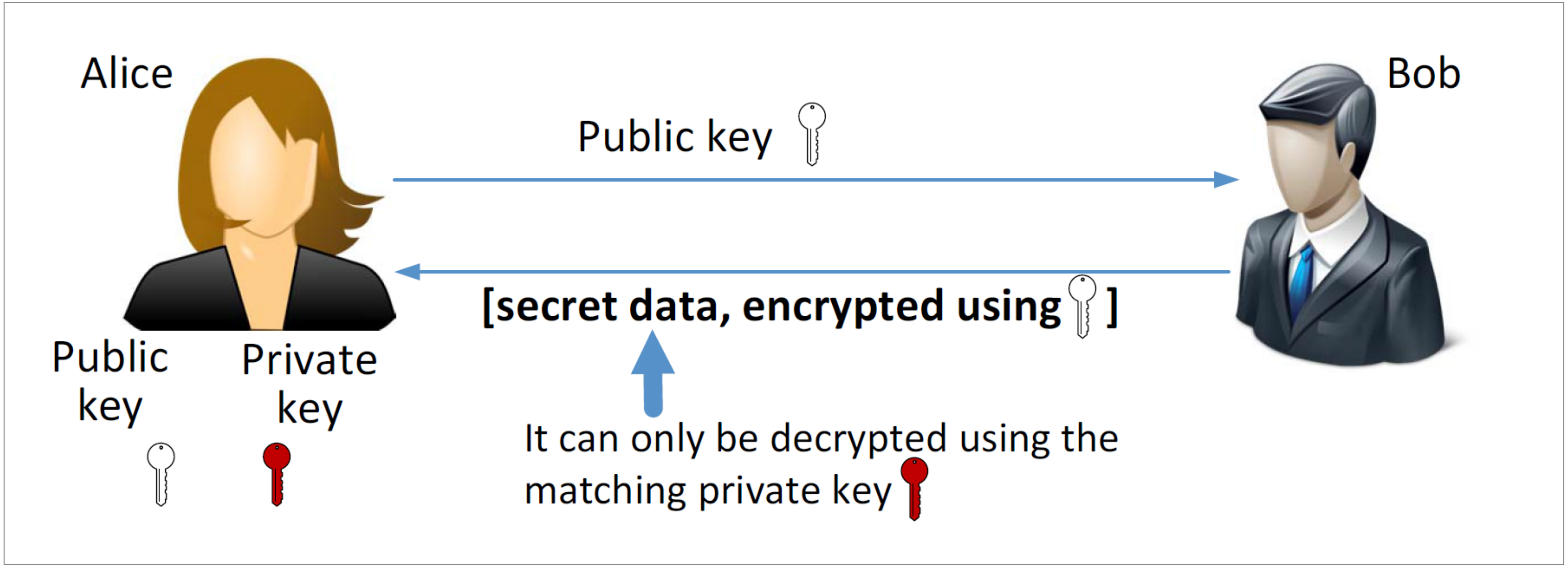
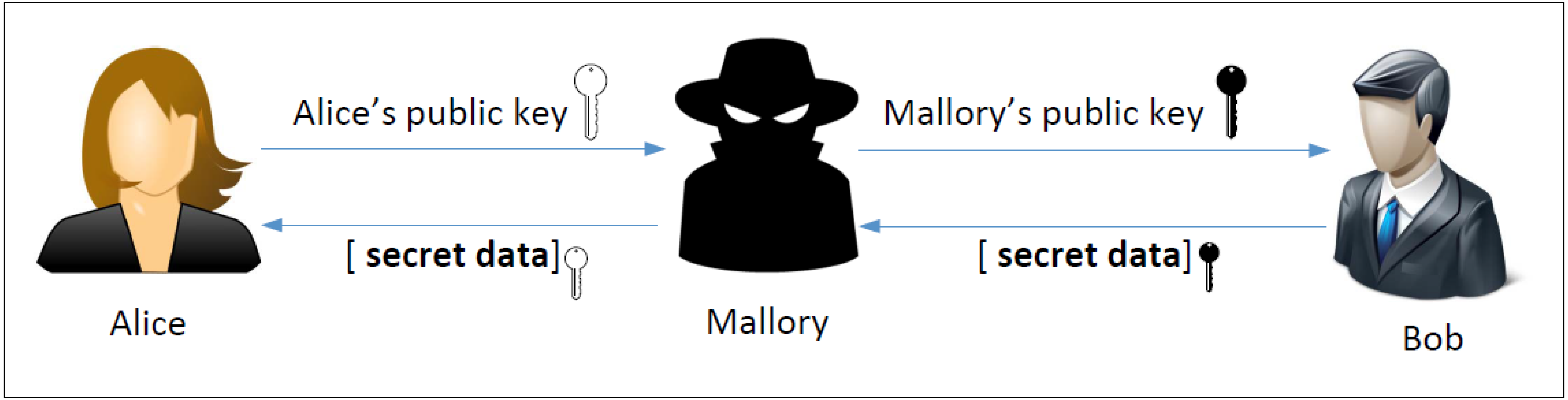
Public Key Infrastructure

Public Key Cryptography



Man-in-the-Middle (MITM) Attack



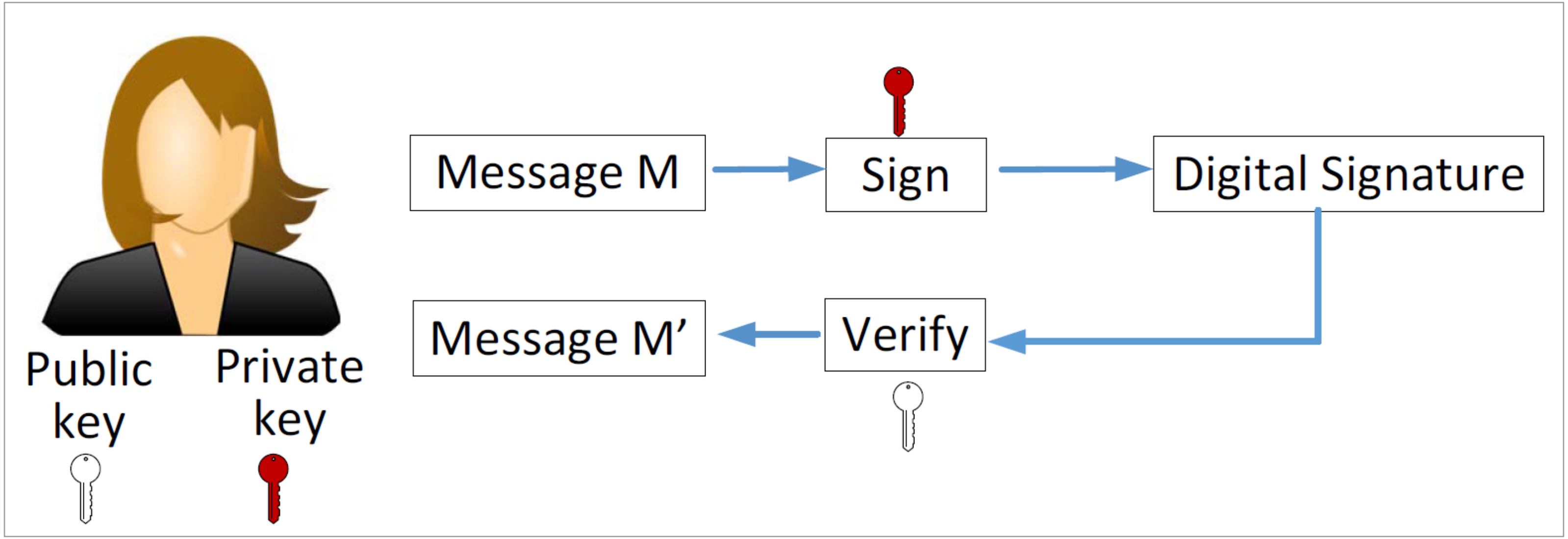
What Is the Fundamental Problem?

Fundamental Problem: Bob has no way to tell whether the public key he has received belongs to Alice or not.

Solution:

- Find a trusted party to verify the identity
- Bind an identity to a public key in a certificate
- The certificate cannot be forged or tampered with (using digital signature)

Digital Signature



- If the signature is not tampered with, M' will be the same as M
- Only Alice can sign (she has the private key)
- Everybody can verify (public key is known publically)

Defeating MITM Attacks using Digital Signature

- Alice needs to go to a trusted party to get a certificate.
- After verifying Alice's identity, the trusted party issues a certificate with Alice's name and her public key.
- Alice sends the entire certificate to Bob.
- Bob verifies the certificate using the trusted party's public key.
- Bob now knows the true owner of a public key.

Public Key Infrastructure

- **Certificate Authority (CA):** a trusted party, responsible for verifying the identity of users, and then bind the verified identity to a public keys.
- **Digital Certificates:** A document certifying that the public key included inside does belong to the identity described in the document.
  - X.509 standard

Digital Certificate

- Let's get paypal's certificates

```
$ openssl s_client -showcerts -connect www.paypal.com:443 </dev/null
```


```
-----BEGIN CERTIFICATE-----
MIIHWTCCBkGgAwIBAgIQLNGVEFQ30N5KOSAFavbCfzANBgkqhkiG9w0BAQsFADB3
MQswCQYDVQQGEwJVUzEdMBsGA1UEChMUU3ltYW50ZWMgQ29ycG9yYXRpb24xHzAd
... (omitted) ...
GN/QMQ3a55rjwNQnA3s2WWuHGPaE/jMG17iiL2O/hUdIvLE9+wA+fWrey5//74xl
NeQitYiySDIepHGnng==
-----END CERTIFICATE-----
```


- Save the above data to paypal.pem, and use the following command decode it (see next slide)

```
$ openssl x509 -in paypal.pem -text -noout
```

Example of X.509 Certificate (1st Part)

The CA's identity (Symantec)

The owner of the certificate (paypal)

```
Certificate:
Data:
  Serial Number:
            2c:d1:95:10:54:37:d0:de:4a:39:20:05:6a:f6:c2:7f
  Signature Algorithm: sha256WithRSAEncryption
  Issuer: C=US, O=Symantec Corporation, OU=Symantec Trust Network,
          CN=Symantec Class 3 EV SSL CA - G3
  Validity
     Not Before: Feb  2 00:00:00 2016 GMT
     Not After : Oct 30 23:59:59 2017 GMT
  Subject: 1.3.6.1.4.1.311.60.2.1.3=US/
           1.3.6.1.4.1.311.60.2.1.2=Delaware/
           businessCategory=Private Organization/
           serialNumber=3014267, C=US/
           postalCode=95131-2021, ST=California,
           L=San Jose/street=2211 N 1st St,
           O=PayPal, Inc., OU=CDN Support, CN=www.paypal.com
```

Example of X.509 Certificate (2^{nd} Part)

Public key

```
 Subject Public Key Info:
     Public Key Algorithm: rsaEncryption
         Public-Key: (2048 bit)
         Modulus:
           00:da:43:c8:b3:a6:33:5d:83:c0:63:14:47:fd:6b:22:bd:
           bf:4e:a7:43:11:55:eb:20:8b:e4:61:13:ee:de:fe:c6:e2:
           ... (omitted) ...
           7a:15:00:c5:01:69:b5:10:16:a5:85:f8:fd:07:84:9a:c9:
         Exponent: 65537 (0x10001)
```

CA’s signature

```
Signature Algorithm: sha256WithRSAEncryption
4b:a9:64:20:cc:77:0b:30:ab:69:50:d3:7f:de:dc:7c:e2:fb:93:84:fd:
78:a7:06:e8:14:03:99:c0:e4:4a:ef:c3:5d:15:2a:81:a1:b9:ff:dc:3a:
... (omitted) ...
fb:00:3e:7d:6a:de:cb:9f:ff:ef:8c:65:35:e4:22:b5:88:b2:48:32:1e:
```

The Core Functionalities of CA

- **Verify the subject**
  - Ensure that the person applying for the certificate either owns or represents the identity in the subject field.

- **Signing digital certificates**
  - CA generates a digital signature for the certificate using its private key.
  - Once the signature is applied, the certificate cannot be modified.
  - Signatures can be verified by anyone with the CA’s public key.

Being a Certificate Authority

- Let's go through the process
  - How a CA issues certificates
  - How to get a certificate from a CA
  - How to set up a web server using a certificate

CA Setup

- Our CA will be called ModelCA
- We need to set up the following for ModelCA:
  - Generate public/private key pair
  - Create a X.509 certificate (who is going to sign it?)
  - We assume ModelCA is a root CA, so it is going to sign the certificate itself, i.e. self-signed.
- The following command generates a self-signed X.509 certificate

```
$ openssl req -x509 -newkey rsa:4096 -sha256 -days 3650
              -keyout modelCA_key.pem -out modelCA_cert.pem
```

Discussion Question

- Question: If the ModelCA's certificate is self-signed, how do we verify it?

- Answer: There is no way to verify it. We just make sure that the certificate is obtained in a trusted way
  - Come with the operating system (if we trust OS, we trust the cert.)
  - Come with the software (if we trust the software, we trust the cert.)
  - Manually added (if we trust our own decision, we trust the cert.)
  - Sent to us by somebody whom we don't trust (don't trust the cert.)

Get a Certificate from CA: Step 1

- Step 1: Generate a public/private key pair

RSA key size

```
$ openssl genrsa -aes128 -out bank_key.pem 2048
```

Encrypt the ouput file using AES (128-bit)

Contains both private and public keys

Get a Certificate from CA: Step 2

- Step 2: Generate a certificate signing request (CSR); identity information needs to be provided

```
$ openssl req -new -key bank_key.pem -out bank.csr -sha256
```

```
$ openssl req -in bank.csr -text -noout
Certificate Request:
    Data:
        Version: 0 (0x0)
        Subject: C=US, ST=New York, L=Syracuse, O=Example Inc,
                 CN=example.com/emailAddress=email@example.com
```

CA will verify this subject information

CA: Issuing X.509 Certificate

- We (the bank) need to send the CSR file to ModelCA.
- ModelCA will verify that we are the actual owner of (or can represent) the identity specified in the CSR file.
- If the verification is successful, ModelCA issues a certificate

The CSR file

The X.509 certificate will be saved here

```
$ openssl ca -in bank.csr -out bank_cert.pem -md sha256
             -cert modelCA_cert.pem -keyfile modelCA_key.pem
```

ModelCA’s self-signed certificate

ModelCA’s private key

Deploying Public Key Certificate in Web Server

- We will first use openssl's built-in server to set up an HTTPS web server

```
$ cp bank.key bank.pem
$ cat bank.crt >> bank.pem
$ openssl s_server -cert bank.pem -accept 4433 -www
```

- Access the server using Firefox (https://example.com:4433), we get the following error message. Why?

```
example.com:4433 uses an invalid security certificate.

The certificate is not trusted because no issuer chain was provided.
The certificate is only valid for example.com

(Error code: sec_error_unknown_issuer)
```

Answer to the Question in the Previous Slide

- Firefox needs to use ModelCA's public key to verify the certificate
- Firefox does not have ModelCA's public key certificate
- We can manually add ModelCA's certificate to Firefox

Goto `Edit -> Preference -> Advanced -> View Certificates`

Import `ModelCA_cert.pem`

Apache Setup for HTTPS

- We add the following VirtualHost entry to the Apache configuration file:

```
<VirtualHost *:443>
    ServerName example.com
    DocumentRoot /var/www/Example
    DirectoryIndex index.html

    SSLEngine On
    SSLCertificateFile      /etc/apache2/ssl/bank_cert.pem   ①
    SSLCertificateKeyFile   /etc/apache2/ssl/bank_key.pem    ②
</VirtualHost>
```

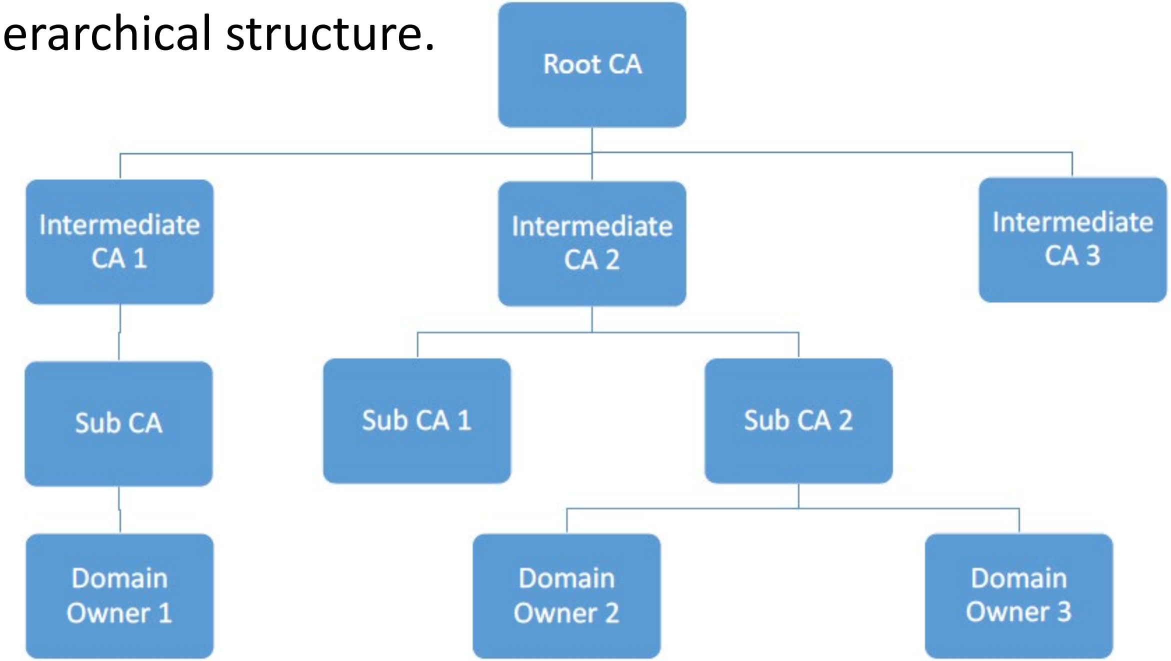
The server's certificate

The server's private key

Note: Apache configuration file is located at
`/etc/apache2/sites-available/default`

Root and Intermediate Certificate Authorities

There are many CAs in the real world, and they are organized in a hierarchical structure.



Root CAs and Self-Signed Certificate

- A root CA's public key is also stored in an X.509 certificate. It is self-signed.
- Self-signed: the entries for the issuer and the subject are identical.

Same

```
Issuer: C=US, O=VeriSign, Inc., OU=VeriSign Trust Network,
    OU=(c) 2006 VeriSign, Inc. - For authorized use only,
    CN=VeriSign Class 3 Public Primary Certification Authority - G5
Subject: C=US, O=VeriSign, Inc., OU=VeriSign Trust Network,
    OU=(c) 2006 VeriSign, Inc. - For authorized use only,
    CN=VeriSign Class 3 Public Primary Certification Authority - G5
```

- How can they be trusted?
  - Public keys of root CAs are pre-installed in the OS, browsers and other software

Intermediate CAs and Chain of Trust

```
$ openssl s_client -showcerts -connect www.paypal.com:443

Certificate chain
 0 s: ... /CN=www.paypal.com
   i: ... /CN=Symantec Class 3 EV SSL CA - G3
-----BEGIN CERTIFICATE-----
MIIHWTCCBkGgAwIBAgIQLNGVEFQ30N5KOSAFavbCfzANBgkqhkiG9w0BAQsFADB3
...
-----END CERTIFICATE-----
 1 s: ... /CN=Symantec Class 3 EV SSL CA - G3
   i: ... /CN=VeriSign Class 3 Public Primary Certification
              Authority - G5
-----BEGIN CERTIFICATE-----
MIIFKzCCBBOgAwIBAgIQfuFKb2/v8tN/P61lTTratDANBgkqhkiG9w0BAQsFADCB
...
-----END CERTIFICATE-----
```

Paypal's certificate

Intermediate CA's certificate

B

A

A is used to verify B

Something else is need to verify A (certificate from another intermediate CA or root CA)

Manually Verifying a Certificate Chain

- Paypal.pem: Save Paypal's certificate to a file called
- Symatec-g3.pem: Save certificate from "Symantec Class 3 EV SSL CA – G3"
- VeriSign-G5.pem: Save the VeriSign-G5's certificate from the browser

Root CA's certificate

```
$ openssl verify -verbose -CAfile VeriSign-G5.pem
                          -untrusted Symantec-G3.pem Paypal.pem
Paypal.pem: OK
```

Chain of certificates

Creating Certificates for Intermediate CA

- When generating a certificate for an intermediate CA, we need to do something special:

```
$ openssl ca -in modelIntCA.csr -out modelIntCA_cert.pem -md sha256
             -cert modelCA_cert.pem -keyfile modelCA_key.pem
        -extensions v3_ca
```

- The extension field of the certificate will look as follows:

```
X509v3 extensions:
  X509v3 Basic Constraints:
      CA:TRUE
```

TRUE means the certificate can be used verify other certificates, i.e, the owner is a CA. For non-CA certificates, this field is FALSE.

Apache Setup

- A server has a responsibility to send out all the intermediate CA's certificates needed for verifying its own certificate.
- In Apache, all certificates including those from Intermediate CAs are put inside the certificate file listed in the directive.

```
<VirtualHost *:443>
    ServerName example.com
    DocumentRoot /var/www/Example
    DirectoryIndex index.html

    SSLEngine On
    SSLCertificateFile      /etc/apache2/ssl/bank_cert2.pem
    SSLCertificateKeyFile   /etc/apache2/ssl/bank_key.pem
    SSLCertificateChainFile /etc/apache2/ssl/modelIntCA_cert.pem
</VirtualHost>
```

Trusted CAs in the Real World

- Not all of the trusted CAs are present in all browsers.
- According to W3Techs in April 2017, Comodo takes most of the market share followed by IdenTrust, Symantec Group, GoDaddy Group, GlobalSign and DigiCert.
- The list of trusted CAs supported by browser can be found:
  - **For the Chrome browser:**
    - Settings -> Show advanced settings -> Manage Certificates
  - **For the Firefox browser:**
    - Edit -> Preferences -> Advanced -> Certificates -> View Certificates -> Certificate Manager -> Authorities

How PKI Defeats the MITM Attack

- Assume that Alice wants to visit `https://example.com`
- When the server sends its public key to Alice, an attacker intercepts the communication. The attacker can do the following things:
    - Attacker forwards the authentic certificate from example.com
    - Attacker creates a fake certificate
    - Attacker sends his/her own certificate to Alice

Attacker Forwards the Authentic Certificate

- Attacker (Mike) forwards the authentic certificate
- Alice sends to the server a secret, encrypted using the public key.
- The secret is used for establishing an encrypted channel between Alice and server
- Mike doesn’t know the corresponding private key, so he cannot find the secret.
- Mike can’t do much to the communication, except for DoS.
- **MITM attack fails**.

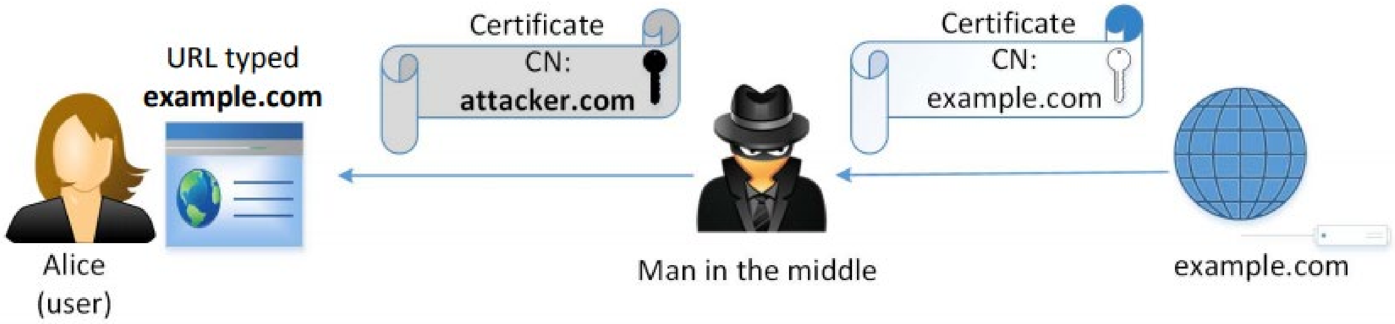
Attacker Creates a Fake Certificate

- Attacker (Mike) creates fraudulent certificate for the example.com domain.
- Mike replaces the server’s public with his own public key.
- Trusted CAs will not sign Mike’s certificate request as he does not own example.com.
- Mike can sign the fraudulent certificate by himself and create a self-signed certificate.
- Alice’s browser will not find any trusted certificate to verify the received certificate and will give the following warning:

```
example.com uses an invalid security certificate.
The certificate is not trusted because it is self-signed.
```

- **MITM attack fails** if the user decide to terminate the connection

Attacker Sends His/Her Own Certificate



- Attacker’s certificate is valid.
- Browser checks if the identity specified in the subject field of the certificate matches the Alice’s intent.
  - There is a mismatch: attacker.com ≠ example.com
- Browser terminates handshake protocol: **MITM fails**

Emulating an MITM Attack

- DNS Attack is a typical approach to achieve MITM
  - We emulate an DNS attack by manually changing the /etc/hosts file on the user's machine to map example.com to the IP address of the attacker's machine.
- On attacker's machine we host a website for example.com.
  - We use the attacker's X.509 certificate to set up the server
  - The Common name field of the certificate contains attacker32.com
- When we visit example.com, we get an error message:

```
example.com uses an invalid security certificate.
The certificate is only valid for attacker32.com
(Error code: ssl_error_bad_cert_domain)
```

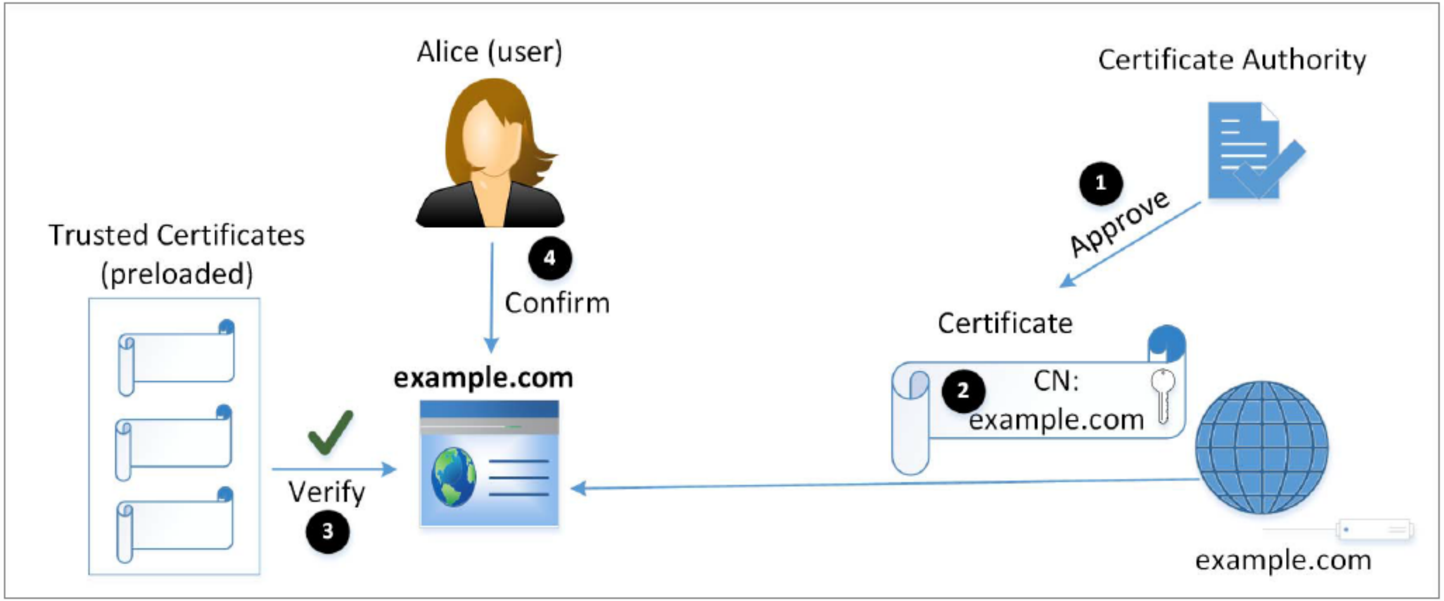
The Importance of Verifying Common Name

- During TLS/SSL handshake browsers conduct two important validations
  1) Checks whether the received certificate is valid or not.
  2) Verifies whether the subject (Common Names) in the certificate is the same as the hostname of the server.
- Not verifying the common name is a common mistake in software

The Man-In-The-Middle Proxy

- Proxy creates a self-signed CA certificate, which is installed on the user's browser
- The routing on the user machine is configured; all outgoing HTTPS traffic is directed towards the proxy machine
- When user tries to visit an HTTPS site:
  - Proxy intercepts communication
  - Creates a fake certificate
  - Browser already has the proxy's certificate in its trusted list to be able to verify all the fake certificates
  - Proxy becomes MITM

Attacks Surfaces on PKI



Attack on CA’s Verification Process

- CA’s job has two parts:
  - Verify the relationship between certificate applicant and the subject information inside the certificate
  - Put a digital signature on the certificate
- **Case study: Comodo Breach [March 2011]**
  - Popular root CA.
  - The approval process in Southern Europe was compromised.
  - Nine certificates were issued to seven domains and hence the attacker could provide false attestation.
  - One of the affected domain (a key domain for the Firefox browser): `addons.mozilla.org`

Attack on CA’s Signing Process

- If the CA’s private key is compromised, attackers can sign a certificate with any arbitrary data in the subject field.

- **Case Study: the DigiNotar Breach [June-July 2011]**
  - A top commercial CA
  - Attacker got DigiNotar’s private key
  - 531 rogue certificates were issued.
  - Traffic intended for Google subdomains was intercepted: MITM attack.

- How CAs Protect Their Private Key
  - Hardware Security Model (HSM)

Attacks on Algorithms

- Digital Certificates depend on two types of algorithms
  - one-way hash function and digital signature
- **Case Study: the Collision-Resistant Property of One-Way Hash**
  - At CRYPTO2004, Xiaoyun Wang demonstrated collision attack against MD5.
  - In February 2017, Google Research announced SHAttered attack
    - Attack broke the collision-resistant property of SHA-1
    - Two different PDF files with the same SHA-1 has was created.
- Countermeasures: use stronger algorithm, e.g. SHA256.

Attacks on User Confirmation

- After verifying the certificate from the server, client software is sure that the certificate is valid and authentic
- In addition, the software needs to confirm that the server is what the user intends to interact with.
- Confirmation involves two pieces of information
  - Information provided or approved by user
  - The common name field inside the server’s certificate
  - Some software does not compare these two pieces of information: security flaw

Attacks on Confirmation: Case Study

Phishing Attack on Common Name with Unicode

- Zheng found out several browsers do not display the domain name correctly if name contains Unicode.
- `xn–80ak6aa92e.com` is encoded using Cyrillic characters. But domain name displayed by browser likes like `apple.com`
- Attack:
  - Get a certificate for `xn–80ak6aa92e.com`
  - Get user to visit `xn–80ak6aa92e.com`, so the common name is matched
  - User’s browser shows that the website is apple.com. **User can be fooled**.
- Had the browser told the user that the actual domain is not the real apple.com, the user would stop.

Types of Digital Certificate

- Domain Validated Certificates (DV)
- Organizational Validated Certificates (OV)
- Extended Validated Certificates (EV)

Domain Validated Certificates (DV)

- Most popular type of certificate.
- The CA verifies the domain records to check if the domain belongs to applicant.
- Domain Control Validation (DCV) is performed on domain name in the certificate request.
- DCV uses information in the WHOIS database
- DCV is conducted via
  - Email
  - HTTP
  - DNS

Organizational Validated Certificates (OV)

- Not very popular type of certificate.
- CAs verify the following before issuing OV certificates:
  - Domain control validation.
  - Applicant’s identity and address.
  - Applicant’s link to organization.
  - Organization’s address.
  - Organization’s WHOIS record.
  - Callback on organization’s verified telephone number.

Extended Validated Certificates (EV)

- CAs issuing EV certificates require documents that are legally signed from registration authorities.
- EV CA validate the following information:
  - Domain control validation.
  - Verify the identity, authority, signature and link of the individual.
  - Verify the organization's physical address and telephone number.
  - Verify the operational existence.
  - Verify the legal and proper standings of the organization.
- EV certificate, hence, costs higher but is trustworthy.

How Browsers Display Certificate Types

Chrome browser

Cannot be verified	Not secure | ~~https~~://test-sspev.verisign.com:2443/test-SSPEV-revoked-verisign.html
DV/OV Certificate	Secure | https://www.microsoft.com/en-us/
EV Certificate	PayPal, Inc. [US] | https://www.paypal.com/us/home

Firefox browser

Cannot be verified	https://test-sspev.verisign.com:2443/test-SSPEV-revoked-verisign.html
DV/OV Certificate	https://www.microsoft.com/en-us/
EV Certificate	PayPal, Inc. (US) | https://www.paypal.com/us/home

Transport Layer Security

Overview of TLS

- Transport Layer Security (TLS) is a protocol that provides a secure channel between two communicating applications. The secure channel has 3 properties:
  - Confidentiality: Nobody other than the two ends of the channel can see the actual content of the data transmitted.
  - Integrity: Channel can detect any changes made to the data during transmission
  - Authentication: At least one end of the channel needs to be authenticated, so the other end knows who it is talking to.

TLS Layer

- TLS sits between the Transport and Application layer
  - Unprotected data is given to TLS by Application layer
  - TLS handles encryption, decryption and integrity checks
  - TLS gives protected data to Transport layer

Application Layer
TLS Layer
Transport Layer (TCP Protocol)
Network Layer (IP protocol)
Data Link Layer
Physical Layer

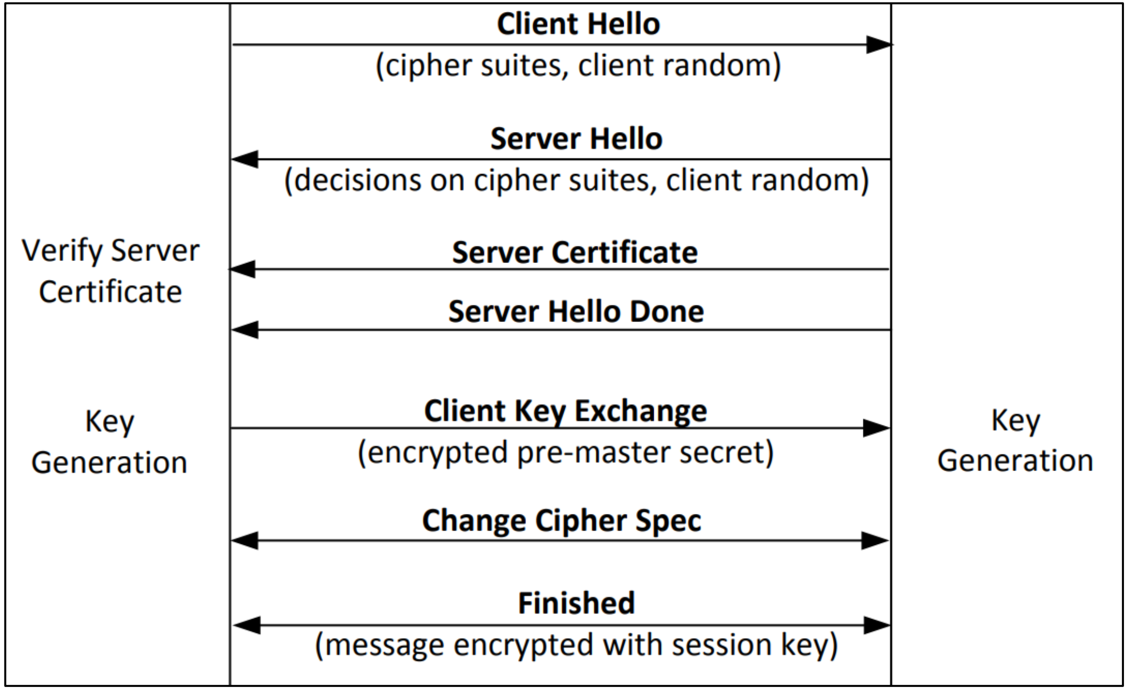
TLS Handshake

- Before a client and server can communicate securely, several things need to be set up first:
  - Encryption algorithm and key
  - MAC algorithm
  - Algorithm for key exchange

- These cryptographic parameters need to be agreed upon by the client and server

- This is the primary purpose of the handshake protocol

TLS Handshake Protocol



Network Traffics During TLS Handshake

Since TLS runs top of TCP, a TCP connection needs to be established before the handshake protocol. This is how the packet exchange looks between a client and server during a TLS handshake protocol captured using Wireshark:

No.	Source	Destination	Protocol	Info
1	10.0.2.45	10.0.2.35	TCP	59930 –> 11110 [SYN] Seq=0 Win=14600 Len=0 MSS=1460...
2	10.0.2.35	10.0.2.45	TCP	11110 –> 59930 [SYN, ACK] Seq=0 Ack=1 Win=14480...
3	10.0.2.45	10.0.2.35	TCP	59930 –> 11110 [ACK] Seq=1 Ack=1 Win=14720 Len=0...
4	10.0.2.45	10.0.2.35	TLSv1.2	Client Hello
6	10.0.2.35	10.0.2.45	TLSv1.2	Server Hello, Certificate, Server Hello Done
8	10.0.2.45	10.0.2.35	TLSv1.2	Client Key Exchange, Change Cipher Spec, Finished
9	10.0.2.35	10.0.2.45	TLSv1.2	New Session Ticket, Change Cipher Spec, Finished