Lecture 25: Security Authentication, TLS/SSL

COMP 332, Spring 2023

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Acknowledgements: materials adapted from Computer Networking: A Top Down Approach 7th edition: ©1996-2016, J.F Kurose and K.W. Ross, All Rights Reserved as well as from slides by Abraham Matta at Boston University, and some material from Computer Networks by Tannenbaum and Wetherall.

Today

1. Announcements
   - Homework 9 due Wednesday, May 10 at 11:59p (no written)

2. Network security
   - authentication
   - message integrity

3. Transport layer security
   - overview
   - toy TLS
   - real TLS

What is network security?

Goal: enable secure communication over insecure channel

Confidentiality

- only sender, intended receiver understand message contents
  - sender encrypts message
  - receiver decrypts message
- use cryptography: public/private key vs symmetric key

Authentication

- sender, receiver want to confirm identity of each other
- use nonce to confirm liveness, Certificate Authority to confirm identity

Message integrity

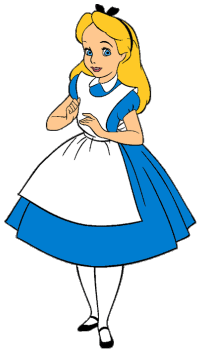
- sender, receiver want to ensure message not altered (in transit, or afterwards) without detection

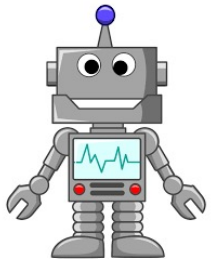
Network Security

AUTHENTICATION

Recall: ap5.0 man-in-the-middle attack

Trudy poses as Alice (to Bob) and as Bob (to Alice)





I am Alice

I am Alice

Nonce

Nonce

$K_A^-(\text{Nonce})$

$K_T^-(\text{Nonce})$

Send me your public key

Send me your public key

K_A^+

K_T^+

$K_A^+(m)$

$K_T^+(m)$

$m = K_A^-(K_A^+(m))$

$m = K_T^-(K_T^+(m))$

sends m to Alice encrypted with Alice's public key

Distinguishing Alice's vs. Trudy's public key

Use certification authority (CA)

- binds public key to particular entity
  - e.g., Alice, Bob, website, …
- 100s of certification authorities

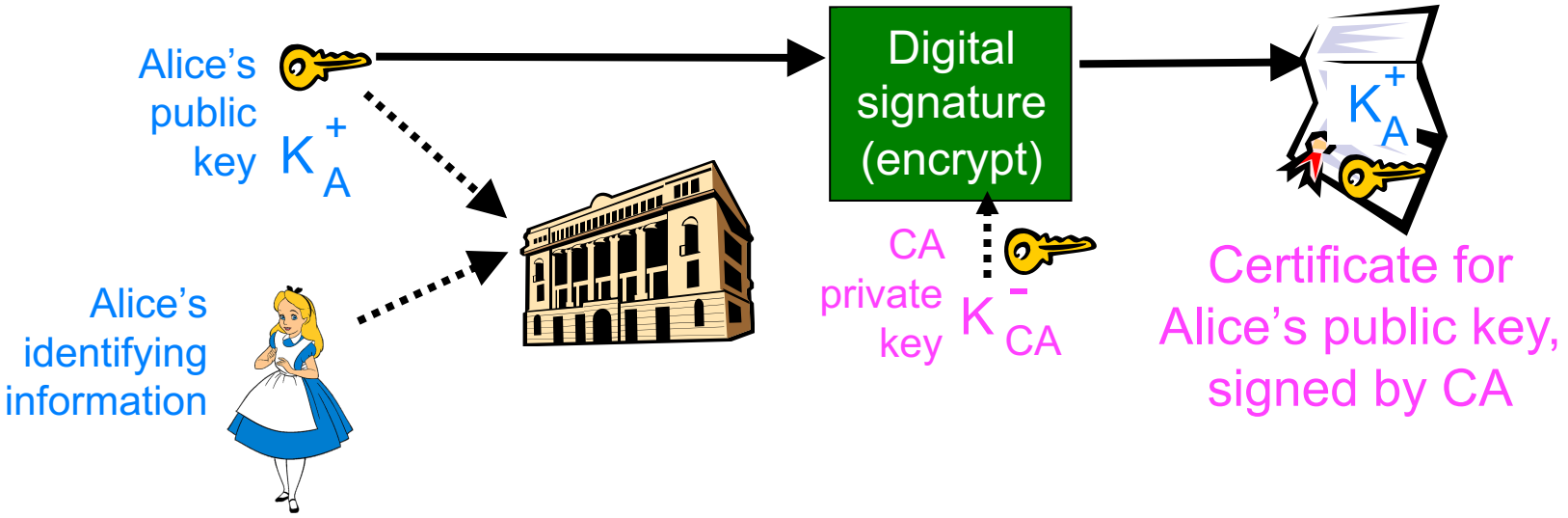
Aside

- CAs are critical but potentially weak link …

How certification authorities work

Alice registers her public key with CA

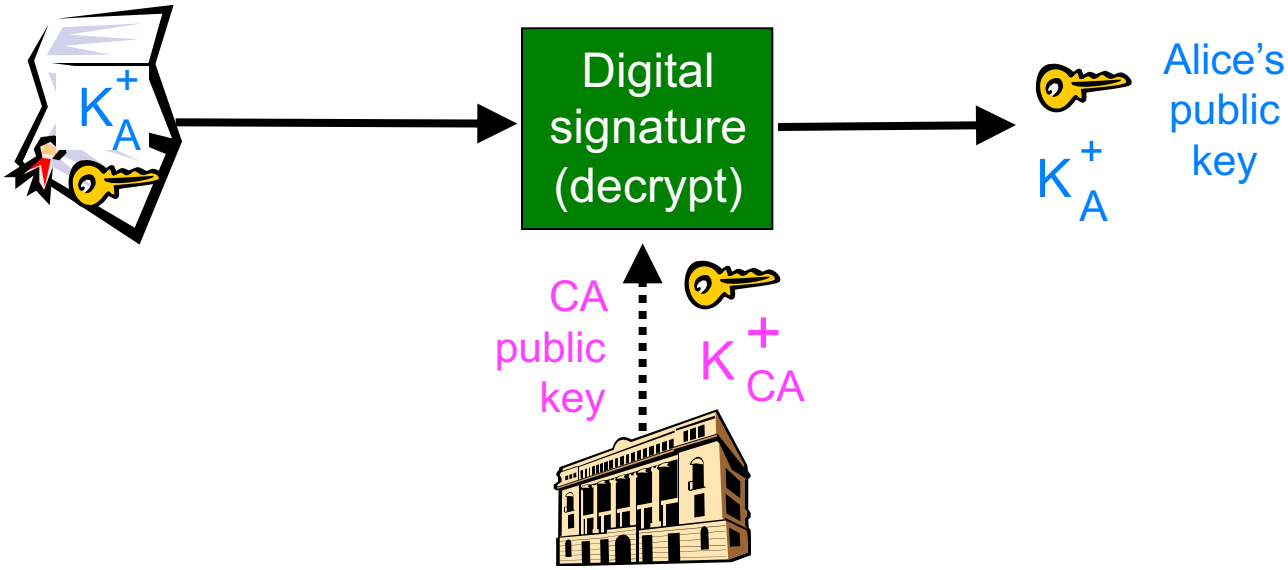
- Alice provides proof of identity to CA
- CA creates certificate binding Alice to its public key
  - certificate digitally signed by CA



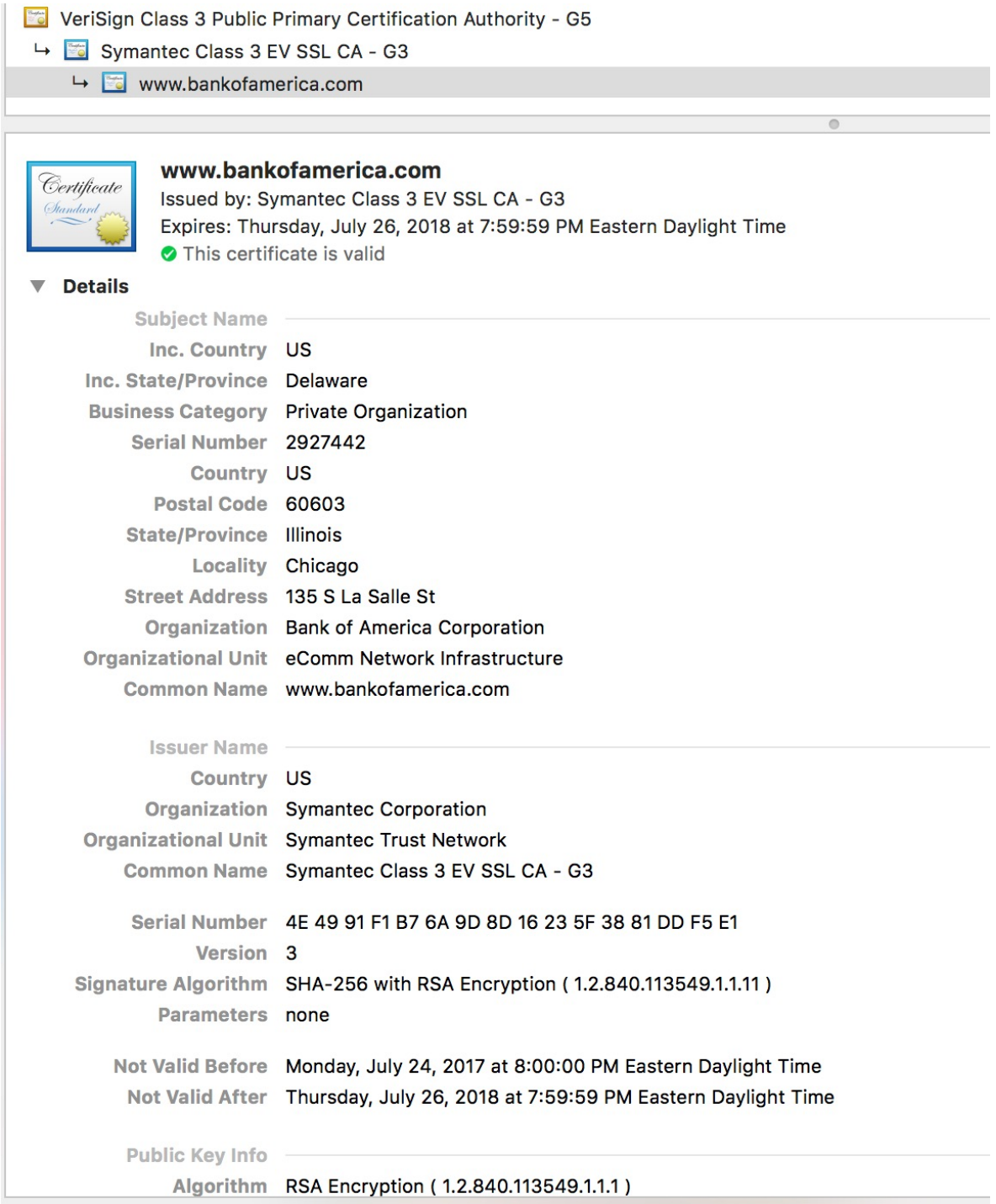
Certification authorities

When Bob wants Alice's public key

1. gets Alice's certificate from Alice or elsewhere
2. applies CA's public key to Alice's certificate
3. gets Alice's public key



Example


VeriSign Class 3 Public Primary Certification Authority - G5
Symantec Class 3 EV SSL CA - G3
www.bankofamerica.com
www.bankofamerica.com
Issued by: Symantec Class 3 EV SSL CA - G3
Expires: Thursday, July 26, 2018 at 7:59:59 PM Eastern Daylight Time
This certificate is valid
Details
Subject Name
Inc. Country US
Inc. State/Province Delaware
Business Category Private Organization
Serial Number 2927442
Country US
Postal Code 60603
State/Province Illinois
Locality Chicago
Street Address 135 S La Salle St
Organization Bank of America Corporation
Organizational Unit eComm Network Infrastructure
Common Name www.bankofamerica.com
Issuer Name
Country US
Organization Symantec Corporation
Organizational Unit Symantec Trust Network
Common Name Symantec Class 3 EV SSL CA - G3
Serial Number 4E 49 91 F1 B7 6A 9D 8D 16 23 5F 38 81 DD F5 E1
Version 3
Signature Algorithm SHA-256 with RSA Encryption (1.2.840.113549.1.1.11)
Parameters none
Not Valid Before Monday, July 24, 2017 at 8:00:00 PM Eastern Daylight Time
Not Valid After Thursday, July 26, 2018 at 7:59:59 PM Eastern Daylight Time
Public Key Info
Algorithm RSA Encryption (1.2.840.113549.1.1.1)

Network Security

MESSAGE INTEGRITY

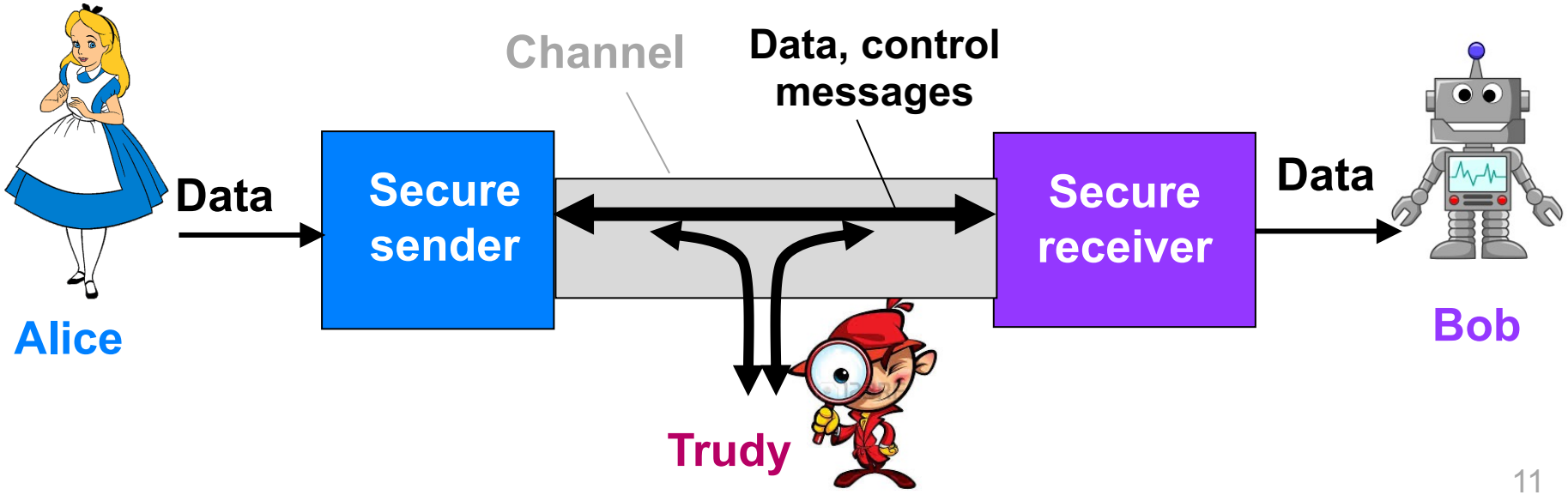
Message integrity

Alice and Bob must be able to detect whether msg changed

1. verify msg originated from Alice
2. verify msg not tampered with on way to Bob

Solution

– digital signatures: cryptographic technique like hand-written signature



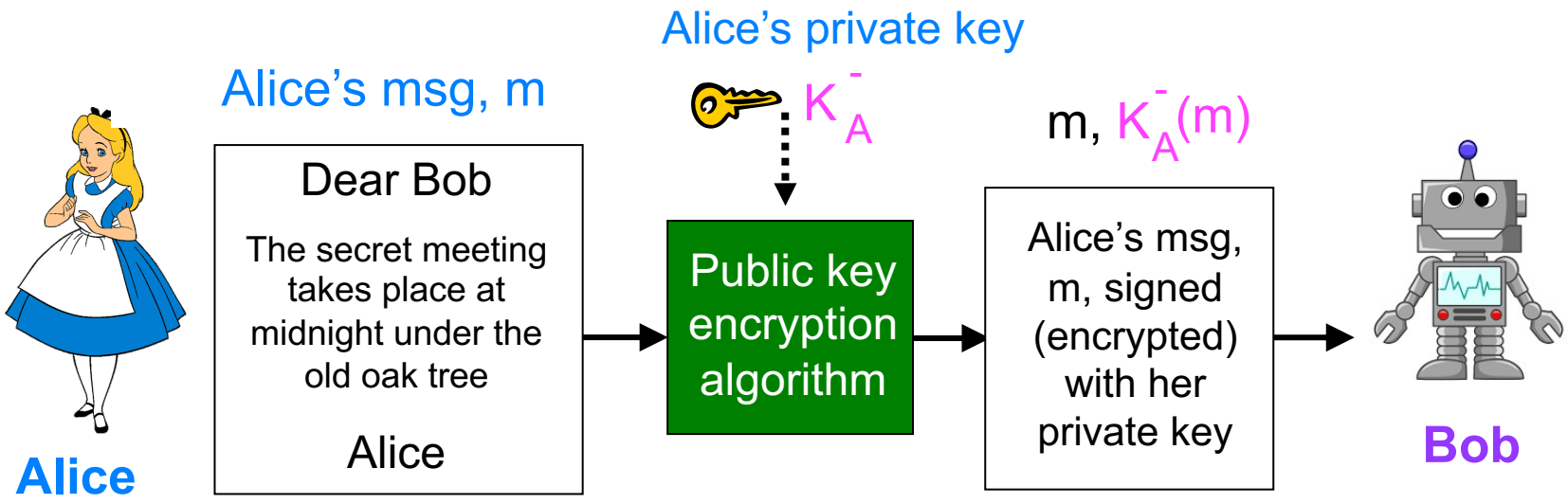
Simple digital signature for message, m

Sender (Alice)

- encrypts msg m with her private key K_A^- to create signed message, $K_A^-(m)$
- proves she is owner/creator

Recipient (Bob)

- applies Alice's public key K_A^+ to $K_A^-(m)$
- if $K_A^+(K_A^-(m)) = m$ whoever signed m was Alice or has Alice's private key



Problem for digital signatures

Public key cryptography is expensive

- more expensive the longer the message is
- Why?

Solution

- sign digital ``fingerprint" of msg rather than msg itself

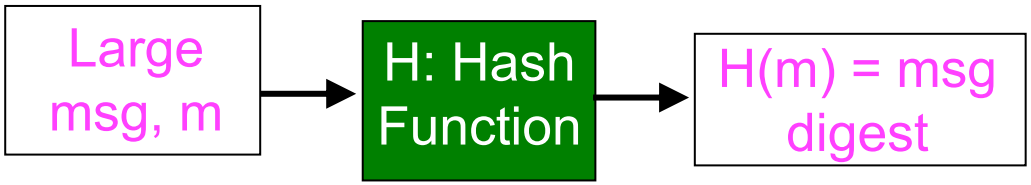
Message digest

Message digest

Desired features are what hash function gives

- fixed-length
- easy-to-compute
- 2 msgs unlikely to have same digest

Apply hash function H to m



Hash function properties

- many-to-1 function
- produces fixed-size msg digest, H(m)
- given message digest H(m), computationally infeasible to find m' such that H(m) = H(m')

Some hash function standards

MD5 hash function (RFC 1321)

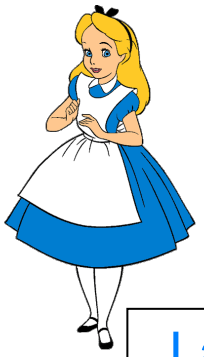
- computes 128-bit message digest in 4-step process.
- "cryptographically broken and unsuitable for further use"
  - CMU Software engineering Institute

SHA-1

- 160-bit message digest
- many vulnerabilities, browsers will no longer use/accept

SHA-2, SHA-3

Use signed message digest as digital signature



Alice sends digitally signed message

Large msg,m

H: Hash function

H(m)

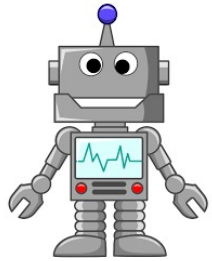
Alice's private key K_A^-

Digital signature (encrypt)

Encrypted msg digest $K_A^-(H(m))$

+

Bob verifies signature, integrity of digitally signed msg



Encrypted msg digest $K_A^-(H(m))$

Large msg, m

Alice's public key K_A^+

Digital signature (decrypt)

H: Hash function

H(m)

H(m)

equal ?

Transport Layer Security

OVERVIEW

TLS aka SSL

Secures data at and above transport layer

- provides confidentiality, integrity, authentication
- SSL: Secure Sockets Layer, predecessor to TLS
- TLS: Transport Layer Security

Available to all TCP applications

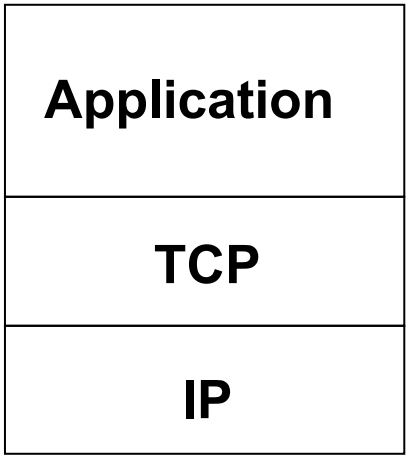
- first setup TCP connection, then run TLS as application

Widely deployed

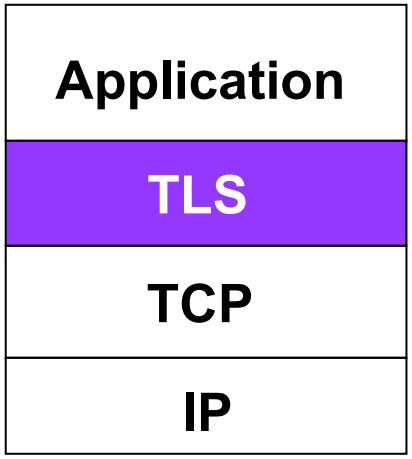
- supported by almost all browsers, web servers
- billions $/year over SSL
- HTTP + SSL = HTTPS

Where TLS sits in Internet stack

TLS provides application programming interface to apps



Normal application



Application with TLS

Very likely your operating system using open source library

- https://www.openssl.org/
- https://firefox-source-docs.mozilla.org/security/nss/index.html

TLS goals

Send byte streams & interactive data

- why?

Want set of secret keys for entire connection

- why?

Want certificate exchange as part of protocol handshake phase

- why?

Transport Layer Security

TOY TLS

A simple secure channel

Handshake

- Alice and Bob use their certificates, private keys to authenticate each other and exchange shared secret

Key derivation

- Alice and Bob use shared secret to derive set of keys

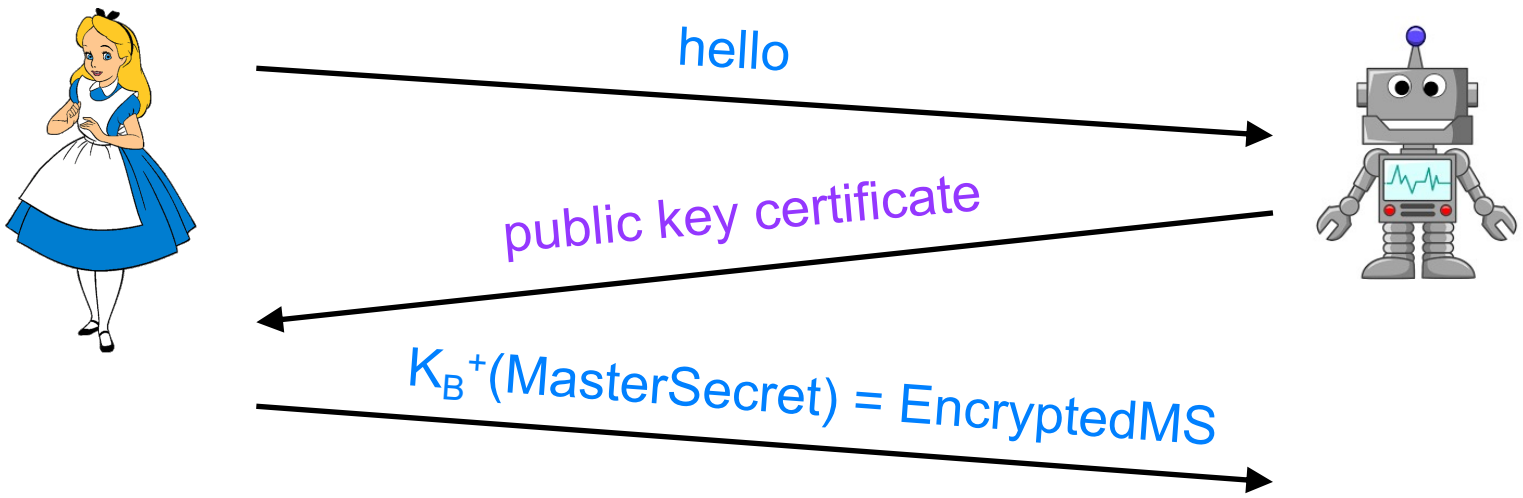
Data transfer

- data to be transferred is broken up into series of records

Connection closure

- special messages to securely close connection

A simple handshake



Derive keys from master secret

- use key derivation function (KDF)
  - takes master secret and additional random data and creates keys

Key derivation

Don't use same key for more than one cryptographic operation

- keys for message authentication code (MAC): like hash
- keys for encryption

Encryption keys

- K_c = encryption key for data sent from client to server
- K_s = encryption key for data sent from server to client

MAC keys

- M_c = MAC key for data sent from client to server
- M_s = MAC key for data sent from server to client

Data records

Why not encrypt data in constant stream as we write it to TCP?

- where to put MAC?
  - if at end, no message integrity until all data processed
- e.g., instant messaging
  - how can we do integrity check over all bytes sent before displaying?

Solution: break stream in series of records

- each record carries MAC
- receiver can act on each record as it arrives

More attacks

What if attacker replays or re-orders records?

- Solution: put sequence # into MAC (no seq # field)
- MAC = MAC(M_x, sequence || data)

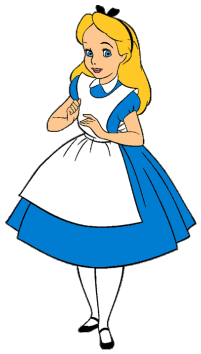
What if attacker replays all records?

- Solution: use nonce

What if attacker forges TCP connection close?

- Solution: have record types, with one type for closure
  - type 0 for data
  - type 1 for closure
- MAC = MAC(M_x, sequence || type || data)

Summary



hello

certificate, nonce

K_B^+(MasterSecret) = EncryptedMS

type 0, seq 1, data

type 0, seq 2, data

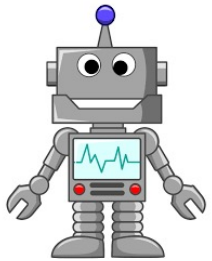
type 0, seq 1, data

type 0, seq 3, data

type 1, seq 4, close

type 1, seq 2, close

Encrypted



bob.com

Transport Layer Security

REAL TLS

Toy TLS is incomplete

How long are fields? Which encryption protocols? How do client and server negotiate encryption algorithms?

TLS Handshake

- confidentiality
  - client and server negotiate encryption algorithms before data transfer
    - i.e., negotiate ciphersuite
  - derive keys used in data exchange
- integrity
  - check if handshake tampered with based on hash of handshake msgs
- authentication
  - using public key and server's certificate
  - optional client authentication

TLS cipher suite

Negotiation: client, server agree on cipher suite

- client offers choice server picks one

TLS_RSA_WITH_3DES_EDE_CBC_SHA

Key exchange algorithm: public-key

Symmetric encryption algorithm: block cipher to encrypt msg stream

MAC algorithm

Which ciphersuites are supported depends on TLS version

- TLS 1.2 supports many cipher suites
- TLS 1.3 supports many fewer cipher suites

Cipher suites

```
▼ TLSv1 Record Layer: Handshake Protocol: Client Hello
    Content Type: Handshake (22)
    Version: TLS 1.0 (0x0301)
    Length: 144
  ▼ Handshake Protocol: Client Hello
      Handshake Type: Client Hello (1)
      Length: 140
      Version: TLS 1.0 (0x0301)
    ▶ Random: 5ae5dac626d5483a3ea908c593979d44170f3e628f26688d...
      Session ID Length: 32
      Session ID: e84d0000076240b35c57828829153be712af150acb327e17...
      Cipher Suites Length: 32
    ▼ Cipher Suites (16 suites)
        Cipher Suite: TLS_EMPTY_RENEGOTIATION_INFO_SCSV (0x00ff)
        Cipher Suite: TLS_ECDHE_ECDSA_WITH_AES_256_CBC_SHA384 (0xc024)
        Cipher Suite: TLS_ECDHE_ECDSA_WITH_AES_128_CBC_SHA256 (0xc023)
        Cipher Suite: TLS_ECDHE_ECDSA_WITH_AES_256_CBC_SHA (0xc00a)
        Cipher Suite: TLS_ECDHE_ECDSA_WITH_AES_128_CBC_SHA (0xc009)
        Cipher Suite: TLS_ECDHE_ECDSA_WITH_3DES_EDE_CBC_SHA (0xc008)
        Cipher Suite: TLS_ECDHE_RSA_WITH_AES_256_CBC_SHA384 (0xc028)
        Cipher Suite: TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA256 (0xc027)
        Cipher Suite: TLS_ECDHE_RSA_WITH_AES_256_CBC_SHA (0xc014)
        Cipher Suite: TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA (0xc013)
        Cipher Suite: TLS_ECDHE_RSA_WITH_3DES_EDE_CBC_SHA (0xc012)
        Cipher Suite: TLS_RSA_WITH_AES_256_CBC_SHA256 (0x003d)
        Cipher Suite: TLS_RSA_WITH_AES_128_CBC_SHA256 (0x003c)
        Cipher Suite: TLS_RSA_WITH_AES_256_CBC_SHA (0x0035)
        Cipher Suite: TLS_RSA_WITH_AES_128_CBC_SHA (0x002f)
        Cipher Suite: TLS_RSA_WITH_3DES_EDE_CBC_SHA (0x000a)
```

TLS Client Hello

```
▶ Frame 50: 203 bytes on wire (1624 bits), 203 bytes captured (1624 bits) on interface 0
▶ Ethernet II, Src: Apple_73:43:26 (78:4f:43:73:43:26), Dst: JuniperN_1e:18:01 (3c:8a:b0:1e:18:01
▶ Internet Protocol Version 4, Src: vmanfredismbp2.wireless.wesleyan.edu (129.133.187.174), Dst:
▶ Transmission Control Protocol, Src Port: 63173, Dst Port: 443, Seq: 41885059, Ack: 3555367379,
▼ Secure Sockets Layer
  ▼ TLSv1 Record Layer: Handshake Protocol: Client Hello
      Content Type: Handshake (22)
      Version: TLS 1.0 (0x0301)
      Length: 144
    ▼ Handshake Protocol: Client Hello
        Handshake Type: Client Hello (1)
        Length: 140
        Version: TLS 1.0 (0x0301)
      ▶ Random: 5ae5dac626d5483a3ea908c593979d44170f3e628f26688d...
        Session ID Length: 32
        Session ID: e84d0000076240b35c57828829153be712af150acb327e17...
        Cipher Suites Length: 32
      ▶ Cipher Suites (16 suites)
        Compression Methods Length: 1
      ▶ Compression Methods (1 method)
        Extensions Length: 35
      ▶ Extension: supported_groups (len=8)
      ▶ Extension: ec_point_formats (len=2)
      ▶ Extension: status_request (len=5)
      ▶ Extension: signed_certificate_timestamp (len=0)
      ▶ Extension: extended_master_secret (len=0)
```

TLS handshake

Alice

1. Client hello ➔
   client nonce, ciphersuites

3. Verifies certificate
   generates premaster secret

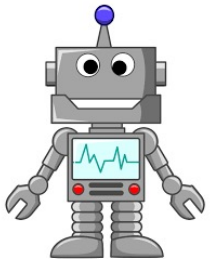
4. Premaster secret ➔
   encrypted with Bob's public key from certificate

6. Generate symmetric keys
   client nonce, server nonce, premaster, ciphersuite

8. Client hello done ➔
   MAC of all handshake msgs encrypted with client symmetric key

7. Encrypted data ➔

Bob



➔ 2. Server hello
   server nonce, chosen ciphersuite, RSA certificate

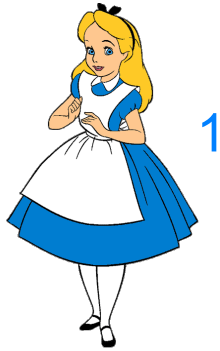
5. Generate symmetric keys
   client nonce, server nonce, premaster, ciphersuite

➔ 7. Server hello done
   MAC of all handshake msgs encrypted with server session keys

Protect handshake from tampering

➔ 8. Encrypted data

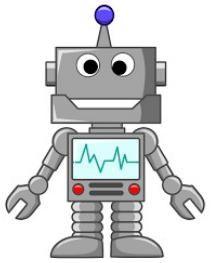
Why 2 random nonces?



Alice

1. Client hello ➔
client nonce, ciphersuites

Bob



➔ 2. Server hello
server nonce, chosen ciphersuite, RSA certificate

Suppose Trudy sniffs all messages between Alice & Bob

- next day, Trudy sets up TCP connection with Bob
  - replays sequence of records
  - Bob (Amazon) thinks Alice made two separate orders for same thing

Solution

- Bob sends different random nonce for each connection
  - causes encryption keys to be different on the 2 days
  - Trudy's messages will fail Bob's integrity check

Key derivation

Client nonce, server nonce, pre-master secret

- input into pseudo random-number generator to get master secret

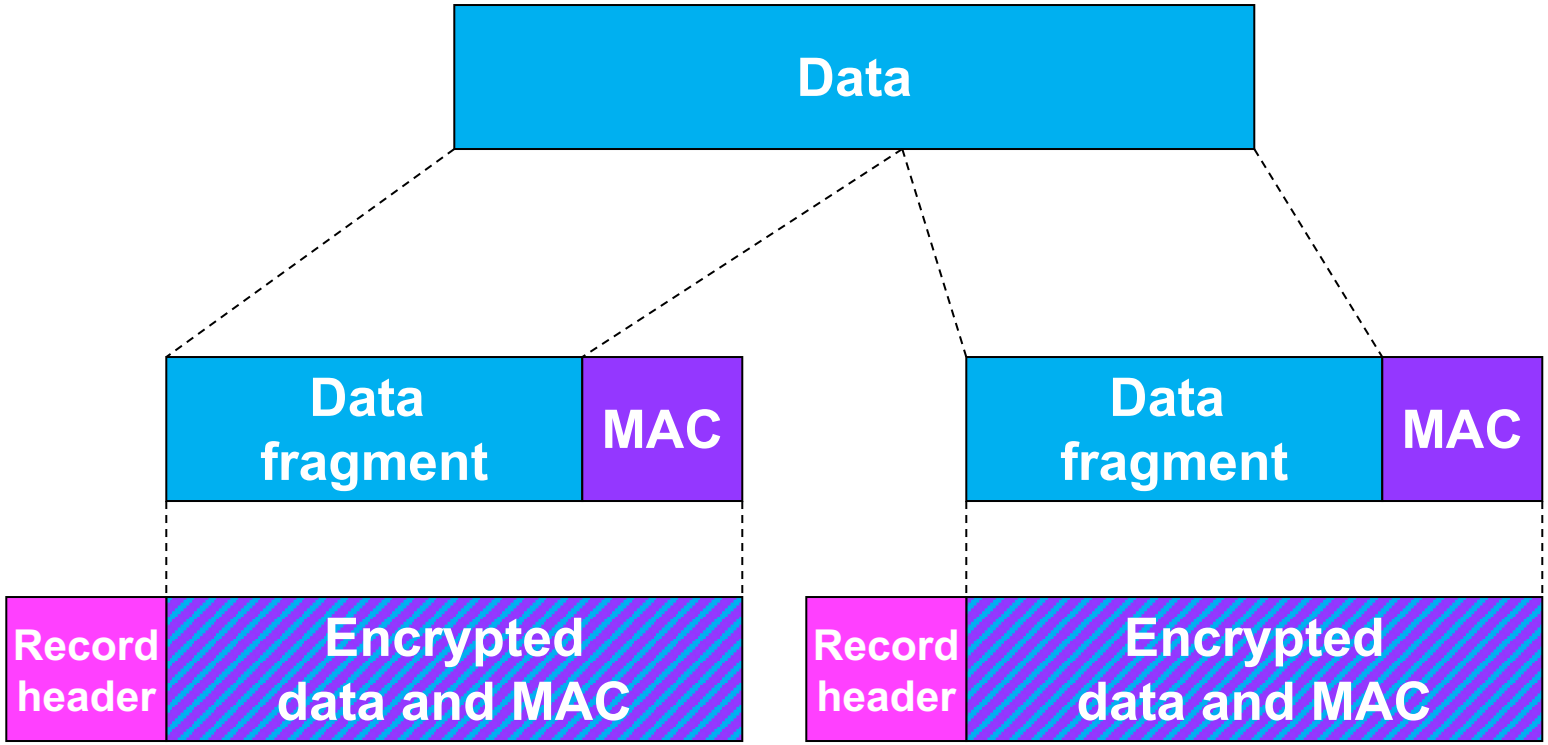
Master secret, new nonces

- input into another random-number generator to get key block

Key block sliced and diced

- client MAC key
- server MAC key
- client encryption key
- server encryption key
- client initialization vector (IV)
- server initialization vector (IV)

SSL record protocol



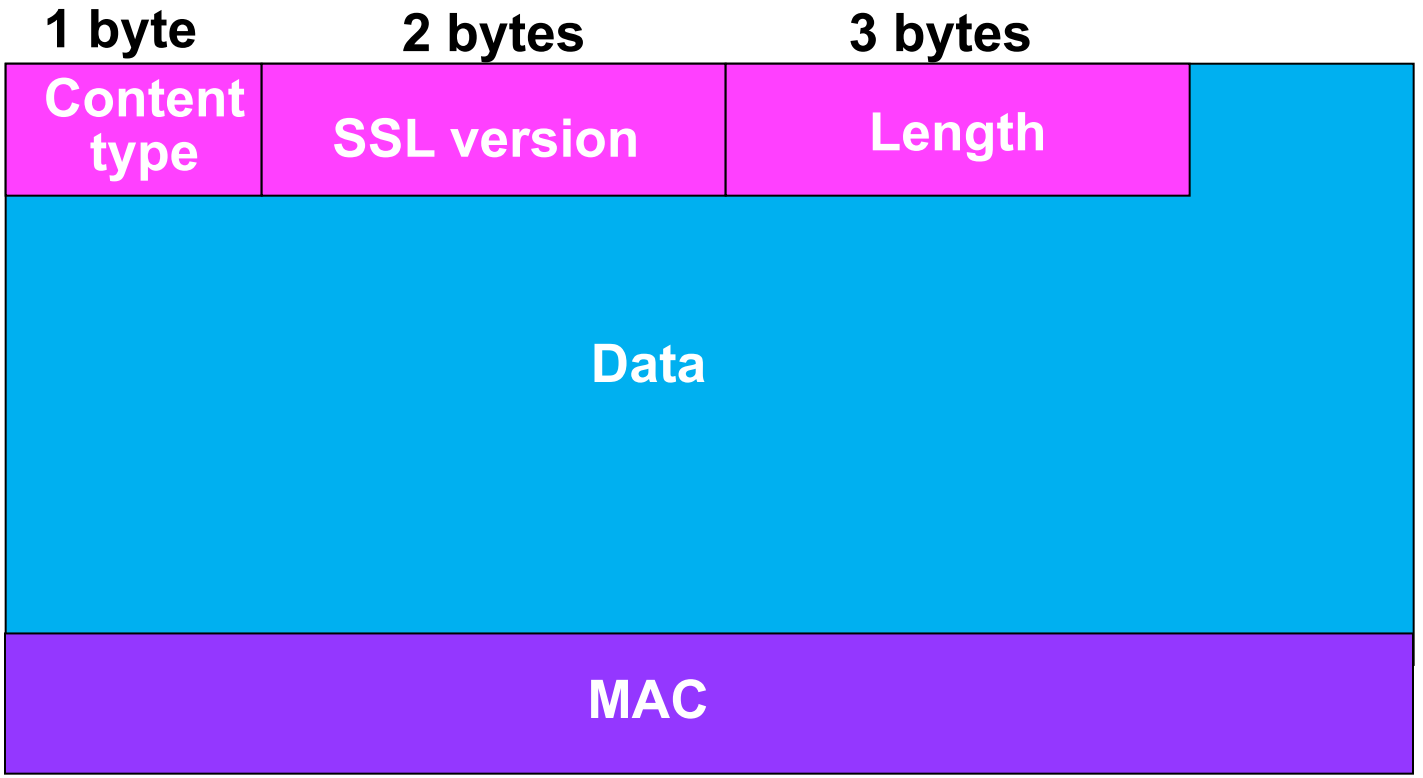
Record header: content type; version; length

MAC: includes sequence number, MAC key M_x

Fragment: each SSL fragment 2^{14} bytes (~16 Kbytes)

These records are pushed into TCP socket

SSL record format



Data and MAC encrypted (symmetric algorithm)

Wireshark

Look at TLS traffic and openssl s_client traffic

Openssl s_client

```
> echo -e "GET / HTTP/1.1\r\nHost: www.wesleyan.edu\r\n\r\n" | openssl s_client -ign_eof -connec
t www.wesleyan.edu:443
CONNECTED(00000003)
depth=3 C = SE, O = AddTrust AB, OU = AddTrust External TTP Network, CN = AddTrust External CA R
oot
verify return:1
depth=2 C = US, ST = New Jersey, L = Jersey City, O = The USERTRUST Network, CN = USERTrust RSA
Certification Authority
verify return:1
depth=1 C = US, ST = MI, L = Ann Arbor, O = Internet2, OU = InCommon, CN = InCommon RSA Server C
A
verify return:1
depth=0 C = US, postalCode = 06457, ST = CT, L = Middletown, street = 237 High Street, O = Wesle
yan University, OU = ITS, CN = www.wesleyan.edu
verify return:1
---
Certificate chain
 0 s:/C=US/postalCode=06457/ST=CT/L=Middletown/street=237 High Street/O=Wesleyan University/OU=I
TS/CN=www.wesleyan.edu
   i:/C=US/ST=MI/L=Ann Arbor/O=Internet2/OU=InCommon/CN=InCommon RSA Server CA
 1 s:/C=SE/O=AddTrust AB/OU=AddTrust External TTP Network/CN=AddTrust External CA Root
   i:/C=SE/O=AddTrust AB/OU=AddTrust External TTP Network/CN=AddTrust External CA Root
 2 s:/C=US/ST=New Jersey/L=Jersey City/O=The USERTRUST Network/CN=USERTrust RSA Certification Au
thority
   i:/C=SE/O=AddTrust AB/OU=AddTrust External TTP Network/CN=AddTrust External CA Root
 3 s:/C=US/ST=MI/L=Ann Arbor/O=Internet2/OU=InCommon/CN=InCommon RSA Server CA
   i:/C=US/ST=New Jersey/L=Jersey City/O=The USERTRUST Network/CN=USERTrust RSA Certification Au
thority
---
Server certificate
-----BEGIN CERTIFICATE-----
```