CSE 410/565 Computer Security
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Lecture 12: Public Key Infrastructure

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Lecture Outline

- Public key infrastructure
- Certificates
- Trust models
  - hierarchical model
  - networked PKIs model
  - web browser multiple CAs model
  - user-centric web of trust of PGP

Public Key Infrastructure

- Possibly the biggest challenge in public-key cryptography is ensuring the authenticity of public keys
  - Alice wants to encrypt a message for Bob using his public key
  - but Alice doesn't know Bob personally
- We have already seen that public keys can be managed through the use of certificates
  - there is a trusted certification authority with a known public key
  - the CA issues certificates by signing a user's identity along with her public key
  - Bob's public key pk_B is authentic if it matches his key in $\mathsf{cert}_B = \mathsf{sig}_{CA}(B, pk_B)$

Public Key Infrastructure

- A public-key infrastructure (PKI) is a system for managing trust in the public keys through the use of certificates
  - it is the basis of a pervasive security infrastructure whose services are implemented and delivered using public-key techniques
- Ideally, a PKI should function without active participation of the user
  - when we say that a network user Alice performs various operations, it is implies that her software does this
  - Alice might not be even aware of the PKI-related procedures
- A PKI's goal is to eliminate the need for users to share precomputed symmetric keys and enable the use of public-key cryptography

Public-Key Infrastructure

- There are many components to a PKI
  - certificate issuance
    - before a certificate can be issued, the identity and credentials of the user must be verified using non-cryptographic means
    - a secure procedure must be used to generate the public and private keys for the certificate's owner
    - the certificate must be securely transmitted to its owner
  - certificate revocation
    - this is done before a certificate's expiration date under unforeseen circumstances
    - for example, if a private key is lost or stolen
    - additional infrastructure is need to recognize revoked certificates

Public-Key Infrastructure

- PKI components (cont.)
  - key backup/recovery/update
    - key backup refers to secure storage of users' private keys by the administrator of the PKI
    - key recovery is a protocol that allows a lost or forgotten key to be restored or re-activated
    - key update occurs when a key is to be changed (e.g., a certificate is about to expire)
  - timestamping
    - the times at which a key is issued, revoked, or updated may be important
    - such timestamps are often included in the certificate

Public-Key Infrastructure

- Once a PKI is built and operational, it allows various applications to be built on top of it
  - such applications can be called PKI-enabled services
- Examples of PKI-enabled services include
  - secure communication
    - secure email protocols include Secure Multipurpose Internet Mail Extensions (S/MIME) and Pretty Good Privacy (PGP)
    - secure web service access is provided through Secure Sockets Layer (SSL) or Transport Layer Security (TLS)
    - secure virtual private networks (VPNs) use the Internet Protocol Security (IPsec) protocols

Public-Key Infrastructure

- Examples of PKI-enabled services (cont.)
  - access control
    - access control provides the means of managing user privileges through authentication, authorization, and delegation
    - access control normally requires user authentication via a password or cryptographic identification scheme
  - privacy architecture
    - a privacy architecture permits the use of anonymous or pseudonymous credentials
    - such credentials (or certificates) allow an individual to show membership or another property without specifying their identity

Certificates

- Certificates are important building blocks of PKIs
- It is generally assumed that there is a trusted CA
  - each user has access to an authentic copy of the CA's public key
- In its simplest form, a certificate is a CA's signature on an identity and the identity's public key
- A valid CA's signature of this form is treated as a confirmation that the public key belongs to that identity
  - i.e., it is assumed that the CA verifies the identity before signing any given key
- X.509 v3 is a popular type of certificate

Certificates

- X.509 certificates contain the following fields:
  - data
    - version
    - serial number
    - signature algorithm
    - issuer name
    - validity period
    - subject name
    - subject public key and public key algorithm
    - optional fields
  - signature on all of the above fields

Certificates

- X.509 certificates were originally defined using X.500 names for subjects
- X.500 names have a hierarchical format:

  C = US
  O = University at Buffalo
  OU = Department of Computer Science and Engineering
  CN = Chunming Qiao

  – here C denotes country, O denotes organization, OU denotes organizational unit, and CN denotes common name
- This format ensures that everyone has a unique global name
  – it could be used as a global phone directory
- No global X.500 directory exists today

Certificates

- Example X.509 certificate

Data:
Version: 3
Serial Number: 32:73:4D:44:25:6E:73:C2
Certificate Signature Algorithm: PKCS #1 SHA-256 With RSA Encryption
Issuer: CN = Google Internet Authority G3
O = Google Trust Services
C = US
Validity:
Not Before: September 25, 2018, 7:43:00 AM GMT
Not After : December 18, 2018, 7:43:00 AM GMT
Subject: C = US, ST = California, L = Mountain View,
O = Google LLC,
CN = www.google.com

Certificates

- Example X.509 certificate (cont.)

  Subject Public Key Info:
  - Public Key Algorithm:
    - Algorithm Identifier: Elliptic Curve Public Key
    - Algorithm Parameters: ANSI X9.62 elliptic curve prime256v1 (aka secp256r1, NIST P-256)
  - Subject's Public Key:
    - Key size: 256 bits
    - Base point order length: 256 bits
    - Public value: 04 5a cd 02 99 d4 9a a0 ab 0f 9f c0 9e d1 c5 2d

      ...

  Certificate Signature Value:
  - Size: 256 Bytes / 2048 Bits
  - 88 14 32 8e 8f 32 95 8f d4 a4 85 0d 2f 55 23 78
  - 4b 58 6d cf b4 5e 1c 2b a8 3f 1c 6c 83 7e 6a fa
  - ...

Certificates

- Certificate life-cycle management has several phases, which include:
  - registration
  - key generation (and backup), key distribution
  - certificate issuance
  - certificate retrieval and validation
  - certificate expiration
- Additionally, we might have:
  - key update
  - key recovery
  - certificate revocation

Certificates

- During the validation, the following steps take place
  - verify the integrity and authenticity of the certificate by verifying the CA's signature
    - it is assumed that the CA's keys is known a priori or can be reliably verified using external resources
  - verify that the certificate has not expired
  - verify that the certificate has not been revoked
  - if applicable, verify that the certificate's usage complies with the policy constraints specified in the certificate's optional fields

Certificates

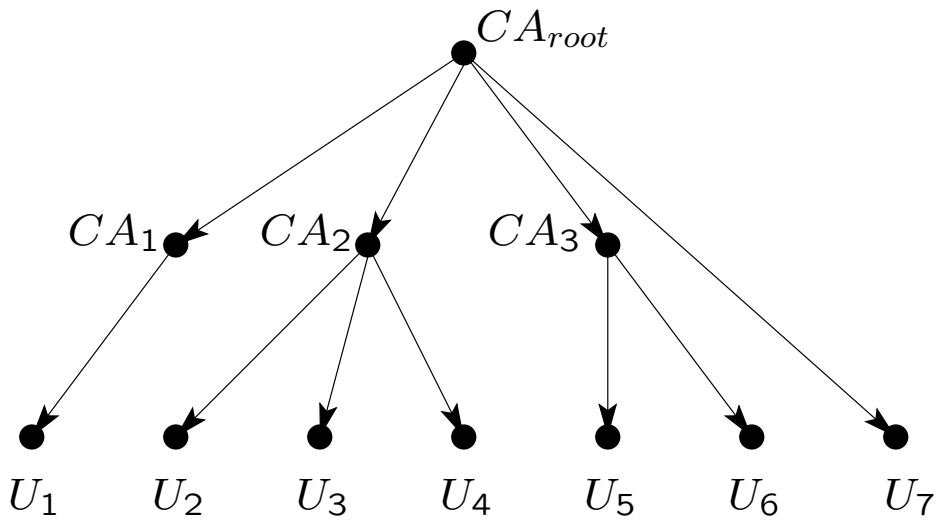
- A PKI needs a mechanism to verify that a certificate has not been revoked prior to its expiration date
- A certificate revocation list (CRL) is the most common technique
  - a CRL is a list of the serial numbers of certificates that are revoked but not expired
  - this list is prepared by the CA and is signed
  - it is updated periodically and is made available at a public directory
- For efficiency reasons, delta CRLs can be used
  - instead of containing all revoked certificates, delta CRLs contain the changes since the most recent previously issued CRL or delta CRL
- Alternatively, an online certificate status protocol can be used to query a certificate's status in real time

Trust Models

- Often there is more than one CA that can sign certificates
  - a certificate can be verified by following a certificate path from a trusted CA to a given certificate
  - each certificate in the path is signed by the owner of the previous certificate in the path
  - if all certificates in the path can be verified, the last certificate is considered to be valid
- A trust model specifies the way in which a certificate path should be constructed, e.g.,
  - for example, strict hierarchy; networked PKIs; web browser model; and user-centric model (or web of trust)

Trust Models

- Strict hierarchy model
  - there is a single root CA that has a self-signed self-issued certificate
    - the root CA is called trust anchor
  - the root CA may issue certificates for other CAs
  - any CA can issue certificates for end users



Trust Models

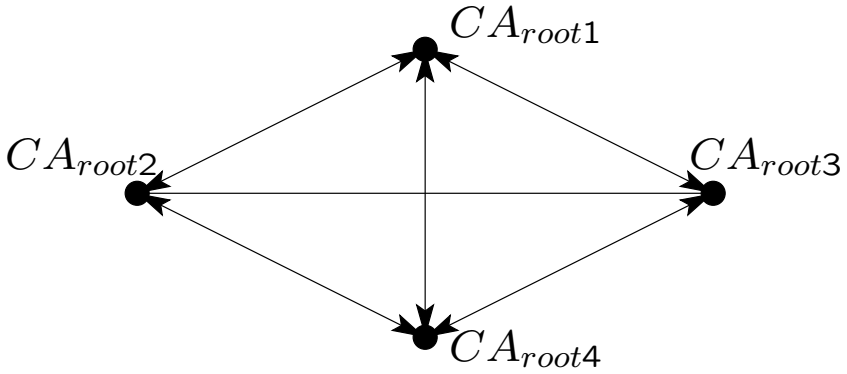
- Strict hierarchy model
  - what is the meaning of a directed edge?
  - usage example: Alice would like to verify a certificate of user U_3
    - U_3 sends to Alice
    - Alice performs certificate path validation by

Trust Models

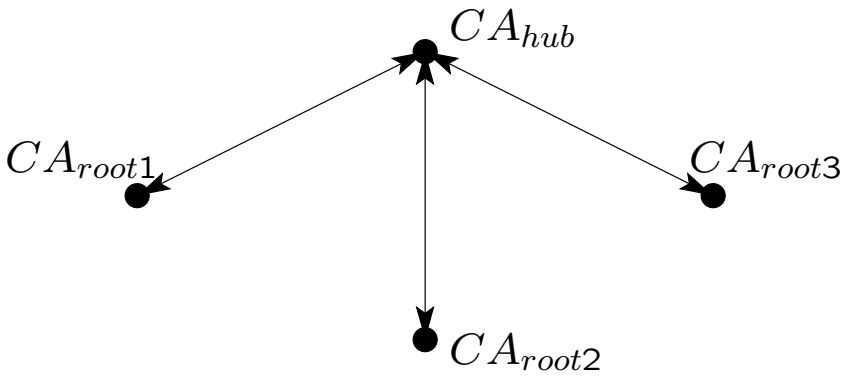
- Networked PKIs model
  - sometimes it might be desirable to connect root CAs of two or more different PKI domains
    - this can be called PKI networking and it creates one large PKI with users in different domains
  - cases when one CA signs the certificate of another CA are called cross-certification
  - in mesh configuration, there are several root CAs and all of them cross-certify one another
    - the number of cross-certifications for n root CAs is _____
  - in hub-and-spoke configuration, root CAs each cross-certify independently with a new hub CA
    - the number of cross-certifications for n root CAs is _____

Trust Models

- Networked PKIs model (cont.)
  - example mesh configuration



  - example hub-and-spoke configuration



Trust Models

- Networked PKIs model (cont.)
  - to validate Bob's certificate, Alice must be able to find a path of certificates from her trust anchor CA_{root_i} to Bob
    - this process is called path discovery
  - assume that Bob's certificate is signed by CA_{root_j}
  - what path does Alice construct in mesh configuration?
  - in hub-and-spoke configuration?

Trust Models

- Web browser model
  - most web browsers come preconfigured with a set of independent root CAs
  - all of them are considered to be trusted by a user of the browser
  - security considerations for this model:
    - users normally don't have information about the security of these pre-configured root CAs
    - the list is editable, but many users are not even aware of it
    - there might be no mechanism to revoke a root CA from a web browser
    - there might be no automated way to update root CAs' certificates
    - if permitted, most users choose to proceed with expired certificates

Trust Models

- Pretty Good Privacy (PGP)
  - PGP is used for email, where each user is her own CA
  - a PGP certificate contains an email address (UID), a public key (PK), and one or more signatures on this (UID, PK) pair
  - when a Alice creates her key, she first self-signs it:
    cert(Alice) = (data, sig_A(data)), where
    data = (UID = alice@buffalo.edu, PK = 0xBEEF1234)
  - later, other users may add their signatures to Alice's key, so she has
    cert(Alice) = (data, sig_A(data), sig_B(data), sig_C(data), . . .)

Trust Models

- Pretty Good Privacy (PGP) (cont.)
  - when Bob wants to sign Alice's key, he needs to
    - retrieve a copy of Alice's key (from Alice or a key server)
    - verify Alice's identity
    - ensure that the key he has for Alice is the same as what Alice has
      - this is done by comparing the fingerprints of Alice's key and Bob's version of Alice's key
    - sign Alice's key
    - send the updated certificate to Alice or a key server
  - if Bob performed all checks, he is likely to trust the key
  - he can encrypt emails to Alice or receive signed emails from her

Trust Models

- Pretty Good Privacy (PGP)
  - Alice keeps a collection of certificates she obtained from different sources in a data structure called a keyring
  - she is able to declare how much she trusts the owner of a certificate
    - often the choices are implicitly trusted, completely trusted, partially trusted, or untrusted
  - Alice's own key is implicitly trusted
  - if Alice is convinced that Bob's public key is valid and Bob would not to sign invalid keys, she declares Bob's key completely trusted
  - she can also set how the trust of unknown keys is computed
    - e.g., she can set that keys with the distance larger than 3 from her should not be trusted

Trust Models

- PGP web of trust
  - each user can set the trust of a key at signing time and also choose how trust of unsigned keys is computed
  - key servers are a convenient way of store and access keys
    - examples: keyserver.pgp.com, pgp.mit.edu, etc.
    - different key servers synchronize their datasets

S/MIME Client Certificates

- There are other certificate or PKI architectures for email
- UB offers client certificates for signing and encryption
  - the key is generated by UBIT and is signed by UB's key
  - you can trust that signed emails from UB accounts were sent by the account owners
  - see https://email.buffalo.edu/ClientCertificate.html for more information

Future of PKI

- There are several difficulties that prevent a large-scale deployment of PKIs
  - the first problem is who should be responsible for development, maintenance, and regulation of PKIs
  - the second problem is what standards should be used in PKIs
  - the third problem is that different PKIs are needed in different environments
  - also, a lack of PKI-compatible applications is slowing the deployment of PKIs
    - this is a chicken-and-egg problem

Are There Alternatives?

- Emerging technologies might provide alternative solutions to having PKI
  - one example is contract signing using blockchain technology
    - blockchain offers immutable storage organized by time
    - contract signing could be realized using digital signatures
      - this requires having an authentic copy of the signer's key as otherwise the security guarantees don't hold
    - by reliably storing one's consent to executing the contract on the blockchain, we could have similar legal protection
      - laws and regulations often lag behind technological changes

Summary

- Public key infrastructure targets solving the problem of public-key management between users who don't know each other
  - this is often addressed through the use of certificates
  - many different architectures for building trust exist
  - different applications use different models
    - multiple CA certificates on the web
    - web of trust in PGP
- No large-scale public PKI is currently in place