Rusted Anchors: A National Client-Side View of hidden Root CAs in the Web PKI Ecosystem

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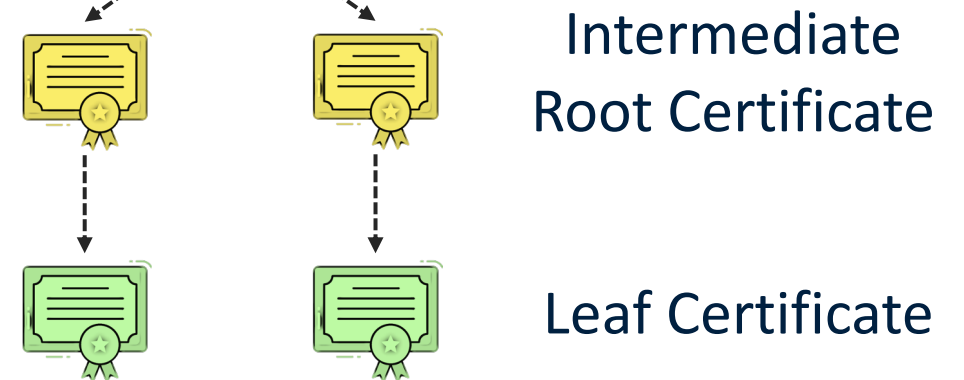
Summary

- The first client-side, nation-wide view of hidden root CAs in the Web PKI Ecosystem.

- Collected 1.17 million hidden roots from volunteers' local root stores and characterized 5,005 organizations that hold them.

- Uncovered the massive and dynamic hidden CA ecosystem, revealed the serious flawed implementations, and shed light on the landscape of Web PKI security.

Background

Trust Model in Web PKI

TLS

Certificate Exchange

Clients

Server

Certificate Authority

Root Certificate

Intermediate Root Certificate

Leaf Certificate

Root Certificates as the trust anchors

The connection will only be considered **authenticated** if the **root** is **trusted**.

Trust Anchors - Root Stores

- Public root stores

Mozilla   Microsoft   Apple

~ 590 Root Certs*

Pre-configured on local operation systems/browsers

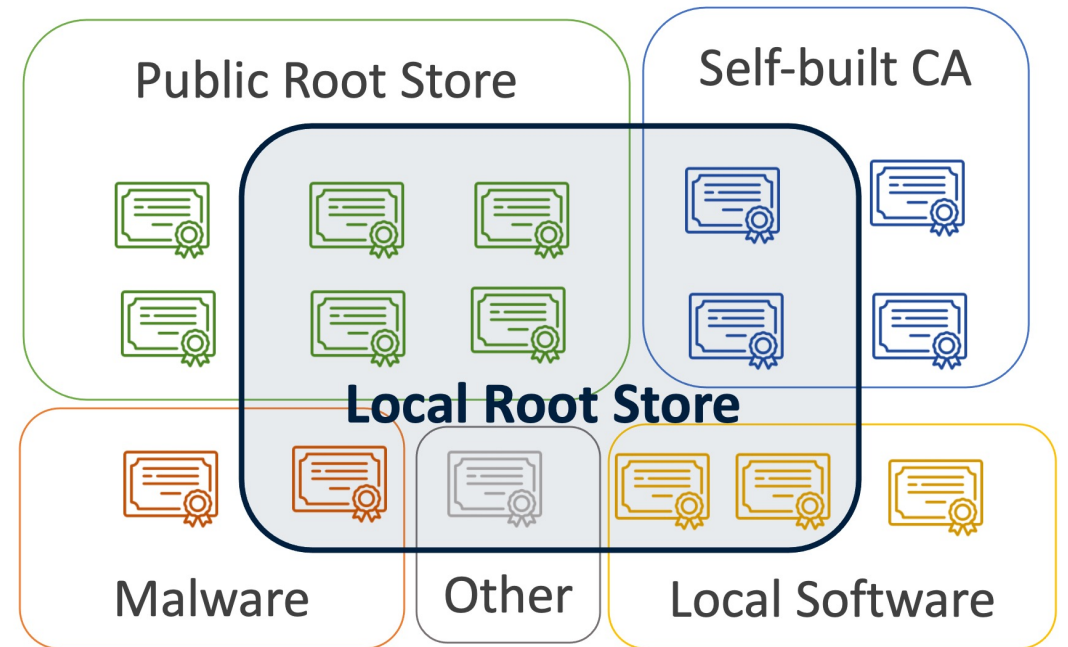Being rigorously reviewed and supervised

Common CA Database

Home | Policy | For CAs | For Root Stores | Resources   ☷ CCADB

Common CCADB Policy

* according to the snapshot statistics in Sept. 2020

- Root stores in the wild

Local root store could be modified by several parties…

Public Root Store   Self-built CA

Local Root Store

Malware   Other   Local Software

Overview of real-world CA ecosystem

Security Incidents of Unregulated Root Stores

• Modifications of local trust lists could pose serious security problems.

Alert (TA15-051A)

Lenovo Superfish Adware Vulnerable to HTTPS Spoofing

Original release date: February 20, 2015 | Last revised: September 30, 2016

Print   Tweet   Send   Share

Systems Affected

Lenovo consumer PCs that have Superfish VisualDiscovery installed.

ars TECHNICA   BIZ & IT   TECH   SCIENCE   POLICY   CARS   GAMING & CULTURE

SNOOPING AT SCALE —

Kazakhstan spies on citizens' HTTPS traffic; browser-makers fight back

Kazakhstan gov required citizens to install self-signed root certificate.

DAN GOODIN - 12/19/2020, 11:45 PM

Revoking Trust in one CNNIC Intermediate Certificate

Kathleen Wilson | March 23, 2015 | 96 responses

Mozilla was recently notified that an intermediate certificate, which chains up to a root included in Mozilla's root store, was loaded into a firewall device that performed SSL man-in-the-middle (MITM) traffic management. It was then used, during the process of inspecting traffic, to

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NEWS

Worse than Superfish? Comodo-affiliated PrivDog compromises web security too
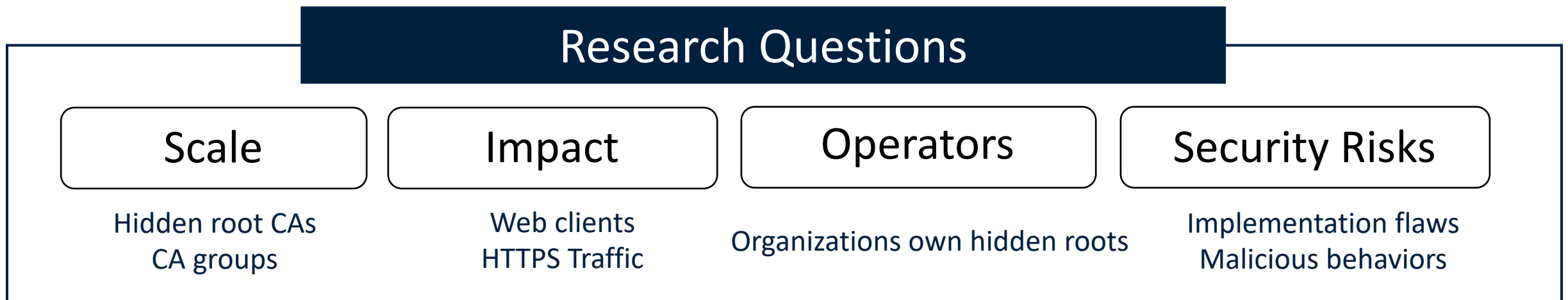
By Lucian Constantin
PCWorld | FEB 23, 2015 12:37 PM PST

Research Goal: Explore "Hidden" Root Ecosystem

Hidden root CAs: root certificates absent from public root programs while have been imported into local root stores (gained trust from web clients).

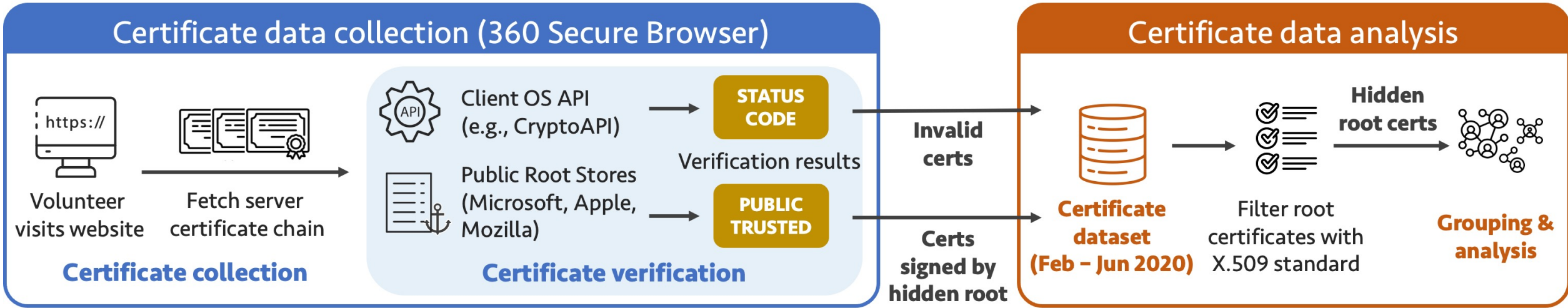**Previous studies**: all lack the client-side view of local root stores.

We give the first client-side, nation-wide view of hidden root CAs in the Web PKI ecosystem

Research Questions

Scale	Impact	Operators	Security Risks
Hidden root CAs CA groups	Web clients HTTPS Traffic	Organizations own hidden roots	Implementation flaws Malicious behaviors

Methodology

Methodology Overview

Certificate data collection (360 Secure Browser)

- **Certificate collection**: Volunteer visits website → Fetch server certificate chain
- **Certificate verification**: Client OS API (e.g., CryptoAPI) → STATUS CODE; Public Root Stores (Microsoft, Apple, Mozilla) → PUBLIC TRUSTED; Verification results
- Invalid certs; Certs signed by hidden root

Certificate data analysis

- Certificate dataset (Feb – Jun 2020) → Filter root certificates with X.509 standard → Hidden root certs → Grouping & analysis

• Collaborate with **360 Secure Browser** (over 100 million monthly active users in China mainland)

STATUS CODE — Verified by operating system API CryptpAPI on Windows

COMMON_NAME_INVALID, DATE_INVALID
AUTHORITY_INVALID, REVOKED, …

PUBLIC TRUSTED — Examine whether the root includes in public root programs

Check in backstage by matching the public key
Unset when the root is excluded

• Chains with **invalid verification results** or **link to hidden roots** would be collected

Identify Hidden Root Certificates

- **Collected data**: (anonymized)client ID, time of collection, hashes and PEM encoding of certificates, public flags, verification results.

```
{
    "client_id": 1579968000000, "host": example.com,
    "collected_time": 2020-02-01T00:00:00Z,
    "leaf_sha1": "35 FE 12 … 83 5A FB",
    "parents_sha1": ["A3 A1 … D7 3A", "A8 98 … 54 36"],
    "status_code": [AUTHORITY_INVALID, WEAK_KEY, DATE_INVALID],
    "public_trusted": False
    "certs_pem": [(leaf_cert_pem), (parent1_pem), (parent2_pem)]
}
```

Example of collected data

Chains may be disordered or incomplete

- **Filter root certificates**

RFC 5280

Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile, MAY 2008

Requirements of root cert

basicConstraints: CA = True

keyUsage: KeyCertSign

subject == issuer (non empty)

subjectKeyIdentifier == authoritykeyIdentifier

```
TBSCertificate
    issuer
        countryName = US, organizationName = cPanel, Inc.,
        commonName = cPanel, Inc. Certification Authority
    validity
        notBefore = 20210311000000Z, notAfter = 20210610000000Z
    subject
        commonName = sigsac.hosting.acm.org
    subjectPublicKeyInfo
        subjectPublicKey = D4 06 E9 CE … 8E 33 45 C1 (2048 bits)
    extensions
        subjectKeyIdentifier: keyIdentifier = C0 73 03 … 52 A0 9F
        authorityKeyIdentifier: keyIdentifier = 7E 03 5A … 6A C7 65
        basicConstraints: cA = FALSE
        keyUsage = digitalSignature, keyEncipherment
Signature = 5E AB F4 D0 CD C6 … 9C CE F0 D1 79 26 (2048 bits)
```

Part of an X.509 Version 3 certificate

Classify Hidden Root Groups

- **Target**: inferring certificate ownership

Common CA Database

Home | Policy | For CAs | For Root Stores | Resources

m CCADB

Public knowledge base not suitable

- **Our approach**: leverage `subject distinguished names`

```
subject:
    commonName = GlobalSign Root CA
    organization = GlobalSign nv-sa
    organizationUnit = Root CA
    countryName = BE
    ……
```

subject template example:

commonName = whistle.[0-9]*

Drain algorithm to identify templated subject

- **Grouping criteria**: identical (non-empty) or templated field values.

Scale and Impact Analysis

Overview of Collected Dataset

Type of Root Cert	Filtering Condition	# Distinct Root Certs	# Cert Chains	# Leaf Certs	# FQDNs
	PUBLIC_TRUSTED=FALSE, Trusted by at least one client	1,175,145 (98.24%)	222,977,356	59,817,585	1,333,931
Hidden CAs	PUBLIC_TRUSTED=FALSE, Rejected by all clients	21,010 (1.76%)	263,109	112,946	15,566
Public Trusted CAs	PUBLIC_TRUSTED=TRUE, STATUS_CODE has bits set	615	241,541,342	3,647,095	1,871,131

- 1.19 million hidden roots collected in 5 months, with 98.24% having been implanted into local root stores.

- 222 million HTTPS traffic, 1.33 million FQDNs, and 5.07 million web clients have been affected.
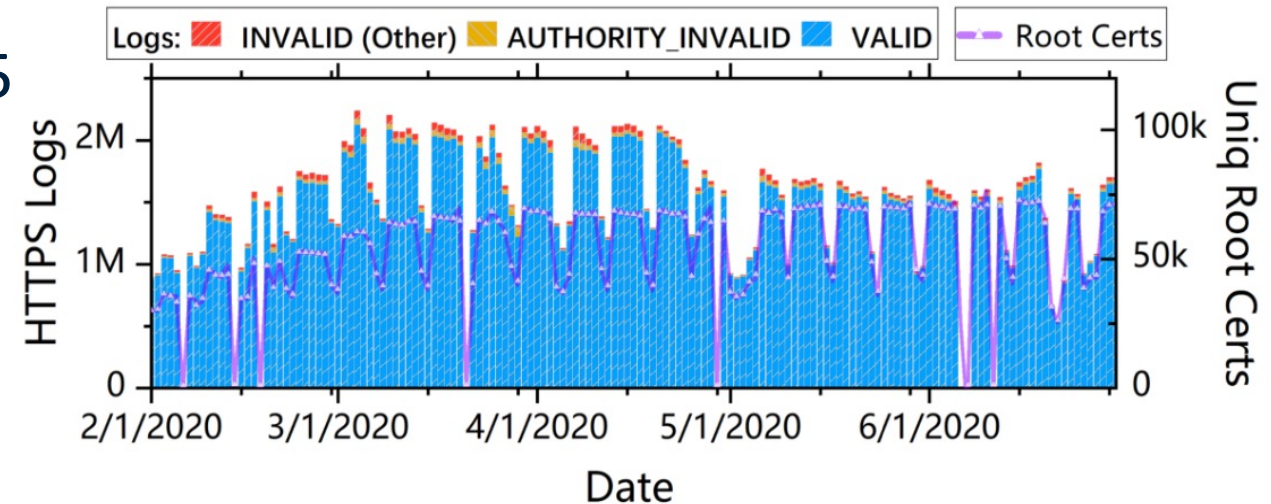
Daily count of hidden roots and associated HTTPS web visits

Hidden CA Group Overview

- Found **5,005** groups on 1.17 million hidden roots (imported by clients).

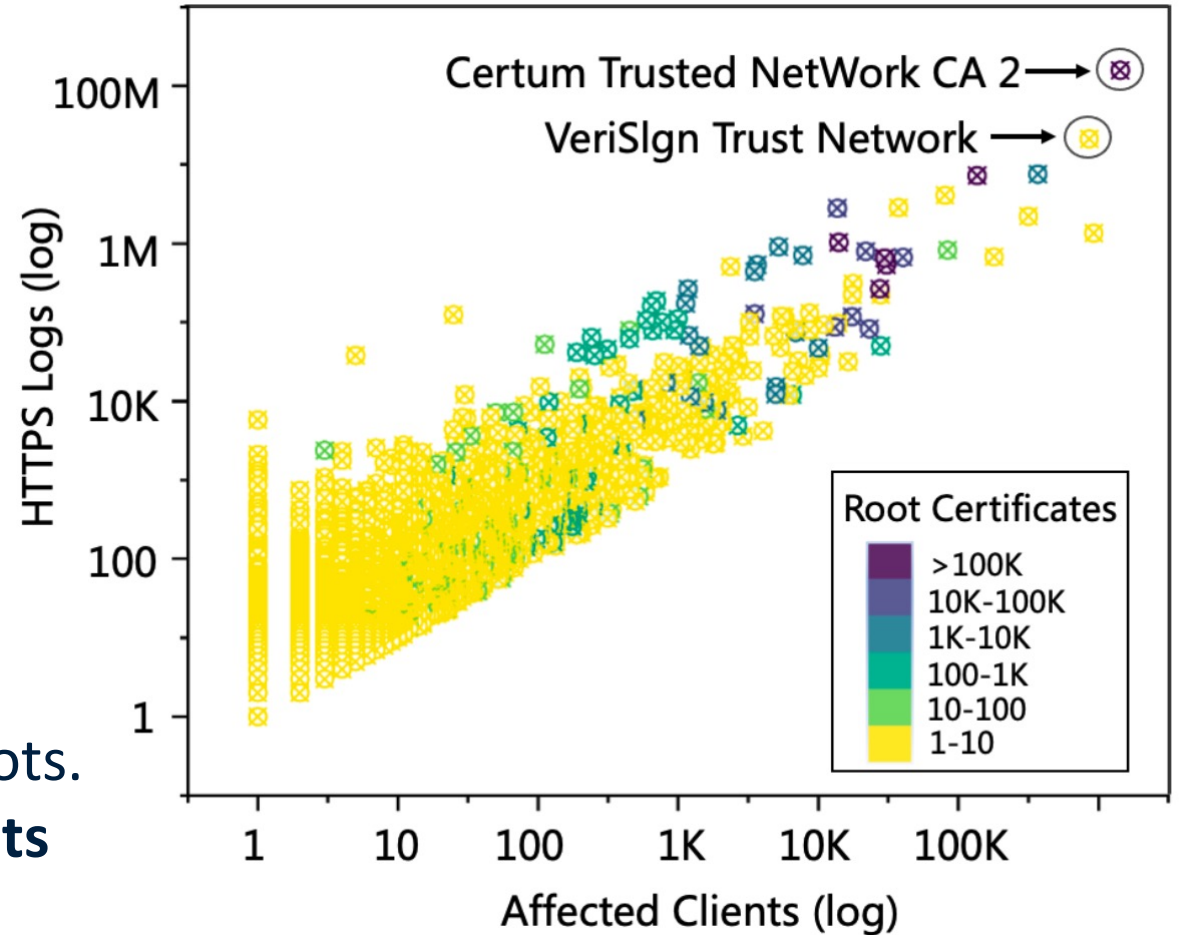- Root certificates in **one group** are considered from **the same organization**.

Distribution

Long tail distribution: 4,362 groups (87.2%) holds only one cert.

Top Groups

The largest group holds 254k roots. **Top 100 groups**: over **1000 clients** and **5000 HTTPS visits**.

Size and impact of certificate groups

Dymanically Updating Ecosystem

- **Active time**: days when certificate chains linked to the roots when captured in our datasets.

Top 100 groups: **146 days** on average.

- **Stability:** the **coefficient of variation** of daily HTTPS visits on active days

The ecosystem of hidden root CAs is **dynamic and updating**, as new **emerging** CAs and **retiring** ones are both observed.
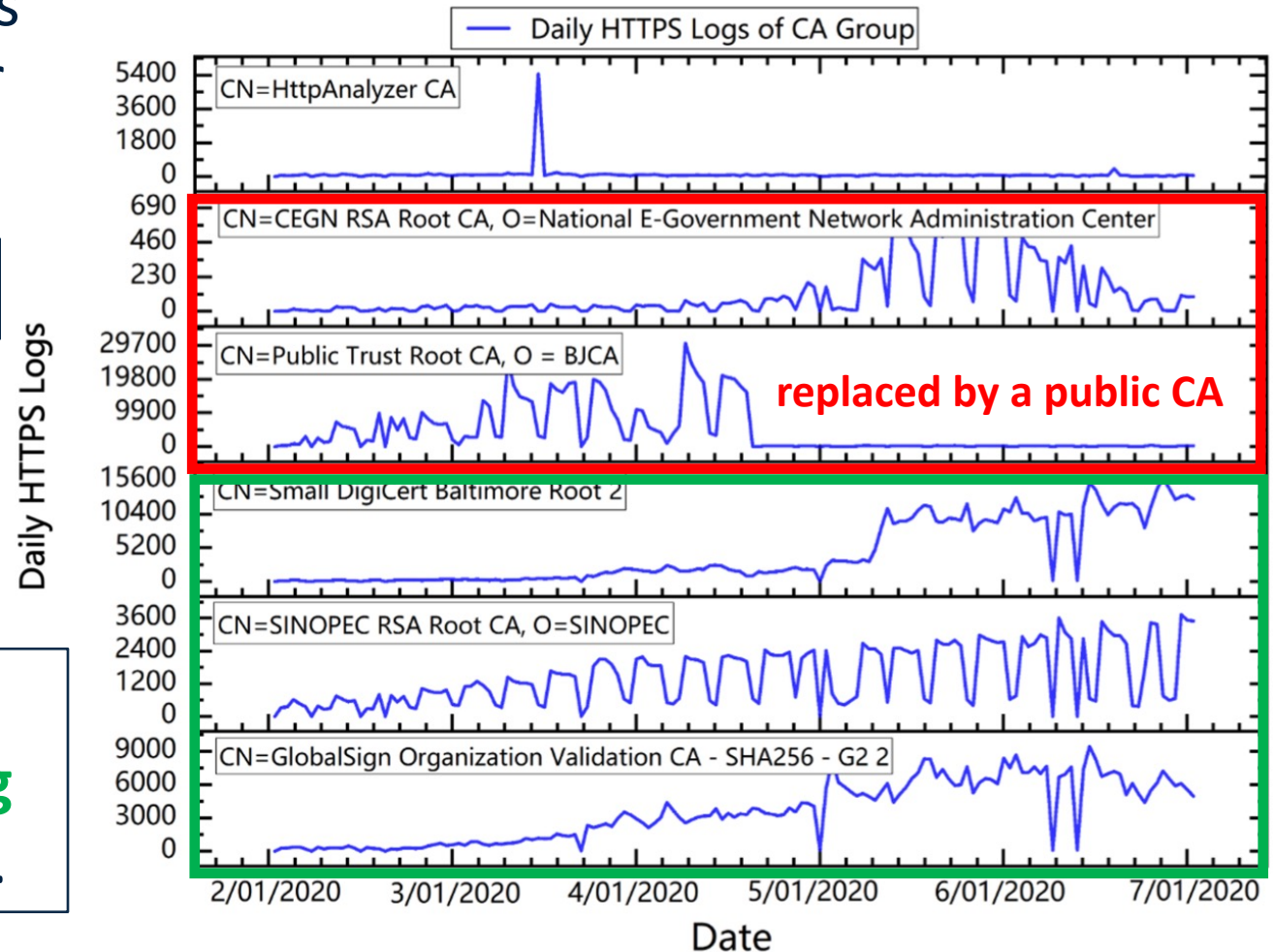
Temporary, retiring, and emerging group examples

- **Infer CA group categories**: 3 security researchers manually inspect the semantics in `subject` fields, and search keywords/hashes when subject is not identifiable.

Categories	# clusters (groups)	# hidden root certs	# affected connections	# affected clients	Invalid (Authority)	Invalid (Other)	Example of hidden root certificate
Enterprise Self-built	24	48	2,071,344	199,743 (3.94%)	35.54%	75.66%	CN = SZSE ROOT CA, O = Shenzhen Stock Exchange
Digital Authentication	13	18	3,261,905	539,711 (10.65%)	28.37%	96.66%	CN = CFCA ACS CA, O = China Financial Certificate Authentication
Government Self-built	13	16	314,351	62,032 (1.22%)	30.46%	89.67%	O = National E-Government Network Administration Center
Fake Authentications	11	817,532	192,901,548	**2,798,985 (55.21%)**	**0.00%**	0.25%	CN = VeriSlgn Class 3 Public Primary Certification Authority - G4
Packet Filter	11	15,587	3,622,177	73,725 (1.45%)	13.57%	14.39%	CN = NetFilterSDK 2
Proxy/VPN	10	90,131	3,050,138	1,029,648 (20.31%)	2.26%	4.27%	CN = koolproxy.com, O = KoolProxy inc
Security Software	2	7,187	509,645	4,719 (0.09%)	0.01%	0.32%	O = Beijing SkyGuard Network Technology Co., Ltd
Parent Control	1	7,554	70,8129	7,787 (0.15%)	0.00%	0.57%	CN = UniAccessAgentFW 2
Unknown	15	207,957	14,048,377	289,198 (5.07%)	2.89%	4.73%	CN = VRV NDF RootCA 2

- Three major sources of hidden Cas are identified: **Self-built CAs** (50 groups), **Fake root CAs** (11 groups) and **Local software CAs** (24 groups).

  (15 of the top 100 groups could not be identified, marked as "Unknown")

Self-built Certificate Authorities

Categories	# roots	# conns	# clients	%error	Example
Enterprise	48	2,071,344	199,743	75.66%	CN=SZSE ROOT CA, O=Shenzhen Stock Exchange
Digital Authentication	18	3,261,905	539,711	96.66%	CN=CFCA ACS CA, O=China Finnacial Certificate Authentication
Government	16	314,351	62,031	89.67%	O=National E-Government Network Administration Center

- **Widely used**: organizations as government agencies and enterprises still use self-built CAs to issue website certificates (for 3,311 FQDNs we observed).

- **Incorrectly implemented**: over 75% chains linked to self-built Cas received verification errors. The most common error is `WEAK_SIGNATURE_ALGORITHM` (78.3%).

- **Publicly deployed**: active scanning experiments find 2,439 FQDNs (73.6%) are publicly accessible websites that still linked to self-built CAs.

Fake Certificate Authorities

- **Fake root CAs**: **impersonate trusted CAs** with deceptive subject names. None of their public keys are located in the official lists of public trusted CAs.

Examples of fake Certificate Authorities

Subject Common Name	# hidden roots	# connections	# FQDNs
Certum Trusted Net**W**ork CA 2	254,414	158.54M	1,137,121
VeriS**I**gn Class 3 Public Primary Certificate Authority - G4	2	21.20M	210
GlobalSign Root **CA**	1,419	7.61M	6,023
GlobalSign**ature Certificates CA** 2	1	2.85M	74,555

Wide impact range:

11 groups, 817K hidden roots, 192M HTTPS connections

High trusted rate:

0.0001% connnections receive `AUTHORITY_INVALID` error.

- **Uncover behind owners**: match certificates in:

Threat Intelligences

Sandbox Logs of Malware

Find 44 fake roots associated with: Trojan, CoinMiner, Adware…

Local Software

- **Local software**: imported at software installation, for (benign) purposes as virus detection, download acceleration and ad blocking.

| Categories	# groups	# roots	# conns	# clients	% error	Example
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- **Traffic owned by local software**: shows a **much lower percentage** (3.58% in this study) than previous works (commonly over 50% for HTTPS interceptions).

   From our (client-side) perspective, "user-informed" or "regulated" interceptions may not predominate as commonly expected.

Implementation Flaws

Irregular Key Usage and Management

- **Direct signing with root certificates**: Over 97% chains are signed directly by root certificates. 41.4% of self-built CAs issued chains are directly signed.

- **Public key sharing**: Prevalent in the hidden CA ecosystem, with 144 groups (22.4%) suffering from this threat (including two security software).
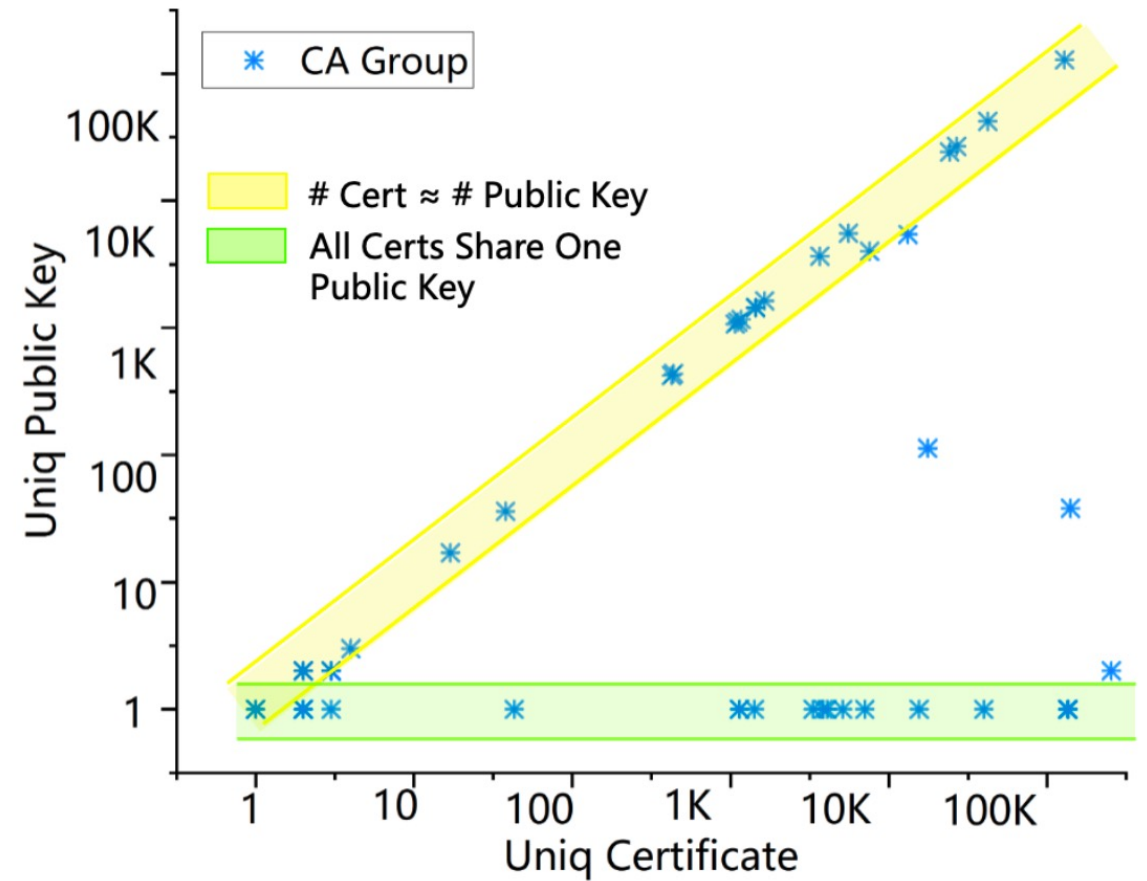
Count of hidden roots and public keys in each group

- **Baseline of validity**: 6 months to 16 years according to security standards. Less than 40 years for all roots in public programs with an median value of 20 years.

Unreasonable settings:

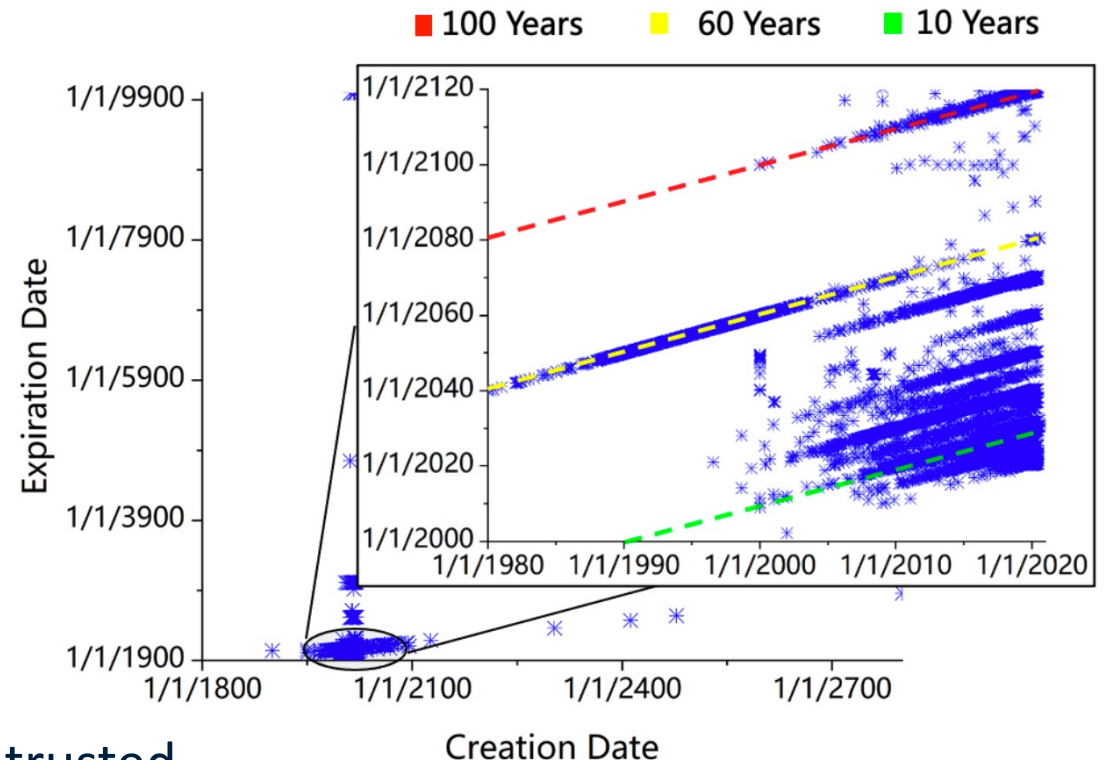Created in the year 1899

Experated in the year 9999

Long validity periods:

79% are valid for over 60 years

317 are valid for over 100 years

Delayed revocation:

23 roots that should be revoked are still active, trusted by over 34K clients and affecting 264K HTTPS traffic.

Creation dates and expiration dates of hidden roots

Non-compliant Certificate Content

- **Identify content in-compliance** by **Zlint**, a certificate linter with 266 lints specified by X.509 standards and CA/Browser Forum.

Zlint **ERROR** messages of hiddend root certificates

Error Type	# Lints	# Cert Errors	Example
Missing extensions	15	954,453 (79.46%)	Missing key identifier
Invalid values	49	121,745 (10.14%)	Negative serial number
Missing fields	3	89,763 (7.47%)	Missing CA organization
Vulnerable values	6	35,228 (2.93%)	RSA key < 2048 bits

- **Problematic content of root certificates:**

    1,201,189 **ERROR** reported of 73 lints, over 87% of roots violating at least one basic requirement. Most roots miss critical extensions such as key identifiers (could lead verification errors). Vulnerable settings are also prevalent, e.g., weak public keys.

Non-compliant Certificate Content

- The implementation of **leaf certificate** signed by hidden CAs is even **more worrisome**.
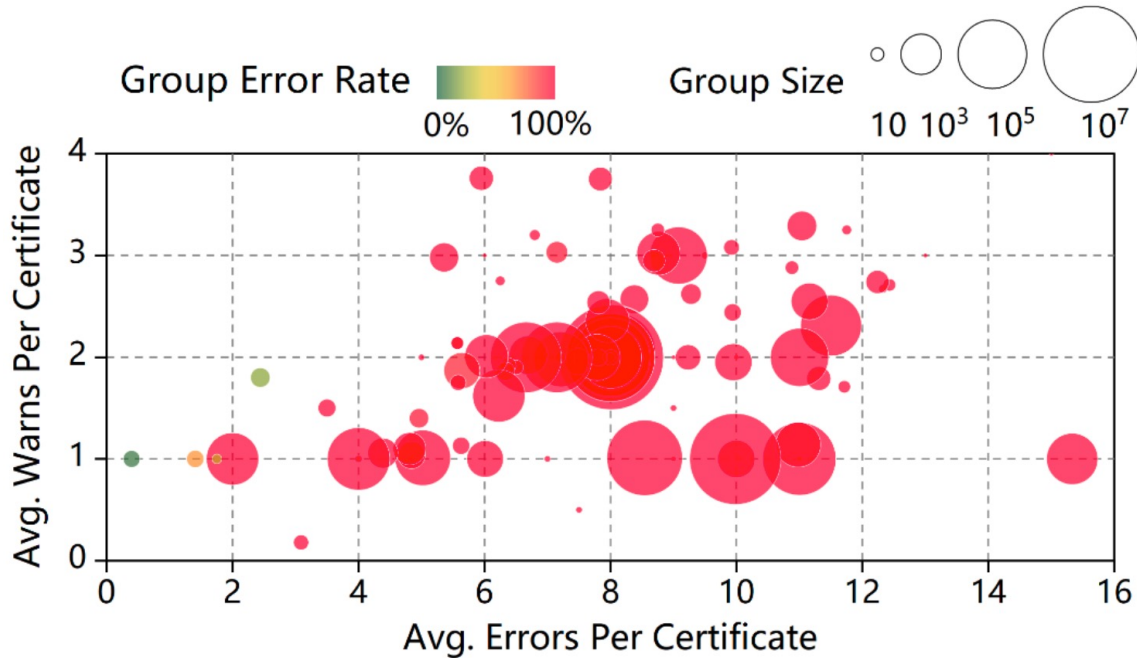
Zlint **ERROR** ratio of leaf certificates in top 100 groups

Problematic content of leaf certificates:

8.14 **ERROR** and 1.93 **WARNING** messages for each leaf certificate on average.

Vulnerable settings are more common than root certificates (e.g., 1024-bit RSA keys).

85 of the top 100 hidden root groups sign every leaf certificate with implementation flaws.

The performance of hidden CAs on compliance is significantly worrisome than public trusted CAs (only 0.02% ERROR rate, 2018[1]) .

[1] Kumar, Deepak, et al. "Tracking certificate misissuance in the wild." *2018 IEEE Symposium on Security and Privacy (SP)*. IEEE, 2018.

Cryptographic Practice Issues

- **Cryptographic flaws** are the most serious errors of hidden CAs.

Signature algorithms of hidden certificates

Signature Algorithm	Root Certs	Leaf Certs
SHA-256 with RSA	1,041,118 (88.59%)	59,553,038 (99.56%)
SHA-256 with ECDSA	128,857 (10.97%)	190,241 (0.32%)
SHA-512 with RSA	102 (0.01%)	640 (0.00%)
SHA-1 with RSA	5,005 (0.43%)	69,419 (0.12%)
Other	63 (0.01%)	4247 (0.01%)

Public key strength of hidden certificates

Key Type	Root Certs	Leaf Certs
RSA (2048-bit)	1,038,534 (88.37%)	1,451,858 (2.43%)
ECDSA (256-bit)	128,857 (10.97%)	190,114 (0.32%)
RSA (4096-bit)	781 (0.07%)	661 (0.00%)
RSA (1024-bit)	6,905 (0.59%)	58,165,008 (97.24%)
RSA (256-bit)	-	5,905 (0.01%)
Other	68 (0.01%)	4039 (0.01%)

- **Cryptographic practice issues:**

  Vulnerable algorithms as **SHA-1** (should be banned since 2016) are still in use.

  Up to **97% leaf certificates** signed by hidden roots use **weak public keys** (nearly 90% of certificates issued by public CAs had a key strength of 2048-bit or above in 2013[2]).
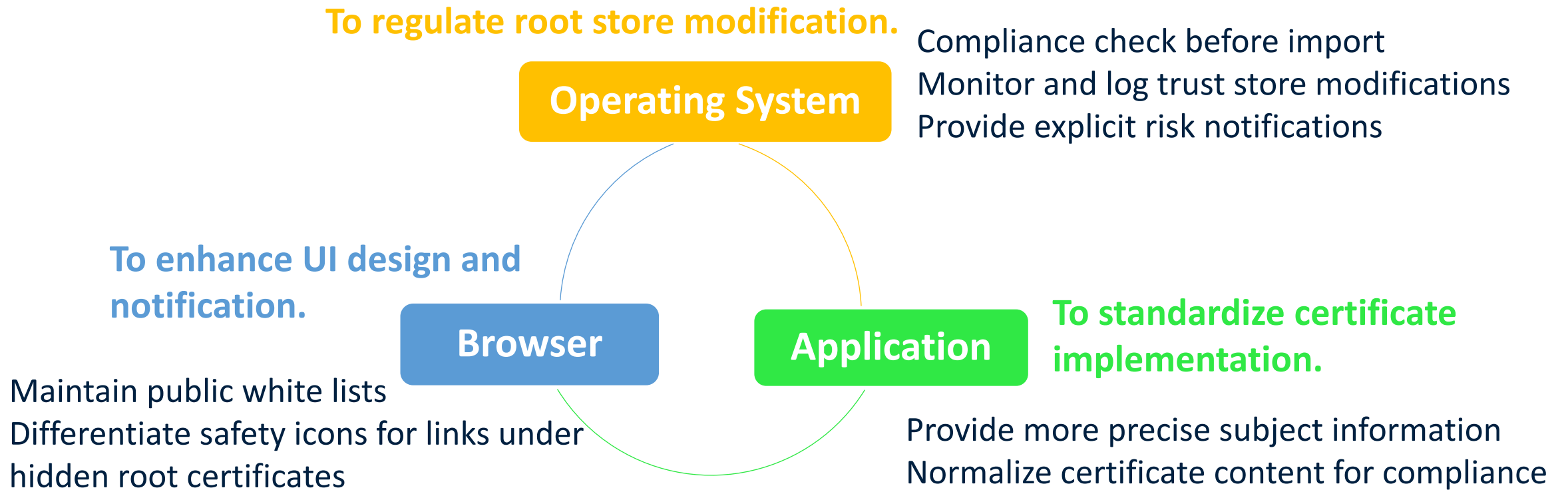
[2] Durumeric, Zakir, et al. "Analysis of the HTTPS certificate ecosystem." *Proceedings of the 2013 conference on Internet measurement conference*. 2013

Conclusions

- The *Hidden Root Ecosystem* is **large-scale, highly active and widely incluential**, which plays an important role in Web PKI, despite being less noticed before.

- Through comprehensive measurement studies, we identified its scales, usages, and distribution resources. And **demonstrated numerouse implementation flaws**.

- The community should immediately **review the security of the local root store**, and seek a best security practice to regulate and manage hidden root CAs.

Recommendations

It's impractical to rigorously check and block all roots outside the public trust list. However, at least **several parties** could cooperate to **mitigate the potential risks**:

To regulate root store modification.

Operating System

Compliance check before import
Monitor and log trust store modifications
Provide explicit risk notifications

To enhance UI design and notification.

Browser

Application

To standardize certificate implementation.

Maintain public white lists
Differentiate safety icons for links under hidden root certificates

Provide more precise subject information
Normalize certificate content for compliance

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