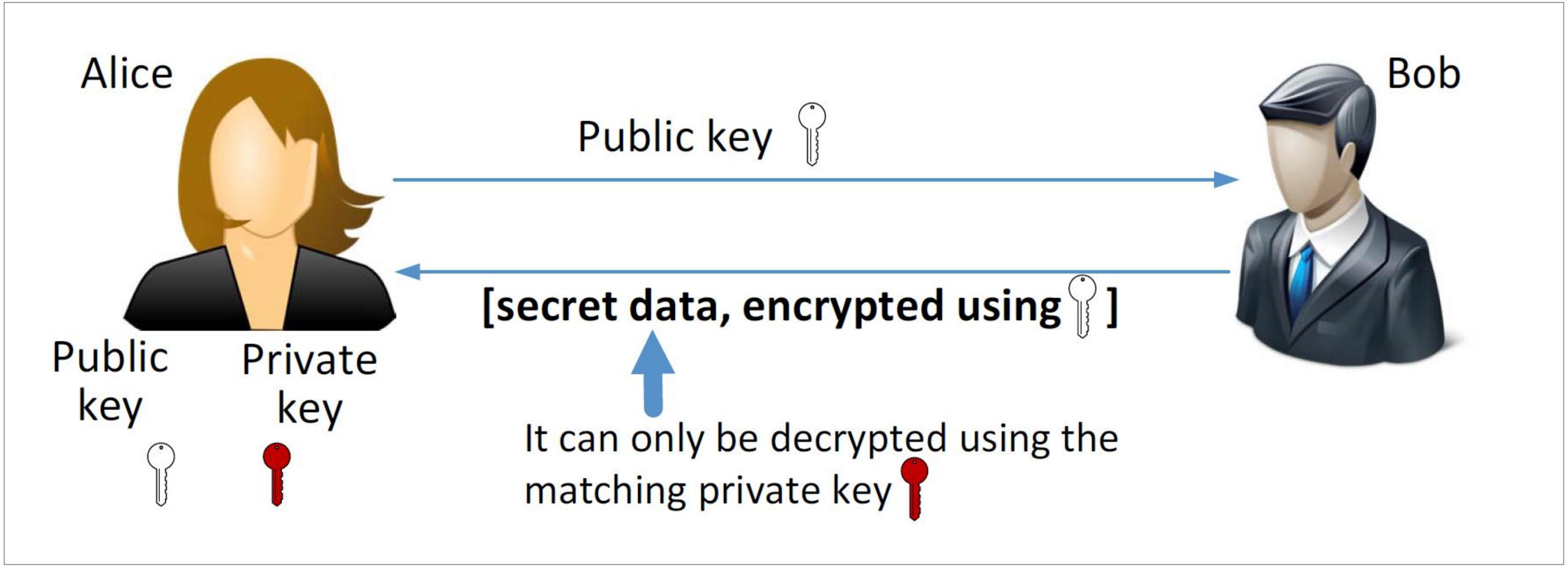
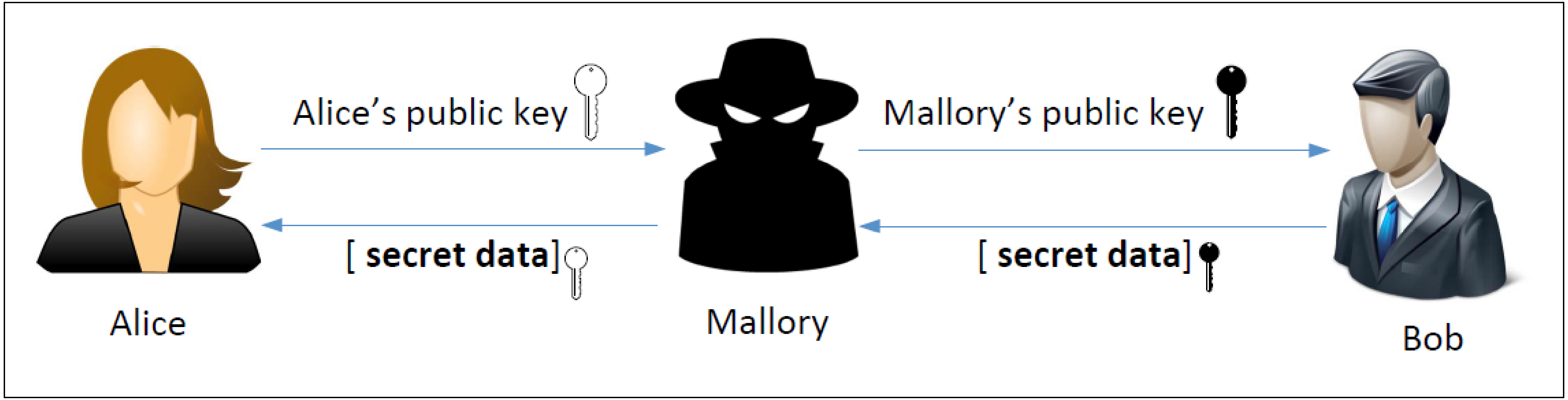
Public Key Infrastructure

Public Key Cryptography



Man-in-the-Middle (MITM) Attack



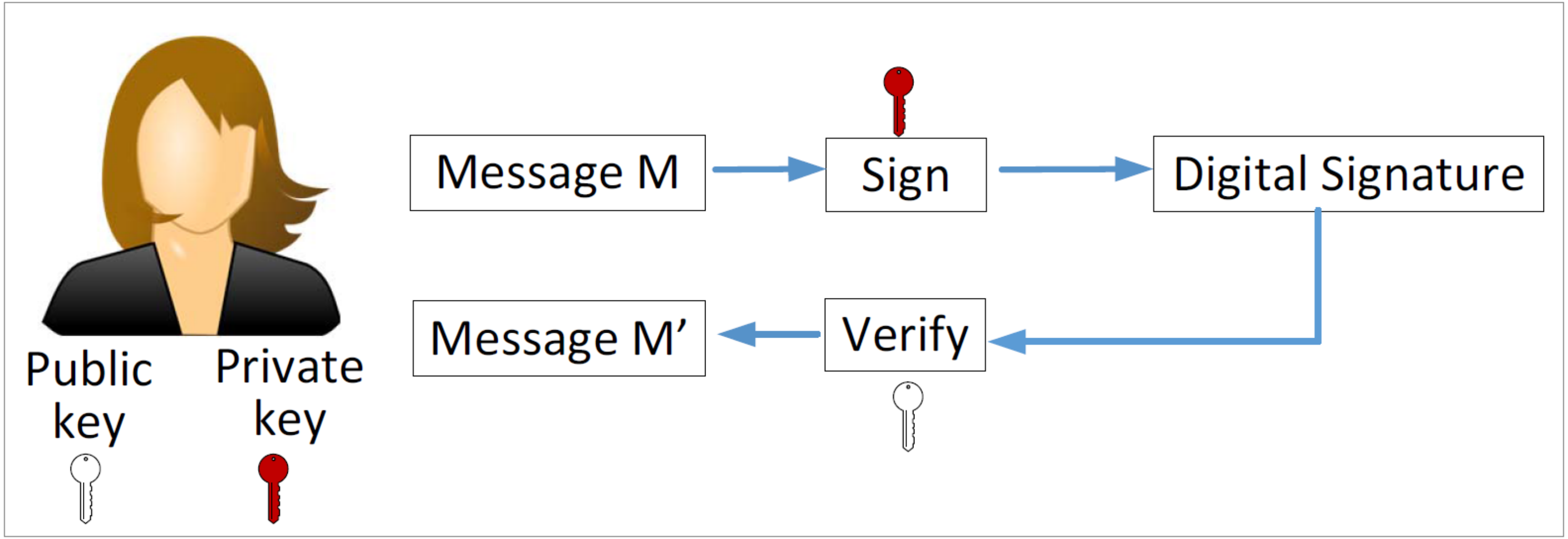
What Is the Fundamental Problem?

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

CA's signature

```
 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)
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**

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

RSA key size

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>
```

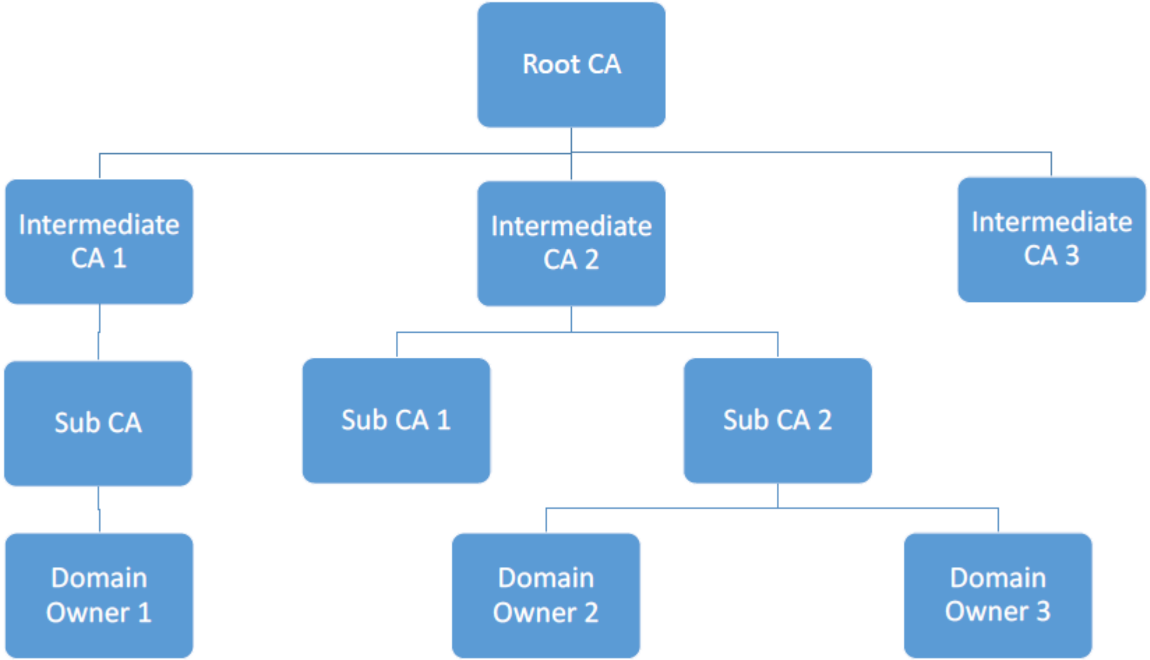
The server's certificate

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 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 bank32.com
    DocumentRoot /var/www/html
    DirectoryIndex index.html

    SSLEngine On
    SSLCertificateFile      /home/seed/cert/bank_cert2.pem
    SSLCertificateKeyFile   /home/seed/cert/bank_key.pem
</VirtualHost>
```

Restart Apache

```
// Test the Apache configuration file for errors.
$ sudo apachectl configtest
// Enable SSL
$ sudo a2enmod ssl
// Enable the sites specified in default-ssl
$ sudo a2ensite default-ssl
// Restart Apache
$ sudo service apache2 restart
```

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.**

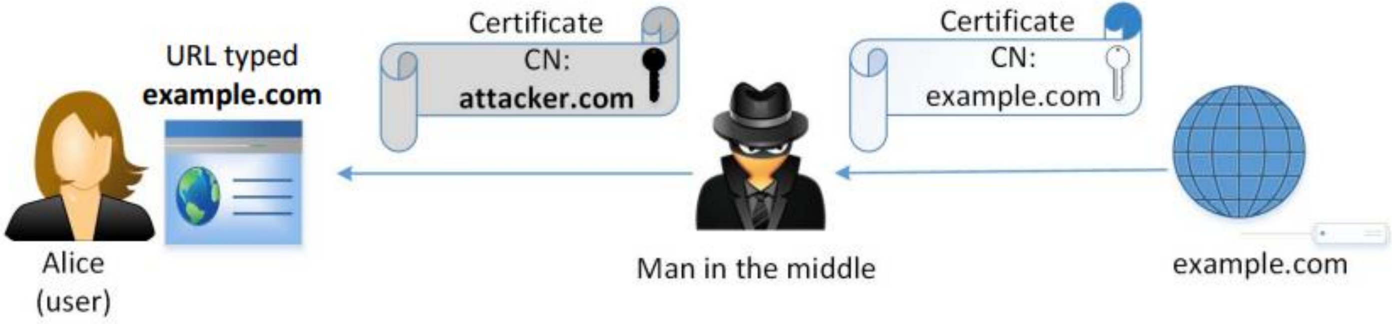
Attacker Creates a Fake Certificate

- **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)
```

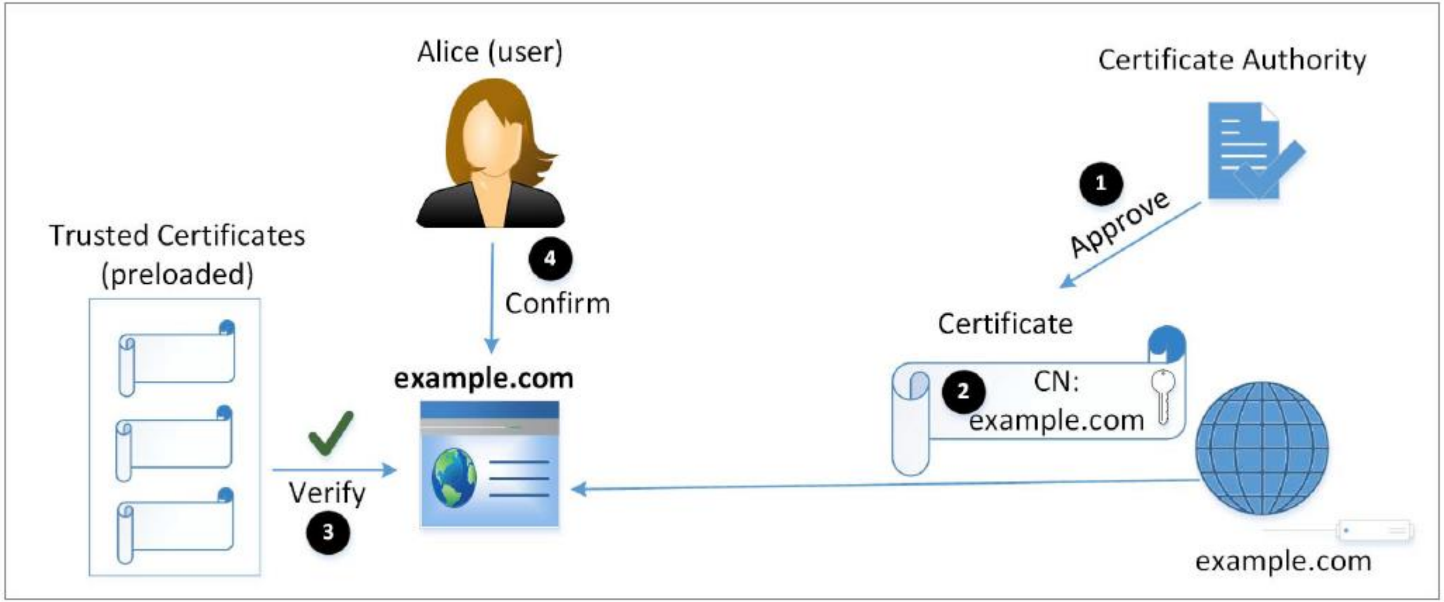
The Importance of Verifying Common Name

- **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 DiigiNotar 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

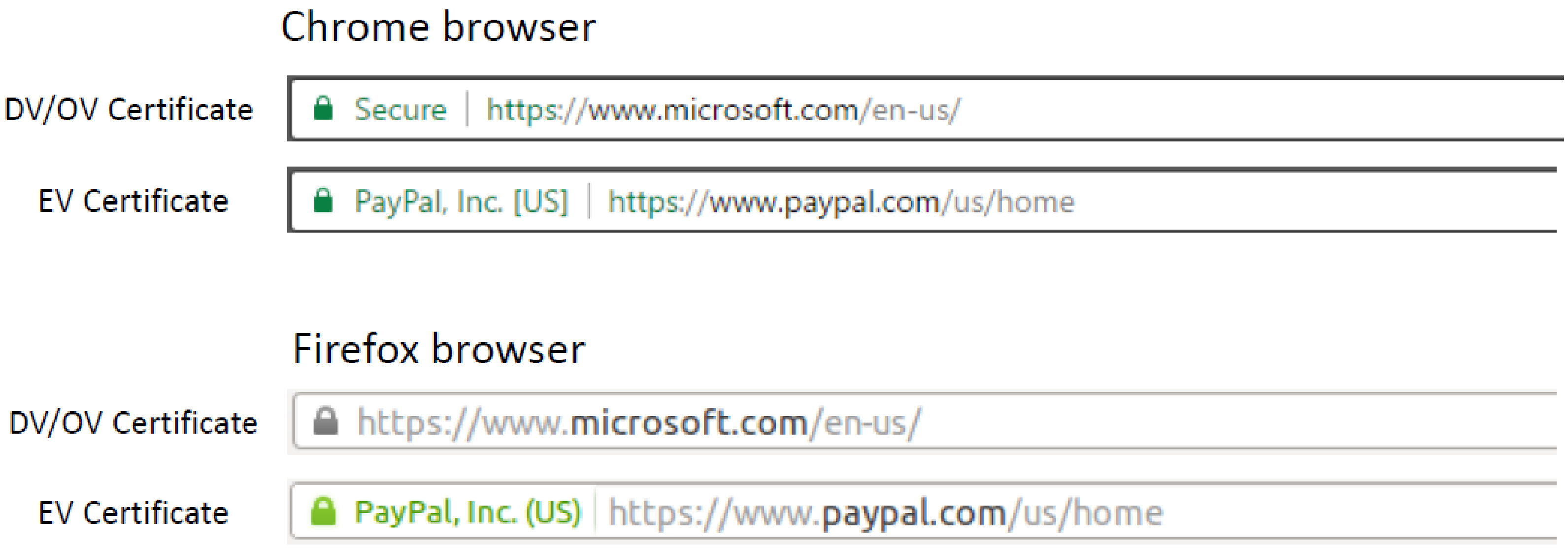
Organizational Validated Certificates (OV)

- 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



Summary

- MITM attacks on public key cryptography
- Public-Key Infrastructure
- X.509 digital certificate
- Certificate Authority and how CA signs certificate
- How PKI defeats MITM attacks
- Attacks on PKI
- Different types of digital certificate