CSE 3400/CSE 5850 - Introduction to Computer & Network Security / Introduction to Cybersecurity

Lecture 12

Public Key Infrastructure

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***Adapted from the textbook slides**

Outline

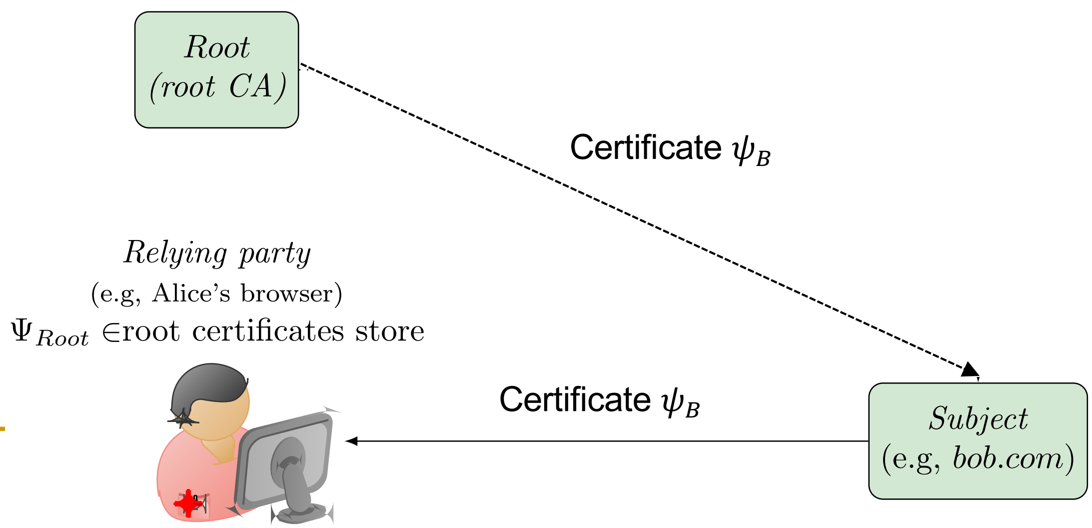
- Motivation.
- Public key infrastructure (PKI) components.
- PKI goals.
- X.509 PKI concepts.
- Intermediate CAs and trust path verification.
- Certificate revocation.

Public keys are very useful…

- Secure web connections.
- Software signing
- Secure messaging, email.
- Cryptocurrency and blockchains.
- But … how do we know the public key of an entity? And how can we trust that this entity is indeed who claims to be and that she owns a specific public key?
    - Mainly: the key must be signed by a **trusted Certificate Authority (CA).**
- ***Public key infrastructure (PKI)*** defines how to issue, manage and use such certificates.

Public Key Certificates & Authorities

- **The big picture:** when receiving a party's (the **subject**) public key, it will be accompanied with a certificate.
  - A valid certificate means that the entity is who claims to be and she owns the corresponding the public key.
- **Certificate:** signature by a **Certificate Authority (CA)** over subject's public key and attributes.
- **Attributes:** identity (ID) and others…
  - Validated by CA (liability?)
  - Used by **relying party** for decisions (e.g., use this website?)



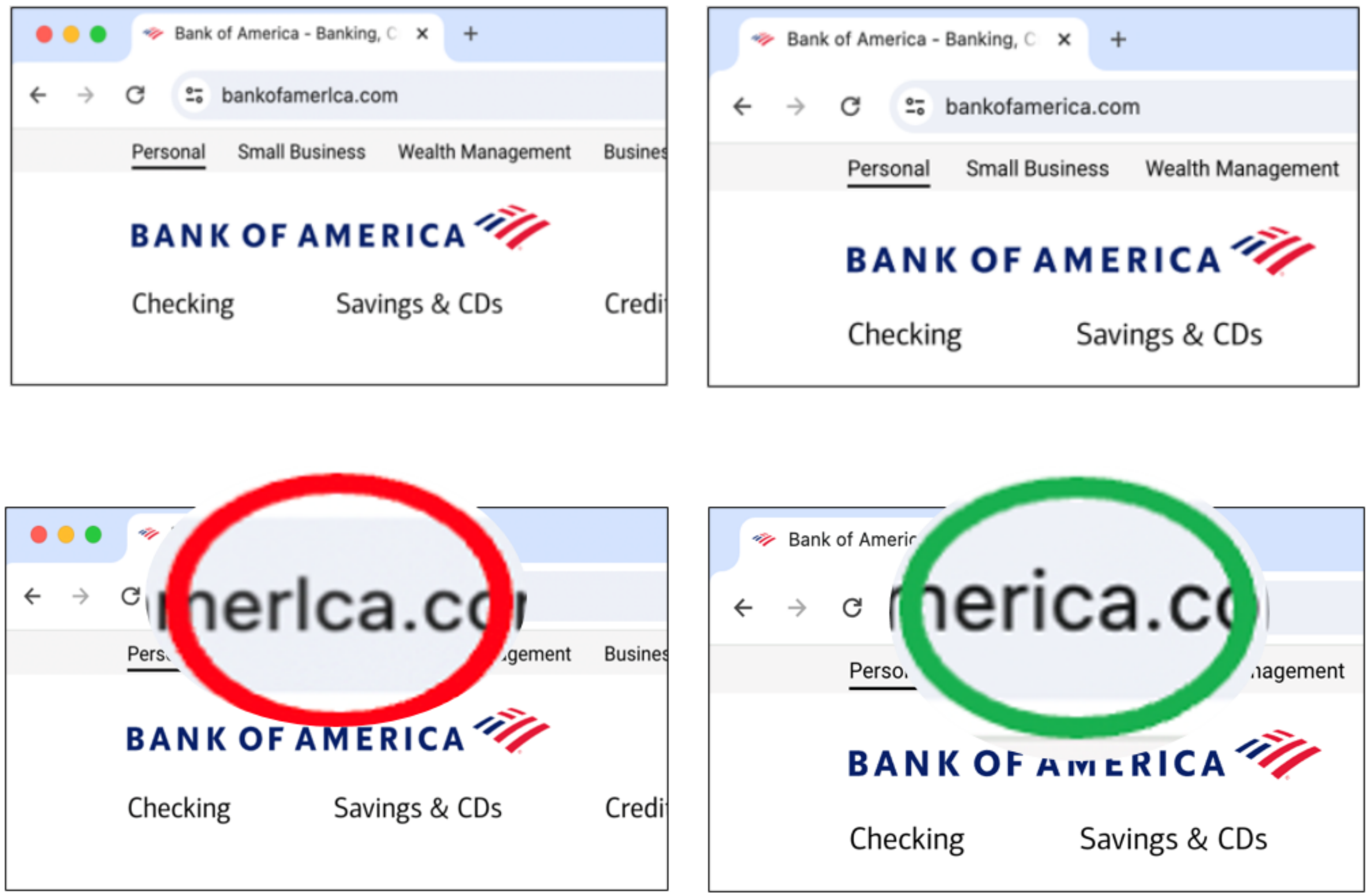
Certificates are all about **Trust**

- Certificate: $\psi_{Bob} = Sign_{CA.s}(Bob.com, Bob.e, \ldots)$
  - CA attests that Bob’s public key is $Bob.e$
- Do we **trust** this attestation to be true?
- Special case of **trust management**
  - Important problem far beyond PKI… still not resolved!

Rogue Certificates

- Rogue certificates: certificates that contain wrong or misleading information.
  - So they should fail PKI validation.
- Attacker goals:
  - Impersonate: web-site, phishing email, signed malware..
  - Equivocating (same name): circumvent name-based security mechanisms, such as *blacklists, access-control* …
- Types of misleading names:
  - Combo names: bank.com vs. accts-bank.com, bank.accts.com, …
  - Domain-name hacking: accts.bank.com vs. accts-bank.com, … or accts-bank.co
  - Homographic: paypal.com [l is L] vs. paypaI.com [i is I]
  - Typo-squatting: bank.com vs. banc.com, baank.com, banl.com,…

Example of Homographic Attacks

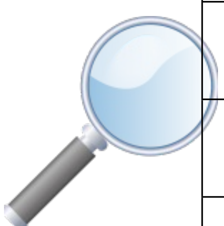


PKI Failures

- Although the signature over the certificate verifies correctly, there is still a failure and the certificate must be revoked.
  - This is called a PKI failure.
- PKI failures include:
  - Corrupt CA.
  - Validation failure.
  - Exposed CA private key.
  - Cryptanalysis certificate forgery.
    - Find collisions in the hash function used in the HtS paradigm,
    - or exploit some vulnerability in the digital signature scheme used for signing.

Some Infamous PKI Failures

CA, year(s)	Description and Reference
Verisign, 2001	VeriSign issues Microsoft code-signing certificates to attacker [167].
Thawte, 2008	Validation failures of Thawte and StartSSL [455].
Comodo, 2008	CertStar, a reseller of Comodo, issued certificates without validation [299].
Comodo, 2011	Rogue certificates for major sites (e.g., Gmail) [261, 291, 343].
DigiNotar, 2011	DigiNotar CA compromised, 531 rogue certificates found, including for **.google.com*, used for MitM against Iranian users [291, 440].
TurkTrust, 2011-2012	TurkTrust issued intermediary CAs certificates to end entities; abused to issue certificate for **.google.com* (detected on Dec. 2012) [282].
Trustwave, 2012	Trustwave issued intermediary CA certificate for eavesdropping [368].
ANSSI, 2013	ANSSI (French CA) issued intermediary CA certificate for MitM [445].
NICCA, 2014	Intermediary CA NICCA (India) issued rogue certs for Google domains [284].
CNNIC, 2015	Rogue certificates issued by MCS (Egypt), certified by CNNIC (China) [152, 332].
WoSign, 2015	WoSign and StartCom (owned by WoSign) removed from revoked as CAs after validation and other failures
Symantec, 2015-17	Symantec issued unauthorized certs for over 176 domains [352].
DarkMatter, 2019	Mozilla, Google revoke intermediary CA of surveillance firm DarkMatter [68], refuse to make it a root CA.
Let's Encrypt, 2020	Let's Encrypt detected a bug in their CAA-validation code, affecting 3 million certificates [1].
TrustCor, 2022	Root CA TrustCor exposed as related to Spyware [318].



PKI Goals/Requirements

- **Trustworthy issuers:** Trust anchor/root CAs and Intermediary CAs; Limitations on Intermediary CAs (e.g., restricted domain names)
- **Accountability:** identify issuer of a given certificate
- **Timeliness:** limited validity period, timely **revocation**
- **Transparency:** public log of all certificates; no ‘hidden’ certificates!
- **Non-Equivocation:** one entity – one certificate
- **Privacy:** why should CA know which site I use?

X.509 Certificates

Part of the X.500 Global Directory Standard

The X.509 Standard Certificate Format

- Published by ITU (International Telecommunication Union) in 1988 as part of the X.500 global directory standard.
- Idea: Signature binds **public key** to distinguished name (DN) and to other attributes
  - Some defined in X.509 standard, others in \`extensions\`
- Used widely despite complaints about its complexity.
  - SSL/TLS, code-signing, IP-Sec, …

X.509 V1 Certificate Format

Signed fields	Version
	Certificate serial number
	Signature Algorithm Object Identifier (OID)
	Issuer Distinguished Name (DN)
	Validity period
	Subject (user) Distinguished Name (DN)
	Subject public key information — Public key Value; Algorithm Obj. ID (OID)
	Signature on the above fields

X.509 V1 Certificate Format

- **Version:** the version of X.509 (for V1 it is 1 and so on).
- **Certificate serial number:** a serial number of the certificate, unique among all the certificates issued by this CA.
- **Signature algorithm OID:** an object identifier (OID) for the signature algorithm used to sign the certificate.
- **Issuer DN:** the Distinguished Name (DN) of the issuer of the certificate.
- **Validity period:** the period during which the certificate is supposed to be valid.
- **Subject DN:** the Distinguished Name (DN) of the subject of the certificate, i.e., the entity to whom the certificate was issued.
- **Subject public key information:** includes two parts, one containing the certified public key, and the other providing an OID to identify the public key algorithm with which this public key is to be used.
- **Signature (produced by CA):** a signature over the above fields.

X.509 Certs & Subject Identifiers

- V1: Distinguished Name (for subject & issuer)
- V2: Unique identifiers (for subject & issuer)
- V3: Extensions (used in practice)
  - Some defined in X.509, others elsewhere

X.509 Certificate Format – Later Versions

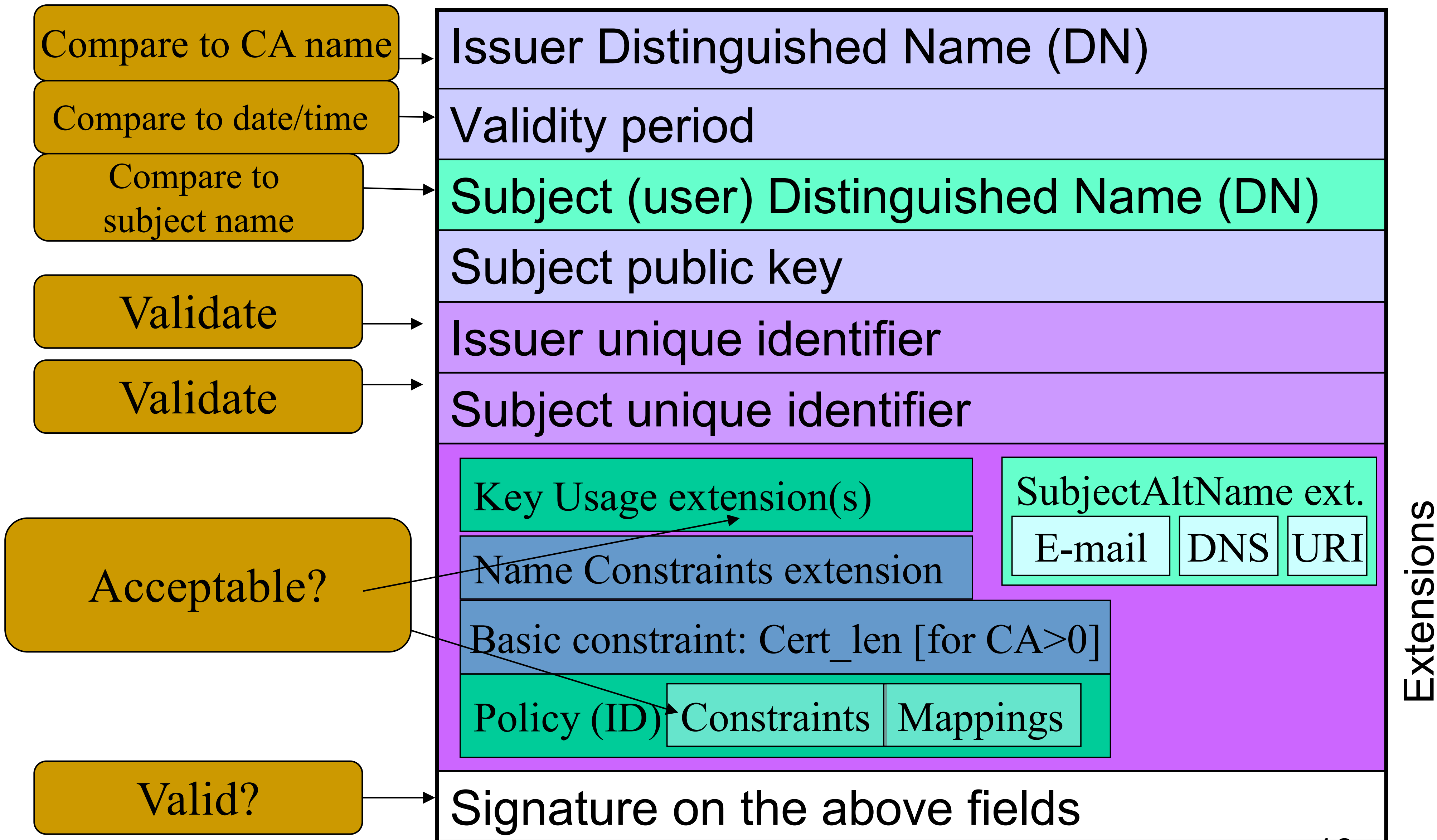
Signed fields

Version
Certificate serial number
Signature Algorithm Object Identifier (OID)
Issuer Distinguished Name (DN)
Validity period
Subject (user) Distinguished Name (DN)
Subject public key information — Public key Value; Algorithm Obj. ID (OID)
Issuer unique identifier (from version 2)
Subject unique identifier (from version 2)
Extensions (from version 3)
Signature on the above fields

X.509 Certificate Format – Later Versions

- **Issuer and subject unique identifiers (V2):**
  - Added to ensure uniqueness to handle situations where the DN may fail to ensure uniqueness.
  - Not widely used.
- **Extensions (V3):**
  - Additional fields to increase the expressiveness of X.509 certificates to facilitate more applications and end users.
  - Examples include limitations on which application the certificate or public key can be used for, certificate path constraints, policy constraints, etc.
  - We will not cover these in this course. More details are in a Network Security course.

X.509 Certificate Validation (simplified)

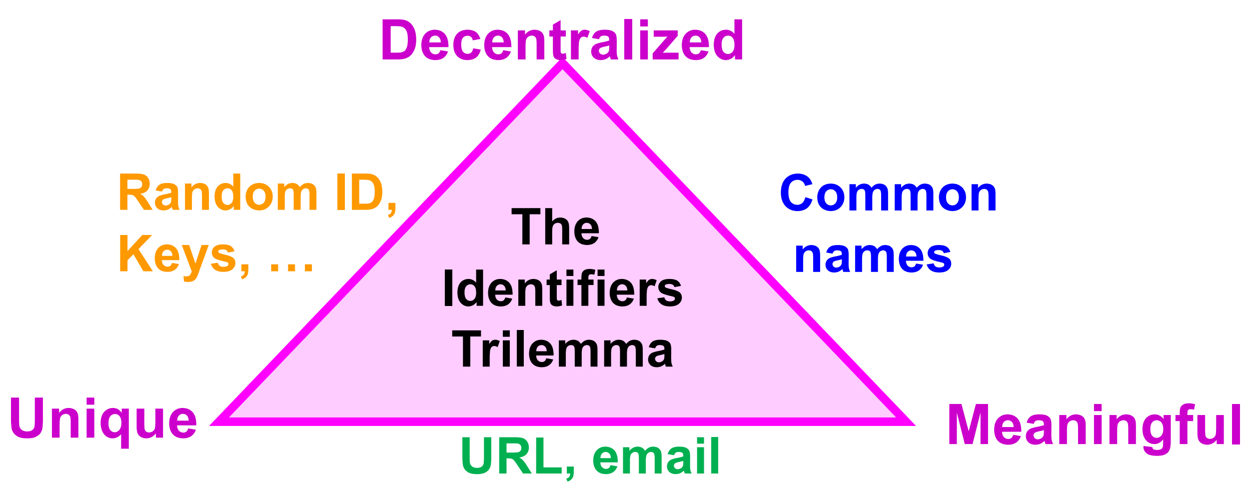


Distinguished Names

- Most certificates contain identifiers.
- Influenced by telecommunication providers.
  - Phone directory services are based on common names.
- Basic goals of identifiers:
  - Meaningful (to humans)
    - Memorable, reputation, etc.
  - Unique identification of entity (owner)
  - Decentralized - with accountability: assigned by trusted (certificate) authorities
    - Accountability: identification of the signing authority

The Identifiers Trilemma

- Achieving the three goals: Meaningful, Unique, Decentralized, seems very challenging!
- Examples of achieving any two of the goals:
  - Unique + Meaningful: URL, email
  - Meaningful + Decentralized: common name
  - Unique + Decentralized: hash of key

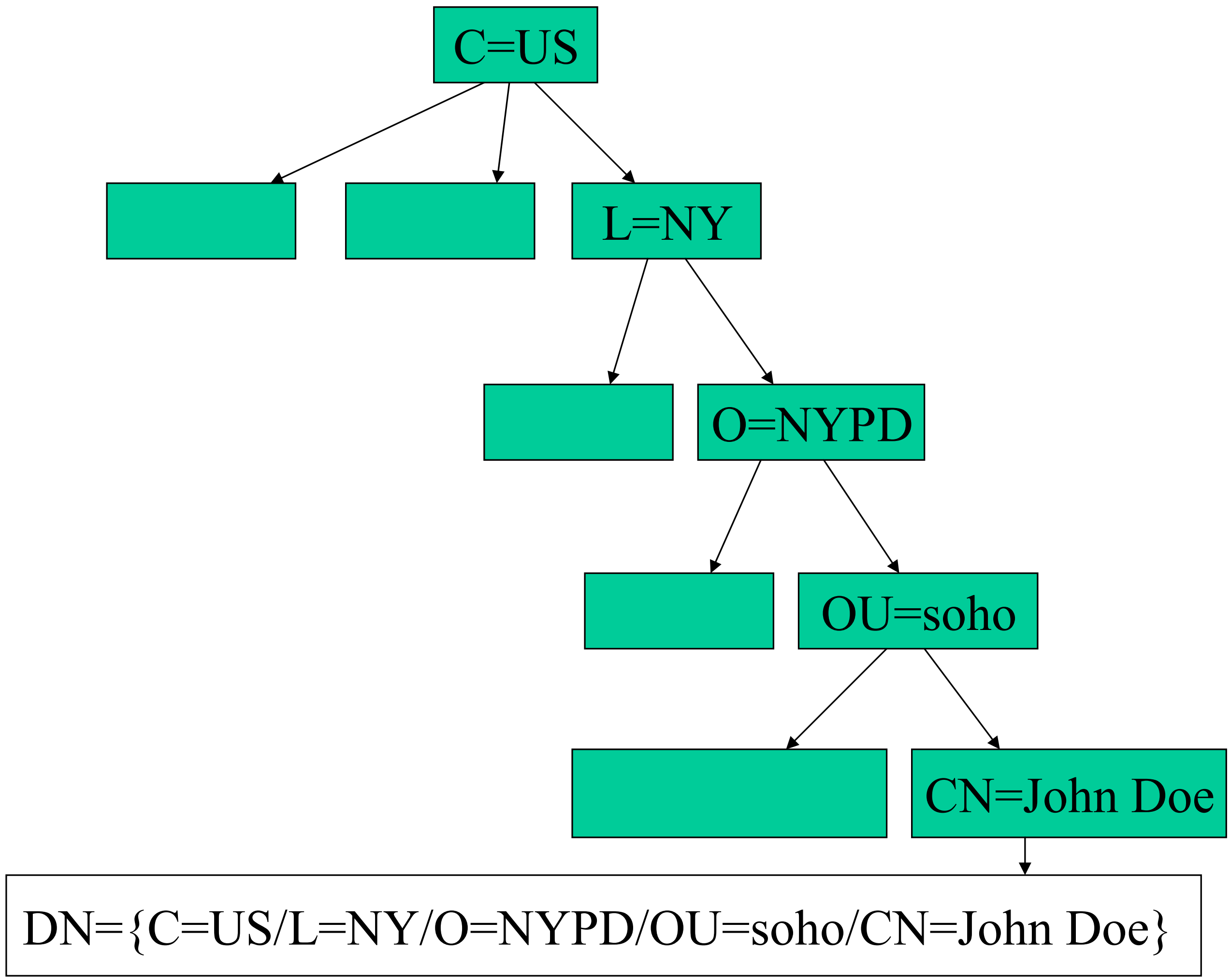


X.500 Distinguished Names (DN)

- Sequence of keywords, a string value for each of them →*hierarchical DN.*
  - Keywords facilitate entities sharing same common name.
    - Still uniqueness is not 100% guaranteed.
  - Meaningful, readable representation.
  - Distributed directory; each issue manages their issued DNs.

Keyword	Meaning
C	Country
L	Locality or city name
O	Organization name
OU	Organization Unit name
CN	Common Name

Distinguished Name (DN) Hierarchy



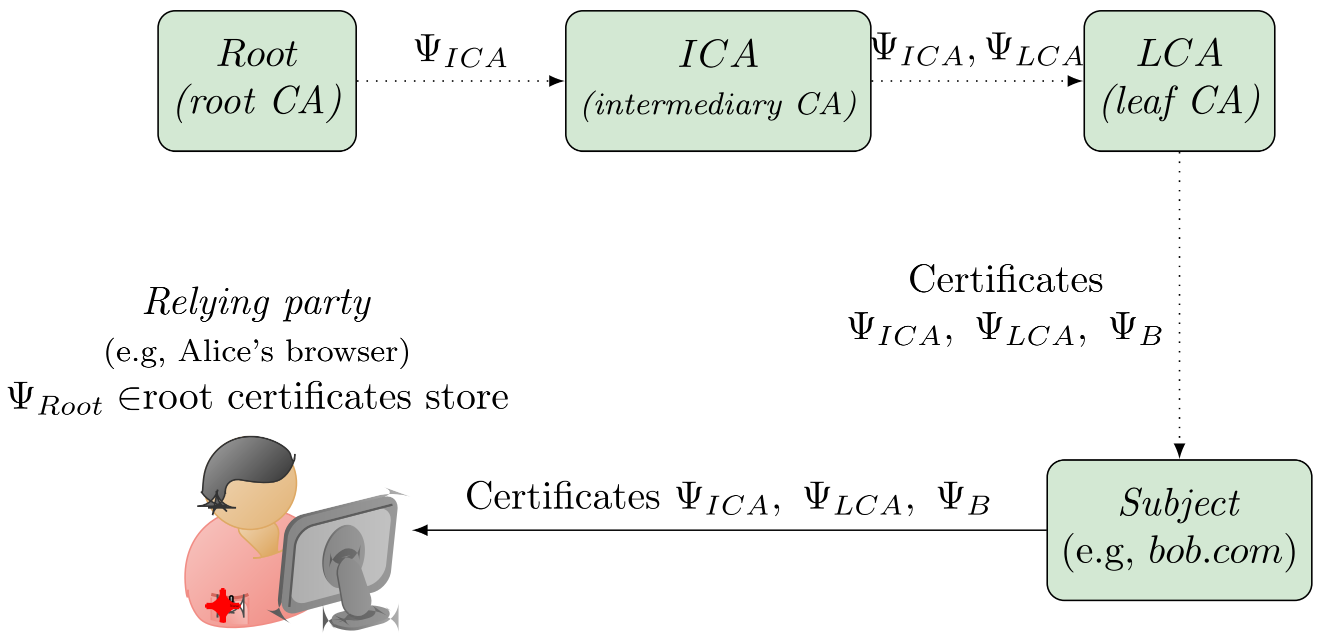
Intermediate CAs and Path Verification

Why Intermediate CAs?

- Relying parties rely on root CA(s) to establish trust in a certificate of a particular subject party.
- Large number of subjects to certify.
  - One (or a few) root CAs cannot handle all the load.
- A root CA certifies other CAs to become intermediate CAs.
  - So the root CA A certifies intermediate CA B, then B will sign certificates for subjects (B is an issuer).
  - Intermediate CAs can certify (beside subjects) other intermediate or leaf CAs.
  - Leaf CAs can certify only subjects.
- Certificate path validation allows validating such certificates that are issued by intermediate CAs.
  - Like tracing them back to the root CA.
- *Who certifies a root CA?*

X.509 Validation of Certificate Paths

- Simply, validate all certificates in the chain all the way to the root CA.
- The root CA (self-signed) certificate is in the root store in Alice's browser.
- Let's trace the example below.



Certificate Revocation

Certificate Revocation

- Reasons for revoking certificates
  - Security issues:
    - Key compromise, CA compromise
  - Administrative issues:
    - Affiliation changed (changing DN or other attribute), public key has been replaced, subject has ceased operation (company dissolving).
- How to inform relying parties? Few options usually under three categories:
  - Prefetch: have revocation info in advance.
  - As-needed: ask for this info when receiving a certificate and want to validate.
  - Neither: does not fall under any of the above, usually called network-assisted techniques.

Certificate Revocation Techniques

- Prefetch:
  - Cons: higher storage and communication overhead,
  - Pros: lower response delay
- As needed:
  - Cons: higher response delays, reliability issues, privacy concerns.
  - Pros: lower storage and communication overhead
- We will study two techniques:
  - Distribute ***Certificate Revocation List (CRL) --*** *Prefetch*
    - This is part of the X.509 standard.
  - Ask - ***Online Certificate Status Protocol (OCSP)*** – *As needed*

CRLs

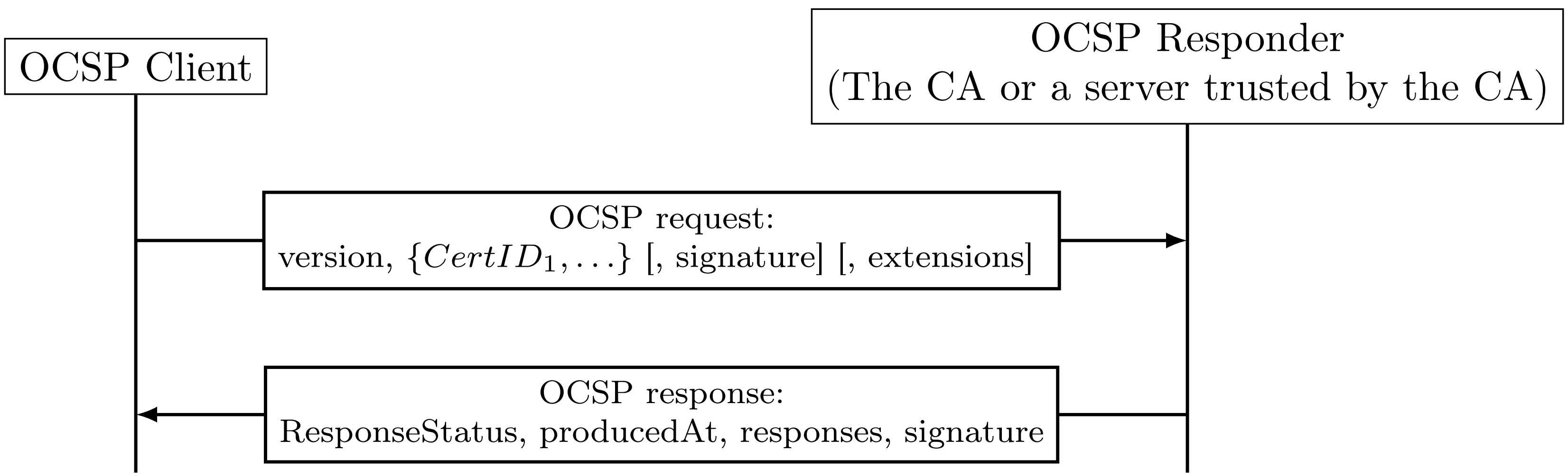
- A certificate revocation list (CRL) is simply a list of revoked certificates.
  - Distributed periodically by CAs.
- If CRLs contain all revoked certificates (which did not expire)… it may be huge!
  - Yes, large storage and communication overhead.
- CRLs are not immediate
  - Who is responsible until CRL is distributed?
  - Frequent CRLs ➔ even more overhead!

CRLs Optimization Solutions

- More efficient CRL schemes:
  - CRL distribution point: split certificates to several CRLs
  - Authorities Revocation List (ARL): list only revoked CAs
  - Delta CRL – only new revocations since last `base CRL`
    - Need to keep CRLs for long period to check deltas → complicates implementation
- Browsers mostly do not check CRLs. Instead, they usually use:
  - The Online Certificate Status Protocol (OCSP)

Online Certificate Status Protocol (OCSP)

- Improve efficiency and freshness compared to CRLs.
- Client asks CA about cert during handshake.
- CA signs response (real-time).



OCSP Challenges

- Privacy (expose domain and client to CA), load on CA, response delay, reliability (what if CA fails).
- Ambiguity:
  - When an OCSP server (or CA) cannot resolve the request, it replies with ”certificate status is unknown”.
- Reliability or failed requests.
  - Client failed to establish a connection with the OCSP server.
  - Or client’s request is invalid (not signed, or not authorized), so no response will be received.

Ambiguous/Failed OCSP Responses

- What should the client do?
  - Wait forever – unrealistic!
  - Hard-fail: terminate the connection since certificate is unknown/not received.
    - Safe!
  - Ask user: application display a message asking the user how to proceed.
  - Soft-fail: pretend that a response has been received and continue as the certificate is not revoked.
    - Common choice for browsers!
    - But, a man in the middle (MitM) attacker may block the OCSP response to make a revoked cert go through!

Conclusion

- PKI is an essential component of the Internet.
- Yet, it is a complicated module with many issues related to security, privacy, and performance.
  - To many, this is a solved problem, but that is not the case.
  - Several open questions related to how to detect rogue certificates, how to handle CA failure, revocation, etc., how to audit these parties, how to reduce trust,…
  - How to handle all these issues in an efficient way?
    - Remember, we all want a Web that is highly responsive!

Covered Material From the Textbook

- Chapter 8:
  - Sections 8.1,
  - and Sections 8.3 and 8.4 (only the topics we covered from both sections)

Thank You!