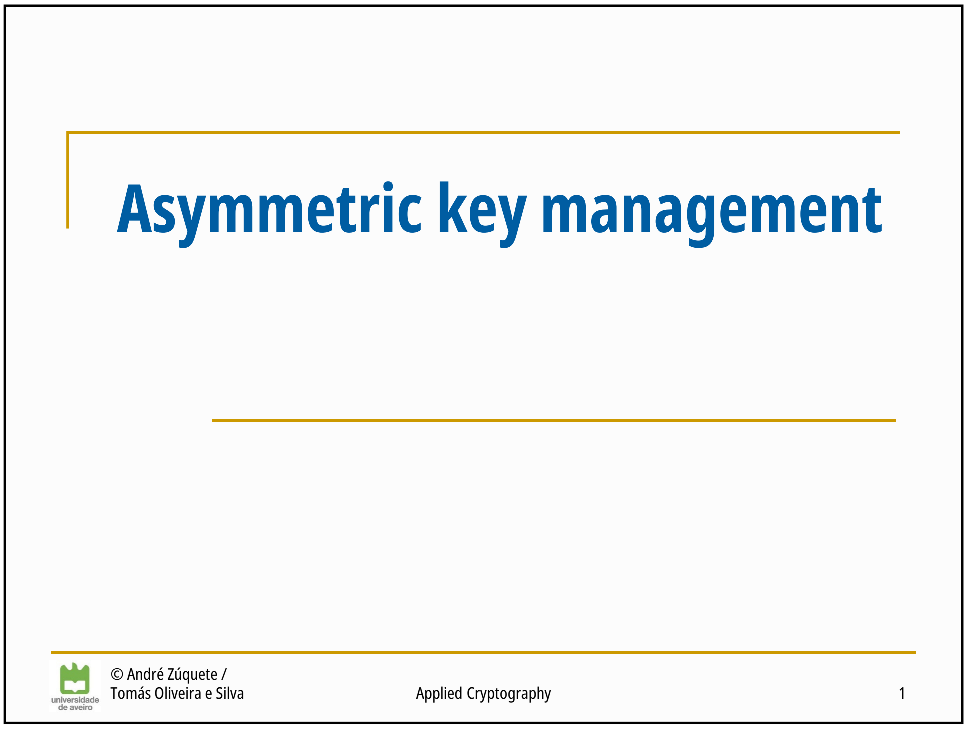
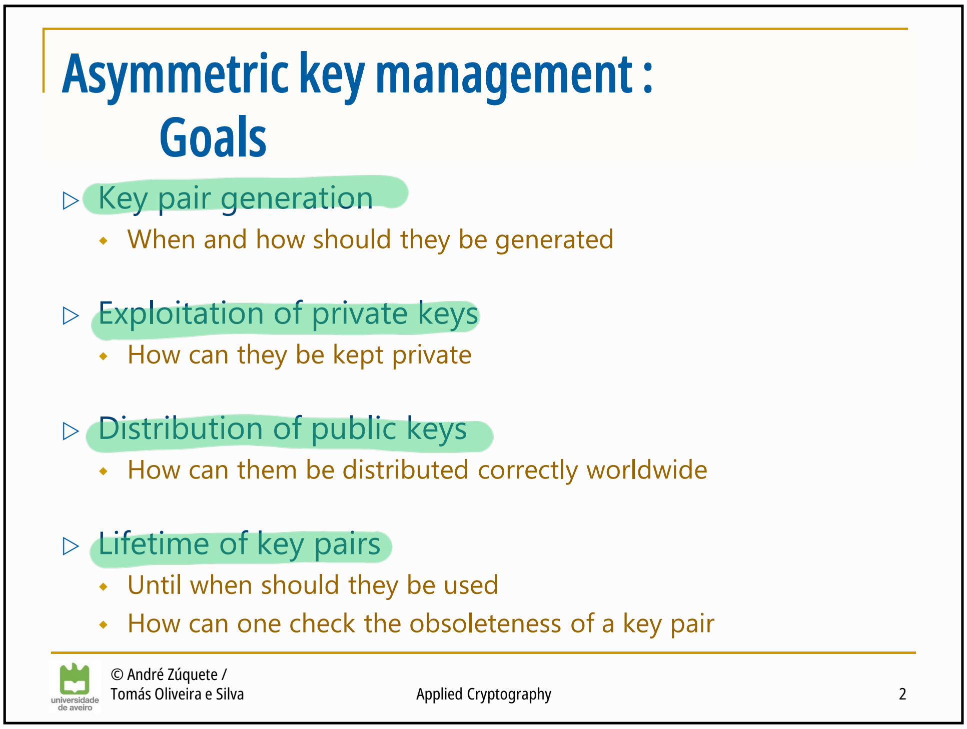
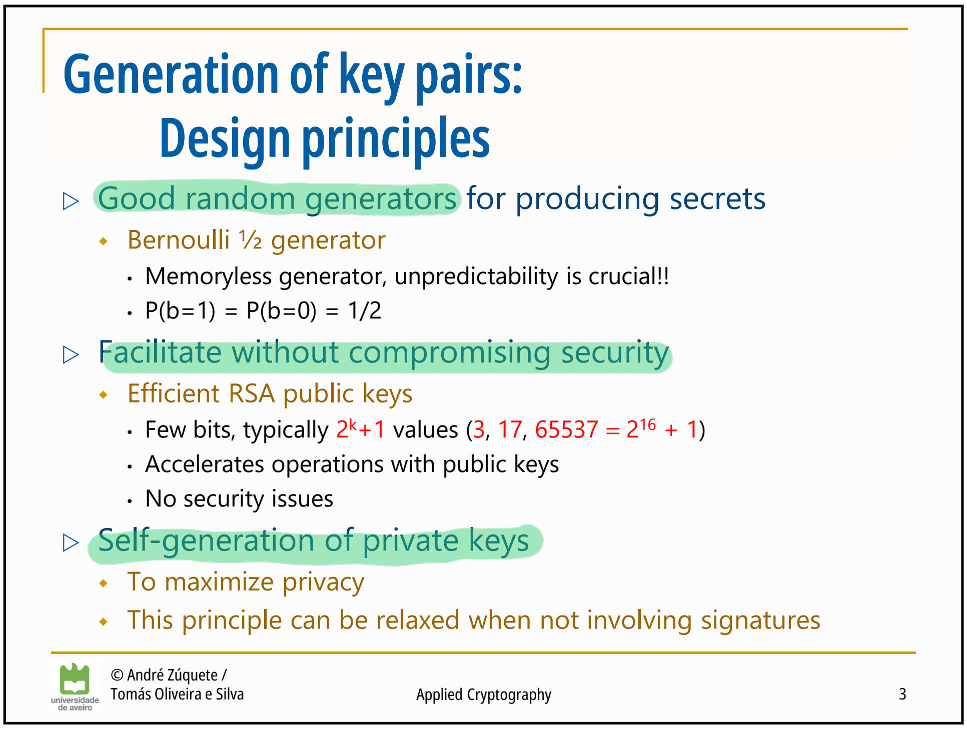


Asymmetric key management



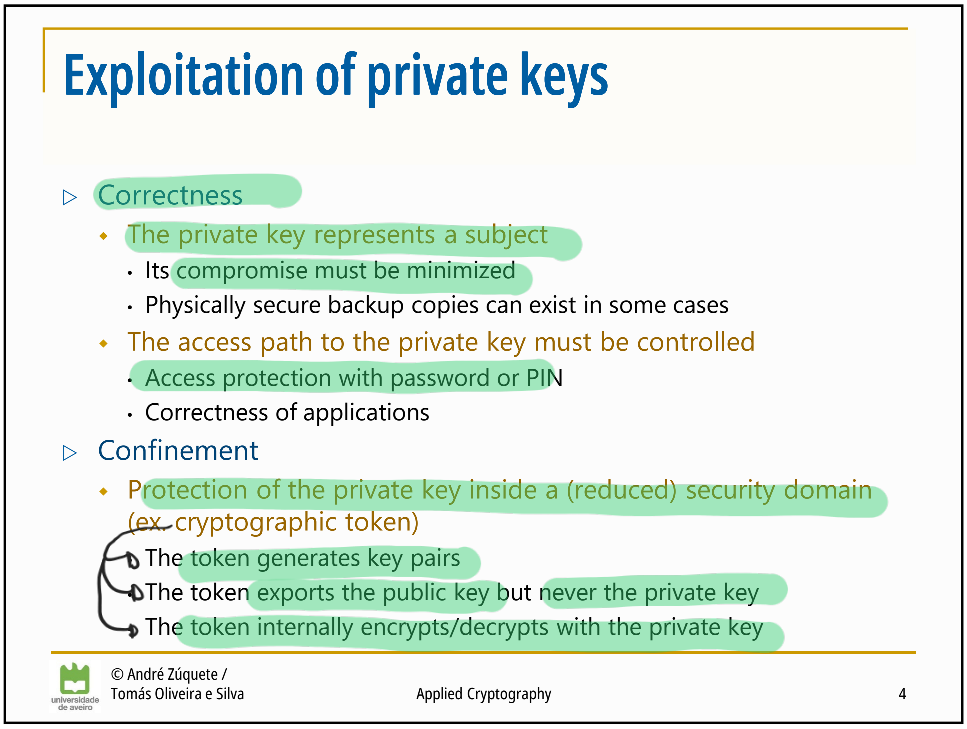
Asymmetric key management : Goals

- Key pair generation
  - When and how should they be generated
- Exploitation of private keys
  - How can they be kept private
- Distribution of public keys
  - How can them be distributed correctly worldwide
- Lifetime of key pairs
  - Until when should they be used
  - How can one check the obsoleteness of a key pair



Generation of key pairs: Design principles

- Good random generators for producing secrets
  - Bernoulli ½ generator
    - Memoryless generator, unpredictability is crucial!!
    - P(b=1) = P(b=0) = 1/2
- Facilitate without compromising security
  - Efficient RSA public keys
    - Few bits, typically 2^k+1 values (3, 17, $65537 = 2^{16} + 1$)
    - Accelerates operations with public keys
    - No security issues
- Self-generation of private keys
  - To maximize privacy
  - This principle can be relaxed when not involving signatures



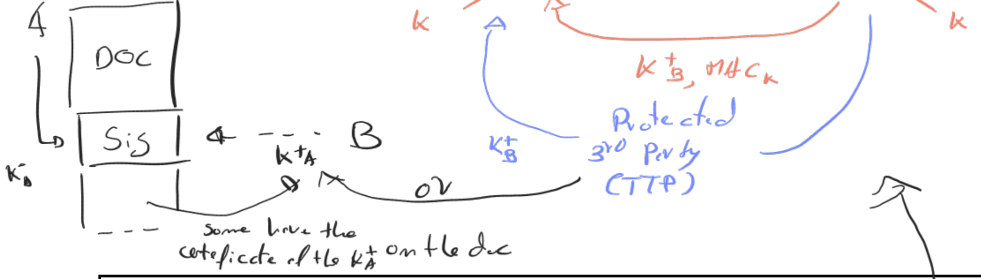
Exploitation of private keys

- Correctness
  - The private key represents a subject
    - Its compromise must be minimized
    - Physically secure backup copies can exist in some cases
  - The access path to the private key must be controlled
    - Access protection with password or PIN
    - Correctness of applications
- Confinement
  - Protection of the private key inside a (reduced) security domain (ex. cryptographic token)
    - The token generates key pairs
    - The token exports the public key but never the private key
    - The token internally encrypts/decrypts with the private key

MRZ -> Machine Readable Zone, está no BI

TPM -> chip for cryptographic operations

$A \xrightarrow{\{m\}_{K^+_B}} B$


4
Doc
Sig
K^-_A
B
K^+_A
or
K^+_B
Some have the certificate of the K^+_A on the doc
k
A
k
K^+_B, MAC_K
Protected 3rd Party (TTP)

Distribution of public keys

- ▷ Distribution to all **senders** of confidential data
  - Manual
  - Using a shared secret
  - Ad-hoc using digital certificates

Sec

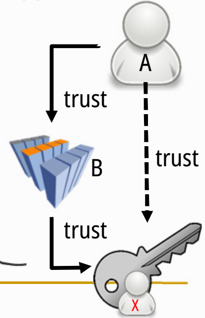
Pub

- ▷ Distribution to all **receivers** of digital signatures
  - Ad-hoc using digital certificates

Pub

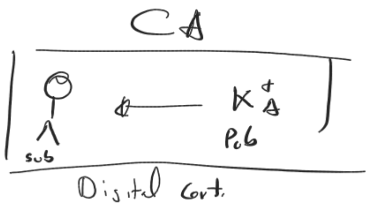
- ▷ Trustworthy dissemination of public keys
  - Transitive trust paths / graphs

    If entity A trusts entity B and B trust in K_X^+,
    then A trusts in K_X^+
  - Certification hierarchies / graphs



Public key (digital) certificates

- ▷ Documents issued by a Certification Authority (CA)
  - Bind a public key to an entity
    - Person, server or service
  - Are public documents
    - Do not contain private information, only public one
  - Are cryptographically secure
    - Digitally signed by the issuer, cannot be changed
- ▷ Can be used to distribute public keys in a trustworthy way
  - A certificate receiver can validate it
    - With the CA's public key
  - If the signer (CA) public key is trusted, and the signature is correct, then the receiver can trust the (certified) public key
    - As the CA trust the public key, if the receiver trusts on the CA public key, the receiver can trust on the public key



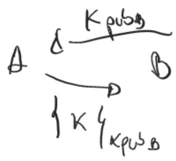
Public key (digital) certificates

- ▷ X.509v3 standard
  - Mandatory fields
    - Version
    - Subject → Entity
    - Public key
    - Dates (issuing, deadline)
    - Issuer
    - Signature
    - etc.
  - Extensions
    - Critical or non-critical
- ▷ PKCS #6
  - Extended-Certificate Syntax Standard
- ▷ Binary formats
  - ASN.1 (Abstract Syntax Notation)
    - DER, CER, BER, etc.
  - PKCS #7
    - Cryptographic Message Syntax Standard
  - PKCS #12
    - Personal Information Exchange Syntax Standard
- ▷ Other formats
  - PEM (Privacy Enhanced Mail)
  - base64 encodings of X.509

Key pair usage

- ▷ A key pair is bound to a usage profile by its public key certificate
  - Public keys are seldom multi-purpose
- ▷ Typical usages
  - Authentication / key distribution
    - Digital signature, Key encipherment, Data encipherment, Key agreement
  - Document signing
    - Digital signature, Non-repudiation
  - Certificate issuing
    - Certificate signing, CRL signing
- ▷ Public key certificates have an extension for this
  - Key usage (critical)

Servers fazem

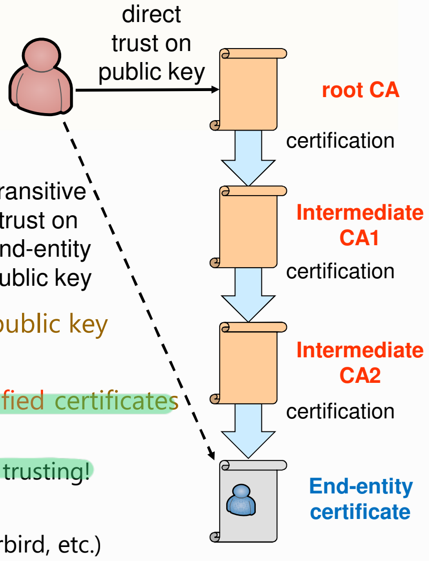


Certification Authorities (CA)

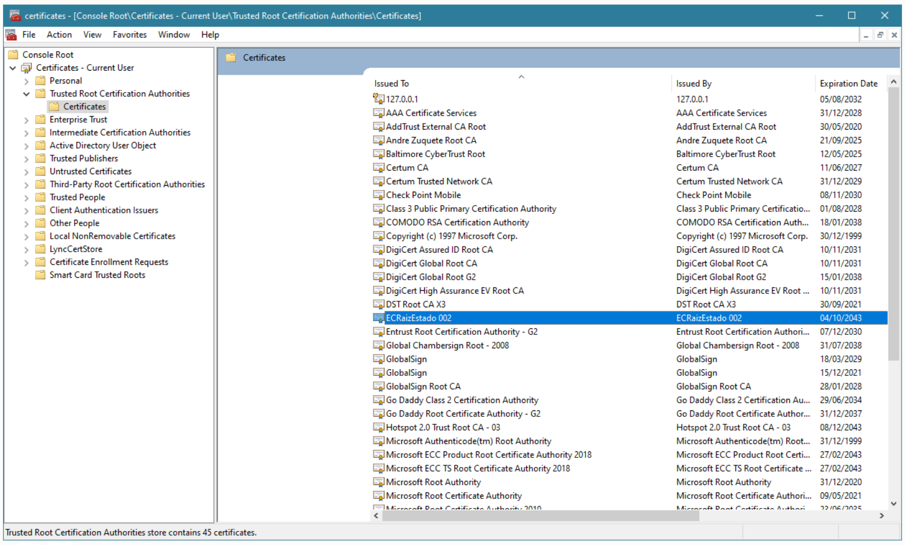
- ▷ Organizations that manage public key certificates
- ▷ Define policies and mechanisms for
  - Issuing certificates
  - Revoking certificates
  - Distributing certificates → Não muito comum
  - Issuing and distributing the corresponding private keys
- ▷ Manage certificate revocation lists
  - Lists of revoked certificates

CA types

- ▷ Intermediate CAs
  - CAs certified by other Cas
- ▷ Root CAs
  - CAs for which one has a trusted public key
  - Trust anchor
  - Usually implemented by self-certified certificates
    - Issuer = Subject
    - Self-certification is not a reason for trusting!
  - Manual distribution
    - Tools' repositories (Firefox, Thunderbird, etc.)
    - Operating systems' repositories



Certificates of Root CAs: Windows 10



certificates - [Console Root\Certificates - Current User\Trusted Root Certification Authorities\Certificates]

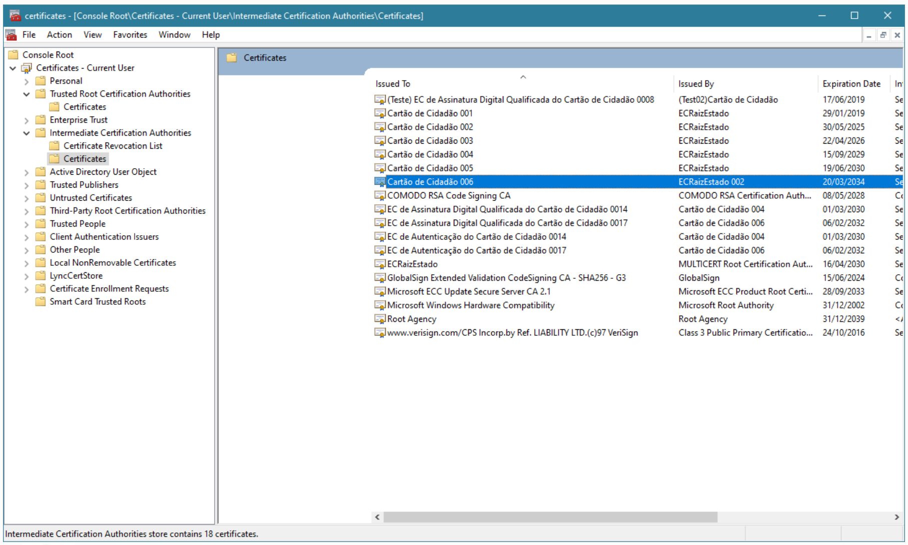
- Console Root
  - Certificates - Current User
    - Personal
    - Trusted Root Certification Authorities
      - Certificates
    - Enterprise Trust
    - Intermediate Certification Authorities
    - Active Directory User Object
    - Trusted Publishers
    - Untrusted Certificates
    - Third-Party Root Certification Authorities
    - Trusted People
    - Client Authentication Issuers
    - Other People
    - Local NonRemovable Certificates
    - LyncCertStore
    - Certificate Enrollment Requests
    - Smart Card Trusted Roots

Certificates

Issued To	Issued By	Expiration Date
127.0.0.1	127.0.0.1	05/08/2032
AAA Certificate Services	AAA Certificate Services	31/12/2028
AddTrust External CA Root	AddTrust External CA Root	30/05/2020
Andre Zuquete Root CA	Andre Zuquete Root CA	21/09/2025
Baltimore CyberTrust Root	Baltimore CyberTrust Root	12/05/2025
Certum CA	Certum CA	11/06/2027
Certum Trusted Network CA	Certum Trusted Network CA	31/12/2029
Check Point Mobile	Check Point Mobile	08/11/2030
Class 3 Public Primary Certification Authority	Class 3 Public Primary Certificatio...	01/08/2028
COMODO RSA Certification Authority	COMODO RSA Certification Auth...	18/01/2038
Copyright (c) 1997 Microsoft Corp.	Copyright (c) 1997 Microsoft Corp.	30/12/1999
DigiCert Assured ID Root CA	DigiCert Assured ID Root CA	10/11/2031
DigiCert Global Root CA	DigiCert Global Root CA	10/11/2031
DigiCert Global Root G2	DigiCert Global Root G2	15/01/2038
DigiCert High Assurance EV Root CA	DigiCert High Assurance EV Root ...	10/11/2031
DST Root CA X3	DST Root CA X3	30/09/2021
ECRaizEstado 002	ECRaizEstado 002	04/10/2043
Entrust Root Certification Authority - G2	Entrust Root Certification Authori...	07/12/2030
Global Chambersign Root - 2008	Global Chambersign Root - 2008	31/07/2038
GlobalSign	GlobalSign	18/03/2029
GlobalSign	GlobalSign	15/12/2021
GlobalSign Root CA	GlobalSign Root CA	28/01/2028
Go Daddy Class 2 Certification Authority	Go Daddy Class 2 Certification Au...	29/06/2034
Go Daddy Root Certificate Authority - G2	Go Daddy Root Certificate Author...	31/12/2037
Hotspot 2.0 Trust Root CA - 03	Hotspot 2.0 Trust Root CA - 03	08/12/2043
Microsoft Authenticode(tm) Root Authority	Microsoft Authenticode(tm) Root...	31/12/1999
Microsoft ECC Product Root Certificate Authority 2018	Microsoft ECC Product Root Certi...	27/02/2043
Microsoft ECC TS Root Certificate Authority 2018	Microsoft ECC TS Root Certificate ...	27/02/2043
Microsoft Root Authority	Microsoft Root Authority	31/12/2020
Microsoft Root Certificate Authority	Microsoft Root Certificate Authori...	09/05/2021
Microsoft Root Certificate Authority 2010	Microsoft Root Certificate Authori...	23/06/2035

Trusted Root Certification Authorities store contains 45 certificates.

Certs. of Intermediate CAs: Windows 10



certificates - [Console Root\Certificates - Current User\Intermediate Certification Authorities\Certificates]

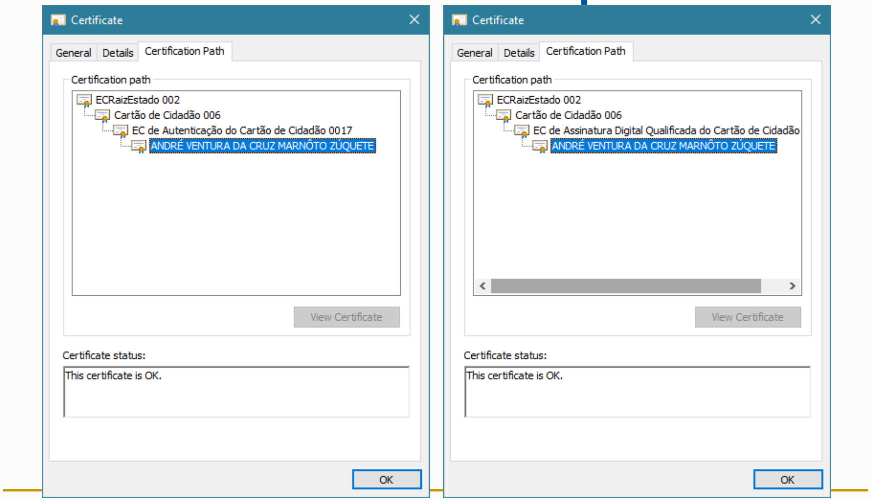
- Console Root
  - Certificates - Current User
    - Personal
    - Trusted Root Certification Authorities
      - Certificates
    - Enterprise Trust
    - Intermediate Certification Authorities
      - Certificate Revocation List
      - Certificates
    - Active Directory User Object
    - Trusted Publishers
    - Untrusted Certificates
    - Third-Party Root Certification Authorities
    - Trusted People
    - Client Authentication Issuers
    - Other People
    - Local NonRemovable Certificates
    - LyncCertStore
    - Certificate Enrollment Requests
    - Smart Card Trusted Roots

Certificates

Issued To	Issued By	Expiration Date	In
(Teste) EC de Assinatura Digital Qualificada do Cartão de Cidadão 0008	(Test02)Cartão de Cidadão	17/06/2019	Se
Cartão de Cidadão 001	ECRaizEstado	29/01/2019	Se
Cartão de Cidadão 002	ECRaizEstado	30/05/2025	Se
Cartão de Cidadão 003	ECRaizEstado	22/04/2026	Se
Cartão de Cidadão 004	ECRaizEstado	15/09/2029	Se
Cartão de Cidadão 005	ECRaizEstado	19/06/2030	Se
Cartão de Cidadão 006	ECRaizEstado 002	20/03/2034	Se
COMODO RSA Code Signing CA	COMODO RSA Certification Auth...	08/05/2028	Co
EC de Assinatura Digital Qualificada do Cartão de Cidadão 0014	Cartão de Cidadão 004	01/03/2030	Se
EC de Assinatura Digital Qualificada do Cartão de Cidadão 0017	Cartão de Cidadão 006	06/02/2032	Se
EC de Autenticação do Cartão de Cidadão 0014	Cartão de Cidadão 004	01/03/2030	Se
EC de Autenticação do Cartão de Cidadão 0017	Cartão de Cidadão 006	06/02/2032	Se
ECRaizEstado	MULTICERT Root Certification Aut...	16/04/2030	Se
GlobalSign Extended Validation CodeSigning CA - SHA256 - G3	GlobalSign	15/06/2024	Co
Microsoft ECC Update Secure Server CA 2.1	Microsoft ECC Product Root Certi...	28/09/2033	Se
Microsoft Windows Hardware Compatibility	Microsoft Root Authority	31/12/2002	Co
Root Agency	Root Agency	31/12/2039	<A
www.verisign.com/CPS Incorp.by Ref. LIABILITY LTD.(c)97 VeriSign	Class 3 Public Primary Certificatio...	24/10/2016	Se

Intermediate Certification Authorities store contains 18 certificates.

Certification hierarchies (or chains, paths): Cartão de Cidadão example



Certification path

- ECRaizEstado 002
  - Cartão de Cidadão 006
    - EC de Autenticação do Cartão de Cidadão 0017
      - ANDRÉ VENTURA DA CRUZ MARNÓTO ZÚQUETE

Certificate status:

This certificate is OK.

Certification path

- ECRaizEstado 002
  - Cartão de Cidadão 006
    - EC de Assinatura Digital Qualificada do Cartão de Cidadão
      - ANDRÉ VENTURA DA CRUZ MARNÓTO ZÚQUETE

Certificate status:

This certificate is OK.

Certification hierarchies: PEM (Privacy Enhanced Mail) model

- Distribution of certificates for PEM (secure e-mail)
  - Worldwide hierarchy (monopoly)
  - Single root (IPRA)
  - Several PCA (Policy Creation Authorities) bellow the root
  - Several CA below each PCA
    - Possibly belonging to organizations or companies
- Never implemented
  - Forest of hierarchies
    - Each with its independent root CA
    - Oligarchy
  - Each root CA negotiates the distribution of its public key along with some applications or operating systems
    - ex. Browsers, Windows

4

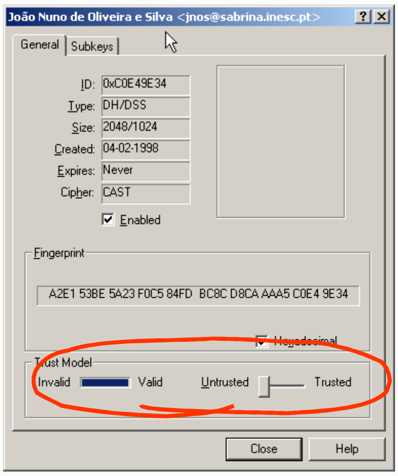
Certification hierarchies: PGP (Pretty Good Privacy) model

- Web of trust
  - No central trustworthy authorities
    - Each person is a potential certifier
    - Can certify a public key (issue a certificate) and publish it
  - People uses 2 kinds of trust
    - Trust in the keys they know
      - Validated using any means (FAX, telephone, etc.)
    - Trust in the behavior of certifiers
      - Assumption that they know what they are doing when issuing a certificate
- Transitive trust
  - If

    Alice trusts Bob is a correct certifier; and
    Bob certified the public key of Carl,
  - then

    Alice trusts the public key belongs to Carl

PGP public key certificates: Validity vs. trust

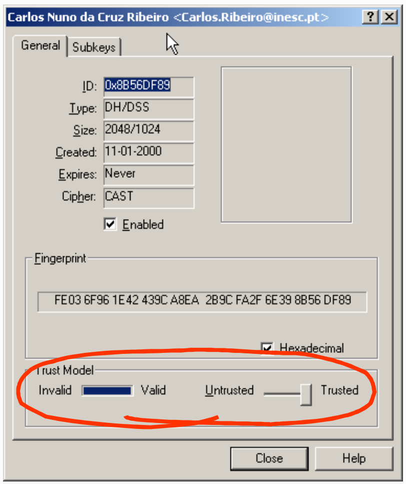


João Nuno de Oliveira e Silva <jnos@sabrina.inesc.pt>

ID: 0xC0E49E34
Type: DH/DSS
Size: 2048/1024
Created: 04-02-1998
Expires: Never
Cipher: CAST
☑ Enabled

Fingerprint
A2E1 53BE 5A23 F0C5 84FD BC8C D8CA AAA5 C0E4 9E34
☑ Hexadecimal

Trust Model
Invalid ▬ Valid
Untrusted ▯—— Trusted

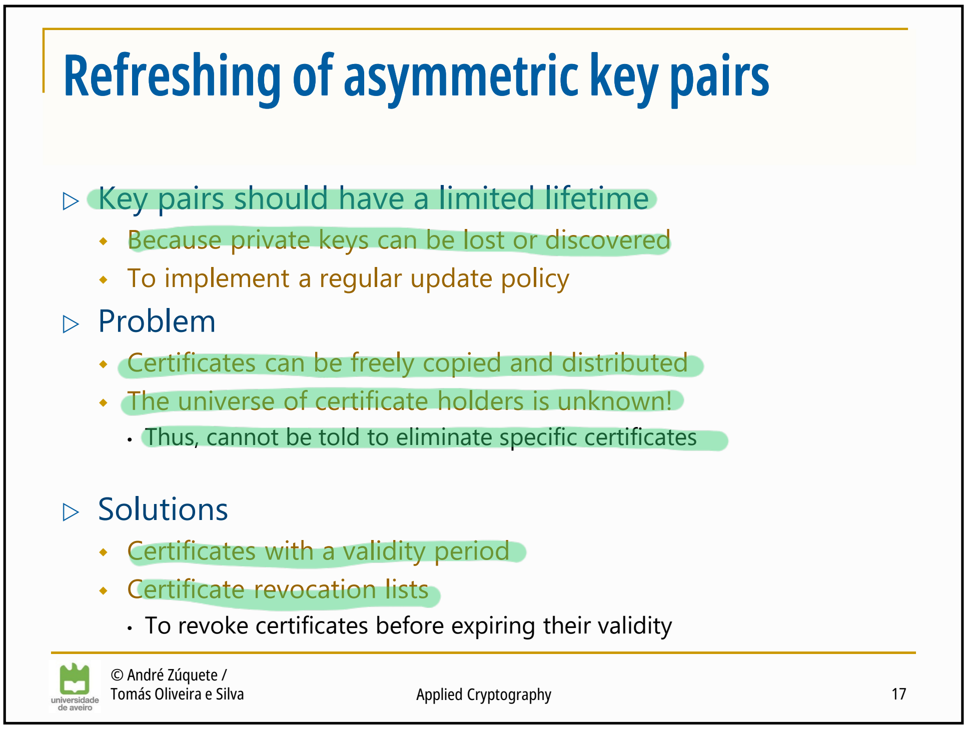


Carlos Nuno da Cruz Ribeiro <Carlos.Ribeiro@inesc.pt>

ID: 0x8B56DF89
Type: DH/DSS
Size: 2048/1024
Created: 11-01-2000
Expires: Never
Cipher: CAST
☑ Enabled

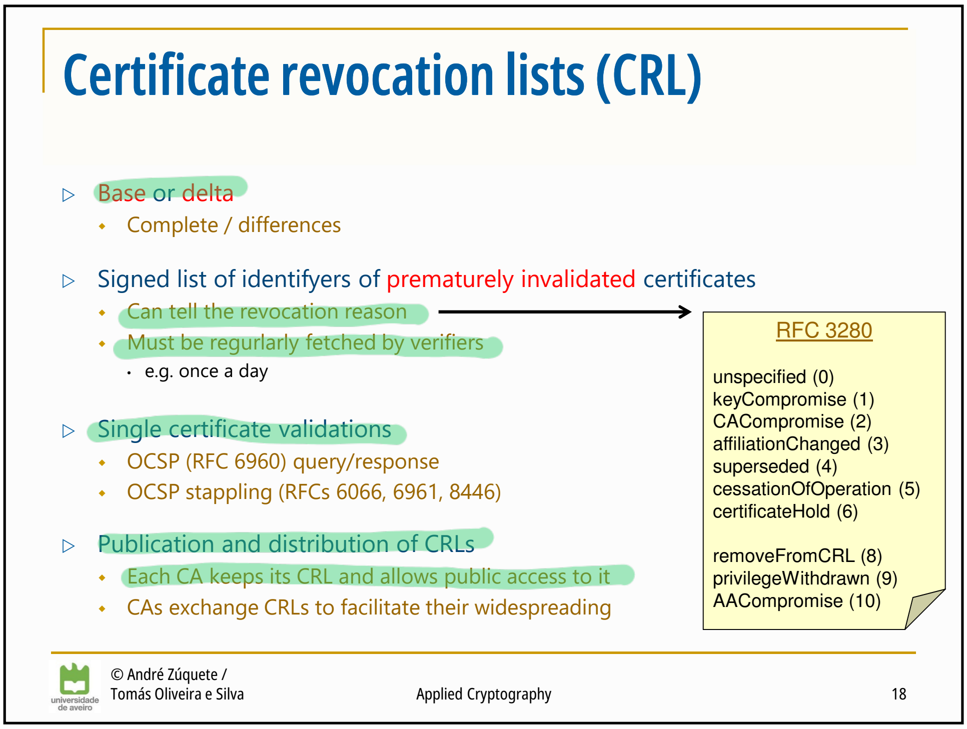
Fingerprint
FE03 6F96 1E42 439C A8EA 2B9C FA2F 6E39 8B56 DF89
☑ Hexadecimal

Trust Model
Invalid ▬ Valid
Untrusted ——▯ Trusted



Refreshing of asymmetric key pairs

- Key pairs should have a limited lifetime
  - Because private keys can be lost or discovered
  - To implement a regular update policy
- Problem
  - Certificates can be freely copied and distributed
  - The universe of certificate holders is unknown!
    - Thus, cannot be told to eliminate specific certificates
- Solutions
  - Certificates with a validity period
  - Certificate revocation lists
    - To revoke certificates before expiring their validity



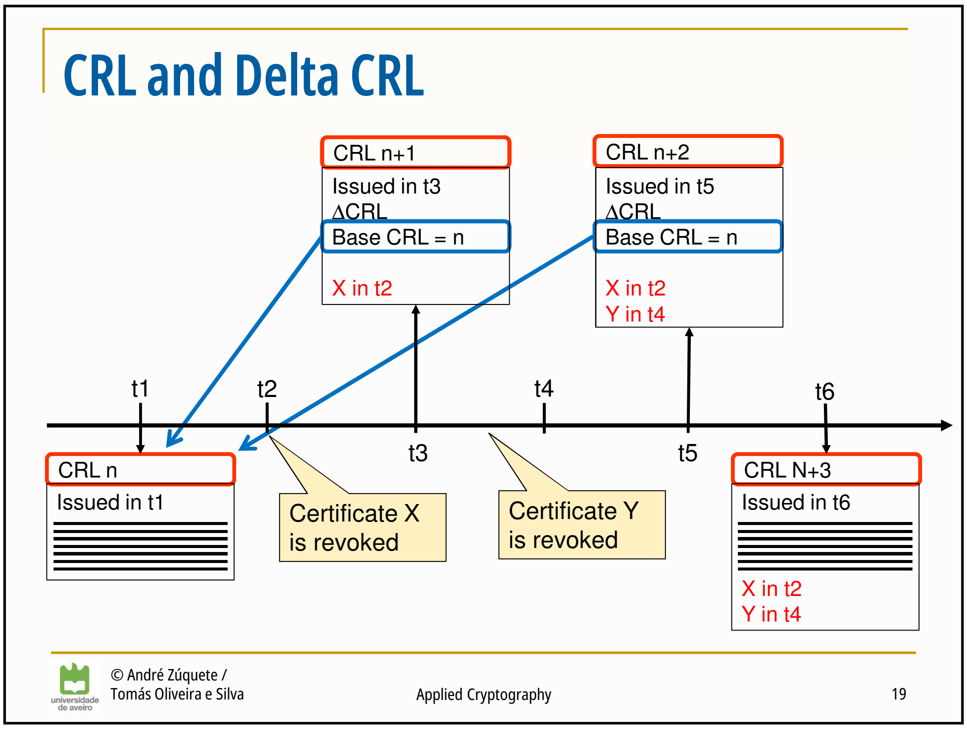
Certificate revocation lists (CRL)

- Base or delta
  - Complete / differences
- Signed list of identifyers of prematurely invalidated certificates
  - Can tell the revocation reason
  - Must be regurlarly fetched by verifiers
    - e.g. once a day
- Single certificate validations
  - OCSP (RFC 6960) query/response
  - OCSP stappling (RFCs 6066, 6961, 8446)
- Publication and distribution of CRLs
  - Each CA keeps its CRL and allows public access to it
  - CAs exchange CRLs to facilitate their widespreading

RFC 3280

unspecified (0)
keyCompromise (1)
CACompromise (2)
affiliationChanged (3)
superseded (4)
cessationOfOperation (5)
certificateHold (6)

removeFromCRL (8)
privilegeWithdrawn (9)
AACompromise (10)



CRL and Delta CRL

CRL n+1

Issued in t3

ΔCRL

Base CRL = n

X in t2

CRL n+2

Issued in t5

ΔCRL

Base CRL = n

X in t2

Y in t4

t1 t2 t3 t4 t5 t6

CRL n

Issued in t1

Certificate X is revoked

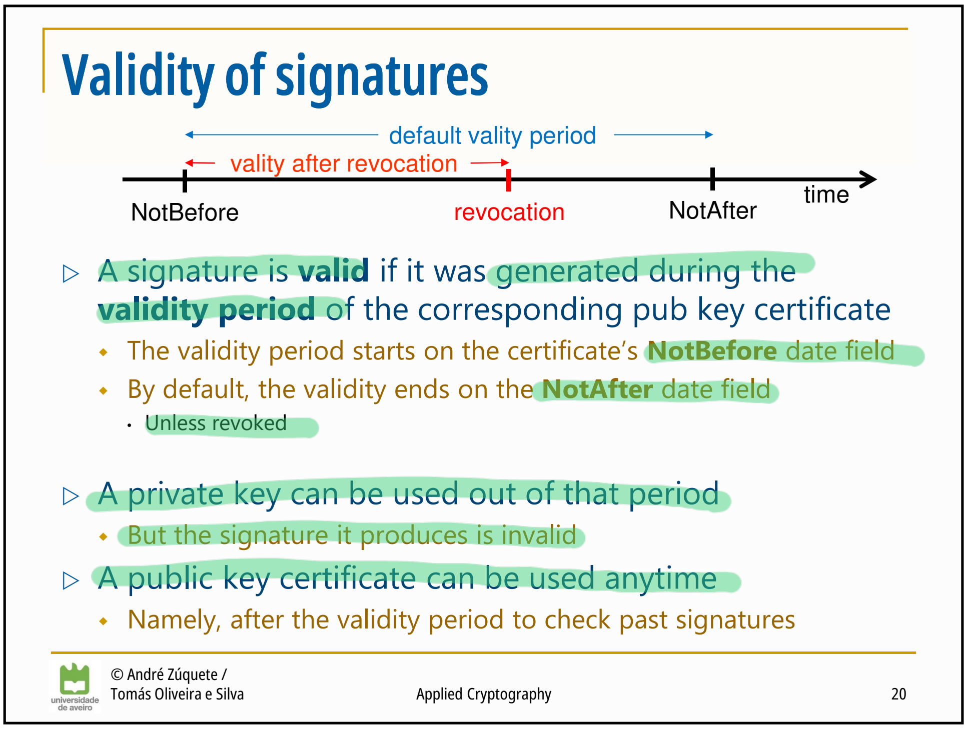
Certificate Y is revoked

CRL N+3

Issued in t6

X in t2

Y in t4



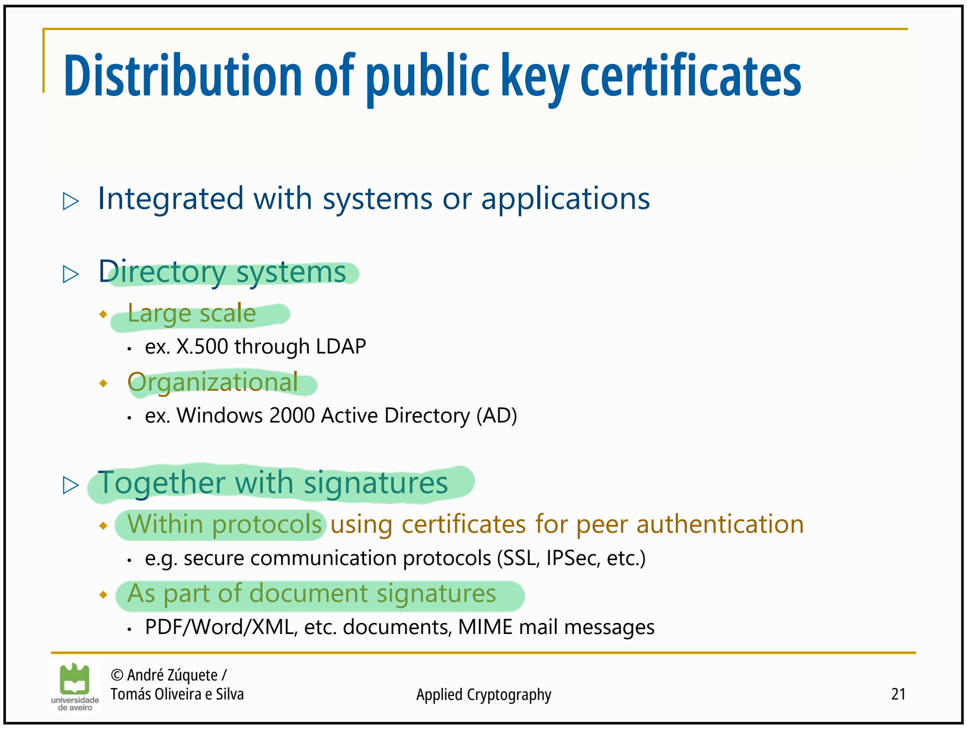
Validity of signatures

default vality period

vality after revocation

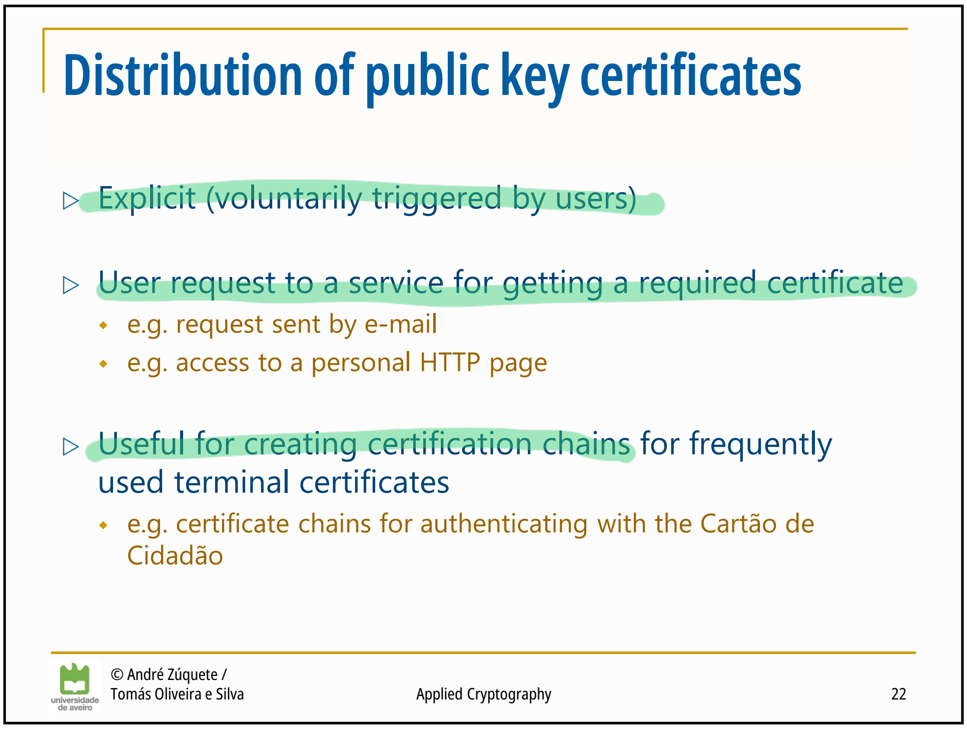
NotBefore revocation NotAfter time

- A signature is **valid** if it was generated during the **validity period** of the corresponding pub key certificate
  - The validity period starts on the certificate's **NotBefore** date field
  - By default, the validity ends on the **NotAfter** date field
    - Unless revoked
- A private key can be used out of that period
  - But the signature it produces is invalid
- A public key certificate can be used anytime
  - Namely, after the validity period to check past signatures



Distribution of public key certificates

- ▷ Integrated with systems or applications
- ▷ Directory systems
  - Large scale
    - ex. X.500 through LDAP
  - Organizational
    - ex. Windows 2000 Active Directory (AD)
- ▷ Together with signatures
  - Within protocols using certificates for peer authentication
    - e.g. secure communication protocols (SSL, IPSec, etc.)
  - As part of document signatures
    - PDF/Word/XML, etc. documents, MIME mail messages

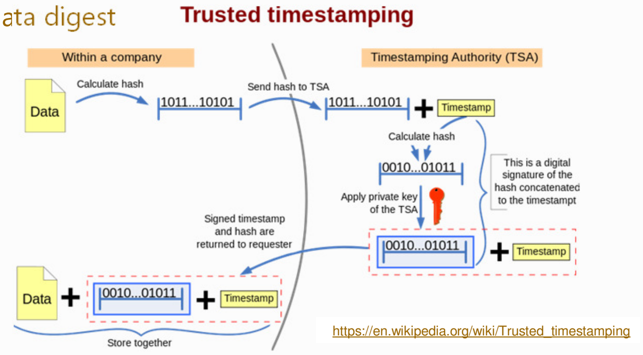


Distribution of public key certificates

- ▷ Explicit (voluntarily triggered by users)
- ▷ User request to a service for getting a required certificate
  - e.g. request sent by e-mail
  - e.g. access to a personal HTTP page
- ▷ Useful for creating certification chains for frequently used terminal certificates
  - e.g. certificate chains for authenticating with the Cartão de Cidadão

Time Stamping Authority (TSA)

- ▷ A service that provides signatures over a timestamp
  - Linked with a data digest



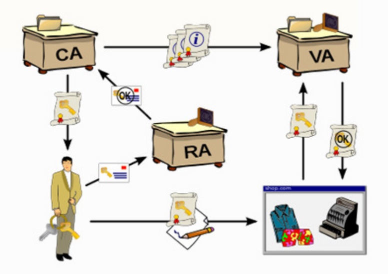
https://en.wikipedia.org/wiki/Trusted_timestamping

- ▷ This is useful for adding trust to a data signature date
  - The signature date becomes linked to the signed data

PKI (Public Key Infrastructure)

- ▷ Infrastructure for enabling the use of keys pairs and certificates
  - Creation of asymmetric key pairs for each enrolled entity
    - Enrolment policies
    - Key pair generation policies
  - Creation and distribution of public key certificates
    - Enrolment policies
    - Definition of certificate attributes
  - Definition and use of certification chains (or paths)
    - Insertion in a certification hierarchy
    - Certification of other CAs
  - Update, publication and consultation of CRLs
    - Policies for revoking certificates
    - Online CRL distribution services
    - Online OCSP services
  - Use of data structures and protocols enabling inter-operation among components / services / people

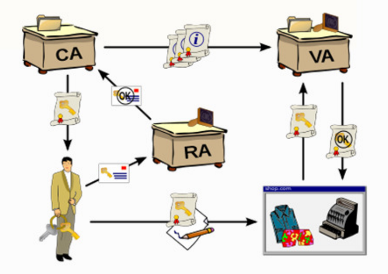
PKI entities: Registration Authority (RA)



- ▷ The actual interface with certificate owners
  - Identification and authentication of certificate applicants
  - Approval or rejection of certificate applications
  - Initiating certificate revocations or suspensions under certain circumstances
  - Processing subscriber requests to revoke or suspend their certificates
  - Approving or rejecting requests by subscribers to renew or re-key their certificates

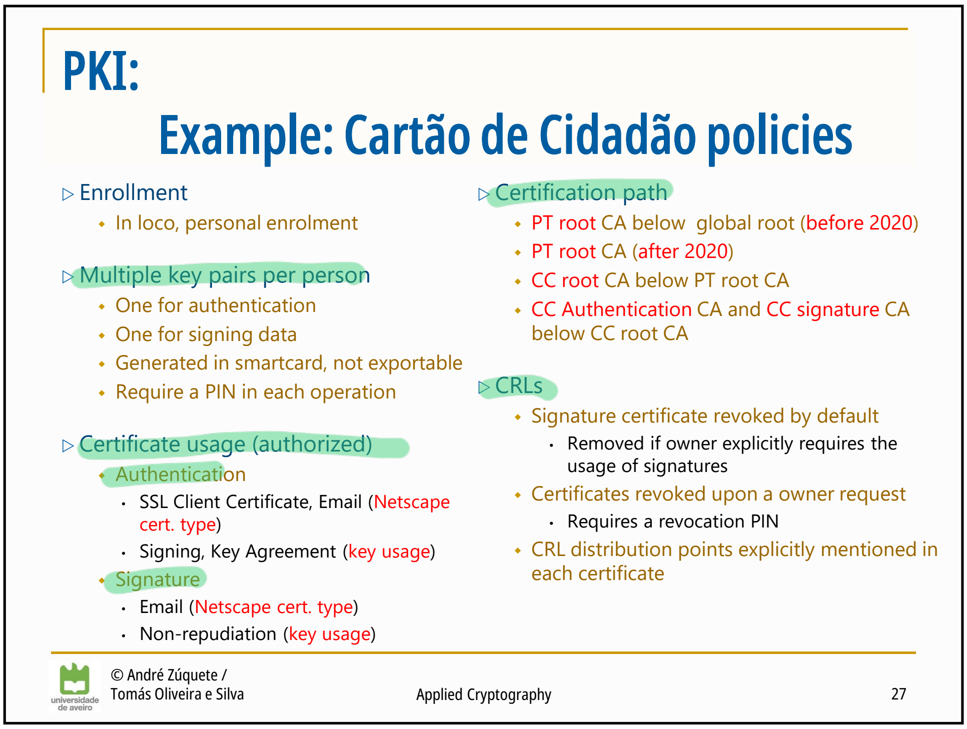
Image src: https://en.wikipedia.org/wiki/Public_key_infrastructure

PKI entities: Validation Authority (VA)



- ▷ A service that helps to validate certificates
  - OCSP service

Image src: https://en.wikipedia.org/wiki/Public_key_infrastructure



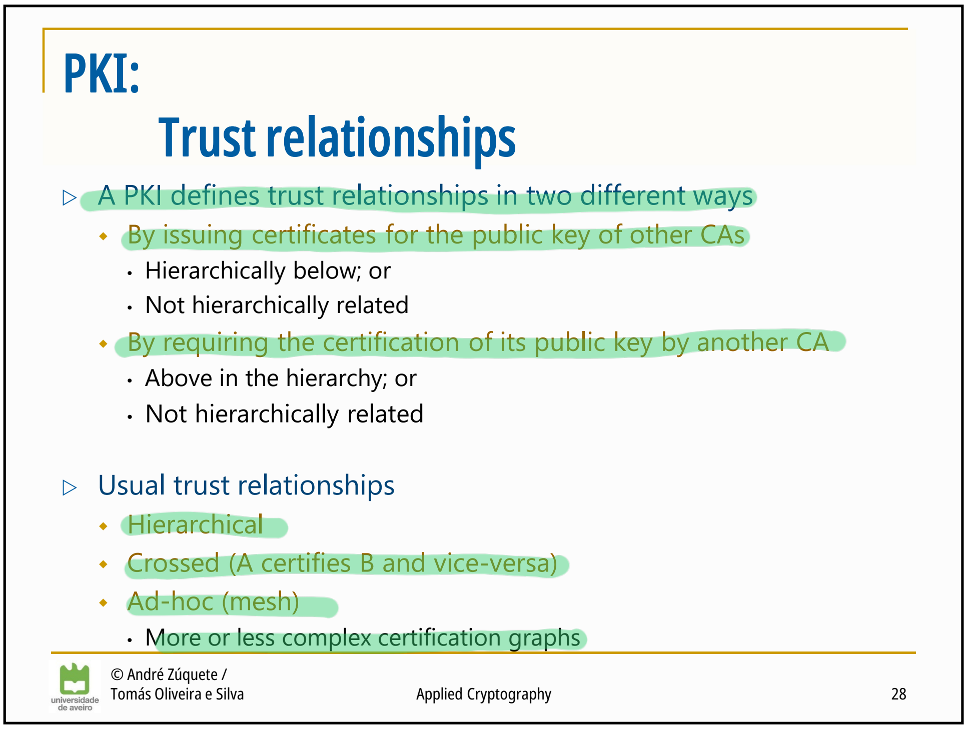
PKI:

Example: Cartão de Cidadão policies

- ▷ Enrollment
  - In loco, personal enrolment
- ▷ Multiple key pairs per person
  - One for authentication
  - One for signing data
  - Generated in smartcard, not exportable
  - Require a PIN in each operation
- ▷ Certificate usage (authorized)
  - Authentication
    - SSL Client Certificate, Email (Netscape cert. type)
    - Signing, Key Agreement (key usage)
  - Signature
    - Email (Netscape cert. type)
    - Non-repudiation (key usage)
- ▷ Certification path
  - PT root CA below global root (before 2020)
  - PT root CA (after 2020)
  - CC root CA below PT root CA
  - CC Authentication CA and CC signature CA below CC root CA
- ▷ CRLs
  - Signature certificate revoked by default
    - Removed if owner explicitly requires the usage of signatures
  - Certificates revoked upon a owner request
    - Requires a revocation PIN
  - CRL distribution points explicitly mentioned in each certificate

MHEEEE!

MEEE!!

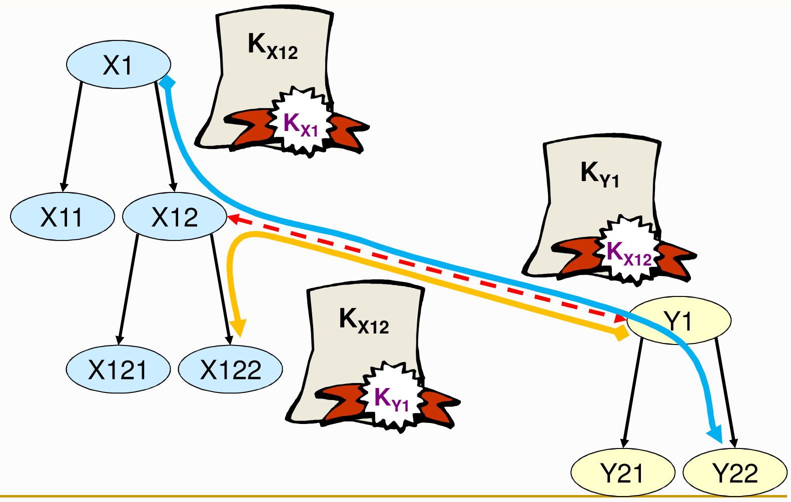


PKI:

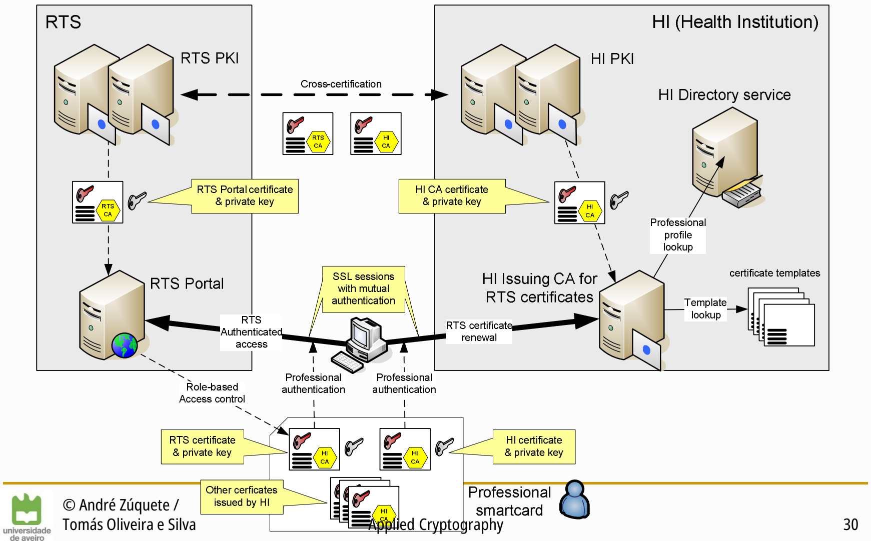
Trust relationships

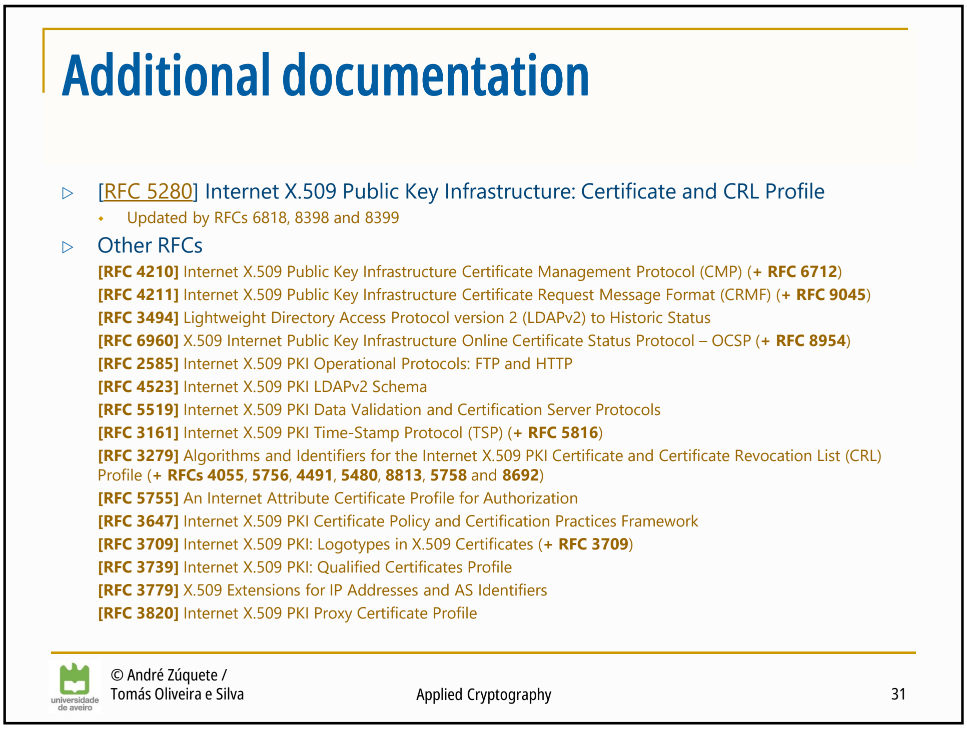
- ▷ A PKI defines trust relationships in two different ways
  - By issuing certificates for the public key of other CAs
    - Hierarchically below; or
    - Not hierarchically related
  - By requiring the certification of its public key by another CA
    - Above in the hierarchy; or
    - Not hierarchically related
- ▷ Usual trust relationships
  - Hierarchical
  - Crossed (A certifies B and vice-versa)
  - Ad-hoc (mesh)
    - More or less complex certification graphs

PKI:
Hierarchical and crossed certifications



Cross-certification of PKIs:
A practical example


RTS
HI (Health Institution)
RTS PKI
HI PKI
Cross-certification
RTS CA
HI CA
HI Directory service
RTS CA
RTS Portal certificate & private key
HI CA certificate & private key
HI CA
Professional profile lookup
RTS Portal
SSL sessions with mutual authentication
HI Issuing CA for RTS certificates
certificate templates
RTS Authenticated access
RTS certificate renewal
Template lookup
Role-based Access control
Professional authentication
Professional authentication
RTS certificate & private key
HI CA
HI CA
HI certificate & private key
Other cerficates issued by HI
HI CA
Professional smartcard



Additional documentation

- [RFC 5280] Internet X.509 Public Key Infrastructure: Certificate and CRL Profile
  - Updated by RFCs 6818, 8398 and 8399
- Other RFCs

  [RFC 4210] Internet X.509 Public Key Infrastructure Certificate Management Protocol (CMP) (+ **RFC 6712**)

  [RFC 4211] Internet X.509 Public Key Infrastructure Certificate Request Message Format (CRMF) (+ **RFC 9045**)

  [RFC 3494] Lightweight Directory Access Protocol version 2 (LDAPv2) to Historic Status

  [RFC 6960] X.509 Internet Public Key Infrastructure Online Certificate Status Protocol – OCSP (+ **RFC 8954**)

  [RFC 2585] Internet X.509 PKI Operational Protocols: FTP and HTTP

  [RFC 4523] Internet X.509 PKI LDAPv2 Schema

  [RFC 5519] Internet X.509 PKI Data Validation and Certification Server Protocols

  [RFC 3161] Internet X.509 PKI Time-Stamp Protocol (TSP) (+ **RFC 5816**)

  [RFC 3279] Algorithms and Identifiers for the Internet X.509 PKI Certificate and Certificate Revocation List (CRL) Profile (+ **RFCs 4055**, **5756**, **4491**, **5480**, **8813**, **5758** and **8692**)

  [RFC 5755] An Internet Attribute Certificate Profile for Authorization

  [RFC 3647] Internet X.509 PKI Certificate Policy and Certification Practices Framework

  [RFC 3709] Internet X.509 PKI: Logotypes in X.509 Certificates (+ **RFC 3709**)

  [RFC 3739] Internet X.509 PKI: Qualified Certificates Profile

  [RFC 3779] X.509 Extensions for IP Addresses and AS Identifiers

  [RFC 3820] Internet X.509 PKI Proxy Certificate Profile