# Public Key Infrastructure Fundamentals

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Thanks to Paul van Oorschot



iMinds CONNECT.INNOVATE.CREATE

## Goals

- Understand how public keys can be distributed and revoked on a large scale
- Understand what a CA-based PKI is and what the problems are with their deployment
- Understand how multiple CAs can interoperate depending on their trust relationship

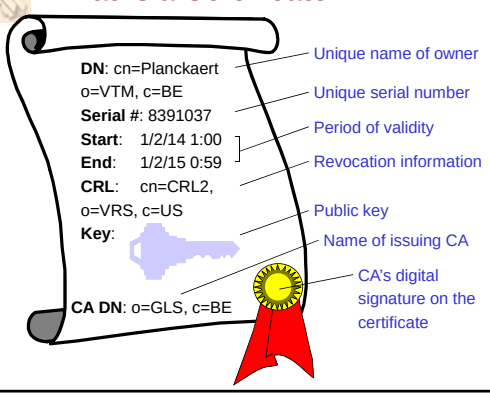
2

## How to establish public keys?

- point-to-point on a trusted channel
  – *mail business card, phone*
- direct access to a trusted public file (registry or database)
  – *authentication trees*
- on-line trusted server (bottleneck)
  – OCSP*: Online Certificate Status Protocol*
- off-line servers and certificates
  – *PKI: Public Key Infrastructure*
- implicit guarantee of public parameters
  – *identity based and self-certified keys*

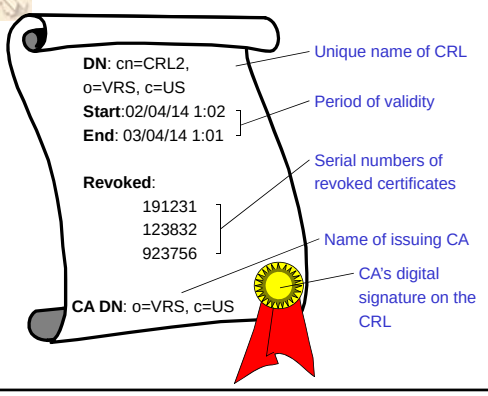
3

## What is a Certificate?




4

## What is a Certificate Revocation List?




5

## PKI Overview

1. Background:
   Keys and Lifecycle Management
2. PKI components ( “puzzle pieces”)
3. Trust Models

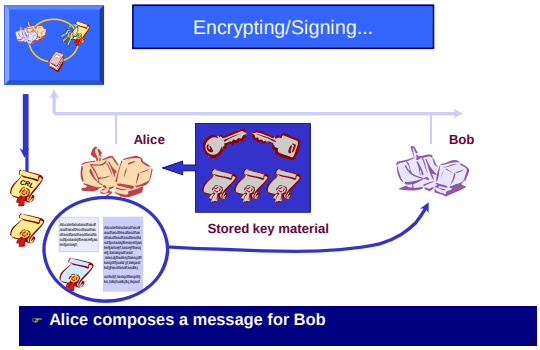
6

Background:

## Keys and Lifecycle Management

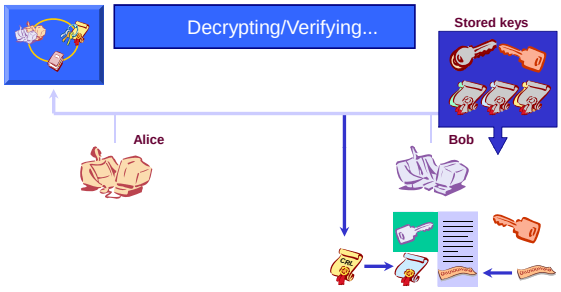
7

## Sending secure e-mail



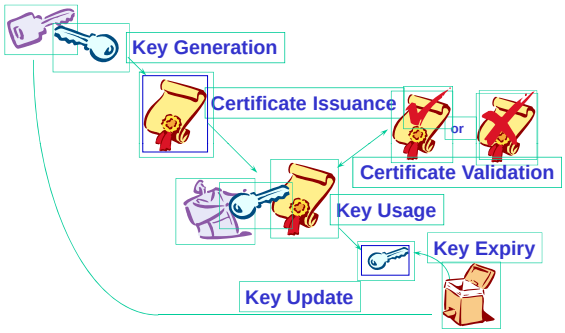

- Alice composes a message for Bob

## Receiving secure e-mail



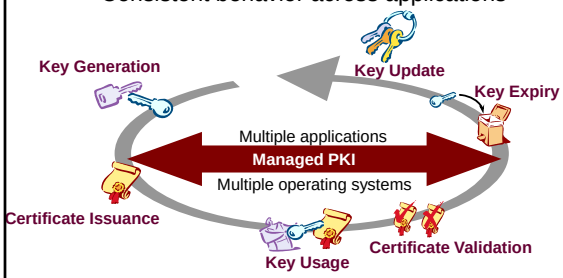

- Bob uses the one-time symmetric key to retrieve the message text and signed hash

## Key Lifecycle Management



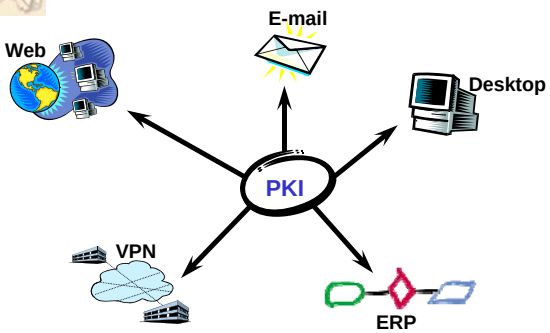

## Fundamental PKI features

- Automated and transparent key and certificate lifecycle management
- Consistent behavior across applications




11

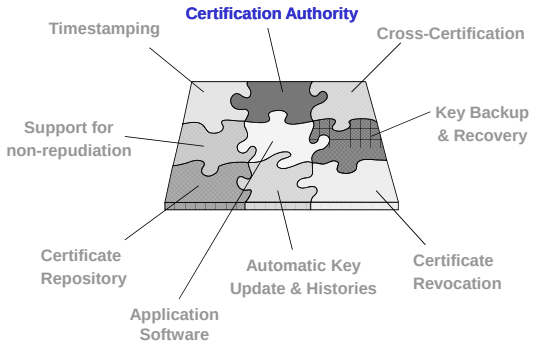
## PKI should provide Unified Security




This vision from late 1990s has never materialized!

12

## Certification Authority



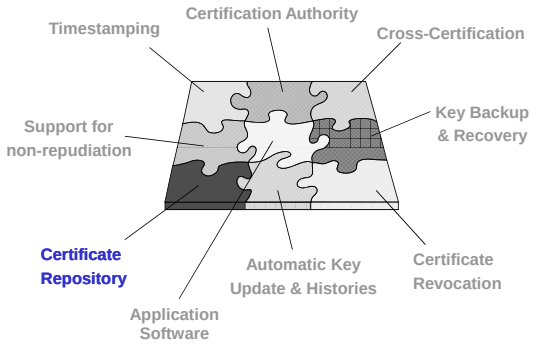

13

## Certification Authority

- Issue certificates for all entities / devices (for multiple applications) from a single CA
  - single system saves h/w, s/w, training, personnel
- Flexible certificate policy / security policy
  - tailor to needs of environment, application or entity (e.g. certificate lifetime, crypto algorithms, keylengths, password rules, ...)

14

## Certificate Repository



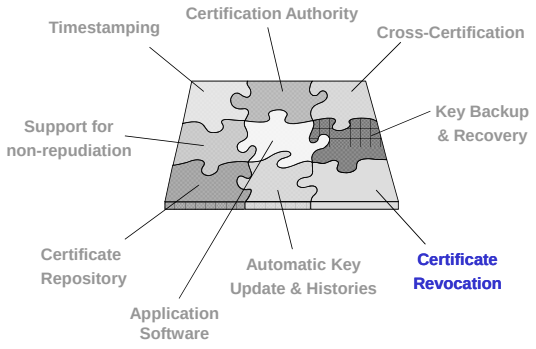

15

## Certificate Repository

- LDAP-compliant directory stores certificates
  - standards-based for interoperability
- Directory products built specifically to address scalability issues
  - X.500 or proprietary schemes to replicate data (scales to millions of users)

16

## Certificate Revocation System




17

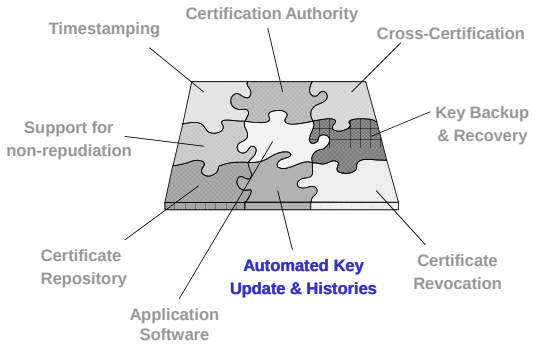
## Certificate Revocation

- Automated CRL publishing
  - when certificate revoked, CRL can be automatically published to directory providing near-immediate availability
  - automated CRL checking by application
  - want to avoid applications which require manual end-user actions to check CRLs for each application or certificate usage

March 2001: Verisign has issued two certificates to fake Microsoft employees
- Problem: IE did not implement revocation checking

18

## Automated Key Update & History



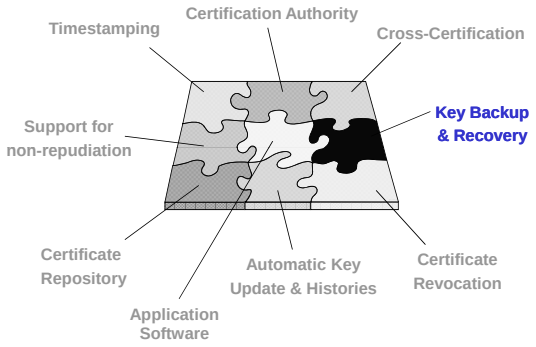

19

## Automated Key Update & History

- Users should never even need to know they have their own certificates (password only)
- If key management is not automated or does not provide key history . . .
  - when certificate expires, lose access to all past encrypted data, e-mail, . . .
  - user must request new certificate and repeat entire registration process
- Should replace key, not just new expiry date
- Transparent triggering mechanism, ideally

20

## Key Backup & Recovery




21

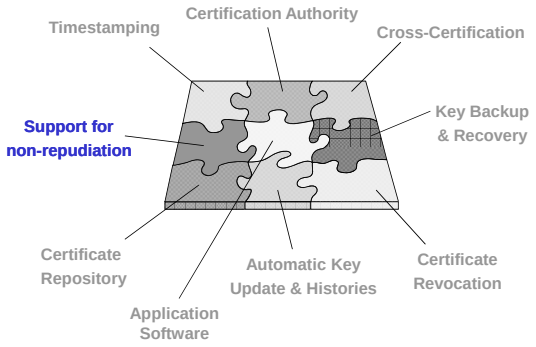
## Key Backup & Recovery

- Enterprise will lose valuable (stored) data if keys used to encrypt data are not backed up
  - 20-40% of users forget passwords / year
  - employees leave the organization
- Allows the enterprise to control the backup
  - not reliant on 3rd parties
  - should be configurable to require multiple administrators to authorize access

Key recovery/backup should not be confused with **key escrow**; governments have tried to impose this for encryption keys used for communication

22

## Support for Non-Repudiation



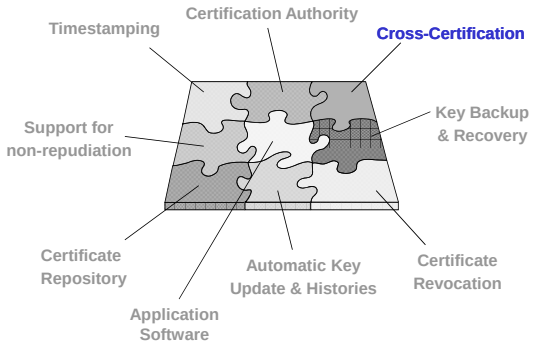

23

## Support for Non-Repudiation

- Must use separate key pairs for digital signatures and encryption
  - want backup of encryption keys, **do not** want backup of signature private keys
- Separate key pairs allows lifecycles to be managed independently
- Different policy controls for each key pair
  - security requirements per pair may differ, e.g. valid lifetimes

24

## Cross-Certification



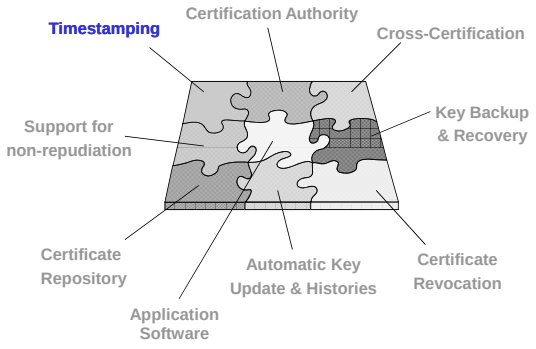

25

## Cross-Certification (cf. Trust models)

- Sufficiently flexible to model existing business relationships
  - includes 1-1 relationships and hierarchies
  - cross-certificate associated with an organization (vs. a service provider)
  - compare to web trust model: trust anyone signed by browser-embedded CAs
- Enterprise manages cross-certification policy & procedures, to reduce business risk
  - cross-certifcates created by authorized administrators, transparent to end-user

26

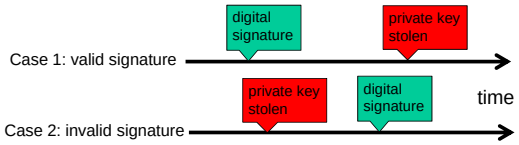
## Timestamping




27

## Timestamping

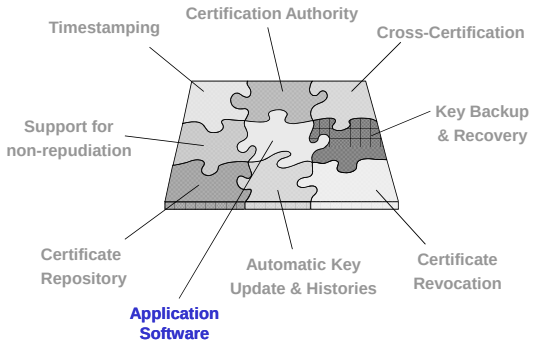
- Legal requirements
- Business requirements related to fixing transactions in time
- Technical requirements related to certificate revocation (non-repudiation)




Question: why is it not sufficient to include a timestamp in the signed text?

28

## Application Software




29

## Application Software

- Designed to be enabled to use the PKI ("PKI-ready")

application software
(email, file encryption, VPN, web security/SSL, ...)

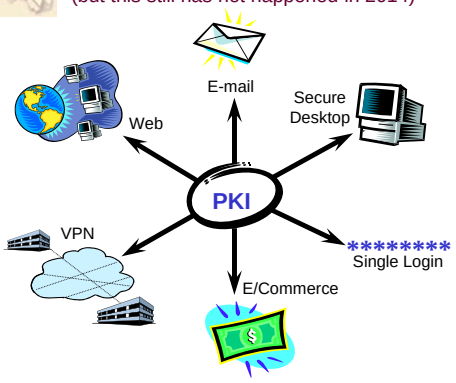
PKI

key & certificate lifecycle mgmt
(certificate validation, key update, ...)

crypto algorithms (symmetric encryption, signature, hash, MAC, key establishment, …)

30

PKI-ready application software completes the picture (but this still has not happened in 2014)




31

## Summary - Essential PKI Components

Much more than a "certificate server" or set of toolkit calls

- Certification Authority
- Revocation system
- Certificate repository ("directory")
- Key backup and recovery system
- Support for non-repudiation
- Automatic key update
- Management of key histories
- Cross-certification
- PKI-ready application software

32

## More info: IETF PKIX Working Group

www.ietf.org

- de facto standards for Internet PKI, X.509-based
- Certificate & CRL Profile [PKIX-1]: RFC 2459
- Certificate Mgmt Protocols [PKIX-CMP, PKIX-3]: RFC 2510
- PKIX roadmap: www.ietf.org/internet-drafts/draft-ietf-pkix-roadmap-01.txt

33

## PKI vs. Privilege Management

- Public key certificate binds a public key to an entity
- Establishes who owns a key vs. what privileges that key / owner is granted
- Certificate-processing software (relying party) may implicitly grant privileges
- Privilege Management Infrastructure (PMI) makes privileges explicit
- PMI may utilize PKI as base infrastructure
- example: attribute certificates

34

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35

## Key generation: where?

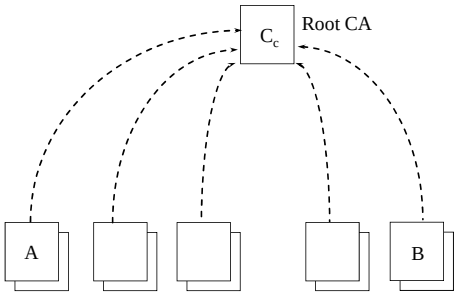
- CA generates key for user
  - absolute trust
  - need transport of private keys
  - easier management for backup/recovery
- user generates his/her key
  - does user have the expertise? (ok if smart card)
  - need to transport of public keys (integrity channel)
- specialised third party generates keys

36

## Trust Models

37

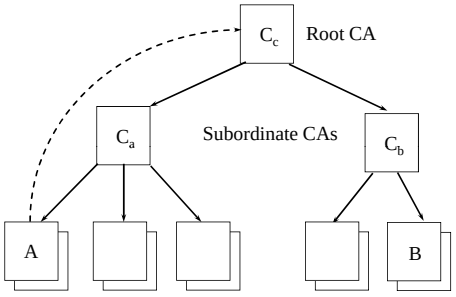
## Hierarchical trust model




Relying parties transfer risk to the Root CA

38

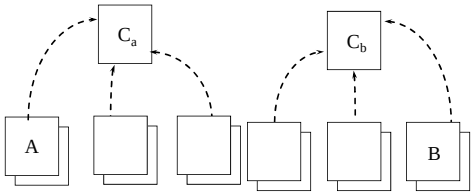
## Hierarchical trust model




Root CA "deputizes" subordinate CAs, which issue certificates

39

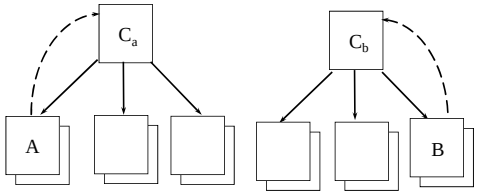
## Enterprise trust model




Relying parties transfer risk to their local CA

40

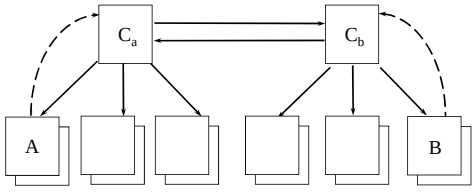
## Enterprise trust model




The same local CA issues certificates to these parties

41

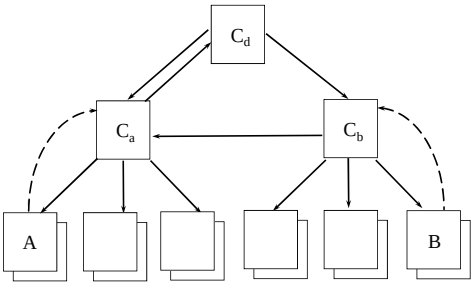
## Enterprise trust model




Qualified relationships between CAs are established

42

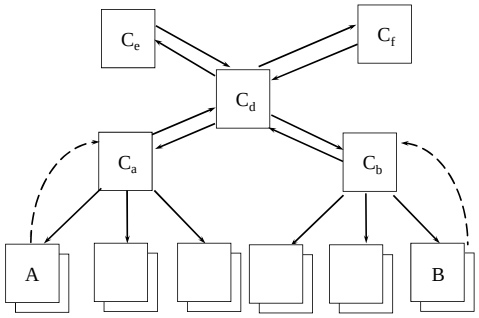
## Enterprise trust model




Hierarchical relationships are a special case

43

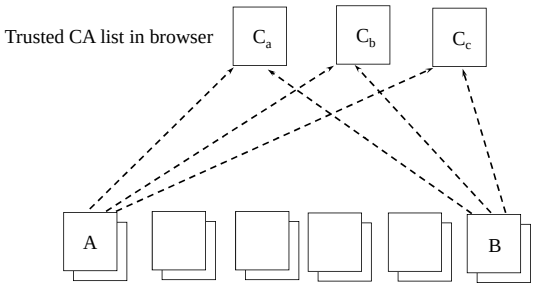
## Enterprise trust model




Spoke-and-hub model is another special case

44

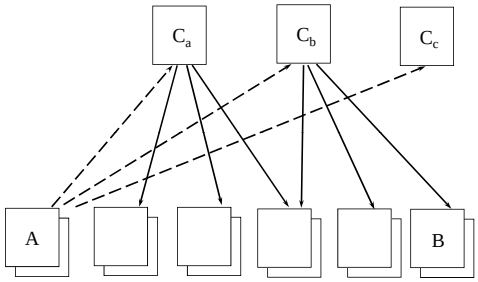
## Browser trust model




All relying parties rely on public keys of same set of CAs

45

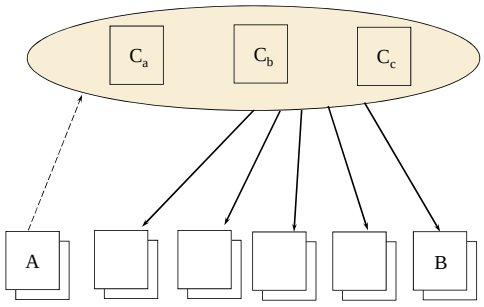
## Browser trust model




Each of these CAs defines its own community of trust

46

## Browser trust model




A relying party trusts the union of these communities

47

## The CA Mess on the web

**[Eckersley10] "An observatory for the SSLiverse"**

- 10.8M servers start SSL handshake
- 4.3M use valid certificate chains
- 650 CA certs trustable by Windows or Firefox (industry: only 65 main)
- 1.4M unique valid leaf certs
  - 300K signed by one GoDaddy cert
- 80 distinct keys used in multiple CA certs
- several CAs sign the IP address 192.168.1.2 (reserved by RFC 1918)
- 2 leaf certs have 508-bit keys
- Debian OpenSSL bug (2006-2008)
  - resulted in 28K vulnerable certs
  - fortunately only 530 validate
  - only 73 revoked

How can we fix this mess?

48

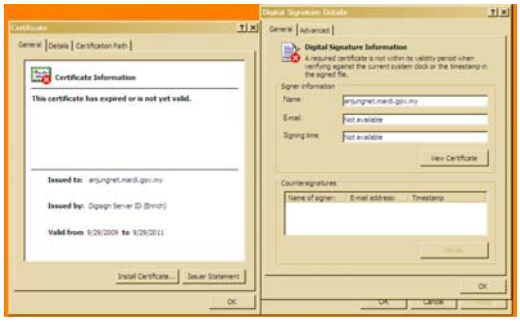
## CA incidents

- March 2011 – Comodo: 9 fraudulent certs
  - via RA GlobalTrust.it/InstantSSL.it
- Summer 2011 – DigiNotar: 500+ fraudulent certs
  - meet-in-the-middle attack against Google users in Iran (300K unique IPs, 99% from Iran)
  - filed for bankruptcy 20 September 2011
- January 2013 – Turktrust CA incident
- (Globalsign) – may have been hacked in 2011
- (Versign) – may have been hacked in 2010
- Bit9, a company that provides software and network security services to the U.S. government and at least 30 Fortune 100 firms lost signing key in February 2013

49

## CA incidents

- Malware signed by key of Government of Malaysia



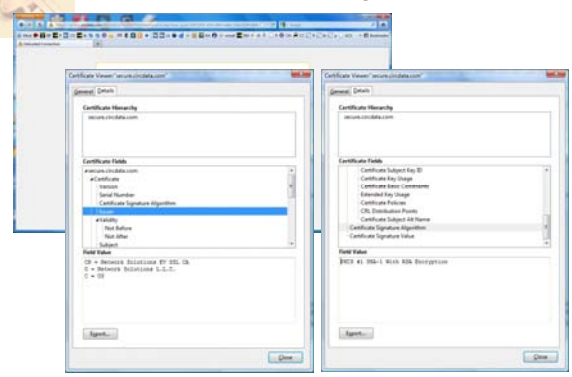
50

## Improvements to CA ecosystem

- DANE – based on DNSSEC – specify restrictions for a given SSL/TLS server
  - would need hard fail
- CA Authorization (RFC 6844): tell CA - if you are not one of the CAs on this list, don't issue certs for this domain (competition issue?)
- Pinning: tell clients - cert for this site look like this; if you detect something else, this may be a breach (more likely a misconfiguration)
  - not for “smal” sites? (need bootstrap)
- Cert Transparency: certs public

51

## CA common problem



52

## Personal trust model ( and related: “web-of-trust”)

- all entities are end-users (CAs do not exist)
- keys are essentially self-guaranteed
- some end-users may also be *introducers*
- end-user imports public keys of others

**CHARACTERISTICS**

- suits individuals, not enterprise/corporations
- user-centric
- requires security-aware end-users
- poor scalability

53

## PGP/GPG Key Servers

- Centralized support for web of trust: servers that hold huge public key rings
  - update to each other, accept and send updates from/to everyone
  - better than everyone keeping a huge key ring
  - server addresses included with PGP/GPG software
  - concerns: privacy, user registration/verification (are you Bill Gates?) and key revocation

Example: PGP Global Directory

54

## Trust models & Revocation

- public-key systems are commonly engineered with long-life certificates
- certificates bind a key-pair to identity (and potentially privilege information)
- circumstances change over certificate life
  - keys may become compromised
  - identifying information may change
  - privilege may be withdrawn
- need ability to terminate the binding expressed in the certificate
- revocation: most difficult issue in practice

55

## Revocation options

**mechanisms indicating valid certificates**

- short-lifetime certificates

**mechanisms indicating invalid certificates**

- certificate revocation lists - CRLs (v1 X.509)
- CRL fragments (v2 X.509), including ...
  - segmented CRLs (CRL distribution points)
  - delta CRLs
  - indirect CRLs

**mechanisms providing a proof of status**

- status-checking protocols (OCSP, ValiCert)
- iterated hash schemes (Micali)
- certificate revocation trees

56

## CRL: properties

- basic CRL
  - simplicity
  - high communication cost from directory to user
- improved CRL
  - very flexible
  - more complex
  - reduced communication and storage

57

## Online Certificate Status Protocol (OCSP) [RFC 2560]

- on-line query to
  - CA
  - or Trusted Responder
  - or CA designated responder
- containing
  - hash of public key CA
  - hash of public key in certificate
  - certificate serial number

58

## OCSP: signed answer

- status
  - good: not revoked
  - revoked
  - unknown
- time
  - thisUpdate
  - nextUpdate
  - producedAt

59

## OCSP: evaluation

- [+] positive and negative information
- [-] need to be on-line
  - risk for denial of service
  - not always possible
- ! OCSP may send you freshly signed but old information

If a browser gets **no answer** to an OCSP request, it just goes on as if nothing happened (usability is more important than security)

http://blog.spiderlabs.com/2011/04/certificate-revocation-behavior-in-modern-browsers.html

60

## Revocation summary

- established standards for basic revocation
  - ITU-T X.509: 1997, ISO/IEC 9594-8: 1997
  - v2 CRLs
- more sophisticated solutions may be needed for specific applications
- revocation of higher level public keys is very hard (if not impossible)
  - e.g. requires browser patch
- even after 15 years of PKI history, revocation is problematic in practice

61

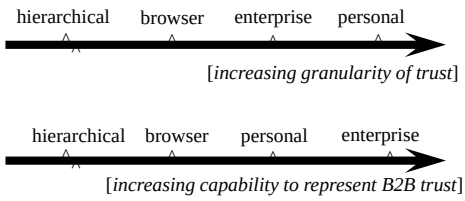
## Characterizing questions for trust models

- what are the types/roles of entities involved
- who certifies public keys
- are trust relationships easily created, maintained, updated
- granularity of trust relationships
- ability of particular technology to support existing business models of trust
- how is revocation handled?

. . . of end-users . . . of certification authorities

62

## Trust model continuums




**Many other continuums can be formulated**

63

## Trust model summary

Key idea: manageability of trust relationships

Each model has its place --

- personal trust model: okay for security-aware individuals working in small communities
- browser model: simple, large communities, everyone trusts all CAs defined by s/w vendor
- hierarchical model: best given an *obvious* global root and a *grand design* methodology
- enterprise trust model: best between peer organizations, where trust flexibility is required
- global PKI will include variety of trust models

64

## Identity based encryption

- Extra material for information

65

## Identity-Based Encryption (IBE)

- IBE is an old idea
  - Originally proposed by Adi Shamir, S in RSA, in 1984
  - Not possible to build an IBE system based on RSA
- First practical implementation
  - Cocks IMA 2001 and Boneh-Franklin Algorithm Crypto 2001
  - Bilinear Maps (Pairings) on Elliptic Curves
    - Based on well-tested mathematical building blocks
  - Public Key Algorithm used for Key Transport
- The IBE breakthrough is having major impact
  - Now over 400 scientific publications on IBE and Pairing Based Cryptography
  - Major deployments in industry
- Standardization Efforts
  - IBE mathematics is being standardized in IEEE 1363.3
  - IETF S/MIME Informational RFC

66

## IBE Public Keys … Introduce This Elegance

Public-key Encryption where Identities are used as Public Keys

- **IBE Public Key:**

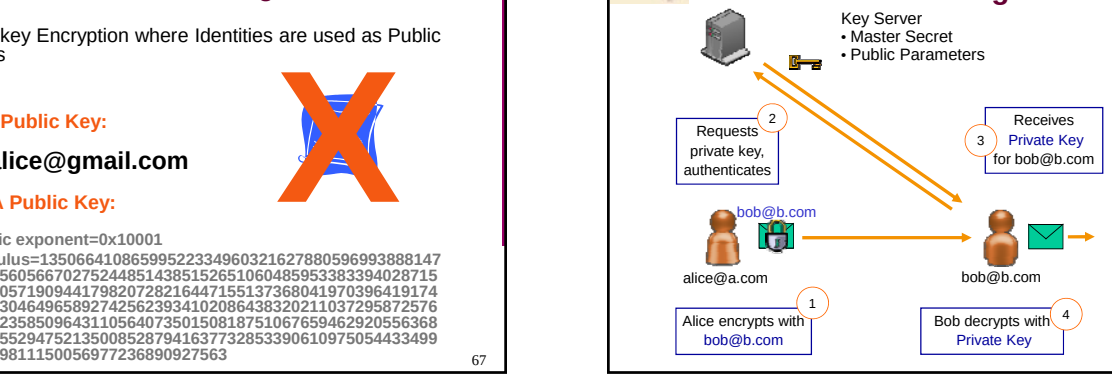
  **alice@gmail.com**

- **RSA Public Key:**

  Public exponent=0x10001
  Modulus=135066410865995223349603216278805969938881475605667027524485143851526510604859533833940287150571909441798207282164471551373680419703964191743046496589274256239341020864383202110372958725762358509643110564073501508187510676594629205565685529475213500852879416377328533906109750544334999811150056977236890927563

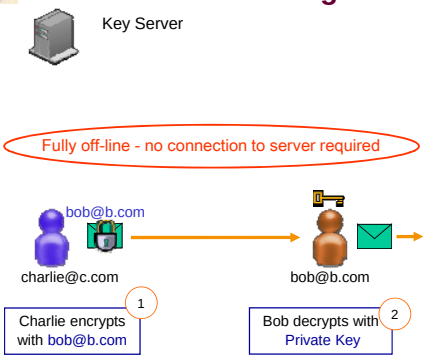
67

## How IBE works in practice Alice sends a Message to Bob




68

## How IBE works in practice Alice sends a Message to Bob




69

## IBE Public Key Composition

v2 ||
public key definition version

ibe-server.acme.com#1234 ||
server location and public parameter version

week = 252 ||
key validity period

bob@acme.com
e-mail address

70

## IBE Benefits

**Dynamic "As Needed" Public and Private Key Generation**
- No pre-generation or distribution of certificates
- Built-in Key Recovery – No ADKs
- Allows content, SPAM, and virus scanning at enterprise boundary
- Facilitates archiving in the clear per SEC regulations

**Policy in the Public Key**
- e.g. Key Validity Period
- No CRLs

**Dynamic Groups**
- Identities can be groups and roles; no re-issuing keys when group or role changes

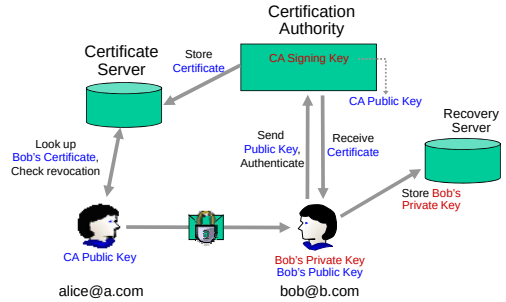
**Minimal System State**
- Master Secret / Public Parameters (~50KB) all you need for disaster recovery
- End user keys and message not stored on server
- Server scalability not limited by number of messages

**Benefits claimed to lead to:**
- High system usability
- Highly scalable architecture
- Low operational impact
- Fully stateless operation

71

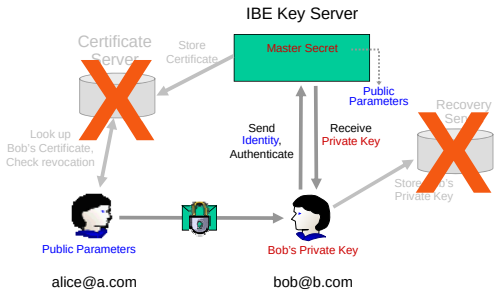
## Public Key Infrastructure

**Certificate Server binds Identity to Public Key**




72

## Identity Based Encryption
### Binding of Identity to Key is implicit




73

## IBE summary

- Sounds cool
- Lack of revocation means short-lived keys hence high overhead for recipient
- Key escrow is problematic (definitely for signatures)
  - can be avoided but only with a complex scheme that needs PKI anyway
- How do you know what the system parameters used by people with the address xx@hotmail.com?
  - Can these system parameters be revoked?

74

## PKI

- Public key cryptography and public keys are essential for large scale secure systems
- PKI as we know today is designed for an off-line world in 1978
- Global PKI is very hard
  - who is authoritative for a given namespace?
  - liability challenge
- Revocation is always hard
- Things are much easier if relying party is the same as issuing party: no certificates are needed

75