Chapter 48

Public Key Infrastructure

Terence Spies
Hewlett Packard Enterprise, Cupertino, CA, United States

The ability to create, manipulate, and share digital documents has created a host of new applications (email, word processing, and e-commerce websites) but also created a new set of problems, namely, how to protect the privacy and integrity of digital data when stored and transmitted. The invention of public key cryptography in the 1970s [8] pointed the way to a solution to those problems: most important, the ability to encrypt data without a shared key and the ability to "sign" data, ensuring its origin and integrity. Although these operations are conceptually straightforward, they both rely on the ability to bind a public key (which is typically a large essentially random number) reliably with an identity sensible to the application or user (for example, a globally unique name, a legal identifier, or an email address.) Public key infrastructure (PKI) is the umbrella term used to refer to the protocols and machinery used to perform this binding.

The most important security protocols used on the Internet rely on PKI to bind names to keys, a crucial function that allows authentication of users and websites. A set of attacks in 2011 called into question the security of the PKI architecture [18,19], especially when governmental entities might be tempted to subvert Internet security assumptions. A number of interesting proposed evolutions of the PKI architecture have been proposed as potential countermeasures to these attacks. Even in the face of these attacks, PKI remains the most important and reliable method of authenticating networked entities.

1. CRYPTOGRAPHIC BACKGROUND

To understand how PKI systems function, it is necessary to grasp the basics of public key cryptography. PKI systems enable the use of public key cryptography and also use public key cryptography as the basis for their operation. Although there are thousands of varieties of cryptographic algorithms, we can understand PKI operations by looking at only two: signature and encryption.

Digital Signatures

The most important cryptographic operation in PKI systems is the digital signature. If two parties are exchanging some digital document, it may be important to protect those data so that the recipient knows that the document has not been altered since it was sent, and that any document received was indeed created by the sender. Digital signatures provide these guarantees by creating a data item, typically attached to the document in question that is uniquely tied to the data and the sender. The recipient then has some verification operation that confirms that the signature data matches the sender and the document.

Fig. 48.1 illustrates the basic security problem that motivates signatures. An attacker controlling communications between the sender and receiver can insert a bogus document, fooling the receiver. The aim of the digital signature is to block this attack by attaching a signature that can only be created by the sender, as shown in Fig. 48.2.

Cryptographic algorithms can be used to construct secure digital signatures. These techniques (for example, the Rivest–Shamir–Adleman (RSA) Algorithm or Digital Signature Algorithm) all have the same three basic operations, as shown in Table 48.1.

Public Key Encryption

Variants of the three operations used to construct digital signatures can also be used to encrypt data. Encryption uses a public key to scramble data in such a way that only the holder of the corresponding private key can unscramble it (Fig. 48.3).

Public key encryption is accomplished with variants of the same three operations used to sign data, as shown in

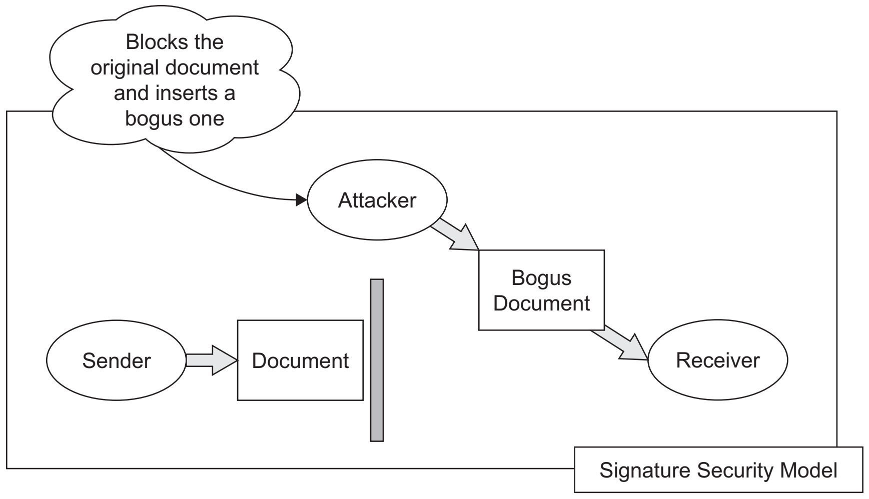


FIGURE 48.1 Block diagram of altering an unsigned document.

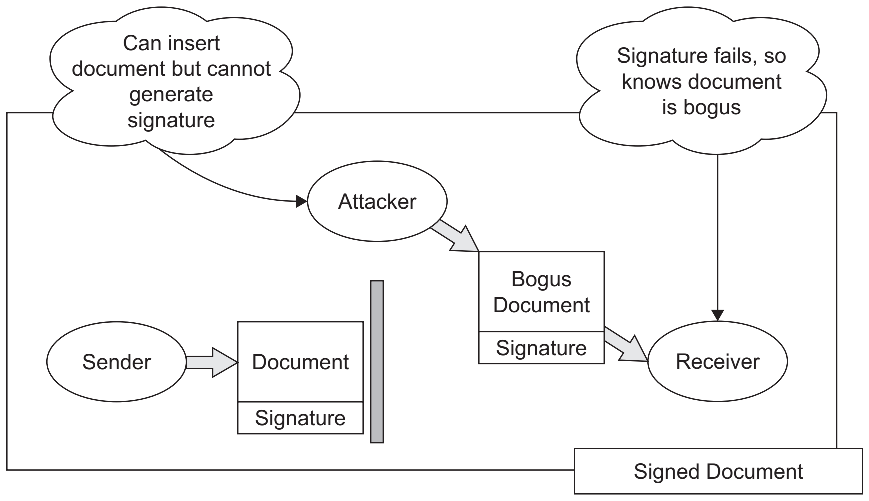

Can insert document but cannot generate signature
Signature fails, so knows document is bogus
Attacker
Bogus Document
Signature
Sender
Document
Signature
Receiver
Signed Document

FIGURE 48.2 Block diagram showing prevention of an alteration attack via a digital signature.

TABLE 48.1 Three Fundamental Digital Signature Operations

Key generation	Using some random source, the sender creates a public and private key, called K_{public} and $K_{private}$. Using K_{public}, it is cryptographically difficult to derive $K_{private}$. The sender then distributes K_{public} and keeps $K_{private}$ hidden.
Signing	Using a document and $K_{private}$, the sender generates the signature data.
Verification	Using the document, the signature, and K_{public}, the receiver (or any other entity with these elements) can test that the signature matches the document and could be produced only with the $K_{private}$ matching K_{public}.

Table 48.2. Note that in actual implementations, the algorithms used to encrypt and sign may be different.

The security of signature and encryption operations depends on two factors: first, the ability to keep the private key private; and, second, the ability to tie a public key reliably to an application or user identity. If a private key is known to an attacker, he can then perform the signing operation on arbitrary bogus documents, and can also decrypt any document encrypted with the matching public key. The same attacks can be performed if an attacker can convince a sender or receiver to use a bogus public key.

PKI systems are built to distribute public keys securely, thereby preventing attackers from inserting bogus public keys. They do not directly address the security of private keys, which are typically defended by measures at a particular end point, such as keeping the private key on a

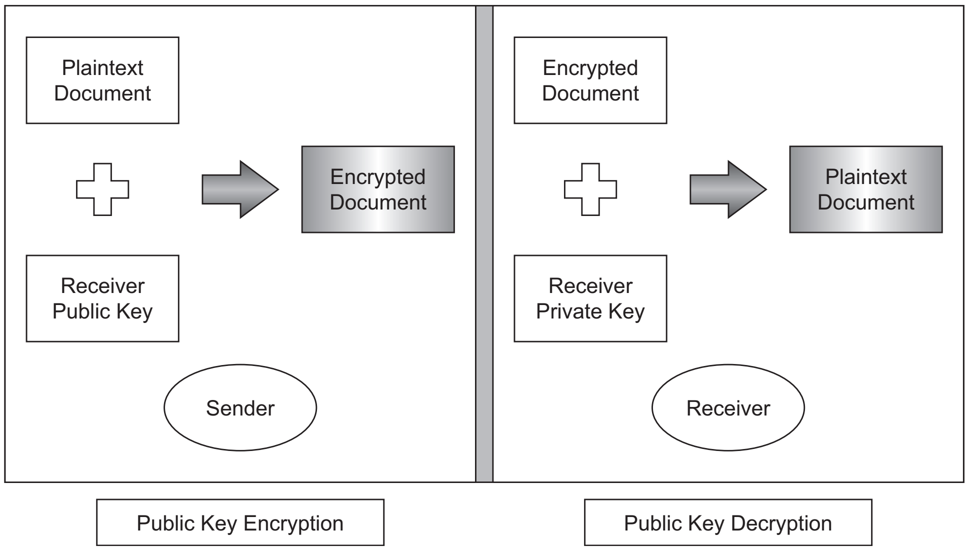


FIGURE 48.3 The public key encryption and decryption process.

TABLE 48.2 Three Fundamental Public Key Encryption Operations

Key generation	Using some random source, the sender creates a public and private key, called K_{public} and $K_{private}$. Using K_{public}, it is cryptographically difficult to derive $K_{private}$. The sender then distributes K_{public} and keeps $K_{private}$ hidden.
Encryption	Using a document and K_{public}, the sender encrypts the document.
Decryption	The receiver uses $K_{private}$ to decrypt the document.

smart card, encrypting private key data using operating system facilities, or other, similar mechanisms. The remainder of this section will detail the design, implementation, and operation of public key distribution systems.

2. OVERVIEW OF PUBLIC KEY INFRASTRUCTURE

PKI systems solve the problem of associating meaningful names with essentially meaningless cryptographic keys. For example, when encrypting an email, the user will typically specify a set of recipients that should be able to decrypt that mail. The user will want to specify these as some kind of name (email address or a name from a directory), not as a set of public keys. In the same way, when signed data are received and verified, the user will want to know what user signed the data, not what public key correctly verified the signature. (By way of contrast, some systems such as the Bitcoin currency protocol use keys directly as identities and thereby avoid some of the complexities associated with PKI-based designs.) The design goal of PKI systems is to connect user identities securely and efficiently to the public keys used to encrypt and verify data.

The original Diffie–Hellman article [8] that outlined public key cryptography proposed that this binding would be done through storing public keys in a trusted directory. Whenever users wanted to encrypt data other users, they would consult the "public file" and request the public key corresponding to some users. The same operation would yield the public key needed to verify the signature on signed data. The disadvantage of this approach is that the directory must be online and available for every new encryption and verification operation. (Although this older approach was never widely implemented, variants of this approach are now reappearing in newer PKI designs. For more information, see the section on Alternative Public Key Infrastructure Architectures.)

PKI systems solve this online problem and accomplish identity binding by distributing "digital certificates," data structures that contain an identity and a key, bound together by a digital signature. They may also provide a mechanism to check the validity of these certificates. Certificates, which were first invented by Kohnfelder in 1978, are essentially a digitally signed message from some authority stating that "Entity X is associated with public key Y." Communicating parties can then rely on this statement (to the extent that they trust the authority signing the certificate) to use the public key Y to validate a signature from

X or to send an encrypted message to X. Because time may pass and identities may change between when the signed certificate was produced and when someone uses that certificate, it may be useful to have a validation mechanism to check that the authority still stands by a particular certificate. We will describe PKI systems in terms of producing and validating certificates.

There are multiple standards that describe how certificates are formatted. The X.509 standard, promulgated by the International Telecommunication Union (ITU) [12], is the most widely used and is the certificate format used in the Transport Layer Security/Secure Socket Layer (TLS/SSL) protocols for secure Internet connections, and the Secure/Multipurpose Internet Mail Extensions (S/MIME) standards for secured email. The X.509 certificate format also implies a particular model of how certification works. Other standards have attempted to define alternate models of operation and associated certificate models. Among the other standards that describe certificates are: Pretty Good Privacy (PGP) and the Simple Public Key Infrastructure (SPKI) [spki]. In this section, we will describe the X.509 PKI model and then describe how these other standards attempt to remediate problems with X.509.

3. THE X.509 MODEL

The X.509 model is the most prevalent standard for certificate-based PKIs, although the standard has evolved such that PKI-using applications on the Internet are mostly based on the set of Internet Engineering Task Force (IETF) standards that have evolved and extended the ideas in X.509. X.509-style certificates are the basis for SSL, TLS, many virtual private networks, the US Federal Government PKI, and many other widely deployed systems.

The History of X.509

A quick historical preface here is useful to explain some of the properties of X.509. X.509 is part of the X.500 directory standard owned by the ITU Telecommunications Standardization Sector. X.500 specifies a hierarchical directory useful for the X.400 set of messaging standards. As such, it includes a naming system (called "distinguished naming") that describes entities by their position in some hierarchy. A sample X.500/X.400 name might look like this:

- CN = Joe Davis, OU = Human Resources, O = WidgetCo, C = US

This name describes a person with a Common Name (CN) of "Joe Davis" that works in an Organizational Unit (OU) called "Human Resources," in an Organization called "WidgetCo" in the United States. These name components were intended to be run by their own directory components (so, for example, there would be "Country" directories that would point to "Organizational" directories, etc.), and this hierarchical description was ultimately reflected in the design of the X.509 system. Many of the changes made by IETF and other bodies that have evolved the X.509 standard were made to reconcile this hierarchical naming system with the more distributed nature of the Internet.

The X.509 Certificate Model

The X.509 model specifies a system of Certifying Authorities (CAs) that issue certificates for end entities (users, websites, or other entities that hold private keys). A CA-issued certificate will contain (among other data) the name of the end entity, the name of the CA, the end entity's public key, a validity period, and a certificate serial number. All of this information is signed with the CA's private key. (Additional details on the information in a certificate and how it is encoded is in Section 6.) To validate a certificate, a relying party uses the CA's public key to verify the signature on the certificate, checks that the time falls within the validity period, and may also consult a server associated with the CA to ensure that the CA has not revoked the certificate.

This process leaves out on important detail: Where did the CA's public key come from? The answer is that another certificate is typically used to certify the public key of the CA. This "chaining" action of validating a certificate by using the public key from another certificate can be performed any number of times, allowing for arbitrarily deep hierarchies of CAs. Of course, this must terminate at some point, typically at a self-signed certificate that is trusted by the relying party. Trusted self-signed certificates are typically referred to as "root" certificates. Once the relying party has verified the chain of signatures from the end-entity certificate to a trusted root certificate, it can conclude that the end-entity certificate is properly signed, and then move onto whatever other validation steps (proper key usage fields, validity dates in some time window, etc.) are required to trust the certificate fully. Fig. 48.4 shows the structure of a typical certificate chain.

One other element is required for this system to function securely: CAs must be able to "undo" a certification action. Whereas a certificate binds an identity to a key, there are many events that may cause that binding to become invalid. For example, a CA operated by a bank may issue a certificate to a newly hired person that gives that user the ability to sign messages as an employee of the bank. If that person leaves the bank before the certificate expires, the bank needs some way to undo that certification. The physical compromise of a private key is another circumstance that may require invalidating a certificate. This is accomplished by a validation protocol in which (in the abstract) a user examining a certificate can ask the CA

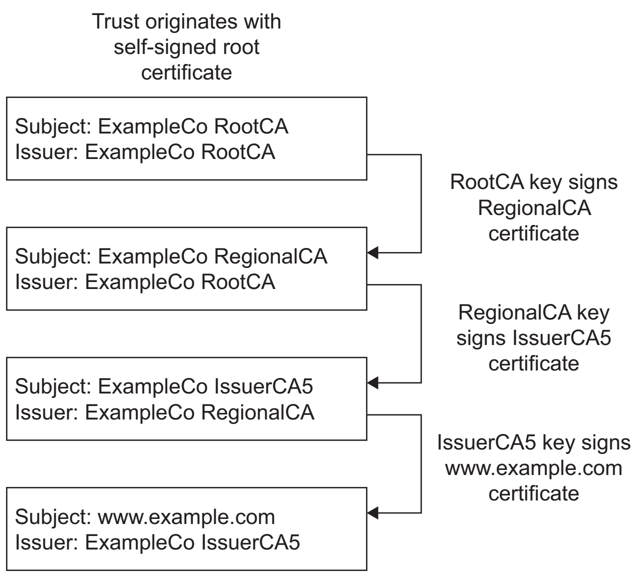

Trust originates with self-signed root certificate
Subject: ExampleCo RootCA
Issuer: ExampleCo RootCA
RootCA key signs RegionalCA certificate
Subject: ExampleCo RegionalCA
Issuer: ExampleCo RootCA
RegionalCA key signs IssuerCA5 certificate
Subject: ExampleCo IssuerCA5
Issuer: ExampleCo RegionalCA
IssuerCA5 key signs www.example.com certificate
Subject: www.example.com
Issuer: ExampleCo IssuerCA5

FIGURE 48.4 Sample X.509 certificate chain. *CA*, Certifying Authority.

whether a certificate is still valid. In practice, revocation protocols are used that delegate processing revocation checks to a dedicated set of servers.

Root certificates are critical to the process of validating public keys through certificates. They must be inherently trusted by the application, because no other certificate signs these certificates. This is most commonly done by installing the certificates as part of the application that will use the certificates under a set of root certificates. For example, Internet Explorer uses X.509 certificates to validate keys used to make TLS/SSL connections. Internet Explorer has a large set of root certificates installed that can be examined by opening the Internet Options menu item and selecting "Certificates" in the "Content" tab of the Options dialogue. A list like the one in Fig. 48.5 will appear.

In Windows, the list of allowed root certificates for a given computer can be viewed in the Control Panel under Administrative Tools/Manage Computer Certificates. Both certificate dialogues can also be used to inspect these root certificates. Microsoft Root certificate details are shown in Fig. 48.6. The meaning of these fields will be explored in subsequent sections.

4. X.509 IMPLEMENTATION ARCHITECTURES

Although in theory the Certification Authority is the entity that creates and validates certificates, in practice it may be desirable or necessary to delegate the actions of user authentication and certificate validation to other servers. The security of the CA's signing key is crucial to the security of a PKI system. By limiting the functions of the server that holds that key, it should be subject to less risk of disclosure or illegitimate use. The X.509 architecture defines a delegated server role, the Registration Authority (RA), which allows delegation of authentication. Subsequent extensions to the core X.509 architecture have created a second delegated role, the Validation Authority (VA), which owns answering queries about the validity of a certificate after creation.

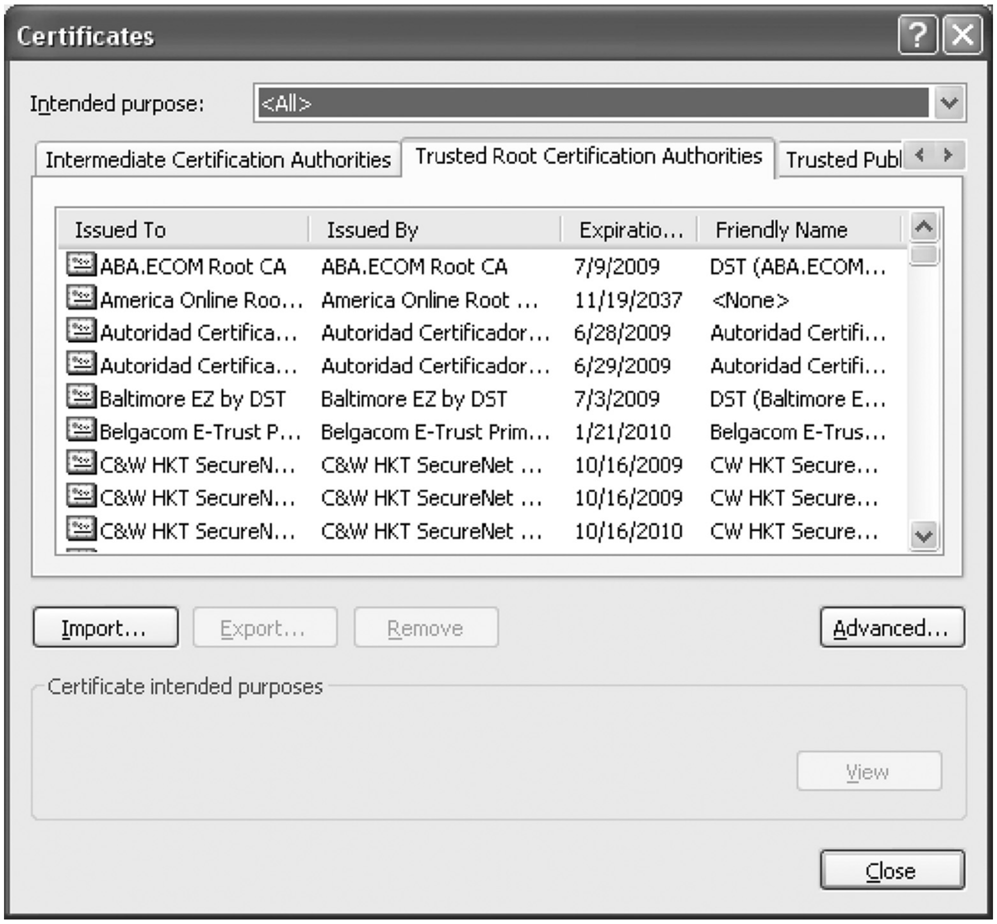
An RA is typically used to distribute the authentication function needed to issue a certificate without needing to distribute the CA key. The RA's function is to perform the authentication needed to issue a certificate, and then send a signed statement containing the fact that it performed the authentication, the identity to be certified, and the key to be certified. The CA validates the RA's message and issues a certificate in response.

For example, a large multinational corporation wants to deploy a PKI system using a centralized CA. It wants to issue certificates on the basis of in-person authentication, so it needs some way to distribute authentication to multiple locations in different countries. Copying and distributing the CA signing key creates a number of risks, not only because the CA key will be present on multiple servers, but also because of the complexities of creating and managing these copies. Sub-CAs could be created for each location, but this requires careful attention to controlling the identities allowed to be certified by each sub-CA (otherwise, an attacker compromising one sub-CA could issue a certificate for any identity he liked.) One possible way to solve this problem is to create RAs at each location and have the CA check that the RA is authorized to authenticate a particular employee when a certificate is requested. If an attacker subverts a given RA signing key, he can request certificates for employees in the purview of that RA, but it is straightforward, once discovered, to deauthorize the RA, solve the security problem, and create a new RA key.

VAs are given the ability to revoke certificates (the specific methods used to effect revocation are detailed in the X.509 Revocation Protocols section) and offload that function from the CA. Through judicious use of RAs and VAs, it is possible to construct certification architectures in which the critical CA server is accessible to only a small number of other servers, and network security controls can be used to reduce or eliminate threats from outside network entities.

5. X.509 CERTIFICATE VALIDATION

X.509 certificate validation is a complex process that can be done to several levels of confidence. This section will outline a typical set of steps involved in validating a certificate, but it is not an exhaustive catalog of the possible methods that can be used. Different applications will often require different validation techniques, depending on the application's security policy. It is rare for an application to


Certificates

Intended purpose: <All>

Intermediate Certification Authorities | Trusted Root Certification Authorities | Trusted Publ

Issued To	Issued By	Expiratio...	Friendly Name
ABA.ECOM Root CA	ABA.ECOM Root CA	7/9/2009	DST (ABA.ECOM...
America Online Roo...	America Online Root ...	11/19/2037	<None>
Autoridad Certifica...	Autoridad Certificador...	6/28/2009	Autoridad Certifi...
Autoridad Certifica...	Autoridad Certificador...	6/29/2009	Autoridad Certifi...
Baltimore EZ by DST	Baltimore EZ by DST	7/3/2009	DST (Baltimore E...
Belgacom E-Trust P...	Belgacom E-Trust Prim...	1/21/2010	Belgacom E-Trus...
C&W HKT SecureN...	C&W HKT SecureNet ...	10/16/2009	CW HKT Secure...
C&W HKT SecureN...	C&W HKT SecureNet ...	10/16/2009	CW HKT Secure...
C&W HKT SecureN...	C&W HKT SecureNet ...	10/16/2010	CW HKT Secure...

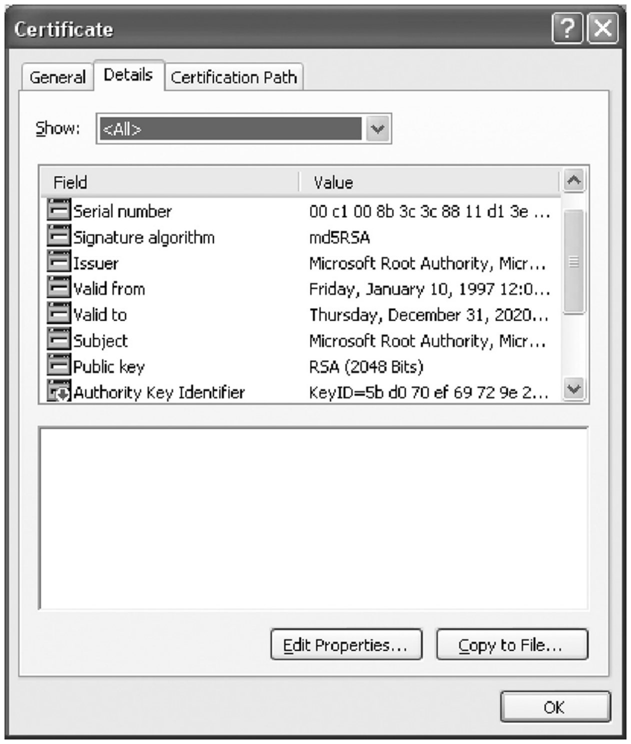
FIGURE 48.5 Microsoft Internet Explorer trusted root certificates.

implement certificate validation, because there are several application program interfaces and libraries available to perform this task. Microsoft CryptoAPI, OpenSSL, and Java JCE all provide certificate validation interfaces. The Server-based Certificate Validity Protocol (SCVP) can also be used to validate a certificate. However, all of these interfaces offer a variety of options, and understanding the validation process is essential to using these interfaces properly.

Although a complete specification of the certificate validation process would require hundreds of pages, we supply a sketch of what happens during certificate validation. It is not a complete description and is purposefully simplified. The certificate validation process typically proceeds in three steps and typically takes three inputs. The first is the certificate to be validated, the second is any intermediate certificates acquired by the applications, and the third is a store containing the root and intermediate certificates trusted by the application. The following steps are a simplified outline of how certificates are typically validated. In practice, the introduction of bridge CAs and other nonhierarchical certification models have led to more complex validation procedures. IETF Request for Comments (RFC) 3280 [11] presents a complete specification for certificate validation, and RFC 4158 [7] presents a specification for constructing a certification path in environments where nonhierarchical certification structures are used.

Validation Step 1: Construct the Chain and Validate Signatures

The contents of the target certificate cannot be trusted until the signature on the certificate is validated, so the first step is to check the signature. To check the signature, the certificate for the authority that signed the target certificate must be located. This is done by searching the intermediate certificates and certificate store for a certificate with a Subject field that matches the Issuer field of the target certificate. If multiple certificates match, the validator can search the matching certificates for a Subject Key Identifier extension that matches the Issuer Key Identifier extension in the candidate certificates. If multiple certificates still match, the most recently issued candidate certificate can be



Show: <All>

Field	Value
Serial number	00 c1 00 8b 3c 3c 88 11 d1 3e ...
Signature algorithm	md5RSA
Issuer	Microsoft Root Authority, Micr...
Valid from	Friday, January 10, 1997 12:0...
Valid to	Thursday, December 31, 2020...
Subject	Microsoft Root Authority, Micr...
Public key	RSA (2048 Bits)
Authority Key Identifier	KeyID=5b d0 70 ef 69 72 9e 2...

FIGURE 48.6 View of the fields in an X.509 certificate using Microsoft Internet Explorer.

used. (Note that, because of potentially revoked intermediate certificates, multiple chains may need to be constructed and examine through Steps 2 and 3 to find the actual valid chain.) Once the proper authority certificate is found, the validator checks the signature on the target certificate using the public key in the authority certificate. If the signature check fails, the validation process can be stopped, and the target certificate deemed invalid.

If the signature matches and the authority certificate is a trusted certificate, the constructed chain is then subjected to Steps 2—4. If not, the authority certificate is treated as a target certificate, and Step 1 is called recursively until it returns a chain to a trusted certificate or fails.

Constructing the complete certificate path requires that the validator be in possession of all certificates in that path. This requires that the validator keep a database of intermediate certificates or that the protocol using the certificate supplies the needed intermediates. The SCVP provides a mechanism to request a certificate chain from a server, which can eliminate these requirements. The SCVP protocol is described in more detail in a subsequent section.

Step 2: Check Validity Dates, Policy and Key Usage

Once a chain has been constructed, various fields in the certificate are checked to ensure that the certificate was issued correctly and that it is currently valid. The following checks should be run on the candidate chain:

The certificate chain times are correct. Each certificate in the chain contains a validity period with a not before and not after time. For applications outside validating the signature on a document, the current time must fall after the not before time and before the not after time. Some applications may require "time nesting," meaning that the validity period for a certificate must fall entirely within the validity period of the issuer's certificate. It is up to the policy of the application if it treats out-of-date certificates as invalid or treats it as a warning case that can be overridden by the user. Applications may also treat certificates that are not yet valid differently from certificates that have expired.

Applications that are validating the certificate on a stored document may have to treat validity time as the time when the document was signed, as opposed to the time when the signature was checked. There are three cases of interest. The first, and easiest, is where the document signature is checked, and the certificate chain validating the public key contains certificates that are currently within their validity time interval. In this case, the validity times are all good, and verification can proceed. The second case is where the certificate chain validating the public key is currently invalid because one or more certificates are out of date and the document is believed to be signed at a time when the chain was out of date. In this case, the validity times are all invalid, and the user should be at least warned.

The ambiguous case arises when the certificate chain is currently out of date but the chain is believed to have been valid with respect to time when the document was signed. Depending on its policy, the application can treat this case in several different ways. It can assume that the certificate validity times are strict, and fail to validate the document. Alternatively, it can assume that the certificates were good at the time of signing, and validate the document. The application can also take steps to ensure that this case does not occur, by using a time-stamping mechanism in conjunction with signing the document, or provide some mechanism for resigning documents before certificate chains expire.

Once the certificate chain has been constructed, the verifier must also verify that various X.509 extension fields are valid. Some common extensions that are relevant to the validity of a certificate path are:

- BasicConstraints: This extension is required for CAs, and limits the depth of the certificate chain below a specific CA certificate.
- NameConstraints: This extension limits the namespace of identities certified underneath the given CA certificate. This extension can be used to limit a specific CA to issuing certificates for a given domain or X.400 namespace.

TABLE 48.3 Data Fields in an X.509 CRL

Version	Specifies the format of the CRL. Current version is 2.
SignatureAlgorithm	Specifies the algorithm used to sign the CRL
Issuer	Name of the Certifying Authority issuing the CRL
thisUpdate	Time from when this CRL is valid
nextUpdate	Time when the next CRL will be issued

CRL, Certificate Revocation List.

TABLE 48.4 Format of a Revocation Record in an X.509 CRL

Serial Number	Serial number of a revoked certificate
Revocation date	Date the revocation is effective
CRL extensions	[Optional] specifies why the certificate is revoked

CRL, Certificate Revocation List.

- KeyUsage and ExtendedKeyUsage: These extensions limit the purposes for which a certified key can be used. CA certificates must have KeyUsage set to allow certificate signing. Various values of ExtendedKeyUsage may be required for some certification tasks.

Step 3: Consult Revocation Authorities

Once the verifier has concluded that it has a suitably signed certificate chain with valid dates and proper KeyUsage extensions, it may want to consult the revocation authorities named in each certificate to check whether the certificates are currently valid. Certificates may contain extensions that point to Certificate Revocation List (CRL) storage locations or to Online Certificate Status Protocol (OSCP) responders. These methods allow the verifier to check that a CA has not revoked the certificate in question. The next section details these methods in more detail. Note that each certificate in the chain may need to be checked for revocation status. The next section on certificate revocation details the mechanisms used to revoke certificates.

6. X.509 CERTIFICATE REVOCATION

Because certificates are typically valid for a significant period of time, it is possible that during the validity period of the certificate a key may be lost or stolen, an identity may change, or some other event may occur that causes a certificate's identity binding to become invalid or suspect. To deal with these events, it must be possible for a CA to revoke a certificate, typically by some kind of notification that can be consulted by applications examining the validity of a certificate. Two mechanisms are used to perform this task: CRLs and the OCSP.

The original X.509 architecture implemented revocation via a CRL. A CRL is a periodically issued document containing a list of certificate serial numbers that are revoked by that CA. X.509 has defined two basic CRL formats, V1 and V2. When CA certificates are revoked by a higher-level CA, the serial number of the CA certificate is placed on an Authority Revocation List (ARL), which is formatted identically to a CRL. CRLs and ARLs, as defined in X.509 and IETF RFC 3280, are ASN.1 encoded objects that contain the information shown in Table 48.3.

This header is followed by a sequence of revoked certificate records. Each record contains the information shown in Table 48.4.

The list of revoked certificates is optionally followed by a set of CRL extensions that supply additional information about the CRL and how it should be processed. To process a CRL, the verifying party checks that the CRL has been signed with the key of the named issuer, and that the current date is between the thisUpdate time and the nextUpdate time. This time check is crucial because if it is not performed, an attacker could use a revoked certificate by supplying an old CRL where the certificate had not yet appeared. Note that expired certificates are typically removed from the CRL, which prevents the CRL from growing unboundedly over time.

The costs of maintaining and transmitting CRLs to verifying parties has been repeatedly identified as an important component of the cost of running a PKI system [3,13], and several alternative revocation schemes have been proposed to lower this cost. The cost of CRL

Note: CRLs can only revoke certificates on time boundaries determined by the nextUpdate time. If a CA publishes a CRL every Monday, for example, a certificate that is compromised on a Wednesday will continue to validate until its serial number is published in the CRL on the following Monday. Clients validating certificates may have downloaded the CA's CRL on Monday and are free to cache the CRL until the nextUpdate time occurs. This caching is important because it means that the CRL is downloaded only once per client per publication period rather than for every certificate validation. However, it has the unavoidable consequence of having a potential time lag between a certificate becoming invalid and its appearance on a CRL. The online certificate validation protocols detailed in the next section attempt to solve this problem.

distribution was also a factor in the emergence of online certificate status-checking protocols such as OCSP and SCVP.

Delta Certificate Revocation Lists

In large systems that issue many certificates, CRLs can potentially become lengthy. One approach to reducing the network overhead associated with sending the complete CRL to every verifier is to issue a Delta CRL along with a Base CRL. The Base CRL contains the complete set of revoked certificates up to some point in time, and the accompanying Delta CRL contains only the additional certificates added over some time period. Clients that are capable of processing the Delta CRL can then download the Base CRL less frequently and download the smaller Delta CRL to obtain recently revoked certificates. Delta CRLs are formatted identically to CRLs but have a critical extension added in the CRL that denotes that they are a Delta, not Base CRL. IETF RFC 3280 [11] details how Delta CRLs are formatted, and the set of certificate extensions that indicate that a CA issues Delta CRLs.

Online Certificate Status Protocol

The OSCP was designed with the goal of reducing the costs of CRL transmission and eliminating the time lag between certificate invalidity and certificate revocation inherent in CRL-based designs. The idea behind OCSP is straightforward. A CA certificate contains a reference to an OSCP server. A client validating a certificate transmits the certificate serial number, a hash of the issuer name, and a hash of the subject name to that OSCP server. The OSCP server checks the certificate status and returns an indication as to the current status of the certificate. This removes the need to download the entire list of revoked certificates and also allows for essentially instantaneous revocation of invalid certificates. It has the design trade-off of requiring that clients validating certificates have network connectivity to the required OCSP server.

OSCP responses contain the basic information as to the status of the certificate in the set of "good," "revoked," or "unknown." They also contain a thisUpdate time, similar to a CRL, and are signed. Responses can also contain a nextUpdate time, which indicates how long the client can consider the OSCP response definitive. The reason the certificate was revoked can also be returned in the response. OSCP is defined in IETF RFC 2560 [14].

7. SERVER-BASED CERTIFICATE VALIDITY PROTOCOL

The X.509 certificate path construction and validation process requires a nontrivial amount of code, the ability to fetch and cache CRLs, and, in the case of mesh and bridge CAs, the ability to interpret CA policies. The SCVP [9] was designed to reduce the cost of using X.509 certificates by allowing applications to delegate the task of certificate validation to an external server. SCVP offers two levels of functionality: Delegated Path Discovery (DPD), which attempts to locate and construct a complete certificate chain for a given certificate, and Delegated Path Validation (DPV), which performs a complete path validation, including revocation checking, on a certificate chain. The main reason for this division of functionality is that a client can use an untrusted SCVP server for DPD operations, because it will validate the resulting path itself. Only trusted SCVP servers can be used for DPV, because the client must trust the server's assessment of a certificate's validity.

SCVP also allows certificates to be checked according to some defined certification policy. They can be used to centralize policy management for an organization that wishes all clients to follow some set of rules with respect to what set of CAs are trusted, what certification policies are trusted, etc. To use SCVP, the client sends a query to an SCVP server, which contains the following parameters:

- ***QueriedCerts.*** This is the set of certificates for which the client wants the server to construct (and optionally validate) paths.
- ***Checks.*** The Checks parameter specifies what the client wants the server to do. The checks parameter can be used to specify that the server should build a path, should build a path and validate it without checking revocation, or should build and fully validate the path.
- ***WantBack.*** The WantBack parameter specifies what the server should return from the request. This can range from the public key from the validated certificate path (in which case the client is fully delegating certificate validation to the server) to all certificate chains that the server can locate.

- ***ValidationPolicy*.** The ValidationPolicy parameter instructs the server how to validate the resultant certification chain. This parameter can be as simple as "use the default RFC 3280 validation algorithm" or it can specify a wide range of conditions that must be satisfied. Some of the conditions that can be specified with this parameter are:
    - ***KeyUsage and Extended Key Usage*.** The client can specify a set of KeyUsage or ExtendedKeyUsage fields that must be present in the end-entity certificate. This allows the client to accept, for example, only certificates that are allowed to perform digital signatures.
    - ***UserPolicySet*.** The client can specify a set of certification policy Object Identifier (OIDs) that must be present in the CAs used to construct the chain. CAs can assert that they follow some formally defined policy when issuing certificates and this parameter allows the client to accept only certificates issued under some set of these policies. For example, if a client wanted to accept only certificates acceptable under the Medium Assurance Federal Bridge CA policies, it could assert that policy identifier in this parameter. For more information on policy identifiers, see the section on X.509 Extensions.
    - ***InhibitPolicyMapping*.** When issuing bridge or cross-certificates, a CA can assert that a certificate policy identifier in one domain is equivalent to some other policy identifier within its domain. By using this parameter, the client can state that it does not want to allow these policy equivalences to be used when validating certificates against values in the UserPolicySet parameter.
    - ***TrustAnchors*.** The client can use this parameter to specify some set of certificates that must be at the top of any acceptable certificate chain. By using this parameter, a client could, for example, say that only VeriSign Class 3 certificates were acceptable in this context.
    - ***ResponseFlags*.** This specifies various options as to how the server should respond (if it needs to sign or otherwise protect the response) and if a cached response is acceptable to the client.
    - ***ValidationTime*.** The client may want a validation performed as if it were a specific time, so that it can find whether a certificate was valid at some point in the past. Note that SCVP does not allow for "speculative" validation in terms of asking whether a certificate will be valid in the future. This parameter allows the client to specify the validation time to be used by the server.
    - ***IntermediateCerts*.** The client can use this parameter to give additional certificates that can potentially be used to construct the certificate chain. The server is not obligated to use these certificates. This parameter is used where the client may have received a set of intermediate certificates from a communicating party, and is not certain whether the SCVP server has possession of these certificates.
    - ***RevInfos*.** Like the IntermediateCerts parameter, the RevInfos parameter supplies extra information that may be needed to construct or validate the path. Instead of certificates, the RevInfos parameter supplies revocation information such as OSCP responses, CRLs, or Delta CRLs.

8. X.509 BRIDGE CERTIFICATION SYSTEMS

In practice, large-scale PKI systems proved to be more complex than could easily be handled under the X.509 hierarchical model. For example, Polk and Hastings [15] identified a number of policy complexities that presented difficulties when attempting to build a PKI system for the US Federal Government. In this case, certainly one of the largest PKI projects ever undertaken, they found that the traditional model of a hierarchical certification system was simply unworkable. They stated:

> *The initial designs for a federal PKI were hierarchical in nature because of government's inherent hierarchical organizational structure. However, these initial PKI plans ran into several obstacles. There was no clear organization within the government that could be identified and agreed upon to run a governmental "root" CA. While the search for an appropriate organization dragged on, federal agencies began to deploy autonomous PKIs to enable their electronic processes. The search for a "root" CA for a hierarchical federal PKI was abandoned, due to the difficulties of imposing a hierarchy after the fact.*

Their proposed solution to this problem was to use a "mesh CA" system to establish a Federal Bridge Certification Authority. This Bridge architecture has since been adopted in large PKI systems in Europe and the financial services community in the United States. The details of the European Bridge CA can be found at http://www.bridge-ca.org. This part of the chapter will detail the technical design of bridge CAs, and the various X.509 certificate features that enable bridges.

Mesh Public Key Infrastructures and Bridge Certifying Authorities

Bridge CA architectures are implemented using a nonhierarchical certification structure called a mesh PKI. The classic X.509 architecture joins together multiple PKI systems by subordinating them under a higher-level CA. All certificates chain up to this CA, and that CA essentially

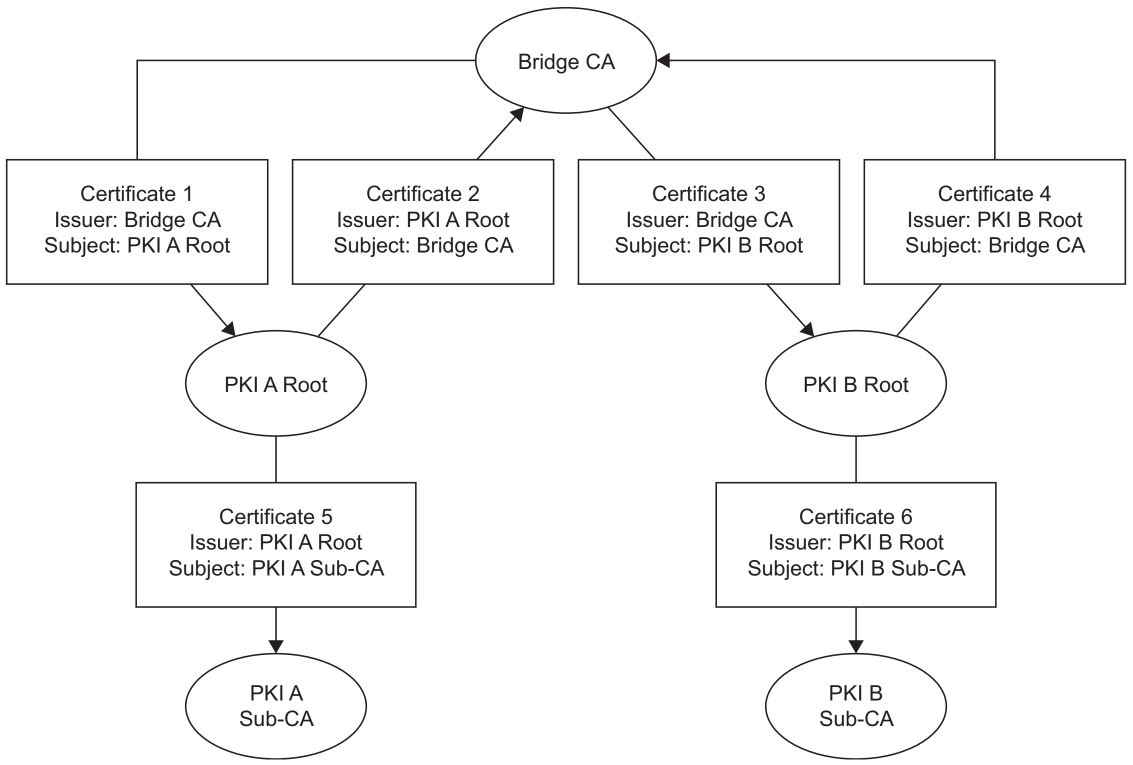


FIGURE 48.7 Showing the structure of two public key infrastructures (PKIs) connected via a bridge Certifying Authority (CA).

creates trust between the CAs below it. Mesh PKIs join together multiple PKI systems using a process called "cross-certification" that does not create this type of hierarchy. To cross-certify, the top-level CA in a given hierarchy creates a certificate for an external CA called the Bridge CA. This bridge CA then becomes, in a manner of speaking, a sub-CA under the organization's CA. However, the Bridge CA also creates a certificate for the organizational CA, so it can also be viewed as a top level CA certifying that organizational CA.

The end result of this cross-certification process is that if, two organizations, A and B have joined the same bridge CA, the can both create certificate chains from their respective trusted CAs through the other organization's CA to end-entity certificates that it has created. These chains will be longer than traditional hierarchical chains but have the same basic verifiable properties. Fig. 48.7 shows how two organizations might be connected through a bridge CA, and what the resultant certificate chains look like.

In the case illustrated in Fig. 48.7, a user that trusts certificates issued by PKI A (that is, PKI A Root is a "trust anchor") can construct a chain to certificates issued by the PKI B Sub-CA, because it can verify Certificate 2 via its trust of the PKI A Root. Certificate 2 then chains to Certificate 3, which chains to Certificate 6. Certificate 6 then is a trusted issuer certificate for certificates issued by the PKI B Sub-CA.

Mesh architectures create two significant technical problems: path construction and policy evaluation. In a hierarchical PKI system, there is only one path from the root certificate to an end-entity certificate. Creating a certificate chain is as simple as taking the current certificate, locating the issuer in the subject field of another certificate, and repeating until the root is reached (completing the chain) or no certificate can be found (failing to construct the chain.) In a mesh system, there can be cyclical loops where this process can fail to terminate with a failure or success. This is not a difficult problem to solve, but it is more complex to deal with than the hierarchical case.

Policy evaluation becomes much more complex in the mesh case. In the hierarchical CA case, the top-level CA can establish policies that are followed by Sub-CAs, and these policies can be encoded into certificates in an unambiguous way. When multiple PKIs are joined by a bridge CA, these PKIs may have similar policies but may be expressed by different names. PKI A and PKI B may both certify "medium assurance" CAs that perform a certain level of authentication before issuing certificates, but may have different identifiers for these policies. When joined by a bridge CA, clients may reasonably want to validate certificates issued by both CAs, and understand the policies under which that those certificates are issued. The Policy-Mapping technique allows similar policies under different names from disjoint PKIs to be translated at the bridge CA.

TABLE 48.5 Data Fields in an X.509 Version 3 Certificate

Version	Version of Standard Used to Format Certificate
Serial number	A number, unique relative to the issuer, for this certificate
Signature algorithm	The specific algorithm used to sign the certificate
Issuer	Name of the authority issuing the certificate
Validity	The time interval for which this certificate is valid
Subject	The identity being certified
Subject public key	The key being bound to the subject
Issuer unique ID	Obsolete field
Subject unique ID	Obsolete field
Extensions	A list of additional certificate attributes
Signature	A digital signature by the issuer over the certificate data

Although none of these problems is insurmountable, they increase the complexity of certificate validation code and helped drive the invention of server-based validation protocols such as SCVP. These protocols delegate path discovery and validation to an external server rather than require applications to integrate this functionality. This may lower application complexity, but the main benefit of this strategy is that questions of acceptable policies and translation can be configured at one central verification server rather than distributed to every application doing certificate validation.

9. X.509 CERTIFICATE FORMAT

The X.509 standard (and the related IETF RFCs) specify a set of data fields that must be present in a properly formatted certificate, a set of optional extension data fields that can be used to supply additional certificate information, how these fields must be signed, and how the signature data are encoded. All of these data fields (mandatory fields, optional fields, and the signature) are specified in Abstract Syntax Notation (aka ASN.1), a formal language that allows for exact definitions of the content of data fields and how those fields are arranged in a data structure. An associated specification, Determined Encoding Rules (DER), is used with specific certificate data and the ASN.1 certificate format to create the actual binary certificate data. The ASN.1 standard is authoritatively defined in ITU Recommendation X.693. (For an introduction to ASN.1 and DER, see [kaliski].)

X.509 V1 and V2 Format

The first X.509 certificate standard was published in 1988 as part of the broader X.500 directory standard. X.509 was intended to provide public key–based access control to an X.500 directory, and defined a certificate format for that use. This format, which is now referred to as X.509 v1, defined a static format containing an X.400 Issuer name (the name of the CA), an X.400 Subject name, a validity period, the key to be certified, and the signature of the CA. Whereas this basic format allowed for all basic PKI operations, the format required that all names be in the X.400 form and it did not allow for any other information to be added to the certificate. The X.509 v2 format added two more Unique ID fields but did not fix the primary deficiencies of the v1 format. As it became clear that name formats would have to be more flexible and certificates would have to accommodate a wider variety of information, work began on a new certificate format.

X.509 V3 Format

The X.509 certificate specification was revised in 1996 to add an optional extension field that allows a set of optional additional data fields to be encoded into the certificate (Table 48.5). This change may seem minor, but in fact it allowed certificates to carry a wide array of information useful for PKI implementation, and also for the certificate to contain multiple, non-X.400 identities. These extension fields allow for key usage policies, CA policy information, revocation pointers, and other relevant information to live in the certificate. The V3 format is the most widely used X.509 variant and is the basis for the certificate profile in RFC 3280 [11] issued by the IETF.

X.509 Certificate Extensions

This section is a partial catalog of common X.509 V3 extensions. There is no existing canonical directory of V3 extensions, so there are undoubtedly extensions in use outside this list. The most common extensions are defined in RFC 3280 [11], which contains the IETF certificate profile, which are used by S/MIME and many SSL/TLS implementations. These extensions address a number of deficiencies in the base X.509 certificate specification, and which in many cases are essential for constructing a practical PKI system. In particular, the Certificate Policy, Policy Mapping, and Policy Constraints extensions form the basis for the popular bridge CA architectures.

Authority Key Identifier

The Authority Key Identifier extension identifies which specific private key owned by the certificate issuer was used to sign the certificate. The use of this extension allows a single issuer to use multiple private keys and unambiguously identifies which key was used. This allows issuer keys to be refreshed without changing the issuer name and enables handling events such as an issuer key being compromised or lost.

Subject Key Identifier

Like the Authority Key Identifier, the Subject Key Identifier extension indicates which subject key is contained in the certificate. This extension provides a way to identify quickly which certificates belong to a specific key owned by a subject. If the certificate is a CA certificate, the Subject Key Identifier can be used to construct chains by connecting a Subject Key Identifier with a matching Authority Key Identifier.

Key Usage

A CA may wish to issue a certificate that limits the use of a public key. This may lead to an increase in overall system security by segregating encryption keys from signature keys, and even segregating signature keys by use. For example, an entity may have a key used for signing documents and a key used for decryption of documents. The signing key may be protected by a smart card mechanism that requires a personal identifier number per signing, whereas the encryption key is always available when the user is logged in. The use of this extension allows the CA to express that the encryption key cannot be used to generate signatures, and notifies communicating users that they should not encrypt data with the signing public key. The key usage capabilities are defined in a bit field, which allows a single key to have any combination of the defined capabilities (see checklist, "An Agenda for Action to Define Key Usage Capabilities").

Subject Alternative Name

This extension allows the certificate to define non-X.400−formatted identities for the subject. It supports a variety of namespaces, including email addresses, Domain Name System names for servers, Electronic Document Interchange party names, Uniform Resource Identifiers, and Internet Protocol (IP) addresses, among others.

An Agenda for Action to Define Key Usage Capabilities

The currently defined key usage capabilities/bits that need to be completed are as follows (check all tasks completed):

_____**1.** ***digitalSignature***: The key can be used to generate digital signatures.

_____**2.** ***nonRepudiation***: Signatures generated from this key can be traced back to the signer in such a way that the signer cannot deny generating the signature. This capability is used in electronic transaction scenarios where it is important that signers cannot disavow a transaction.

_____**3.** ***keyEncipherment***: The key can be used to wrap a symmetric key that is then used to bulk encrypt data. This is used in communications protocols and applications such as S/MIME, in which an algorithm such as Advanced Encryption Standard (AES) is used to encrypt data, and the public key in the certificate is then used to encipher that AES key. In practice, almost all encryption applications are structured in this manner, because public keys are generally unsuitable for the encryption of bulk data.

_____**4.** ***dataEncipherment***: The key can be used to encrypt data directly. Because of algorithmic limitations of public encryption algorithms, the keyEncipherment technique is nearly always used instead of directly encrypting data.

_____**5.** ***keyAgreement***: The key can be used to create a communication key between two parties. This capability can be used in conjunction with the encipherOnly and decipherOnly capabilities.

_____**6.** ***keyCertSign***: The key can be used to sign another certificate. This is a crucial key usage capability because it essentially allows creation of sub-certificates under this certificate, subject to basic-Constraints. All CA certificates must have this usage bit set, and all end-entity certificates must NOT have it set.

_____**7.** ***cRLSign***: The key can be used to sign a CRL. CA certificates may have this bit set or they may delegate CRL creation to a different key, in which case this bit will be cleared.

______**8.** ***encipherOnly***: When the key is used for keyAgreement, the resultant key can be used only for encryption.

______**9.** ***decipherOnly***: When the key is used for keyAgreement, the resultant key can be used only for decryption.

Policy Extensions

Three important X.509 certificate extensions (Certificate Policy, Policy Mapping, and Policy Constraints) form a complete system for communicating CA policies regarding how certificates are issued or revoked, and how CA security is maintained. They are interesting in that they communicate information that is more relevant to business and policy decision making than the other extensions that are used in the technical processes of certificate chain construction and validation. As an example, a variety of CAs run multiple Sub-CAs that issue certificates according to a variety of issuance policies, ranging from "Low Assurance" to "High Assurance." The CA will typically formally define in a policy document all of its operating policies, state them in a practice statement, define an ASN.1 OID that names this policy, and distribute it to parties that will validate those certificates. The policy extensions allow CAs to attach a policy OID to its certificate, translate policy OIDs among PKIs, and limit the policies that can be used by Sub-CAs.

Certificate Policy

The Certificate Policy extension, if present in an issuer certificate, expresses the policies that are followed by the CA, both in terms of how identities are validated before certificate issuance and how certificates are revoked, as well as the operational practices that are used to ensure integrity of the CA. These policies can be expressed in two ways: as an OID, which is a unique number that refers to one given policy, and as a human-readable Certificate Practice Statement (CPS). One Certificate Policy extension can contain both the computer-sensible OID and a printable CPS. One special OID has been set aside for "AnyPolicy," which states that the CA may issue certificates under a free-form policy.

IETF RFC 2527 [6] gives a complete description of what should be present in a CA policy document and CPS. More details on the 2527 guidelines are given in the PKI Policy Description section.

Policy Mapping

The Policy Mapping extension contains two policy OIDs: one for the Issuer domain and the other for the Subject domain. When this extension is present, a validating party can consider the two policies identical, which is to say, the Subject OID, when present in the chain below the given certificate, can be considered to be the same as the policy named in the Issuer OID. This extension is used join together two PKI systems with functionally similar policies that have different policy reference OIDs.

Policy Constraints

The Policy Constraints extension enables a CA to disable policy mapping for CAs farther down in the chain, and to require explicit policies in all of the CAs below a given CA.

10. PUBLIC KEY INFRASTRUCTURE POLICY DESCRIPTION

In many application contexts, it is important to understand how and when CAs will issue and revoke certificates. Especially when bridge architectures are used, an administrator may need to evaluate a CA's policy to determine how and when to trust certificates issued under that authority. For example, the US Federal Bridge CA maintains a detailed specification of its operating procedures and requirements for bridged CAs at the US Chief Information Officers office website (http://www.cio.gov/fpkipa/documents/FBCA_CP_RFC3647.pdf). More information about the Federal Bridge CA can be found at http://www.idmanagement.gov. Many other commercial CAs, such as VeriSign, maintain similar documents.

To make policy evaluation easier and more uniform, IETF RFC 2527 [6] specifies a standard format for CAs to communicate their policy for issuing and revoking certificates. This specification divides a policy specification document into the following sections:

- ***Introduction*:** This section describes the type of certificates that the CA issues, the applications in which those certificates can be used, and the OIDs used to identify CA policies. The Introduction also contains the contact information for the institution operating the CA.
- ***General Provisions*:** This section details the legal obligations of the CA, any warranties given as to the reliability of the bindings in the certificate, and details as to the legal operation of the CA, including fees and relationship to any relevant laws.
- ***Identification and Authentication*:** This section details how certificate requests are authenticated at the CA or RA, and how events such as name disputes or revocation requests are handled.
- ***Operational Requirements*:** This section details how the CA will react in case of key compromise, how it renews keys, how it publishes CRLs or other revocation information, how it is audited, and what records are kept during CA operation.
- ***Physical, Procedural, and Personnel Security Controls*:** This section details how the physical location of the CA is controlled and how employees are vetted.
- ***Technical Security Controls*:** This section explains how the CA key is generated and protected though its life cycle. CA key generation is typically done through an

audited, recorded key generation ceremony to assure certificate users that the CA key was not copied or otherwise compromised during generation.

- ***Certificate and CRL Profile*****:** The specific policy OIDs published in certificates generated by the CA are given in this section. The information in this section is sufficient to accomplish the technical evaluation of a certificate chain published by this CA.
- ***Specification Administration*****:** The last section explains the procedures used to maintain and update the certificate policy statement itself.

These policy statements can be substantial documents. The Federal Bridge CA policy statement is at least 93 pages long, and other certificate authorities have similarly exhaustive documents. The aim of these statements is to provide enough legal backing for certificates produced by these CAs so that they can be used to sign legally binding contracts and automate other legally relevant applications.

11. PUBLIC KEY INFRASTRUCTURE STANDARDS ORGANIZATIONS

The PKI X.509 (PKIX) Working Group was established in the fall of 1995 with the goal of developing Internet standards to support X.509-based PKIs. These specifications form the basis for numerous other IETF specifications that use certificates to secure various protocols, such as S/MIME (for secure email), TLS [for secured Transmission Control Protocol (TCP) connections], and Internet Protocol Security (for securing internet packets).

Internet Engineering Task Force Public Key Infrastructure X.509

The PKIX working group has produced a complete set of specifications for an X.509-based PKI system. These specifications span 36 RFCs; at least eight more RFCs are being considered by the group. In addition to the basic core of X.509 certificate profiles and verification strategies, the PKIX drafts cover the format of certificate request messages, certificates for arbitrary attributes (rather than for public keys), and a host of other certificate techniques.

Other IETF groups have produced a group of specifications that detail the use of certificates in various protocols and applications. In particular, the S/MIME group, which details a method for encrypting email messages, and the SSL/TLS group, which details TCP/IP connection security, use X.509 certificates.

In May 2015, the IETF established the Automated Certificate Management Environment (ACME) working group to build protocols that would simplify the issuance of certificates with the goal of making encrypted network connections easier to establish and thus, it was hoped, more commonplace. The ACME group published a draft RFC for the ACME protocol, which enables a CA to establish domain ownership and create certificates with little or no user intervention. This protocol was then used to create the "Let's Encrypt" CA, which issues zero-cost certificates using ACME. Websites can use Let's Encrypt (https://letsencrypt.org) to provision certificates automatically and thereby enable encryption with no need to pay a commercial CA. This approach has proven popular, with more than a million certificates issued in the first year of operation. Several commercial CAs have followed with offerings of low- or zero-cost domain authentication certificates, and this approach may lead to wider use of encrypted SSL/TLS connections for Web communications.

SDSI/SPKI

The Simple Distributed Security Infrastructure (SDSI) group was chartered in 1996 to design a mechanism for distributing public keys that would correct some of the perceived complexities inherent in X.509. In particular, the SDSI group aimed to build a PKI architecture [sdsi] that would not rely on a hierarchical naming system, but would instead work with local names that would not have to be enforced to be globally unique. The eventual SDSI design, produced by Ron Rivest and Butler Lampson, has a number of unique features:

- ***Public key-centric design*****.** The SDSI design uses the public key itself (or a hash of the key) as the primary identifying name. SDSI signature objects can contain naming statements about the holder of a given key, but the names are not intended to be the "durable" name of a entity.
- ***Free-form namespaces*****.** SDSI imposes no restrictions on what form names must take and imposes no hierarchy that defines a canonical namespace. Instead, any signer may assert identity information about the holder of a key, but no entity is required to the use (or believe) the identity bindings of any other particular signer. This allows each application to create a policy about who can create identities, how those identities are verified, and even what constitutes an identity.
- ***Support for groups and roles*****.** The design of many security constructions (access control lists, for example) often includes the ability to refer to groups or roles instead of the identity of individuals. This allows access control and encryption operations to protect data for groups, which may be more natural in some situations.

The SPKI group was started at nearly the same time, with goals similar to the SDSI effort. In X, the two groups were merged, and the SDSI/SPKI 2.0 specification was produced, incorporating ideas from both architectures.

Internet Engineering Task Force Open Pretty Good Privacy

The PGP public key system, created by Phillip Zimmermann, is a widely deployed PKI system that allows for the signing and encryption of files and email. Unlike the X.509 PKI architecture, the PGP PKI system uses the notion of a "Web of Trust" to bind identities to keys. The Web of Trust (WoT) [1] replaces the X.509 idea of identity binding via an authoritative server with identity binding via multiple semitrusted paths.

In a WoT system, the end user maintains a database of matching keys and identities, each of which is given two trust ratings. The first trust rating denotes how trusted the binding is between the key and the identity, and the second denotes how trusted a particular identity is to "introduce" new bindings. Users can create and sign a certificate, and import certificates created by other users. Importing a new certificate is treated as an introduction. When a given identity and key in a database are signed by enough trusted identities, that binding is treated as trusted.

Because PGP identities are not bound by an authoritative server, there is also no authoritative server that can revoke a key. Instead, the PGP model states that the holder of a key can revoke that key by posting a signed revocation message to a public server. Any user seeing a properly signed revocation message then removes that key from the database. Because revocation messages must be signed, only the holder of the key can produce them, so it is impossible to produce a false revocation without compromising the key. If an attacker does compromise the key, production of a revocation message from that compromised key actually improves the security of the overall system, because it warns other users not to trust that key.

12. PRETTY GOOD PRIVACY CERTIFICATE FORMATS

To support the unique features of the WoT system, PGP invented a flexible packetized message format that can encode encrypted messages, signed messages, key database entries, key revocation messages, and certificates. This packetized design, described in IETF RFC 2440, allows a PGP certificate to contain a variable number of names and signatures, as opposed to the single-certification model used in X.509.

A PGP certificate (known as a transferable public key) contains three main sections of packetized data. The first section contains the main public key itself, potentially followed by some set of relevant revocation packets. The next section contains a set of User ID packets, which are identities to be bound to the main public key. Each User ID packet is optionally followed by a set of Signature packets, each of which contains an identity and a signature of the User ID packet and the main public key. Each of these Signature packets essentially forms an identity binding. Because each PGP certificate can contain any number of these User ID/Signature elements, a single certificate can assert that a public key is bound to multiple identities (for example, multiple email addresses that correspond to a single user), certified by multiple signers. This multiple signer approach enables the WoT model. The last section of the certificate is optional and may contain multiple subkeys, which are single-function keys (for example, an encryption-only key) also owned by the holder of the main public key. Each of these subkeys must be signed by the main public key.

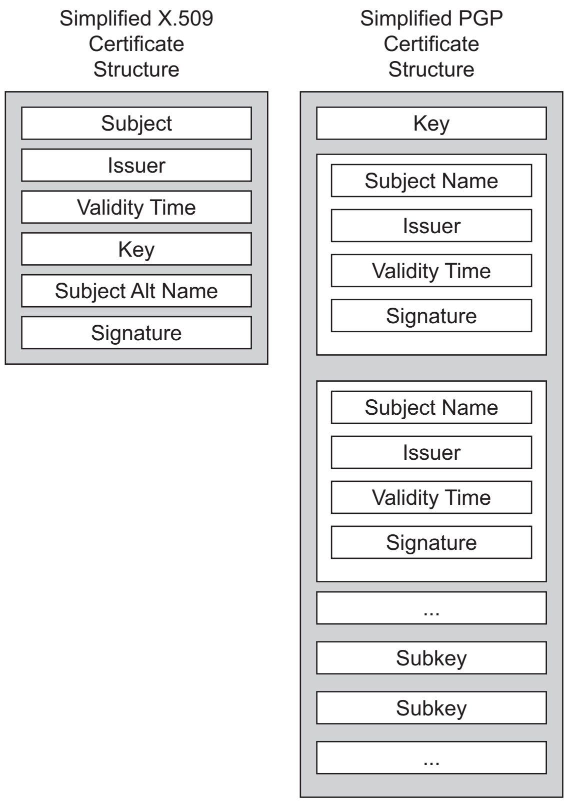


FIGURE 48.8 Comparing X.509 and Pretty Good Privacy (PGP) certificate structures.

PGP Signature packets contain all information needed to perform a certification, including time intervals for which the signature is valid. Fig. 48.8 shows how the multiname, multisignature PGP format differs from the single-name, single-signature X.509 format.

13. PRETTY GOOD PRIVACY PUBLIC KEY INFRASTRUCTURE IMPLEMENTATIONS

The PGP PKI system is implemented in commercial products sold by the PGP Corporation and several open source projects including Gnu Privacy Guard and OpenPGP. Thawte offers a WoT service that connects people with "WoT notaries" that can build trusted introductions. PGP Corporation operates a PGP Global Directory that contains PGP keys along with an email confirmation service to make key certification easier. The OpenPGP group (www.openpgp.org) maintains IETF specification (RFC 2440) for the PGP message and certificate format.

14. WORLD WIDE WEB CONSORTIUM

The World Wide Web Consortium standards group published a series of standards on encrypting and signing eXtensible Markup Language (XML) documents. These standards, XML Signature and XML Encryption, have a companion PKI specification called XML Key Management Specification (XKMS).

The XKMS specification describes a meta-PKI that can be used to register, locate, and validate keys that may be certified by an outside X.509 CA, a PGP referrer, an SPKI key signer, or the XKMS infrastructure itself. The specification contains two protocol specifications: XML Key Information Service Specification (X-KISS) and XML Key Registration Service Specification (X-KRSS). X-KISS is used to find and validate a public key referenced in an XML document, and X-KRSS is used to register a public key so that it can be located by X-KISS requests.

15. IS PUBLIC KEY INFRASTRUCTURE SECURE?

PKI has formed the basis of Internet security protocols such as S/MIME for securing email, and SSL/TLS protocols for securing communications between clients and Web servers. The essential job of PKI in these protocols is to bind a name such as an email address or domain name to a key that is controlled by that entity. As seen in this chapter, that job boils down to a CA issuing a certificate for an entity. The security of these systems then rests on the trustworthiness of the CAs trusted within an application. If a CA issues a set of bad certificates, the security of the entire system can be called into question.

The issue of a subverted CA was largely theoretical until attacks on the Comodo and DigiNotar CAs [18,19] in 2011. Both of these CAs discovered that an attacker had bypassed their internal controls and obtained certificates for prominent Internet domains (google.com, yahoo.com) These certificates were revoked, but the incident caused the major browser vendors to revisit their policies about what CA roots are trusted, and the removal of many CAs. In the case of DigiNotar, these attacks ultimately led to the bankruptcy of the company.

By attacking a CA and obtaining a false certificate for a given domain, the attacker can set up a fake version of the domain's website and, using that certificate, create secure connections to clients that trust that CA's root certificate. This secure connection can be used as a "man-in-the-middle" server that reveals all traffic between the client (or clients) and the legitimate website.

Can these attacks be prevented? There are research protocols such as "Perspectives" [20] that attempt to detect false certificates that might be signed by a legitimate CA. These protocols use third-party repositories to track what certificates and keys are used by individual websites. A change that is noticed by only some subset of users may indicate an attacker using a certificate to gain access to secured traffic.

In 2015, the IETF published RFC 7469, which specifies "certificate pinning," a method to allow websites to specify an acceptable key or certificate that cannot be changed outside a specified time window. The pinning method (which is now implemented in several browsers) prevents a rogue CA from publishing illegitimate certificates for a given site. To pin a certificate, the site sends a hash that must match the SubjectPublicKeyInfo field of a certificate in the site's certificate chain. Although a malicious actor could spoof this field, it would fool only browsers that had not visited the legitimate site. Once a browser has seen the pinning data, it will refuse to connect to sites with nonconforming certificate chains. Pinning can also be used in other protocols by providing a way to communicate an essentially permanent constraint on the certificate chain used to validate an entity. Pinning has become more popular over time and may evolve into a standard mechanism to limit CA-based attacks on Internet protocols.

Some other products that rely on PKI certification have introduced new features to make these attacks harder to execute. Google's Chrome browser also has incorporated security features [21] intended to foil attacks on PKI infrastructure. The Mozilla Foundation, owners of the Firefox browser, have instituted an audit and review system that requires all trusted CAs to attest that they have specific kinds of security mechanisms in place to prevent the issuance of illegitimate certificates.

As a general principle, systems built to rely on PKI for security should understand the risks involved in CA compromise, and also understand how critical it is to control exposure to these kinds of attacks. One simple mechanism for doing this is to restrict the number of CAs that are trusted by the application. The large number of roots trusted by the average Web browser is large, which makes auditing of the complete list of CAs difficult.

16. ALTERNATIVE PUBLIC KEY INFRASTRUCTURE ARCHITECTURES

PKI systems have proven to be remarkably effective tools for some protocols, most notably SSL, which has emerged as the dominant standard for encrypting Internet traffic. Deploying PKI systems for other types of applications or as a general key management system has not been as successful. The differentiating factor seems to be that PKI keys for machine end-entities (such as websites) do not encounter usability hurdles that emerge when issuing PKI keys for human end-entities. Peter Guttman [notdead] has a number of overviews of PKI that present the fundamental difficulties of classic X.509 PKI architectures. Alma Whitten and Doug Tygar [17] published "Why Johnny Can't Encrypt," a study of various users attempting to encrypt email messages using certificates. This study showed substantial user failure rates resulting from the complexities of understanding certificate naming and validation practices. A subsequent study [10] showed similar results when using X.509 certificates with S/MIME encryption in Microsoft Outlook Express. Most of the research on PKI alternatives has focused on making encryption easier to use and deploy.

17. MODIFIED X.509 ARCHITECTURES

Some researchers have proposed modifications or redesigns of the X.509 architecture to make obtaining a certificate easier, and lower the cost of operating applications that depend on certificates. The goal of these systems is often to allow internet based services to use certificate based signature and encryption service without requiring the user to consciously interact with certification services or even understand that certificates are being used.

Perlman and Kaufman's User-Centric Public Key Infrastructure

Perlman and Kaufman proposed the "User-centric PKI" [Perlman], which allows the user to act as his own CA, with authentication provided through individual registration with service providers. It has several features that attempt to protect user privacy by allowing the user to pick what attributes are visible to a specific service provider.

Guttman's Plug and Play Public Key Infrastructure

Guttman's proposed "Plug and Play PKI" [gutmann-pnp] provides for similar self-registration with a service provider and adds location protocols to establish how to contact certifying services. The goal is to build a PKI that provides a reasonable level of security and that is essentially transparent to the end user.

Callas' Self-assembling Public Key Infrastructure

In 2003, Jon Callas [5] proposed a PKI system that would use existing, standard PKI elements bound together by a "robot" server that would examine messages sent between users, and attempt to find certificates that could be used to secure the message. In the absence of an available certificate, the robot would create a key on behalf of the user, and send a message requesting authentication. This system has the benefit for speeding deployment of PKI systems for email authentication, but loses many of the strict authentication attributes that drove the development of the X.509 and IETF PKI standards.

18. ALTERNATIVE KEY MANAGEMENT MODELS

PKI systems can be used for encryption as well as digital signatures, but these two applications have different operational characteristics. In particular, systems that use PKIs for encryption require an encrypting party to have the ability to locate certificates for its desired set of recipients. In digital signature applications, a signer only requires access to his own private key and certificate. The certificates required to verify the signature can be sent with the signed document, so there is no requirement for verifiers to locate arbitrary certificates. These difficulties have been identified as factors contributing to the difficulty of practical deployment of PKI-based encryption systems such as S/MIME.

In 1984, Adi Shamir [16] proposed an Identity-Based Encryption (IBE) system for email encryption. In the identity-based model, any string can be mathematically transformed into a public key, typically using some public information from a server. A message then can be encrypted with this key. To decrypt, the message recipient contacts the server and requests a corresponding private key. The server is able to derive a private key mathematically, which is returned to the recipient. Shamir disclosed how to perform a signature operation in this model, but did not give a solution for encryption.

This approach has significant advantages over the traditional PKI model of encryption. The most obvious is the ability to send an encrypted message without locating a certificate for a given recipient. There are other points of differentiation:

- ***Key recovery.*** In the traditional PKI model, if a recipient loses the private key corresponding to a certificate, all messages encrypted to that certificate's public key cannot be decrypted. In the IBE model, the server can recompute lost private keys. If messages must be recoverable for legal or other business reasons, PKI systems typically add mandatory secondary public keys to which senders must encrypt messages.

- ***Group support.*** Because any string can be transformed into a public key, a group name can be supplied instead of an individual identity. In the traditional PKI model, groups are either done by expanding a group to a set of individuals at encrypt time or by issuing group certificates. Group certificates pose serious difficulties with revocation, because individuals can only be removed from a group as often as revocation is updated.

In 2001, Boneh and Franklin gave the first fully described secure and efficient method for IBE [4]. This was followed by a number of variant techniques, including Hierarchical Identity-Based Encryption (HIBE) and Certificateless Encryption. HIBE allows multiple key servers to be used, each of which controls part of the namespace used for encryption. Certificateless [2] Encryption adds the ability to encrypt to an end user using an identity, but in such a way that the key server cannot read messages. IBE systems have been commercialized and are the subject of standards under the IETF (RFC 5091) and the Institute of Electrical and Electronics Engineers(1363.3).

19. SUMMARY

A PKI is the key management environment for public key information about a public key cryptographic system. As discussed in this chapter, there are three basic PKI architectures based on the number of Certificate Authorities (CAs) in the PKI, in which users of the PKI place their trust (known as a user's trust point), and the trust relationships between CAs within a multi-CA PKI.

The most basic PKI architecture is one that contains a single CA that provides the PKI services (certificates, certificate status information, etc.) for all users of the PKI. Multiple CA PKIs can be constructed using one of two architectures based on the trust relationship between CAs. A PKI constructed with superior−subordinate CA relationships is called a hierarchical PKI architecture. Alternatively, a PKI constructed of peer-to-peer CA relationships is called a mesh PKI architecture.

Directory Architectures

As discussed in this chapter, early PKI development was conducted under the assumption that a directory infrastructure (specifically a global X.500 directory) would be used to distribute certificates and CRLs. Unfortunately, the global X.500 directory did not emerge, which resulted in PKIs being deployed using various directory architectures based on how directory requests are serviced. If the initial directory cannot service a request, the directory can forward the request to other known directories using directory chaining. Another way a directory can resolve an unserviceable request is to return a referral to the initiator of the request indicating a different directory that might be able to service the request. If the directories cannot provide directory chaining or referrals, pointers to directory servers can be embedded in a PKI certificate using the Authority Information Access and Subject Information Access extensions. In general, all PKI users interface to the directory infrastructure using the Lightweight Directory Access Protocol regardless of how the directory infrastructure is navigated.

Bridge Certification Authorities and Revocation Modeling

Bridge Certification Authorities provide the means to leverage the capabilities of existing corporate PKIs as well as federal PKIs. PKIs are being fielded in increasing size and numbers, but operational experience to date has been limited to a relatively small number of environments. As a result, there are still many unanswered questions about the ways in which PKIs will be organized and operated in large-scale systems. Some of these questions involve the ways in which individual certification authorities (CAs) will be interconnected. Others involve the ways in which revocation information will be distributed.

Most of the proposed revocation distribution mechanisms have involved variations of the original CRL scheme. Examples include the use of segmented CRLs and Delta CRLs. However, some schemes do not involve the use of any type of CRL (online certificate status protocols and hash chains).

A model of certificate revocation presents a mathematical model for describing the timings of validations by relying parties. The model is used to determine how request rates for traditional CRLs change over time. This model is then extended to show how request rates are affected when CRLs are segmented. This chapter also presented a technique for distributing revocation information, overissued CRLs. Overissued CRLs are identical to traditional CRLs but are issued more frequently. The result of overissuing CRLs is to spread out requests from relying parties and thus to reduce the peak load on the repository.

A more efficient use of Delta CRLs employs the model described in a model of certificate revocation to analyze various methods of issuing Delta CRLs. It begins with an analysis of the "traditional" method of issuing Delta CRLs and shows that under some circumstances, issuing Delta CRLs in this manner fails to provide the efficiency gains for which Delta CRLs were designed. A new method of issuing Delta CRLs, sliding window Delta CRLs, was presented. Sliding window Delta CRLs are similar to traditional Delta CRLs, but provide a constant amount of historical information. Whereas this does not affect the request rate for

Delta CRLs, it can significantly reduce the peak request rate for base CRLs. The chapter provided an analysis of sliding window Delta CRLs along with advice about how to select the optimal window size to use when issuing Delta CRLs.

Finally, let us move on to the real interactive part of this chapter: review questions/exercises, hands-on projects, case projects, and the optional team case project. The answers and/or solutions by chapter can be found in Appendix K.

CHAPTER REVIEW QUESTIONS/ EXERCISES

True/False

1. True or False? The most important security protocols used on the Internet do not rely on PKI to bind names to keys, a crucial function that allows authentication of users and websites.
2. True or False? To understand how PKI systems function, it is not necessary to grasp the basics of public key cryptography.
3. True or False? The most important cryptographic operation in PKI systems is the digital signature.
4. True or False? Using RSA, variants of the three operations used to construct digital signatures can also be used to encrypt data.
5. True or False? PKI systems solve the problem of associating meaningful names with essentially meaningless cryptographic keys.

Multiple Choice

1. What model is the most prevalent standard for certificate-based PKIs?
   A. X.510
   B. SPKI
   C. TLS
   D. X.509
   E. S/MIME
2. What model specifies a Web of Trust system for certifying user email encryption keys?
   A. PGP
   B. X.509
   C. SPKI
   D. X.512
   E. ASN.1
3. Although in theory the ________________ is the entity that creates and validates certificates, in practice it may be desirable or necessary to delegate the actions of user authentication and certificate validation to other servers.
   A. Evolution
   B. Residue class
   C. Peer-to-peer (P2P)
   D. Certification Authority
   E. Security
4. What process would typically NOT be done as part of certificate validation?
   A. Expiration checking
   B. Revocation checking
   C. Parity checking
   D. Extension checking
   E. Constraint checking
5. The contents of the target certificate cannot be trusted until the integrity of those contents is validated, so the first step is to check the:
   A. Physical world
   B. Data retention
   C. Standardization
   D. Permutation
   E. Signature

EXERCISE

Problem

What are some complexities associated with issuing certificates for end users (in an application such as S/MIME) as opposed to machines (as in TLS)?

Hands-on Projects

Project

Describe the major differences between symmetric key distribution systems and public key systems such as PKI.

Case Projects

Problem

How does PKI provide management and control?

Optional Team Case Project

Problem

What are the core components of a PKI?

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