Web site security: authentication, encryption, and public-key certificates

Designing Secure Systens

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University of Birmingham

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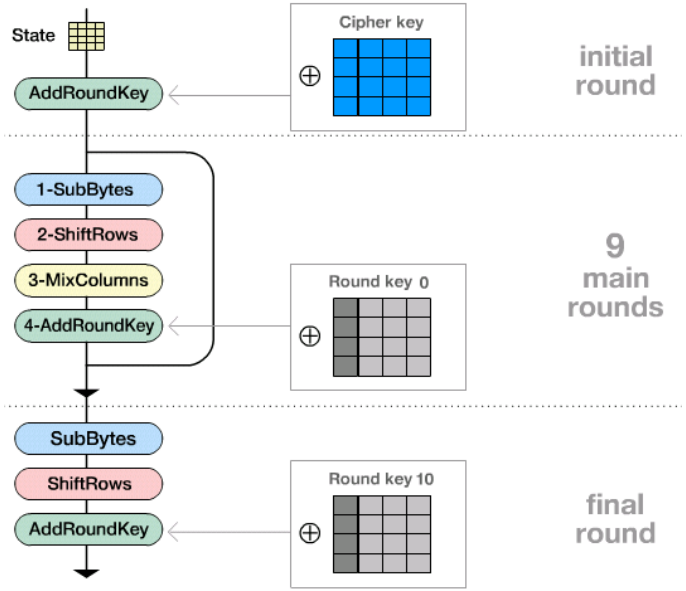
2) Authenticating websites and encrypting web traffic
3) The Certificate Authority model and its problems
   - The currently-used system
4) Certificate transparency
   - The being-rolled-out system
5) Certificate revocation

1. Cryptography

Symmetric key encryption (e.g., AES)

AES block cipher (a permutation substitution network)



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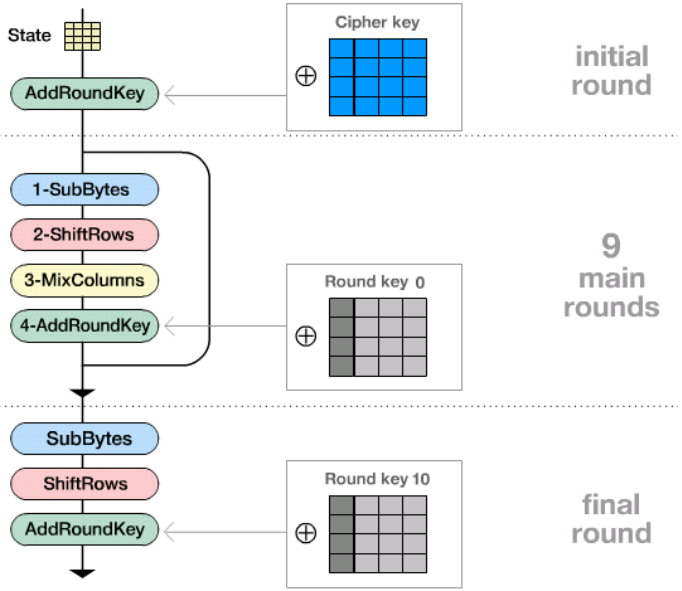
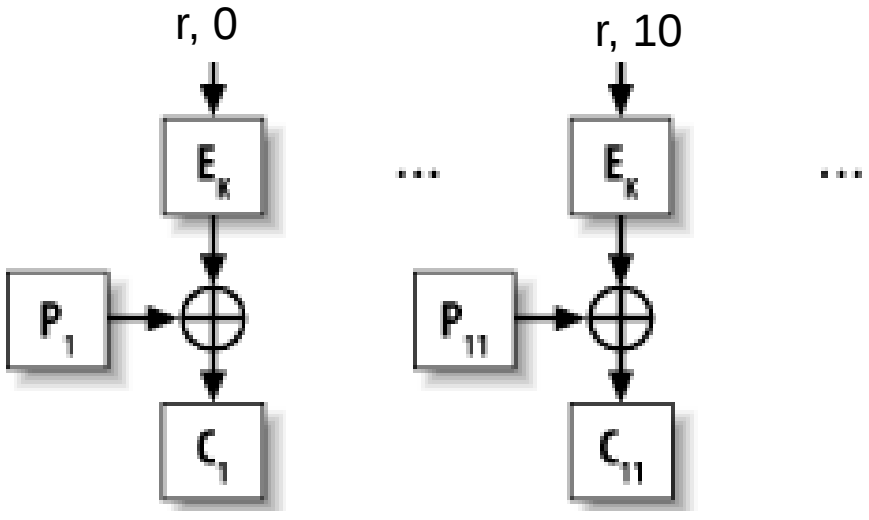


Counter-mode (a mode of operation for block ciphers)



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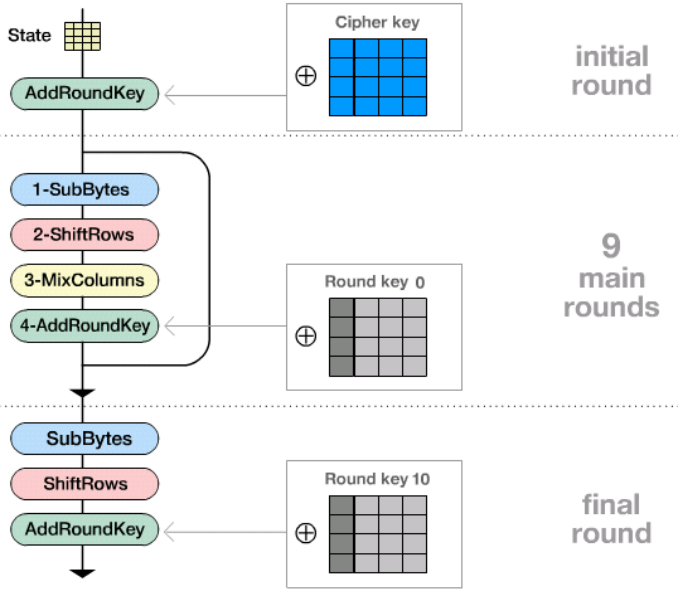

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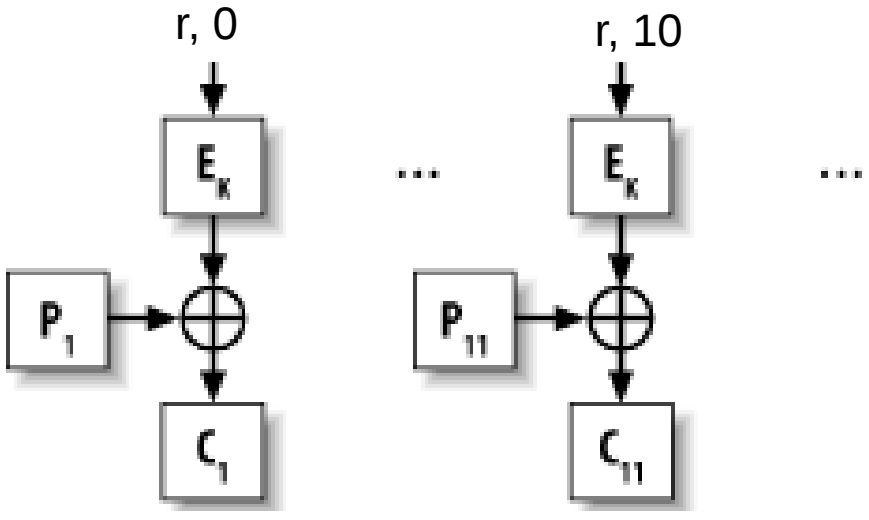

dec(k, r, **enc(k, r, m)**) = m

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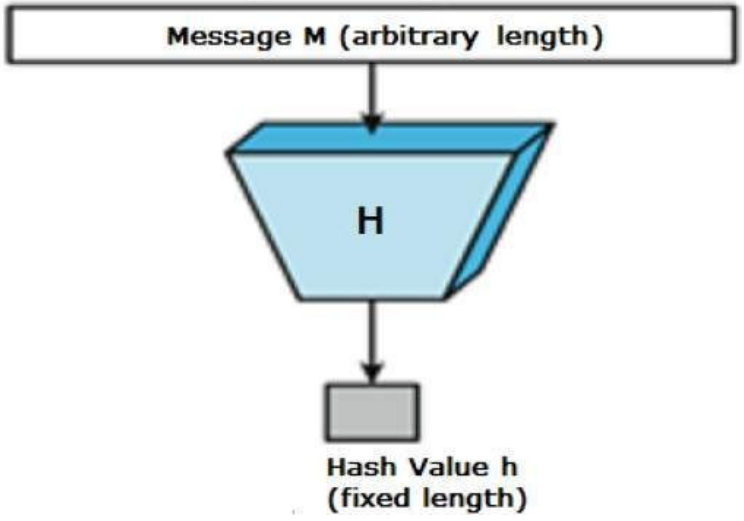
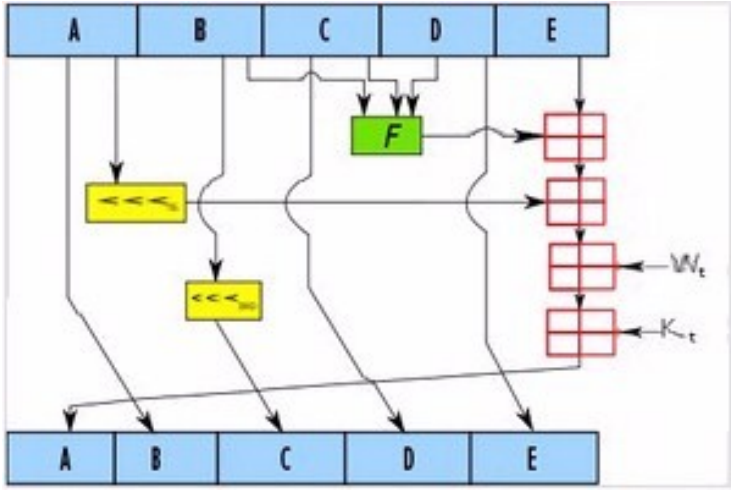
Hash functions (e.g., SHA2)





H : {messages of any size} → {256-bit messages}

such that:

H(x) = H(y) implies x = y with huge probability

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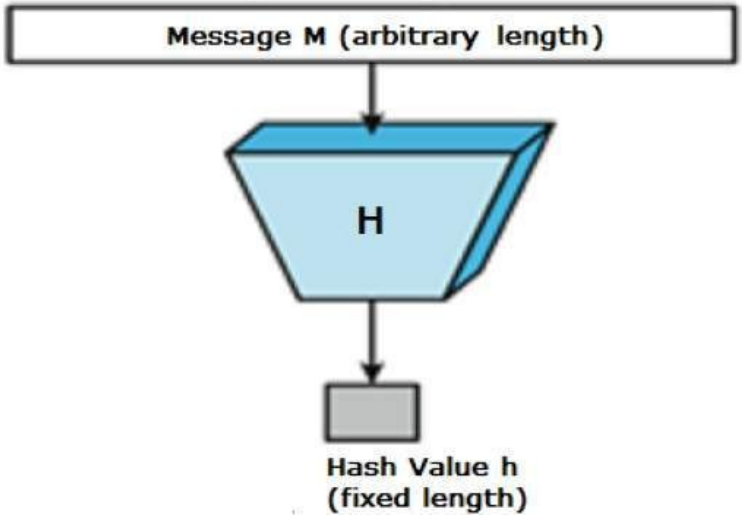

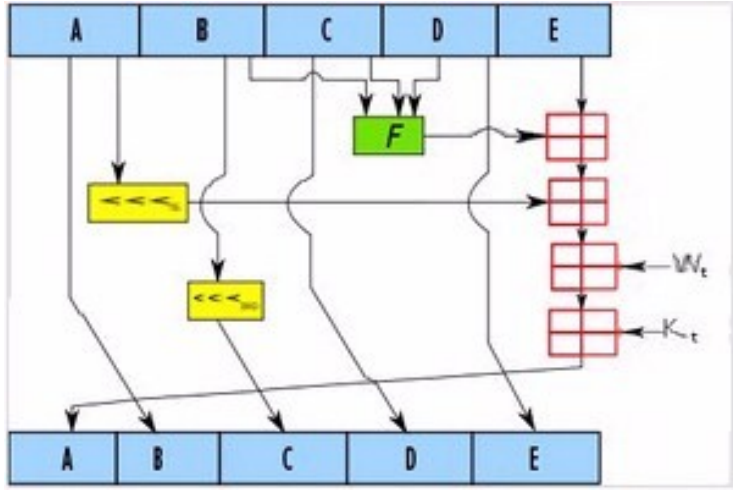

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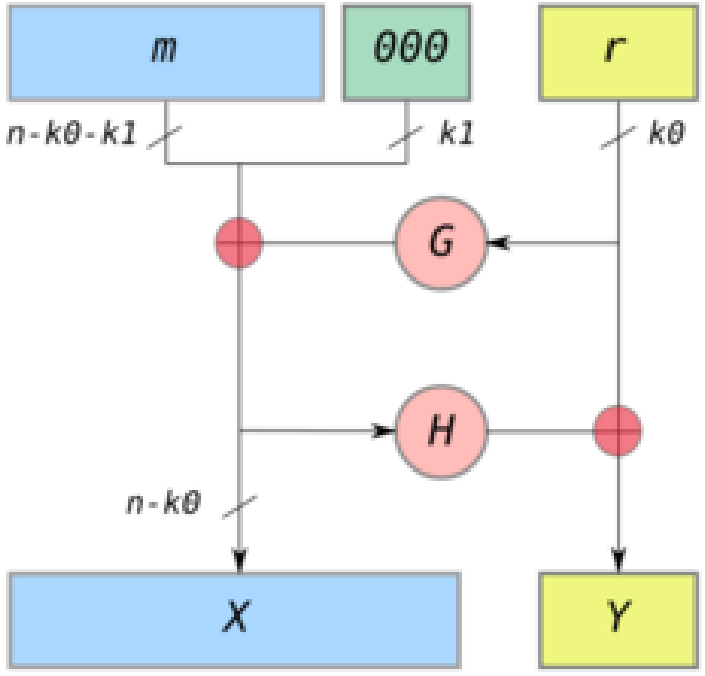
Public-key encryption (e.g., RSA-OAEP)

p, q prime
n = p*q
e * d = 1 mod (p-1)(q-1)
$C = M^e \bmod n$
$M = C^d \bmod n$



dec(dk(k), **enc(ek(k), r, m)**) = m

Hybrid encryption

- Unlike the case for symmetric key encryption, there are no “block modes” for public key encryption
  - Because public key encryption is too slow to do for very long messages.
- To encrypt a long message m using public key encryption with a public key pk:
  - Choose a random symmetric key, k
  - Encrypt m with k: c1=enc(k, r1, m)
  - Encrypt k with pk: c2=enc(pk, r2, k)
- Send c1, r1, c2.

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Digital signatures (e.g., Schnorr)

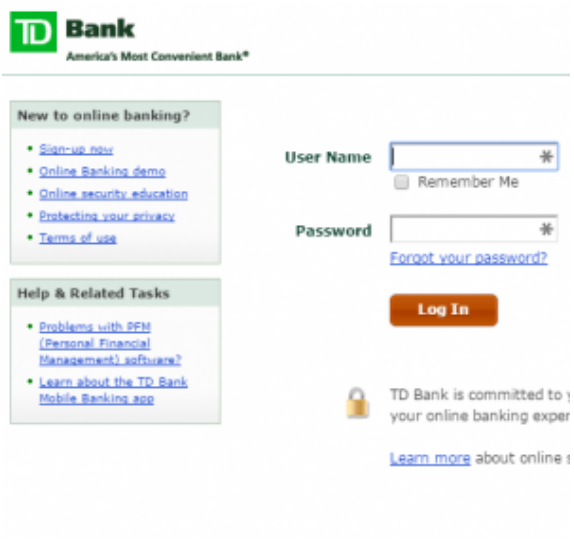
– Initialization (security parameter k) p, q, two large primes such that $q \mid (p-1)$ $2^{k-1} \leq q < 2^k$ g, element of $\mathbb{Z}_p^\star$ of order q f, hash function secret key $x \in \mathbb{Z}_q^\star$ public key $y = g^{-x} \bmod p$	– Signature – $K \in \mathbb{Z}_q^\star$ – $r = g^K \bmod p$ – $e = f(m, r)$ – $s = K + xe \bmod q$ – $\sigma_1 = r$ and $\sigma_2 = s$ – Verification – $e \stackrel{?}{=} f(m, r)$ – $r \stackrel{?}{=} g^s y^e \bmod p$

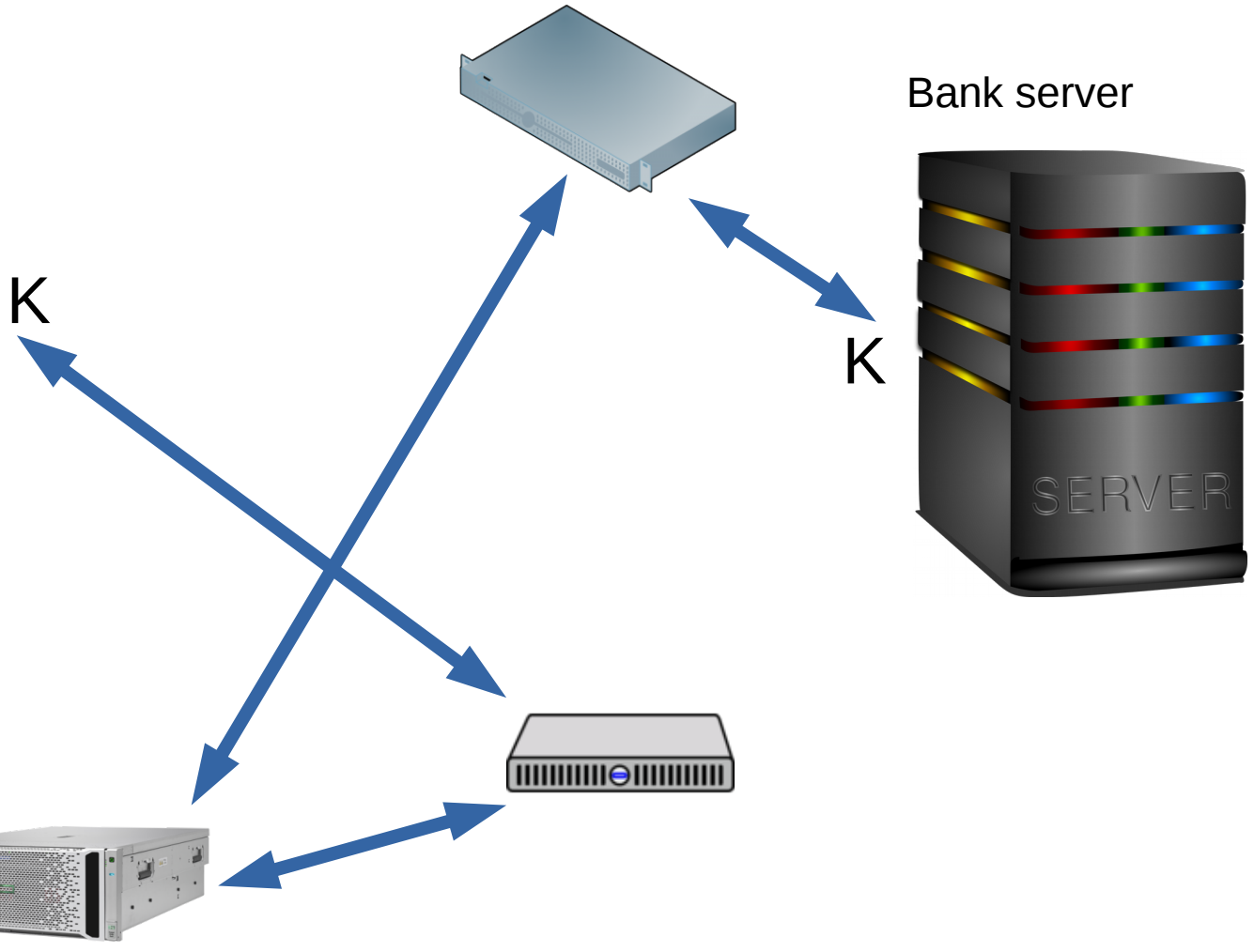
checksig(vk(x), m, **sign(sk(x), r, m)**) = true

2. Authenticating websites and encrypting web traffic

Encrypting browser-server communication: Encrypt with a shared key K

Browser

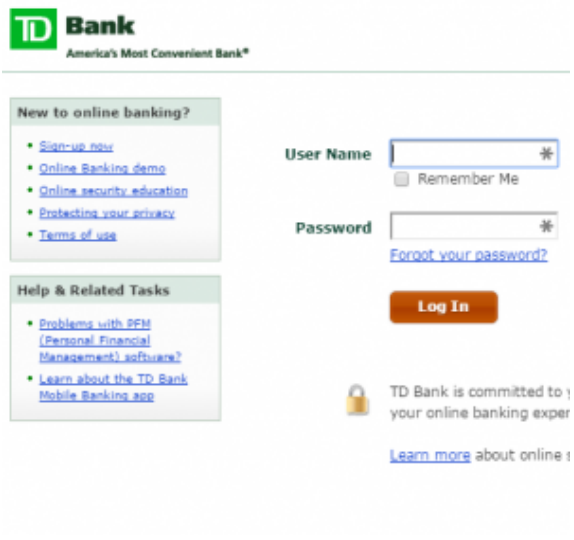




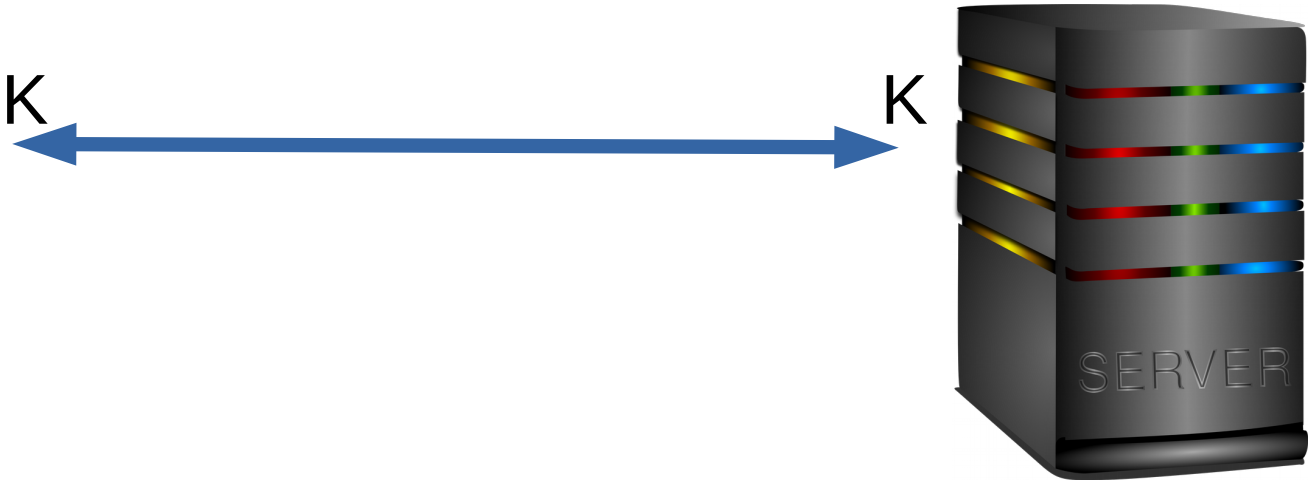
Bank server

Encrypting browser-server communication

Browser



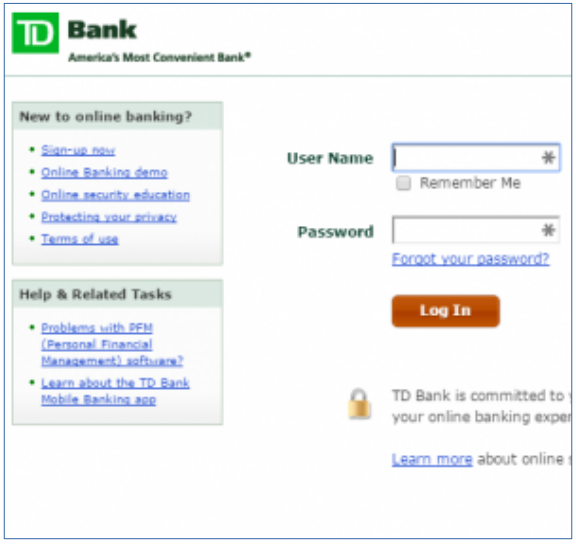
Bank server



How to set up the shared key?

Let’s say the server has a public key pk

Browser



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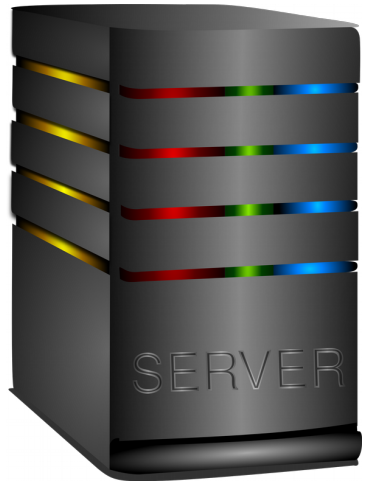


“hello”, random rb

pk, random rs

random pms
encrypted with pk

K = f(pms, rb, rs)

K = f(pms, rb, rs)

That’s TLS (in abstract form).

Issue: how can the Browser know it has the right pk?

3. The Certificate Authority model

TLS

- In TLS, the session encryption key is established from the server's public key.
- Thus, the browser needs to obtain the server's public key.
- How to achieve that?
  - The server sends it!
  - But how can the browser authenticate it?

How can a browser verify that
a given public key belongs to a given website?

Certificate authorities

- A certificate authority (CA) is a trusted party that asserts that a given public key belongs to a given website.
- The CA signs a certificate

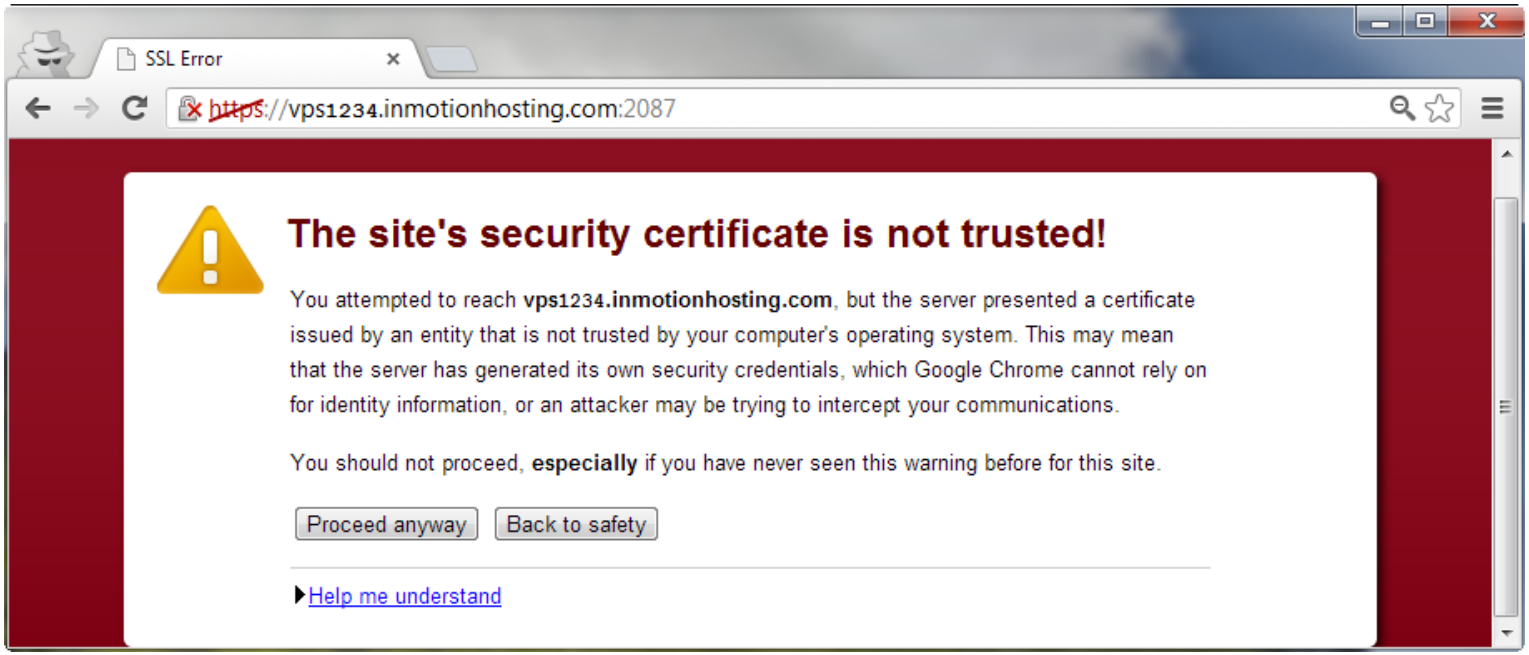
  Sign(sk_{CA}, (“HSBC Bank”, pk))

- The browser knows the verification key vk_{CA} needed to verify this signature.
  - It has lots of CA verification keys built in.

Problems with the CA model

- Usability:

  Incomprehensible certificate warnings



- Insecurity:

  Fake certificates… Any CA can sign an key

CA model broken

- **Comodo** reseller account broken into and used to fraudulently issue nine certificates, for Google, Microsoft, Yahoo, Mozilla, Skype. Comodo suggested attack was from Iran-based IP address. (March 2011)
- Wildcard certificate for Google issued by **DigiNotar**'s systems under the control of an attacker. Reported that Iranian government used certificates to spy on citizens. (August 2011)
- MitM attack against Facebook in Syria, by click-through of self-signed certificates, allegedly inserted by Syrian Telecom Ministry. (May 2011)
- **Trustwave** issued a MitM certificate for a company, allowing it to issue valid certificates for any server; used for *data loss prevention* and monitoring of staff use of Gmail and hotmail. (Feb 2012)

How to avoid attacks like these?

How to ensure that a browser obtains the correct public key for a website?

Interlude: recalling the twelve principles

1. Secure the weakest link
2. Defend in depth
3. Fail secure
4. Grant least privilege
5. Economise mechanism
6. Authenticate requests
7. Control access
8. Assume secrets not safe
9. Make security usable
10. Promote privacy
11. Audit and monitor
12. Proportionality principle

Principles that seem relevant to the CA model

1. Secure the weakest link
Significant weak link: *any* CA can sign a cert. for *any* domain.

2. Defend in depth
No layering of security

3. Fail secure
CA model fails insecure: invalid certs allow click-through

4. Grant least privilege
Not present. CAs have too much privilege

8. Assume secrets not safe. CA signing keys may not be safe.

9. Make security usable
Users don't understand certificate warnings

11. Audit and monitor
No opportunity for domain owners to audit what certificates are being used.

(a) Difference observation

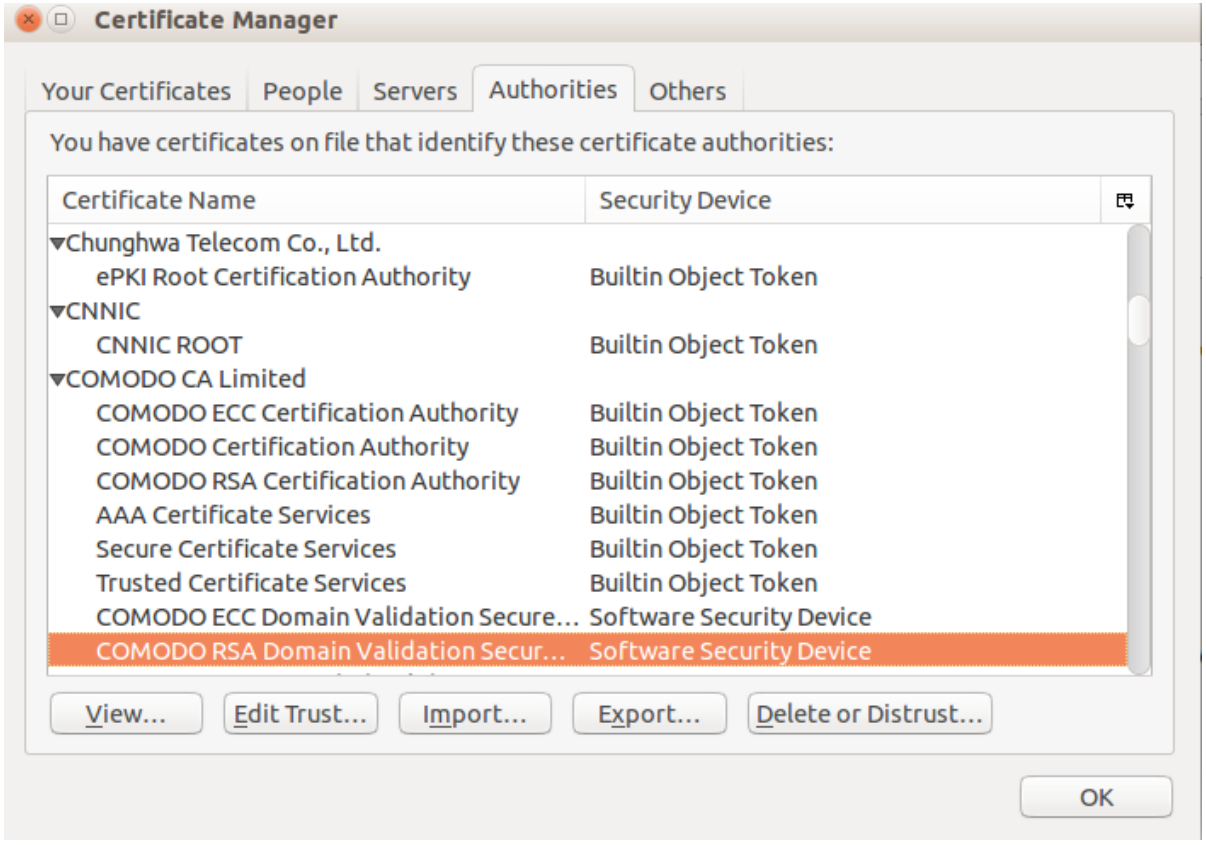
- Perspectives (2008): the browser asks a set of observers (called notary servers), in order to obtain “independent” views.
  - Strength: hard to attack
  - Weaknesses: false positives in case that a website genuinely has several keys or is transitioning between keys; Reveal browsing history to notaries.
- DoubleCheck (2009), Convergence (2011) are variations on this idea.
- CertificatePatrol is another variation, focussing on observing differences across time rather than space.

Overall weakness: pushing problem to user.

(b) Scope restriction

- Focusses on the problem that, in the CA model, ***any*** CA in your browser can certify ***any*** website you visit.

- There are >1000 certificates in your Firefox browser.



(b) Scope restriction

- Public-key pinning:
  A mechanism for domain owners to specify which CAs are authorised to issue certificates for them.
  - Example: Google Chrome knows not to accept certificates for google.com from illigitimate CAs.
- DANE: Build in to DNSSEC. Only a parent domain can sign certificates for sub-domains.

- Weaknesses:
  - Difficult to scale
  - Requires trust in scope definition

(c) Certificate transparency [Laurie, Kasper, Langley 2012]

Aim: ensure that whenever a CA signs a certificate, there is persistent evidence of this fact. A CA cannot sign certificates inadvertently/sneakily.

Mechanism: An *append-only public log* is maintained, consisting of certificates issued by all CAs.

- A certificate is accepted only if it is included in the log. (The certificate comes with proof that it is included in the log.)
- Domain owners can check that certificates about them in the log are really theirs.

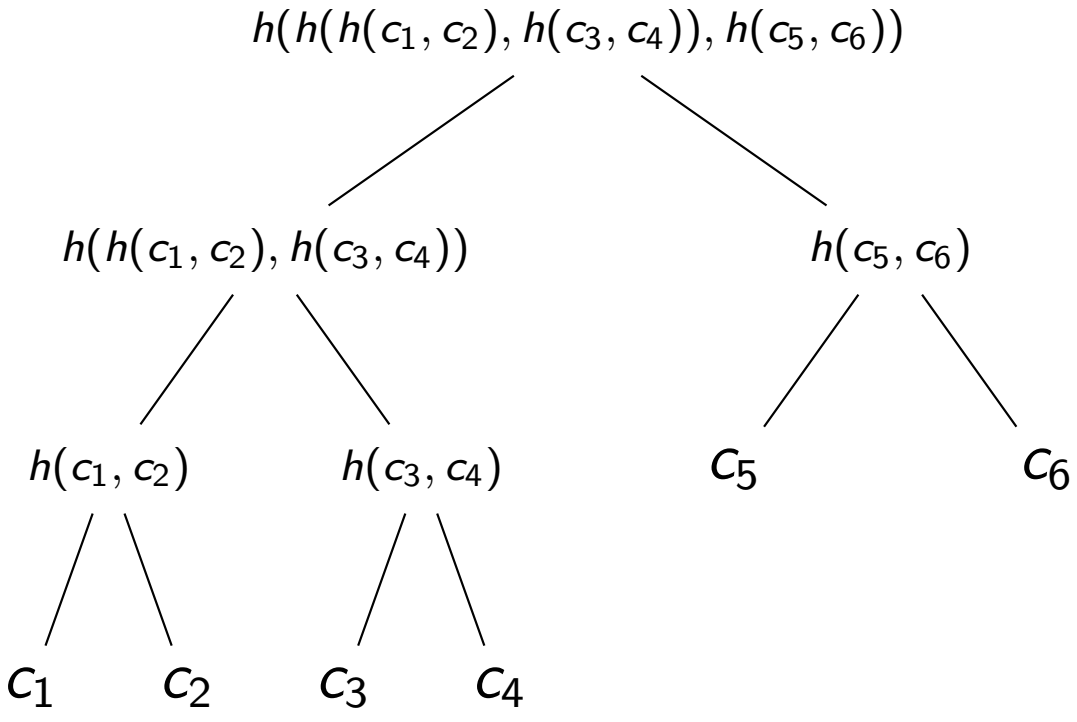
Users' client software checks the proofs, and also checks that the log is append-only and linear.

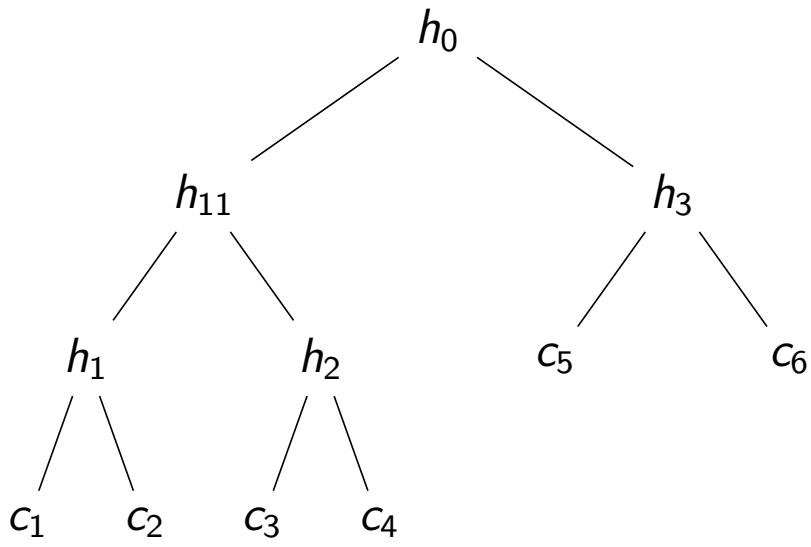
Status: IETF draft; RFC. *January 2015:* Google Chrome checks Google's CT logs for EV certificates.

4. Certificate transparency

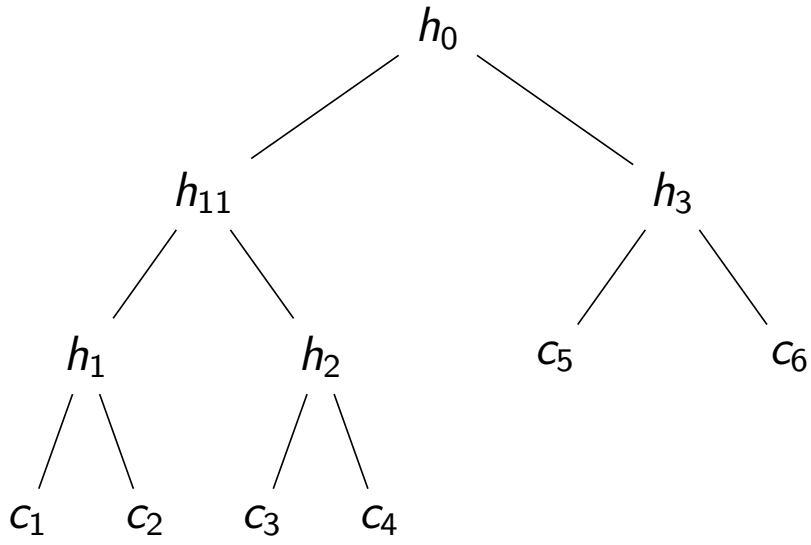
Certificate transparency: append-only public log

A log storing certificates $c_1, c_2, c_3, c_4, c_5, c_6$:





$\mathsf{prove\_presence}(c_{11}, h_{21})$
$= (c_{12}, h_5, h_{14}, h_{16}, h_{20})$.



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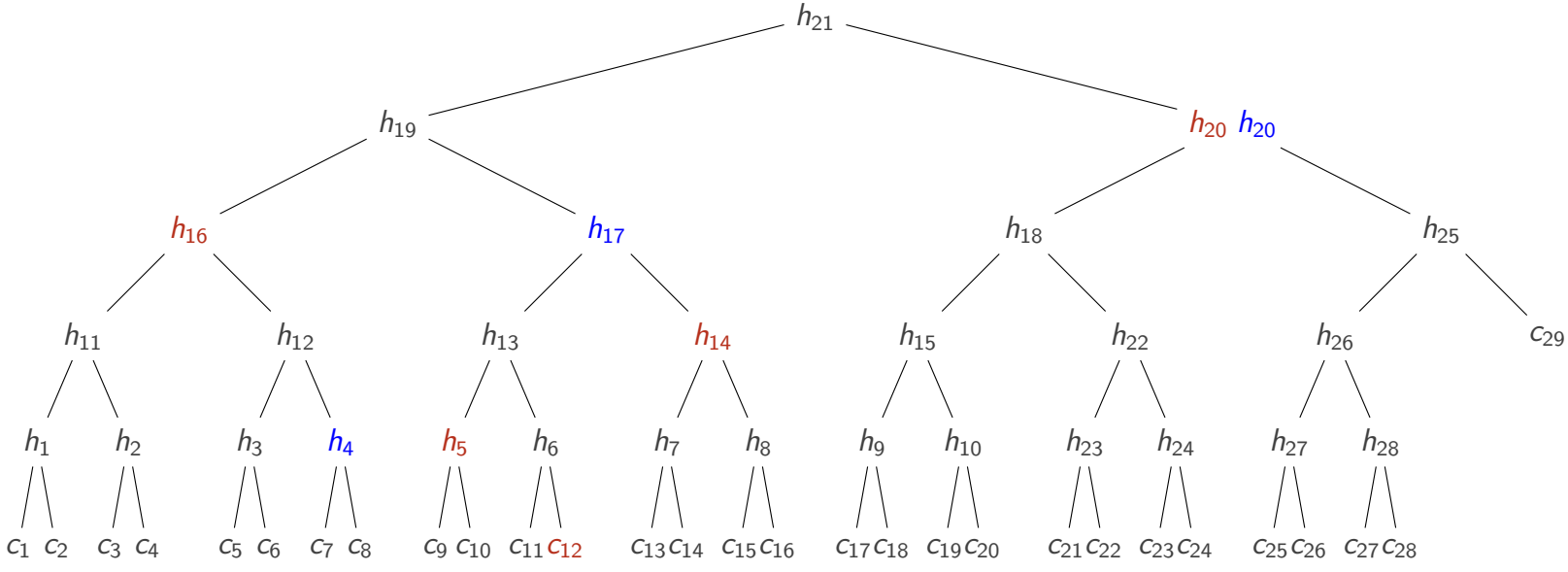
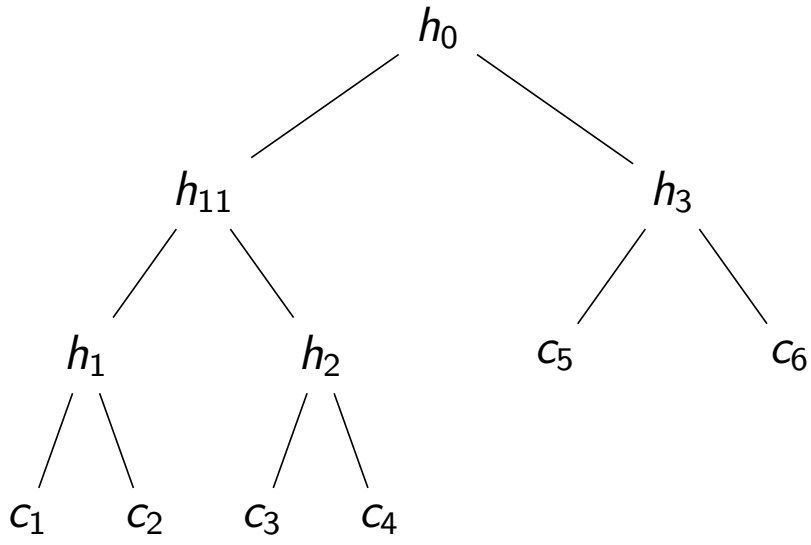
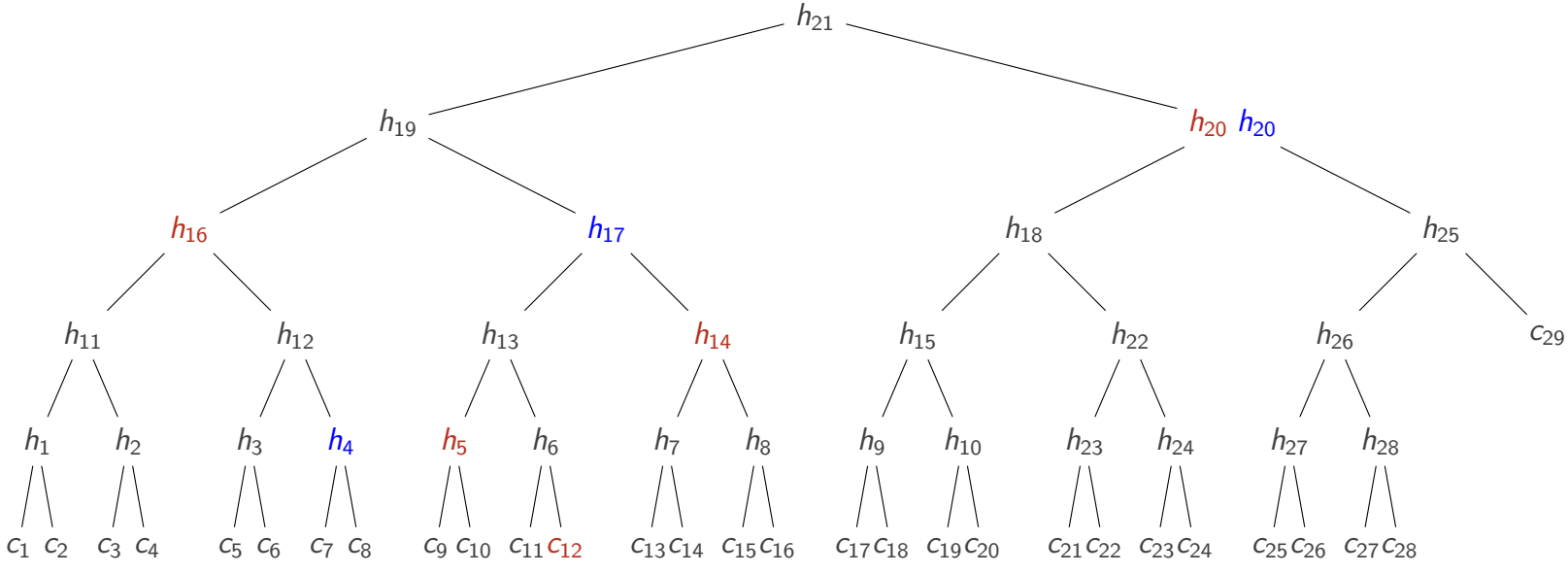




prove_presence(c_{11}, h_{21})
$= (c_{12}, h_5, h_{14}, h_{16}, h_{20})$.

prove_extension(h_0, h_{21})
$= (h_{11}, h_3, h_4, h_{17}, h_{20})$.



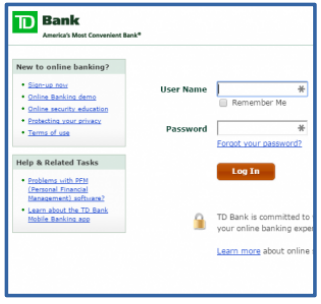
Algorithms on chronological trees (ChronTrees)

Algorithm	Complexity	Typical size 10^9 certif.
request_h()	$O(1)$	0.25 KB
prove_presence(h, *cert*)	$O(\log n)$	2 KB
prove_extension(h_1, h_2)	$O(\log n)$	2 KB

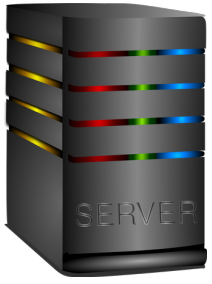
Certificate transparency: summary of operation

- A CT log maintains a list of all issued certificates.
- If a certificate is present in the log, it adds assurance as to the validity of the certificate, because. . .
- A domain owner can discover all the certificates about it that are present in the log.
- Browsers consult the log to verify that certificates presented to them are present in the log:
  - The log is organised as a Merkle tree, to facilitate *proofs of presence*.
- Browsers can also verify that the log is being maintained 'append only':
  - The Merkle tree organisation also facilitates *proofs of extension*.

CT is vulnerable to a *fork attack*



Browser sees a version of the log that contains an **invalid** certificate for the server.



Server sees a version of the log that contains only **valid** certificates for the server.

Browser and Server are seeing different views of the log. This kind of attack could be perpetrated by a powerful adversary, such as a government.

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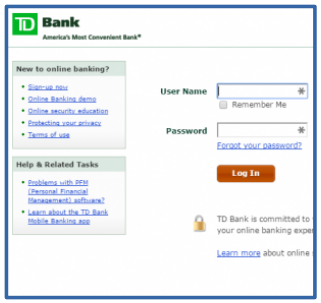

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Possible solution: *gossip protocols*

Revisiting the principles w.r.t. the CT model

1. Secure the weakest link
Significant weak link: *any* CA can sign a cert. for *any* domain. *Still true, but the domain owner now knows.*

2. Defend in depth
CA and log maintainer provide layering.

3. Fail secure
CT aim is to force hard-fail.

4. Grant least privilege
CA privilege much reduced

8. Assume secrets not safe.
Usefulness to attacker of CA signing key much reduced

9. Make security usable
Aim for users not to have to see cert warnings - hard fail instead

11. Audit and monitor
Certificate logging increases transparency

5. Certificate transparency: revocation

Key revocation

- If the secret key corresponding to a public key is accidentally divulged, or access to it is lost, then the key has to be *revoked*.
  - Revocation can be caused by lost/forgotten passwords, hacked accounts, lost computers or storage, etc.
- To support this, we need more than a *proof of presence*, i.e. a proof that the certificate was once issued.
  - We need *proof of currency* in the log: a proof that the certificate was issued, and has not subsequently been revoked.
  - Another way to see this is: we need *proof of absence* of a revocation in the log.
    current $=$ present $\wedge$ $\neg$revoked
- Technical challenge: extend CT to support efficient proofs of absence

Algorithms on chronological trees (ChronTrees)

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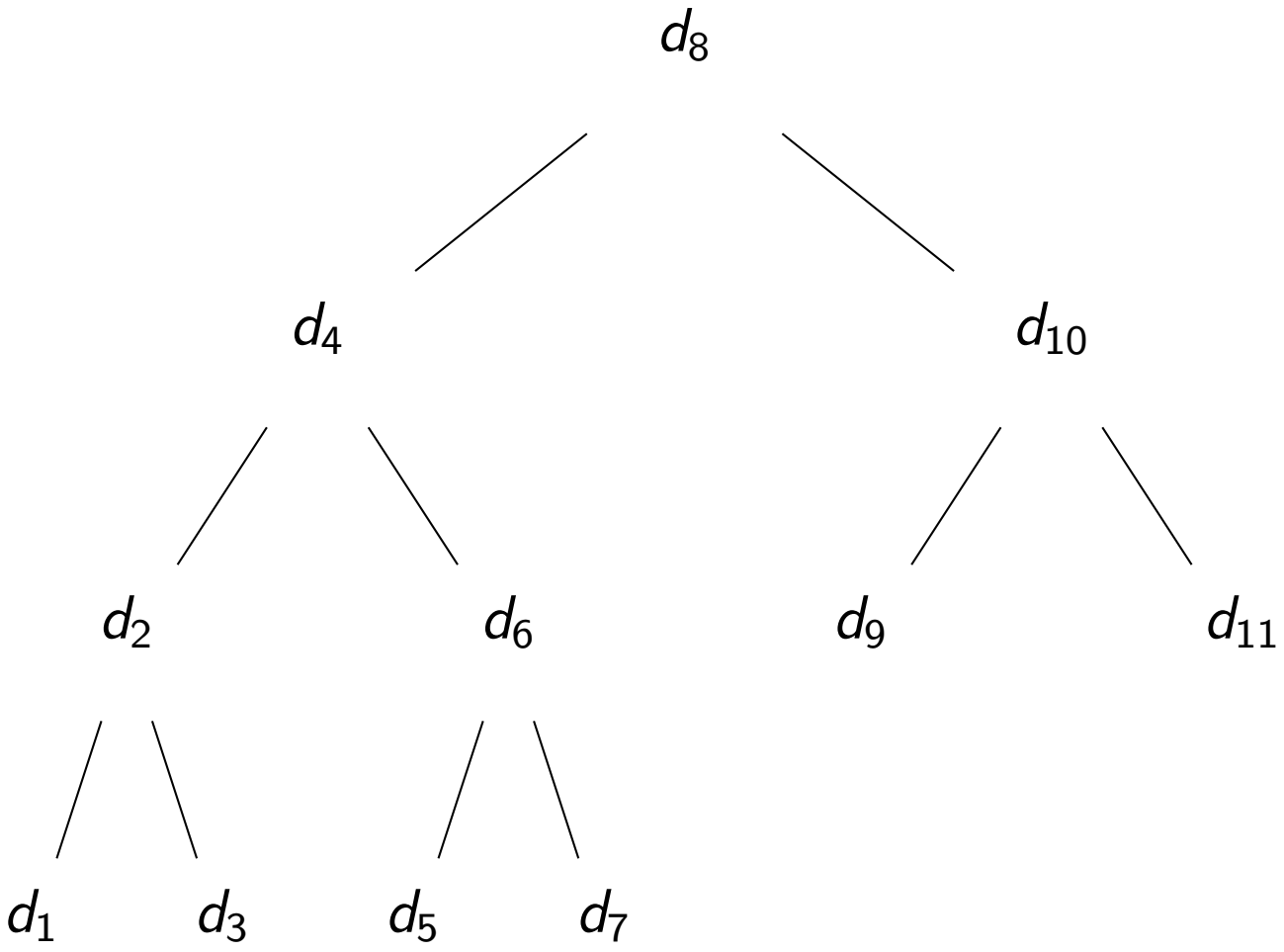
prove_extension(h_1, h_2)	$O(log\, n)$	2 KB
prove_absence(h, *subj*)	$O(n)$	60 GB
prove_current(h, *cert*)	$O(n)$	60 GB

Lexicographic trees (LexTrees)

Arrange as binary search tree in lexicographic order of subject, with $d_i = (subj_i, cert_i)$:



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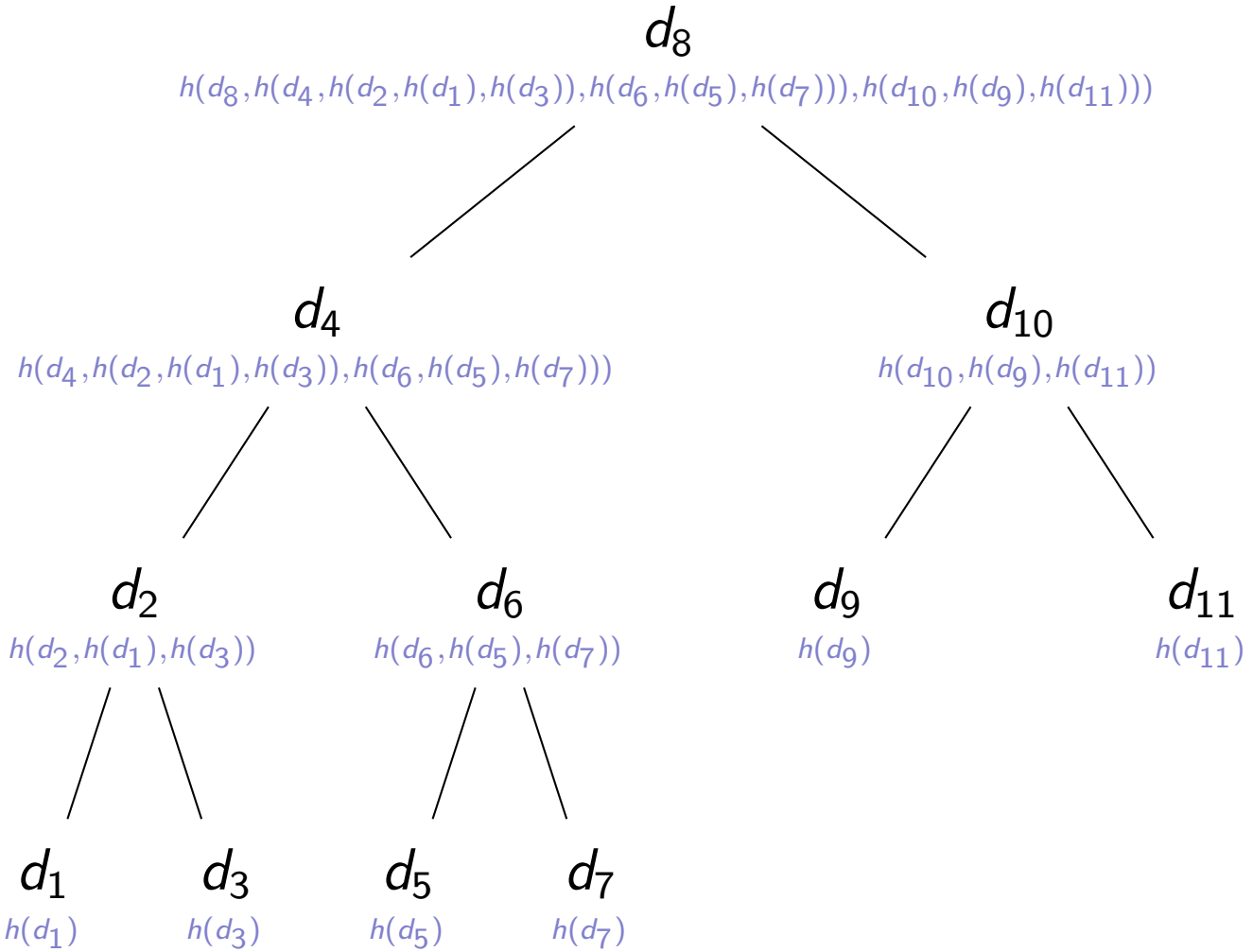


Proof of absence in a LexTree

To prove there is no key for *subj*, the log maintainer provides a proof of adjacent presence:

- proof of presence for $subj_1$;
- proof of presence for $subj_2$;
- proof that $subj_1$ and $subj_2$ are neighbours;

Client verifies the proofs, and also that $subj_1 < subj < subj_2$ lexicographically.

Certificate issuance and revocation transparency

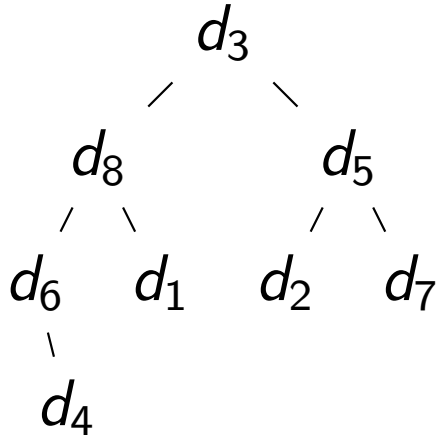
Somehow, get the best of both worlds:

- Use LexTree idea to produce proof of presence and proof of absence.
- Use ChronTree idea to produce proof of presence and proof of extension.

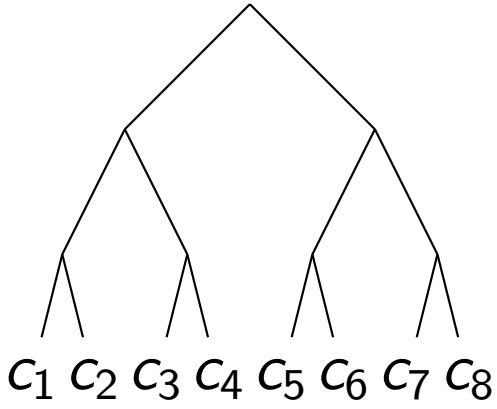
We call this *certificate issuance and revocation transparency* (CIRT).

Certificate Issuance and Revocation Transparency

LexTree

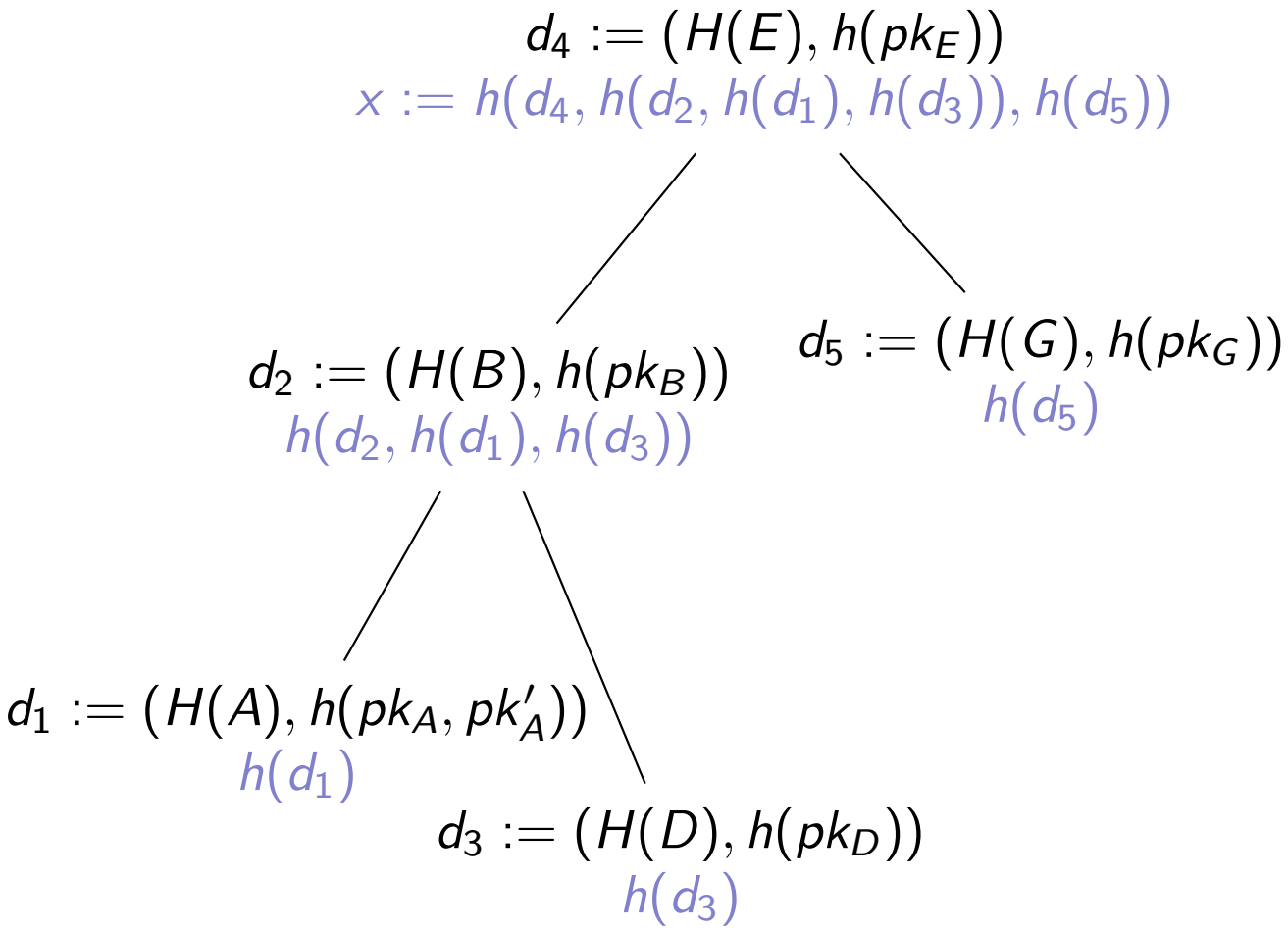


ChronTree



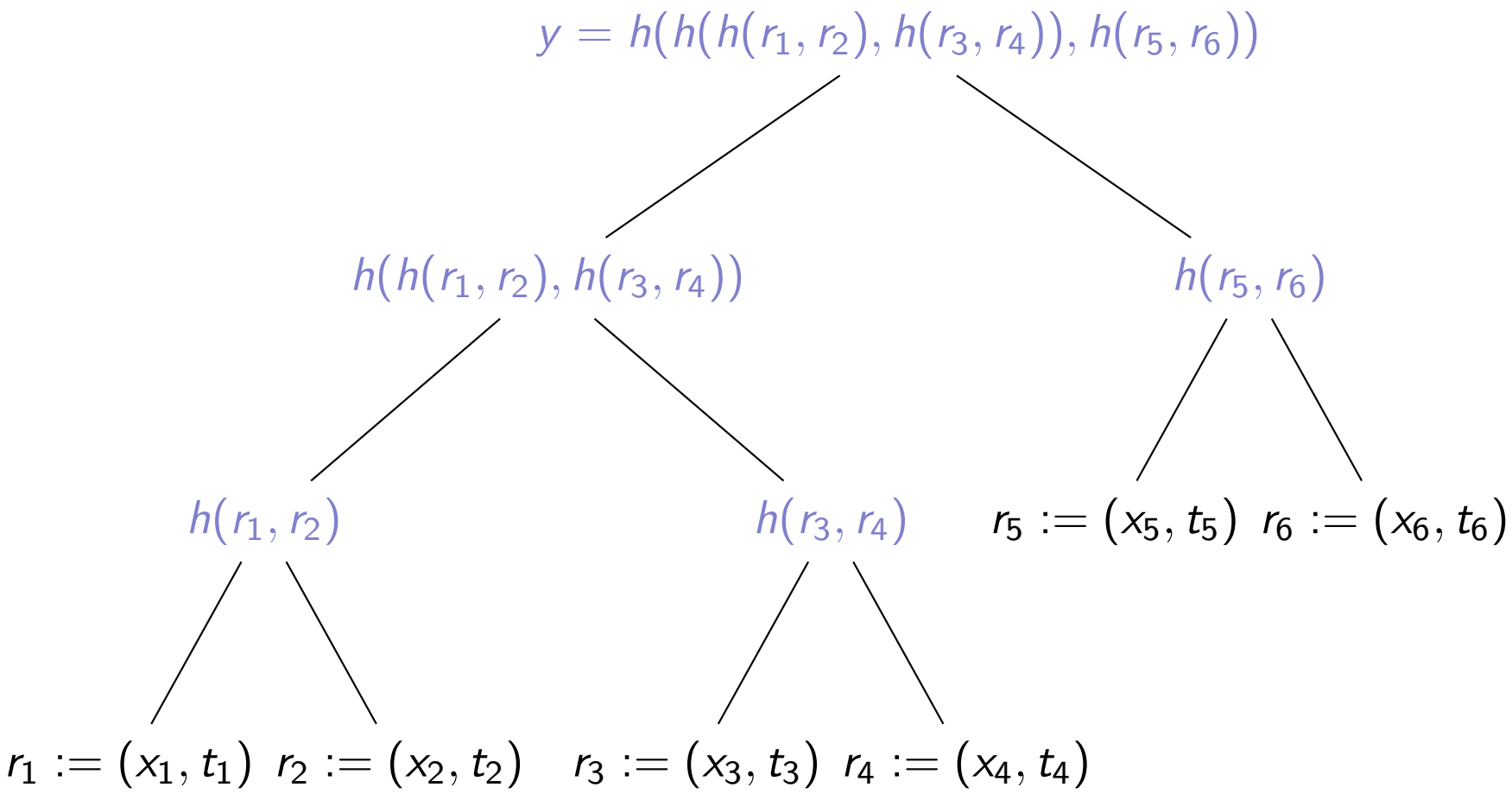
Proof of		
presence	$O(\log n)$	$O(\log n)$
absence	$O(\log n)$	$O(n)$
extension	$O(n)$	$O(\log n)$
consistency	$O(n)$	

CIRT data structures: lextree



The sequence of root-tree hashes is $x_1, x_2, \ldots$.

CIRT data structures: chrontree



The sequence of root-tree hashes is $y_1, y_2, \ldots$.

Consistency checking

Two ways to check ChronTree/LexTree sync:

- Total: receive all updates, and check everything.
- Random: user client software specifies random i, and requests proof that $\mathrm{LT}(l_i) = \mathrm{LT}(l_{i-1}) + c_i$.

Algorithms on CIRT data structure

Algorithm	Complexity
request_h()	$O(1)$
prove_presence(y, *cert*)	$O(log\, n)$
prove_extension(y_1, y_2)	$O(log\, n)$
prove_absence(y, *subj*)	$O(log\, n)$
prove_current(y, *cert*)	$O(log\, n)$
prove_consistent_part(y, b)	$O(log\, n)$

CIRT: summary of operation

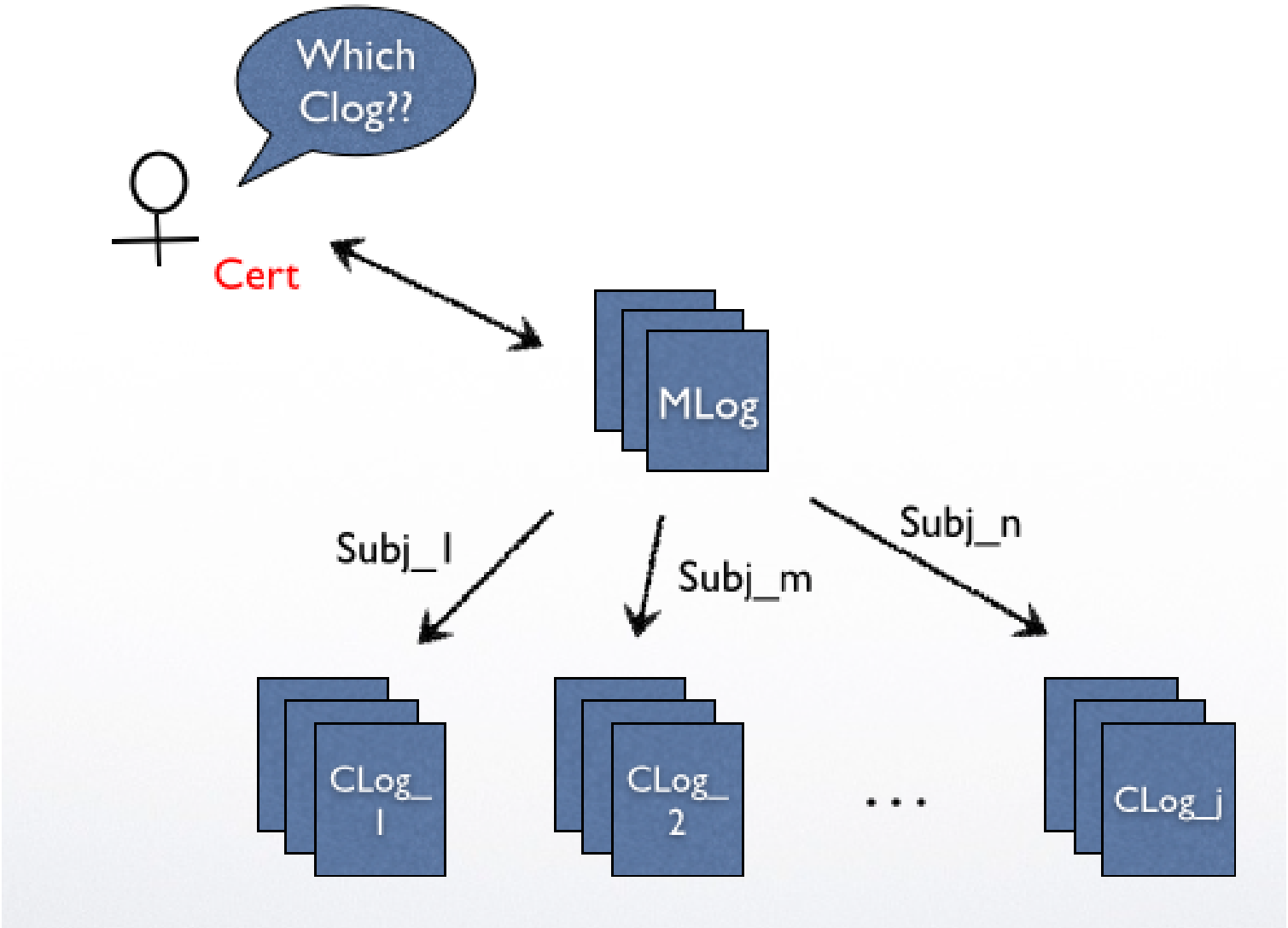
- A CT log maintains a list of all issued certificates.
- If a certificate is present in the log, it adds assurance as to the validity of the certificate, because. . .
- A domain owner can discover all the certificates about it that are present in the log (easier now!)
- Browsers consult the log to verify that certificates presented to them are current in the log:
  - The log is organised using Merkle trees, to facilitate *proofs of currency*.
- Browsers can also verify that the log is being maintained 'append only' (a bit more complex now)
  - The proof of extension is done at two levels: extension of the ChronTree, and append-only of each LexTree.

DTKI

Distributed **T**ransparent **K**ey **I**nfrastructure

- Minimisation of monopoly
- Free of trusted parties
- Formalisation of data structure
- Proofs of data structure properties

Mapping log (Mlog)



Conclusions

- Authenticating websites is a surprisingly hard problem.
- The CA model that we have been using for 20+ years is no longer adequate
- Certificate transparency seems to be the most promising upcoming solution
- Related to the blockchain - also trendy :-)
- Certificate revocation can also be solved in this framework
- Still need to detail a solution for the fork attack