Module 7: Cryptography

Module Objectives

Module Title: Public Key Cryptography

Module Objective: Explain how the public key infrastructure (PKI) supports network security.

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Topic Title	Topic Objective
Integrity and Authenticity	Explain the role of cryptography in ensuring the integrity and authenticity of data.
Confidentiality	Explain how cryptographic approaches enhance data confidentiality.
Public Key Cryptography	Explain public key cryptography.
Authorities and the PKI Trust System	Explain how the public key infrastructure functions.
Applications and Impacts of Cryptography	Explain how the use of cryptography affects cybersecurity operations.

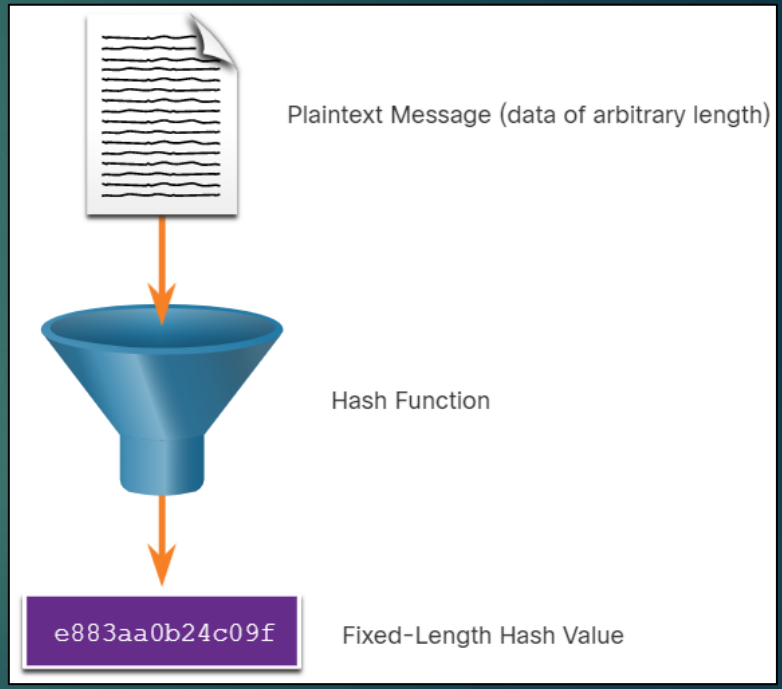
Cryptography

Securing Communications

- Organizations must provide support to secure the data internally as well as externally.
- The four elements of securing communications are:
  - **Data Integrity** - Guarantees that the message was not altered.
  - **Origin Authentication** - Guarantees that the message is not a forgery and it actually comes from whom it states.
  - **Data Confidentiality** - Guarantees that only authorized users can read the message.
  - **Data Non-Repudiation** - Guarantees that the sender cannot repudiate, or refute, the validity of a message sent.

Cryptographic Hash Functions

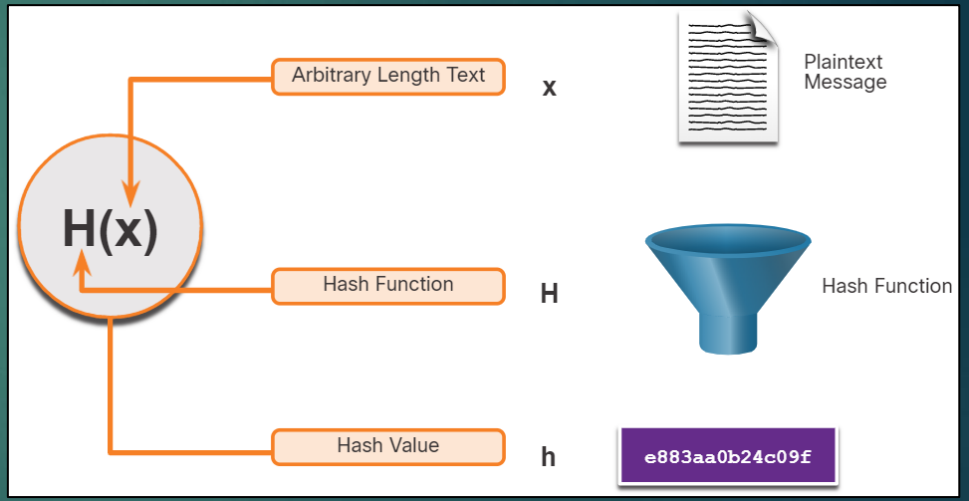
- Hashes are used to verify and ensure data integrity.
- Hashing is based on a one-way mathematical function that is relatively easy to compute, but significantly harder to reverse.
- A hash function takes a variable block of binary data, called the message, and produces a fixed-length, condensed representation, called the hash.
- The resulting hash is also sometimes called the message digest, digest, or digital fingerprint.
- With hash functions, it is computationally infeasible for two different sets of data to come up with the same hash output.
- Every time the data is changed or altered, the hash value also changes.



Cryptographic Hash Operation

- Mathematically, the equation ***h= H(x)*** is used to explain how a hash algorithm operates.
- As shown in the figure, a hash function H takes an input x and returns a fixed-size string hash value h.

- A cryptographic hash function should have the following properties:
  - The input can be any length.
  - The output has a fixed length.
  - H(x) is relatively easy to compute for given x.
  - H(x) is one way and not reversible.
  - H(x) is collision free, meaning that two different input values will result in different hash values.



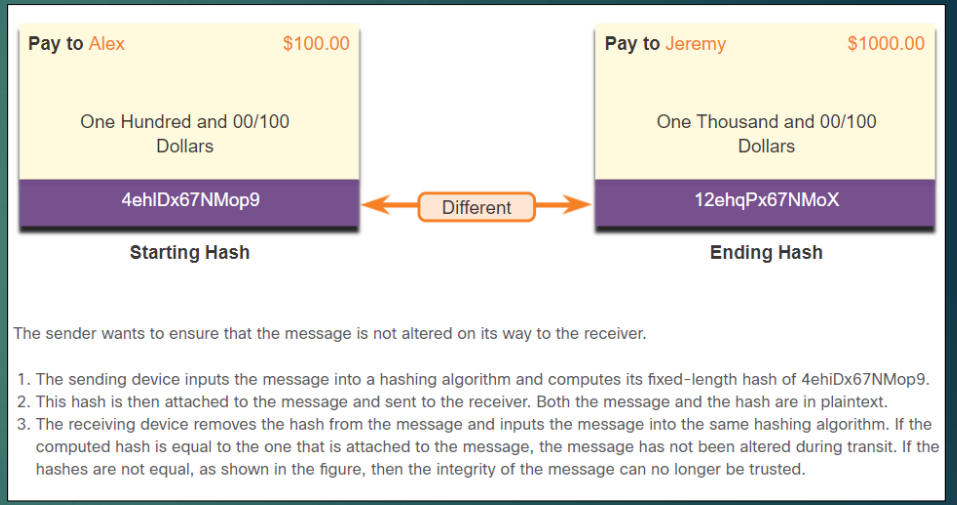
Cryptography

MD5 and SHA

- Hash functions are used to ensure the integrity of a message either accidentally or intentionally.

There are four well-known hash functions:

- **MD5 with 128-bit digest** - A one-way function that produces a 128-bit hashed message. MD5 is a legacy algorithm.
- **SHA-1 -** Very similar to the MD5 hash functions. SHA-1 creates a 160-bit hashed message and is slightly slower than MD5.
- **SHA-2 -** If you are using SHA-2, then SHA-256, SHA-384, and SHA-512 algorithms should be used.
- **SHA-3 -** Next-generation algorithms and should be used whenever possible.



Origin Authentication

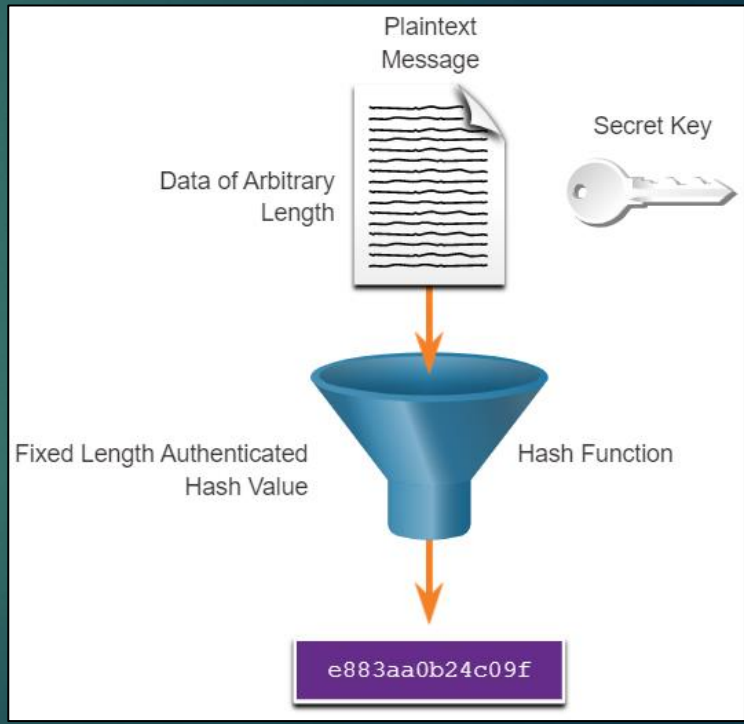
- To add origin authentication and integrity assurance, use a keyed-hash message authentication code (HMAC).
- HMAC uses an additional secret key as input to the hash function.

Note: *Other Message Authentication Code (MAC) methods are also used. However, HMAC is used in many systems including SSL, IPsec, and SSH.*

Origin Authentication (Contd.)

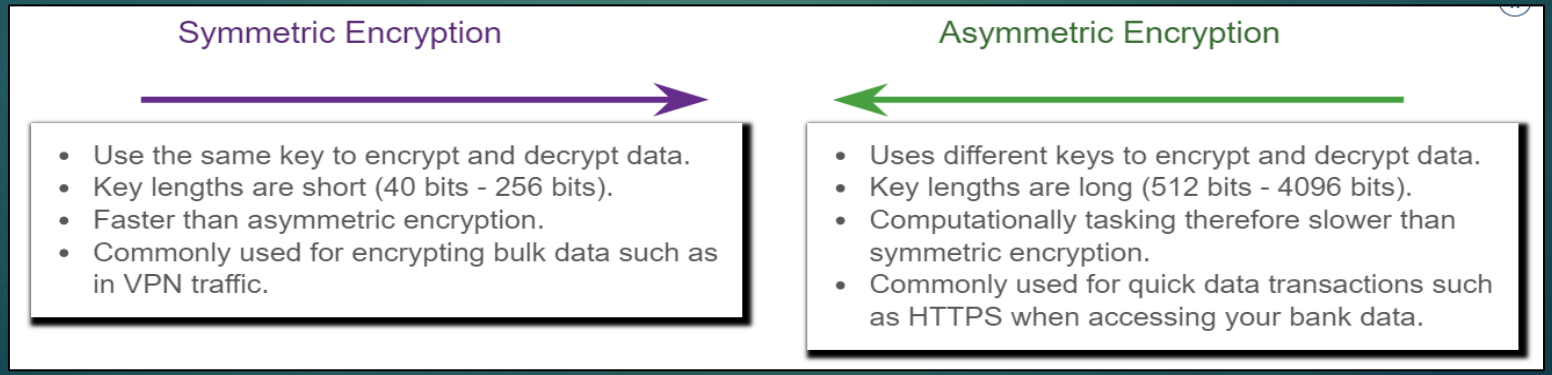
HMAC Hashing Algorithm

- An HMAC is calculated using any cryptographic algorithm that combines a cryptographic hash function with a secret key.
- Only the sender and the receiver know the secret key, and the output of the hash function depends on the input data and the secret key.
- Only parties who have access to that secret key can compute the digest of an HMAC function.
- If two parties share a secret key and use HMAC functions for authentication, a properly constructed HMAC digest of a message that a party has received indicates that the other party was the originator of the message.



Data Confidentiality

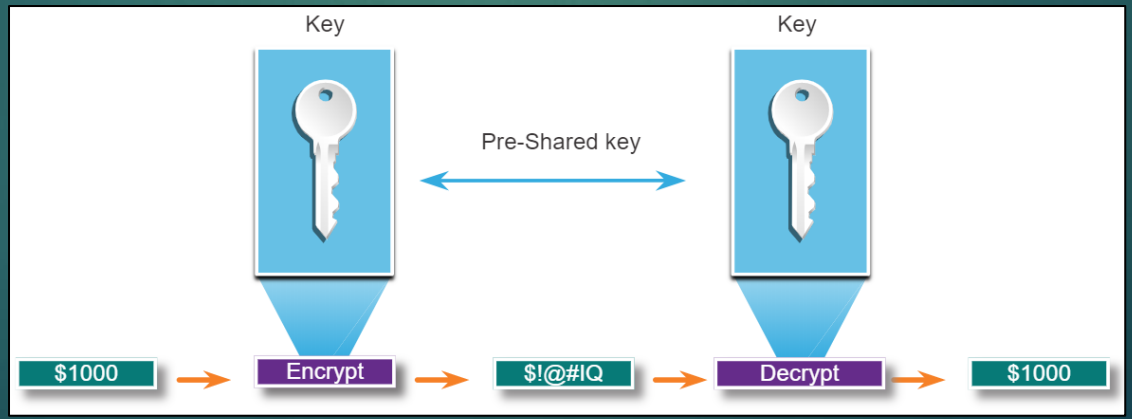
- There are two classes of encryption used to provide data confidentiality; asymmetric and symmetric. These two classes differ in how they use keys.
- Symmetric encryption algorithms such as Data Encryption Standard (DES), 3DES, and Advanced Encryption Standard (AES) are based on the premise that each communicating party knows the pre-shared key.
- Data confidentiality can also be ensured using asymmetric algorithms, including Rivest, Shamir, and Adleman (RSA) and the public key infrastructure (PKI).
- The figure highlights some differences between symmetric and asymmetric encryption.



Confidentiality

Symmetric Encryption

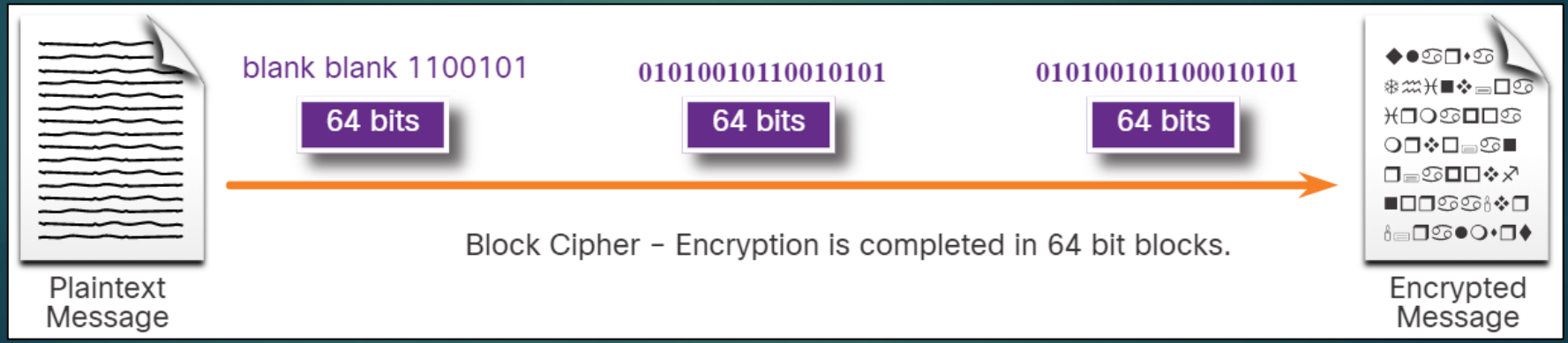
- Symmetric algorithms use the same pre-shared key (secret key) to encrypt and decrypt data.
- Symmetric encryption algorithms are commonly used with VPN traffic because they use less CPU resources than asymmetric encryption algorithms.
- When using these algorithms, the longer the key, the longer it will take for someone to discover the key.
- Most encryption keys are between 112 and 256 bits. Use a longer key for more secure communications.
- Symmetric encryption algorithms are sometimes classified as a block cipher or a stream cipher.



Symmetric Encryption (Contd.)

Block Ciphers

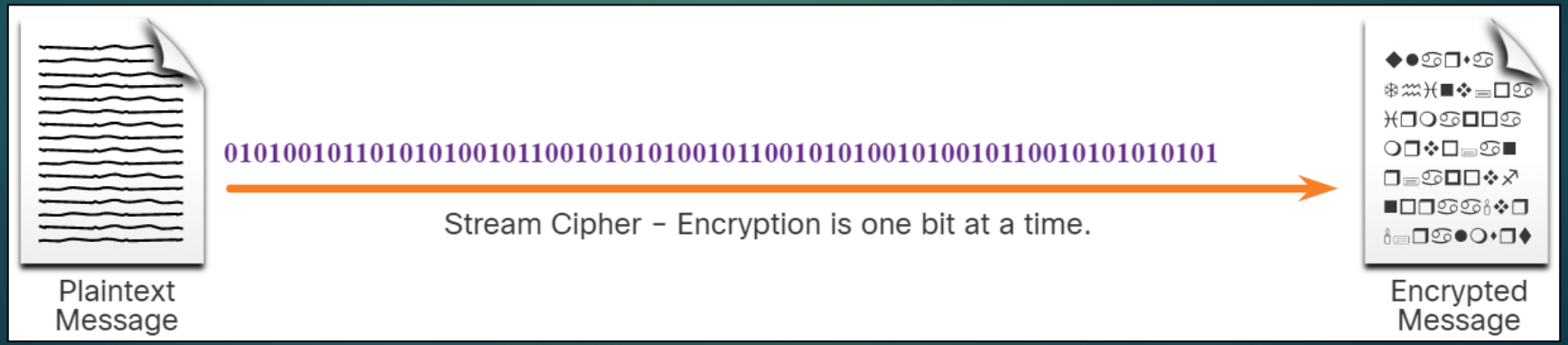
- Block ciphers transform a fixed-length block of plaintext into a common block of ciphertext of 64 or 128 bits.
- Common block ciphers include DES with a 64-bit block size and AES with a 128-bit block size.



Symmetric Encryption (Contd.)

Stream Ciphers

- Stream ciphers encrypt plaintext one byte or one bit at a time.
- Stream ciphers are basically a block cipher with a block size of one byte or bit.
- Stream ciphers are typically faster than block ciphers because data is continuously encrypted.
- Examples include RC4 and A5 which is used to encrypt GSM cell phone communications.



Symmetric Encryption (Contd.)

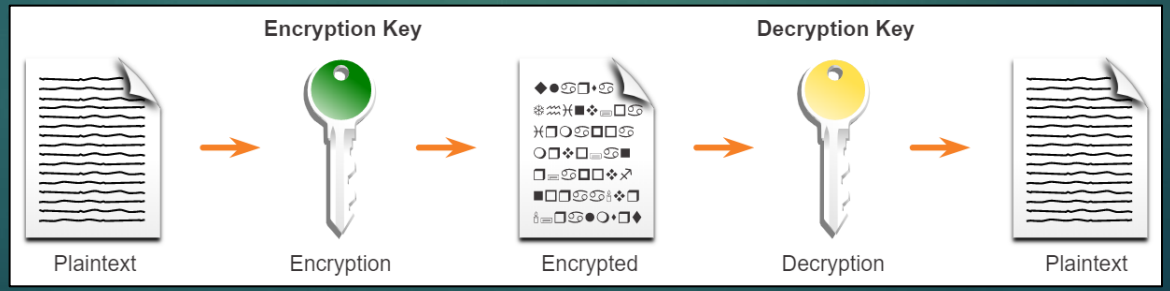
Well-known symmetric encryption algorithms are described in the table.

Symmetric Encryption Algorithms	Description
Data Encryption Standard (DES)	This is a legacy algorithm. It uses a short key length that makes it insecure.
3DES (Triple DES)	This is the replacement for DES and repeats the DES algorithm three times. It should be avoided as it is scheduled to be retired in 2023. If implemented, use very short key lifetimes.
Advanced Encryption Standard (AES)	It offers combinations of 128-, 192-, or 256-bit keys to encrypt 128, 192, or 256 bit-long data blocks.
Software-Optimized Encryption Algorithm (SEAL)	It is a stream cipher that uses a 160-bit encryption key and has a lower impact on the CPU compared to other software-based algorithms.
Rivest ciphers (RC) series algorithms	RC4 is a stream cipher that was used to secure web traffic. It has been found to have multiple vulnerabilities which have made it insecure. RC4 should not be used.

Confidentiality

Asymmetric Encryption

- Asymmetric algorithms, also called public-key algorithms, are designed in a way that the encryption and the decryption keys are different.
- Asymmetric algorithms use a public key and a private key. Both keys are capable of the encryption process, but the complementary paired key is required for decryption.
- The process is also reversible. Data that is encrypted with the public key requires the private key to decrypt.
- Asymmetric algorithms achieve confidentiality and authenticity by using this process.
- Asymmetric encryption can use key lengths between 512 to 4,096 bits.
- Asymmetric algorithms are substantially slower than symmetric algorithms.



Asymmetric Encryption (Contd.)

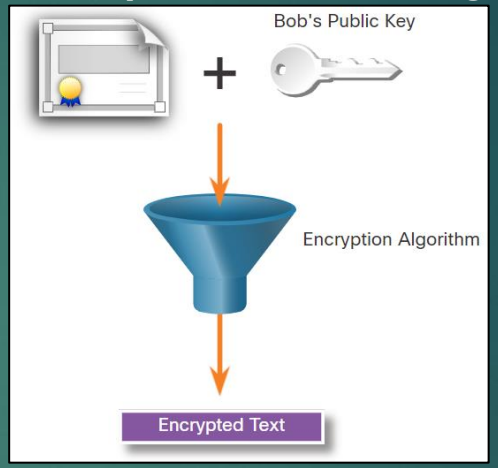
Common examples of asymmetric encryption algorithms are described in the table.

Asymmetric Encryption Algorithms	Key Length	Description
Diffie-Hellman (DH)	512, 1024, 2048, 3072, 4096	This algorithm allows two parties to agree on a key that they can use to encrypt messages they want to send to each other. The security depends on the assumption that it is easy to raise a number to a certain power, but difficult to compute which power was used, given the number and the outcome.
Digital Signature Standard (DSS) and Digital Signature Algorithm (DSA)	512 – 1024	It specifies DSA as the algorithm for digital signatures. DSA is a public key algorithm based on the ElGamal signature scheme. Signature creation speed is similar to RSA, but is 10 to 40 times slower for verification.
Elliptic curve techniques	224 or higher	Elliptic curve cryptography can be used to adapt many cryptographic algorithms, such as Diffie-Hellman or ElGamal. The main advantage of elliptic curve cryptography is that the keys can be much smaller.

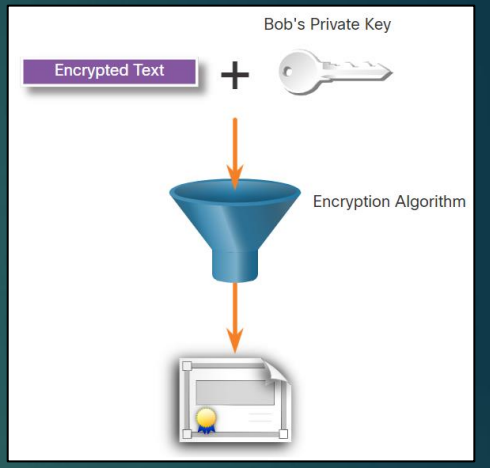
Asymmetric Encryption - Confidentiality

- Asymmetric algorithms are used to provide confidentiality without pre-sharing a password.
- The confidentiality objective of asymmetric algorithms is initiated when the encryption process is started with the public key.
- The process can be summarized using the formula: **Public Key (Encrypt) + Private Key (Decrypt) = Confidentiality**
- When the public key is used to encrypt data, the private key must be used to decrypt data.
- Only one host has the private key; therefore, confidentiality is achieved.

Example: Data exchange between Bob and Alice



Alice acquires and uses Bob's public key to encrypt a message and then send it to Bob.



Bob decrypts the message with the private key and as he is the only one with the private key, confidentiality is achieved.

Asymmetric Encryption - Authentication

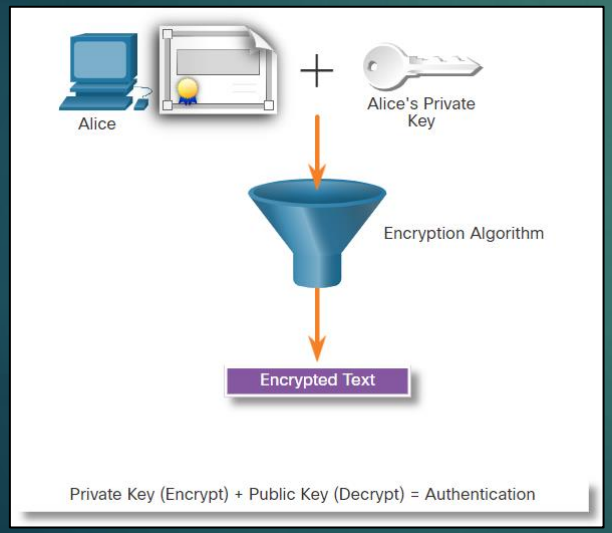
- The authentication objective of asymmetric algorithms is initiated with the private key encryption process.
- The process can be summarized using the formula: **Private Key (Encrypt) + Public Key (Decrypt) = Authentication**
- When the private key is used to encrypt the data, the corresponding public key must be used to decrypt the data.
- Because only one host has the private key, only that host could have encrypted the message, providing authentication of the sender.
- When a host successfully decrypts a message using a public key, it is trusted that the private key encrypted the message, which verifies who the sender is. This is a form of authentication.

Asymmetric Encryption - Authentication (Contd.)

- Let's see how the private and public keys can be used to provide authentication to the data exchange between Bob and Alice.

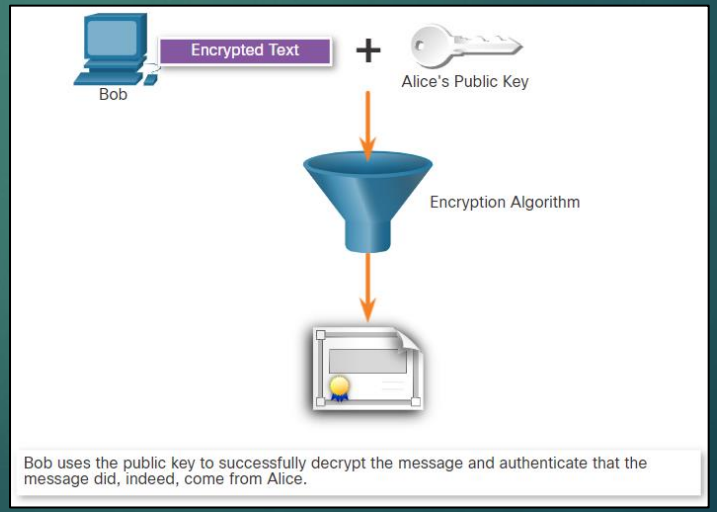
Alice uses her private key

Alice encrypts a message using her private key and sends it to Bob.



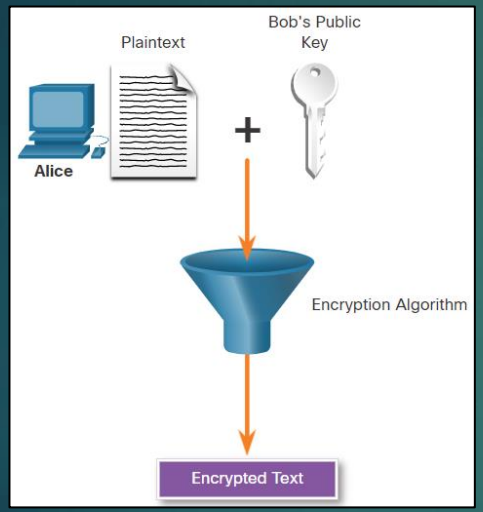
Bob decrypts using the public key

After Bob obtains Alice's public key, he uses it to decrypt the message and to authenticate that the message has been received from Alice.

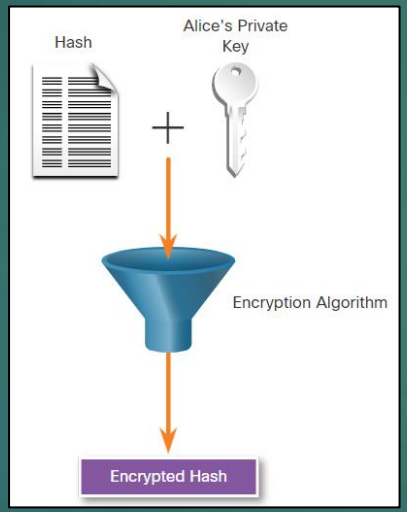


Asymmetric Encryption - Integrity

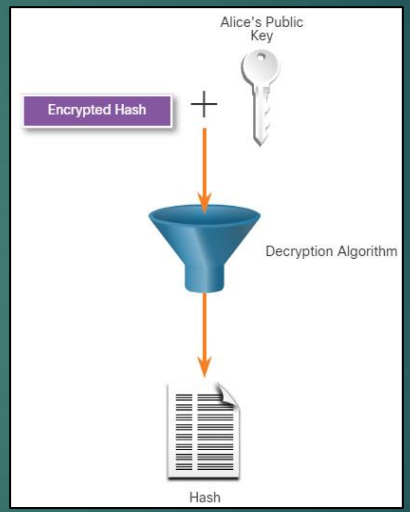
- Combining the two asymmetric encryption processes provides message confidentiality, authentication, and integrity. In this example, a message will be ciphered using Bob's public key and a ciphered hash will be encrypted using Alice's private key.



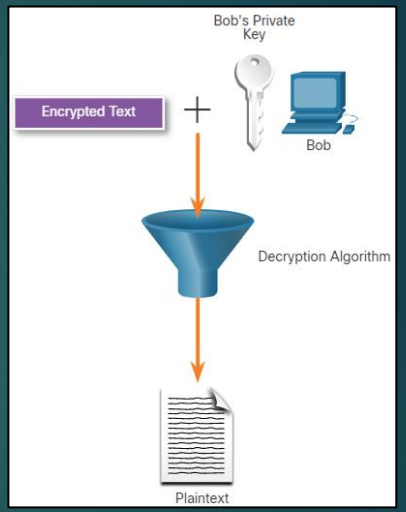
Alice uses Bob's Public Key



Alice encrypts a hash using her private key



Bob uses Alice's public key to decrypt the hash

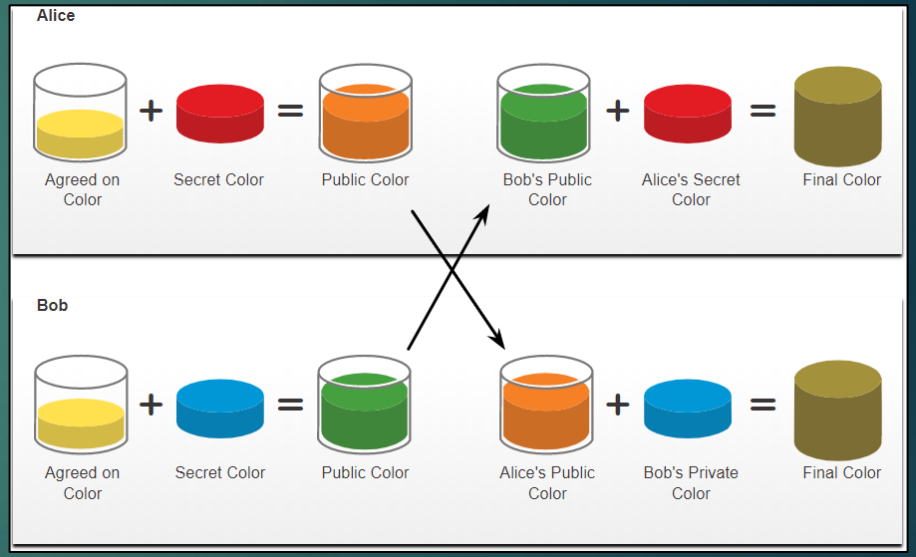


Bob uses his private key to decrypt the message

Confidentiality

Diffie-Hellman

- Diffie-Hellman (DH) is an asymmetric mathematical algorithm that allows two computers to generate an identical shared secret without having communicated before.
  - The new shared key is never actually exchanged between the sender and receiver.
  - The key can be used by an encryption algorithm to encrypt traffic between the two systems as both parties know it.
  - Following are two examples of instances when DH is commonly used:
    - Data is exchanged using an IPsec VPN
    - SSH data is exchanged
  - The security of DH is based on the fact that it uses very large numbers in its calculations.



DH operation

Diffie-Hellman (Contd.)

- Diffie-Hellman uses different DH groups to determine the strength of the key that is used in the key agreement process. The higher group numbers are more secure, but require additional time to compute the key.
- The following identifies the DH groups:
  - DH Group 1: 768 bits
  - DH Group 2: 1024 bits
  - DH Group 5: 1536 bits
  - DH Group 14: 2048 bits
  - DH Group 15: 3072 bits
  - DH Group 16: 4096 bits

***Note**: A DH key agreement can also be based on elliptic curve cryptography. DH groups 19, 20, and 24, are supported by Cisco IOS Software.*

Using Digital Signatures

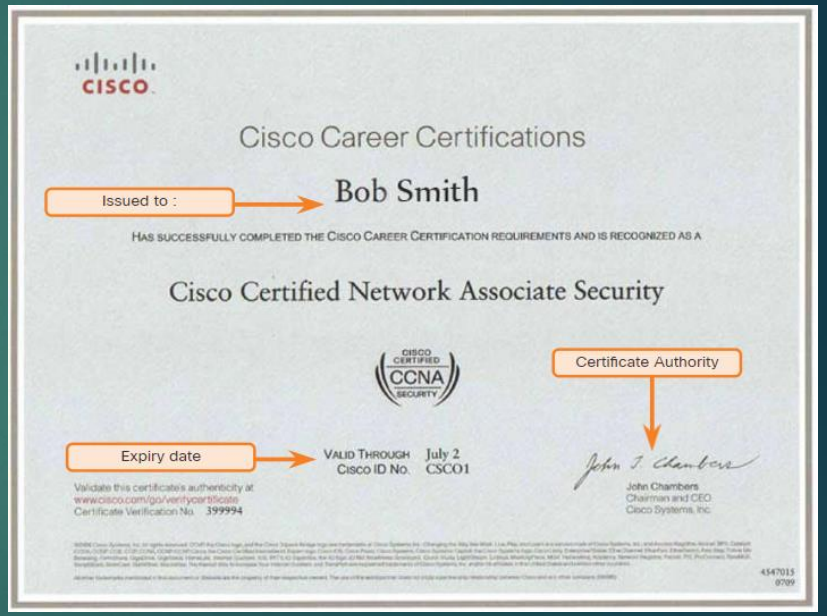
- Digital signatures are a mathematical technique used to provide authenticity, integrity, and nonrepudiation.
- Digital signatures use asymmetric cryptography.
- Digital signatures are commonly used in the following two situations:
  - **Code signing -** Code signing is used to verify the integrity of executable files downloaded from a vendor website. It also uses signed digital certificates to authenticate and verify the identity of the site that is the source of the files.
  - **Digital certificates -** These are used to authenticate the identity of a system with a vendor website and establish an encrypted connection to exchange confidential data.
- The Digital Signature Standard (DSS) algorithms used for generating and verifying digital signatures are:
  - **Digital Signature Algorithm (DSA)**
  - **Rivest-Shamir Adelman Algorithm (RSA)**
  - **Elliptic Curve Digital Signature Algorithm (ECDSA)**

Digital Signatures for Code Signing

- Digital signatures are commonly used to provide assurance of the authenticity and integrity of software code.
- Executable files are wrapped in a digitally signed envelope, which allows the end user to verify the signature before installing the software.
- Digitally signing code provides several assurances about the code:
  - The code is authentic and is actually sourced by the publisher.
  - The code has not been modified since it left the software publisher.
  - The publisher undeniably published the code. This provides nonrepudiation of the act of publishing.
- The purpose of digitally signed software is to ensure that the software has not been tampered with, and that it originated from the trusted source as claimed.

Digital Signatures for Digital Certificates

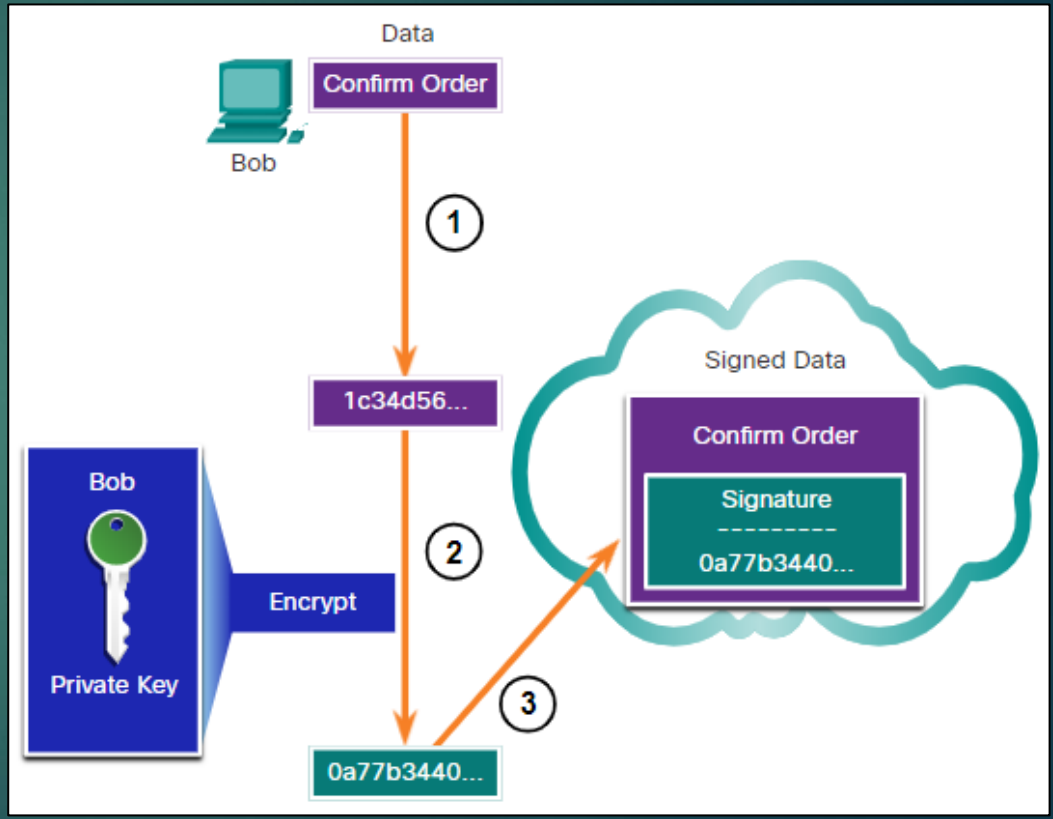
- A digital certificate enables users, hosts, and organizations to securely exchange information over the Internet.
- It is used to authenticate and verify that a user who is sending a message is who they claim to be.
- Digital certificates can also be used to provide confidentiality for the receiver with the means to encrypt a reply.
- Digital certificates are similar to physical certificates.
- Digital certificate independently verifies an identity.
- In other words, a certificate verifies an identity, a signature verifies information coming from an identity.



Digital Signatures for Digital Certificates (Contd.)

This scenario will help you understand how a digital signature is used.

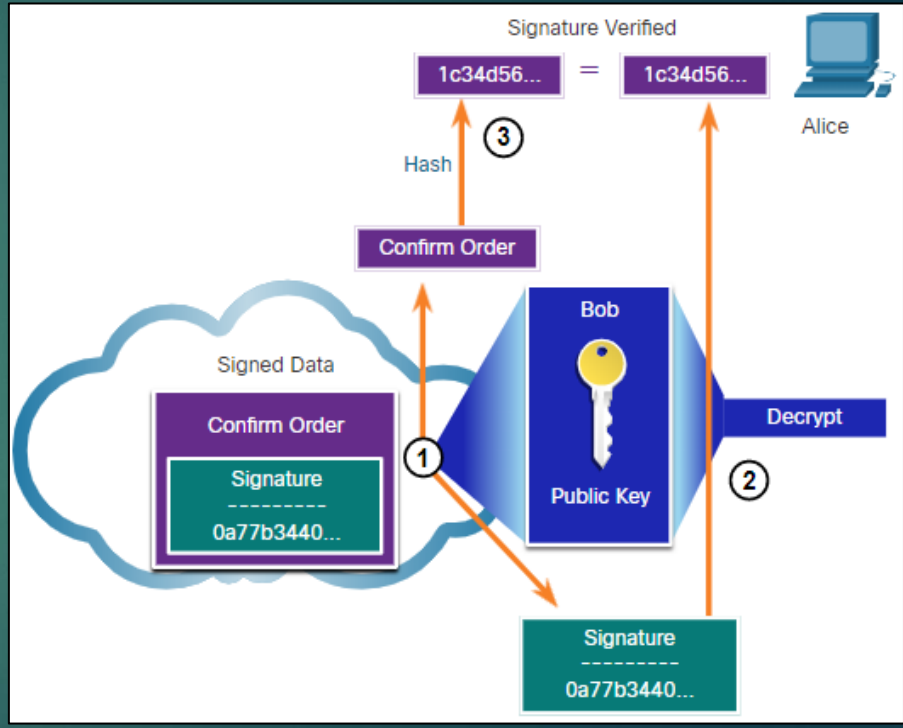
- Bob is confirming an order with Alice, which she is ordering from Bob's website.
- Bob confirms the order and his computer creates a hash of the confirmation.
- The computer encrypts the hash with Bob's private key.
- The encrypted hash, which is the digital signature, is added to the document.
- The order confirmation is then sent to Alice over the internet.



Digital Signatures for Digital Certificates (Contd.)

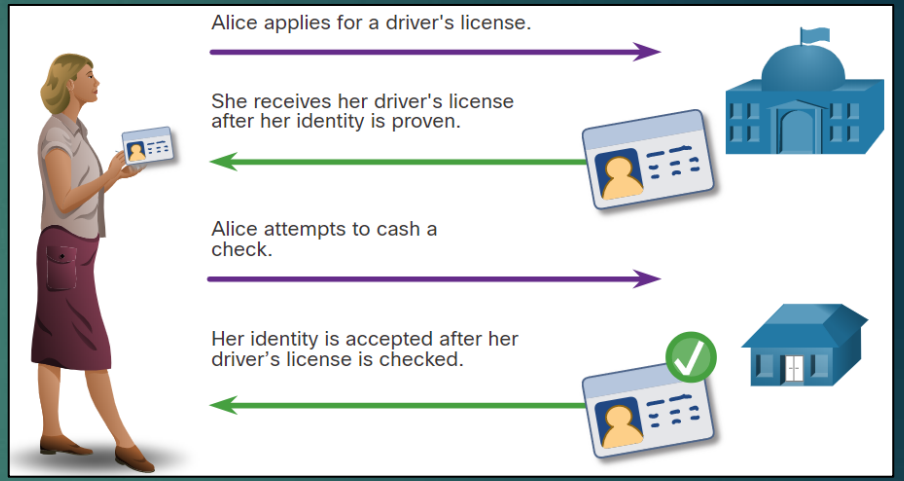
When Alice receives the digital signature, the following process occurs:

- Alice's receiver accepts the order confirmation with the digital signature and obtains Bob's public key.
- Alice's computer then decrypts the signature using Bob's public key which reveals the assumed hash value of the sending device.
- Alice's computer creates a hash of the received document, without its signature, and compares this hash to the decrypted hash.
- If the hashes match, the document is authentic. This means the confirmation was sent by Bob and has not changed since signed.



Public Key Management

- When establishing an asymmetric connection between two hosts, the hosts will exchange their public key information.
- Trusted third parties on the Internet validate the authenticity of these public keys using digital certificates. The third-party issues credentials that are difficult to forge.
- From that point forward, all individuals who trust the third party simply accept the credentials that the third-party issues.
- The Public Key Infrastructure (PKI) consists of specifications, systems, and tools that are used to create, manage, distribute, use, store, and revoke digital certificates.

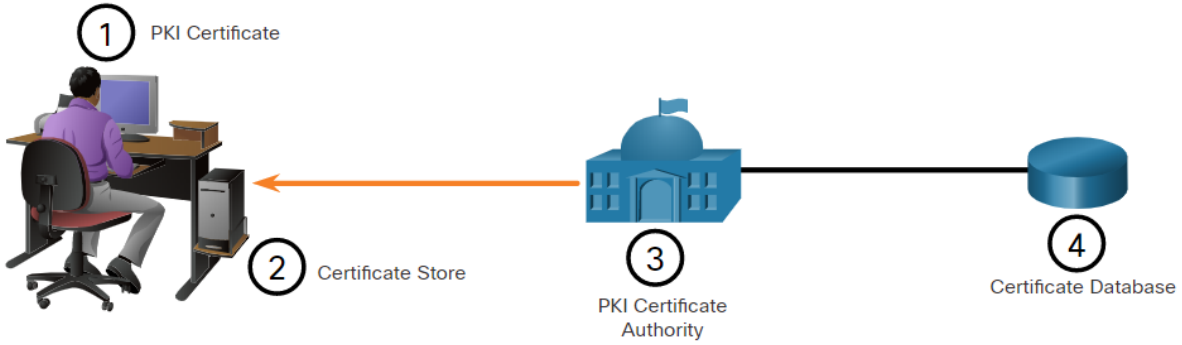


Illustrates how a driver's license is analogous to a digital certificate

- The Certificate Authority (CA) creates digital certificates by tying a public key to a confirmed identify, such as a website or individual.

The Public Key Infrastructure

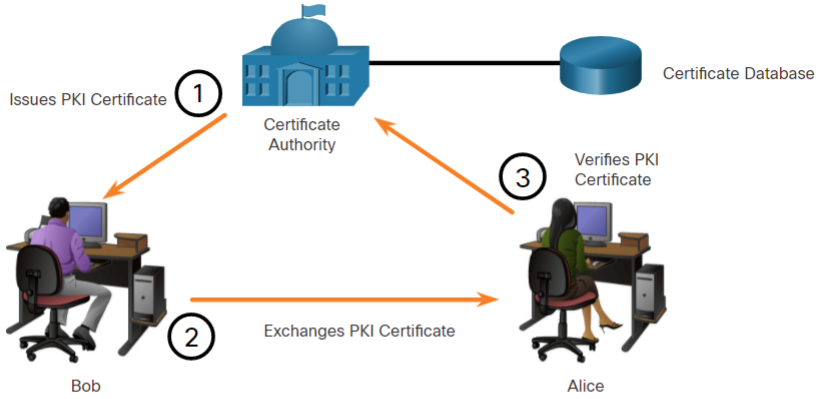
- PKI is needed to support large-scale distribution and identification of public encryption keys.
- The PKI framework facilitates a highly scalable trust relationship.
- It consists of the hardware, software, people, policies, and procedures needed to create, manage, store, distribute, and revoke digital certificates.
- The figure shows the main elements of the PKI.



1. PKI certificates contain an entity's or individual's public key, its purpose, the certificate authority (CA) that validated and issued the certificate, the date range during which the certificate is valid, and the algorithm used to create the signature.
2. The certificate store resides on a local computer and stores issued certificates and private keys.
3. The PKI Certificate of Authority (CA) is a trusted third party that issues PKI certificates to entities and individuals after verifying their identity. It signs these certificates using its private key.
4. The certificate database stores all certificates approved by the CA.

The Public Key Infrastructure (Contd.)

- The below figure shows how the elements of the PKI interoperate:



1. **Issues PKI Certificate**. Bob initially requests a certificate from the CA. The CA authenticates Bob and stores Bob's PKI certificate in the certificate database.
2. **Exchanges PKI Certificate**. Bob communicates with Alice using his PKI certificate.
3. **Verifies PKI Certificate**. Alice communicates with the trusted CA using the CA's public key. The CA refers to the certificate database to validate Bob's PKI certificate.

***Note**: Not all PKI certificates are directly received from a CA. A Registration Authority (RA) is a subordinate CA and is certified by a root CA to issue certificates for specific uses.*

The PKI Authorities System

- Many vendors provide CA servers as a managed service or as an end-user product.
- Organizations may also implement private PKIs using Microsoft Server or Open SSL.
- CAs issue certificates based on classes which determine how trusted a certificate is.
- The class number is determined by how rigorous the procedure was that verified the identity of the holder when the certificate was issued.
- The higher the class number, the more trusted the certificate.
- Some CA public keys are preloaded, such as those listed in web browsers.

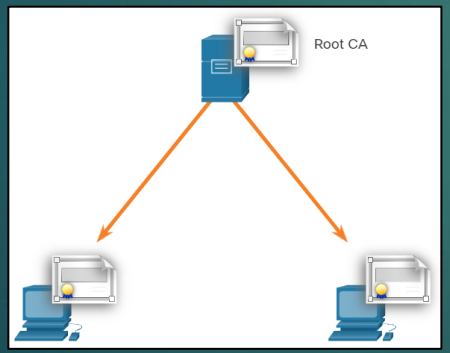
Class	Description
0	Used for testing in situations in which no checks have been performed.
1	Used by individuals who require verification of email.
2	Used by organizations for which proof of identity is required.
3	Used for servers and software signing.
4	Used for online business transactions between companies.
5	Used for private organizations or government security.

Note: *An enterprise can also implement PKI for internal use. PKI can be used to authenticate employees who are accessing the network. In this case, the enterprise is its own CA.*

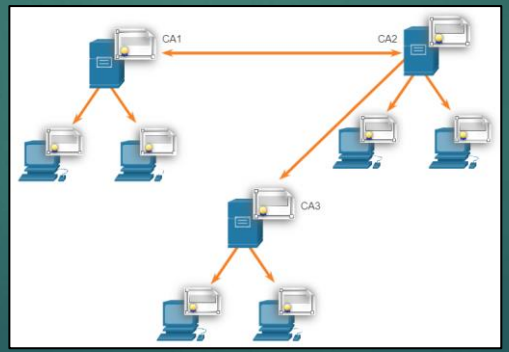
The PKI Trust System

PKIs can form different topologies of trust which are as follows:

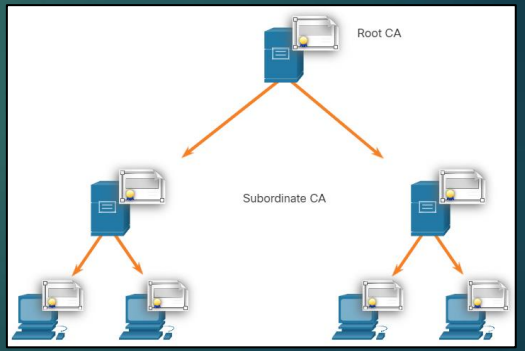
- **Single-Root PKI Topology:** The simplest is the single-root PKI topology. The root CA issues all the certificates to the end users within the same organization. On larger networks, PKI CAs may be linked using two basic architectures:
- **Cross-certified CA topologies**: A peer-to-peer model in which individual CAs establish trust relationships with other CAs by cross-certifying CA certificates.
- **Hierarchical CA topologies**: The root CA (highest level CA), can issue certificates to end users and to a subordinate CA.



Single-Root PKI Topology



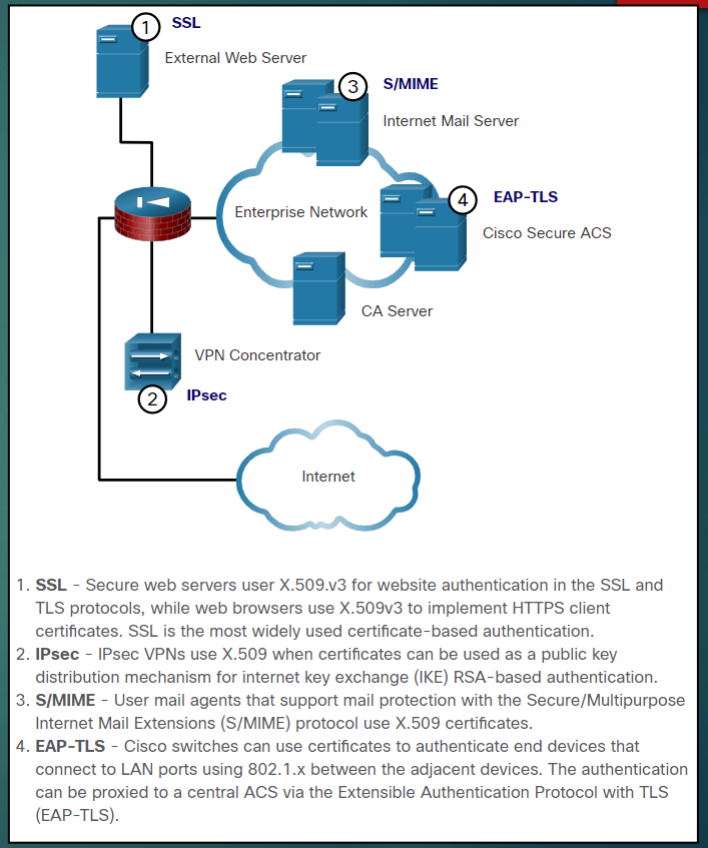
Cross-certified CA Topologies



Hierarchical CA Topologies

Interoperability of Different PKI Vendors

- Interoperability between a PKI and its supporting services is a concern because many CA vendors have proposed and implemented proprietary solutions.
- To address this interoperability concern, the IETF published the Internet X.509 Public Key Infrastructure Certificate Policy and Certification Practices Framework (RFC 2527).
- The X.509 version 3 (X.509 v3) standard defines the format of a digital certificate.



X.509v3 Applications

Certificate Enrollment, Authentication and Revocation

- All systems that leverage the PKI must have the CA's public key, which is called the self-signed certificate.
- The CA public key verifies all the certificates issued by the CA and is vital for the proper operation of the PKI.
- The certificate enrollment process is used by a host system to enroll with a PKI. To do so, CA certificates are retrieved in-band over a network, and the authentication is done out-of-band (OOB) using the telephone.
- The system enrolling with the PKI contacts a CA to request and obtain a digital identity certificate for itself and to get the CA's self-signed certificate.
- The final stage verifies that the CA certificate was authentic and is performed using an out-of-band method such as the POTS to obtain the fingerprint of the valid CA identity certificate.
- A digital certificate can be revoked if key is compromised or if it is no longer needed.

***Note**: Only a root CA can issue a self-signed certificate that is recognized or verified by other CAs within the PKI.*

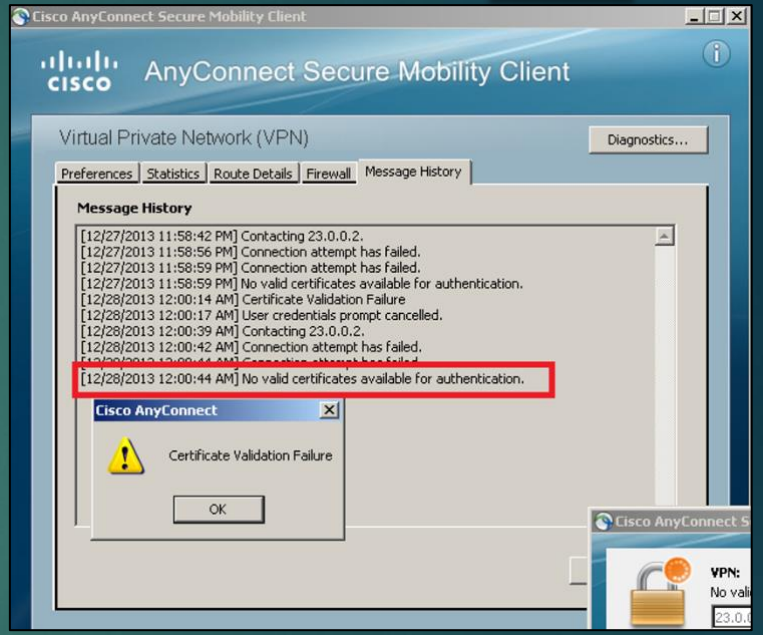
PKI Applications

The following provides a short list of common uses of PKIs:

- SSL/TLS certificate-based peer authentication
- Secure network traffic using IPsec VPNs
- HTTPS Web traffic
- Control access to the network using 802.1x authentication
- Secure email using the S/MIME protocol
- Secure instant messaging
- Approve and authorize applications with Code Signing
- Protect user data with the Encryption File System (EFS)
- Implement two-factor authentication with smart cards
- Securing USB storage devices

Encrypted Network Transactions

- Threat actors can use SSL/TLS to introduce regulatory compliance violations, viruses, malware, data loss, and intrusion attempts in a network.
- Other SSL/TLS-related issues may be associated with validating the certificate of a web server. When this occurs, the web browsers will display a security warning. PKI-related issues associated with security warnings include:
  - **Validity date range** - The X.509v3 certificates specify "not before" and "not after" dates. If the current date is outside the range, the web browser displays a message.
  - **Signature validation error** - If a browser cannot validate the signature on the certificate, there is no assurance that the public key in the certificate is authentic.



Encryption and Security Monitoring

- Network monitoring becomes more challenging when packets are encrypted.
- As HTTPS introduces end-to-end encrypted HTTP traffic (via TLS/SSL), it is not as easy to peek into user traffic.
- Security analysts must know how to circumvent and solve these issues. Here is a list of some of the things that a security analyst could do:
  - Configure rules to distinguish between SSL and non-SSL traffic, HTTPS and non-HTTPS SSL traffic.
  - Enhance security through server certificate validation using CRLs and OCSP.
  - Implement antimalware protection and URL filtering of HTTPS content.
  - Deploy a Cisco SSL Appliance to decrypt SSL traffic and send it to intrusion prevention system (IPS) appliances to identify risks normally hidden by SSL.

Encryption and Security Monitoring (Contd.)

- Cryptography is dynamic and always changing. A security analyst must maintain a good understanding of cryptographic algorithms and operations to be able to investigate cryptography-related security incidents.
- There are two main ways in which cryptography impacts security investigations.
  - First, attacks can be directed to specifically target the encryption algorithms themselves.
  - After the algorithm has been cracked and the attacker has obtained the keys, any encrypted data that has been captured can be decrypted by the attacker and read, thus exposing private data.
  - Secondly, the security investigation is also affected because data can be hidden in plain sight by encrypting it.

Public Key Cryptography Summary

What Did I Learn in this Module?

- The four elements of secure communications: data integrity, origin authentication, data confidentiality, and data non-repudiation.
- A hash function takes a variable block of binary data, called the message, and produces a fixed-length, condensed representation, called the hash.
- There are two classes of encryption that are used to provide data confidentiality: asymmetric and symmetric.
- Symmetric encryption algorithms, such as DES, 3 DES, and AES are based on the premise that each communicating party knows the pre-shared key.
- Asymmetric algorithms (public key algorithms) are designed so that the key that is used for encryption is different from the key used for encryption.
- Data confidentiality can also be ensured using asymmetric algorithms, including Rivest, Shamir, and Aldeman (RSA) and PKI. The process is summarized using this formula: Public key (Encrypt) + Private Key (Decrypt) = Confidentiality.

What Did I Learn in this Module? (Contd.)

- The authentication objective of an asymmetric algorithm is initiated when the encryption process is started with the private key. The process can be summarized with this formula: Private Key (Encrypt) + Public Key (Decrypt) = Authentication.
- Diffie-Hellman (DH) is an asymmetric mathematical equation algorithm that allows two computers to generate an identical shared secret key without having communicate before.
- Digital signatures are a mathematical technique used to provide three basic security services: authenticity, integrity, and non-repudiation. Digital signatures are commonly used in code signing and digital certificates.
- The Public Key Infrastructure (PKI) consists of specifications, systems, and tools that are used to create, manage, distribute, use, store, and revoke digital certificates.
- There are many common uses of PKIs including a few listed here: SSL/TLS certificate-based peer authentication, HTTPS Web traffic, secure instant message, and securing USB storage devices.
- A security analyst must be able to recognize and solve potential problems related to permitting PHI-related solutions on the enterprise network.