Public Key Infrastructures

Foundations for secure e-commerce (bmevihim219)

Dr. Levente Buttyán
associate professor
BME Hálózati Rendszerek és Szolgáltatások Tanszék
Lab of Cryptography and System Security (CrySyS)
buttyan@hit.bme.hu, buttyan@crysys.hu

Technical issues

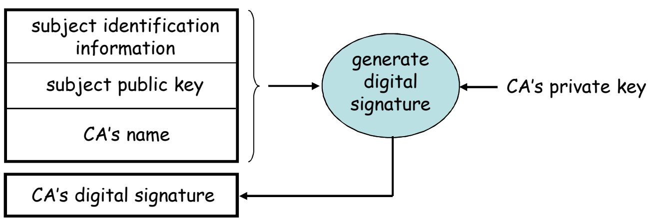
- basic concepts
  - certificate, certification authority, certificate chain (or path), certificate update and revocation
- PKI components and architectures
  - CA, RA, repository, archive, users; hierarchical, mesh, and bridge architectures
- life cycle of a certificate
  - application, issuance, distribution and use, revocation, expiration
- key-pair management issues
  - key-pair generation, private-key protection, management requirements for different key-pair types

The need for certificates

- distribution of public keys
  - confidentiality is not needed
  - authenticity is indispensable
- public keys can be distributed via secure out-of-band channels
  - physical contact
  - download public key from web site and check its hash value via phone
- these solutions are not always practical and they don’t scale

Basic idea of certificates

- concept invented by Kohnfelder in 1978 in his BSc thesis at MIT
- name and public key is linked together by the digital signature of a trusted entity called certification authority (CA)



- in order to verify a certificate you need to have an authentic copy of the public key of the CA
- advantages:
  - only the CA’s public key need to be distributed via out-of-band channels (scales better)
  - certificates can be distributed without any protection (why?)

Certificate chains

- a single CA cannot issue certificates to everyone in the world
  - practically infeasible
  - a single CA wouldn't be trusted by everyone
- if there are more CA's, then the following may happen:
  - you have a public-key certificate [Alice, K_{Alice}, TrustMe, $Sig_{TrustMe}$]
  - you don't have the public key of TrustMe
  - but you may obtain a certificate that contains TrustMe's public key [TrustMe, $K_{TrustMe}$, SuperTrust, $Sig_{SuperTrust}$]
  - …
- a certificate chain is a sequence $Cert_1$, $Cert_2$, …, $Cert_k$ of certificates, such that
  - $Cert_i = [S_i, K_{S_i}, CA_i, Sig_{CA_i}]$ (i = 1, 2, …, k)
  - S_1 = Alice, $S_i = CA_{i-1}$ (i = 2, …, k)
  - the public key of CA_k is known

Certificate chains (cont'd)

- notes:
  - all CAs in the chain must be trusted by the verifier in order to be able to accept the public key of Alice
  - there may be multiple chains leading to Alice some of which may be trusted
- example:
  - consider two certificate chains leading to A:

    [A, K_A, CA_1**, Sig_{CA_1}] [CA_1, K_{CA_1}, CA_2*, Sig_{CA_2}] [CA_2, K_{CA_2}, CA_3*, Sig_{CA_3}]

    [A, K_A, CA_1**, Sig_{CA_1}] [CA_1, K_{CA_1}, CA_4*, Sig_{CA_4}]

  - Red has K_{CA_3}, and trusts CA_1, CA_2, and CA_3
  - Blue has K_{CA_4}, and trusts CA_1, and CA_4
  - Red accepts the first chain, Blue accepts the second chain

Validity periods and revocation

- for security reasons, key-pairs shouldn't be assumed to be valid forever
  - certificates have a scheduled validity period
  - Cert = [S, K_S, valid_from, expires_on, CA, Sig_{CA}]
  - a certificate shouldn't be used outside its validity period …
  - … unless it is to reconfirm an earlier action in the same way as it would have occurred within the validity period (e.g., to verify the signature on an old document)

- if a private key is compromised or suspected to be compromised, then the corresponding certificate needs to be revoked
  - certificate revocation is the dark side of public-key crypto

PKI components: Certification Authority (CA)

- collection of hardware, software, and staff (people)

- main functions:
  - issues certificates for users and other CAs
  - maintains certificate status information and Certificate Revocation Lists (CRLs)
  - publishes currently valid certificates and CRLs
  - maintains archives of status information on expired certificates

- must comply with strict security requirements related to the protection and usage of its private keys (basis of trust)
  - uses tamper resistant Hardware Security Modules that enforce security policies (access and usage control)
  - defines and publishes its certificate issuing policies
  - complies with laws and regulations
  - is subject to regular control (by national supervising authority)

PKI components: Registration Authority (RA)

- approves certificate applications, but doesn't itself issue certificates (RA is not CA)
  - identifies and authenticates subscribers, provides collected attribute information to the CA
  - authorizes requests for key-pair or certificate generation or recovery from back-up
  - authorizes requests for certificate suspension or revocation
  - distributes personal tokens (which contain issued private key) and collects obsolete tokens

PKI components: repositories and archives

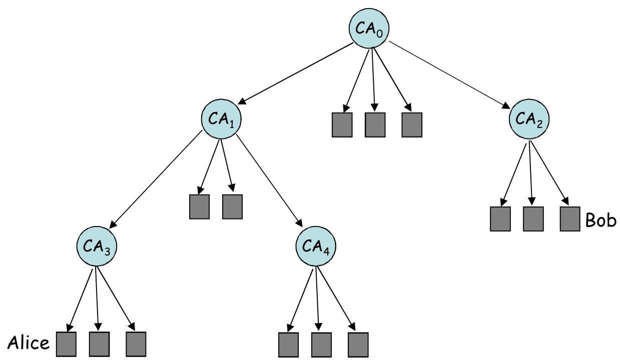
- repository
  - a directory service for the distribution and management of certificates and certificate status information (e.g., CRLs)
  - typically based on the X.500 directory standard (or a subset, such as the Lightweight Directory Access Protocol (LDAP))
  - format of directory entries must be generally agreed on (standards)
- archive
  - long term storage of status information of expired certificates
  - used to check if an old certificate was valid at a given time in the past (e.g., in case of disputes)
  - integrity of the archive must be strongly protected

PKI components: users

- organizations or individuals that use the PKI, but do not issue certificates

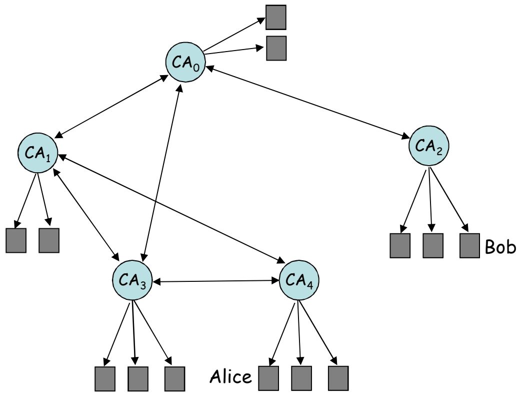
- two types:
  - certificate holders
    - have certificate(s) (own key pairs)
    - can use their own private key(s) (e.g., to sign documents)
  - relying parties
    - rely on certificates (and other components of the PKI) to verify if a public key belongs to a given entity and is valid
  - individuals and organizations may be both certificate holders and relying parties

PKI architectures: hierarchical



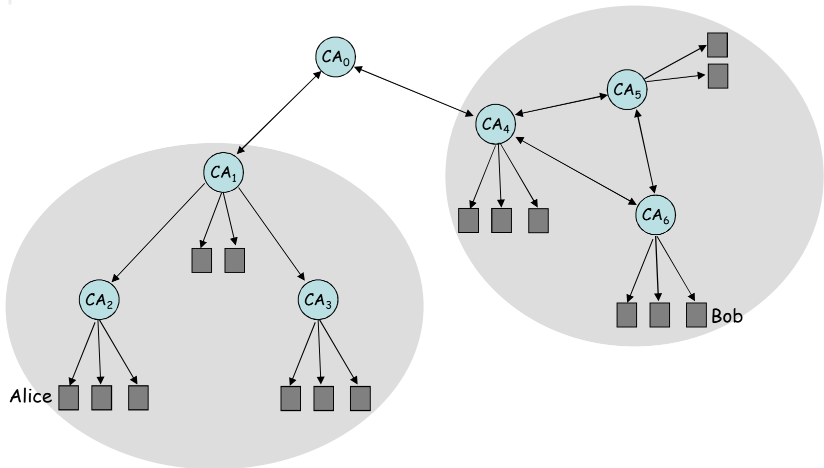
- top-down hierarchy
- certificate chains always start at the root CA
- every relying party must know the public key of the root CA

PKI architectures: mesh



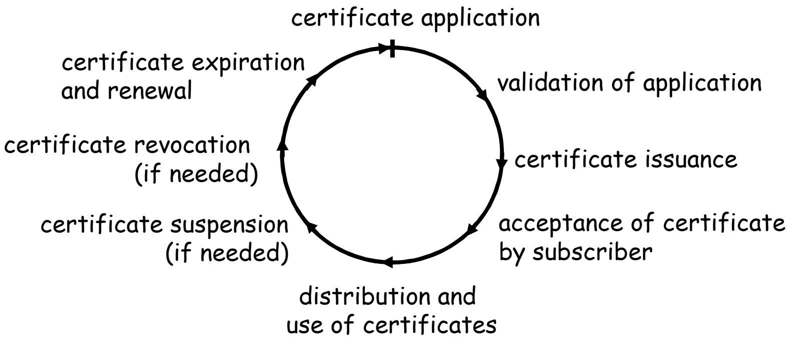
- CAs cross certify each other
- a relying party knows the public key of a CA near itself (usually the one that issued its certificate)
- a path needs to be found and verified from that CA to the target certificate

PKI architectures: bridge



- bridge CA connects enterprise PKIs (regardless of their architecture)
- relying parties need the same information as before (public key of their root or nearest CA)

Life cycle of a certificate



Applying for a certificate

- subscriber registers with the CA
  - establishment of a relationship between the subscriber and the CA
  - general subscriber information is provided to the CA
    - e.g., name, address, …
- subscriber requests a certificate from the CA
  - certificate request contains more specific information regarding the requested certificate
    - e.g., type of certificate, public-key, other specific fields requested for the certificate
  - may not be a conscious action (e.g., employee of a company)
  - in case of a third party CA, a subscriber must always explicitly request the issuance of a certificate and explicitly accept the issued certificate

Validation of application

- the CA needs to verify
  - the identity of the subscriber (subject authentication)
  - that the public-key (if provided) and other subscriber information originates from the subscriber and have not been tampered with in transit (public-key verification)
- subject authentication
  - method depends on the type of the requested certificate (assurance level)
  - for high assurance level certificates, usually personal presence is required
    - subject presents identification documents
    - CA may obtain further information from third party databases
    - most reliable form of authentication
  - low assurance level certificates may be obtained via an entirely on-line process
- public-key verification
  - if the CA generates the key-pair, then the problem is trivial
  - if the public key is provided by the subscriber, then a certificate issued by another CA may attest that the given public key really belongs to the given subscriber

Certificate issuance

- certificate is signed by a signing device using the CA's private key
- a copy of the certificate is forwarded to the subscriber
- a confirmation of acceptance is returned by the subscriber (if needed)
- a copy of the certificate is sent to the repository (directory service)
- a copy of the certificate is archived
- transaction is logged in an audit journal

Distribution of certificates

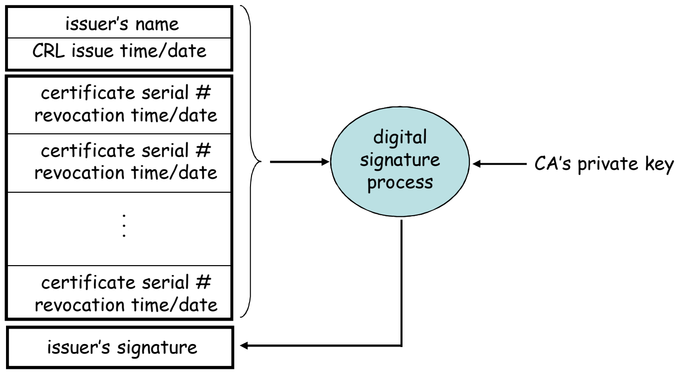
- via the repository (directory) service
- individually
  - the signer usually has a copy of her certificate
  - attach the certificate (chain) to the digitally signed document
  - potential disadvantages:
    - waste of bandwidth or storage space, as the verifier may already have a copy of the certificate
    - multiple chains may exist from the verifier to the signer; which one to attach?
  - advantage:
    - easier to archive signed document with the corresponding certificate chain (and certificate status information)
- other means
  - web
  - e-mail
  - DNS

Certificate revocation

- sometimes certificates need to be revoked before their expiration time
  - detected or suspected key compromise
  - change of data contained by the certificate (e.g., name, e-mail)
  - change of subject-CA relationship (e.g., employee leaves the company)
- who can request a revocation?
  - the subscriber is authorized to request the revocation of her own certificate
  - officers of the CA are also authorized to revoke a certificate under well-specified circumstances
  - other people may be authorized (e.g., employer)
  - in any case, the requesting party is authenticated by the CA and a log is generated
  - (RA may have the responsibility to approve revocation requests)

Certificate Revocation Lists (CRL)

- a CRL is a time-stamped list of revoked certificates signed by the CA and made available to certificate users (e.g., published regularly in the directory or on a web site)

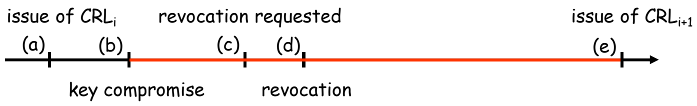


CRLs (cont'd)

- the CA issues CRLs regularly (hourly, daily, or weekly)
- a new CRL is issued even if no new revocations happened since the last CRL (why?)

- advantages:
  - CRLs can be distributed in the same way as certificates
  - no need for trusted servers and secure communication links

- disadvantage:
  - time granularity is limited to CRL issue period
    - key is suspected to be compromised now, but certificate users will be aware of that only when the next periodic CRL is issued



Immediate revocation

- the CA can operate a trusted on-line server that can be queried for the revocation status of a given certificate in real-time
  - server's response must be authenticated and its freshness must be ensured
  - server should be highly available to users
  - revocation requests must be quickly processed by the CA
- example: OCSP – Online Certificate Status Protocol (RFC 2560)

Key-pair generation

- on the key owner's system
  - possibly in the hardware (smart card) or software module where the private key will be stored later
  - preferable for digital signature keys (easier to ensure non-repudiation as the private key never leaves the key owner's system)
- on the CA's system
  - private key should be securely transported to the key owner's system
  - higher quality keys can be generated (more resources, stronger controls)
  - preferable for encryption keys (if private key needs to be backed up or archived)

Private-key protection

- protection of the private-key from unauthorized access is of paramount importance
- the private key is typically stored in
  - a tamper resistant hardware module or token (e.g., smart card, PCMCIA card, …)
  - an encrypted file within a computer or regular data storage media (e.g., CF card, USB key, …)
- access to the key needs to be protected via one or more authentication mechanisms
  - typically, passwords and PINs
    - can be used directly in case of hardware tokens
    - encryption keys can be derived from them in case of encrypted files
  - biometric checks

Management requirements for different keys

- RSA has the interesting property that the same key pair can be used for both encryption and digital signature
- however, such double use of key-pairs is not advisable; users should have different key-pairs for different applications
- the main reason is in the difference in key management requirements
  - digital signature
    - private key should never leave the key owner's system
    - private key doesn't need back up and archive (why?)
    - public key (certificate) needs to be archived
  - encryption
    - private key often needs to be backed up and archived (why?)
    - public key usually doesn't need to be archived

  → the two applications have conflicting requirements

Management requirements … (cont'd)

- more reasons
  - in general, an encryption key pair may not necessarily be used for digital signature (and vice versa)
    - it is better to design a system assuming that different algorithms (and thus key-pairs) will be used for digital signature and encryption
  - implementations that support encryption may be subject to more strict export controls
    - length of encryption key is often limited
    - if the same key is used for digital signature, then the digital signature key is smaller than it could be
  - key escrow
    - private keys used for encryption may be made available for government officials for escrow purposes
    - digital signature keys should not be disclosed in this way

X.509 standard

- certificate formats
- X.500 names, object identifiers
- CRL format and optimization methods

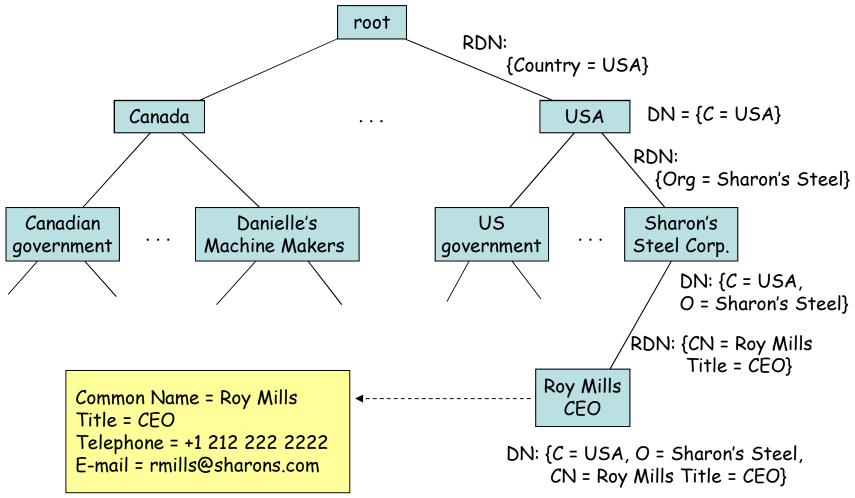
Basic X.509 certificate format

Field	Description
Version	X.509 version (currently 1, 2, or 3)
Serial number	unique identifier of this certificate assigned by the issuing CA
Signature Alg ID	object identifier of the signature algorithm used to sign this certificate
Issuer's X.500 name	
Validity period	start and expiry date of the certificate
Subject's X.500 name	
Subject public key info (alg ID and key value)	value of the public key together with the object identifier of the algorithm with which the key should be used
Issuer unique identifier	bit strings used to make the CA's and the subjects name unambiguous in case the same name has been reassigned to different entities through time (optional, version 2 only)
Subject unique identifier	
Signature of issuer	signature of the issuing CA

X.500 names

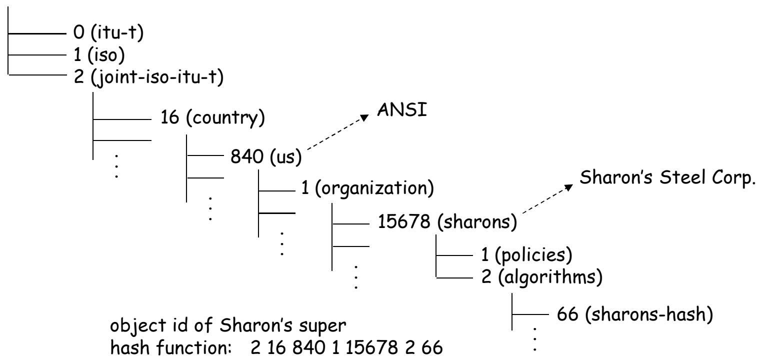
- in X.509 v1 and v2, X.500 names are used to identify subjects and issuers
- it is assumed that the subject and the issuer both have an X.500 directory entry (they are registered in the directory)
- X.500 directory entries are logically organized in a tree (Directory Information Tree - DIT)
- each entry (except the root) has a distinguished name (DN)
- the DN for an entry is constructed by joining
  - the DN of the parent in the DIT, and
  - a relative distinguished name (RDN)
    - a collection of attribute values that distinguishes this entry from other children of its parent
    - usually, the collection consists of a single attribute value

X.500 names (an example)



Object registration

- international standards describe how different objects (e.g., algorithms) should be identified and registered
- object identification works on the basis of a hierarchical structure of different value assigning authorities (e.g., national standard organizations)
- each authority is responsible for managing its sub-tree
- example: Sharon's Steel has a super hash function



Object registration (more examples)

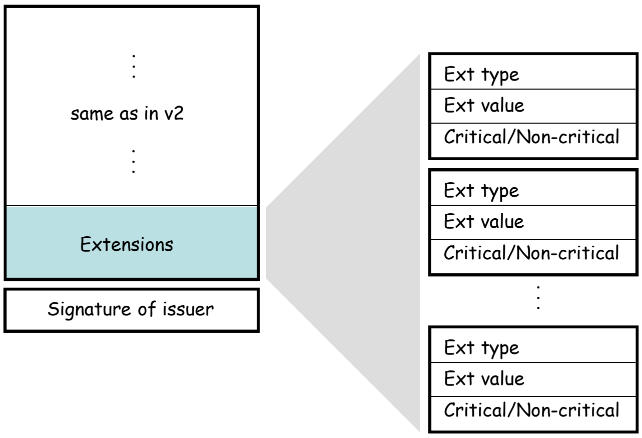
- DSA digital signature with SHA-1
  object id:
    iso (1) member-body (2) us (840) x9-57 (10040) x9algorithm (4) dsa-with-sha1 (3)
  source of spec:
    ANSI X9.57

- RSA digital signature with MD5
  object id:
    iso (1) member-body (2) us (840) rsadsi (113549) pkcs (1) pkcs-1 (1) md5withRSAencryption (4)
  source of spec:
    RSA Data Security Inc. PKCS #1

Defects of X.509 v1 and v2

- multiple certificates per subject
  - the same subject needs different certificates for different key-pairs
  - X.509 v1 and v2 cannot distinguish different certificates conveniently (only via their serial number)
- additional subject identifying information
  - X.500 DN doesn't contain enough information to identify the subject
- application specific name forms
  - some applications need to identify users by using application specific name-forms
  - e.g., for e-mail, the public key should be bound to an e-mail address
- certification policies
  - different certificates are issued under different policies
  - certificate users need to know the level of assurance that they can have in a given certificate
- delegation and limitations
  - when CA X issues a certificate to CA Y, X may want to recognize only a subset of the certificates issued by Y and its subordinate CAs
  - there's a need to limit the length of certificate chains

X.509 v3 certificate format



X.509 v3 certificate format (cont'd)

- extension types must be registered (see object registration)
  - communities can define their own extension types
  - most important extension types are standardized
- critical / non-critical flag
  - non-critical:
    - if you don't know this ext type, you can safely ignore this extension
    - e.g.: e-mail address or alternative name
  - critical:
    - it is safe to use this certificate only if you recognize this extension type (you shouldn't ignore this extension)
    - e.g.: an extension that limits the type of applications where the certificate should be used
  - critical extensions lead to interoperability problems
    → most extensions should be flagged non-critical

Standard certificate extensions

- key and policy information
  - these extensions are used to convey additional information about the subject and the issuer keys (e.g., key identifier)
  - help to find certificate chains
- subject and issuer attributes
  - these extensions support alternative names and convey more attribute information (e.g., postal address, phone number)
- certification path constraints
  - these extensions help to limit the length of certificate chains
- extensions related to CRLs
  - …

Key and policy info extensions

- Authority Key Identifier
  - can be used to easily find the issuing CA's public key (needed to verify the certificate)
    - can be an explicit key id
    - or a pointer to another certificate, where the signing key is certified by another CA (pointer can be the name of the CA and serial number of the certificate)
- Subject Key Identifier
  - enables different keys used by the same subject to be distinguished conveniently
- Key Usage
  - indicates the purpose for which the key should be used (e.g., digital signature, non-repudiation, key-encryption, DH key agreement, data encryption, certificate signing, CRL signing)
  - usually flagged as critical
- Private-Key Usage Period
  - validity of a certificate can be longer than the period in which the private key is effectively used for signing
  - this extension indicates the usage period of the private key

Key and policy info extensions

- Certificate Policies
  - identifies policies under which the CA issued the certificate
  - certificate policies have object identifiers (see object registration)

  a **certificate policy** is a named set of rules and practices that are applied by the CA when issuing certificates and that should be followed by the certificate users when they use certificates

  may contain:
  - community and applicability restrictions
    - e.g., Sharon's CA issues certs for Sharon's employees and for signing e-mails only
  - identification and authentication policy
    - practices followed by the CA to authenticate certificate subjects
  - key management policy
    - the measures taken by the CA to protect its own crypto keys
  - operational policy
    - e.g., specifies the frequency at which the CA issues CRLs
  - local security policy
    - the measures taken by the CA to protect its computing environment
  - legal provisions
    - a statement of limitations of liability
  - policy administration
    - identification of the policy defining authority and indication of how the policy definition is maintained and published

Subject and issuer attr extensions

- Subject Alternative Name
  - this extension can carry an alternative name of the subject (e-mail address, domain name, web URL, …)

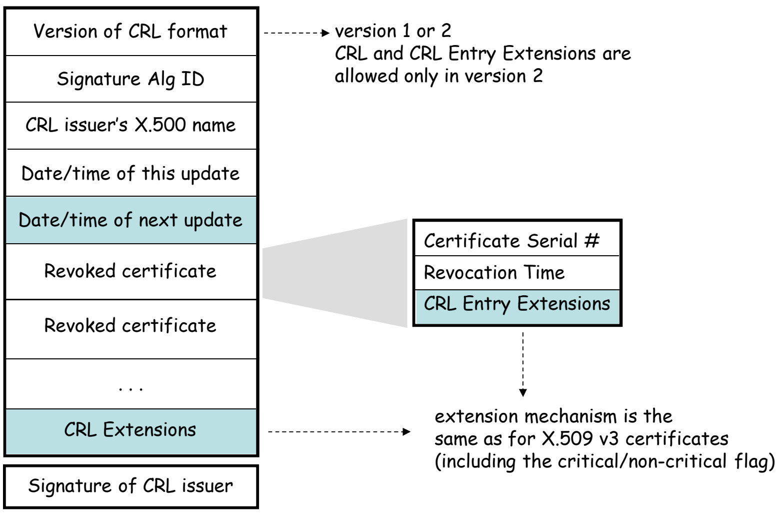
- Issuer Alternative Name
  - same as for subject

- Subject Directory Attributes
  - provides general means for conveying additional information about the subject
  - contains X.500 attribute values (e.g., Phone = +1 212 222 2222)

Certification path constraints

- Basic Constraints
  - indicates whether the subject can act as a CA
  - if so, then it may also specify the length of a certificate chain that may stem from this certificate
- Name Constraints
  - restricts the name space that will be considered acceptable in subsequent certificates in any chain stemming from this certificate
  - example:
    - subject is bme.hu
    - the subject name of any further certificate should end with bme.hu
    - acceptable names: hit.bme.hu, vik.bme.hu
    - non-acceptable names: crysys.hu, epfl.ch
- Policy Constraints
  - restrictions on the policies that may be used by the CAs that issued the certificates following this certificate in the chain

X.509 CRL format



Extensions related to CRLs

- general extensions
- CRL distribution points
- Delta-CRLs
- Indirect CRLs
- Certificate suspension

General extensions

- CRL Number (CRL extension)
  - helps a certificate user to see if any past CRLs has been missed
  - also needed to support Delta-CRLs
- Reason Code (CRL entry extension)
  - gives a reason of the revocation: Key Compromise, CA Compromise, Affiliation Change, Superceded, Cessation of Operation, Certificate Hold
- Invalidity Date (CRL entry extension)
  - indicates a date at which the revoked compromised key was known to still be good
- Authority Key Identifier (same as for X.509 v3)
- Issuer Alternative Name (same as for X.509 v3)

Issues related to CRL size

- when verifying a certificate, the appropriate CRL needs to be fetched and verified
- to avoid communication (and storage*) overhead, CRLs shouldn't be very large
- a useful technique is the following (used in early versions of X.509)
  - each CA maintains two CRLs
    - one for revoked end-user certificates
    - another for revoked CA certificates (very short CRL, usually empty)
  - in a certificate chain, there's only one end-user certificate and multiple CA certificates → a potentially long CRL need to be processed only for the verification of the end-user certificate
  - growing end-user population is still a problem
- size of a CRL depends on
    - size of the population
    - certificate validity period (expired certs need not be kept on CRL)
  - reducing the validity period is undesirable
    - more user inconvenience
    - higher demand on archive resources

  → population size must be limited

* CRLs may be archived together with signed documents

CRL distribution points

- in the current version of X.509, this problem is solved by
  - allowing to arbitrarily partition the population
  - associating a CRL distribution point to each partition
    - the CRL distribution point is not a CA; it doesn't issue CRLs
  - inserting a pointer in the certificate to the CRL distribution point where revocation of this certificate may appear (certificate extension)
- supporting extensions:
  - Certificate Distribution Points (certificate extension)
    - identifies the CRL distribution points where a revocation of this certificate can appear
    - identifies the CRL issuer (if not the same as the certificate issuer, see Indirect CRLs later)
    - can be an X.500 name, a web URL, an e-mail address …
  - Issuing Distribution Point (CRL extension)
    - gives the name of the CRL distribution point for this CRL
    - signed by the CA that issued the CRL (together with other entries of the CRL)
    - prevents attackers from substituting an empty CRL obtained from distribution point A in place of a non-empty CRL at distribution point B

Delta CRLs

- another mechanism to reduce the size of CRLs
- a delta-CRL is a digitally signed list of changes that have occurred since the issuance of the last complete CRL
  - reduces communication overhead
  - certificate using systems should be capable of maintaining their own database of certificate revocation information
  - the delta-CRL is used to update these local databases
- supporting extension:
  - Delta CRL Indicator (CRL extension)
    - identifies the CRL as being a delta-CRL only
    - carries the CRL number of the base CRL (the complete CRL to which the changes should be applied)

Indirect CRLs

- it is possible that the CRL is issued by a different CA than the one that issued the certificates on the CRL
- thus, one CRL can contain revoked certificates issued by different CAs
- advantage:
  - a CRL can be created that contains ALL revoked CA certificates (not only those issued by a given CA)
  - when verifying a certificate chain, the user needs to fetch only two CRLs
    - the above indirect CRL (to verify the revocation status of any CA in the chain)
    - the end-user CRL of the last CA in the chain (to verify the status of the target certificate)
- supporting extensions:
  - CRL Distribution Points (certificate extension)
    - identifies the CRL issuer that issues CRLs on which a revocation of this certificate can appear
  - Certificate Issuer (CRL entry extension)
    - indicates who was the issuer of this revoked certificate

Certificate suspension

- sometimes it is not clear whether a certificate should be revoked or not
- examples:
  - an unusually high value e-banking transaction
    - Alice pays her bills using e-banking: she transfers a rather small amount from her account every month
    - once Alice decides to buy a car: she transfers a huge amount from her account
    - this is suspicious !
  - two transactions in a short time but far apart from each other
    - Alice uses a digital check system, where checks are signed by her smart card
    - the bank receives two checks one signed at 10:17 in the US, and another signed at 10:35 on the same day in Germany
    - this is suspicious too!
- supporting extension:
  - Reason Code (CRL entry ext) = Certificate Hold

Attribute certificates

- identity certificates bind a public key to a subject
- attribute certificates bind one or more attribute values to a subject
- attribute certificates can be used for flexible authorization
- why should public-key certificates be used with caution for authorization?
  - the authority that is appropriate to certify identity of a person associated with a public key may not be appropriate to certify authorization information
  - differences in dynamics of the two types
    - the person authorized to perform a particular function may vary monthly, weekly, or even daily
    - public-key certificates are typically valid for a year or more
- X.509 supports attribute certificates
  - they have a similar structure and managed in a similar way (including revocation) as public-key certificates