ARPKI: Attack Resilient Public-Key Infrastructure

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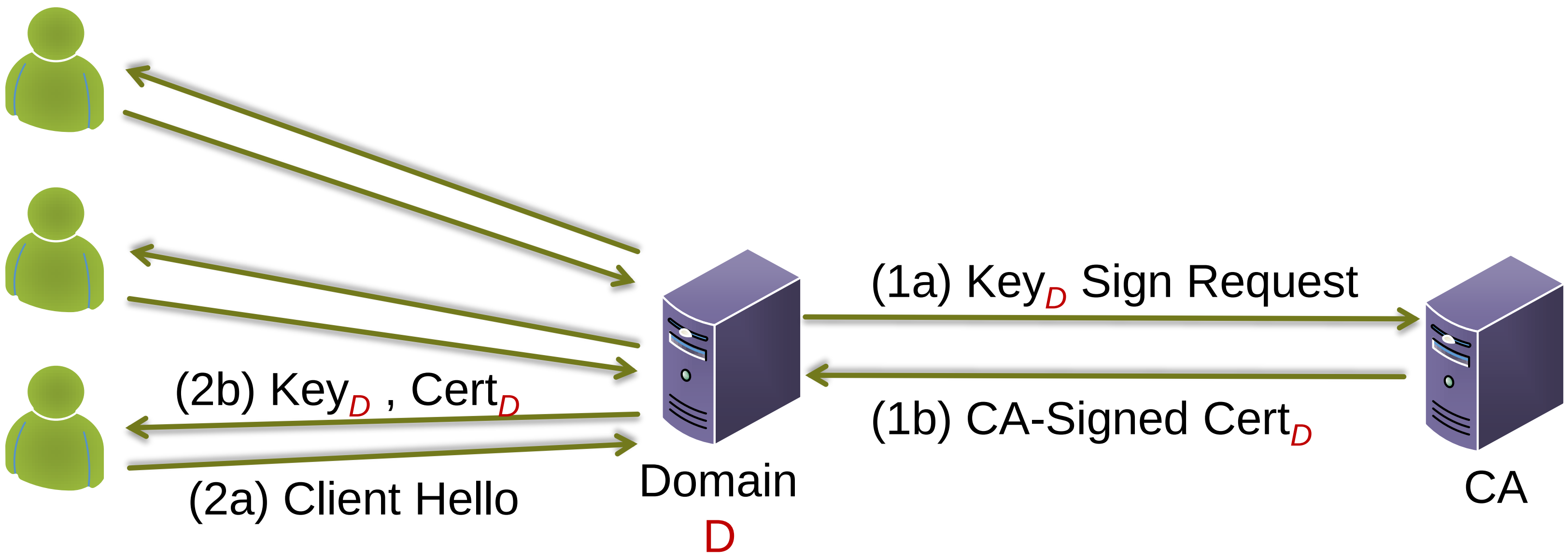
PUBLIC KEYS AND CERTIFICATES

- Public key allows anyone to encrypt a message that only the owner of the associated private key can decrypt
- Problem: how do I know I have the right key for service x?
  - Direct exchange scales poorly
  - Unknown which websites you want to access
- Public key infrastructure
  - Certificates bind identities to public keys
  - Browser delivered with keys for trusted Certificate Authorities
  - Root of trust – chained to actual certificate for some domain
- Use case: online banking, shopping, account access

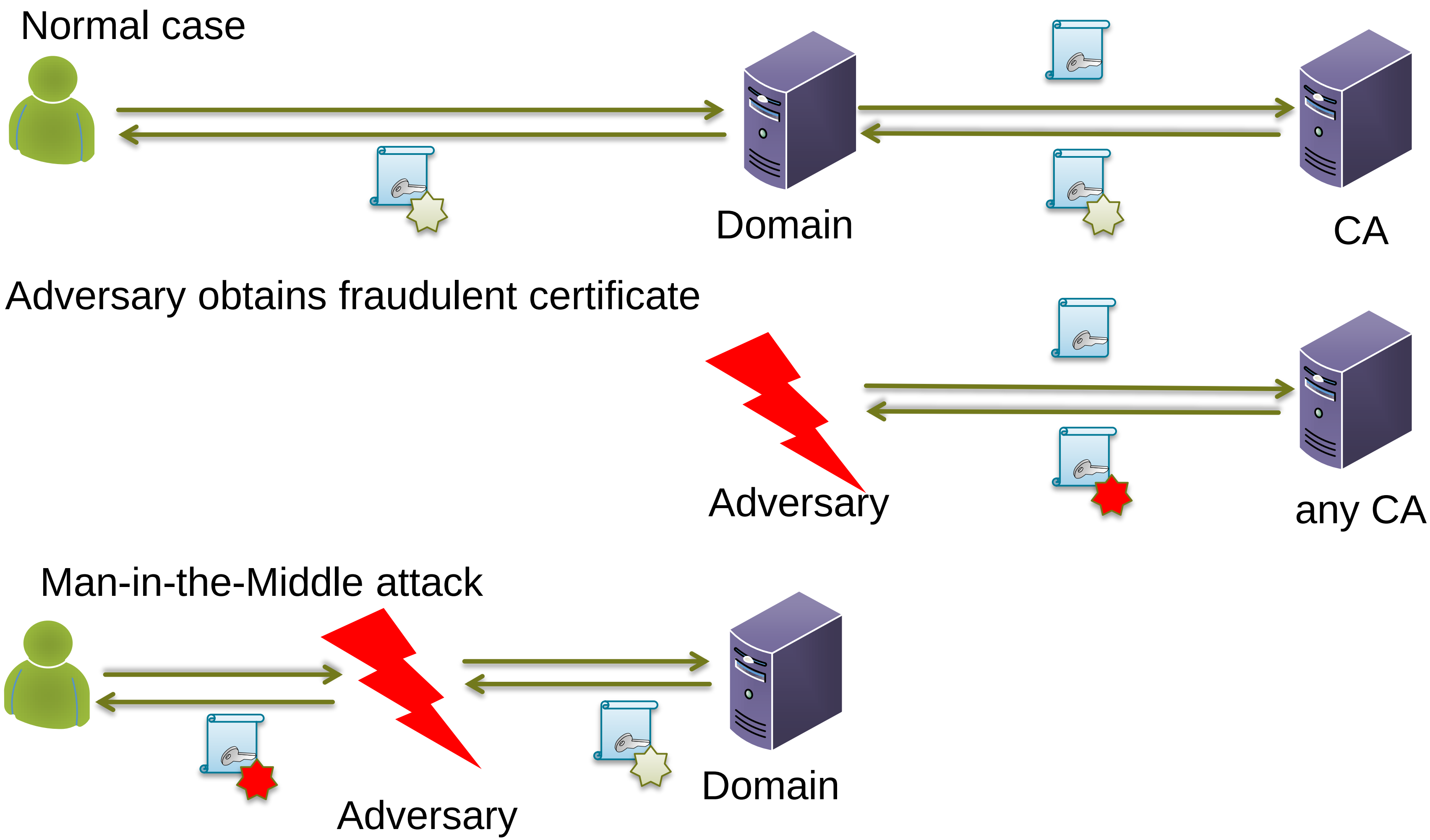
SSL / TLS X.509 PKI



CA Breaches

- 2010: VeriSign hacked, successfully and repeatedly
  - Revealed in U.S. SEC filing in October 2011
- Mar 2011: attack on Comodo reseller
  - Fraudulent certificates for: Google, Yahoo, Microsoft domains
- Aug 2011: DigiNotar – issued fraudulent certificates for Google
  - Used for spying on Iran’s citizens by its government in August 2011
- Oct 2011: Stuxnet – certificates from 2 Taiwanese CAs
- Dec 2012: EGO receives signing certificate from TurkTrust
- **Possibly a large number of CA breaches remain undetected**

MAN-IN-THE-MIDDLE ATTACK

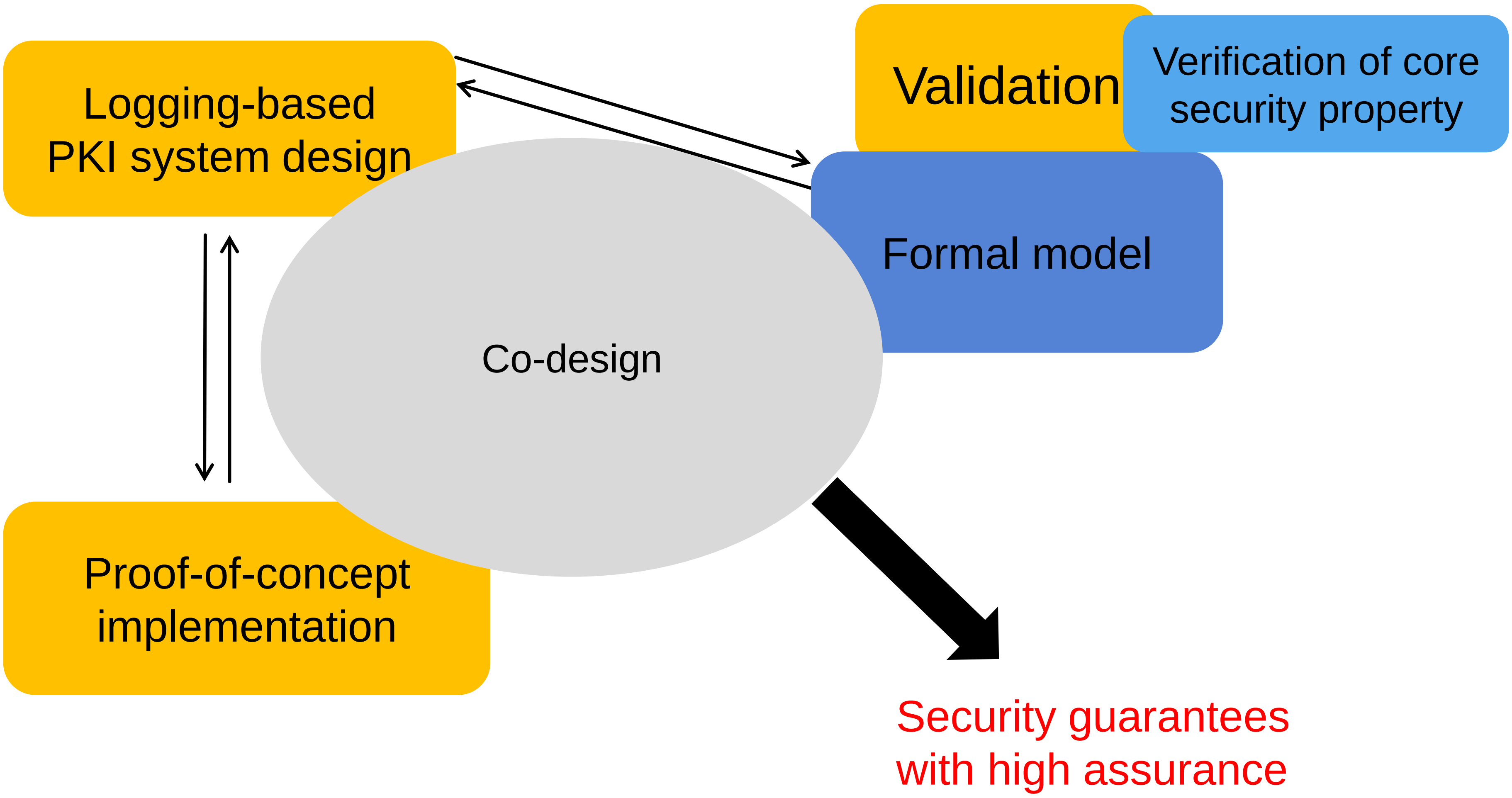


CERTIFICATE LOGGING

- CAs are vulnerable and represent a single point of failure
- Unauthorized certificates become visible
  - Public logs of all valid certificates are kept
  - Certificate must be in log to be usable
  - Deterrence of misbehavior
- Logs struggle with:
  - Increased system complexity
  - Certificate update and revocation
  - Key loss – Domains and Certification Authorities

- Google plans Certificate Transparency rollout for EV certs in 2015

CONTRIBUTIONS



CONTRIBUTIONS

- New logging-based PKI system
  - Mitigates the problem of fraudulent certificates
  - First co-designed PKI
- Validation through formal verification of core security property in model
- Proof-of-concept implementation
- Substantially stronger security guarantees with high assurance

Approach: Attack Resilient PKI

- Co-design of formal model and design
  - Makes all possible requirements precise
  - Tight link between design, model and implementation

- Incremental verification
  - Provides quick feedback on issues with design

- High-level prototype
  - Message-flow and all checks visible
  - Ensures no re-engineering of implementation is needed

Attack Resilient PKI – Certificate Format

- Combines 2 standard X.509 certificates
- Client requires proof that certificate is in the log
  - Signed by the log server – non-repudiable
  - Verified and signed by 2 CAs
- Contains domain’s policy
  - Trusted entities
  - Update/revocation parameters
- All communication signed – attributable to entities

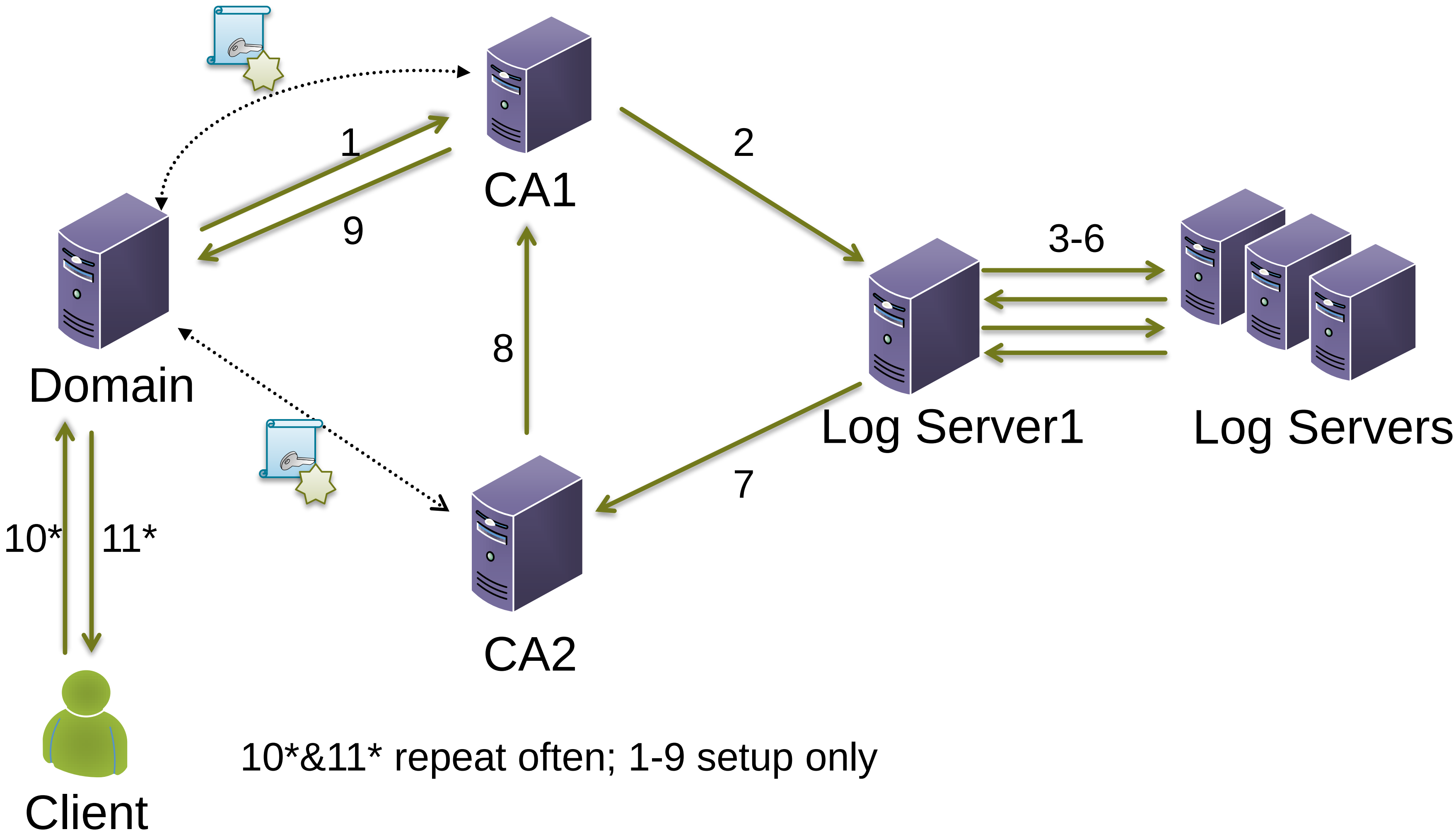
POLICIES – whom to trust

- ARPKI certificates include policy
  - Trusted log/CA servers
  - Update requirements, etc.

- Domain must have unique policy, so:
  - domain can only have one single certificate

- Separate out policy:
  - PoliCert paper at CCS 2014

ARPKI Certificate Registration



10*&11* repeat often; 1-9 setup only

OUR GOALS

- Reduce trust in any single component
  - CA private key compromise tolerable
  - Resilience against even two compromised entities
- Adversarial event protection
  - Make attacks visible
  - Prevent attacks where possible
- High assurance guarantees
  - Formal model of specification
  - Analysis with tool-support

Critical Infrastructure Requires Proof of Correctness

- Manual verification is complicated by system complexity
  - Results in low confidence
- Ad hoc design will likely result in vulnerable system
- Accountable Key Infrastructure [WWW'13] analysis shows:
  - Proposed off-line validators insufficient
  - Unspecified min/max parameters
- Formal verification is necessary

PKI – CRITICAL INFRASTRUCTURE

- Tool-supported analysis required
  - We use the Tamarin prover
- Manual analysis infeasible – low confidence
  - For systems of this scale, with many interactions, manual analysis and reasoning generally fails as state space is too large
- Discovered issues in analysis of AKI:
  - Proposed off-line validators insufficient
  - Missing synchronization requirements on log servers
  - Observation of integrity must be mutual
  - Unspecified min/max parameters

DESIRED SECURITY PROPERTIES

- Connection integrity
  - Client connecting based on certificate – must be communicating with legitimate domain owner
- Legitimate initial certificate registration
- Legitimate certificate updates
- Visibility of attacks

Attack Possibilities

- Attack requires at least *n* compromised entities (default:3)

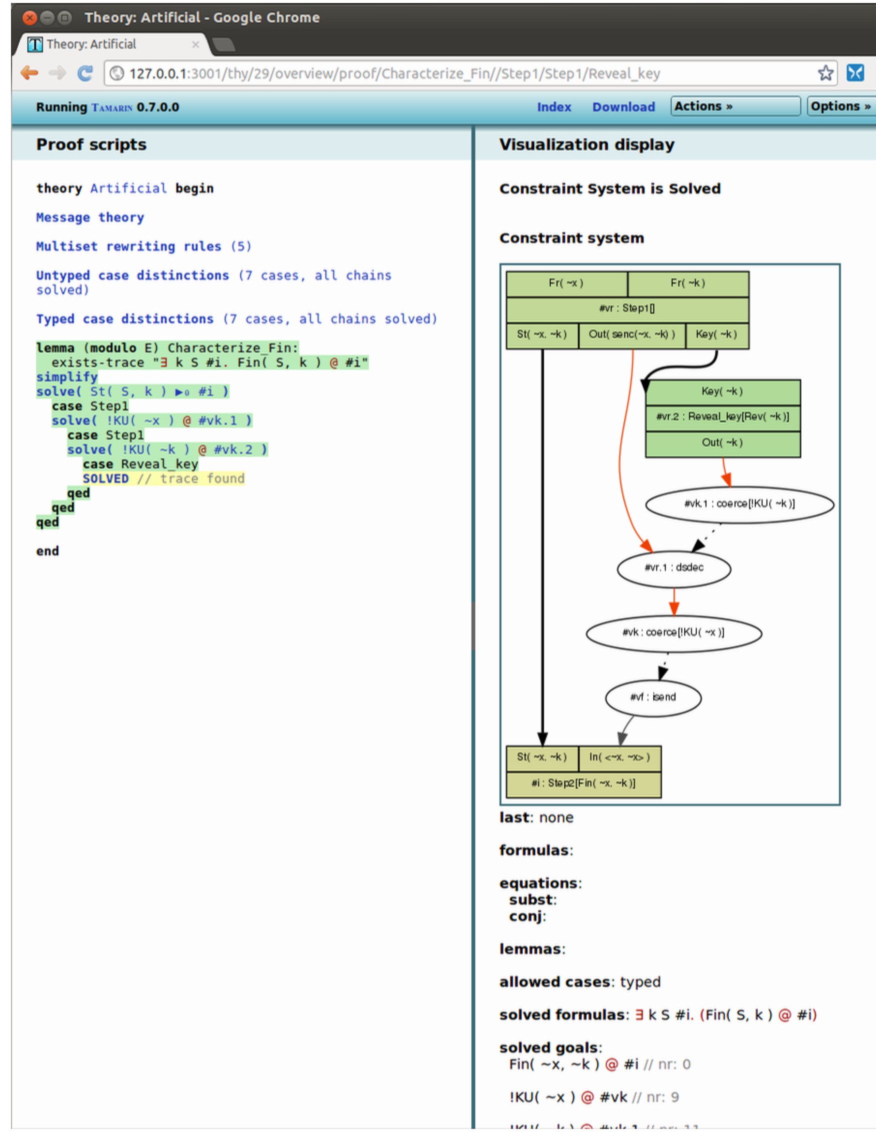
- Security parameter *n* can be increased
  - Resilient to *n*-1 compromised entities
  - More overhead and latency
  - Must be done for the whole system, not possible on a per-domain basis

FORMAL VERIFICATION

- Core security property
  - Prevents impersonation attack
  - Property formally specified and
  - Proven in 80 minutes on 32GB + 16 Cores
- Verified in the *n*=3 setting
  - Tool-supported proof with Tamarin prover
  - Full model is 23 rules, 1k lines of code
  - Verified 5 lemmas
- Tamarin extended – largest verification by Tamarin, by far.

Formal Verification

```
theorem core_security_property:
 "(∀ a b reason oldkey key
         t1 t2 t3 t4 .
  ( Gen_ltk(a,oldkey,'trusted')@t1
  & AskedForARCert(a, oldkey)   @t2
  & ReceivedARCert(a, oldkey)   @t3
  & ConnAcc(b, a, reason, key) @t4
  & t3 < t4)
 ⇒ ( (¬ (∃ t. K(key) @t)) ) "
```

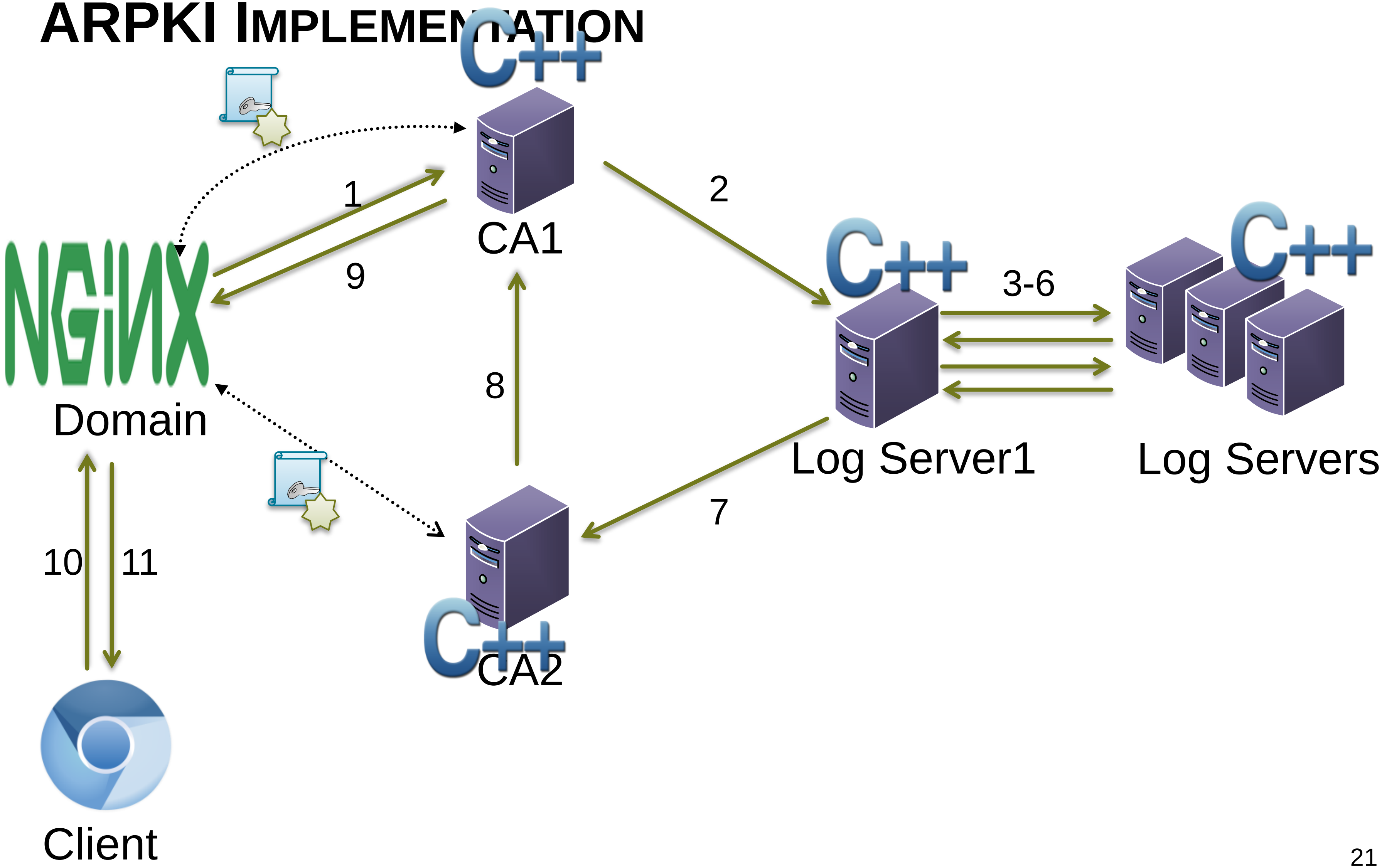


ABSTRACTIONS IN FORMAL MODEL

- Abstracted logs from Merkle hash trees
  - Tamper-proof, represented as lists
- Abstracted ILS quorum finding
  - Set of ILSs represented by single ILS – no quorum modeling

- Formal model very close to design
  - Differences are nevertheless possible – not verifiable
  - Implementation may differ from design

ARPKI IMPLEMENTATION



ARPKI Implementation

- Small overhead
- Browser side validation averages 2.2ms
  - Standard validation: 0.7ms
  - Confirmations: 1.5ms
- No additional TLS level roundtrip
  - Possibly additional TCP roundtrip for large certificates (> 4kB)
- Incrementally deployable

Related Work

- CA-centric
  - Certificate Revocation List (CRL)
  - Online Certificate Status Protocol (OCSP)
  - Short-lived certificates
  - Must trust single CA, no attack visibility or prevention
- Client-centric
  - Perspectives
  - Convergence
  - Must trust single CA, additional latency, privacy issues
- Log-based
  - EFF: Sovereign Keys
  - Google: Certificate Transparency (CT)
  - Accountable Key Infrastructure (AKI)

COMPARISON TO LOG-BASED APPROACHES

Property	CT	AKI	ARPKI
Resilient against	0	1	2+
Update/Revocation	Restricted	Restricted	✓
Formal validation	✗	✗	✓

CONCLUSIONS

- New PKI proposal
  - Resilient against *n*-1 compromised entities
  - Formally verified co-designed model's main security property using the Tamarin prover
- Proof-of-concept implementation
  - Small overhead, incremental deployment possible
- Improvements over existing approaches
- Open questions:
  - CA certificate management
  - Policies and business models
- http://www.netsec.ethz.ch/research/arpki