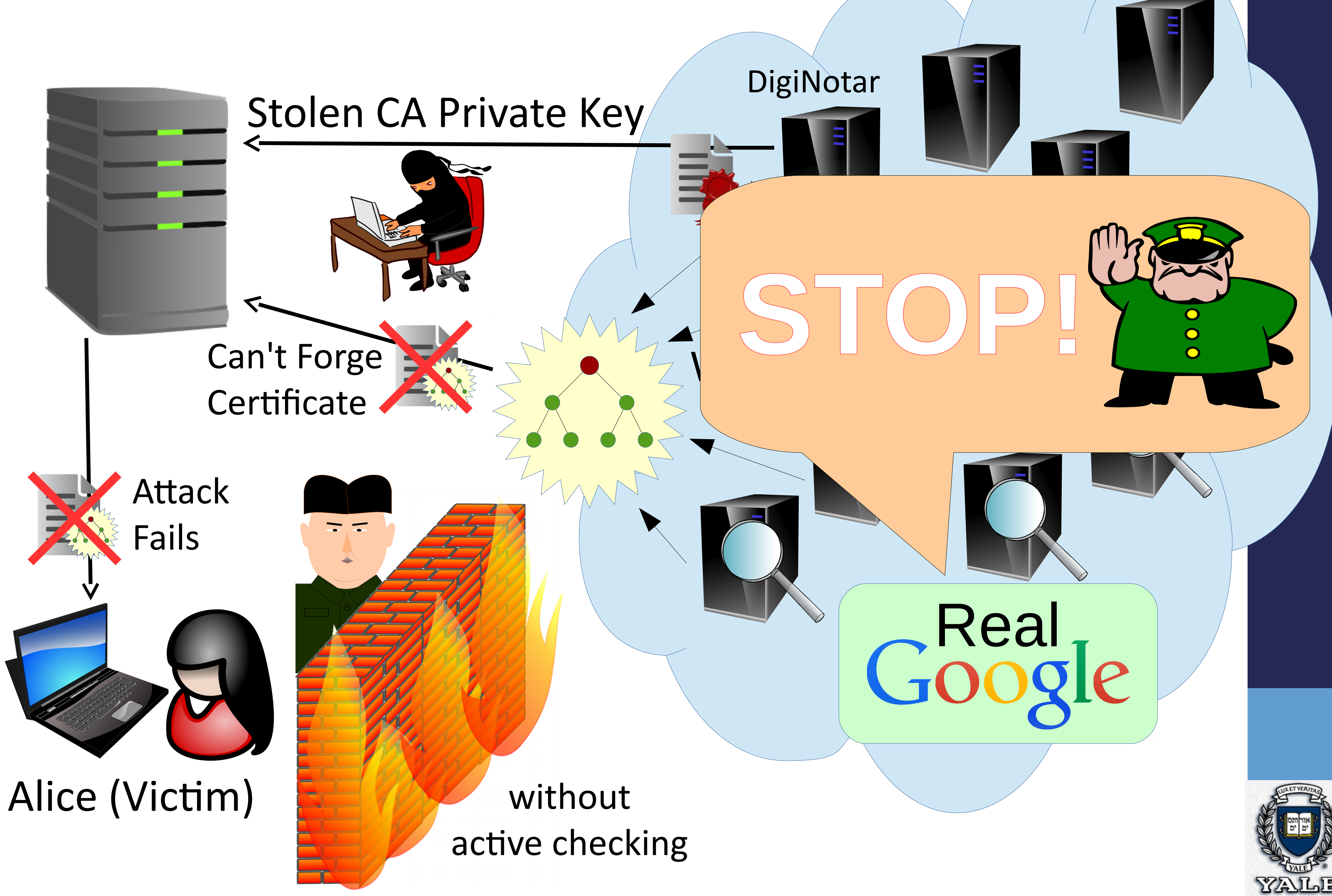
Current version with exceptions for availability:

- Protects from anyone predicting the future
- Protects from anyone rigging the outcome
- *Not yet* fully bias-protected if leader malicious

Shamir secret-sharing version can fix bias risk

- Collective commits to *single unknown value*
- Ensures *exactly that value* as ultimate output

Certificate Cothorities



Certificate Cothorities

Proactive protection against fake certs, MITM

- Ideal: browser vendor leads a cothority
  - CAs join, check and collectively sign all certs
  - Any CA can block signature if cert violates policy
    - e.g., only Google CA can sign 'google.com' cert
- Alternative: root CA leads a cothority
  - Migrates sub-CAs into cothority membership, phases out availability of delegated authority
- Alternative: based on Certificate Transparency
  - Log servers as cothorities, collectively signed SCTs

A Better Blockchain?

Decentralized consensus, secure ledgers

- Without proof-of-work, massive power waste
- Without risk of temporary forks
- Without 51% attack vulnerability
- Stronger protection for clients, “light” nodes
  - Just check *one* log-head signature for correctness
- Efficient: with FawkesCoin hash-based ledger, just *one* public-key crypto operation per round
- Scalable: every server need not store, verify every record throughout blockchain history

Conclusion

Cothorities build on old ideas

- Distributed/Byzantine consensus protocols
- Threshold cryptography, multisignatures

Show that they can scale to thousands of servers

- Strongest-link security among many witnesses
- Practical: demonstrated for 4000+ servers
- Efficient: 1.5-second signing latency at scale

More details: http://arxiv.org/abs/1503.08768